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DEVELOPMENT AND CONSTRUCTION OF CRYOGENIC PERMANENT MAGNET UNDULATORS FOR ESRF-EBS

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Abstract

The ESRF Extremely Brilliant Source (ESRF-EBS) is on operation for Users since August 2020 after 20 months of shutdown. This first of a kind fourth generation high energy synchrotron is based on a Hybrid Multi-Bend Achromat lattice. The main goal of the ESRF-EBS is to reduce the horizontal emittance, which leads to a significant increase of the X-ray source brilliance. To cover the intensive demand of short period small gap undulators at ESRF-EBS, a new design for a 2 m Cryogenic Permanent Magnet Undulator (CPMU) has been developed. Six CPMUs will be installed in the next years; the first two CPMUs have been constructed and actually used on ID15 and ID16 beamline, the third one is under constructing. An intensive refurbishment work has been done on the existing insertion devices to adapt them to the new accelerator which has shorter straight section and closer dipoles to the IDs than in the old one.

This contribution will review the development, construction and commissioning of the new CPMUs, and the refurbishment work done on the existing ones to adapt them to the new accelerator.

INTRODUCTION

The European Synchrotron Radiation Facility (ESRF) is an intense X-ray source located in Grenoble, France. It is a centre of excellence for fundamental and innovation-driven research. ESRF owes its success to the international cooperation of 22 partners. A major upgrade project known as ESRF-EBS was launched in 2015 and achieved in 2020. It aims to reduce the horizontal emittance from 4 nm.rad down to less than 140 pm.rad. The brilliance of ESRF-EBS is increased by a factor of 30 compared to the precedent one, mainly due to this drastic decrease of the horizontal emittance. The Double Bend Achromat lattice is replaced with a Hybrid Multi Bend Achromat one [1,2].

Permanent magnet undulator are composed of permanent magnets whose direction of magnetization rotates between one magnet and the next magnet by 90° creating an almost sinusoidal magnetic field along the undulator axis [3]. The permanent magnets are installed on two girders separated by an air gap in which the electron beam circulates in a vacuum chamber. A variant of this technology consists in replacing certain permanent magnets by poles made of soft magnetic materials in order to increase the magnetic peak field in the air gap.

Undulators are able to produce very intense and concentrated radiation in a narrow energy band. The spectrum is made up of several harmonics, the fundamental resonant harmonic depends of the electron beam characteristics and the undulator deflection parameter $K = 0.934\ \lambda_u[\mathrm{cm}]\ B[\mathrm{T}]$, where λ_u is magnetic period, and B is the magnetic peak field. In-vacuum undulators eliminate the limitation of reducing the magnetic air gap due to the presence of the vacuum chamber by installing the two magnetic girders directly in a large vacuum chamber. The reduction of the air gap (5-6 mm for ESRF) results in a significant increase of the magnetic peak field. The period can be shortened to reach greater number of periods for a given length, which leads to a significant increase of the undulator performances in terms of brightness. CPMUs take benefit from improved magnetic properties of in-vacuum undulator permanent magnet at low temperature [4,5], the remanence B_r is increased leading to higher magnetic field, than shorter period to enhance farther the brightness of the undulator.

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CPMU DESIGN

Permanent Magnet Grade

Praseodymium Iron Boron ($Pr_2Fe_{14}B$), Neodymium Iron Boron ($Nd_2Fe_{14}B$) and mixed Praseodymium and Neodymium $(Pr_{0.8}Nd_{0.2})_2Fe_{14}B$ are suitable grades for CPMUs. The use of ($Nd_2Fe_{14}B$) grade is limited to 130 K because of the magnet Spin Re-orientation Transition phenomenon (SRT) [6]. However, the two other grades are not limited by this phenomenon, the remanence continue to increase when lowering the temperature at least to the liquid nitrogen one [7]. Figure 1 shows the variation of the $(Pr_{0.8}Nd_{0.2})_2Fe_{14}B$ remanence versus temperature. The remanence increases from 1.41 T at 300 K to 1.62 T at 80 K, and the coercivity increases from 2 T at 300 K to 7 T at 80 K. This permanent magnet grade provided by Magsound-Konit is used for the construction of U18 and U20.5 new CPMUs.

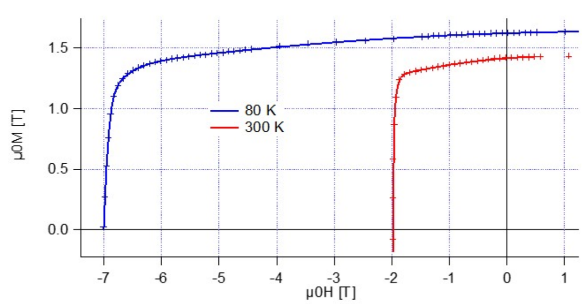

Figure 1: Magnet remanence versus temperature.

Magnetic Design

The magnetic design of the CPMUs is done with Radia [8] software as shown in Figure 2. The pole is in Fe-Co material with a Nickel coating. The permanent magnet of

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CPMU U20.5 is constituted by two half magnets to experience more flexibility during assembly and shimming. The main parameters of CPMUs is given in Table 1.

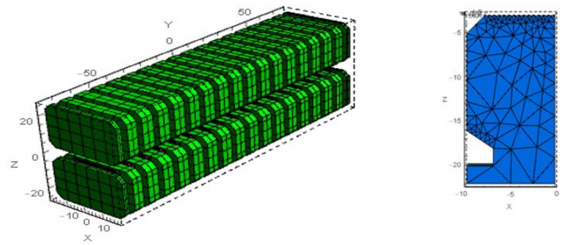

Figure 2: Magnetic structure (left), half pole (right).

Table 1: Main Parameters of the Two CPMUs

Parameters	U18	U20.5
ID length [m]	1.5	2
Period [mm]	18	20.5
Gap [mm]	6	6
Field B [T]	1.07	1.22
Parameter K	1.81	2.33

Figure 3 presented the brilliance of the two CPMUs calculated with SRW [9] software. The CPMU technology combined with the low horizontal emittance of EBS ESRF 135 pm.rad. allow to reach higher brilliance.

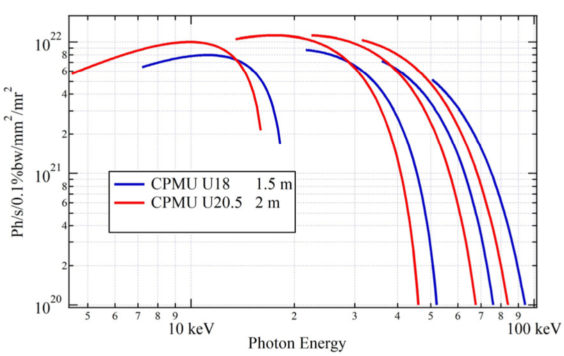

Figure 3: Brilliance of U18 and U20.5 CPMUs.

Mechanical Design

The mechanical design of the CPMU is presented in Figure 4. It consists of a metallic carriage with a frame fixed on a base. Two out-vacuum girders are fixed on the frame and move vertically on slides to open and close the undulator gap. The magnetic system is mounted on two in-vacuum girders installed in a large ultra-high vacuum chamber and connected to the out-vacuum girders by columns. The distribution of the columns between the upper and lower girders is staggered to reduce mechanical deformation due the magnetic forces, only the columns in the middle of the girders are fixed and opposite. The carriage is equipped with two motors, one for the gap and one for the vertical offset movements, additional motors enable taper and pitch correction of the undulator. The CPMU is cooled down with close loop liquid nitrogen circulating in the in-vacuum girders through a hole, leading to a good distribution of the temperature on the girders and therefore on the magnets. The design of all the mechanical parts installed in the vacuum chamber (transition, copper foil tender, cooling tubes, absorbers, …) have been modified and adapted to the new cooling system.

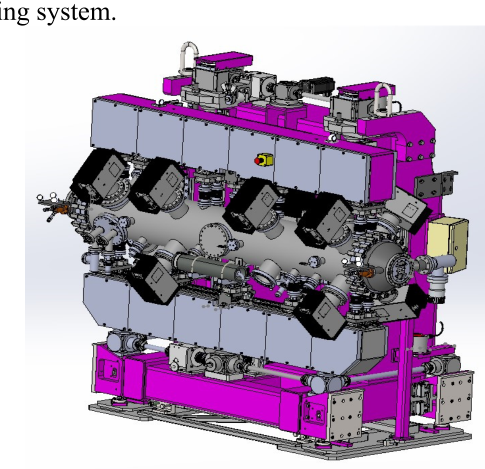

Figure 4: 2 m CPMU mechanical design.

MAGNETIC MEASUREMENTS AND CORRECTIONS

The magnetic system of the CPMU is assembled and corrected at room temperature using conventional magnetic measurement benches enabling both Hall probe and Stretched wire measurements [10]. The figures of merit during the magnetic assembly and corrections of the CPMU are the field integrals, the trajectory straightness and the phase error. The magnetic errors are minimized in order to reduce the effect on the electron beam dynamics and to improve the undulator performances in terms of photon spectrum. The magnetic measurement at cryogenic temperature are performed with a special magnetic bench integrated in the vacuum chamber, performing both Hall probe and Stretched wire measurements.

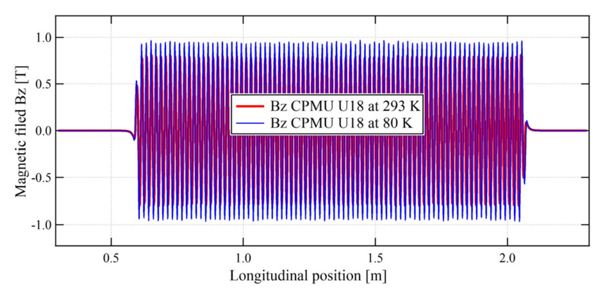

Figure 5: Magnetic field B_z at 293 K and at 80 K.

Figure 5 shows the enhance of the measured magnetic field B_z of CPMU U18 when lowering the magnet temperature from room temperature to 80 K, the gain is of 16%. The undulator phase error corrected at room temperature maybe degraded at low temperature due to mechanical contraction, a vertical adjustment of the undulator columns is used to bring this phase error to lower value.

Figure 6 presents a comparison of the flux spectrum at minimum gap of 6 mm of CPMU U18 calculated from the

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magnetic measurement and from the simulated magnetic field. The reduction of the flux on 9th harmonic is about 24 % corresponding to a rms phase error of 3.2°.

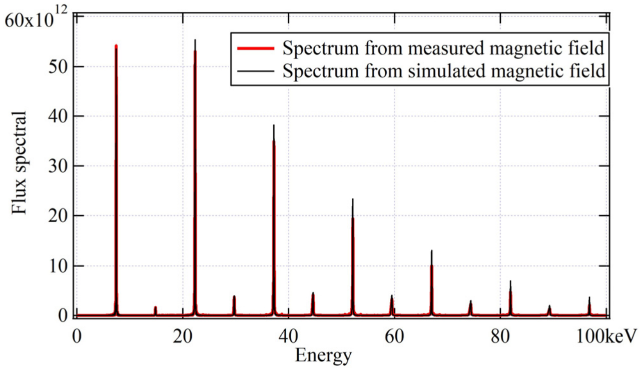

Figure 6: Flux spectrum of CPMU U18.

COMMISSIONING AND SPECTRUM MEASUREMENT

CPMUs U18 and U20.5 have been installed respectively on ID15 and ID 16. The optimisation of the CPMUs offset consist of aligning the magnetic system with electron beam. For a given gap, the girders are moved up and down in order to minimize the beam losses. The beam Close Orbit Distortion (COD) is measured to quantify the residual magnetic errors of the CPMUs. There is no dedicated corrector for the CPMUs, the residual errors are taken in account by the storage ring correctors. So far, the two CPMUs are operating well on the beamlines and in the storage ring, except the transition of CPMU U18 which have been replaced due to a fingers deformation and melting. A new design is on progress, it will be installed and tested in this summer shutdown.

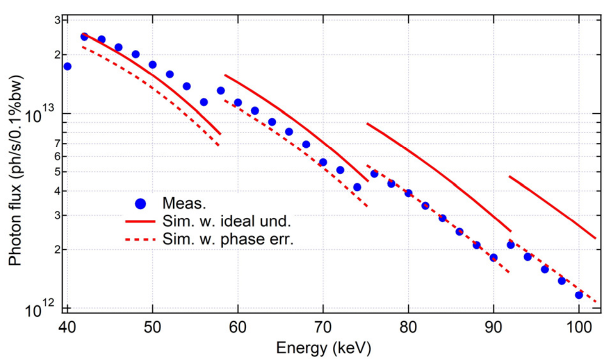

Figure 7: Flux spectrum of CPMU U18 measured on ID15 beamline.

Figure 7 presents the flux spectrum of CPMU U18 measured on ID15 beamline in a slit of 0.2 × 0.2 mm^2 in the energy range of 40 – 100 keV, it is in a good agreement with the estimated one.

REFURBISHMENT WORK ON EXISTING IDs

The installation of the new EBS storage ring required the installation of new insertion devices and also an important refurbishment of the existing ones. All the straight section of EBS are 5 m long, so the existing 6 and 7 m long straight sections have been reduced to 5 m which required engineering modifications of the existing IDs. Six beamlines were impacted by this modification. The magnetic system of in-air insertion devices has been modified and others have been used to reconstruct new EBS 2.3 m standard and revolver undulators.

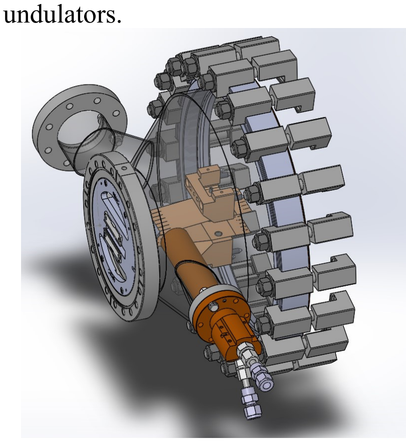

Figure 8: New end chamber with absorber and transition.

The existing In-vacuum undulators and CPMUs are closer to the permanent magnet dipoles (DLs) than in the old machine, which required the integration of a new absorber at both upstream and down stream of the ID. The end vacuum chamber (figure 8), the transition and the water-cooling system have been also modified. All the refurbishment work was carried out at the ESRF site and completed before the end of the long shutdown.

CONCLUSION

A 2 m CPMU design for the EBS-ESRF has been presented. It includes a new cooling system and modification of the mechanical parts installed in the vacuum chamber. The two first CPMUs U18 and U20.5 are constructed and in operation respectively on ID15 and ID16. The commissioning of the CPMUs with electron bean has been performed to correct the undulators offset and the beam close orbit. The transition of CPMU U18 have been replaced due to an operation issue. A transition new design is on progress, it will be tested in this summer. Three CPMUs are actually in construction at ESRF at different level of progress. The most advanced one is a 2 m U18 which will be installed this summer on ID27. An important refurbishment work was done on existing insertion devices to adapt them to the EBS straight section length and also to the closer distance with the permanent magnet dipoles.

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