RF GUN STUDIES FOR THE SwissFEL INJECTOR

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Abstract

The Paul Scherrer Institut (PSI) has a project to build a compact, high brightness free electron laser. For this purpose a new 2.5-cell RF gun has been designed at PSI and is now ready to be manufactured. The RF gun plays an important role in preserving beam emittance and hence to deliver a high quality beam to the injector. We present beam dynamic studies on the effect of cell length variations using two different codes OPAL and ASTRA. Furthermore laser spot size and RF gradient are scanned to find the best working point of the injector. The simulation results show that the SwissFEL injector requirements ($\epsilon \leq 0.4$ μm normalized projected emittance) can be achieved with this new RF gun design.

INJECTOR DESCRIPTION

The first part of the SwissFEL injector test facility consists of a 2.5 cell RF gun, a solenoid for emittance compensation and invariant envelope matching, a triplet of quadrupoles for emittance measurements and two TW S-Band structures. A spectrometer is placed after the RF Gun to measure energy and energy spread [1] (see Fig. 1). The main parameters for the low energy part are listed in Tab.1.

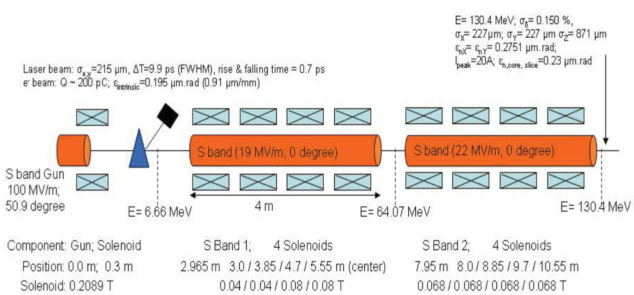

Figure 1: The low energy section of the SwissFEL

Table 1: Crucial parameters of SwissFEL injector

Parameter	200 pC	10 pC
Gun Gradient	100 MV/m	100 MV/m
Beam peak current	20 A	3A
Laser trans. spot size	215 μm	101 μm
Laser pulse length	9.9 ps	3.7 ps
Thermal emittance	0.195 μm	0.07 μm
Proj. emittance at 130 MeV	0.273 μm	0.1 μm
Energy	130.4 MeV	130.5 MeV
Relative energy spread	0.16 %	0.02 %

The RF gun has 2.5 cells with symmetric feeds in the middle cell and racetrack shape in order to minimize the dipole and quadrupolar components. The cathode is integrated in the flat backplane made from copper. No cathode plug is used in order to reduce dark current. In Tab. 2 the main parameters are listed.

Table 2: RF gun main parameters

Parameter	Value
Operating gun gradient	100 MV/m
Frequency	2998.8 MHz
Operating temperature	40 °C
Mode separation	≥15 MHz

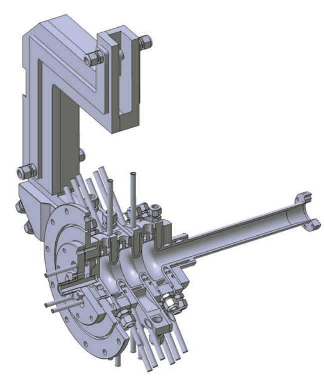

Figure 2: A 3D view of the SwissFEL RF gun

BEAM DYNAMICS STUDIES

The beam dynamics of the injector has been studied using the two codes OPAL [2] and ASTRA [3]. The length of the half cell (where the cathode is located and where space charge forces are most relevant) have been varied as described in [4]. In addition, the effects of the laser spot size and gradient on the injector performance have been carefully evaluated.

The Object Oriented Parallel Accelerator Library Framework

The Object Oriented Parallel Accelerator Library (OPAL) Framework [2] is a tool for charged-particle optic calculations in large accelerator structures and beam lines including 3D space charge. OPAL is built from first principles as a parallel application and, hence, admits simulations of any scale; on a laptop and up to the largest High Performance Computing clusters available today. With this tool we are able to perform precise start-to-end simulations of the full FEL, excluding the undulator.

Input Beam

The input beam used in the simulation is the same for both codes. It has a longitudinal flat-top shape with a FWHM of 9.9 ps and 0.7 ps rise/fall time (see Fig. 3) and uniform transverse distribution. The thermal emittance is calculated according Eq. 1 [5]

$$\epsilon_{th} \approx \sigma_{x,y} \sqrt{\frac{h\nu - \phi_W + \phi_{Schottky}}{3 m_e c^2}} \quad (1)$$

where $\sigma_{x,y}$ is the laser spot size and $\phi_{Schottky}$ takes into account the Schottky effect.

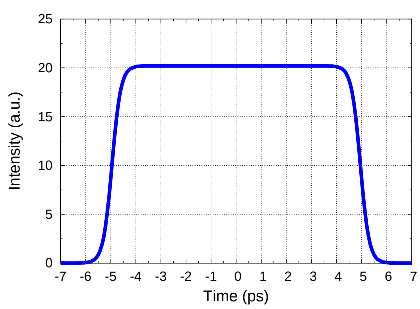

Figure 3: Laser temporal distribution

Simulations have been carried out using the same RF and magnet field distribution for both codes, but with a different number of macroparticles: 250k and 1.2M for ASTRA and OPAL respectively, taking advantage of the parallel nature of OPAL.

RF GUN, HALF CELL LENGTH VARIATION

The length of the half cell of the RF gun has been varied. For each variation (defined as ΔL) an optimization of the solenoid field has been made in order to get the invariant envelope matching. In Figs. 4 and 5 the emittance and beam matching as function of the half cell length variation are plotted. The beam matching is defined as

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

where α_0,β_0 and γ_0 are the optical functions integrated along the bunch, and α,β and γ are the optical functions within a single slice. In general the overall injector performances are robust with respect to variation of the half cell length. In particular within -1 mm and +2 mm there are no changes in terms of projected and core emittance. The matching can be kept below 1.1 for the same range of variation. Since no significant improvements can be obtained with different lengths the nominal dimensions are kept for the final design of the RF gun.

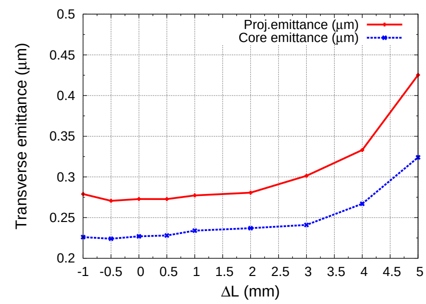

Figure 4: Emittance vs half cell length variation

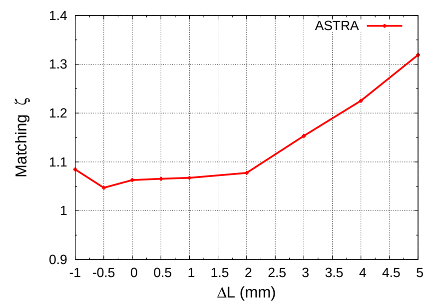

Figure 5: Matching vs half cell length variation

RF GUN GRADIENT AND LASER SPOT SIZE SCAN

RF gun gradient and laser spot size have been varied keeping the geometry of the gun constant. In this case the reference design geometry (ΔL=0) has been chosen. For each step an optimization of the solenoid field has been made.

RF Gradient

When we change the gradient on the gun (i.e. the input power) we can also reduce the laser spot size due to the Schottky effect. A scan of the gun gradient has been done and for each step different laser spot size (i.e. thermal emittance) has been considered. The laser spot size scales with the gradient on the cathode through the quantum efficiency expressed by Eq. 3 [5]

$$QE \cong \frac{1 - R(\omega)}{1 + \frac{\lambda_{opt}(\omega)}{\lambda_{e-e}(\omega)}} \frac{(\hbar\omega - \phi_{eff})^2}{8\phi_{eff}(E_F + \phi_{eff})}. \quad (3)$$

The correlation between gradient on the cathode and QE is given by the ϕ_{eff} term which can be expressed as Eq. 4 where E_k is the gradient on the cathode in MV/m :

$$\phi_{eff} = \phi_w - \phi_{Schottky} = \phi_W - 0.037947\sqrt{E_k|_{MV/m}}. \quad (4)$$

The projected emittance at the injector output has a minimum around 100 MV/m (see Fig. 6), this is confirmed by both codes and proves that there is no reasons to push the gradient on the cathode further.

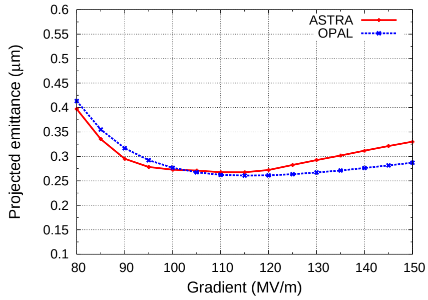

Figure 6: Projected emittance at the injector output as function of the gun gradient

Laser Spot Size

The laser spot size was scanned within a large range of variation, for each value the thermal emittance was calculated according to Eq. 1 and the gun solenoid field optimized to have the invariant envelope matching at the first TW structure. The gun gradient has been set at 100 MV/m. The optimum laser spot size for both codes is around 200 μm (see Fig. 7).

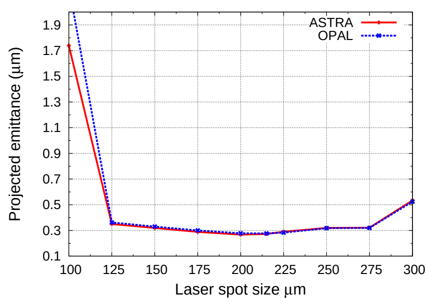

Figure 7: Projected emittance at the injector output as function of the laser spot size

INJECTOR PERFORMANCES

The overall injector performances using the parameters listed in Tab. 3 are plotted in Figs. 8 and 9. Note that OPAL does not use the canonical momenta and hence there is a difference in emittance inside solenoidal fields between OPAL and ASTRA.

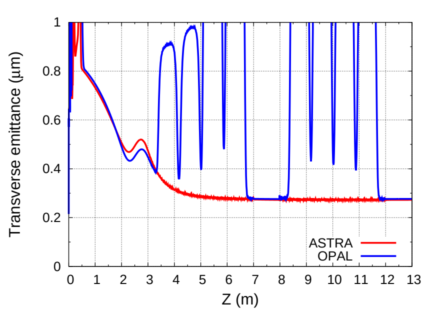

Figure 8: Projected emittance along the injector

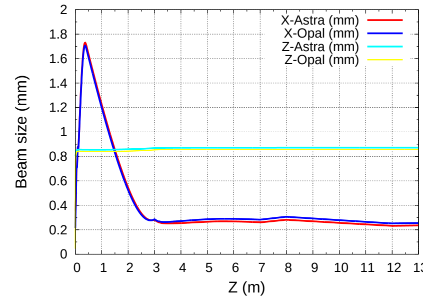

Figure 9: Longitudinal and transverse beam size along the injector

Table 3: SwissFEL injector parameters

Parameter	**Q=200 pC**
Laser spot size	215 μm 1σ
Laser duration (FWHM)	9.9 ps
RF Gun gradient	100 MV/m
Gun solenoid field	0.2097 T
1st TW gradient	19 MV/m
1st TW solenoid fields	0.04/0.04/0.08/0.08 T
2nd TW gradient	22 MV/m
2nd TW solenoid fields	0.068/0.068/0.068/0.068 T

CONCLUSIONS

This study demonstrated that the current design of the SwissFEL RF gun is able to deliver a high quality beam. The projected emittance at the injector output can be kept below the target of 0.4 μm with a very good matching (below 1.1). We show that the RF gun gradient can be set safely at around 100 MV/m reducing the risk of breakdown. The laser spot size should be set at around 200 μm (at 1σ) which is easily achievable with the current laser system. The gun solenoid plays an important role in order to get the invariant envelope matching at the entrance of the first TW structure and also for space charge compensation. The injector performance is largely insensitive to variation in cell length. This study demonstrated as well a very good agreement between OPAL and ASTRA for precise beam dynamics simulation in electron linacs.

REFERENCES

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