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THE ARC-EN-CIEL RADIATION SOURCES

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Abstract

The ARC-EN-CIEL (Accelerator-Radiation for Enhanced Coherent Intense Extended Light) project proposes a panoply of light sources for the scientific community on a 1 GeV superconducting LINAC (phase 2) on which two ERL loops (1 and 2 GeV) are added in phase 3. LEL1 (200-1.5 nm), LEL2 (10-0.5 nm) and LEL4 (2-0.2 nm) are three kHz High Gain Harmonic Generation Free Electron Laser sources seeded with the High order Harmonics generated in Gas, with 100-30 FWHM pulses. A collaboration, which has been set-up with the SCSS Prototype Accelerator in Japan to test this key concept of ARC-EN-CIEL, has led to the experimental demonstration of the seeding with HHG and the observation up the 7th non linear harmonic with a seed at 160 nm. LEL3 (40-8 nm) installed on the 1 GeV loop is a MHz FEL oscillator providing higher average power and brilliance. In addition, in vacuum undulator spontaneous emission source extend the spectral range above 10 keV and intense THz radiation is generated by edge radiation of bending magnets. Optimisations and light sources characteristics are described.

INTRODUCTION

Table 1: List of radiation sources on ARC-EN-CIEL. Phase : P. 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

ARC-EN-CIEL [1] aims at providing the user community with coherent femtosecond light pulses covering from UV to soft X ray. ARC-EN-CIEL 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 on different phases, according to the electron beam energy, the average current and the light sources available for the users (see Table 1). ARC-EN-CIEL comports 13 beamlines : 4 FEL lines among which three are HHG seeded ones, as demonstrated on the SCSS Prototype Accelerator in Japan [2], one FEL oscillator, 6 spontaneous radiators in the X ray range, one in the VUV, 2 THz ones, as shown in fig.1.

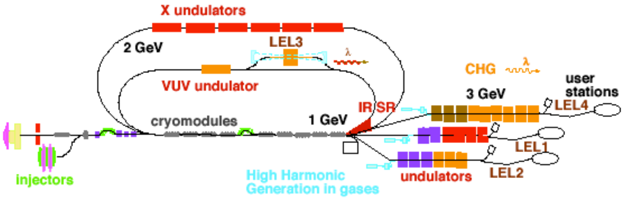

Figure 1: General scheme of ARC-EN-CIEL

THE CONSTITUTING ELEMENTS

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

Phase	1	2	3, 1 loop	3, 2 loops	3
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

Two guns are foreseen : a first one based on a modified Zeuthen RF gun [3] for high peak brightness for phase 1 and 2, and a second one (AES/JLab type [4]) with high average current for phase 3. The accelerator comports from 3 (phase 1) to 10 cryomodules (phase 2 and 3) and two energy recovery / re-acceleration loops at 1 and 2 GeV. Table 2 gives the beam parameters taken for FEL simulations, derived from beam dynamics calculations performed with ASTRA, CSR-Track and TRAFFIC-4 for Phase 1 and 2, and using 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 beams recombination at low energy at the loop entrance and separation at the exit of the accelerating structures via kicker magnets.

The HHG seeded FELs are based on the HGHG scheme where after the modulator and the dispersive section, the radiator can be tuned on the 1st, 2nd, 3rd or harmonic of the subharmonic of the fundamental (harmonic cascade scheme [6]). The undulator choice (see Table 3) relies on SOLEIL know-how [7] and magnetic field evaluation using analytical expressions [8] or RADIA calculations [9]. Mainly, the modulators are in vacuum ones (and even cryogenic ones [10]) and 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 2 meters length segments with a FODO lattice in between two segments with average betatron functions of 2.6 m. After each undulator module will be placed Optical Transition Radiator screens and Beam Position Monitors.

The harmonic generation in gas results from the strong non linear interaction of a focused intense laser on rare gases atoms, such as Ar, Xe, Ne and He [13]. HHG radiation is tunable in the VUV-XUV window [14], linearly polarised, presents a high temporal [15] and spatial [16] coherence, emitting very short pulses (attosecond pulses in a femtosecond envelop) at a relatively high repetition rate (up to few kHz).

The HHG seed can be injected inside the modulator via a set of two spherical or toroidal mirrors for focusing inside the undulator, and two periscope mirrors for introducing the light through a chicane. For the first, third and fifth harmonics, mirrors are high reflectivity multilayers (oxides and fluorides). In the VUV, Al metallic and then SiC mirror can be used. In the soft X ray, X ray multilayers are available [17]. In normal incidence (as for LEL3), multilayers around 13 nm present a high reflectivity thanks to the development carried out for lithography.

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

	LEL1	LEL2	LEL3	LEL4
Type	HHG seeded	HHS 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
Δλ/ λ (0.01%)	2-0.5	2-0.5	5-1	2-1

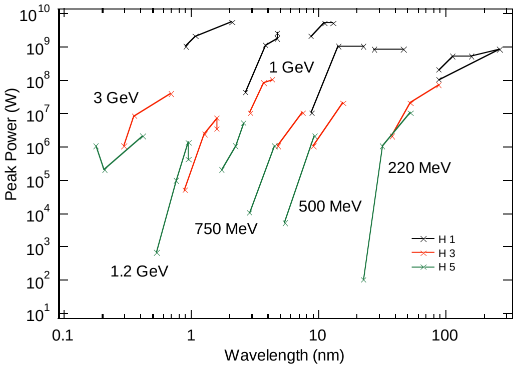

Figure 2: Wide spectral range covered by the HHG seeded FEL sources on the fundamental (black), third (red) and fifth (green) harmonics of the radiator.

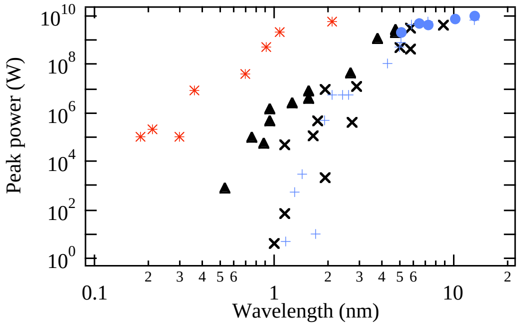

Figure 3: Short wavelength spectral range covered by the HHG seeded FEL sources. Seed 30-50 kW, 50 fs-FWHM: LEL1 (Phase 2), (+) planar (o) helical configuration ; LEL2 (x) E=1 GeV, (Δ) E=1.2 GeV; * LEL4 in Phase 3.

The FEL sources (see Table 4) have been simulated using PERSEO Time Dependent [18] using a Filling factor [19] of 0.1 for describing the transverse overlap between the electron and the seed beams and GENESIS 1.3 [20], coupled to SRW [21] for further propagation of the FEL wavefront to the beamlines.

Seeded FEL sources cover a wide spectral range (see fig. 2) via combined sets of gap and electron beam energies (kicker at 500 MeV for LEL1, 0.8-1.2 GeV by phase tuning for LEL2, 3 GeV for LEL4). A closer zoom for short wavelength radiation is shown in fig. 3. Fine tuning will result from a simultaneous gap change of the undulators and wavelength modification of the Ti:Sa laser illuminating the gas cell for the HHG production, coupled to a change in the monochromators. Further spectral tuning can be achieved with a combined chirp on the laser and the electron beam.

Pulse duration and spectral width decrease along the path in the radiator and start to increase again after saturation. The minimum of pulse duration is reached earlier on the harmonics than on the fundamental. The FEL pulse duration and spectral width does not vary significantly when the seed pulse duration is changed from 150 fs to 50 fs.

Simulations show a great sensitivity of the FEL peak power to different parameters (see Table 5).

Table 5: Peak power P sensitivity to different parameters

Parameter	P reduction
Emittance : 1.8 to 1.5 π mm.mrad	Factor 10
peak current : 2 kA to 1.5 kA	Factor 2
Energy spread : 0.06% to 0.08%	Factor 10
Synchronisation : ±35 fs	10%
Spectral tuning : ±0.025 nm @38 nm	10%

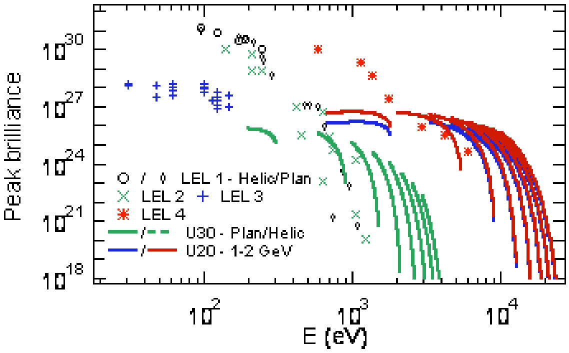

Fig. 4 : Peak Brilliance of ARC-EN-CIEL (10 kHz assumed for phase 2, 20 mA average current for phase 3).

The FEL oscillator uses an optical resonator composed of two spherical mirrors of 16 and 20 m raddi of curvature separated by a 34 m length, for insuring the proper synchronism condition with the electron bunch spacing (4.5 MHz). 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. The absorbed power by the mirrors has been limited to 2 kW, assuming cryogenic cooling as usually done on the SOLEIL beamlines. The use of deformable mirrors is foreseen. LEL3 is complementary to LEL1, since it provides to the users a source with higher average and lower peak power.

Radiation from the spontaneous emission undulator sources has been calculated using SRW. The peak brilliance is plotted in fig. 4. Figure 5 presents the spectral energy per pulse and the average spectral power of the THz emission.

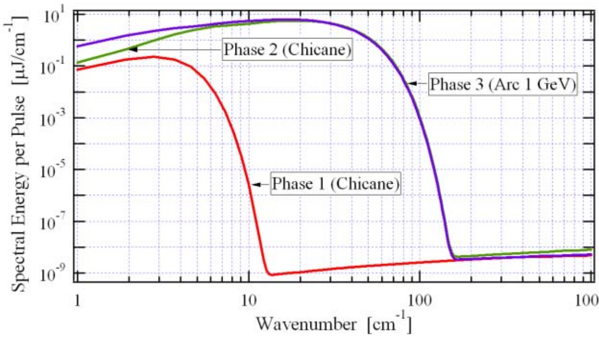

Figure 5: Terahertz spectral energy per pulse collected by 60 mrad (H) x 40 mrad (V) aperture ports.

REFERENCES

[1] M. E. Couprie et al., FEL07, 505
[2] G. Lambert et al, Nature Physics 889 (2008) 296
[3] J.H. Han et al, EPAC04, 357
[4] T. Rao et al, PAC05, 2556.
[5] A. Loulergue “ARC-EN-CIEL project electron beam dynamics” these proceedings
[6] L. Giannessi et al., New Jour. Phys. 8, 294(2006)
[7] C. Benabderrahmane et al, PAC07, 929-931
[8] P. Elleaume et al., Nucl. Inst. Meth. A 455, (2000) 503
[9] P. Elleaume, O. Chubar, J. Chavanne, PAC97, 3509
[10] T. Hara et al. Phys. Rev. Special Topics 7, 050702 (2004), H. Kitamura Proceed. Synch. Rad.Inst. 2006, SRI May, Daegu, Korea; C. Kitegi et al., EPAC 06, 3559; T. Tanabe et al., AIP Conference Proceedings 879, 283 (2007); C. Benabderrahmane et al., these proceed.
[11] S. Sasaki Nucl. Ins. Meth. A331 (1993) 763
[12] J. Bahrdt et al., Proceed. FEL2004, JACoW, 610-613
[13] P. Salières et al., Opt. Phys. 41, 83 (1999)
[14] Z. Chang et al, Phys. Rev. Lett. 79 (1997), n°16, 2967; Seres, J. et al. Nature. 433, 596 (2005) ; E. Gibson et al. Phys. Rev. Lett. 92 (03), 3001 (4) (2004);M. Zepf PRL99 (2007) 143901
[15] H. Merdji et al, Phys. Rev. A 74 (2006) 043804
[16] L. Le Déroff et al, Phys. Rev. A61, 19 (2000), 43802
[17] P. Zeitoun et al, Appl. Phys. B 78, 983 (2004),
[18] L. Giannessi, proceedings of FEL06, 91 (2006)
[19] W. Colson P. Elleaume Appl. Phys. B 29, (1982)10
[20] GENESIS, S. Reiche, NIM A 429, (1999) 243
[21] O. Chubar et al, “Numerical Propagation Simulations and Coherence Analysis of SASE Wavefronts” ELBE XXX, to be published in Nucl. Inst. Meth.