ELECTRON BEAM LONGITUDINAL PHASE SPACE MANIPULATION BY MEANS OF AN AD-HOC PHOTOINJECTOR LASER PULSE SHAPING*

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Abstract

In a seeded FEL machine as FERMI, the interplay between the electrons energy curvature and the seed laser frequency chirp has a relevant impact on the output FEL spectrum. It is therefore crucial controlling and manipulating the electron beam longitudinal phase space at the undulator entrance. In case of very short bunches, i.e. high compression scheme, the longitudinal wakefields generated in the linac induce a positive quadratic curvature in the electrons longitudinal phase space that is hard to compensate by tuning the phase of the main RF sections or the possible high harmonic cavity. At FERMI we have experimentally exploited a longitudinal ramp current distribution at the cathode, obtained with an ad-hoc photoinjector laser pulse shaping, to linearize the longitudinal wakefields in the downstream linac and flatten the electrons energy distribution, as theoretical foreseen in [1]. Longitudinal phase space measurements in this novel configuration are here presented, providing a comparison with the typical longitudinal flat-top profile.

INTRODUCTION

The very high quality of the FEL radiation output relies on the optimization of the high brightness electron beams that represents the medium where the FEL process is stimulated and amplified. Therefore great effort has been spent to produce high peak current (~kA) and low transverse emittance electron beams. In order to have FEL emission at the wavelength λ_0, it is necessary to satisfy the well known resonant condition $\lambda_0 = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$, where $K = \frac{eB_u\lambda_u}{2\pi m_e c}$, B_u and λ_u are the magnetic field and period of the undulator, m_e is the electron mass and γ is the electron beam Lorentz factor. As a consequence only electrons with the resonant energy participate to the FEL process, so controlling and eventually manipulating the electrons longitudinal phase space (LPS) has a high priority.

Several elements along the linac contribute in defining the electrons LPS. The first one comes from the linac sections that provide an energy gain E that can be written as $E(t) = \sum_i eV_i \sin\left(\omega_{rf}t + \phi_i\right)$, where t is the bunch internal temporal coordinate, ω_{rf} is the rf frequency, and V_i and ϕ_i are the rf voltage and phase of the i^{th} section. The accelerating sections provide a negative quadratic chirp to the electrons energy curvature. The second contribution is given by the magnetic chicanes that are usually implemented to longitudinally compressed the beam before sending it to the undulator chain. A magnetic chicane has momentum compaction $R_{56}<0$ and without sextupole the second order term $T_{566}\sim -3/2R_{56}$. Thus the magnetic chicane provides a negative quadratic chirp to the LPS. A high harmonic rf cavity is usually implemented to compensate the LPS non linearity introduced by rf sections and chicane, by phasing it close to the maximum decelerating voltage. Another important contribution to the LPS comes from the longitudinal wakefields (LW) generated in the rf sections, that become relevant after the compression. The positive quadratic chirp introduced by the LW is hard to compensate by detuning the phase of the rf sections because of the high order terms in the wake potential function. Moreover, tuning the high harmonic cavity voltage can in principle help but at the cost of jeopardizing the linearity of the compression.

A possible solution has been proposed in [1] and consists in shaping the bunch current profile at the injector exit in order to linearize the LW of the downstream linac sections. The basic assumption is that the output bunch configuration is largely predetermined by the input bunch configuration. The manipulation of the longitudinal density distribution at the beginning of the linac has been proposed as the required additional free parameter. Multi-particles tracking code simulations showed that a linearly ramped current distribution at the injector exit could be well suitable for linearizing the LW generated in the downstream linac sections. In this paper we report the generation of a linearly ramped bunch profile at the FERMI injector, obtained by temporal shaping the photoinjector laser (PIL).

FERMI LAYOUT

The experiment has been performed in the FERMI linac that is routinely used to drive a HGHG seeded soft X-ray FEL [2] and whose layout is sketched in figure 1. The electron beam is generated in a 1.6-cell RF photocathode gun [3] and accelerated up to about 100 MeV by a two-sections linac (L00) and then up to about 320MeV by a four-sections linac (L01).

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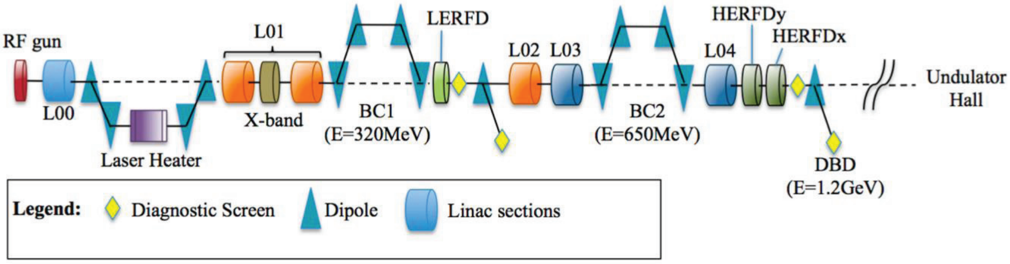

Figure 1: FERMI linac layout including the RF photocathode gun, linac L00, L01, L02, L03, and L04, the laser heater for microbunching instabilities suppression, the X-band cavity and the two bunch compressors (BC1 and BC2). RF defecting cavities for time-slice parameters diagnostic are installed after BC1 (LERFD) and at the linac end (HERFD).

This latter is set off-crest to impose the energy correlation needed for the compression that is realized in the upstream magnetic chicane (BC1). L00 and L01 sections are S-band Travelling Wave (TW) cavities and an X-band cavity, resonating at the forth harmonic of the main RF system, is located in between L01 to linearize the LPS before compression. After BC1 two linacs (L02 and L03) comprised respectively by 3 TW cavities and by 2 Backward Travelling Wave (BTW) cavities accelerate the beam up to about 650 MeV and could be optionally set off-crest to further compress the beam in a second magnetic chicane (BC2) [4]. Finally linac L04, including 5 BTW sections, accelerates the beam up to 1.4GeV. Three RF deflecting cavities are installed along the linac. A low energy rf deflecting cavity (LERFD) is located after BC1 for studying the time-sliced beam parameters after the first compression stage. Two high energy rf deflecting cavities (HERFD) stretching alternatively the beam vertically and horizontally, are placed at the linac end. The measurement of the electrons LPS at the end of the linac is performed by using the vertical HERFD (HERFDy) in combination with an energy spectrometer, named diagnostic beam dump (DBD) [5]. The beam vertically stretched by the HERFD and horizontally energy-dispersed by the DBD dipole is intercepted by a YAG screen, that images the electrons LPS.

TRACKING CODE SIMULATIONS

FERMI has been routinely running for Beam-lines users experiments [2, 6] with a 500 pC electron bunch, generated by a temporal flat-top photoinjector laser and compressed by only the first magnetic chicane (BC1). The longitudinal phase space (LPS) usually measured in DBD is reported in Figure 2. Fitting the electrons energy curvature with a third order polynomial provides a quadratic energy chirp of about 21 MeV/ps^2 and a cubic chirp of 50 MeV/ps^3. These are far from the requirements of the FERMI conceptual design report [7], where a maximum quadratic chirp of about 0.8 MeV/ps^2 was specified. The residual electrons energy curvature did not prevent the operation of FEL-1 and FEL-2 and intense photons have been produced from 65 to 4 nm. Nevertheless a broadening of the FEL spectrum has been observed, together with shot-to-shot jitter of the emitted central wavelength, which is instead well below the specifications [8].

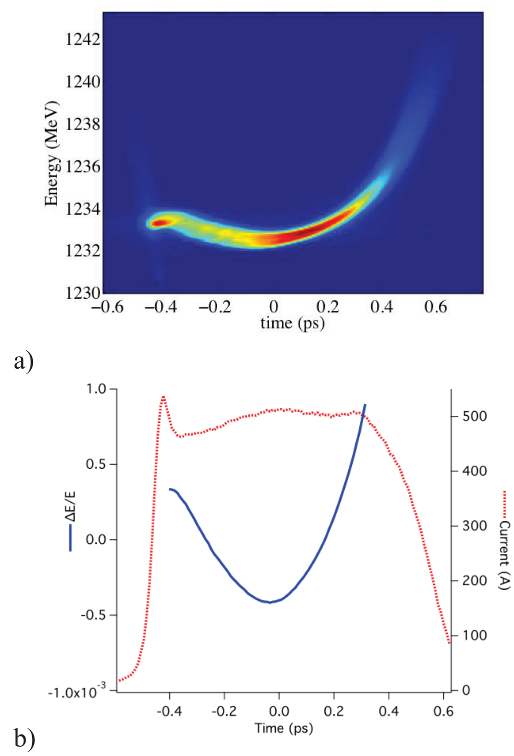

Figure 2: Measurements of the LPS (a) and of the slice current and relative energy spread (b) of the nominal flat-top 500pC-bunch, compressed by using only BC1.

In order to overcome this issue, we have evaluated the possibility to compensate the positive quadratic chirp by exploiting the second magnetic chicane (BC2) T_{566} term and compress the beam in two stages. We performed 1-D simulations with LiTrack (see Figure 3a) and we found out a configuration that we experimentally tested, improving the quadratic chirp by a factor 2. Unfortunately the BC2 had to be operated at a large angle to provide a sufficiently strong quadratic component, enhancing the microbunching instabilties and deteriorating the FEL performance (see [9]). We have therefore studied the possibility to shape the bunch

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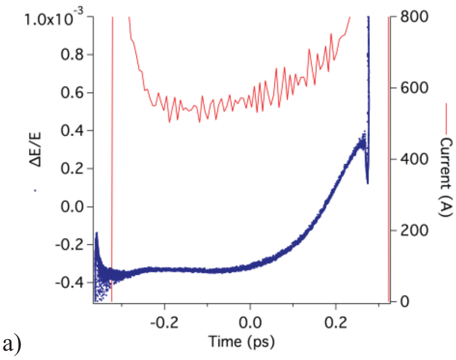
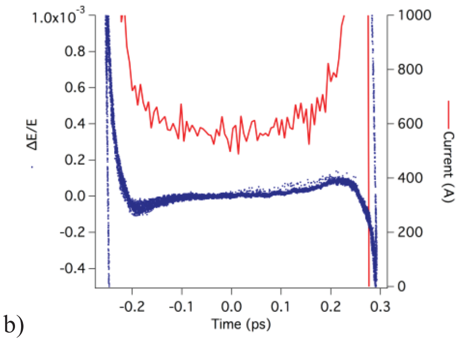
current profile at the injector exit in order to reproduce the linearly ramped distribution predicted in [1].



a)



b)

Figure 3: Litrack simulation results at the end of the linac: comparison between the flat-top (a) and the ramped bunch profile (b), both compressed with BC1 and BC2. Bunch charge: 500 pC.

It has been shown in [10] that shaping the temporal photoinjector laser profile with a quadratic ramp allows to extract from the cathode an electron bunch that evolves under the space charge into the desired charge distribution. Litrack simulation of the ramped bunch profile has shown that a relevant improvement in the final LPS flatness can be obtained, as shown in Figure 3b.

EXPERIMENTAL RESULTS

The FERMI PIL pulse shaping system, described in [3, 11], has a UV temporal shaping setup based on 4-f system, which incorporates high efficiency transmission gratings and a piezo-deformable mirror as a phase modulator. Figure 4 shows the quadratic ramped profile of the PIL that has been produced and sent on the photocathode. The extracted electron bunch has been propagated along the linac and longitudinally compressed with both BC1 and BC2 with a compression scheme very similar to that one presented in Figure 3. Preliminary measurement of the longitudinal phase space of this electron beam has shown an impressive improvement in the flatness of the energy-time dependence.

Details analysis of the experimental observations are on going and a complete characterization of the produced linearly ramped bunch is going to be provided [12].

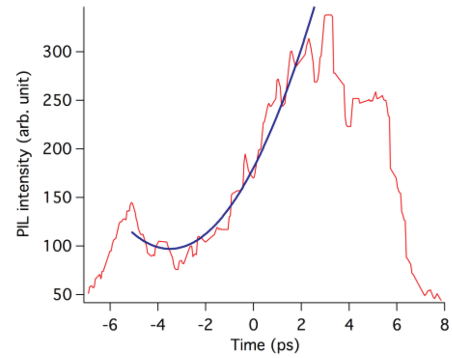


Figure 4: Temporal PIL profile and the corresponding quadratic fitting.

CONCLUSION

We have reported in this paper the generation of a linearly ramped electron beam obtained by shaping the photoinjector laser profile. The produced beam has been compressed and accelerated up to the end of the linac. Preliminary experimental results show a very promising linearization of the longitudinal phase space of this bunch as theoretically predicted in [1].

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