LUNEX 5 FEL LINE UNDULATORS AND MAGNETIC ELEMENTS

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Abstract

LUNEX 5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) aims at investigation the production of short intense and coherent pulses in the soft X-ray region with innovative schemes (such as echo and seeding with harmonics generated in gas) and compact design. The undulators of the FEL line are designed to provide high field short period devices: modulators are in-vacuum undulators with a period of 30 mm and 0.27 m long, radiators are in-vacuum undulators with a period of 15 mm and 3 m long with a cryogenic option, relying on SOLEIL development experience of NdFeB U20 hybrid in-vacuum undulators and 2 m long PrFeB U18 cryogenic undulator operated at 77 K installed on a long straight section of SOLEIL, and ESRF development experience of many in-vacuum undulator and 2 NdFeB U18 cryogenic undulators operating at 150 K. In addition, the line comports electromagnetic quadrupoles for the beam focusing, chicane dipoles for the beam compression and an electromagnetic bending magnet for the beam dump. A prototype of cryo-ready radiator is under design. Variable permanent magnet quadrupoles are under study for the transport of the Laser WakeField Accelerator towards the undulators.

INTRODUCTION

LUNEX5 is a French Free Electron Laser (FEL) test facility project aims at investigating the production of short, intense, and coherent pulses in the soft x-ray region (4-40 nm) [1]. It consists in a Free Electron Laser (FEL) in the seeded configuration (High order Harmonic in Gas seeding and Echo Enable Harmonic Generation) with a 15 mm period in vacuum (potentially cryogenic) undulator of 15 and 30 mm period) [2] using a Conventional Linear Accelerator (CLA) of 400 MeV or a Laser WakeField Accelerator (LWFA) [3] ranging from 0.4 to 1 GeV. The undulators are used either to modulate the electron bunch energy at the external laser seed (modulator) or for the amplification and emission (radiator). The LWFA will be provided first by the 60 TW laser of LOA, by the 10 PW APOLLON laser of ILE (Institut de Lumière Extrême) before a dedicated laser system.

LUNEX5 FEL LINE

Figure 1 presents the LUNEX5 FEL line. It is constituted by short period and high field undulators for the modulators and radiators, electromagnetic quadrupoles for the beam focusing, chicane dipoles for the beam compression and electromagnet bending magnet for the beam dump. Compact and high gradient permanent magnets quadrupoles are needed to focus the high diverging LWFA beam in the transfer line.

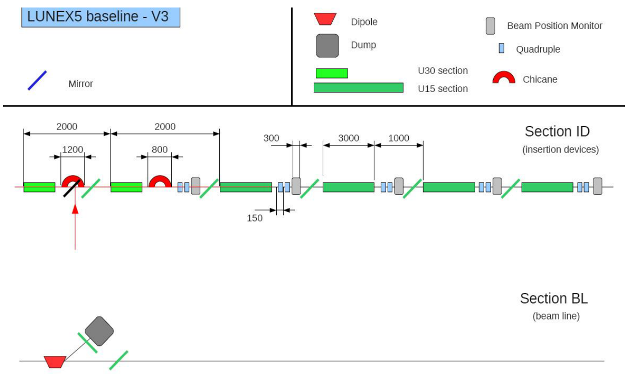

Figure 1: LUNEX5 FEL line.

UNDULATORS

Radiator Undulator

In-vacuum undulator technology is widely used to produce short period small gap undulators. The permanent magnet arrays are mounted on beams inside the vacuum chamber to eliminate the physical limitation of the magnetic gap due to the vacuum chamber [4]. The radiator is an in vacuum undulator with a small gap of 3 mm. The permanent magnet material is NdFeB and the poles material is vanadium permendur. The radiator is a 3 m long undulator with a relatively short period of 15 mm. The magnetic design of the radiator is presented in Figure 2.

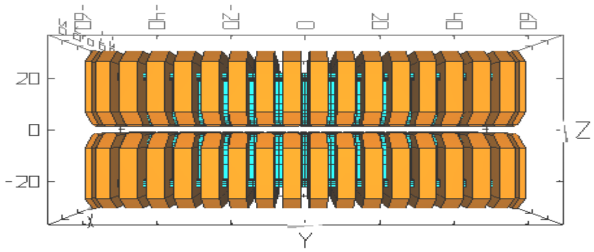

Figure 2: Radiator RADIA [5] model.

The peak magnetic field of the in-vacuum undulators can be increased while operating at cryogenic temperature [6]. When cooling down the NdFeB permanent magnets, the remanence Br increases down to a certain temperature at which the process is limited by the appearance of the Spin Reorientation Transition (SRT) phenomenon [7]. However, when cooling down

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PrFeB permanent magnet, the remanence Br increases without being affected by the SRT phenomenon. In both cases, the coercivity being also enhanced at cryogenic temperature, the resistance to radiation is significantly improved. ESRF Built and install in the storage ring 2 U18 cryogenic undulators using NdFeB cooled down at 150 K [8] and SOLEIL built and install in the storage ring a cryogenic undulator using PrFeB cooled down at 77 K. Radiators could also be cryogenic with PrFeB permanent magnets enabling cooling down the magnets to the liquid nitrogen temperature of 77 K [9]. Figure 3 presents the magnetic field variation versus gap of the radiator for the two technologies (In-vacuum technology at 293 K and cryogenic technology at 77 K). Calculations are performed with the RADIA code.

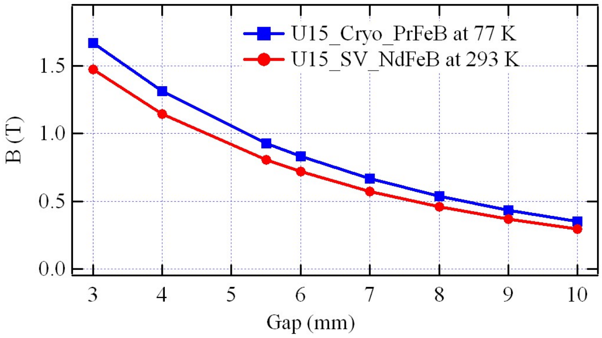


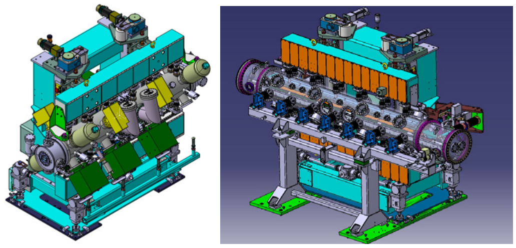
Figure 3: Radiator magnetic field variation versus gap for in vacuum and cryogenic undulator technologies. Calculations performed with RADIA, the remanent field of PrFeB (NdFeB) is 1.35 T at room temperature and 1.57 T at 77 K (1.22 T at room temperature).

Table 1 presents the main characteristics of the radiator for both technologies.

Table 1: Main Characteristics of Radiator Undulator

Characteristics	In-vacuum	Cryogenic
type	Hybrid	Hybrid
Br (T)	1.22	1.57 (77 K)
Magnet	NdFeB	PrFeB
Peak field (T)	1.48	1.72
Gap (mm)	3	3
Period (mm)	15	15
Length (m)	3	3

The mechanical design of the radiator will be adapted from SOLEIL in vacuum undulator (Figure 4-a) and PrFeB cryogenic undulator (Figure 4-b) designs. The length of the vacuum chamber and the number of rods will be increased and the carriage will be adapted to the length and the magnetic forces of the magnetic system. The extension of the mechanical carriage design to accommodate a 3 m long magnetic system will be carried. The issues related to the RF transitions (finger type) adapted to a cylindrical chambers will also be analysed, after further analysis of the impedance budget. Reduction of the length taken by these elements between radiator segments is crucial from a FEL point of view.



a) b)

Figure 4: Mechanical Design, (a) in vacuum undulator, (b) PrFeB cryogenic undulator.

SOLEIL has a dedicated clean room for the magnetic and mechanical assembly of in vacuum undulators. A 5.5 m magnetic bench performs Hall probe and rotation coil magnetic measurement. In case of choosing cryogenic undulator technology, a dedicated magnetic bench at low temperature should be designed to perform 3 m long. It will be adapted from the present SOLEIL in vacuum measurement bench, which has been developed for the cryogenic PrFeB undulators (figure 5).

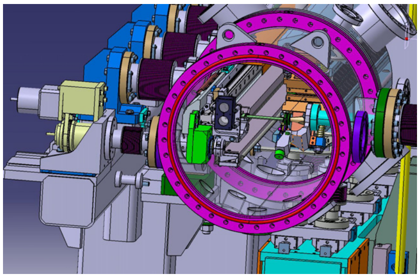


Figure 5: SOLEIL PrFeB Cryogenic undulator mechanical design.

Modulator Undulator

The modulator is in vacuum technology undulator with a small gap of 3 mm. The permanent magnet materiel is NdFeB and the poles material is vanadium permendur. The magnetic design of the modulator is presented in Figure 6.

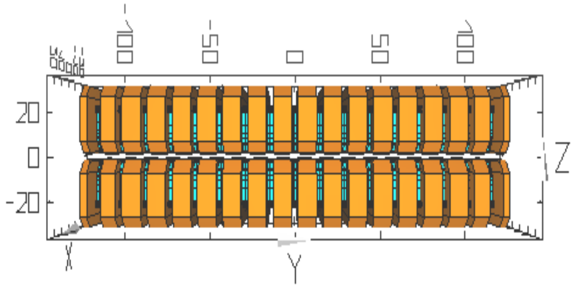


Figure 6: Modulator RADIA model.

Figure 7 presents the magnetic field variation versus gap of the modulator for in vacuum technology, using RADIA calculations.

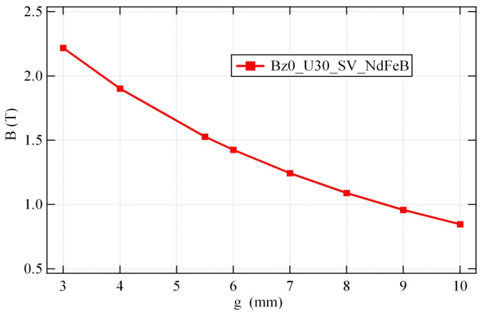


Figure 7: Modulator magnetic field variation versus gap for in vacuum undulator technologies. Calculations performed with RADIA, with remanent field of 1.22 T.

Table 2 presents the main characteristics of the modulator undulator

Table 2: Main Characteristics of Modulator Undulator

Characteristics	In-vacuum
type	Hybrid
Br (T)	1.22
Magnet	NdFeB
Peak field (T)	2.2
Gap (mm)	3
Period (mm)	30
Length (m)	3

MAGNETIC ELEMENTS

Permanent Magnet Quadrupole

The large energy spread and large beam divergence make the matching, emittances and peak current preservation from LWFA to the undulator line very concerning. A way to contain these degradations is to place a first set of three quadrupoles (figure 8) as close as possible from the source with drawbacks of large gradient. The use of small gap permanent magnet is then an issue. A possible beam line with this first triplet, located at only 50 mm from the source and separated by 50 mm with a maximum gradient of 130 T/m over 100 mm bore length at 400 MeV [10].

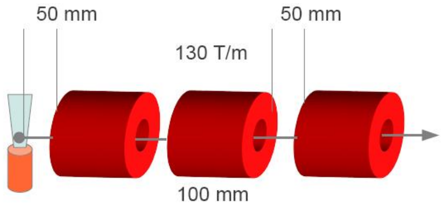


Figure 8: Triplet of permanent magnet quadrupole close to the source of LWFA.

Compact permanent magnet quadrupole with high and variable gradient is under studies. A preliminary design using Halbach **[11]** cylinder with 10 mm bore diameter allows reaching a high gradient of 150 T/m (figure 9).

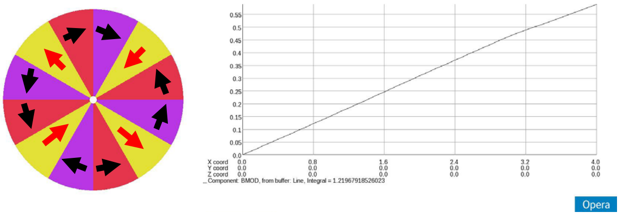


Figure 9: permanent magnet quadrupôle.

Quadrupôles

The LUNEX5 quadrupoles design is performed with TOSCA software [12] as shown in Figure 10. Because of the variable gradient in order to use different beam energies, the standard quadruoples are resistive magnets, the magnetic field being produced by four coils alimented by a DC current. The variation of the DC current enables the variation of the magnetic field and the gradient of the quadrupole. The coils are mounted on four poles which concentrate and define the quadruople magnetic field path.

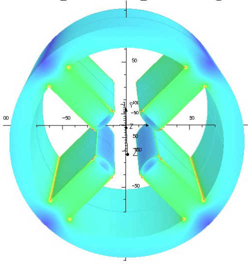


Figure 10: Magnetic design of the quadrupôle using TOSCA software.

The quadrupole yoke is manufactured on two parts. Every part represents a half quadrupole. Two coils are mounted on each half quadrupole. The quadrupoles are equipped with special shims which are adjusted during the magnetic measurement to guaranty a good alignment of the magnetic centre and low harmonic components. The quadrupoles are air cooled to reduce the infrastructure cost. A dedicated rotation coil magnetic bench [13] will be used for the magnetic measurements of the quadrupoles. This bench has been developed for the magnetic measurements of SOLEIL storage ring quadrupoles. The resolution for the measurement of the harmonic component is less then 2.10^{-4} and less than 20 µrad on the tilted angle. The magnetic measurement of the quadrupoles could be also performed by using the stretch wire bench developed by ESRF for the measurement of the storage ring upgrade quadrupoles [14].

Chicanes

All the chicanes of LUNEX 5 are designed with RADIA software as shown in Figure 11. The chicanes are made by four identical dipoles. As for the quadrupôles, the dipoles of the chicanes are resistive. The magnetic field is produced with coils mounted on a C shape yoke. A power supply generates current and aliments the coils. The magnetic field of the dipole is designed for beam energy of 400 MeV and also allows working at 1 GeV.

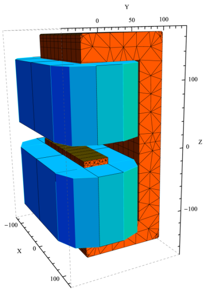


Figure 11: RADIA model of chicane dipole.

The vertical field integral I_z along the longitdunal coordinate of the chicane dipole is presented in figure 12. The needed field integale of 95 Tmm is obtained by current density of 1.5 A/mm². The coils are air cooled.

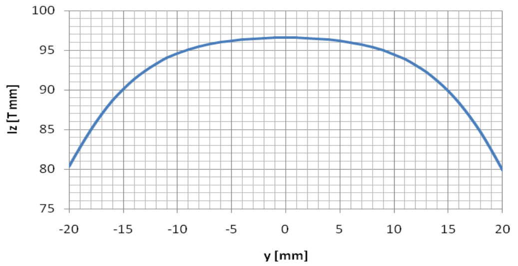


Figure 12: Field integral I_z versus dipole transverse position y.

The dipole are made in two identical parts. Each part reprents half of dipole which consists of half a C shape core and a coil. The different type of chicanes are presented in table 3.

Table 3: Different Type of Echo Chicanes

Chicanes	Iz (T.mm)	Gap (mm)	Length (mm)	Number of dipoles
Echo 1	95	25	250	4
Echo 2	52.5	25	150	4

The magnetic measurements of the chicane dipoles are performed with the Hall probe and rotation coil of SOLEIL insertion devices magnetic bench. The magnetic field is measured with a precision of 3 G and the field integral with a precision of 5 G. Cm.

Beam Dump Dipole

The LUNEX "beam dump" dipole deviate the electron beam from the beam line axis with an angle of 90°. This deviation angle needs a field integral of 2.1 Tm for an energy of 400 MeV. The TOSCA design of this dipole is presented in figure 13. The dipole is curved with 90° angle and generates a magnetic field of 1.6 T at 25 mm gap. This dipole could be made by 2 dipole of 45° deviation angle for each one. Additional permanent magnet will be prepared for radiation safety redundancy.

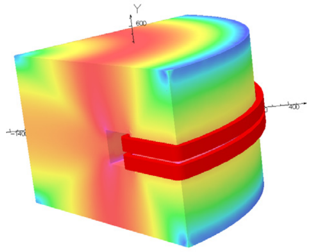


Figure 13: TOSCA magnetic design of beam dump dipole.

CONCLUSION

LUNEX5 project will investigate seeding schemes and prepare the path towards the 5th generation light sources. A 3 m cryo-ready undulator will be design and constructed in the next few years. We present the magnetic design of the undulators and magnetic elements of LUNEX5 FEL line. A challenging compact and high gradient permanent magnet quadrupole prototype will be design and constructed next year.

ACKNOWLEGMENTS

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REFERENCES

[1] M.E. Couprie et al, Proceeding FEL 2011, Shanghai, 208-211, M. E. Couprie et al., these proceedings.
[2] C. Evain et al., Proceeding IPAC 2012, New Orleans, 1712-1714, M. Labat et al., these proceedings.
[3] V. Malka et al., Nature Physics 4 (2008), 447-453.
[4] S. Yamamoto et al, Rev. Sci. Instrum. 63, 400 (1992)
[5] O. Chubar et al., J. Syn. Rad., 5 1998, 481-484.
[6] T. Hara et al. Phys. Rev. Spec. Top. Accelerators and Beam. 7, 050702 (2004).
[7] D. Givord, S.H. Li, R. Perrier de la Bathie, Solid State Commun. 51, (1984) 857-860.
[8] J. Chavanne et al, Proceeding of EPAC 2008, Genova, Italy, pp 2243-2245.
[9] C. Benabderrahmane et al., Proceeding FEL 2011, Shanghai, 524-526.
[10] A. Loulergue et al., Proceeding IPAC 2012, New Orleans, 1611-1613, A. Loulergue et al., these Proceedings.
[11] K. Halbach, Nuclear Instruments and Methods Elsevier (1981), 187.
[12] TOSCA software developed by http://www.vector-fields.com
[13] A. Madur et al., IMTC conference 2006, Sorento.
[14] G. Le Bec et al. Phys. Rev. Spec. Top. Accelerators and Beam. 15, 022401 (2012).