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A New Storage-Ring Light Source

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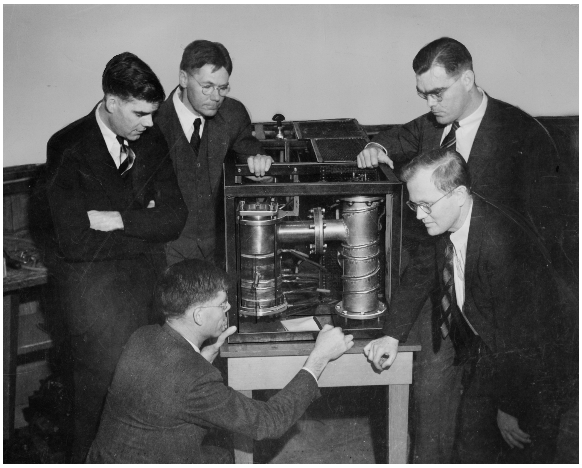
A recently proposed technique in storage ring accelerators is applied to provide potential high-power sources of photon radiation. The technique is based on the steady-state microbunching (SSMB) mechanism. As examples of this application, one may consider a high-power DUV photon source for research in atomic and molecular physics or a high-power EUV radiation source for industrial lithography. A less challenging proof-of-principle test to produce IR radiation using an existing storage ring is also considered.

Keywords: Coherent radiation source, Storage ring, Steady-state Microbunching, Lithography.

1. Coherent E&M radiation field

This conference is about Yang-Mills field. Here I wish to talk about the coherent radiation of the electromagnetic field, the very first known Yang-Mills field (although abelian). Let me start with a short remind of how the technology of coherent E&M radiation has evolved over time. Generation of coherent E&M radiation first started with the technology of vacuum tubes of the early 1900s. The uses included radios, antenna, television, and then sped up by the war efforts, the radars. The invention of klystron in 1937 pushed this line of technology to high sophistication. We also have microwave ovens and wi-fi.



[Courtesy: Stanford News Service]

Invited to the Conference on 60 Years of Yang-Mills Gauge Field Theories
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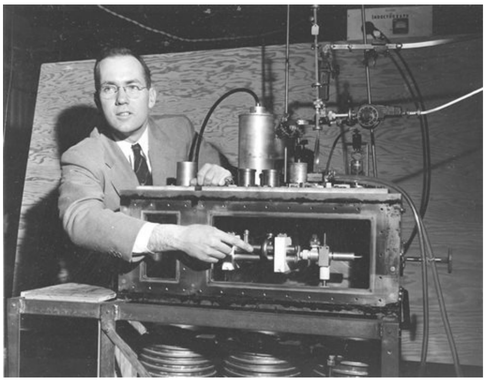
But the need of coherent radiation continued to grow, particularly towards higher frequencies. The approach based on vacuum tubes and klystron technology ran into a severe limit when the radiation frequency is pushed up towards 100 GHz (10^{11} Hz). As the desired frequency increases, the electron-beam/vacuum-tube system gets smaller due to the necessary boundary conditions of the radiation fields, and the required technology becomes increasingly difficult. The difficulty originates from the dominance of the boundary conditions for the coherent radiation field imposed by its being confined to the interior of the devices.

A break through occurred in 1955 when laser was invented. Boundary condition imposed by the coherent field is no longer a limitation, and lasers completely took over as the ideal source of coherent radiation at high frequencies.



[Courtesy: AP Photo/File]

But lasers are still bounded. Although the radiation field is in free space, the radiating electrons are bound by the atoms.[a] The energy levels available to lasers are limited by the available discrete energy levels in atoms and molecules, and as a result, the radiation frequency is limited to 10^{15} Hz, or deep ultraviolet frequencies. For a long while, there seemed no hope for coherent radiation with higher frequencies, such as soft or hard Xray (approaching 10^{18} Hz) simply because there were no available discrete energy levels at those frequencies.

Then the history is such that the electron beam technology returned to the stage, this time without boundary conditions[2]. With the invention of the free electron laser in 1971, not only the electromagnetic fields have no boundary conditions, but also neither do the radiating electrons – thus the term “free” electron laser. Coherent Xrays became possible this way. FEL is a tremendous game changer. The trick here is to somehow make the free electron beam to “microbunch”.

[a]Alternatively one might say that the radiation still has to satisfy the boundary condition within the confinement of the atoms.

[Courtesy: Chuck Painter / Stanford News Service]

Microbunching is a wonderful thing. The microbunched electron beam not only allowed the radiation frequency to be raised to Xrays, but also due to the coherence of the radiation process, the power of radiation is increased by a factor of N, where N, the number of electrons in the microbunch, is a very large number. The peak power of the FEL radiation is therefore extremely high. When the LCLS FEL radiation was commissioned in 2009[3], the peak Xray brilliance was raised by 10 orders of magnitude overnight, mostly due to the microbunching factor of N. Not only the power source has changed, all the experimental instrumentation, detection, and methodology all had to change.

So the fact that these E&M radiations are coherent serves *two* purposes, both are important. First and more obvious, when coherent, the radiation is a laser and comes with all its analyzing and signal carrying power. Second and perhaps less noted, the coherence also makes the raw radiation wattage extremely high due to the additional factor of N.

In passing, I should mention that the pathway to free up the bound electrons as a means to reach higher frequencies applied to both the electron beam and the laser technologies. In the laser technology, high harmonic generation (HHG) technique was invented[4], which is another idea trying to free up the bound electrons in atoms. Perhaps we summarize the landscape with the following table.

	Bound systems		Free systems
Electron beam technology	vacuum tubes klystrons (10^{11} Hz)	$\to$	free electron lasers (FEL) (10^{18} Hz)
Laser technology	molecular lasers atomic lasers (10^{15} Hz)	$\to$	high harmonic generation lasers (HHG) (10^{18} Hz)

As mentioned, the peak power has been raised to extreme high levels by the FEL. However, application demand never ceases. FELs have the drawback that although its peak power is extremely high, its average power is low. This is because FELs use linear accelerators, and linear accelerators have notoriously low repetition rates.

The issue of repetition rate brings us to the consideration of storage rings. The traditional synchrotron radiation from a storage ring produces high power mainly because the beam circulates with high repetition rates – the beam is reused every revolution. There are of course many electrons in the beam and they all radiate, and that gives a high radiation power, but the electrons all radiate individually, and that is no comparison with the high peak power in the FELs when electrons radiate coherently.

It seems apparent that to make a next step in the development of high power coherent radiation sources, one must try to keep the extremely high peak power, while somehow maintain a high repetition rate. Repetition rate is readily available from storage rings. The high peak power requests the beam to be microbunched. This leads to the introduction of a "steady state microbunching" (SSMB) technique to be applied to electron storage rings as powerful radiation sources [1]. If developed, the very large number of coherent electrons will also likely outcompete the HHG.

2. Lithography and Moore's Law

Powerful radiation sources have applications in many areas, from research tools to industrial applications. Perhaps let me mention one of the possible industrial applications, namely to lithography, as one prominent example.

Semiconductor industry is important contributor in our economy. Its 2012 worldwide business:

10-20 B$	wafer fabrication equipment
250 B$	semiconductor devices
~2 T$	consumer electronics

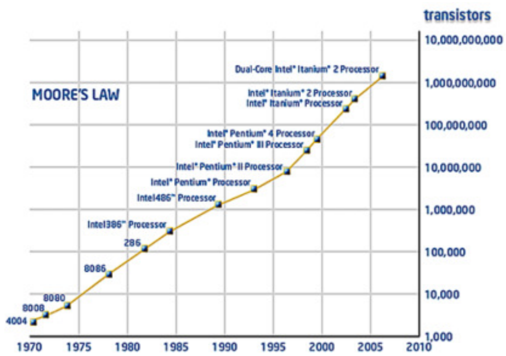
And the industry is still growing rapidly. Its growth is best represented by the

Moore's law (Gordon Moore, 1965):

> The number of transistors that could be fit on a chip of a given size at an acceptable cost doubles every two years.

(Incidentally, in accelerator field, there is a famous "Livingston chart", which says the equivalent accelerator beam energy doubles every two years – same rate as Moore's law.)

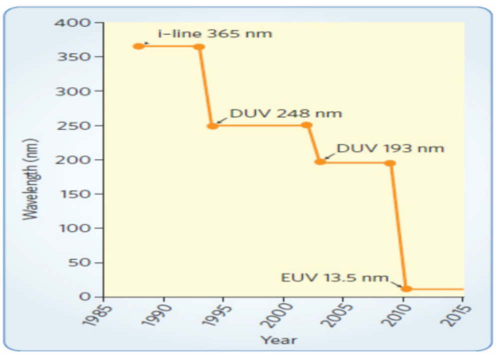
	Year	Transistors
4004	1971	2,250
8008	1972	2,500
8080	1974	5,000
8086	1978	29,000
286	1982	120,000
386™ processor	1985	275,000
486™ DX processor	1989	1,180,000
Pentium® processor	1993	3,100,000
Pentium II processor	1997	7,500,000
Pentium III processor	1999	24,000,000
Pentium IV processor	2000	42,000,000



[Courtesy: 林合俊 陳虹宇 周展弘 陳玟儒 吳萱郁, 2014]

Note that Moore's law is not just a passive curiosity. It is a result of market demand (2 T$, and growing). The semiconductor industry runs on the Moore model and is compelled to follow it. Breaking from Moore's law has severe economic consequences.

Moore's law is maintained by continually miniaturizing the transistors. As the resolution of lithography to produce the chips becomes finer, the required wavelength of the lithography light becomes shorter. To fulfill the industrial needs, the power of the radiation also needs to be very high. Present day lithography uses DUV (deep ultraviolet, 365, 248, 193 nm), but DUV is falling behind. We are presently dangerously near the point of departure from Moore's law.



[Courtesy: 林合俊 陳虹宇 周展弘 陳玟儒 吳萱郁, 2014]

We need a radiation source of high power with shorter wavelengths. The next advance proposes to use EUV (extreme ultraviolet, 13.5 nm) light. EUV is presently industry's best hope for keeping up with Moore's law. Choice of 13.5 nm is due to a window of high reflectivity of multilayered mirrors. Bandwidth is $\sim \pm 2\%$. If made available, EUV light can sustain Moore's law for $\sim$10 more years. Soft Xrays or electron beams may be considered after EUV.

But EUV photons are difficult to generate. Existing techniques fall short on the required power. ASML, the Netherlands, the world's leading provider of lithography systems, after much R&D efforts and spending on EUV, is pushing the technology of laser-produced plasma (LPP) devices. Their record power so far is $\sim$75 W per tool. The industry aims for $\gtrsim$1 kW per tool. Since too much is at stake, there has been a need of ideas to provide a high power EUV light source.

3. The SSMB Approach

One presently conceived approach for producing EUV light of kW level is to use accelerators. There are two types of accelerators: circular ones (storage rings) and linear ones (linacs).

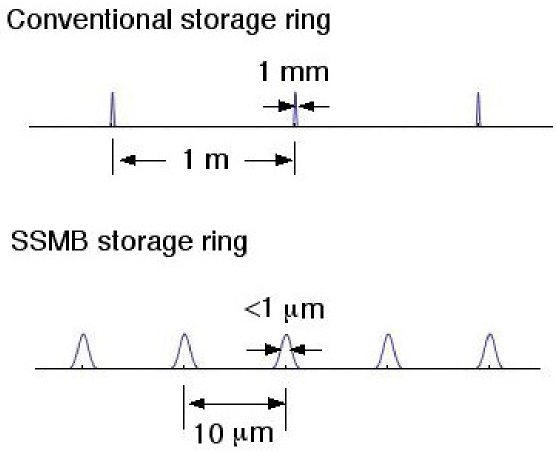
- Linacs (FELs) produce EUV radiation that has high peak power, but low average power because of their low repetition rates.
- Storage rings have high repetition rates but low peak power.

To achieve kW power, we need both high peak power and high repetition rate.

The low repetition rate of FELs can be partially solved by invoking superconducting linac technology, raising repetition rate from 60 or 120 Hz to $\sim$1 MHz. However, the electron beam is thrown away after usage, so it requires too much power to run, unless one invokes another technology called energy recovery linacs to recover and reuse the electron beam energy. Superconducting, energy recovery FEL EUV source is a feasible approach. It is also expensive.

An alternative approach, adopted by SSMB, is to combine the strengths of linacs and storage rings[1]. With a conventional room-temperature electron storage ring, the SSMB utilizes only off-the-shelf hardware and its cost can be a small fraction of the SC/ERL linac FEL alternative. However, being a new proposed technique untested in existing storage rings, it is still in an early R&D stage. R&D efforts and a proof-of-principle test are required before it can be considered a feasible alternative for actual applications.

The basic idea of SSMB is to manipulate the beam's dynamics in a storage ring so that its distribution is not the conventional Gaussian with a typical bunch length $\sim$a few millimeters, but microbunched with each microbunch having a length $<$ a few μm, and in the case of EUV application, $<$13.5 nm so that all electrons in each microbunch and its neighboring microbunches radiate coherently. The two cases are sketched below (note the very different length scales):



The functioning of SSMB lies in finding a way to make the beam microbunched in the first place, and then in addition make them stay microbunched in the turn-by-turn environment of a storage ring.

- The beam is microbunched and strongly focused, so it readily radiates at the desired short wavelength (13.5 nm for lithography) at an appropriate radiator, yielding high peak power $\propto N^2$ instead of $\propto N$.
- The beam is microbunched in a steady state in a storage ring, so it radiates every turn with a high repetition rate. With a bunch spacing of 10 μm, the repetition rate is 300 GHz.

These two features, microbunching and steady-state, lead to the term "steady state microbunching".

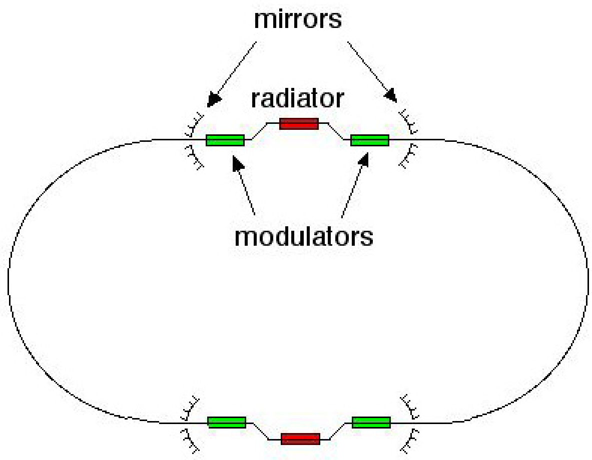
With the high repetition rate, radiation per bunch passage is far weaker than what is demanded by a superconducting linac FEL (by 5-6 orders of magnitude). The electron beams are not disrupted by each passage through the radiator. This device is not an FEL.

SSMB uses a natural equilibrium state of the electron beam. The microbunch structure can not be produced by chopping the beam with fast electronics or laser techniques using present technologies. Instead, it is reached because the electron beam chooses it as its steady state when the storage ring environment is so provided.

The required hardwares are simple: Take an electron storage ring of $\sim$1 GeV, and insert three appropriate undulator magnets, each about 3-4 m long, in its circumference. To one of the undulators, add an IR laser (called "seed laser"). The storage ring is conventional, the undulators are routine components in accelerator applications. The seed laser requires high power, comparable to what is needed for the superconducting linac option.

SSMB can be scaled to a range of frequencies from IR to EUV. As mentioned, kW EUV sources are useful for the industry. Multi-kW IR or DUV radiation are potentially research tools for atomic or molecular physics.

A schematic of the layout of the facility looks like the following figure. It shows a facility with two SSMB radiation tools arranged back to back in a single storage ring.



Each tool consists of a radiator sandwiched between two modulators. A radiator is an undulator magnet that resonates at the desired radiation wavelength λ (13.5 nm for EUV, for example). This is where coherent radiation is emitted and delivered to the users. A modulator is also an undulator magnet, resonant at a longer wavelength $M\lambda$ where M is an integer, typically 15-20. The two modulators around each radiator are "seeded" with a laser with wavelength $M\lambda$. By the action of this seed laser, the electron beam will find its microbunched steady state and stay there turn by turn if other storage ring parameters are chosen properly.

The seed laser's another important function is to strongly focus the microbunches to allow the harmonic generation factor M. The SSMB storage ring is therefore "strong focusing" in its longitudinal beam dynamics, a new regime of storage ring operation that provides tight control of the beam's longitudinal emittance and consequently promises further possible applications beyond SSMB.

Around the seed laser, we have two mirrors to form a laser cavity. One technical requirement is that the mirrors must have high reflectivity (higher than $\sim$0.999) at the desired wavelength $M\lambda$.

Table below shows some example applications of SSMB as IR, DUV and EUV sources. (As proposed in [1], SSMB can also be applied to *lower* the coherent radiation frequency, e.g. to THz, by beating two modulations with nearby IR frequencies.) The advertised radiation power for the three cases are in the range of multiples of kW, readily orders of magnitude higher than other approaches, again due to the high repetition rate of a storage ring and the microbunched coherence nature of the electron beam. However, there are caveats.

		IR SPEAR3	DUV SPEAR3	EUV dedicated ring	
E_0	beam energy	900	900	580	MeV
C	ring circumference	234	234	100	m
α_C	ring mom. comp. factor	1.9	0.57	0.16	10^{-6}
I_0	average beam current	8.5	4.7	1.12	A
L_m	modulator length	3.7	3.2	3.4	m
λ_m	seed laser wavelength	13.2	3.5	0.37	μm
P_{seed}	seed laser power	15	15.7	11	kW
L_r	radiator length	3.5	3.3	3.54	m
λ_r	SSMB rad. wavelength	0.94	0.205	0.0133	μm
P_r	SSMB rad. power	85	41	4.06	kW

Two caveats:

(1) The first is that the required seed laser has high power and the mirrors will have to stand its radiation heating while maintaining their high reflectivity. In case the seed laser power must be reduced, the intended radiation power will be reduced by the same factor. For example, in the IR case, if the seed laser is limited to 1 kW, the IR radiation per radiator is reduced to 5.6 kW, which is still a high level. Another approach, much more intriguing and exciting, is to self-seed the modulators, sparing the seed laser altogether, although mirrors will still be needed.

(2) The SSMB mechanism has only existed on paper and on computer simulation studies. It has not been scrutinized with experimental tests. Feasibility is not established. One of the main next activities is to try a proof-of-principle test on an existing storage ring.

4. Proof-of-principle test proposal

We considered two operation cases using the existing storage ring SPEAR3.

(1) Without a seed laser: Setup consists of only a single modulator with mirrors, without a seed laser and without a radiator. The microbunching originates from the self-modulation due to the accumulated spontaneous radiation from the undulator. The microbunching is to be built up from the white noise of the beam distribution. This intriguing possibility is one of the ideas to be explored in the PoP test. This is work in progress.

(2) With a seed laser: Augment the single modulator with a seed laser. Fill 1% of the ring with electrons. The beam is expected to be fully microbunched at the

modulation wavelength.

	without seeding	with seeding	
Modulation wavelength (λ)	10	10	μm
Cavity Q	500	500	
Undulator strength parameter K	30	30	
Undulator period	20	20	cm
# of undulator periods	10	10	
Electron beam energy	1	1	GeV
Momentum compaction factor (α_C)	1.3	0.3	10^{-5}
Beam current	500	54	mA
Seed laser power	-	190	W

5. Conclusion

It is time to conclude. Instead of talking about how great SSMB is, I wish to conclude with a recollection of memory 41 years ago of what led to my standing here today talking about the SSMB.

That should begin with my first involvement in the field of accelerator physics. It all started when Professor Yang in early 1973 advised me to take an accelerator physics course by Professor Ernest Courant. It was all very innocent at the beginning. Following his advice, I happily took the course and wholly enjoyed it. It was real fun! In 1973 later, my last year of PhD study at Stony Brook, Professor Yang arranged me to study half time under Professor Courant at Brookhaven Lab, which I also enjoyed.

Then came the time of my graduation and decision was to be made of which field I should focus after graduation. My thesis was on high energy theory. Naturally I had initially considered high energy physics as my career choice. Professor Yang talked to me one day. He told me that I could find a job in high energy theory and that I could do well. But he advised me to instead consider accelerator physics as my career choice, arguing that HEP field is more crowded and that it is better and more rewarding for a young researcher to choose a field that is less crowded like is the case of accelerator physics. He must have lectured for 10 minutes, or at least it felt so. His lecture I summarize as follows.

Yang's lecture 1973&1974 on career choices:

Choose 僧少粥多 Few monks, much congee
(accelerator physics)

Don't choose 粥少僧多 Many monks, little congee
(high energy physics)

But now this was a much more serious matter for the then-young me. His argument was convincing and I did enjoy my studies on accelerator physics at the time. But hesitating I did.

I hesitated, if I recall, for a few weeks. After all, I enjoyed both high energy physics and accelerator physics. While still hesitating, Professor Yang asked me again about my decision. As I hardly started to explain my reasons of hesitation that he became impatient with me – for the one and only time that I could recall. He said in a raised voice, and I quote, "I strongly dispute your reasons", and continued to give his lecture again. The time was about April 1974.

To make the story short, I did not actually disagree with him, but his persuasion pushed me into a final decision. For 41 years now, I have thoroughly enjoyed this field. It is so much fun and indeed few other monks came sharing my congee. I wish to thank Professor Yang for his strong and timely advice at a time when I most needed it.

After me, Professor Yang also advised several talented physicists to accelerator physics. Examples abound, but comes to mind quickly are Juinn-Ming Wang, Sam Krinsky, Ron Ruth, Bill Weng, Jie Wei, Lihua Yu, Shyh-Yuan Lee, and Steve Tepekian. They all did very well. The field of accelerator physics owes much to professor Yang's early vision.

Without Yang's advice at a critical time, I would not be here today talking about SSMB.

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