Review of Future European Synchrotron Radiation Projects

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Abstract

The future European synchrotron radiation projects offer a wide and bright palette of sources. Successful operational experience with the high brightness third generation synchrotron radiation sources and a growing user community, as well as the maturing of the field of experimentation using synchrotron radiation, are shaping the requirements for the future projects. Changing access requirements result in a variety of proposals for national, home based machines that would allow for enough beam time for the development of new experimental techniques and for the preparation of experiments on the less accessible, top performance machines. The new designs, pushing towards the fourth generation of sources, exhibit a certain degree of specialisation. Among the directions pursued are higher average and peak brightness, with the corresponding high coherent flux, circular polarisation and shorter pulses for time resolved studies.

1 GROWING DEMAND

Storage ring based synchrotron radiation sources[1] are big scientific projects that are used by many small groups of researchers from universities and industry. Thus, at present, the total number of users of synchrotron radiation in Europe is close to 6000, a number that, according to an OECD panel estimate, will double by the end of the century.

Synchrotron radiation is playing an increasingly important role in such fields as biology and medicine, chemistry and physics. Its role is also growing rapidly in technological applications. To give but one example from the field of large biomolecules structure determination, any recent issue of either Nature or Science journals will contain at least one or two papers based on research using synchrotron radiation.

With the successful operation of the third generation high brightness sources[2] (e.g. ELETTRA[3], ESRF[4]), users appetite for high quality, undulator based sources has been growing dramatically. New techniques that are being developed at the sources presently in operation result in more stringent demands on the quality of the future sources. Among them are high brightness, high degree of coherence and fast switchable elliptical polarisation of the light

There is now a strong push for new, high performance national based sources[5] (see Table 1), either replacing the present facilities (DIAMOND, SOLEIL), or introducing the new ones (ANKA, LSB, SLS). The new projects are optimised for record high brightness in the VUV and soft X-ray spectral region. This will lead to a European network of sources that will be able not only to cover the increasing demand, but will allow a proverbial "suitcase scientist" to prepare and develop her experiments at home, making for more efficient use of the less accessible, hard X-ray machines like ESRF.

2 BROAD SPECTRAL COVERAGE

The future net of the European synchrotron radiation sources will offer bright, tuneable photon beams with photon energies ranging from a few eV to hundreds of keV.

The main emphasis for the majority of the new projects is on undulator radiation. Figure 1 shows the wavelength ranges as a function of machine energy that are accessible with these devices. With the electron energies in these proposals not exceeding 3 GeV, this covers the range from infra-red to soft X-rays. Complementing these, the two high energy machines, ESRF and PETRA[6] will cover the hard X-rays region up to hundreds of keV.

The new projects also plan to extend their coverage to hard X-rays (albeit with lower brightness), employing superconducting devices: wavelength shifters in straight sections, or (DIAMOND, SLS) dipole magnets integrated into the lattice.

Table 1: Main parameters of the future ring based European synchrotron radiation projects.

Project	Country	Energy [GeV]	Circumf. [m]	Emittance [nm·rad]	Current [mA]
ANKA	D	2.5	97.2	45 - 80	200 (400)
DIAMOND	UK	3.0	345.6	14.5	300
LSB	E	2.5	251.8	8.3	200
SLS	CH	2.1	270.0	2.3 - 3.6	400
SOLEIL	F	2.15	336	2.7 - 15	500

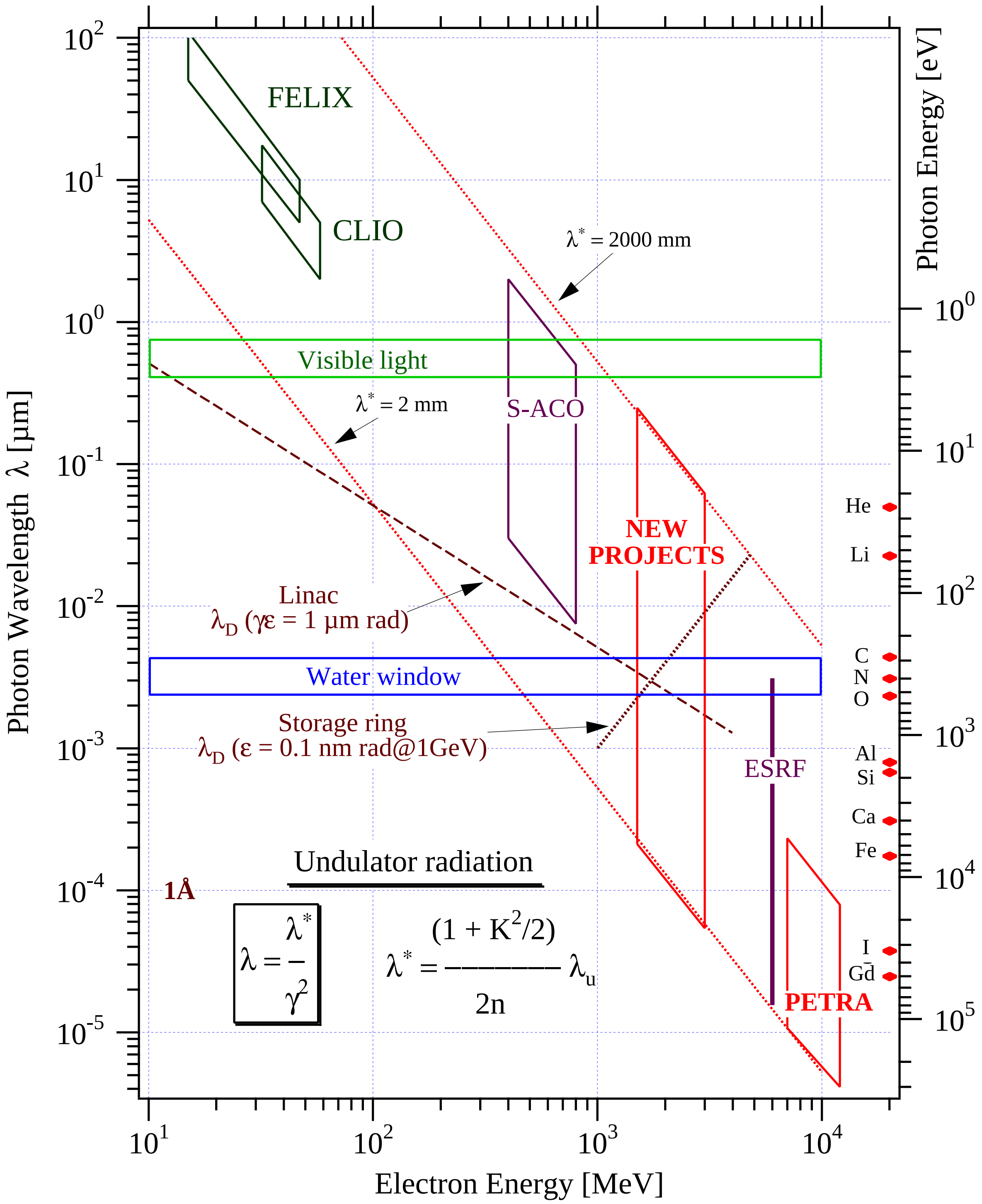

Figure 1: Universal undulator radiation diagram. The wavelength ranges of undulator radiation attainable at the European synchrotron radiation sources (including the future projects). Radiation wavelength is plotted against the electron energy on a log log scale. The two dotted parallel lines represent the range accessible at a given energy. As a lower limit, an undulator with effective period of 2 mm is chosen (e.g. period of 18 mm, ninth harmonic and K = 1.4). The upper limit is represented by an effective period of 2000 mm (e.g. period of 200 mm, first harmonic and K = 6). Diffraction limits for the linacs (normalised emittance of 10^{-6} m·rad) and for storage rings (0.1 nm·rad @ 1 GeV) are indicated in the plot. The K-absorption edges of some elements are shown as well.

2.1 Low photon energies

Several of the proposed projects, DIAMOND, SOLEIL and SLS have incorporated into their designs very long (14 - 20 meters) straight sections. Comparatively long period (up to 500 mm), very long undulators that can be realised as fixed gap, electromagnetic devices will provide nearly diffraction limited sources of photons in the energy range from a few eV to a few hundred eV (see Figure 2). The coherent flux from these devices will exceed 10^{15} photons per second into 0.1% bandwidth.

Furthermore, these devices would be capable of generating elliptically polarised light in the region between 10 and 1000 eV. The helicity of the light could be switchable at a rate of tens of Hz.

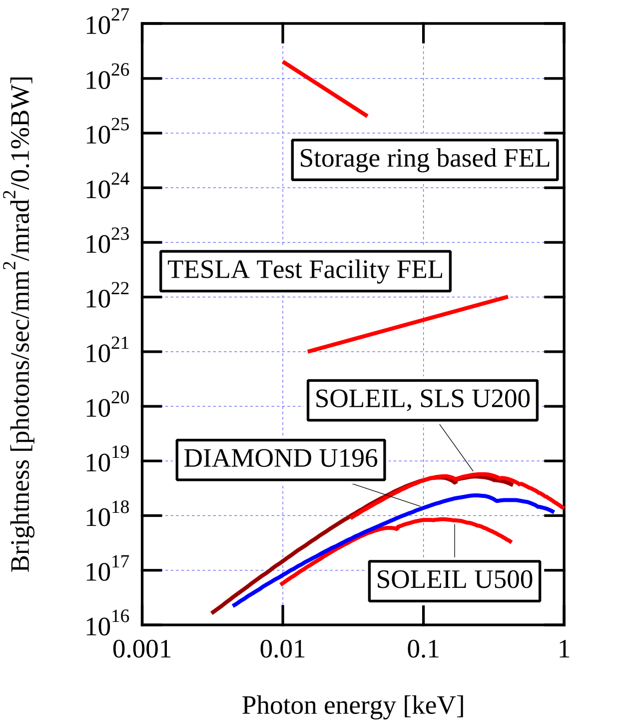

Figure 2: Low photon energy end of the spectrum, covered by long period, very long undulators planned for in the future projects.

This part of the spectrum (up to UV region) will also be covered by the storage ring based Free Electron Lasers (FEL)[7], capable of producing much higher average brightness (on the order of 10^{26}). The FEL action results in micro-bunching of the electron beam on the wavelength scale, and the radiation from such a micro-bunch is proportional to the square of the number of particles in it.

Linac based FELs working in the so-called Self Amplified Spontaneous Emission (SASE) regime are under development at SLAC and DESY. The proposed TESLA FEL project[8] would be able to extend the FELs coverage of this region into the water window (see Fig. 1) with average brightness on the order of 10^{22}

2.2 High photon energies

The high end of the photon spectrum will benefit from very high brightness undulator based sources installed on the high energy electron rings ESRF and PETRA. Future plans at ESRF include lowering the horizontal electron beam emittance down to 3 nm·rad and the vertical emittance down to 0.006 nm·rad. This will extend the coverage up to 100 keV photon energies.

PETRA ring at DESY, used at present as an injector for HERA, was recently modified to serve as a synchrotron radiation source[6]. It is capable of ramping 60 mA beams of electrons or positrons from 7 GeV up to the energy of 12 GeV. A low emittance mode (8 nm·rad at 7 GeV) is under investigation. In the future this new source will be able to extend the coverage up to 200 keV.

The new projects, based on storage rings with energy below 3 GeV, are planning to use multipole wigglers, superconducting and normal bending magnets to extend the spectral coverage to hard X-rays (see Fig. 4).

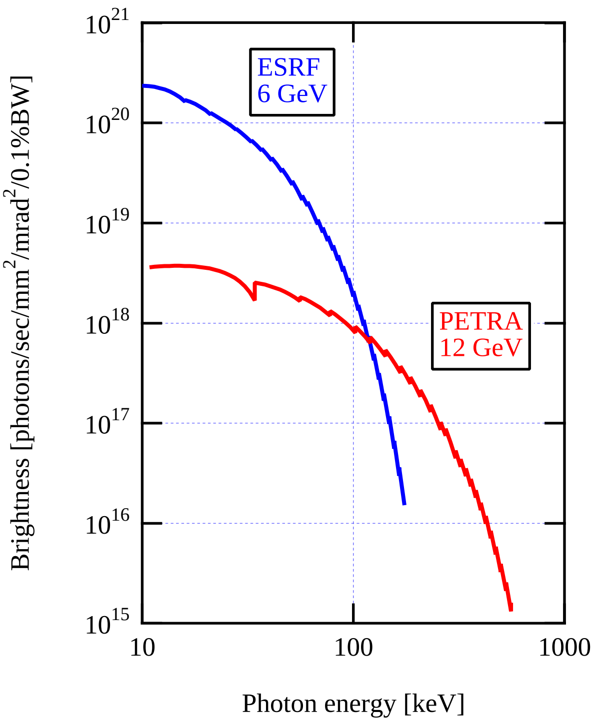

Figure 3: Very high photon energy end of the spectrum, covered by high energy machines.

2.3 VUV and soft X-rays region

Here is where most of the proposed projects are optimised for the highest brightness (DIAMOND, LSB, SLS, SOLEIL). Undulators with periods ranging from 80 mm down to 15 mm are capable of delivering brightness in the range of 10^{19} - 10^{21} photons/s/mm^2/mrad^2/0.1%BW. The majority of users will be served by these sources. Design performance is illustrated in Fig. 4 for the case of SLS.

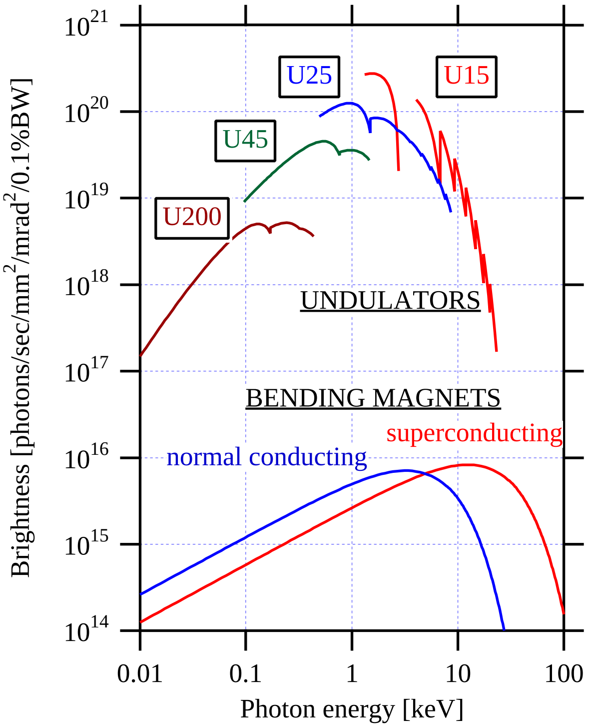

Figure 4: Brightness from proposed medium energy rings, illustrated on an example of the Swiss Light Source.

3 PERFORMANCE OPTIMISATION

The main figure of merit for the new projects is the high brightness. Most of the designs opt for low emittance lattices to achieve this, the ultimate goal being the so-called diffraction limited source (when the effective source phase space is dominated by the diffraction limit at a given wavelength, corresponding roughly to λ/10)[9].

3.1 Quest for small emittance

The equilibrium emittance in a storage ring is determined mainly by the energy E, bending angle per bend θ and optics in the dipole magnets (expressed by the lattice form-factor F_{lattice}:

$$\varepsilon \propto E^2 \cdot \theta^3 \cdot F_{\text{lattice}}$$

The shaping of the beta and dispersion functions in the dipoles is very close to the optimum. One trick, that gains about a factor of two in emittance and that is being used by several existing and proposed sources, is to allow for non-zero dispersion in the straight sections. First proposed by M. Eriksson[10] for the MAX II design, it also allows for local chromaticity correction in the straights, resulting in overall reduction of sextupole strengths. The disadvantage of this method, especially for the lattices with vertical emittance already at or below the diffraction limit, is that the horizontal beam size is increased by a chromatic contribution, proportional to the amount of dispersion and to the energy spread in the beam. For example, in the high brightness optics option of SOLEIL, with 2.7 nm·rad emittance, the contribution to the beam size from about 20 cm dispersion in the straight offsets the gain in brightness, corresponding to an equivalent emittance of 5 nm·rad with zero dispersion (nevertheless, achieving higher brightness, than the nominal design lattice with zero dispersion and 7.7 nm·rad emittance).

Significant reduction in emittance in the future designs can then only be achieved by reducing the bending angle per dipole θ, resulting in many cells, large ring size designs (see e.g. some of the damping rings designs for the future linear colliders). One should not forget, that LEP at injection energy (20 GeV) stores full current beams with an equilibrium emittance of the order of 2 nm·rad. And the layout of LEP lattice is far from optimum utilisation of this “tunnel with a future” as far as the synchrotron radiation production is concerned.

3.2 Peak brightness, short pulses

The maximum peak current in a storage ring (at equilibrium) is probably limited to about 500 A. Compared to typically 0.5 A average current in the present designs, this limits the *peak brightness* to the region of 10^{23} - 10^{24}. FEL projects mentioned above promise to deliver up to ten orders of magnitude higher performance, reaching peak brightness on the order of 10^{34}!

In addition, since the highest peak currents are achieved well above the turbulent bunch lengthening threshold, the increased energy spread deteriorates the peak brightness of lattices with finite dispersion in the straight sections.

Short pulses of synchrotron radiation are of great interest for time resolved studies. Making bunches shorter than 1 mm (at equilibrium) will be a difficult task. It is interesting to note here a small and negative momentum compaction factor optics option developed for SOLEIL that achieves this value of bunch length at low currents, at the same time maintaining a low equilibrium emittance.

3.3 Coherent flux

Equally important for the optimisation of the properties of the future sources of synchrotron radiation, high brightness also insures a *high degree of coherency* of the source, i.e. high number of photons emitted into a diffraction limited phase space volume at a given wavelength. Using the so-called “resolution-luminosity”, or half Airy disk criterion[11] for the phase space acceptance, we show in Fig, 5 the coherent photon flux that will become available in the future from the undulators at the high brightness sources.

X-ray microscopy, holography and phase contrast imaging, are the main techniques, pioneered in the past few years at the existing second and third generation sources, that will benefit from the higher coherent power that will become available at the future machines.

Here again, the storage ring and linac based FELs have the potential of delivering considerably higher coherent photon flux.

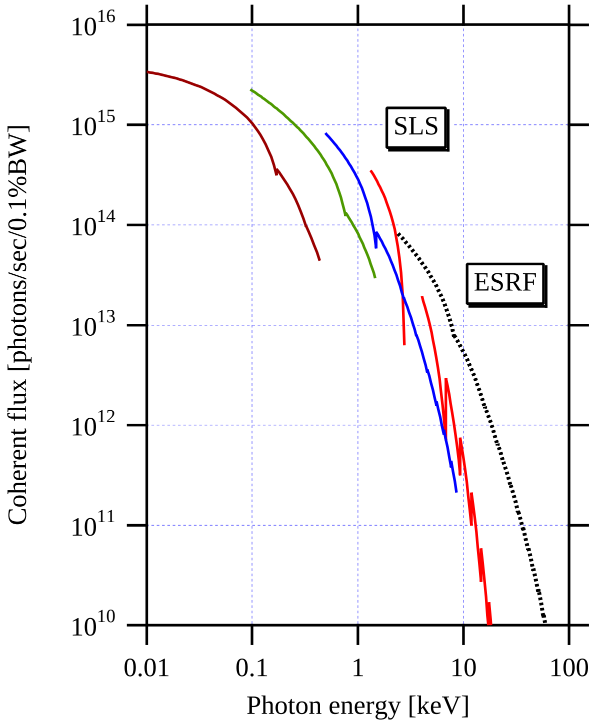

Figure 5: Coherent photon flux (into a phase space acceptance defined according to a half Airy disk criterion) that will become available at the future sources. Not to crowd the picture, only SLS undulators and ESRF (dotted curve) examples are shown.

4 PRESENT STATUS

The new projects: ANKA, DIAMOND, LSB, SLS and SOLEIL have formed a New European Light Sources Group that seeks to optimise the available resources and costs by pushing the issue of standardisation. The fields involved include instrumentation (BPMs), RF, controls, power converters, magnets and vacuum system. The subgroups have had meetings (involving specialists from the existing sources) and a number of interesting proposals are under study (e.g. a common klystron standard, common control system, a magnetic measurement laboratory for possible common use, that is at present under construction in Barcelona by the LSB group).

ANKA[12], recently *approved* for construction, targets industry as a major customer. Low-cost, high performance compact light source will offer *full service* in microfabrication and analysis by mixed service and research groups.

DIAMOND is proposed as a replacement for the veteran SRS that has been serving some 2000 mainly hard X-ray researchers since 1981. Its scientific case accepted, it is awaiting further political decisions.

LSB, enjoying strong support from the local authorities is under consideration by the Spanish government.

SLS has been granted planning funds by the Swiss government. The project will be submitted by the relevant minister to government approval in December 1996 and to Parliament approval in the first half of 1997.

SOLEIL, now a joint CEA and CNRS French science agencies project, is expecting government approval in the spring of 1997. The construction start is slated for the beginning of 1999.

ACKNOWLEDGEMENTS

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REFERENCES

[1] For some recent European synchrotron radiation sources reviews see:
H. Zyngier, “European Synchrotron Radiation Storage Rings”, in Proc. IEEE Part. Accel. Conf., Dallas, 1995, p. 155
M. W. Poole, “A Review of Proposed New European Synchrotron Light Sources”, in Proc. EPAC’94, London, p. 99
V. P. Suller, “Review of the Status of Synchrotron Radiation Storage Rings”, in Proc. EPAC’92, Berlin, p. 77

[2] Y. Petroff, “Results on 3d Generation X-ray sources”, these Proceedings.

[3] C. Bocchetta, “Operational Experience with ELETTRA”, these Proceedings

[4] J. M. Lefebvre, “Higher Brilliance at the ESRF”, these Proceedings

[5] see contributions to these Proceedings

[6] K. Balewski et al., An Undulator at PETRA II - a New Synchrotron Radiation Source at DESY”, in Proc. IEEE Part. Accel. Conf., Dallas, 1995, p. 275

[7] M. E. Couprie, “FELs using Storage Rings”, these Proceedings

[8] J. Rossbach, “Studies on a Free Electron Laser for the TESLA Test Facility”, in Proc. IEEE Part. Accel. Conf., Dallas, 1995, p. 189
see also: Fourth generation light sources, 10th ICFA Beam Dynamics Workshop proceedings, Grenoble, Jan. 22-25, 1996

[9] L. Farvacque, “SR-related Accelerator Physics Issues” these Proceedings

[10] M. Eriksson, “Novel Techniques used in Max II”, these Proceedings

[11] M. R. Howells and B. M. Kincaid, “The Properties of Undulator Radiation”, in Proceedings of the NATO Advanced Study Institute on New Directions in Research with Third-Generation Soft X-Ray Synchrotron Radiation Sources, ed. by A. S. Schlachter and F. J. Wuilleumier, Kluwer Academic Publishers, 1994

[12] H. O. Moser et al., “ANKA, a Synchrotron Light Source for Microstructure Fabrication and Analysis”, in Proc. IEEE Part. Accel. Conf., Dallas, 1995, p. 272; see also contribution in these Proceedings

[13] J. Bordas, “The Spanish Project for a Synchrotron Laboratory at Barcelona”, these Proceedings