THE RF INJECTOR FOR THE FERMI@ELETTRA SEEDED X-RAY FEL

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Abstract

In the framework of the FERMI@ELETTRA project, aimed to build an x-ray FEL source based on laser-seeded harmonic generation, a crucial role is played by the electron source. This has to produce a very high quality beam, in terms of low emittance and uncorrelated energy spread. A very attractive solution is the SLAC/BNL/UCLA 1.6 cell s-band gun based upon the demonstrated high performance of this design and its descendants. This paper describes the results of the optimization studies based on the gun III design and carried out with two space charge tracking codes (GPT and ASTRA) for nominal operating parameters. In particular two different bunch charge regimes has been explored: low (few hundreds of pC) and high ($\sim 1nC$). In the first case, the limited charge extracted from the photocathode allows to propagate a bunch with an initial higher density and to compress it along the linac down to a few hundreds of fs, attaining a high peak current bunch with a very low slice emittance. The second case has been investigated in order to verify the possibility to produce a "1ps plateau" bunch with acceptable peak current and a slice emittance lower than 2 mm mrad. We present simulation results for both cases.

INTRODUCTION

The FERMI@Elettra project [1] seeks to produce coherent EUV to soft x-ray radiation using a cascaded harmonic FEL interaction driven by a $\sim$ 1.2 GeV electron beam. The project makes use of the existing GeV linac at Sincrotrone Trieste, but will replace the current thermionic injector with a high brightness rf photoinjector. Additional improvements to the linac rf systems will increase the repetition rate to 50 Hz.

The injector major systems are: photocathode laser, RF gun, booster linacs, emittance compensation solenoids, and laser heater. A diagnostics beamline will be incorporated in a branch line following the RF gun, to allow analysis of the beam phase space at the exit of the gun. A high quality electron source is essential to meet the requirements for photon production in the FERMI @ Elettra FEL. Two different bunch charge regimes have been explored; low (few hundreds of pC) and high ($\sim 1nC$). In the first case, the limited charge extracted from the photocathode allows production of a relatively short bunch and to compress it at higher energies down to a few hundreds of fs, attaining a high peak current bunch with a very low slice emittance. The second case is optimized for the possibility to produce a longer bunch required for the harmonic cascade (FEL-II).

An S-band rf photocathode gun, with spatial and temporal control of the photocathode laser system, will provide high brightness electron bunches at up to 50 Hz rate. Flexibility in bunch parameters will be incorporated into the systems design and specifications. Accelerating sections raise the beam energy to $\sim$ 100 MeV at the exit of the injector.

The difference between "European" S-band and "U.S." S-band frequencies makes it difficult to take an established S-band gun design and apply it directly to the FERMI@Elettra project, however existing designs may be scaled to the required frequency. Operating at up to 50Hz pulse rate sets demands on the thermal control of the gun, however there are designs, such as the LCLS gun, that operate at similar high repetition rate. An attractive choice for the electron gun is the SLAC/BNL/UCLA 1.6 cell s-band gun III, based upon the demonstrated high performance of this design and its descendants. This class of rf gun has some known limitations and issues which may require some modification of the rf cavity circuit parameters.

This paper will concentrate on beam dynamics simulations using a frequency scaled (to 2997 MHz) rf gun and injector linac. Details of the short bunch case will be presented, with emphasis on parameter optimization and sensitivity studies. Detailed modeling of the laser heater performance will be reported in future work.

THE FERMI@ELETTRA PHOTOINJECTOR

A schematic view of the photoinjector of the FERMI@ELETTRA X-ray FEL is reported in figure 1 [2].

The layout of the photoinjector up to the end of the second booster linac section is shown in Figure 1. The low energy transport line from the rf gun to the entrance of the first booster linac (S0A) is instrumented to allow two modes of operation: direct transport and deflection to an energy analyzing beamline. Two horizontal and vertical dipole correctors (TRIM) and two BPMs are positioned to allow for trajectory corrections. A single magnetic quadrupole is included to compensate for any residual phase-induced quadrupole field components in the rf gun or linac coupling cells that may interfere with emittance compensation. Standard in-line and interceptive diagnostics provide information on bunch current, transverse distribution and emittance. An energy analyzer comprised of a 90-degree bend

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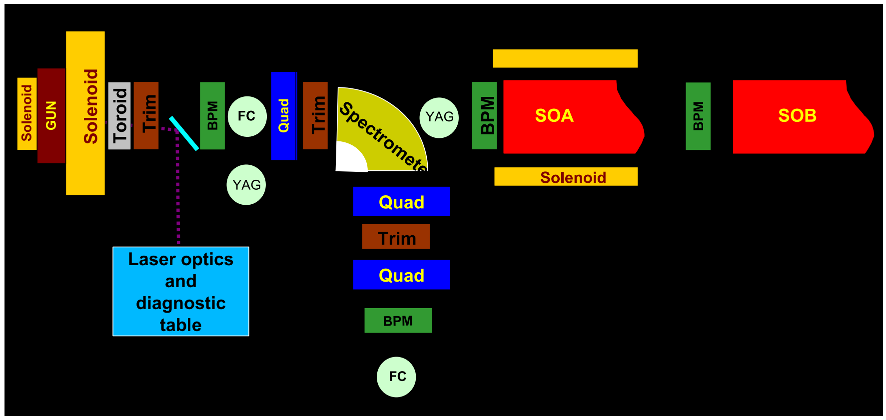


Figure 1: The Photoinjector Layout

and three quadrupoles will be used to measure the beam energy and energy spread. Deploying a streak camera to the end of the spectrometer beamline may allow for detailed study of the beam longitudinal phase space profile.

The accelerating sections SOA and SOB are $2/3\pi$ traveling wave SLAC-type structures, with a total length of 3.2m [3]. In our simulations we have chosen to assume conservative accelerating gradients for the gun and also for the SOA and SOB sections, so to have a safe margin in the optimization of the photoinjector parameters. The accelerating gradients are:

- RF gun : $E_{acc} = 110MV/m$
- SOA-SOB: $E_{acc} = 15MV/m$

Since the maximum accelerating field of the SOA section is not so high, we have foreseen a long solenoid around the SOA and SOB section in order to provide the additional focusing necessary for the emittance compensation.

BEAM DYNAMICS SIMULATION

The beam dynamics studies were carried out by using two space charge tracking codes: ASTRA [4] and GPT (General Particles Tracer) [5]. We have been evaluating the possibility to operate the X-ray FEL in two different regimes: low-charge/short-bunch and high-charge/long-bunch. The goal of the first option is to provide a bunch with a 200fs longitudinal flat core with a high peak current ($\sim 1kA$). In the next section we present the photoinjector optimization and the sensitivity studies performed for this first case. The second option aims to produce at the undulator entrance a longer bunch ($\sim 1ps$) with a reasonable peak current. In the last section we present preliminary studies about this case. In table 1 we report the main parameters relative to the two options.

SHORT BUNCH CASE

We have performed a large simulation campaign in the low charge regime by varying the charge extracted from the

	Low Charge short bunch	High Charge long bunch
Beam energy	95 MeV	95 MeV
Bunch Charge	330 pC	1 nC
Peak Current	60 A	100 A
Bunch Length (FWHM)	5.5 ps	10 ps
Projected emittance	0.8 μm	1.2 μm
Slice Emittance	0.7 μm	1.0 μm
σ_E (uncorr.)	3keV	3keV

Table 1: Main beam parameters at the exit of SOB in the two options we consider.

cathode (around 400pC) and the bunch length (around 5ps) in order to produce a bunch at the exit of the photoinjector consistent with the requirements coming from the linac optimization [6]. Taking into account the emittance growth in the linac and bunch compressors, emittance values targeted for the injector are obviously more restrictive than those required at the entrance of the undulator. Accordingly, the goal on the normalized emittance values at the end of the photoinjector is less than 1.5 mm mrad for the projected emittance and less than 1.0 mm mrad for the slice emittance, which should present a flat-like behavior along the bunch, at least concerning the central core [7]. In addition we have found that the longitudinal bunch profile at the exit of the photoinjector represents a very strong constraint from the point of view of the transport through the linac. A variation in the bunch length greater than 10% leads to a “mismatching” with the bunch compressor parameters setting [8]. Following the linac requirements we have fixed the charge per pulse extracted from the cathode to 330 pC and have optimized the bunch length (FWHM) at the exit of SOB section to about 5.5ps. We have studied several longitudinal laser pulse width in order to obtain the desired bunch length at the entrance of the linac. We have considered a laser spot size of 1 mm radius and uniformly distributed transversely, so that the electron bunch has a consequent thermal emittance of about 0.6 mm mrad, as given by the formula: $\epsilon_{th}(mm\,mrad) = (0.16 + 0.93 \cdot \sigma_x(mm))$ [9].

Following the classical technique of emittance compensation [10] well described in literature, we have optimized the RF gun injection phase, obtaining 24 deg (with respect to the RF zero crossing), and the strength of the compensation solenoid, obtaining 2450 Gauss. In this condition, the matching point, where the SOA section has to be installed, was found to be at a distance of 1.4m from the cathode surface. As foreseen the low accelerating gradient of SOA is not sufficient to compensate the emittance completely, so it is necessary to add a focusing element - a long solenoid around the SOA section, which is set to 700 Gauss. Figure 2 shows the projected emittance behavior, the RMS radial dimension of the bunch and the bunch energy along the photoinjector beamline. At the end of SOB the projected radial emittance attains the value of 0.8 mm mrad.

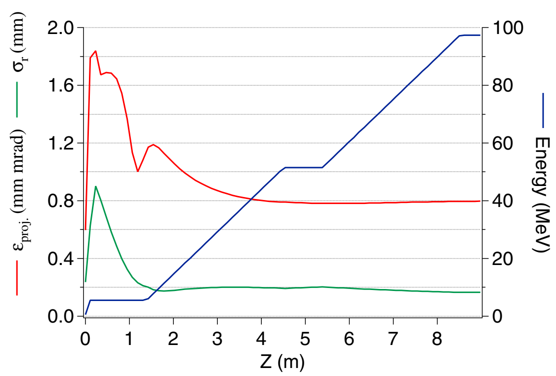
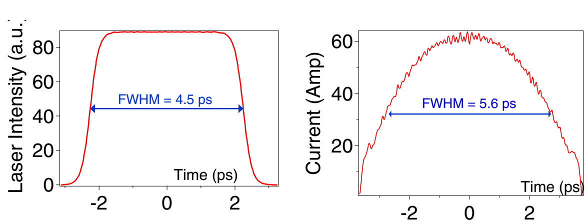


Figure 2: Projected radial emittance, radial spot dimension and energy along the photoinjector beamline

A good solution that fits the linac requirements concerning the longitudinal bunch profile consists in starting with a laser profile as in Figure 3(a) (FWHM=4.5ps and rise/fall time=0.5ps).



(a) (b)

Figure 3: a) Temporal laser profile; b) Longitudinal bunch profile at the exit of SOB.

The electron bunch originated from that laser profile is stretched during the propagation in the photoinjector by the space charge effect, and at the exit of SOB the bunch profile attains to a $FWHM \sim 5.6ps$ (figure 3(b)), with a peak current greater than 60 A. The plots in figures 2 and 3 refer to a GPT tracking simulation with 200000 particles and we have verified excellent agreement with ASTRA results. This number of particles is acceptable not only from the point of view of the optimization of the emittance compensation procedure, but even for the slice analysis. We divided the longitudinal bunch profile at the the end of SOB in 100 slices and we calculated the emittance and the energy spread of each slice, obtaining the plot reported in figure 4.

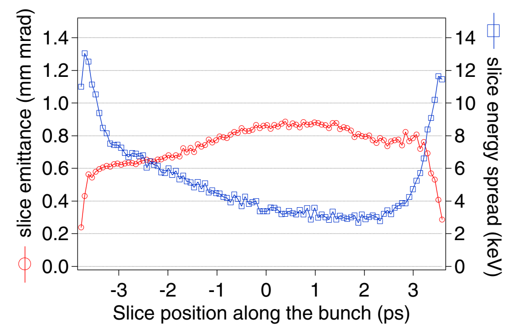


Figure 4: Slice emittance and slice energy spread along the bunch at the exit of SOB.

The slice emittance is kept quite constant around a value of 0.65-0.70 mm mrad along a large part of the bunch, while the slice energy spread, excluding the head/tail spikes, varies from a minimum of 2keV to a maximum of 4keV.

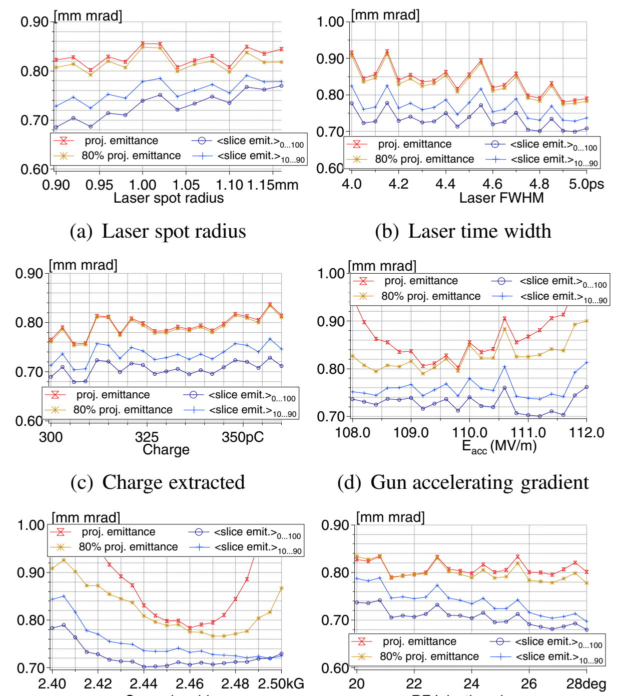
SENSITIVITY STUDIES

The emittance is the key parameter to be investigated for a sensitivity study concerning the photoinjector beam dynamics, even to verify the stability of the optimized machine setting. At this purpose we have varied independently the laser pulse parameters (radial spot size, time width and the pulse energy, that determines the extracted charge) and the gun parameters (accelerating gradient, RF injection phase and solenoid strength) in a reasonable range around the optimum short bunch optimized solution. Then we analyzed the variation of the bunch emittance at the exit of SOB. In particular we have compared the projected emittance averaging on all the particles with the 80%-projected emittance, obtained by averaging over the particles contained in the 80% longitudinal core of the bunch. Moreover we have calculated the average of the slice emittance over all the slices and over all the 80% slices core. The results are reported in figure 5.

Executing a linear or a parabolic fitting of the emittance curves plotted in figure 5, we have obtained the emittance sensitivity relative to each of the six parameters. Since the slice emittance results to be quite insensitive to these parameters variation, we take in account the projected emittance.

In particular we report in table 2 the minimum variation of each parameter that provides a 5% increase in the projected emittance.

This study demonstrates the good stability in terms of



(a) Laser spot radius

(b) Laser time width

(c) Charge extracted

(d) Gun accelerating gradient

(e) Gun compensation solenoid

(f) Gun phase

Figure 5: Sensitivity studies: emittance behavior vs. laser and gun parameters.

Table 2: Sensitivity to a 5% emittance variation.

Parameters	Variation
Laser spot radius	$> 20\%$
Laser FWHM	-10%
Charge	+ 17%
Gun E_{acc}	$\pm 1.1\%$
Gun solenoid	$\pm 0.8\%$
RF injection phase	$\pm 8 deg$

transverse emittance of the solution we found for the low charge short bunch case.

By randomly varying the six parameters together, in the above defined range, we performed a statistical analysis of the projected emittance values that are possible to obtain at the exit of SOB and we plot the results in figure 6.

The probability to have a projected emittance less than 0.90 mm mrad is more than 90%.

LONG BUNCH CASE

The optimization study relative to the high charge long bunch regime is in a very early stage, so here we give only some preliminary results. The machine layout has to be the same for both regimes, so in particular we have to optimize the injector parameters keeping constant the SOA position. Up to now we have considered a 1nC bunch, generated with

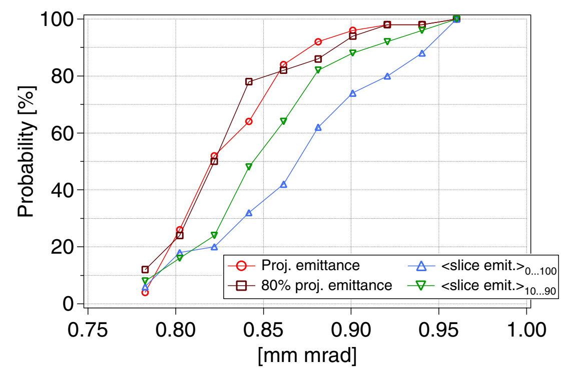


Figure 6: Each point refers to the probability to have a projected emittance less than the value on the x-axis.

a laser pulse FWHM of 10ps (rise/fall time equal to 0.5ps) and we obtained at the exit of SOB a projected emittance close to $\sim 1.2\ \mu m$. The slice parameters analysis has just revealed that it is going to be more difficult to keep the slice emittance value constant along the bunch as we obtained in the short bunch regime.

CONCLUSION

We have discussed the layout of the photoinjector of the FERMI@ELETTRA X-ray FEL, presenting the optimized configuration for the short bunch case, with a projected emittance close to $0.8\ \mu m$ and a slice emittance $\sim 0.7\ \mu m$. The found solution results very stable as the sensitivity studies has revealed. The long bunch regime has to be investigated more in the future.

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