THE DIAGNOSTICS OF THE FERMI@ELETTRA BUNCH COMPRESSORS

M. Veronese*, S. Di Mitri, M. Ferianis, Sincrotrone Trieste, Trieste, Italy

Abstract

Bunch compressors (BC) are key components of the seeded FEL FERMI@ELETTRA. A complete set up of non destructive diagnostics is foreseen to provide the required stability for the production of sub-psec electron bunches. Main task of these diagnostics is to provide the error signals to the feedback systems used to stabilize the energy and the peak current of the electron bunch which are crucial parameters for optimum FEL operation. The different operation regimes foreseen for FERMI [1] call for a flexible set-up, for both the bunch compressors and the associated diagnostics. In this paper we present the adopted diagnostics for the measurement of position, energy and energy spread; both “energy” BPM, in between bunch compressors (BC), and optical transition radiation (OTR) screen plus wire scanner have been adopted. The design of a relative bunch length monitor needed for the determination of the optimal compression and for peak current stabilization is presented as well. The scheme is based on non-invasive techniques, namely the detection of the coherent synchrotron radiation (CSR) from the last bending of the BC plus the coherent diffraction radiation (CDR) from a downstream slit. Finally, a technique for the bunch phase measurement is presented.

INTRODUCTION

The FERMI FEL, presently under construction at the Elettra Laboratory, is based on a seeded HGHG scheme. Two FEL undulator chains FEL1 and FEL2 are foreseen according to the needs of the FERMI scientific community, to lase in two adiacent UV spectral regions (100-40nm and 40-10nm) with different pulse lengths. The FERMI layout has been described in detail in [1], its main parameters are presented in Table 1. High charge (~nC) electron bunches are produced in a RF photo-injector, with bunch length (L_B) of about 10psec$_{FWHM}$. The acceleration is provided by normal conducting S-band RF structures and the bunch compression is achieved by two magnetic chicanes. Up to now, two main bunch regimes have been studied: the “medium bunch” (L_B=600fs$_{FWHM}$) optimized for the FEL1 operation and the “long bunch” (L_B=1.4ps$_{FWHM}$) which is best suited for FEL2. High quality beams (low emittance, low energy spread, high current stability and high energy stability) are needed to obtain high quality FEL output radiation. Non-standard diagnostics and instrumentation suitable to fully characterize and monitor the beam during the machine operation have to be developed according to the specific beam parameters and machine requirements.

*E-mail: marco.veronese@elettra.trieste.it

Table 1: Fermi@Elettra parameters

Parameter	FEL 1 (medium bunch)	FEL 2 (long bunch)
Wavelength	100-40 nm	40-10 nm
Electron Beam Energy	1.2 GeV	1.2 GeV
Bunch Charge	0.8 nC	1 nC
Peak Current	800 A	500 A
Bunch Length (FWHM)	600 fs	1400 fs
Energy Spread (slice)	100 KeV	100 KeV
Norm. emittance (slice)	1.5 mm mrad	1.5 mm mrad
Repetition Rate	10-50 Hz	50 Hz
Photon Pulse Length (FWHM)	≤ 100fs	~ 1000 fs

BUNCH COMPRESSORS

Bunch compressors are used to produce high peak current electron bunches needed to obtain GW peak power FEL radiation generation. Several aspects have to be considered to avoid beam quality degradation (e.g. CSR induced emittance dilution). In particular, the stabilisation of the peak current and the energy in the chicane are needed to guarantee the long term stability of the FEL output [2]. The bunch compression is obtained with two magnetic chicanes located at the nominal energies of 220 MeV (BC1) and 600 MeV (BC2) respectively. This design allows for both single and double compression schemes, with a total compression factor ranging from 2 up to about 100 [3].

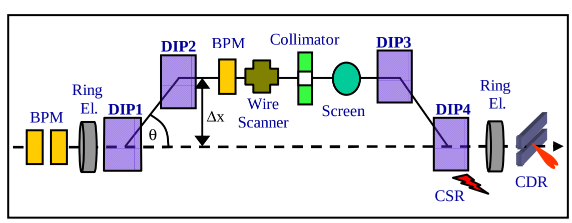

Figure 1: Bunch Compressor Diagnostics layout.

The conceptual scheme is the same for BC1 and BC2, but some components are adapted according to the different bunch parameters. In Fig. 1 the bunch compressor scheme is sketched together with the foreseen diagnostics. The main parameters of BCs for a double compression scheme are summarized in Table 2.

Table 2: Fermi bunch compressors parameters.

Parameter	**BC1**	**BC2**
Number of magnets	4	4
Magnetic length	0.5 m	0.5 m
Distance DIP1-DIP2	2.5 m	2.5 m
Distance DIP2-DIP3	1 m	1 m
Distance DIP3-DIP4	2.5 m	2.5 m
Nominal DIP angular range	66.8 :77.2 mrad	53.1:77.5 mrad
Commis. DIP angular range	50 : 80 mrad	50 : 80 mrad
Linac phases ranges	L1=-42° : -20°	L1=-42° : -20° L2,3=-20° : -10°

From Table 2 it can be seen that even if the bending angles are quite small they span over a wide relative range [3]. This fact, together with the dispersion and the energy spread, has a deep impact on the electron beam parameters in the chicanes (see Table 3) and on their measurement.

Table 3: Main beam parameters at BC1 and BC2.

Parameter	**BC1**	**BC2**
Energy Range	220 : 260 MeV	580 : 615 MeV
Rel. En. Spread	2.3 : 2.7 %	0.97 : 1.05 %
Beta (β_x)	16 m (z=31 m)	23 m (z=98 m)
Dispersion (D_x)	0.165 : 0.255 m	0.155 : 0.24 m
Transverse displacement (Δx)	0.165 : 0.255 m	0.155 : 0.24 m
Energy Spread Beam size ±3σ	28 : 44 mm	10 : 15 mm
Betatron Beam size ±3σ	1.4 mm	2.0 mm

In particular, in the area between DIP2 and DIP3, where all diagnostics will be located, the beam size is expected to be dominated by the dispersion.

DIAGNOSTICS

We will now discuss the diagnostics according to the measured parameter: energy, energy spread, bunch arrival time, relative bunch length.

Energy Measurement

The transverse displacement of the beam centroid (Δx of Fig.1) spans, for the BC1 and BC2 ranges, over approximately 100mm. If we consider building the BCs with a wide vacuum chamber, then for that chamber a width of at least 150mm is needed to allocate the wide electron beam (±3σ beam size of 35mm) and its displacements. Taking in account a beam transversely centred at Δx=200 mm, the rms energy stability required by the FEL (ΔE/E=0.1%) will translate in terms of rm displacement variations to 200 µm (at nominal BC1 operating conditions). To correctly operate the feedback system, the resolution of the position measurement has to be at least four times better than the value we want to stabilize within, which means that a single shot resolution of 50 µm is needed. This is a very tough value to be met on a 150mm chamber width and with a beam size of 35mm. Therefore, we plan to put the second and the third dipoles of the chicanes and all the related diagnostics on a transverse high precision translator stage. This will allow us to reduce the vacuum chamber transverse size to about 60 mm and thus to use an “energy BPM”. Another possible approach to the problem has been proposed at DESY; it is based on the measurement of the relative time difference between two pulses generated in a transverse strip-line arrangement [4]. Its applicability to Fermi will be evaluated in the near future.

Energy Spread Measurement

The energy spread is a crucial parameter for the machine operation and it has to be carefully monitored. It will be measured by means of a wire-scanner on multi shot basis and by an OTR screen plus a CCD camera, shot by shot. Both techniques are destructive and the measurements will be performed during the commissioning and, periodically, during the operation to check the long term stability of the energy spread. As depicted in Fig. 1, in between the wire-scanner and the OTR screen, we plan to install a collimator. With this geometry the energy spread of the beam can be measured upstream and downstream of the collimator and its effect can be followed step by step. The energy spread can be directly extracted from the measurement of the transverse size of the beam since the dispersion in the middle of the chicane is known and dominates the beam size. The needed resolution is different for the two bunch compressors. For BC1 the minimum δE/E is 2.3% which will reflect in a 28 mm beam size (±3σ beam). The needed relative resolution is estimated to be 2%, which means 0.56 mm, in terms of spatial resolution. For BC2 the energy spread will be smaller and it will have a small operation range. Then for a 0.95% δE/E will reflect in a ±3σ beam size of 10 mm and to appreciate the changes in energy spread we will need to have a 1% relative resolution which means 100 microns spatial resolution. This resolution level can be achieved with an OTR screen plus a CCD detector, higher resolutions will be achieved by the wire-scanners [5].

Bunch Arrival Time Measurement

The bunch arrival time measurement will be provided by a new kind of diagnostics. The concept has been proposed at DESY [6] and will make use of the optical pulses from the ultra stable timing distribution system [7] to measure the bunch arrival time relative to the optical clock pulse. This technique is non-destructive and it has shown so far a resolution better than 100fs. Two devices, one at the entrance and one at the exit of each chicane, will be installed. The signal from the device at the entrance of BC1 will provide a direct measure of the total initial jitter from the injector.

$$\Sigma_f^2 = \left(\frac{r_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\phi}{c_0 k_{RF}}\right)^2 + \left(\frac{1}{C}\right)^2 \Sigma_i^2 \quad (1)$$

As can be seen from Eq. 1 the coupled measurement of the jitter at the entrance and at the exit of the chicane initial will give us the RF contribution of the timing jitter.

Relative Bunch Length Measurement

The needs for peak current stabilisation push to develop a non-destructive relative bunch length monitor, so that its signal can be fed to the feedbacks systems that will keep the peak current stability acting on the phases of the RF accelerating sections. For this purpose we will develop power monitors based on the detection of coherent synchrotron radiation (CSR) [8] and coherent diffraction radiation (CDR) [9]. We plan to implement a redundant system based on the detection of the CSR emitted from the last dipole of the chicanes and on the detection of the CDR emitted from a slit placed downstream the chicane.

Coherent radiation is emitted from short electron bunches, in the case of a Gaussian bunch where σ_z is the sigma of the distribution, it is emitted at wavelengths longer than roughly $2\pi\sigma_z$. For electron bunches with psec and sub-psec duration the coherent emission is in the mm/sub-mm wavelength spectral range. An overview of the related physics can be found in [10]. The CSR spectral angular distribution of a N-electrons bunch can be related to the spectral angular distribution of a single electron as shown in Eq. 2.

$$\left.\frac{d^2I}{d\nu d\Omega}\right|_{N-el.} = \left[N + N(N-1)\left|F(\rho(t))\right|^2\right]\left.\frac{d^2I}{d\nu d\Omega}\right|_{1-el.} \quad (2)$$

Where $F(\rho(z))$ is the Fourier transform of the longitudinal normalized bunch distribution $\rho(t)$. From Eq. 2 we can see that the total N-electron CSR angular distribution is the sum of the incoherent synchrotron radiation of N electrons ($\propto$ N) and a coherently enhanced term ($\propto N^2$). The frequency behaviour of the coherently enhanced term depends on the square of the Fourier Transform of $\rho(t)$. As the bunch gets shorter the $F(\rho)$ get spectrally broader and the emitted power increases. To evaluate the emission properties (spectral distribution and intensity) we have computed the CSR spectra angular distribution in two steps. In the first we have calculated $F(\rho)$, by means of the FFT of the bunch profile coming from Elegant simulations (shown in Fig. 2). In the second, to calculate the single electron spectral-angular distribution, since the circular motion approximation is not sufficient in our case, we have used a numerical code written by O.Grimm at DESY.

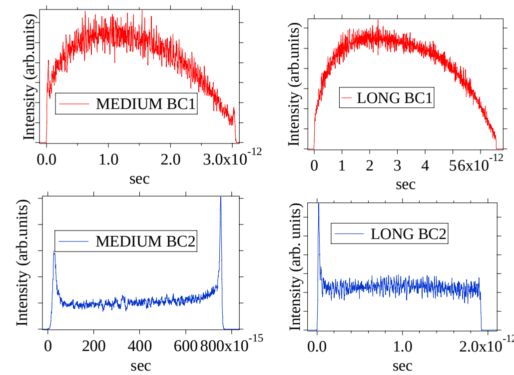

Figure 2: Longitudinal electron distributions at BC1 exit (red) and BC2 exit (blue) for the “medium bunch” (left) and the “long bunch” (right).

The code implements a full Liénardt-Wiechert potential formalism, and makes a tracking of a single electron through an arbitrary magnetic field. In the calculation both velocity and acceleration terms are included as well as the finite dimensions of the dipoles, the contributions of both 3rd and 4th bending magnets and the shielding effects of the vacuum chamber walls (in a parallel perfectly conducting planes approximation). Some results of these simulations are shown in Fig.3 for the CSR emission from the last bending magnet of BC1 for the “medium bunch” and in Fig.4 for the “long bunch” case. Plotted are the angle integrated spectral intensity distributions, for a detector (30x30 mm) placed 150 mm downstream the last bending of BC1 and normal to the edge radiation direction centred 25 mm away from the straight beam path.

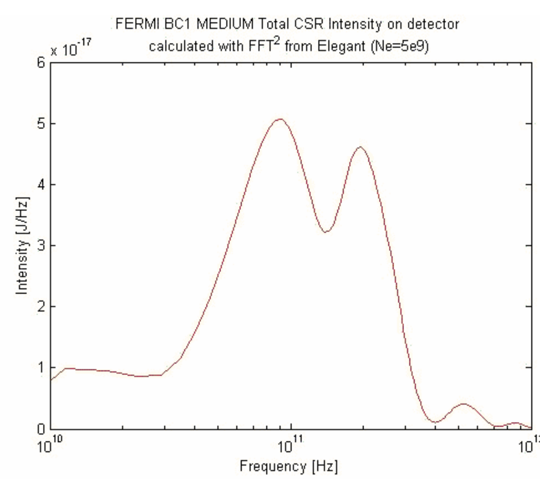

Figure 3: Expected spectral distribution of the radiation extracted from the 4th dipole of BC1 for the “medium bunch.

These results suggest that, for the CSR emitted from the bunch compressors of FERMI the Gaussian bunch plus circular motion approximations [8] might not be sufficient. They also indicated that the choice of the frequency range for the detectors has to be done with special care for narrowband detectors. Moreover considering both BC1 and BC2 the core of CSR emission is in a critical spectral region (between 10GHz and 1THz) for the detectors.

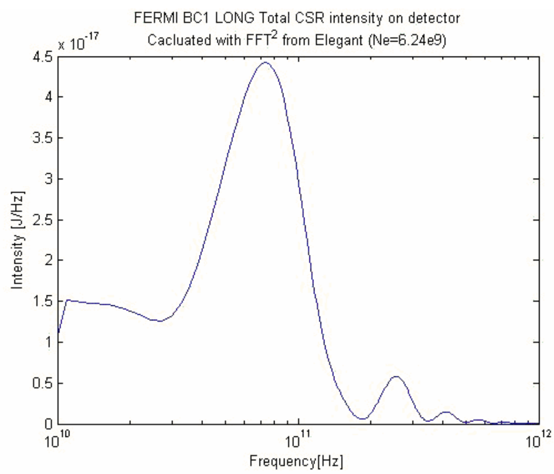

Figure 4: Expected spectral distribution of the radiation extracted from the 4th dipole of BC1 for the "long bunch".

In this region the detection of CSR can be done by RF diodes or pyrodetectors. The diodes have higher sensitivity in the sub-THz range, but are limited at about 600GHz while pyrodetectors offer a wider operation range starting from about 150GHz. We plan to use the pyrodetectors for their flexibility and ease of use, but RF diodes may be employed especially for the case of "long" bunch in BC1. The total energy per pulse emitted in the spectral range from 10 GHz to 1THz is of about 10μJ for the "medium bunch" and of about 4μJ for the "long bunch". In the spectral range of the pyrodetector (e.g. Coherent/Molectron P4-42) the energy per pulse is respectively of 1.5μJ and 0.3μJ. In this case a simple estimate gives us a sensitivity of 0.04% sufficient to fulfil the 2% of the feedback requirements (to obtain 10% current stability). Other factors should also be considered: the efficiency of the radiation collection, the absorption and reflection from air and from the vacuum window.

A second coherent radiation source, a CDR source (e.g. an OTR screen with a small aperture) will be installed immediately downstream the bunch compressors. It is meant to add redundancy to the CSR system. We have performed some calculations to evaluate its application to FERMI diagnostics. Our calculation started from the CDR description given in [11] for a relativistic electron beam. Here γ is the Lorentz factor of the electrons passing through a hole of radius "b" in a circular screen of radius "a". It is worth saying that the infinite screen approximation is satisfied if $a > \lambda\gamma$. For FERMI BC1 "medium" bunch we can consider: λ=3 mm and γ=430 then the condition becomes a > 1.3 m. This shows that a large screen and a large detector angular acceptance are desirable to avoid low frequency intensity suppression. On the other hand a compromise has to be found to meet space requirements. This led us to choose a screen radius "a" of 60 mm and an angular acceptance of 0.2 rad. The effect of the hole radius has to be considered, for CDR emission, the smaller the hole radius is, the better. On the other side the higher is the radius, the smaller is the impact of the CDR emitter on the beam dynamics. CDR Spectral distributions calculated with a rectangular distribution approximation of the longitudinal bunch profile are shown in Fig. 5 for two extreme cases: BC1 "long bunch" and of BC2 medium bunch for different values of the hole radius.

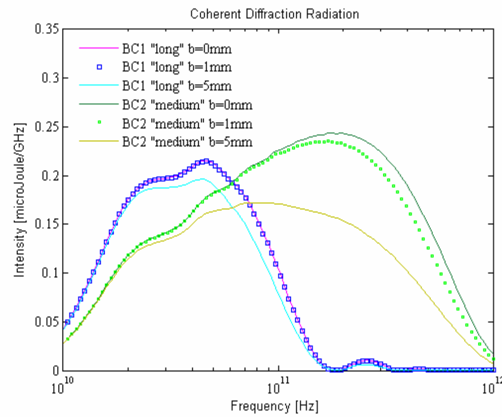

Figure 5: CDR spectral distributions for "medium bunch" at the exit of BC2 and the "long bunch" at the exit of BC1 for values of b=0, 1, 5 mm.

The calculation indicates that, for the "long" bunch at BC1 a quite large hole can be used without loosing too much in intensity, while the hole size effect is more important in the case of the "medium" bunch in BC2.

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REFERENCES

[1] M. Cornacchia, *et al.* EPAC 06, 145, (2006).
[2] J. Wu, *et al.* PAC 05, 1156, (2005).
[3] S. Di Mitri, ELETTRA, ST/F-TN-06/09, (2006).
[4] K. Hacker, *et al.* EPAC 06, 1043, (2006).
[5] K. Wittenburg, Tesla Report 2000-18 (2000).
[6] F. Loehl, *et al.* EPAC 06, 2781, (2006).
[7] M. Ferianis, *et al.* FEL 05, 134, (2005).
[8] J. Wu, *et al.* PAC 05, 428, (2005).
[9] E.Chiadroni, *et al.* EPAC 06, 1127, (2006).
[10] O. Grimm, EPAC 06, 1040, (2006).
[11] S. Casalbuoni, *et al.* TESLA Report 2005-15 (2005).