

A Possible Future

Microfabrication for Millimeter V

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Large and small scales are intertwined throughout physics. Huge accelerators produce beams for atomic, nuclear, and particle science. In an interesting, new twist, microfabrication could be the key to the accelerators of the future.

INSTRUMENTS AND THEIR CAPABILITIES often determine the frontiers of science. The particle physics frontier is the highest achievable energy, and there has been exponential growth in energy because of breakthrough concepts, inventions and discoveries, and application of new technologies to particle acceleration. The Fermilab Tevatron is an example—there the earlier breakthrough concepts of strong focusing and colliding beams are combined with superconductivity, one of the great discoveries of modern physics, and the application of superconducting technology to accelerator magnets.

Synchrotron radiation sources are having profound impact on a wide range of sciences from condensed matter physics to protein crystallography. Those synchrotron radiation sources were made possible by the invention of klystrons which are efficient high power radio-frequency (rf) amplifiers, strong focusing, and sophisticated magnet technology.

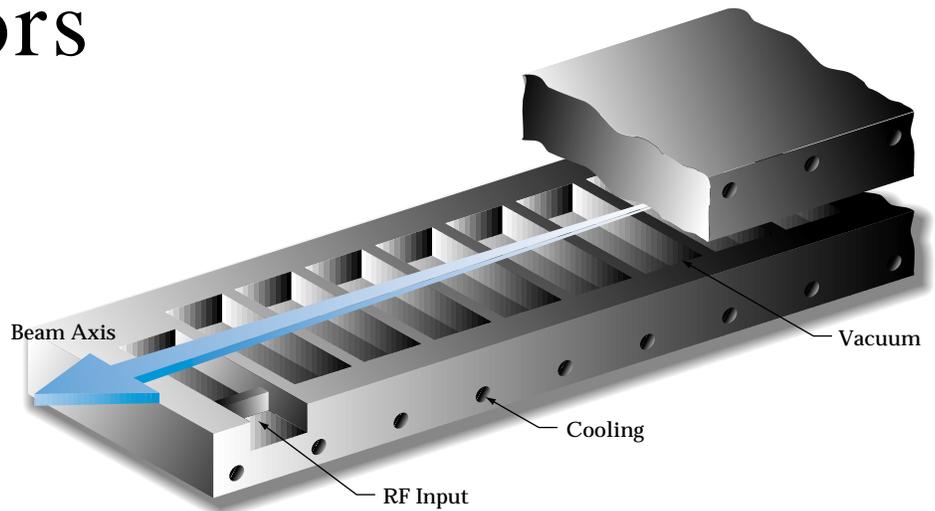
What concepts, discoveries, and/or technologies will determine the future frontiers of accelerator-based sciences? In the near term the CERN Large Hadron Collider and the NLC—or ILC—the international linear collider being designed jointly by KEK and SLAC, depend on extensions of magnet and rf technologies. Superconducting rf is becoming more and more important for high current applications in nuclear and particle physics, for single-pass coherent light sources and for linear colliders with the TESLA project at DESY. However, none of these are breakthroughs—and without breakthroughs the costs of accelerators are becoming formidable.

ve Accelerators

Our interest has been in exploring new technologies which are riskier but have breakthrough potential. One such technology is micromachining that makes it possible to think about millimeter-wavelength accelerators that have millimeter-size features. These accelerators have potential for both particle physics and synchrotron radiation, but they cannot be realized from straightforward extrapolations of long wavelength accelerators like the classic SLAC 10-cm wavelength, S-band linac. We do not imply that there are not formidable problems; rather we see an opportunity if the problems posed can be solved either through technological developments or conceptual insights.

MICROFABRICATION

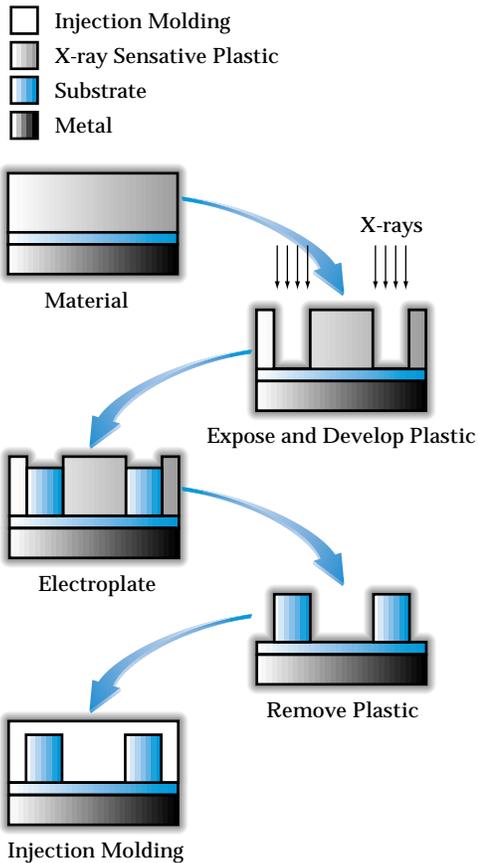
In the last few decades microfabrication has made impressive progress. High speed milling machines and shaped diamonds allow 2–5 μm precision. Tiny high pressure water jets and laser beams provide fast and precise cutting. Pressureless wire electrodischarge machining reaches the accuracy limits (below 1 μm) of the best measuring devices. Ion etching and lithographic techniques, the workhorses of the semiconductor industry, have been modified for mechanical manufacturing. The youngest offspring is shape deposition manufacturing where metallic powder is injected into the melt-pool of a scanning laser focus.



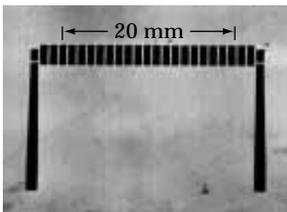
Traditionally linac structures are cylindrical, but a more open structure is needed for adequate vacuum pumping as dimensions shrink to the millimeter scale. The planar, muffin-tin geometry shown in the illustration above seems to be the best candidate. It consists of two separate halves with a wide gap in between that provides sufficient pumping conductance. This simple two-dimensional structure has mechanical tolerances in the 1 to 3 μm range. These tolerances and the planar geometry make wire electrodischarge machining and deep X-ray lithography with the German acronym LIGA that stands for Lithographie, Galvanoformung, Abformung meaning lithography, electroforming, and molding.

Electrodischarge machining (EDM) is a relatively cheap and conceptually simple process, and the tolerances achieved are remarkable. The workpiece and an electrode are immersed in a dielectric fluid, and a high voltage pulse produces an arc between the electrode and workpiece which erodes the surface. Since the electrode is eroded as well, it has to be replaced, and a wire electrodischarge machine uses a thin, spooled

A muffin-tin accelerator structure.



Simplified lithography process.



A 94 GHz muffin-tin accelerator fabricated with LIGA by Argonne National Laboratory scientists (top) and the center of a 25-cell, 91 GHz accelerator machined with EDM at Ron Witherspoon, Inc. (bottom).

tungsten wire that cuts through the workpiece like a fretsaw. The cutting speed strongly depends on the thickness of the workpiece and the desired surface finish. Today, the best machines cut 1 mm per minute in a 1 mm thick copper sheet with sub-micron precision and 1 μm surface roughness. A nearly optical surface roughness of 0.1 μm is possible at lower speeds.

LIGA has been developed primarily at Karlsruhe, Germany, for fabricating microstructures with extreme height to width ratios. In a first step (Lithographie) a thick resist layer of plastic is irradiated through a mask by synchrotron radiation (see illustration on the left). By developing the exposed resist layer, a template is produced which can be filled with a metal by electroforming (Galvanof ormung). After stripping the unexposed resist a metallic microstructure is obtained. A third and fourth step allow for mass fabrication. A negative of the microstructure is obtained by injection molding of thermoplastic material (Abformung). This negative serves as a template for subsequent electroforming processes. Many structures can thus be made from the original master.

Today LIGA is an advanced technology. Many components such as acceleration sensors, microturbines, electrostatic motors, and linear actuators are being manufactured by industry. The achievable accuracy is around 1 μm or better, and structure depths of 600 to 800 μm are possible. This is exactly what is needed for a muffin-tin structure.

Both EDM and LIGA have the promise of meeting the tolerances

required for accelerator applications, and they have relative advantages and disadvantages that could prove crucial. Two drawbacks of EDM are that the structure must be constructed in layers and diffusion bonded together and that the process is not well suited for mass production. LIGA is expensive for prototype fabrication since it requires an X-ray mask which typically must be manufactured in three steps, a synchrotron radiation beam line for a many-hour exposure of the plastic resist, and facilities for developing the resist and electroforming the structure which proves to require care and experience. It should be much cheaper when producing large numbers of identical structures because molding can be used. Open questions depend on the application and relate to surface quality and the suitability of electroformed copper for high gradients.

mm-WAVE POWER SOURCES

In many ways the availability of high power sources is critical for accelerator development, and at the present time such sources for mm wavelengths are scarce. The only real high power sources are gyrotron oscillators with up to 1 MW power, and they are large and expensive. Modifying them to be amplifiers reduces the power rating and efficiency dramatically. The Naval Research Laboratory, working in collaboration with CPI and Litton, is developing a 100 kW gyrotron amplifier. Another candidate for high power at short wavelengths is the ubitron, but it is better suited as an oscillator, and significant development is needed for it to be a high power amplifier.

Microfabrication offers a new and different approach to a mm-wave power source—a large number of small, simple, and cheap tubes with a minimal power distribution network in contrast to the usual configuration of a small number of high power tubes with a complex distribution circuit. A mm-wave klystron should be able to generate up to 150 kW and would have good efficiency. Using permanent magnet focusing, developed at SLAC for X-band (3 cm wavelength), such klystrons would meet the goal of being small, simple, and cheap.

A 150 kW klystron would be an ideal power source for compact, low energy accelerators, but high energy accelerators require substantially more power. Possible ways to achieve that are discussed in the high energy accelerator section.

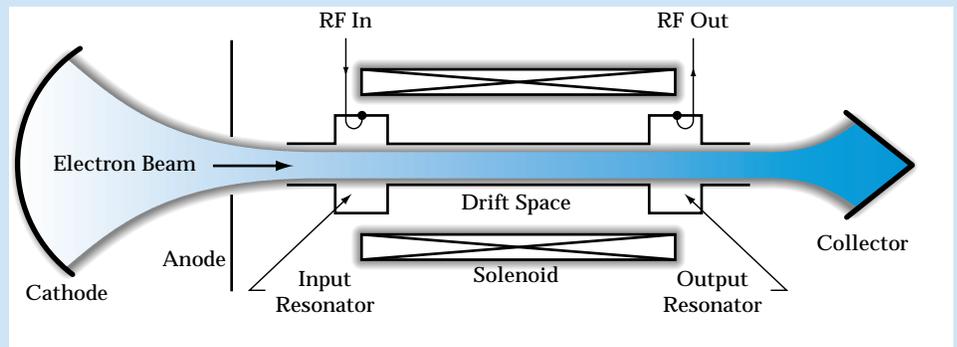
COMPACT, LOW ENERGY ACCELERATORS

An advantage of mm-wave accelerators is the small, planar geometry. Complex structures can be realized with lithography on a single support with no extra fabrication costs, and the designer's skill—rather than cost or space—becomes the limiting factor. This leads to new ideas for compact, low energy accelerators that could include a small, light linac for medical applications, a space-based accelerator, or a compact synchrotron radiation source.

Some applications require standing wave cavities where forward and backward traveling waves conspire such that the accelerating gradients have alternating signs from cell-to-cell. It isn't possible to feed many

cells of a standing-wave cavity from a single input coupler, and these structures are also sensitive to fabrication errors. The solution is to use specially designed coupling cells that do not contribute to the acceleration but increase and symmetrize the coupling. Such a structure is normally complicated and expensive, but with lithography one gets it for free.

Klystron Amplifier Principle

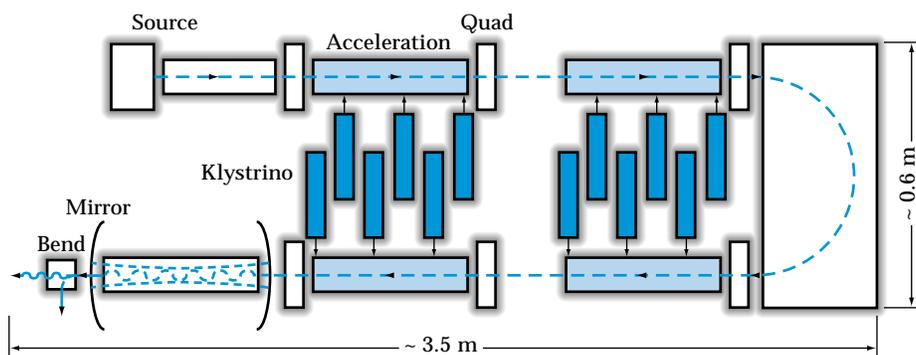


Basic klystron arrangement.

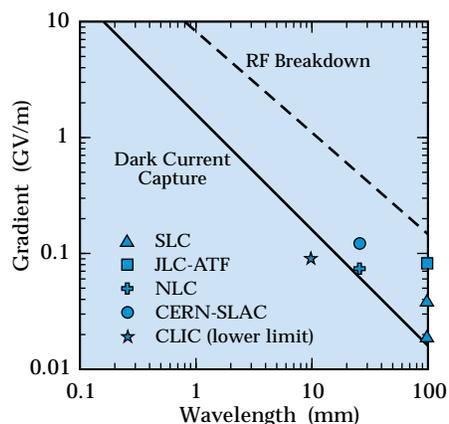
THE PRINCIPLE OF THE KLYSTRON AMPLIFIER is shown in the figure above. A heated cathode emits a continuous electron beam of relatively low density. The beam is accelerated and at the same time focused by an electrostatic anode before entering an input

resonator that is fed by a low power input signal. There the beam receives a velocity modulation that depends on the input signal. This dependence makes the klystron an amplifier, as opposed to an oscillator. This is critical because it allows control of the multiple klystrons needed in an accelerator. After a drift space, where the beam is focused magnetically, the originally continuous beam is bunched which corresponds to a large

rf current. It enters the output resonator where it loses energy to an external load (usually the accelerator). The leftover beam with a strongly reduced kinetic energy is dumped into the collector. The klystron as described would be fully operational, but it would have low efficiency and low gain. High power klystrons have additional idling resonators between the input and output resonators to improve the bunching process.



A compact, tunable radiation source. The linac is composed of 16 cm long rf structures with 140 cells each. Every structure is powered by a 100 kW klystron.



Gradient limits from dark current capture and rf breakdown together with achieved gradients.

A mm-wave rf undulator is under development at Argonne National Laboratory's Advanced Photon Source. When a relativistic electron beam travels through an rf undulator, it is subjected to transverse forces from the rf fields, and it radiates coherent, quasi-monochromatic radiation similar to that from a conventional magnetic undulator. At around 100 GHz the undulator period can be as short as 1 mm. This is substantially smaller than possible with a magnetic undulator, and the electron beam energy can be lowered for the same photon energy.

Scientists at the Technische Universitaet in Berlin are interested in low energy accelerators with gradients between 1 and 10 MV/m, and the main concerns are small size, low weight, and low cost. One example is a compact 50 MeV linac that could power either an undulator or a free electron laser and generate tunable radiation down to 50 nm wavelength. The figure at the top of the page shows some details. The klystron and beam focusing device are integrated such that the whole accelerator fits on one table apart from power supplies. For the future it would be attractive to have integrated machine modules. That means a certain number of rf structures together with

a klystron, beam monitors, and magnetic focusing devices are mounted on a single support and all fabricated lithographically. A module then needs only connections to the power supplies, vacuum pumps, and low power electronics to become a working accelerator.

PARTICLE PHYSICS

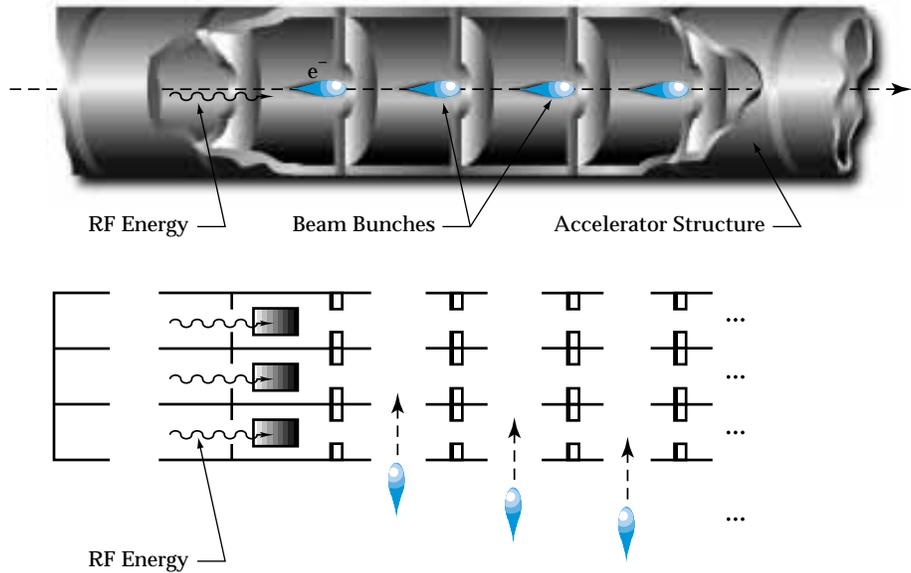
The potential advantage of mm-wavelength accelerators for particle physics is a higher accelerating gradient. It is known from experience with 1–10 cm wavelengths that gradients are limited by dark current capture, which is the acceleration of field emitted electrons to relativistic energies, and by rf breakdown which is a complex phenomenon involving field-emitted electrons, X rays, ions, rf fields, and surface conditions. The maximum gradients from these phenomena scale approximately inversely with wavelength as shown in the figure on the left.

These wavelength dependencies give mm-wavelengths breakthrough potential, but short wavelength, high gradient accelerators require much more than a straightforward extrapolation from longer wavelengths. Our colleague Dave Whittum of SLAC has a lighthearted, but also serious, transparency that summarizes the situation were such an extrapolation made, "The power source doesn't exist; the accelerator would melt in one shot; the beam density dilution is unacceptably large; the beams destroy themselves during the collision; and the collider would require a dedicated power plant." This is fertile ground for imaginative solutions.

Begin with pulsed temperature rise and associated destructive effects. Radio-frequency losses are concentrated on the surface, and the resultant heat does not diffuse significantly into the metal during the rf pulse. The surface volume is repeatedly stressed beyond the yield strength and eventually the surface could fail. This has been seen with 40°C temperature rise in high power laser mirrors where surface quality is critical.

Forty degrees is far below the temperature rise for interesting accelerating gradients, but there is anecdotal evidence that pulsed temperature rises well above that do not cause problems for rf cavities. An experiment using power from the X-band klystrons is in progress to study this systematically. The first run had the tentative result that rf properties of copper were not affected after 10^7 pulses with over 100°C pulsed temperature rise. This apparatus will also allow testing of materials with higher yield strength and testing of ideas to reduce pulsed temperature rise such as a thin diamond coating that is transparent to rf but serves as a heat sink thereby reducing the temperature rise by up to a factor of three.

Beam-induced fields, or wakefields, reduce the beam phase space density. If the reduction is sufficiently large, it is impossible to focus tightly at the interaction point. Wakefield effects are proportional to charge, offset of the trajectory from the center of the aperture, and vary inversely with the cube of the wavelength. The latter is obviously bad for short wavelengths. The best way to reduce wakefields is to precisely align the beam and accelerator.



Experiments with a prototype X-band structure have demonstrated that wakefields can be detected and are precise position monitors. A wakefield-derived signal can be used as the input to a feedback loop that maintains alignment. Such feedback loops could provide the wakefield control that is needed for millimeter wavelengths. To the degree they do not, the charge will have to be lowered.

But, since luminosity depends on the beam charge as well as phase space density, this is also bad. It is possible to get high luminosity with low charge individual bunches by accelerating a large number of bunches, one behind the other, with a long rf pulse (see the illustration at the top of the page). This cannot be extended to millimeter wavelengths because the pulsed temperature rise is proportional to the square root of the rf pulse length. Dave Whittum has conceived of a simple, elegant way to accelerate multiple bunches: let

The conventional and matrix accelerator approaches to multiple bunch acceleration.

the rf and beam travel in perpendicular rather than parallel directions. This “matrix accelerator,” shown on the previous page, accelerates multiple bunches while keeping the rf in a single cell for only a short time. Like many conceptual breakthroughs, this solves a problem but introduces new ones which, hopefully, are easier to solve. Parallel beams must be combined; the rf structure remains to be designed and shown to be practical (lithography could be the key); and a source for the required high power rf needs to be invented.

To put a scale to the rf power, the gradient depends on the square root of the rf power, and a muffin-tin structure requires 40 MW input power for 200 MV/m gradient. If such powers are possible they require both a power source beyond the 150 kW klystron we discussed and pulse compression. A high power ubitron may be the right power source. We will know better when the klystron development is further along. With a ubitron one could reach multi-megawatt power levels for several microseconds. This must be compressed down to a few nanoseconds to have the appropriate peak power and pulse length for the matrix accelerator. Pulse compression is routine; it is used in the SLAC Linear Collider and is part of the NLC rf system. The new aspects are the degree of compression and the almost certain need for active switching of high power rf which has been demonstrated at moderate powers.

SOME OF WHAT we have written about is futuristic; some is not. Some will come to pass, and some will not. The 150 kW klystron and low energy compact accelerators could be realized in the near term. When they are, they will be direct results of thinking about and applying microfabrication to accelerators.

A millimeter-wavelength, 5 TeV collider is an ambition to study physics at a new energy frontier. It will take originality and creativity to make it possible, and even so it may never be. It is a promising direction, and, as with all basic research, one pursues it for that reason while at the same time realizing that the unexpected is expected. 