ELECTRON-BEAM OPTIMIZATION STUDIES FOR THE FERMI@ELETTRA FREE-ELECTRON LASER

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Abstract

FERMI@Elettra is a single-pass free-electron laser, based on seeded high-gain harmonic generation scheme. Presently, the first phase of the project (covering the spectral range between 100 nm and 20 nm) is under commissioning. The free-electron laser performance depends on the quality of the electron beam used in the generation of the radiation. In the case of the FERMI linear accelerator, the quality of the electron beam is strongly influenced both by the wake-fields present in the accelerating sections and by possible misalignment of the various accelerator components. In order to investigate and compensate these effects, we performed a study, based on local trajectory bumps. We demonstrate that this approach significantly improves the electron-beam quality and, eventually, the free-electron laser performance.

INTRODUCTION

An electron beam, usually provided by a linear accelerator (Linac) or by a storage ring (SR), should have high intensity, small dimensions and reduced spread in energy in order to be suitable for most of nowadays applications, like high-brilliance colliders and free-electron lasers (FELs'). One of the most commonly used figure of merit for the beam quality is the (normalized) emittance, a quantity that is proportional to the area of the phase space occupied by the beam. In the case of storage rings the beam must be kept stable and one of the main concerns is the cope with the instabilities. One of the main challenges for Linacs is to preserve the horizontal (vertical) emittance along the whole accelerator, limiting the emittance degradation due to instabilities. These can be either shot-to-shot related (jitter) or static systematic distortions [1]. Systematic phenomena that can cause an emittance increase are related to the interaction of the electron bunch with its surrounding environment (beam pipes, accelerating structures, discontinuities, etc.), which is referred as wake-fields [2], or to the misalignment between accelerating sections and quadrupoles. These effects have been widely investigated for linear colliders in terms of luminosity performance and emittance growth [3, 4, 5]. Jitter instabilities are instead related to stochastic phenomena, like vibrations of the magnets, current ripple of power supplies, noise in the phases of the accelerating fields and so on.

In order to prevent the blow-up of the emittance, local trajectory bumps can be applied [6, 7]. It is possible to distort the trajectory in order to create a controlled, local misalignment in the machine by using steering magnets. These bumps decrease the emittance dilution introducing a well defined and controllable dispersion in the beam [8], which can be set in amplitude and betatron phase, in order to compensate the instabilities and misalignments introduced in previous parts of the accelerator.

In this paper we present an implementation of the local-bumps method by means of trajectory variations around the accelerating cavities. We measured the beam geometrical properties as a function of the amplitude of the trajectory bumps. The study was motivated by the need of reducing misalignment errors of the accelerating structures and of investigating the effects of the geometrical wake-fields on the electron beam.

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METHOD

FERMI Linac

The layout of the FERMI Linac is shown in fig. 1. It provides the electron beam necessary for the operations of the FEL radiation source. It accelerates the 4 MeV electrons produced by the photo-cathode (injector) up to about 1.2 GeV. For a detailed description of the machine, see [9].

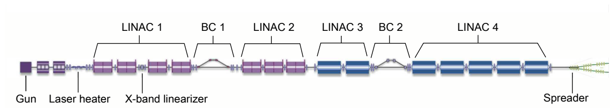


Figure 1: Schematic layout of a the Fermi@Elettra Linac. The machine, composed of 14 accelerating structures, raises the electron energy from 4 MeV to about 1.2 GeV.

Measurements

In order to evaluate the correct alignment of the accelerating cavities with respect to the beam position monitors (BPM) we performed trajectory scans. Using the trajectory feedback capabilities [10], we are able to vary the beam trajectory at different BPMs' positions all along the machine. In particular, by properly selecting BPMs in between one or more accelerating cavities of the Linac, we are able to introduce and control one or more trajectory bumps around one or more accelerating structures. By measuring the beam properties at a downstream screen, we investigate the alignment of the cavities and the effects of wakefields on the electron beam. The bumps are performed in

ISBN 978-3-95450-115-1

a controlled way, as a suitably designed feedback system [10] closes them and no additional trajectory perturbations are introduced. From the transversal beam profile one can extract directly the information about the horizontal (vertical) beam dimensions, i.e. the standard deviation, $\sigma_{x(y)}$. In principle, the latter would not be enough to characterize the emittance. However, the dominant contribution to the projected emittance growth along the Linac is due to the projected banana shape of the beam [11, 12]. Furthermore we are interested in limited variation of the trajectory around each section, so we think that the beam divergence can be considered constant. This assumption is reasonable because the main contribution of the transverse wake-fields is the dipolar one and, if the beam dimensions are small, all the particles in the same slice feel the same kick. This assumption is confirmed by numerical simulations.

All measurements were performed as scans of two variables, the position in an initial BPM, where the trajectory bump was started, and the position in a final BPM where the bump was closed. This kind of 2D scans result in a surface. The usual scan range was of about 3 mm around the nominal center for both BPMs'. In order to determine the relative position between an accelerating section and the upstream and downstream BPMs' only two scans are in principle needed, one for horizontal and one for the vertical plane. The presented measurements were performed with a 350 pC bunch, with bunch length of 2.5 ps (standard deviation) at the gun, compressed by a factor 5.

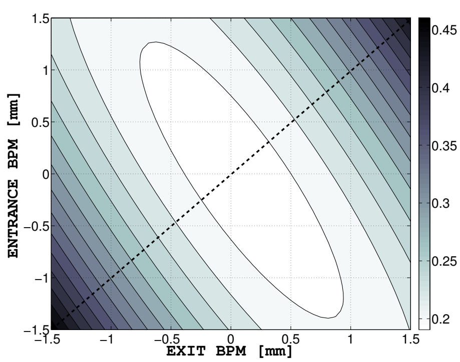
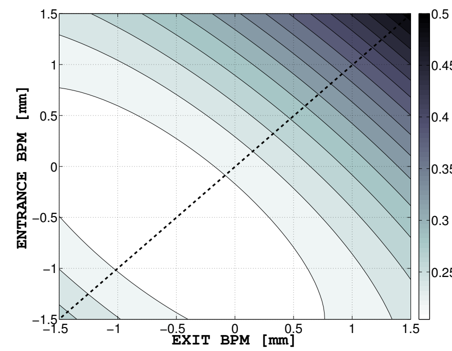
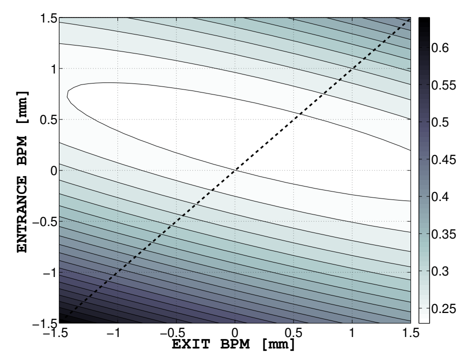


Figure 2: Example of measurements of the transverse σ_y for vertical plane. The presented measurement was performed around the third section of Linac 4. The color scale, shown for each figure, is expressed in mm. To obtain these figures, raw data was cleaned of the spikes and smoothed out.

In fig. 2 an example of the obtained surface for the vertical alignment is reported. In this case the trajectory bump was performed around the third section of Linac 4. It is possible to identify a central region where the beam transverse dimension is small, while if the trajectory bump is larger than ∼0.5 mm the transverse dimension become 50% (or more) larger than the minimum. The surface exhibits an high degree symmetry with respect to the diagonals of the scan range. If the bump is symmetric, (e.g. + 1 mm at entrance, -1 mm at exit), the interaction of the head with the tail in the first half of the accelerating cavity is exactly compensated by one of equal intensity, but opposite sign and there is no net increase of the transverse dimension of the beam. If instead the bump is parallel (e.g. + 1 mm at entrance, +1 mm at exit) the effect of the interaction between the head and the tail of the bunch builds up along the whole cavity and it is not compensated: the bunch exhibits a pronounced banana shape, and the transverse dimensions at the screen are increased.



(a) Misalignment



(b) Tilt

Figure 3: Example of misalignment (top panel, first section of Linac 3) and tilt (bottom panel, second section of Linac 3) between accelerating cavity and BPMs. The color scale, shown for each figure, is expressed in mm.

The symmetry of the surface is one of the figure of merit we selected. From the above considerations we can determine that the alignment between the accelerating cavity and the upstream and downstream BPMs is good. We can estimate the sensitivity of our measurement to be about 150 μm, which is an order of magnitude larger than the noise in the BPMs' reading, which is of about 20 μm. Repeating the measurements several times, we obtained a reproducibility of the results within 10%.

In case of misalignments (rigid shifts) or tilts one can observe different shapes of the transverse profile surface. In presence of a misalignment, see fig. 3(a), we observe that

ISBN 978-3-95450-115-1

the surface is not symmetric with respect to the symmetric bump axis and the minimum is shifted. In the presence of a tilt, see fig. 3(b), the surface is symmetric with respect to an axis that has an angle with respect to symmetric bump axis.

Simulations

In order to check the results we have found and to validate the wake-field model for the machine (cfr. [12]), we performed some numerical simulations of the beam dynamics. This is really important for Fermi because the whole matching procedure is based on particle tracking code [13]. In our investigation we used elegant simulation code [14]. We were able to reproduce the surfaces we measured using a realistic beam profile.

In order to evaluate the agreement between the wake-field model and the measurements we focused on diagonal bumps, in particular the parallel ones (dashed line in fig. 2): along this direction, in fact, the effect of the wake-fields on the electron bunch is the strongest. In the fig. 4 the simulated and measured values of the transverse profile are reported, as a function of the amplitude of the bump. The crosses are the measured values and the filled line correspond to a simulations, performed using a realistic beam profile. We found a satisfactory agreement between measurements and simulation. The presented results show that the method we applied can be useful to evaluate the wake-field contributions for an accelerating structure or other Linac elements.

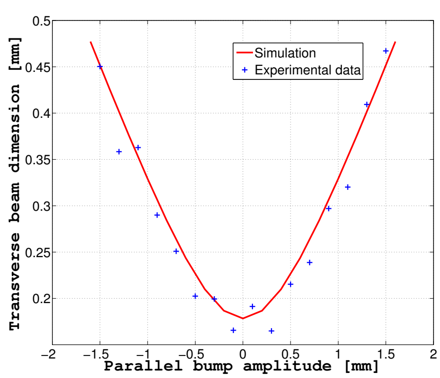


Figure 4: Comparison between measured data (crosses) and simulation (filled line) of the transverse profile of the beam as a function of amplitude of the parallel bump. Simulation was performed using a realistic beam profile and the third section of Linac 4 was investigated. Vertical transverse beam size are reported.

CONCLUSIONS

We presented a beam-based alignment procedure for the accelerating structures of a Linac. It was successfully applied to the last part of the Fermi@Elettra Linac (Linac 3 and Linac 4). A figure of merit for the alignment of the accelerating structure has been selected and described and examples of both aligned and misaligned cavities were presented. The improvement was measured in a reduction of the emittance at the Linac end by a factor ∼50% in the horizontal and a ∼30% improvement in the vertical plane. This is a significant improvement of the beam quality, and can positively impact on the FEL performance.

The measured profiles were also compared to particle tracking simulations. We determined that the main contribution to the emittance dilution can be evaluated by measuring the transverse profile of the beam only. This confirms the hypothesis of negligible contribution of the beam divergence to the emittance during this kind scans. We found a good agreement between measurements and simulations when a realistic beam profile was used. The wake-field model of the machine has been tested with measurements on the machine. We are planning to investigate the possible usage of this method as a bunch length diagnostics. Further, we would like to evaluate the effect of the trajectory bumps and emittance growth directly on the FEL performance. The procedure here described is completely general and can be successfully applied to other Linac-based facilities.

ACKNOWLEDGEMENT

The authors thank M. Cornacchia for the very useful discussions and suggestions for the implementation of the simulations. The authors thank also the Fermi team and the Fermi machine operators for their precious assistance.

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ISBN 978-3-95450-115-1