

# FURTHER STUDIES IN THE FERMI@ELETTRA PHOTOINJECTOR OPTIMIZATION

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## Abstract

In the framework of the FERMI@elettra project we are presently studying an electron beam configuration satisfying the bunch energy distribution requirements coming from the FEL photon production system. The multi-particle tracking results concerning the photoinjector, which include the RF gun and the first two accelerating sections, are presented in this paper. We describe two possible electron bunch configurations which satisfy the FEL operation modes. Both injector configurations match the linac requirements for a 'ramped' current profile at the exit of the photoinjector. Sensitivity studies and time and energy jitter estimations are presented for both cases.

## INTRODUCTION

Several configurations of the electron bunch delivered to the undulator chain by the linac accelerator have been considered in the optimization study process for the FERMI@elettra project. After considerations of performance optimization in the remainder of the FERMI linac [1], a new type of laser excitation at the photocathode, consisting in a ramped current distribution, is proposed. In particular, the linac studies show that the accelerating structure wakefield and chicane CSR effects require an initial electron beam distribution with a quasi-linear head-tail ramp in the instantaneous current in order to produce a 'flat-flat' beam profile (i.e. uniform in current and energy) at the entrance of the FEL undulators. This linac requirement translates to photoinjector in the problem of finding a special laser shape that extracts from the cathode a bunch that evolves along the gun machine section (mainly a drift at low energy), producing the desired output profile. In this paper two possible 'ramped' bunch solutions are presented. These two FERMI photoinjector configurations are suitable for the machine operation in the so called medium and long bunch modes [2].

## PHOTOINJECTOR CONFIGURATIONS

For the FERMI@elettra project two machine operating modes are proposed that provide at the undulator entrance two different bunches in term of length and peak current [3]. These two mode require the gun to provide two different beams, presented in Table 1. To produce a

Table 1: Main beam parameters required at the exit of injector in the two studied configurations.

Parameters	Medium	Long
E	95 MeV	95 MeV
Q	800 pC	1 nC
$I_{peak}$ A	80 A	100 A
$L_b$ (FWHM)	8 ps	10 ps
$\epsilon_{proj.}$	$<1.5 \mu\text{m}$	$1.5 \mu\text{m}$
$\epsilon_{slice}$	$<1.0 \mu\text{m}$	$<1.0 \mu\text{m}$
$\sigma_E$ (uncorr.)	$<2 \text{keV}$	$<2 \text{keV}$

quasi-linear head-tail current ramp in the bunch an unconventional shape of the laser pulse has to be introduced. In the simulations performed so far a transverse cylindrical distribution (top hat with 1mm edge radius) has been used while a time-varying intensity is used to produce the variation in instantaneous current along the bunch. This particular shaping is achievable with the appropriate design of the drive laser optical system [4].

### Medium bunch case

The first case (so called medium bunch case) requires from the photoinjector a bunch charge of 800pC and a current profile, in the ramped part, with a length of about 8ps.

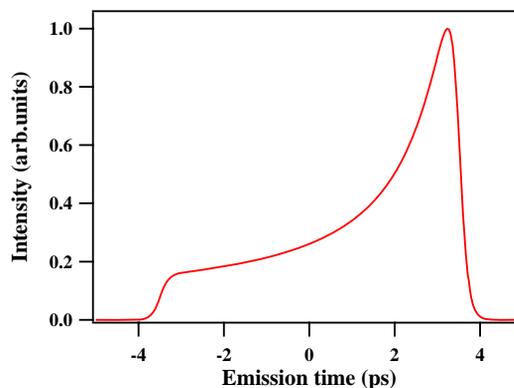


Figure 1: Longitudinal laser pulse shape: temporal intensity modulation.

Figure 1 shows the shape chosen for laser pulse intensity [2]. The curve is a Fermi-edge (with 7ps FWHM, 0.5ps of rise/fall time) multiplied by a polynomial ( $0.26 + 0.05 \cdot t + 0.012 \cdot t^2 + 0.008 \cdot t^3 + 0.0019 \cdot t^4$ ). A bunch generated

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by such a laser pulse propagates in the FERMI Gun machine section producing the output current profile shown in Figure 2.

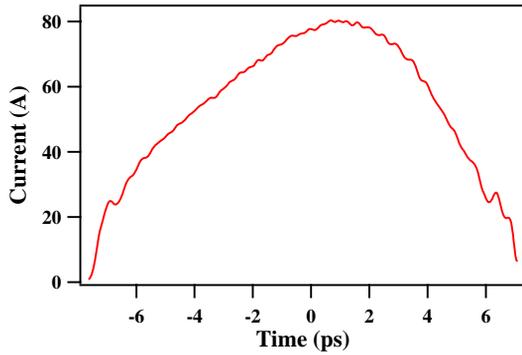


Figure 2: Current profile of the output bunch (head on the left).

Because of the highly non-linear charge distribution of the ramped profile, it is difficult to find an injector parameter configuration that completely satisfies the invariant envelope equation, performing perfect emittance compensation for all slices. Since each slice contains a different amount of charge, it evolves in a particular and unique way in the gun drift. Thus an average setting has been found that minimizes the projected emittance at the exit of the photoinjector (see Figure 3), which reaches 1.39 mm mrad. In the core 80% of the bunch particles the emittance is reduced to 1.21 mm mrad.

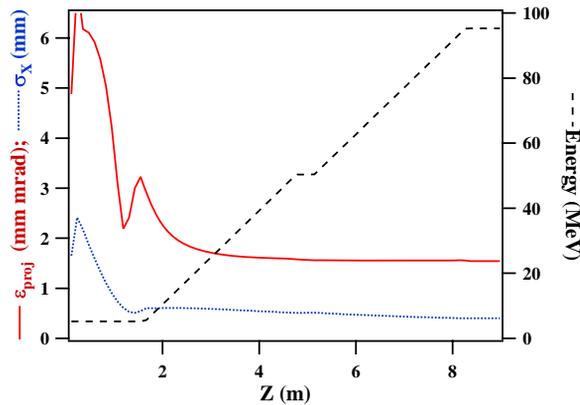


Figure 3: Transverse normalized emittance, radial spot dimension and energy along the photoinjector beamline for the medium bunch regime.

The slice analysis of the bunch at the injector exit, see Figure 4, shows that the slice emittance is affected by the current ramp and presents an head-tail increase from 0.7 up to 1.1 mm mrad.

*Long bunch case*

The second, or “long bunch”, case represents the configuration with higher bunch charge (1 nC) and longer drive

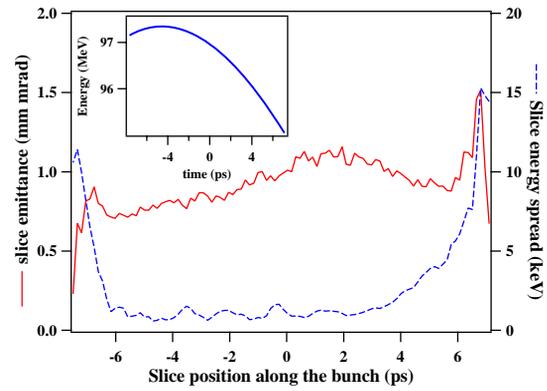


Figure 4: Slice emittance and slice energy spread at the injector exit for the medium bunch case calculated at the exit of the photoinjector machine section. Plot inside: Longitudinal phase space. Bunch head is to the left.

laser pulse. Figure 5 shows the laser shape chosen for the long case. The curve has FWHM of 10ps and the slope is driven by polynomial as  $35 + 10 \cdot t + 1.5 \cdot t^2$ . The output current profile is also shown and it reaches a peak current of 100 A. The useful bunch part (from head to the current drop) is about 10ps and this satisfies the linac requirements (Table 1).

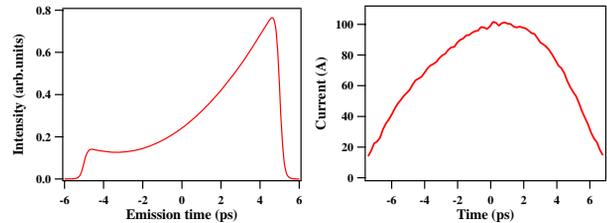


Figure 5: Longitudinal laser pulse shape: temporal intensity modulation on the left. Output current profile on the right.

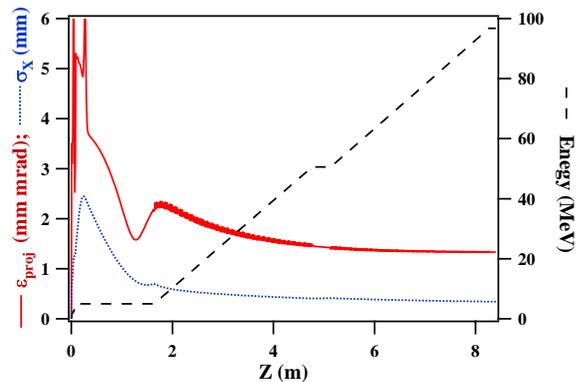


Figure 6: Transverse normalized emittance, radial spot dimension and energy along the photoinjector beamline for the long bunch regime.

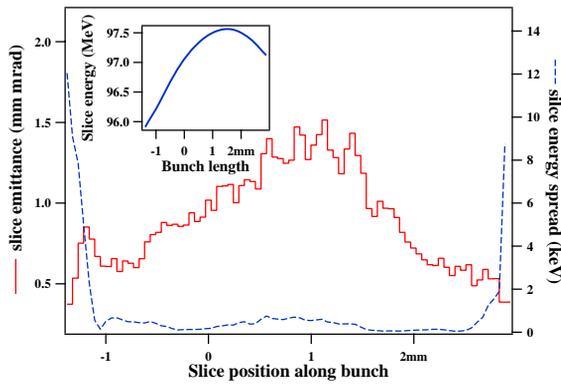


Figure 7: Slice emittance and slice energy spread at the injector exit for the long bunch case calculated at the exit of the photoinjector machine section. Plot inside: Longitudinal phase space. Bunch head is to the left.

Figure 6 shows the evolution of the transverse beam emittance, spot size and beam energy in this case. A final projected emittance of 1.33 mm mrad is achieved. Similarly to the medium bunch case The slice emittance also presents an head-tail ramp (see Figure 7).

### SENSITIVITY AND JITTER STUDIES

The time of flight, the energy, the energy spread and the emittance at the end of the injector have been identified as the main output parameters whose shot to shot variation should be quantified, as well the slice properties of the bunch. To identify the main sources of variation for each of these, a single-parameter sensitivity study has been performed for the two cases, with results shown in Table 2. The time of flight is sensitive to gun parameters, while the emittance is more effected by a solenoid variation.

By randomly sampling each injector parameter within a specified tolerance range fixed by present technology (see Table 3), one thousand injector cases have been tracked (with 50000 particles), obtaining a statistical evaluation of the expected jitter. Results are presented in Table 4. Figures 8 and 9 show the jitter distributions for the emittance and the time of flight and their histograms. The gun solenoid has been neglected in this analysis due to the high stability ( $10^{-5}$ ) provided by DC power supplies. The bunch time of flight jitter is about 300 fs at the injector exit and, linked to the energy jitter, it is propagated through the whole machine [5]. This effect became an issue in the synchronization in the undulators between bunch and a short seed laser.

In order to consider the optical matching between the injector and the linac, an analysis of the jitter in the Twiss parameters has been also carried out on the same ensemble of bunches. The results are reported in Table 4. The average  $\alpha_x$  and  $\beta_x$  are respectively -0.09 and 18m for the medium case (0.77 and 21m for the long), but the jittered outputs are spread out with a standard deviation respectively of 0.15

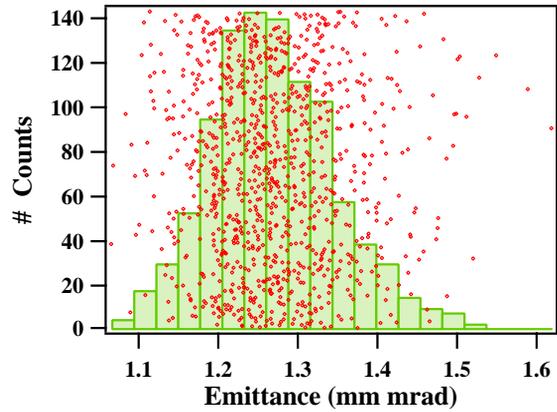


Figure 8: Projected transverse emittance jitter at the injector exit obtained by randomly sampling input injector parameters.

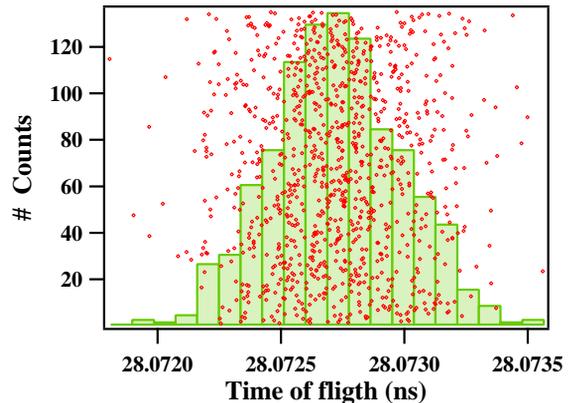


Figure 9: Electron bunch time of flight jitter at the injector exit obtained by randomly sampling input injector parameters.

and 2.1m (0.26 and 6.3m for the long case). This should be taken into account for the finalization of the optics matching.

Parameters	Tolerances
RF injection phase	0.1 deg
Laser time jitter	200 fs
Gun Eacc	0.25%
SOA Eacc	0.25 %
SOA RF phase	0.1 deg
Charge	4%
Laser spot size	4%
Laser pulse length (FWHM)	5%

Table 3: Tolerance budget for the injector parameters.

### Further analysis

A further analysis of the injector output bunches from the jitter simulations has been implemented. Polynomial fittings of the longitudinal phase space and current bunch

Table 2: Minimum parameters variation, for the medium bunch and long bunch (in parentheses) cases, providing a fixed variation of the outputs, indicated in brackets in the first row. The average slice emittance  $\langle \epsilon_{slice} \rangle$  is calculated over all the slices. n/s = not sensitive.

Parameters (variation)	$\Delta I$ (1%)	$\Delta T$ (100fs)	$\sigma_E$ (10keV)	$\Delta E/E$ (0.1%)	$\epsilon_{proj}$ (10%)	$\langle \epsilon_{slice} \rangle$ (10%)
<i>Gun</i> $B_{sol}$ (%)	1.5 (2.2)	> 10 (10)	1.1 (5)	n/s (n/s)	0.2 (0.8)	2 (1.2)
<i>Gun</i> $E_{acc}$ (%)	0.47 (0.6)	0.13 (0.15)	0.12 (0.17)	0.96 (1.6)	0.33 (0.5)	4.3 (0.9)
<i>Gun</i> $RFphase$ (deg)	0.65 (1.0)	2.8 (0.3)	0.8 (0.28)	3.8 (1.8)	0.5 (2.9)	4.8 (4.6)
<i>SOA</i> $E_{acc}$ (%)	20 (n/s)	2.0 (2.0)	3.9 (1.1)	0.21 (0.2)	n/s (n/s)	n/s (n/s)
<i>SOA</i> $RFphase$ (deg)	6.2 (n/s)	n/s (n/s)	0.1 (0.22)	1.9 (0.7)	n/s (n/s)	n/s (n/s)

Table 4: Simulation results of the output jitter for the medium and long bunch cases.

Output parameter	RMS jitter medium	RMS jitter long
Arrival Time (fs)	351	266
Peak Current (%)	2.4	3.3
Energy (%)	0.17	0.17
$\sigma_E$ (keV)	42	24
Emittance <sub>x</sub> (%)	13.1	6.3
$\alpha_x$	0.15	0.26
$\beta_x$ (m)	2.1	6.3

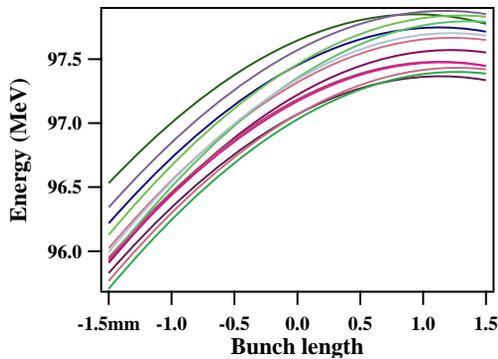


Figure 10: Twelve polynomial curve fits (fourth order), randomly sampled in the thousands performed, of the longitudinal phase spaces of bunches simulated for the long case. Bunch head is on the left.

profile have been performed for each simulated case. Figure 10 shows twelve fourth order polynomial curve fits of the longitudinal phase spaces of the bunches simulated for the long case, while Figure 11 shows the current profile cases. The curves show the synchronous bunch core (3mm) while the bunch tails are neglected.

After fitting all simulation results, a statistical analysis of the fit coefficients has been performed [6]. These statistical characterization can be used to reconstruct analytically the injector output particle distribution with respect to the jitter.

### CONCLUSION

Injector optimization of the medium and long bunch ramped cases have been described. The ramped current distributions have been presented as possible interesting so-

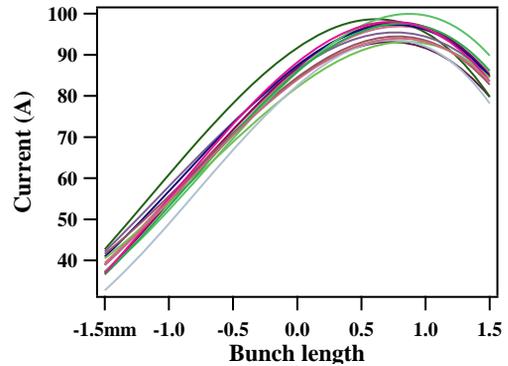


Figure 11: Twelve polynomial curve fits (fourth order), randomly sampled in the thousands performed, of the current profile of bunches simulated for the long ramped case. Bunch head is on the left.

lutions for the FERMI@elettra FEL operation with respect to the “standard” flat-top distribution despite the slight projected emittance increase. The jitter studies have shown that time jitter remains a critical parameter for seeded machine FELs and it will drive the future improvements in the performance of the laser and RF systems.

### REFERENCES

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