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MECHANICAL ENGINEERING SOLUTIONS FOR COXINEL PROJECT*

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Abstract

COXINEL (COherent Xray source INferred from Electrons accelerated by Laser) is a European Research Council (ERC) advanced grant aiming at the demonstration of Free Electron Laser amplification using electrons generated by laser plasma acceleration. A special electron beam transfer line with adequate diagnostics has been designed for this project. Strong-focusing variable-field permanent magnet quadrupoles, energy de-mixing chicane and a set of conventional quadrupoles condition the electron beam before its entrance in an in-vacuum U20 undulator. This article describes some of the features incorporated into the design of the magnets, girders, vacuum chambers and diagnostic equipment for this experimental machine. Progress on the equipment preparation and installation is presented as well.

INTRODUCTION

When a short multi-TW laser pulse propagates through a gaseous medium, it drives strong plasma waves in its wake. The electric field generated by these plasma waves can exceed by few orders of magnitude those technically achievable with conventional linear accelerators. This accelerating technic is called Laser Wakefield Accelerator (LWFA) [1, 2].

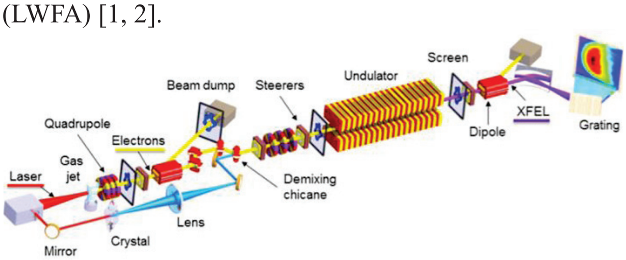

Figure 1: COXINEL's schematic layout.

Using LWFA to operate a Free Electron Laser (FEL) remains very challenging. Among others projects [3, 4] COXINEL aims at using a LWFA to drive an FEL, taking advantage of a specific design of the transfer line to handle divergence and energy spread [5]. The key concept relies on an electron beam longitudinal and transverse manipulation in the transport towards an undulator: a set of strong quadrupoles handles the large divergence of the electron beam and then a "demixing" chicane sorts the electrons in energy and reduces the slice energy spread [6, 7] (see Figure 1).

EXPERIMENT HALL

The experiment hall, called "Salle jaune", is located in "Laboratoire d'Optique Appliquée (LOA)" in Palaiseau, 10 km far from SOLEIL synchrotron site.

The hall is partially covered by a one-tonne crane, which is not sufficient for transportation of the main girders. Some architectural modifications have been performed in the hall in order to free more space for COXINEL installation. Although, there is only 11 meter available between the electron source and the hall's wall. This limited space imposed some trade-off in the choice of installed devices as well as the assembly and alignment sequences. Each different device has been characterized independently and installed on its girder prior to shipping and installation on the LOA site.

GENERAL LAYOUT AND INSTALLATION

Furthermore, all the main components will be presented starting from the electron source down to the final detector following the electron beam direction. A 3D view of COXINEL installation generated by CATIA is presented in Figure 2.

Electrons are produced by one of the two powerful 60 TW laser beam of the LOA "salle jaune laser". The laser beam is focused in a gas jet located in a dedicated chamber called LWFA vacuum chamber. Three permanent magnet variable-gradient (up to 200 T/m) quadrupoles, so called QUAPEVA, placed near to the source inside the LWFA chamber focus strongly the beam. Each QUAPEVA has its independent motorized adjustment table in Z and X directions.

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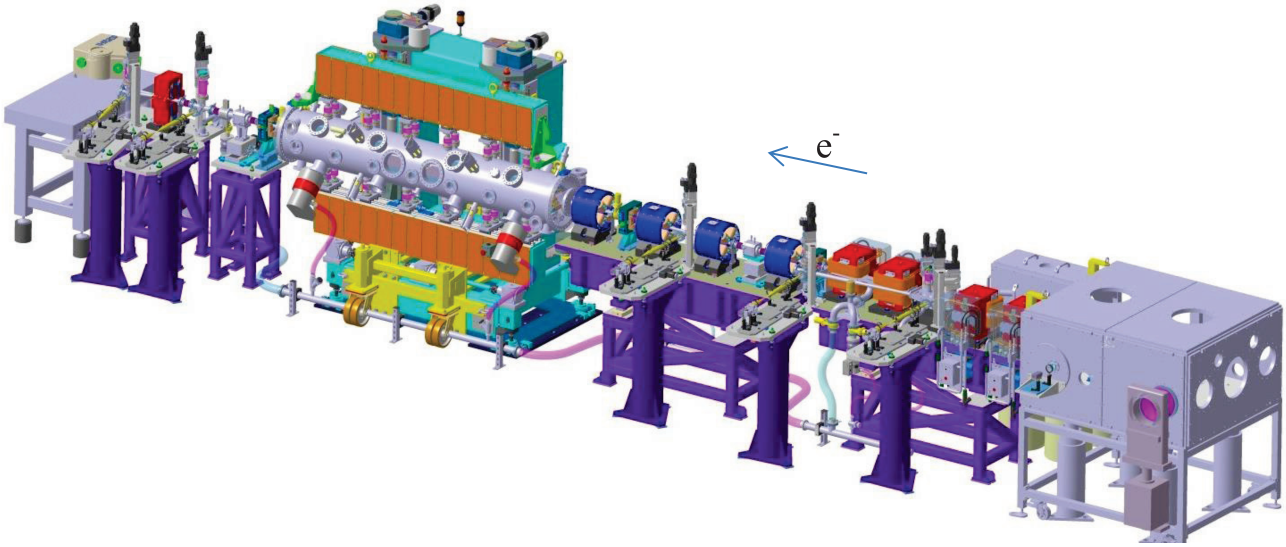

Figure 2: From right to left following the electron beam: LWFA vacuum chamber, magnetic chicane dipoles (in red), quadruplet of quadrupoles (in blue), U20 undulator, beam dump dipole (red) and the spectrometer.

An integrating current transformer (ICT) from BERGOZ is located after the QUAPEVAs inside the LWFA chamber for electron beam charge measurements. The electrons pass then through the first steerer. In order to keep the transport line as compact as possible, the exit panel on the LWFA vacuum chamber has been modified creating an hollow cylinder in which the steerer as well as a gate valve have been installed (see Figure 3).

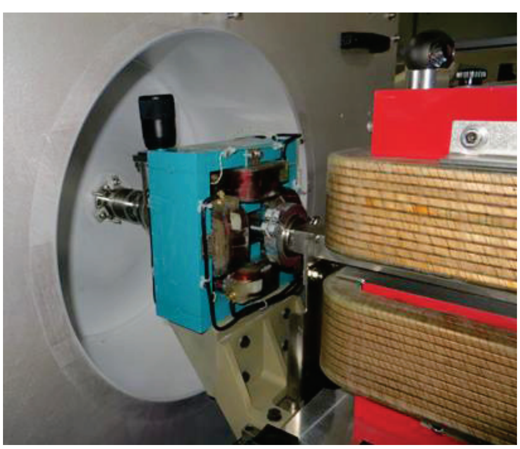

Figure 3: The first steerer and vacuum separation gate valve installed inside the LWFA hollow panel.

The magnetic chicane is composed of four water-cooled and variable field dipoles. Key parameters of chicane dipoles are presented in Table 1.

Table 1: Chicane Dipole Parameters

Parameter	Unit	Value
Gap	mm	25
Yoke length	mm	200
Magnetic field @ 150 A	T	0.55
Technology		Water cooled

A first design of air cooled dipole led to excessive coil heating. The design was then renewed to a water-cooled version, enabling also to get more compact components (see Figure 4). The dipoles are mounted on the top of the girder with calibrated shims, allowing magnets to be fixed in position, height and roll to meet the specifications. This girder has been fabricated by ALSYOM. The positioning precision of each dipole with respect to the beam axis shall not exceed 25 microns.

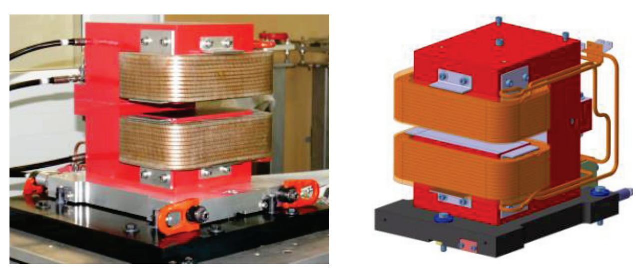

Figure 4: 3D model (right) and fabricated chicane dipole (left).

In total, five imagers are actually installed on the COXINEL transfer line, a sixth one will be added in a near future for the next run. Imager 2 and 3 are placed in the middle of the chicane off-axis for energy and energy spread measurement (see Figure 5). Different screens of 1” size, mounted on a motorized arm at 45°, intercept the beam. The extracted light through a window is imaged via lenses onto a CCD camera.

The second and third dipoles are shifted laterally by 16 mm with respect to the beam axis. This permits the use of the most uniform part of dipolar magnetic field for the deviated electron beam. The first and second dipole pairs are installed in a face to face configuration in order to ease the access to diagnostic elements installed in the

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middle of the chicane. A second steerer is installed on the same girder as the magnetic chicane at the exit side (see Figure 6).

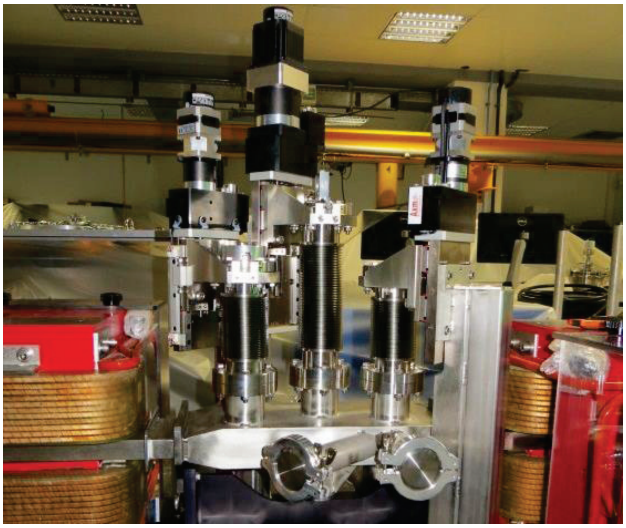


Figure 5: Diagnostic equipment in the middle of magnetic chicane.

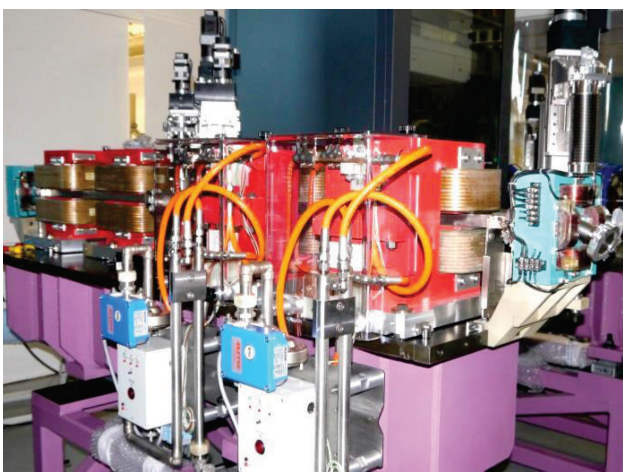


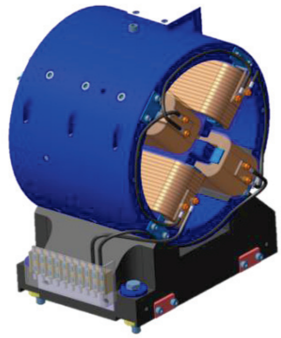
Figure 6: Magnetic chicane and steerers.

After the magnetic chicane and the second steerer, a set of 4 quadrupoles is installed on an independent girder, also manufactured by ALSYOM. These electromagnetic and air-cooled quadrupoles have been measured by SOLEIL's stretched wire bench in the magnetic measurement Lab (Table 2).

Table 2: Quadrupole Parameters

Parameter	Unit	Value
Bore diameter	mm	24
Yoke length	mm	200
Maximum gradient	T/m	20
Technology		Water cooled

Dimensions for the height and thickness of shim packs used to position the magnet on the girder are defined at this stage. The general view of the quadrupole is shown in Figure 7. The quadrupoles are aligned with respect to the beam axis with a precision of 20 microns. The reference axis has been defined using a laser tracker and some fiducial references were taken for all magnetic elements on the magnetic measurement benches and reported on the LOA site.



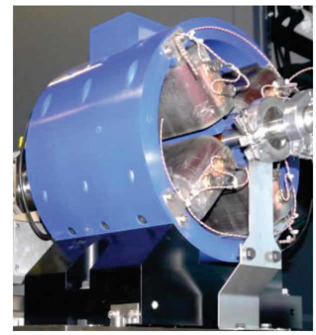


Figure 7: 3D model (left) and produced quadrupole (right).

The space between the quadrupoles has been used optimally in order to keep the installation as compact as possible. Thus, the cavity BPM (cBPM), the Imager 4 as well as the pre-undulator steerer are placed in between the quadrupoles on the same girder (see Figure 8).

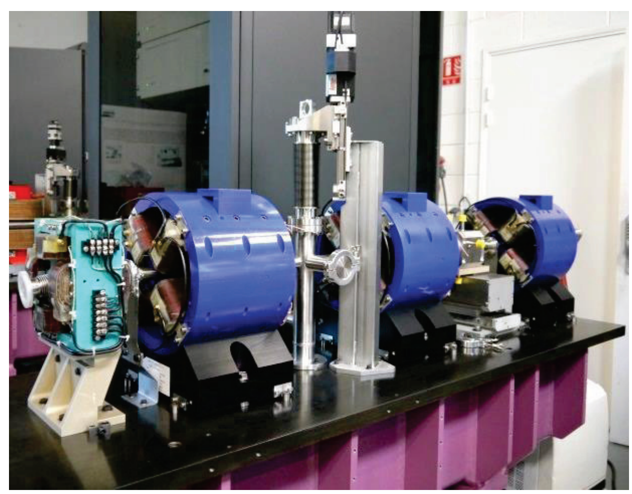


Figure 8: Quadrupole girder including the cBPM, Imager 4 and pre-undulator steerer.

For the first phase of COXINEL experiment, a SOLEIL's spare in-vacuum U20 undulator has been used. Table 3 presents the parameters of this undulator.

Working usually under storage ring vacuum conditions (~10^{-9} mbar), the pumping system has been modified for COXINEL needs. All ion pumps as well as Titanium Sublimation pumps (TSP) have been disassembled and replaced by two 300 l/s PFEIFFER turbomolecular pumps with magnetic levitation rotors in order to reduce as much

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as possible the impact of pump vibration on the stability of the undulator (see Figure 9).

Table 3: U20 In-vacuum Undulator Parameters

Parameter	Unit	Value
Magnetic period	mm	20
Magnetic length	mm	1950
Minimum gap	mm	5.5
Peak field	T	1.5
Magnet technology	-	$Nd_2Fe_{14}B$

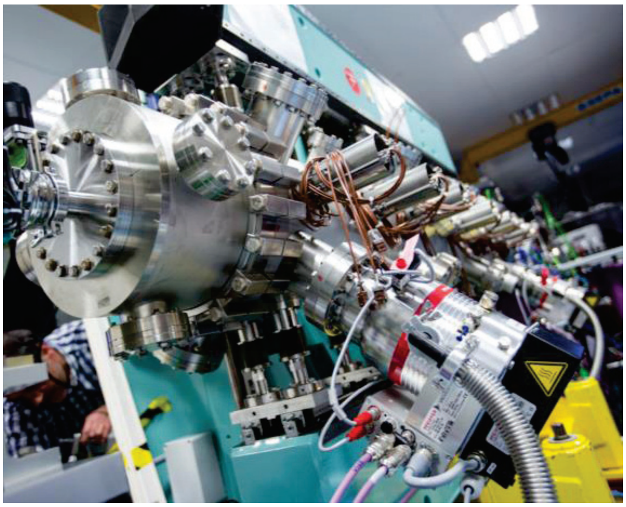

Figure 9: SOLEIL U20 in-vacuum undulator equipped with turbomolecular pumps.

An U20 in-vacuum undulator weights around 4 tonnes. Special transport tooling with retractable wheels has been developed in order to run the whole carriage on the floor without using the crane (see Figure 10). BOVIS Company had in charge the undulator transportation between SOLEIL and LOA experiment hall.

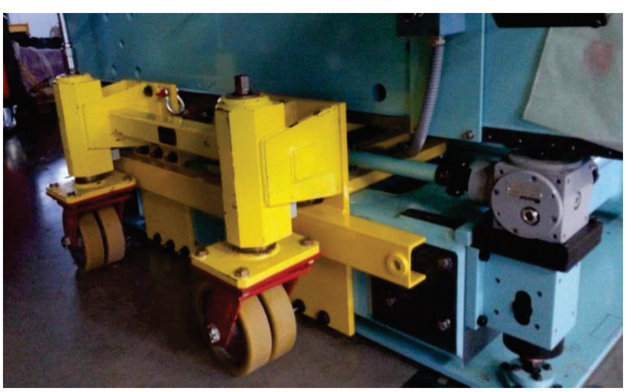

Figure 10: Special transport tooling for in-vacuum undulator.

An R&D program on the construction of a cryo-ready undulator is under way in the frame of a French-Swedish collaboration agreement. The choice of the period has been studied regarding its use on both LUNEX5 and SOLEIL 2.75 GeV storage ring. The use of a specific grade of $Pr_2Fe_{14}B$ with poles in Vanadium-Permendur enables operation both at room temperature and at 77 K. (Table 4). This U15 undulator will replace the U20 on the COXINEL layout in medium term.

A Stripline is also under study and it will be installed at the exit of the U20 undulator even if it will have to be removed when the 3m cryo-ready U15 undulator is ready because of a lack of space.

The following devices are placed directly after the undulator: 4th steerer, ICT-2, cavity BPM-2 and Imager 5 (see Figure 11 and Figure 12). A spectrometer for the spontaneous emission and Free Electron Radiation characterization is also installed at the exit of the undulator [8, 9].

Table 4: U15 Cryo-ready Undulator Parameters

Parameter	Unit	Value
Magnetic period	mm	15
Magnetic length	mm	3000
Minimum gap (COXINEL)	mm	3
Magnet technology	-	$Pr_2Fe_{14}B$
Peak field @ 239K	T	1.53
Peak field @ 80 K	T	1.67

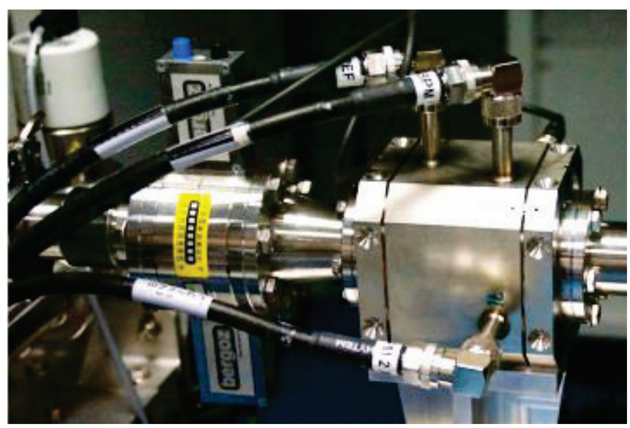

Figure 11: ICT-2 and cavity BPM-2 at the exit of the undulator.

A permanent magnet dipole enabling a 1 T field for deflecting the electrons towards the dump is under measurement at SOLEIL's magnetic lab for the next phase of the installation. An overview of all installed devices is shown in Figure 12.

COXINEL's general vacuum system is composed by a primary circuit all along the line and four PFEIFFER turbomolecular pumps at different locations: two (80 l/s) on the chicane girder, one (80 l/s) on the quadrupoles girder and one (80 l/s) at the end of the line. The vacuum level in the transfer line is about 10^{-5} mbar whereas in the

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LWFA chamber, it is a few 10^{-3} mbar. The U20 undulator has its own independent pumping system.

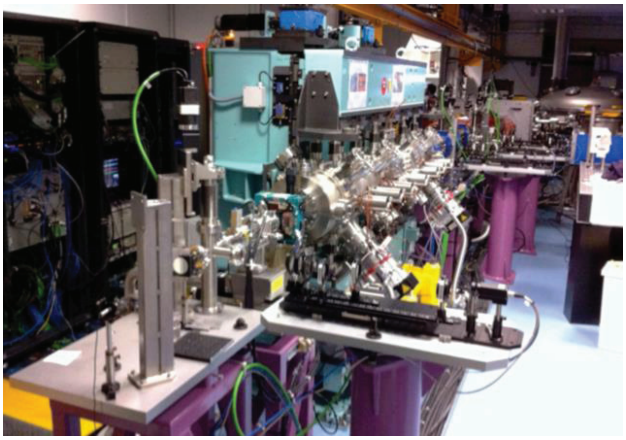

Figure 12: COXINEL installed in LOA's "Salle jaune".

CONCLUSION

The COXINEL LWFA-FEL line is assembled in LOA experiment hall and is operational since February 2016. Since all the equipment had already been tested and pre-aligned at SOLEIL before shipping to LOA, the installation has been done only in few days.

Because of some parallel experiments in the LOA's experiment hall, only few weeks of data collection could be performed since the installation. The LWFA electron beam has been successfully transported through the line. The preliminary results are encouraging for the pursuit of this experiment. Next series of tests and data collection will be performed before the end of this year [5].

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