THE ARC-EN-CIEL FEL PROPOSAL

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Abstract

ARC-EN-CIEL (Accelerator-Radiation for Enhanced Coherent Intense Extended Light) aims at providing the user community with coherent femtosecond light pulses covering from UV to soft X ray in France. It is based on a CW 1.3 GHz superconducting linear accelerator delivering high charge, subpicosecond, low emittance electron bunches at high repetition rate. Phase 1 exploits the different sources of seeding with 220 MeV at 1 kHz, in particular High order Harmonic generation in Gas (HHG), to improve the longitudinal coherence and shorten the output radiation wavelength in a rather compact device. Phase 2 is based on a CW 10 KHz 1 GeV superconducting linear accelerator for HHG seeded High Gain Harmonic Generation (HGHG) extending to 1 nm. In phase 3, fs undulator sources in the IR, VUV and X ray and a FEL oscillator in the 10 nm range will be implemented on two ERL beam loops for beam current or energy enhancement.

INTRODUCTION

France is now equipped with a third generation synchrotron light source under commissioning [1] at Saint-Aubin, close to Paris. The Storage Ring consists in a 357 m circumference ring, with 16 cells and 24 straight sections, out of which up to 21 will house insertion devices (ID). High brilliance radiation, from the VUV up to the hard X ray domain will be provided to external users in 2007 with the low emittance (3.7 nm.rad) beam at the 2.75 GeV. Innovative ID's are under construction to provide the best possible performances in a wide energy range (5 eV to 50 keV) [2].

Prospects concerning the Fourth Generation Light Source in France are based on the ARC-EN-CIEL project [3], following a long tradition in FEL in France, in particular in storage ring based FELs (ACO [4], Super-ACO [5]) and on infra-red LINAC based FELs (CLIO [6], ELSA [7]). After considering the installation of an FEL in the VUV on SOLEIL in the oscillator or coherent harmonic generation configurations, it was decided to propose an independent LINAC based dedicated facility providing coherent radiation down to 1 nm, for easier access of the users. The possible implementation of the first and potentially second phase of ARC-EN-CIEL in the former tunnel of the Accélérateur Linéaire de Saclay, at l'Orme des Merisiers, next to SOLEIL, would make a very attractive acclerator based light source complex.

From the beginning, the project aims at developing a strong synergy between the FEL and the laser communities, leading to couple the electron beam and lasers. The innovative choice of seeding the FEL with High order Harmonic produced in Gas, at a high repetition rate leads to a significant shortening of the wavelength of the seed, in addition to the advantages of seeding with respect to SASE (pulse to pulse intensity stability, reduction of jitter, compactness, enhanced longitudinal coherence). Indeed, more than 70% of the users intend to perform pump-probe experiments and a high stability is requested, confirming the choices of seeding and High Gain Harmonic Generation, as discussed in the frame of the user workshop "Applications of VUV X fs tunable sources combining accelerators and laser: "slicing" at SOLEIL and the ARC-EN-CIEL project" (Feb. 3-4 2004, Orsay). Besides, propositions of plasma acceleration and Thomson scattering emerged from the laser-electron beam combination.

The request of high repetition rate (1-10 kHz) in order to couple as efficiently as possible the electron beam with the high harmonics produced in gas led to the choice of a superconducting type of Linear Accelerator. Expertise exits in DAPNIA in CEA and in SOLEIL with the superconducting RF cavity. A high repetition rate of the photon source is also desirable for users. A 100 fs pulse corresponds to the typical demand.

ARC-EN-CIEL is planned into three phases: a first phase reaching an energy of 220 MeV for HGHG sources in the VUV, a phase 2 at 1 GeV with HGHG sources down to 1 nm using High Harmonics produced in gas, and a phase 3 including two recirculation loops, for Energy Recovery or energy enhancement where undulators (12 m long, period 30 and 20 mm) are installed, providing subpicosecond radiation in the VUV and X ray ranges (5.10^{12} phot/s/0.1%bw for 0.1 mA average current). In addition, a 0.1-1 kW average power, 0.1-1 % bandwidth FEL oscillator, installed in the first loop, could cover the 120-10 nm, thanks to recent development of multilayer mirrors for lithography, and SiC mirrors in normal incidence. Harmonics can also be produced from the FEL oscillator, with 500 MW at 4.5 nm and 10 MW at 2.7 nm. The beam at 2 GeV from the loop will allow shortening further the radiation wavelength down to 0.4 nm with an additional undulator section. Expected radiation from ARC-EN-CIEL is illustrated in figure 1, comparing radiation of its three phases with respect to the insertion devices of SOLEIL. THz radiation will also be provided. The present work, part from the detailed analysis of the components of the project, is concentrating on the progress on several key elements.

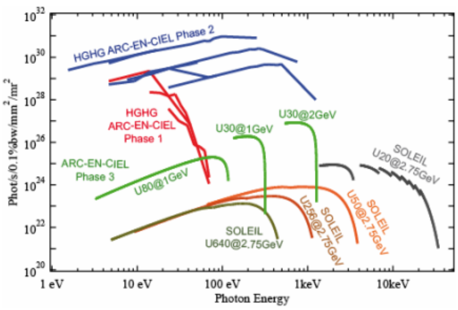

Figure 1 : Peak brilliance. Phase 1 : HGHG radiation + seeding wavelength, P_{seed} = 100 kW for HHG harmonics n°7-9, 600 kW for n°3-5. 1 kA, F= 0.1. Phase 2 :HGHG radiation 1.5 kA, 1.35 π mm.mrad, 0.0004% slice energy spread, 200 fs, beta=2 m, F = 0.088. Phase 3 : spontaneous emission of undulators of period 30 and 80 mm calculated with SRW. Undulator period length in mm in ID name.

THE ACCELERATOR

The gun

The choice of the gun is not completely defined. It should provide 1 nC for 2πmm.mrad total emittance ε. At the beginning, we have considered a Zeuthen photo-injector [8], with a CsTe cathode, to be modified for operation at 1 KHz. This requires a coupler modification with respect to the present design. The active removal of the power can be performed via a phase inversion during falling time. A longer term system is based on a superconducting gun, as presently developed by Rossendorf [9], where emittance compensation and reliability can still be an issue. We also thought about the adaptation of the CeB6 thermo-ionic gun developed at RIKEN for the SCCS project, and the recent very spectacular results in terms of beam stability and emittance [10] bring us to go further in the analysis of this solution for ARC-EN-CIEL. Besides, R&D is going on the cathode materials in LSI (Polytechnique) with the use of Carbon nanotubes.

The cryomodules

ARC-EN-CIEL is based on TESLA type cavities at 1.3 GHz, to be operated in CW mode. The elliptical 9-cell cavities routinely provide 25 MV/m accelerating gradient, while recent advances in the cavity design and integration procedures indicate the possibility of pushing the gradient to 35 MV/m, which is a target parameter for the International Linear Collider. The design of the cryomodule may be revisited for a better cryogenic efficiency accounting for the CW operation.

Studies concerning the compensation of the microphonics are presently under way at CEA-DAPNIA and BESSY [11]. The microphonics have been analysed with appropriate techniques and different compensation schemes are elaborated using active piezoelectric tuners. However, the large number of the transverse mechanical eigen-modes of the cavity represents a strong limitation for the compensation. A passive damping of these modes by a careful design and mounting of the cavity-tuner system in the cryomodule would alleviate the complexity of the active compensation scheme and improve its efficiency.

The electron beam dynamics

Calculations performed for ARC-EN-CIEL phase 1 accelerator consider an RF gun, a first cryomodule bringing the energy to 100 MeV, a third harmonic cavity compensating the non linearity of the longitudinal phase space, a S-chicane compressor, and a second cryomodule raising the energy to 220 MeV. 6 additional modules are included in phase 2. ASTRA [12] is used to simulate the RF gun and the cavity modules, and CSRTrack code [13] for the compression scheme, taking into account Coherent Synchrotron Radiation in the chicane.

Figure 2a presents the evolution of the different emittances along the bunch compressor. The total emittance is raised to 2.7 πmm.mrad in the compression process through the chicane (from 2.1 to 0.1 mm/ 300 fs rms). With an adequate electron beam optics [14], the slice emittances along the bunch remain almost unchanged (ranging from 0.7 to 1.1) with a small mismatch from slice to slice. The compressor creates a correlated emittance that reaches 0.18 π mm.mrad, betraying a spread of the slices in the transverse phase space. It is the main contribution to the total emittance increase by strong mismatching.

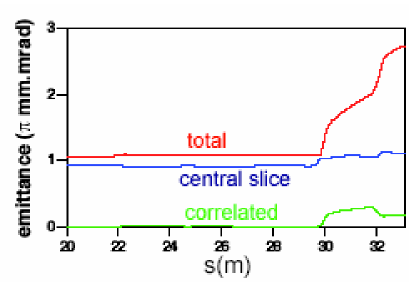

Figure 2 : Evolution of the emittance along the chicane. Chicane parameters: total length: 10 m, R56=0.15 m, dipole length : 0.3 m. First dipole at s=23 m.

The influence of the laser pulse length on the optimization of the different emittances while keeping a constant space charge density was also investigated. A longer laser pulse is favorable in the compressor, for avoiding emittance degradation due to coherent synchrotron radiation, the longitudinal wake function being proportional to $\sigma_l^{-4/3}$, with σ_l the beam length.

Although the output bunch is also compressed down to 300 fs, its mean length through the chicane is longer and the emittance is smaller. In order to avoid beam degradation due to non linear part of the R_{566} coefficient, the voltage of the harmonic cavity has to be increased to give an invert sign of the non linear component. For longer laser pulse and longer electron beam length before the chicane, the energy variation is more important and the deformation of phase space is larger (see fig. 3). Systematic simulations done for different pulse lengths (20-40 ps range) and harmonic cavity voltages (20-25 MV/m range), keeping the final bunch length constant at 0.1 mm bring to a minimum of the total emittance for E_H=22 MV/m. In Fig. 4, one finds at the end of the S-chicane, a minimum total emitance at 2.1 π mm.mrad for the laser pulse length σ_l=25 ps. The total emittance globally increases with the laser pulse length apart for σ_l=20 ps, for which it is higher. The central slice emittance decreases with the laser pulse length (radial laser spot reduction). Further studies concern the pre-injection in the case of the thermo-ionic gun (SCSS type) will be studied, calculations for the phase 2, including the second bunch compressor and for phase 3 with ERL loops.

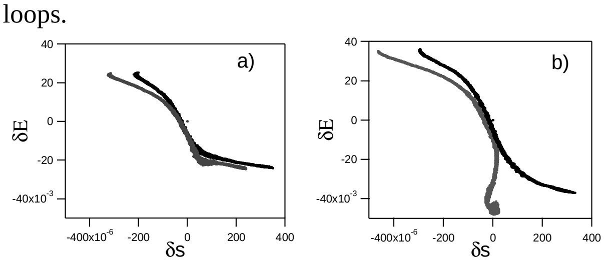

Figure 3 : Longitudinal phase space representation for a laser pulse length of a) 20ps, b) 40 ps for different voltages of the harmonic cavity. Black (resp. grey): E_H=22 (resp. 20)MV/m.

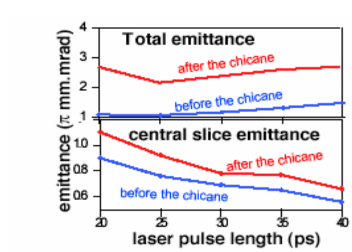

Figure 4 : Emittance evolution versus the laser pulse length.

THE LASER SYSTEM AND SYNCHRONISATION

The laser system

One passive mode locked Ti:Sa based oscillator is foreseen, delivering 1 W at 76 MHz repetition rate (around 13 nJ /pulse). This will feed three independent high power, multiple repetition rate, laser systems.

The first system, devoted to the photo-injector should provide ~50-100 µJ pulse energy in the UV (266 nm), producing a 1 nC electron beam following interaction with a photocathode with 1 % quantum efficiency. Special attention will be paid to the laser beam transverse features (dimensions and shape) for preventing the electron beam emittance increase [15]. A laser amplifier delivering at least 1 mJ in the IR (800 nm), followed by a regenerative amplifier and single pass preamplifier, both pumped by a 15 W Q-switched solid state laser can be adopted. Very highly efficient third harmonic generation will be performed with an ultra short pulse (~50 fs) on a sufficiently thin nonlinear crystal (BBO), in order to reduce pulse distortion. A prism or gratings based UV stretcher will bring the duarton up to 20 ps.. Transverse and longitudinal measurement as well as shaping of the laser pulse call for a complete setup including a DAZZLER system [16] in the IR, spectral interferometric techniques (either self-referencing, like SPIDER [17] or not), a beam transverse filter and deformable mirror with high dynamics. Such approaches are under study on the CEA-SLIC servers LUCA (20 Hz) and PLFA (1 kHz) [18]. Recent promising developments by FASTLITE [19] of a Dazzler operating in the UV domain Dazzler, should allow a direct shaping of the laser beam issued by THG process. Otherwise, we intend to develop brand new solutions for a dedicated UV regenerative amplifier, based on the amplification and Kerr properties of crystals like Ce^{3+}:$LiCaAlF_6$ [20].

The second one, a broadband system, includes non linear processes like Optical Parametric Amplification, Third and Fourth Harmonic Generation (THG, FHG) and HHG, for two color pump-probe based experiments. It is based on Chirped Pulse Amplification (CPA) technique, on a basis of a 10 mJ, kHz or multi-kHz system, in which a 4-pass amplifier is injected with the beam issued a first regenerative amplifier. The first two systems will operate at a multi-kHz rate, while the third will be limited to few Hz (eventually few tens of Hz).

The third laser system will deliver high energy (1 J), short duration pulses and will be mainly devoted to plasma acceleration and Thomson scattering.

The synchronisation

The synchronisation of the RF and the master clock in respect to the femtosecond time scale taking into account the natural pulse-to-pulse jitter for a Ti:Sa oscillator of a few tens of fs lead to adopt a frequency-stabilized laser oscillator. Care will be devoted to minimize the intrinsic jitter encountered by the e- beam through its travel in the accelerator to the wiggler. The jitter between the different laser branches distributed on relatively long distance (~ 100 m) should also be reduced and environmental contributions such as slow thermal drift should be lowered. Moreover, unlike the accelerator beneficing of the vacuum technique, inherent jitter sources along the complex laser system (stretcher /compressor pair, regenerative /multipass amplifiers, thermal lensing…) is under study in CEA-SPAM. Measurement of the synchronisation between the laser pulse and the electron is a key issue, the development of the electro-optical measurement has been set-up on the ELYSE gun at LCI (Orsay). The first step of measurements leads to a resolution of 250 fs.

THE LIGHT SOURCES

The undulators

ARC-EN-CIEL phase 1 plans to use a 20 mm period in-vacuum hybrid undulator as a modulator (50 periods), and a 30 mm Apple-II undulator as a radiator (400 periods). Identical sections of modulator and radiator will be added for the second phase of ARC-EN-CIEL (4 to 8 m for the modulator, and 4 sections of 4 m for the radiator). Such undulators are currently developed for SOLEIL third generation facility.

The choice of such radiator type undulators follows estimations of magnetic performance of an Apple-II type undulator with a small period based on magnetostatic calculations performed using the Radia computer code [21]. The expected horizontal and vertical peak fields of an Apple-II at 30 mm period and 6 mm vertical gap are $B_x = B_z \approx 0.63$ T; corresponding to the effective deflection parameter $K \approx 2.5$ (see fig. 5).

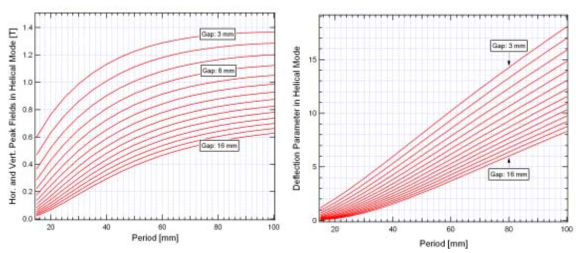

Figure 5. Peak magnetic fields (left) and deflection parameters (right) as functions of period of an Apple-II undulator in helical mode at different vertical gaps. Calculations done for NdFeB magnet blocks with remnant magnetization of 1.22 T and transverse dimensions 30 mm x 30 mm, horizontal gap between movable and fixed magnet arrays : 1 mm.

Seeding with High Harmonics generated in gas

Collaborations have been set up for demonstrating the feasibility to seed a LINAC based FEL with HHG on SCSS phase 1 in Japan [22] and on SPARC in Italy [23]. Tests of the chambers and of the optical transport have been performed this year with the Luca laser, and seeding will be performed at SCSS on fall 2006 and in summer 2007 on SPARC. This will provide an experimental demonstration of the concept for ARC-EN-CIEL. FEL radiation based on analogous systems for ARC-EN-CIEL is calculated using PERSEO 1D code [24] with a gain reduction due to the filling factor [25] and recently compared with GENESIS1.3 [26] integrated in a new test version of SRW [27] allowing the wavefront to be transported in the beamline to the user sample (see fig. 6).

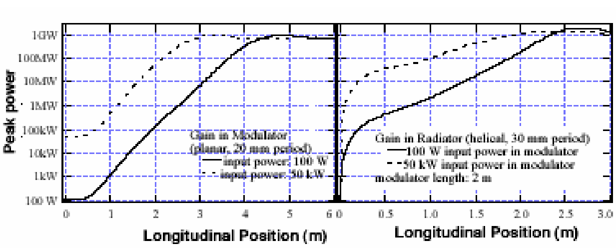

Figure 6: Steady-state GENESIS simulations for ArcEnCiel phase 1, 1 – 1 HGHG scheme, 266 nm seed: a) gain in modulator, b) gain in radiator (30 mm period helical mode).

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