DESIGN STUDY OF A SUPERCONDUCTING SOR FACILITY*

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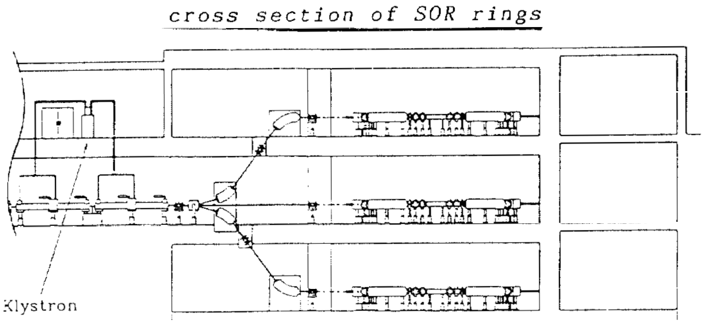
This paper describes the design study on a synchrotron orbital radiation (SOR) facility composed of a superconducting linac and storage rings. The rings using superconducting magnets and a superconducting cavity can store electron beams of 1 GeV with beam current of 200 mA. Design features are as follows: (1) Superconducting magnets and a superconducting cavity are employed to save both operating power and space. (2) High vacuum in the beam chamber is expected shortly after the start of initial operation, because electrons are accelerated by the superconducting linac and injected at full energy of 1 GeV. (3) Each storage ring has three super periods in the lattice, and three long drift spaces for electron beam injection, cavity installation and optional insertion devices, respectively. (4) A superconducting TW linac as the injector can save electric power and increase electric field gradient. (5) The accelerating guides of the superconducting traveling wave linac are indirectly cooled with LHe flows in order to make maintenance and cryostat construction easier. (6) An optional acceleration and storage system of positrons can be installed.

Introduction

In past several years the SOR facility has become one of the most interesting scientific instruments. Many construction plans of electron storage rings are now proposed. The application of the SOR to X-ray lithography is particularly very attractive for industrial production of VLSI because of high intensity X-ray beam. Interesting wavelengths for the X-ray lithography are around ten Å, and the X-ray intensity of around 50 mW/Å/mrad^2 at the wavelength of 10 Å is required for acceptable throughput of lithography system. For such wide use of the SOR facilities, however, some modifications of conventional rings are required for their cost reduction and simple operation. With such requirements we have designed an SOR facility with the following features.

(1) A superconducting linac injects electrons with full energy into several storage rings.
(2) Each storage ring has three superperiods in their lattice.
(3) Superconducting magnets and a superconducting cavity are used in the storage ring.

Full energy injection has the great advantage in lifetime of electron beam stored with high current. Generally speaking, the beam lifetime is limited by quantum fluctuations, Touschek effect and scattering with residual gases. However, the scattering of electrons by residual gases in the vacuum chamber causes the most impotant problem for the beam life time of high energy stored current. The degree of vacuum becomes worse because of emission of gaseous matters from the vacuum chamber wall by irradiation of SOR. In addition to recent remarkable developments in baking methods, it is the most powerful baking procedure to expose the wall for the SOR [1] . Faster baking of the chamber wall will be accomplished by higher energy electron injections. This is the reason why we adopt the full energy injection to our system.



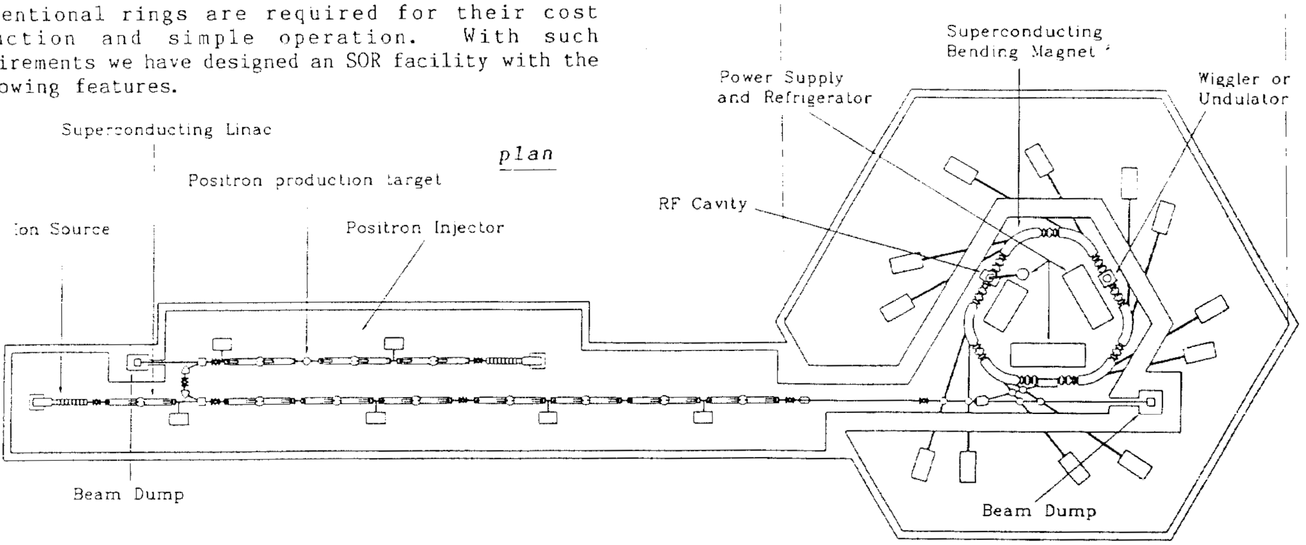


Fig.1 Conceptual view of the SOR facility

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Injector linac

The linac has to accelerate electrons or positrons up to 1 GeV for the full energy injection. In case of a normal conducting accelerator, however, very high power klystrons are used for increasing the electric field of the accelerator, or the accelerator is so long that it is not so attractive for industrial uses. It is the reason why we are studying superconducting traveling wave accelerators. The reduction of the peak power of klystrons is very important subject. Recently, superconducting cavities made of niobium having high residual resistance ratio were developed and become available for practical use with the high Q values. However, the field gradient rarely exceeded 10 MV/m. Thermal breakdown of superconductivity was the main reason for this, that is, it is supposed that normal conducting area extends successively from the defects by thermal conduction of the cavity surface heated with RF power to the cavity. In this point of view, high field gradient is expected to be only achieved in the short period excitation of a superconducting cavity. SLAC has already got some attractive experimental results in the pulsed operation mode of superconducting cavities [2].

The cavity must be excited within several micro-seconds before the breakdown of superconductivity occurs. The disk loaded superconducting wave guide acceleration structure is adopted in this design. This type of accelerating guide has some advantages in cost because of easy fabrication.

The accelerating wave guide is composed of the inner surface made of pure niobium and the outer backing made of copper or aluminum. The cooling pipes for the indirect cooling are attached around the accelerating wave guide.

Parameters of the linac are shown in Table 1. The operating mode is $2/3\pi$ because of less number of disks compared with that of $1/2\pi$. The operating frequency is chosen to be 2856 MHz. The choice is reasonable for the disk aperture and the inner diameter of the accelerating wave guide.

The Q value also seems reasonable from the viewpoint of the RF power consumption on the accelerating wave guide wall.

The Q value is

$Q_{sc} = Q_{nc} \cdot R_{nc}/R_{sc}$, $R_{sc} = R_{BCS} + R_{res}$

Q_{sc} : the Q value of the superconducting cavity

Q_{nc} : the Q value of the normal conducting cavity

R_{sc} : the surface resistance of the superconducting cavity

R_{nc} : the surface resistance of the normal conducting cavity

R_{BCS} : the BCS resistance

R_{res} : the residual resistance

The residual resistance is changeable with its surface treatment condition but is not so important at S-band and 4.2 K. R_{BCS} is about $2\mu\Omega$ at S-band, and the Q value of around 8×10^7 is expected at 2856 MHz in the $2/3\pi$ mode accelerating wave guide structure [3] . The total heat, P, to be cooled for the whole length of the accelerator wave guides, is as follows.

$P = P_{rf} + P_{st} = \omega E t R/SQ + qV/E$

P_{rf} : the dissipated RF power in the cabity

P_{st} : the heat-in-leak

ω : the angular frequency

S : the elastance per unit length

E : the field strength

t : the RF pulse length

R : the pulse repetition rate

V : the total accelerating voltage

q : the heat-in-leak per unit length

Figure 2 shows duty ratio versus electric field at f = 2856 MHz, S = 90 MΩ/μsec·m, V= 1 GV and P = 40 W. It seems possible to operate the accelerator at R = 20 pps, E = 40 MV/m, t = 7μsec and q = 1W/m, so the Q value of 8×10^7 is an acceptable level.

Table 1 Parameters of linac

Energy (GeV)	1
Peak current (mA)	10
Beam pulse width (μsec)	<1
Repetition rate (pps)	20
---Accelerator guide---	
Type of structure	$2/3\pi$ mode TW
Frequency (MHz)	2856
Length of accelerating guide (m)	1.575
Total number of guides	16
Group velocity (vg/c)	0.001
Filling time (μsec)	5
Guide diameter, 2b (cm)	8.063
Iris aperture diameter, 2a (cm)	1.2
Disk thickness, t (cm)	0.5
Field gradient (MV/m)	40
Operating temperature (K)	4.2
r_0/Q (kΩ/m) and Q_0	5.4 and 8×10^7
---RF source---	
Klystron peak power (MW)	30
Pulse length (μsec)	7
Number of klystrons	4

Fig.2 The maximum duty versus field gradient in case of P = 40 W:
(1) q = 1.25 W/m;
(2) q = 1.00 W/m;
(3) q = 0.75 W/m.

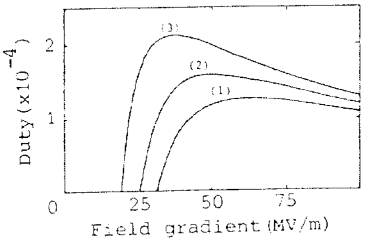
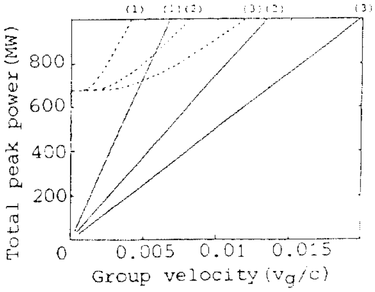


Fig.3 Total peak power versus group velocity at accelerating guide section length: (1) 1 m; (2) 2 m; (3) 3 m. The dotted line and the solid line are for copper conductor guides and for super-conductor guides, respectively.



The total peak power, Pt, required without the beam loading, is

$P_t = E v_g V / L S \eta$

where L is the section length of the accelerating wave guide and vg is the group velocity. Here η is the section efficiency defined for a constant gradient section by

$\eta = \{1-\exp(-2\tau)\}/2\tau$

where τ is the attenuation constant. Because τ is approximately zero in case of a superconducting wave guide, $\eta \approx 1$ [4] . Figure 3 shows Pt versus vg for the superconducting wave guide in comparison with the normal conducting copper. The total RF peak power required for the normal conducting wave guide is more than 680 MW for accelerating electrons up to 1 GeV, while the power required for the superconducting wave guide is only 100 MW at the filling time of five micro-seconds.

However, the most important factors in a superconducting accelerating guide is supposed to be the repetition rate and the exciting pulse length, which is somewhat longer than the filling time, as mentioned above. Furthermore, we already have started the apprication R&D of the newly developed high Tc superconducting materials such as Ba-Y-Cu-O compound system to the linac and cavities [5].

Electron storage ring

The simplest structure SOR ring is the circular machine having one magnet. However, the magnet has to have simultaneously many functions such as bending, focussing and chromaticity correction of the electron beam. Therefore, it is difficult to achieve a stable electron storage in the ring with less number of magnets. Another problem is in kicker magnet system in small rings which adopt full energy injection.

Considering such conditions, we designed the lattice having three superperiods with six bending magnets. Its circumference is 24.9 m, and the beam focussing is performed by fifteen quadrupole magnets. Twelve sextupole magnets are engaged in chromaticity correction. An RF cavity, septum magnets and insertion devices as option are installed in three long straight sections, individually. Users are able to utilize more intense beam and shorter wavelengths of X-ray with the optional insertion device such as wigglers or undulators.

Table 2 shows the main parameters of the storage ring. The superferric bending magnets shown in Fig.4 produce the high quality field of 1.7 Tesla. As a superferric magnet consumes less electric power and makes the field strength more stable and more uniform than a conventional magnet and an air-core magnet, it is advantageous to use it for bending magnets of storage rings.

The nominal stored energy of electrons is 1 GeV. The brightness of X-ray at 1 GeV reaches the maximum value at about 10 Å in wavelength which is preferable for X-ray lithography. It should also be noticed that only minimal shieldings are required for personnel protection when the electron energy is less than 1 GeV. The betatron tunes designed are available for four-turn injection of electrons which is able to lower the damping rates of kicker magnets.

In future if higher field and quality superconducting magnets for SOR are developed, it is easy to replace the lattice magnets with the new ones to get higher energies of stored electrons or positrons.

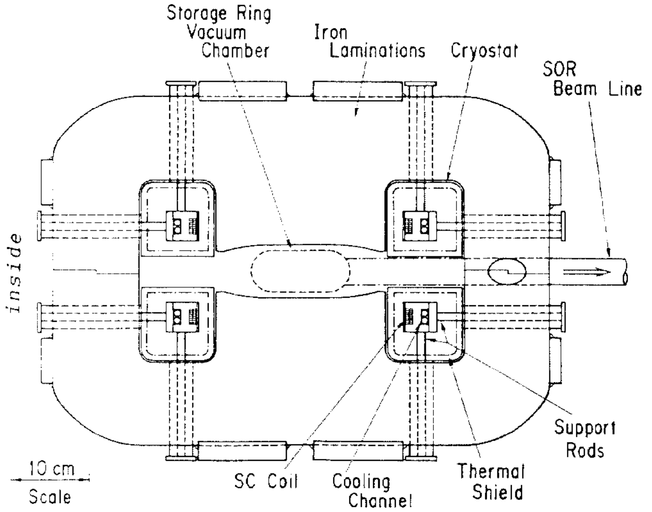


Fig.4 Cross section of the bending magnet

Table 2 Parameters of SOR ring

Energy (GeV)	1.00
Beam current (mA)	200
Circumference (m)	24.9
Number of symmetric cells	3
Harmonic number	41
Bending radius (m)	1.96
Length of straight sections (m)	3.2 1.0
Critical wave length (Å)	11.0
Maximum radiation power (mW/Å·mA·mrad)	0.5
Revolution time (ns)	83
Energy loss per turn (keV)	45
Damping time of betatron oscillation (ms)	3.7
Damping time of synchrotron oscillation (ms)	1.8
Horizontal tune	2.25
Vertical tune	1.25
Maximum horizontal beta (m)	3.9
Maximum vertical beta (m)	14.6
Maximum horizontal dispersion (m)	2.7
Momentum compaction factor	0.016
Natural horizontal chromaticity	-2.0
Natural vertical chromaticity	-3.6
Number of bending magnets	6
Bending field (T)	1.7
Length of bending magnet (m)	2.05
Field index of bending magnet	0.0
Number of quadrupole magnets	15
Field gradient of quadrupole magnet (T/m) QF1	19.0
QF2	8.6
QD1	19.3
Length of quadrupole magnet (m)	0.2
RF frequency (MHz)	494
Peak RF voltage (kV)	91
RF bucket height (%)	0.56

Conclusion

The SOR facility designed here is available for X-ray lithography as well as basic and applied research, e.g. EXAFS, tomograph, and fluorescence micro analysis [6]. The SOR factory having several rings installed one or a few floors is very much attractive for VLSI factories and research centers.

Our design bases on using the high gradient superconducting accelerating wave guides and the superferric bending magnets for the total cost and size optimization. As there are not so many data of the maximum field gradient of the superconducting accelerating wave guides, however, it should be defined in $2/3\pi$ mode traveling wave accelerating guides.

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