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PERMANENT MAGNET STORAGE RINGS FOR MICROLITHOGRAPHY AND FEL SOURCES

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SUMMARY

Permanent magnet technology is rapidly improving and it seems possible now to design and build dedicated electron storage rings for peculiar applications such as microlithography and free electron laser. A low capital cost as well as a low operational cost (no power supplies) may lead to industrial solutions.

In this paper we describe two possible design studies for machines at energies of 240 and 500 MeV with some indications on an efficient injector.

INTRODUCTION

With only few exceptions, all storage rings presently in use for synchrotron radiation purposes were built for elementary particle physics. Obviously, dedicated storage rings can be better adjusted to synchrotron light performances (low emittance, high photon flux and brilliance). Recent design are trying to do that but still on a classical design basis which is not very well matched to industrial production. The capital cost is rather high and the operation cost is high too for these relatively small machines.

Injectors are even worse ; they are either old accelerators surviving at high operational and maintenance costs, or new accelerators making use of an old technology.

Finally, it appears that no much accelerator developments followed the new interest in small electron storage rings.

The present proposition deals with a ring design based on permanent magnet technology, in order to lower the capital cost as well as the operation cost (no power supplies, water cooling, electrical consumption). A dedicated injector follows the idea that it should be a small fraction of the total cost of a synchrotron radiation complex (small building area, minimum type and number of basic components). Moreover such an injector will be used only during short periods of time as compare to the useful storage time in the ring. With this in mind it looks reasonable to help developing a high current, high gradient linear accelerator as a compact injector for a small storage ring. Such linacs are already under development for high energy physics.

The final aim is to bring the cost of a small electron storage ring, including its injector, to a low level such that microlithography applications can be envisaged from an industrial point of view. Moreover free electron laser (FEL) storage ring sources are competing with other FEL sources. A reduction in the cost of very small electron storage rings will then be of great help in that domain too.

PARAMETERS FOR PERMANENT MAGNET STORAGE RINGS

Good synchrotron radiation sources require small beam transverse emittances. The transverse emittance is defined as follows :

$$E_y = \frac{\sigma_y^2}{\beta_y} = \bar{U}_y \left(\frac{\sigma_E}{E}\right)^2$$

where σ_y is the r.m.s. beam transverse dimension ($y = x$ or z) and β_y the envelope function ; $\bar{U}_y$ is an invariant related to the lattice and σ_E/E is the r.m.s. beam energy spread :

$$\frac{\sigma_E}{E} \simeq 0.86\ 10^{-3}\ \frac{E_{[\mathrm{GeV}]}}{\rho^{1/2}_{[\mathrm{m}]}}$$

The nominal energy E, for a dedicated ring, is mainly determined by user's considerations such as the wavelength range from wigglers and ondulators.

The bending radius ρ is related to the bending field of the dipole magnet, B, through the following relation :

$$E_{[\mathrm{GeV}]} = .3\ B_{[\mathrm{T}]}\rho_{[\mathrm{m}]}$$

It follows that small values of B will favour small emittances, but also large radii. Then, a compromise is necessary to maintain a reasonable ring circumference, knowing that a large fraction of that circumference comes from the long straight sections equipped with ondulators or multipole wigglers (each being about 3 meters long).

In some cases it is still necessary to keep the bending field, B, as high as possible to make the damping times as small as possible leading to higher injection rates. However this argument fails in the present case where single shot injection is foreseen.

The next step to reduce the emittance is to design a very strong focusing lattice which makes the transverse invariant $\bar{U}_y$ small. Keeping at the same time the envelope function small enough will lead to small beam sizes and consequently to small vacuum chamber apertures.

The simplest method to do that is to build a FODO channel where the bending magnets are placed between a focusing quadrupole F and a defocusing quadrupole D. Periodic sets of such elementary cells will constitute the arcs of the ring.

Matching of the long straights to the arcs is then easily done by a few additional quadrupoles.

In a first approach one can ignore the long straight sections and keep only the arcs which properties are sufficient to describe the transverse emittances.

Considering the quadrupoles as thin lenses and the space between quadrupoles filled by straight magnets, the transfer matrix, in the plane of curvature, for a half FODO cell is :

$$T = \begin{Vmatrix} 1 & 0 & 0 \\ -\frac{K\ell}{2} & 1 & 0 \\ 0 & 0 & 1 \end{Vmatrix} \begin{Vmatrix} 1 & \rho\sin\theta & 2\rho\sin^2\frac{\theta}{2} \\ 0 & 1 & 2\mathrm{tg}\frac{\theta}{2} \\ 0 & 0 & 1 \end{Vmatrix} \begin{Vmatrix} 1 & 0 & 0 \\ \frac{K\ell}{2} & 1 & 0 \\ 0 & 0 & 1 \end{Vmatrix}$$

where K is the normalized gradient, $K = G/B\rho$, ℓ the quadrupole length and θ the bending angle of the magnets. We have to notice that for straight magnets the focusing due to edge effects compensates exactly the focusing due to the curvature. By identification of the transfer ma-

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trix with the TWISS matrix it is possible to deduce the betatron phase shift per period, ϕ, as well as the betatron envelope function β and the dispersion function η at the center of the quadrupoles F and D, in the horizontal plane[1,2,3] :

$$\sin\frac{\phi}{2} = \frac{K\ell}{2}\,\rho\theta$$

$$\beta_{F,D} = \frac{2\rho\theta[1 \pm \sin\phi/2]}{\sin\phi}$$

$$\eta_{F,D} = \frac{2\rho\theta^2[1 \pm \frac{1}{2}\sin\phi/2]}{1-\cos\phi}$$

The invariant $\bar{U}_x$, which enters in the definition of the horizontal emittance, is given by[4] :

$$\bar{U}_x \simeq 2 < \frac{1}{\beta}[\eta^2 + (\beta\eta' - \frac{1}{2}\beta'\eta)^2] >$$

where β and η, and their derivative with respect to the azimuthal position, are evaluated in the horizontal plane, and the mean value < > is taken over the magnet length.

In the vertical plane, where no bending normally occurs, the dispersion function η is zero and so is the vertical invariant. However, due to magnet misalignement, the horizontal and vertical motions couple together leading to a finite vertical beam size. The coupling coefficient estimated from existing machines is roughly $\bar{U}_z/\bar{U}_x \simeq .04$.

For small θ, it can be shown that[3,5] :

$$\bar{U}_x \simeq \frac{4\rho\theta^3}{\sin^2\phi/2.\sin\phi}\,[1 - \frac{3}{4}\sin^2\phi/2 + \frac{1}{60}\sin^4\phi/2]$$

This relation shows a minimum for $\phi = 120°$. Moreover, short bending magnets and high quadrupole gradients are necessary to make small emittances as well as small β values, and hence small beam sizes.

Here comes out the interest of using permanent magnet dipoles and quadrupoles. For instance, in the case of small aperture quadrupoles, it seems easier and cheeper to produce very high gradients[6], up to 200 Tesla/meter. For dipoles, the permanent magnet technology should permit to reduce their length, and increase their number, without additional cost and with less worry concerning the fringing fields. Notice that with short dipoles the sagitta, the pole width and the beam emittance are reduced.

The previous set of formulae permits quick design approaches. Two examples are shown in table 1 : the first case corresponds to a low energy machine (E = 240 MeV) suitable for a free electron laser source, while the second case corresponds to a medium energy machine (E = 500 MeV) with usefull wavelengths extending into the range 10 - 40 Å, suitable for microlithography. For each machine, it is clear that the total circumference will depend on the choice of the number of straight sections, considering that one straight section would be about 1 meter long for wigglers and 3 meters long for ondulators.

PERMANENT MAGNET QUADRUPOLES AND DIPOLES

Permanent magnet quadrupoles having a gradient of 23 T/m, for an internal radius of 1.3 cm, have been already built[7]. They make use of rare earth cobalt material (S_mCo_5). More recently, K. HALBACH[6] has proposed a new design for an hybrid (REC with steel), adjustable gradient quadrupole with value up to 200 T/m.

Here, conservative values of 50 T/m are considered ; moreover an internal quadrupole radius of 1 cm will satisfy the ring acceptance (± 10 $\sigma_{x,z}$) including allowance for closed orbit errors (± 5 mm) and vacuum chamber thickness (∿ 2 mm). In that case an hybrid quadrupole[8] would have a transverse area of active REC material of 11.5 cm^2 which gives a volume of about 100 cm^3 for the longer quadrupole (table 1). The cost of REC is estimated (in U.S.) at 1.5 \$/cm^3, which brings the price of a quadrupole to 150 \$, showing that the material is not a cost dominating factor. It is difficult to estimate the manufacturing cost because no experience is available in building these devices. Prototypes under construction in U.S. Laboratories will permit soon to investigate the properties of such variable gradient REC quadrupoles.

Energy	E	240	500	MeV
Bending field,	B	1.2	1.0	T
Bending radius,	ρ	.666	1.666	m
Energy spread,	σ_E/E	$2.5\ 10^{-4}$	$3.3\ 10^{-4}$	
Number of dipoles,		12	16	
Dipole length,		.35	.65	m
Quadrupole gradient,	G	50	50	T/m
Quadrupole length,	ℓ	7.9	8.8	cm
Betatron functions,	β_F	1.50	2.8	m
	β_D	.11	.2	m
Dispersion functions,	η_F	.35	.49	m
	η_D	.14	.19	m
Horizontal invariant,	$\bar{U}_x$	.26	.28	m
Horizontal emittance,	E_x	$1.7\ 10^{-8}$	3.10^{-8}	m.rd
Maximum beam sizes at quadrupole centers,	σ_x	.16	.3	mm
(4 % coupling),	σ_z	.03	.06	mm

Table 1 - Design examples

The dipole case is quite different. For instance an hybrid dipole (REC with steel) which satisfies the low energy case of table 1, with B = 1.2 T, a magnetic length of 35 cm and a gap height of 2 cm will have a volume of active REC material of about 5000 cm^3 and a corresponding price of 7500 \$ which is much too high if compared to a classical electro-magnet. A remedy to the cost problem consists of using ferrite instead of REC[8]. That brings the remanent field, B_r, down from 9 to 3.5 Kgauss, but the estimated price (in U.S.) per cm^3 is down by a factor close to fifty (∿ .03 \$/cm^3 for ferrite). For the previous example (first case of table 1) the volume of ferrite would be 42.000 cm^3 and the price 1300 \$. For the second case in table 1 the numbers will be up by 20 %.

Here again the manufacturing costs are difficult to estimate. At ORSAY it is envisaged to build a prototype dipole as the first step of a possible small test bed permanent magnet storage ring.

A serious problem, connected to the dipoles, comes from the temperature coefficient of ferrite $\frac{\Delta B_r}{B_r} \simeq 2.10^{-3}/°C$ which is sufficiently large that one might think of putting a thermally insulating jacket around each dipole. Moving gap is also envisaged.

The cost for the magnetic part of a small permanent magnet storage ring, finally should not exceed 50 K\$.

Rough extrapolations, from existing storage rings, for the other components seem to indicate that the magnetic part has now become a small fraction of the total cost. For microlithography applications, the goal is to keep the total cost, including the injector, below 3 M\$, which then makes the storage ring price competitive with the price of a conventional electron lithography machine.

INJECTION SYSTEM

The design examples given in table 1 become quite simple when used with a single bunch circulating. A bunch current of 100 mA would be reasonable for most application and would correspond to 2 to 4.10^{10} stored particles.

According to the very small acceptance of the rings, no much provision is left for closed orbit manipulations. A single shot injection method, using a single kicker, is suitable as it does not lead to stored beam disturbance. Taking into account the lack of injection efficiency, as observed on most existing machines, it happens finally that the injector must provide the following minimum beam characteristics :

pulse length	20	ns
peak current	500	mA
emittance	π	mm.mrd
energy spread	1‰	

Present generation of linear accelerators can do that, but with accelerating gradients of the order of 15 MV/m, which obviously is too low to make a compact machine at 500 MeV.

The high energy physics community is pushing to develop very high gradient accelerating structures, up to 100-150 MV/m. A first step which looks realistic and not too far away, and which does not introduce too many problems in connection with the peak power sources, would be a gradient of the order of 50 MV/m. Then a 500 MeV linac would be only 10 meters long.

From conventional iris loaded structures one can expect some increase in the accelerating field without increasing the electrical field on the walls, by increasing the iris thickness. However that method does not improve the shunt impedance and the quality factor and hence is power consuming. Klystrons with 35-40 MW peak power (4 to 5 μs pulse length) are already available and by feeding a pulse compression network, using storage cavities9), one can increase the useful peak power by a factor 3 to 4.

With all these assumptions, a rough estimate leads to the design parameters given in table 2.

Peak power/klystron		40	MW
RF pulse length		5	μs
Storage cavities	coupling factor	7	
	quality factor	150.000	
Length of accelerating section		2.5	m
RF frequency		3	GHz
Accelerating mode		T.W.,$2\pi/3$	
Iris diameter		21	mm
Shunt impedance (copper)		70	MΩ/m
Q factor		15200	
Filling time		.68	μs
Stored energy		72	J
Energy gain		125	MeV
Beam loading parameter		$1.7\ 10^{-5}$	eV/C

Table 2 - Design parameters for a compact linac

With this slightly unconventional linear accelerator the low energy machine will need two sections with two klystrons, while the medium energy machine will need four sections with four klystrons. The number of klystrons is perhaps high but they will be used at a low repetition rate ($\gtrsim$ 1 sec.). The price for a four sections linac should be of the order of 1 M\$ which does not contradict the aim of 3 M\$ for the total capital cost of a complete microlithography storage ring complex.

The expected energy dispersion from the injector is of the order of 7.10^{-3} ; if too high an energy compression must be added to the linac.

CONCLUSION

The aim was to demonstrate the possibility of building small storage rings using permanent magnet technology, and compact linac injectors. However it remains to perform some more prototype work on dipole, quadrupole and high gradient section, before an exact detailed cost can be achieved. The final goal being an industrial production, a small test bed storage ring including the associated injector would certainly be of a great help.

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