OPTIMIZATION OF THE BEAM LINE CHARACTERISTICS BY MEANS OF A GENETIC ALGORITHM

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Abstract

The optimization of the optics in a LINAC requires a very demanding tuning of the involved parameters, particularly in the case of high brightness electron beams applied to the production of X-ray in a Thomson back-scattering source. The relationship between the parameters is non-linear and it is not possible to treat them as independent variables, causing the impossibility of setting them handily. A genetic algorithm is a powerful tool able to circumvent this difficulty. We have applied the genetic algorithm to the case SPARC/PLASMONX to perform the optimization of the beam line parameters necessary to produce a high brilliance X-ray beam in a back scattering Thomson experiment [1] .

INTRODUCTION

The recent advance in the technology of high brightness electron beams has opened a wide range of options in the field of the X-ray generation, making possible the design and realisation of Thomson sources, which have been so far put into operation only as test experiments [2,3], but not yet as user facilities. Many projects world-wide are anyway ongoing to realise user facilities mainly oriented to medical applications

Despite all these endeavours, the determination of the parameters of a beam line allowing to reach contemporarily optimum values of beam emittance, current and focussing remains a challenging problem, not only from the experimental point of view, but even from the aspect of the simulations. The whole parameter ensemble that characterizes a beam line constitutes a set of several quantities linked by non trivial and non linear relationships that do not allow defining easily an optimized configuration. An optimization technique has been developed in the last years in the framework of the upgrading of the electron beam properties from photoinjectors [4], but usually the optimization of the beam line is made by changing the input values of the parameters by hand.

A genetic algorithm can be used to circumvent this difficulty. Here we present the innovative application of a genetic code, that works in series with the transport code Astra [5] managing its input parameters. The iterations proper of the genetic algorithm lead to a fast and precise convergence on a good solution, estimated by means of the magnitude assumed by an ad hoc function, the ‘fitness function’, defined as a weighted combination of the physical quantities that have to be optimized.

THE GENETIC ALGORITHM

The genetic algorithms encode solutions to specific problems on a simple chromosome-like data structure and apply iterated recombination operators. They are particularly suitable to solve problems that have nonlinear character and where it is not possible to treat each parameter as a variable which can be fixed independently from all other ones.

The definition of a beam line able to achieve very high brightness beam, in fact, involves a number of input parameters quite large. The determination of their values is so critical that it is not conceivable to vary them handily in the input data of a transport code integrating the beam dynamics evolution equations. Even the indications of the theory and the existing scaling laws set up a guide to find ot the working region in the input parameter space, but not just the best point.

The genetic algorithm is particularly suitable to circumvent these difficulties because it controls automatically the optimization process over a large number of parameters. The parameters involved in the problem, in our case the specifications of the elements of the beam line, are considered as genes. A string of genes represents an individual or a chromosome. An ensemble of interacting chromosomes constitutes a generation. The first generation is constituted by a certain number of chromosomes whose genes are randomly distributed in assigned ranges. The reproduction of the chromosomes is obtained by crossing them over two by two, exchanging stochastically their genes. The evolution toward better individuals is regulated by a fitness function $F_{fitness}$ that evaluates the goodness of each chromosome and allocates to the best ones a larger reproductive opportunity. Each generation is never worse than the preceding one because the best chromosome is always reproduced in the successive generations.

The probability that a couple, with i≠j, produces, by crossing, an individual of the new generation is

$$P_{ij} = \frac{F^i_{fitness} \cdot F^j_{fitness}}{\sum_{i,j} F^i_{fitness} \cdot F^j_{fitness}} .$$

In this way, the couples whose partners have larger fitness function consequently have a larger probability to reproduce themselves. During each crossing over there exists a small probability that a gene undergoes a mutation. This expedient prevents the possibility that the iteration stops on a local solution and cannot evolve further.

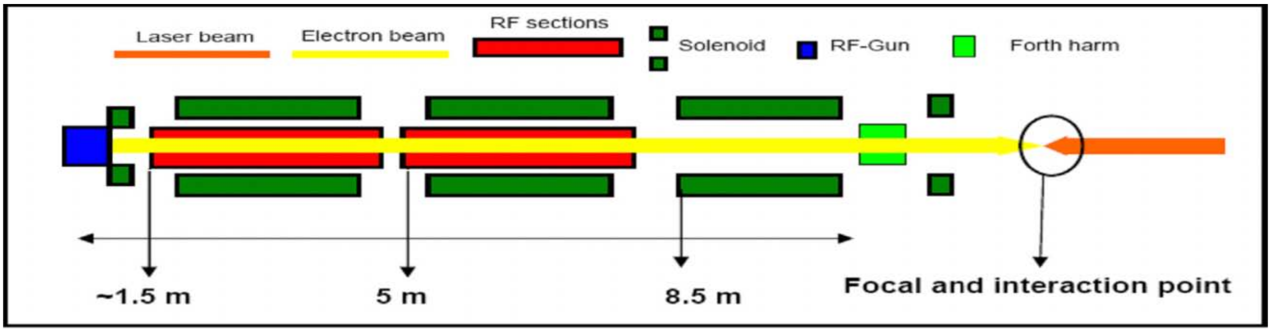

Figure 1: Beam line adopted for the case of the incoherent Thomson back-scattering.

HIGH BRIGHTNESS BEAMS IN THE INCOHERENT THOMSON SCATTERING

The incoherent back-scattering Thomson between a high brightness electron beam and a high power laser is a promising tool for producing intense, tunable and monochromatic X-rays. The mean energy of the radiated photons, or, as well, their wavelength λ_R, is substantially fixed by the laser wavelength λ_L and by the mean energy of the electron beam, i.e. γ, through the resonance condition:

$$\lambda_R = \lambda_L(1 + a_{L0}^2)/4\gamma^2$$

where a_{L0} is the laser parameter.

The value of the photon energy determines the kind of applications. For example, photons of 20 KeV ($\lambda_R \approx 0.65$ Angstrom) are used in mammography, while photons of higher energy are employed in radiography or non invasive angiography. For the case of the Ti:Sa lasers where λ_L=0.8 µm, the energy value of 20 KeV is obtained with γ=60, corresponding to a mean energy of the beam of about 30 MeV.

Once that the energy of the electron bunch in the focal point results fixed it remains to investigate the other characteristics that the bunch should have for radiating at the maximum level.

In the incoherent scattering, whose properties have been widely studied theoretically [6,7], the radiated photons number scales proportionally with the number of electrons involved in the scattering and whit the electron beam focal spot $(1/\sigma_r)^2$. This quantity depends, on the total number of electrons extracted from the cathode and on the geometrical and temporal overlapping between the bunch and the laser pulse.

Since the charge extracted from the cathode is a fixed parameter, an upgrading in the radiation can be obtained by controlling transversally and longitudinally the length of the bunch. The photon number and the spectrum of the radiation depend also on the transverse emittance of the beam $\varepsilon_{x,n}$, on its envelope σ_x and on the energy spread $\Delta\gamma/\gamma$. The emittance and the energy spread influence the focusing of the electrons and the bandwidth. This last quantity, however, can be regulated by varying the acceptance of the X-rays detector, exploiting the frequency-angle correlation typical of the Thomson scattering. As the total photon number depends on a_{L0}^2, the best configuration of the scattering is obtained by compressing transversally both laser and electron pulses.

Handle optimizations made on the electron bunch [8] have shown that a level of 7.710^8 photons per pulse in a 10% of bandwidth can be reached if a bunch of 10^{10} electrons, length 20 psec, emittance of about 1mm mrad or less and energy spread of about 10^{-4} impinges a laser with energy E_L=5 J. The focal spot size of the beam and the waist of the laser pulse should be compressed up to few µm.

BEAM GENERATION BY USING THE GENETIC ALGORITHM

The beam line shown in Figure 1 concerns the layout for the SPARC/PLASMONX experiment [8]. It comprises a gun, a focusing solenoid, two TW structures (inserted into solenoids) and a final focusing solenoid. A forth harmonics structure is placed before the focusing solenoid. The nominal electron bunch of the SPARC project has a total charge of 1 nC and is extracted from the cathode with a 30 psec laser pulse. The aim of our analysis is the tuning of the beam line parameters by the innovative application of the genetic code to produce an electron bunch as good as possible to improve the X-ray intensity produced in the back-scattering Thomson experiment. The result of the analysis is a set of parameters that, in the genetic language, we call the best chromosome. The genetic optimization is compared with that optimization previously obtained by hand, the we have called the reference one.

The optimization plays with the following parameters: the gun electric field gradient dE_g/dz, the gun injection phase Φ_g, the gun maximum magnetic field B_g, the first accelerating structure gradient dE_1/dz, the first structure injection phase Φ_1, the first structure maximum magnetic field B_1, the first solenoid position z_1, the analogous quantities for the second structure dE_2/dz, Φ_2, B_2,z_2, the magnetic field and position of the third structure B_3 and z_3, and the injection phase and position of the forth harmonic cavity Φ_{IVH} and z_{IVH}.

The genetic code launches the code Astra which tracks the bunch for each beam line configuration (30 chromosomes). The bounds of the genes are reported in Tab. 1, and have been chosen around the values of the reference case

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Table 1: Genes values for the reference case, for the best chromosome and the genes bounds used in the code.

Gene	Ref. case	Lower bound	Upper bound	Best solution
dE_g/dz (MV/m)	120	119	121	120.116
Φ_g (°)	0	-1	1	0.663
B_g (T)	0.2707	0.26	0.28	0.27012
dE_1/dz (MV/m)	13.4	13	14	13.39
Φ_1 (°)	-30	-32	-29	-31.722
B_1 (T)	0.12	0.11	0.13	0.1137
z_1 (m)	1.322	1.2	1.4	1.356
dE_2/dz (MV/m)	6.55	6	7	6.711
Φ_2 (°)	88	87	89	87.53
B_2 (T)	0.1145	0.105	0.125	0.1205
z_2 (m)	5	4	6	5.482
B_3 (T)	0.1145	0.105	0.125	0.1115
z_3 (m)	8.5	7.5	9.5	8.98
Φ_{IVH} (°)	180	175	185	175.88
z_{IVH} (m)	11.7	11.65	11.75	11.707

The genes of the optimized chromosome, that represents the genetic solution, are shown in the fifth column of Table 1. In Fig. 2 and Fig. 3 the black curves (b) represent respectively the emittance and the transverse distribution of the best chromosome. The final energy of the beam is 29.61 MeV.

The values of the parameters of the run optimized by hand are shown in the second column of Tab 1. The emittance of this case is presented in Fig. 2 (red curve (a)) while its transverse distribution in the focal point is shown in Fig. 3 (red curve (a)). The final energy of the beam is 29.77 MeV.

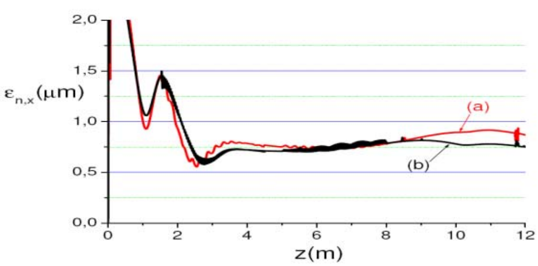

Figure 2: Transverse normalized emittance (mm-mrad) versus z (m) for: (a) reference case optimized by hand, (b) best chromosome

The transverse distribution (Fig. 3) in either cases have been obtained focusing the beam with the same solenoid.

The transverse focalization is the most important parameter for maximizing the photon number produced in the scattering. Since it depends critically on the emittance and on the energy spread of the beam before the focalization, we have defined as fitness function the quantity $F_{fitness} = 1/(\varepsilon_{n,x} \cdot \Delta\gamma/\gamma)$ evaluated at 12 m, before the last solenoid.

We note that the larger adjustments made by the genetic algorithm respect to the reference case regard the positions of the second and third solenoids, with variations respectively of 9.6% and 5.34%, the maximum magnetic field of the first and second structures, respectively 6% and 5.5%. Considerable variations are presented also by the injection phase in the first structure and in the forth harmonic cavity by B_3, z_1 and dE_2/dz.

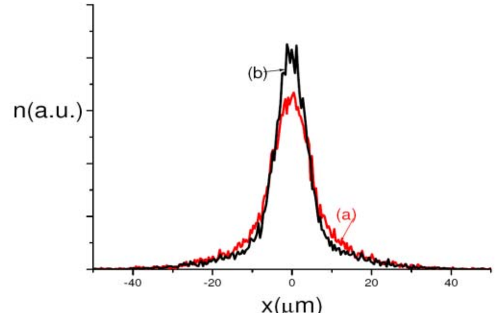

Figure 3: Beam transverse distribution n (arbitrary units) along x (μm) for: (a) reference case optimized by hand, (b) best chromosome

In Fig. 4 the spectrum of X rays radiated, in a single scattering with a Ti:Sa laser [7] collected in a solid angle of 6 mrad, is shown for the reference case (a) and for the best chromosome (b). The reference case optimized by hand has yield a number of about 7.7 10^8 photons, whereas the best chromosome has yield 1.12 10^9 with an increase of about 40%.

The result obtained by means of the genetic code shows the validity of this numerical method that could be used, with very good results to produce high brightness electron bunch useful for FEL [9] or in the field of the data analysis.

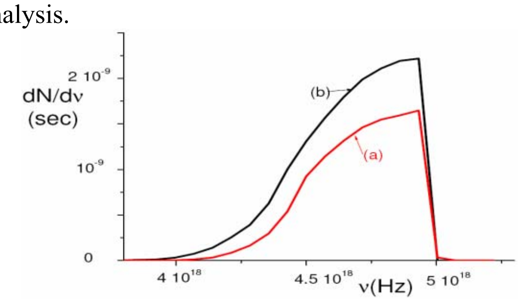

Figure 4: Spectrum of X rays radiated for the reference case (a) and for the best chromosome (b)

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