COMPACT SYNCHROTRON X-RAY SOURCES

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Abstract

Compact electron storage rings are now being developed in Europe, Japan and the U.S.A. to meet the forseen needs of X-Ray Lithography in producing next generation micro-chips. Superconducting,dipoles are used in many of these rings in order to make the system as compact as possible.

Introduction: X-Ray Lithography

The last thirty years have seen a remarkable increase in the complexity of integrated circuits - from a few components per chip in the early 60's to the 4 Megabit DRAM of today. This enormous increase has been brought about partly by a modest increase in the area of the chip, but principally by a dramatic reduction in minimum feature size, from ~ 20 μm in the 60's to less than 1 μm today.

All mass produced IC's are made by the photo lithography process, in which the image of a "master" mask is projected onto the surface of a silicon wafer which has been coated with photoresist. Present day lithography uses visible light at wavelenghts of 436 nm or 365 nm, the so called G and I lines of the mercury arc source. Using lenses with very large numerical apertures, in the range NA=0.4-0.5, resolutions of ~ 0.7-0.5 μm can be achieved, but only at the expense of small depth of focus ~1.5-1.0μm. Such small depths of focus raise serious problems of process control and process yield a production situation. Moving to the deep UV wavelengths of 248 nm or 198 nm will make it possible to achieve resolutions below 0.5 μm, but only at the expense of even smaller depths of focus, ~0.5 μm, and more difficult optics.
The 16M Bit DRAM requires a line width of ~0.5 μm, 64 MB will need ~0.35 μm and 256 MB will need ~0.2 μm. Optical lithography will be adequate for 16MB and may be adequate for 64 MB, but new technologies will be needed for 256 MB.

The most promising of these technologies is X-ray lithography. The technique is a simple shadow printing process in which a collimated beam of X-rays is shone through a mask, which is accurately positioned about 40 μm above the wafer surface. Resolution, which is determined principally by diffraction and by the finite source size, can be ~0.1 μm. The optimum wavelength, determined by diffraction, by contrast between the transparent and opaque regions of the mask and by energy deposition in the resist is ~0.6 - 1.2 nm.

Many different types of source have been used or proposed for X-ray lithography : electron bombardment sources with conventional or rotating anodes, laser plasma, Z pinch plasma, plasma focus and storage rings. All are capable of producing the resolution required. However, simple analysis shows that, to achieve the throughputs of present day optical steppers, X-ray outputs of a kilowatt or more are needed. This conclusion applies equally to the isotropic sources which have a relatively short source to mask distance but an inverse square intensity variation, and to the storage ring which has longer distances but a I/R variation in the total energy deposited - because the beam is vertically collimated. At present, none of the alternative sources come anywhere near this power requirement, whereas the storage ring can provide it with ease. Compact storage ring X-ray sources are therefore being developed in Europe, Japan and the U.S.A. with a view to their utilization as production tools for the next generation of micro chips.

Field Strength and Scaling Laws

As noted above, the wavelength required is determined by lithography considerations to be 0.6nm - 1.2nm. This requirement sets the critical wavelength of the storage ring λ_c, defined as the mid point of the spectrum, having equal energies above and below. Critical wavelength is related to field and bending radius by:

$$\lambda_c = 20.7/\, R^2 B^3 \quad (\mathrm{nm,m,T})$$

Thus, for a fixed wavelength requirement, the bending radius scales as $B^{-3/2}$, which implies a considerable advantage for superconducting magnets. Conventional rings have B~1.3T whereas the compact superconducting rings have B~4.5T, ie a factor 6.4 in radius. For example at λ_c = 0.9nm R conventional = 3.2 m and R superconducting, = 0.5m. Compactness is the major advantage of superconductivity, partly because it reduces the requirement for space in a wafer fabrication facility, where space is extremely expensive. More importantly the compact ring can be asembled and tested at the producer's factory before being shipped intact to the customer as a proven unit. Such considerations are very important in an industrial production situation.

Another advantage of the compact ring is its reduced damping time at injection

$$\tau_n = 7.54 \times 10^4 \; \frac{CR}{J_n E_i{}^3}$$
(S,m, MeV)

Where J_n are the partition coefficients between longitudinal and transverse motions and E_i is the electron energy.
If we assume that the ring circumference C is related to bend radius R by a numerical factor 2πf, we may write;

$$E_i = \frac{214}{B} \quad \frac{f}{\lambda_c \tau_n J_n} \quad 1/3$$

where E_i and τ_n refer to the electron beam at injection, but B and λ_c are for full energy. In other words, for a prescribed λ_c and a required damping time at injection, the injection energy scales as 1/B, ie a factor of

3.5 between conventional and superconducting rings.

Design Choices

Given the advantages outlined above, most rings for lithography are now being built with superconducting magnets. Having made this choice, the next decision as sketched in Fig 1, is "how many?". The most compact and , in principle, the simplest configuration is the single magnet with a circular orbit. This approach was first proposed by Trinks and Nolden (1) and has subsequently been adopted by Sumitomo Heavy Industries for AURORA (2). Although simple in concept, the single magnet approach becomes complicated in practice because of the need to fit all components for injection, acceleration etc within the magnet aperture. For this reason, many groups have turned to the two sector racetrack design, which separates the functions and provides adequate space for injection, RF, focussing and correction magnets etc in the two straight sections. Furthermore, unlike the single magnet ring, the lattice can be strong focussing. On the debit side, 180° bending magnets with open access for the tangentially emitted X-rays and with good quality field profiles (particularly around the end turns) are extremely difficult to make. More bending magnets are helpful in providing space for insertion devices and in reducing the beam size (emittance~ N^{-3}). Shimano et al have proposed a three sector ring (3) for lithography; NIJI3 is a four sector machine (4). However, minimum emittance is not so important in lithography as in most research applications of synchrotron radiation, but the cryogenic cost and integrated end field error increases with the number of separate magnet units. For this reason, the racetrack design has so far been the favourite choice.

A potentially helpful feature of superconducting magnets is the availability of large suface areas at 4.2K, offering very substantial cryopumping capacities. Opinions differ as to whether this "free" capacity should be utilized in the beam pipe. In favour are the arguments that photodesorption by the emitted X-rays can have a drastic effect on lifetime and that enclosing the beam within a cryopumped pipe will minimize the chance of photodesorbed molecules finding their way back to the beam. Against is the argument that any vacuum incident will necessitate warming up the dipoles. The debate is certainly not settled and both alternatives are being pursued.

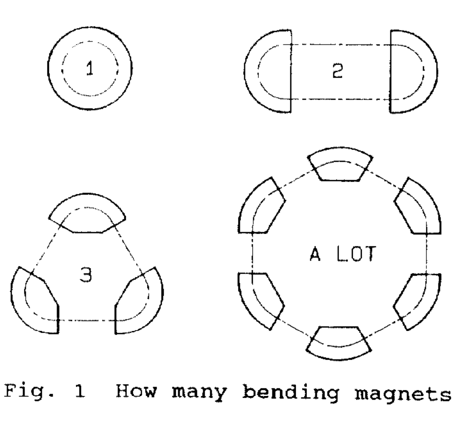

Fig. 1 How many bending magnets?

Also concerning the magnet is the old debate about using iron or not. On the one hand, iron yokes provide an effective shielding of the fringe field and some augmentation of the aperture field. On the other hand, they are heavy and produce significant distortions of the aperture field. This distortion seams to be more severe in a compact ring than in the traditional high energy ring, because the bending radius is so small and because the need for an open X-ray exit slot introduces a further assymmentry. Here again the debate is not settled and rings are being built and operated with and without iron yokes.

Injection energy is also a much debated topic in the design of rings. At the one extreme, full energy injection can virtually guarantee the accumulation of sufficient stored beam, allows rapid beam cleaning of the vacuum system and offers the possibility of almost continuous operation. At the other extreme, injection at low energy is cheaper, more compact and requires less radiation shielding because most beam loss occurs during injection. In the event, most groups have steered a middle course, injecting at energies of 50-200MeV, in a multi-turn, multi-shot mode. Using one or more kickers, 3-6 Turns are injected per shot, after which the excited beam is allowed to shrink via radiation damping before injecting the next shot. At 100 MeV for example, with a 10m circumference and 0.5m bend radius, the longitudinal damping time is 0.38sec, allowing injection rates of a few Hz.

For the future, there will undoubtedly be economic incentives to move to lower injection emergies. NTT have given an interesting lead here, with super ALIS injected at 15MeV. Damping times are extremely long at this energy (110 sec at C=10m and R=0.5m) and multi shot injection becomes impossible. One must therefore inject as many turns as possible in a single, high current, shot and than ramp immediately. The sudden rise of circulating current can cause beam loading problems at the RF cavity, but these problems appear to have been solved in super ALIS, with a stored current of 100mA. This excellent achievement will most certainly provide an increasing interest in low energy injection for the future.

A resonance injection scheme is used in AURORA. In operation, it is essentially a time reversal of the resonance extraction process used in synchrotrous and cyclotrons. The horizontal tune is set near to the half integer resonance and, during injection a pulsed coil is excited to bring regions outside the central orbit onto resonance. Electrons injected in this situation tend to spill towards the central orbit and, if the pulsed coil is now switched off, they may be captured in stable orbits.

Survey of Compact Rings

Table 1 lists, worldwide, all new rings known to the author which have been designed wholly or partly for X-ray lithography. The first 4 rings use normally conducting magnets and the remaining 6 are superconducting.

CAMD will be the centre piece of the Lousiana State University Centre for Advanced Microstructures and Devices. It is a 4 sector Chasman - Green lattice and is currently under construction by Maxwell Brobeck Corporation. The contract was awarded in 1988 and operation is scheduled for 1992. Although designed for nominal operation at 1.37T, the bending magnets are designed to reach 1.6T, thereby reducing λ_c from the nominal 0.95 nm to 0.6 nm.

Luna is a 4 sector ring constructed by Ishikawajima - Harima Heavy Industries at their Tsukuba laboratory. It uses 4 90^o conventional magnets and is injected by a 45 MeV linac which was also built by IHI. Because the damping time is very long at injection, conventional multi-shot injection is not possible and a single shot of 2-3 turns is the usual limit. However IHI have plans to side step this limitation by ramping quickly to 300 MeV and down again after each shot, thereby shrinking the beam sufficiently to allow another shot.

The Normal-conducting Accelerating Ring NAR forms part of the storage ring complex at NTT's LSI Laboratories in Atsugi and was built by Toshiba. It is a 4 superperiod Chasman Green lattice and is intended not only as a storage ring, but also as a high energy injector for other rings. The beam extraction system can supply electrons with energies ranging from 200 MeV to 600 MeV. Like super ALIS, NAR is injected at the low energy of 15 MeV using a high current linac produced by Mitsubishi. Because of their very large dynamic range ~ 53:1, special care has been needed in the design of magnets and their power supplies. The maximum current achieved so far is disappointing in comparison with Super ALIS. The main current limiting factors are thought to be rf capture efficiency, magnet field tracking and the limited number of turns which may be injected in a single shot.

The Sortec Corporation is a collaboration between the Japanese Ministry of Trade and Industry and 13 Japanese companies, to develop X-ray lithography. The storage ring Sortec 1 is a 4 superperiod Chasman-Green lattice which is injected at full energy by a booster synchrotron running at 1.2 Hz and fed by a 40 MeV linac. Design stored beam current was achieved just 1 month after switch on, emphasising the inherently conservative nature of full energy injection.

First of the superconducting rings in Table 1 is Aurora, constructed and operated by Sumitano Heavy Industries at Tanashi City, Japan. As already noted, it is a circular weak focussing ring using a resonance injection scheme. The magnet is a large superconducting solenoid with an ion yoke. Saturation of the ion during ramping causes a progressive shift in tune, which results in a more favourable operating point at full energy but makes it necessary to jump over resonances during the ramp. Injection is at 150 MeV from a racetrack microtron, also built by SHI. Problems with this microtron have so far limited its current to 7μA, but SHI have nevertheless succeeded in accumulating a stored beam of 40mA and work is in hand to increase the microtron output to 5mA.

COSY is a two sector racetrack ring at the Fraunhofer Institut fur Mikrostrukturtechnik in Berlin. The ring was initially constructed with conventional bending magnets to carry out injection studies using the 50 MeV racetrack Microtron produced by Scanditronix. During this phase, stored currents of up to 95 mA were accumulated. The

Table 1: Survey of Compact Rings Worldwide

Name	CAMD	Luna	NAR	Sortec 1	Aurora	COSY	Helios 1	NIJI3	Super ALIS	SXLS
Location	University	IHI	NTT	Sortec	SHI	IMT	O I	ETL	NTT	BNL
	Louisiana	Tsukuba	Atsugi	Tsukuba	Tokyo	Berlin	Oxford	Tsukuba	Atsugi	Long Island
	USA	Japan	Japan	Japan	Japan	Germany	England	Japan	Japan	USA
Orbit perimeter	55.2 m	23.5 m	52.8 m	45.7 m	3.14 m	9.6 m	9.6 m	15.54 m	16.8 m	8.503 m
Electron energy	1200 MeV	800 MeV	800 Mev	1000 Mev	650 Mev	592 Mev	700 Mev	615 MeV	600 Mev	700 Mev
Bending field	1.37 T(1.6)	1.33 T	1.44 T	1.2 T	4.33 T	4.47 T	4.5 T	4.10 T	3.0 T	3.87 T
Bending radius	2.93 m	2.0 m	1.85 m	2.78 m	0.5 m	0.44 m	0.52 m	0.5 m	0.66 m	0.6037 m
Critical Wavelength	0.95 nm	2.2 nm	2.02 nm	1.55 nm	1.02	1.20 nm	0.84 nm	1.2 nm	1.73 nm	0.98 nm
Design current	400 mA	50 mA	500 mA	200 mA	300 mA	100 mA	200 mA	200 mA	500 mA	200-500 mA
Achieved current		15 mA	20 mA	200 mA	45 mA	1 mA		70 mA	100 mA	
Des'n X-Ray power	25 kW	0.93 kW	9.73 kW	6.37 kW	9.5 kW	2.4 kW	8.4 kW	5.05 kW	8.3 kW	7 - 17.6 kW
Achieved XR power		0.28 kW	0.39 kW	6.37 kW	1.4 kW	0.02 kW		1.8 kW	1.7 kW	
Design lifetime	8 hour	0.5 hour	> 24 hour	> 4 hour	20 hour	6 hour	5 hour		> 24 hour	6
Achieved lifetime		0.5 hour	3 hour	8 - 9 hour	1-20 hour	12 hour		1 hour	2 hour	
Max σ h	0.75 mm	1.9 mm	0.6 mm	1.45 mm	1.3 mm	3.6 mm	1.0 mm	1.9 mm	< 1 mm	1.0 mm
Max σ v	0.5 mm	0.76 mm		0.52 mm	0.1 mm	3.1 mm	0.8 mm	0.3 mm		1.0 mm
Max σ' h		1.6 mrad		0.54 mrad	2.0 mrad	2.3 mrad	1.3 mrad			1.0 mrad
Max σ' v	0.1 mrad	0.53 mrad		0.37 mrad	0.16 mrad	3.2 mrad	0.5 mrad			1.0 mrad
No of dipoles	8	4	8	8	1	2	2	4	2	2
Dipole beam pipe	warm	warm	warm	warm	warm	cold	cold	warm	warm	warm
Dipole yoke	iron	iron	iron	iron	iron	no iron	no iron	no iron	iron	no iron
RF frequency	500 MHz	178.5 MHz	125 MHz	118 MHz	190.8 Mhz	500 Mhz	500 Mhz	154.3 Mhz	125 Mhz	211 Mhz
Injection energy	200 MeV	45 MeV	15 MeV	1000 Mev	150 MeV	50 Mev	200 Mev	180 Mev	15 MeV	200 MeV
Injector type	Linac	Linac	Linac	Sync'tron	Microtron	Microtron	Linac	Linac	Linac	Linac
Injector current	25 mA	100 mA	200 mA	30 mA	7 uA (5 mA)	30 mA	20 mA	50 mA	200 mA	
Reference	5	6	7	8	2	9	10	11	12	13

conventional dipoles were then replaced by superconducting dipoles, constructed by Interatom. Currents of ~ 40 mA could then be accumulated at injection, with beneficial effects on vacuum being observed from the added cryopumping. Unfortunately the dipole field quality is distorted by ferromagnetic transitions in parts of the stainless steel structure; this has restricted the accumulated current at injection and made ramping to full energy very difficult.

Helios 1 is the Oxford ring described in the next section.

NIJI 3 (rainbow 3) is one of 4 compact rings at Japan's Electrotechnical Laboratory; all are injected by the 500 MeV linac TELL. The ring, which has been built as a collaboration between ETL and Sumitomo Electric Industries uses 4 90^o superconducting dipoles in a 2 superperiod lattice of the Chasman Green Type, with 2 long straight sections and 2 short. The superconducting dipoles, which also contain a quadrupole winding, are unusual in that they use a Cos θ winding configuration, with no gap for the emitted X-rays. One X-ray beam is extracted from the end of each magnet, the remaining X-ray flux being absorbed on cooled absorbers within the magnet aperture. The ring also features a 'wobbling magnet' to sweep the emitted X-ray beam up and down, thereby scanning the full lithography field. In most other rings, this function must be performed by a grazing incidence mirror.

Super ALIS, at NTT's Atsugi Labs, was constructed in collaboration with Hitachi. It has a racetrack configuration with longer than usual straight sections to accommodate an electrostatic inflector for low (15 MeV) injection as well as a magnetic inflector for high (up to 600 MeV) injection, together with several correction magnets. Like NIJI 3, magnetic wobbling is used to sweep the X-ray beam over the lithography mask. The superconducting magnets have ion yokes and a warm bore, with the pumping provided by NEG pumps. After experiencing poor vacuum lifetimes, the original copper X-ray absorbers were replaced by ultra high purity silicon, which gives much less photodesorption. Of all the superconducting compact rings, Super ALIS currently holds the world record for stored beam, at 100 mA.

SXLS is currently under construction at the Brookhaven National Synchrotron Light Source, in collaboration with Gruman Aerospace and General Dynamics. It is a racetrack configuration and, like Cosy, will start with conventional bending magnets (B = 1.1 T) for injection studies up to 200 MeV. For this early phase of its operation, SXLS will be installed close to the NSLS X-ray ring and will be supplied with beam from the present NSLS injector. In phase 2 of the project, the conventional dipoles will be replaced with superconducting dipoles, built by General Dynamics, the existing low power rf cavity will be replaced by a high power system and the ring will be moved to a dedicated facility, with its own 200 MeV linac.

Helios 1

Helios 1, now starting commissioning at Oxford Instruments, was begun in 1987 following the award of a contract from IBM for a compact X-ray source to be installed in its new Advanced Lithography Facility at the IBM East Fishkill plant in New York State USA. Large design inputs have been made by staff at the UK Science and Engineering Council's Daresbury Laboratory, who have worked closely with Oxford throughout the project.

Fig. 2 shows a recent picture of Helios 1 after completion of assembly in the Oxford clean room, before moving into its shielded enclosure for commissioning with beam. It is a compact racetrack design, with two superconducting gradient dipoles and 4 horizontally focussing quadrupoles. One conventional and four superconducting sextupoles are provided for chromaticity correction and we also have a combined octupole/skew quadrupole.

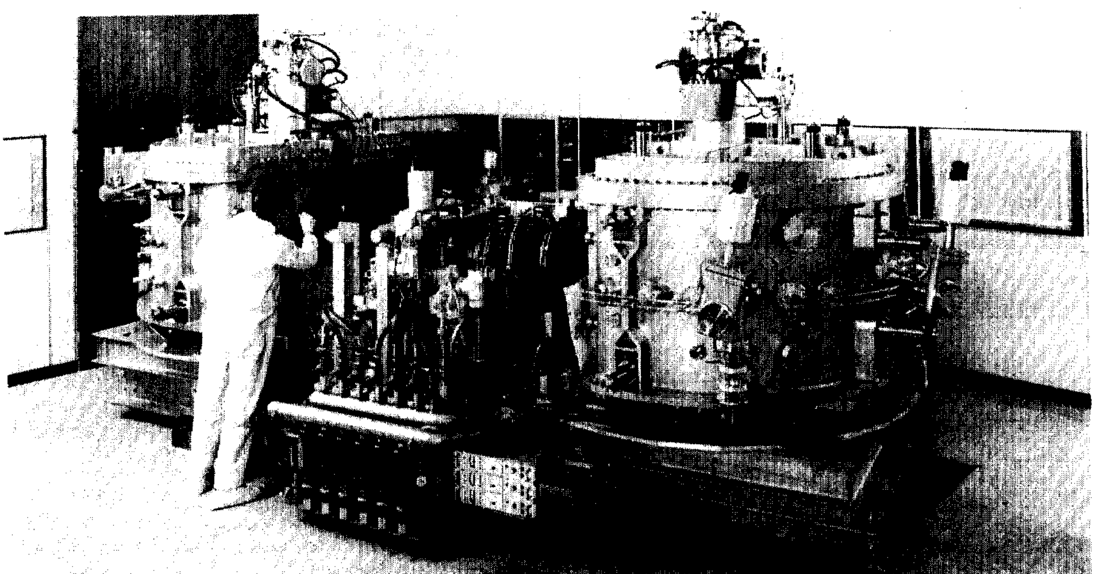

Fig. 2 Helios 1 on completion of assembly in the clean area.

Injection is at 200 MeV from a 2 section linac supplied by CGR MeV. The linac runs at 3 GHz and a subharmonic 500 MHz pre buncher is provided at the low energy end to reduce injection losses at the (500 MHz) ring. The linac output beam is first dispersed by a 40^{o} bending magnet so that a momentum selection of $\pm$ 0.5% can be made at tungsten slits, after which the remaining transfer line is achromatic. Injection is via a pulsed septum and a single kicker. During tests, beams of > 20 mA have been transported through the septum, with an energy spread of $\pm$ 0.5% and emitances of ~ 1 mm mrad horizontally and ~0.4 mm mrad vertically.

The ring rf cavity is more or less an exact copy of the Daresbury SRS cavity and is powered by a standard 60 kW 500 MHz TV transmitter.

Fig 3 shows one of the superconducting dipoles in its operational cryostat. The cryogenic vacuum space is common with the beam space, thereby bringing about 7 m^2 of 4.3 K cryopumped surface into the ring vacuum. A completely clear gap is left for the X-ray beam exit around the full 2π radians so that all X-rays are either transmitted down one of the 22 beam ports or dumped on a water cooled copper absorber located immediately inside the outer vacuum tank wall. The 4.3 K magnet vessel is completely surrounded by an 80 K radiation shield, which has a special collimated slot to permit free egress of the X-rays while minimizing the ingress of thermal radiation.

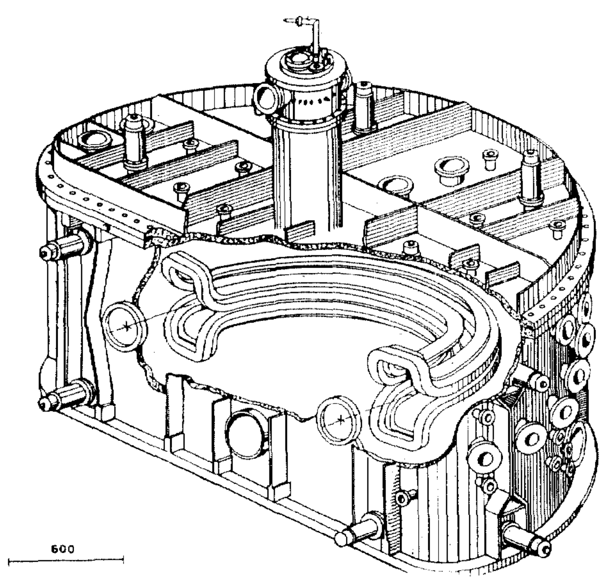

Fig.3 Cutaway view of the dipole magnet inside its operational cryostat.

No iron is used in the magnets, which comprise 4 coils of rectangular section, carefully optimized to give a field quality of ~ 2 x 10^{-4}. These coils have turned up ends, which provide better vertical aperture, reduced peak field on the superconductor, lower stresses and better field quality - but are extremely difficult to manufacture! After fabrication and before assembly into their operational cryostats, the magnets were tested in a 'tub' cryostat. Field quality was measured using a specially constructed 'mouse' which carries an array of Hall probes through the magnet aperture, following the electron beam path. Measured errors were generally on the order of a few parts in 10^4.

With Helios 1 now starting its commissioning, plans are already under way for its successor. Helios 2 will generally follow the Helios 1 design, with very many detailed improvements, principally in the areas of improved access and maintenance. In the interests of achieving a more compact layout, it will be injected at 100 MeV, using a racetrack microtron.

Conclusions

Compact rings are beginning to demonstrate the performance required by the semiconductor industry. They are but one link in a chain of technologies: X-ray masks, water steppers, resists etc. which must be complete before the production of next generation microchips by X-ray lithography can become a reality. Nevertheless, good progress is being made on all fronts and the prospects for eventual success are good.

For the future, it is likely that the emphasis in compact ring design will shift from accelerator physics and optimum performance to the more commercial considerations of reliability, up-time and cost. It will be against these criteria that the present debates about number of sectors, warm/cold bore, iron or not etc. will eventually be settled.

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References

1 Trinks U and Nolden F, Nucl. Inst. Meth. 200 (1982) 475-479
2 Takahashi N, Nucl. Inst. Meth. B24/25 (1987) 425-428
3 Shimano T et al. Proc 1987 IEEE Particle Accelerator Conference Washington DC
4 Tominasu T et al. Japan Jnl. Appl. Phys. 26 741 (1987)
5 Craft BC et al. Nucl. Inst. Meth. B40/41 (1989) 379-383
6 Mandai S Particle Acc. Vol 33 (1990) 45-50
7 Shibayama et al. Rev. Sci. Inst. Vol 6 No 2 part 11 A (1989) 1779-1782
8 Nakamura S et al papers TUP 03R TUP 04R and TUP 05R at this conference.
9 Weihreter E et al paper THO 01A at this conference
10 Wilson M N et al Microcircuit Engineering 89 (1990) 225-228 Els+evier
11 Tominasu T et al Proc 7th Symp. Acc. Sci. Tech. 12-14 Dec 89, Osaka University, Japan.
12 Hosokawa T et al Rev. Sci. Inst., Vol 60 No 7 Part 11A (1989) 1783-1785
13 Murphy JB et al papers THP 29R and THS 12A at this conference.