LONGITUDINAL ELECTRON BEAM DIAGNOSTICS FOR THE FERMI@ELETTRA FEL

M. Veronese, A. Abrami, E. Allaria, L. Badano, P. Craievich, S. Di Mitri, M. Ferianis, L. Fröhlich, S. Grulja, G. Penco, M. Predonzani, F. Rossi, C. Svetina, C. Spezzani, M. Tudor, M. Trovo, Sincrotrone Trieste S.C.p.A., Trieste, Italy
R. Appio, Lund University, Lund, Sweden
A. O. Borga, NIKHEF, Amsterdam, The Netherlands
F. Cianciosi, ESRF, Grenoble, France
L. Pavlovic, University of Ljubljana, Ljubljana, Slovenija
M. Petronio, DI3, University of Trieste,Trieste, Italy

Abstract

Frontier fast dynamics science is founded on accelerator based photon pulsed source operating now from THz to hard x-rays. The longitudinal electron bunch properties play a crucial role to assure the needed high performances and reliability at most advanced accelerator based facilities. Therefore most FELs are equipped with this a new class of demanding longitudinal diagnostics. FERMI@Elettra, the most recent running seeded FEL designed to cover the VUV/Soft x-ray range, is a brilliant example. Tight design tolerances together with the seeded scheme called for state of the art longitudinal diagnostics. We present the FERMI@Elettra longitudinal electron beam diagnostics that have been designed, installed and successfully commissioned at the FERMI@Elettra accelerator. In particular we describe: the low energy longitudinal profile system using Cherenkov radiation, the coherent radiation bunch length monitors (CBLM), the bunch arrival monitors (BAM), the low energy (LERFD) and high energy (HERFD) RF deflectors, the electro optical sampling stations (EOS) and the bunching strength monitor system based on coherent UV transition radiation. We introduce the design of these diagnostics and present the latest results obtained.

INTRODUCTION

FERMI@Elettra has been equipped with several longitudinal diagnostics to provide the necessary information for the commissioning and operation of the accelerator. The focus on diagnostics has been given to understanding the longitudinal parameters of the electron bunch in the gun area, downstream the two bunch compressors and at full energy and finally before entering the FEL undulator chains. Table 1 gives a global view of the installed diagnostics, the accelerator section were they are installed and the information they provide. Conceptually these instruments can be divided in four groups: Cherenkov, laser based (EOS and BAM), coherent radiations based (CBLM and seed bunching system) and deflecting cavities (LERFD and HERFDs). All of the systems have strongly benefit from discussions, suggestions and collaborations with other laboratories, such as DESY, LBLN, INFN-LNF, SLAC, STFC-ALICE.

Table 1: Longitudinal Diagnostics of FERMI@Elettra

Diagnostics	Area	Measurement
Cherenkov	Injector	Long. Phase Space
CBLM	BC1, BC2	Bunch Length
BAM	BC1, BC2 FEL1, FEL2	Arrival Time
LERFD	BC1	Long. Profile Slice emittance Slice en. spread
HERFD	LINAC END	Long. Profile Slice emittance Slice en. spread
EOS	FEL1, FEL2	Long. Profile Arrival Time

LOW ENERGY LONGITUDINAL PHASE SPACE

The first longitudinal diagnostic installed in FERMI is devoted to longitudinal phase space characterization at low energy. It is based on two aerogel Cherenkov emitters with index of refraction n equal to 1.008 and length of 5 mm. One is installed in the injector straight line and one in the injector spectrometer line. The electron beam energy is 4.6 MeV. The light emitted by these aerogels is transported through a 20 m dedicated mirror transport system composed of 3 parabolic mirrors, 12 flat mirrors, motorized with 13 axis. The radiation is detected by means of a Hamamatsu FESCA200 streak camera capable of 150 fs resolution in single shot mode. A complete description of the system and detailed results will be reported in a forthcoming publication. Here we report some preliminary measurement performed on the electron bunch profile at the exit of the gun. Figure 1 shows the signal detected at the streak camera sensor, measured for an electron beam generated with a flat top laser profile of duration of 4 ps at the gun, with a charge of 240 pC and an energy of 4.6 MeV. The

ISBN 978-3-95450-121-2

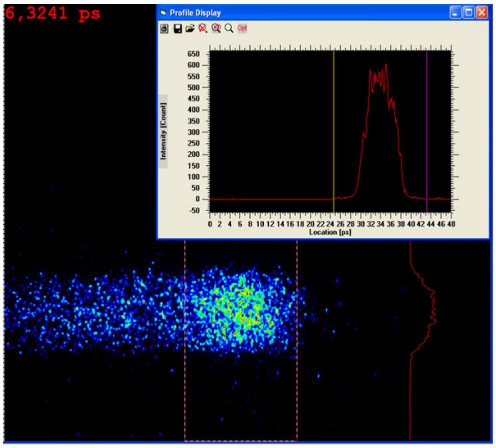

Figure 1: Cherenkov pulse as detected by the Fesca 200 streak camera. The inset shows the pulse longitudinal profile.

measured Cherenkov radiation pulse is shown in upper inset of figure 1, it has a FWHM of 6.4 ps. Figure 2 shows a the data acquire with the Cherenkov diagnostic as a function of the electron beam charge, compared with simulations with the ASTRA code for a flat top laser of duration 4ps and 4.6 MeV energy out of the gun. The simulation shows a nice agreement to the measurement.

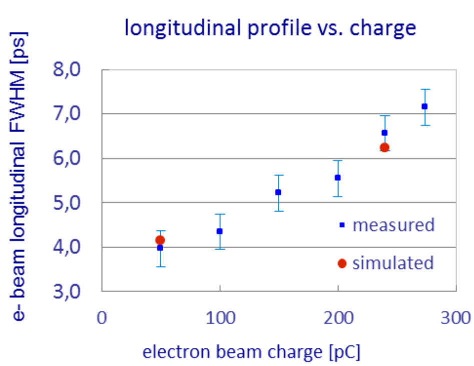

Figure 2: Cherenkov pulse duration vs charge. Measured data in blue and simulation in red.

BUNCH ARRIVAL MONITOR

The bunch arrival monitor (BAM) of FERMI@Elettra exploits the DESY scheme [3], based on the EO modulation concept has been adopted. A train of ultra-stable (time and amplitude) optical pulses are amplitude modulated by the electric signal generated from a RF pick-up by the electron beam passing in the beam pipe. The FERMI design adopts a compact pick-up and relays on the pulsed optical timing system of FERMI@Elettra, as described in [1]. The optical master oscillator (OMO) is a soliton fiber laser running at a repetition rate of 157.790MHz phase locked to the Reference Master Oscillator by the balanced optical microwave phase detector (BOM-PD), designed at MIT [2]. The path between the OMO and each link end point is entirely in fiber. The dispersion compensation assures the shortest pulses at the link cross-correlators. A specifically designed and engineered, by MENLO SYSTEMS Gmbh, device called Fiber Link Stabilization (FLS) compensates the path length variations are compensated by the combined action of a piezo-mirror, on the short time scale, and a motorized translation stage, for the drifts. At the remote end of the stabilized link there is the receiver with a fiber amplifier and a 10% reflecting Faraday Rotator Mirror (FRM). The link stabilization is performed up to this point. The BAM [4] is based on an Electro Optical modulator driven by the high bandwidth pulsed signal from the RF pick-up. Only one laser pulse of the 157.79 MHz train is modulated by the electron beam at 10 Hz. The modulation, seen as a change in pulse amplitude, is converted from optical to electrical signal and then sampled with an ADC. Since the modulation amplitude depends on the relative temporal position on the optical pulse with respect to the slope of the RF signal the time jitter is directly mapped into amplitude shot to shot variations. On the first BAM system installed downstream of BC1, a typical rms noise below 10 fs has been measured for the whole acquisition and synchronization path. The BAM has been used for physics studies as well as to monitor time jitter related issues. For an uncompressed beam at BC1 a time jitter of 70 fs is typically measured. In figure 3, as an example, we report the time jitter measured with the BAM due to a clear effect of phase jitter in the Klystron 3.

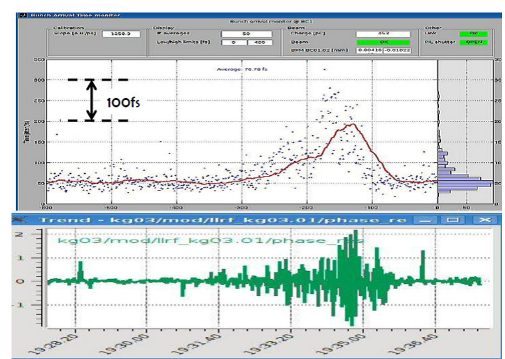

Figure 3: BAM signal upper graph and klystron 3 phase lower graph.

COHERENT BUNCH LENGTH MONITOR

The Coherent Bunch Length Monitor (CBLM) has been designed to allow for relative bunch length measurements in a range from 5 ps to 0.15 ps FW (flat top current profile). To allow for this very wide range of bunch lengths two coherent radiation sources are used. The first source is the coherent radiation from the bending magnets of the BC1 compressor. The second is coherent radiation from a ceramic gap. The diagnostics based on the first source covers the range from 1ps to 0.15 ps FW. The rest of the range, i.e. from 1 ps to 5 ps FW, is covered by the system based

ISBN 978-3-95450-121-2

on the radiation emitted from the gap. Simulation studies on the coherent gap radiation emission were conducted [6] to lead it design for FERMI. The system design and its first operation with beam have been described in [5].

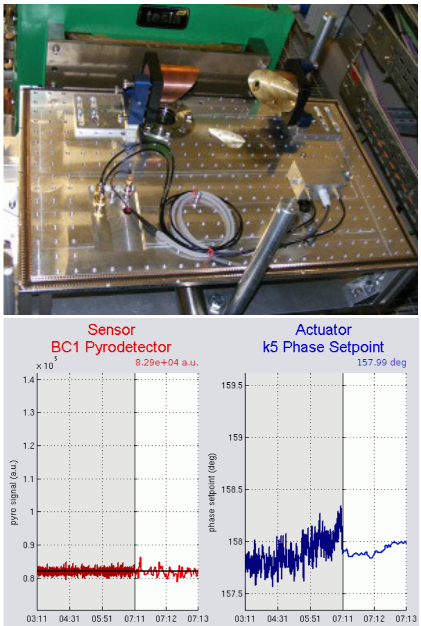

Figure 4: View of the in air part of the CER/CSR transport system of CBLM (upper image) and (lower images) compression feedback in action, pyrodetector signal in red and K5 actuator phase in blue.

Figure 4 (upper image) shows the CER/CSR transport system. The radiation emitted by the beam in the chicane is reflected upwards by an holey mirror. The vacuum air boundary is made by a Z-cut quartz window. The radiation passing the window is then collimated by the first off axis parabolic mirror and then focused by the second off axis parabolic mirror on to the pyrodetector. The pyrodetector signal digitized by fast ADCs is currently routinely used as a on line monitor for the longitudinal compression in both BC1 and BC2. The signal is also used in slow compression feedback system, since the bunch length is one of the most crucial parameters to keep stable in order to guarantee optimal FEL performances. As an example, figure 4 (lower image) shows the pyrodetector signal, in red, as the phase of the linac 5 section upstream the first bunch compressor, in blue, is changed to keep the bunch length constant.

RF DEFLECTORS

The complete characterization of the electron beam phase space by means of measurements of the bunch length and of the transverse slice emittance is one of the most important tasks for FERMI. For this reason both low energy (LERFD) and high energy (HERFD) RF deflectors have been developed The low energy RF deflector RF design [7] was developed for design electron beam energy of 250MeV on the base of a few constraints: the minimum peak voltage $V_\perp = 2.3MV$ (due to the resolution requirements for slice emittance), the working RF frequency $f_{RF} = 2998MHz$, the RF pulse length $t_{RF} \leq 3\mu s$ and the maximum available RF power $P_{RF} = 5MW$; The LERFD shown in figure 5 (left) is a standing wave (SW) structure composed of 5-cells operating on the π-mode. It should be noted that a careful investigation on the wakefield induced by the LERFD showed that the passive influence of the low-energy deflector on the electron beam can be neglected. At high energy two RF deflectors are foreseen to operate in the two transverse planes. The two share the same RF design and the first (the vertical) is being commissioned. The RF design [8] was developed for electron beam energy of 1.2GeV with same working RF frequency of LERFD. Resolution requirements for slice measurements lead to minimum peak voltage $V_\perp = 18MV$ considering a filling time $t_f \leq 3\mu s$, a maximum length of $2m$ and the maximum available RF power $P_{RF} = 15MW$.The HERFD shown in on the right of figure 5 is a traveling wave (TW) structure which has a phase advance of $2\pi/3$ per cell. For a seeded FEL slice parameters are very important and the RF deflectors are devised specifically to provide these information. In figure 6 we give a an example. The upper image shows a graph of the slice emittance for an electron beam with 100pC charge, showing a flat region in the central slices and slice emittance well below the projected of $1.8mmmrad$. The lower images shows a slice emittance measurement for an uncompressed beam with a typical value of 100 KeV rms.

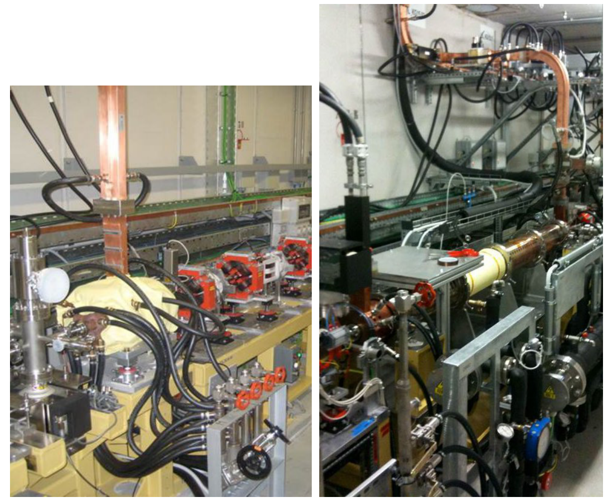

Figure 5: LERFD (left) and HERFD (right) installed in FERMI@Elettra.

ELECTRO OPTICAL SAMPLING

One Electro Optical Sampling (EOS) diagnostics per each FEL line has been devised. Figure 7 shows the layout of the EOS installed in the FEL1 line of FERMI@Elettra. This instrumentation is based on a TC780 Menlosystems fiber laser, installed directly in the tunnel to minimized

ISBN 978-3-95450-121-2

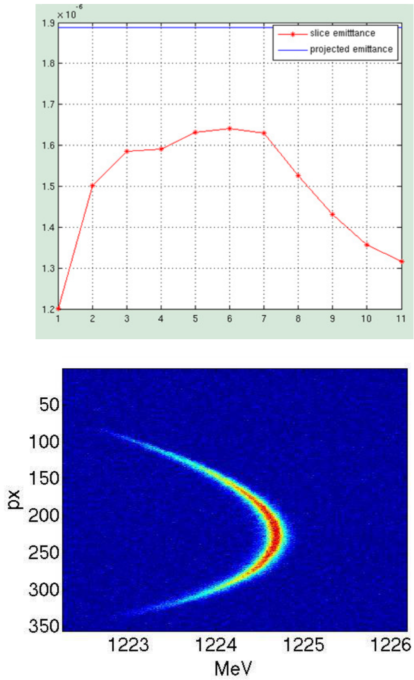

Figure 6: Slice emittance (upper image) and slice energy spread (lower image) measurements performed with the vertical HERFD.

pointing and time stability issues that may be related to a long optical transport system. The laser is a frequency doubled 1560nm femtosecond fiber laser, emitting at 780 nm, with a repetition rate of 78.895 MHz, providing an energy per pulse of 0.8 nJ and a pulse duration of 110 fs FWHM. The laser is phase locked to one of the pulsed timing system links, by means of electronics that converts optical pulses to RF and extracts a 1.499 GHz reference used by the RRE locking electronics. The coarse time alignment is provided by phase shifting the 1.499 GHz reference with a vector modulator while keeping the laser locked, thus producing an effective delay of the exit time of the pulse from the TC780 laser. The fine temporal alignment is provided by a 200mm travel delay line. A remotely controlled polarizer and a zero order $\lambda/2$ waveplate allow for adjustment of the polarization. Before entering in the vacuum chamber the laser beam passes through a cylindrical lens. The vacuum chamber is equipped with a 3 axis high precision manipulator that a present houses: an OTR screen (a $1\mu m$ aluminum foil) used for coarse time alignment, a YAG:Ce crystal for beam size measurement and two electro optic crystals. For the initial commissioning of the system we have considered to prefer signal to noise ratio over resolution, thus we have installed a 1 mm thick ZnTe crystal and a GaP 0.4mm thick crystal. The crystals EO response has been tested using a THz emitter before installing them in EOS diagnostics [10]. The laser beam propagation direction has an angle of 30 deg with the normal to the surface of the crystal. The entrance and exit windows are made of fused silica to reduce reflections. A the exit of the vacuum

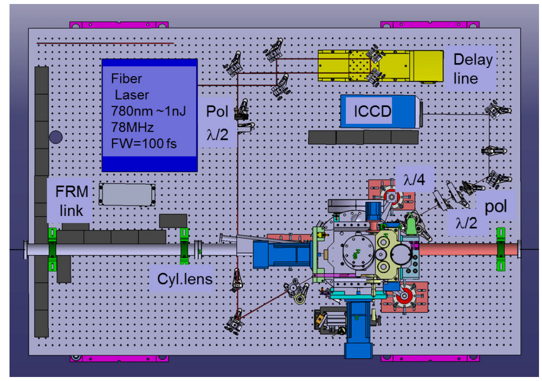

Figure 7: EOS FEL1 layout top view. Electron beam traveling in the beam pipe from left to right.

chamber the laser passes through the polarization analysis system usually set in cross polarizers configuration. This consists of two zero order waveplates, a $\lambda/4$, followed by a $\lambda/2$ and a finally a Wollaston prism. The majority of the intensity goes to a dump, while the other branch is directed toward the PCO Dicam Pro intensified gated camera (ICCD). The ICCD is used with a gate time of 10 ns to select only the laser pulse in the 78.895 MHz train that has been affected by the electro optical effect induced by the electron beam. The laser spot size on the crystal is measured with a CCD thus allowing a geometrical calibration of the EOS time scale. This station serves also as seed laser vs electron beam coarse temporal alignment diagnostics, in fact the OTR screen is used both to emit OTR as the electron beam passes through it and to reflect the seed laser (260nm). Both signals are then detected by the same fast photodiode and acquired by a high bandwidth oscilloscope. Their temporal alignment can then be measured with an accuracy better than 10 ps. The system was initially installed in the SPARC branch line (LNF-INFN), were a lot of operational experience was gained. It was then been moved in FERMI@Elettra. Figure 8 shows a sequence of 50 EOS acquisitions at 1 Hz, the pulse duration is in good agreement with other diagnostics and simulations, the time jitter measured so far is of the order of 80 fs rms.

SEED BUNCHING MONITOR

Finally we will present some results on the seed bunching diagnostics. The capability of the seed laser energy modulation to be converted in a longitudinal current modulation is one of the most important longitudinal characteristics of a seeded electron beam entering the radiator undulators of the FEL. To measure it, the simplest idea is to use a radiation mechanism that converts this modulation in a coherent emission of radiation. Moreover, in this way all the measurement will include all the parameters that affect its magnitude: the seed laser power, the seed laser vs electron beam transverse alignment, the temporal alignment and finally the dispersive section strength. The seed laser in the FEL1 chain has a wavelength of 260 nm, thus the current

ISBN 978-3-95450-121-2

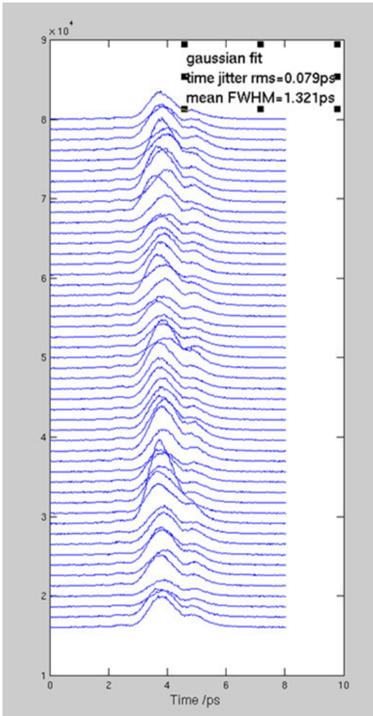

Figure 8: EOS signal profile of 50 shots. Data acquired in horizontal polarization using a ZnTe 1 mm thick crystal.

modulation is emitted at a wavelength of 260nm and its harmonics. For our first setup we chose transition radiation as radiation emission mechanism and setup a two foil system that is being used mainly considering forward transition direction. Peculiar experimental constraints are present in this case: such as the need to avoid the seed laser contamination at 260 nm, the need to filter other unwanted radiation such as coherent optical transition radiation (COTR) from microbunching in the beam. For this reason we devised a setup composed of two $1\mu m$ Al foils, the first set at normal incidence, while the second is set at 45deg. Both are emitters of forward transition radiation, but the second can also act as mirror for the first and the second harmonic (260nm and 130 nm). In this specific case we installed the detector, an aluminum coated photodiode from IRD, downstream the foil and after a first bending magnet in the main beam dump line. With the aluminum coating the detection band goes from 17nm to 80nm, so the coherent radiation detected is indeed coherent UV/VUV transition radiation (CUVTR). In figure 9 we show the intensity of the coherent radiation emitted as a function of the seed laser time delay. There is a qualitative agreement with the same time scan performed recording the FEL intensity).

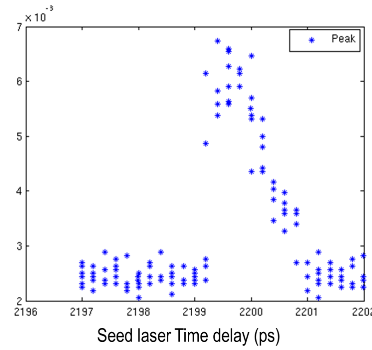

Figure 9: CUVTR intensity vs seed laser time delay.

ACKNOWLEDGMENT

We would like to thank H.Loos, J.Frish, D.Fritz, P. Krejcik and S.Jamison for discussions and many useful information and suggestions on CBLM and EOS design. We would like to thank D.Filippetto, M.Bellaveglia, A.Cianchi, A.Mostacci, G.Gatti, L.Giannessi for their support during the tests at SPARC (LNF-INFN) and M.Ferrari, S.Biedron and S.Milton for endorsing this fruitful collaboration. Finally we would like to thank R.Sauro and all colleagues from diagnostics group. This work was partially supported by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3.

REFERENCES

[1] M. Ferianis et al., “All-Optical Femtosecond Timing System for the FERMI@Elettra FEL”, FROAI2, proceedings of the FEL 2011 conference, Shanghai (2011).

[2] J. Kim et al. ”Drift-free Femtosecond Timing Synchronization of Remote Optical and Microwave Sources”, Nature Photonics 2, 733 - 736 (2008)

[3] F. Loehl, ”Optical Synchronization of a Free Electron Laser with femto-second precision”, Ph.D. Thesis at Hamburg University, 2009

[4] Leon Pavlovic, ”Bunch Arrival Monitor (BAM for FERMI; Report on developments and results, prototype and 1st final unit”, FERMI diagnostic area internal technical report, December 2010

[5] M. Veronese et al., “First Operation of the FERMI@Elettra Bunch Length Monitor System”, WEPB41, Proceedings of FEL2010, Malm, Sweden (2010).

[6] R.Appio et al., “Simulations of the Coherent Gap Radiation for the Bunch Length Monitor of FERMI@Elettra”, MOPD37, Proceedings of DIPAC2011, Hamburg, Germany (2011).

[7] P.Craievich et al., “Fermi Low-Energy Transverse RF Deflecting Cavity”, TUPC080, Proceedings of EPAC08, Genoa, Italy (2008).

[8] P. Craievich et al., “A transverse RF deflecting cavity for the FERMI@Elettra project”, Proceedings of DIPAC 2007, Venice, Italy, (2007).

[9] M.Veronese et al., “The Electro-Optic Sampling Stations For FERMI@Elettra, a Design Study”, TUPTPF026, Proceedings of BIW08, Tahoe City, California (2008)

[10] M.Veronese et al., “Laboratory Characterization of Electro Optical Sampling (EOS) and THz Diagnostics for FERMI by Means of a Laser Driven Pulsed THz Source”, TUPC12, Proceedings of FEL2009, Liverpool, UK, (2009)

ISBN 978-3-95450-121-2