# COMPARATIVE STUDY OF THE FERMI@ELETTRA LINAC WITH ONE AND TWO-STAGE ELECTRON BUNCH COMPRESSION

S. Di Mitri<sup>#</sup>, M. Cornacchia, P. Craievich, G. Penco, S. Spampinati, Sincrotrone Trieste (ELETTRA), Trieste, Italy M. Venturini, A.A. Zholents, LBNL, Berkeley, CA 94704, U.S.A.

### Abstract

Two machine configurations of the electron beam dynamics in the FERMI@elettra linac have been investigated, namely the one-stage and the two-stage electron bunch compression. One of the merits of the onestage compression is that of minimizing the impact of the microbunching instability on the slice energy spread and peak current fluctuations at the end of the linac. Special attention is given to the manipulation of the longitudinal phase space, which is strongly influenced by the linac structural wake fields. The electron bunch with a ramping peak current is used in order to obtain, at the end of the linac, an electron bunch characterized by a flat peak current profile and a flat energy distribution. Effects of various jitters on electron bunch energy, arrival time and peak current are compared and relevant tolerances obtained.

# **INTRODUCTION**

FERMI@elettra is an S-band linac-based Free Electron Laser (FEL) implementing High Gain Harmonic Generation (HGHG) in the 100–4 nm output wavelength range. The commissioning of the photo-injector has already started and the user facility will provide the first light at the beginning of 2011. The reader is referred to [1] for the relevant beam and machine parameters. The machine layout is shown in Figure 1.



Figure 1. Split schematic of FERMI@elettra: accelerating structures (Gun, L0–L4), compressors (BC1, BC2), high energy transfer line, FEL lines and dumps (DBD, MBD).

FERMI was initially designed with two compression options in mind allowing for the desired total compression factor C=10 to be realized either at once through one magnetic chicane (BC1) or over two magnetic chicanes (BC1 and BC2), each one compressing by a factor C = 3.5 and 2.5 respectively. A systematic comparison of the linac performance in the two cases has

#simone.dimitri@elettra.trieste.it

never been presented before. The article is organised as follows. Section II recalls the relations between the compression scheme and the Microbunching Instability ( $\mu$ BI) [2,3]. Section III considers the effects of geometric wake fields on the beam dynamics. Section IV is focused on the emittance growth by chromatic aberration. Section V compares the jitter studies and in particular the RF tolerance budget for the two options. Section VI shows the results from 6-D particle tracking. A summary of the linac performance in the two cases is given in Section VII.

# MICROBUNCHING INSTABILITY

### Coherent Synchrotron Radiation (CSR)

CSR induces projected emittance growth via energy loss in the compressor dispersive region. Due to the moderate compression, the FERMI electron beam is always longer than the slippage length [5]; so, the corresponding energy loss per chicane in the stationary regime of emission (the retarded angle is  $\gamma\theta$ >>1) is never bigger than 0.1%, that is negligible w.r.t. that induced by the linac wakefields. This energy loss also induces a recoverable trajectory distortion  $\leq 300\mu$ m at the chicane exit. In the long bunch regime, the emittance growth per dipole magnet does not depend much on the line-charge distribution and it behaves as follows:

$$\frac{\Delta \varepsilon_x}{\varepsilon_x} \cong \frac{1}{2} \frac{\beta_x}{\varepsilon_{x,N}} \gamma \theta^2 \sigma_{\delta,CSR}^2 \sim \frac{\beta_x}{\gamma \varepsilon_{x,N}} \frac{\theta^2}{\sigma_z^2} \quad (1)$$

(an additional factor  $\theta^{4/3} \sigma_z^{-2/3}$  would be added for a short Gaussian bunch).  $\beta_x$  and  $\epsilon_{x,N}$  are the betatron function and the normalized emittance in the bending plane, respectively;  $\theta$  is the bending angle and  $\sigma_z$  the bunch length. Owing to the  $\sigma_z^{-2}$  dependence in (1), the emittance growth is estimated as the bunch is fully compressed in the  $3^{rd}$  dipole magnet of the BC1 one-stage and of the BC2 two-stage, giving 15% and 8%, respectively.  $\beta_x$  is already 4 times higher in BC2 than in BC1 but a flexibility is present to shrink it up to a factor 2 in both chicanes.

# Longitudinal Space Charge (LSC)

Owing to the combined action of LSC, CSR and dispersive motion in the compressors, FERMI acts like a huge amplifier of small density and energy modulations [3]. Since the 1-D LSC impedance per unit length in free space does not depend explicitly on the bunch length [6], it is not a relevant parameter to compare the two compression schemes, where the same charge but

different bunch lengths in different linac portions are adopted. Nevertheless, the µBI gain is excited by the energy modulation  $\frac{\Delta \gamma}{\gamma} = \frac{I}{\gamma_0 I_A} \frac{|Z(k)|}{Z_0}$  induced by LSC along

the linac and it depends on the compression parameters:

$$G(k) = Ck | R_{56} | \frac{\Delta \gamma}{\gamma} \exp \left| -\frac{1}{2} \left( Ck | R_{56} | \frac{\sigma_{\gamma}}{\gamma} \right)^2 \right|$$
(2)

The following notations are used: Z(k) is the LSC impedance for the *k* wavelength number,  $Z_0$  is the vacuum impedance,  $I_A$  the Alfven current for electrons, I is the beam current and  $\gamma$  is the Lorenz factor.

Eq.(2) shows that the one-stage compression is more efficient in suppressing the  $\mu$ BI for three reasons: i) BC1 one-stage foresees a stronger *C* and R<sub>56</sub> than in BC1 two-stage (10 and -51mm, respectively, instead of 3.5 and -27mm). Modulations with short wavelengths are exponentially suppressed and the wavelength range in which such exponential suppression is effective increases with *C*R<sub>56</sub>. At the same time, the stronger R<sub>56</sub> that is a larger bending angle in the magnetic chicane does not provide any relevant counterpart from CSR enhancement; ii) the relative energy spread in BC1 is twice that in BC2 (2% instead of 1%), so providing a more efficient Landau damping; iii) the absence of BC2 prevents the energy modulation cumulated upstream of it to transform into density modulation.

These considerations are consistent with the studies presented in [3], where the instability gain function for a single bunch compressor lattice was shown to be significantly lower than in the case of the two bunchcompressor lattices. A metric to compare the performance between the two lattices is the evaluation of the increase in beam slice energy spread caused by the microbunching instability and seeded by shot noise. This is shown in Fig. 2, 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 (LH) for the two lattices. These results where obtained using the same 2-D Vlasov solver as in [3] except for a modified and presumably more accurate [4], model of the LSC impedance that includes averaging of the longitudinal electric field over the tranverse beam density. The error bars indicate the spread in the outcome corresponding to different seeds used for the generation of shot noise.



Figure 2. Final vs. initial uncorrelated energy spread for one-stage compression with  $R_{56}$ =-51mm and for two-stage compression with  $R_{56}$ =-35mm both in BC1 and in BC2. In both cases the total compression is c=10.4 and the peak current 800A.

# **GEOMETRIC WAKEFIELDS**

### Longitudinal Wakefield

The short-range wake function for the FERMI linac was calculated over a meaningful range of FERMI parameters and fitted to [7]:

$$w(s) = A \frac{Z_0 c}{\pi a^2} \exp\left(-\sqrt{s/s_0}\right)$$
(3)

where A and  $s_0$  are geometric constant, c is the speed of light and a is the iris radius of the accelerating structure.

According to (3), in the one-stage compression a shorter bunch is affected by longitudinal wakefield along a longer path than in the two-stage option. The wakefield 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 was successfully studied to minimize the nonlinear energy chirp [8]. Then, the correlated energy spread is minimized at the linac end with a proper setting of the linac RF phases (off-crest acceleration) and also taking advantage of the wakefield energy loss; the final energy chirp is minimized to the 0.1% rms level. The total energy loss by longitudinal wakefield in the one-stage compression is not a big issue. being approximately 15MeV that is ~1% of the linac energy budget.

#### Transverse Wakefield

The short-range wake function for the FERMI linac was calculated over a meaningful range of FERMI parameters and fitted to [9]:

$$w(s) = \frac{4Z_0 c}{\pi a^4} s_1 \left[ 1 - \left( 1 + \sqrt{\frac{s}{s_1}} \right) \right] \exp\left( -\sqrt{s/s_1} \right)$$
(4)

where  $s_1$  is a geometric constant. w(s) increases monotonically for  $s \le 1.5$  mm.

The transverse wake field induces projected emittance growth by lateral head-tail deviation [10]; this is minimized by the one-stage compression that sees a shorter bunch travelling over a longer path than in the two-stage option. In spite of this, some emittance bumps must be implemented in L3 and L4 (they have stronger wakefields than L1 and L2); they allow the emittance compensation at the linac end, in both planes, so that the final beam size distortion is less than one unperturbed standard deviation ( $\Delta \epsilon / \epsilon \le 50\%$ ) [11].

### **CHROMATIC ABERRATION**

The transverse emittance might be diluted by full chromatic filamentation (pessimistic scenario):

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{1}{2} \beta (k_1 l)^2 \sigma_\delta^2 \tag{5}$$

where  $k_l l$  is the normalised integrated quadrupole gradient and  $\sigma_{\delta}$  is the rms energy spread. In both compression schemes, the energy spread is limited by the dipole magnet field quality to 2% at BC1 and it diminishes to 1% at the BC2 location. The quadrupole gradients were sized for a smooth optics and to avoid any emittance growth by filamentation. The analytical estimate over all quadrupoles summed squared gives  $\Delta \epsilon / \epsilon \cong 5\%$ , while no effect is shown by the particle tracking.

# JITTER STUDY

### RF Tolerance Budget

The specifications for the RF phase and peak voltage stability were evaluated and compared for the two compression options at a time in which the final beam energy was allowed to be in the range 1.0–1.2GeV. At that time, the one-stage compression was implemented also increasing the energy spread by running L1 more off-crest than in the two-stage. So, the jitter study specified the L1 phase stability to 0.05 S-band deg instead of 0.1 S-band deg in the two-stage case. The complete RF tolerance budget for those configurations is here listed in Table 1.

Basing on some technical considerations and on some recent measurements at the Elettra laboratory, the tighter admissible FERMI linac RF stability is now set *a priori* to  $0.1^{\circ}$  rms S-Band phase jitter and to 0.1% rms peak voltage jitter, over at least 1h. Owing to the relation between the phase jitter  $\Delta \phi$  ( $\leq 0.1^{\circ}$  S-band) and the energy jitter  $\Delta E/E$  ( $\leq 0.1\%$ ):

$$\frac{\Delta E}{E_0} = \Delta \phi \cos \phi_0 \tag{6}$$

- where  $\phi_0 = \pi/2$  is for on-crest acceleration – a new constraint on the maximum L1 off-crest phasing was fixed to 25<sup>°</sup> (instead of the previous 48<sup>°</sup> and 36<sup>°</sup> for the one and the two-stage compression, respectively). This prescription goes in the same direction of a final beam energy  $\geq 1.2$ GeV and of an energy spread  $\leq 2\%$  at BC1 (see Section IV). Apart from L1, all other current tolerances for the linac setting are as in Table 1.

Table 1. RF tolerance budget for the two-stage and the one-stage compression, *before* the L1 phase optimization.

| Parameter            | Two-stage | One-stage |
|----------------------|-----------|-----------|
| L1 phase [deg]       | 0.10      | 0.05      |
| X-band phase [deg]   | 0.30      | 0.35      |
| L2 phase             | 0.10      | 0.20      |
| L3 phase             | 0.10      | 0.15      |
| L4 phase             | 0.10      | 0.10      |
| L1 voltage [%]       | 0.10      | 0.10      |
| X-band voltage [%]   | 0.50      | 0.30      |
| L2 voltage [%]       | 0.10      | 0.15      |
| L3 voltage [%]       | 0.10      | 0.08      |
| L4 voltage [%]       | 0.05      | 0.05      |
| Gun timing [fs]      | 250       | 350       |
| Charge [%]           | 3.0       | 5.0       |
| BC1 dipole field [%] | 0.02      | 0.01      |
| BC2 dipole field [%] | 0.02      | -         |

### Compression factor

An intrinsic advantage of the two-stage compression is that of self-stabilize the shot-to-shot variation of the total *C*. Let us assume an RF and/or a timing jitter makes the beam more (less) compressed in BC1; a shorter bunch then generates stronger (weaker) 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  $\mathcal{C}$ . In the one-stage compression, where *C* >>1 and  $\phi_0 <<1$ , the  $\mathcal{C}$  sensitivity to phase jitter is [12]:

$$\frac{\Delta C}{C_0} = -C_0 \frac{\Delta \phi}{\phi_0} \tag{7}$$

giving an expected C shot-to-shot jitter of 4%. This result is still compatible with the FEL requirement of a final peak current jitter  $\Delta I/I \le 10\%$ . Notice that such dynamics was already included in the global jitter study performed for the one-stage compression and that led to the tolerance budget listed in Table 1.

### START-TO-END SIMULATIONS

A start-to-end simulation with  $10^6$  particles has been carried out with *elegant* code [13]. All collective effects previously described in this paper have been included. A uniform beam heating at low energy has also been included in the simulation, so that the uncorrelated energy spread before compression is approximately 10 keV rms. The final particle longitudinal distribution is shown in Figure 3-top and bottom line for the two- and one-stage compression, respectively. No difference in the slice emittance is observed in the two cases.

During explorative studies, it has been observed that, unlike the one-stage compression, the two-stage allows one to obtain a flat longitudinal phase space ( $\sigma_{\delta} < 0.1\%$ ) and current profile ( $\Delta I/I_{core} < 10\%$ ) even for *C* 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 wakefields in the low-gap undulator vacuum chamber.



Figure 3. Two- and one-stage compression with C=10, top and bottom line, respectively. Relative energy spread vs. bunch duration (left) and current profile (right) at the entrance of the undulator.

# SUMMARY OF PERFORMANCE

The key parameters making a difference between the two- and the one-stage of compression are: i) the µbi gain, practically suppressed in the one-stage; ii) the flatness in the energy and current profile, not really manageable within the 0.1% and 10% level, respectively, in the one-stage for C > 10, while a greater flexibility in the beam shaping is provided by the two-stage scheme.

As for other aspects of beam dynamics, a CSR induced emittance growth in the 8–15% range is expected; it can be further reduced by a factor 2 with proper optics matching. The 1% energy loss induced by the structural longitudinal wakefields in the one-stage scheme is in the linac energy budget, while trajectory bumps must be adopted in both schemes to compensate the transverse wakefield effect. The peak current jitter is 4% in the onestage vs. a self-compensation in the two-stage, but still in the 10% FEL specification.

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