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A NEW X-RAY BEAM FOR THE ESRF BEAMLINES, OPTO-MECHANICAL GLOBAL SURVEY

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Abstract

With the new Extremely Brilliant Source (EBS), ESRF beamlines (BL) will have to adapt their optical configurations to use the new beams optimally. Preparing the photon beam for an experiment by a BL implies successive interactions between the different components that produce, transport and manipulate this beam. A cascade of topics and cross-linked processes optimize the photon beam parameters. The scientific application defines the baseline parameters such photon energy, beam sizes and flux. These will in turn define the most appropriate source characteristics, for which an optical scheme must be developed and implemented to tailor the X-ray beam properties to the experimental requirements. In this phase simulation software tools such as OASYS, are employed for optics and source calculations and ANSYS and COMSOL for FEA thermos-elastic analyses. Finally, the implementation phase interconnects the string of technical components, involving the whole spectrum of engineering issues. This paper deals with this cascade of tasks and describes the sequence of parameters and calculations flow required to exploit an X-ray light source.

INTRODUCTION

The EBS (Extremely Brilliant Source) [1] project is based upon a reduction of the horizontal emittance of the ESRF electron storage ring. Table 1 gives details on changes in major parameters.

The new EBS straight sections are reduced in length, leading to a need to adapt the existing collection of undulator carriages. Beamlines using canted undulators reset their source point and their location.

Table 1: Emittance and Straight Section Main Parameters for the Current ESRF and New EBS Storage Rings

Configuration	Current SR	EBS
Hor_Emittance (pm)	4000	147
Ver_Emittance (pm)	4	4
Straight section (m)	6 and 7	5.5
Bending magnet source	Dipole from DBA lattice	Small Insertion device

At the same time, new undulators require specific strategies for their gaps and periods. Recent cryogenic, in-vacuum undulators with 22, 18 and now 14mm periods, 6mm (and 5mm) gap increase peak flux and energy tunability. The recent topping-up hybrid mode (7/8+1) produces a reduced vertical size of the X-ray beam as seen at some BL, modifying as a consequence the optics illumination. Thus, monitoring on-live the X-ray beam characteristics is a "daily issue" and an important topic. Scientists at the BL must react to any changes, in collaboration with the other engineering specialists like storage-ring, optics, mech. Eng. FEA. Since recent years, optics simulation tools are implemented in user-friendly software environment to make the chain of design and optimizing beamlines faster and easier. An example of such effort is OASYS suite [2].

FROM THE PRESENT STORAGE RING TO THE NEW EBS SOURCE

The photon beam is produced by an electron beam stored in a magnetic lattice. The fundamental properties of this X-ray beam are first determined by the electron ring. The ESRF electron storage ring, implemented in 1990, is based on a double-bend-achromat (DBA) lattice. It consists of al-ternating low- and high-beta straight sections for installing insertion devices, offering respectively an electron source of small size and large divergence, or large size and small divergence, in the horizontal plane Fig. 1 shows schemati-cally the horizontal emittance characteristics of this alter-nating

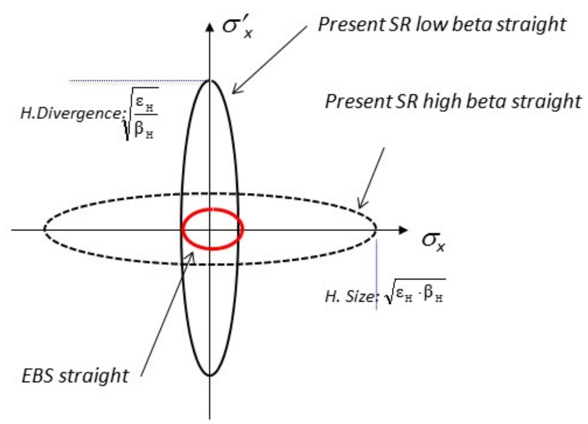

Figure 1: Schematic representation of the electron phase space in the horizontal plane comparing the case of present storage ring and the new EBS lattice. Originally the low beta was aimed at hosting wigglers, while the high beta hosted undulators. The emittance reduction factor of EBS is 1/30 as compared to the older facility.

The choice of a lattice configuration with high and low beta sections was driven at the time by the difficulties in building high performance undulators, as compared to less demanding wiggler technologies giving a broad energy spectrum without the need to tune the magnetic gap. With time and experience, undulator performance has improved

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to a degree that very few ESRF beamlines still use wigglers. Device periods have had a tendency to reduce with beamlines using 42 mm period arrays moving to periods as low as 14 mm and a progressive reduction of magnetic gaps from 15 to 6 and soon 5 mm, through the use of in-vacuum undulators operating at room- or cryogenic-temperatures [1].

THE EBS-READINESS REVIEW PLAN FOR ESRF BEAMLINES

One of the strategic issues for the ESRF to secure BL optics, stands in assessing the power issues of the new beam on the existing beamlines, what we call the "EBS- readiness review" plan. This is being implemented at pre-sent, after ranking BLs according to their capability to op-erate with the new source with at least equivalent perfor-mance as with the original ESRF source, then according to the necessary degree of intervention to achieve optimum performance with the EBS. The first ones to be considered are the existing "low beta beamlines" those where the beam power is dispersed thanks to a large divergence, thus pro-ducing a lower power density on the optical elements. With EBS, these beamlines will see a smaller beam, with a new power density increased by a factor of two to five [3].

There are two parallel considerations to implement such an undulator at the beamline:

From the science applications view point, the key energies must be accessible with relevant flux. The photon energy, or the photon wavelength depends on the deflection parameter K [4], which can be approximated on axis by:

$$\lambda_{Ph} = \frac{\lambda_u}{2 \cdot \gamma^2}\left(1 + \frac{K^2}{2}\right)$$

with λ_{Ph} the resonance photon wavelength, λ_u the undulator period and γ= electron energy/$m_e c^2$ (m_e = electron mass, c = velocity of light)

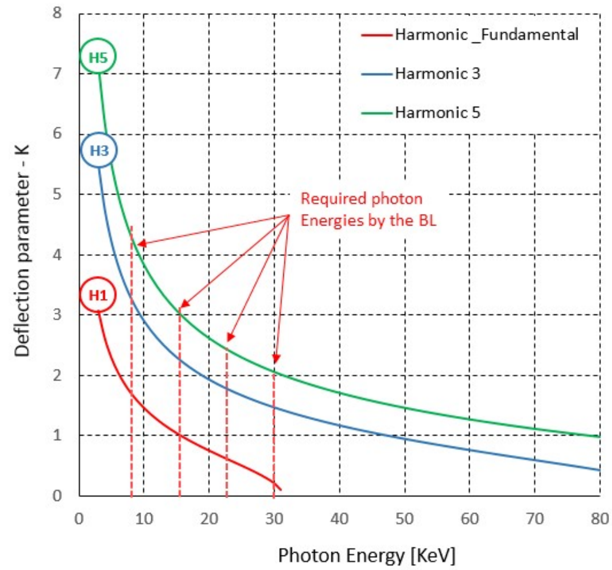
A dialog is developed between beamline scientists, insertion device, and advanced analysis calculation groups to define the possible undulator choices, this ends-up with a compromise between gap and period giving the required K value. The ID design makes use of the proportionality of K with the magnetic field at the axis $\tilde{B}$:

$$K = \frac{\lambda_u \cdot e \cdot \tilde{B}}{2 \cdot \pi \cdot m_e \cdot c}$$

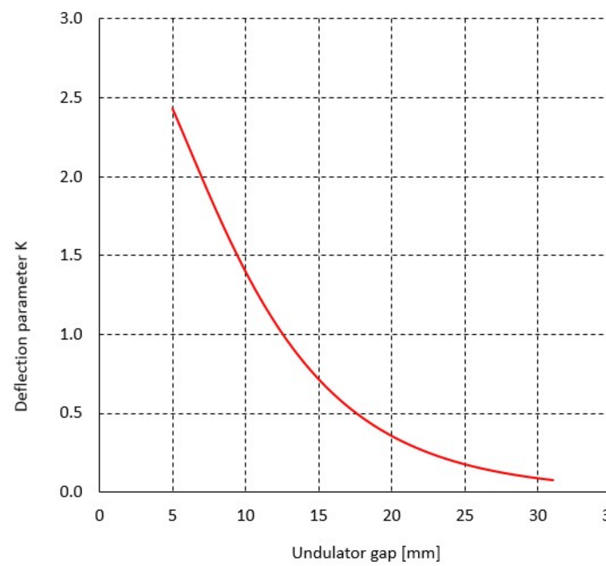
In turn, the magnetic field depends on the gap [5]:

$$\tilde{B} = \frac{1}{\cosh(\pi \cdot \frac{g}{\lambda_u})}$$

where g (und. gap) must also fit with the vacuum wall, respecting a given radio-frequency minimum distance with e^- beam. For the EBS, $g_{min} \geq 6\ or\ 5mm$ (likely after EBS commissioning). Figure 2 represents how gap considerations can meet with the energy choice for the scientific applications with the technical constrains. This also applies to higher spectrum harmonics, like H3, H5. In fact, from the magnetic field optimization, the ratio g/λ_u is a suitable figure of merit to optimize.



(a)



(b)

Figure 2: The K value is defined through two main processes, from science (a) where the energy targets are initially defined, and from the insertion device engineering (b), where the undulator gap provides a K value. Dotted lines in (a) represent the different energies choice from experiments. Figure 2b shows how the undulator (cryo permanent magnet with a period of 22mm) can meet the K value, enabling the BL to perform scientific research.

SEARCH FOR EXPLOITING WITH EBS HIGHER DEGREE OF COHERENCE

The lower EBS beam size (reduced by a factor of 10) increases the coherent fraction of the X-ray beam. This property is of major importance for optimizing experimental methods based on interference and diffraction of wavefronts. Experimental techniques such as phase contrast imaging, coherent diffraction imaging (CDI), holog-

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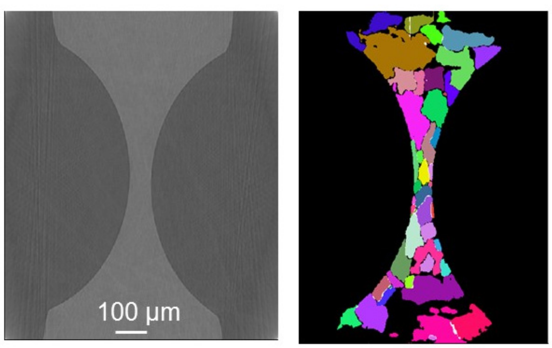
raphy, ptychography and X-ray photon correlation spectroscopy (XPCS) all exploit this characteristic. The transverse coherence length gives an estimation of the length of the illuminated area across which the beam can be considered coherent, thus allowing coherence experiments. It is proportional to the wavelength λ_{ph} and beamline length L_{BL} and inversely proportional to the photon source size s [6]:

$$L_{coh} = \frac{\lambda_{ph} \cdot L_{BL}}{2 \cdot s}$$

Thus, with ESRF long beamlines and using optics that adequately preserve the wavefront quality, high coherence beamlines are available, even above 30 keV. The EBS BM18 imaging project as well as several other ESRF beamlines are specifically designed to exploit the improved coherence properties of the new source.

As an example of beam aspect, in relation with mechanical engineering, the following inquiry, qualifies the deformation works performed in the frame of the ESRF-Compound refractive lens development, a DCT (differential contrast tomography) of a single Al lens is illustrated in Fig. 3. It reveals a structure made by grains of increasing grain size, suggesting a dynamic recrystallization, due to excessive punching velocity thus inducing an adiabatic thermal process.



(a) (b)

Figure 3: a) A classical transmission radiography of a single lens. b) A differential contrast tomography. The refractive lens is produced by cold-punching. Grain sizes are revealed. The quick deformation produced a high temperature rise of the material and then a dynamic recrystallization- Courtesy W. Ludwig-ESRF-ID11.

OASYS : A BEAMLINE OPTICS SIMULATION TOOL

The OASYS package [2] is an open source suite of different software tools, connected together by means of a workflow-based graphical environment implemented using Orange [7]. This package is an open source project for synchrotron virtual experiments and data visualization, developed in an academic environment. OASYS includes modules for X-ray tracing, synchrotron wave optics (SRW), toolboxes (XOPPY), partial coherence (COMSYL), etc…

This tool, enables quick and easy analysis, from individual optical elements to a full beamline simulation. Figure 4 shows a typical workflow representing the simulation of a complete beamline.

Within the scope of the EBS-readiness project, we are particularly concerned with the beam power handling of the beamlines. A cascade of calculations is implemented for each case, where we can calculate the flux, and its related power spread and spectrum, and the way it is transmitted. The spectrum limitation by means of attenuation or critical angle reflection mirrors is simulated in the existing configuration. Thermo-mechanical analyses are then applied, in these two cases, which are aimed at determining stresses for attenuators, and deformations for mirrors. OASYS is also aimed at computing the full beamline performance, including most of beam distortions due to optical imperfection. Mirror figure errors can be provided by a specific historical measurement database, including a large collection of achieved reflecting surfaces (specific widgets). In the same way, a database of thermal slope errors surfaces provided by FEA tools should be included soon, in order to add-up all of major effects. At present this link is operated manually.

PROCESS OF X-RAY BEAMLINE DESIGN

For the EBS source there are several scenarios for the beamline design but all involve close interaction between the ESRF engineering groups and the BL scientists. New 'EBS beamlines' are generally designed from scratch. In contrast, for existing beamlines, the design process may be limited to a check that the existing instrumentation can perform to a level which is at least equivalent to that achieved with the existing source or may include re-design/refurbishment of critical components which allow the beamline to reap the benefits, either partially or fully, of the new source parameters. One of the primary choices is the selection of the source. This is determined principally by the energies in which the experiments are planned in accordance with the scientific case of the beamline. Parameters such as energy tunability and polarization control may also influence this choice as well as the radiated power. At the ESRF the choice of source parameters is conducted in consultation with the Magnets and Insertion Device Group. Tools integrated into OASYS greatly facilitate the simulation of spectral brilliance, emitted power etc.

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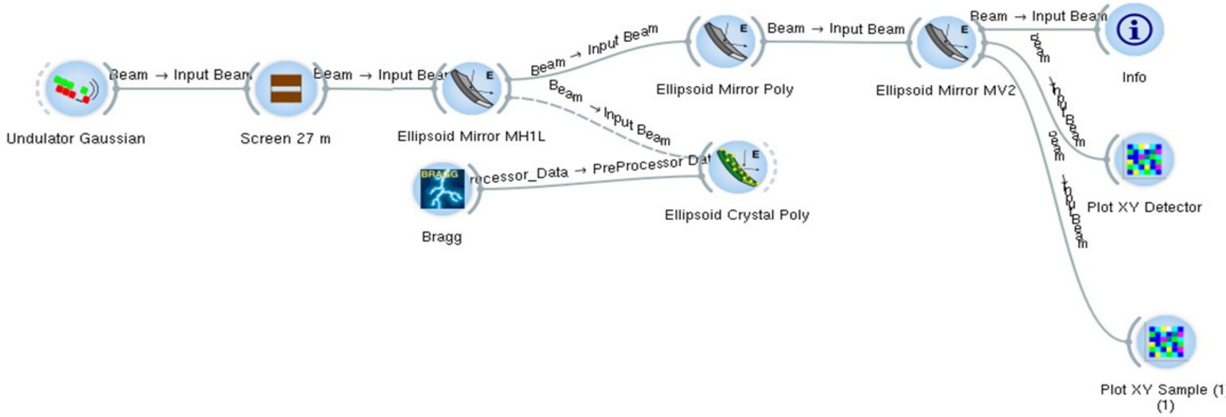


Figure 4: OASYS display window, enables to compute a full beamline string of components. Here the ID24 spectroscopy sample is illustrated. This model represents part of a beamline scheme, enabling a complete simulation of the arrangement.

The power transmitted to the critical beamline components is controlled by tuning of the primary slit opening; these are adapted to the emission angle of the central cone of the required undulator peak, in order to keep maximize the useful photon flux illuminating the sensitive optical components without subjecting them to unnecessary absorbed power.

There are several ways of dealing with the transmitted power. Amongst the most common are:

- Cut the low energy part of the spectrum by means of attenuators.
- Cut the high energy part of the spectrum with mirrors, operated in total reflection.

For the engineering design of these two cases, the material stresses, and deformations resulting from the absorbed power are simulated. Figure 5 gives an example of spectral filtering using mirror optics. The strategy commonly used at the ESRF is to reduce the thermally induced deformation of the optical surface, using a optimized notch profile of the silicon substrate [8,9,10]. The criteria in that case is defined such that thermal deformations should be negligible relative to the intrinsic polishing quality of the native optical surface. Since the two effects are essentially uncorrelated the overall slope error, ε_{rms} of the thermally deformed optic can be estimated by:

$$\varepsilon_{rms} = \sqrt{\varepsilon_{rms\ slope-error}^{\ 2} + \epsilon_{rms\ thermal\_slope}^{\ 2}}$$

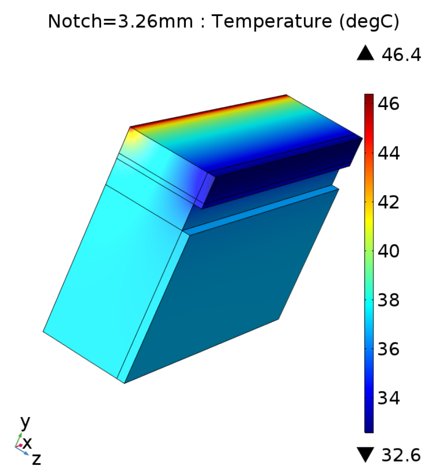
REVIEWING QUICKLY OPTICAL CASES

Experience tells us that beam is not fixed forever. Random events come, and disturb the beamline operation.

First, the optical quality of the optics can be processed with OASYS, using specific formatted files from the optical metrology lab.

Second, thermally deformed surfaces can be provided by FEA tools, to OASYS using Matlab scripts.

The results are more complete real case optical propagation, better predicting practical sample illumination. We are at present implementing a roadmap aimed at completing OASYS with specific modules, as shortly described in Fig. 6.



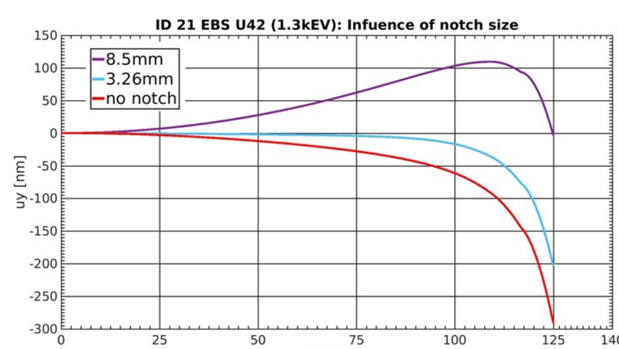


Figure 5: A ‘smart’ profiled mirror, consisting in making longitudinal groves each side on the substrate, with optimised depth, in order to minimize deformation of the reflecting surface upon power absorption. The horizontal axis represents half length of the mirror, the vertical axis being the thermal slope (in nano-rad).
The thermal slope is restricted to $\epsilon_{Therm\_slope} \leq 200nrd$ although it produces smooth image density gradient.

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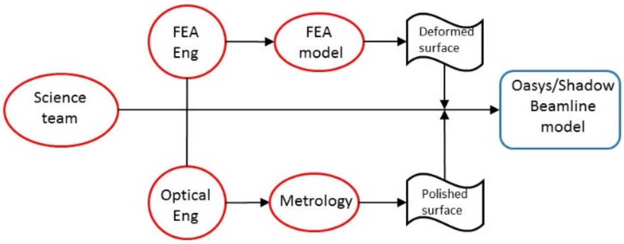

Figure 6: The science team proceeds to a beamline model with OASYS. This model can consider an ideal case. With FEA Eng, and Optics Eng, real/simulated surfaces can be implemented, involving surface distortions in the transmitted beam. This process corresponds to a specific module of OASYS, including a COMSOL application builder, operated by scientists.

CONCLUSION

The ESRF instrument division the ISDD (Instrument Support and Development Division) is committed in an optics calculation roadmap leading to better integrate the chain of actors, from scientists, to engineers, involving metrology lab phase. The OASYS suite, created 4 years ago, is also itself within a roadmap. It requires more software support, in order to resolve the various interactions with user's platforms. This should be triggered soon. For the ESRF beamlines, a review priority is set, and a relative long calculation chain is starting, including the recent new phase II beamlines, described in Technical Design Reports.

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