4 Radiation Sources

One of the main motivations to build SLS is to have a very bright source of photons in a wide spectral range. This is achieved on one hand with a very low emittance of the electron beam in the storage ring and on the other hand with the use of a variety of special Insertion Devices (ID) which can be optimized to the special demands of a certain experiment. Beside these ID's also the Dipole Magnets are used as radiation sources.

The Insertion Devices are based on series of alternating Dipoles forcing the electrons to sinusodial trajectories. Their magnetic field is produced by both electromagnets with normal and supraconductivity technology and permanent magnetic structures. The latter are dominant in short period structures. Insertion Devices with relatively low magnetic fields emit radiation which shows interference effects leading to high brilliance. They are called undulators. The same magnetic arrangements but with higher fields show incoherent behaviour and show a radiation spectrum which is comparable to that of the radiation out of the bending magnets but shifted towards higher energy combined with higher flux. These insertions are called wigglers.

In a first step the construction of five experiments with three undulators, one wiggler and one bending magnet has started or is foreseen. The radiation covers the energy range from 10eV up to 40keV which corresponds to wavelength from 100nm in the vacuum-ultraviolett to 0.03nm in the x-ray regime. Beside this the radiation of one bending is used for electron beam diagnostics. Table t41_a gives an overview over some properties of the radiation sources.

In the following first some radiation properties are explained and then first the undulators of the first set of experiments followed by the wiggler and the dipole are characterised in detail.

Name	U200	U55	U17	W40
Type	Electromagnet	Pure Permanent NdFeB	Hybrid SmCo	Hybrid NdFeB
Polarisation	eliptically	eliptically	linear	linear
Energy Range [eV]	10 - 300	200 (90) - 2000	7k - 17.5k	5k - 40k
Harmonics	1,3,5	1,3,5	3 - 13	up to 2000
Period λ_u [mm]	212	55	17	60
Max. length L_u [m]	2 x 4.4	2 x 1.6	2	2
Number of periods	2 x 21	2 x 28	117	33
Min. gap g_{min} [mm]	18 (fixed)	18 (14)	4	7.5
B_{max} (verti./horiz.) [T]	0.4 / 0.1	0.8 / 0.4	1.0	1.9
K_{max} (verti./horiz.)	7.9 / 2.0	4.5 / 2.2	1.65	10
$\beta_{x,y}$ [m]	4.1 / 6.1	1.8 / 4.3	1.2 / 2.6	1.2 /2.6

Table t41_a: First set of Insertion Devices at the SLS

4.1 Radiation Properties

While the emitted radiation spectrum of the bending magnets and wigglers is continuous, synchrotron radiaton from an undulator shows a line spectrum. At some wavelength, given by

$$\lambda_N = \frac{\lambda_U}{2\gamma^2 N}\cdot\left[1+\frac{K^2}{2}+\gamma^2\theta^2\right], \quad \text{with} \quad K = 0.934B[T]\lambda_U[cm]$$

there are interference effects because the emitted light overcomes the electrons by exactly one wavelength. The intensity at these resonance wavelength increases with the square of the number of periods which is typically for coherence effects.

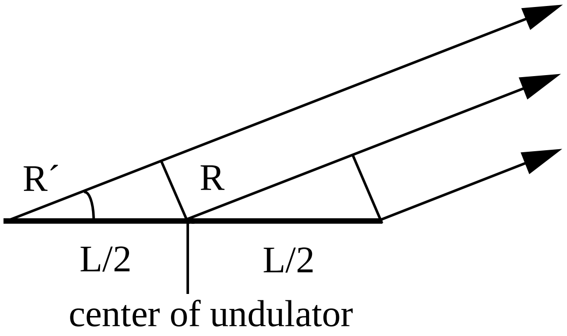
The parameter of interested in such an intensity peak is the brilliance which is the flux in the central cone in a certain bandwidth divided by the source size and her divergence.

$$B = \frac{\text{Flux}}{(2\pi)^2\,\varepsilon_{xT}\cdot\varepsilon_{yT}} \qquad \left[\frac{\text{photons}}{\text{s}\cdot\text{mm}^2\cdot\text{mrad}^2\cdot 0.1\%\text{BW}}\right],$$

where the photon flux from an undulator device, tuned *on resonance*, is:

$$\text{Flux} = \tfrac{1}{2}\cdot 1.43\cdot 10^{14}\cdot N\cdot Q_n\cdot I[A] \qquad \left[\frac{\text{photons}}{\text{s}\cdot 0.1\%\text{BW}}\right]$$

and Q_n (<1) is a function of the undulator parameter K (see e.g.[1]) The source parameters for the synchrotron light are given by the properties of the electron beam and by diffraction effects. The latter one occurs, because even a single electron produces a finite source size and finite angular spread for the photons. This effect can be explained with the depth of field effect due to the finite length of the undulator (see Fig. f41_a).



<u>Fig. f41_a:</u> Depth of field effect in an undulator

Summarising, the brilliance depends on the undulator performance, field strength, number of periods and field quality, as well as on the storage ring parameter: emittance, emittance-coupling, beta-functions, energy spread and of course, current and lifetime

The insertion devices are placed in straight sections of different length, in which the electron beam size can be individually adjusted to each insertion by the help of four quadrupoles on each side of an undulator. In figure f41_a the beta functions in the three types of straight sections are shown.

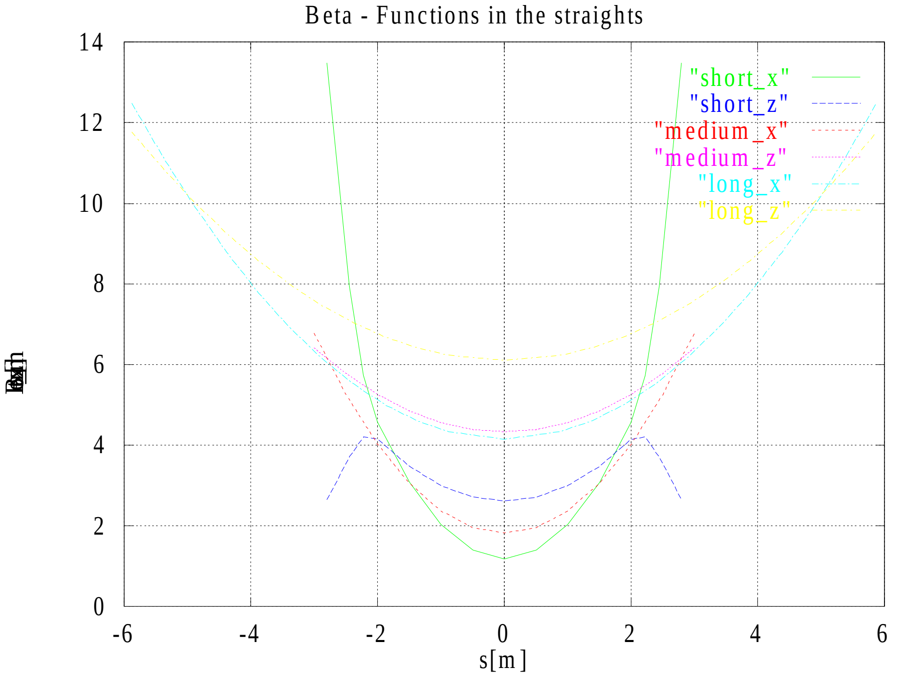


Fig. f41_b: Vertical and horizontal Beta function of the electrons in the straight sections. The vertical beta function in the short sections where the minigap insertion devices will be installed shall be further reduced to about one meter.

The energy spread of the electron beam.increases also the wavelength spread This is taken into account with a degrating factor μ_λ :

$$\mu_\lambda = \sqrt{1+\left(\frac{2(\sigma_E/E)N}{0.36}\right)^2}$$

In the following we list all the formulae [2] which were used to calculate the brightness curves of Figure f43_a and the source parameters in Table t41_b. Furthermore, the source area in phase space is a convolution of the electron beam phase space and the diffraction limited photon beam phase space:

$\varepsilon_{xT} = \Sigma_x \cdot \Sigma'_x$ total emittance in x (similarly in y)

$\Sigma_{\mathrm{x}}^2 = \sigma_x^2 + R^2$ $\left(\Sigma_{\mathrm{x}} = \text{horizontal source size}\right)$

$\Sigma'^2_{\mathrm{x}} = \sigma'^2_x + R'^2$ $\left(\Sigma'_{\mathrm{x}} = \text{horizontal source divergence}\right)$

$\sigma_{\mathrm{x}}^2 = \varepsilon_x \beta_x$ $\left(\sigma_{\mathrm{x}} = \text{electron beam size}\right)$

$\sigma'^2_{\mathrm{x}} = \dfrac{\varepsilon_x}{\beta_x}$ $\left(\sigma'_{\mathrm{x}} = \text{electron beam divergence}\right)$

$\varepsilon_R = 0.12\lambda \cdot \sqrt{\mu_\lambda}$ "diffraction emittance"

$R' = 0.58\sqrt{\dfrac{\lambda}{L}} \cdot \sqrt{\mu_\lambda}$ "diffraction divergence"

$R = \dfrac{\varepsilon_R}{R'}$ "diffraction size"

		U200	**U55**	**U17**
	@	157eV	700eV	12.4keV
Beam	σ_x [μm]	140	92	76
	$\sigma_{x'}$ [μrad]	34	51	63
	σ_y [μm]	17	14	7
	σ_y' [μrad]	3	3	7
Diffraction	ε_R [nm]	0.97	0.22	0.026
	R [μm]	55	16	3
	R' [μmrad]	18	14	9
Source	Σ_x [μm]	151	94	76
	Σ_x' [μmrad]	38	53	64
	Σ_y [μm]	58	21	10
	Σ_y' [μmrad]	18	14	11
	ε_{xT} [nm]	5.8	5.0	4.9
	ε_{yT} [nm]	1.0	0.3	0.1

Table t41_b: : Source parameters for undulator radiation with 1% coupling.
For the U17 a reduced vertical beta function of 1m is assumed.

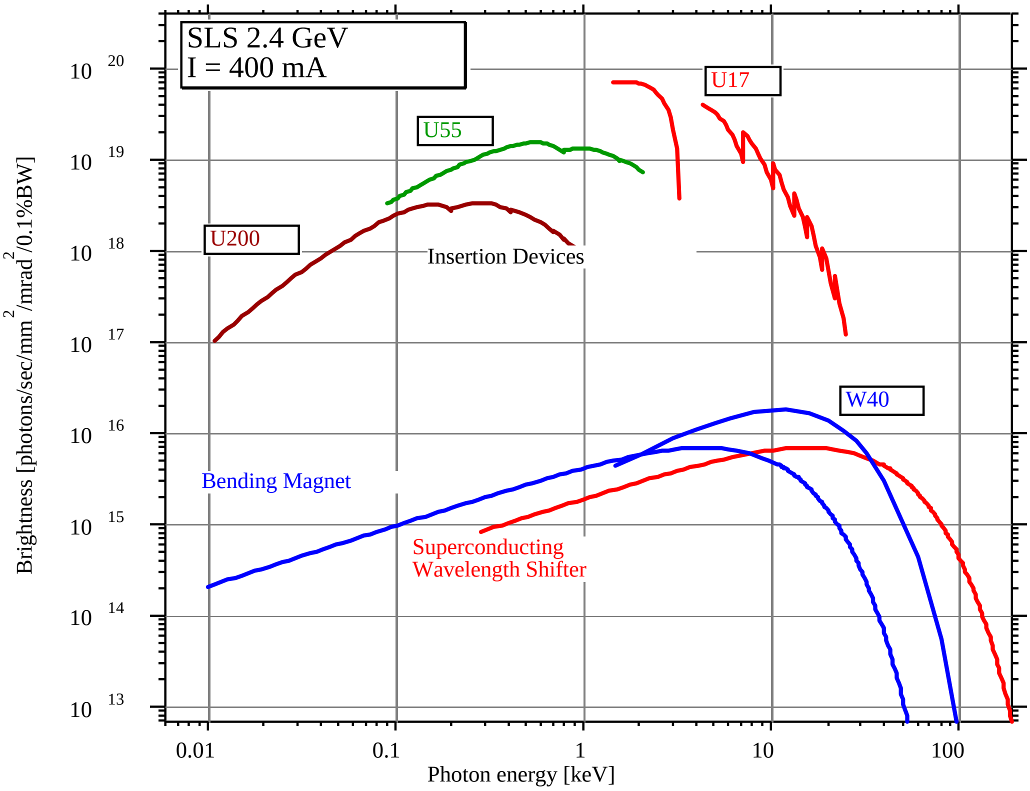


Figure f41_c: Brightness of insertion device and bending magnet based sources at SLS,

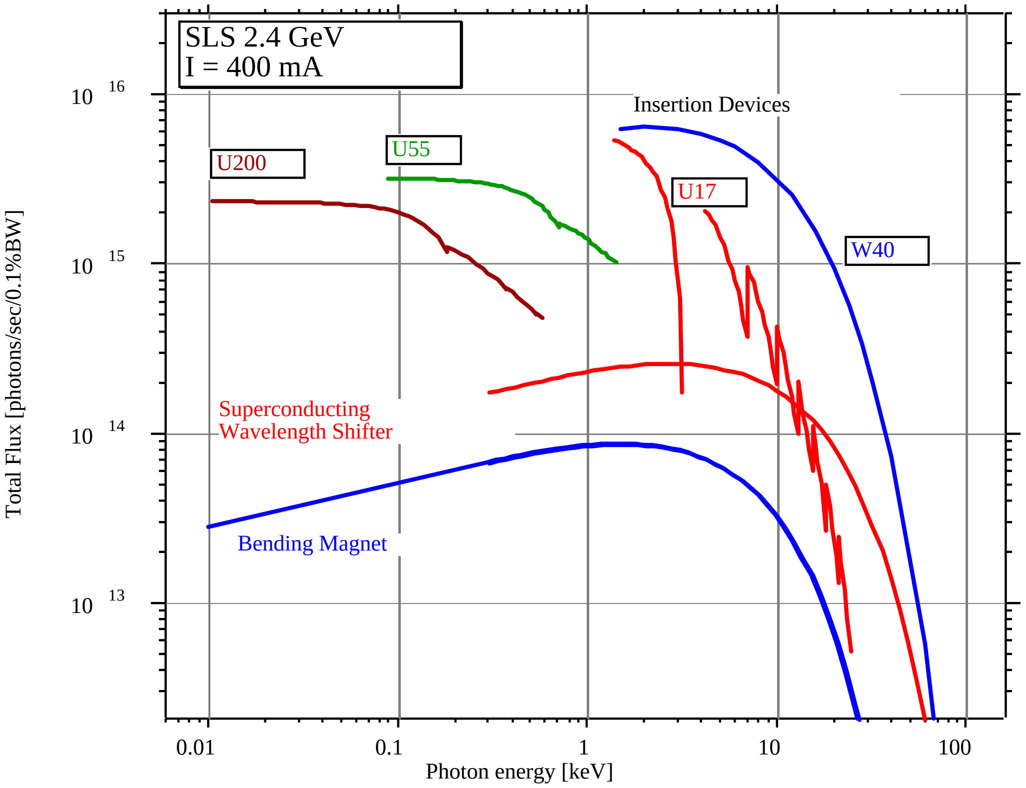


Figure f41_d: Total flux of insertion device and bending magnets based sources at SLS.

High brightness also insures a high degree of coherency of the source, i.e. high number of the so-called “resolution-luminosity” , or half Airy disk criterion [3] for the phase space. Acceptance, Figure f41_e shows the coherent fraction of the photon flux from the SLS undulators.

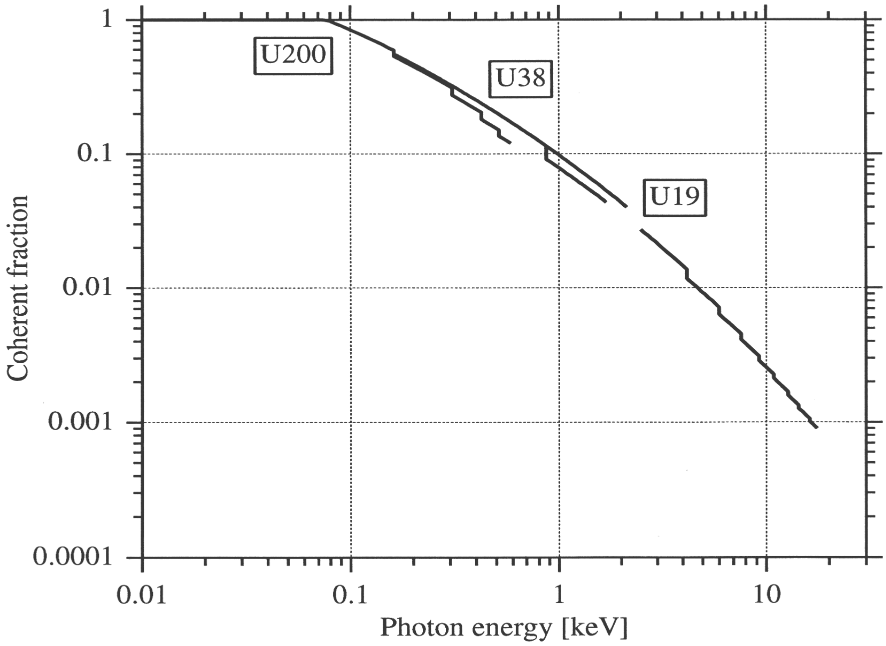


Figure f41_e: Coherent fraction (half Airy disk criterion) plot for the SLS sources.

4.2 Insertion device -based sources

U200 undulator for SIS beamline 9L

This electromagnetic undulator should produce linear as well as elliptically polarized light covering the region of lowest photon energies from about 10eV to about 300eV. The helicity of the light should be switchable between left and right hand circular polarization. To reach this low energies a period length around 200mm is required which is best done with an electromagnetic scheme. Three different types of such magnets have been built recently. ESRF[4] has developed a combination of permanent magnet together with a electromagnetically field component. Super-Aco[5] has constructed a crossed magnetic scheme, where a vertical and a horizontal electromagnet are placed at the same place while one of them can be shifted a fraction of a period to provide in addition linear polarized light under an angle of 45degree.ELETTRA[6] has designed a magnetic scheme where in a dipole configuration alternates with a quadrupole scheme powered as a horizontal dipole. This allows free access from the side which is important for measurement and choice of the vacuum chamber, which is a disadvantage in the Super ACO solution.

Also very recently an idea came up to shift the harmonics in the spectrum of a linear polarized undulator from odd integer to rational values [7]. This reduces the signal underground on the probe because the monochromators accept beside the wavelength of interest integer harmonics as well. The transmittance decreases with higher energies but as for a fundamental of 10eV the harmonics are not far away it results in a significant underground.

The shift of the harmonics is introduced by the means of phase errors which theoretically should follow a quasiperiodic distribution mathematically expressed through a fibonacci row. In practice with a limited number of periods in the magnet the quasiperiodicity is fulfilled not only with some irrational numbers in the fibonacci row but a certain range of numbers. The phase error can be introduced with periodicity or with amplitude distortions. An electromagnet allows to introduce reversible amplitude variations.

The ELETTRA scheme will best be suited for the demands of the low energy SIS beamline. For practically and physically reasons, the 10m long free space for the insertion is filled with two magnets rather than with a single but huge device. The separation in combination with the long straight section allows a scheme where the fast switchability of the orientation of the circular polarity is achieved optically in the beamline instead of pulsing the magnetic field. Both solutions are under construction in different facilities (ELETTRA, ESRF and Super ACO have build magnets which can be switched up to 100Hz whereas BESSY [8] and Spring8 [9] preferred an optical switching system) . From the storage ring point of view an optically switching is preferable because there is no influence on beam stability and the other experiments. The price to pay is less periods because a chicane system for deflection of the electrons and phase matching of the two magnets is needed.

The degree of polarization depends on the energy. As there is a mismatch between maximum field strength in vertical and horizontal direction the degree of polarization increases with energy and reaches maximum where the vertical field equals the horizontal. An ideal circular polarized undulator has no harmonics on axis, so that no harmonic suppression is required. Though with the elliptically light from a real magnet there are also some harmonics on axis but with low intensity.

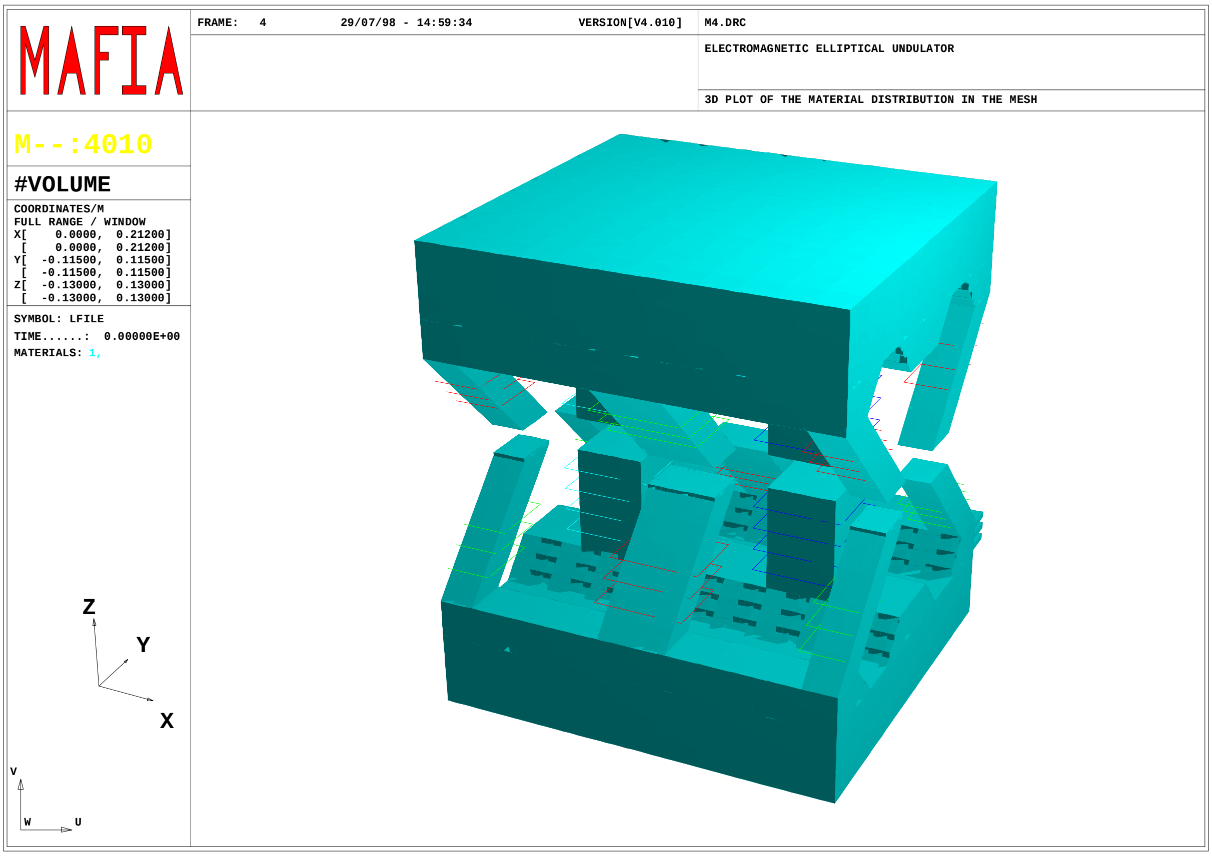


Figure 4.2 a : Elliptical electromagnet designed by ELETTRA [ref] One period is shown. The horizontal poles are of quadrupol shape, powered as a horizontal dipol

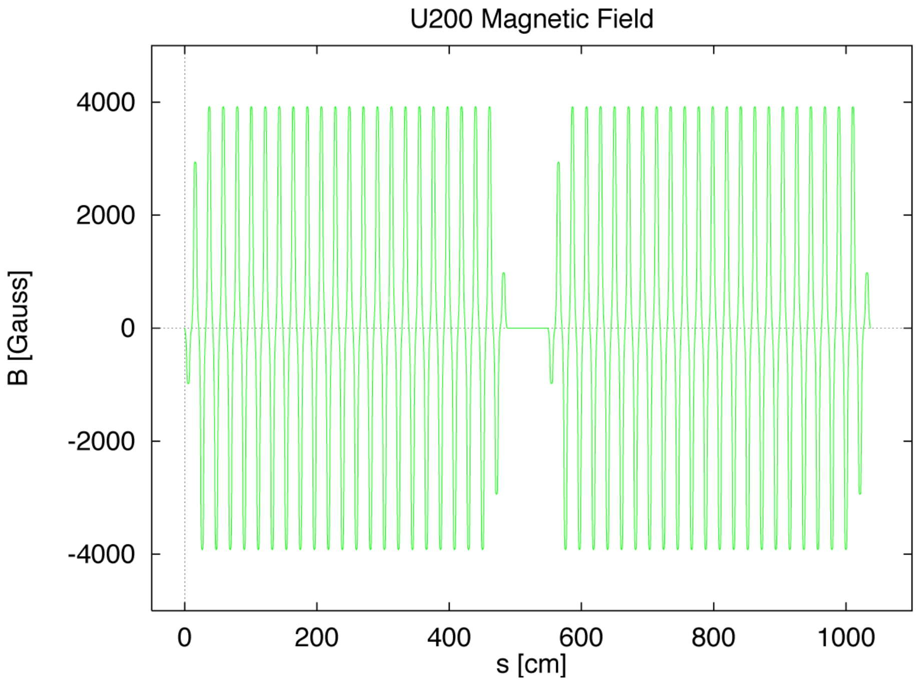


Figure 4.2 c : Vertical magnetic field for two magnets in the 10m long straight section

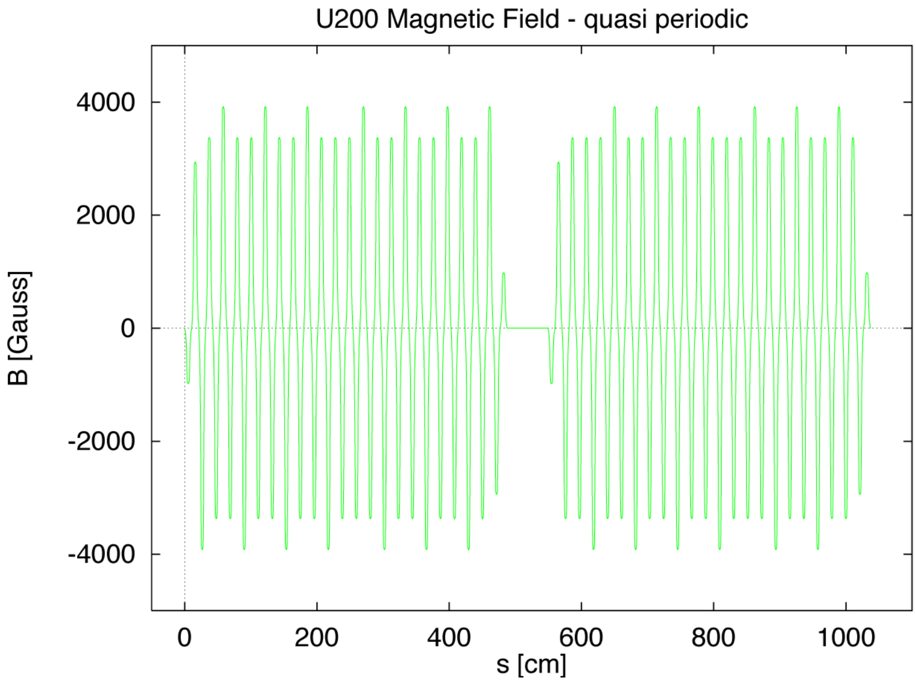


Figure 4.2 d : The same field as above with quasiperiodic field variation, used to shift integer harmonics to rational ones

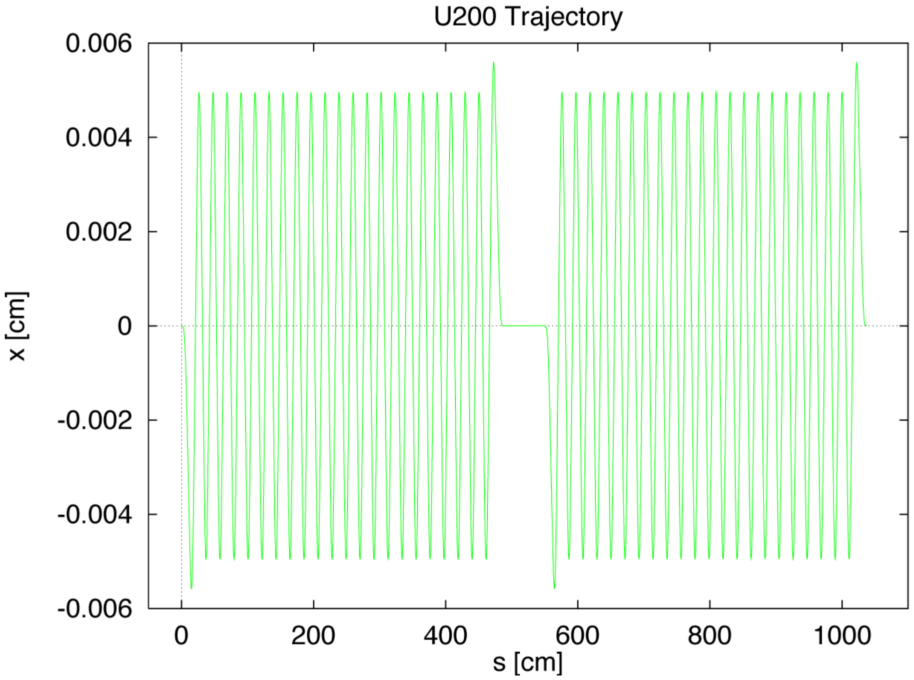


Figure 4.2 e Trajectory in normal undulator configuration

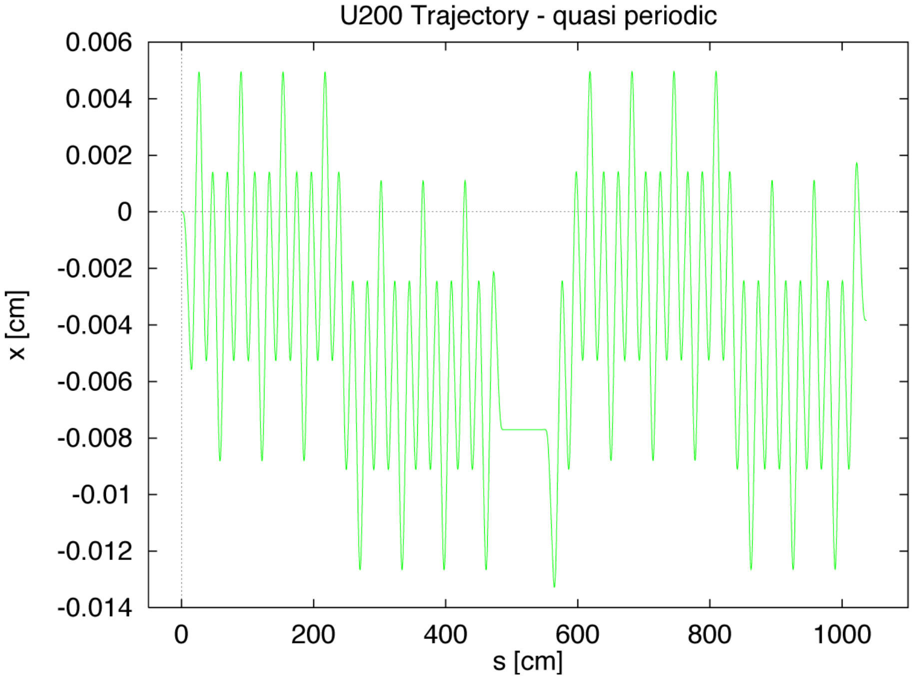


Figure 4.2 f Trajectory in quasi-periodic configuration

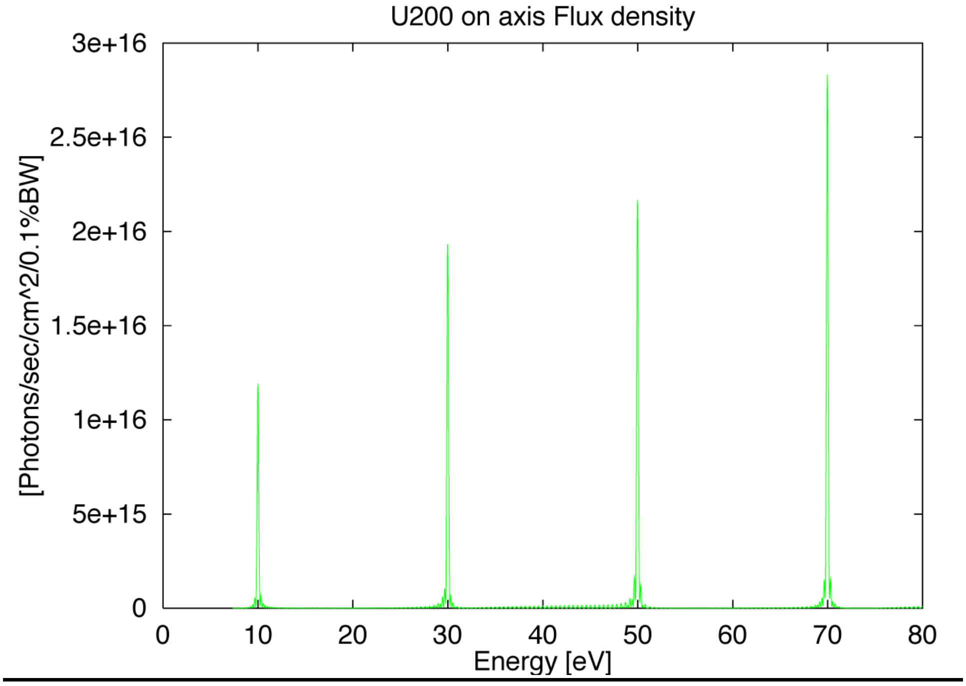


Figure 4.2 g On axis flux density for phase matched undulators

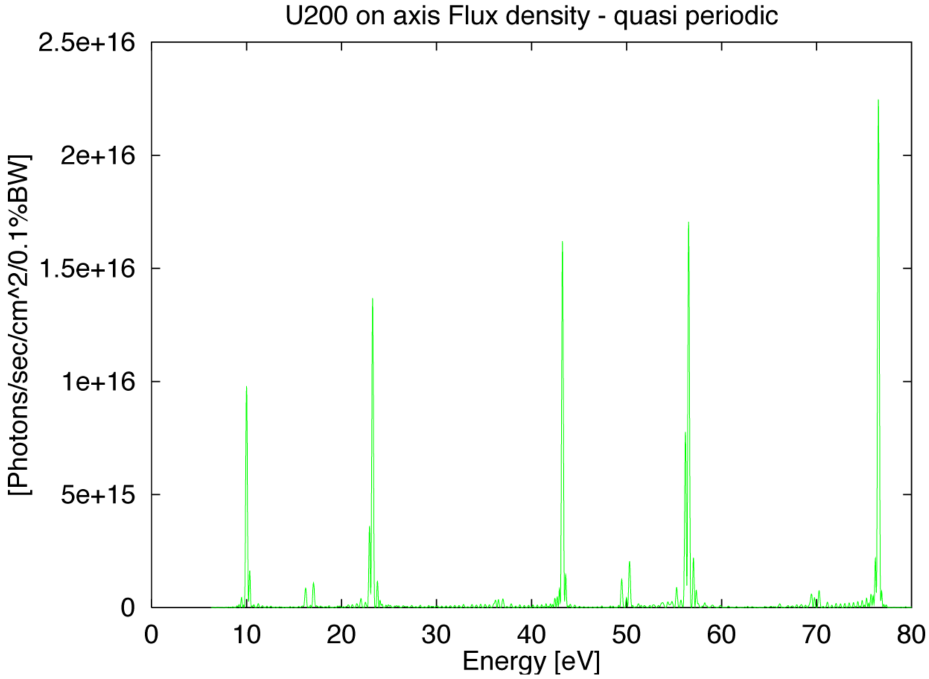


Figure 4.2 h On axis flux density in quasi-periodic case

U55 undulator for SIM beamline 7M

(will be updated)

U17 In Vacuum undulator for protein crystallography beamline 6S

Should produce the hardest X-ray energies reachable at SLS with undulators. This device extends the SLS spectrum coverage up to 15 keV, using high harmonics and has to have a very small gap. Given the minimum working gap of 4 mm, the period length was chosen to insure the continuous coverage (with higher harmonics) of the spectrum in this region.

The main specifications include:

- undulator period λ_u = 17 mm
- variable gap between 3 and 30 mm
- length of about 2 m
- max. field: 1 T (K_{max} = 1.65)
- possibility to add a second section without compromising the use of high harmonics
- "good field" region: ± 13 mm horizontal
- vacuum pressure better than ca. 0.1 nT (without beam)
- good RF shield to give low coupling impedance
- smooth transition to the standard vacuum chamber (diamond shape with inner dimensions of $72 \cdot 34$ mm^2)

The basic properties of these three undulators are listed in Table t41_a. Since we have four quadrupoles on each side of an undulator, we have the flexibility to adjust the β-values individually for each undulator. In addition, two more quadrupoles can be installed to decrease the vertical beta function down to 1 m.

For the production of hard X-ray radiation with very high fluxes, the installation of mini-gap multipole wigglers based on permanent-magnet technology has been choosen.

W40 wiggler for material science beamline 4S

(will be updated)

4.3 Bending magnets based sources

SLS lattice optimization for minimum emittance requires very tight focusing of the electron beam in the bending magnets. This, in turn, leads to comparatively high brightness of sources based on these dipoles (cf. Figure f41_c).

With superconducting devices one is able to extend the photon energy coverage to hard X-rays. The two options under consideration are: so-called "wavelength shifters" and dipole magnets.

The present lattice would allow integration of *superconducting dipoles*, replacing some of the central dipoles in the TBA arcs, without adversely affecting the equilibrium emittance of the beam. Under study at present is a superconducting dipole with maximum magnetic field of 5.8 T, providing synchrotron radiation with critical photon energy of 15 keV (compared to 4 keV for the normal conducting dipoles). More detailed superconducting dipole specifications are given in section 2.3 on magnets.

Short (4 meters) straight sections can house wavelength shifter devices with similar or even higher field. Again, the impact on the overall ring performance is minimized due to very tight focusing possible in these straight sections (β functions below 1 meter). In the minimum emittance optics (cf. section 2.1 on lattice) with non-zero dispersion in the straights, each of these devices increases the equilibrium emittance by about 10%.

The summary of the sources based on bending magnets is given in Table t42_a, similar to the Table 4.1b for undulators.

Table t43_a: Source parameters for bending magnets (at critical energy)

Magnetic field	[T]	1.3	
Critical photon energy	[keV]	4	15
Horizontal β function	[m]	0.4	
Vertical β function	[m]	5.1	
Dispersion function	[m]	0.027	
Σ_x	[μm]	41	
Σ'_x	[μrad]	180	
Σ_y	[μm]	17	
Σ'_y	[μrad]	160	
Angular flux	[ph/s/0.1%BW/mrad]	$1.3 \cdot 10^{13}$	
Brightness	[usual units!]	$8 \cdot 10^{15}$	

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