ELECTRON BEAM SIMULATIONS FOR THE FERMI PROJECT AT ELETTRA

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Abstract

FERMI at ELETTRA is a project aiming at the construction of a single-pass user facility for the spectral range from 100 nm to 10 nm. Starting point is the existing 1.2 GeV, 3 Ghz linac. Downstream of the linac two undulator beamlines will serve the wavelength range from 100 nm to 40 nm and from 40 nm to 10 nm, respectively. The former beamline will be based on a single-stage High Gain Harmonics Generation (HGHG) scheme, while for the latter a double stage HGHG scheme is foreseen.

In this paper we present the results of both numerical and analytical studies aimed to optimize the electron beam characteristics for the 100-40 nm HGHG. In particular, care has been taken to include realistic models for the injector.

INTRODUCTION

The FEL-I phase of the Fermi at Elettra project involves the construction of a single-pass FEL user facility for the spectral range of 100 nm to 40 nm. The laser will be driven by the existing normal conducting 1.2 GeV linac [1].

Studies on a reliable representation of the linac sections and of their influence on the beam dynamics are here presented; these topics are essential for realistic start-to-end simulations, as well as to guarantee the final desired beam quality (Table 1) [2].

LAYOUT

Fig.1 and Fig.2 show the scheme for the linac layout and for the undulators line, respectively. As for the linac, a new rf photo-cathode gun [3] provides a high quality electron beam (see Table 2).

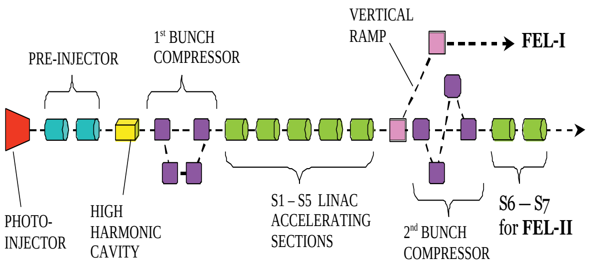

Fig.1 Schematic layout of the linac configuration for the FEL-I and FEL-II stages.

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A 100 MeV pre-injector of two (2/3) π travelling wave accelerating sections (TWs) gets the beam out of the space-charge energy domain and creates an energy-position correlation suitable for the following bunch compression.

An X-band harmonic cavity (HC) linearizes the compression process in order to permit a uniform charge density in the bunch and to remove excessive current spikes which may drive the coherent synchrotron radiation (CSR) instability.

After the chicane, five (3/4)π backward travelling wave sections (BTWs) allow the beam to reach the fixed target energy of 700 MeV. Quadrupole triplets between the sections provide the necessary transverse focusing.

Table 1. Electron beam target parameters at the end of the linac for FEL-I stage.

	FEL-I	
Wavelength target	100 40	nm
Beam energy	0.70	GeV
Bunch charge	1.0	nC
Peak current	0.8	kA
Bunch duration (σ_t)	500	fs
Energy spread (σ_δ)	0.7	MeV
Emittance	1.5	μm rad
Repetition rate	50	Hz

The electron beam is taken to the surface undulator hall through a dogleg, which is achromatic and nearly isochronous: its 5° bending angle avoid a further beam quality degradation due to the CSR.

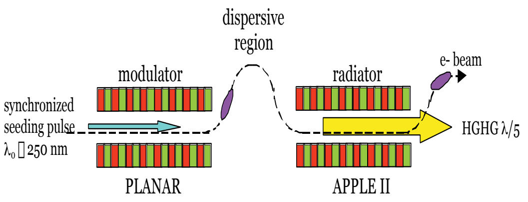

Fig.2 Set-up of the FEL-I undulators line based on a single-stage HGHG mode of operation.

HGHG using an external laser as input seed is foreseen for FEL-I. Such a technique allows the optimization of the stability and of the flexibility of the system, as well as the spectral properties of the output signal. The undulators line consists of sections of about 2.5 m, separated by drift sections 0.75 m long dedicated to diagnostics and quadrupole focusing (FODO lattice). Planar undulators will be used in the upstream areas, where mainly the electron-bunching process is important. APPLE-II type of undulators, allowing the control of the polarization of the output signal, will be used to produce the final radiation [1].

RF PHOTO-INJECTOR

Simulations have been performed with a maximum of 10^5 macro-particles for 1 nC of total charge.

The ASTRA tracking code [4] simulates the beam generation in the rf photo-cathode gun and its transport to the end of the first section of the pre-injector. It takes into account 1D space-charge effects.

The new gun for the Fermi at Elettra project is a re-scaled version of the LCLS gun model [3]; it comprises an external solenoidal field of 0.3 T. Ferrario's working point [5] defines the distance from the cathode at which the total emittance (geometric and thermal) reaches a minimum; here the emittance is freezed by the solenoid [6]. Table 2 lists the parameters of the electron beam at the exit of the gun [3,6], in agreement with the specifications for FEL-I (see Table 1).

Table 2. Electron beam parameters at the exit of the rf photo-cathode gun. Simulations by ASTRA code.

Beam parameter	Gun field [MV/m]		Units
	140	120	
Beam size rms	340	330	μm
Normal. emittance rms	0.57	0.63	μm rad
Electron energy (E)	8	6	MeV
Bunch length (σ_z)	900	930	μm
Energy spread (σ_δ)	0.21	0.27	%
Peak current (I)	0.104	0.102	kA

BUNCH COMPRESSION

The beam distribution generated by ASTRA is transported by ELEGANT [7] to the magnetic chicane. The appropriate energy-position correlation is created by the "out of crest" acceleration in the second section of the pre-injector.

The following HC is described by a π-mode standing wave pill-box. It linearizes the longitudinal phase space in order to increase the compression efficiency. Its parameters are estimated by means of analytical formulas [8] and refined through an optimization in ELEGANT.

The bunch compressor is a symmetric structure of 4 rectangular bending magnets. The optics limits the effects of CSR, mainly the transverse emittance growth and the micro-bunching in the energy distribution. CSR has been taken into account also in the drifts following the dipoles.

A compression factor of 7 produces a peak current of 1 kA in a symmetric charge distribution, which may be modified at occurrence by a proper setting of the HC and of the bunch compressor. The beam parameters before and after the compression are listed in Table 3. The present scheme provides R_{56} = - 1.1 × 10^{-2} m and T_{566} × $\sigma_{\delta,i}$ = 1.8 × 10^{-5} m. The emittance growth is limited to 10% in both planes by the optics arrangement.

Table 3. Electron beam parameters before and after the compression.

Beam parameters	Before	After	Units
Electron energy (E)	78.1	68.3	MeV
Bunch length (σ_z)	907	128	μm
Energy spread (σ_δ)	3.2	3.5	%
Peak current (I)	0.1	1.0	kA

LINAC

Wakefield in the BTW sections

The accomplishment of the FEL-I phase foresees the beam acceleration in 5 linac sections, each giving a maximum energy gain of 150 MeV (conservative value).

The Green functions for the transverse and longitudinal wakefield in the Elettra linac sections have been studied and well defined through numerical calculations [9]. The longitudinal wakefield interacts with the charged particles changing their energy. Thus it perturbs the bunch energy distribution inducing a correlated energy spread. The FEL-I electron beam simulations presented here include the longitudinal wakefield only, which is expected to be much stronger with respect to the SLAC-type [10] and TESLA [11] cases (Fig.3).

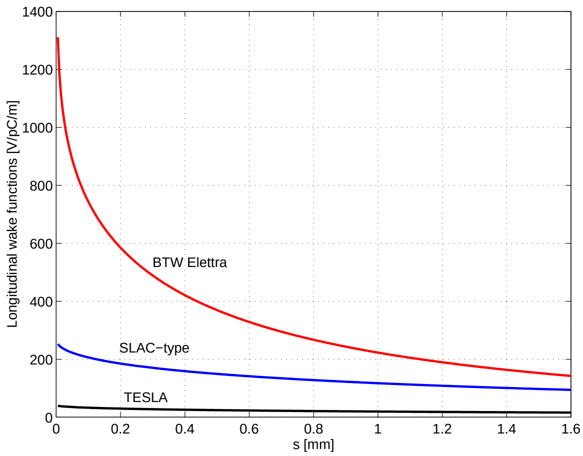

Fig.3 Wake function (in V/pC/m unit) vs. longitudinal coordinate behind the electron bunch in the ELETTRA, TESLA and SLAC-type accelerating sections. The origin s=0 coincides with the unit charge position generating the wakefield.

Studies on the reliability of the ELEGANT tracking in presence of wakefields have been carried out through a comparison with results obtained from an analytical treatment of the wake potential [12,13]. The beam transport has been investigated both for the case of a single section (i) and for the whole linac (ii). A gaussian distribution has been used as input, with initial central energy and energy spread negligible with respect to the total energy gain.

In the analytical treatment the beam is propagated through (3/4)π TW sections. The ELEGANT simulation is performed using analogous π-mode SW sections, instead [7]. Simulations show that the particle distribution is practically unmodified by the propagation in one accelerating section.

Fig.4 for case (i) and Table 4 for the case (ii) permit a comparison of the final correlated energy spread obtained with the two methods. In both cases the agreement is quite good; the discrepancies are in the tolerances of the different wakefield implementations (few percent).

It is worth pointing out that there exists a minimum for the correlated energy spread induced by the simultaneous interaction of the accelerating field and of the wakefield with the electron beam. In particular, larger amplitudes of the rf voltage (that is larger energy gains) counteract the wakefield effect, thus reducing the growth of energy spread.

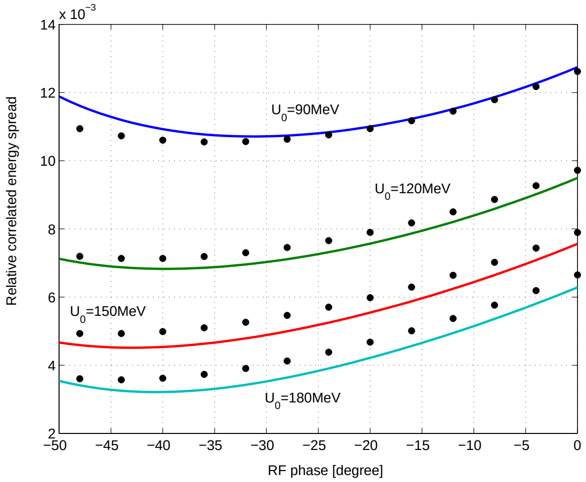

Fig.4 Relative correlated energy spread as function of the rf phase, at different energy gains in one accelerating section of the Elettra linac. Comparison of results from the analytical treatment of the wake potential (solid lines) and from ELEGANT tracking (dots).

Table 4. Results from the analytical method and ELEGANT tracking along 5 linac sections.

	Analytical Method	ELEGANT
Central Energy [MeV]	699.6	699.3
Relative Correlated Energy Spread (rms)	0.44%	0.45%

Arbitrary initial conditions in the energy and charge distributions cannot be described analytically in a satisfactory way. However, such distributions have been approximated by means of known functions in the analytical treatment. In these cases the two methods produce results differing to 30% as maximum, but the qualitative behaviour of the curves is still very similar.

Wakefield compensation

The evolution of phase space along the linac shows that the wakefields enhance a nonlinear region in the bunch energy-position correlation, producing a minimum at $\delta \approx -0.2\%$ for the correlated energy spread (corresponding to the highest peak in Fig.5); it is located in the bunch tail ($t > 0$ in Fig.6).

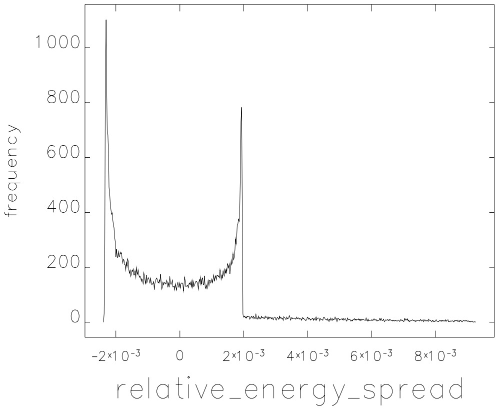

Fig.5 Frequency histogram of the relative correlated energy spread in the elecron bunch at the exit of the FEL-I linac. A large amount of the particles assumes an energy spread $\delta \approx -0.2\%$, as shown by the highest peak.

The minimization of the correlated energy spread can be performed in a similar way both by the analytical treatment and by ELEGANT: the rf phases are forced to the minimum, accordingly with the constraint of a final beam energy of 700 MeV. This condition requires thus maximum peak voltages.

A very simple linac optimization foresees identical parameters for the 5 sections, with maximum peak voltage (150 MeV energy gain) and -31° rf phase for an "out of crest" bunch acceleration. The optimization provides σ_z = 128 μm and σ_δ = 0.2%, at a central energy of 699.5 MeV.

However, the FEL performance is determined by the uncorrelated slice-energy spread at the maximum current, i.e., the total energy spread over a cooperation length of the FEL [14]. In our case the typical cooperation length (L_c) is less than 2 μm. From Fig.6 and Fig.7 it follows that at the peak of the bunch-current the correlated energy spread is linear. Hence, the total energy spread within a cooperation length can thus easily be estimated by $L_c \cdot \sigma_\delta / 2\sigma_z = 1.6 \cdot 10^{-5}$, well below the limit stated in Tab.1. We also note that the estimated peak current of ~ 1 kA for FEL-1 fully satisfies the condition quoted in the table.

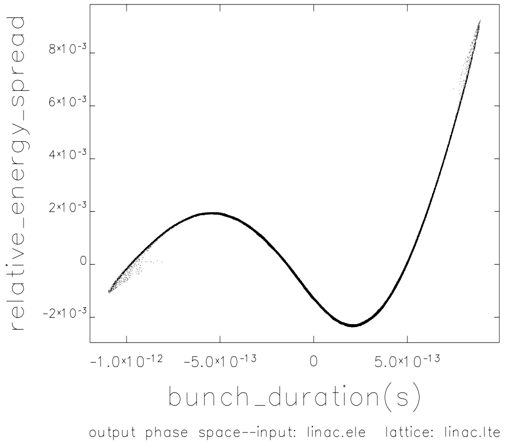

Fig.6 Longitudinal phase space (relative correlated energy spread vs. time) of the bunch at the exit of the FEL-I linac. The rf phases of the accelerating sections have been set for the wakefield compensation.

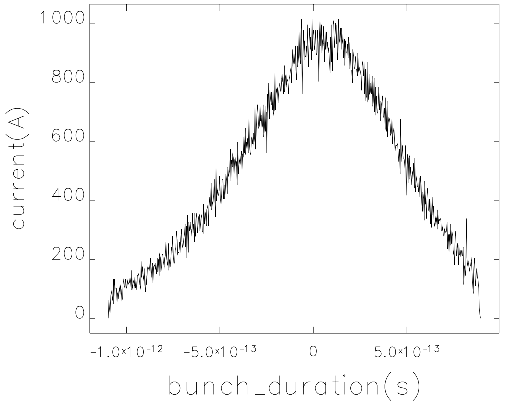

Fig.7 Current distribution along the bunch at the exit of the FEL-I linac.

CONCLUSIONS

Electron beam simulations for the FEL-I phase [1] of the Fermi at Elettra project [2] have been performed. Special care has been taken in the study of the longitudinal dynamics in the Elettra linac sections.

A fast analytical algorithm has been developed [12,13] to evaluate the evolution of the correlated energy spread in presence of longitudinal wakefields [9], as well as to optimize the rf phases for the wakefield compensation. The algorithm provides the same results obtained by the ELEGANT tracking on analytical beam distributions. It allows qualitative estimations in more realistic cases.

The strong longitudinal wakefield in the Elettra linac sections does not result to be critical for the FEL-I phase: the correlated energy spread has been minimized to the 0.2% rms value. It provides slice features in full agreement with the specifications [1,2]. Moreover, a wide fraction of the electron bunch is compatible with the seeded mode of operation; in this case, the central energy deviation may be easily compensated by the tuning of the wavelength through the gap variation of the undulator.

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