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BEAM PHYSICS HIGHLIGHTS OF THE FERMI@ELETTRA PROJECT*

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Abstract

The electron beam dynamics in the Fermi Linac has been studied in the framework of the design of a single-pass free electron laser (FEL) based on a seeded harmonic cascade. The wakefields of some accelerating sections represent a challenge for the preservation of a small beam emittance and for achieving a small final energy spread. Various analytical techniques and tracking codes have been employed in order to minimize the quadratic and the cubic energy chirps in the longitudinal phase space, since they may cause a degradation of the fel bandwidth. As for the transverse motion, the beam breakup (BBU) instability has been recognized as the main source of emittance dilution; the simulations show the validity of local and non-local correction methods in order to counteract the typical "banana" shape distortion of the beam caused by the instability.

INTRODUCTION

FERMI@Elettra [1] is designed for an initial complement of two FELs, providing tunable output over a range from ~100 nm to ~10 nm. The pulses duration goes from less than 100 fs to approximately 1 ps. The accelerator [2] is about 150 m long and is constituted by an RF photo-injector [3] followed by 3 types of accelerating structures [4] and 2 magnetic chicanes. A laser heater and a high harmonic cavity are foreseen at low energy (see, Fig.1). The final beam energy is fixed to 1.2 GeV. The machine is able to provide different scenarios for the final electron bunches with small transverse emittance, small final energy spread and bunch length from 100's fs to 2 ps [2]. Each case is related to a different fel operation. In our recent studies, the electron beam dynamics in the Fermi Linac is dominated by relatively long bunches in presence of normal conducting linac wakefields [4]. The Backward Travelling Wave accelerating structures (BTW), placed in the last part of the Linac, provide a high accelerating gradient, but their small iris of 5 mm generates short range wakefields which represent a challenge for the preservation of a small transverse emittance and for achieving a small final energy spread.

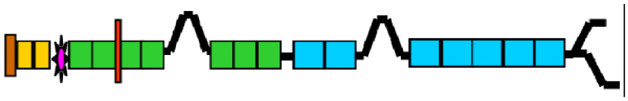

Figure 1: Schematic of Fermi Linac layout. The 3 types of accelerating structures are in different colours. The BTW structures are in blue.

LINEARIZATION OF THE LONGITUDINAL PHASE SPACE

Quadratic Energy Chirp

The longitudinal wakefields and the RF waveform contribute to the formation of a quadratic chirp of the beam energy distribution. A decelerating high harmonic cavity allows for linearizing the phase space [5], where the higher the cavity frequency, the lower the voltage required. Figure 2 shows how an increase of 40% of the cavity voltage leads to a reduction of 70% of the rms correlated energy spread in the bunch core. After changing the cavity voltage, the upstream linac phases have been rearranged in order to apply the same compression factor.

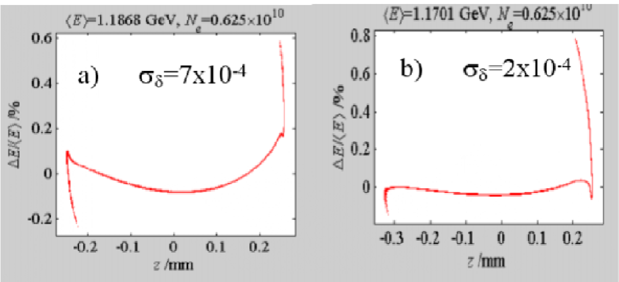

Figure 2: Longitudinal phase space at the Linac end. a) partial linearization; b) linearization improved by increasing the high harmonic cavity voltage. LiTrack [6] simulation.

Cubic Energy Chirp

The cubic energy chirp mainly affects the bunch edges during the magnetic compression. The sign of the cubic term is related to the topology of the longitudinal phase space and to the current profile (see, Fig.3). A relevant cubic energy chirp has 3 mainly consequences: i) it reduces the efficiency of the compression for the bunch core, since during the compression, the edges attract particles from the core reducing the current in this region; ii) the spikes may be dangerous sources of Coherent Synchrotron Radiation (CSR), with a direct impact on the transverse emittance and on the energy distribution; iii) wakefield excited by a leading edge spike may cause additional energy spread in the undulator vacuum chambers. The manipulation of the cubic term is possible by mean of the harmonic cavity set off-crest. However, this knob may be weak and in this case a significant increase is needed in the amplitude of the cavity voltage, losing beam energy.

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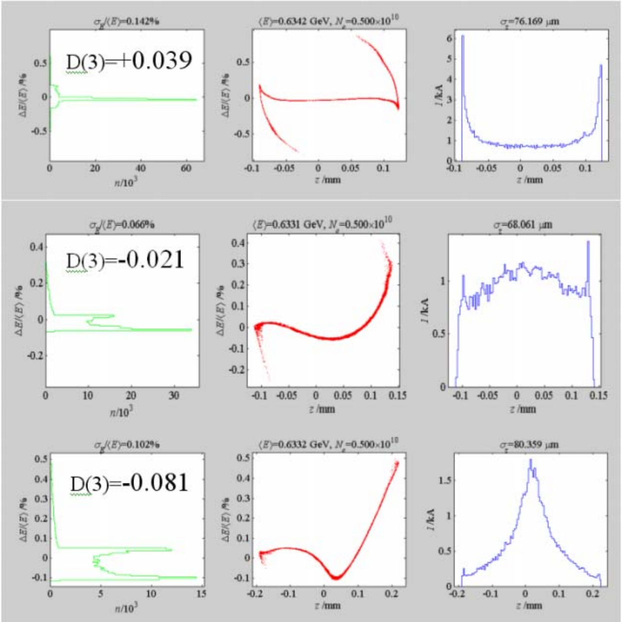


Figure 3: from left to right, energy distribution, longitudinal phase space and current profile at the Linac end. Each row of plots corresponds to a different value of the cubic energy chirp, called D(3) in units of 0.01mm^{-3}. The positive sign is related to an over-compression of the bunch edges (top), while a negative sign is related to their under-compression (bottom).

REVERSE TRACKING

Reverse tracking is an efficient method for the optimization of the longitudinal dynamics in the whole machine. It consists in tracking the desired final beam from the end to the beginning of the accelerator. The simulation result is the electron beam desired at injection. In such a way, all effects perturbing the beam dynamics, like RF curvature, wakefields and higher order optics are automatically compensated by the beam itself, properly prepared at the injection. The technique is analytically correct for frozen beams, that is we require a frozen particle distribution in the accelerating structures and a frozen energy distribution in the chicanes. In this approximation, the equation of motion can be reversed and the solution exists.

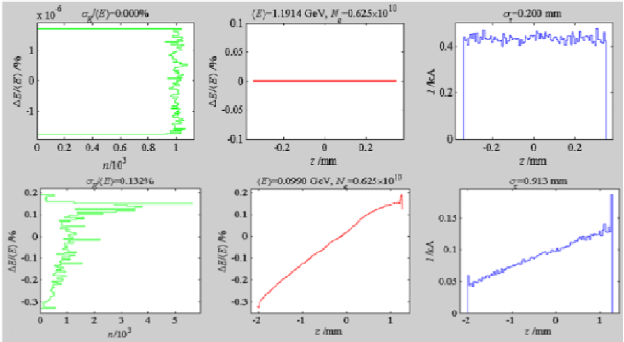


Figure 4: top, beam desired at the undulators' entrance. Bottom, electron beam required at the Injector end.

For our specific case, a final beam with a flat current profile and a linear phase space corresponds to an initial beam with a ramped current profile (see, Fig.4). The beam shaping at the photo-cathode has been simulated in order to provide such solution; then, the tracking into the Linac has confirmed the prediction of a final flat current profile and a quite linear phase space [7]. In addition to the forward tracking, this prediction has been also understood by the evaluation of the longitudinal wake function convoluted with a ramped particle distribution. Figure 5 shows that the resulting longitudinal wakefield for this case is linear. On the contrary, an initial parabolic current profile generates a strongly nonlinear longitudinal wakefields, bringing nonlinear contributions to the phase space.

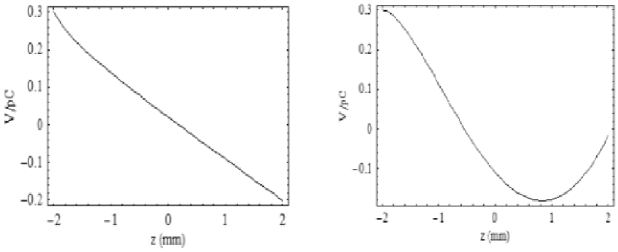
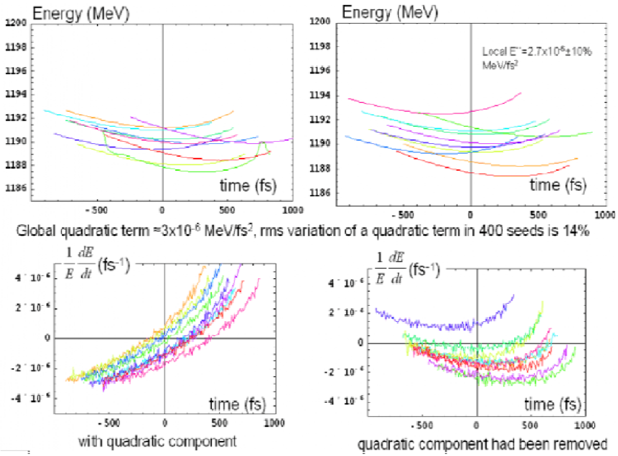


Figure 5: Longitudinal wakefield generated in the BTW structures resulting from the convolution of their longitudinal wake function with a particles distribution characterized by a ramped current profile (left) and a parabolic one (right).

PHASE SPACE JITTERS

Voltages and phases jitters have been included in the simulation of the Fermi Linac. Figure 6 shows (top left) the jittered phase space over 10 randomly chosen seeds. In general, we can evaluate the higher order components of the energy chirp and the jitter of each component w.r.t its nominal value, defined by the tracking of the beam without errors.



Global quadratic term ≈3x10^{-6} MeV/fs^2, rms variation of a quadratic term in 400 seeds is 14%

with quadratic component

quadratic component had been removed

Figure 6: top left, jittered longitudinal phase space. Bottom left, first derivative of the energy w.r.t. time, normalized to the average energy, is plotted for each seed. The quadratic chirp for this case is 3x10^{-6} MeV/fs^2 with a

jitter of 14% over 400 random seeds. We have also artificially subtracted to it the quadratic component of the energy chirp (bottom right); the parabolic shape of the first derivative is evidence of residual cubic energy chirp.

The aim of this analysis relies on the following thought: a quadratic and a cubic chirp generate a frequency chirp and a spread of the fel bandwidth, respectively. A seed laser with a linear frequency chirp allows for compensating for a frequency chirp due to a quadratic energy variation in the electron beam. For this purpose, a small jitter of the 2nd order component is required. After that, a small component at the 3rd order may be achieved using a particular beam at the injection as predicted by the reverse tracking.

BEAM BREAKUP INSTABILITY

The beam breakup instability has been recognized as the main source of transverse emittance dilution in the FERMI Linac. An ensemble of corrected trajectories including random errors has been studied and the corresponding typical "banana" shaped transverse distribution for each plane. The banana shape can be seen in the transverse particle coordinate versus the bunch duration (see, Figure 7). We may associate for each banana a parameter that is defined as the transverse deviation of the bunch tail w.r.t. the head in units of rms beam size. Simulations show that the banana shape obtained after a simple trajectory correction in the FERMI Linac – thus without any particular approach to preserve the emittance – is about 6 times larger than the beam size (rms value). Thus, the deviation at the undulators entrance is too large.

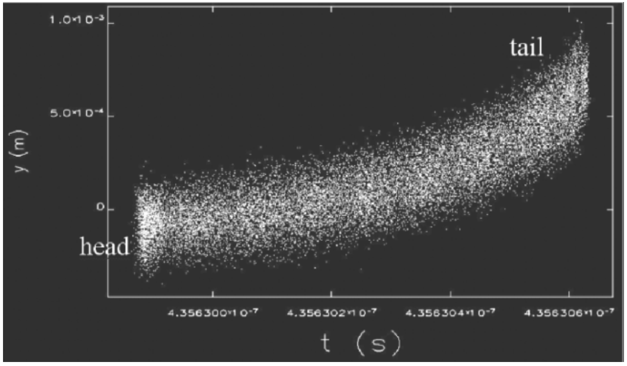


Figure 7: "banana" shape at the Linac end after a trajectory correction (vertical position coordinate is vs. bunch duration). Elegant [8] tracking result with 200.000 macroparticles .

For this reason, a local bump has been applied at the beginning of the Linac region where the transverse wakefields are strongest, that is in front of the first BTW structure (see, Fig.1). Figure 8 shows that the change of the trajectory in the following structures allows for compensating the emittance dilution and for reducing the final banana shape to the level of 1 rms beam size.

Unfortunately, local methods of correction have the disadvantage to be dependent on the particular conditions of operation at their specific location. For this reason, a study of the trajectory jitter, generated by a jitter in the beam launching error, has been made and jitter in the banana shape computed. Figure 9 shows that a properly corrected banana shape is not dramatically affected by this jitter, since it remains below the 1 sigma level. It has also been verified that a non-local correction performed using many bpms and steerers distributed along the line is equally efficient and allows for reducing the maximum strength required by the steerers for the emittance preservation.

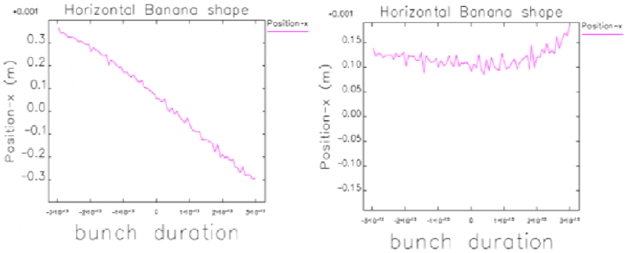


Figure 8: "banana" shape at the Linac end in the horizontal plane, before (left) and after (right) the trajectory bump. The transverse deviation of the bunch tail w.r.t. the head is reduced from 6 σ_x to 1 σ_x.

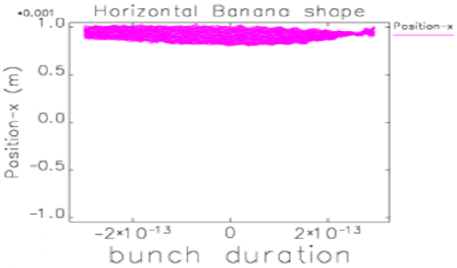


Figure 9: Jitter of the "banana" shape at the Linac end in (horizontal plane) after the trajectory bump (see, Fig.8, right). The emittance is still preserved.

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