Review of Compact Synchrotron Light Sources

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Abstract

To extend the use of synchrotron radiation (SR) outside the field of fundamental research for various industrial applications, great effort has been made in the last years by many groups to develop and build compact electron storage rings. An overview of the worldwide activities in this field is given and the basic concepts of such synchrotron radiation sources are presented with a brief outline of the main development challenges.

1. INTRODUCTION

During the last 25 years the concepts and the technology of synchrotron radiation sources have been subject to a remarkable evolution. Also in this rather specialized field, the development process seems to follow Darwin's principle of occupying every 'ecological niche': After the first direct observation of SR in 1947 in a weak focusing synchrotron, SR has been used parasitically from the first generation of electron synchrotrons and storage rings, designed for high energy physics experiments. Second generation machines are dedicated to the production of SR, using new lattice types (e.g. Chasman-Green and triple bend achromat lattices) optimized for low emittances. A third generation of SR-sources, which is presently under construction, takes full advantage of undulators to boost the brilliance by several orders of magnitude for experiments in basic and applied science, where SR has been used with great success during the last two decades. As a complement to these rings compact SR-sources have been developed by many groups for very promising industrial applications in the field of microstructure manufacturing. A size comparision of these different kinds of machines is given in fig. 1, showing the footprints of BESSY I, a typical second generation source, BESSY II, a proposal for a third generation ring, LUNA, a conventional compact source and COSY, a superconducting compact machine.

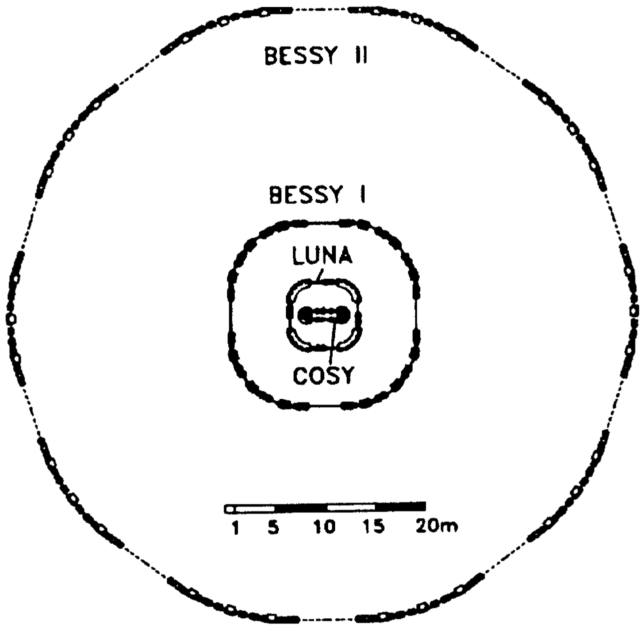

Fig. 1: Footprints for BESSY II, BESSY I ($\lambda_c = 20$ Å), the conventional compact source LUNA ($\lambda_c = 22$ Å), and the superconducting COSY ring ($\lambda_c = 12$ Å).

2. POTENTIAL APPLICATIONS

2.1 X-Ray Lithography

The driving force for the development of small and economic SR-sources was X-ray lithography, a possible method for mass production of future generations of microchips. This technique, which uses X-rays to shadow print the structures of a mask onto the surface of a silicon wafer coated with a photoresist, has been under development since the late seventies [1] to overcome some inherent limitations of conventional lithography - limited resolution and small depth of focus. Although present day optical lithography has pushed the limits down to about 0.35 μm line width, X-ray lithography with the potential of 0.1 μm structure dimension is still considered as an important technology for future chip generations beyond the 64 Mbit DRAM. Typical parameters of an optimized X-ray lithography source are: critical wavelength $\lambda_c = 0.8\text{-}1.5$ nm, radiated power $P_\gamma \sim 3$ mW per mrad of horizontal opening angle, horizontal and vertical beam dimension $\sigma_{x,y} \geq 1$ mm, vertical divergence of the beam $\sigma'_y \geq 1$ mrad.

2.2 LIGA-Process

A second potential industrial application of SR is in the field of micromechanics. In the LIGA process [2], deep X-ray lithography has been combined with a galvanoforming technique for mass production of very small devices for micromechanics, integrated optics, microsurgery and many other fields. For these applications, resist layers up to several 100 μm thickness have to be exposed, so the necessary wavelength is in the range of $\lambda_c = 0.2$ nm.

2.3 Digital Subtraction Angiography

Another potential application of SR is in the field of medical diagnostics of coronary vessels. An X-ray absorption image of the coronary vessels can be produced with two quasi-monochromatic photon beams of different energy, 100 eV below and above the iodine k-edge of the contrast solution at 33.17 keV.

Subtracting the two images digitally, contrast enhancements up to 10^4 have been achieved. The necessary photon flux is of the order of 10^{11} photons/(mm^2·sec) and can only be provided by a powerful SR source [3]. This method is still in the development phase with animal and human subjects.

3. BASIC DESIGN CONSIDERATIONS

Small size and low investment and operation cost are the central criteria for a SR source to be used for industrial purposes. Therefore, in contrast to most second and third generation rings where low emittance/high brilliance is the essential figure of merit, simple lattices with small straight sections and a minimum number of components are favored for compact sources. The basic properties of a SR source can be obtained from the following equations, which relate the critical wavelength λ_c, the beam energy E, the current I, the radiated power P_γ, the dipole field B, and the bending radius ρ:

$$\lambda_c\,[\mathrm{nm}] = \frac{1.864}{E^2\,[\mathrm{GeV}]\,B\,[\mathrm{T}]} \qquad (1)$$

$$E\,[\mathrm{GeV}] = 0.2998\;B\,[\mathrm{T}]\,\rho\,[\mathrm{m}] \qquad (2)$$

$$P_\gamma\,[\mathrm{W/mrad}] = 7.871\,\frac{I\,[\mathrm{A}]\,E\,[\mathrm{GeV}]}{\lambda_c\,[\mathrm{nm}]} \qquad (3)$$

In fig. 2 the dependence of the bending radius on the dipole field is plotted for fixed λ_c. This shows the merits of superconducting magnets, particularly for small λ_c. With conventional dipoles fields up to about 1.5 T can be generated where the limit is given by saturation effects. The first superconducting magnets built for compact SR-sources produce fields of 3-4.5 T. It is still an ongoing debate whether the pros of superconducting magnets pay for their cons: Conventional magnet rings use conservative and well proven technology with high reliability based on decades of experience, so there is practically no risk and sound estimates can be made for total up-time and running costs. On the other hand, the prospects to reach fields even beyond the 6 T range with future improvements in superconducting magnet technology are very promising. However, this new technology has not reached a comparable level of maturity yet, although the feasability of superconducting compact rings could be demonstrated by several groups in a relatively short time.

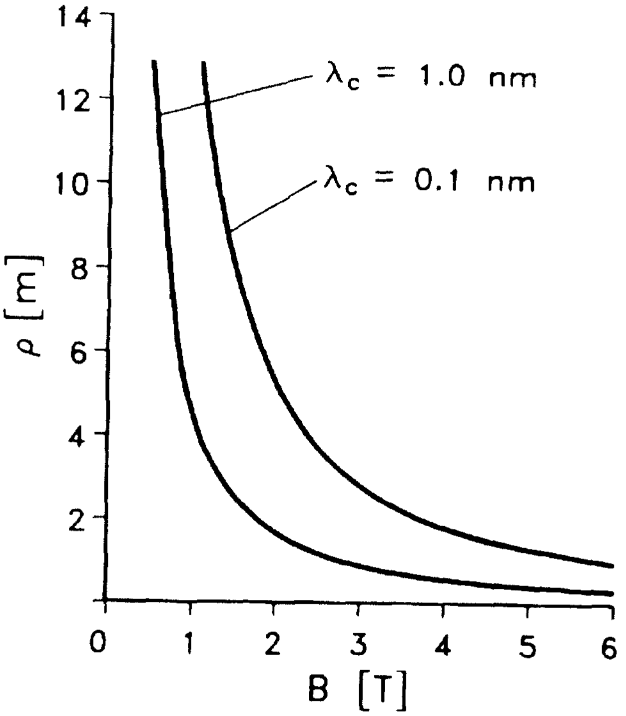

Fig. 2: Bending radius vs bending field for a given λ_c.

The simplest lattice is a weak focusing guide field with circular symmetry. For SURF II [4], operated by NBS, a surplus synchrotron magnet has been transformed into a 284 MeV storage ring. Klein Erna [5] was an early proposal for a similar superconducting machine, and AURORA [11] is the first superconducting ring based on this concept which has been constructed. Weak focusing however puts a natural limit on the beam size. If smaller beam dimensions are desired a racetrack configuration with two 180° bending magnets can be adopted. As a consequence, space for quadrupoles and other components is available in the straight sections, which relaxes the engineering problems significantly, a design which has first been proposed for COSY [6]. At higher energies superconducting 180° dipoles become rather large and expensive, so structures with a fourfold or even higher lattice symmetry are more adequate. For compact rings with conventional magnets on the other hand, slimlined Chasman-Green- and modified FODO-structures with a minimum number of cells are commonly used. Hybrid rings, such as conventional magnet machines with several superconducting wigglers [7] or a combination of superconducting bending magnets and conventional dipoles [8] are a third alternative for the design of compact SR sources. Although these schemes offer an extended spectral range thanks to the different field levels involved, no prototype hybrid ring has been built yet.

3.1 Superconducting Bending Magnets

With their strongly curved coils, high field induced forces and complex mechanical and cryogenic structures the construction of superconducting magnets for compact rings represents a new challenge in superconducting magnet technology. Magnets have been built with different coil configurations, using iron yokes or air cores and cold or warm electron beam chambers. Pure air coil magnets have the advantage of linearity, and the fields can be calculated in three dimensions with the help of Biot-Savarts law. On the other hand, they have large stored energies and strong fringe fields. Non-isomagnetic lattice- and tracking calculations are therefore important for a complete optical description. Flat coils are easier to fabricate but have stronger higher multipole terms in the fringe field. Turned up coil ends provide improved field quality and better vertical aperture but are very difficult to manufacture. Iron yokes contribute to the bending field thus reducing the field at the coils, and they provide an effective shielding of the fringe fields. A disadvantage, however, is the non-linear behaviour and the higher weight.

3.2 Low Energy Injection

To minimize cost and size of the injector, it is essential to inject electrons at rather low energies using microtrons or linacs as preaccelerators. The guide field is then ramped to the operation field level in contrast to most second and third generation storage rings, which inject at full energy. Low energy injection is complicated by the fact that the damping times

$$\tau_i\,[\text{msec}] = \frac{\rho\,[\text{m}]\,L\,[\text{m}]}{13.2\;J_i\,E^3\,[\text{GeV}]} \quad , \quad i = \varepsilon,x,y \qquad (4)$$

become very large (L orbit length, J_i damping partition number), which makes the beam sensitive to all kinds of dynamic perturbations. Different schemes have been used for injection:

An extreme case is SuperALIS [9] where electrons from a 15 MeV linac are captured under the condition of negligible radiation damping by multi-turn injection. Beam currents up to 200 mA have been injected in a single shot. Strong detuning of the rf-cavity and control of the tuning angle during ramping is essential to compensate for the heavy beam loading and to guarantee Robinson stability.

Most compact rings operate at 50-200 MeV injection energy where sufficient damping is available to make multi-cycle/multi-turn accumulation possible. In contrast to the usual assumption that the time between injection cycles should be of the order of the damping time to allow the beam to shrink and clear part of the occupied phase space, higher stacking efficiencies have been obtained in some rings with much shorter repetition cycles. This is the case for Aladdin and has been studied by tracking calculations in the full six dimensional phase space. The combined effects of betatron coupling and an energy mismatch between the injector and the storage ring appear to provide an explanation of the observed behaviour [10].

A very challenging injection scheme has been developed to inject electrons from a 150 MeV microtron into AURORA [11]. This method is the time reversed process of resonance extraction used for many synchrotrons. The horizontal half integer resonance is excited in the outer region of the acceptance using a fast perturbator magnet to produce a modified octupole field. Electrons are then injected and trapped on stable orbits after the perturbating field is switched off. Good capture efficiency could be proved by the accumulation of currents up to 300 mA with only 0.3 mA from the microtron.

Besides weak radiation damping several other processes affect the beam particularly at low energy: Coulomb scattering between the beam electrons and the nuclei of residual gas atoms and Touschek scattering limit the beam lifetime, and multiple scattering between electrons leads to emittance blow-up. Probably the most dangerous effects, however, originate from ions trapped in the electric potential of the electron beam with the consequence of an increase in local pressure, as well as tune shifts and tune spread due to the effective field produced by the ion cloud [12]. Good vacuum conditions (residual pressure below 10^{-9} mbar) to reduce the ion production rate and the use of adequate methods to limit the influence of the ions are essential for the accumulation of high beam intensities at low energy. For example, ion clearing with electrostatic fields and excitation of coherent betatron motion have proved to enhance the achievable stored current significantly [13].

To study and optimize the injection process in greater detail, some of the superconducting compact rings have been operated with conventional dipoles prior to the installation of the superconducting magnets. Using a racetrack microtron currents up to ~100 mA could be accumulated at 50 MeV in COSY [15]. Remarkable intensities of 1.3 A have been injected in the SXLS phase I ring with the NSLS booster at 200 MeV [14].

4. SURVEY OF COMPACT SR-SOURCES

A list of 14 compact rings which have been built with emphasis on applications outside the field of basic research is given in table 1. The superconducting rings are dedicated exclusively to X-ray lithography, whereas some of the conventional magnet rings cover a larger area of applications, including lithography, the LIGA-process, and analytical methods in applied science. In the following only a few examples can be described in some detail.

AURORA, developed by Sumitomo Heavy Industries as a tool for X-ray lithography. is a superconducting weak focusing ring with circular symmetry [16]. An orbit circumference of 3.14 m makes this machine the most compact arrangement, however a weight of 120 tons for the iron yoke must be accepted. Motivated by the circular symmetry a conceptual design for a photon storage ring has been proposed which consists of an electron storage ring with radius r surrounded by a circular mirror of radius R to reflect all SR-photons back onto the electron orbit. This photon storage ring is supposed to function like a FEL with an infinite number of periods, the discrete wavelengths of which depend only on the ratio r/R. A continuous output power of several 10 kW is expected for sub-mm wavelengths.

CAMD, the center for Advanced Microstructures and Devices established at Louisiana State University is a multipurpose SR facility with strong emphasis on education and lithography applications [18]. The ring built on a commercial basis by Brobeck, Inc. has a four cell Chasman-Green lattice and uses conventional bending magnets with 1.37 T nominal field, however with the potential of 1.6 T to reach beam energies up to 1.4 GeV. Together with a 4 T wiggler this gives the spectral flexibility necessary for the anticipated research program. Commissioning started in Oct. 1991 and a first beam has been stored in Jan. 1992.

COSY, developed at BESSY as a prototype X-ray lithography source for the Fraunhofer Institut für Mikrostrukturtechnik, is the first superconducting racetrack ring designed with the aim of a compact, low cost SR-source. This configuration became very popular for many X-ray lithography sources. A lattice with two unsymmetrical cells has been chosen with the unusual feature that positive and negative momentum compaction factors can be obtained from minor modifications of the optics. If necessary, the head-tail instability can thus be suppressed by choosing a

Table 1: ***Survey of Compact SR-Source Projects***

(d design, a achieved, RM racetrack microtron, L linac, BS booster synchrotron)

Project name Institution/Location/Country	λ_c [nm]	E [MeV] d	E [MeV] a	B [T]	ρ [m]	L [m]	I [mA] d	I [mA] a	No. of Dipoles	Magnet Layout bore	Magnet Layout core	E_{inj} [MeV]	I_{inj} [mA]	Injector
Superconducting rings														
AURORA [11] SHI/Tokyo/Japan	1.02	650	650	4.34	0.5	3.14	300	300	1	warm	iron	150	>300	RM
COSY [15] BESSY/Berlin/Germany	1.2	592	550	4.47	0.44	9.6	100	1	2	cold	air	50	100*	RM
HELIOS [20] OI/Oxford/Great Britain	0.84	700	700	4.5	0.52	9.6	200	300	2	cold	air	185	540	L
MELCO [24] Mitsubishi/Amagosaki/Japan	0.7	800		4.5	0.59	9.2	220		2		iron	20-800		BS
NIJI III [25] SEI/ETL/Tsukuba/Japan	1.3		615	4.1	0.5	15.5	200	200	4	cold	air	280		L
SIBERIA SM [22] INP/Novosibirsk/Russia	0.86	600		6.	0.33	10	300		8	warm	iron	60		L
SuperALIS [9] NTT/Atsugi/Japan	1.73	600	600	3.0	0.66	16.8	500	200	2	warm	iron	15		L
SXLS [26] BNL/Brookhaven/USA	0.98	700		3.87	0.60	8.5	500		2	warm	air	200	1300 *	L/BS
Conventional magnet rings														
CAMD [18] Brobeck/Baton Rouge/USA	0.95	1200		1.37	2.92	55.2	400		8			200		L
LUNA [21] IHI/Tsukuba/Japan	2.18	800	800	1.33	2.01	23.5		50	4			45	100	L
NAR [27] NTT/Atsugi/Japan	2.02	800	800	1.44	1.85	52.8	500	50	8			15		L
NIJI II [28] ETL/Tsukuba/Japan	3.7	600	600	1.4	1.43	17		120	4			200		L
SORTEC [23] Sortec/Tsukuba/Japan	1.55	1000	1000	1.2	2.78	45.7	200	200	8			1000		BS
TNK [29] ZRIPP/Zelenograd/Russia	0.67	1600		1.09	4.91	115.73	300		24			450		BS

* Achieved with normally conducting dipole magnets.

negative momentum compaction instead of installing sextupoles for chromaticity compensation. The feasability of low energy injection was demonstrated in an early phase with conventional bending magnets by the accumulation of currents up to 100 mA in a 10 Hz multi-cycle stacking process using a 50 MeV microtron. Unfortunately the field quality of the superconducting dipoles, designed and manufactured by Siemens, was very poor because of ferromagnetism in the stainless steel structure. Nevertheless, the first stored electron beam in a superconducting ring could be obtained with COSY in November 1988 and a current of 1 mA ramped to an energy of 550 MeV [19].

HELIOS is the first compact source which has been built on a commercial basis in response to an order from industry [20]. The machine, developed for IBM by Oxford Instruments Ltd., is a centerpiece of the Advanced Lithography Facility at East Fishkill/USA. All components of the racetrack ring are mounted on a common girder. To minimize risks, injection is at 200 MeV using a linac. Much effort has been made to determine the field distribution of the superconducting dipoles with a field plotting 'mouse', which measures the field at 4.2 K along the design orbit in the cold bore of the magnet. Commissioning at the customer's sitehas been completed and routine operation started in the beginning of 1992 with 10 h lifetime for 200 mA and maximum currents of 300 mA.

LUNA, developed by Ishikawajima-Harima Heavy Industries, is so far the smallest ring with conventional magnets dedicated to X-ray lithography [21]. Four cells with 90° sector magnets give an orbit circumference of 23.5 m. Electrons from a 45 MeV linac are injected in a single shot due to the very long damping time. About 100 mA could be captured and 50 mA ramped up to 800

MeV. There are plans for a modified injection process by ramping repetitively to an intermediate energy to damp the beam. Based on the LUNA prototype, a modified ring has been designed with E = 1.05 GeV, λ_c = 1.21 nm, B = 1.4 T, I = 300 mA, L = 27 m for a commercial X-ray lithography facility.

SIBERIA-SM is a compact ring under development at the Institute of Nuclear Physics in Novosibirsk [22]. The lattice has a fourfold symmetry with eight superconducting 6T-dipoles. To minimize cryogenic losses, all dipoles will be powered in series with cold current leads. The magnet follows a new design with iron inside the wedge-shaped coils which saturates and contributes to the aperture field, and a return yoke outside the coil to minimize the stray fields. Prototype magnets have been tested and fields up to 6.7 T were reached after several quenches. Although SIBERIA-SM is a dedicated machine for lithography, the superconducting dipole is intended to be used also as a basic module for other storage rings. A 1.2 GeV ring with 16 magnets (λ_c = 0.21 nm) has been proposed for micromechanical applications, and a 2.4 GeV ring with 32 magnets can produce the high photon energies (λ_c = 0.054 nm) necessary for material science and digital subtraction angiography. This modular approach is presented in another paper in these proceedings.

SORTEC is a collaboration between thirteen Japanese companies and MITI to develop the tools for X-ray lithography. High reliability, low development risk and short commissioning time have been important criteria leading to a conservatively designed conventional magnet 1 GeV ring with a booster synchrotron running at 1.2 Hz for injection at full energy [23]. The design parameters were reached in Oct. 1989 after a commissioning period of only one month. In the meantime the typical lifetime is 13 h at the design current of 200 mA with a vacuum pressure of $8\cdot10^{-10}$ Torr and a residual pressure without beam of $2\cdot10^{-11}$ Torr. Lifetimes in excess of 50 h can be obtained by shifting the tune to a coupling resonance. There are plans to increase the beam current up to 500 mA after an upgrade of the rf-system and the installation of SR-absorbers.

5. CONCLUSION

In the last years several conventional magnet compact rings have come into operation and superconducting SR sources have demonstrated their feasability. The challenge of low energy injection stimulated new ideas like the concept of resonance injection and the range of accessible injection energies has been extended down to 15 MeV. Superconducting dipoles with different concepts are in operation, which helps to bring this technology to maturity. First prototype magnets are under test to increase the bending field to the 6-7 T level for future hard X-ray compact sources. All these efforts contribute to make SR available for a growing variety of potential applications outside the domain of basic research.

6. ACKNOWLEDGEMENTS

For information used in this review I am grateful to M. Kodaira, G. Kulipanov, S. Mandai, J. Murphy, S. Okuda, V. Saile, M. Wilson, T. Tomimasu and H. Yamada.

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