SPARC PHOTOINJECTOR WORKING POINT OPTIMIZATION, TOLERANCES AND SENSITIVITY TO ERRORS

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Abstract

A new optimization of the SPARC photo-injector, aiming to reduce the FEL saturation length, is presented together with Start-to-End simulations. A systematic scan of the main parameters around the operating point showed that the probability to get a projected emittance exceeding 1 μm is only 10 % and the slice emittance remains below 1 μm in all cases.

INTRODUCTION

The SPARC [1] injector will be the first one driving a saturating SASE FEL without the use of a compressor scheme. The FEL requirements in terms of beam current have pushed the design towards the limits of the state-of-the-art for what concerns pulse charge and pulse shape. In order to reach this goal with a good level of confidence we have explored a range of parameters that are not far from the previous best performances obtained in photo-injector laboratories [2]. The design goal of the SPARC accelerator is to provide a 155 MeV bunch with less than 2 μm for the projected emittance and less than 1 μm for the slice emittance of 50% of slices. Detailed analysis of the SPARC-FEL operation including different errors in the undulator showed that the previous set of beam parameters [3] giving a peak current I ≈ 85 A does not leave a significant contingency margin to ensure full saturation and testing of harmonic generation in the 14.5 m allocated for the undulator. The peak current, which, in the range of the diffraction dominated SPARC FEL is the key parameter for shortening the FEL gain length, should then be increased. A safer set of parameters requires a beam having 100 A in 50% of the slices with a slice emittance ≤1 μm. For this purpose a new optimization, with Start-to-End simulations and parametric sensitivity studies aiming to reduce the FEL saturation length, was performed. The best performance in terms of increasing final current was obtained with a scaling approach [4] in which more charge is launched from the cathode. The scaling law indicates that the preservation of the beam plasma frequency requires that the spot size be scaled according to $\sigma_x \propto \left(Q/\sigma_z\right)^{1/2}$. The configuration that meets the requirement with the minimum emittance corresponds to a working point with 1.1 nC and a pulse length of 10 psec.

START TO END SIMULATIONS

The accelerator consists of a 1.6 cell RF gun operated at S-band with a peak field on the cathode of 120 MV/m and an incorporated metallic photo-cathode followed by an emittance compensating solenoid and three accelerating sections of the SLAC type (S-band, travelling wave), the first one embedded in an array of 13 coils. A transfer line allows the matching with the undulator optics.

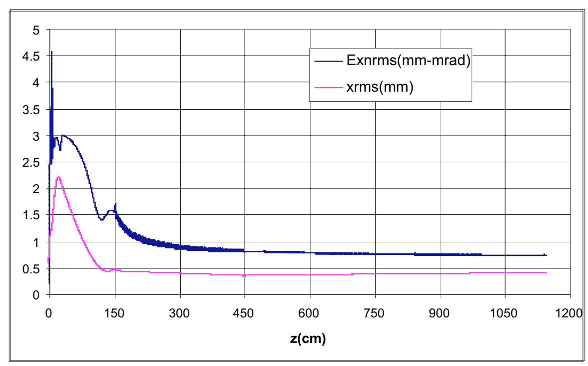

Figure 1: PARMELA computed rms normalized emittance and rms horizontal envelope vs z from gun to the linac output for Q=1.1 nC, τ=10 psec, ε_{th}=0.34 μm, laser spot radius=1.13 mm.

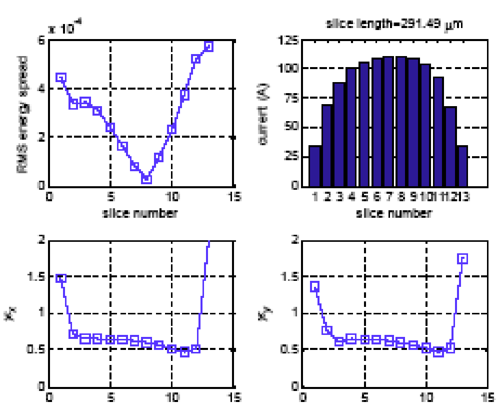

Figure 2: Computed slice parameters: slice energy spread, slice current, x and y rms normalized slice emittance

In Fig. 1 the rms normalised emittance and the rms envelope from the gun to the linac output, as computed by PARMELA [5], are shown for the best case (ε_n =0.71 μm) with increased current (I=100 A) [6]. In this study, a thermal emittance linearly increasing with the radius and equal to 0.3 μm/1 mm of radius and a rise time of 1 psec (derived from previous optimization studies) were assumed. It has to be noted that the charge/pulse-length scaling from the parameters found for the original 85 A working point (ϕ_{gun}=33°, B_{sol}= 2.73 kG, and average longitudinal fields in TW section 1 of B=750 G, E=25 MV/m, TW sections 2 and 3 E =12.5MV/m) preserves the emittance compensation scheme. The plots of Fig. 2 refer to the slice analysis for the same case: 85% of the particles are in slices with an emittance smaller than 0.7 μm, 54% have current ≥100 A and 70% have a current ≥90 A. In this analysis the slice length has been taken approximately equal to one cooperation length (~300 μm).

Two triplets are used to match the optical functions of the beam at linac exit to the values desired at the undulator entrance. This solution, as compared to a doublet and a triplet configuration which was also suitable, has been chosen in order to assure flexibility to the line [7]. In Fig. 3, the rms horizontal beam size from the end of the linac (corresponding to z=0 in the plot) to the undulator input is shown. The matching has been performed with MAD [12] including the focal effects of 6 undulator sections interleaved by small horizontally focusing quadrupoles. The effect of each undulator section on the beam has been simulated as a vertically focusing quadrupole.

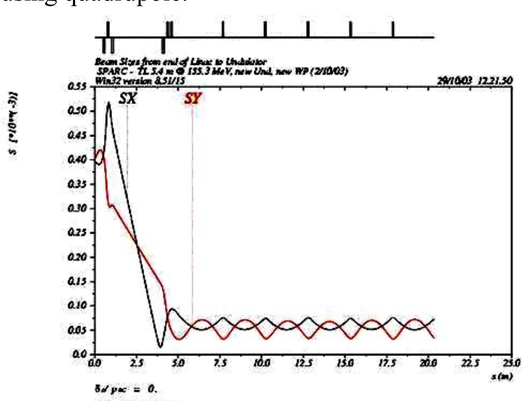

Figure 3: rms beam sizes in mm (black horizontal, red vertical) from the Linac output to the undulator output.

A slice analysis has been carried out in order to evaluate the mismatch of the single slices of the bunch. The relative mismatching parameter:

$$M = 0.5(\beta_o\gamma - 2\alpha_o\alpha + \gamma_o\beta)$$

(α_o, β_o and γ_o being the undulator matched parameters) results to be lower than 1.2 for 85% of the beam.

The undulator parameter set used for the simulation of the SPARC FEL are summarized in Table 1 [8].

Table 1: Undulator parameter set

Period	2.8 cm
# Periods/section	77 (+1 for matching)
Number of Sections	6
K	2.145

The simulation has been performed by using GENESIS 1.3 [9] in time dependent mode, and taking into account the bunch distribution as provided by PARMELA. In Fig.4 the FEL power as a function of z is shown. The saturation length is shorter than 9 m, with a net gain of 2 m compared to the previous optimization.

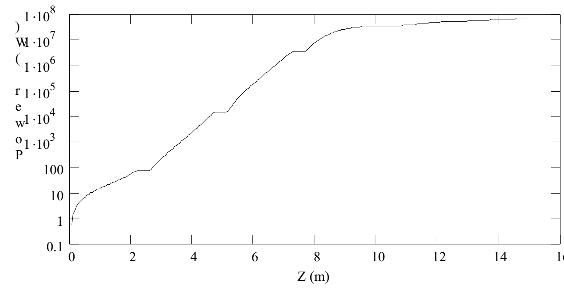

Figure 4: Power vs. z for the SPARC FEL, from GENESIS (final step in STE) simulation

PARAMETER SENSITIVITIES

In order to investigate the stability of the SPARC working point and to predict the most probable values of the projected and slice emittance in realistic conditions, a sensitivity study to various types of random errors in the SPARC accelerator was performed [10]. The study was divided in two steps. In the first one the tolerances of the main tuning parameters were set using the criterion of having a maximum increase of the projected emittance of 10% with respect to the nominal case (0.71 μm). In the second step these errors were combined in the defined tolerance ranges and a statistical analysis was performed in order to study the effect of the combination of errors on the projected and slice emittance and on the mismatching at the entrance of the undulator. The sensitivity of the projected emittance to errors of individual parameters that can fluctuate during the machine operation was studied by PARMELA code extensive simulations. The parameters that have been considered are relative to the gun system only and the data were studied at the linac exit.

Table 2: Minimum variation of the single parameters value for a 10% emittance increase

Gun Phase jitter	± 3°
Charge fluctuation	+ 10%
Gun magnetic field	± 0.4%
Gun electric field	± 0.5 %
Spot radius dimension	± 10%
Spot ellipticity	3.5% (xmax/ymax=1-1.035)

Step 1: the resulting tolerances on the different tuning parameters are listed in Table 2. It can be seen that the most critical parameters are the electric field amplitude and the spot ellipticity.

Step 2: one hundred PARMELA runs were performed, each one with random error sets within the tolerance limits. PARMELA was interfaced with a MATLAB based program that accepts in input the limits of variation of the single parameters and generates a number of input files in which the six parameters of interest are varied randomly in the pre-defined ranges according with the sampling technique of the "latin hypercube", an algorithm implemented in the MATLAB statistical toolbox. The numbers used are uniform distributions with average values and rms widths listed in Table 3. The interval of errors distribution is $\pm\sqrt{3}\ \sigma$ around the average value.

Table 3: Variation of parameters for combined tolerance study of errors in SPARC gun

Parameter	Average value	RMS value
Gun phase	31.5°	1.74°
Charge	1.15 nC	0.032 nC
Gun B field amplitude	2733 gauss	5.8 gauss
Gun E field amplitude	119.9 MV/m	0.32 MV/m
spot radius	1.132	0.068 mm
Ellipticity	1	0.02

The results of the simulations were used to construct the curve plotted in Fig. 5 that gives the probability to obtain an emittance greater or equal than the corresponding value on the abscissa: for example the probability to get a normalized projected emittance ≥ 1 μm is less than 10%.

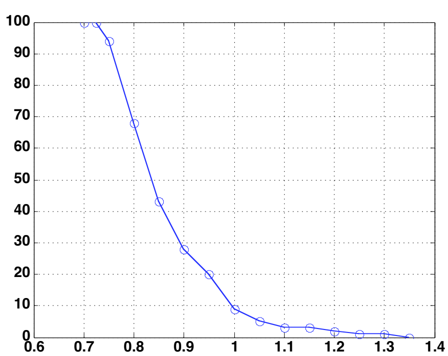

Figure 5: Probability vs emittance over 100 simulations

Concerning the slice emittance, in the 100 simulations it does not exceed 0.9 μm for the 9 central slices out of 13 slices, as it can be seen in Fig. 6 in which two extreme cases obtained from the error simulations are compared with the ideal case.

The effect of random errors on the transverse phase space orientation at the entrance of the undulator has also been investigated. The distribution of the average and the rms mismatching factor are respectively 1.3 and 0.32.

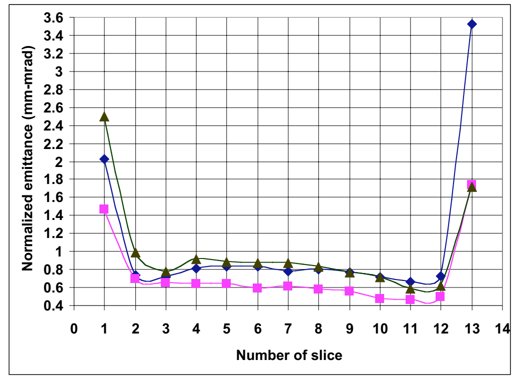

Figure 6: Interval of variation of slice emittance over 100 simulations

CONCLUSIONS

Start-to-End simulations showed that, with a 1.1 nC charge in a 10 ps long bunch we can deliver at the undulator entrance a beam having 100 A in 50% of the slices with a slice emittance ≤1 μm, thus reducing the FEL-SASE saturation length to 9 m at 500 nm wavelength. The stability of the nominal working point and its sensitivity to various types of random errors, under realistic conditions of the SPARC photo-injector operation has also been studied. On this basis it can be concluded that combining multiple errors on tuning parameters the projected and slice emittance values remain within the limits of the SPARC design. Additional systematic investigations taking into account element misalignments, orbit steering and wake fields [11] effects are under way.

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