LUNEX5: A FRENCH FEL TEST FACILITY LIGHT SOURCE PROPOSAL

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Abstract

LUNEX5 is a new Free Electron Laser (FEL) source project aimed at delivering short and coherent X-ray pulses to probe ultrafast phenomena at the femto-second scale, to investigate extremely low density samples as well as to image individual nm scale objects. The proposed machine layout is based on a 400 MeV superconducting Conventional Linear Accelerator (CLA) mainly composed of 2 XFEL type cryomodules together with a normal-conducting high brightness photo RF gun. Such a mature and reliable technology is able to deliver high quality electron bunches up to few kHz suitable for user experiments. Furthermore, the last decade improvements in synchronization and stability offer a fertile land to explore the different and innovative seeded FEL operations aiming at producing higher coherence and energetic X-rays for the pilot user benefits. In parallel of the CLA branch, the very promising and highly innovative Laser Wake-Field Accelerator (LWFA) enables to produce very short electron bunches in the range of the femto-second and high peak current up to few GeV, as a FEL bench test using the same undulator lines.

INTRODUCTION

LUNEX5 [1] objectives are manifold. The first one is to build a demonstrator of a fourth generation light source between 40 and 4 nm with typically 20 fs pulses, incorporating the new seeding concepts (seeding with High order Harmonics Generation (HHG) [2, 3, 4] and Echo Enable Harmonic Generation (EEHG) [5]). These new concepts should enable further FEL sources cost reduction. As a second objective, this radiation will be used by the pilot user experiments. In addition, as a test platform to develop the fifth generation FEL, the CLA is replaced by a LWFA [6] using the same undulator line as sketched in figure 1.

CLA BRANCH

Super Conducting L-band

The 400 MeV CLA in its baseline version delivers one electron bunch at 50 Hz. The superconducting RF, based on the XFEL technology [7] (two 1.3 GHz cryomodules (CM) and a third harmonic one), is more attractive than the warm option, as it achieves better performance, for comparable investment and operational costs in pulsed operation. The long RF pulse (1.4 ms with 500 µs flat-top) at 50 Hz opens the door to operate, as a further upgrade, with macro-pulses containing up to a hundred of bunches. Such a pulsed operation with a duty cycle around 10 % allows for the use of 2 CM, operated at 24 MV/m, with a total cryogenic heat load below 120 W at 2 K, which is suited to the capability of the first phase cryogenic station. At low beam current, the optimum coupling depends mainly on the level of peak detuning induced by the microphonics (~15 Hz). A trade-off between cryogenic load and RF power with a reasonable duty cycle around 10 % requires lowering Q_L down to ~10^7, at the expense of a 50 % increase in peak RF power. The use of one RF transmitter system for each cavity will allow achieving the highest stability in phase and amplitude, which is mandatory for the FEL performance. Although the Solid State Amplifiers (SSA) technology [8] is not yet currently used in such application (12 kW CW and up to 16 kW peak at 1.3 GHz), its extreme modularity and the elimination of HV equipment bring significant advantages as compared to the vacuum tubes, while the cost remains

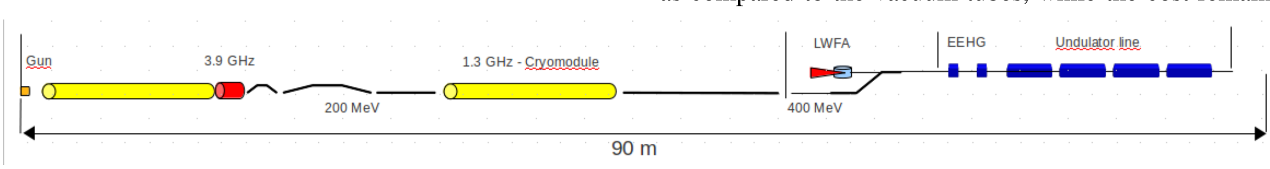

Figure 1: LUNEX5 accelerator layout.

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comparable. Moreover, the SSA uses switching mode power supplies with switching frequencies far beyond the cavity bandwidth, which results in a strong reduction of the phase noise. A last upgrade is to operate in CW mode with an additional cryomodule in order to reduce the gradient from 24 to 16.5 MV/m hence keeping the cryogenic load at a reasonable level.

The Gun

The normal conducting 1.3 GHz RF photo-injector developed by the PITZ collaboration [9] at DESY-Zeuthen, since 2000, is regarded as a good candidate. It delivers 1 nC bunch charge with a low emittance suitable for FEL operation as required by LUNEX5. In the latest version, the total transverse normalized emittance has been measured down to 1 πmm.mrad for 1 nC with an accelerating voltage of 60 MV/m and a flat top laser profile of 20 ps with a rise time of about 2 ps. The gun will be powered by a 10 MW Multi Beam Klystron. The HV will be pulsed by a commercial solid state modulator.

Beam Dynamics Simulations

Beam dynamics simulations have shown that a flat top profile (can beer like) is desirable to optimize the beam emittance compensation [10] and consequently the FEL output power. According to simulations performed with ASTRA [11] code along the RF-gun and the first cryomodule up to about 200 MeV, the total transverse emittances are of the order of 0.9 πmm.mrad for 1 nC bunch and about 50 A peak current. A magnetic compressor, located just downstream of the first cryomodule, further increases the peak current. To contain the emittance degradation, we opt for a S-chicane compressor with rather low magnetic field. Upstream to the compressor, a third harmonic cavity with about 16.5 MV/m in opposite phase linearises the longitudinal phase space profile. CSRtrack [12] simulation through the compressor exhibits an horizontal emittance increase up to 1.2 πmm.mrad, mainly induced by the Coherent Synchrotron Radiation (CSR) effect. The peak current is increased from 50 to 500 A. The final section accommodates the second cryomodule, a long free section for an optional additional one, an achromatic dogleg

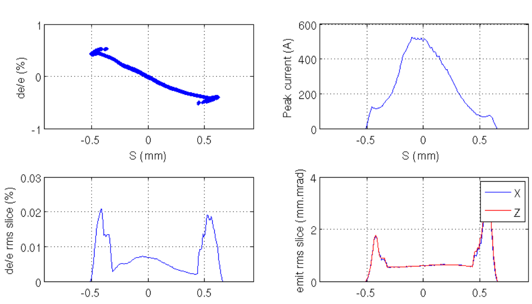

Figure 2: Longitudinal chirped phase space and slice parameters along the bunch in the undulator section at 400 MeV, (1nC).

dedicated to collimation and finally a matching section for the downstream 4 undulalor sections. The second cryomodule is running on crest to get the maximum acceleration and to reach a final energy of 400 MeV.

Simulations performed along this section shows that the main total and slice parameters remain unchanged except the relative energy spread that is naturally decreased below 0.02 % in the core region (Figure 2). Optimizing the CLA working point with respect to the FEL process requires further investigations.

LWFA BRANCH

The Source

As a test platform to develop the fifth generation FEL, the CLA is replaced by a Laser Wake-Fields Accelerator (LWFA) using the same undulator line as sketched in Figure 1. Short electron beams (1 or 2 ps rms) of about 20 pC charge and few kA peak current [13] with an energy ranging from 0.4 to 1 GeV are obtained over a few cm acceleration. The present best energy spread, of about 1%, is still large, but reduction towards 0.1% is expected in a near future. Just like the acceleration, the transverse phase space is also very strongly focused, producing beam size of μm and divergence of mrad with a normalized emittance in the order of 1 πmm.mrad.

Transfer Line

Together, the large energy spread and large beam divergence make the matching, emittances and peak current preservation from LWFA to the undulator line very concerning. A way to contain these degradations is to place a first set of three quadrupoles as close as possible from the source with the drawbacks of large gradient. The use of small gap permanent magnet is then an issue [14]. A possible beam line with this first triplet, located at only 5 cm from the source and separated by 5 cm with a maximum gradient of 130 T/m (over 100 mm bore length) at 400 MeV, allows to contain the emittances growth and bunch lengthening. Based on an optimistic 0.1% energy spread, the emittances dilution induced by higher order chromatic effect is contained to about 20%. The bunch lengthening induced by the large divergence is also contained to about 100%, from 2 fs to 4 ps.

Including the 20 pC space charge effect, the emittances are further increased up to 50% in both planes while the bunch length is not affected any more. All these effects mainly happen in the first matching triplet of quadrupoles. As for the CLA case, the figure 3 plots the main slice relevant parameters at the undulator line entrance. The peak current is still higher than 2 kA. A specific slice emittance profile exhibiting a decrease from the tail to the front is shown. This correlation emerges from particles having a large divergence (large emittance) which are slowed down and drift from the head toward the tail of the bunch.

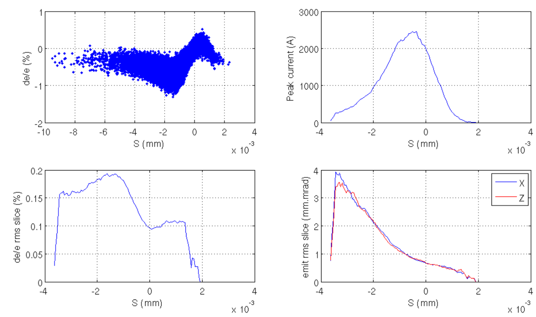

Figure 3: Longitudinal chirped phase space and slice parameters along the bunch in the undulator section at 400 MeV, (20 pC).

FEL LINE

Single pass Free Electron Lasers are high quality light sources, which can be operated over a very large spectral range: from visible to hard X-rays. They provide very high brightness and ultra-short pulses essential to many user applications. The LUNEX5 facility aims both at the optimization of compact FEL configurations for short wavelength generation and at the delivery of high quality photon beams at the targeted wavelength of 20 and 12 nm. The proposed FEL line to be implemented is of high flexibility, i.e. allowing for the test and optimization of various FEL configurations: amplifier, cascade, Echo Enable Harmonic Generation (EEHG), etc... The FEL line will consist in two modulator sections, each one being followed by a magnetic chicane, and in four radiator sections. The modulator sections are short InVac U30 undulators with 10 periods and the radiator section are long InVac U15 undulators with 200 periods. The FEL tunability simulated with GENESIS [15] in steady state mode with an amplifier configuration over the four U15 sections and 10 kW seed is presented in Figure 4. In the case of the CLA-FEL, the tunability is achieved changing both the harmonics seeded and the undulator gap.

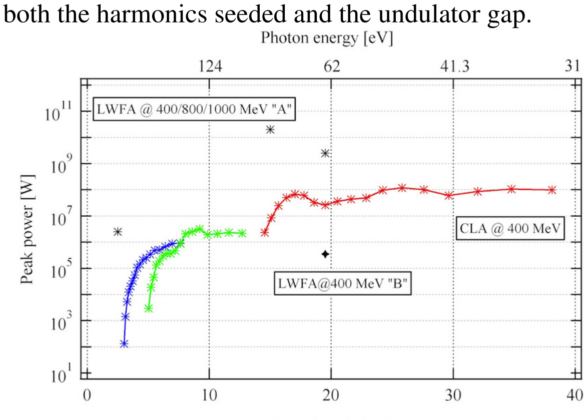

Figure 4 : Spectral tunability calculation of the LUNEX5 FEL with the CLA (red, green, blue) operated at 400 MeV and LWFA (black) branch with 0.1% (A) and 0.5% (B) energy spread.

The seed wavelength and the undulator resonant wavelength can be tuned from 15 to 40 nm. In the case of the LWFA-FEL, the tunability is achieved changing the electron beam energy via the laser parameters.

SYNCHRONIZATION

High-precision synchronization and stabilization techniques are crucial for fourth and five generation light sources and seeded x-ray free electron lasers. The general principle is to use distributed optical fiber links, and to monitor their variations of optical length in real time. Two solutions based on CW [16] or pulsed [17] laser have already been developed for other FEL facilities. They both give extremely good results with reported jitters below 10 fs. Parts of the pulsed option systems being commercially available it will be considered as the current option for LUNEX5.

CONCLUSION

LUNEX5 is aiming for ultra short FEL pulses quest, production and use for creating a unique center of exchange of ideas and works, for setting a bridge between different scientific and technical domains, for providing a coupled CLA-LWFA based test facility for FEL for complementary use, for searching of scientific excellence in setting a new collaborating project in the Saclay Plateau area. It is still very flexible, aiming at advancing on the different R&D subjects. It will pave the path towards a next generation of light sources (4GLS+, 5GLS) with its vision of science.

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