STANFORD LINEAR ACCELERATOR CENTER

Beam Line

Spring 2002, Vol. 32, No. 1

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

SUMMER 2002 VOL. 32, NO. 1

The *Beam Line* is published periodically by the Stanford Linear Accelerator Center, 2575 Sand Hill Road, Menlo Park, CA 94025, Telephone: (650) 926-2585. EMAIL: beamline@slac.stanford.edu
FAX: (650) 926-4500

Issues of the *Beam Line* are accessible electronically on the World Wide Web at http://www.slac.stanford.edu/pubs/beamline. SLAC is operated by Stanford University under contract with the U.S. Department of Energy. The opinions of the authors do not necessarily reflect the policies of the Stanford Linear Accelerator Center.

Cover: Aerial photograph of the Stanford Linear Accelerator Center and the Stanford Synchrotron Radiation Laboratory, one of several laboratories around the world working on the development of advanced X-ray light sources. See articles on pages 6 and 32.

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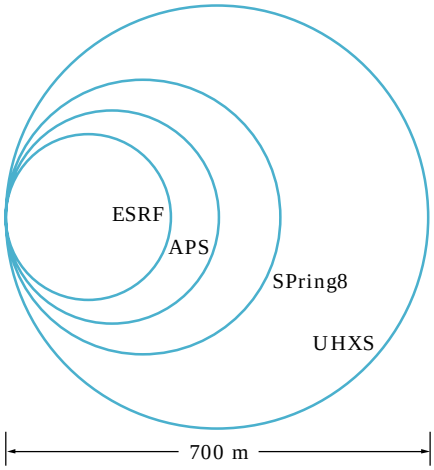
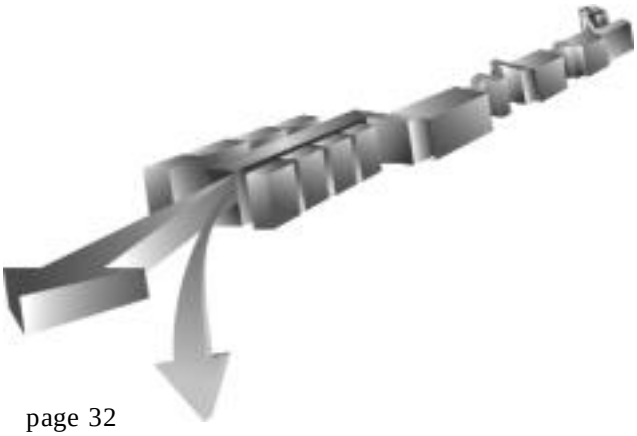
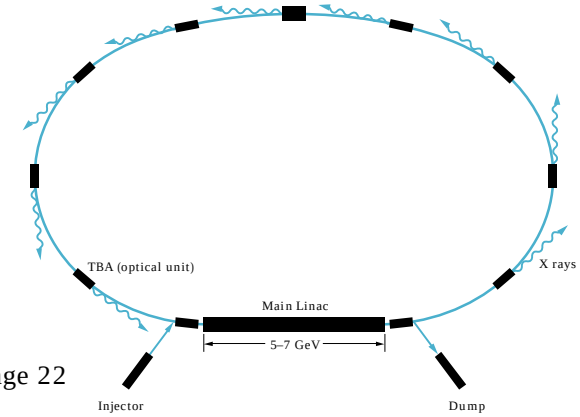




CONTENTS



page 22

Rene Donaldson Retires

After 35 years in the main stream of the American program of particle-physics and accelerator research, SLAC *Beam Line* Editor Rene Donaldson has retired as of February 2002. Rene's career in scientific publication began with a brief stint at the Lawrence Berkeley Laboratory in 1967. She then moved on to Fermi National Accelerator Laboratory near Chicago, returning to Berkeley in 1985 as a key member of the Superconducting Super Collider (SSC) Central Design Group, directed by Maury Tigner of Cornell. Tigner has recently written of his work with Rene during those earlier days:

Rene Donaldson in San Diego's Old Town. (Photo by Tony Donaldson)

While I have many fond memories of the times she was an essential part of the Snowmass organization the most vivid memories are of our time together at the SSC Central Design Group in Berkeley. Being a very visible activity on the national stage, we were under enormous pressure from many different interest groups and had many bosses to please. This made our public relations documents and reports of special importance and Rene handled all this with great aplomb and powerful attention without which success would have been impossible.

Rene joined the staff of the Stanford Linear Accelerator Center in 1989, at a time when the original *Beam Line* was essentially an in-house newsletter aimed at the SLAC staff. She and Michael Riordan have been the central figures in transforming the *Beam Line* into a journal that during the last ten years has become a well-respected vehicle for communicating the purposes, achievements, and plans of our fields of study: fundamental and applied research in the physical sciences and the machines that make much of it possible.

In all of this work—at Fermilab, Berkeley and Stanford—Rene has acted as writer, editor, illustrator, layout designer, publisher, conference coordinator, exhibit designer and whatever else she needed to be to get the job done. There is no one who has combined knowledge, skill, and energy any better. She leaves the fold with the thanks and best wishes of the physics community. We do, and shall, miss her.

The Donaldsons (Rene and husband Tony) have now moved on to new quarters in the Arizona-New Mexico region, where there are strong ties to their lifelong interests in the beauty of the natural world and in the lives and art of early humans. The stage is set for a new chapter in the long adventure. Hail and farewell.

Bill Kirk

FOREWORD

HERMAN WINICK

This special issue of the *Beam Line* is concerned with the development of powerful new sources of X radiation for use in advanced studies in the physical sciences. Readers will be familiar with the fact that synchrotron light sources have had a spectacular evolution. It all started from humble beginnings about 30 years ago with parasitic operations exploiting the radiation from bending magnets of colliding-beam storage rings—the first generation. In the 1980s dedicated facilities—the second generation—were constructed in China, France, Germany, Japan, the UK, and the US. The 1990s saw the construction in these and more countries (Brazil, India, Italy, Korea, Russia, Switzerland, Taiwan and Thailand). Several of these were more advanced rings with brighter electron beams and many straight sections between bending magnets for insertion devices to make even brighter X rays—the third generation.

This evolution has been driven by a veritable revolution brought about by the use of synchrotron radiation in several fields of basic and applied research and a growing user community, now numbering about 20,000 scientists worldwide. The reason is the capability of synchrotron radiation, over a broad spectral range extending from the infrared to ultraviolet and X rays, as an experimental tool. It provides information, often unavailable by any other means, relevant to the structure of matter (that is, the arrangements of atoms in complex materials) and the electronic and magnetic properties of matter. Impact has been strong in fields such as:

- *Structural molecular biology,* including the determination of the structure of viruses and proteins and facilitating drug design.
- *Molecular environmental science,* determining the chemical form of contaminants in soil and water—knowledge that is critical to developing strategies for separation, remediation, and storage of contaminants.
- *Materials science,* understanding the structural and electronic properties of a wide range of materials including catalysts, polymers and semiconductor materials.
- *Medical diagnostics and therapy,* utilizing X-ray beams well-defined in energy and direction to minimize risk and damage to healthy tissue.

STORAGE RINGS

Compared with conventional X-ray tubes, synchrotron radiation offers extremely high brightness, tunable, pulsed, polarized radiation. The most advanced sources provide 13 orders of magnitude higher brightness (a measure of the concentration of the radiation) than the best rotating anode X-ray tubes. Around the world there are now about 50 storage ring sources in operation, about 10 more in construction, and about 15 more in various stages of design awaiting construction approval. The most powerful facilities are the 6–8 GeV hard X-ray (5–50 keV) rings in Europe, Japan, and the US with circumferences of 850 meters to 1450 meters. Some of these facilities conduct 30–60 simultaneous experiments and serve 2000 or more users annually. Yet the user community continues to grow, leading to the construction of new rings and the development of ideas for future sources

with even higher performance. The articles in this issue describe some of the most important directions for these future sources. The first two articles describe storage rings.

INTERMEDIATE ENERGY LIGHT SOURCES

The high performance and relatively moderate cost of these 2.5–4 GeV machines make them the popular choice, with six now in construction and more proposed. This popularity is largely due to the high performance of these machines, resulting from recent technological developments as described in the article by Jeff Corbett and Tom Rabedeau. These include shimming of undulator magnets to near perfection, which increases high harmonic content, and the use of in-vacuum small gap, short period undulators. These developments allow these relatively low energy rings to deliver hard X-ray (5–50 keV) performance that is closer to that of the larger (6–8 GeV) rings than was previously thought possible. When operational these new rings, including a replacement of the venerable SPEAR ring, will go a long way in meeting the continued growth in user demand around the world.

THE ULTIMATE HARD X-RAY STORAGE RING-BASED LIGHT SOURCE

Possible future 6–8 GeV rings with circumference of about 2 km or more could provide X-ray brightness that significantly exceeds that of any present facility, opening new research opportunities. Plans are being made to eventually use the PETRA electron ring at DESY for this purpose and perhaps one of these will eventually be built in the existing large tunnels now being used for B-Factories at SLAC and KEK. The challenges to be faced in realizing such an ultimate machine are described in the article by Pascal Elleaume.

LINAC-BASED MACHINES

In storage rings, quantum emission of radiation from the bending magnets reacts on the electron beam to produce energy spread and growth in beam size and emittance (the product of beam size and divergence). This emittance increases quadratically with electron energy and with the third power of the angle of bend in each bending magnet. To minimize these effects the highest performance rings use short bending magnets with low magnetic field (to reduce radiation emission by bending the beam gently in an arc with a large radius of curvature) separated by many quadrupoles to refocus the beam after its dispersion in the bending magnets. This leads to geometries with many magnetic elements and large circumference as described by Pascal Elleaume.

These fundamental limits on electron beam brightness and pulse length in storage rings can be overcome in linac-based light sources. The ultimate in large bending radius is a linac. With no bending magnets the beam properties are determined by the electron source. Rather than increasing with electron energy, emittance in a linac decreases linearly with electron energy. However, the precision with which bright linac beams must be made, accelerated, and used in undulators poses severe challenges. Several relatively recent developments have dealt with these challenges, opening a path

to the use of high energy linacs to provide higher performance than any storage ring. One of these is the high brightness electron source, particularly the laser-driven radio-frequency gun initially developed at Los Alamos National Laboratory. Another is the improved capability to accelerate, compress, and transport such bright electron beams, as demonstrated in the SLC beams at SLAC. A third is the precision undulator, as developed in many light source facilities. In combination these developments have opened two main directions for future linac-based light sources as described in the article on the energy recovery linac by Sol Gruner and Donald Bilderback and the article on the X-ray free-electron laser by Claudio Pellegrini and Joachim Stöhr.

Energy Recovery Linacs as Synchrotron Light Sources

To bring operating costs to a reasonable level the energy is recovered from the electrons after they are used—a novel idea first proposed 37 years ago and now attracting much interest. The principle has been tested at low energy at the Jefferson Laboratory where a recirculating linac is used to drive an infrared free-electron laser. Sol Gruner and Don Bilderback describe the challenges and opportunities provided by a higher energy ERL, delivering X rays with higher brightness and shorter pulses than any storage ring.

X-ray Free-Electron Lasers

The dream of a fully coherent X-ray laser seems now to be in reach. With bright 15 GeV electron beams and 100 meter long undulators it is possible to produce sub-picosecond X-ray pulses with nine orders of magnitude higher peak brightness than the best present third generation storage rings. The Linac Coherent Light Source project at SLAC is on a path to operate such a machine in 2008. A similar project is proposed at DESY, to couple an X-ray laser to the proposed TESLA linear collider project. Claudio Pellegrini and Joachim Stöhr describe these projects, the challenges to be met, the extraordinary properties of the radiation, and the new science that is envisioned.

Much of this new science exploits the sub-picosecond pulses of the X-ray FEL and ERL. Interest in this new time domain for X-ray studies has stimulated other approaches to achieving short pulses, although with lower intensity than ERLs or FELS. A technique for extracting radiation from a 100 femtosecond slice of a stored electron beam is being pursued at the Advanced Light Source at Lawrence Berkeley National Laboratory and elsewhere. The Sub-Picosecond Photon Source (SPPS) project, now in construction at SLAC, will produce a similar short pulse of X rays by compressing the electron beam in the SLAC linac and using spontaneous radiation from an undulator at the end of the linac. These sources will enable researchers to begin to get experience with X-ray pulses at the 100 femtosecond level well before an X-ray ERL or FEL is available.

Intermediate-Energy Light

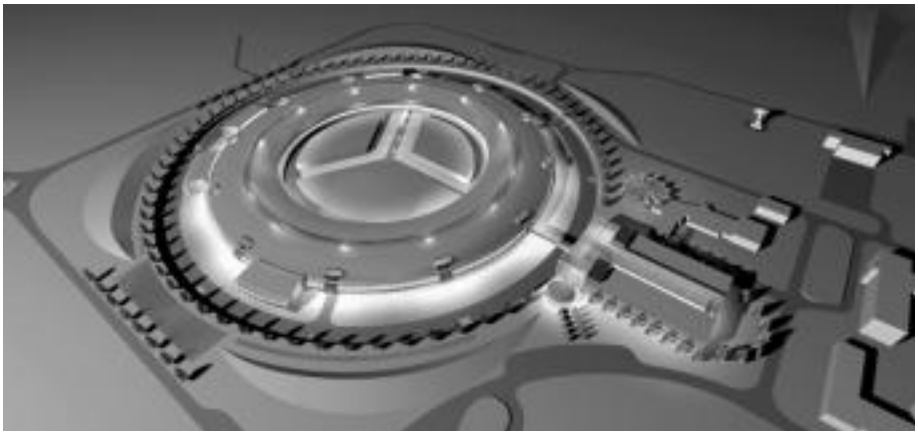
by JEFF CORBETT & THOMAS RABEDEAU

The high performance and relatively moderate cost of these 2.5–4 GeV machines make them the popular choice, with six now in construction and more proposed.

INCREASINGLY, ATOMIC SCALE information underlies scientific and technological progress in disciplines ranging from pharmaceutical development to materials synthesis to environmental remediation. While a variety of research tools are used to provide atomic scale information, synchrotron radiation has proved invaluable in this quest. The rapid growth of soft- and hard X-ray synchrotron light sources stands as stark testimony to the importance and utility of synchrotron radiation. Starting from just a handful of synchrotron light sources in the early 1970s, this burgeoning field now includes over 70 proposed, in-construction, or operating facilities in 23 countries on five continents. Along the way, synchrotron light facilities have evolved from small laboratories extracting light parasitically from storage rings designed for high-energy physics research to large, dedicated sources using the latest technology to produce extraordinarily bright photon beams.

The basic layout of a multi-GeV storage ring light source employs periodic bending magnets to guide a charged particle beam around the storage ring. As the charged beam is accelerated in an arc, it produces a sweeping fan of synchrotron radiation that extends from the infrared part of the electromagnetic spectrum (<1 eV) to hard X rays (>20 keV). Quadrupole magnets keep the electrons tightly focused, and a radio-frequency acceleration system replenishes beam energy lost to radiation emission. To optimize the output radiation, a premium is placed on high current electron beams with small cross section and extreme position stability. Magnetic insertion devices are used to further enhance

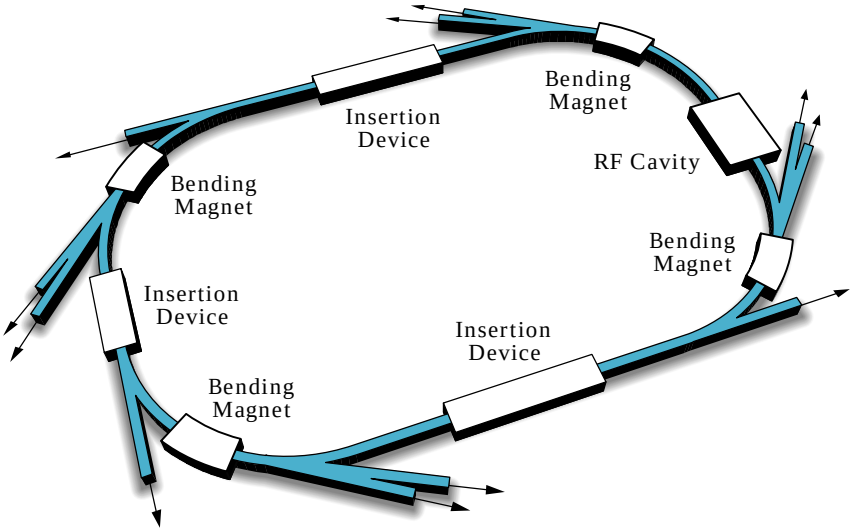
Sources



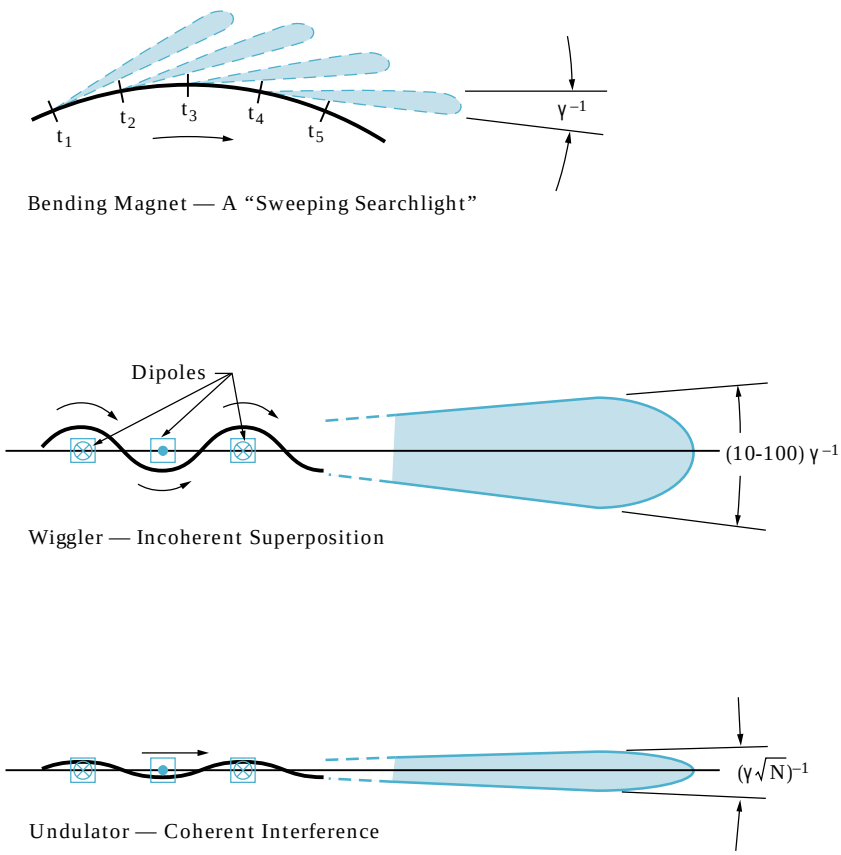
Artist's rendition of the DIAMOND light source under construction in the UK.

radiation output by a factor of 10 or more over bend magnet sources. The storage ring vacuum chamber includes exit ports to allow portions of the radiation fan to propagate down photon beam transport lines to optical systems and experimental stations. A typical storage ring features 10 or more such radiation ports. The photon beam from each port can be subdivided into several separate beams, each of which can serve an independent experimental station. All told, 50 or more scientific teams can simultaneously and independently conduct research using intense photon beams from a single intermediate-energy synchrotron radiation facility.

As suggested above, today's synchrotron light sources are the product of several generations of light source technology. The first-generation of hard X-ray light sources utilized storage rings



Basic components of a storage ring light source. Not shown is the injection system.



Bend magnet sources produce a sweeping beacon of light. Insertion devices consist of an array of magnet poles each of which acts as an individual bend magnet source. The characteristic photon emission angle γ^{-1} is related to the electron beam energy by $\gamma = 1957E$ (GeV). [$\gamma = E/mc^2$]

designed for high-energy physics research. Despite the difficulties of working parasitically to research programs with different objectives and operational requirements, the unique properties of synchrotron light (energy tunability, brightness, time structure and polarization characteristics) rendered these early research programs extremely successful. These early successes, coupled with the scarcity of available beam time, spawned demand for facilities dedicated to the production of synchrotron light. The resulting second-generation machines were optimized to produce VUV and X-ray light from bend magnets and featured many beam extraction ports for cost effective operation.

Starting in the late 1980s, second-generation light sources gave way to third-generation light sources featuring the workhorse of modern synchrotron light production—the insertion device (ID). As shown in the figure at left, the first IDs consisted of a sequence of short back-to-back dipole magnets arranged to enhance radiation output from the electron beam. In this configuration, the radiation intensity is amplified by the strength and number of dipoles N contained in the ID. These so-called *wiggler* magnets soon evolved into more sophisticated *undulator* devices to further enhance photon beam brightness. Radiation from each of the undulator poles constructively interferes with radiation from each of the other poles to produce a highly forward-directed and quasi-monochromatic photon beam. Viewed along the undulator axis, the output intensity can scale as N^2 rather than as N in a wiggler.* The energy of the photon beam depends on the energy of the electron beam and the strength and spacing of the poles. The photon beam energy from an undulator can be tuned by adjusting the magnetic field strength.

* *In the extreme case, undulators can cause the electron beam to "lase" into a coherent fourth-generation photon beam (see Pellegrini and Stöhr, this issue), but the more common application is to utilize the less-coherent spontaneous radiation.*

The pioneering third-generation machines fell into two distinct groups: smaller low energy rings (< 2 GeV) optimized for ultraviolet and soft X-ray production from undulators, and larger high-energy rings (6–8 GeV) optimized for hard X-ray science. While recent innovations in superconducting magnet technology have been used to boost radiation output of the low-energy machines into the 10 keV range, undulators on third generation, high-energy machines remain the pre-eminent sources for high brightness, hard X-ray science.

More recently, a new class of third-generation light source is rapidly gaining popularity. This new class of machines, the intermediate energy light source (ILS), occupies the ~3 GeV middle ground between low-energy and high-energy storage rings.

The concept of an intermediate energy light source is hardly new as a number of first- and second-generation machines have operated in this energy range since the 1970s. What distinguishes third-generation ILS machines is the combination of high operating current, low beam emittance, and advanced insertion device technology. At present eight such machines are proposed or under construction in Armenia, Australia, Canada, China, France, Spain, the United Kingdom, and the US. Although the smaller ILS machines cannot provide the ultimate hard X-ray brightness nor the total number of beam lines of the larger 6–8 GeV machines, these ILS class sources fulfill regional needs for highly capable multiport X-ray sources that can be constructed and operated at moderate cost. The ILS

A Prototypical Intermediate Energy Light Source

TO ILLUSTRATE THE PROPERTIES of a third-generation light source in the intermediate energy range, we simulated the performance of a relatively conventional 3.3 GeV storage ring with 307 meter circumference and 500 mA stored current. Similar to many storage rings now in operation, this ILS ring utilizes vertical focusing in the dipole magnets and low dispersion in the straight sections to reduce horizontal emittance (ε_x = 9.9 nm-rad). Presented in the illustrations on pages 12 and 13 are the calculated emission spectra from bend magnet, wiggler (W70) and small gap undulator (U20) sources on this ring. The characteristics of these sources are listed in the table below. While the wiggler is a conventional out-of-vacuum geometry, the undulator model assumes the addition of extra vertical focusing magnets to reduce the vertical source size (*for example*, β_y = 2 meters) permitting use of small pole gap, in-vacuum magnet technology.

To place the ILS performance into context, the ILS sources are benchmarked by sources on a representative third generation, high-energy light source, the HLS. The HLS features twice the energy of the ILS, half the emittance of the ILS, similar magnetic lattice functions as the ILS, and 200 mA stored current. A description of the HLS source parameters is listed in the table. Examination of this table reveals that the HLS is a high performance composite of the current operating characteristics of the three existing high-energy, third generation light sources. While the overwhelming majority of insertion devices installed on these high-energy rings are undulators, the performance comparison includes both wiggler (W70) and typical hybrid undulator (U32) sources for completeness. Note, however, that the technical challenges associated with the power radiated by high flux wigglers on high energy machines are significant. These challenges, coupled with the brightness advantages of undulators, have rendered undulators the insertion device of choice on high energy rings except in specialized applications such as those requiring very high photon energies.

ILS and HLS Source Characteristics

Parameter	*ILS/HLS Bend*	*ILS/HLS W70*	*ILS U20/HLS U32*
energy (GeV)	3.3/6.6	3.3/6.6	3.3/6.6
current (mA)	500/200	500/200	500/200
emittance x(nm-rad)	9.9/5.0	9.9/5.0	9.9/5.0
coupling (%)	1.0/1.0	1.0/1.0	1.0/1.0
energy spread (%)	0.1/0.1	0.1/0.1	0.1/0.1
sigma x(mm)	0.127/0.109	0.302/0.216	0.302/0.216
sigma x′ (mrad)	0.163/0.147	0.033/0.024	0.033/0.024
sigma y (mm)	0.041/0.029	0.022/0.016	0.014/0.016
sigma y′ (mrad)	0.008/0.0057	0.0045/0.0032	0.007/0.0032
magnet gap (mm)	na	16.0/16.0	5.0/10.0
B_{peak} (T)	1.12/0.7	1.05/1.05	0.95/0.78
period (mm)	na	70.0/70.0	20.0/32.0
number periods	na	50/50	100/109

class machine can provide competitive performance for all but the most demanding high brightness, hard X-ray applications. In addition, the specific design goals of ILS machines can be tailored to regional interests and machine technology can be matched to local industrial strengths.

One of the fathers of modern insertion device technologies, Klaus Halbach (shown above with grandson) of Lawrence Berkeley National Laboratory worked on early wiggler magnets and envisioned the permanent magnet undulator configuration that has become an industry standard for insertion device design.

SOME OF THE MOST significant technical advances stimulating the growth of ILS class storage rings have been in the field of insertion device design. The first important breakthrough originated at the high-energy light source laboratories where scientists using small pieces of magnetic foil and/or tuning stubs developed techniques to adjust the magnetic field quality of undulators to achieve near-ideal field quality. Properly tuned the undulators can achieve bright X-ray beams at higher photon beam energies than thought feasible a decade ago. Technologies were then developed to place the undulator magnets directly into the storage ring vacuum chamber. Coupled with focusing techniques to squeeze the dimensions of the charged particle beam, this permits use of undulators with very small magnet gaps and shorter magnetic periods for photon production at higher X-ray energies. Together these improvements permit undulators in an ILS machine to operate with high brightness in the 10–15 keV photon energy range.

The trend toward construction of mid-size storage rings is also made possible by recent developments in accelerator and beam line technology. In particular, modern light sources benefit from magnet and

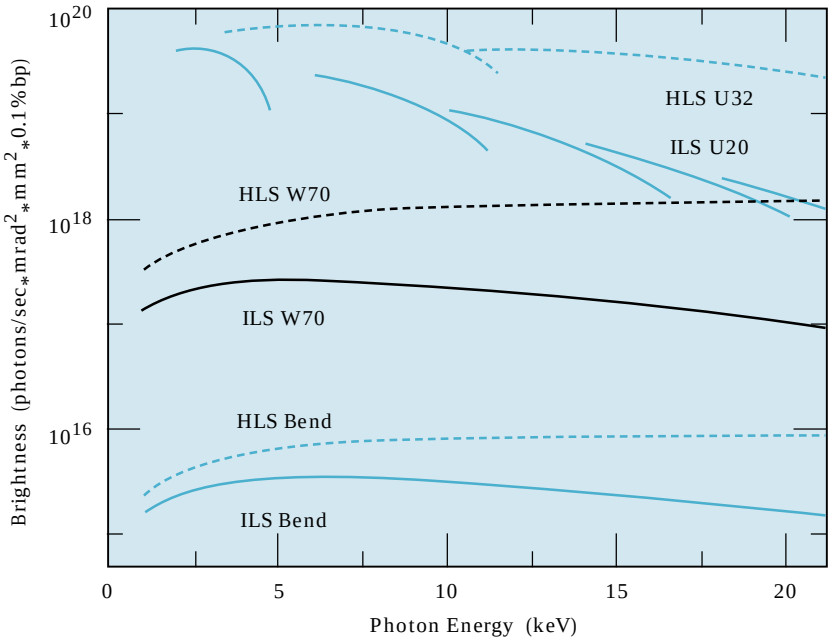
vacuum chamber fabrication experience from their predecessors and from advances in feedback control and radio-frequency acceleration developed at third-generation light source facilities working with the high-energy physics community. Photon beam lines have seen advances in high heat-load materials, high precision mirrors, and the development of liquid nitrogen cooled monochromators. Computer technology has also allowed accelerator scientists to predict light source behavior under increasingly demanding conditions and to understand complex electron beam dynamics. Photon beam line designers and synchrotron radiation scientists also use sophisticated computer programs to analyze thermal stress problems and photon beam optics.

The rapid growth of synchrotron radiation light sources stands as a stark testimony to the importance and utility of synchrotron radiation.

AN IMPORTANT aspect of intermediate energy light source performance is the match between the radiation source characteristics and requirements of the experimental sample irradiated by the beam. Perhaps the source characteristic of greatest importance is the source phase space, with a small source phase space implying a highly collimated laser-like beam. More technically, source phase space is the product of the transverse cross section of the radiation at the source and the angular spread of photon emission, where the angular spread includes both charged particle beam parameters and photon emission effects.

At the sample, one is interested in the photon beam acceptance or the product of the cross-sectional area of the sample and the angular spread of the photon beam that can be usefully coupled into the sample. A sample with a small acceptance phase space demands a high brightness beam at the source and brightness-preserving optics to conduct the X-ray beam to the sample. Combining the concepts of source phase space and sample acceptance phase space we arrive at the notion of mapping the radiation source phase-space into the sample acceptance phase space in order to determine the capabilities of a given light source for a particular measurement. The widely quoted figures-of-merit flux and brightness represent two extremes of source performance. They are typically employed when the sample acceptance is significantly larger or smaller than the source phase space, respectively. Unfortunately, these merit-functions often fail to represent accurately the requirements of many experiments that do not fall neatly into the category of flux- or brightness-limited measurements. Specifically, large classes of experiments require a photon beam with modest angular collimation and spot size. For such experiments, the best figure-of-merit explicitly maps the source phase space into the sample acceptance phase space. With appropriate optics to transform from source to sample, this approach provides a means to relate the demands of a given experiment to the light source properties.

In macromolecular crystallography, for instance, a typical sample with ~0.1 mm transverse dimensions and ~2 mrad angular acceptance has approximately 0.2 mm-mrad sample acceptance phase space in each transverse direction. Since the sample acceptance significantly exceeds the source phase space of typical third generation hard X-ray undulators, the flux from the entire central cone of the undulator radiation can be imaged onto the sample. In contrast to undulators, a typical wiggler on a low emittance ring overfills the horizontal phase- space acceptance while under filling the vertical acceptance. The accepted wiggler flux on the sample is often comparable with the accepted undulator flux despite several orders of magnitude difference in source brightness. This surprising result underscores the importance of selecting



Calculated X-ray beam brightness from bend magnets, wigglers (W70), and undulators (U20 and U32) on ILS and HLS class storage rings. The HLS U32 spectrum includes only the fundamental and third harmonic tuning curves, while the ILS U20 spectra includes the tuning curves for the fundamental and odd harmonics through ninth order.

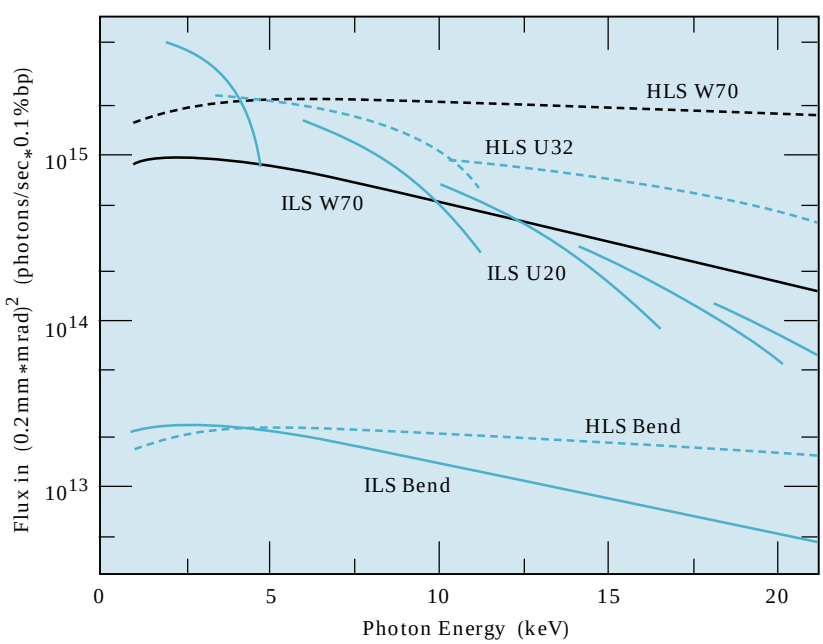
the appropriate figure-of-merit for the science in question.

Relating the photon beam requirements to the design of a storage ring, we find specifications for flux, brightness, and particularly phase space matching from a high current ILS class machine readily meet or exceed the needs of the synchrotron radiation user community for a wide range of applications. To illustrate this point, consider the comparison between a prototypical 3.3 GeV, 500 mA intermediate energy light source and a 6.6 GeV, 200 mA high energy light source (HLS) (see sidebar on page 9).

The X-ray emission spectra from representative bend magnets and insertion devices on these two rings illustrate the relative performance of these classes of synchrotron radiation sources. The X-ray brightness for bend magnet, wiggler (W70), and undulator (U20 and U32) sources demonstrate that for brightness-limited measurements, undulators on either ring outperform either wiggler or bend magnet sources (see figure above). While the ILS U20 in-vacuum undulator provides high brightness below approximately 15 keV, the HLS U32 provides higher brightness at these energies and sustains high brightness to much higher energies. Nonetheless, many high brightness applications do not require high energies and as such are well served by a small gap undulator on an ILS class machine.

Next consider the relative source performance for the (0.2 mm-mrad)^2 phase-space acceptance of a typical macromolecular sample as described. Despite the differences in storage ring characteristics, the figure below demonstrates that the undulator performance is roughly equivalent in the 7–15 keV energy range owing to the relatively small gap of the U20 undulator. Given the small sample acceptance phase space, what is more surprising is the efficacy of the W70 wiggler. These examples demonstrate that experiments which do not fully exploit the extraordinary brightness of an undulator are well served by a wiggler in a high current, intermediate energy storage ring.

THE EXPANDING worldwide investment in synchrotron light facilities is testimony to the social and scientific impact of synchrotron radiation research in the physical, biological, and environmental disciplines. To meet growing user demand, many laboratories are turning to high current, third generation, intermediate energy storage rings. These ILS machines are relatively low risk construction projects that rely upon proven technology developed throughout the evolution of many storage rings. Through the construction of mid-size, moderate cost, high performance X-ray machines, regional governments can cultivate local synchrotron radiation communities and promote private, industrial, and government-sponsored research and development efforts while stimulating local economic activity.



Calculated X-ray flux accepted by the (0.2 mm-mrad)^2 phase-space of a typical macromolecular sample.

The Ultimate Hard X-Ray Storage-Ring-Based Light Source

by PASCAL ELLEAUME

6–8 GeV rings with circumference of about 2 km or more could provide X-ray brightness that significantly exceeds that of any present facility, opening new research opportunities.

OVER THE PAST thirty years, the storage-ring-based synchrotron light source has proven to be an outstanding success, both as a scientific tool and a major accomplishment of accelerator technology. In the 1960s storage rings were designed as electron-positron colliders for particle physics research. The scientific potential of synchrotron radiation was very quickly recognized, and in the 1970s parasitic programs started in many laboratories. With the growing demand for such radiation coming from many fields of science, new higher performance storage rings were designed and optimized exclusively for the production of such radiation. Today, more than 60 dedicated synchrotron radiation facilities are in operation throughout the world.*

Their increasing performance has resulted in a number of totally new applications in scientific disciplines such as physics, chemistry, biology, and medicine and also in industrial areas such as microelectronics, pharmaceutics, metallurgy, and plastic materials. This success is due largely to the properties of the radiation: the flexible polarization and the high intensity and concentration in a narrow forward cone similar to, or even narrower than, laser beams. In the VUV and X-ray range of the electromagnetic spectrum these sources can produce photon fluxes on the small samples

* *A database of web addresses of synchrotron radiation facilities is kept at the following web address: http://srs.dl.ac.uk/SRWORLD/index.html or http://www-ssrl.slac.stanford.edu/sr_sources.html.*

under study which are 10^6 to 10^{10} higher than those available from low cost tubes, such as those extensively used for medical radiography. Also important is the fact that this high radiation flux is available over a broad spectral range, enabling an experimenter to select the precise wavelength of interest or to scan over a range of wavelengths. This tunability is indeed critical to many experiments. Other properties of synchrotron radiation include the ability to conduct many simultaneous experiments, the high stability of the X-ray beams, and the extreme reliability of the sources.

With the immense growth in the user community and the number of applications that have been made possible by the increasing performance of synchrotron light sources, one can ask whether even higher performance is possible in future storage rings. This article presents a description, and the associated engineering and physics challenges, of what could be an ultimate storage ring source optimized to produce hard X-ray radiation. It is based on a study made at the European Synchrotron Radiation Facility (ESRF).*

TO ADDRESS THE DESIGN issue of such a source, one must first review how the radiation is produced. In the past the most important sources of radiation were the bending magnets of the storage ring. The choice of the electron energy was related to the critical energy of the radiation,

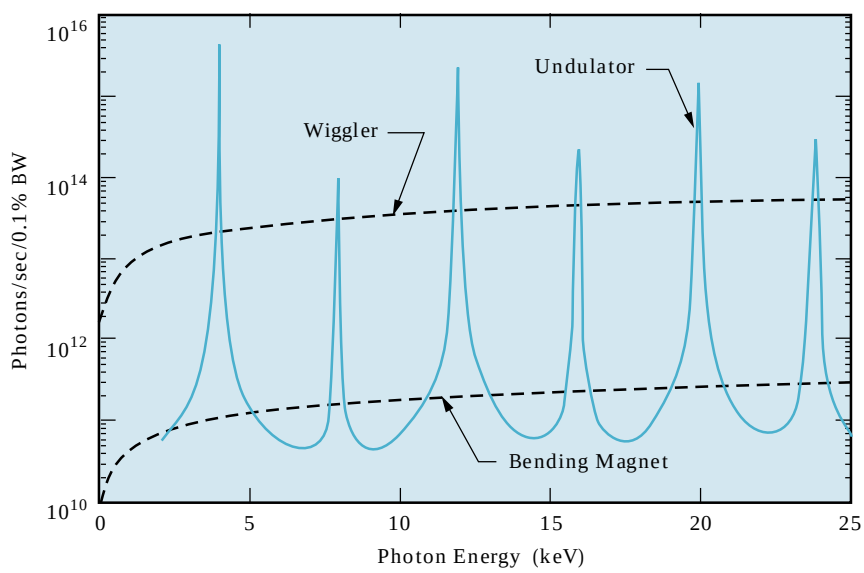
* *A. Ropert, J.M. Filhol, P. Elleaume, L. Farvacque, L. Hardy, J. Jacob, U. Weinrich, "Towards the Ultimate Storage Ring Based Light Source," EPAC 2000. Available at http://accelconf.web.cern.ch/accelconf/e00/PAPERS/TUZF101.pdf*

which is related to the electron energy E and the magnetic field B of the magnet according to

$$\varepsilon_c[\text{keV}] = 0.665\ B[T]E^2[\text{GeV}].$$

The intense and therefore useful flux extends from the infrared up to about four times this critical energy and then falls off rapidly. Assuming that a 1.5 T magnetic field is used (close to economical optimum for a conventional magnet), an electron energy of 1 GeV (7 GeV) is necessary to reach a critical energy of 1 keV (50 keV).

Until the mid 1980s this was the basis of the selection of the electron energy in relation to the energy spectrum to be covered. In the early 1980s, it was recognized that one could accumulate the radiation from a number of such bending magnets with alternating field polarity which result in an approximately sinusoidal trajectory of the electron beam. The flux from those devices, called wigglers, which could be located in the straight sections between the bending magnets, is proportional to the number of bends. As the number of periods of oscillation is increased, there is an increasing interference in the radiation produced by an electron in each period with the radiation emitted at the other periods. This interference results in the enhancement of the



Comparison of spectra produced by an undulator, a wiggler, and a bending magnet type of source installed on the UHXS. The collection aperture is located at a distance of 50 m from the source. The flux is collected over an aperture of 0.5×0.5 mm^2. The bending magnet and wiggler type sources present continuous spectra while the undulator presents a series of intense peaks. The peaks are harmonically related starting from the fundamental around 4 keV. The photon energy of each peak can be tuned by changing the undulator field. The collection of high flux through such a narrow aperture reduces the power to a few hundred watts.

spectral flux at some particular photon energies ε_n. To distinguish them from wigglers, these devices are called undulators.

Contrary to bending magnet radiation, which is broadband, undulator radiation is made of a series of narrow peaks of emission (see figure on facing page). The energy ε_n of the peaks is a multiple of a fundamental energy ε_1 ($\varepsilon_n = n\varepsilon_1$) which depends on the electron energy E and the undulator period λ_0 according to

$$\varepsilon_1[\text{keV}] = \frac{0.95E^2[\text{GeV}]}{\lambda_0[\text{cm}](1 + K^2/2)}$$

where K is a dimensionless factor proportional to the product of the peak undulator field and the period. The precise location of these interference peaks can be tuned by varying K which can be accomplished by varying the magnetic field. As a result of this interference, the peak spectral flux grows more rapidly than linearly with the number of periods, and it is concentrated in very narrow emission cones.

However, one must consider that electron beams in storage rings are made of a collection of electrons with slightly different directions of propagation and a range of energies. The angular spread increases the cone angle of emission. Similarly, the electron energy spread increases the spectral width of the peak. Both effects reduce the peak spectral flux that can be collected through some narrow aperture and made to strike a small sample. In other words, to fully benefit from the properties of an undulator, a highly collimated electron beam with a small energy spread is required.

The quantity used to characterize the degree of collimation of the electron beam is the emittance. It is approximately expressed as the product of the angular divergence and the transverse size at the source. The lower the emittance, the brighter the electron beam and the brighter the radiation that it can produce.

The recent third generation sources, which started operation in the 1990s, are designed to accommodate many undulators and to optimize their performance using low emittance electron beams. As an example, the ESRF operates with an electron emittance in the horizontal (vertical) plane of 4 nm (0.03 nm) corresponding to a horizontal (vertical) rms beam size and divergence of 400 μm and 10 μrad (10 μm and 3 μrad). For comparison, this is 10 (1000) times smaller than the emittance of the light produced by a helium neon laser. The classical figure of merit used to characterize the undulator emission is the brilliance (also called brightness). It is equal to the total spectral flux produced by the undulator normalized to the product of the horizontal and vertical emittance of the light. Undulator emission is typically 10^3–10^4 more brilliant than the radiation from bending magnets and, indeed, it has opened new fields of scientific experimentation.

SYNCHROTRON radiation light sources are expensive devices, costing typically several hundred million dollars. The cost is essentially dictated by the size of the infrastructure required (ring, injector, beam lines, technical

Optimizing Dynamic Aperture

IN STORAGE RINGS, electrons make transverse horizontal and vertical oscillations around a reference orbit. However, electrons executing a large oscillation may not follow stable trajectories and are ultimately lost on a wall of the vacuum chamber. To avoid such losses, the number of oscillations per circumference (called the tune number) must be carefully selected. In addition, the spread of tune from one electron to the other must be controlled within narrow limits. The quadrupoles used between the bending magnets have a focusing strength inversely proportional to the electron energy. As a result, they induce a so-called chromatic aberration with a tune varying from one electron to the next, depending on its energy. Note the similarity with chromatic aberration induced by the focal length varying with wavelength in visible optics. For the beam to be stable, the chromatic aberration must be compensated.

Special types of magnets called sextupoles provide this compensation. Roughly speaking, sextupoles can be regarded as focusing elements with a focal strength varying linearly with the transverse position of the electron. However, sextupoles also produce additional aberrations which make large transverse oscillations unstable. In other words, electrons travelling far away from the sextupole's axis will not execute stable oscillations. By analogy with the physical aperture set by the transverse dimension of the vacuum chamber, the stability limit imposed by the sextupoles is called dynamic aperture. The design and location of the sextupoles must be carefully selected in order to correct the chromatic aberration while keeping a large dynamic aperture. This optimization is particularly delicate for such a small emittance lattice.

The small emittance and high current results in a high density of the electron beam. As a result of the high density, a large number of collisions take place every second between electrons within a single bunch. The colliding electrons may lose or gain energy to the point that their associated trajectory in the ring becomes unstable. The stored electron beam lifetime is therefore reduced by this intra-beam scattering (also called Touschek scattering). Contrary to modern hard X-ray sources operating with a lifetime in the 50–100 hours, the UHXS will have a shorter lifetime around 5–10 hours. As mentioned earlier, the remedy might simply be to re-inject a small current every 5 to 10 minutes using a continuously running injector system. It is likely that such a source will require a number of slow and fast active stabilization feedback systems to prevent the onset of transverse and longitudinal instabilities and to maintain a stability of the centre of gravity of the beam to a fraction of the beam size. Such feedback systems have already been implemented on a number of rings and the associated technology is considered to be mature. Other challenges in the design of such a source include tight mechanical tolerances in the machining of magnets, precise alignment, sensitivity to ground vibrations. Even though such tolerances have not yet been worked out in detail for the UHXS, the very successful experience with third generation sources makes us optimistic. The full exploitation of such a facility with more than 40 undulator beam lines would normally require the construction of a large experimental hall around the accelerator tunnel. Alternatively, one may consider recycling an existing large sized tunnel such as those in use for PEP or PETRA to house this new facility.

facilities). The size of the ring is the direct consequence of the electron energy and therefore of the range of photon energy over which the source is optimized. A 6–8 GeV, 1 km perimeter hard X-ray source can be 10 times more expensive than a 1 GeV, 100 meter perimeter source, but the spectrum and therefore the scientific applications are different. One should also keep in mind that the simultaneous and transparent operation of a number of experimental stations or beam lines (50–100 on a 6–8 GeV ring) reduces the cost per experiment.

The present trend in the development of new synchrotron radiation facilities is towards 2.5–3.5 GeV, 200–400 meter perimeter type sources. There are a number of facilities under construction and a number of others are being envisaged. They are described in the previous article. The medium energy makes them suitable to cover a large spectral range from the VUV to the hard X ray. These facilities will perform less well above about 10 keV than the present 6–8 GeV hard X-ray sources (APS, ESRF, SPring8), but they are less expensive and can therefore be financed at a national or regional level. Several of them intend to compensate for the expected short lifetime of the stored beam by using continuous injection and to extend the photon energy range of the undulator radiation by placing the ID magnet arrays in the vacuum chamber to allow a magnetic gap as small as 3–5 mm instead of the 10–15 mm achieved in most present facilities in operation. The reduction of the magnetic gap in the undulators allows a reduction of the

period, thereby shifting the spectrum to higher energies. Optimizing an undulator with magnets in-vacuum and a magnetic gap of 5 mm instead of 10 mm allows a reduction (and therefore a saving) of the electron energy by 16 percent. However, both the gap and the electron energy reduction result in a shorter lifetime and an increased sensitivity to beam instabilities.

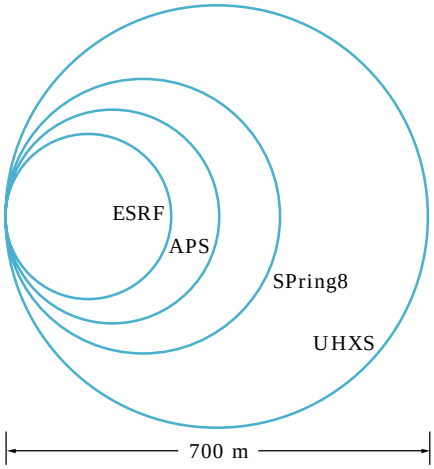
The ultimate hard X-ray source (UHXS) is a large capacity source (40–50 beam lines) covering the 0.5–500 keV range with emphasis on very high brilliance in the 10–20 keV range, which is increasingly in demand for applications in structural molecular biology and many other applications. This is obtained by simultaneously running a high electron current of 500 mA and achieving a very small emittance of the electron beam, around 0.2 nm in the horizontal plane and smaller than 0.01 nm in the vertical plane. Such circulating current and emittances are respectively 2.5–5 times larger and 40–80 times smaller than what is achieved in present synchrotron radiation facilities of similar energy. The brightness of the radiation varies linearly with the stored current and inversely with the emittance, or in some cases with the square of the emittance.

The operation of a 500 mA current requires a power of 7 MW of radio-frequency to be sent to the beam through a series of radio-frequency cavities. These cavities must produce a total accelerating voltage of 14 MV

Flux and Brilliance

Comparison of flux and brilliance between the ESRF and some proposed sources including the UHXS storage ring source, the Cornell Energy Recovery Linac, and X-ray FEL sources based on Self-Amplified Spontaneous Emission (SASE). Part of the data in this table has been taken from the report "ERL_CHESS_memo_01_002.pdf" available from http//erl.chess.cornell.edu/Papers/Papers.htm

Source Type	*ESRF Storage Ring*	*UHXS Storage Ring*	*Cornell ERL*	*LCLS SASE FEL*	*TESLA SASE FEL*
Electron Energy [GeV]	6	7	5.3	15	25
Average Current [mA]	200	500	100	7.20E-5	0.063
Hor. Emittance [nm]	4	0.2	0.15	0.05	0.02
Vert. Emittance [nm]	0.01	0.005	0.15	0.05	0.02
FWHM Bunch Length [ps]	35	13	0.3	0.23	0.09
Undulator Length [m]	5	7	25	100	200
Fundamental [keV]	8	12	8	10	12.4
Average Flux [Ph/s/.1%]	1.3E+15	2.0E+16	1.5E+16	2.4E+14	4.0E+17
Average Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.1E+20	3.5E+22	1.3E+22	4.2E+22	8.0E+25
Peak Brilliance [Ph/s/.1%/mm^2/mrad^2]	3.3E+22	1.0E+25	3.0E+25	1.2E+33	7.0E+33



Size of the UHXS compared to the presently operated hard X-ray synchrotron source ESRF (Europe), APS (US), SPring8 (Japan). The larger size of the UHXS is imposed by the requirement of an ultra-small emittance.

over the circumference. This voltage and power is necessary to compensate for the energy and power loss by the electrons due to synchrotron radiation emission in the bending magnets and undulators. At this high current, some instabilities can occur through the interaction of the beam with the higher order resonant mode of the radio-frequency cavities (HOM). Recent development in the engineering of radiofrequency cavities makes stable operation possible at such a high current by either using super-conducting technology or by using conventional room temperature copper cavities equipped with heavy dampers for the HOMs.

An electron energy of 7 GeV has been selected for the UHXS, which is a compromise between lifetime, beam stability, and cost. The beam lines where the X-ray beams are processed are equipped with mirrors to refocus the beam on the samples and monochromators to select a narrow slice in the spectrum.

One of the major difficulties with the use of radiation in such a facility is the extreme heat load imposed by the X-ray beam on the mirrors and monochromators. A typical undulator beam of the UHXS type produces a continuous-wave X-ray power of 50 kW and a power density close to 1 kW/mm^2 at a distance of 40 meters from the undulator. To maintain a narrow energy resolution, the monochromators are normally made of silicon crystals cooled by liquid nitrogen. Diamond crystals may also be used. A narrow slit (typically 0.5×0.5 mm) is placed in front of the crystal. This reduces the power to 250 W while transmitting most of the flux available on the peak of the undulator spectrum. Most of this power is dissipated in the monochromator's crystal.

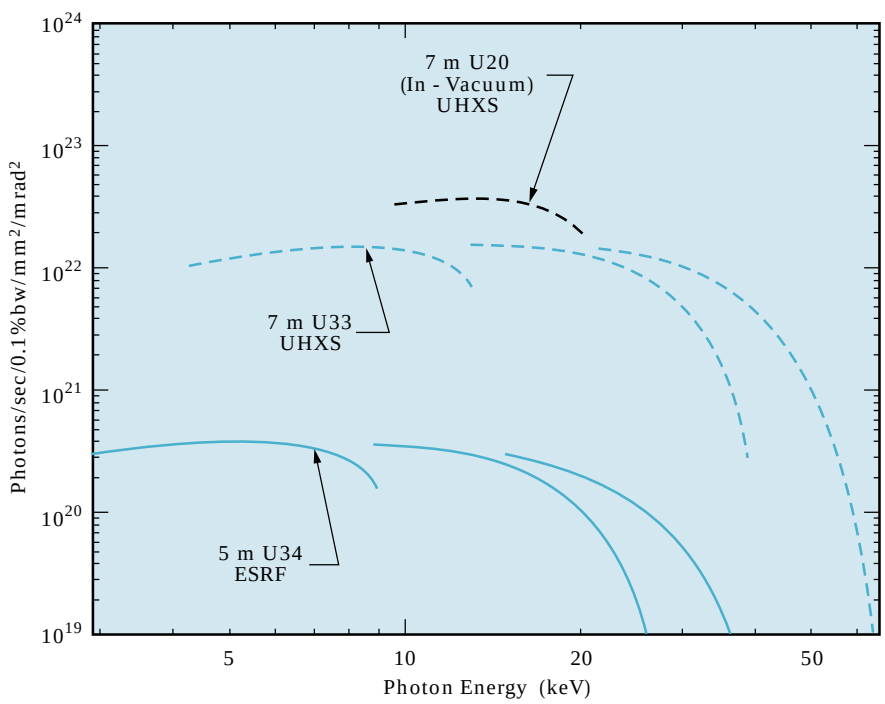
The selection of a small electron beam emittance is therefore essential since it reduces the cone of emission of the undulator emission and allows the collection of the useful undulator radiation over a small aperture. In other words, the reduction of the emittance of the electron beam results in an important reduction of the power transmitted through the slit without sacrificing any flux at the photon energy of interest. Another benefit of small emittance is the high transverse coherence of the X-ray beam. The high coherence opens the door to a number of new experiments making use of this spatial coherence (Speckle, Holography). The achievement of the small emittance is therefore essential and is a major challenge.

While a 7 GeV ring could be built with a circumference of 500 meters but with a rather large emittance, around 20 nm, the achievement of a 0.2 nm emittance requires a perimeter of about 2200 meters. This is because the electron beam emittance in a storage ring is determined largely by the emission of synchrotron radiation in the bending magnets, which perturb the electron orbits by exciting oscillations, the so-called betatron oscillations. These excitation effects are mitigated by segmenting the bending magnets into a large number of short units with rather low magnetic field, separated by quadrupole magnets which refocus the electron beam from one

bending magnet to the other. The extra space required by these quadrupoles and the large number of low-field bending magnets are the reasons for the increase in the circumference. As a result of these factors the electron beam emittance in a storage ring scales approximately inversely as the third power of the circumference.

The figure at left presents the size of the UHXS compared to the present hard X-ray synchrotron sources in operation in Europe (ESRF), United States (APS), and Japan (SPring8). Such a ring would contain 160 bending magnets and 720 quadrupole magnets to be compared to 64 and 320 at the ESRF. Indeed, the size of the circumference is the price to pay for the low emittance. The figure below presents the expected brilliance from a conventional fully tunable 7 meters long undulator. Apart from the heat load and magnet lattice design, there are several other challenges (see box on page 18).

It is interesting to compare the performance of such a ring with the alternative types of sources presently envisaged for the future such as the energy recovery linac (ERL) (see article by Sol Gruner and Donald Bilderback in this issue) and self amplified spontaneous emission free electron laser (SASE) (see article by Claudio Pellegrini and Joachim Stöhr in this issue). The table on page 19 presents a comparison of the flux, average brilliance, and peak brilliance of different projects compared to those presently achieved at the ESRF. The electron beam is made of a series of short bunches spaced in time periodically at the radio-frequency period of the accelerating cavities. The peak brilliance is defined as the average brilliance multiplied by the duty factor, defined as the ratio of the peak current to the average current. Note that the flux and average brilliance of this source compares very favorably with those expected in the Cornell ERL and LCLS SASE projects; however, the electron bunch length of the UHXS is expected to be 50 times longer.



Predicted brilliance versus photon energy for the ultimate hard X-ray source (UHXS) compared with those presently achieved at the ESRF. A gain of brilliance close to two orders of magnitude is reached.

Energy Recovery Linacs as Synchrotron Light Sources

by SOL M. GRUNER & DONALD H. BILDERBACK

Pushing to higher light-source performance will eventually require using linacs rather than storage rings, much like colliding-beam storage rings are now giving way to linear colliders.

SYNCHROTRON RADIATION sources have proven to be immensely important tools throughout the sciences and engineering. In consequence, synchrotron radiation usage continues to grow, assuring the need for additional synchrotron radiation machines well into the foreseeable future. Storage rings, the basis for all major existing hard X-ray synchrotron facilities, have inherent limitations that constrain the brightness, pulse length, and time structure of the X-ray beams. Since large synchrotron X-ray facilities are expensive and take many years to bring to fruition, it is important to consider if there are alternatives to storage rings that offer advantages. The Energy Recovery Linac (ERL) is a proposed alternative synchrotron radiation source that will extend synchrotron radiation science into new realms not possible with storage rings while still being able to serve most existing storage ring applications.

The usage of synchrotron radiation has become more specialized and sophisticated. Although no single source will meet every need, the trend is towards higher brilliance and intensity, and shorter bunches. These trends are driven by a desire to study smaller and smaller samples that require more and more brilliance, because tiny samples tend to have both low absolute scattering power and require micro X-ray beams. An increasing number of experiments also require transversely coherent X-ray beams. It can be shown that transverse coherence increases with the brilliance of the source. Another trend is towards examination of time-resolved phenomena in shorter and shorter time windows.

The time resolution of many experiments is ultimately limited by the duration of the X-ray pulse. If the time envelope of the X-ray pulse is sufficiently short and the source is sufficiently brilliant, it can be shown that an increasing number of X rays will also be longitudinally coherent, that is, in the same quantum mode. So the optical characteristics generally desired from synchrotron radiation sources are brilliance and short pulses.

These desired characteristics immediately translate into requirements on the electron bunches. The average brilliance scales inversely to the bunch transverse emittances and linearly with the average current. Peak values scale inversely with the bunch length. Thus, the most desired characteristics of an synchrotron radiation source are a high average current of very short, very low emittance bunches. With this in mind, let's look at the characteristics of storage rings and linacs as sources of bunches for synchrotron radiation.

ALL EXISTING HARD X-RAY (that is, photon energies greater than about 5 keV) synchrotron radiation sources rely on storage rings. Storage ring technology is well-understood and is near fundamental limits of minimum transverse emittances, intensity and bunch length (see other articles in this issue). The limits arise from the requirement that the particles be stored in stable equilibrium orbits, despite energy and momentum perturbations arising from the emission of synchrotron radiation, the radiofrequency acceleration system, intrabeam scattering (Touschek effect), and small errors in the magnetic bending

and focusing systems, or their alignment, leading to coupling between the horizontal and vertical orbits. These perturbations, which are specific to the given lattice of magnetic optical elements that comprise the storage ring, damp the initial bunch emittance, cross-sectional distribution, and bunch length to equilibrium values in a time which is typically milliseconds long, that is, many thousands of revolutions around the ring. While the equilibrium damping behavior endows storage rings with excellent stability, it also decouples the critical characteristics of stored bunches from those of the initially injected bunches. That is to say, bunches which are injected into the storage ring with smaller emittances or lengths than characteristic of the lattice will equilibrate to the larger values typical of the storage ring. As examples, values for some state-of-the-art synchrotron radiation facilities are given in the table below.

The long damping times of storage rings suggest a way around the equilibrium limitations of the lattice, namely, use the bunches to produce synchrotron radiation long before equilibrium is attained. In this case, the bunch properties, and therefore the quality of the synchrotron radiation will be limited not by the lattice, but by the electron source itself. Modern radio-frequency and direct-current photocathode-based injectors can produce bunches which are both short and have small emittances in all dimensions. Moreover, properly designed linacs can accelerate bunches with very little emittance degradation. An obvious approach is then to couple a suitable photoinjector with a high energy linac to produce a stream of bunches which can then be passed through an undulator to produce brilliant synchrotron radiation. The drawback to this idea is that significant currents (~100 mA) and energies (~ 3-8 GeV) are usually needed to obtain adequately intense synchrotron radiation with state-of-the-art undulators. These values represent enormous beam powers; for example, a continuous 100 mA, 5 GeV beam (such as a hypothetical continuously operating linac might deliver) would carry 500 MW of power, equivalent to the power output of a large commercial electrical generating station. It would be economically unfeasible to consume this much electrical power on an on-going basis.

In a storage ring, the requirement of continuously supplying such a high power is circumvented by storing the high energy particles and replacing only the power lost to synchrotron radiation, which is typically ~10^{-4} of the power in a continuous beam, such as the linac example

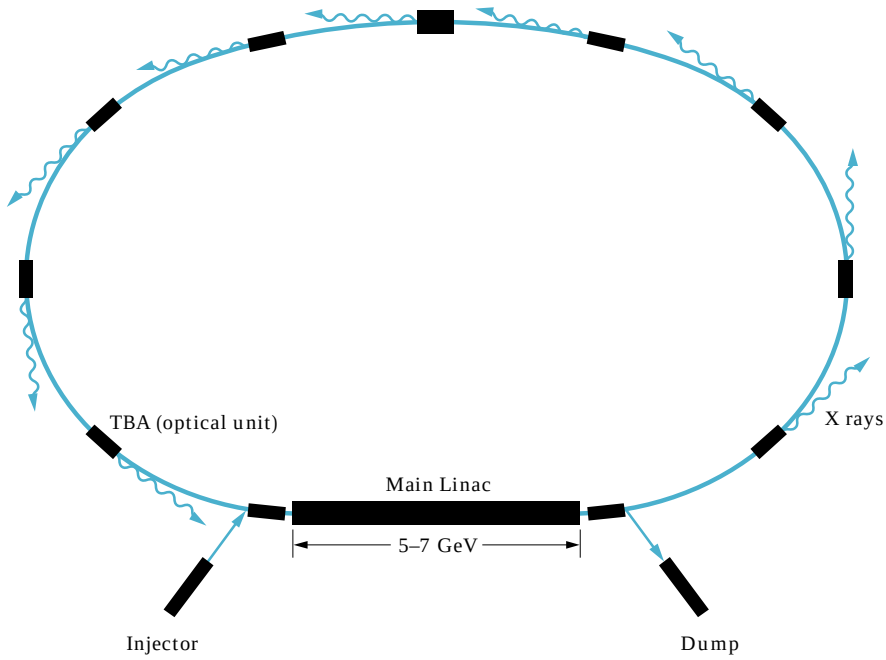
Basic Parameters

Some basic parameters of a few existing third generation storage rings compared to a possible Energy Recovery Linac in high-current and low-current modes.

Machine	*Energy* (GeV)	*Ave. Current* (mA)	*Horizontal Emittance* (nm-rad)	*Bunch Length* (ps fwhm)
ESRF	6	200	4	35
APS	4	100	4	73
SPring 8	8	100	6	36
ERL (low emittance)	5.3	100	0.15	0.3
ERL (very low emittance)	5.3	10	0.015	0.3

described in the preceding paragraph. Therefore it is only necessary to provide a relatively small amount of radio-frequency power to replace synchrotron radiation losses. Of course, it is possible to couple a low duty-cycle photoinjector, with concomitant low average current, to a high energy linac, because the average power scales with the average current. This is exactly what will be done at the X-ray Free Electron Laser (XFEL) sources now being contemplated (see Claudio Pellegrini & Joachim Stöhr in this issue).

YET THERE IS A WAY to use high duty-cycle, high energy linacs without consuming large amounts of power: Superconducting linacs may be efficiently used as both linear accelerators and decelerators–an idea suggested by Maury Tigner in 1965. When used as an accelerator, the electron bunch gains energy at the expense of an electromagnetic (EM) field resonant in the linac; when used as a decelerator, the EM field gains energy from the bunch. The distinction between the linear accelerator and decelerator is simply one of bunch position relative to the phase of the resonant traveling EM wave. For relativistic bunches, which, by definition always have speeds close to the speed of light, this distinction is simply one of carefully timing the arrival of the bunch at the entrance of a linac relative to the phase of the radio-frequency wave. In order to efficiently store the energy recovered from the bunch, it is necessary that the resonant Q of the linac be very high, usually in the range of 10^{10}. This requires the use of a superconducting (SC) linac to circumvent the wall losses of normal conducting linacs, such as the SLAC linac.



A schematic layout of an ERL synchrotron light source. 10 MeV electrons made in the injector are bent by a weak bending magnet into a few hundred meter long superconducting linac and brought to full energy in a single pass. The electrons are then guided around a one-turn arc made, for example, of triple bend achromat (TBA) magnets with undulators producing the X rays. The electrons have a path length such that they return out of phase with the linac and their energy is recovered before being steered to the dump at an energy of about 10 MeV by another weak field magnet. The low energy at which the electrons are dumped greatly reduces the problem of residual radioactivity generated in the dump.

The figure shows a schematic layout of such an Energy Recovery Linac (ERL) and illustrates how it can be used as a superior synchrotron radiation source. A brilliant electron injector is used to obtain relativistic (say, 10 MeV) bunches with very low transverse and longitudinal emittances. These are then accelerated in an SC linac to energies in the range of 3–8 GeV. The resultant bunches are then guided around a transport

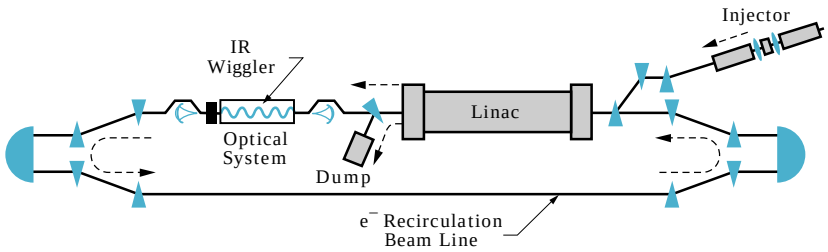
loop, very much like a section of a third generation ring, consisting of a lattice of electron-optical elements interspersed with undulators to produce synchrotron radiation. The loop length is carefully adjusted so the bunches arrive back at the linac 180 degrees out of accelerating phase. They then decelerate through the linac and emerge with the original injection energy, less synchrotron radiation losses. These low energy bunches are bent aside by a weak dipole magnet and sent to a beam dump. Disposing of the electron beam at very low energy results in much less induced radioactivity in the beam dump–an important advantage of energy recovery. The essential distinction between an ERL and a storage ring, then, is that the electrons are recycled in a storage ring whereas only the electron energy is recycled in an ERL. This allows bunch manipulations in an ERL which would be unfeasible in a storage ring.

But can energy recovery be made to work on a practical basis? A pioneering experiment was done in the mid-1970s with a SC linac at the Illinois superconducting microtron. Experiments at other labs followed, in concert with increasingly sophisticated superconducting linacs and superconducting radio-frequency structures developed, for example, at Cornell and Stanford. The CESR storage ring at Cornell, the CEBAF machine at the Thomas Jefferson National Accelerator Facility (Jefferson Laboratory), and LEP at CERN, all of which are driven by SC radio-frequency structures, have proven the practicality of SC accelerating structures for large machines.

The most convincing demonstration of ERL technology, however, has been the commissioning in the last few years of a 48 MeV, 5 mA ERL at Jefferson Lab as a driver for an IR Free Electron Laser (see figure on facing page). This user facility produced >1 kW of IR power on a routine basis. It's energy recovery efficiency is better than 99.97 per cent. (It may be a good deal better. The actual efficiency has never been measured to higher accuracy.)

ERLs have tremendous potential as synchrotron radiation sources. As opposed to storage rings, the essential bunch characteristics are determined primarily by the injector, not by the entire ring. This greatly eases the task of upgrading the facility as injectors improve. Since bunches are not stored, there is no decay of a fill. Complex bunch trains can be readily implemented by programming the timing of the laser illuminating the photocathode electron source. Another major advantage is the ability to control the cross-sectional properties of the bunch. In storage rings, the bunches tend to be flat in cross section and have a vertical emittance which is orders of magnitude smaller than the horizontal emittance. By contrast, the beams in an ERL are naturally round with equal emittances in the horizontal and the vertical, which can be very advantageous for certain X-ray optics. As discussed below, ERL sources are being contemplated with flux and brilliance exceeding all existing storage rings.

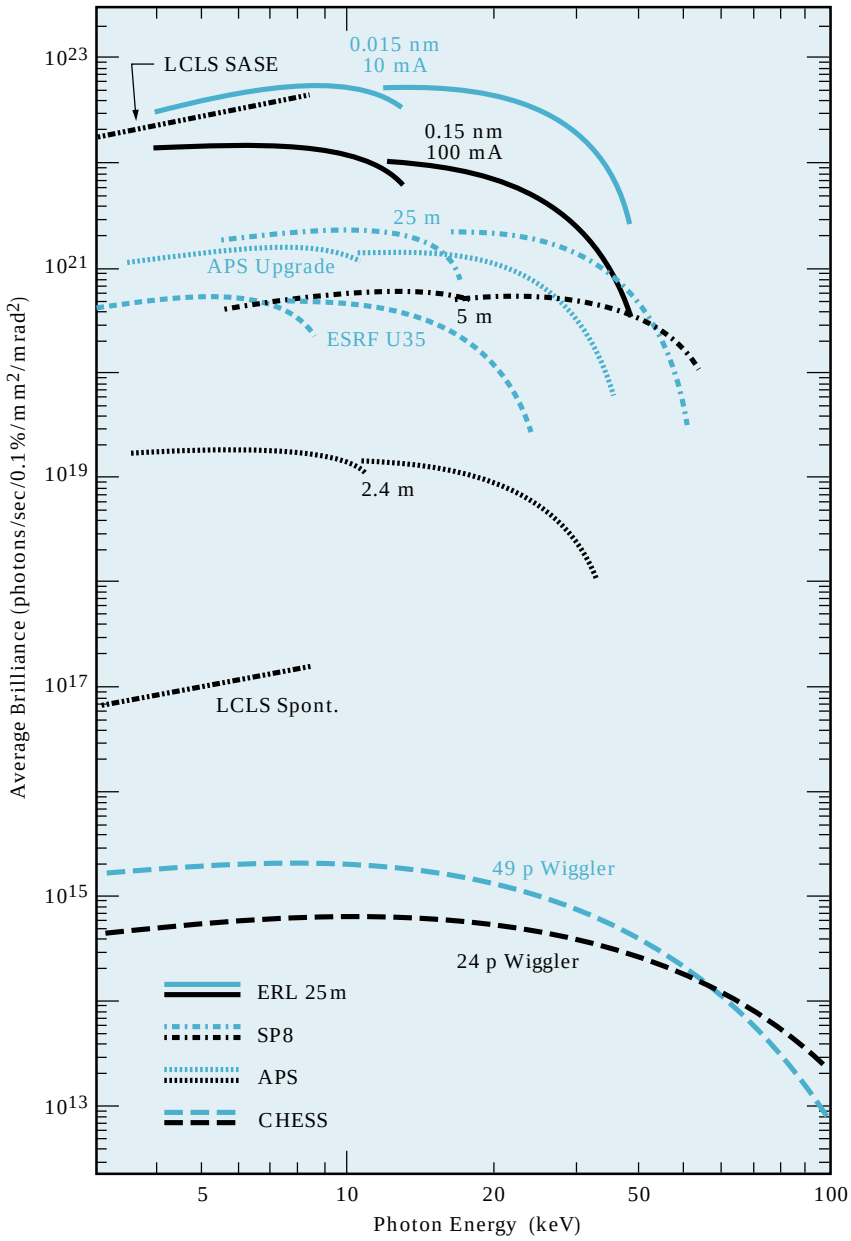
ERLs also lend themselves to the production of very short X-ray pulses. Studies of phenomena on the 100 femtosecond time-scale are



Jefferson Laboratory IR-FEL. The Jefferson Laboratory IR-FEL is also a single-pass machine. Electrons from the injector are brought up to energy in the linac and then pass through a wiggler magnet to create the Infrared Radiation (IR). Mirrors at the ends of the wiggler magnet intensify the IR beam. The electrons circulate around the rest of the lattice before their energy is recovered in another pass through the linac, after which they are sent to the dump. (Source: Jefferson Laboratory web site)

rapidly emerging as one of the next frontiers of X-ray science. Our understanding of the initial events in chemical and solid-state systems has been revolutionized within the last decade by spectroscopies with femtosecond optical lasers. What is lacking is the associated structural information. This may be obtained by pump-probe experiments in which systems are pumped with an optical laser and then probed, after an adjustable time delay, with a very short X-ray pulse. Typical storage ring bunches are some 20–100 picoseconds long, which severely limits experiments on faster time scales. By contrast, the bunches out of an ERL photoinjector may be only a few picoseconds long. Moreover, ERLs allow phase-space manipulations with bunch compressors to create very short bunches. As an example, the CEBAF machine, which is based on a multi-pass superconducting linac, has achieved bunches shorter than 100 fs rms.

Many novel possibilities are made feasible by the ability to adjust the charge and timing of bunches with appropriate manipulation of the laser system driving the photocathode. For example, the minimum emittance of a photoinjector is limited by space charge effects near the photocathode electron source. The emittance of the photoinjector can be decreased by sacrificing photocurrent. Thus one can envision operating an ERL in a high-flux, relatively low brilliance mode or a lower-flux, higher brilliance mode simply by reprogramming the laser illuminating the photocathode. (As indicated in the next two figures, in both modes, the flux and brilliance can still be extraordinary). As another example, the repetition rate of pump-probe experiments with femtosecond lasers is frequently limited to low values (say 10 kHz) by the laser. In these cases it is desirable to have a very short, high charge (for peak intensity) bunch at 10 kHz. One can imagine operating a general purpose ERL with small charge bunches at very high repetition rates (for example, GHz) interspersed with high-charge bunches at 10 kHz. A "buffer zone" of a micro-second with no bunches on either side of the large bunch would allow isolation of the



Expected average brilliance (above) and coherent flux (facing page) for an ERL based on the Cornell/Jefferson Laboratory design described in http://erl.chess.cornell.edu/Papers/ERL_Study.pdf. The ERL may be operated either in a high-flux mode (100 mA, 0.15 nm emittance), or, by reducing the photocathode current to decrease the photoinjector emittance, in a lower flux mode with very high brilliance (10 mA, 0.015 nm emittance).

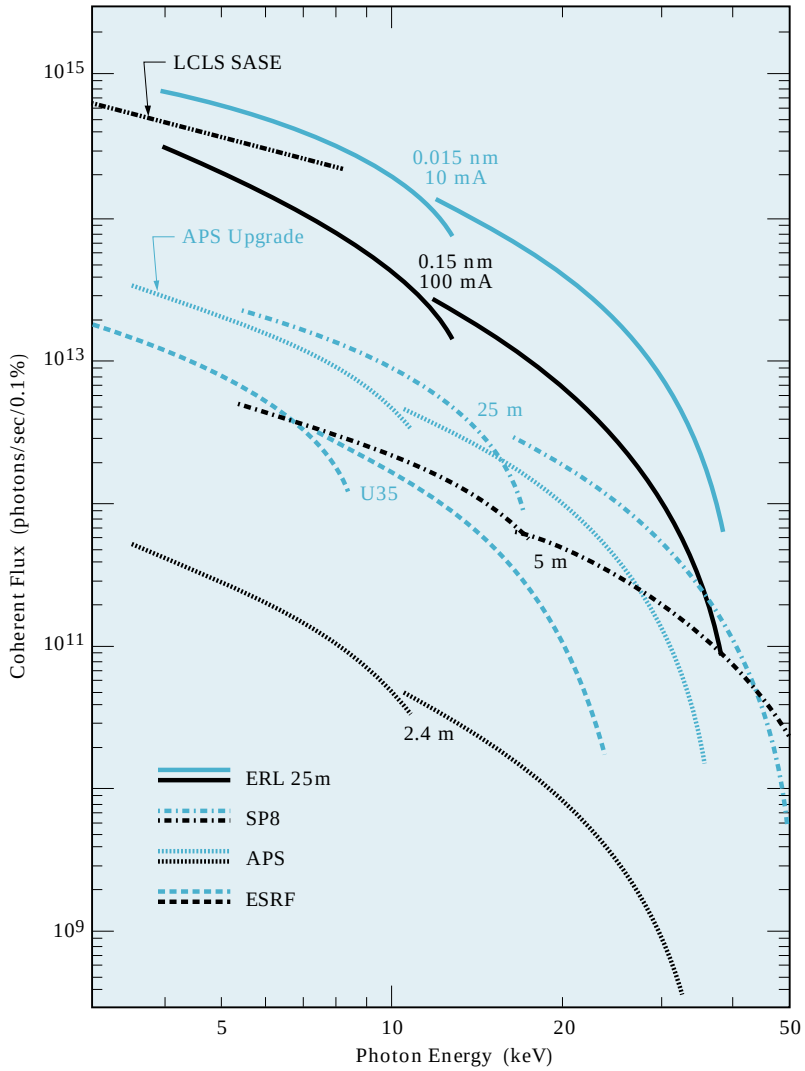
X-ray pulse from the large bunches at the appropriate experimental station. Most other users with time-integration windows exceeding a few milliseconds would be insensitive to this bunch pattern.

ALTHOUGH consideration of ERLs as synchrotron sources has been going on for only a few years, they have already generated a great deal of excitement in the synchrotron radiation community. Nikolai Vinokurov and Gennady Kulipanov and colleagues at the Budker Institute of Nuclear Physics in Novosibirsk had suggested a specialized ERL machine in the mid-1990s. Geoff Krafft and David Douglas at Jefferson Laboratory and Maury Tigner at Cornell, and perhaps others as well, were also thinking about the possibilities of more general purpose ERL synchrotron radiation sources. By late 2000, ERL synchrotron radiation projects were being seriously considered at Cornell University (in collaboration with scientists at Jefferson Laboratory), at Brookhaven National Laboratory (BNL) and at Lawrence Berkeley National Laboratory (LBNL). The focus of the Cornell effort is on a general purpose synchrotron radiation source; the BNL efforts are on ERLs for both synchrotron radiation and heavy ion physics applications; and the machine being considered at LBNL is specialized for the generation of short X-ray pulses at low duty cycle. Interested readers may find articles on all three efforts in the March and May 2001 issues of *Synchrotron Radiation News*. The Cornell web site (http://erl.chess.cornell.edu) has

descriptions of the Cornell/Jefferson Laboratory work, as well as links to other ERL web sites. The projections given below are based on the ERL being designed by Cornell and Jefferson Laboratory staff.

The figures in these two pages show the average brilliance and coherent flux vs. X-ray energy for various machines and for a 5.3 GeV ERL for reasonable assumptions of photoinjector emittances and undulators. The curves show the expected ERL performance under two modes of operation: A high current, "low-emittance" (100 mA; 0.15 nm-rad) mode and a lower current, even lower-emittance (10 mA; 0.015 nm-rad) mode. It is assumed that the SC linac operates at 1.3 GHz with every radio-frequency bucket filled, which corresponds to bunches of 77 and 8 pC, respectively. The advantage of high repetition rate operation is that a reasonable average current can be achieved with low-charge bunches, which is desirable since space charge is the primary mechanism for emittance growth at the photocathode. These bunches are considerably smaller than the ~1 nC bunches required by XFELs. For most users, the ERL will seem like a continuous source of X rays. Larger bunches at lower duty cycle—and with lower brilliance—are likely to be possible for special applications. The great advantage of an ERL is that beams for these special applications can be quickly implemented by simply reprogramming the photoinjector.

There are numerous challenges to building an ERL to these performance levels. These issues were explored in a workshop at Cornell University in August 2000. No ERL has ever been constructed to operate at these simultaneous values of energy, average current and emittance. Likewise, a photoinjector with the requisite specifications has never been built. The shortest pulses will present special challenges, as will the X-ray optics required to realize the full potential of the synchrotron radiation beams. Significantly, the workshop concluded that the requisite performance levels can be achieved by straightforward improvements of existing technology and that no new break-throughs or radically new technology will be required. However, there are many issues—beam stability, halo control, the negative effects of coherent synchrotron radiation, photoinjector design, and photocathode lifetime. which will require prototyping before an optimum large ERL facility can be confidently designed. Fortunately,



almost all of these questions can be addressed with a small, low energy (for example, 100 MeV) ERL prototype. Cornell University has proposed building a small prototype to address such issues for the community at large.

ERLS AND XFELS are both based on linac technology, both are limited by photoinjectors, both will optimally utilize long undulators and both will deliver short bunches. How do these two synchrotron radiation sources differ? From a physics point of view, the biggest difference is that the self-amplified spontaneous emission (SASE) process to generate synchrotron radiation is fundamentally different from the spontaneous synchrotron radiation process so far considered for the ERL. In order to achieve SASE in the hard X ray, higher energy linacs, bunches with higher peak current and far longer undulators will be required.

The essential distinction between an ERL and a storage ring is that the electrons are recycled in a storage ring whereas the electron energy is recycled in an ERL.

From a user point of view, however, ERLs of the Cornell or BNL designs and an XFEL of the LCLS or TESLA designs couldn't be more different. The first difference is that almost all the applications now being performed at storage rings sources are directly transferable to the ERL. For these users, the design of the beam lines, and the way in which the experiments are carried out, will be very similar to those at storage ring sources. The extra few orders of magnitude improvement in beam characteristics will, however, have significant consequences for the experiments that can be performed. The more brilliant beams will allow smaller and weaker scattering samples to be examined. For instance, the practical limits of photon correlation spectroscopy experiments will be pushed into faster time regimes. Inelastic scattering experiments may well be extended to the sub-meV regimes, thereby greatly expanding the kinds of experiments that can be done. The round source size will extend the limits of what can be done with microbeams. With improved X-ray optics, ERLs may make feasible 10 to 30 nm diameter hard X-ray beams. Thus, ERLs automatically have a huge natural constituency of advocates, namely, almost all users of existing storage rings when these users begin to demand more and better synchrotron radiation resources. Of course there will also be applications that take advantage of the distinctive characteristics of ERL synchrotron radiation beams, such as short pulses, as discussed earlier.

By contrast, XFEL beams will be so intense that single-pulse specimen and X-ray optics damage become over-riding issues. As opposed to the ERL, few experiments can be transferred from storage rings to the XFEL without big changes in the way in which the experiments are performed. The community will

have to develop new ways of doing practically every kind of synchrotron radiation experiment. The peak intensity of the XFEL pulses is so high for many experiments that a new sample, or a new illuminated area of sample, will be required for each pulse. Yet the number of photons available per pulse (~10^{12} for a single sub-ps pulse from the SLAC LCLS, about equivalent to 0.1 to 1.0 seconds of monochromatic beam at the APS) will limit the information available from a given sample. Thus, the emphasis at an XFEL will shift to developing techniques to average and merge data from different samples. The extreme properties of the X-ray beams (for example, enormous peak electric fields, full transverse coherence) will enable unique areas of investigation, which is very exciting. But at the same time, it is safe to predict that the learning curve in utilization of XFELs will be long. One of the most interesting cultural changes in synchrotron radiation usage in recent years is the growing number of users who are not X-ray experts. The use of XFELs by these communities will likely come years after XFELs first turn on.

Finally, we can't resist pointing out that a high duty cycle XFEL will consume an enormous amount of electrical energy, unless, of course, it is also an ERL. The potential benefits of merging ERL and FEL technology, already demonstrated in the Jefferson Lab IRFEL, are likely to become compelling.

FOR MORE THAN 30 years, the focus of the synchrotron radiation community has been bigger and better storage rings; now the ultimate storage ring is in sight (see article by Pascal Elleaume in this issue). ERLs and XFELs are emerging as alternative synchrotron radiation sources with interestingly different properties. The first three generation sources were primarily incremental improvements of a single technology, namely storage rings. The future of next generation sources is likely to be much richer than in the past. ERLs and XFEL are both more appropriately termed alternative technology synchrotron radiation sources, since they utilize linacs rather than storage rings.

ERLs, XFELs, and, no doubt, synchrotron radiation machines not yet invented, are the creative fruits of an emerging new generation of accelerator physicists. Culturally, accelerator physics has been the sibling of high energy physics activity, because new high energy physics experiments required new accelerators. Yet accelerators are but one tool towards the end of understanding the fundamental constituents of Nature. The trends in recent years are leading science in new directions. High energy physicists are increasingly looking to the skies to understand the fundamental constituents. And accelerator physicists are increasingly finding other science areas challenging and attractive. In a very real sense, both ERLs and XFELs are consequences of a maturation of accelerator physics designed specifically from the very start to expand what can be done with synchrotron radiation. We look forward to the next decade when ERLs and XFELs will take the frontiers of synchrotron radiation to new vistas.

X-ray Free-Electron Lasers -

by CLAUDIO PELLEGRINI & JOACHIM STÖHR

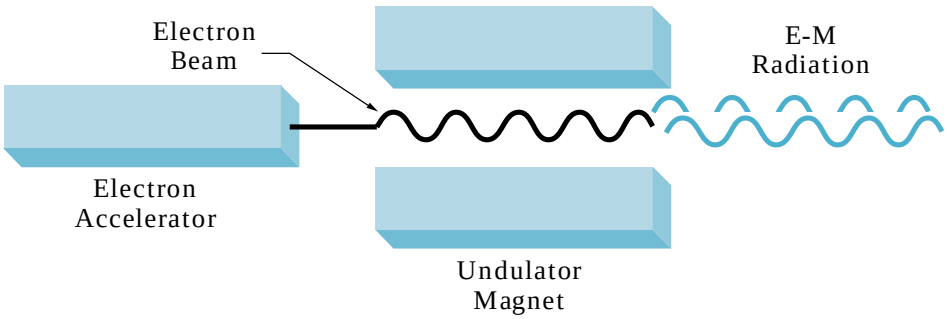
With advances in technology, it is now possible to realize the dream of a fully coherent X-ray laser.

CREATING MATTER from the vacuum, taking an atomic scale motion picture of a chemical process in a time of a few femtoseconds (1 fs = 10^{-15} sec) or unraveling the complex molecular structure of a single protein or virus. These are some of the new exciting experiments envisioned with a novel radiation source, the X-ray free-electron laser (FEL).

John Madey and collaborators built the first FEL in the 1970s. It is a powerful and challenging combination of particle accelerator and laser physics and technology. Until recently FELs have been operating at infrared or near ultraviolet wavelengths. A combination of theoretical, experimental, and technological advances has made possible their extension to the X-ray region. X rays have allowed us to see the invisible for almost a century. With their help we have been making great progress in understanding the properties of materials and of living systems. Today the best sources of X rays utilize synchrotron radiation from relativistic electron beams in storage rings. The most advanced, so called third generation facilities, combine storage rings and undulator magnets, and are used by thousands of scientists around the world.

USEFUL AS THEY ARE these facilities have limitations. The minimum X-ray pulse duration is about 50 picoseconds (1 ps = 10^{-12} sec), and the number of photons that one can focus on a small sample is limited. Future experiments will need X-ray pulses with a

– *Principles, Properties and Applications*



Schematic representation of a SASE free-electron laser.

large number of photons focused on a sample as small as a molecule, squeezed in a time a thousand times shorter, to study the dynamics of atomic and molecular processes. X-ray free-electron lasers can satisfy these requirements, as shown in the table.

AN FEL CONSISTS OF A LINEAR accelerator followed by an undulator magnet, as shown in the figure. The undulator has a sinusoidal magnetic field of period λ_w, usually a few centimeters, and amplitude B_w, typically about 1 tesla. In this field a single electron moves along a sinusoidal, oscillating trajectory, and radiates an electromagnetic wave-train with a number of waves equal to the number of undulator periods, N_w. The wavelength of this spontaneous radiation is equal to the undulator period reduced by a relativistic contraction factor inversely proportional to the square of its energy. This makes it easy to shorten the wavelength by increasing the electron beam energy, and for GeV electron beams one can produce

Undulator Radiation Characteristics

Some typical characteristics of the undulator radiation from third-generation ring-based light sources, and free-electron laser light sources. The emittance is in nm rad; the pulse length in picoseconds; the average and peak brightness are in photons/sec/mm^2/mrad^2/0.1% bandwidth; the peak power in watts.

	Third Generation	*SASE-Free-Electron Laser*	*Short pulse SASE-Free-Electron Laser*
Wavelength range, nm	1-0.1	1-0.1	1-0.1
Emittance, nm-rad	2	0.03	0.03
Pulse length, ps	15-30	0.06	0.01
Average brightness	10^{20}	10^{22}	10^{21}
Peak brightness	10^{23}	10^{33}	10^{33}
Peak power, W	10^{3}	10^{10}	10^{10}

wavelengths of about 1 Å, the size of an atom. The radiation is within a narrow wavelength band, equal to the inverse of the number of undulator periods, which for an X-ray FEL can be a few thousand. The radiation within this energy band is very well collimated, with an opening angle of a few microradians. The number of photons spontaneously emitted from one electron within this energy band and angle is however rather low, about one photon per 100 electrons. In an FEL the electron beam has a large number of electrons, about 10^9 to 10^{10}. In this case a phenomenon of self-organization of the electrons, known as the FEL collective instability, can greatly increase the number of photons per electron and the total X-ray intensity. This instability transforms an electron beam with a random electron position distribution into one in which the electrons are clustered in groups regularly spaced at about 1 Å, producing what could be called a 1-dimensional relativistic electron crystal. The radiation from this crystal has new and exciting properties.

Consider an ensemble of electrons propagating through an undulator. The total radiation field they generate is the sum of the fields generated by all electrons. When the electrons enter the undulator, there is no correlation between their position and the X-ray radiation wavelength. As a result the fields they generate superimpose at random, with a partial cancellation, as shown at the left in the next figure. What the beam produces in this case is called "spontaneous undulator radiation", and its intensity is proportional to the number of electrons, N_e.

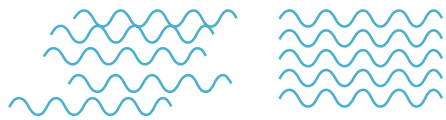
If we could order the electrons so that they were all within a fraction of the radiation wavelength, or

separated by a wavelength, the radiation fields would superimpose in phase, as shown at the right in the figure. The intensity is then proportional to the number of electrons squared, a huge gain. The effect is similar to what you would have during a large party if instead of having all the people talking casually, producing a lot of noise, you could organize them in a well performing choir, all persons singing exactly the same note in perfect tune. The results would probably break all the glasses and windows in the room!

While we do not know how to control the electron position at the Ångstrom level, we can conveniently let nature order the electrons for us, using the FEL collective instability. The way it works is:

- Electrons propagating through the undulator interact with the electromagnetic field generated by other electrons. The interaction changes their energy, and the change is modulated at the X-ray wavelength.
- Within the undulator the trajectory of electrons with larger (smaller) energy is bent less (more). As a result the electrons will bunch together within a wavelength.
- The electromagnetic fields emitted by the bunched electrons superimpose in phase, and the total field amplitude increases. Thus the electron energy change is larger, and the bunching mechanism is stronger.

The end result is that the amplitude of the electromagnetic field grows exponentially. The growth rate is called the gain length and is the most important FEL parameter.



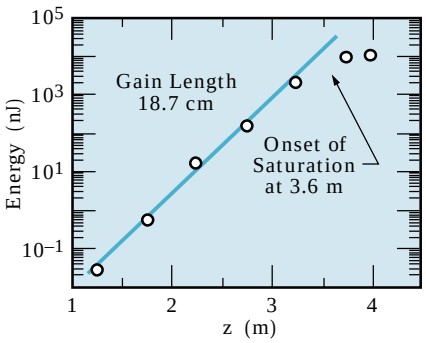
The superposition of the fields generated from many electrons; on the left is the spontaneous radiation case, on the right the free-electron laser case.

The exponential growth saturates when all the electrons are well ordered, and sing perfectly in tune!

The instability can start with the aid of an external electromagnetic field, in which case the system is a high gain FEL amplifier, or it can start from the random synchrotron radiation noise produced by the electron beam at the undulator entrance, a Self Amplified Spontaneous Emission FEL (SASE-FEL). A one-dimensional theory of a SASE-FEL, describing all its properties with a single parameter ρ, was developed in 1984 by Roldolfo Bonifacio, Claudio Pellegrini and Lorenzo Narducci.

In the X-ray region ρ is about 10^{-3} or less. This means that saturation is reached in about 1000 undulator periods, and that one thousandth of the electron beam kinetic energy is transformed into photons. Consider as an example a 1 Å X-ray SASE-FEL with 15 GeV electron energy, and $\rho \sim 10^{-3}$. In this case the number of photons per electron within the same frequency band and angle is about 1000, a gain of 100,000 over the spontaneous radiation case.

The instability develops if the electron beam has an energy spread smaller than ρ, and a radius and angular spread similar to that of the



Exponential growth and saturation in the VISA experiment at 830 nm, in a 4 m long undulator.

LCLS Parameters

ENERGY SPREAD, PULSE LENGTH, emittance are rms values. Brightness is in the same unit as the earlier table. The energy spread is the local energy spread within 2π cooperation lengths. A correlated energy chirp of 0.1 percent is also present along the bunch.

Electron Beam	
Electron energy, GeV	14.3
Emittance, nm rad	0.05
Peak current, kA	3.4
Energy spread, %	0.02
Pulse duration, fs	230
Undulator	
Period, cm	3
Field, T	1.32
K	3.7
Gap, mm	6
Total length, m	100
Radiation	
Wavelength, nm	0.15
FEL parameter, ρ	5×10^{-4}
Field gain length, m	11.7
Bunches/sec	120
Average Brightness	4×10^{22}
Peak brightness	10^{33}
Peak power, GW	10^{10}
Intensity fluctuations, %	8

X-ray beam. The gain must also be large enough to overcome radiation losses due to diffraction. This means that as the FEL wavelength is reduced the electron beam must satisfy more stringent , and this requires avoiding damaging collective effects in the accelerator. Operating an X-ray SASE-FEL is a balancing act between controlling the unwanted collective effects in the accelerator, and letting the FEL instability develop in the undulator.

IN A WORKSHOP held at SLAC in 1992 to discuss the possibility of developing advanced, fourth generation X-ray sources, Claudio Pellegrini showed that using a novel electron source, the photoinjector, developed by John Fraser, Richard Sheffield, and Edward Gray at Los Alamos, and the new linac technologies developed for the SLAC linear collider, it was possible to build a 1Å X-ray SASE-FEL. A study group coordinated by Herman Winick developed this concept, calling it the Linac Coherent Light Source (LCLS). A design group directed by Max Cornacchia continued the project development until its approval by the Department of Energy. A group at DESY in Germany also became interested in this work and developed its own SASE-FEL project as part of the TESLA linear collider project.

The first experimental observations of the FEL instability were done in 1998 by a UCLA-Kurchatov group, which demonstrated exponential gain over about 4 gain lengths, in a 60 cm long undulator, at a wavelength of 16 mm. A much larger gain, 3×10^5 at 12 μm, was obtained in the same year, using a 2 meter long undulator by a UCLA-Kurchatov-LANL-SSRL group. In 2000-2001 three SASE-FELs have reached a gain larger than 10^7 and saturation: LEUTL, at Argonne, at 530 and 320 nm in a 20 meter long undulator; VISA, a BNL-SLAC-LLNL-UCLA collaboration, in a 4 meter long undulator, using a beam with characteristics similar to those required for LCLS, as shown in the figure; and TTF, at DESY, at 92 nm, the shortest wavelength for an FEL, with a 15 meter undulator.

These results support the feasibility of LCLS and the TESLA X-ray FEL project. The main difference between these projects is the linear accelerator, an existing room temperature linac for LCLS at SLAC, and a future superconducting linac for TESLA. The LCLS project is scheduled to start operation in 2008. Its characteristics are given in the table.

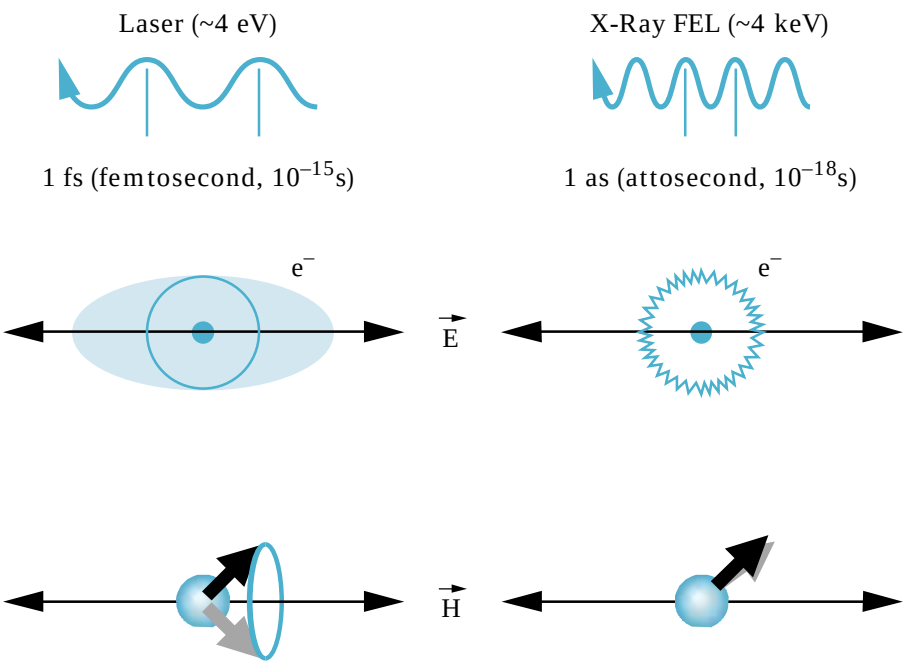
WHEN THE LCLS was first discussed, an overriding concern was the destructive power of its X-ray beam, an extraordinary beam with a peak power of about 10 GW. Wouldn't such a beam simply destroy everything put in its path, from X-ray optics to the sample itself? Traditionally X rays have been used as a gentle probe of matter, avoiding radiation damage caused by the beam itself. While some of the excitement surrounding LCLS is based on utilization of the high power to create new forms of matter, there are fortunately also ways to use its X rays as a gentle probe.

X rays, like visible light, are electromagnetic waves. In the case of light the wave oscillation period is

about 1 fs, while for X rays it is 1000 times faster. The LCLS beam has a peak power of 10 GW in a 100×100 μm^2 area near the undulator exit, corresponding to peak electric and magnetic fields of 2 volts/Ång-strom and 60 tesla, respectively. Focusing the beam by state-of-the-art methods to $1\times1\mu m^2$ the field strength grows to 200 volts/Ångstrom and 6,000 tesla, strong enough to pull electrons out of atomic shells. For the focused LCLS beam the magnetic fields rival the exchange fields in ferromagnets, and would affect all magnetic interactions in matter. These numbers appear to confirm our worst fears–that nothing would survive the LCLS beam.

Fortunately, the very rapid variation of the fields with time saves the day. Just as humans cannot hear very high frequencies because our eardrums cannot follow the rapid movement of the sound waves, matter becomes insensitive to high frequency fields because the electron charge or spin cannot follow them. While the most intense visible lasers can ionize atoms by the shear strength of the electric field, converting a material into a plasma, the thousand times faster oscillating fields of X rays only cause the electrons and spins to quiver, as illustrated in the figure.

In addition, one can minimize the interaction of the X rays with the



Distortion of the electron orbit and spin direction in an atom by strong oscillating electric and magnetic fields for typical laser and X-ray frequencies. For lasers, the field frequency is comparable to the Bohr orbit frequency of valence electrons, and the spins can precess back and forth by a large angle around the strong magnetic field. For X rays the electrons and spins cannot follow the fast fields and just quiver.

Snapshots with atomic resolution and femtosecond time intervals of a molecular dissociation will be made possible by X-ray FELs. The real space images would be reconstructed from ultrashort X-ray diffraction patterns.

mirrors and other optical elements, due mostly to the photoelectric effect, by choosing materials with a small atomic number to build them.

Three general classes of experiments have been proposed for LCLS. In the first the X-ray beam is used to probe the sample without modifying it, as is done in most experiments today. In the second class, X rays are used to induce non-linear photoprocesses or produce states of matter with extremely large temperature and pressure. In the third class the ultra-fast nature of the LCLS pulse is used to obtain a snapshot of the structure of the sample before the effects of radiation damage set in.

The LCLS can be used for all three types of experiments. The unfocused X-ray beam size at the exit of the undulator is about 100×100 μm^2, the diameter of a fine needle. At a typical experimental station located about 200 meters from the undulator exit, the size expands to only 200×200 μm^2. This beam can be focused by state-of-the-art techniques to about 0.1×0.1 μm^2 with maybe a factor of 10 loss in power. This beam size is about the size of a virus or the smallest structures that can be lithographically fabricated today on an electronic chip. Through variable focusing the flux density of the X-ray beam can therefore be tuned by a staggering factor of about one million.

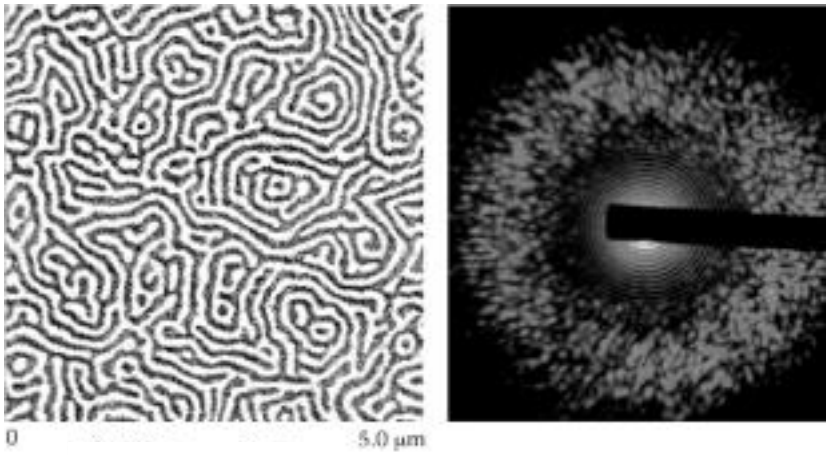
THE X-RAY PHOTON flux typically delivered to a sample in today's synchrotron radiation experiments is about 10^{12}-10^{13} photons/sec. It typically takes one second to record a diffraction pattern of a sample. From the diffraction pattern we can then construct a real space image of the atomic positions in the sample. Because of the time duration of the measurement only the average position of the vibrating atoms can be observed. LCLS can give the same number of X rays obtained now in 1 second in an ultra-fast pulse of about 100 femtoseconds.

This time is hard to imagine. It is so short that sound would travel only the distance of one atom, and the fastest "thing" we know, light, would travel only about 50 μm or the width of human hair. It is also the time with which atoms, the building

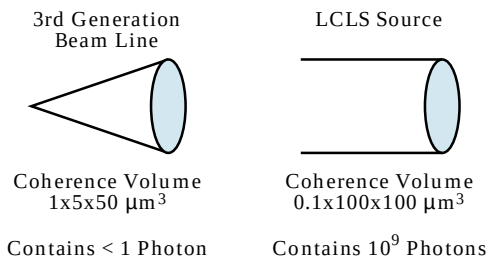
blocks of materials, vibrate. Hence LCLS will allow us not only to "see" the invisible, down to the size of an atom, but also to take snapshots of the motion of atoms and of ultra-small, so called nanoscale, objects like molecules and clusters. This is illustrated in the figure, showing schematically how a small molecule separates from a bigger molecule, a chemical process called dissociation. Today we can only imagine such a movie, but with LCLS we will be able to record it and then play it back to look at the detailed process.

The spontaneous emission of radiation from X-ray tubes or synchrotron radiation sources is chaotic or incoherent by nature. At first sight it is surprising that it permits us to observe X-ray diffraction phenomena, originating from interference. Under certain conditions, incoherent sources can be a source of coherent X rays. It all depends on the experimental geometry and on the dimensions of interest in the sample! If the sample is far from the source, the X-ray phase and amplitude is well defined over a certain small sample volume, and one can get interference from structures within that volume. Examples are Bragg peaks or small-angle scattering peaks, which reflect "structure" within a coherence volume of a few hundred Ångstroms. To extend the structural sensitivity to larger, say micrometer, dimensions the X-ray coherence volume must be increased beyond these dimensions. If this is done by moving the sample further from the source, the cost is a reduced intensity.

Only with the advent of high brightness third generation synchrotron sources have such experiments become practical. An example is the



Left: Magnetic worm domain pattern of CoPt alloy with perpendicular anisotropy, recorded by transmission X-ray microscopy. Right: Coherent X-ray diffraction or speckle pattern from a 5 µm diameter region of the same sample, selected by a 5 µm circular aperture. The central rings are the Fraunhofer diffraction pattern from the circular aperture which are well separated from the speckle pattern of the smaller magnetic domains.



Comparison of the coherence properties of a state-of-the-art third generation beam line with that of an XFEL.

coherent diffraction or "speckle" pattern shown on the previous page. The pattern arises from the magnetic worm domains in a CoPt alloy, shown on the left. The speckle image on the right was recorded in transmission through a 5 μm diameter aperture, which defines the lateral X-ray coherence. The speckle pattern contains the detailed information on the true structure of the sample in the illuminated area. Any change of the magnetic structure of the sample would be reflected by an intensity change in the speckle pattern. With LCLS a speckle pattern can be recorded in a single shot, opening the door for femtosecond dynamics on the nanoscale. Inversion of the magnetic speckle pattern, using techniques such as oversampling, also promises to give ultrafast real space images of nanostructures. Besides magnetic thin films, systems of interest include various materials undergoing phase transitions, simple and complex fluids or glasses, and correlated materials with complex charge and spin ordering dynamics.

On a typical undulator beam line on a third generation X-ray facility, equipped with a monochromator of 0.01 percent bandpass, the X-ray beam is coherent within a micrometer size volume, as shown in the next figure. The number of photons in the coherence volume, the degeneracy parameter, scales linearly with the source brightness and with the third power of the wavelength and is on average less than one. Therefore all present day diffraction experiments are based on single photon interference effects.

In contrast, the LCLS radiation has unprecedented coherence, about 10^9 photons in the coherence volume. The energy of coherent photons can be pooled to create multiphoton excitations and carry out nonlinear X-ray experiments. This is a largely unexplored area of science.

In its initial configuration the LCLS pulse duration is about 200 femtoseconds. Even though this is hundred times shorter than in storage rings, it can probably be further reduced to about 1/10 of this value. Several schemes to achieve ultrashort pulses have been proposed. They all use an energy-position correlation in the electron bunch, and, as a result, in the X-ray pulse. A short X-ray pulse is then obtained by slicing out part of the bunch with a monochromator. A promising scheme using this approach and two undulators has been studied, and could be implemented in LCLS.

THE EXPERIMENTS with LCLS and TESLA will cover a wide range of fields, from high-energy physics, to atomic physics, plasma physics, chemistry, materials science, condensed matter physics, and biology. Here we can only mention some of the present ideas and explain why they are expected to break truly new ground.

The very first LCLS experiment will be aimed at understanding the fundamental interaction process of the high power X-ray beam with atoms, molecules and clusters. It will explore the formation of hollow atoms, where the X rays can strip electrons from the inside out. It will also study multiphoton processes enabled by the large coherent intensity. Finally, it will investigate the disintegration and explosion of clus-

ters, yielding information on the time scale of the damage caused by the X-ray beam, a fundamental question for other experiments.

A second proposed experiment uses LCLS to create and investigate warm (WDM) and hot (HDM) dense states of matter that exist in astronomical objects and are important for inertial fusion. Conventional lasers have provided limited information on these systems, because they cannot penetrate the high-density matter, and few theories can make any prediction.

The study of molecular reactions is the very heart of chemistry. With ultrafast laser spectroscopy we can catch a glimpse of electron transfer processes in response to an optical excitation pulse. But despite their great success, conventional lasers can only study electronic excitations, and cannot "see" the positions of the atoms during the various transformation stages. This is, of course, the domain of X rays, and LCLS will permit us to take diffraction snapshots as shown in the earlier figure. The importance of these experiments is underscored by the fact that many important discoveries in biology and chemistry can be traced back to the determination of a structure.

Another experiment, similar to that shown in the "speckle" figure, pushes the envelope in probing ordering phenomena in hard and soft condensed matter on the important nanometer length scale, which cannot be seen by optical photons, over a broad range of time scales. This area is not only scientifically interesting, but it constitutes the competitive arena of future technological devices.

LCLS also holds great promise for structural biology. Today, radiation damage is one of the main obstacles in determining the structure of proteins that cannot be crystallized, like cell membrane proteins, which constitute nearly half of all proteins. With the peak brightness of LCLS the structure of a virus or even a single protein molecule may be determined by recording a three dimensional array of ultrafast diffraction patterns, each recorded in a single shot on a new sample before radiation damage sets in.

Finally, just as the application of conventional lasers has been accompanied and driven by the R&D on lasers themselves, LCLS will also have an R&D program, exploring new ways to improve its characteristics.

THE HISTORY of and experience with three generations of synchrotron radiation sources has taught us that the above experiments are at best the tip of the iceberg of scientific opportunities. It is safe to predict that we have not yet thought of the most important experiments that eventually will be done with this new class of radiation sources–X-ray free electron lasers! Quoting Antoine de Saint-Exupery (The Wisdom of the Sands), "The most important task before us may be . . . *not to foresee it, but to enable it.*"

Astrophysics Faces the Millennium VI

People, Places, Papers, and Power

by VIRGINIA TRIMBLE

When I was very young, I met an elderly member of the Sedgwick family, who had known someone, who had known someone, who had known Newton.

—Prof. Sir William H. McCrea (1904–2000)

SINCE SIR BILL was, in all other respects a gentleman of extreme probity (who will be quoted again), I have every reason to suppose this is true. It is, anyhow, perfectly possible, as you can figure out for yourself, if you get out your envelope back* and remember that Sir Isaac's dates were 1642–1727 (he managed, after all, to buy into the South Sea Bubble twice). That all of modern science is remarkably close to us, even in so ephemeral a unit as human generations, is a point to which we will return in this sixth, and probably last, episode of the continuing story of triumphs and tribulations of the Astrophysics Family over the past centuries. The thrust this time will be not the specific scientific advances (as in parts I to IV) or the synergistic technologies (as in part V), but some aspects of who has contributed to astronomy, where and how, and the ways in which the results of their endeavors have been promulgated. Some aspects you will have known before or recognize as just what you expected. Others may surprise. Inevitably, I

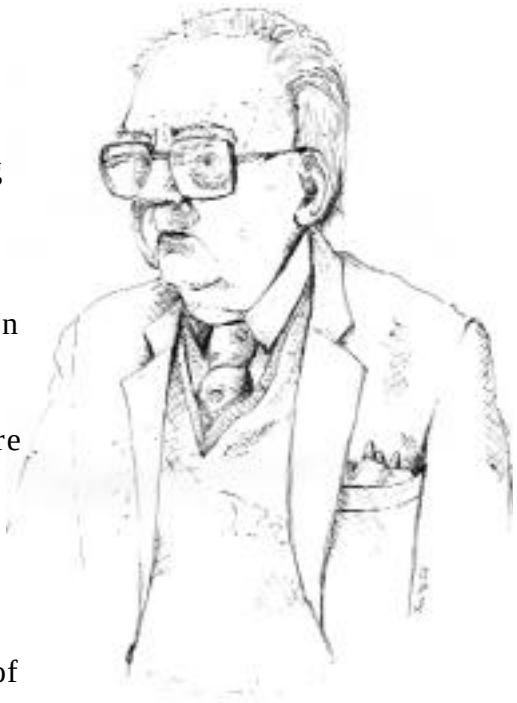
* *You may also need a pen or pencil, and I will buy dinner at the 2003 April APS meeting for anybody who remembers the Harry Lauder joke of which this is reminiscent.*

will succumb to the temptation of "why" and will try, at least, to be honest about where there are supporting data and where I'm just guessing.

PLACES AND PALABRAS

"'I'm learning Chinese,' said Wernher v. Braun," according to Tom Lehrer (or Wernher versus Braun, as a helpful copy editor once expanded the name). In other words, the world center of science in general and of particular sciences has shifted many times in the past and will surely shift again in the future. Thus, a thousand years ago, if you wanted to study astronomy, it would have been perfectly reasonable to go to China (if you had known about it), where they were compiling the Soochow Star Chart, recording the brightness of the supernova of 1054, and even forecasting some eclipses. And it may well be reasonable to go there for astronomical education again some day.

Before that, of course, came "the Greeks." Remember, however, first that they built on a Babylonian foundation of careful observations of positions of Venus, times of eclipses, and so forth, and, second, that "Greece" was, depending on your point of view, either bigger or more movable then than now, including southern Italy (the Pythagoreans), Asia Minor (Thales of Miletus, Anaximander), and Alexandria (Ptolemy, Aristarchus, Eratosthenes), though even then people went abroad for their graduate studies, as for instance Eudoxus of Cnidus, to interact with Plato in Athens. One suspects that the international language of science (natural



Sketch of Bill McCrea drawn by Jonathan Hare in 1996.

philosophy) in those days was broken Greek. At other distant times, there have been centers of excellence in astronomy in the Yucatan peninsula; Baghdad; Moslem Spain; Turkey, India, and Samarkand; and elsewhere.

Closer to the present, both the supporters of the Aquinian synthesis (Winter 1999 *Beam Line*, Volume 29, No. 3) and the framers of the ideas and instruments that eventually overthrew it were scattered across the face of western Europe, from Ireland (where, in the 700s, they had kept better track of the date of Easter than had Rome) eastward. Thus, you might, within a decade either side of 1600, have gone, with equal good sense, to study with Digges in England, with Kepler in Prague, or with Galileo in Padua, though it would have been a tactical error to go to Rome to study with Giordano Bruno after about the middle of 1600. They and their students often wrote in, and presumably spoke, Latin as well as their vernaculars (and no, I don't know whether Copernicus's first language was Polish or German). These were, as you know, also the places where many of the other foundations of modern learning were being established, and probably even then, they had significantly larger per capita incomes than most of the rest of the world. Co-development with other sciences and correlation with disposable income have always been characteristic of the astronomical centers, though I think these are not the whole story. Tycho's observatory at Hven is said to have cost about the same fraction of the income of the Denmark of Fredrick II as the European Southern Observatory did of the income of its member countries.

From the middle of the seventeenth century into the 1800s, most of the people to be found in indices of books on history of astronomy lived in places where the vernacular was English, French (including Huygens in Paris, despite his name), or German. The first modern, national observatories arose primarily to serve the needs of navigation, beginning with Paris in 1667 and Greenwich in 1675, followed by San Fernando (Spain) in 1757 and Coimbra (Portugal) 1772, all with almanacs in the vernacular and, often, coordinates centered at their own locations. What we now call Germany and Italy followed a different pattern, and by 1800 there were observatories in, at least, Heidelberg, Potsdam, Krakow, Munich, Hohenpeissenberg, and Göttingen; and Naples, Padua, Palermo, Torino, Trieste, and Pisa. None was a national observatory, and one is enormously tempted to say that the lag as well as the multiplicity were caused by the lack of political unity. It is also true that their locations put them in less urgent need of accurate astronomical information for navigational purposes than was the case for England, France, Spain, and Portugal.

Astronomy, along with the rest of modern science, flowed gradually back from Western Europe to China, India, Japan, the Middle East, and other places where it had once flourished. "Why?" is irresistible here, but all I think I know about the topic has been said better by Jared Diamond (*Guns, Germs, and Steel*, 1999, but the book is really about geography, agriculture, technology, and demographics).

The eventual 500 pound gorilla appeared as a very small marmoset with the founding of the US Naval Observatory (again navigationally motivated and first urged by John Adams) in 1830 and the first college observatory at Harvard in 1839. Next were Cincinnati (1843), supported by the citizens of the city, and Dudley Observatory (Albany, NY, 1856), the creation of a private philanthropist. Notice also that these four illustrate the four main ways in which American astronomy supports its activities to this day. National and educational funding are part of the world pattern, but community and private funding are as American as maize (started here and slow to catch on elsewhere).

At present, US-based astronomers make up about one-third of the membership of the International Astronomical Union; publish a comparable fraction of the papers in astronomy, astrophysics, and cosmology; and educate a comparable fraction of the PhDs and postdocs entering the field. International mobility is probably rather higher than in most (other?) branches of physics. The international language is broken English

(I speak it myself after a couple of conference weeks). And the number of IAU members resident in a given country is a reasonable proxy for gross national product (see table on page 54). The table is neither alphabetical by country nor in order by population or GNP, but attempts to group the countries meaningfully. It is discussed a bit more under "People."

Somehow the properties of the places where these various centers appeared do not seem to have mattered as much as you might suppose. Alexandria, Athens, and Baghdad are indeed relatively cloudless, and the proximity of cities mattered little in pre-Edisonian times. But neither England, Germany, nor most of France are known primarily for their sunny skies. The same can be said for the Netherlands, which had a large, active astronomical community well before the advent of radio astronomy enabled its practitioners to peer through their clouds. In fact, the focussing of astronomers around clear, dry, high, dark mountains began only with the development of the California sites at Mt. Hamilton (Lick Observatory) and Mt. Wilson-Palomar. And, though the telescopes themselves are now more than ever concentrated to such sites (including the still clearer, dryer, higher, and darker reaches of space), the advent of remote observing means that the astronomers need not be.

It is therefore no surprise that people today do astronomy in more countries, cities, universities, observatories (some in name only), and all the rest than ever before. Good locations and large disposable income matter, of course, but (perhaps above some critical threshold level) do not dominate. McCrea (I said you would meet him again), when asked to provide an autobiography about 15 years ago, wrote instead on "clusterings of astronomers," mostly ones of which he had been part in his 65 year career. They were clusterings in four-dimensional space (Cambridge under Eddington, the Admiralty during World War II, UC Berkeley under Otto Struve, Warner and Swasey under McCuskey, this last quite focussed on certain aspects of stellar astronomy, and so forth). McCrea suggested a variety of causes (with interesting names like "the boat race effect" and "the Halley effect"), but feared his paper might well have been rejected by a refereed journal for lack of quantitative data.

THE JOURNAL OF THE SOCIETY OF SUCCESSFUL MAMMOTH HUNTERS

I have said before, and continue to think it true, that our modern professional societies with their meetings and publications are the remote descendents of a hunting party hunkering down around the fire to exchange stories about who did what during the current hunt, how it compares with previous hunts, and what they hoped to accomplish next time, and of painting a somewhat idealized version of the day's activities on cave walls. That is, they serve to validate a community and its shared store of knowledge, customs, and experiences.

The first purely secular (but largely amateur) scientific society was the Royal Society of London, founded in 1660, with its *Philosophical Transactions* appearing on the scene in 1665. Various other national, state, and city academies of science and their publications followed, beginning slowly in French-, German-, Italian-, and Scandinavian-speaking lands, and continuing down to the present, with flurries of activity whenever periods of international upheaval resulted in new, newly-Westernized, or newly re-established countries.

On the astronomical front, the national observatories published their almanacs, beginning with *La Connoissance* des Temps* from Paris in 1679 and the

* *No this isn't a typrographical error, just an old spelling, preserved, for instance, in the English cognate "reconnoiter," to be compared with "reconnaissance" related to the modern French spelling and "recognizance," more directly from the Latin recognoscere, to recall. While we're looking at words, the mythical society of course consisted of successful hunters of mammoths—the successful mammoths got away—but misplaced modifiers are almost as old a part of the scientific tradition as the ordeal or qualifying exam.*

Nautical Almanac and Astronomical Ephemeris from Greenwich and London in 1767, and eventually other kinds of papers as well. Observatory publications (of which more later) have no direct equivalent in most other sciences, except perhaps museum publications in taxonomy.

The first astronomical society, the Astronomical Society of London, and the first non-observatory regular publication, *Astronomische Nachrichten*, arose almost simultaneously in 1820 and 1821 respectively. Among the "causes for which I have no real evidence" you can include the thought that England, a long-unified country with a single focus of culture in London, "should" have begun with a society, holding regular meetings, and with members as close as Bristol and Cambridge designated as non-resident; while Germany, still divided and with many foci of learning, "should" have begun with a journal, whose editor received communications from colleagues all over Europe, and soon the world, had them typeset, and sent them back regularly to all the contributors.

The ASL (whose founding president was William Herschel) was chartered as the more familiar Royal Astronomical Society in 1831, at which point all its roughly 250 members became fellows (The founding population was about 100, that international and generation-transcending constant.) Publication of its *Memoirs* (the first astronomical society publication) began in 1821. Initially, the contents consisted largely of papers that had been presented in brief form at the monthly meetings. Soon it was necessary for the editors to point out that the fact that the President and Fellows had thanked a speaker for his presentation at the end did not necessarily reflect unqualified approval or guarantee space in the *Memoirs*. A small committee reviewed contributions from time to time and recommended to the Council of the Society which ones should be published. Thus *Memoirs* of the RAS can claim also to be the first refereed astronomical publication. Early issues had a very few items in French, but *Mem. RAS* soon became relentlessly monoglot, as did the other publication, *Monthly Notices of the Royal Astronomical Society* (debut 1827, now publishing 36 issues per year, and one of the leading three or four in the field worldwide).

Contrasting in many ways was *Astronomische Nachrichten*, for its first quarter century very much a one-man operation. The man was Heinrich Christian Schumacher, born in Bramstedt, duchy of Holstein (German-speaking but subject to the King of Denmark since about 1460). With functional literacy in five or six languages, Schumacher offered to publish astronomical contributions in "any European language." French and English were common from the beginning, and the fraction of English-language text has increased monotonically from a significant minority in the 1920s to nearly 100 percent at present (though the journal has become a marginal one after 40 years of near isolation in East Germany). The German society, Astronomische Gesellschaft, founded in 1863 in the context of the gradual unification of the country, assumed responsibility for *AN* late in the nineteenth century.

The first American astronomical journal (called the *Astronomical Journal*)* was a deliberate, though monoglot, imitation of *AN*, started by Benjamin Apthorpe Gould in 1849, after he had visited Schumacher and studied with Gauss (yes, that Gauss). Publication stopped at the onset of the War Between the States, but resumed, at Dudley Observatory, in 1896. The journal survives, now owned by the American Astronomical Society (founded in 1899 by about 100 people, under the name of the Astronomical and Astrophysical Society of America).

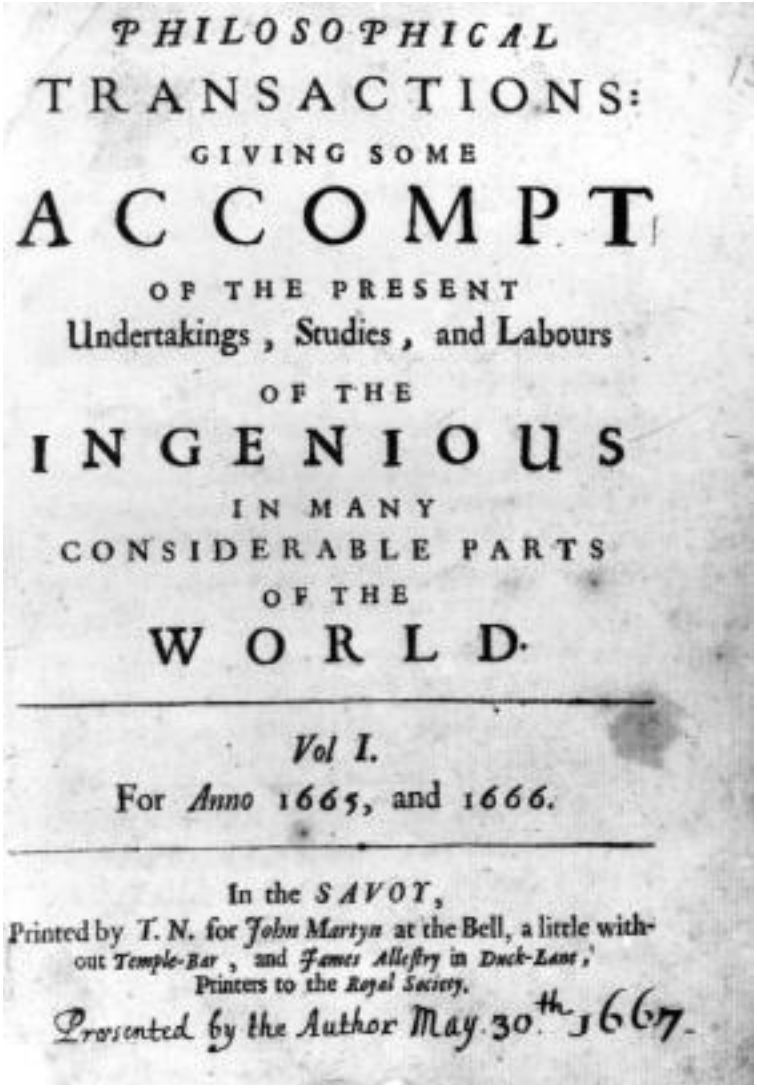
Somewhat later come national societies and/or publications in France (1887), Italy (1872), Belgium (1880), Canada (1868), Japan (1908), South Africa (1912), China (1922), New Zealand (1920), Poland (1925), Ireland (1937),

* *Yes, but remember that the answer to "who was born on Lincoln's Birthday?" is Charles Darwin, and to the others, "Mr. and Mrs. Grant," "1812-1815," and "future Americans, under George Washington, as well as the French and Indians."*

Netherlands (1921), Scandinavia (1916), Czechoslovakia (1947), and the Soviet Union (1924).

Astrophysics originally meant the application of spectroscopy to astronomical objects. It began with the recognition of sodium lines in the spectrum of the sun by Kirchhof and Bunsen (1858–1859) and spread rapidly through the scientific world, gaining converts from physics, chemistry, traditional astronomy (occasionally), and less likely disciplines, including medicine and brewing, in communities where amateur and professional astronomers still mingled. Stress and strain arose between the "new" (astrophysical) and "old" (positional) astronomers, with harsh words uttered on all sides. In England, the RAS and its publications managed to absorb the new topics, and issues of *MNRAS* from the 1920s and 1930s consist primarily of astrophysics, in the original sense, as well as the newer one of applying modern physics to problems of stellar, galactic, and cosmic structure and evolution. The American community partially fractured with the founding of the *Astrophysical Journal* in 1895 by George Ellery Hale and a few associates. It eventually spread over the entire country, and later the world, and the entire range of astronomical subfields, though there have been times when the editors thought it necessary to say explicitly that they would welcome papers in instrumentation, radio astronomy, and so forth (and were not always believed). The German and French communities also bifurcated as they grew, with *Zeitschrift für Astrophysik* in 1930 and *Annales d'Astrophysique* in 1938. Both were originally in the vernacular, but contained a good many papers in English by the time of their 1969 demise. *ApJ* was English-only from the beginning and remains so, though the second commonest phrase in its referees' reports is, "The English is perfectly awful." The commonest, of course, is some polite variant of, "the author hasn't cited enough of my papers."

No other national communities spawned separate astrophysics publications, and the practitioners either


PHILOSOPHICAL
TRANSACTIONS:
GIVING SOME
ACCOMPT
OF THE PRESENT
Undertakings, Studies, and Labours
OF THE
INGENIOUS
IN MANY
CONSIDERABLE PARTS
OF THE
WORLD.

Vol I.
For Anno 1665, and 1666.

In the SAVOY,
Printed by T. N. for John Martyn at the Bell, a little without Temple-Bar, and James Allestry in Duck-Lane,
Printers to the Royal Society.
Presented by the Author May 30th 1667.

turned to academy proceedings and journals of physics in their home countries, or, increasingly to the *ApJ*.

RUN-AWAY EVERYTHING?

"Is your journal still growing exponentially?" "No," said the editor of one of the higher-profile ones a while back.

"It's only about 5 percent per year." Apart from the misunderstanding of what is meant by "exponentially" incorporated in this response, it is interesting because (a) it is roughly true for numbers of astronomical words published during the 1990s, (b) it is rather steeper than the growth in numbers of astronomers during the same period, and (c) it must also be steeper than the 300 year average. Five percent per annum is a doubling time of 14.2 years or a factor of 2×10^6 in 300 years. Early volumes of the *Phil. Trans. Roy. Soc.* already carried more than one astronomical paper per year, and while the current literature is more than you would care to read, it comprises at very most 10^5 papers per year, not something $\times10^6$ (that is average growth rate 4 percent or a bit less per year). Point (d), you do not need to be told, is that this cannot keep up forever.

Returning to the present, it is true that there are "more" (1) astronomical societies, many of the recent ones belonging either to relatively new countries (the separate pieces of the former Czecholovakia, Yugoslavia, and Soviet Union) and developing countries, or to subspecialties, like divisions of solar physics, plasma astrophysics, and high energy astrophysics within larger organizations; (2) conferences (the growth rate for these was a good deal more than 5 percent a year, I think, but have not collected the supporting data); (3) papers; and (4) pages per paper (see figures on pages 50 and 51), though, looking back at the screeds of the 1700s, this must have gone through a relative minimum in the days of Schumacher and Gould (each of whom, incidentally, is worth very much more than the one-line mentions they get here).

Item (1) is (again without concrete evidence) part of the "validation" function of the campfire conversations and cave paintings for new platoons of mammoth hunters. Item (4) as the graphs show is not peculiar to astronomy or to the US from World War II up to 1981, though only the US astronomy curve has been extended to the present. Those are real data, collected by laboriously looking individually at, for instance, 31,161 papers published in the *Journal of the Chemical Society of London* between 1898 and 1965 and somewhat smaller numbers in each of 21 other journals and letters sections. The data almost went unpublished, because the first referee (the hero of the "5 percent a year" story, not entirely by chance) felt firmly that papers had got longer because they were reporting more science, that this was all to the good, and I should say so. I was not about to say so, and there the data might well have languished.

Enter again, however, Prof. W. H. McCrea, to whom I sent a copy of the manuscript (for reasons long forgotten). His response was that he could think of several explanations, not related to content, and a test to distinguish content-related from other hypotheses. These included increased numbers of authors for whom English was not the first language, less firm grounding in English grammar on the part of the native speakers (yes, his was exquisite), and enormous reduction in the amount of work involved in putting words and pictures on paper compared to the days of his first publications, when manuscripts were truly written by hand (and sometimes sent to the editor that way) and diagrams were drawn in India ink on Bristol board by the author. Word processors and computer-drawn diagrams became common about the time he stopped reading the literature (several years of blindness preceding his death), and I both shudder to think what he would say about the current mean paper and increasingly concur that ease of casting forth words is not an unalloyed good. At any rate, his comments inspired me to inflict the manuscript on a couple of historians of science and another editor. No two put forward quite the same set of whys, and the paper eventually appeared with a discussion section resembling the instructions for interpreting Rorschach ink blots (did you know Rorschach was only 37 or 38 when he died?).

Now comes the surprise. What there are not more of is journals in which to publish those more-and-longer astronomical papers. And there has been a gradual accompanying shift in publication patterns. Many of the prolific and well-known astronomers of the nineteenth

century placed half or more of their papers in academy proceedings and other venues in which astronomy rubbed pages with physics, biology, and so forth. Nearly all produced books recording their more extended efforts. And they made use of observatory publications, some restricted to authors at the particular observatory, many not.

I have found citations or library listings for more than 200 of these. They appeared regularly or sporadically, over a few years for some and many decades for others, were typically exchanged for other observatory publications rather than being sold by subscription (a blessing for astronomers in countries whose currencies were not freely convertible), and they carried something like 1/6th of the abstracted literature during their heyday before 1940. Their names are a litany of the exotic—Aarhus and Abastumani, Delaware and Dunsink, Lembang and Lemberg, Perth and Poona, Zose and Zurich. Some, like the series from Harvard and Groningen, were famous and carried fundamental papers. All are gone (except, perhaps, in virtual form as numbered lists of papers published by the staff in ordinary journals). The last to provide important results in separate, observatory publication form was the Dominion Astrophysical Observatory in Vancouver. I still use one or two of its late products.

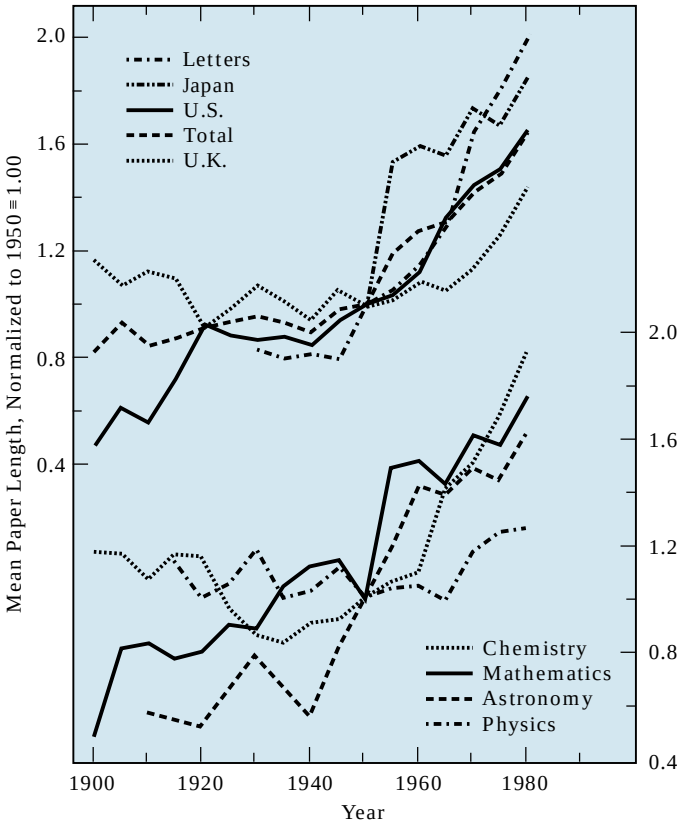
In contrast, the turn of the (new) century astronomer or astrophysicist publishes nearly all his papers in one or a few specialized journals (plus conference proceedings) and produces monographs only of the text and trade book variety, if at all. And the list of possible journals has shrunk. Five European ones (two French, two German, and one Dutch) merged in 1969 to form "the European journal" *Astronomy and Astrophysics*. *Bulletin of the Astronomical Institute of Czechoslovakia* and *Irish Astronomical Journal* (whose establishment was part of the post-war "validation" process) have since folded, aiming their former authors toward *A&A*.

The result is very considerable concentration of power in a few editorial hands. And, although two of those are mine, it is not a trend that I can regard as altogether benign. You will think immediately of the various sorts of web and Internet postings as a contrary trend, and you will be right to a certain extent. But the high-prestige ones are also under some control by small numbers of (I think) human beings, and the free-for-all ones are unlikely to be read. This was, of course, also true for the more obscure paper journals. The difference is that at least a few paper copies of these remain. I have read (not necessarily for very good reasons) publications from Dorpat (started in 1817) and Dushanbe (1934) and in the past few weeks papers from the 1728 and 1767 volumes of *Phil. Trans. Roy. Soc.* (special thanks to Brenda Corbin of US Naval Observatory for making these available), and rather doubt that the same will be possible for papers now posted when the year 2274, or even 2074, rolls around, though even the later of these is no more distant from us than Sir Isaac from Sir Bill.

Incidentally, detailed data exist to support the above remarks about publication patterns and have, so far, been rejected by two editors.

PEOPLE

The first astronomer could have flourished any time after 1366, the first physicist and the first scientist not until after about 1840, reflecting simply the first appearances of the words. The latter two are usually credited to William Whewell, though cases can be made for Mary Sommerville and an anonymous reviewer. "Scientist," at least, did not enter the lexicon without opposition, and Jacques Cattell, publishing his first directory about a century ago, chose to call it *American Men of Science*, rather than American Scientists, thereby setting the stage for decades of dispute and the even less euphonious present title, *American Men and Women of Science*. For once, "persons" would have been better, and "scientists" best of all. The three words are, in any case, now all normative, though if physicists and scientists are the equivalent of artists and pianists,



The Words In Mean Paper Index (WIMPI) for technical journals published in the U.S., U.K., and Japan in chemistry, math, astronomy, and physics. Letters journals were rare before the 1960s, and Japan ended paper rationing in the mid 1950s. Resonably careful account was taken of changes in page size, type font, and format in the journals over the years, virtually all of which increased the number of words per page, without arresting the inevitable upward creep in numbers of pages per paper.

we perhaps still need the equivalents of painters and piano players.

The first thing to be said about all three communities over the decades and centuries is, of course, "more." The cliche that more than half of all the scientists (astronomers, genome sequencers, dot.com-start-up entrepreneurs) who ever lived are still alive says just that the doubling time is less than the mean life time (so it could, in principle, be true even for all of humanity). All of the older professional societies to which I belong were started by 50–100 people, apparently, as noted above, a sort of critical mass. This includes American Physical Society (1898), American Astronomical Society (1899), the International Astronomical Union (1919), the American Association for the Advancement of Science (1850), and the Royal Astronomical Society (1820). All have grown considerably faster than their host populations to something $\times 10^3$ (RAS, AAS, IAU), something $\times 10^4$ (APS), or something $\times 10^5$ (AAAS) members.

The "more" are by no means uniformly distributed across the face of the earth, as the table shows (see page 54). There are stray factors of two, depending on just who you count, a strong dependence on national income, and, perhaps, threshold effects. Notice that the countries of Eastern Europe and the former Soviet Union seem to be over-achieving in astronomers. You are fairly unlikely to guess which country is most off scale (and I have yet to have anyone in an audience get it right who did not have specialized knowledge), for it is Vatican City, with five IAU members in a total population of less than 1000. If you are tempted to protest that probably none of them was born there, the same is true for a quarter of the Americans, a percentage which has held steady for a century (yes, there are data), but seems poised to grow rapidly in the near future, as has perhaps already happened for the physics community (no, I don't have data).

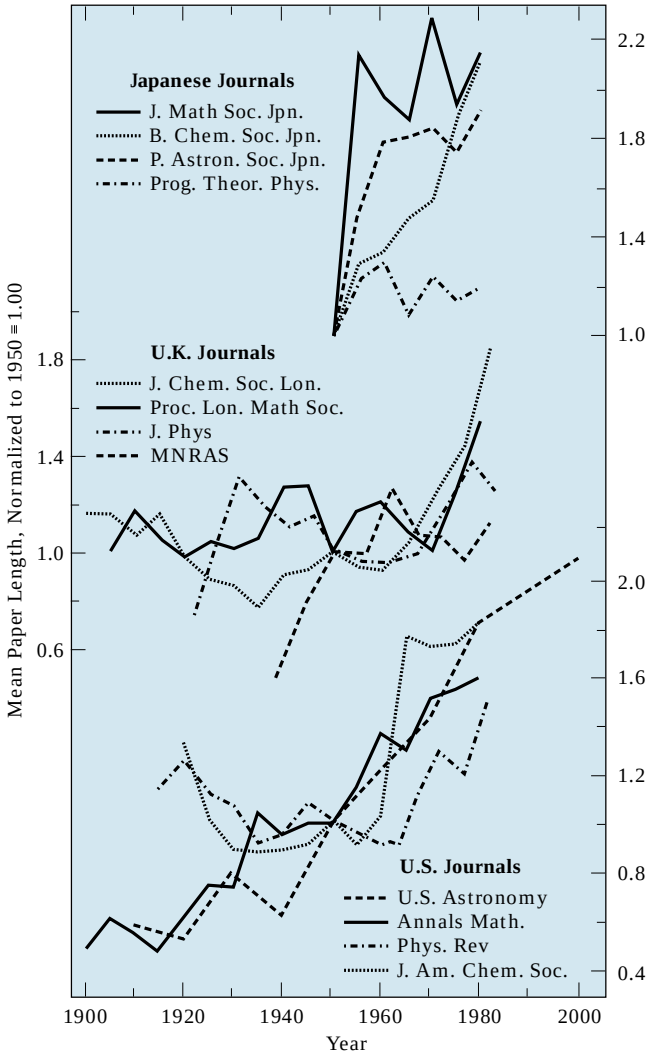
Nor are the people who do astronomy random samples of the national populations from which they are drawn. The great amateur astronomers of the seventeenth, eighteenth, and nineteenth centuries were all persons (well, all right, men, but more of this later) of at least modest independent means, provided by inherited land or the church (Bradley and Michell held orders) or brewing (Hevelius and Carrington, the co-discoverer

of white-light solar flares) or medicine (Draper of the catalogue). Data collected by Lankford show directly that elite astronomers in the US before 1940 were very much more likely to have had white collar or professional fathers than the general run of the population, with (from less direct data) the general run of astronomers somewhere in between.

Has this become less true through time? Probably, though I have no American data and only one British anecdote.* But two recent papers (one published, one submitted, in the journal *Scientometrics*) show that the current Danish scientific community members have/had parents on average about one social class (in a set of five) higher than the national population, and that, among young scientists in Croatia (!) the women come from higher up the food chain than do the men, which brings us, of course, to "the emancipation of women," as it is called in that Croatian paper (the referee suggested an alternative).

If you are a physicist, you know that most of your colleagues are men, though how often you are really aware of this probably depends on which side of the fence you sit on. I once silenced a large committee with the remark, "Have you noticed that it is easier to ask what may be a stupid question of a member of your own gender?" Quite possibly none of the (15:2) men had ever had the opposite experience. You also know that the F:M ratio drops as you go up the hierarchy from graduate student to members of the National Academy and Nobel Prize winners. If you "do the numbers," you will discover that the leaky pipeline is leakier for women than for men all the way from junior high school (sorry, middle school) to Department Chair and beyond, and also that the F:M ratio is slightly larger in astronomy than in physics at all levels.

** Once more Sir William, escorting me from London down to Sussex after an RAS meeting in about 1969, "Hmpmp. I seem to have a first class ticket, so I expect you better have one too." Experience never repeated with any younger astronomer.*



Further details of WIMPI-creep, broken down by journal. The curve for US astronomy (including Astrophysical Journal *and* Astronomical Journal*) has one additional point for 2000, showing that the increase in paper length continues. This is true even, for instance, for* Physical Review Letters*, where the four-page limit is now occasionally breached, and letters shorter than the maximum have gradually become scarcer than feathers on physicists.*

Rather than attempting to say anything about how or why, I would rather explore just a bit of the history of the process by which women have "broken into" astronomy. The first of whom we hear are assisting male relatives. Caroline Herschel is the best known, but there were also Sophia Brahe and Elizabeth Hevelius earlier and Margaret Huggins, whose husband (Sir William) is credited with the discovery that some nebulae are truly diffuse gas, not just unresolved star clusters. She was born the year (1848) Caroline Herschel died, and Cecilia Payne (1900–1974) could perfectly well have met her (but did not). Before I forget, Miss Herschel was the first woman to receive a Medal of the Royal Astronomical Society, in 1828. The second was Vera Rubin in 1996. Miss Herschel, Mrs. Sommerville, Lady Huggins, and Agnes Clerke (an astronomy popularizer of the late nineteenth century) were elected honorary fellows of the RAS.

Stage two are "the computers." Once upon a time, computers were people, hired to process data. The large American observatories all had them from the mid nineteenth century into the 1960s (I overlapped the last few at Mt. Wilson-Palomar). At Harvard, nearly all were women (of the upper classes as a rule, though Wilhelmina Fleming began as Pickering's housekeeper), elsewhere many but not all. The phenomenon was not unique to American observatories, though the ratio of computers to (male) astronomers was somewhat higher here than in the UK, Germany, and France from the 1880s to the 1930s. Nor, indeed, was the concept unknown outside astronomy. Three examples come to mind: (1) the women who scanned photographs from the bubble chambers of early nuclear and particle physics; (2) the women (possibly imaginary, but believable) who appear as co-authors with Cyril Burt on the papers reporting heritability of various traits in identical twins; and (3) the woman, described as "a computer" who carried out the tedious work of comparing many signatures to establish whether a particular one had been traced at the turn of the century (mentioned in an article on Hetty Green in the April 23–30, 2001, issue of the *New Yorker*). Even theorists sometimes had assistance with their computing, for instance Donna Elbert, who appeared on a good many of the papers of S. Chandrasekhar.

A woman named Ethel F. Bellamy, who originally assisted her uncle F. A. Bellamy in processing geodesy and earthquake data at Oxford, bridged the gap to a paid computer, working under Professor Turner, and indeed on to the third stage of independent scientist (seismologist) when World War II left her without supervision. She died in 1960 and must have been born about 1880. Her obituary appears in Volume 2 of the late, lamented *Quarterly Journal of the Royal Astronomical Society*. Also a bridger was Maria Mitchell (1818–1889) in the US, who began by assisting her father, worked as a computer for USNO, and ended on the faculty at Vassar.

Cecilia Payne (later Gaposchkin), who made a cameo appearance in the Spring 1994 *Beam Line*, Vol 24, No. 1, was by no means the first woman to earn a PhD in astronomy, but she does seem to have been the first to formulate her own problem (what are stars made of?), solve it (hydrogen and helium, mostly), and continue to work in the field the rest of her life. For more recent events in this aspect of demographics, circumspexi!

POWER, PAY, AND PRESTIGE

It has been nearly 20 years since I first wrote that if you want your papers to be cited a great deal, it pays to be a mature, prize-winning theorist, working on high energy astrophysics or cosmology at a prestigious institution. It also pays to be male. Large coefficients of correlation among desirable circumstances (academy memberships, directorships, large salaries, employment at a highly-ranked institution, winning prizes, being elected to society offices, having your papers accepted and widely cited . . .) were characteristic of the early American astronomical community as profiled by Lankford, and they remain so. If the correlation coeffi-

cients have gone down, it is perhaps only because there are now so many of us that few know all the others, introducing some randomness into the process. The people (OK men) who have chaired the decadal reviews of American astronomy make up a very small sample of six, who hale from Lick Observatory, Harvard, Princeton (one each the University and IAS), Caltech, and Berkeley. Astronomers at these places make up only 10 percent of AAS membership, so said chairs are not a random sample.

A curious counterexample is associated with various operations of the US government. Women could compete freely for NSF post-doctoral fellowships (though not quite for the predoctoral ones) long before they could apply with equal freedom for observatory and university positions. The hard working people who have run the various astronomy and astrophysics program at both NSF and NASA over the years have typically not come from the institutions correlated with NAS membership and large citation rates. And Dorrit Hoffleit (b. 1907 and still going strong at Yale) reports that she took a factor of two pay cut to return to Harvard just after World War II from a civil service (equal-pay) position at Aberdeen Proving Ground.

I won't absolutely swear that money talks, but it definitely murmurs from time to time. During the relatively stable period from 1900 up to the US entry into World War II, a miscellany of numbers (a few from Dr. Hoffleit, a few from Mrs. Fleming's diary, a few from my own family) indicate the following hierarchy: male astronomers at Harvard were paid more than male astronomers at Mt. Wilson, who were paid more than women astronomers anyplace (who were about on par with other women white collar workers), who were paid more than male laborers, who were paid more than female laborers. Unless corrected for inflation, the numbers all sound absurdly small (the Harvard male salary that Mrs. Fleming envied was $2500 per year), but the hierarchy remains true down to the present, except that some kinds of traditionally masculine blue collar work are now better remunerated than traditionally female white collar work.

Of the various, documented underrepresentations of women, the one that has changed most rapidly is service in professional organizations. No woman presided over the American Astronomical Society from its 1899 founding to 1975. There was one in the 1970s, two in the 1990s, and two (already, including a president-elect) in the 2000s.

Committee women are still outnumbered by committee men, but by a smaller factor than women by men among the general society membership. The International Astronomical Union has yet to elect its first female president, but has had half a dozen women among its vice presidents and secretaries general, all within my memory (which does not go back to the founding in 1919). If you have your APS directory handy, you can chart similar trends in its leadership.

Make of it all what you will. My relevant action items are (a) try to keep an eye out for the possibility that we may be encouraging women graduate students to do theses in less prestigious subfields than the guys (no data, just a recent suspicion), and (b) settle down and do the requisite paper work to apply for the next pay rank, so that I will no longer be the oldest Professor IV in the entire UCI school of physical sciences!

Finally, it must be said that there are a great many wonderful stories (a few of which I know) not told here, of the beginnings of the individual journals and societies, the "pro-am" connection in astronomy (another of its unique aspects), the tragic (and occasionally happy) effects of wars and (other forms of) politics, the transformation of our community from a family to a village and, soon, to a town, and much else.

Astronomers as an Economic Bellwether

Country	*N: No. of IAU Members in 2000*	*N÷GDP (dollars 1995)*
USA	2235	2.7×10^{-10}
Canada	199	3.0×10^{-10}
Australia	191	4.8×10^{-10}
New Zealand	26	4.0×10^{-10}
South Africa	46	1.7×10^{-10}
UK (Britain)	535	4.3×10^{-10}
France	609	4.6×10^{-10}
Germany	488	2.9×10^{-10}
Italy	409	3.4×10^{-10}
Netherlands	167	8.7×10^{-10}
Belgium	88	3.7×10^{-10}
Denmark	52	4.2×10^{-10}
Norway	22	1.8×10^{-10}
Sweden	95	5.4×10^{-10}
Switzerland	70	4.0×10^{-10}
Vatican City	5	2.9×10^{-8}
Iceland	4	7.8×10^{-10}
Ireland	33	4.9×10^{-10}
Portugal	17	1.3×10^{-10}
Spain	204	3.6×10^{-10}
Austria	31	1.8×10^{-10}
Finland	37	3.6×10^{-10}
Greece	89	6.4×10^{-10}
Turkey	53	1.4×10^{-10}
Israel	45	9.6×10^{-10}
Japan	448	1.4×10^{-10}
Korea (South)	51	8.0×10^{-11}
China, ROC	23	7.4×10^{-11}
China, PR	368	8.6×10^{-11}

Country	*N: No. of IAU Members in 2000*	*N÷GDP (dollars 1995)*
Russia	344	5.0×10^{-10}
Armenia	31	3.3×10^{-9}
Estonia	22	2.4×10^{-9}
Latvia	8	7.9×10^{-10}
Lithuania	12	7.9×10^{-10}
Georgia	19	2.4×10^{-10}
Tajikistan	8	1.9×10^{-9}
Ukraine	119	9.5×10^{-10}
Uzbekistan	8	1.3×10^{-10}
Poland	117	4.4×10^{-10}
Czech Rep.	71	6.4×10^{-10}
Slovak Rep.	27	5.8×10^{-10}
Croatia	13	6.2×10^{-9}
Bulgaria	50	1.5×10^{-9}
Hungary	41	5.4×10^{-10}
Rumania	37	3.1×10^{-10}
Algeria	3	2.5×10^{-11}
Egypt AR	39	1.3×10^{-10}
Iran	15	3.9×10^{-11}
Saudi Arabia	11	5.3×10^{-11}
India	227	1.4×10^{-10}
Indonesia	13	1.3×10^{-11}
Malaysia	7	3.0×10^{-11}
Mexico	83	1.1×10^{-10}
Argentina	90	2.5×10^{-10}
Brazil	109	1.0×10^{-10}
Chile	368	2.2×10^{-10}
Peru	1	8.7×10^{-11}
Uruguay	6	2.0×10^{-10}
Venezuela	11	5.8×10^{-11}

Things to Read

John Lankford, **American Astronomy: Community, Careers, and Power 1859–1940**, Univ. of Chicago Press, 1997.

Jared Diamond, **Guns, Germs, and Steel**, the 1999 winner of the Phi Beta Kappa award for science writing.

William H. McCrea, "Clustering of Astronomers" in *Annual Reviews of Astronomy and Astrophysics* 25, 1 (1987).

Andre Heck. **Star Guides**. Now online through the NASA and Strassburg centers for astronomical data. Some of the numbers require thoughtful interpretation (for example, the American branch of Oxford University Press is not actually pre-Columbian, though the Oxford branch is).

Michael Hoskin, Ed., **A Concise History of Astronomy**, Cambridge Univ. Press, 1999.

Dennis Danielson, Ed., **The Book of the Cosmos**, Perseus Publishing, 2000.

Edward Harrison, **Cosmology, the Science of the Universe** (second edition), Cambridge University Press, 1999.

Virginia Trimble. Oh, absolutely anything she wrote! But data alluded to here appear in: PASP 96, 1007, 1984 (paper lengths), QJRAS 26, 40, 1985 (citation rates), PASP 100, 646, 1988 and *Scientometrics* 48, 403, 2000 (aspects of current American astronomical community), *Scientometrics* 20, 71, 1991 (effects of degree from prestigious institution), QJRAS 34, 235 & 301**,** 1993 (more citation rates), IOP Encyclopedia of Astronomy and Astrophysics, 2000 (societies and journals, abbreviated version, with M. A. Hoskin)

Oxford English Dictionary remains the source, but when you don't have time to lift it, **Funk and Wagnalls** isn't bad.

There is a whole book, each, on the origins of the American Astronomical Society (edited by David DeVorkin), the International Astronomical Union (written by Adriaan Blaauw), two on the Royal Astronomical Society, and undoubtedly many others. You may or may not want to know that much about the subject.

CONTRIBUTORS

JEFF CORBETT is an accelerator physicist at the Stanford Linear Accelerator. He holds a BS degree in EECS from UC Berkeley and a PhD in Applied Plasma Physics and Fusion Engineering from UC Los Angeles where he worked on TCX-II and the TEXTOR tokamak in Jülich, West Germany. Originally from the San Francisco peninsula, he returned to the area in 1989 to work on SPEAR, PEP, and the SLC damping rings. He is currently coordinating the accelerator physics effort for the SPEAR 3 light source at SSRL.

TOM RABEDEAU studied phase transitions of two dimensional systems in his thesis work at the University of Washington. Rather than graduate into a real, three dimensional world, he subsequently utilized synchrotron radiation to probe thin film and interfacial phenomena during post docs at Harvard University and the IBM Almaden Research Lab. In 1993 he joined the SSRL staff where most of his time has been spent developing synchrotron beam line optics and instrumentation.

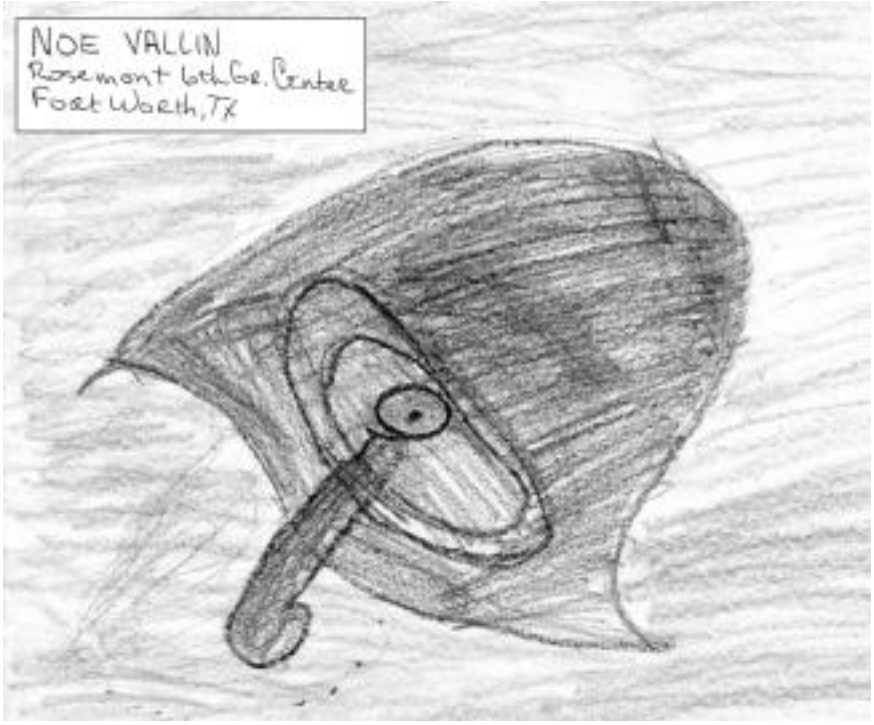
PASCAL ELLEAUME is Director of the Machine Division at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. After graduating at the Ecole Normale Superieure in Paris, he has made his PhD in an international collaboration which developed the first storage ring Free Electron Laser on the storage ring ACO at LURE, Orsay. He joined the ESRF in 1986 and became the leader of the insertion device group. His topics of interest include storage ring physics, synchrotron radiation and free electron lasers.

SOL GRUNER is Professor of Physics at Cornell University and Director of the Cornell High Energy Synchrotron Source (CHESS). He received his Ph.D. from Princeton University and then joined the Princeton faculty until moving to Cornell in 1997. His professional interests are in the continuum from soft-condensed matter physics to biological physics. He has also spent a large part of his career developing synchrotron radiation instrumentation and techniques with which to probe the structure and properties of materials. Current interests include the structure of self-assembling membrane and copolymer systems, the effects of pressure on proteins, and imaging pixel array X-ray detectors. Gruner and Maury Tigner, the Director of the Cornell Laboratory of Nuclear Studies, are leading the effort at Cornell to develop an Energy Recovery Linac synchrotron radiation X-ray source.

DONALD BILDERBACK is Associate Director for the Cornell High Energy Synchrotron Source and Assoc. Adjunct Professor of Applied and Engineering Physics at Cornell University. He received his PhD in Physics at Purdue University in 1975. He has made his career in building up synchrotron radiation sources and X-ray optics at CHESS and is a generalist in synchrotron radiation experimental research. In 1995–1996 he was a visiting scientist at Hasylab at DESY.

CLAUDIO PELLEGRINI is a Professor of Physics at UCLA and Chair of the Department of Physics and Astronomy. He studied in Rome, and worked at the Frascati National Laboratory on one of the first electron-positron colliders, Adone. He moved to Brookhaven in 1978 and UCLA in 1989. In Frascati his main research interests were the physics of relativistic electron beams and collective instabilities. He did the first theoretical model of the Head-tail instability in storage rings, and developed, with Rodolfo Bonifacio and Lorenzo Narducci, the first theory of a Self Amplified Spontaneous Emission free-electron laser (SASE-FEL). In 1992 he proposed the development and construction of a 0.1 nm X-ray SASE-FEL using the SLAC linac, what is now the LCLS project. He has been awarded the International FEL Prize and the American Physical Society Wilson Prize. He has been a member of HEPAP and of the SLAC and Cornell Scientific Advisory Committees.

JOACHIM STÖHR joined Stanford as Professor and SSRL as Deputy Director in January 2000, coming from the IBM Almaden Research Center where he was a research staff member for 15 years and managed several departments including condensed matter science and magnetic materials and phenomena. Before IBM he was a senior staff scientist at Exxon Corporate Research Laboratory. His research has focused on the development of soft X-ray techniques for the study of materials surfaces and interfaces. He played a major role in developing surface extended X-ray absorption fine structure (SEXAFS) and he also developed the near edge X-ray absorption fine structure (NEXAFS) technique. More recently he has turned his attention to the use of polarized X rays for the study of magnetic materials and phenomena and he pioneered X-ray magnetic dichroism spectro-microscopy for the study of ferro- and antiferromagnetic structures with nanoscale dimensions.



VIRGINIA TRIMBLE submitted her first scientific paper, on the astronomical significance of the shafts leading out of the King's chamber in Cheops' pyramid, exactly half way between the year when Cecilia Payne completed her thesis showing that the stars are made mostly of hydrogen and helium and the present moment (2001 – 1963 = 1963 – 1925). Trimble's PhD dissertation concerned the Crab Nebula, the remnant of a supernova seen in 1054, and showed that relativistic particles and magnetic field were pressing outward to accelerate the expansion of the nebula. The two drawings (by Texas sixth graders Noe Vallin and Santos Castillo, students of Sallie Teames in Fort Worth) derive from a Chandra X-ray satellite image which shows how that relativistic energy is fed from the central pulsar via a jet into the body of the nebula. A possible lesson to be drawn from this quarter's "Universe at Large" piece is that scientific problems look different to different generations. The original drawings are in various shades of blues and purples, while "my" Crab Nebula was staunchly black and while. By the time another 38-year interval has elapsed, Noe and Santos could easily have had PhD students who have had students of their own, and their drawings will surely be at least three dimensional and perhaps four. The drawings, incidentally, were part of a group of several dozen kids' interpretations of astronomical images that were displayed at the summer 2001 meeting of the American Association of Physics Teachers, where Trimble was the Klopsteg Memorial Lecturer.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