Hard X-Ray Synchrotron Light Source for Industrial and Materials Research Applications

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Abstract

Synchrotron radiation is about to become an industrial tool. The requirements originating from industrial production or from an industry-related analytical environment will have a significant influence on the machine design. This is demonstrated for the case of the hard X-ray synchrotron light source proposed for Mainz. The source is intended to provide radiation mainly for deep X-ray lithography as part of the LIGA-process in microfabrication and for analytical and diagnostic purposes in materials research and microtechnology. It offers up to 48 bending magnet beamlines with a characteristic wavelength of 2 Å. To minimize technological risks both during construction and operation an electron energy of 2.5 GeV and normal conducting magnets will be used. Based on the missing magnet concept, a FODO lattice with a beam emittance of $3\ 10^{-7}$ m rad and four dispersion-free straight sections to accommodate insertion devices, injection elements and RF structures has been designed.

1. INTRODUCTION

Storage rings adapted to produce synchrotron radiation (SR) for specific technologies like e. g. the future mass production of complex integrated electronic circuits have been developed [1] and are utilized in Europe, USA and in particular in Japan to promote the industrial implementation of X-ray lithography.

For fabricating microstructures with extreme structural heights, the so called LIGA-method has been developed by W. Ehrfeld and co-workers at the Karlsruhe Nuclear Research Center [2-3]. The technique is based on a combination of deep-etch X-ray lithography, electroforming and molding processes and may be utilized to produce a large number of three-dimensional microstructure products in the field of sensors, compound materials, filtration, fluid dynamics, microoptics, synthetic fibers, communication techniques and microelectronics. In the first step of the process, shadow printing is applied to transfer the pattern from a high contrast X-ray mask into a resist layer with a thickness of up to 1000 μm so that a resist relief may be generated with extremely high precision and with a depth to width ratio of up to 1000. The deep-etch lithography process makes use of highly intense and collimated SR with a characteristic wavelength of 2-5 Å. By means of subsequent replication processes, the resist reliefs may be transformed into complementary relief structures and a wide variety of materials may be utilized.

Microfabrication and nearly all modern technologies heavily rely on the development of new materials. Here SR has proven to be a valuable analytical tool to monitor structure and structural changes by e. g. small angle X-ray scattering techniques or the application of EXAFS. In general, analytical methods like X-ray absorption and reflection techniques will be used for the support of industrial production processes as well as in protein cristallography and molecular biology research. Therefore, in addition to the commercialization of micromachining techniques like e. g. the LIGA-method, industrial participation is expected to become an important aspect for the synchrotron light source in Mainz, proposed recently [4].

2. DESIGN SPECIFICATIONS

For basic research applications, third generation synchrotron light sources will have a very low beam emittance to produce SR with high brilliance [5]. The commercial use of SR rather calls for high flux, high stability and reliability of the machine, a cost-effective production of SR, and a large number of beamlines in order to reduce the fee for single users.

For deep-etch lithography, a SR spectrum with a characteristic wavelength of $\lambda_c = 2\text{-}3$ Å is required in order to optimize the accuracy of the structure transfer which is impaired due to Fresnel diffraction or the production of high energy photoelectrons in the resist material (typically PMMA). In case of very high resist structures, energy dose considerations for the developing process of the resist material restrict the characteristic wavelength to $\lambda_c = 2$ Å.

A small divergence of the SR is mandatory to avoid an oblique energy dose deposition in the resist at the absorber edges. This mainly concerns the vertical direction. Therefore any additional emittance contribution to the (inevitable) natural divergence of the SR should be avoided. Here a small natural beam emittance and a small emittance coupling factor k are required.

In the lithographic process both the X-ray mask and the resist are moved vertically to achieve a homogeneous irradiation on an area of typically some thousand mm². The distance of the scanning system from the source point is typically 15-20 m to reduce the obliqueness of the X-ray beam due to the various horizontal angles from slightly different source points. In view of the large distance, a contribution of the finite beam-width to the divergence of SR may be neglected.

For materials research experiments, a small natural emittance ε_0 is required for good energy resolution. It turns out, that in typical X-ray absorption and reflection experiments again the vertical divergence is of primary concern. Assuming a small coupling factor k (typically 0.05 - 0.1) and taking $\varepsilon_z = k\varepsilon_0$, the standard deviation σ_z of the overall vertical divergence is given by:

$$\sigma_z = [\sigma_n^2 + \varepsilon_z (1 + \alpha_z^2)/\beta_z]^{1/2} \qquad (1)$$

Here $\sigma_n = mc^2/E$ denotes the natural divergence, α_z and β_z the Twiss parameters at the source point. The contribution of ε_0 to σ_z will be negligible in case $\varepsilon_0 < 5\ 10^{-7}$ mrad.

Photon flux is another important issue. Here typical values of 10^{12} to 10^{13} photons/s, mrad and 0.1 % bandwidth are required for experimental purposes down to wavelengths of about 0.5 Å. A later extension of the intensity spectrum to even shorter wavelengths and higher intensities will be possible due to the future installation of wigglers and undulators in straight sections.

Although the whole facility will clearly be dedicated to the commercial use of synchrotron radiation, there will be a number of beamlines available for basic research, especially in the field of materials research. Here the synchrotron light source Mainz will serve as a regional High Tech Center to boost synergy effects in an industrial and fundamental research environment.

3. STORAGE RING LAYOUT

3.1. Intensity Spectrum

In order to avoid any technical risk and to achieve a high reliability of the machine, normal conducting bending magnets have been chosen with a maximum induction of B =1.5 T and without gradient. An electron beam energy of E = 2.5 GeV results from the choice λ_c = 2 Å. With these parameters and a beam current of I = 100 mA an intensity spectrum like in fig. 1 is obtained. It is evident that even at λ = 0.5 Å, a typical wavelength used in protein cristallography experiments, the intensity is still high enough.

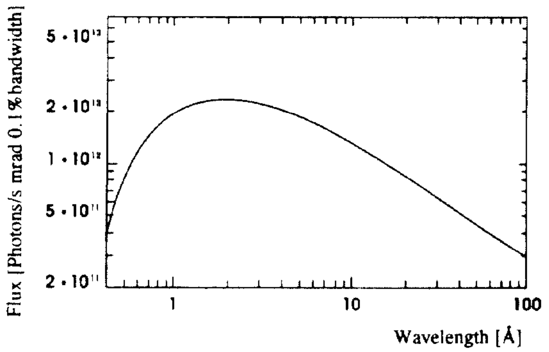

Fig. 1 Intensity spectrum for E = 2.5 GeV, B = 1.5 T and I = 100 mA.

3.2 Magnet Lattice

The storage ring lattice is based on a simple separated function FODO arrangement of magnets. At four straight sections, two adjacent cells with only one bending magnet create a vanishing dispersion function D_x in the straight region (see fig. 2). The location of the dispersion suppressor regions generates a four-fold supersymmetry of the storage ring. Therefore, one of these sections is used to install RF-cavities, thus minimizing the occurrence of synchro-betatron resonances, whereas the others are well suited to accommodate the injection elements as well as insertion devices at a later stage of the project.

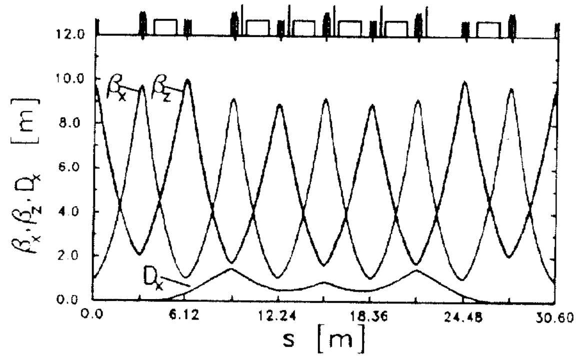

Fig. 2 Lattice functions in one supersymmetric cell of the storage ring. Straight lines denote the sextupoles.

The magnet lattice structure has been designed to obtain an equilibrium emittance of $\varepsilon_0 = 3\ 10^{-7}$ m rad, to meet the above demands. There is ample space available for the installation of a closed orbit measuring system, correction elements, vacuum pumps etc. The vertical aperture requirements in the bending magnets are kept small due to vertical beta functions well below values of 10 m. Therefore the running costs will be reduced. The parameter list for the storage ring is given in Table 1.

Table 1
Parameter list storage ring

Nominal beam energy [GeV]	2.5
Natural emittance at 2.5 GeV [m rad]	$3.\ 10^{-7}$
Nominal current [mA]	100.0
Circumference [m]	122.4
No. superperiods	4
Tunes Q_x, Q_z	6.4/4.4
Natural chromaticities ξ_x,ξ_z	-8.1/-5.8
Momentum compaction	0.03
Harmonic number	204
Natural energy spread [%]	0.09
Energy loss per turn [MeV]	0.62
No. dipole magnets/L [m]	24/1.46
Bending radius [m]/B_{max} [T]	5.56/1.5
No. quadrupoles	40
Max. Gradient [T/m]/L [m]	12/0.4

Due to modest focusing strengths of the F and D quadrupole families and the rather small beta functions of the lattice, weak sextupole strengths are required to correct for the natural chromaticities. This in turn leads to small tune shifts as function of momentum deviation (see fig. 3) and a corresponding large momentum acceptance. In addition, a very small sensitivity for closed orbit deviations is achieved.

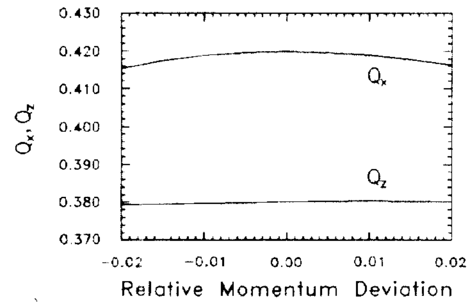

Fig. 3 Momentum - dependent tune shifts

The almost linear situation with respect to beam dynamics is also demonstrated by performing tracking calculations with amplitudes larger than the physical aperture of the machine. The calculations show extremely small tune shifts of $\Delta Q_{x,z} < 0.01$ for amplitudes larger than 25 mm in the straight section.

A general view of the storage ring and the injection system is given in fig. 4. At each vacuum chamber in the 24 bending magnets two flanges are installed for the extraction of SR, resulting in 48 SR beamlines at the final phase of the machine. As an additional potential for a later extension, insertion devices like normal wigglers, undulators and superconducting wigglers will be installed in the straight sections of the storage ring to perform experiments where extremely high flux or hard X-rays will be needed in angiography as well as solid state and protein cristallography experiments.

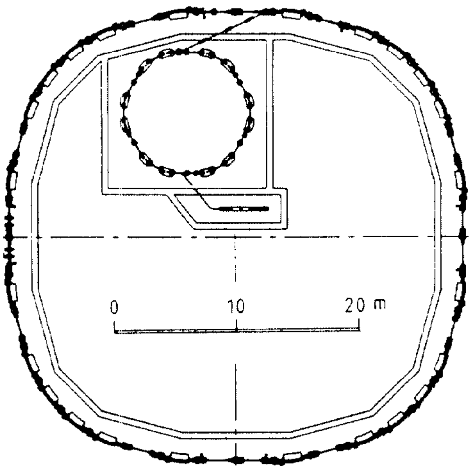

Fig. 4 General view of the storage ring and the injection system

3.3 Injection System

For the electrons circulating in the storage ring a beam lifetime of about 10 h is expected. Therefore injection will take place after typically 5 hours utilizing the injection system inside the storage ring (see fig. 4). For the injection process, the magnetic field of the storage ring elements must be lowered according to an injection energy of 600 MeV, which turned out to be a good compromise for a cost-effective but highly reliable injection system taking into account lifetime considerations due to Touschek scattering, rest-gas scattering as well as aperture limits for the injection process. A 20 MeV Linac will serve as preinjector for a booster synchrotron which accelerates electrons ten times a second up to the final energy of 600 MeV.

For the booster synchrotron, a six-fold symmetry lattice is chosen. Vertical stability is obtained due to a small gradient in the dipole magnets and the use of edge focusing. Another six horizontal focusing quadrupole magnets will give some freedom for the choice of the optimum tunes of the FODO lattice.

4. CONCLUSION

A synchrotron radiation source for commercial applications has been proposed, adapted to the requirements of deep-etch X-ray lithography and the analytical support of industrial production processes. The storage ring concept is based on a simple FODO lattice with dispersion-free straight sections for the future installation of insertion devices. Emphasis was put on the construction of a highly reliable system, the reduction of the running costs for the whole facility and the minimization of user fees.

5. REFERENCES

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