OPTIMIZATION STUDIES OF THE FERMI@ELETTRA PHOTOINJECTOR

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Abstract

In the framework of the FERMI@ELETTRA project the optimized electron beam characteristics depend on the two operating modes: FEL1 (100nm-40nm) with a photon pulse length ∼100fs and FEL2 (40nm-10nm) with a long photon pulse (∼1ps) for high resolution spectral bandwidth. Multi-particle tracking code results of the photoinjector, which includes the RF gun and the first two accelerating sections are presented and two possible electron bunch lengths that satisfy the two FEL operation modes are analyzed. The injector optimization relative to the two options, aimed at producing a very low projected emittance (around 1mm mrad) with a uniform behavior of the slice parameters (emittance and energy spread) along the bunch, is described in this paper. Moreover sensitivity studies, time and energy jitters estimates 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, in order to satisfy different users' requirements and to enhance flexibility in the machine design. An initial low charge bunch case was studied,that delivers at the undulator entrance a 1kA-bunch with a 200fs uniform central core, a projected emittance of 1.5mm mrad and slice emittances ∼1mm mrad. This regime is called "short bunch" [1]. Timing jitter studies have shown that this configuration is not suitable for the seeded FEL scheme with the short laser pulse (∼100fs) of interest for FERMI users. However the "short bunch" option is still valid due both to its good performance and because it represents an interesting back-up option and/or a start-up operation mode if a long seed laser is used. In order to accommodate the timing jitter requirements, without increasing the seed laser length, a longer bunch solution with a higher charge (∼800pC) was introduced. This regime is called "medium bunch", and it consists of a 600fs-1kA bunch at the end of linac. In addition a "long bunch" solution was studied, consisting of a ∼1ps bunch with a lower peak current (∼500Amps) [2]. Following the linac optimization and the compression schemes, the three regimes have been translated into requirements on the bunch at the exit of the photoinjector, summarized in Table 1. The optimization studies of the medium and the long bunch cases are described in this paper.

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Parameters	Short	Medium	Long
E	95MeV	95MeV	95MeV
Q	330pC	800pC	1nC
I_{peak}	60A	80A	100A
L_b (FWHM)	5.6ps	9ps	10ps
$\epsilon_{proj.}$	$<1.5\mu m$	$<1.5\mu m$	$<1.5\mu m$
ϵ_{slice}	$<1.0\mu m$	$<1.0\mu m$	$<1.0\mu m$
σ_E (uncorr.)	<2keV	<2keV	<2keV

Table 1: Main beam parameters at the exit of injector in the three options.

THE MEDIUM BUNCH CASE

As mentioned above, with a seed laser length ∼100fs and an electron bunch length ∼200fs at the undulator entrance, timing synchronization is a critical issue. To overcome this problem, a medium bunch was considered, consisting of a 600fs electron bunch with the same peak current (∼1kAmp). This is translated in an increase of the extracted charge up to 800pC and in a longer drive laser pulse at the cathode (9ps as FWHM, with 0.5ps of rise/fall time). Using the space charge codes (GPT and ASTRA), emittance compensation studies have been performed, taking into account certain beamline constraints. The first constraint comes from diagnostics equipment installed between the gun and the first booster section to measure and control the quality of the beam extracted from the cathode [3]. This is a critical issue in the space budget and

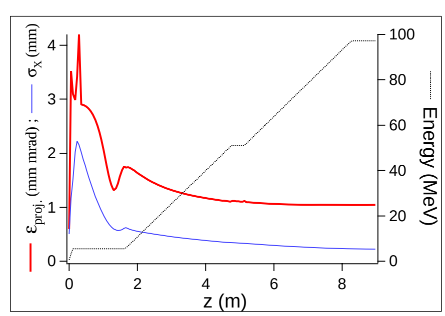

Figure 1: Transverse normalized emittance, radial spot dimension and energy along the photoinjector beamline for the medium bunch regime.

it requires moving the matching point far away from the cathode, with implications for the emittance compensation scheme. Moreover, a conservative value of 110MV/m for the gun accelerating gradient was assumed, even though better performance can be obtained by increasing it up to 140MV/m. Figure 1 shows the optimized emittance compensation scheme obtained with this layout. We have considered a transverse flat-top distribution with an edge radius of 1 mm, so that the electron bunch has a thermal emittance of $\sim$ 0.6mm mrad, as given in [4]. In this configuration the normalized RMS emittance reaches 1.0mm mrad. The slice analysis of the bunch at the injector exit, see Figure 2, shows that the slice emittance is kept quite constant around 0.7mm mrad along the bunch, thus satisfying the requirements of Table 1.

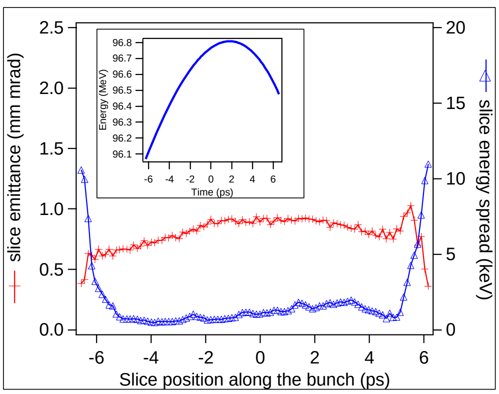

Figure 2: Slice emittance and slice energy spread at the injector exit for the medium bunch case. Inside plot: Longitudinal phase space including longitudinal wakefields. Bunch head is on the left.

LONG BUNCH CASE

The “long bunch” case represents the configuration at high bunch charge (1nC) and a relatively long drive laser pulse ($\sim$10ps). This is a “standard” case common to several photoinjector sources (e.g. LCLS). Taking into account the constraints mentioned above the system optimization led to a normalized RMS transverse emittance at the injector exit of $\sim$1.1mm mrad. The slice analysis of the output bunch, shown in Figure 3 shows that the slice emittance satisfies the machine demands, while the slice energy spread is in the 100’s eV range. This low value of the energy spread is due to the large number of macro-particles used in the simulation (1 million in this case) and therefore it is more credible than the larger value of figure 2 obtained with a smaller number of macro-particles. In addition it is also due to the removal of RF curvature derived correlations in the longitudinal phase space.

SENSITIVITY STUDIES

The time of flight, the energy, the energy spread, the peak current, and the emittance at the end of the injector have

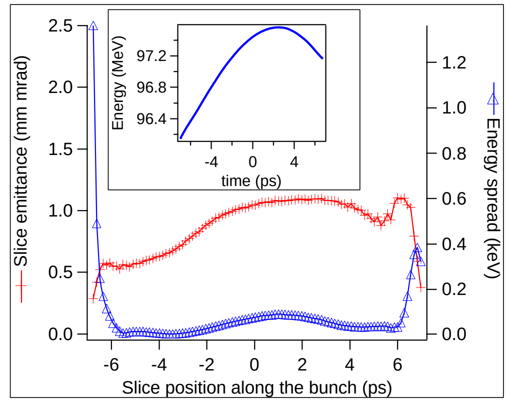

Figure 3: Slice emittance and slice energy spread at the injector exit for the long bunch case.

been identified as the main output parameters whose shot variation should be quantified, as well the slice properties of the bunch. To identify the main sources of jitter, a single injector parameter sensitivity study was performed for the medium and for the long bunch case, with results shown in Table 2. By randomly sampling each injector parameter in the tolerance range obtainable with present technology (see Table 3), hundreds of injector cases have been tracked with GPT and ASTRA (50000 particles), thus obtaining a statistical evaluation of the expected jitter. The gun solenoid was neglected in this analysis due to the high stability (10^{-5}) of the present DC power supplies. As the sensitivity studies have demonstrated, the laser time jitter remains a critical issue for the ultimate time jitter of the bunch at the injector exit. The output stability obtained with a conservative value of 300fs in the laser time jitter was compared with the results obtained in more stringent scenarios (200fs and 100fs), as shown in Table 4. The time jitter at the injector exit can not be reduced to less than 250fs without improving the stability of other injector parameters, for example the bunch charge.

RAMPING CURRENT DISTRIBUTION

It has been demonstrated that in order to compensate wakefield effects in the linac sections, at the exit of the photoinjector the electron bunch should have a linearly ramped peak current distribution instead of a flat top [2]. This requirement translates to the photoinjector optimization as a large perturbation due to the strong nonlinearity of the space charge fields at the cathode and in the drift between the gun and the first booster. To produce a ramped current bunch, a special initial profile had to be found that evolves along the injector to produce the final desired shape. In order to solve this problem, the longitudinal space charge fields at the cathode was investigated, since it is mainly responsible for blowing out the particles, especially in case of high peak current. Figure 4 shows the optimized current profile at the cathode and the evolved charge distribution at the injector exit for a 800pC bunch.

Parameters (variation)	ΔI **(1%)**	ΔT **(100fs)**	σ_E**(10keV)**	$\Delta E/E$ **(0.1%)**	ϵ_{proj} **(5%)**	$<\epsilon_{slice}>$ **(5%)**
$GunB_{sol}$ (%)	1.6 (2.3)	>5 (5)	n/s (n/s)	n/s (n/s)	0.2 (0.7)	4.2 (0.3)
$GunE_{acc}$ (%)	0.5 (0.6)	0.14 (0.15)	2 (0.2)	4 (2.7)	0.5 (0.4)	1.3 (0.7)
$\phi_{gun}(deg)$	1.3 (1.4)	0.24 (1.0)	0.32 (0.3)	2 (1.8)	1.8 (3.0)	2.6 (2.7)
Charge (%)	1.6 (1.5)	6.2 (>10)	n/s	n/s	3.2 (6.0)	3.8 (7.0)
Laser pulse length (%)	3.9 (4.0)	n/s (2.5)	n/s (5.0)	n/s	7.5 (6.0)	8.5 (9.0)
Laser time jitter (fs)	500 (1000)	92 (150)	145 (230)	950 (1500)	700 (2000)	1500 (2500)
$SOAE_{acc}$ (%)	n/s (n/s)	2.0 (1.8)	2.4 (1.4)	0.21 (0.25)	n/s	n/s
$\phi_{SOA}(deg)$	$>5(>5)$	$>5(0.12)$	0.16 (0.27)	1.1 (0.8)	n/s (n/s)	n/s (n/s)
$SOBE_{acc}$ (%)	n/s	n/s	16	0.21	n/s	n/s
$\phi_{SOB}(deg)$	n/s	n/s	0.3	n/s	n/s	n/s

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

Parameters	**Tolerances**
RF injection phase	0.1deg
Laser time jitter	100-300fs
Gun Eacc	0.25%
SOA Eacc	0.25%
SOA RF phase	0.1deg
Charge	4%
Laser spot size	4%
Laser pulse length (FWHM)	5%

Table 3: Tolerances Budget for the injector parameters

RMS laser time jitter	**300fs**	**200fs**	**100fs**
Arrival Time (fs)	384 (290)	332 (250)	250 (224)
Peak Current (%)	3.6 (3.1)	3.0 (3.1)	3.3 (3.1)
Energy (%)	0.18 (0.17)	0.18 (0.17)	0.17 (0.17)
σ_E (keV)	24 (15)	19 (17)	17 (10)
ϵ_{proj} (%)	6.8 (5.4)	6.1 (5.1)	6.5 (5.1)
α	0.49 (0.23)	0.27 (0.27)	0.24 (0.24)
β (m)	3.7 (3)	3.0 (3.3)	3.7 (2.7)

Table 4: Comparison between the output jitter assuming a laser time jitter of 300fs, 200fs and 100fs, for the medium (and long) bunch cases.

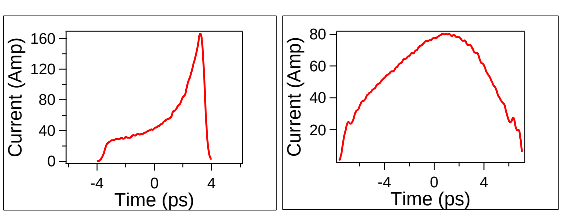

Figure 4: Ramping current distribution at the cathode (left) and at the injector exit (right), for a 800pC bunch.

Concerning the emittance compensation, since each slice contains differing amounts of charge, each then evolves in a particular and unique way (for a fixed injector setting). Thus an "average" setting has been found that minimizes the projected emittance at the exit of the photoinjector, obtaining ~1.4mm mrad. For 80% of the bunch particles the emittance is reduced to 1.2mm mrad. As expected, the ramping current distribution affects the slice emittances, which are modulated very similarly to the charge distribution (see Figure 5), from 0.7 (head) to 1.1 mm mrad (tail).

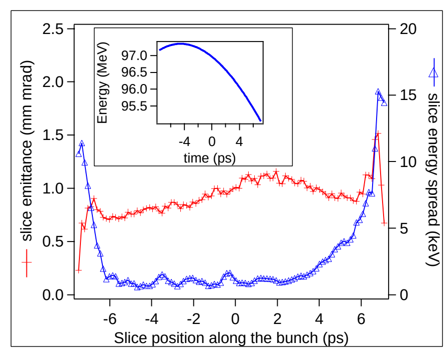

Figure 5: Slice emittance (red line) and slice energy spread (blue line) along the ramp medium bunch calculated at the exit of the photoinjector. Inside plot: Longitudinal phase space including longitudinal wakes. Head is on the left.

CONCLUSION

Injector optimization of the medium and long bunch cases have been described. A ramping current distribution has been presented as interesting alternative to the "standard" flat-top distribution.

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