SwissFEL INJECTOR DESIGN: AN AUTOMATIC PROCEDURE

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Abstract

The first section of FEL injectors driven by photocathodes RF guns is dominated by space charge effects due to the low beam energy and the high charge density. An optimization of several parameters such as the emittance and the mismatch along the bunch has to be carried out in order to optimize the final performances of the machine. We focus on the design optimizations of the SwissFEL injector driven by the new PSI RF gun. This device, presently under construction at PSI, is planned to be installed at the end of 2013 in the SwissFEL Injector Test Facility (SITF) to be tested. Due to the number of variables and constraints influencing the beam properties, we developed a code to automatically perform such an optimization. We used this code to optimize the 200 pC operating point of SwissFEL and to fine tune other charge configurations down to 10 pC. With this optimization we obtained a noticeable reduction of the slice emittance with the new PSI gun compared to the CTF2 gun, presently installed in the SITF and on which the old lattice optimization was based. The same code with minor modifications has been successfully applied to the facility.

THE AUTOMATIC OPTIMIZER

The optimization code is based on a Matlab function [1] used to iteratively run a space charge tracking code, in our case Astra [2]. The steps of the function are:

1. The input file is written with given starting parameters (lattice, initial electrons phase space, RF and magnet parameters);
2. The job is submitted to a computer cluster;
3. A sub-function checks if the job finished to run and at this moment the figure of merit (FOM) is calculated;
4. A new input file is generated based on the results of the previous simulation;
5. The job is submitted to the cluster.

These points are repeated until the FOM variation is smaller than a user defined tolerance. The code finds a solution for a typical case of three variables in about 20 iterations and in less than hundred for six or seven variables cases. Each iteration with 5000 particles takes about 5 minutes on the PSI computer cluster running with 8 cores. In maximum about 8 hours we can therefore have a solution. In our case the Matlab function *fminsearch*, based on the derivative-free method, is driving the optimization, but it can be substituted by any Matlab minimizing function or by a user defined algorithm. In the next section the application of this optimizer to the SwissFEL injector is presented.

THE SWISSFEL OPTIMIZATION

The SwissFEL photoinjector is based on a 3 GHz RF gun pulsed by a UV laser (266.7 nm wavelength) on a copper cathode. The photoelectrons are accelerated by two S-band cavities up to about 130 MeV energy, before entering the laser heater and being further accelerated to ~330 MeV and compressed [1]. All the optimizations presented in this paper are run up to the exit of the fourth structure at energy of about 250 MeV (to be well out of the space charge regime) with the laser heater off except when the emittance preservation is checked in this line and beyond.

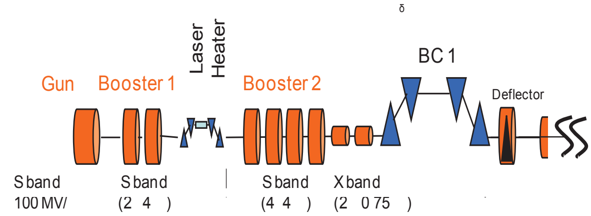

Figure 1: SwissFEL schematic layout [1].

The final slice emittance at the first undulator entrance downstream the main linac strongly depends on the final emittance at the end of the injector (less than 10% difference for the optimized case [1]). In this space charge dominated regime the emittance is influenced by several parameters. The most effective ones are acting at the lowest beam energy between the gun and the first accelerating cavity (E<8 MeV), where we can obtain 30% emittance variation with less than 1% change, so a careful optimization is mandatory [3].

The first parameter, which is fixed during the optimization, is the gun phase, determined by minimizing the energy spread. This is another fundamental quantity for the final beam quality and, with fixed gun geometry and gradient, it depends only on the phase.

Defined in this way the gun phase, the final injector emittance depends strongly on the strength of the solenoid at the gun exit, the laser pulse shape both in longitudinal (fixed by the final current at the entrance of BC1) and in the transverse direction, and the position of the first accelerating cavity. The dependence on the gradient, phase and magnetic field of the first accelerating structure and the corresponding solenoid around it is weaker. In a multivariable problem it is extremely important to restrict the number of variables as much as possible, to ease the convergence of the algorithm and to avoid being trapped in a local minimum. Because of this in the first step of the optimization we varied only the strength of the gun solenoid, the transverse size of the laser, and the position of the first accelerating cavity. Only after a good point has been found, we include the other variables in the optimizer to refine the result.

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To ensure the lasing for the majority of the electron pulse is also important to optimize the mismatch along the bunch, defined as:

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

where the *0* index indicates the Twiss parameters of the projected bunch. This parameter has to be as close as possible to 1.

As a figure of merit in the optimizer we therefore typically define a weighted average of the slice emittance and the mismatch parameter in the central part of the bunch (normally along 2/3 of the entire bunch length).

The Possible Guns for SwissFEL

The SITF design in [4] was based on the CTF2 gun version 5, presently installed in the SwissFEL Injector Test Facility (SITF), received on loan from Cern. A new gun, designed and manufactured at PSI has been optimized for the specific needs of SwissFEL (repetition rate up to 100 Hz, suppression of the dipolar and quadrupolar modes, improved pumping system) [5]. The field balance has also been improved, as it can be seen in Fig. 2. This gun will be installed in the next winter shut-down in SITF to be tested. We used this field map for all the optimizations we will present in the next sections, except in case differently specified.

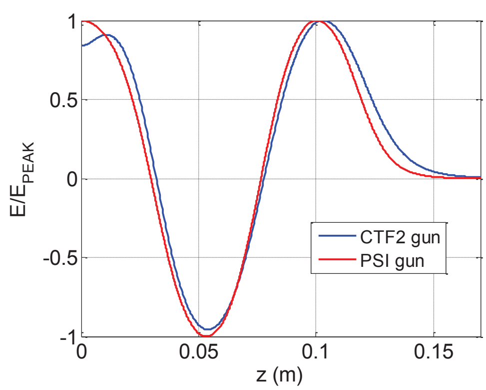

Figure 2: Renormalized to the maximum CTF2 and PSI gun 1D field maps along the longitudinal axis.

To be consistent with the old injector optimization, if not differently specified, we assumed a thermal emittance as a function of the laser beam size of 910 nm/mm [6] and the pulse length and the charge to 9.9 ps FWHM and 200 pC respectively assumed in the old design [4].

Among the several optimizations we selected the two which give a mismatch parameter smaller than 1.05 and the minimum emittances. In Fig. 3 the emittance along the bunch corresponding to these configurations are compared.

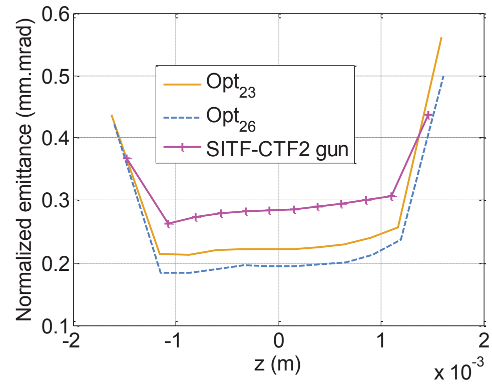

Figure 3: Emittance along the bunch for the two best configurations using the PSI gun, compared to the CTF2 based design.

In Fig. 4 the mismatch parameter along the bunch for the same cases is shown.

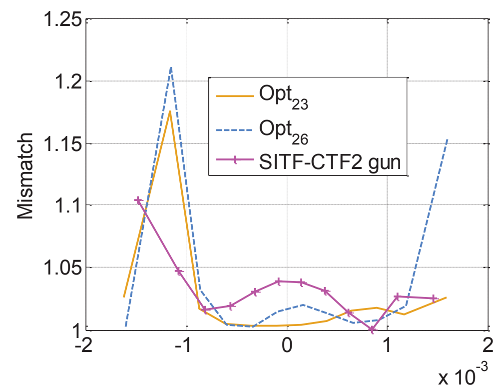

Figure 4: Mismatch parameter along the bunch for the two best configurations using the PSI gun, compared to the CTF2 based design.

The Opt_23 is the case obtained staying on-crest in the first two accelerating cavities in the injector and the Opt_26 is the one where some velocity bunching (30 degrees off-crest) is applied to the same cavities.

Start-to-end simulations indicated that the slice emittance can be preserved in the linac up to the entrance of the Aramis undulator line only in the Opt_23, whereas in the other case the emittance is degraded in the vertical plane.

The most crucial parameters of the Opt_23 configuration, considered the new injector design for SwissFEL, are reported in Table 1.

The new PSI gun field map and its optimization into the injector allow decreasing the slice emittance by more than 30% and keeping below 1.02 the mismatch along majority of the bunch in the simulations.

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Table 1: Key Parameters of the Optimized Configuration for SwissFEL (Opt_23) Compared to the CTF2 case

	PSI gun	CTF2 gun
Charge (pC)	200	
Laser pulse length (ps)	9.9 (FWHM)	
Gun gradient (MV/m)	100	
Laser sigma (mm)	0.33	0.55
Gun phase (deg)	-2.6	-3.3
Gun solenoid (T)	0.2069	0.2081
First structure position (m)	3.76	2.95
Projected emittance (mm.mrad)	0.25	0.35
Slice emittance (mm.mrad)	0.21	0.32

Recently J. Han proposed a new S-band gun design for FELs based on a coaxial coupler layout [7]. The author demonstrated the advantage of this configuration, since it allows positioning the first focusing solenoid closer to the cathode. The optimizer has been used to quantify the impact that such a modification would have in the SwissFEL injector case. In Fig. 5 the emittance along the bunch of the optimized cases are compared for the different scenarios.

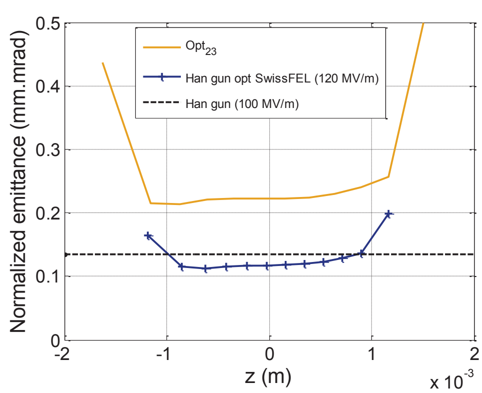

Figure 5: Emittance along the bunch for the coaxial coupler design and the new PSI gun case (at 100 MV/m peak field on axis).

In Fig. 6 the mismatch parameter referring to the possible gun layouts is shown.

This gun design should further reduce the slice emittance by about 25% with respect to the new PSI gun layout. A design in C-band based on this idea has been started and the optimizer has been used to design the injector layout [8].

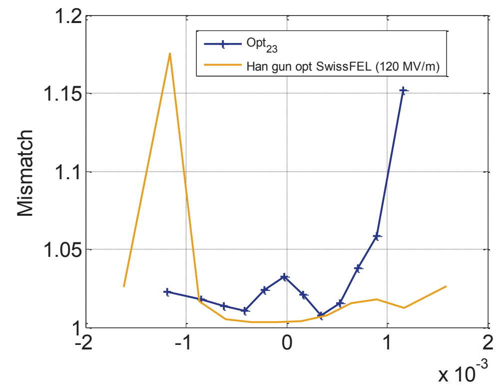

Figure 6: Mismatch parameter along the bunch for the coaxial coupler design (Han) and the new PSI gun case (at 100 MV/m peak field on axis).

Alternative Options

We explored other possible configurations to further optimize the SwissFEL injector not only in terms of emittance and mismatch. We tried to relax the RF tolerances and to minimize the microbunching instability [9] by reducing the compression factors in the bunch compressors increasing the current at the entrance of BC1.

We explored the possibility of compromising a higher emittance with an initially shorter laser pulse. As staring point we calculated the initial transverse size as a function of the parameters of the nominal 10 ps case, by keeping constant the volumetric charge density ρ, defined as:

$$\rho \equiv \frac{Q}{L_z\,\sigma^2} \tag{3}$$

where Q, L_z and σ are the charge the pulse length and the transverse dimension respectively.

From this relation we could compute the thermal emittance as a function of the laser pulse length and have in this way a guess of the minimum emittance we can have as a function of the pulse length. For each case we used the optimizer to refine the result minimizing both the emittance and the mismatch. In Fig. 7 the good agreement among these previsions and the optimizations is shown.

We had to exclude this option for SwissFEL, because the ratio between the current at the injector exit and at the cathode decreases with short pulses, as shown in Fig. 8, due to the longitudinal space charge.

This effect can be mitigated by going off-crest in the first two cavities, but in this case the emittance wouldn't be preserved downstream the main SwissFEL linac, because of the residual chirp (analogously to the Opt_26 configuration).

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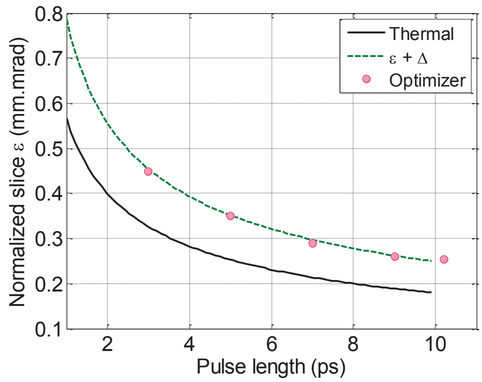

Figure 7: Thermal emittance, minimum expected emittance calculated by assuming the difference between the Opt_23 case and the thermal emittance, and optimized with the optimizer as a function of the initial pulse length.

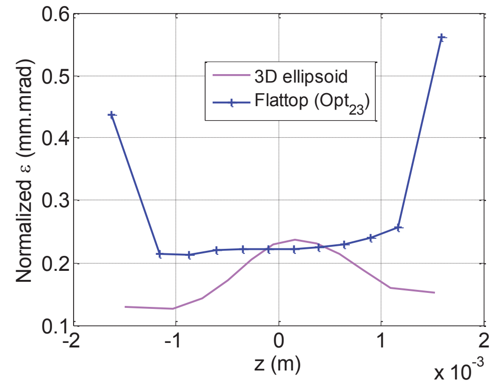

Figure 9: Emittance along the bunch for the 3D ellipsoid and the flat-top optimized distribution. At the highest peak current of the 3D distribution corresponds the emittance of the Opt_23 configuration.

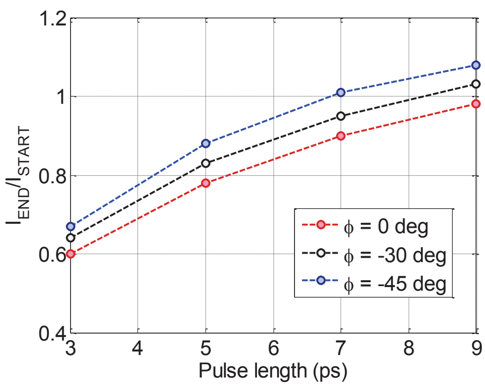

Figure 8: Current at the end of the injector as a function of the initial laser pulse length.

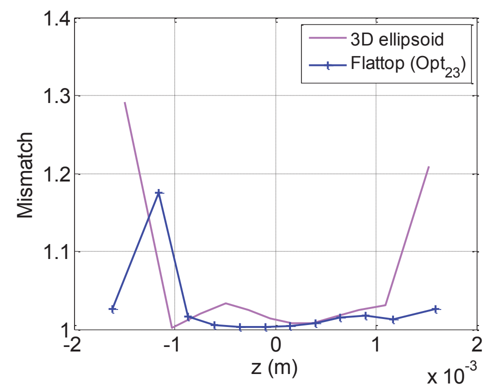

Figure 10: Mismatch parameter along the bunch for the 3D ellipsoid and the flat-top optimized distribution.

A theoretical study indicated that the optimal laser shape would be a 3D ellipsoid [10]. This kind of shape compensates for the space charge forces and in this way a flat mismatch along the bunch can be theoretically obtained [11]. We run the optimizer to analyze also this possibility.

In this case emittance and mismatch are comparable to the values obtained with the optimizer using a flattop distribution, as shown in Fig. 9 and in Fig. 10 respectively.

In our case, therefore, this option has been eliminated, because it is not dramatically improving the injector performances we can have with the standard flattop distribution.

Several Charges Optimization

SwissFEL will run at several charges from 10 pC up to 200 pC to satisfy the requests of different users. We re-optimized the injector by keeping constant the starting position of the first cavity for 10 pC, 50 pC and 100 pC.

Also in these cases the laser pulse lengths have been fixed by the required injector current at the entrance of BC1 [4]. To have a good starting point we calculated for each case the laser transverse size to keep constant the volumetric charge density ρ, as:

$$\sigma = \sqrt{\left.\frac{L_z \sigma^2}{Q}\right|_{200pC} \frac{Q}{L_z}} \tag{3}$$

Starting from these initial conditions the optimizer is run to further refine the results in terms of mismatch and emittance. In all these cases the solutions with a mismatch in the central part of the bunch greater than 1.05 are rejected. In Table 2 the summary of these optimizations is shown.

Table 2: SwissFEL Injector Optimization Using the New PSI Gun for Several Charges. In parentheses the values corresponding to the CTF2 gun are reported.

Q (pC)	Projected emittance (mm.mrad)	Slice emittance (mm.mrad)
10	0.090 (0.096)	0.076 (0.080)
50	0.16 (0.174)	0.135 (0.160)
100	0.20 (0.233)	0.16 (0.230)
200	0.25 (0.35)	0.21 (0.32)

The beneficial effect of the new PSI gun and the re-optimizations is from 5% for lower to more than 30% for higher charges.

Thermal Emittance

All the optimizations presented in this paper up to this section have been performed assuming the thermal emittance measured at LCLS [6]. To choose the laser wavelength several aspects have to be considered. A longer wavelength would be preferable from the beam dynamics point of view, because it would give a smaller thermal emittance. In despite of that the quantum efficiency would be smaller. To investigate the effect of the laser wavelength in SwissFEL we measured the thermal emittance as a function of the laser frequency in SITF [12]. Using these values as input for the generation of the particle distribution we verified the effect of the wavelength on the final emittance while keeping a limit on the mismatch parameter using also in this case the optimizer.

In Table 3 the optimized slice emittances are summarized for the two extreme SwissFEL charge cases.

Table 3: SwissFEL Injector Optimizations Using the New PSI Gun for Several Laser Wavelengths. The cases in parentheses correspond to the optimized case assuming LCLS measurement with only the different thermal emittance as input (rescaling).

λ (nm)	Thermal emittance/sigma (nm/mm)	10 pC slice emittance (mm.mrad)	200 pC slice emittance (mm.mrad)
266.7	910 @ LCLS	0.076	0.21
266.7	682 @ SITF	0.055 (0.060)	0.170 (0.185)
260	758 @ SITF	0.060 (0.064)	0.18 (0.195)
275	595 @ SITF	0.049	0.155 (0.170)

The reduction of the emittance obtained using the thermal emittance measured at SITF is shown in Fig. 11 and in Fig. 12 for the two SwissFEL extreme charges.

As a compromise between quantum efficiency and final emittance the 266.7 nm seems to be the best choice, because of the rapid degradation of the quantum efficiency at longer wavelengths [13].

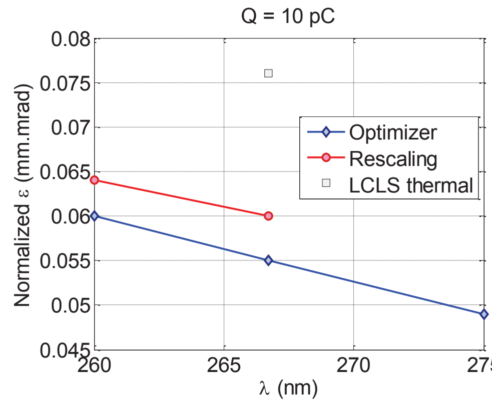

Figure 11: Slice emittance as a function of the measured thermal emittances in the SITF for the 10 pC case. The case corresponding to the LCLS measurement used for the previous optimizations is also reported. The rescaling case corresponds to the Opt_23 layout with only the SITF measured thermal emittance without further optimizations.

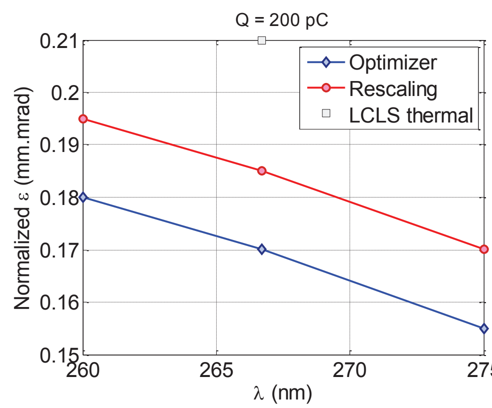

Figure 12: Slice emittance as a function of the measured thermal emittances in the SITF for the 200 pC case. The case corresponding to the LCLS measurement used for the previous optimizations is also reported. The rescaling case corresponds to the Opt_23 layout with only the SITF measured thermal emittance without further optimizations.

The SwissFEL design has been re-optimized based on this measured thermal emittance.

The resulting emittance is about 20% smaller than the Opt_23 case, as shown in Fig. 13. This is coming from the new layout re-optimized and from the smaller thermal emittance used as input.

The key parameters of these optimizations are reported in Table 4.

In the next winter shut down the new PSI gun will be installed in SITF using this layout according to Table 4.

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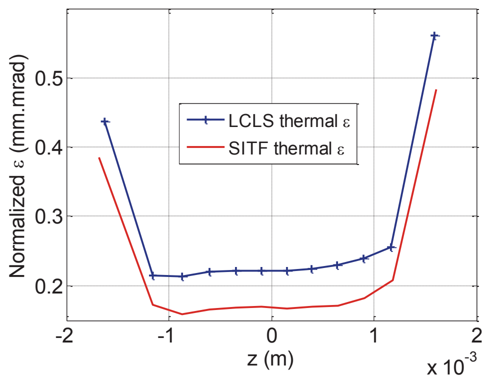

Figure 13: emittance along the bunch for the SwissFEL design assuming the LCLS and the SITF measured thermal emittance value for 266.7 nm laser wavelength.

Table 4: Optimized SwissFEL Injector Using the Thermal Emittance Measured at SITF

	682 nm/mm
Charge (pC)	200
Laser pulse length (ps)	9.9 (FWHM)
Gun gradient (MV/m)	100
Laser sigma (mm)	0.38

THE APPLICATION OF THE OPTIMIZER IN THE MACHINE

The structure of the automatic optimizer could be very easily adapted to be applied directly to the machine. To do this it's enough to send the settings to the machine control system instead of writing an Astra input file, and to measure the emittance and the mismatch instead of running the simulations. The Matlab based GUI written to do such optimization is shown in Fig. 14.

In the GUI the method to measure the emittance can be selected in a menu and the FOM can be defined. At each step the Twiss parameters, the emittances and the mismatch parameters with respect to the design values are computed.

The most important difference of the code applied to the machine with respect to the one used in the simulations is the way the noise is treated. In the case of the simulations this problem was solved by simply increasing the number of particles, considering the limited amount of time necessary to have a meaningful solution. In the case of the machine it was necessary to dedicate more attention to this aspect. In the optimization only the cases for which the measured emittances differ more than the standard deviation of the previous measurement are considered. Until now this was enough to obtain reasonable results. If necessary other tricks have to be applied: this measurement can be repeated several times or the changed parameters can be varied of a larger amount.

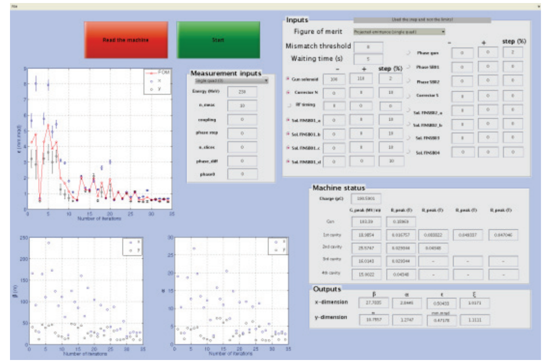

Figure 14: GUI developed to perform the emittance optimization in the machine. This particular test has been carried out with the X-band installed without power (minimum projected emittance 0.5 mm.mrad).

To have a robust and evident test of the optimizer we intentionally strongly degraded the emittance to about 4 mm.mrad, and after that we left the code recovering. In Fig. 15 the FOM (defined in that case as the geometric average of the projected horizontal and vertical emittances) is plotted as a function of the iteration number.

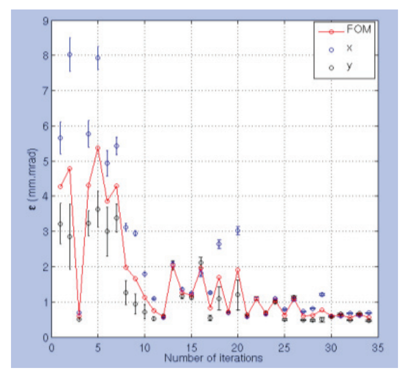

Figure 15: FOM and H and V projected emittances during the optimizer run in SITF.

As it can be seen the code brought back the emittance to slightly less than the emittances measured in that machine configuration.

CONCLUSIONS

The new PSI gun and the new optimization of the injector allows decreasing the simulated slice emittance of more than 30% in the 200 pC case. Several charges configurations have been optimized for the different operation modes. The thermal emittance as a function of the laser wavelength has been measured and this information with other constraints has been used to check the final wavelength for SwissFEL. Assuming the value measured at the SITF the design for SwissFEL has been refined. The new gun will be installed in the next winter shut-down to profit and to verify this design. Other more exotic possibilities have been explored for SwissFEL, as the best shape for the initial laser pulse and a higher current at the exit of the injector.

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To perform very fast all these optimizations it was crucial to develop a tool which is automatically changing all the variables in the injector to find the best solution in terms of slice emittance and mismatch along the bunch. The same tool with some minor modifications has been also successfully applied to the machine.

REFERENCES

[1] "SwissFEL conceptual design report", 2010.
[2] Flottmann et al., Desy, Hamburg.
[3] S. Bettoni et al., "Beam dynamics simulations for the SwissFEL injector test facility", IPAC2011 proceeding.
[4] "SwissFEL injector conceptual design report", 2010.
[5] J. Y. Raguin, "The SwissFEL RF gun: RF design and thermal analysis", LINAC 2012.
[6] Y. Ding et al. , "Measurements And Simulations Of Ultralow Electron Beams In The Linac Coherent Light Source".
[7] J. Han et al., "Design of a high repetition rate S-band photocathode gun", NIM A, 647 (2011), 17-24.
[8] M. Schaer et al., "Optimization studies for the SwissFEL RF-gun", IPAC2013 proceeding.
[9] S. Bettoni et al., "Microbunching instability studies in SwissFEL", IPAC2012 proceedings.
[10] C. Limborg et al., "Optimum electron distributions for space charge dominated beams in photoinjectors", SLAC-PUB-11899.
[11] M. Krasilnikov, "Cathode laser pulse shaping for high brightness electron sources (PITZ Experience), ICFA Workshop on Future Light Sources.
[12] C. Vicario et al., "Photocathode laser wavelength-tuning for thermal emittance and quantum efficiency studies", this conference.
[13] S. Reiche, H. H. Braun, private communication.

ISBN 978-3-95450-126-7