Chapter 6

Schemes of Magnetic Bunch Length Compression

This Chapter\(^1\) discusses some general principles for the design of the magnetic compression scheme of the electron bunch duration for a seeded FEL. Although neither a general receipt nor an obvious solution exist for this problem, our considerations start from the FEL requirements about the final peak current and bunch length of the electron beam. We stress that the seeding option for the FEL imposes some constraints on the bunch length that are not usually present in a SASE FEL design. Once the machine working point - in terms of compression factor and electron beam parameters - has been determined, some discussions about the impact of the compression scheme on the suppression of the microbunching instability are presented. Finally, the feasibility of the proposed scheme(s) is demonstrated with particle tracking.

6.1 Working Point

We consider the machine working point as the ensemble of parameters that define the bunch length compression factor and the final electron beam parameters. We start from the requirement for the output photon pulse duration, whose minimum value is usually specified by fast dynamics experiments. In a seeded FEL, this is approximately the duration of the external seeding laser. It is 100 fs long in FERMI@Elettra. The final electron bunch duration has to be long enough

\(^{1}\)This Chapter is based on the following work: *Suppression of microbunching instability with magnetic bunch length compression in a linac-based fel*, Phys. Rev. Special Topics – Accel. and Beams, 13, 010702 (2010), by S. Di Mitri, M. Cornacchia, S. Spampinati and S. V. Milton.
to accommodate the seeding pulse and the arrival time jitter of the electrons with respect to the seed laser. In a two-stage harmonic cascade such as FERMI FEL2, which is implementing the fresh bunch technique to reach the smallest wavelength of 4 nm, the seeding laser pulse length actually counts for two. If we estimate a final time jitter of 150 fs (rms value), the electron bunch duration in FERMI cannot be shorter than approximately 600 fs fwhm (100 fs additional margin has been taken to avoid longitudinal overlap of the two seeding pulses interacting, respectively, in the first and in the second stage of the harmonic cascade). At the same time, the electron bunch peak current is usually determined by the users’ specification for the number of photons per pulse, which is particularly important for experiments of nonlinear dynamics. Simulations of the FEL process in FERMI show that the goal of \(10^{12}\) photons per pulse at 4 nm fundamental wavelength can be achieved with a peak current as high as 900 A [29]. The total charge is therefore determined by the peak current times the final bunch length, in the approximation of an ideal hard edge current profile. Actually, a factor usually equal to or smaller than 0.8 has to be included in this calculation that takes into account the real efficiency of the bunch length compression process. As already shown in this Thesis, this efficiency is limited by the nonlinear longitudinal dynamics introduced by (residual) high order energy chirps during the magnetic compression. The total electron charge in FERMI has therefore been fixed at 800 pC. We point out that by limiting the final bunch duration to the strict minimum value of 500 fs (the shot-to-shot stability of the FEL output intensity would then be suffering because of less space along the bunch left for accommodating the time jitter with respect to the seed laser) and assuming a compression efficiency of 0.9, the beam charge out of the injector could be in principle diminished to 450 pC. Some optimizations in this sense could be carried out in a future tuning of the FERMI FEL, if they turn out to be compatible with the users’ experimental program.

The electron bunch length before compression is determined by the final bunch length times the (effective) compression factor. For the same peak current, the degrading effect of structural wake fields and CSR emission is minimized by the shortest duration, smallest charge of the electron bunch. The minimum electron bunch duration out of the RF photo-injector is often limited to a few ps by the photo-injector pulse shaping and repulsive SC forces. In general, a too short bunch at non-relativistic velocities suffers from transverse emittance degradation due to SC forces that must be counteracted with external focusing. At the same time, the charge density cannot be arbitrarily diluted by enlarging the transverse laser spot size because the minimum emittance achievable (the so-called thermal emittance) is proportional to its radius. At the end, a 3-D charge density that permits full control of the transverse and longitudinal emittance should be chosen. The specification on the transverse (slice) emit-
tance comes from the FEL requirement in order to reach saturation at the shortest wavelength. The FERMI FEL2 performance goal sets this value to 1 mm mrad normalized emittance at 1.5 GeV. Assuming an emittance degradation not bigger than 20% along the whole beam transport and compression, the injector should provide a slice emittance of approximately 0.8 mm mrad. Particle tracking studies show that this goal is achieved with 800 pC charge distributed along 10 ps (fwhm value) and with a photo-injector laser radius of 0.7 mm [29]. In conclusion, the total compression factor is fixed by the ratio of the final vs. the initial electron bunch duration that is 11 in case of FERMI. Relying on this theory, a working point for the FERMI magnetic compressors can be fixed, as it is depicted in Table 6.1. This is consistent with the electron beam specifications in Table 2.2.

<table>
<thead>
<tr>
<th>Table 6.1: Main linac and magnetic chicanes nominal setting.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak Current</strong></td>
</tr>
<tr>
<td>L1 RF phase</td>
</tr>
<tr>
<td>BC1 bending angle</td>
</tr>
<tr>
<td>BC1 $R_{56}$</td>
</tr>
<tr>
<td>BC1 Lin. Compr. Factor</td>
</tr>
<tr>
<td>L2, L3 RF phase</td>
</tr>
<tr>
<td>BC2 bending angle</td>
</tr>
<tr>
<td>BC2 $R_{56}$</td>
</tr>
<tr>
<td>BC2 Lin. Compr. Factor</td>
</tr>
</tbody>
</table>

The FERMI moderate compression factor of 10 could be achieved either with a one-stage or a two-stage magnetic compression scheme. Nevertheless, the two schemes might lead to some differences in the final current shaping, transverse emittance and energy distribution, mainly due to a different balance of the strength of collective effects such as CSR emission and microbunching instability. In the following, the issue of the emittance preservation is recalled with a special attention to the slice and the projected dynamics. The impact of the compression scheme on the development of the microbunching instability is treated in the next Section.

At the first stage of optimization, the horizontal, vertical and longitudinal particle motion are assumed to be uncoupled. The particle configuration generated in each plane at the end of the injector is taken as a reference, since the electrons are already ultra-relativistic and the particle spatial distribution is frozen for any practical purpose. Assuming that the injector is able to produce a beam whose parameters satisfy the FEL performance, the beam transport and manip-
ulation in the main linac should not degrade the area in each 2-D phase space by more than \(\sim 20\%\). Simulations indicate that this threshold can be satisfied for the longitudinal core of the bunch, while it is harder to apply it when also the bunch edges are included. These regions are characterized by a lower charge density, therefore they are subjected to a different dynamics at very low energy, where the beam is generated in the presence of important SC forces that strongly depend on the charge density. This different dynamics of the bunch edges with respect to the core leads to a mismatch of the local distribution function (defined in the transverse and in the longitudinal phase space) with respect to the rest of the bunch. Moreover, the finite length of the bunch enhances a nonlinear behaviour of the space charge electric field at the bunch edges that introduces in turn a local nonlinear energy chirp. For all these reasons, particle dynamics in the bunch head and tail is usually studied only with particle tracking codes and the final beam quality is referred to \(\sim 80\%\) of the beam population contained in the bunch core.

Figure 6.1 shows the evolution of the projected and slice horizontal emittance along the FERMI electron beam delivery system, from the injector end to the undulator entrance. Perturbative effects such as CSR emission and optical aberrations are included in the particle tracking performed with \texttt{elegant}. The same beam parameters and machine set up as in Figure 5.1 are used. Both in the case of low (top) and high (bottom) charge in the one-stage compression, the discrepancy between the slice and the projected emittance originates in the injector (the initial particle file was generated with GPT \cite{144}, as described in \cite{29}) and it is preserved along the FERMI linac. The projected emittance bump in correspondence of BC1 is due to slice misalignment induced by the dispersive motion in the BC1 magnetic chicane: a \(\sim 1\%\) correlated energy spread, required for bunch length compression, makes different slices to follow different trajectories. Their transverse misalignment translates into the projected emittance growth. This growth is recovered in the case of low charge, weak compression, as the dispersion bump closes at the end of the chicane. It is not, instead, for the high charge case. The (average) slice emittance is preserved as at the injector level in both cases.
Figure 6.1: Projected and slice horizontal emittance along the FERMI linac. Top plot: projected (upper line) and slice (lower line) emittance along the FERMI linac for $C = 6.5$. Bottom plot: projected (upper line) and slice (lower line) emittance for $C = 10$. The slice emittance is averaged over the entire bunch length divided in 50 slices. The projected emittance is for 100% of the beam population. The (average) slice emittance is preserved as at the injector level in both cases.
6.2 Two-Stage Compression

The amplification of the energy modulation and emittance blow up induced by the microbunching instability in the presence of magnetic bunch length compression has been discussed in the previous Chapter. Some cures such as laser heater and optics tuning in order to mitigate or even suppress the instability have been discussed. We now want to show that a magnetic chicane downstream of the first one could be used for the same purpose, once a different compression scheme than the usual multi-stage is adopted. It will be shown that, after removing the linear energy chirp required for the compression at low energy, an additional and properly tuned $R_{56}$ transport matrix element is able to dilute the initial energy modulation and to suppress the current spikes created by the microbunching instability without affecting the bunch length. A by-product of the study is the observation that a single compressor is more effective than the two-compressors scheme in reducing the unwanted modulations caused by the microbunching instability. The study is based on analytical calculations and on elegant simulation results.

As a preliminary discussion, let us start with a conventional two-stage compression scheme. The FERMI layout is taken as a case study. If the uncorrelated energy spread is included in the physics modeling, the larger the negative $R_{56}$ in BC1 is, the bigger the uncorrelated energy spread out of the chicane will be by virtue of the preservation of the longitudinal emittance and the smaller the compression factor in BC2 should be to maintain the nominal total compression action. If the particle longitudinal cross-over in BC1 is efficient enough, it is expected that no density clusters are enhanced by the dispersive motion in the chicane. Unfortunately, the above statement becomes less and less valid the longer the wavelengths considered. Based on these considerations, we will show that two schemes can alternatively be adopted to smear an initial density modulation. The first is the one-stage compression scheme. In the second, BC2 is re-introduced in the layout but the energy chirp required by the compression in BC1 has to be removed at the entrance of BC2. This approach requires that the sign of $R_{56}$ be equal in BC1 and in BC2. In practice, the scheme evolves towards a one-stage compression in which the final bunch length is determined by BC1 only, while the modulation washing out is made even more effective by BC2.

At first, we calculate the bunching factor at the exit of the first stage of compression, BC1, with a compression factor of 3.5 (slightly relaxed with respect to the nominal value of 4.5 for the two-stage compression in FERMI) established by $R_{56} = -31 \text{ mm}$ and a properly set energy chirp. Then, we consider an additional positive $R_{56}$ transport matrix element (called DC) immediately downstream of BC1. In the latter case, $R_{56} = -33.8 \text{ mm}$ giving $C=4.5$ in BC1 is stronger than in the former case but the total compression factor is re-established by the DC.
element that has $R_{56} = 2.9 \text{ mm}$ corresponding to $C=1/3$. Now, two sinusoidal density modulations of amplitude 0.03% at 10 $\mu$m and 1% at 100 $\mu$m are considered. The density modulations are superimposed to the initial beam current profile shown in Figure 6.2.

![Figure 6.2: Initial unperturbed electron beam current profile. Input file provided by G. Penco (ST).](image)

The two initial density modulations induce energy modulations of amplitude 0.3 keV and 5 keV at the entrance of BC1, at the wavelengths of 10 $\mu$m and 100 $\mu$m, respectively. Table 6.2 shows the bunching factor calculated with eq.3.80 and eq.3.81, respectively, at the end of compression in the BC1-only and in the BC1+DC scheme. The total compression factor is 3.5 in both cases. As expected, the DC option reduces the bunching by a factor 4.5 at 10 $\mu$m, while it is almost inefficient at 100 $\mu$m because the longitudinal phase mixing is no longer effective at such a long wavelength. As additional check, an initial density modulation of 0.03% at 100 $\mu$m is considered. The final bunching is still not affected by the DC option, so demonstrating that the effect of phase mixing is more sensitive to the wavelength than to the modulation amplitude.

On the basis of the results in Table 6.2, one might think of further increasing the positive $R_{56}$ in DC while reducing the negative $R_{56}$ in BC1; in this way the total compression factor is kept constant and the longitudinal phase mixing becomes effective even at longer wavelengths. As a matter of fact, this scheme
Table 6.2: Bunching factor after compression for the BC1-only and the BC1+DC scheme.

<table>
<thead>
<tr>
<th>Initial Density Modulation</th>
<th>BC1 only</th>
<th>BC1 + DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03% at 10 µm</td>
<td>9 \cdot 10^{-3}</td>
<td>2 \cdot 10^{-3}</td>
</tr>
<tr>
<td>1.00% at 10 µm</td>
<td>0.146</td>
<td>0.188</td>
</tr>
<tr>
<td>0.03% at 100 µm</td>
<td>8 \cdot 10^{-3}</td>
<td>11 \cdot 10^{-3}</td>
</tr>
</tbody>
</table>

is equivalent to a two-stage compressor with unequal weight between BC1 and BC2: the stronger the first chicane is, the more effective the instability suppression becomes. The implications of this preliminary study lead to consider the advantages of a single compressor over two. This is discussed in the next Section.

6.3 One-Stage Compression

The one-stage compression scheme optimizes the suppression of the instability with respect to the two-stage compression for two reasons: firstly, the phase mixing is more effective in BC1 due to the larger $R_{56}$ and to the larger relative energy spread (see eq.3.85). Secondly, the absence of the high energy compressor does not provide the opportunity to transform the energy modulation accumulated by LSC downstream of BC1 into current modulation. These considerations are consistent with the studies presented in [141], where the instability gain function for a single bunch compressor lattice was shown to be significantly lower than in the case of the two bunch-compressor lattices. Owing to the sensitivity of harmonic cascade FELs to the slice energy spread – and of FERMI in particular [15, 16] –, it is important to reduce this parameter to the minimum. A metric to compare the performance between the two lattices is therefore the evaluation of the increase in beam slice energy spread caused by the microbunching instability and seeded by shot noise. This is shown in Figure 6.3 (compare with the analytical prediction in Figure 5.29), where the slice energy spread at the exit of the linac is reported as a function of the slice energy spread at the exit of the laser heater for the two lattices. In both cases the total compression is $C=10.4$ and the peak current 800A. These results have been obtained by using the same 2-D Vlasov solver as in [141] except for a modified and presumably more accurate model of the LSC impedance that includes averaging of the longitudinal electric field over the transverse beam density [142]. The error bars indicate the spread in the outcome corresponding to different seeds used for the generation of shot noise. First simulations with IMPACT and Vlasov solver based on 1-D
impedances [141] (not reported here) show the minimum of the curve in Figure 6.3 to be 9 keV and 15 keV, respectively, for the one-stage and two-stage compression. They predict a final slice energy spread of 120 and 180 keV rms. Now, a more accurate treatment of the transverse dynamics lowers the minimum to 6 keV and 11 keV, providing a final slice energy spread of 80 keV and 140 keV rms. Whatever the modeling used is, a one-stage compression minimizes the amount of uncorrelated energy spread provided by the laser heater, required to suppress the microbunching instability.

![Figure 6.3: Final vs. initial uncorrelated energy spread for one- and two-stage compression in FERMI@Elettra. Vlasov solver simulation result. Figure courtesy of M. Venturini (LBNL).](image)

In spite of the great advantage of suppressing the microbunching instability with minimum energy spread, the shortcoming of a one-stage compression is that a short bunch is affected by longitudinal wake field along a longer path than in the two-stage option, where the path to a short final bunch proceeds in two stages. The wake field corrupts the longitudinal phase space by increasing the energy spread, by reducing the average beam energy and by inducing nonlinearities in the energy distribution. A manipulated current profile, already shown in Figure 6.2, has been successfully studied to overcome this problem. At the same time, a positive aspect of the one-stage compression, performed early enough in the linac, is that of minimizing the effect of the transverse wake field, since the induced wake potential is reduced by a shorter bunch length.
To demonstrate the attraction of the one-stage compression scheme for a realistic model of linac-based FEL and for FERMI in particular, the 6-D tracking of a 5 million particle file is here shown according to the parameters in Table 6.3. All collective effects previously described in this Thesis are included. A uniform beam heating at 100 MeV is also included in the simulation, so that the uncorrelated energy spread before compression is approximately 10 keV rms. Figure 6.4 depicts the properties of the FERMI@Elettra bunch, compressed by a factor 10 in BC1 with $R_{56} = -46$ mm. As already discussed in Section 5.5, 3-D effects are marginal for such compression factor. The initial density modulation of 0.03% at 30 $\mu$m wavelength, superimposed to the initial beam, is washed out at the linac end. For comparison, the final bunch after two-stage compression is shown in Figure 6.5. No difference in the slice emittance is apparent for the two cases in Figure 6.6. The projected normalized horizontal emittance for 60% of the particles in the transverse phase space is 0.8 mm mrad. Unlike the one-stage compression, the two-stage allows one to obtain a flat longitudinal phase space ($\sigma_\delta \leq 0.1\%$) and current profile ($\Delta I/I \leq 10\%$ in the bunch core) even for a compression factor in the range 10–30. The current spikes at the bunch edges can be manipulated in both schemes by moving the charges towards the tail, so avoiding high spikes in the head that could excite damaging wake fields in the low-gap undulator vacuum chamber.

Table 6.3: FERMI parameters for the one-stage compression.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial energy</td>
<td>100</td>
<td>MeV</td>
</tr>
<tr>
<td>Energy at BC1</td>
<td>320</td>
<td>MeV</td>
</tr>
<tr>
<td>Charge</td>
<td>0.8</td>
<td>nC</td>
</tr>
<tr>
<td>Initial peak current</td>
<td>80</td>
<td>A</td>
</tr>
<tr>
<td>Initial bunch length, rms</td>
<td>3.71</td>
<td>mm</td>
</tr>
<tr>
<td>Final bunch length, rms</td>
<td>0.08</td>
<td>mm</td>
</tr>
<tr>
<td>BC1 compression factor</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$R_{56}$ in BC1</td>
<td>-46</td>
<td>mm</td>
</tr>
<tr>
<td>Initial uncorrelated energy spread, rms</td>
<td>10</td>
<td>keV</td>
</tr>
<tr>
<td>Initial modulation amplitude</td>
<td>0.03</td>
<td>%</td>
</tr>
<tr>
<td>Initial modulation wavelength</td>
<td>30</td>
<td>$\mu$m</td>
</tr>
</tbody>
</table>

From the point of view of the stability, the two-stage compression has the intrinsic advantage of self-stabilizing the shot-to-shot variation of the total compression factor, $C$. Let us assume an RF and/or a time jitter makes the beam more (less) compressed in BC1; a shorter bunch then generates stronger (weaker)
Figure 6.4: Final particle distributions after one-stage compression.
Figure 6.5: Final particle distributions after two-stage compression.
longitudinal wake field in the succeeding linac so that the energy chirp at BC2 is smaller (bigger). This in turn leads to a weaker (stronger) compression in BC2 that approximately restores the nominal total $C$. In the one-stage compression, where $C \gg 1$ and the phase is far enough from the accelerating crest, the sensitivity of $C$ to phase jitter is [146]:

$$\frac{\Delta C}{C_0} = -C_0 \frac{\Delta \phi}{\phi_0}$$  \hspace{1cm} (6.1)

where the accelerating crest is for $\phi_0 = \pi/2$. Basing on some technical considerations and recent measurements at the Elettra laboratory, an admissible value for the shot-to-shot variation of the FERMI linac RF phase is 0.1 degree S-Band and 0.1% for the peak voltage (rms values). Given the phase jitter $\Delta \phi \leq 0.1$ deg and the energy jitter $\Delta E / E_0 \leq 0.1\%$, their relation:

$$\frac{\Delta E}{E_0} = \Delta \phi \cos \phi_0$$  \hspace{1cm} (6.2)

sets a new constraint on the maximum L1 off-crest phasing, finally fixed to -25
deg. This prescription goes in the same direction of a final beam energy equal or bigger than 1.2 GeV and of an energy spread smaller than 2% at BC1. So, using this prescription in eq. 6.1, we find a shot-to-shot jitter in \( C \) of 4% in the one-stage compression. This result is fairly compatible with the FEL requirement of a final peak current jitter \( \Delta I/I \leq 10\% \). For completeness, we report in Table 6.4 the tolerance budget for the one-stage and two-stage compression as already computed in [29], whereas the one-stage scenario is updated with the aforementioned prescriptions on the RF phase of L1.

Table 6.4: Jitter tolerance budget for the one- and two-stage compression scheme.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Two-stage</th>
<th>One-stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 phase [deg]</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>X-band phase [deg]</td>
<td>0.30</td>
<td>0.35</td>
</tr>
<tr>
<td>L2 phase [deg]</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>L3 phase [deg]</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>L4 phase [deg]</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>L1 voltage [%]</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>X-band voltage [%]</td>
<td>0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>L2 voltage [%]</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>L3 voltage [%]</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>L4 voltage [%]</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Gun timing [fs]</td>
<td>250</td>
<td>350</td>
</tr>
<tr>
<td>Charge [%]</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>BC1 dipole field [%]</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>BC2 dipole field [%]</td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

6.4 Enhanced Phase Mixing

As anticipated at the beginning of this Section, we also want to show an alternative compression scheme that is even more effective than a pure single compressor in suppressing the beam microbunching. It requires that the correlated energy spread, needed for bunch length compression in BC1, be removed before passing through a second chicane. When this happens, the rotation of the longitudinal phase space can be made large enough so that phase mixing is maximized in the second chicane. At the same time, the second chicane does not change the overall bunch length that therefore depends on the \( R_{56} \) in BC1 only.
Its only task is to smear the microbunching modulations. In this case the energy and density modulation washing out is more efficiently provided by two magnetic chicanes having $R_{56}$ of the same sign. In fact, the energy modulation smearing is induced by a complete rotation of the longitudinal phase space; the two chicanes must therefore stretch the particles in the same direction.

To illustrate this process, we consider a line-charge that has a Gaussian energy distribution with $<E> = 320$ MeV and $\sigma_E = 10$ keV. A linear energy chirp of 0.036 $ps^{-1}$ and an energy modulation with amplitude $A_E = 1\%$ and wavelength $\lambda_E = 30 \, \mu m$ are superimposed to it. The linear transport matrix formalism is used to propagate the line-charge through drift sections and $R_{56}$ elements. Figure 6.7 shows that, after the linear energy chirp is removed, the residual energy chirp changes sign over one modulation period, so that particles lying on opposite fronts of the modulation can be (de-)compressed in BC2 by the same factor: the longitudinal phase space becomes folded and the initial energy modulation is removed, turning into an almost totally uncorrelated energy spread. This is shown in Figure 6.8. At the same time, the particle crossover in the $z$ coordinate damps the initial current spikes, therefore suppressing the microbunching instability.

![Figure 6.7: Longitudinal phase space before (left) and after (right) energy chirp removal.](image)
Figure 6.8: Longitudinal phase space evolution during enhanced phase mixing. (a) An energy modulation is superimposed to the linear energy chirp entering BC1 (10 keV rms uncorrelated energy spread). (b) As a result of the bunch length compression in BC1, the longitudinal phase space looks rotated. (c) The longitudinal phase space is flattened by removing the linear energy chirp. (d) A further rotation allows the particles to longitudinally cross-over. Tracking code developed by S. Spampinati (ST).

Figure 6.9 shows the instability gain function for the one-stage compression scheme and for the enhanced phase mixing (where $R_{56} = -30$ mm in BC2) in FERMI@Elettra. BC1 is at 320 MeV, BC2 is at 600 MeV and they are separated by a 30 m long S-band linac. By virtue of the off-crest phasing of this linac, the energy chirp required for compression in BC1 is removed before the beam enters BC2. In the latter case, the gain is clearly reduced and it practically goes to zero for initial wavelengths shorter than 100 $\mu$m. Particle tracking is carried out with elegant in order to obtain a complete and realistic picture of the dynamics discussed so far, including LSC, CSR and longitudinal structural wake fields, and to support the analytical result in Figure 6.9. The FERMI linac RF phasing is re-adjusted to cancel the linear chirp at BC2. Figure 6.10 and 6.11 show a portion of the bunch core at the entrance and at the exit, respectively, of BC2 characterized by $R_{56} = -30$ mm. At the end, the longitudinal phase space becomes folded,
the energy spread is uncorrelated, for any practical purposes, on the slice scale of microns and the charge clusters are largely suppressed. To make the dynamics more evident, an initial modulation amplitude of 1% is introduced at 30 µm wavelength, corresponding to an initial bunching factor of $7 \cdot 10^{-2}$. After BC2, the bunching factor calculated for 3 µm wavelength shrinks to approximately $3 \cdot 10^{-5}$. CSR introduces some energy deviation between particles of different bunch slices. Since this happens in a dispersive region, it may increase the particle transverse invariant. At the same time, the phase space rotation leads to particle longitudinal crossover between adjacent slices, finally affecting the horizontal slice emittance. Figure 6.12 shows the slice emittance at the exit of BC2 ($R_{56} = -30$ mm), after the linear energy chirp removal; the bunch head is for negative time coordinates. The short dashed line is for the horizontal emittance, the long dashed line is for the vertical emittance. The projected normalized horizontal emittance for 60% of the particles in the transverse phase space is 2 mm mrad.

Figure 6.9: Instability gain vs. compressed modulation wavelength for one-stage compression (dotted line) and enhanced phase mixing (solid line). The wavelength in the abscissa axis is computed as the modulation wavelength before the total compression.
Figure 6.10: Particle distributions of the bunch core at the entrance of BC2.

Figure 6.11: Particle distributions of the bunch core downstream of BC2.
6.5 Conclusions

Some guidelines for the design of the magnetic compression scheme have been given, according to the requirements expressed from the FEL performance goal. The principles depicted in this Chapter refer to the specific case of a seeded X-ray FEL and only magnetic compression of the bunch length has been considered. The effect of magnetic bunch length compression on the microbunching instability development in a linac-based FEL has been investigated. In particular, the reduction of the instability gain by particle longitudinal phase mixing has been demonstrated analytically. It has been shown that the efficiency in removing the beam microbunching is much more sensitive to the initial modulation wavelength than to the amplitude. The natural consequence of this dynamics is the adoption of a single compression scheme. The feasibility of this scheme has been demonstrated by means of a 3-D particle tracking for the FERMI@Elettra FEL, with promising results for the preservation of the beam quality. In addition to this, a different promising configuration shows up. If the linear energy chirp at the exit of BC1 could be removed by dedicated accelerating structures, then particle longitudinal crossover is enhanced in BC2. The effect is optimized by two chicanes, BC1 and BC2, with the same sign of $R_{56}$. As a result, the energy modulation is damped, together with the associated current.
spikes. The FERMI@Elettra case study has been analyzed in some details. The 1-D beam transport has been verified against the 3-D particle tracking performed with \texttt{elegant}, including collective effects, for a compression factor of 10 in BC1. The study shows that this alternative scheme of compression is successful and even more efficient than the single compression for initial modulations whose wavelength is of the order of tens of $\mu$m. It may even be applicable to longer wavelengths and/or higher compression factors, although these more extreme situations need to be confirmed by further investigations.