ENERGY SPREAD IN BTW ACCELERATING STRUCTURES AT ELETTRA

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Abstract

The FEL project FERMI@ELETTRA will use the existing 1.0 GeV Linac, based on Backward Travelling Wave (BTW) structures, to produce VUV radiation between 100-10 nm. The project will be articulated in two different phases (100-40nm/40-10nm) and will require high quality beam with short bunches (500/160 fsec). Hence, wakefield effects have to be considered with respect to the electron beam quality. The single bunch energy spread induced by the short-range longitudinal wakefield is analyzed and results of start-to-end simulations are reported.

INTRODUCTION

The Fermi@Elettra project aims to construct a single-pass FEL user-facility in the spectral range 100-10 nm using the existing normal conducting 1.0 GeV linac. Fig.1 shows the proposed machine layout for the two phases of the project: FEL-I (100-40 nm) and FEL-II (40-10 nm) [1]. At present the linac is operated less than two hours a day as injector of the storage ring Elettra and, at least for the next two years, until the new injection system will be fully commissioned, this function has to be preserved. This implies that all the activities related to FERMI have to be scheduled without interfering with the normal operation of the machine.

More details on the machine upgrading and layout modifications can be found in [2].

The new scheme for the machine foresees an RF photo-cathode gun [3], providing a high quality electron beam, whose parameters are directly related to the ones required at the entrance of the undulator lines (table 1). Then, a 100 MeV pre-injector, composed by two 3 m accelerating sections with focusing solenoids, get the beam out of the space-charge energy domain and creates an energy-position correlation for bunch compression.

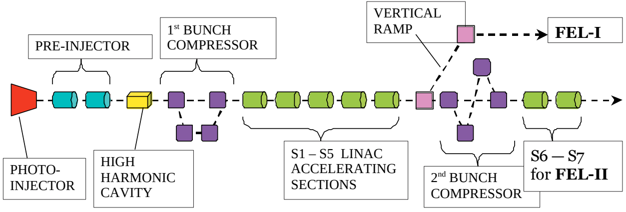

Figure 1: Schematic layout of the configuration for the FEL-I and FEL-II stages.

After the first magnetic chicane, five accelerating structures of the existing linac, equipped with an RF pulse compression system (SLED), allow the beam to reach the target energy required by FEL-I, 700 MeV. In total the present linac includes seven 6 m accelerating sections, 3/4π backward travelling wave (BTW), composed by 164 nose-cone cavities magnetically coupled. The remaining two accelerating sections will be located after the second bunch compression and will be used for the second phase of the project FEL-II up to 1.0 GeV. Quadrupole triplets between the sections provide the necessary transverse focusing. As reported in table 1, FEL operations require a high quality beam with ultra short bunches, hence the wakefield effects have to be considered carefully. That is, the short-range longitudinal wakefields increase the single bunch energy spread, while short-range transverse wakefields may increase the emittance of the bunch.

In this paper the single bunch energy spread induced by short-range longitudinal wakefields and accelerating voltage is analyzed for the FEL-I. The minimum single bunch energy spread at the exit of the linac has been calculated by varying the energy gain and RF phase of the BTW sections. Finally the results have been compared with those obtained from start-to-end simulations with ELEGANT [4] in presence of longitudinal wakefields.

Table 1: Electron beam parameters at the end of the linac for FEL-I and FEL-II

	FEL-I	FEL-II	
Wavelength target	100 40	40 10	nm
Beam energy	0.70	0.55 1.00	GeV
Bunch charge	1.0	1.0	nC
Peak current	0.8	2.5	kA
Bunch duration (σ_t)	500	160	fs
Energy spread (σ_δ)	0.7	1.0	MeV
Emittance	1.5	1.5	µm
Repetition rate	50	50	Hz

LONGITUDINAL DYNAMICS IN FEL-1

The FEL-I wavelengths foresees the acceleration to 700 MeV of a bunch with σ_z=120µm and total charge Q= 1nC at in five BTW sections. Note that with a negligible beam loading each section of the present linac can provide an energy gain up to 170 MeV. The beam energy spread is determined by the accelerating field produced by the external generator and the wakefields excited by the beam in the accelerating structures. For our BTW structures the wake potentials have been numerically evaluated and the wake function obtained by a fitting based on analytical estimations [5]. Figure 2 shows the numerical results obtained for the longitudinal wake potentials of Gaussian bunches with lengths ranging from 1000 µm up to 50 µm (solid lines); the black dashed line represents an analytic approximation of the longitudinal wake function.

As already shown in [6], for a Gaussian bunch the RMS energy spread can be easily evaluated by knowing four integral parameters of the wake fields: the loss factor $K_\parallel$, the average wake energy spread ΔW and the Fourier sine/cosine part $I_{sin,}/I_{cos}$. Table 2 summarizes the computed integral parameters in our case.

To minimize the single bunch energy spread at the end of the linac we have used a routine that allows the compensation of the longitudinal wakefields through the tuning of the RF phase and amplitude of the accelerating sections. We have individually set each accelerating module, fixing their maximum energy gain and RF phase, in order to reach the minimum energy spread with the constraint of a final energy of 700 MeV. Note that in practice, on the present plant, we can do that with an extreme flexibility since we have one RF plant for each accelerating section.

The optimization has been made under the assumption that the initial energy spread, at the exit of the first bunch compressor, is negligible with respect to the total energy gain for section. Furthermore we have considered an initial energy of 68.3 MeV [7] and a maximum energy gain for section of 170 MeV with a gradient of 28 MV/m. The results show that the optimization foresees identical parameters for the five BTW sections, in terms of maximum energy gain U_0 and optimum RF phase ϕ_{opt}, table 3 summarizes the obtained values. The minimum relative energy spread at ϕ_{opt}=-40.8° RF phase is roughly 2.5 times smaller than the corresponding at ϕ_{opt}=0°, on crest acceleration and energy spread due to the wakefields only, but we have to accept an accelerating efficiency reduction of 24%.

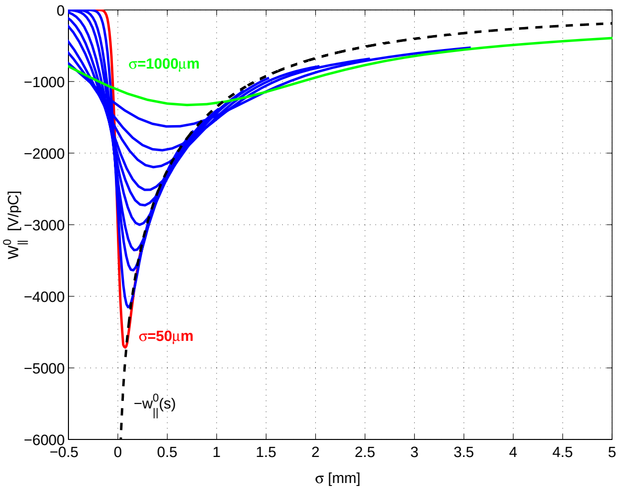

Figure 2: Longitudinal wake potentials (solid lines) and longitudinal wake function (black dashed line) of the BTW structure.

Table 2: Integral parameters of the wake potentials in the BTW structure

σ_z [μm]	$K_{\|\|}$ [V/pC]	I_{cos} [V/pC]	I_{sin} [V/pC]	ΔW [V/pC]
120	-2298.3	-0.009598	-7.860948	1118.4

Figure 3 shows the energy gain as a function of the distance s to the bunch center for different input phases ϕ_{opt}. The effect of the compensation of the wakefields can be seen as a decreasing of the difference between the relative maximum and minimum of the energy gain in the range considered $-3\sigma_z/3\sigma_z$.

Table 3: Minimum single bunch energy spread vs. the maximum energy gain in the BTW structure

U_0 [MeV]	ϕ_{opt}	$\Delta U/\langle U\rangle$ %
128.6	0.0°	0.80
129.0	-4.3°	0.75
130.0	-8.3°	0.70
140.0	-23.2°	0.53
150.0	-31.0°	0.44
160.0	-36.5°	0.37
170.0	-40.8°	0.32

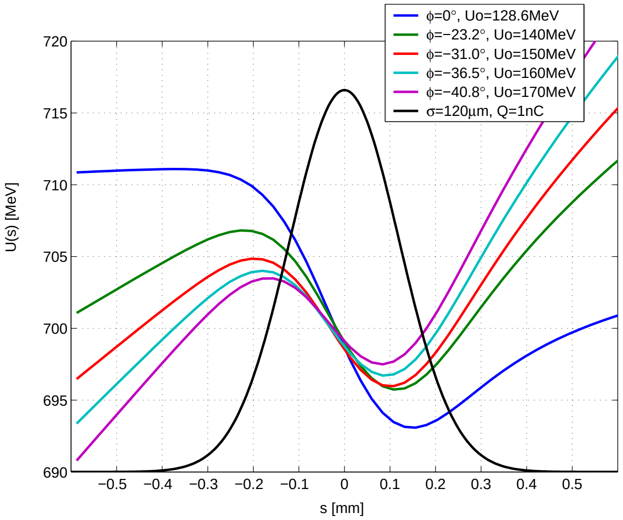

Figure 3: Energy gain of an electron inside the bunch as a function of the distance to the bunch center at the end of the linac.

RESULTS FROM START-TO-END SIMULATION

The results carried out with the previous analytical method have been compared with those obtained with the tracking code ELEGANT [6] in presence of longitudinal wakefields. As input we have used a relativistic Gaussian bunch distribution with negligible energy spread, compared with the total energy gain along the five BTW sections, 120μm bunch length, 1 nC charge. The optimization has been made using the same parameters for the BTW sections of the previous case and maximum energy gain per section of 150 MeV (keeping a safe margin of more than 10%).

Figure 4 shows the obtained results. With the same RF phase, ϕ_{opt}=-31°, the two energy gain distributions, analytical method (red curve) and ELEGANT tracking (green points), show an excellent coincidence with a final correlated energy spread obtained with ELEGANT of 0.45%.

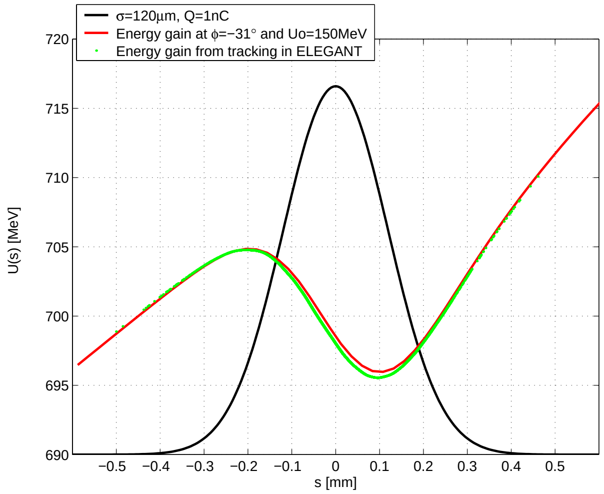

Figure 4: Energy gain comparison between analytical method (red line) and ELEGANT (green line).

More realistic conditions describing the initial energy and charge distributions (i.e. taking into account a non-negligible energy spread) produce results in good agreement with those discussed.

As an example, assuming 4 % or 2.7 MeV input energy spread after the pre-injector (see Fig. 1), we can obtain an electron bunch with an RMS length of σ_z = 128 µm and a correlated energy spread of σ_δ = 0.2 % at a central energy of 699.5 MeV, see Fig. 5. This value is slightly higher than the one quoted in Tab. 1. 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 [8]. In our case the typical cooperation length (L_c) is less than 2 µm [7]. From Fig. 5 and Fig. 6 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 $L_c\cdot\sigma_\delta/2\sigma_z = 1.6\cdot10^{-5}$, 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.

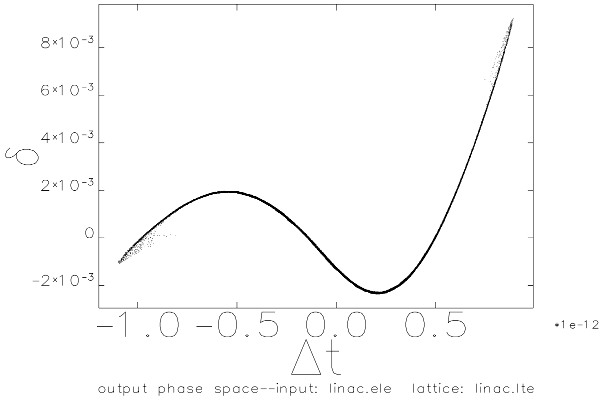

Figure 5: Longitudinal phase space (relative energy spread vs. time) at the exit of the FEL-I linac after the wakefield compensation.

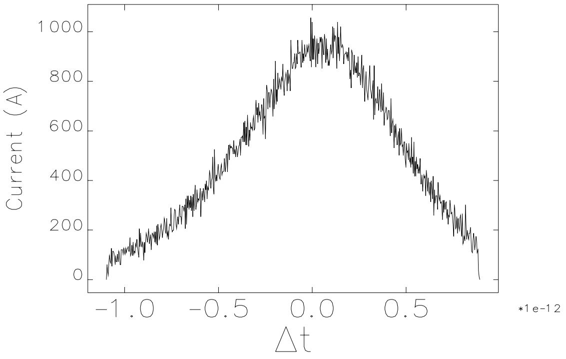

Figure 6: Current distribution along the bunch at the exit of the optimised FEL-I linac.

CONCLUSION

The single bunch energy spread induced by longitudinal wakefields and accelerating voltage of the BTW sections of the FERMI project has been analyzed for the first phase of the project FEL-I. We have carried out a very simple optimization to compensate the effect of the longitudinal wakefields foreseeing identical RF parameters for the five BTW sections utilized for FEL-I. Start-to-end simulations have also been performed, both to confirm the previous results, and to support the consistency of the ELEGANT tracking. Excellent agreements between two methods have been found.

The results obtained in more realistic case analyzed with start-to-end simulations have shown that the longitudinal wakefields in the BTW sections are not critical for the FEL-I stage. Actually, the correlated energy spread has been minimized down to the 0.2% RMS. It provides slice features concerning the longitudinal dynamics in full agreement with the specifications.

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