ESRF Insertion Devices

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Abstract

The ESRF 6 GeV storage ring has been designed to provide a low emittance lattice incorporating 32 straight sections each 6 metres long. Most of the straights will accommodate Insertion Devices which will be the primary source of radiation. A review of the technology used to build them is given with their implications to their performance. The effect of the Insertion Devices on the stored electron beam is discussed together with the consequence on the required field quality. The hard X-ray beams that will be generated are of unprecedently high spectral brilliance and power density.

Introduction

The performance of the Insertion Devices (IDs) as a synchrotron radiation source depends essentially on the following parameters :

- Electron (or Positron) energy
- Minimum magnetic gap
- Electron/Positron emittance

In order to cover the hard X-ray range (1to 100 keV), a 6 GeV electron energy has been chosen. The lattice has been optimized to achieve a small emittance of 6.8 10^{-9} m [1]. Both these parameters enable the use of Insertion Devices with a magnetic gap as small as 10 mm. To simplify the machine commissioning and the construction of the IDs and their associated vacuum chamber, a conservative choice of 20 mm has been made for the first generation of IDs.

Technology

It is planned to segment the IDs into 3 sections, each 1.7 metres long. The justification comes from an easier design of the mechanical support and vacuum chamber and from a higher flexibility to adjust the power density incident on the first optical element of the beam line.

Several magnet technologies can be used to build the IDs :

- Permanent magnets (with or without steel pole parts).
- Room temperature electromagnets.
- Superconducting electromagnets.

Figure 1 presents the peak field B_o versus the spatial period λ_o obtained from each.

- The permanent technology is characterized by the remanent field B_r of the magnet blocks. B_o (λ_o) is presented for B_r = 1.1, 0.9, 0.5 and 0.2 T. The curves correspond to a pure permanent magnet design. A hybrid design (permanent magnet plus iron pole pieces) would give a slightly higher field :+ 30 % (+ 6 %) at 20 cm (5 cm) period

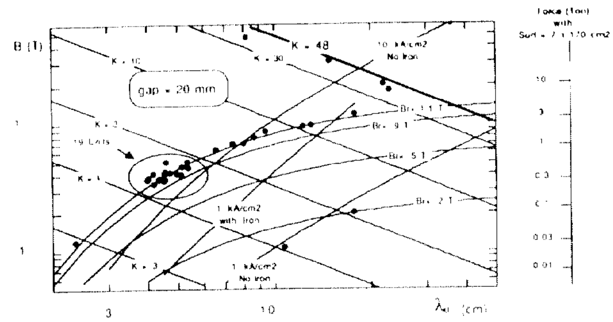

Fig.1 ESRF IDs in a field vs. period diagram

- The curve for electromagnet is calculated for a maximum current density of 1 kA/cm^2 and a coil vertical thickness equal to one quarter of the period.
- Two other curves are presented and correspond to a field entirely generated by coils of current density 1 and 10 kA/cm^2 without any iron part. these curve are drawn to give an idea of what can be obtained from superconducting electromagnets. In fact current densities higher than 10 kA/cm^2 can easily be obtained with superconducting coils, but the vessel requirements result in a larger magnetic gap and therefore a field reduction. The 10 kA/cm^2 curve therefore gives a conservative indication of what is attainable with a superconducting electromagnet. A higher current density curve can easily be drawn since the field is roughly proportional to the current density.

Figure 1 also locates as dotted points a primary statistic of the IDs required by the users of the ERSF from [2]

Several comments can be made :

- More than 50 % of the required IDs are undulators, tunable between 4 and 20 keV through the first and third harmonic which can best be obtained (in the 20 mm gap limitation) from a 5 cm K=2.2 B_o=0.5 T permanent magnet undulator.
- Room temperature electromagnets come into competition for wigglers of high field (B > 1.5 T) and long periods (λ_o >15 cm). They are then cheaper than permanent magnet devices. Users interested by a non efficient magnet technology (low field out of a given period or, conversely large period for a given field) may also use room temperature electromagnets at lower field than 1.5 T.
- The large majority of user requirements can be fulfilled principally by permanent magnet magnet technology and secondly room temperature electromagnets. The use of a superconducting electromagnet will only be considered if one wants a photon critical energy higher than 50 keV (B > 2 T).

- Straight lines corresponding to a given deflection parameter K ($=0.934 \cdot B[T] \cdot \lambda_0[cm]$) value are also presented in figure 1. The K=48 line is emphasized since it corresponds to a ±4 mrad of horizontal angle of the emission, the highest angle accepted by the storage ring vacuum chamber.

The magnetic force tending to close the two magnet jaws of the ID is also presented in figure 1 assuming a 7 cm magnet block width and a 1.7 meter long ID

Overview of the effect on the stored beam

IDs are non essential magnetic components of the storage ring. Since their purpose is essentially to serve as radiation source. On a long term basis the goal is to give freedom to any user to vary the field of the ID in order to match his experiment. To achieve that, they must be decoupled as much as possible from the stored beam. The perturbations induced by an ID on a stored beam have been studied in [3]. The main effects are reviewed in the following :

As the field of an ID is varied, closed orbit displacements may occur. Maintaining a closed orbit RMS deviation below 1/10 th of the RMS beam size requires that the integral of the vertical (horizontal) magnetic field along the axis of propagation of the electrons of a single ID is smaller than 8 E-5 Tm (4 E-5 Tm).If say, 16 IDs (located ramdomly along the lattice) are to be tuned independently from each other, the tolerance becomes 2 E-5 Tm vertically (1e-5 Tm horizontally). Very Precise magnetic field measurement are required to fullfill these specifications.

The field variation of an ID also induces some extra focusing of the beam which results in a betatron tune variation. Such effects cannot be avoided and are easily predictable from the field measurement. For a typical ESRF full undulator of 0.5 T vertical field and 5 meters length, the induced focusing is essentially vertical and is equal to 1.4 e-3, which is likely to be hardly detectable. In addition, a small modulation of the vertical beta functions (< ± 2%) will be generated. The simultaneous operation of 16 of these IDs would give a quite measurable quantity (16 times more focusing and roughly 4 times more modulation of the beta function) which may result in life time variations and/or closed orbit displacements. If necessary, the extra focusing and the associated modulation of the beta function can be easily compensated by slightly tuning the quadrupoles located on both sides of the ID.

The focusing discussed above depends on the transverse injection point in the ID resulting in nonlinear effects. Figure 2 presents the modification of the dynamic aperture by such nonlinearities induced by 1 to 15 undulators (each 6 meters long, 5.5 cm period, .63 T field) located on a high beta section [2]. The resulting reduced vertical aperture is still twice the vacuum chamber physical aperture.

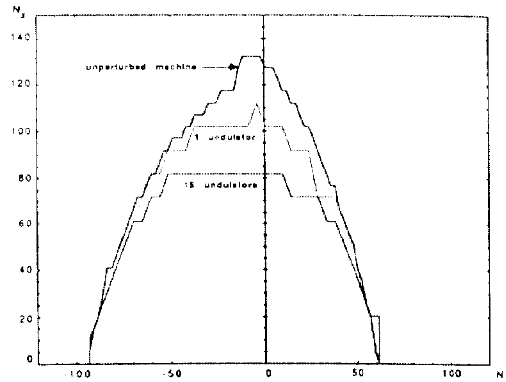

Fig.2 Effects of undulators on dynamic aperture

The perturbations discussed above scale as 1/E (closed orbit deviations) or as 1/E2 (focusing) where E is the electron energy. Therefore the operation of the ESRF at 6 GeV offers the best chance of success in accommodating a large number of long Insertion Devices compared to the new generation of lower energy machines. In other words the field specifications for the IDs of the ESRF are relaxed compare to these machines. Due to the higher energy of photon generated, a similar conclusion can be drawn for the field specifications required for the spectral purity of the radiation generated by the undulators.

An other source of perturbation induced (indirectly) by the IDs is the possible unsmoothness of the narrow vacuum chamber required. Such an effect essentially results in a lower maximum current in the single bunch mode (fast head tail instability), it has been studied in [4]. The cure is to taper the height of the connection between the ID chamber and the adjacent chambers.

An other indirect perturbation may come from the ions trapped in the ID field. Such trapping is predicted to be less severe (than in existing machines) due to the low emittance [1,5]. If it is still a problem positrons will be used insted of electrons.

Overview of Radiation Properties

Figure 3 presents the spectral brilliance in units of Photon/sec/mm^2/mrad^2/.1% of energy bandwidth for various generic Insertion Devices:

- Undulators of period 80, 50, 35 and 23 mm with a magnetic gap tuned between 20 mm and infinity observed on their fundamental and third harmonic resonant photon energy
- A 10 pole wiggler having a 1.5 T field
- The two bending magnets with 0.85 and 0.4 T field.

Interference occurs in the undulator emission resulting in a high brilliance at the fundamental resonant energy and its harmonics (essentially the odds). Photon energy tuning of undulator radiation absolutely requires the tuning of the undulator field.

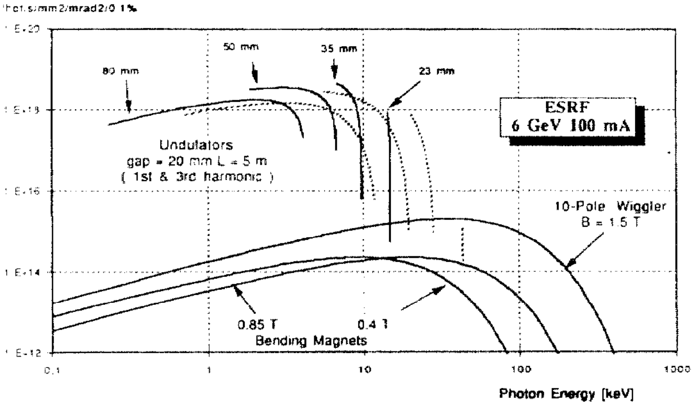

Fig.3 Brilliance (in Phot/s/mm2/mrad2/.1%) of IDs on the ESRF

This is illustrated in Figure 4. It shows the spectrum of the radiation from an undulator section having a 48 mm period, a 0.5 T field (K = 2.3), a length of 1.5 m and obseved from a 30 metre distance through a 1*1 mm pinhole. The dark curve corresponds to the minimum gap of 20 mm (K=2.3), the dotted curve corresponds to a 32 mm gap (K=1.05). It is clear from figure 4 that such an ID allows a complete tuning of the photon energy between 2 to at least 25 keV by a proper choice of gap and harmonic.

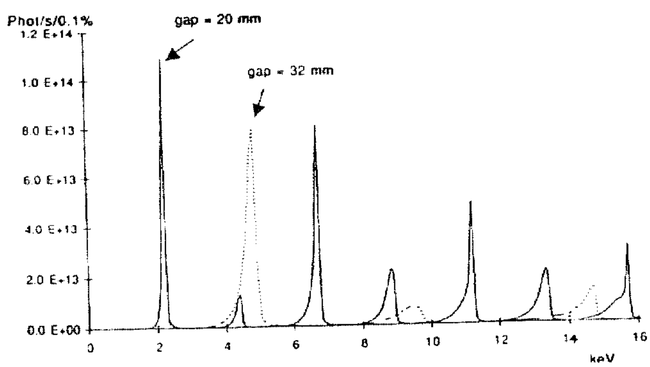

Fig.4 Radiation spectrum from an undulator seen through a pinhole.

In addition to generating a high spectral brilliance, the ESRF Insertion Devices can generate high power and high power densities. The maximum useful power is not likely to be limited by the ID length or the stored current as in most existing facilities but rather by the highest power density allowed by the first optical element in the beam line. This is illustrated in figure 5 (similar to figure 1) on which lines of power densities 30, 10 and 3 W/mm2 (generated at a distance of 30 metres from source) are superimposed. The power integrated over all angles which depends on the peak field and ID length but not the period, is shown as a second vertical axis. These figures have been calculated for a nominal 100 mA stored beam and a single 1.7 m long ID section.

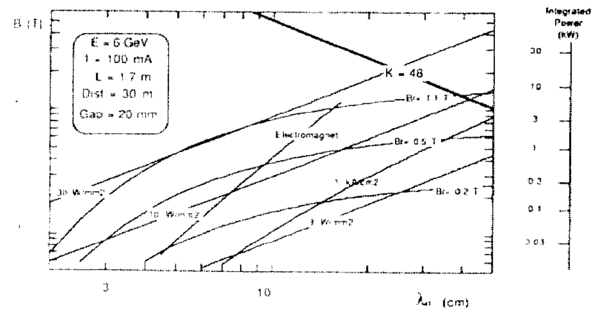

Fig.5 Power and power densities generated by IDs on the ESRF

Such high powers and power densities will not only distort the optical elements but also cause severe heating in the front-ends of the beam line and the ring vacuum chamber itself (if the beam is mis-steered). To overcome these difficulties, interlock systems, able to shut the RF down if a misalignment is observed on the photon beam, will be implemented and tested with gradually increasing stored current and ID length.

References

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