

## THE ARC-EN-CIEL FEL PROPOSAL

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### Abstract

ARC-EN-CIEL (Accelerator-Radiation Complex for Enhanced Coherent Intense Extended Light), the French project of a fourth generation light source, aims at providing the user community with tunable, adjustable polarisation, coherent femtosecond light pulses covering from UV to soft X ray. A CW superconducting linear accelerator will deliver high charge, subpicosecond, low emittance electron bunches with a high repetition rate (1 kHz). Calculations (using ASTRA and CSRTrack) are presented and are focused on the optimization of the total and the slice emittance by varying the laser pulse length. The FEL is based on the injection of High Harmonics Generated in Gases (HHG) in a High Gain Harmonic Generation scheme, leading to a rather compact solution. The produced radiation (calculated with PERSEO and SRW) extending down to 0.8 nm with the Non Linear Harmonics reproduces the good longitudinal and transverse coherence of the harmonics in gas.

### INTRODUCTION

Short pulses Free Electron Laser (FEL) in the VUV-soft X ray spectral range seems very attractive sources for time-resolved studies in various scientific domains. France has a long tradition on FEL activities : on ACO [1] and Super-ACO [2] storage rings with the first time-resolved pump-probe user experiments with synchrotron radiation [3] and on Linear Accelerators such as CLIO [4] and ELSA [5]. Coherent Harmonic Generation was also carried out on ACO and on Super-ACO, leading to coherent radiation on the fifth harmonic at 100 nm in 1991 [6]. ARC-EN-CIEL (see fig. 1) [7] is planned into three phases: a first phase reaching an energy of 220 MeV for HHG sources in the VUV, a phase 2 at 1 GeV with HHG sources down to 1 nm using High Harmonics produced in gas, and a phase 3 including recirculation loops. From the scientific case 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), it appears that a 100 fs pulses with a high repetition rate is desirable (1 kHz), confirming the choice of a superconducting LINAC. As more than 70% of the users intend to perform pump-probe experiments and a high stability is requested, the radiation source is based on seeding and High Gain Harmonic Generation. Indeed, seeding with coherent light at short wavelength such as High order Harmonics generated in gas jets (HHG) is

proposed. Therefore, collaborations have been set up for demonstrating the feasibility to seed a LINAC based FEL with HHG on SCSS phase 1 in Japan [8] and on SPARC in Italy [9]. Here, further studies on ARC-EN-CIEL phase 1 are presented.

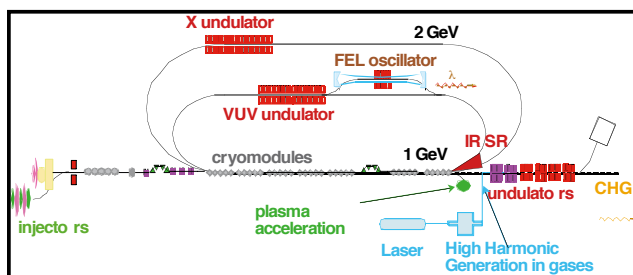


Figure 1: ARC-EN-CIEL scheme

### THE LASER SYSTEM

The laser, which illuminates the photocathode is typically 20 ps long (2.1 mm rms). The laser system is based on a main oscillator, synchronized with the RF of the LINAC, and separated into different branches for irradiation of the gun after frequency tripling, for the focusing in the gas for the generation of high harmonics and for further amplification for plasma acceleration.

### ARC-EN-CIEL ACCELERATOR

The ARC-EN-CIEL phase 1 accelerator scheme is based on the TTF2 layout with an RF gun followed by two cavity modules. When the electron energy has reached 100 MeV after the first module, a third harmonic cavity compensates the non linearity of the longitudinal phase space before bunch length compression by mean of a S-chicane compressor type. An identical pre-injection system is planned for Phase 2 and 3. Finally, the second cavity module increases the electron energy to 220 MeV for the first phase, whereas 6 additional modules are included in phase 2.

Numerical calculations using ASTRA [10] have been done to simulate the RF gun and the cavity modules. The CSRTrack code [11] has been used to model the compression scheme, taking into account Coherent Synchrotron Radiation in the chicane.

The RF gun produces a  $1.1 \pi$  mm.mrad total emittance  $\epsilon$  with a total charge of 1 nC. Figure 2a presents the evolution of the emittances (total, central slice and correlated) along the bunch compressor. The compression

process through the chicane, from 2.1 to 0.1 mm rms long (300 fs), increased the total emittance to  $2.7 \pi$  mm mrad. With an adequate electron beam optics [12], 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  $0.18 \pi$  mm mrad, betraying a spread of the slices in the transverse phase space. Although this is a weak effect, it is the main contribution to the total emittance increase by strong mismatching.

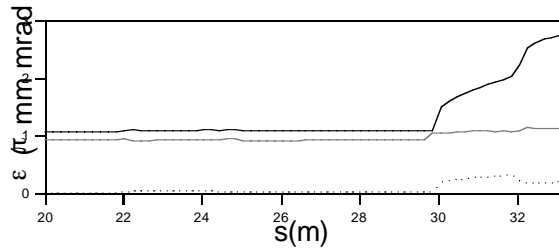


Figure 2 : Evolution of the emittance along the chicane. black line : total emittance, grey line : central slice emittance, dashed line : correlated emittance. Chicane parameters: total length: 10 m,  $R_{56}=0.15$  m, dipole length : 0.3 m. The first dipole is implanted at 23 m.

Further investigations have been done using different laser pulse lengths for optimizing the emittances (total, central slice and correlated). The duration of the laser pulse is increased keeping a constant space charge density (radial spot reduction) in order to have the same accelerator configuration from the gun to the harmonic cavity. A longer laser pulse is favorable in the compressor. In fact, the major cause of emittance degradation comes from the effect of the coherent synchrotron radiation, where the longitudinal wake function is proportional to  $\sigma_l^{-4/3}$ , with  $\sigma_l$  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 should be then smaller, as it is required for the FEL operation. In the other hand, a degradation of the beam parameters may occur because of the non linear part of the  $R_{566}$  coefficient:

$$s' = s_0 + R_{56} \delta + R_{566} \delta^2$$

where  $s'$  and  $s_0$  are the longitudinal coordinate of the electron respectively at the end and at the entrance of the S-chicane,  $\delta$  is the relative energy deviation with respect to the nominal energy of the electron beam, and  $R_{566} = -3R_{56}/2$  the non linear coefficient. In order to cancel this effect, 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 as a consequence longer electron beam length before the chicane, the energy variation is more important. Indeed, the deformation of the longitudinal phase space is more important as it is illustrated in figure 3.

Systematic simulations have been done for different pulse lengths (ranging from 20 ps to 40 ps) and for different harmonic cavity voltages (ranging from 20

MV/m to 25 MV/m), keeping the final bunch length constant at 0.1 mm. A minimum of the total emittance appears for  $E_H=22$  MV/m. Figure 4 illustrates the total and central slice emittances as a function of the laser pulse length  $\sigma_l$ . At the end of the S-chicane, the minimum total emittance reaches  $2.1 \pi$  mm mrad for  $\sigma_l=25$  ps. The total emittance globally increases with the laser pulse length apart for  $\sigma_l=20$  ps, for which it is higher. The central slice emittance decreases with the laser pulse length (radial laser spot reduction).

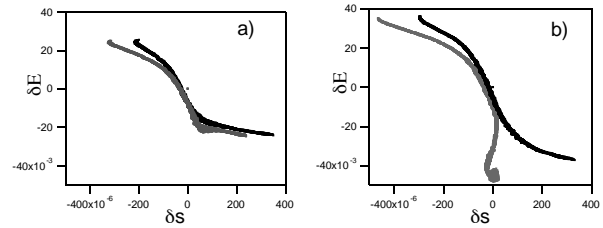


Figure 3 : Longitudinal phase space representation for a laser pulse length of a) 20ps, b) 40 ps for different setting of the voltage of the harmonic cavity. Black points :  $E_H=22$  MV/m, grey points :  $E_H=20$  MV/m.

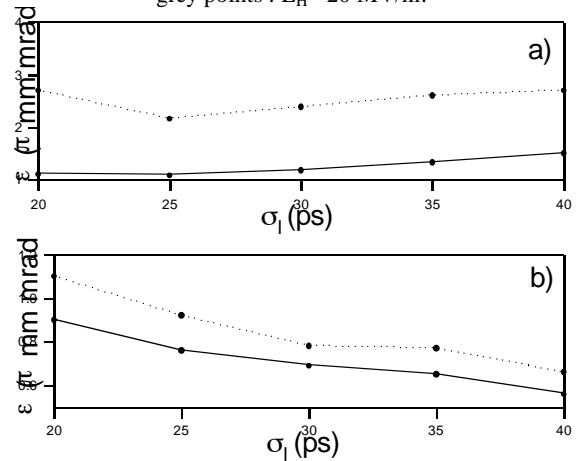


Figure 4 : Evolution of the a) total emittance, b) slice central emittance as a function of the laser pulse length. Lines : at the entrance of the chicane, dashed lines : at the end of the chicane.

Further detailed calculations are under way for the phase 2 with in total 8 cryomodules raising the energy up to 1 GeV, a second bunch compressor and for phase 3 with ERL loops.

## THE EXPECTED RADIATION

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). In order to estimate magnetic performance of an Apple-II type undulator with a small period, series of magnetostatic calculations were performed using the Radia computer code [13]. 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; this corresponds to the effective deflection parameter  $K \approx 2.5$ . This value seems sufficient for all the planned modes of operation of

the ARC-EN-CIEL phase 1. Such undulators are currently developed for SOLEIL third generation facility. 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).

The modulator is adjusted on the fundamental of the seed, whereas the radiator is generally set to its third harmonic. The non linear harmonics of the fundamental of the radiator are also considered. FEL radiation has been calculated using PERSEO 1D code [14] with a gain reduction due to the filling factor  $F$  [15]. The transport of the optical wave of the High Harmonic in gas has been calculated using non pure Gaussian laser beam ( $M^2=2$  to 3) with four mirrors (two for a telescope and two for a periscope). Additional calculations have been performed using GENESIS1.3 [16] integrated in a new test version of SRW [17] allowing then the wavefront to be transported in the beamline to the user sample (see fig. 5).

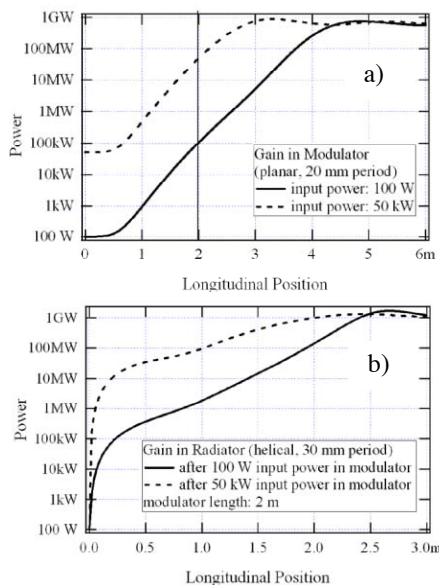


FIGURE 5 : Steady-state GENESIS simulations for the ArcEnCiel phase 1, 1 – 1 HGHG scheme, 266 nm wavelength: a) gain in modulator, b) gain in radiator (30 mm period helical undulator).

The two optional loops, for Energy Recovery or energy enhancement, will host insertion devices (12 m long, period 30 and 20 mm) for the production of fs synchrotron radiation in the VUV and X ray ranges ( $5 \cdot 10^{12}$  phot/s/0.1%bw for 0.1 mA average current), together with a 0.1-1 kW average power, 0.1-1 % bandwidth FEL oscillator, installed in the first loop, covering the 120-10 nm, thanks to recent development of multilayer mirrors for lithography, and SiC 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 to shorter further the radiation wavelength down to 0.4 nm with an additional undulator section.

Fig. 6 shows the expected peak brilliance versus the wavelength for the different phases. THz radiation will

also be provided. For ARC-EN-CIEL phase 1 and 2, one can see the radiation on the first harmonic of the radiator and its non linear harmonics of order 3 and 5. For the phase 3, sub-picosecond spontaneous emission from the undulators has been calculated using SRW. It is compared to the peak brilliance of the undulators for the SOLEIL third generation light source.

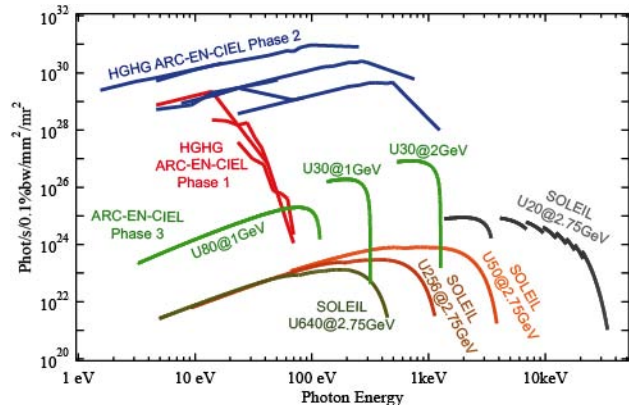


FIGURE 6 : Peak brilliance. Phase 1 : HGHG radiation + seeding wavelength,  $P_{seed} = 100$  kW for H7-9, 600 kW for H3-5. 1 kA,  $F=0.1$ . Phase 2 :HGHG radiation 1.5 kA,  $1.35 \pi$  mm.mrad, 0.0004% slice energy spread, 200 fs,  $\beta=2$  m,  $F=0.088$ . Phase 3 : spontaneous emission of undulators of period 30 and 80 mm.

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