LUNEX5 : A FEL PROJECT TOWARDS THE FIFTH GENERATION IN FRANCE

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Abstract

LUNEX5 (free electron **L**aser **U**sing a **N**ew accelerator for the **E**xploitation of **X**-ray radiation of **5**th generation) aims at investigating the production of short, intense, and coherent pulses in the soft x-ray region (down to 7 nm on the fifth harmonic). It consists in a free electron laser in the seeded configuration (High order Harmonic in Gas seeding and Echo Enable Harmonic Generation) using a Conventional Linear Accelerator (CLA) of 300 MeV. The FEL beamline includes a 15 m in vacuum (potentially cryogenic) undulator of 15 and 30 mm period and is designed also in order to accommodate a Laser Wake Field Accelerator (LWFA) ranging from 0.3 to 1 GeV, relying on electron beam parameters produced and accelerated by either the 60 TW laser of LOA or by the 10 PW APOLLON laser of ILE (Institut de Lumière Extrême).

INTRODUCTION

Recent advances of Linac based fourth generation light sources already provide intense coherent femtosecond pulses in the x-ray range at LCLS [1] and SACLA [2]. Transverse coherence results from the electron beam emittance and the temporal one from the Free Electron Laser (FEL) process. In the SASE configuration [3], the uncorrelated trains of radiation resulting from the interaction of electrons progressing jointly with the previously emitted spontaneous radiation lead to spiky longitudinal and temporal distributions, unless low charge regime allows single spike operation [4]. Seeding with an external laser or a short wavelength coherent light source, such as High order Harmonics generated in gas, allows the saturation length to be shortened, the jitter to be reduced, and the longitudinal coherence to be improved [5, 6, 7]. The Echo Enable Harmonic Generation scheme with a double electron–laser interaction can push the spectral range towards shorter wavelengths when operating on a high order harmonic of the seed wavelength [8, 9, 10].

Besides, Laser Wakefield Accelerator field (LWFA) is rapidly progressing: by using intense laser beams interacting with plasmas, they can provide today high quality energetic particle beams in extremely short bunches (of a few fs) with very high peak currents (of a few kA) [11]. These rather compact accelerators rely on intense longitudinal electric fields in a plasma medium (the electric field in the plasma being more than 10,000 times greater than the electric field generated in RF cavities). In addition to be interesting for the next generation of colliders (upon the BridgeLab initiative [12]), LWFA also appear as attractive candidates for future compact light sources and FELs [13, 14] with GeV electron beams, providing thus an intermediate goal before TeV LWFA colliders of interest in the long term future of high energy physics. Spontaneous emission from electron beams produced by Laser Wake Field Acceleration has already been observed [15, 16] and recent improvements of the electron beam characteristics make them almost suitable for achieving FEL amplification. Programs on generating SASE based FEL with LWFA are under way in Berkeley (OASIS) [17] Stratclyde Univ. [18] and in MPQ Germany [19].

LUNEX5 OBJECTIVES AND PHASES

LUNEX5 aims at investigating the production of short, intense, and coherent pulses in the soft x-ray region with fourth generation light source (4GLS) based on a Conventional Linear Accelerator. LUNEX5 is also oriented towards probing the potentialities of a so-called 5th generation light source (5GLS), using a 0.3-to-1 GeV Laser Wake Field Accelerator and seeded FELs.

The project will be split into two phases:

Phase 1 (5 years) corresponds to the development of seeding schemes (HHG seeding and EEHG) of a fourth generation light source (4GLS) on the 300 MeV CLA and the FEL radiation characterisation. Performances will be discussed with the user community. In view of preparing the 5GLS, the FEL beamline is designed to be adapted to the LWFA by taking into account the parameters of the “salle jaune” 60 TW lasser and of the 10 PW APOLLON laser in the frame of the CILEX EQUIPEX. Possible experimental tests using undulator sections are also envisaged. Indeed, FEL calculations codes and modelling will also be adapted to treat the specificities of LWFA, such as extremely short electron bunches for instance. A particular attention will be paid to the impact on the seeded FEL characteristics played by the slightly higher value of emittance and energy spread on LWFA with respect to those of the CLA. The transport beamline to the undulators will be optimized in particular for preserving the extremely short electron bunch duration. The CLA will also be used to mimic the LWFA performances in reducing the charge and the electron bunch duration. FEL physics studies (pulse splitting, super-radiance…) will be carried out.

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Phase 2 will first consist in using the FEL 4GLS radiation to pilot user experiments, for the study of the excitation and decay dynamics of isolated atoms and molecules and the dynamics of magnetisation in solids. The FEL beamline (seeding laser, electron beam diagnostics, undulators, X-ray beamline including the monochromator) will be then alternatively employed on the CLA and on a LWFA. When the CLA will be without FEL line, it can be used for the characterisation of accelerator equipments (in relationship with the Laboratory of Excellence "Physics of the 2 infinites and the origin" P2IO). The FEL line, when coupled to the CLA, will be open to user operation for the new proposals emerging during the first phase. It will also enable an easy access for the preparation of experimental techniques for applications on hard X-ray FEL, with a limited access. FEL physics and improvements will also be conducted.

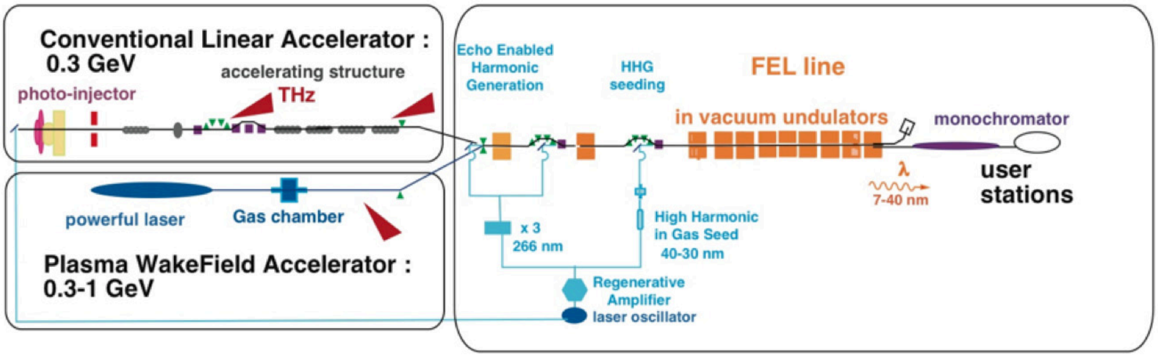

Figure 1: Scheme of LUNEX5 project.

LUNEX5 DESCRIPTION

LUNEX5, the schematic of which is shown in fig. 1, is composed of a 300 MeV CLA, and of a Free Electron Laser beamline, including its undulators. Aiming at further investigating the most recent FEL schemes (seeding with High Order Harmonics in Gas (HHG) and echo enable harmonic generation) as alternatives to SASE, LUNEX5 will provide up to 0.1 GW fundamental radiation in the 40-80 nm with 50 fs or shorter pulse duration, with radiation down to 7 nm on the fifth harmonic of the radiator. The FEL part will integrate leading edge technology short period undulators (potentially cryogenic), chicanes for EEHG, and will deliver x-ray beam to a beamline equipped with a monochromator and an experimental station.

300 MeV Conventionnal Accelerator (CLA)

In the reference case, the LUNEX5 Linac will be composed of a high quality S-Band photo-injector [20, 21, 22] followed by a 150 MeV pre-accelerator based on 3 S-band 3 GHz THALES RF sections, leading to an emittance of about 1 π mm.mrad to a peak current of about 100 A. In order to increase the peak current, the pre-accelerator is followed by an X-band third harmonic cavity and a magnetic chicane. This combination allows a smooth and uniform compression of the bunch length to reach about 500 to 1000 A peak without drastic emittance degradation. An additional set of 3 S-band THALES RF sections completes the acceleration up to 300 MeV, for an overall length of about 35 m. In the reference implementation in the SOLEIL booster arena, the remaining straight space being too short to accommodate both undulators and the beam-line sections, a U-turn section is then necessary giving the benefit of another parallel 50 m for the undulators and beam-line sections. The present two other options under study are the use of superconducting X-FEL type 1.3 GHz cryomodules, or C-band structures, allowing the Linac length to be minimised. Magnets and power supplies are standard components.

Laser Plasma Wakefield Accelerator (LWFA)

The FEL beamline is optimised with estimated performances, which will be updated according to the progress achieved upon the R&D programs under way in France (in particular, at LOA and in the frame of CILEX, where will be explored the laser and plasma conditions to achieve the most suitable electron beam parameters for FEL experiments). The quality of the electron beam depends crucially on the laser beam parameters (energy, spatial shape) and repetition rate. The colliding laser pulse scheme is adopted. The designed experimental area will be fully equipped (vacuum chamber, optics for the two laser beams, fully motorized optics under vacuum, pumping system) to achieve the generation of a very stable electron beam.

FEL Line

The **undulators** with 15 or 30 mm periods are in vacuum ones, with a cryogenic option relying on the SOLEIL experience with the development of the U20 hybrid in vacuum undulators, or the U18 cryogenic undulators [23]. The performances in terms of magnetic field are shown in fig. 2, comparing a room temperature NdFeB based in vacuum undulator and a PrFeB magnets based cryogenic undulator operated at 77 K. The cryogenic undulators enable achieving higher magnetic field for short wavelength operation.

The **High Harmonic in Gas source** consists in the chambers built for the HHG seeding test on SCSS Test

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Accelerator [24]. The Ti-Sa laser source will be shared between the gun, with a dedicated regenerative amplifier, and the EEHG with a tripling, after the same regenerative amplifier as for the HHG seeding. Magnetic chicanes and doglegs will be built for seed injection and EEHG.

The **Monochromator** will be of the modified Petersen type developed at SOLEIL and based on the properties of Varied Line Spacing/ Varied Groove Depth gratings (joint Horiba Jobin-Yvon and SOLEIL development).

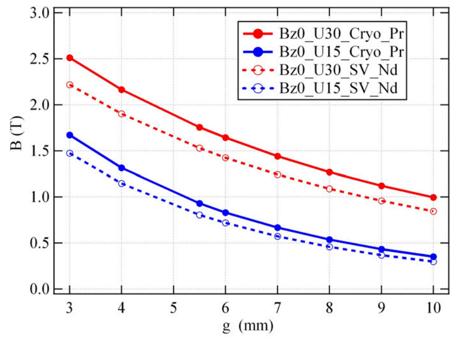

Figure 2: Magnetic field of in vacuum, room temperature, and cryogenic undulator computed with RADIA for U30 (30 mm period) and U15 (15 mm period) versus gap. Case of NdFeB magnets for normal in vacuum (Br= 1.57 T at 77 K, 1.35 T at 21°C), case of PrFeB magnets Br= 1.25 T at 21°C for cryogenic undulator.

Diagnostics

They include combined Yttrium Aluminum Garnet and Optical Transition Radiation screen monitors, 16 Beam Position Monitors or cavity BPMs (resolution better than 3 μm) along the LINAC and between undulators. Four Beam Charge Monitors (Bergoz) provide the charge after the exits of the gun and of the LINAC, after the bend and before the dump. Three wire scanners measure the beam profiles at three points in order to retrieve the LINAC beam emittance. The quadrupole-drift method, using a profile monitor provides the electron beam emittance. The LINAC bunch length is measured using either a dedicated RF vertical deflecting cavity set at zero crossing, or a fast streak camera receiving the undulator light or an electro-optical device using a very short laser pulse. Monitoring the beam profile is achieved in a non destructive way with a Synchrotron Light Monitor. A beam dump, a beam loss monitor and a safety interlock complete this set of diagnostics.

LUNEX5 PERFORMANCES

The first FEL optimizations assume a CLA of 300 MeV, 0.02 % slice energy spread, 2 π mm.mrad emittance in both planes, 400 A peak current and 1 ps bunch length. Fig. 3 shows the peak power calculated with GENESIS [25] using 4 sections of 200x15mm period undulator, with focusing between segments in a FODO lattice, and a HHG seed of 38 nm, 1 kW. Saturation occurs typically after 14 m, whereas in the echo scheme (with a 266 nm laser enabling two laser-electron interactions), the saturation length is reduced significantly to about 3 m [26]. Both configurations cover the 5-80 nm spectral range, with typically 50 fs pulse duration. First calculations with a LWFA (300 MeV, 0.1 %, energy spread, 1 π mm.mrad emittance, 20 fs, 50 pC, HHG seed at 38 nm) and the same undulators lead to saturation after 12 m at 0.2 GW level on the first harmonic. The LWFA enables an easy extension to 1 GeV. With both types of electron beam, THz coherent synchrotron radiation will be generated by the ultrashort electron bunches passing through the bending magnets.

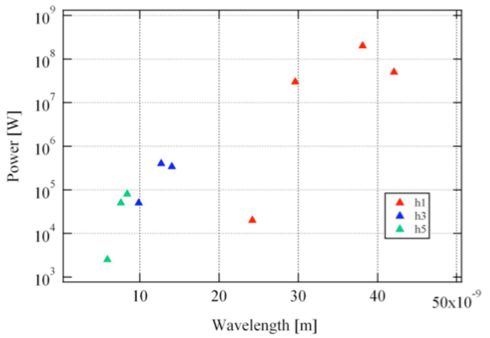

Figure 3: FEL peak power in the HHG seeded configuration calculated with GENESIS in the CLA case on the first (red), third (blue) and fifth (green) harmonic.

LUNEX5 PILOT APPLICATIONS

LUNEX5 has two end stations for time resolved studies of isolated species (TR-AMO) and for condensed matter imaging exploiting the coherence. The TR-AMO end station will consist in a high resolution VG-Scienta electron spectrometer allowing for spectroscopy of cold atoms/molecules, clusters or nanoparticles, issued from a multi-purpose source, to be performed together with the full momentum characterisation of both electrons and ions, the later being measured with an ion momentum spectrometer combining time-of-flight and 2D ion position detection. These spectrometers will be operated in coincidence mode, with the "covariance mapping method" to be developed for vector correlation measurement when the coincidence would fail in case of too many particles to be detected. Time-resolved measurements will be performed by means of pump-probe experiments. For instance the x-ray pulse will excite a dissociative state and an optical fs laser will probe the ro-vibrational state of the fragment. In another scheme, the decay dynamics of an excited atom will be analysed when adding a strong optical laser pulse. The 2nd end station will provide measurements of interferometric patterns on a 2D detector after the coherent beam has been scattered into a thin sample of a few micron size. Lensless imaging technique also relies on very stable setup and accurate algorithms to extract real space images. It is proposed to use an existing mobile setup of LCPMR (presently mounted on SEXTANTS beamline). Magnetization dynamics will be triggered through intense fs laser irradiation, and then probed by x-ray Magnetic linear dichroïc images measurements.

LUNEX5 IMPLEMENTATION

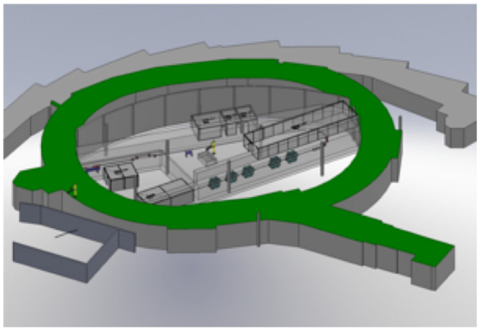

Figure 4: LUNEX5 implementation inside the SOLEIL booster.

In its reference implementation LUNEX5 (see fig. 4) is housed inside the SOLEIL synchrotron building, in a ~1200 m^2 area (25 mx50 m), presently unoccupied at the centre of the Booster tunnel. It requires an additional shielded tunnel, a reinforced shielding inside the booster opposite to the SOLEIL LINAC, a thicker slab for the floor, a handling tool for bringing the equipment inside. The CLA will be built completely independent of the SOLEIL LINAC along the largest diameter of the booster arena (~ 50 m), leaving also fully open the choice of the LINAC technology). A further LWFA would be allocated close to the input of the FEL undulator line for injecting its electron beam directly in the same equipment. The hutch (40 m^2) for the laser feeding the LWFA could be located on the roof of the Booster tunnel. The laser required for the photo injector as well as for the seeding will be housed in a 2nd hutch located also on the Booster roof. Finally the x-ray beamline hutch that will receive the experimental station for the pilot experiments will be installed at the end of the undulator line tunnel. Additionally, 15 m could be added outside, for new applications. Most of the utilities (electrical power, deionised cooling water, chilled water for air conditioning, computer network,..) available nearby, will be supplied into the Booster arena, with a newly built piping distribution inside this arena. Alternative implementation is also considered in the Orme des Merisiers former ALS (Accélérateur Linéaire de Saclay) Tunnel (200 m long, 3 m wide, with shielding) or Hall de Modulateurs (200 m long), in conjunction with the APOLLON laser. It enables an easier coupling with the APPOLON laser for the path towards 5GLS, and the suppression of the U turn for better CLA electron beam performances. A third location could also be envisaged, jointly with the R&D platform of the Pole of P2IO. The SOLEIL installation is presently not classified as a Nuclear Facility Installation (INB). For not entering in this category, the average beam power of the LINAC should be kept below 1 kW, which means, for an energy of 300 MeV, a beam charge less than 3 μC/s. With a 1 nC charge per pulse this would enable a repetition frequency of 3 kHz. Such a high repetition frequency is not required, and operating at 10 or 50 Hz would be sufficient. The 300 MeV beam will have to be stopped in a beam dump and the easiest and cheapest way of implementing it will be to bend the beam trajectory towards the ground and to accommodate the beam dump under the slab. The shielding thickness of the new tunnel to be built will be about 2 m (to be confirmed by radiation computations).

CONCLUSION

LUNEX5 will investigate seeding schemes and prepare the path towards these 5th generation light sources, using Laser Wake Field Accelerators. The Conceptual Design Report is under preparation, with the aim of getting the approval to start a Detailed Design studies.

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