THE STATUS OF LUNEX5 PROJECT

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Abstract

LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) aims at investigating the production of short, intense, coherent Free Electron Laser (FEL) pulses in the 40-4 nm spectral range. It comprises a 400 MeV superconducting Linear Accelerator for high repetition rate operation (10 kHz), multi-FEL lines and adapted for studies of advanced FEL schemes, a 0.4 - 1 GeV Laser Wake Field Accelerator (LWFA) for its qualification by a FEL application, a single undulator line enabling seeding with High order Harmonic in Gas and echo configurations and pilot user applications. Concerning the superconducting linac, the electron beam dynamics has been modified from a scheme using a third harmonic linearizer and a compression chicane to a dog-leg coupled to sextupoles. Besides, the choice of the gun is under revision for achieving 10 kHz repetition rate. A test experiment is under preparation in collaboration with the Laboratoire d'Optique Appliquée, aimed at validating the computed transport performance of longitudinal and transverse manipulation on a LWFA electron beam enabling to provide theoretical amplification.

INTRODUCTION

France has a long history in Free Electron laser, and has obtained the second worldwide FEL on ACO (first visible radiation) in 1983 [1] and first FEL based short wavelength harmonic generation [2]. The Super-ACO FEL, commissioned in 1989 [3], delivered in 1993 the first UV FEL beam [4] to users [5, 6, 7, 8, 9] with first pump-probe two colour experiments. Extensive studies aiming at further understanding the FEL dynamics and at improving its own performance were performed, such as temporal structure [10], short pulse operation [11, 12, 13], interplay with the electron beam [14, 15]. Mirror performance and degradation have been also extensively analysed [16].

An infra-red FEL user facility, CLIO is in operation since 1992 [17].

Considering short wavelength single pass FEL, there have been active collaborations for seeding studies, in particular with high harmonics in gas (HHG) using a 160 nm seed providing radiation down to 27 nm [18] and recently with a 60 nm seed [19] at SCSS Test Accelerator and at SPARC [20]. Short wavelength FEL user facilities (LCLS [21], SACLA [22], FLASH [23] and FERMI [24]) are providing new tools for the investigation of matter.

New researches are going towards exploring how to approach closer the diffraction and Fourier limits in a wide spectral range and with versatile properties. Besides, some other trends are investigating how FEL can become more compact, by seeding schemes and replacing the conventional accelerator by LWFA [25].

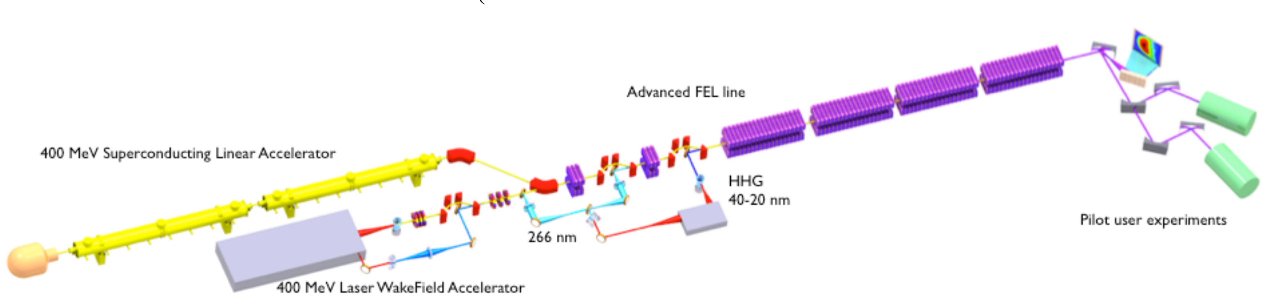

Figure 1: LUNEX5 sketch with two cryomodules (yellow), laser hutch for LWFA (grey), undulators (four radiators and two ECHO modulators) (purple), pilot user experimental sections (green).

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DESCRIPTION OF LUNEX5 DEMONSTRATOR PROJECT

LUNEX5 [26, 27] aims at investigating the production of short, intense, and coherent pulses in the soft X-ray region, using two types of accelerators. On one hand, a 400 MeV superconducting linac will enable a cw operation for high repetition rate and multiple users. On the other hand, a LWFA is also coupled, for qualifying this type of acceleration concept with the FEL TW laserof LOA, before using a dedicated 400 TW laser system. The undulator line will be composed of different cryo-ready undulator segments of 15 and 30 mm period, enabling Echo Enable Harmonic Generation seeding (ECHO) [28] and HHG seeding to be compared. Two pilot user experiments in gas phase and condensed matter are also planned to qualify the FEL performances in the different cases. The LUNEX5 scheme is shown in Fig. 1. The planned spectral range (4-40 nm) from the fundamental, the third and the fifth harmonics is shown in Fig. 2, with CDR electron beam parameters, which are in particular quite optimistic in the LWFA case. On the fundamental wavelength, the FEL radiation ranges between 15 and 40 nm, with a peak power between 10 and 100 MW. With the superconducting linear accelerator, there are more than 10^{11} photons/pulse and 10^{27} peak brightness on the fundamental wavelength.

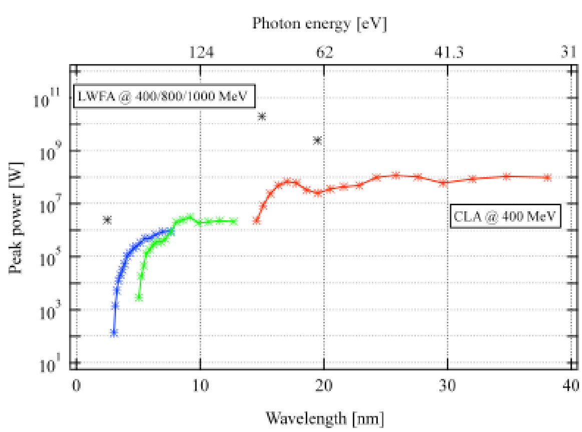
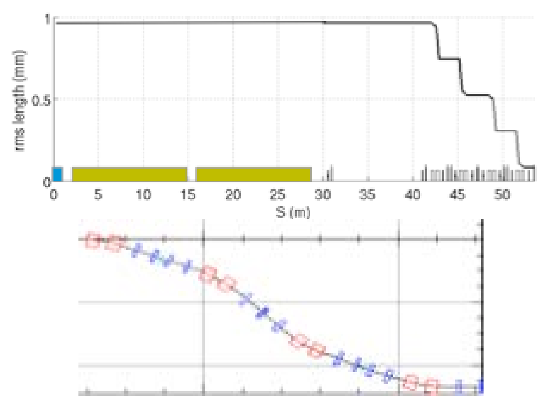


Figure 2: Photon peak power vs energy for a CLA (resp. LWFA) of 400 MeV, with slice energy spread of 0.02 % (resp. 0.1 %), emittance of 1.5 π mm.mrad, peak current of 400 A (resp.10 kA), bunch length of 1 ps (resp. 2 fs).

The conventional accelerator will be a 400 MeV superconducting L-band (1.3 GHz) Linac. It will enable achieving high average current, further upgrading towards CW [29] and multi-user operation. The 12 m long XFEL type cryomodule houses a string of eight 9-cell cavities, each equipped with an adjustable antenna input power coupler, two HOM dampers and a monitoring pick-up; their frequency tuning is ensured by a motor driven mechanism, which changes the cavity length and fast piezo-tuners, for the control of the microphonics. Initially, a pulsed operation (10 % duty cycle, i.e. 100 bunches per macropulse of 500 µs flat-top at 50 Hz repetition rate) of the linac was considered with two cryomodules operating at 24 MV/m (130 W of cryogenic power at 2 K). In the CW operation mode, a third cryomodule will reduce the accelerating gradient from 24 down to 16.5 MV/m, hence keeping the cryogenic load at a reasonable level (< 500 W at 2 K). Each cavity will have its own RF transmitter and LLRF system, for insuring a high stability in phase and amplitude. Solid state amplifiers, capable of delivering up to 20 kW CW at 1.3 GHz, providing modularity and low phase noise, will be developed at SOLEIL. The presently aimed temporal structure, 10 kHz repetition rate is of interest for coincidence, photo-emission and in a longer term, for imaging (Coherent diffraction Imaging). The superconducting linac choice will enable at term to dispatch electrons towards different FEL lines, for a reduced operating cost.

After considering a magnetic compressor combined to a harmonic cavity, a dogleg with sextupoles (Fig. 3a) is adopted. It enables to linearize the phase space, to compress the beam by typically a factor of 10, to increase the peak current and to cancel the second order dispersion (Fig. 3b). It is less versatile but cheaper than the harmonic cavity and chicane scheme.



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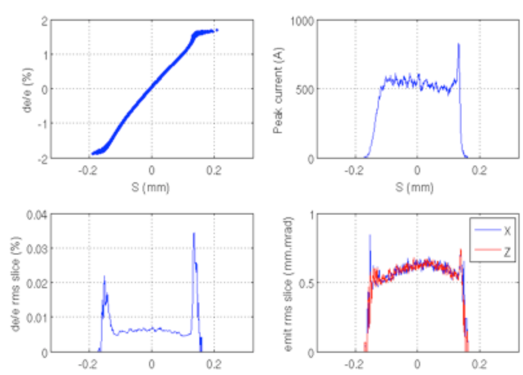

b

Figure 3: a) Scheme of the dogleg b) Energy spread (top left), slice energy spread (bottom left), peak current (top right), slice emittance (bottom right).

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The gun will be either a superconducting one [30] or an APEX type one [31]. The study and test of an elementary RF unit with sc cavity, low level RF and solid state amplifier for CW operation is also under discussion.

The best suitable regime of operation of the LWFA for the FEL application is currently under investigation. One can naturally foresee to operate in the colliding scheme [32, 33] or in the cold injection one [34]. First estimates of optimistic LWFA performance (1 µm transverse size, 1.25 mrad divergence, 1 π mm. mrad emittance, 2 fs duration, 0.1 % energy spread, 20 pC charge, i.e. 4 kA peak current) were first assumed. Now, one considers an electron divergence of typically 1 mrad and an energy spread of the order of 1%. In the transport to the undulator, adequate manipulation of the electron beam phase space is needed to handle the rather large energy spread and divergence.

The FEL line enables different configurations to be studied and compared: echo, HHG seeding [35]. The FEL saturation is generally achieved earlier in the echo case than in the HHG seeding. The FEL is tuned by varying the seeding wavelength and the undulator resonance wavelength, harmonic generation in gas providing a discreetly tunable source from 40 to 15 nm. Further manipulation of the FEL properties such as the two-colour operation, the optical post-compression (FELShaping, OPT2X contracts) are also considered.

LUNEX5 has two end stations for time resolved pump-probe 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, combined with the full momentum characterisation of both electrons and ions (ion momentum spectrometers combining time-of-flight and 2D ion position detection in coincidence mode). 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. Magnetization dynamics will be triggered through intense fs laser irradiation and probed by x-ray magnetic linear dichroïc images measurements.

After the preparation of the CDR, LUNEX5 project is presently under a phase of R&D and complementary studies. Different programs have been funded. Some of them are here further described.

TOWARDS THE DEMONSTRATION OF A LWFA BASED FEL AMPLIFICATION

COXINEL grant aims at demonstrating an appropriate electron beam transport from the source to the undulator. The key concept relies on an innovative electron beam longitudinal and transverse manipulation in the transport towards an undulator: a "demixing" chicane [36] sorts the electrons in energy and reduces the spread from 1 % to a slice one of 0.1 % and the effective transverse size is maintained constant along the undulator (supermatching) by a proper synchronisation of the electron beam focusing with the progress of the optical wave [37]. An example of the baseline implementation is shown in Fig. 4.

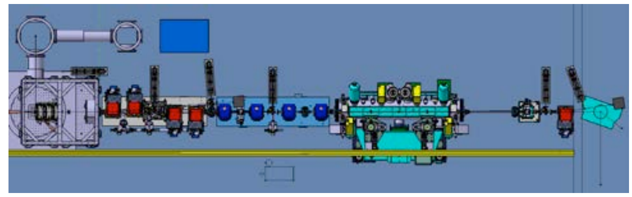

Figure 4: COXINEL transport line scheme.

Equipment is under preparation at Synchrotron SOLEIL. The magnetic design of a permanent magnet quadrupole with variable strength for the focusing of the LWFA diverging electron beam has been proposed in the frame of "Triangle de la Physique" contract QUAPEVA.

Besides, the X-Five grant concerns the optimisation of the LWFA electron beam with a 2x60 TW laser of the Laboratoire d'Optique Appliquée. Coupling both programs enables to prepare a demonstration experiment to observe FEL amplification at 200 nm first and then at shorter wavelength. After successful amplification, further study and potential control of the FEL properties will then follow.

R&D ON A CRYO-READY UNDULATOR

A cryogenic 15 mm period undulator is under design at SOLEIL in collaboration with MAX-LAB. The 3 m long device consists of vanadium-Permendur poles and $Pr_2Fe_{14}B$ magnets. The chosen grade is characterized by a remanence of 1.32 T and a coercitive force of 1900 kA/m at room temperature, leading to an on axis magnetic field peak value of 1.61 T at minimum gap of 3 mm. Once cold at 77 K, the remanence of this material should reach 1.57 T, increasing the undulator field up to 1.77 T at minimum gap. The magnets and poles are fixed on the girders by means of holders, each of them containing one magnet enclosed by two half-poles (see Fig. 5). This design ensures that all the holders are identical, in order to make easier the magnetic optimization steps of the undulator.

The undulator magnetic measurements, which must be performed at 77 K through the small gap of 3 mm and along about 5 m is a critical point. The measurement bench under design consists of a stretched wire and a Hall

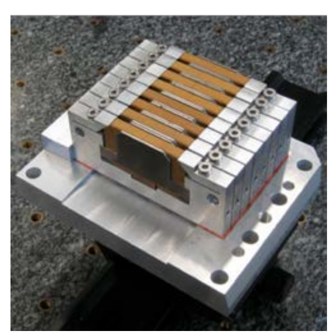

Figure 5: Four period assembly with half-poles.

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probe both installed inside the vacuum chamber. The position and angle of the Hall probe will be controlled by lasers and interferometers and adjusted by piezo-motors in a similar way that the SAFALI system [38].

DEVELOPMENT ON ELECTRO-OPTICAL SAMPLING

The electro-optic detection technique offers the possibility to measure directly, in a non-destructive manner, the shape and the length of individual relativistic electron bunches with a sub-picosecond resolution [39, 40]. The technique relies on the Pockels effect induced by the electric field of a relativistic electron bunch in an electro-optic crystal. The induced birefringence in the crystal is probed using a polarized chirped laser pulse, the temporal pulse shape is retrieved by measuring the optical spectrum of the laser pulse (Fig. 6).

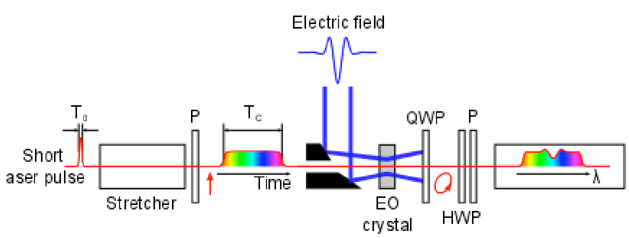

Figure 6: Schematic drawing of spectrally encoded electro-optic detection.

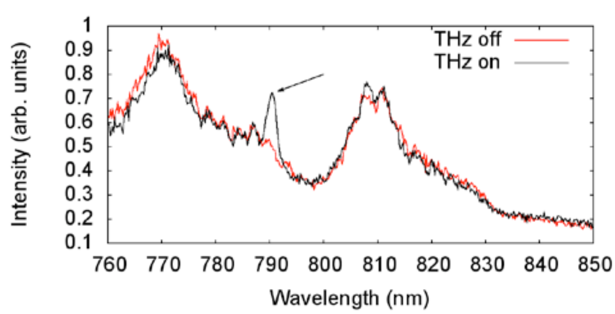

Figure 7: Optical spectrum of the probed laser pulse without (red) and with (black) external electric field in the EO crystal. The arrow indicates the peak corresponding to the THz pulse.

A preliminary experiment was realized at the PhLAM laboratory where a THz pulse was successfully detected in a ZnTe crystal using a 800-nm chirped laser pulse (Fig. 7). This detection technique [40,41] is known as the spectrally encoded electro-optic detection and allows for single-shot recordings of pulse shapes. However, in the future upgrade towards high-repetition rate FELs, single-shot recordings at high acquisition rate (MHz range) will be required and the present classical spectrally encoded technique is limited by the camera speed. Using a novel opto-electronic technique, based on the photonic time-stretch [42,43] well-known in optics and photonics, we demonstrated single-shot recordings up to 88 MHz of CSR pulses on the AILES beamline at Synchrotron SOLEIL [44]. The temporal waveform containing the spectrally encoded signal is stretched in time so that it is slow enough to be detected using a photodetector instead of a spectrometer. This technique enables to overcome the current limitation in acquisition rate of the spectrally encoded electro-optic detection scheme.

CONCLUSION

Some R&D and complementary studies for the LUNEX5 project have been launched. The choice of the superconducting linac is confirmed by the need of high repetition rate operation for scientific application and for multi-FEL operation. Besides, a test experiment for the demonstration of FEL amplification with a LWFA is under preparation. Important funding is still necessary for the LUNEX5 demonstrator.

ACKNOWLEDGMENT

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