DEUTSCHES ELEKTRONEN-SYNCHROTRON

DESY 02–026
March 2002

Photon Ring Multi-User Distribution System for a Soft X-Ray SASE FEL Laboratory

J. Feldhaus, E. L. Saldin, E. A. Schneidmiller
Deutsches Elektronen-Synchrotron DESY, Hamburg

M. V. Yurkov
Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia

ISSN 0418-9833

NOTKESTRASSE 85 - 22607 HAMBURG

DESY 02-026
March 2002

ISSN 0418-9833

Photon Ring Multi-User Distribution System for a Soft X-ray SASE FEL Laboratory

J. Feldhaus [a], E.L. Saldin [a], E.A. Schneidmiller [a] and M.V. Yurkov [b]

[a] *Deutsches Elektronen-Synchrotron (DESY), D-22607 Hamburg, Germany*

[b] *Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia*

Abstract

Although the soft X-ray photon beam from a SASE FEL undulator is in principle a single user tool, just like an optical laser, an optical distribution system based on multifacet reflectors can provide efficient ways to generate a multi-user facility - very similar to present day synchrotron radiation facilities. Multifacet reflectors involve multiple reflections from a series of plane mirrors. They can be repeated a number of times to form a complete ring. In principle, a few tens of beam lines with different experiments can be served by a single FEL source. Using movable mirrors in each photon ring cell it is possible to quickly switch the FEL photon beam from one experiment to the other, thus providing simultaneous multi-user capability.

Preprint submitted to *6 March 2002*

1 Introduction

Free electron lasers (FEL) based on self-amplified spontaneous emission (SASE) represent a new source of high-brightness short wavelength radiation with unprecedented properties in terms of coherence and peak intensity. Today SASE FELs have already operated successfully at VUV wavelengths [1,2] and will soon produce radiation in the EUV and soft X-ray regions [3]. The preferred layout of a SASE FEL is a linear arrangement in which the injector, accelerator, bunch compressors and undulators are nearly collinear, and in which the electron beam does not change the direction between accelerator and undulators. On the other hand, a soft X-ray FEL laboratory should serve several, may be up to ten experimental stations which can be operated independently according to the needs of the user community. The present paper describes a beam distribution system which allows to switch the FEL beam quickly between many experiments in order to make efficient use of the source.

The technical approach adopted in this design makes use of multifacet reflectors, i.e. a sequence of plane mirrors [4,5]. Previously, Vinogradov et al. [6] had recognized the potential of whispering gallery optics in the soft X-ray range. In their theoretical analysis, they derived an analytical expression for the net reflectance after a near-infinite number of grazing-incidence reflections from cylindrical reflectors. Subsequently, Newnam [4] proposed a multiple-facet arrangement of flat mirrors for the end reflectors in FEL resonators operating in the VUV wavelength range. The flat mirror configuration practically eliminates the problem of astigmatism that is inherent in large-angle reflections from a cylindrical reflector.

A possible layout of a soft X-ray FEL laboratory based on a photon ring distribution system is shown in Fig. 1. The layout of the laboratory follows

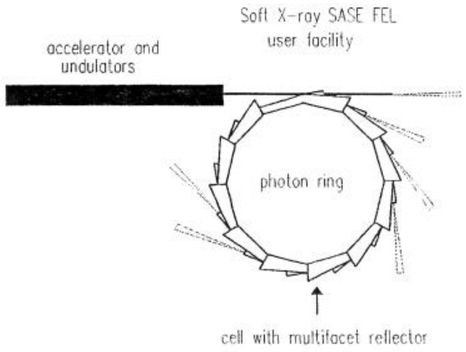

Fig. 1. Top view of a soft X-ray FEL laboratory showing a possible layout

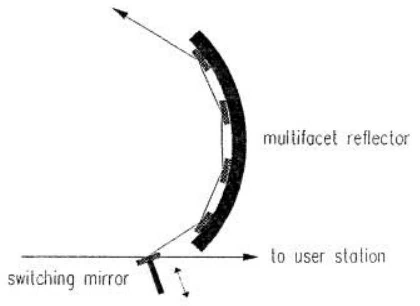

Fig. 2. Optical design of the photon ring cell

a similar approach as used for the synchrotron light sources. The SASE FEL user facility consists of SASE radiation source and the photon beam distribution system. The SASE radiation source is composed of a 1-1.5 GeV linac, bunch compressors and undulators. After the SASE undulator the electrons are stopped in the beam dump while the photons are transferred to the experimental hall. In order to make efficient use of the new source it is proposed to segment the full circumference of a distribution system into arcs which are repeated a number of times to form a complete ring. Each photon ring sector or cell includes a multifacet reflector as "bending" element and a movable mirror. A specific realization of the photon ring cell is sketched in Fig 2. Mirrors are mounted in ultra-high vacuum. The radiation beam transport line guiding photons from the SASE FEL to the experimental hall is connected tangentially to one of the straight sections of the photon ring, and the beam is injected by a deflecting mirror. In order to obtain a useful separation between the experimental areas behind the beam lines, an angle of 15 degrees between two neighboring lines would be desirable. Thus, twenty-four beam lines can be installed on a complete photon ring. Using movable mirrors in each photon ring cell, as shown in Fig. 2, it is possible to quickly switch the FEL photon beam from one experiment to the other thus providing multi-user capability.

Multifacet reflectors involve multiple reflections from a series of plane mirrors. These make use of the principle of total external reflection which occurs for angles of incidence beyond a critical angle (often near 10° grazing-incidence) when the reflective index is less than unity and the material has zero absorption. Any material absorbs light to some degree, but over certain spectral ranges in the VUV-EUV, in which the extinction coefficient is sufficiently small, a few materials do exhibit very high reflectance. Thus, with a sequence of reflections, surprisingly high values of reflectivity at large deflection angles can be obtained. Multifacet reflector transmission is determined by the total deflection angle, the number of facets and the optical constants of the mirror material. At the same time, transmission is independent of the

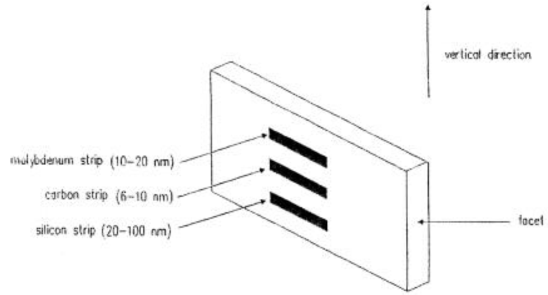

Fig. 3. View of a facet of the reflector system optimized for the wavelength range 6-100 nm. Each facet has three different coatings (C, Mo and Si strips) separated in the vertical direction. The photon beam can be injected into the photon ring at three different vertical positions

radius of the photon ring, because the number of reflections is independent of the radius value.

In principle, one could obtain the same result by using a single reflection from a multilayer mirror. However, multilayers are not apropriate for the broad wavelength range of SASE FELs. In addition, they would absorb too much radiation power and could not survive in the FEL beam. In contrast, the radiation load on the multifacet reflector is rather low because the absorbed power is distributed along the whole number of facets.

The highest efficiency of a multifacet reflector system is achieved if a low-absorbing mirror material and a sufficiently large number of facets are used. For low-absorbing materials the total transmission, i.e. the integrated reflectivity, is approximately equal to

$$R_0(\psi) \simeq \exp(-\psi\gamma/\delta^{3/2}), \quad \text{for} \quad \gamma \ll \delta\ , \quad \epsilon = 1 - \delta + i\gamma$$

where ψ is the arc angle and ϵ is the complex dielectric constant. The candidate mirror materials include C, Ag, Pd, Mo, Al and Si which, based on measured values of the optical constants, should yield high reflectance [7]. In the wavelength range 6-10 nm carbon is preferable which gives a multifacet reflector efficiency $R_0 \simeq 40$ % for an arc angle $\psi = 90°$. In the wavelength range 10-20 nm the most interesting element is Mo, which gives a transportation efficiency $R_0(90°) > 40$ % . In the long wavelength range the best material is Si with $R_0(90°) > 40$ % in the wavelength range 20-100 nm.

In order to obtain effective reflection in a broad wavelength range it is necessary to use different mirror materials. This is easily possible in the proposed distribution system. The plane facets can be used at different vertical level.

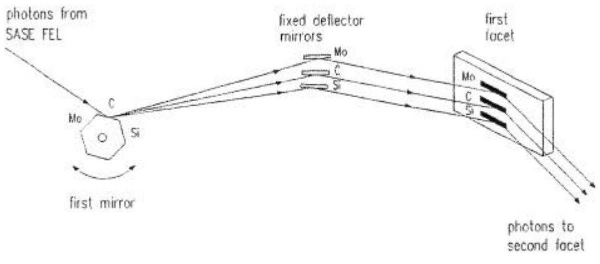

Fig. 4. Concept of the optical injection system optimized for the wavelength range 6-100 nm

For example, the photon beam could be injected into the photon ring at three different vertical positions. Figure 3 shows a view of a facet with three different strip coatings in order to cover the wavelength range 6-100 nm. As mentioned above the best optical coatings for this use are C (6-10 nm), Mo (10-20 nm) and Si (20-100 nm). The proposed substrate material for the plane mirrors is silicon because it can be well polished, and has excellent thermal properties. Therefore we need only two strip coatings, C and Mo, and leave one strip uncoated for the range 20-100 nm. Users can define the radiation wavelength for their experiment independent of each other to a very large extent, since they use three different vertical levels in the photon ring. Fig. 4 shows the concept of the optical injection system. This design makes it possible to make various wavelengths of SASE radiation available in the FEL laboratory quasi-simultaneously.

The system, described above, can provide FEL radiation for 24 user experiments in a quasi-simultaneous mode. Many applications require only very high peak brilliance. Such experiments for which average brilliance and wavelength are not critical, could operate simultaneously at the same radiation wavelength. This could be realized by means of the rotating switching mirrors. The principle design is sketched in Fig. 5. Let us assume that the superconducting accelerator operates with duty factor of 1 % at a repetition rate of 24 Hz. In this case the initial photon beam is transformed into 24 beams. The switching mirrors need to rotate at a frequency of 1 Hz such that each user actually receives one train of pulses with a full duration of 0.5 ms per second. This procedure of pulse train distribution reduces the average brilliance of the SASE FEL, but the peak brilliance remains untouched (apart from the losses in the mirror system). Note also that even if the beam is distributed among 24 users , the average brilliance per user will still be three orders of magnitude higher than that of state-of-art 3rd generation synchrotron radiation sources.

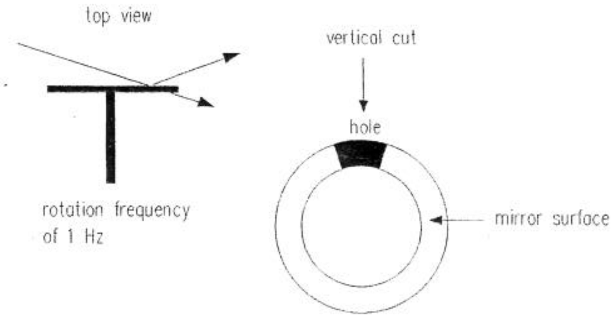

Fig. 5. Different views of a rotating switching mirror. Using rotating mirrors as switching elements between the photon ring cells makes it possible to provide soft X-ray radiation for many user stations. The distribution of photons is achieved on the basis of pulse trains and it is possible to serve one user station with repetition rate up to 1 Hz

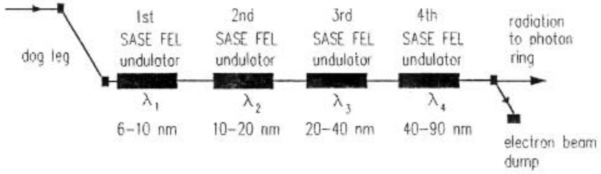

Fig. 6. Setup for simultaneous multi-user mode operation at different wavelengths. In this scheme it is possible to provide in parallel soft X-rays with different wavelengths for different user stations which must use suitable filters. The accelerator operates at fixed electron beam energy. Each SASE FEL operates in the linear regime and the electron beam quality is not destroyed when the electron bunch passes through the sequence of undulators. The peak brilliance will still be 9 orders of magnitude higher than that of 3rd generation SR sources

In addition to quasi-simultaneous operation at different wavelengths or simultaneous operation at the same wavelength, the SASE FEL with photon ring distribution system also offers a possibility for simultaneous multi-user mode operation at different wavelengths. At a fixed electron energy the magnet gap of the FEL undulator can be varied mechanically for wavelength tuning. The wavelength range 6-100 nm at fixed electron energy of 1.5 GeV can be covered by operating the SASE FEL with four undulators which have different periods. These SASE undulators can be placed behind each other assuming that the subsequent undulator radiates at longer wavelength. This unusual arrangement is schematically shown in Fig. 6. Normally if a SASE FEL operates in saturation, the quality of the electron beam is too low for the generation of SASE radiation in a subsequent undulator which is resonant at a different wavelength. However, it is indeed possible to generate low intensity radiation in the linear SASE regime simultaneously in a sequence of undulators which are resonant at different wavelengths. This procedure reduces the peak brilliance of the SASE FEL radiation by about of factor 10, but this is still 9 orders of magnitude higher than that of 3rd generation synchrotron radiation sources. The wavelength selection can be done by suitable filters. Broad band notch filters exist for the VUV and soft X-ray ranges. For example, a (Zr) filter is useful in the 6-18 nm region, (Se + Al) in the 18-35 nm region, (Ti) filter for 35-50 nm region, (Pb) filter for 70-75 nm region, (In) for 75-90 nm, etc. If the power density is too high for transmission filters, one can use reflection filters based on multilayers or gratings.

In conclusion, it should be reemphasized that although the soft X-ray SASE FEL photon beam from each undulator is in principle a single user tool, just like an optical laser, the optical distribution system based on multifacet reflectors, movable mirrors and filters provide efficient ways to generate a multi-user facility - very similar to present day synchrotron radiation facilities. It is a great advantage that accelerator and electron beam transport lines in the new scheme of multi-user facility operate at fixed parameters and that an "electron switchyard" is not required.

Acknowledgments

We thank J.R. Schneider and D. Trines for interest in this work.

References

[1] J. Anduszkow et al., Phys. Rev. Lett. 85(2000)3825

[2] V. Ayvazyan et al., Phys. Rev. Lett. 88(2002)104802

[3] M. Koerfer, "The TTF-FEL status and its future as soft X-ray user facility" presented at 23rd Int. Conf. (Darmstadt, Germany 2001), Nucl. Instrum. and Methods A in press.

[4] B. E. Newnam, in: Laser-Induced Damage in Optical Materials, eds. H. E. Bennett, et al., NBS Special publications, 1985, p. 161

[5] B. E. Newnam, SPIE Vol. 738 Free Electron Lasers (1987), p.1

[6] A. V. Vinogradov, A. V. Kozhevnikov, and A. V. Popov, Opt. Commun. 47(1983)361

[7] I. N. Bukreeva, I. V. Kozhevnikov, and A. V. Vinogradov, Journal of X-ray science and technology 5(1995)396