UNDULATOR OPTIMIZATION FOR ERL BASED LIGHT SOURCES

Robert Rossmanith, Research Center Karlsruhe, Axel Bernhard, Sandra Ehlers, Golo Fuchert, Peter Peiffer, Tilo Baumbach, University Karlsruhe, Germany

Abstract

Conventional synchrotron light sources operate with currents between 200 and 500 mA. The maximum obtainable brilliance is 10^{21} photons per sec, per 0.1 bandwidth, per mm^2 and per $mrad^2$. In this paper the brilliance of photon beams generated by ERL`s are compared with the brilliance produced by synchrotron radiation storage rings.

COMPARISON OF THE AVERAGE BRILLIANCE OF ERL BASED LIGHT SOURCES WITH CONVENTIONAL 3RD GENERATION SOURCES

The wavelength λ emitted from a planar undulator is

$$\lambda = \frac{\lambda_u}{2n\gamma^2}(1+\frac{K^2}{2}) \qquad (1)$$

λ_u is the period length of the undulator, γ is the beam energy divided by the electron rest energy, n is 1, 3, 5,…. and K is

$$K = 0.935.\ B[T].\ \lambda_u\ [cm] \qquad (2)$$

B is the maximum magnetic field in Tesla.

PETRA III is the synchrotron light source with the at the moment highest design brilliance of about 10^{21} photons per sec, per 0.1 bandwidth, per mm^2 and per $mrad^2$ (photon energy circa 10 keV). The minimum gap width of the PETRA III undulators is 9.5 mm, the period length is 23, 31.4 or 29 mm, the total length of one undulator is 2 or 5 m [1]. The design horizontal emittance is 1 nm, the design vertical emittance is 0.01 nm. The total beam current is 100 mA [2].

In ERL based sources the electron beam is produced in electron guns. In most of the designs the normalized emittance of the gun is both horizontally and vertically identical and in the order of one to several µm. Adiabatic damping reduces the emittances to 0.6 nm at 2.5 GeV and 0.085 nm at 6 GeV when it is assumed that the normalized emittances are 1 µm. Fig. 1 shows the calculated brilliance curve [3] for a 2 m long undulator. The undulator parameters are the same as before for PETRA III: the period length is 23 mm, and the assumed k-value ois 2.2. For a better comparison the current is 100 mA.

Comparing the values obtained for the model – ERL with the PETRA III parameters fig. 1 clearly shows that for the given parameters the maximum achievable brilliance in an ERL is somewhat lower than in a storage ring. This is due to the different beam cross- sections In a storage ring the horizontal emittance is significantly higher and the vertical emittance is significantly lower than in an ERL. Only at higher beam energies (6 GeV and higher) the brilliance obtained with an ERL and the brilliance obtained with a storage ring are comparable.

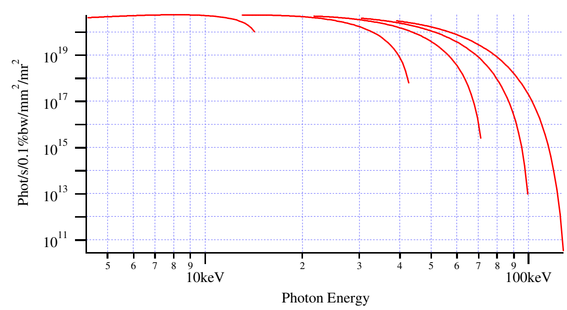

Fig. 1. Calculated brilliance of an ERL based light source. The beam current is 100 mA, the beam energy 6 GeV. The undulator length is 2 m, the period length is 23 mm and k is 2.2. Horizontal and vertical emittance are identical 0.085 nm (normalized emittance 1 µm).

The brilliance in an ERL versus beam energy is shown in fig. 2. The beam current is 100 mA and the normalized emittance is 3 µm. The undulator parameters from fig. 1 are used. At lower beam energies the beam dimension are larger and limit the brilliance. At very high energies the ERL brilliance would exceed the ERL brilliance.

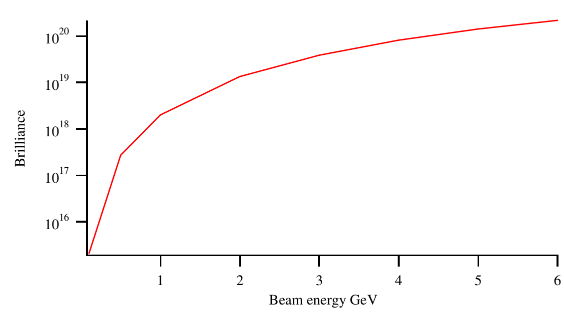

Fig. 2 Brilliance of an ERL for a 100 mA beam (photons per sec, per 0.1 % band width, per mm^2 and per $mrad^2$) . The gun has a normalized emittance of 3 µm, the undulator is 2 m long, the period length is 23 mm and K is 2.2.

In Fig. 2 it is assumed that a conventional undulator with a period length of 23 mm is used. The gap width is 9.5 mm and identical with the gap width of PETRA III. In the following it is investigated if special undulators tailored to the need of an ERL can increase the brilliance of an ERL at lower beam energies.

COMPARISON OF THE OBTAINABLE BRILLIANCE WITH SUPERCONDUCTIVE AND PERMANENT MAGNET UNDULATORS

As mentioned before the reference undulator for a storage ring is the PETRA III undulator, 2 m long with a period length of 23 mm and a K value of 2.2.

One big advantage of the ERL is the fact that the beam passes only once through the undulator or maximal only a few times. In the storage ring the same bunch passes the insertion device $1/\tau$ times per second, where τ is the revolution frequency of the electron beam. Therefore the gap of the undulator in an ERL can be much smaller. The following table shows at which gap width and which period length a superconducting undulator produces a K – value of 2.2 when it is assumed that the current density in the superconducting wire is 1000 A/mm^2 [4].

Table 1: Gap and period length for a superconducting undulator with K = 2.2, current density 1000 A/mm^2

Gap width [mm]	**Period Length [mm]**	**Max. Field in Tesla**
1	9.1	2.6
2	10.8	2.2
3	12.3	1.88
4	13.8	1.68
5	15.3	1.54
6	16.6	1.41
9.5	21.0	1.13

The gap defines both the maximum brilliance and the maximum photon energy. This is shown in fig. 3. In fig. 3 a beam energy of 2 GeV in an ERL is assumed. The electron source has a normalized emittance of 3 µm and the beam current is 100 mA. The brilliance is calculated for a gap width of 1, 4 and 9.5 mm. The length of the undulator is 2 m. The period length and the field values were taken from Table I. The successful operation of a superconductive undulator with a gap width of 2 mm in the Mainz Microtron MAMI was demonstrated several years ago with a beam energy of 855 MeV [5].

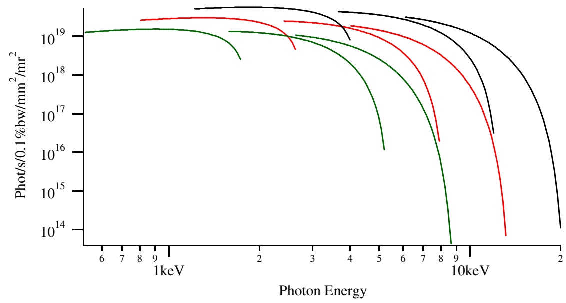

Fig.3 Brilliance curve obtained in an ERL with a 100 mA electron beam at a normalized emittance of 3 µm. The beam energy is 2 GeV. The maximum K value is for all three curves 2.2. The black curve is the brilliance for an undulator with a gap of 1 mm, the red one for a gap of 4 mm and the green one for a gap of 9.5 mm. Period length and field is taken from table I.

Fig. 3 demonstrates that small gap undulators have the advantage to increase the photon spectrum significantly. The influence on the brilliance is visible but not so significant.

This statement is further demonstrated in fig. 4. In this figure the brilliance of a 2 and 3 GeV ERL beam (100 mA) are compared. The black curve shows the brilliance produced by the 3 GeV beam with an undulator gap of 9.5 mm and the red one the brilliance produced by a 2 GeV beam with an undulator gap of 1 mm. In both cases K = 2.2. The values for the period length of the undulator and the field strength are taken from Table I. The normalized emittance is 3 µm. Both curves are almost identical demonstrating that an intelligent use of an undulator can dramatically reduce the costs of an ERL accelerator.

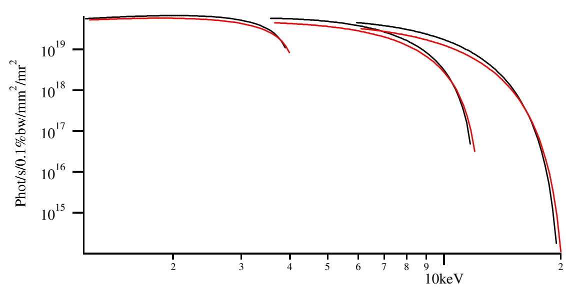

Fig. 4 Comparison of the achievable brilliances with an undulator gap of 9.5 mm at 3 GeV and an undulator gap of 1 mm at 2 GeV. The undulator parameters listed in Table I are used. Both curves are almost identical despite the significant difference in the beam energies.

UNDULATORS FOR ERL - BASED SYNCHROTRON LIGHT SOURCES

As mentioned in the previous chapter the cross-section of the beam in an ERL is round. Therefore the ideal undulator is a combination of two undulators: one with a vertical field and one with a horizontal field. The superposition of the two field components in the position of the beam can increase the field amplitude by about 40 percent. The basic idea is sketched in fig. 5 and was inspired by a similar concept developed for permanent magnet undulators [6]. The aim is to build an undulator which has a higher field for a given gap width compared to the values of the planar undulators listed in Table I. The realization of the sketched concept shown in fig. 5 is difficult from two points of view:

1.) The saturation of the iron
2.) The complex winding technique

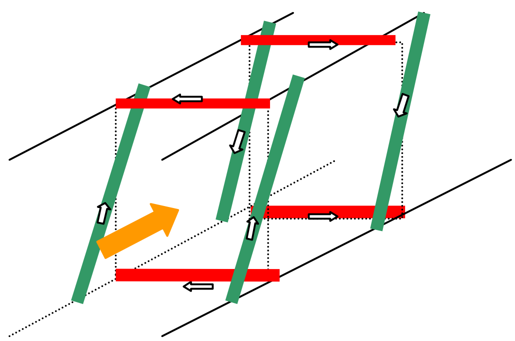

Fig. 5 Principal layout of an optimized superconducting undulator for an ERL based accelerator. The red wires produce a vertical undulator field and the green wires a horizontal undulator field. The yellow arrow marks the beam.

The basic idea is to produce a planar undulator field both in the horizontal and vertiical direction. The green wires in Fig. 5 produce a horizontal undulator field, the red wires a vertical undulator field. The green wires are tilted in order to enable the winding of the undulator.

The field in a superconducting undulator is defined by the magnetic material. The field produced by the superconductive wires saturate the poles of the undulator. One problem is that under certain circumstances the horizontal field can influence the vertical field and vice versa.

The second problem is that the simple winding schemes developed for superconducting undulators cannot be applied any more for such devices.

In order to solve these problems several technical solutions are at the moment under investigation.

THE USE OF LONG UNDULATORS FOR ERL - BASED SYNCHROTRON LIGHT SOURCES

One of the most demanding tasks is to build long undulators with 1000 and more periods. The line width of an undulator scales with 1/N where N is the number of periods. In order to obtain a line width of 10^{-3} 1000 periods are requires. Again this is only possible when the period is short (see Table I).

Different to FELs the radiation in an ERL driven undulator the wavelength of the radiation should be tuneable over a wide range. The tune ability requires that the field error of a superconducting undulator is low for all undulator currents. The measure for the field error is the so-called phase error. In a perfect undulator the electron trajectory and the photons are perfectly in phase and the coherent superposition of photons is perfect. Field errors change the phase relationship between electrons and photons leading to not – perfect at the superposition of photons. The consequence is a reduction of intensity. This is especially the case at higher harmonics (n = 5 and higher in equation (1)). Even if the phase error for the first harmonics is only several degrees the phase error for the nth harmonics is n times higher. Assuming for instance a phase error of 3 degrees for the first harmonics the phase error of the 5 th harmonics is already 25 degrees and leads to a significant reduction of photon intensity. In order to reduce the phase error in general the undulators have to be shimmed, which means that the phase errors are minimized.

Permanent magnet undulators are shimmed mechanically [7] by adjusting the poles. For a long time the shimming of superconducting undulators was difficult since the undulators have to be cooled to 4 degree Kelvin to measure the field. Afterwards the undulators have to be warmed up, shimmed, cooled down again and measured.

As a result the advantage that the superconducting undulator has shorter period lengths was compensated by the fact, that the shimming process was difficult. At the moment an attempt is made to simplify this process.

The new idea is based on Faraday`s law of induction. The principle is explained with the help of fig. 6.

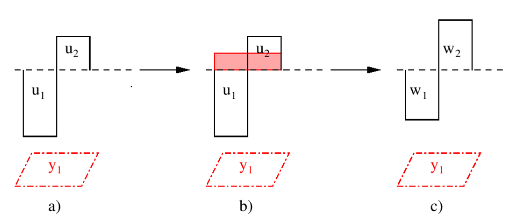

Fig. 6 The principle of induction shimming. The explanation is given in the text [8]

u_1 and u_2 are two neighbouring poles of the undulator. The sinusoidal field in one pole is approximated by a rectangular shape for the sake of simplicity. The integrated field is symbolized in the fig. 6 by a rectangle.

For the compensation of the field error a loop of superconductive material is attached in the gap at the surface of the undulator. The preferred material for the loop is a high temperature superconductor material like YBCO. The thickness of the YBCO material can be as low as 330 nm.

The way how the field compensation acts is explained in the following. Before the undulator is powered (zero undulator current) the current in the YBCO loop is zero (fig. 6 a). It is now assumed that the integrated field in the first loop is different to the integrated field of the second loop (fig. 6 b) when the undulator current is switched on. The non-zero integral field of the two poles leads to a current in the attached loop. Faraday`s law of induction requires that the induced current in this loop compensates the field difference.

In order to compensate the field error of the whole undulator the undulator surface is covered with overlapping loops as shown in fig. 7.

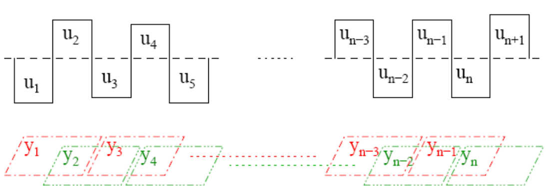

Fig.7 The array of overlapping superconductive loops attached to the undulator surface reduces the phase error for all periods without any mechanical shimming.

The basic idea of the induction shimming is that the high temperature superconductive loops can be fabricated by using lithography techniques and can therefore be produced with very high accuracy.

In a first demonstration experiment the concept of this idea was verified [9]. At the moment experiments are prepared to optimize this simple technique and to convert it into a technical concept.

SUMMARY

ERL and synchrotrons have the potential to produce photon beams with similar values for the brilliance at beam energies of 6 GeV and higher. At lower beam energies ERL based light sources suffer from the fact that in an ERL both the horizontal and the vertical emittance is identical and the emittance reduction due to adiabatic damping scales with $1/\gamma$. In a storage ring in general the vertical emittance is very small.

In order to increase the brilliance at lower beam energies undulators with high magnetic field and short period length can compensate this effect. This is possible with superconductive undulators using both the higher fields and the smaller gaps of this type of undulators. Since the electron beam only passes in an ERL once or at maximum only several times through the undulator a small gap does not affect the beam quality. The beam life time in synchrotrons is very sensitive to small gaps.

A further possibility to increase the brilliance is to build undulators with a combined horizontal and vertical field tailored to round cross section of ERL beams. These undulators are still in an early design phase.

ERLs can be operated with long superconductive undulator in order to increase the brilliance. One problem with long undulators operating at higher harmonics is the compensation of field errors. Recently a new technique was developed to shim the superconductive undulators in a passive way by an array of superconductive HTSC loops. First experiments showed that this is a very promising idea.

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