THE ARC-EN-CIEL FOURTH GENERATION LIGHT SOURCE PROPOSAL

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Abstract

The ARC-EN-CIEL (Accelerator-Radiation for Enhanced Coherent Intense Extended Light) project proposes a suit of novel light sources for the scientific community. Three FEL sources (LEL1, LEL2 and LEL4) sources rely on High Gain Harmonic Generation (HGHG) radiation and their Non Linear Harmonics seeded with the High Order Harmonics generated in Gas (HHG). LEL1 will cover the 200-1.5 nm spectral range with 100-30 fs FWHM pulses at a few kHz and adjustable in polarisation. LEL2 will provide 10-0.6 nm radiation with planar polarisation, in 100-30 fs pulses at a few kHz repetition rate. LEL4 will cover the 2-0.2 nm range, with 50-30 fs pulses at 1 kHz. LEL3 is a FEL oscillator in the 40-8 nm range with a repetition rate of 4.5 MHz. These FEL sources will reach MW to GW of peak power. In addition, undulator radiation will provide 200 fs pulses with energies up to 20 keV. FEL calculations are presented. The ARC-EN-CIEL project is phased according to the required electron beam energy: in phase 1 (220 MeV), the radiation extends down to 30 nm; in phase 1' (800 MeV) and phase 2 (1 GeV), the radiation reaches 1 nm. Phase 3 adds LEL3 and the Energy Recovery Linac loops at 1 GeV and 2 GeV, where undulators emit conventional synchrotron radiation above 20 keV from short period in vacuum undulators and soft-X rays are produced from variable polarisation undulators. The accelerator is based on superconducting technology to enable a high repetition rate. The use of plasma acceleration in the project is under investigation.

INTRODUCTION

ARC-EN-CIEL [1] aims at providing the French user community with coherent femtosecond light pulses covering from UV to soft X ray spectral range. It is based on a 1 GeV CW 1.3 GHz superconducting linear accelerator delivering high charge, subpicosecond, low emittance electron bunches at high repetition rate. It is to be built in several phases, according to the electron beam energy, the average current and the light sources available for the users (see Table 1). It comprises 13 beamlines : 4 FEL lines of which three are HHG seeded, as demonstrated on the SCSS Prototype Accelerator in Japan [2], 6 spontaneous radiators in the X ray range, one in the VUV, 2 THz ones (see fig.1).

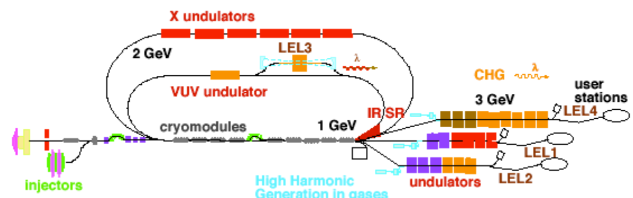


Figure 1 : General scheme of ARC-EN-CIEL.

Table1 : List of radiation sources on ARC-EN-CIEL. P: Phase, M: Modulator, R: Radiator, SR: Synchrotron Radiation, CSR: Coherent Synchrotron Radiation, BC: Bunch Compressor, E: Energy, conf: configuration, BL : beam line, λ: wavelength

	P	E GeV	Type	M/R, N	λ
FEL radiation					
LEL1 Planar helical	1, 1', 2	0.22 - 1	HHG seeded HGHG, conf 1-1 1-3	M :U26 R : HU30	200-1.5 nm
LEL2 Planar branch	2	0.8-1.2	HHG seeded HGHG, conf 1-1 1-3	M :U26, R : U18	10-0.5 nm
LEL4 planar branch	3	3	HGHG conf 1-3and 1-5 HHG seed	M :U35, R :U18,	2-0.2 nm
LEL3	3	1	FEL oscillator	HU30	40-8 nm
Spontaneous emission					
VUV BL	3	1	SR	HU30	0.2-4 keV
X BL	3	2	SR	U 20	1-20 keV
THz Radiation					
	1-1' 2, 3		CSR	Arcs BC1-2	0.1-10 THz

THE ELECTRON BEAM DYNAMICS

A high peak brightness gun based on a 40 MV RF gun [3] in phase 1 and 2 and a second high average current gun (AES/JLab type [4]) for phase 3 are planned. The accelerator comprises from 3 (phase 1) to 10 cryomodules (phase 2 and 3) of 14 MV/m, a third harmonic cavity linearizer, S-chicane magnetic compressors and two energy recovery / re-acceleration loops at 1 and 2 GeV.

Table 2 gives the beam parameters used for FEL simulations and derived from beam dynamics calculations performed with ASTRA for Phase 1 and 2, and BETA and BU for Phase 3 [5]. Simultaneous electron beams (1 kHz high peak current for LEL1 and LEL2 and the high repetition rate (1-100 MHz) for phase 3) operation is insured with low energy beams recombination at the loop entrance and separation at the exit of the accelerating structures via kicker magnets.

Table 2 : ARC-EN-CIEL beam parameters: total (resp. slice) energy spread $\sigma_\gamma/\gamma_{to}$ (resp. $\sigma_\gamma/\gamma_{slice}$), total (resp. slice) beam ε_{tot} emittance ε_{tot} (resp. ε_{slice})

Phase	1	2	3, mode 1	3, mode 2	3
E Energy (Gev)	0.2	1	1-2	1-2	3
Rep. rate (kHz)	1-10	1-10	10^3–10^5	10^3–10^5	1
Charge (nC)	1	1	0.2//1	0.2//1	0.75
ΔT(fs rms)	500-600	200-300	500-600	500-600	200
<I> (μA)	1-10	1-10	10^3-10^5	10^3-10^5	
I_{peak} (kA)	0.8	1.5	0.2	1	
$I_{peak,slice}$(kA)	1	2	1	1	1.5
ε_{tot}(π mm mrad)	2.4	1.6	2	6	
ε_{slice} (π mm mrad)	1	1.2	1	5	1.2
$\sigma_\gamma/\gamma_{tot}$ (%rms)	0.1	0.1	0.1	0.2	
$\sigma_\gamma/\gamma_{slice}$ (%rms)	0.04	0.04	0.04	0.08	0.02

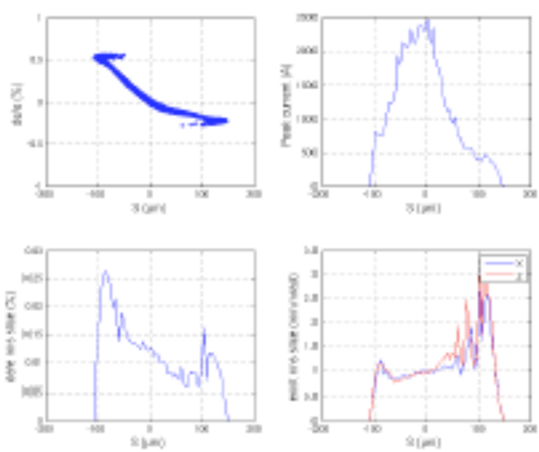


Figure 2: Phase 2 longitudinal phase space, peak current, slice emittances and energy spread at 1 GeV.

In phase 1, a 10 m S-chicane magnetic compressor located downstream of the first cryomodule and a third harmonic cavity allow the bunch to be compressed from 2 mm to 140 μm rms at an energy of 100 MeV while preserving the slice emittance. The current profile exhibits a flat top of 550 fs (150 μm) at a peak current of 800 A with an energy spread of 1 to 2 10^{-4}. At 330 MeV, the maximum energy in phase 1, an energy chirp of a few 10^{-4} is remaining in the central region; it can be canceled by strong off-crest phasing (60°) of the two downstream cryomodules at the expense of an energy reduction down to 220 MeV. In phase 2, the beam is compressed at 100 MeV from 2 mm to 320 μm rms without any emittance deterioration and then at 500 MeV down to 50 μm rms, while preserving the slice emittances. The longitudinal profile exhibits a flat top of 200 fs (60 μm) at 2000 A with an energy spread of 10^{-4} (see fig. 2). At 1 GeV, energy chirp of few 10^{-4} remains in the central region. With a 20 ps laser pulse irradiating the photocathode and 40 MV of accelerating voltage in the gun, the slice emittances is 1 π .mm.mrad; it can be reduced down to 0.6 by lengthening the laser pulse to 40 ps and furthermore to 0.4 by increasing the voltage to 60 MV, hence reaching the cathode thermal emittance limit. The total emittance is more or less unchanged by lengthening the laser pulse from 20 to 40 ps. Ellipsoidal laser pulse shape [6] for space charge cancellation enables to increase the electron density on the cathode with lower accelerating field. Simulations (see. fig.3) predicts 20 % reduction of the central slice thermal emittance for a 20 ps laser pulse. For a longer laser pulse, the reduction is less effective. Changing the standard case (40 MV, 20 ps) into a trapezoidal bunch laser profile with 60 MV, 40 ps, allows increasing the brightness by a factor of about 6, with a current profile close to a flat-top of about 600 fs. For the two ellipsoidal cases, the total brightness exhibits a curved shape along the slices with a minimum in the middle, resulting from the flat-topped current together with smaller emittances on each side. With 40 MV and 20 ps, the ellipsoidal distribution allows the brightness to be enhanced by a factor from 2 to 3. The process is less effective for longer pulses (factor 1.5-2 for 40 ps).

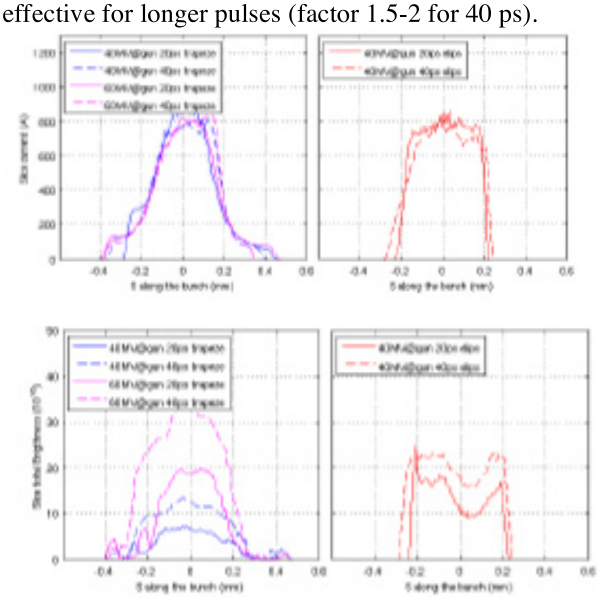


Figure 3: a) Current profile after compression to 800 A b) Slice total brightness after compression.

UNDULATORS

The HHG seeded FELs are based on the HGHG scheme where the radiator, located downstream of the modulator and the dispersive section, can be tuned on the 1st, 2nd or 3rd harmonic of the subharmonic of the fundamental (harmonic cascade scheme [7]). The undulator choice (see table 3) relies on the SOLEIL know-how [8] and magnetic field evaluations using analytical expressions or RADIA calculations [9]. Mainly, the modulators are in vacuum ones (and even cryogenic ones [10]) and the radiators are APPLE-II undulators [11] (APPLE-III type [12] and in-vacuum APPLE-II being also under consideration). The undulators are to be built in segments with a FODO lattice in between. Optical Transition Radiator screens and Beam Position Monitors will be placed downstream each undulator module.

Table 3 : Undulators for ARC-EN-CIEL sources. M : Modulator, R : radiator, * : cryogenic undulators. In vac : in vacuum, L : Length

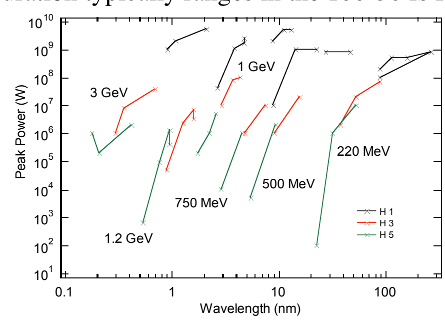
FEL	Type	λ_o mm	K_{max}	Gap_{min}	L (m)
LEL1-M	In vac	26	3.2	3.5	5.2
LEL1-R	Apple-II	30	P:2.16 H:1.5	10 8	21
LEL2-M	In vac	26	3.2	3.5	13
LEL2-R	In vac*	18	3.1*	3.7	9
LEL3	Apple-II	30	P:3.36 H:1.5	6 8	10.5
LEL4-M	In vac *	35	4.8	3.5	24.5
LEL4-R	In vac *	18	3.1*	3.7	18
VUV	Apple-II	30	P:1.1 H:0.7	15.5	2
X	In vac	20	1.9	5.5	2x6

LIGHT SOURCES

Table 4: Characteristics of the main ARC-EN-CIEL FEL sources: λ: wavelength, E: Energy , Pol. Polarisation (P: planar, H: helical), τ: pulse duration, Rep. rate: Repetition rate , DV: divergence, D : transverse dimensions, DL: Diffraction limit, P: Peak power, <P>: average power

	LEL1	LEL2	LEL3	LEL4
Type	HHG seeded	HHG Seeded	Oscillator	HHG seeded
Phase	1, 2, 3	2	3	3
λ (nm)	200-1.5	10-0.6	40-8	2-0.18
E (keV)	0.1-2	0.15-2	0.3-0.15	0.6-6
Pol.	P/H	P	P/H	P
τ (fs) FWHM	100-30	100-30	100-300	50-30
Rep. rate	1-10 kHz	1-10 kHz	4.5 MHz	1 kHz
DV (μrad)	Close to DL	Close to DL	35	Close to DL
D (μm)			100	
P	10 GW-1 MW	4 GW-MW	70-7 MW	5GW-1 MW
<P>	10-0.001 W	4-0.001 W	600-50 W	5W-0.001 W
Δ λ/ λ (0.01%)	2-0.5	2-0.5	5-1	2-1

ARC-EN-CIEL presents three HHG seeded FELs. HHG produced from the strong non linear polarisation induced on the rare gases atoms by the focused intense electromagnetic field of a pump laser [13] are suitable for seeding FELs since the radiation is tunable in the VUV-XUV window [14], linearly polarised, with a high temporal [15] and spatial [16] coherence and very short pulses (attosecond pulses in a femtosecond envelop) at a relatively high repetition rate (up to few kHz). Of interest for ARC-EN-CIEL studies, HHG seeding has been successfully demonstrated on the SCSS Test Accelerator in the frame of a French-Japanese CEA/SOLEIL /RIKEN) collaboration [2]. The HHG seed is injected inside the modulator via a set of two spherical or toroidal high reflectivity mirrors for adjusting the focusing inside the undulator and two periscope mirrors for introducing the light on axis on a chicane of the accelerator [17]. The FEL sources (see Table 4 and fig. 5) have been calculated using PERSEO Time dependent [18] with a Filling factor [19] of 0.1 for describing the transverse overlap between the electron and the seed beam and GENESIS 1.3 [20], coupled to SRW [21] for further propagation of the FEL wavefront to the beamline [22]. Seeded FEL sources cover a wide spectral range via combined sets of gap (fine adjustment) and electrons beam energies (kicker at 500 MeV for LEL1, 0.8-1.2 GeV by phase tuning for LEL2, 3 GeV for LEL4). Further spectral tuning can be achieved with a combined chirp on the laser and the electron beam. Pulse duration typically ranges in the 100-30 fs FWHM.



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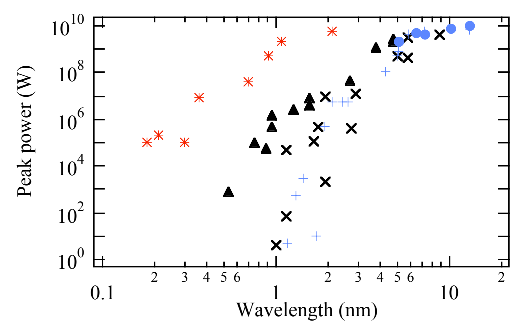

b

Fig. 5: Spectral range covered by the HHG seeded FEL sources of ARC-EN-CIEL a) Wide spectral range : fundamental (black), third (red) and fifth (green) harmonics of the radiator b) Short wavelength spectral range : Seed 30-50 kW, 50 fs-FWHM: LEL1 (Phase 2), (+) planar (o) helical configuration ; LEL2 (x) E=1 GeV, (Δ) E=1.2 GeV; * LEL4 in Phase 3.

LEL3 consists in a FEL oscillator using an optical resonator composed of two spherical mirrors with cryogenic cooling and possibly deformable optics. In normal incidence, multilayers around 13 nm present a high reflectivity thanks to the development carried out for lithography. At 1 GeV, the spectral range in circular (resp. planar) polarisation on the fundamental covers 20-8.5 (resp. 40-10 nm), with peak power of 120 (resp. 50 MW) and average power of 90-550 (resp. 200 W). LEL3 is complementary to LEL1, since it provides to the users a source with higher average and lower peak power.

Table 5 : FEL Oscillator

Mirror radius of curvature	16-20 m
Optical cavity length	34 m
Repetition rate	4.5 MHz
Max. absorbed power on mirrors	2 kW

Radiation from the spontaneous emission undulator sources has been calculated using the SRW computer code. The peak brilliance is plotted in fig. 6. Table 6 presents the THz emission performances.

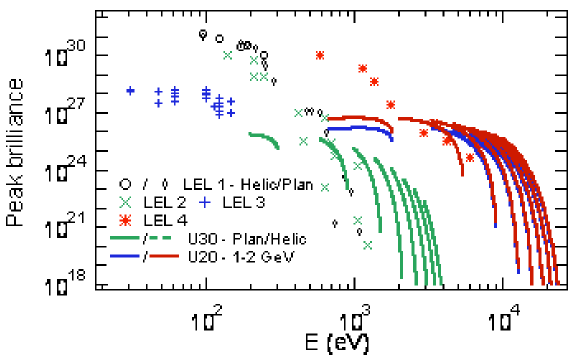

Figure 6: Peak Brilliance of ARC-EN-CIEL (10 kHz assumed for phase 2, 20 mA average current for phase 3).

Table 6: THz magnet edge radiation sources : P : Phase, ΔT_e : RMS electron bunch length, Q: charge, B: magnetic field, M: magnet (C for chicane and A for Arc) f: peak radiation frequency, w: wavenumber, r: rep. rate, e: pulse energy, p: average power, * integrated within spectral range between 0.1 THz and 10 THz, for the horizontal (vertical) beamline acceptance angles 60 mrad (40 mrad).

P	ΔT_e	Q	E	B	M	f/w	r	e*	p*
	ps	nC	GeV	T		THz / cm^{-1}	kHz	μJ	W
1	2	1	0.105	0.17	C	0.084 / 2.8	10	0.27	0.0027
2	0.17	1	0.5	0.46	C	0.62 / 20.8	10	193	1.93
3	0.17	1	1.0	1.17	A	0.57 / 19	1-2.10^4	208	2080-4170

SCIENTIFIC CASE

ARC-EN-CIEL is well adapted for studies in various scientific domains using coherent imaging, linear spectroscopy, pump-probe experiments, non-linear and high intensities studies. ARC-EN-CIEL scientific case has been first discussed during a workshop “application of VUV-X fs tuneable sources combining accelerators and lasers : “slicing” at SOLEIL and the ARC-EN-CIEL project” in Feb. 2004 [23]. The scientific case has been up-dated while preparing the Conceptual Design Report. A New workshop on the Scientific Opportunities in France for a 4th Generation Intermediate Energy Light Source is organised in Paris in October 2008, 23-24 [24]. ARC-EN-CIEL sources can then be optimised again according to the expressed needs.

CONCLUSION

The Conceptual Design Report has been completed [25]. Scenarios for cost reduction question again the type of accelerator (normal or super-conducting) or rise the possibility of operating with a main super-conducting linac of 500 MeV Linac with a recirculation for reaching 1 GeV. A stage of laser-plasma acceleration is also considered. Opening to European or international collaborations or partnerships are also under discussion.

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