ARC-EN-CIEL project electron beam dynamics

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Abstract

ARC-EN-CIEL project is based on the development of fourth generation tunable light source of high brilliance in the VUV to soft X-ray wavelength domain. The project will evolved into three phases : first and second phases are in single pass configuration, while third phase comports recirculation loops. For delivering a high brilliance light source with high peak power short pulses, the high charge electron beam should have subpicoseconde duration with low emittance and energy spread. In order to keep optimal slice characteristics for light production, phase space non linearities due to optics aberrations and collective effects should be minimized. In ERL configuration, the accelerator scheme and focusing should be optimized to take into account collective effects as Beam Break Up instability.

INTRODUCTION

This project is based on the development of a fourth generation subpicosecond light source, with a high brilliance and tunable in the VUV to soft X-ray wavelength domain[1]. ARC-EN-CIEL views two simultaneous modes of operation :

- A high charge, low emittance electron beam for HGHG (High Gain Harmonic Generation) operation : a 1 nC electron bunch charge compressed by two chicanes, with 1 to 10 kHz repetition rate and 1 to 10 μA average current,
- A high average current electron beam for synchrotron radiation operation : a 0.2 to 1 nC electron bunch charge, with 1 to 100 MHz repetition rate and 1 to 100 mA average current.

The HGHG based FEL sets requirements on the beam : high charge, sub-picosecond duration, and low emittance. Optics aberration or collective effects, which are accentuated by high charge, are able to generate non linearities, which damage beam characteristics [2, 3].

Adding recirculation loops allows high average current operation and the energy to be increased by keeping high densities subpicosecond bunch. However, collective effects as Beam Break up instability, form a feedback loop between electron beams and RF cavities. Then, hereafter a threshold current, the oscillation amplitude of the beam transverse position exponentially grows leading to the beam loss [4].

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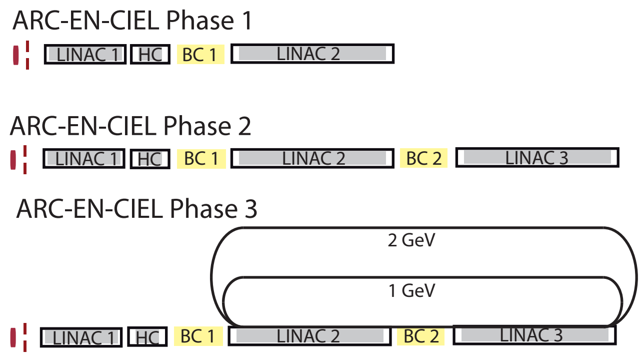

Figure 1: Representation of the ARC-EN-CIEL accelerator for the different phases. LINAC : Linear accelerator composed of cryomodules, HC : third harmonic cavity, BC : bunch compressor. To view all components, the representation is not scaled. Phase 1 is 70 m long, phase 2 : 200 m, phase 3 : 200 m with a radius of the arcs of 15 and 30 meters.

This paper presents the electron beam dynamics for the ARC-EN-CIEL project in single pass and ERL configuration, especially on the conditions for minimizing non linearities and Beam Break Up instability.

SINGLE PASS CONFIGURATION

ARC-EN-CIEL phase 1 and 2 (see fig. 1) aim at providing a 220 MeV and 1 GeV electron beam. The technology employed is a RF gun [5] followed by superconducting TESLA type [6] cryomodules. Chicanes are used to compress the beam duration. In this section, simulations realized for both single pass cases of ARC-EN-CIEL are presented by pointing out the optimisation for the light production.

The RF gun and the cavity modules have been simulated using ASTRA [7]. The laser, which lights the photocathode is 20 ps long (2.1 mm rms) with a cylindrical uniform distribution. To take into account the Coherent Synchrotron Radiation (CSR) in the chicane, the CSRTrack code [8] has been employed to model the compression scheme.

ARC-EN-CIEL phase 1

The RF gun produces a 1.1 $\pi\ mm\ mrad$ total emittance with a total charge of 1 nC. Then a first cryomodule (LINAC1) leads to an energy of 120 MeV. A third harmonic cavity (HC) tuned in order to suppress non linearities (RF and magnetic) is placed before the chicane [9]. Figure

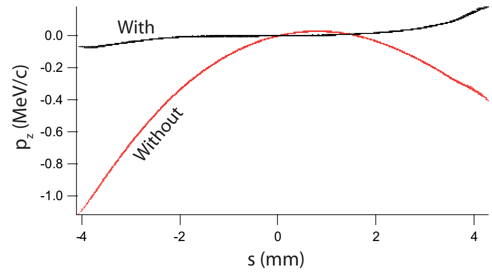

Figure 2: Comparison of the longitudinal phase space of the electron bunch before the chicane without or with a harmonic cavity in the case of ARC-EN-CIEL phase 1. Charge 1 nC, energy 110 MeV.

2 illustrates the effect of the harmonic cavity after the first cryomodule, which highly distorts the beam. However the distortion in the edges of the distribution remains due to the space charge force, which could be linearized by an ellipsoidal shaping of the laser at the cathode [10, 2]. The compression, from 7 to 500 fs rms long is realized thanks to a magnetic chicane (BC1). A compromise between a smaller energy beam chirp and a reduced effect of CSR leads to a ten meters long chicane with a R_{56} coefficient set at $0.2\ m$. The compression increases the total emittance from 1.1 to $2\ \pi\ mm\ mrad$ (see figure 3). Whereas with an adequate optics [11], the slice emittances along the bunch remain almost unchanged (ranging from 1 to 1.5) with a small mismatch from slice to slice. The compressor creates a correlated emittance that reaches $0.2\ \pi\ mm\ mrad$, which denotes a spread of the slices in the transverse phase space. Although weak, it is the main contributor to the total emittance increase by strong mismatching.

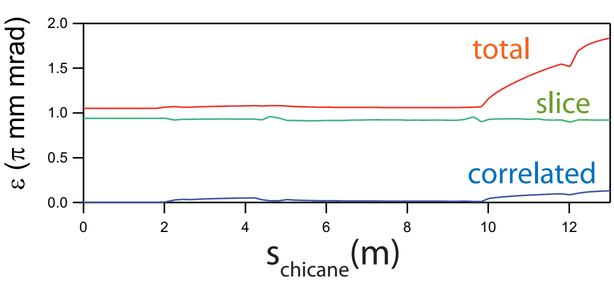

Figure 3: Evolution of the total, central slice and correlated emittance along the chicane at 110 MeV in the case of ARC-EN-CIEL phase 1. Charge 1 nC, energy 110 MeV, compression from 7 ps to 500 fs, R_{56}= 0.2 m, $L_{chicane}$=10m.

Then, the second linac, formed by two cryomodules with a phase adjusted to obtain a minimized energy spread at the end of the accelerator, increases the energy from $110\ MeV$ to $220\ MeV$. The slice energy spread remains low and of the order of $0.05\ \%$.

Figure 4a illustrates the longitudinal phase space representation of the electron beam at the end of the accelerator. It presents distorsions due to the space charge force and the CSR effect in the chicane. In spite of this non linearities, the slice emittance along the bunch remains almost constant with a low value around $1\ \pi\ mm\ mrad$ (see figure 4b). The peak current at the center of the bunch attains $0.9\ kA$.

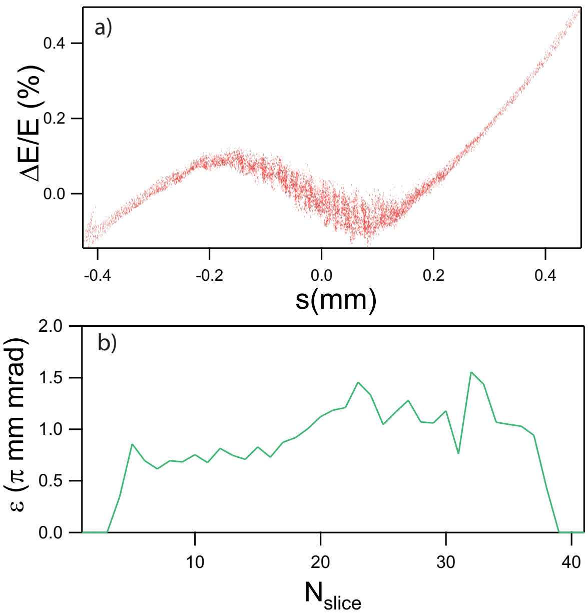

Figure 4: Electron bunch simulations for ARC-EN-CIEL phase 1. a) Longitudinal phase space representation, b) slice emittance along the bunch at the end of the linear accelerator. Charge 1 nC, Energy 220 MeV, bunch duration 500 fs

ARC-EN-CIEL phase 2

For this case, the compression uses a second chicane placed at an energy around 500 MeV. The compression is relaxed in the first chicane from 7 ps to 800 fs compared to ARC-EN-CIEL phase 1. This leads to a conserved slice and total emittance whereas a correlated emittance is created in the chicane. Then, a second linac composed by four cryomodules increases the energy from $110\ MeV$ to $550\ MeV$ and enables adjusting the energy spread chirp for a second chicane ($R_{56} = 0.05\ m$), which compresses the beam from 800 fs to 250 fs with very small degradation of the total and slice emittances. A third linac (five cryomodules) tuned to redress the energy spread brings the energy to 1 GeV. The electron beam slice energy spread and emittance are represented in figure 5. They remain small along the bunch around 0.04% of central slice energy spread, $1.2\ \pi\ mm\ mrad$ of slice emittance, and a peak current of $3\ kA$.

ERL CONFIGURATION

ARC-EN-CIEL phase 3 consists in adding two recirculation loops. The electrons beam is first accelerated during a first pass in the accelerating cavities, and decelerated with

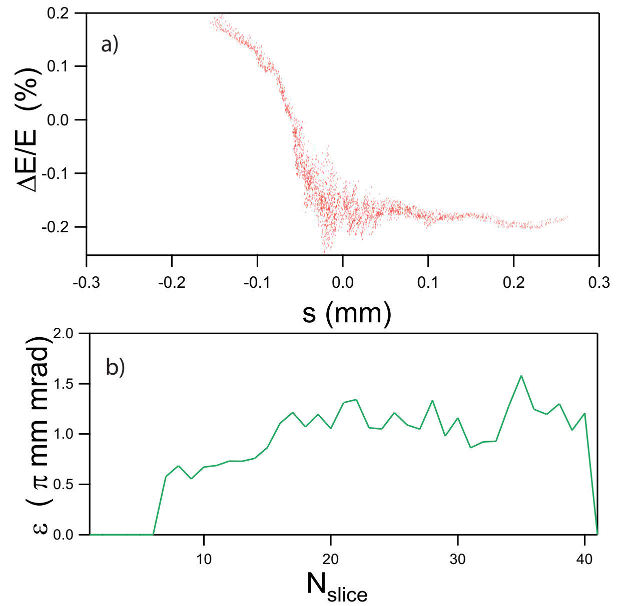

Figure 5: Electron bunch simulations for ARC-EN-CIEL@1 GeV. a) Longitudinal phase space representation, b) slice emittance along the bunch at the end of the linear accelerator. Simulations parameters are : charge=1 nC, Energy=1 GeV, bunch duration =250 fs

an opposite phase during a second pass, while restoring the energy to the high frequency structures. By way of limited numbers of turns, the electron bunch duration can stay in the picosecond order contrarily to storage rings. For Energy Recovery Linac (ERL) mode, higher average current can be obtained. A high current operation requires a separate cw gun based on a DC photoinjector (Jlab type), which provide a 1 to 100 MHz pulsed electrons beam at 0.2 to 1 nC charge. A SRF gun will be employed depending on their development [13].

Arcs optics

Two recirculating loops at 1 and 2 GeV are added to ARC-EN-CIEL phase 2. There lattices are based on the Double Bend Achromat of SOLEIL storage ring without straight sections. Each arc are respectively 50 and 100 m long for 1 end 2 GeV. The optics is design in order to control globally and locally the first and second order isochronism (R_{56} and R_{566}) to prevent over compression or lengthening of the bunches. The chromaticities are also tunable. The optical functions of the 1 GeV arc are sketched on figure 6.

Beam Break up and linac focusing

ARC-EN-CIEL design should takes into account the required conditions, particularly on the transverse focusing, to minimize the Beam Break Up current threshold. Studies of this instability for ARC-EN-CIEL is realized thanks to BI code [12]. From a collective point of view, instabilities become more critical as the case of linear accelerator. Instabilities lead to beam loss at a threshold current, which depends on optics, number of recirculations and cavity quality factor. Transverse beam break up appears to be the limiting factor for ERL [4]. To simulate the transverse transport of the ERL configuration, a code has been developed under Matlab. It allows the parameters of the accelerator and the optical function to be adjusted. Simultaneously the transfer matrix calculated for each element is written in the lattice file BI code input. The matlab code scans the optical functions and optimizes the threshold current for a given accelerator configuration. The quadrupoles are approximated by thin lenses surrounded by two straight sections. The straight length is half the quadrupoles ones L_{qp}. The arc is not yet relevant and is just considered as an ellipse transport with imposed conditions at the entrance and at the exit. The phase advance of the arc is adjusted to maximize the threshold current. The β functions are the same at the entrance and at the exist of the arc, and the α functions are of opposed sign to keep the symmetry.

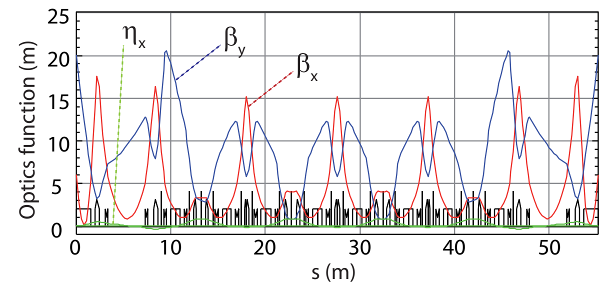

Figure 6: Optics functions versus the position along the arc at 1 GeV. β_x: vertical beta function, β_x: horizontal beta function, η_x: dispersion function.

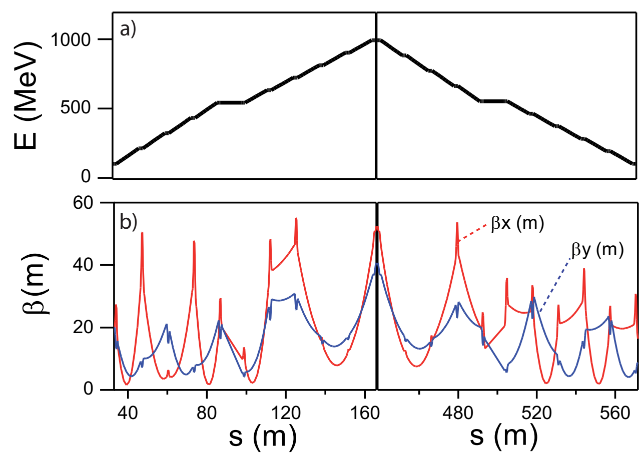

Figure 7: a) Energy and b) beta functions versus the position along the accelerator. Parameters are : drift between the quadrupoles and between the cryomodule and the quadrupole is set at 0.3 m and the length of the quadrupoles at 0.3 m, focusing strength of $2.5\ m^{-2}$ and threshold current of $30\ mA$ for 1 MHz repetition rate.

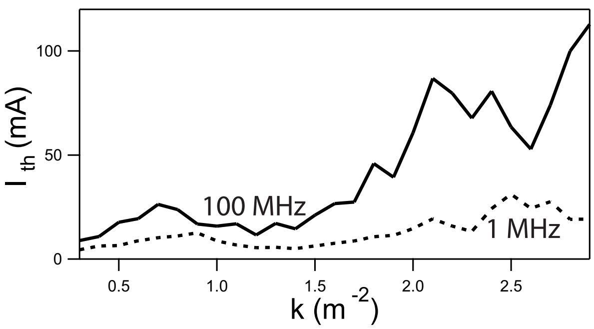

Figure 8: Intensity threshold as a function of the focusing strength of the quadrupoles. Drift between the quadrupoles and between the cryomodule and the quadrupole is set at 0.3 m and the length of the quadrupoles at 0.3 m.

The simulations presented here consider a graded gradient transverse focusing scheme [14] with triplet quadrupoles with a focusing strength arrangement $(-k/2,\ k,\ -k/2)$. In order to keep the symmetry of the optical functions, there are quadrupoles sets between each cryomodules, at the beginning and at the end of the linear accelerator section. Preliminary simulations with a simplified design considering a 1 GeV linear accelerator, have been done with one recirculation. The focusing strength is choose to be constant in the first half of the linear accelerator, when the electrons increase their energy. As a consequence, it results from the simulations an evolution of the current threshold as a function of the focusing strength. Figure 7 illustrates the energy variation along the recirculations loops and the optical function. The focusing scheme enables to adapt the optical function to the case of lower energy of the electrons : in the first half of the accelerator, when the energy increases and in the second half one when the energy decreases. The optical function presented (see Figure 7b) are symmetric compared to the center of the arc. They are comprise between 2 and 55 m.

With a maximum charge in ERL configuration of 1 nC, the average current is 1 mA (resp. 100 mA) for 1 MHz (resp. 100 MHz) repetition rate. As a consequence, the Beam Break Up threshold current should be larger than 1 mA for 1 MHz and 100 mA for 100 MHz. The dashed curve of figure 8 shows that whatever the focusing strength the threshold current of the beam break up instability is higher than 1 mA. So the Beam break up instability does not limit the current of the ERL operation at 1 MHz repetition rate. On the other hand, an operation at 100 mA can be done only for few focusing strength. In fact, the Beam Break up instability is more critical at 100 MHz repetition rate and will need a careful design of the optics.

In a next step, simulations have to be done versus different parameters acting on the transfer matrix from turn to turn and from element to element. For the case of N_r recirculation loops, the Beam Break Up instability becomes critical as the threshold current is smaller of a factor $N_r(2N_r-1)$. As a consequence, the maximum current for the two recirculations needed for $2\ GeV$ is predicted to be around $20\ mA$.

CONCLUSION

ARC-EN-CIEL single pass accelerator has been designed in order to maximize the electron beam brilliance and to optimize parameters as the energy spread for the production of HGHG light. ERL loops could provide in addition synchrotron radiation from undulators and FEL oscillation in the UV-X wavelength domain. BBU instabilities does not limit a high average current operation. But further investigations have to be realized to obtain a high average current with two recirculation loops.

ACKNOWLEDGMENT

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