Machine design and electron beam control of a single-pass linac for free electron laser
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Chapter 7

Electron Beam Control

In this Chapter we describe methods and experimental results related to the control of the longitudinal (acceleration, energy distribution, bunch length compression and microbunching instability) and transverse (optics matching, transport and trajectory control) electron beam dynamics in the FERMI@Elettra beam delivery system. This Chapter is based on the commissioning experiments we carried out from September 2009 to December 2010 [147, 148], when the first lasing of FERMI FEL1 was observed. During the commissioning we have developed some high level software for optics matching, transport, trajectory control and dispersion measurement. We have provided support to the development of other codes devoted to the energy measurement, emittance measurement and transverse phase space reconstruction [149]. We extensively used all the mentioned software and a description of our measurements and comparison with the machine model is reported in the following.

7.1 Longitudinal Phase Space

The longitudinal phase space of the electron beam is investigated both for the projected and the slice beam parameters. Here, we focus on the characterization of the particle energy distribution and measurement of the bunch length by using the beam projection on the screen of the LH spectrometer line. This is shown in Figure 7.1. Once the beam is centered on the screen, its mean energy is simply computed from the dipole magnet calibration table (current vs. energy), which has an accuracy better than $10^{-4}$. According to the design optics of the LH spectrometer line, the resolution for the energy measurement is $4 \cdot 10^{-3}$. A quadrupole magnet in front of the spectrometer is used to shrink the horizontal betatron function at the screen location, so minimizing the geometric contribu-
tion to the image at the screen, while the horizontal dispersion is left to reach 1.7 m. As expected, by turning on the quadrupole upstream of the spectrometer, the energy spread value diminishes because the energy measurement error is minimized.

Figure 7.1: Energy measurement in LH spectrometer line. The energy spread is computed as the ratio between the horizontal size at the screen and the theoretical value of the dispersion at the same location. The dedicated quadrupole in front of the spectrometer is turned off (left) and on (right). Doing this, the measured energy spread reduces from 84 keV to 66 keV rms.

The bunch length is measured in the LH spectrometer line by taking the horizontal beam size $\Delta x$ (fwhm) at the screen. We set the L1 RF phase for on-crest acceleration. Now, assuming that the particles lie on a perfectly sinusoidal RF potential, $\Delta x$ can be related to the bunch length, $\Delta z$, and to the local dispersion function, $\eta_x$, as follows:

$$\Delta z = \frac{\lambda_{RF}}{\pi} \arccos \left(\frac{\Delta x}{\eta_x} - 1\right)$$  \hspace{1cm} (7.1)

The assumption of a beam symmetrically distributed across the RF crest is verified thanks to an occasional vertical deflection observed at the screen, which generates a half-moon shape in the $(x, y)$ plane. The beam horizontal extension at the screen is 17.6 mm. The bunch length is therefore evaluated with eq. 7.1 to
be in the range of 5.7–6.2 ps. The biggest measurement uncertainty comes from
the mean energy jitter of the electron beam. Other bunch length measurements
provided by a Cherenkov detector at the Gun exit and simulation results using
space charge codes are in agreement with the present value [147].

7.2 Trajectory Control

The FERMI electron beam delivery system has no explicit coupling elements and
it consists only of dipole and quadrupole magnets. For each plane, the point-to-
point transfer map between any two points 1 and 2 is given by:

\[
\begin{pmatrix} x \\ x' \end{pmatrix}_2 = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_1
\]

(7.2)

Let the initial point 1 be at a corrector and the final point 2 at a BPM. Two
measurements are required to determine \( R_{12} \) that is the position of the beam
with the nominal trajectory \((x, x')_2\) and after the beam is kicked by an angle \( \theta \),
\((x, x' + \theta)_2\). The difference in the BPM reading between the two measurements
is \( R_{12} = \Delta x / \theta \). In practice, to decrease the sensitivity to the measurement error
one introduces a series of large betatron oscillations by varying the corrector’s
strength in steps. This is the procedure implemented in a MATLAB [150] tool
that allows the measurement of the direct Trajectory Response Matrix (TRM)
of any portion of the FERMI lattice. In principle, any combination of correc-
tors and BPMs can be chosen. The corrector’s strength is varied by an arbitrary
step, usually of 0.03 mrad to have at least 20 micron displacement at any BPM
downstream. During the measurement of the TRM, five kicks with positive and
negative sign are applied to each corrector: if the BPM differential response has
a discrepancy larger than 10% of the absolute value for negative and positive
kicks, then an error message is sent to the user. In this way, the linearity of the
TRM is checked out and identification and exclusion of bad BPMs can be carried
out for good convergence of the steering algorithms.

The position of the beam centroid is usually forced onto the reference axis,
which should coincide with the zero reading of the BPMs. Some uncertainties
are still associated with the electronic center and/or mechanical alignment of
the BPMs. If the BPM offsets are not known \textit{apriori} and possibly larger than
the alignment specifications (see Table 5.1), a better strategy is to reduce the
rms strength of the correctors and to pay less attention to the absolute trajectory
reading. A technique based on the Singular Value Decomposition (SVD) [151]
allows the reduction of the rms strength of the correctors while maintaining a set
of constraints. For this reason it is adopted in the FERMI trajectory manipulation

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tool. Suppose we want to solve the linear equation:

$$\Delta x = A \cdot \theta$$  \hspace{1cm} (7.3)

where the vector $\Delta x = (\Delta x_1, \Delta x_2, ..., \Delta x_M)$ describes the desired correction at $M$ BPMs and $\theta = (\theta_1, \theta_2, ..., \theta_N)$ are the excitation strengths of $N$ correctors that we want to determine to satisfy the constraints described by $\Delta x$. If $M \geq N$, we can decompose the matrix $A$ as:

$$A = U \cdot \begin{pmatrix} w_1 & 0 & \ldots & 0 \\ 0 & w_2 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & w_n \end{pmatrix} \cdot V^t$$  \hspace{1cm} (7.4)

The column vectors of the $M \times N$ matrix $U$ and the $N \times N$ matrix $V$ are orthonormal, $U^t \cdot U = I_N$ and $V^t \cdot V = I_N$, where $I_N$ denotes the $N \times N$ unity matrix. The decomposition of eq.7.4 is performed by a mathematical package of MATLAB. We now want to consider three different cases. First, $N = M$. In this case the matrix $A$ is square and we can write down a formal solution for the corrector strengths vector:

$$\theta = A^{-1} \cdot \Delta x = V \cdot \begin{pmatrix} 1/w_1 & 0 & \ldots & 0 \\ 0 & 1/w_2 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & 1/w_n \end{pmatrix} \cdot U^t \cdot \Delta x$$  \hspace{1cm} (7.5)

If none of the $w_i$ is zero, this is the unique solution of the problem. If one or more of the $w_i$ are zero, the equation may not have an exact solution, but for these $w_i$ one can simply replace $1/w_i$ by zero and with this replacement eq.7.5 still gives the solution in a least square sense. This means it minimizes the distance $r = |A \cdot \theta - \Delta x|$. Furthermore, the solution vector $\theta$ so obtained is the solution with the smallest possible length $|\theta|^2$. Next, we consider the case for which $M < N$. In this case, we can simply add rows with zeroes to the vectors and matrices of eq.7.3 until the matrix is square and then apply the SVD formalism, as described above. In this case, there is at least one zero eigenvalue $w_i$ for every row of zeroes added. Finally, in the case of $M > N$, SVD works just as well. In general, the $w_i$ will not be zero and the SVD solution will agree with the result of a least-square fit. If there are still some small values of $w_i$, these indicate a degeneracy in $A$ that is a BPM is not very sensitive to a certain corrector’s strength. Hence, the corresponding $1/w_i$ should be set to zero, as before. We point out that the corresponding column in $V$ describes a linear combination of corrector excitations, which does not affect the constraints.

Such a formalism is implemented in the MATLAB-based trajectory feedback for FERMI that is routinely used both for trajectory correction (the user stops the
feedback once the constraints are satisfied) and feedback operation at approximately 1 Hz. In particular, the program is capable of displaying any response matrix, as well as its inversion using either regular SVD, Truncated Singular Value Decomposition (TSVD) [152] or Tikhonov regularized SVD [153]. It is also possible to view the singular values for all three inversion options. Still for the TSVD, the given tolerance specifies how small singular values will be included in the inversion. In case the matrix rank is lower than both the number of actuators or sensors, some singular values should be removed in order for the inversion to produce a matrix with non-infinite elements. For the Tikhonov inversion option, small singular values are scaled up which allows inversion of low rank matrices. The Tikhonov parameter will determine the focus of the correction parameter: a value of zero will mean no weight is given to the amplitude of corrector changes when the solution is computed. An increasing value will increase the weight on the norm of corrector changes. In order to give preference to a particular solution with desirable properties – small corrector strengths in our case –, the regularization term is included in the minimization of the following norm:

$$\| A\theta - \Delta x \|^2 + \| \Gamma \theta \|^2$$

(7.6)

for some suitable chosen Tikhonov matrix, $\Gamma$. In our feedback tool, $\Gamma = q \cdot I$, where $q = 1, \ldots, n$ is a positive integer that underlines the importance of minimizing the corrector strengths with respect to satisfying the trajectory constraints. More in detail, given the singular value decomposition of $A$ as in eq.7.4 with singular values $w_i$, the Tikhonov regularized solution can be expressed as:

$$\tilde{\theta} = V D U^T \Delta x$$

(7.7)

where $D$ has diagonal values $D_{ii} = \frac{w_i}{w_i^2 + q^2}$ and is zero elsewhere.

In addition, the trajectory feedback tool has some important capabilities to optimize the trajectory control:

i) the TRM can be visualized in a 3-D contour plot to identify areas of particularly high or poor BPMs sensitivity to the correctors;

ii) a theoretical TRM, direct or inverted, computed by $\text{elegant}$, can be imported, compared with the corresponding measured one via the visualization tool and used for trajectory correction;

iii) experimental and theoretical TRMs can be merged for global trajectory manipulation.

Since the feedback tool manages the correctors’ normalized strength in $\text{mrad}$ and not the correctors’ supplying current in Ampere, the corrector magnets must
be configured for the correct energy. Currently this is done on the feedback startup: in case of a large change in the klystron voltage or phase for the accelerating structures, the beam energy must be updated. In case it would be necessary to measure a response matrix for the power supply currents, an additional script can be run before starting the feedback in order to be able to select power supplies as actuators. The tool is also used to launch successive feedback loops on the beam line. The possible interference of one loop with each other is avoided by verifying the orthogonality of the TRMs. This is done by merging the matrices into a global one, representing it graphically and verifying that the different blocks are diagonal.

Up to three feedback loops in both planes have been run continuously for a few hours: the first TRM was a merged version of the experimental matrix for the injector (in each plane, 2-by-2) and of the theoretical matrix for the rest of the linac (in each plane, 27-by-27); the second TRM is measured and applied to correct the trajectory in the Spreader (in each plane, 11-by-11); the third one is measured and applied to the undulator chain (in each plane, 7-by-7). The resulting trajectory correction for both planes is shown in Figure 7.2. Some large position values correspond to bad BPMs reading.

We stress that the efficient trajectory correction in the linac with a relatively large theoretical TRM is an indirect proof of the agreement between the theoretical optics (quadrupole set) and the real one adopted in the machine. The importance of this result relies on the fact that accuracy of the model is vital for basic optics checkout and requires, for example, accurate representation of magnetic field strengths. As an example, Figure 7.3 compares the horizontal measured (top) and theoretical (bottom) TRM relative to the steering elements from the LH area to the BC1 spectrometer line. In spite of small differences in correspondence of elements at the beginning of the beam line where the LH matching quadrupoles are located, the theoretical matrix was successfully used for trajectory correction as well as the experimental one.

Trajectory correction with the theoretical TRM is shown in Figure 7.4. The horizontal axis runs along the machine, from the Gun exit to the BC1 spectrometer line (approximately at the longitudinal coordinate of 60 m). BPMs used for these measurements are made of striplines and a single shot resolution of 5 µm rms for a charge higher than 50 pC has been measured [154]. This is well below the physical specification of 20 µm rms. The short-term trajectory jitter is usually in the range 10–20 µm rms (again within the physical specification).
Figure 7.2: Global trajectory correction in the horizontal (top) and vertical plane (bottom).
Figure 7.3: Measured (top) and theoretical (bottom) TRM. The direct matrix is made of 13 correctors per plane \( (M=13) \) and 11 BPMs \( (N=11) \) and it is shown in the left side of each plot. The matrix inverted with regular SVD is shown on the right side.
During the commissioning, BPM offsets have been found by looking for the maximum charge transport efficiency through the whole line. In some cases, offsets between 1 and 2 mm have been identified such as in the proximity of the LH, BC1 and DBD spectrometer magnets, but also in straight sections at the end of L2 and L4. In the meantime, the offsets are virtually zeroed via software control. Then, TRMs are applied for trajectory correction. Even when starting from 2 mm displacement at some locations, the trajectory converges well to 10 µm level over all BPMs in a few seconds, the velocity of convergence depending from the feedback gain set by the user.

**Figure 7.4:** Local trajectory correction. Top: vertical plane before correction; the vertical scale is [-1.5, 2.5] mm. Middle: vertical plane after correction with the theoretical matrix shown in Figure 7.3; the first two BPMs in the injector are excluded from the steering algorithm, while all others read beam position around 10 µm. The vertical scale is [-0.5, 2.0] mm. Bottom: horizontal plane after correction. The vertical scale is [-2.5, 4.0] mm.

The feedback is also used to create closed trajectory bumps to minimize
the projected emittance dilution due to transverse wake field instability. This optimization was partially carried out along L3 and L4, characterized by the strongest impedance over the whole linac. Preliminary results depict a reduction of the normalized projected emittance from $10 \pm 1$ mm mrad before the implementation of trajectory bumps to $3 - 4 \pm 0.3$ mm mrad, in both planes, after the bump. The electron beam has 350 pC total charge distributed over 6 ps (fwhm value) and an emittance of approximately 1.5 mm mrad at the exit of the injector. A similar trajectory manipulation is also done along L1 to compensate an unwanted vertical deflection observed at the screen of the BC1 spectrometer line. Possible sources of the vertical head-tail deflection might be identified in the RF kick given by the vertical coupler of the injector accelerating structures as well as in transverse wake field kick in L0 or L1. The model does not foresee any strong effect from the impedances, unless the BPMs and the accelerating structures are misaligned by more than 1 mm; so, we are led to think of time-dependent RF kicks at very low energy. Figure 7.5 shows the beam transverse spot size at the screen of the BC1 spectrometer line. The screen shows a half-moon shape in the vertical plane (left plot). The horizontal axis is proportional to the particle energy while the vertical one, in the presence of deflection, is proportional to the particle phase. The screen is reproducing the particle longitudinal phase space and the shape represents the electron bunch lying on the RF crest of the upstream linac. This shape is therefore representing the on-crest acceleration in L1. The vertical deflection is suppressed after a vertical offset of 400 $\mu$m is imposed across L1. The trajectory bump is implemented by using the theoretical TRM shown in Figure 7.3. So, we think we were compensating the vertical banana shape by exciting vertical transverse wake field in L1.

![Figure 7.5: Suppression of vertical banana shape (left) with trajectory bump (right). Axes scales are pixels.](image-url)
7.3 Residual Dispersion

The dispersion function along the FERMI linac is measured by changing the beam energy through the high voltage of the selected klystron and monitoring the trajectory changes at the BPMs downstream. Dispersion is computed, in each plane, as \( R_{16} = \Delta x / (\Delta E / E_0) \). Figure 7.6 shows the dispersion function from the very first BPM at the Gun exit to the linac end. It is obtained by varying the high voltage of the RF plant supplying the two accelerating structures of L0 by \( \pm 1.5\% \) in seven steps. The linearity of the beam mean energy with the high voltage within this range of variation has previously been verified at the LH spectrometer line. The trajectory is corrected everywhere as shown in Figure 7.4. Our measurements show that the dispersion function is non-zero along the linac in both planes, but with larger excursion in the vertical plane. This could be a consequence of the propagation of a residual dispersion at the linac entrance. It is also consistent with our afore-mentioned guess of a vertical time-dependent RF kick at the entrance of L0. The horizontal dispersion downstream of BC1 is in the 1–5 mm range. Its contribution to the horizontal projected emittance can be estimated with eq. 3.20. This predicts an emittance growth of only 4% for a residual dispersion of 2 mm, unperturbed normalized emittance of 1.5 mm mrad, energy spread of 0.8% (like that used for compression during commissioning) and nominal betatron function of 3 m at the location of emittance measurement. In this case, we do not expect any relevant contribution to the emittance growth during compression. However, other measurements have been carried out in which the horizontal dispersion reaches 10 mm in the same region. In this case, the emittance measurement, which assumes a pure geometric beam size at the screen, is affected by the chromatic particle motion and the effective error on the emittance measurement is of the order of 100%.

Figure 7.6 also shows the closure of the horizontal dispersion bump in BC1, where the two lines in each window refer to the case of BC1 at 0.05 rad and at 0 rad. Notice that the chicane seems to give an unexpected contribution in the vertical plane as well. The effect of the bunch compressor on the dispersion function has been systematically investigated by scanning the compressor strength, as shown in Figure 7.8. The agreement with the model is satisfactory at these early stages. The dispersion bump introduced by the BC1 magnetic chicane is reasonably well closed after the 4-th dipole and, for bending angles up to 0.12 rad, the residual trajectory distortion remains within the 10 \( \mu \)m level at the two BPMs downstream of BC1. The bend magnets trim coils correct the trajectory to the level of 20 \( \mu \)m. These correct for the magnet-to-magnet differences that could in principle corrupt the achromaticity of the chicane.
Figure 7.6: Dispersion function up to BC1 area. The abscissa is the BPM number along the linac.

Figure 7.7: Dispersion function up to linac end. The abscissa is the BPM number along the linac (two more BPMs have been added at the beginning of the beam line with respect to Figure 7.6).
7.4 Optics Matching

The goal of matching is to impose to the beam the design optics functions at a certain point of the lattice. For this purpose a set of quadrupoles is used. During the FERMI commissioning, optics matching is routinely performed at the entrance of the LH area and then repeated in the BC1 area, downstream of the chicane and at the linac end (TLS area). In order to perform the matching, the Twiss parameters of the beam must be known at the entrance of the matching section. To achieve this, the Twiss parameters are measured via the quadrupole scan technique. Doing this, the quadrupole strength is varied and the beam size measured with a YAG or an OTR screen target. Once the measurement is done, the Twiss parameters are back-propagated up to a reference point by running e\textsc{l}e\textsc{gend} with a reverse-ordered lattice file and the quadrupole strengths are acquired from the running accelerator. The initial conditions for the Twiss param-
eters of the beam are so available for estimating the optical functions along the whole accelerator and performing the desired matching with \texttt{elegant}. The user can inspect the matching result before actually setting the calculated quadrupole strengths to the machine. If the resulting matching is not good enough, the user can iterate the matching procedure starting with the previous result. All the intermediate data and results are exchanged via SDDS format files and can be plotted also with standard SDDS based tools.

Although simple in principle, all these steps are rather involved to be done by hand from a Linux shell. The matching procedure has thus been coded in a MATLAB GUI, exploiting the possibility to invoke system commands [155, 156]. Since MATLAB is an interpreted language, it is fast and straightforward to test and modify the procedure during commissioning shifts. At this stage of development, we use traditional SDDS toolkit plot utilities since we are quite acquainted to them and we can directly compare the live data with results and plots from off-line simulations. The matching procedure works reliably. It generally converges in a couple of iterations. The speed of the matching procedure is acceptable and is in the order of 10 to 20 seconds. It is mainly affected by the speed of the actual matching algorithm performed by \texttt{elegant}. The matching tool provides to the user information about the quadrupole strengths required for matching, the expected Twiss parameters along the lattice after matching and in particular at the entrance of the quadrupole used for emittance measurement. Also, a theoretical mismatch parameter [52] is computed. This is used as an indicator of the convergence of the matching loop performed by \texttt{elegant} to the optics constraints fixed by the model. Figure 7.9 shows such a typical data set. So, first step is to verify that the computation, starting from the Twiss parameters of the presumably mismatched beam, succeeded that is the theoretical mismatch parameter is close to 1 in both planes. If this is the case, the computed solution is applied to the machine. The user can immediately guess if the beam is approaching the optics design by looking to the beam spot at the three screens of the diagnostic section in LH, BC1 or TLS. According to the nominal optics and for similar emittance in the horizontal and vertical plane, the beam is expected to be round, have a waist at the screen in the middle and being identical at the outer screens. Figure 7.10 shows the beam spot at the YAG screens in the LH diagnostic area. The beam is propagating through the lattice from left to right plot of Figure 7.10. The theoretical mismatch parameter is very close to the target value of 1 in both planes. Finally, the new beam optics is measured again and another small MATLAB GUI allows the computation of the experimental mismatch parameter, including errors affecting the measurement of emittance and Twiss parameters.

Statistics of the experimental mismatch parameter, mainly collected during measurements in LH and BC1 area, provide a satisfactory overview for the
Figure 7.9: Optics matching output data.

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Theoretical mismatch parameter

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Figure 7.10: Beam spot at the screens of LH area after matching. Rms beam size is approximately 200 µm at the outer screens (first and third image) and 140 µm in the middle screen (second image), in both planes. The beam is round and has a waist at the middle of the section as required from the design optics.
matching procedure. The horizontal mismatch parameter is in the range \([1.005 \pm 0.001, 1.075 \pm 0.020]\), with mean value of 1.03. The vertical mismatch parameter is in the range \([1.002 \pm 0.002, 1.117 \pm 0.124]\), with mean value of 1.05. The vertical parameter assumes higher values during matching in the BC1 area with respect to the LH area. In general, we notice that the quality of the matching seems to depend mainly on the goodness of the initial emittance and beam parameters measurement. Noisy or odd-shaped beams are more difficult to match. After having matched the beam, we load the theoretical optics on the lattice. Once the optics is matched in the LH area, the beam is transported to the BC1 section almost instantly, requiring only small trajectory adjustments with the correctors. Without any further matching in the BC1 area, the experimental mismatch parameter is pretty good, 1.011 and 1.004 in the horizontal and in the vertical plane, respectively. Since the model is also includes BC1 dipole magnets vertical focusing and cavity end RF focusing, the good optics transport is also a confirmation of the correct modeling of such effects on the particle motion. However, we stress that the optics transport is not always so straightforward. Especially in the last two runs of commissioning (from September to December 2010), we have recognized an incorrect optics transport from LH to BC1, independently from the magnetic chicane settings. This bug is still under investigation. The same optical transport, but this time requiring bigger efforts to maximize the transport efficiency with trajectory correction, is repeated after matching in BC1 to upload the nominal optics up to linac end and, again, after matching in TLS to upload the nominal optics in the Spreader. Before imposing the nominal optics to the machine, the matching tool provides data and plots about the present optics along the lattice, the optics expected after applying but starting from the measured Twiss parameters and the nominal optics as a reference. If the mismatch parameter is very close to 1 at the beginning of the line, then the expected optics will be very similar to the nominal one.

### 7.5 Emittance Studies

In spite of the relatively smooth beam transport through the linac, we observe an important and not expected projected emittance growth during bunch length compression in BC1. Further investigations are required to understand this effect in detail. So far, we have collected some data that we are going to interpret, also with the support of simulations. The nominal optics adopted in FERMI from LH to BC1 area is shown in Figure 4.2. Figure 7.11 shows the emittance measurements performed in LH and BC1 area with quadrupole scan technique. Usually, more than 7 values of quadrupole strength and at least 3 images per strength are recorded. Gaussian fitting is applied to the projection of each col-
lected image in the horizontal and in the vertical plane, taking 100% of the pixels. The measurement is therefore providing a 100% statistical projected emittance. Background subtraction is also usually done during the measurement. Two sets of measurements are represented by solid/yellow and dashed/pink line, respectively. The projected emittance is shown as function of the machine configuration and measurement location, as indicated in the abscissa axis. Machine reproducibility and measurement errors lead us to limit the measurement accuracy to $\pm 0.1$ mm mrad normalized emittance, in both planes.

Figure 7.11: Emittance measurements at fixed compression factor.

In the first set of measurements (yellow line) there is a net increase in the horizontal emittance when the beam passes from LH at 100 MeV to BC1 at 350 MeV. BC1 is at zero bending angle. Since the energy spread is relatively small, 0.1%, we neglect chromatic aberrations and residual dispersion. Instead, we suspect transverse wake field generated in L1 or upstream is displacing the bunch tail with respect to the head. Notice that during the measurement the beam is forced to pass at the zero reading of all BPMs in L1. In fact, a 200 $\mu$m horizontal offset in L1 reduces the horizontal emittance closer to the initial value, which is approximately 1.2 mm mrad. As BC1 is turned on at 0.085 rad bending angle, with new optics tuning for this option, both horizontal and vertical emittances slightly
grow. No compression is expected so far because the beam is still running on crest in L1. However, an uncertainty on the effective residual (and nonlinear, due to the RF curvature) energy chirp at the entrance of BC1 could explain a local compression of the bunch head. Since the bigger growth is in the horizontal plane, we suspect a CSR contribution from some energy and/or optics mismatched end of the bunch. After some optics manipulation across BC1, some reduction is observed, especially in the vertical plane. This could indicate the vertical plane suffers from chromatic aberration in the matching quadrupoles downstream of BC1, in the presence of an energy mismatched end of the bunch. As a last step, a smoother optics through the BC1 area seems to slightly reduce such an effect. In the second set of measurements (pink line) there is 20% emittance growth in both planes from LH to BC1 off and then again to BC1 on. This time, when compressing the beam by a factor of 6.5 (linear theoretical), the horizontal emittance blows up by a factor of 2.2. CSR might be acting here, although an emittance growth smaller than 10% is predicted from \texttt{elegant} for a compression factor up to 10. The blow up is then strongly minimized by big trajectory bumps of ±1.5 mm in L1. The final growth is by a factor of 1.5. The vertical emittance is affected by the trajectory bumps as well. We also report of a third set of measurements (not shown here), in which the same mean energy and energy spread at BC1 is achieved than during compression, but with energy chirp of opposite sign. So, while the emittance grew again by a factor of 2 during compression, it is observed no emittance growth at all during bunch lengthening. These additional measurements confirm a CSR effect during compression and seem to remove any suspicion of residual dispersion when the energy spread is high but no compression is going on. Another campaign of emittance studies was made by varying the compression factor. The same compression factor, analytically computed in the linear approximation, is implemented with BC1 at 0.085 rad bending angle first, at 0.050 rad then, by varying the L1 RF phase. Also, a new optics with smaller betatron functions and smoother optics across BC1 is adopted. This is shown in Figure 7.12. For any fixed BC1 setting, the new optics mitigates the emittance growth only for $C > 6.4$, where $\epsilon_{n,x}$ passes from 4.1 to 3.2 mm mrad. The same mitigating effect is observed in the vertical plane. We suspect this is an indication the vertical emittance is suffering from chromatic aberration. Although simulations for a perfectly matched beam predicts the absence of any second order emittance growth, chromatic aberration could play a role for optically mismatched slices. Finally, the nominal optics with smaller bending angle in BC1 and larger energy chirp to restore the same compression factor reduces the horizontal emittance of a big amount, from 3.2 to 2.2 mm mrad for $C = 6.4$. In this case, the smaller bending angle is expected to mitigate CSR and this is confirmed by the measurements. An \texttt{elegant} simulation of the CSR instability and the second order aberration with a self-generated particle beam,
perfectly energy and optically matched to the standard optics lattice, does not predict any important emittance growth. Some small growth becomes evident when using a GPT generated input beam with slice optics greatly mismatched. The simulation results listed in Table 7.1 refer to an ideal 350 pC, 5 ps fwhm long, e1legant-generated beam, with an initial normalized projected emittances of 1.0 mm mrad. The optics mismatch is reproduced by changing a quadrupole setting on purpose. The output normalized projected emittances are listed in Table 7.1, considering either CSR only (1\textsuperscript{st} order tracking), chromatic aberration only (2\textsuperscript{nd} order tracking) or both these effects at the same time. Due to the limited number of particles used, $2 \cdot 10^4$, we limit the accuracy of our results to 0.1 mm mrad. The first value in each Table cell is for the horizontal plane, the second is for the vertical. The simulations result indicate that a big optics mismatch along the whole bunch or part of it, can enhance CSR induced emittance growth up to factor of approximately 2. However, a factor of about 5 is gained in the horizontal plane and a factor of 2 in the vertical plane from chromatic aberration only. This dominates the CSR contribution as well. The same simulations have been repeated with the new optics. Due to the different quadrupole strengths, here the mismatch induces even higher betatron functions and, therefore, stronger effects from chromatic aberration. However, the same CSR effect than with nominal optics is substantially confirmed, while the chromatic aberration effect in the vertical plane is minimized, as expected (1.5 mm mrad instead of 2.5 mm mrad vertical emittance).

<table>
<thead>
<tr>
<th></th>
<th>CSR</th>
<th>Chrom. Aberration</th>
<th>CSR+Chrom. Aberration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$ (L1 on crest)</td>
<td>1.0, 1.0</td>
<td>1.1, 1.0</td>
<td>1.2, 1.0</td>
</tr>
<tr>
<td>$C_2 = 6.4$ (L1 +25 deg)</td>
<td>1.8, 1.1</td>
<td>5.2, 2.1</td>
<td>5.2, 2.1</td>
</tr>
<tr>
<td>$C_3 = 10$ (L1 +28 deg)</td>
<td>2.5, 1.2</td>
<td>-</td>
<td>5.5, 2.5</td>
</tr>
<tr>
<td>$C_4 = 1/5$ (L1 -25 deg)</td>
<td>1.0, 1.1</td>
<td>6.6, 2.5</td>
<td>4.5, 2.5</td>
</tr>
</tbody>
</table>

### 7.6 Microbunching Instability

We conclude this Chapter with a few notes on experimental evidence for CSR and the microbunching instability. As discussed above, a contribution from CSR is suspected from the fast increase of the horizontal emittance during compression. Owing to the non-linearized longitudinal phase space at the entrance of BC1 (the X-band structure is not installed yet), the e1legant simulation predicts a 1 kA, 20 fs long current spike at the bunch head for $C > 3$. If the slice optics of this spike is not well matched to the lattice, it could become the natural source
of the projected emittance blow up depicted in Figure 7.11. Some coherent optical radiation emission is also observed at the second screen downstream of BC1, where the beam is expected to reach a waist. This is shown in Figure 7.13 in which the beam is compressed by a factor of 4. As the computed compression factor reaches the value of 3 or higher, we obtain a fragmented image at the OTR target (middle plot). Saturation of the screen system with the OTR target can be interpreted as coherent optical transition radiation emitted by a very short current spike or extended microbunching along the whole bunch duration. At the moment, we cannot distinguish between these two possible sources. The fragmented image disappears when using the YAG target (left plot) or by inserting an OTR foil upstream of it to introduce an emittance smearing effect (right plot).

Another evidence of microbunching instability is shown in Figure 7.14. Here the beam spot is collected at the last screen of the FERMI electron ebeam delivery system, in front of the main beam dump. The horizontal dispersion is left to reach several meters so that we are effectively projecting the particle energy distribution on the horizontal plane. The total energy spread is expected to be of the order of 0.3% rms. The BC1 linear compression factor is 6.4. Most of the 350
pC beam charge is collected in the brighter spot, approximately in the middle of the dispersed image. The several mm’s long tail on the left side corresponds to higher energy particles. A periodic structure is clearly visible in the high energy region and even more in the low energy portion of the bunch. This image reveals an energy modulation distributed along the whole bunch duration, as predicted by the simulation studies in Section 5.5. Further and more systematic investigations on microbunching instability will be carried out during commissioning in 2011.

**Figure 7.13:** Evidences of COTR during compression.

**Figure 7.14:** Evidences of energy modulation at the main dump.
7.7 Conclusions

We have reported about the commissioning of the FERMI@Elettra electron beam delivery system. Methods and experimental results concerning the control of the longitudinal (acceleration, energy distribution, bunch length compression and microbunching instability) and transverse (optics matching, transport and trajectory control) electron beam dynamics in FERMI have been shown. The longitudinal phase space of the electron beam has been characterized at the beginning of the FERMI commissioning with a simple spectrometer line. Optics has revealed to be an important ingredient for the characterization of the electron beam energy distribution since it optimizes the resolution of the energy measurement. Starting from experimental Twiss parameters of the electron beam, the optics matching and transport through the whole line has been performed with the \texttt{elegant} code, which includes the description of the real accelerating gradients and the RF edge focusing of the structures. The mismatch parameter usually corresponds to a projected emittance growth smaller than 1% in both planes. \texttt{elegant} has also been used to generate for the trajectory theoretical response matrices to correct the real beam trajectory in the linac and in the high energy transfer line. The matrices are imported in a trajectory feedback tool. This is also able to measure experimental response matrices. The theoretical and the experimental ones can be merged for a global trajectory correction along the whole line. The BPMs integrated into the feedback tool read the beam position at the frequency of 10 Hz and their reading is forced to the value determined by the user by the corrector magnets. In this way, the feedback works as a trajectory correction tool as well. It has been verified that the magnetic chicane BC1 does affect neither the trajectory nor the dispersion in the succeeding lattice. The dispersion bump in the chicane has been measured and agrees well with the theoretical expectation. An important horizontal emittance growth appears during the magnetic bunch length compression, especially for compression factors larger than 3. Off-line simulation studies indicate that CSR might be the main responsible of this emittance degradation, especially in the presence of nonlinear compression (the X-band cavity to linearize the longitudinal phase space during compression has not been installed yet) and potential slice optics mismatch. Some evidence for the microbunching instability has been detected for compression factors larger than 3. They are COTR emission downstream of BC1 and an energy modulation of the compressed electron beam. At the end, a comparison of the theoretical expectation and measured values for many electron beam parameters has been produced and summarized in a table of parameters. The uncompressed beam has been well characterized experimentally. A good agreement with the model has been achieved. The uncompressed beam still deviates from the model as for the projected emittance measured after BC1. Fur-
ther investigations are needed to accomplish a full understanding of the physics developing in BC1. Nevertheless, the electron beam quality has revealed to be more than sufficient to generate the first coherent harmonic generation in seeded configuration at 43 nm (FEL fundamental output) in December 2010, after one year, calendar time, of machine commissioning. Table 7.2 shows the comparison of the main electron beam parameters as they have been measured during the commissioning and the model prediction.

Table 7.2: Design and measured main electron beam parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
<th>Measurement</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>350</td>
<td>350 pC</td>
<td>pC</td>
</tr>
<tr>
<td>Charge jitter (rms)</td>
<td>4</td>
<td>0.5</td>
<td>%</td>
</tr>
<tr>
<td>PI laser radius</td>
<td>0.7</td>
<td>0.7</td>
<td>mm</td>
</tr>
<tr>
<td>PI pulse duration (fwhm)</td>
<td>5.0</td>
<td>5.0 ± 0.1</td>
<td>ps</td>
</tr>
<tr>
<td>Bunch duration (fwhm)</td>
<td>6.0</td>
<td>6.0 ± 0.5</td>
<td>ps</td>
</tr>
<tr>
<td>$\epsilon_{N,x}$, $\epsilon_{N,y}$ in LH area</td>
<td>0.8, 0.8</td>
<td>0.8 ± 0.1, 0.9 ± 0.1</td>
<td>mm mrad</td>
</tr>
<tr>
<td>$\epsilon_{N,x}$, $\epsilon_{N,y}$ in BC1 area, C = 1</td>
<td>1.0, 1.0</td>
<td>1.3 ± 0.1, 1.2 ± 0.1</td>
<td>mm mrad</td>
</tr>
<tr>
<td>$\epsilon_{N,x}$, $\epsilon_{N,y}$ in BC1 area, C = 6.4</td>
<td>1.1, 1.1</td>
<td>2.0 ± 0.1, 1.4 ± 0.1</td>
<td>mm mrad</td>
</tr>
<tr>
<td>$\epsilon_{N,x}$, $\epsilon_{N,y}$ at linac end, C = 6.4</td>
<td>1.5, 1.5</td>
<td>3.5 ± 0.5, 2.9 ± 0.1</td>
<td>mm mrad</td>
</tr>
<tr>
<td>$B_{mag,x}$, $B_{mag,y}$ in LH area</td>
<td>1.0, 1.0</td>
<td>1.005 ± 0.003, 1.001 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>$B_{mag,x}$, $B_{mag,y}$ in BC1 area</td>
<td>1.0, 1.0</td>
<td>1.010 ± 0.004, 1.000 ± 0.001</td>
<td></td>
</tr>
<tr>
<td>$&lt; E &gt;$ out of Gun</td>
<td>5.0</td>
<td>4.5 – 4.9 ± 0.1</td>
<td>MeV</td>
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<tr>
<td>$\sigma_{d,tot}$ out of Gun (rms)</td>
<td>40</td>
<td>28 – 44 ± 5</td>
<td>keV</td>
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<tr>
<td>$&lt; E &gt;$ out of L0 (on crest)</td>
<td>96</td>
<td>95 – 102 ± 0.02</td>
<td>MeV</td>
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<td>$\sigma_{d,tot}$ out of L0 (rms)</td>
<td>45</td>
<td>43 – 89 ± 20</td>
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<td>$&lt; E &gt;$ out of L1 (on crest)</td>
<td>345</td>
<td>349 – 357 ± 0.01</td>
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<tr>
<td>$\sigma_{d,tot}$ out of L1 (rms)</td>
<td>200</td>
<td>≥ 135 ± 12</td>
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<tr>
<td>$&lt; E &gt;$ out of L4</td>
<td>1200</td>
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<td>$\sigma_{d,tot}$ out of L4 (rms)</td>
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<td>keV</td>
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<td>$&lt; E &gt;$ jitter out of L0</td>
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<td>keV</td>
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<td>$&lt; E &gt;$ jitter out of L1</td>
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<td>keV</td>
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<tr>
<td>$&lt; E &gt;$ 6hs-stability out of L1 (p2p)</td>
<td>0.3</td>
<td>1.0</td>
<td>MeV</td>
</tr>
<tr>
<td>$\sigma_{d,tot}$ 6hs-stability out of L1 (p2p)</td>
<td>0.3</td>
<td>0.15</td>
<td>keV</td>
</tr>
<tr>
<td>Trajectory jitter (rms)</td>
<td>20</td>
<td>10 – 30 ± 5</td>
<td>µm</td>
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