BEAM DYNAMICS SIMULATIONS FOR THE SwissFEL INJECTOR TEST FACILITY

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Abstract

The SwissFEL under study at PSI will produce 0.1 nm to 0.7 nm wavelength coherent x-ray. The design of the injector is based on the invariant envelope matching scheme, developed for other photoinjectors in the past years. According to this technique the emittance at the exit of the injector can be minimized if some conditions at the entrance of the booster are satisfied. A campaign of simulations has been carried out to verify the impact of the errors of the machine components (RF and magnetic) and laser shaping (transverse and longitudinal) on the final SwissFEL injector emittance. These results have to be used to define the tolerances on the machine and laser.

INTRODUCTION

Low emittance is one of the key points of SwissFEL to reach the laser nominal wavelengths. The invariant envelope matching scheme, used to design the injector, allows minimizing the final emittance if the beam envelope and the projected emittance are respectively minimum and maximum at the booster entrance (Ferrario point) [1]. In the SwissFEL injector design these conditions are satisfied assuming as nominal the parameters in Table 1* [2].

Table 1: Nominal Design Parameters of the SwissFEL Injector (200 pC mode)

Parameter	Value
Gun gradient	100 MV/m
SB01 peak gradient	19 MV/m
SB02 peak gradient	25 MV/m
Gun solenoid peak field	0.2068 T
SB01 solenoid peak field	0.08 T
SB02 solenoid peak field	0.068 T
Laser pulse (FWHM)	9.9 ps
Laser σ_x (radial symmetric)	0.275 mm

If one of the machine parameters or the laser shape is deviating from its nominal value the conditions of the invariant envelope matching could be compromised and the emittance consequently degraded. To determine the emittance variation given by the machine imperfections or the laser shaping we carried out two campaigns of simulations using Astra [3] and Opal [4]. As a reference point to quantify the projected emittance degradation, we use 0.43 mm mrad, which corresponds to the maximum acceptable emittance at the entrance of the undulator.

*There are two SwissFEL nominal operation modes: 10 pC and 200 pC. In this paper we focus on the highest charge one, because this is the most critical one in terms of space charge.

MACHINE TOLERANCES

To study the effect of errors in the machine we wrote a Matlab code to generate the input file up to the end of the fourth structure with all off after the second structure [2], run the simulation and calculate all the beam parameters, like the Twiss functions, the energy spread and the final emittance in a double loop, where we can vary at each iteration the charge (to check the sensitivity of the result) and one of the parameters of the machine around the nominal value.

In Fig. 1 we present a typical output we obtain at the end of a double loop and in Table 2 we report the summary of the results of the simulations.

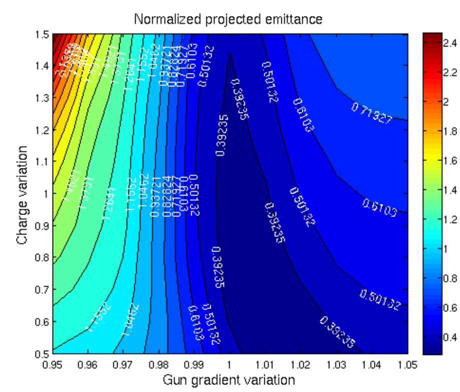

Figure 1: Final normalized projected emittance: loop on the charge and the gun gradient.

Table 2: Final normalized projected emittance. If the variation of the injector parameter is not enough to hit the 0.43 mm mrad limit the emittance for the maximum variation considered is reported.

Parameter	Variation	Projected ε_N (mm mrad)
Gun gradient	0.6%	0.4300
Gun phase	6 degrees	0.4300
Gun solenoid	0.6%	0.4300
SB01 gradient	10%	0.3250
SB01 phase	30 degrees	0.3423
SB01 solenoid	10%	0.3215
SB02 gradient	10%	0.3207
SB02 phase	30 degrees	0.3214
SB02 solenoid	10%	0.3207

The design allows us to stay below the budget emittance with a safe margin in all the elements downstream of the gun. In the low energy part, a precision and stability of the order of half percent is necessary.

The projected emittance can also be degraded by the coupling generated by the quadrupolar component in the solenoids in the low energy part. To study this effect we added quadrupoles at the solenoids edges using a rescaling of the measured ones at LCLS [5]. A scan of the quadrupolar components shows that the expected quadrupolar component of the gun solenoid can increase the emittance by about 50% [6], whereas the contribution of the other solenoids is smaller (below 2% and 0.5% for the first and the second solenoid after the gun, respectively).

LASER SHAPING TOLERANCES

The beam is generated by a 274 nm wavelength Ti:Sapphire** laser developed at PSI [7] and a diamond turned copper plug. The laser shaping closest to the radial distribution assumed in the design is obtained by cutting the 2D Gaussian laser profile by means of an iris, which intercepts part of the radiation upstream the cathode. Also if we assume no errors in the procedure, the cut changes the charge distribution in the bunch and, therefore, affects the beam dynamics of the system. Furthermore there could be an error in the procedure coming from an asymmetry of the laser or in the iris. The longitudinal distribution is obtained via the pulse stacking technique, which gives only an approximation of the flattop distribution assumed for the design. Another effect which could be source of emittance degradation is the Schottky effect, which could be non negligible due to the relatively long pulse length.

We simulated all these aspects to quantify their effects on the final emittance and define the laser specifications.

Transverse Laser Shaping

Given the laser energy and the quantum efficiency, we can calculate the maximum transverse cut in the laser profile we can accept to produce the nominal charge. For the Ti:Sapphire laser and the measured quantum efficiency (~5.10^{-5}) we can accept a cut of slightly less than 0.55σ to produce the nominal 200 pC charge [8]. The projected emittance for slight Gaussian cuts is smaller than for the sharp edges [9].

In terms of the final projected emittance and energy spread a cut from 0.5 up to 1 σ is acceptable, as shown in Fig. 2. The cut affects also the matching along the bunch, which is quantified by the mismatch parameter, defined as:

$$\zeta \equiv \frac{1}{2}\beta_0\gamma - 2\alpha_0\alpha + \gamma_0\beta \qquad (1)$$

where the index 0 refers to the nominal distribution.

From Fig. 3 we can conclude that a cut up to 0.7 σ is acceptable.

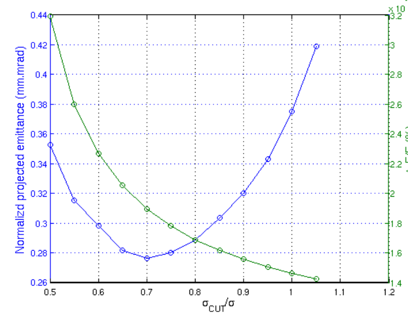

Figure 2: Final normalized projected emittance and energy spread as a function of the cut in units.

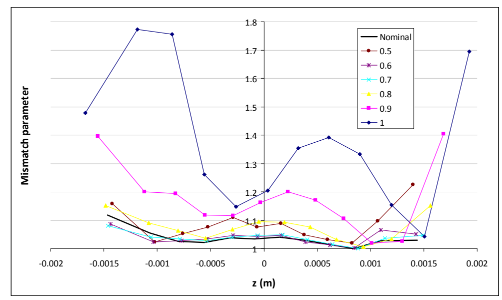

Figure 3: Mismatch parameter along the bunch at the exit of the injector for the several cuts.

These simulations have been carried out assuming a perfect 2D Gaussian and a perfect iris cut. In the next paragraphs we estimate the effect of an error in each one of these elements.

As a first guess we assume that the laser profile is a perfect 2D Gaussian in transverse, and we introduce an error of asymmetry in the iris. To simulate this effect we generate a 2D Gaussian distribution and we select in the (x,y) plane the particles which are inside an ellipse of semi-axes R_x and R_y, where the relation

$$R_y = ratio\ R_x \qquad (2)$$

is satisfied***. To really study only the effect of the asymmetry for each simulation we adjust the charge to have a constant charge density.

A maximum ratio of 0.775 (0.825 in the case of the constant charge) is tolerable, to stay below the emittance of 0.43 mm mrad, as shown in Fig. 4.

To simulate an asymmetry in the starting laser profile upstream the iris we generate a 2D distribution Gaussian with σ_x and σ_y and we do a cut. In this case for a ratio of the σ smaller than 0.55 the final emittance is still below the 0.43 mm mrad limit.

**Two laser systems have been developed and simulated: the Nd:YLF used for the basic commissioning and the more sophisticated to be used in SwissFEL . In this paper we concentrate on the latter one.

***The simulations have been carried on using Astra, which could be enough accurate up to a ratio 2 between x and y. A check with Opal is ongoing.

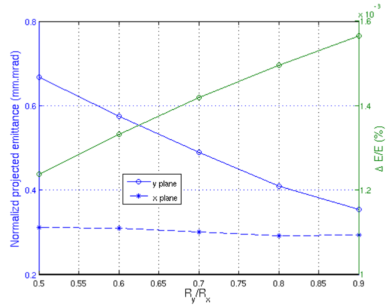

Figure 4: Final normalized projected emittance as a function of the iris asymmetry. The x dimension is kept constant and the y is varied.

Longitudinal Laser Shaping

A typical pulse generated with the pulse stacking has some oscillations in the central part of the profile which can reach more than 20% in amplitude [10]. To study the impact of these spikes we simulate distributions at different amplitudes modulation. We generate for each time step a number of particles N_i proportional to:

$$N_i = \langle t \rangle_i + \Delta t_i \ rand(I_i) \quad (3)$$

where I_i is the intensity, Δt_i is the time step and $<t_i>$ is the average time in the step i.

As shown in Fig. 5, the projected emittance and the energy spread are not dramatically affected by this modulation, but it could trigger micro-bunching instability in the compression chicanes, aspect presently under study.

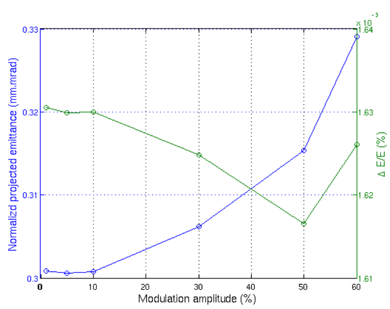

Figure 5: Final normalized projected emittance and energy spread as a function of oscillation amplitude.

The FWHM 9.9 ps bunch length corresponds to about 10 degrees of RF phase. The 2.25 pC/degree rate (measured by means of a Schottky scan) produces a charge variation of about 10% all along the bunch. To study the impact of this effect we convolve the ideal flattop distribution with a linear function with a slope corresponding to 2.25 pC/degree, as shown in Fig. 6. We used a technique similar to the one described for the pulse stacking case to generate the starting distribution and we compute the final normalized emittance.

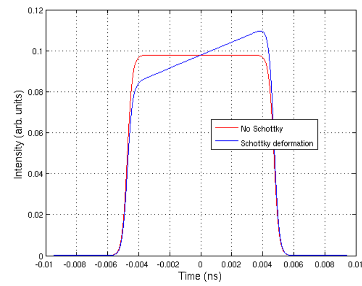

Figure 6: Initial longitudinal bunch shape assumed to simulate the impact of the Schottky effect.

The projected emittance is degraded by 4%, but the different charge density along the bunch causes a ~10% emittance variation along the pulse, as visible in Fig. 7.

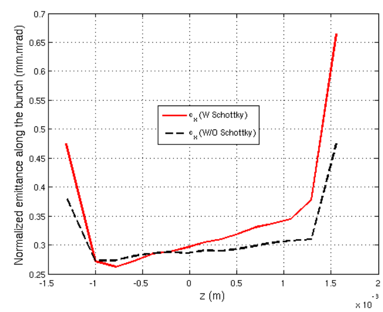

Figure 7: Final normalized emittance along the bunch. The nominal case is reported for comparison.

A pre-shaping of the laser with a linear slope in longitudinal would be necessary to cure this distortion.

CONCLUSIONS

A complete set of simulations has been carried out for the SwissFEL injector test facility. The results are used to define the tolerances on the RF and magnets in the machine and the laser shaping to produce a beam with an emittance smaller than the maximum allowed one at the entrance of the undulator.

REFERENCES

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