ALTERNATIVE SCHEME OF BUNCH LENGTH COMPRESSION IN LINACS FOR FREE ELECTRON LASERS

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Abstract

The aim of this paper is to investigate the effect of an alternative scheme of bunch compression on the development of the microbunching instability. Two cases have been considered, one in the presence of a linear energy chirp at the compressor end and another without it. It is shown that after removing the linear energy chirp, a properly tuned R_{56} transport matrix element is able to dilute the initial energy modulation without affecting the bunch length and to damp the associated current spikes. A by-product of this study indicates that the global compression scheme can be further optimized in the direction of a double compression scheme in which the longitudinal Landau damping is enhanced by increasing the compression factor of the first compressor while reducing that of the second one. The limiting case of such a configuration is the single compression scheme at low energy. The study is based on analytical calculations and on the simulation code LiTrack [1].

DE-COMPRESSOR

Figure 1 shows the FERMI@elettra beam delivery system in its standard layout that includes two magnetic chicanes (BC1 and BC2) with negative R_{56} terms for bunch length compression. A third magnetic insertion achromat, DC0, is virtually inserted immediately downstream of BC1.

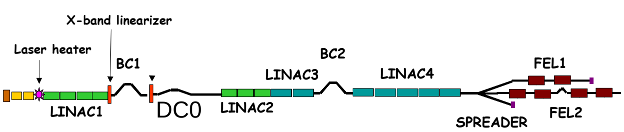

Figure 1: FERMI@elettra layout. The linac includes BC1 and BC2 in the nominal configuration of double magnetic compression. A third achromat called DC0 is sketched downstream of BC1.

Starting from an energy modulation induced, for example, by Longitudinal Space Charge (LSC), Coherent Synchrotron radiation (CSR) excites current spikes in BC1 that are further enhanced in BC2 and have a damaging impact on the FEL performance. This longitudinal beam dynamics is called microbunching instability. We want to explore the possibility of using a DC0 with positive R_{56} to dilute the beam density clusters without affecting the bunch length that is the average beam current after the compression. For the moment, we assume a negligible uncorrelated energy spread. Intuitively, two scenarios can be studied: in the first, the energy modulation amplitude is smaller than the correlated energy spread. Then, the derivative of the energy deviation as a function of distance along the bunch (δ vs. z) has the correct positive sign for bunch compression on both sides of the modulation. When a de-compressing R_{56} term is applied in DC0, particles lying on one side of the modulation are more de-compressed than the particles on the other side. This effect reduces the de-bunching efficiency of DC0. In the second case, the modulation amplitude is larger than the correlated energy spread. Then, the two sides of the energy modulation have derivatives of opposite signs; when adding DC0, some particles are de-bunched while others experience additional bunching. As a result, the current spikes persist with the same (or increased) amplitude.

LONGITUDINAL LANDAU DAMPING

Correlated Energy Spread

In principle the longitudinal Landau damping can contribute to the suppression of the microbunching instability if the uncorrelated energy spread out of BC1 is larger than the energy modulation amplitude [2]. Thus, DC0 may seem to play a role because its positive R_{56} necessitates a larger negative R_{56} in BC1 for the same total compression action, therefore increasing the energy spread by virtue of the higher compression. Unfortunately, the above statement becomes less and less valid the longer the wavelengths in question. The analytical one-dimensional model [3] of the microbunching instability has been applied to FERMI for two wavelengths of the density modulation.

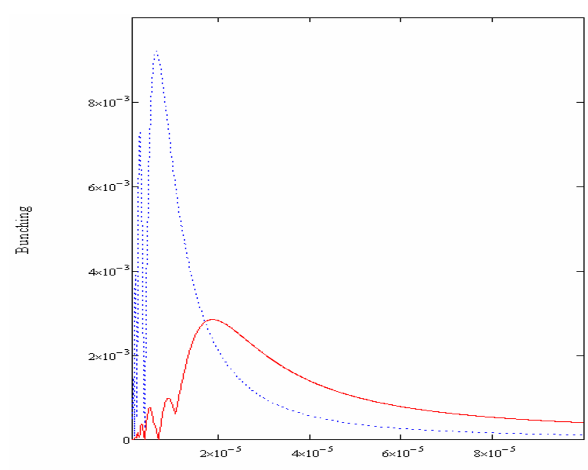

Figure 2: bunching coefficient out of DC0 vs. the compressed density modulation wavelength. The dashed (solid) line is for DC0 switched off (on).

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In the first case, shot noise density modulation induces by LSC energy modulation peaked at 5 µm at the entrance of BC1. Such short wavelengths are Landau damped when DC0 is switched on and the R_{56} in BC1 is made more negative in order to maintain the compression factor constant (see, Figure 2). However, longer wavelengths are expected to really affect the initial bunch distribution. Figure 3 shows that for an initial wavelength of 100 µm, the current modulation does not take advantage from the configuration BC1+DC0 because the Landau damping is no more effective. LiTrack results [4] confirm the analytical prediction for the same case by showing in Figure 4 no special damping of the instability (the current spikes still persist after DC0is switched on).

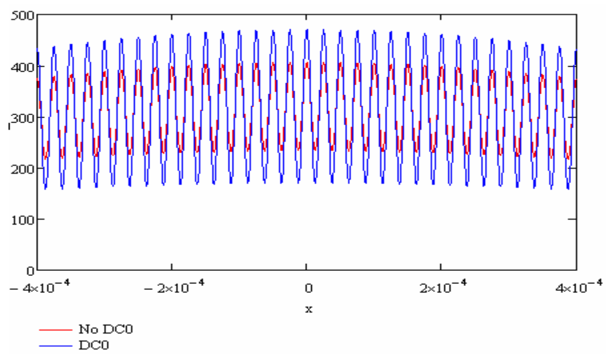


Figure 3: Analytical result for a sample of the current profile downstream of BC1 with (larger amplitude) and without (smaller amplitude) DC0. The longitudinal Landau damping is not effective at this relatively long wavelength.

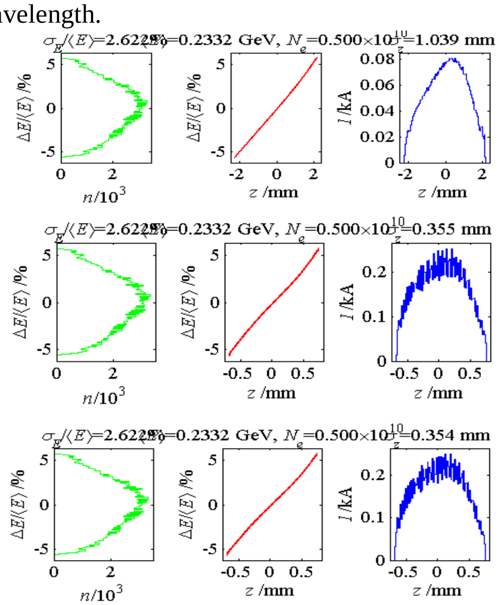


Figure 4: from top line to the bottom, energy distribution (left), longitudinal phase space (centre) and current profile (right) before DC0, after DC0 switched off and after DC0 switched on. The current modulation is still present in the latter case.

Removing the Energy Chirp

We now consider an additional accelerating module located in between BC1 and DC0; it is dedicated to the removal of the linear energy chirp coming out from BC1 by properly running off-crest. As a result, the residual energy chirp entering DC0 is only due to the energy modulation and this is the source of a different dynamics with respect to that discussed so far. In fact, the local energy chirp now changes sign over one modulation period but this time the derivative approximately assumes the same value on both the two fronts (see, Figure 5).

In this case, particles lying of the opposite fronts of the modulation will be (de)compressed by the same compression factor. If the particle longitudinal cross-over is sufficiently large, then the longitudinal phase space becomes folded and the initial energy modulation is washed out becoming uncorrelated energy spread. At the same time, the particle cross-over in the z coordinate damps the initial current spikes, so damping the microbunching instability. Figure 6 shows such behaviour of the longitudinal phase space with the lattice and beam parameters listed in Table 1.

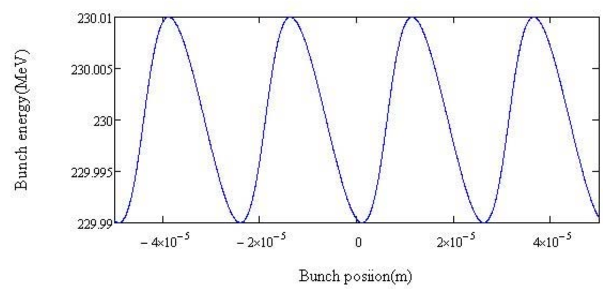
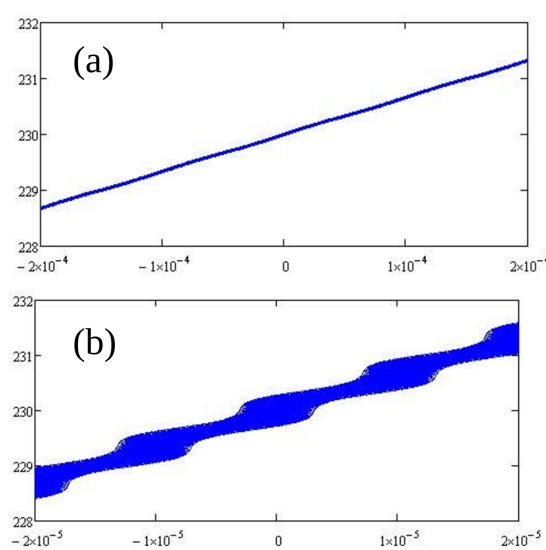


Figure 5: analytical model of the longitudinal phase space downstream of BC1, at the exit of the additional accelerating module. The linear energy chirp has been removed by the module running off-crest.



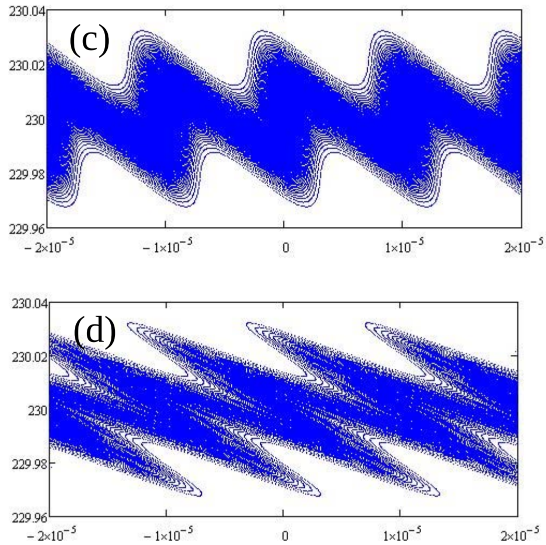


Figure 6: analytical model of the longitudinal phase space (particle energy in MeV vs. bunch length in m). (a) An energy modulation has been superimposed to the linear energy chirp entering BC1. A realistic uncorrelated energy spread is also present. (b) As a result of the bunch length compression in BC1, the longitudinal phase space apparently rotates. The uncorrelated energy spread grows up from plot (a) because of the longitudinal emittance preservation. (c) The additional accelerating module runs off-crest and it flattens the longitudinal phase space by removing the linear energy chirp. (d) A further compression in the second chicane allows the particles to longitudinally cross-over.

Table 1. Parameters of the dynamics shown in Figure 6.

Initial uncorr. energy spread	10	keV
R_{56} in BC1	– 31	mm
R_{56} in DC0	– 80	mm
Total compression factor	10	

SINGLE COMPRESSION SCHEME

One may think of further increasing the positive R_{56} in DC0 while reducing the negative R_{56} in BC1; in this way the total compression factor is kept constant and the Landau damping becomes more effective even for longer wavelengths. As a matter of fact, this scheme 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 by Landau damping becomes. As a limiting case, the single compression scheme optimizes the suppression of the instability for two reasons: firstly, Landau damping is more effective due to the larger R_{56} and a larger relative energy spread for the same absolute spread; the latter has an upper limit dictated by the FEL process. 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 a current modulation. This scheme has been studied for FERMI and the results are very encouraging [5].

In spite of the great advantages of suppressing the microbunching instability, the single compression produces a short bunch that is affected by strong longitudinal wake field along a longer path than in the two-stage option. Wake fields corrupt 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 was successfully studied to overcome this problem [6].

CONCLUSIONS

The hypothesis that a small positive R_{56} transfer matrix element could smooth the density modulation exiting BC1 while keeping largely unaltered the global particle distribution has been disproved by simulations and analytical calculations, with a very good agreement between the two, in the case of a linear energy chirp superimposed to the initial energy modulation. On the other hand, a slightly different configuration is able to achieve the goal. If the linear energy chirp coming out from BC1 is removed by a dedicated accelerating module, located upstream of DC0, then particle longitudinal cross-over is induced in DC0. It therefore washes out the energy modulation and damps the associated current spikes. Obviously, this longitudinal Landau damping is very dependent on the initial modulation amplitude and wavelength and on the strength of the R_{56} terms in BC1 and in DC0. A by-product of this study indicates that the global compression scheme can be further optimized in the direction of a double compression scheme in which the longitudinal Landau damping is enhanced by increasing the compression factor of BC1 while reducing that of BC2 for a fixed total compression. The limiting case of such configuration is the single compression scheme at low energy. This option has, in fact, been recently studied with promising results for the preservation of the beam quality.

ACKNOWLEDGEMENT

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