THE ARC-EN-CIEL FEL PROPOSAL

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Abstract

ARC-EN-CIEL (Accelerator-Radiation for Enhanced Coherent Intense Extended Light), the French project of a fourth generation light source aims at providing the user community with coherent femtosecond light pulses covering from UV to soft X ray [1, 2]. It is based on a CW 1 GeV superconducting 1.3 GHz TESLA type linear accelerator delivering high charge, subpicosecond, low emittance electron bunches with a high repetition rate. The FEL is seeded with High Harmonics in Gases (HHG) in a High Gain Harmonic Generation (HGHG) scheme [3], leading to a rather compact solution. The produced radiation extending down to 0.8 nm with the Non Linear Harmonics reproduce the good longitudinal and transverse coherence of the harmonics in gas. Optional beam loops for enhancing the beam current or the energy will accommodate fs synchrotron radiation sources in the IR, VUV and X ray ranges and a FEL oscillator in the 10 nm range. An important synergy is expected between accelerator and laser communities. Indeed, electron plasma acceleration will be tested for possible future compact electron beam sources for X ray FEL. Fs hard X ray can also be produced by Thomson Scattering.

INTRODUCTION

In order to offer tuneable, adjustable polarisation, high brilliance coherent femtosecond light pulse for scientific applications in the UV-X ray range, ARC-EN-CIEL has then been proposed [1] as a new independent superconducting linear accelerator based radiation facility and an user workshop has been organized [2]. ARC-EN-CIEL is planned into three phases, a first phase reaching an energy of 220 MeV for HGHG sources in the VUV (see Figure 2a), a phase 2 at 1 GeV with HGHG sources down to 1 nm using High Harmonics produced in gas (see Figure 2b), and a phase 3 including recirculation loops. The overall layout of the proposed source is shown in Figure 1. The former hall for the Accélérateur Linéaire de Saclay (ALS) is available for implementation, providing in particular the concrete shielding, a 200 m long tunnel, an adjacent hall, and two large user rooms.

ARC-EN-CIEL PHASE 1

ARC-EN-CIEL phase 1 consists of a master laser system with three branches, an electron gun operating at 1 to 10 kHz, two superconducting accelerating sections, a HGHG experiment with seeding either by an OPA or HHG, and one for Thomson scattering and plasma acceleration.

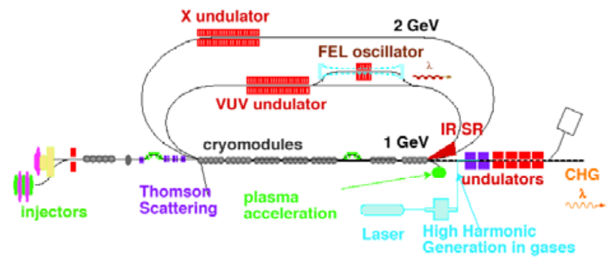

Figure 1: Schematic of ARC-EN-CIEL layout

The accelerator

The phase 1 accelerator system includes a RF gun (operating at 1 to 10 kHz) injecting directly into a module followed by a 3rd harmonic cavity to linearize the energy-phase correlation before a bunch compression in a S type chicane (R56=0.1 m) [4], a second module and the undulator for HGHG experiments. With a 15 MV/m gradient, beam energy close to 250 MeV should be reached. Two modes of operation of the gun are foreseen, one with a low charge and short pulse (0.1 nC, 60 fs rms) and one with a higher charge and a longer pulse (1 nC, 300 fs). Figure 3 shows calculations performed with ASTRA assuming a cylindrical shape distribution for the laser, and taking into account the space charge, wakefield and an acceleration of 15 MV/m, the compression is simulated with TRAFIC4 including Coherent Synchrotron Radiation and 3D space charge.

Two solutions are now discussed for the gun. The first one is based on a PITZ type gun [5] modified for accommodating a 100 kW CW klystron (Thomson TH 2115, 2.5 MW peak power, 150 kW average power) for a 3 KHz operation, a low level RF and amplitude-phase regulations, adapted main RF couplers, high order modes couplers, helium circuits. The design of the cryomodules will be optimized for CW soft X-ray FEL sources. All the power dissipation in the gun cavity would take place during RF filling and falling times. The second solution would be to adopt directly a superconducting gun [6], which would be able to deliver a 7-8 MeV beam, with a transverse emittance of 1 π mm. mrad, 0.25 % energy spread and a temporal duration of 10 ps, aiming a high field gradient of 40 MV/m.

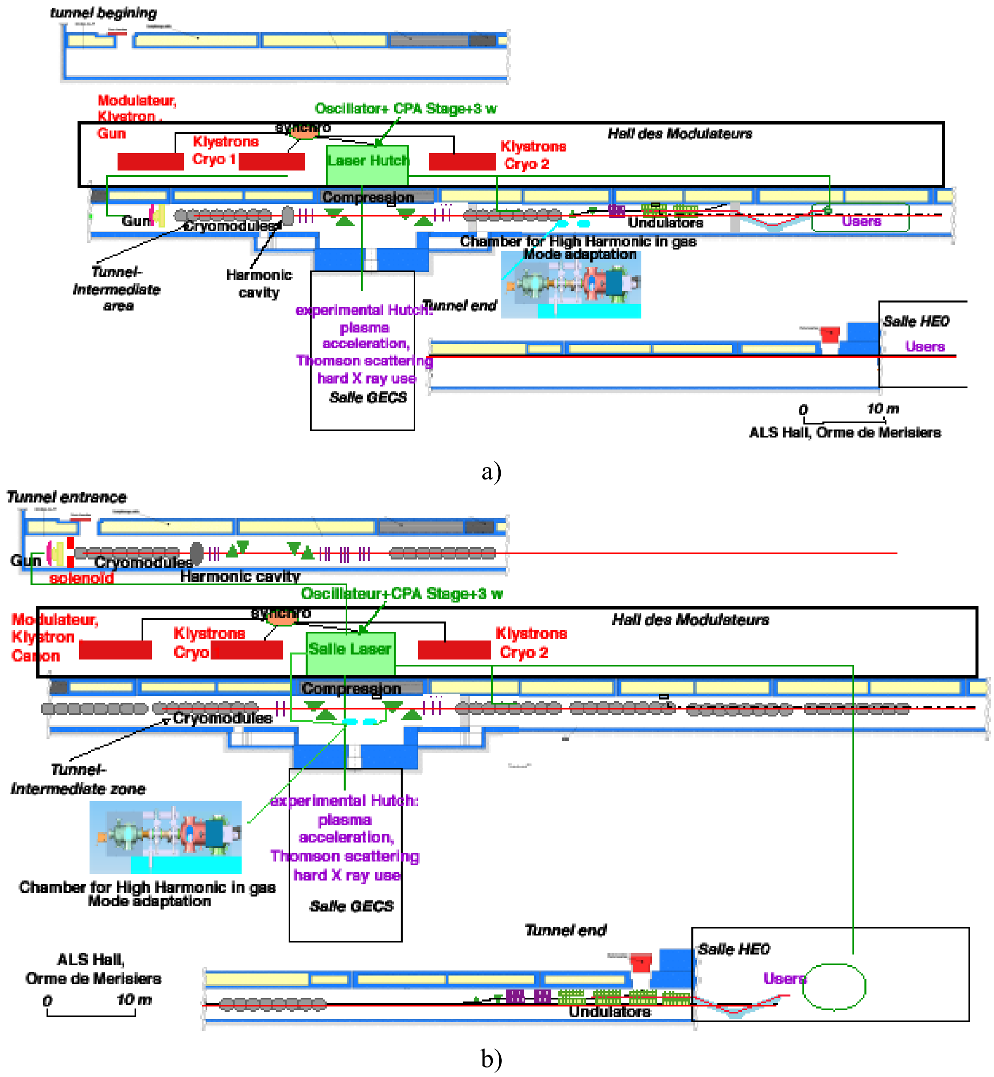

Figure 2: a) Scheme of ARC-EN-CIEL phase 1 in the tunnel of ALS at CEA (Commissariat à l'Énergie Atomique) in Orme des Merisiers. b) Scheme of ARC-EN-CIEL phase 2 in the tunnel of ALS.

Table 1: Electron beam simulation for ARC-EN-CIEL phase 1 : emittance $\gamma\varepsilon_c$, slice $\gamma\varepsilon_s$, total $\gamma\varepsilon_t$ (mm. mrad), energy spread σ_E (MeV), bunch length σ_l (mm rms).

	Uniform laser		Gun exit 4 – 100 MeV		After bunch compressor 1 100 – 220 MeV				
Q	Duration	Radius	$\gamma\varepsilon_t$	σ_l	$\gamma\varepsilon_c$	$\gamma\varepsilon_s$	$\gamma\varepsilon_t$	σ_l	σ_E
1 nC	20 ps	1.5	1.1	2.1	0.1	1.4	1.7	0.1	2
0.1 nC	2 ps	1.5	0.8	0.57	0.25	1.6	2.1	0.02	0.5

The laser and High Harmonic in gas sources

A visible laser-pumped Ti:Sa oscillator, delivering 6-10 nJ at around 60-70 MHz will feed two amplifier systems, equipped with Chirped Pulse Amplification set-up. Both systems will operate at 1 to 30 kHz and will be naturally synchronized, aiming at keeping the mutual jitter to less than 10 fs. The photocathode arm will be optimized for delivering 100 µJ, 10 ps long pulse at 266 nm. A DAZZLER will lead to very short edged (0.5 ps) flat-top electron pulses for the longitudinal pulse shaping. The seeding arm will deliver between 10 µJ and 2.5 mJ in a 50 fs long pulse, in the 160-800 nm spectral range.

The harmonic generation in gas results from the strong non linear polarisation induced on the rare gases atoms, such as Ar, Xe, Ne and He, by the focused intense electromagnetic field E_{Laser} of a "pump" laser [7]. The radiation spectrum is completely tunable in the VUV-XUV region by frequency-mixing techniques applied on the pump laser. High order harmonics are linearly polarized sources between 100 nm and 3 nm (12-400 eV), of high temporal and spatial coherence, emitting very short pulses (less than 100 fs) in a small divergence (1 to 10 mrad), with a relatively high repetition rate (up to few kHz). They have already been successfully employed for amplification in a collisionally pump X ray amplifier in an optical filed ionized plasma at 33 nm [8].

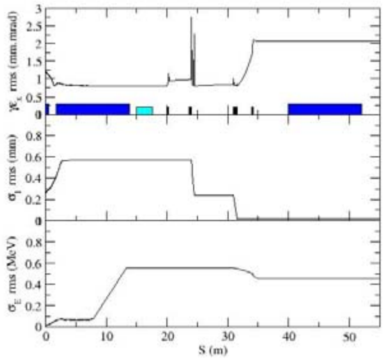

Figure 3: Horizontal emittance, pulse duration and energy spread of the electron bunch for an initial charge of 1 nC. Case of a laser pulse of 20 ps, a bunch compression of 300 fs.

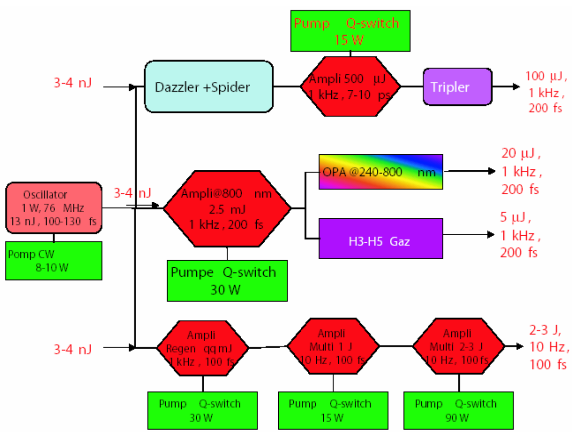

Figure 4: The laser system for ARC_EN-CIEL phase1.

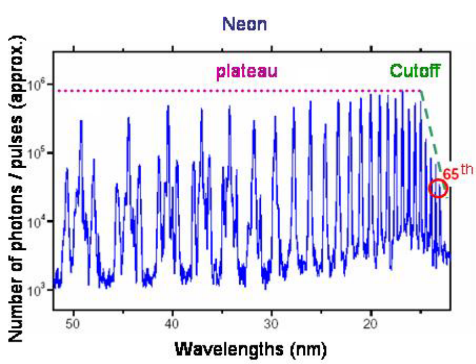

Figure 5: Typical harmonics spectrum produced in a Neon jet. In the plateau region, the harmonics intensities are almost constant with harmonic order. For higher orders, the intensities decrease rapidly in the "cut-off" zone.

Atoms ionize by tunneling of the electrons in the strong external laser field. The ejected free electrons, far from the core, are then accelerated in the external laser field and gain in kinetic energy. Those which are driven back close to the core can either be scattered or recombine to the ground state emitting a burst of XUV photons every half-optical cycle. A typical spectrum of harmonics generation in gas (see Figure 5) consists of a train of XUV bursts, superposition of the high order odd harmonics, separated by twice the fundamental energy and extending down to 10 nm (see Figure 6).

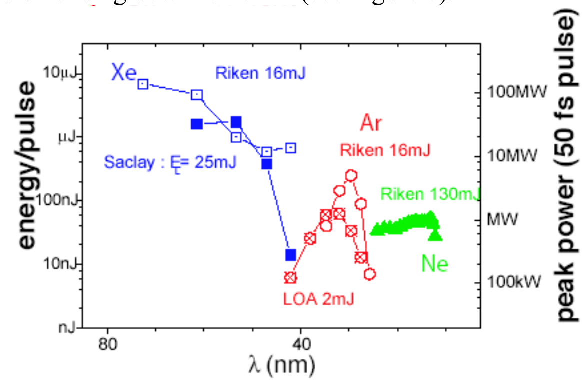

Figure 6: Performances of the harmonics produced in gases.

The HGHG source

A HGHG configuration is chosen: the modulator (planar type) has 50 periods of 30 mm, and the radiator (adjustable polarisation type) has 400 periods of 20 mm. 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 [9]. In order to consider 3D effect, a correction term has been put in the gain, using the dynamical filling factor [10] which considers the wiggling of the electron beam in the undulator. The transport of the optical wave of the High Harmonic in gas according to the implementation given in Figure 2a 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). Figure 7 shows the expected peak power versus the wavelength.

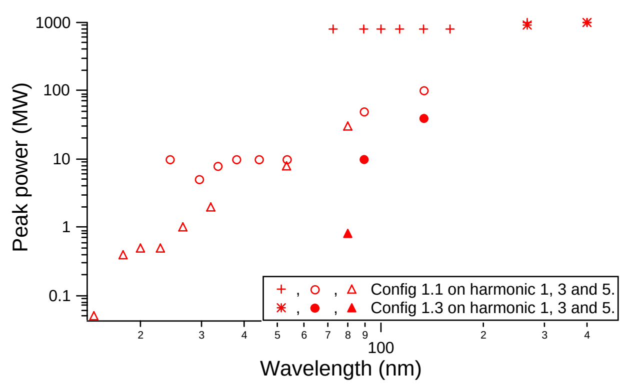

Figure 7: HGHG radiation + for the seeding wavelength, • for the third harmonic, Δ for the fifth harmonic. 1 kA peak power. Filling factor = 0.1

ARC-EN-CIEL PHASE 2

In the case of ARC-EN-CIEL phase 2 (see Figure 2b), the energy will be increased up to 1 GeV. The linac (see table 2) has been designed to deliver a 1 mA, 1 GeV electron beam in one pass, with 8 TESLA superconducting cryomodules composed of 9 cells. A 15 MV/m accelerating gradient in the 1.04 m long cavities results from a compromise between linac cost and cryogenic plant power (1.5 kW). The bunch compression scheme will aim at providing electron bunches in the 200 fs RMS range. Superconducting technology is selected for future energy recovery, more flexible time structure and a high repetition rate for user coincidence experiments. Two injectors are planned leading to different time structures. A pre-accelerating structure will raise the energy up to 50 MeV. Injector 1, an RF laser gun, equipped with a CsTe photocathode, operates with macropulses of 200 µs at 50 Hz (or 1 nC at 1MHz for HGHG, or 0.1 nC at 10 MHz for FEL oscillator). Injector 2 operating in CW is likely to be based on the superconducting technology or on an electrostatic gun.

HGHG light sources will be produced, with the same undulator characteristics, but a longer length (4 to 8 m for the modulator, and 4 sections of 4 m for the radiator). The seed is based on high harmonics in gas and the HGHG radiation is calculated as for ARC-EN-CIEL phase 1. The obtained radiation is shown in Figure 8.

Plasma acceleration and Thomson scattering will also be tested. THz radiation will also be provided.

ARC-EN-CIEL PHASE 3

The two optional loops, for Energy Recovery or energy enhancement, will host insertion devices for the production of femtosecond synchrotron radiation in the VUV and X ray ranges, together with a FEL oscillator, installed in the first loop, which covers the 120-10 nm, thanks to recent development of multilayer mirrors for lithography, and to SiC in normal incidence. It offers 0.1-1 kW average power, at 0.1-1 % bandwidth. Harmonics can also be produced from the FEL oscillator, with 500 MW at 4.5 nm and 10 MW at 2.7 nm. Using 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.

Table 2: Main linac characteristics

Linac		
Energy	MeV	1000
Length	m	96
Injection energy	MeV	50
Number of modules		8
Number of klystrons		16
Power per klystron	kW	100
Cavities		
Number		64
HF Frequency	GHz	1.3
Gradient	MV/m	15
Length	m	1.04
Q_0 (quality factor)		10^{10}
Dissipation	W	23.5
Temperature	K	2
Q_{ex} (coupling critical parameter)		10^7
HF power for 1 mA	kW	16.3
Beam		
Intensity per 1 passage	mA	1
Intensity with ER	mA	5-10
Bunch Charge	nC	1
Bunch Frequency	MHz	≤ 10
Transverse Emittance	m.rad	$2\ 10^{-6}$
Energy spread		1.10^{-3}

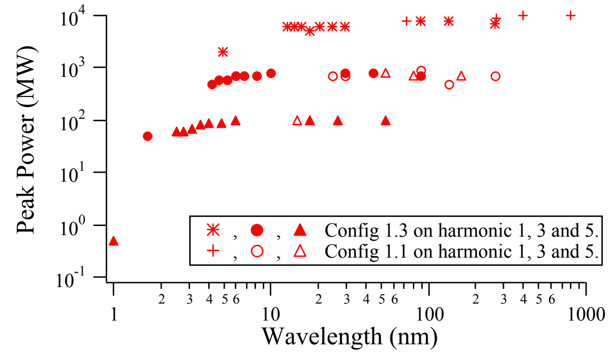

Figure 8: HGHG radiation for ARC-EN-CIEL Phase 2. 1.5 kA, 1.35 π mm.mrad, 0.0004% slice energy spread, 200 fs, beta=2 m, filling factor = 0.088.

Two 12 m long planar to helical permanent magnets (period 30 and 20 mm) will be placed, out of the vacuum chamber gap. The first one will be inserted on the first loop for fs VUV radiation, and the second one in the larger loop for fs X ray radiation. In the VUV, the flux on the fundamental for K=2 is of the order of 5.10^{12} phot/s/0.1%bw for an average current of 0.1 mA. These values are also obtained in the X ray range. One order of magnitude would be gained with in vacuum superconducting undulators.

In addition, an 8-10 keV X ray source, produced by Thomson scattering, will be implemented. For a laser operating at 6 Hz, with 2 J 20 fs pulses, the produced X ray beam presents a 20 fs pulse duration, with an opening angle of 3 mrad.

REFERENCES

[1] ARC-EN-CIEL, M.-E. Couprie et al.,"ARC-EN-CIEL, une installation innovante de source de 4e génération", rapport, http://www.lure.u-psud.fr/congres/femto/, G. Lambert et al., « The ARC-EN-CIEL FEL proposal », Proceed. SPIE conf, 50th anniver., San Diego, Aug. 2005.

[2] Workshop « Applications des sources accordables VUV-X femtosecondes combinant accélérateur et lasers : « slicing » à SOLEIL et le projet ARC-EN-CIEL », 3-4 feb 2004, Orsay, http://www.lure.u-psud.fr/congres/femto/.

[3] L.-H. Yu et al *Science* 289, 2000, 032.

[4] A. Loulergue, A. Mosnier, EPAC 2000.

[5] B. Dwersteg et al. *NIM* A 393 (1997) 93-95.

[6] V.N. Volkov et al, *PAC 2001*, 2218; M. Ferrario et al, Epac 2004.

[7] P. Salières et al., Adv. At., Mol., *Opt. Phys.* 41, 83 (1999).

[8] P. Zeitoun et al, Nature 431, (2004), 426.

[9] PERSEO, Luca Giannessi see. www.perseo.enea.it.

[10] W. Colson P. Elleaume Appl. Phys. B 29, (1982)10.