EXPERIMENT PREPARATION TOWARDS A DEMONSTRATION OF LASER PLASMA BASED FREE ELECTRON LASER AMPLIFICIATION

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Abstract

One direction towards compact Free Electron Laser is to replace the conventional linac by a laser plasma driven beam, provided proper electron beam manipulation to handle the value of the energy spread and of the divergence. Applying seeding techniques also enables to reduce the required undulator length. Rapidly developing Laser Wakefield Accelerators (LWFA) are already able to generate synchrotron radiation. With the presently achieved electron divergence and energy spread an adequate beam manipulation through the transport to the undulator is needed for FEL amplification. A test experiment for the demonstration of FEL amplification with a LWFA is under preparation in the frame of the COXINEL ERC contract in the more general context of LUNEX5. Electron beam transport follows different steps with strong focusing thanks to variable strength permanent magnet quadrupoles, demixing chicane with conventional dipoles, and a second set of quadrupoles for further focusing in the undulator. Progress on the equipment preparation and expected performance are described.

INTRODUCTION

More than 30 years after the first Free Electron Laser (FEL) [1], FEL based fourth generation light sources [2] presently offer femtosecond tuneable radiation in the X – ray domain with LCLS in USA [3], SACLA in Japan [4] and in the VUV- soft X-ray with FLASH in Germany [5] and FERMI in Italy [6]. FEL oscillators being limited to VUV [7], single optical pass FEL devices are preferred for short wavelength operation. After the first coherent harmonic generation experiments [8], seeding has demonstrated major advantages in terms of spectral purity [9-12]. Besides the preparation of additional FEL light sources for users around the world, new schemes are also under investigation. In view of the fifth generation light sources [13], several approaches are considered. One direction goes towards the improvement of FEL performance in a wide spectral range and with versatile properties and flexibility for users. Another one aims at reducing the size either by exploring further seeding and / or by replacing the conventional linear accelerator by a compact alternative one. Indeed, the rapidly developing Laser WakeField Accelerator (LWFA) [14, 15] are now able to generate synchrotron radiation [16]. With an electron divergence of typically 1 mrad and an energy spread of the order of 1 %, an adequate beam manipulation through the transport to the undulator is required for FEL amplification. Different strategies have been proposed, such as a decompression chicane [17], or a transverse gradient undulator [18].

The studies presented here take place in the context of the LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) collaboration, aiming at investigating the production of short, intense, coherent pulses in the 40-4 nm spectral range [19] with a 400 MeV superconducting linac and a LWFA both connected to a single FEL for advanced seeding configurations. Both accelerators are complementary: The conventional linac will enable studies of advanced FEL schemes, future upgrade towards high repetition rate and multi-user operation. The LWFA has first to be qualified by the FEL application. LUNEX5, after the completion of a Conceptual Design Report [20], is presently in a phase of R&D and complementary studies. In this frame, after transport calculation of longitudinal and transverse manipulation of a LWFA electron beam showing that theoretical amplification is possible, a test experiment is under preparation, with the support of different grants.

GENERAL DESCRIPTION

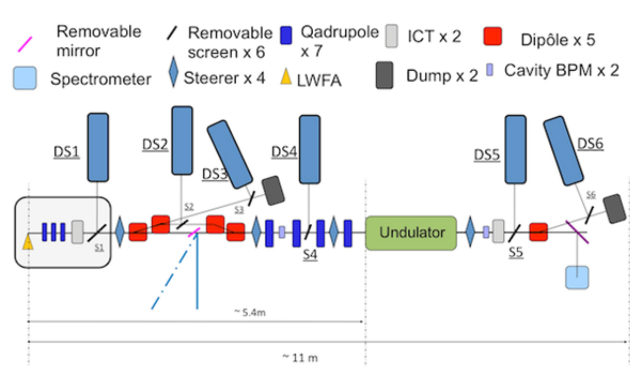

Figure 1: Scheme of the main components.

COXINEL grant aims at demonstrating FEL amplification with a LWFA. First, it intends to provide an appropriate electron beam transport from the source to the

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undulator. Typical electron beam parameter sets are considered at 400 MeV : a 1 π mm.mrad emittance with a beam size of 0.75 µm and a divergence of 1 mrad, a bunch duration of 3 fs and an energy spread of 1%, a bunch charge of 30 pC, leading to a peak current of 4 kA. The key concept relies on an electron beam longitudinal and transverse manipulation in the transport towards an undulator: a set of strong quadrupoles handle the large divergence of the electron beam, then a "demixing" chicane sorts the electrons in energy and reduces the spread from 1 % to a slice energy spread of 0.1 % and finally the transverse density is maintained constant all along the undulator (supermatching) by a proper synchronisation of the electron beam focusing and the progress of the optical wave along the undulator [21]. Calculations are carried out for an ultimate 40 nm wavelength and a 400 MeV electron beam. First tests will be performed at 200 nm with a 180 MeV electron beam, and a U20 undulator.

For this purpose, a transport line has been designed to be as compact as possible, as shown in Fig. 1. It comports a first set of strong permanent magnet based variable quadrupoles to handle the large electron beam divergence, a chicane with four dipoles for the electron beam decompression, a second set of four quadrupoles, an undulator, a beam dump dipole, and a series of diagnostics: two cavity BPMs (before and after the undulator), screens for the beam profile [22] and charge monitors.

THE ELECTRON SOURCE

Electrons are produced by an intense 2 x 60 TW laser of the "Laboratoire d'Optique Appliquée (LOA)" focused in a gas jet located in a dedicated chamber. The development of the best LWFA parameters for the FEL application is performed in the frame of the X-Five grant.

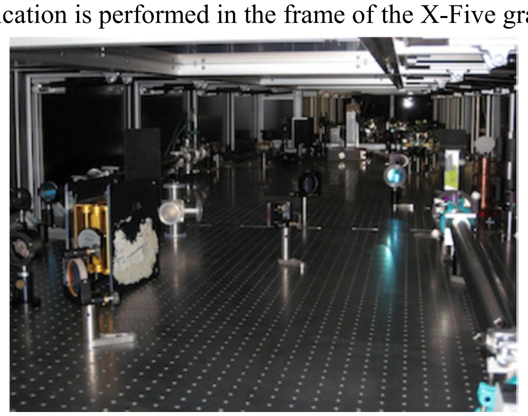

Figure 2: Picture of the LOA laser system.

THE TRANSPORT LINE

The equipment of the transport line is under preparation at Synchrotron SOLEIL.

The First Triplet of Highly Focusing Permanent Magnet Quadrupoles of Variable Strength

A gradient of 200 T/m is required, with an adjustment of the strength. Considering a bore diameter of 10 mm electromagnetic technology can't be employed. In this scope, the design of a permanent magnet quadrupole with variable strength for the focusing of the LWFA diverging electron beam is presently finalised in the frame of the "Triangle de la Physique / Valorisation" QUAPEVA contract in collaboration with Sigmaphi company.

The Decompression Magnetic Chicane

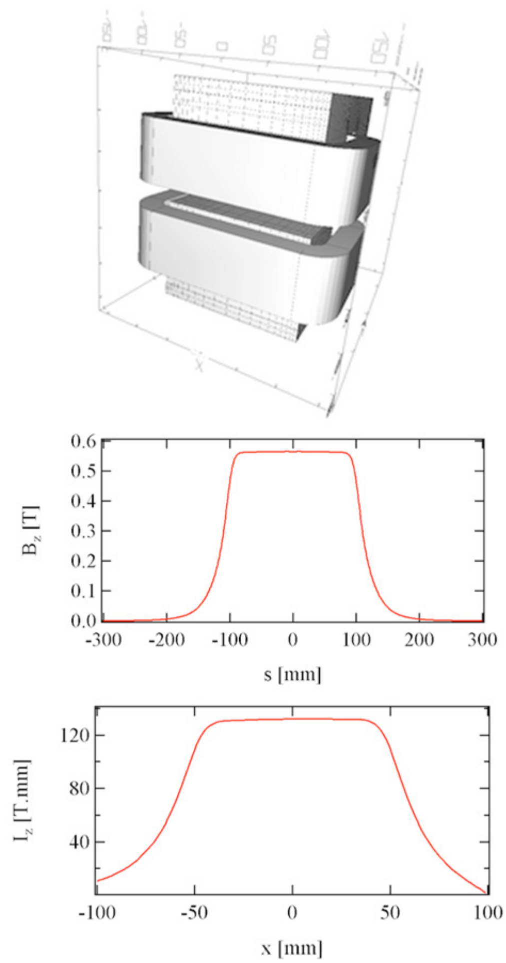

Figure 3: RADIA calculation of the chicane dipole: model, magnetic field versus longitudinal coordinate, field integral versus transverse direction. Gap: 25 mm.

The chicane is composed of four dipoles of 0.565 T for a 25 mm gap, on axis field integral of 132 T.mm enabling a 99 mrad deviation. The dipoles are variable and compact. A first design of air cooled dipole led to a coil heating. The design was then renewed to a cooled version, enabling also to get more compact components. The dipoles have been modelled both under TOSCA [23] and RADIA [24] software, as shown in Fig. 3. The power supplies of the dipoles provide 150 A, 8 V.

The beam pipe encloses the additional radial orbit displacement of 32 mm. In the chicane some diagnostics and the seeding mirror will also be installed, as shown in Fig. 4. They include a stopper for the infra-red laser generating the electrons, an electron beam profile monitor, a screen for the measurement of the electron beam energy. There is a special port for entering the seed laser with two possible angles, for either the 200 nm or the 40 nm seeding wavelengths.

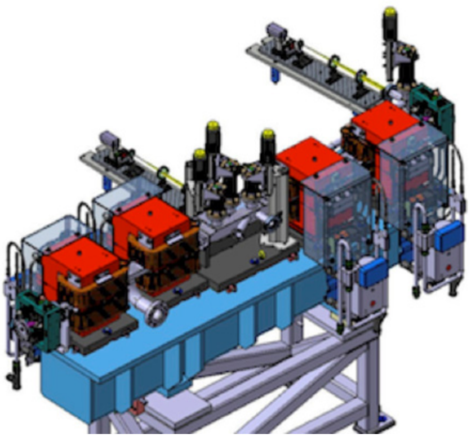

Figure 4: Catia view of the magnetic chicane with the seeding port and the diagnostics.

The Steerers

Two steerers (see fig. 5) are located at the entrance and at the exit of the chicane. They provide a 350 G magnetic field in both horizontal and vertical directions. The steerer power supply provides 10 A, 10 V.

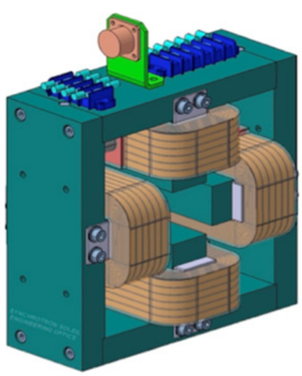

Figure 5: View of the beam transport steerers.

The Second Set of Quadrupoles (Quadruplet)

The quadrupoles are electromagnetic, air-cooled. The quadrupoles are modelled in TOSCA. They provide a 20 T/m gradient. The general view of the quadrupoles is shown in Fig. 6.

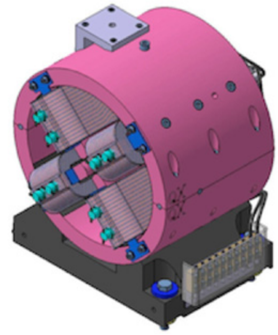

Figure 6: View of one air-cooled quadrupole.

THE FEL LINE

Figure 7: Example of SOLEIL U20 in-vacuum undulator.

Table 1: Characteristics of the Undulators

Characteristic	Unit	U20	U15
Period	mm	20	15
Technology		under vacuum	under vacuum, cryogenic
Permanent magnets		$Nd_2Fe_{14}B$	$Pr_2Fe_{14}B$
Poles		Vanadium-Permendur	Vanadium-Permendur
Number of periods		98	200
Minimum gap	mm	5.5	3
Peak field at 293 K	T	1.05	1.53
Peak field at 77 K	T		1.67
Deflection parameter (293 K)		1.96 at 293 K	2.4 at 77 K
Magnetic length	m	2	3

The FEL line comprises first the undulator with two beam steerers and two cavity BPM (of SwissFEL type [25]). Two different undulators will be used with first, a 2-m long typical U20 in-vacuum undulator of SOLEIL and then, a 3 m long cryo-ready undulator U15 (see Table

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1 and Fig.7) thanks to the development of an existing U18 cryogenic undualtor at SOLEIL [26].

A R&D program on the construction of a cryo-ready 3 m long 15 mm period undulator is under way in the frame of a French-Swedish collaboration. The choice (see Fig. 8) of the period has been studied regarding its use both for LUNEX5 -either with the superconducting linac or with the LWFA- and for its use on the 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. The module scheme has been modified for using half-poles, enabling an easier swapping.

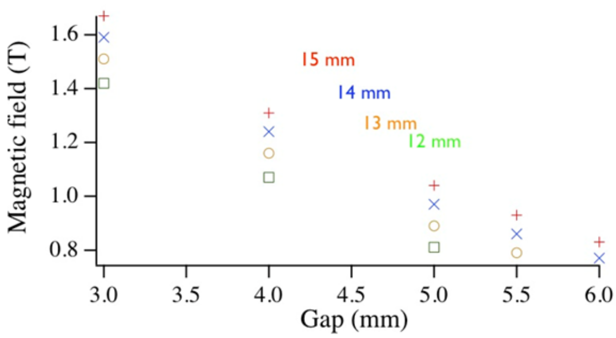

Figure 8: Peak magnetic field versus gap and period in the case of the cryogenic undulator.

A dipole, similar to the chicane one, will be pushed to higher current, providing a 1 T field for deflecting the electrons towards the dump.

A spectrometer for the spontaneous emission and Free Electron Radiation is under study. It will be installed at the exit of the undulator.

A resonant stripline BPM is also under study and it will be installed in the case of the 2 m undulator.

The general integration of the transport and FEL lines is shown in Fig. 9. The whole set occupies a length of the order of 11 m. For limiting the length, the cavity BPM and the steerer at the entrance of the undulator have been located inside de quadruplet of quadrupoles. Three pumping stations will also be installed (typically one in the chicane, one on the seeding port and one between quadrupoles of the second set).

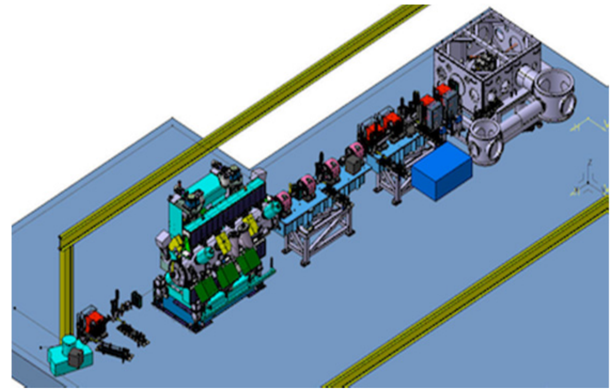

Figure 9: CATIA general integration view of the COXINEL LWFA demonstration set-up. General view of the COXINEL LWFA demonstration set-up (from right to left) : LWFA chamber (grey) with the first set of quadrupoles and a current beam transformer, magnetic chicane (red), quadruplet of quadrupoles (pink), undulator (case of 2 meter U20 undulator), dipole for beam dump (red), spectrometer (blue).

CONCLUSION

The preparation of the test experiment for a demonstration of LWFA based FEL amplification is in progress. Each different piece of equipment will be characterised independently prior to installation on the LOA site. Besides, tolerance and sensitivity parameters calculations are carried out in parallel.

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