BEAM OPTICS MEASUREMENTS AT FERMI BY USING WIRE-SCANNER

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Abstract

Measuring and controlling the electron beam optics is an important ingredient to guarantee high performance of a free-electron laser. In the FERMI linac, the Courant-Snyder parameters and the transverse emittances are routinely measured by detecting the beam spot size as a function of a scanning quadrupole placed upstream (i.e. quadrupole scan method). The beam spot size is usually measured with an OTR screen that unfortunately suffers from coherent optical transition radiation (C-OTR) that introduces spurious light and corrupts the image. Moreover, the beam size at the end of the FERMI linac is focused to a few tens of microns and this makes it difficult to precisely measure it with the OTR system, which has an estimated resolution of 20 μm. For this reason, a wire-scanner system has been installed at the end of the linac just in the waist of the optics channel. The wire-scanner is a SwissFEL prototype (Paul Scherrer Institut, Villigen CH) installed in FERMI in order to study the hardware and beam loss monitor performances at the GeV energy scale. The beam optics measurements performed with the wire-scanner is here presented, and the obtained results are more in agreement with the theoretical expectations. A more reliable beam optics estimation at the end of the linac has allowed better matching it to the nominal lattice and transporting it up to the undulator chain, providing important benefits to the FEL performance.

INTRODUCTION

FERMI is a single-pass seeded free-electron laser (FEL) based upon the High Gain Harmonic Generation (HGHG) principle [1]. It is composed by two FEL lines that are now completely commissioned and in operation for providing intense photons (~100s uJ/pulse) for Users experiments: FEL-1 covers the range from 100nm to 10nm and FEL-2 from 20nm to 4nm [2,3].

The FERMI FEL high performance strongly relies on the capability of producing very high quality and bright electron beams.

The electron beam is generated in a RF photoinjector [4], and accelerated to 1.2-1.5 GeV by an S-band linac [5]. Two magnetic bunch compressors are placed respectively at 300MeV and at 650MeV and are utilized to shorten the electron bunch from few ps to hundreds of fs, increasing the peak current to 500-800A according to the desired operation parameters. One of the main goals in the beam transport and optimization from the injector to the undulators consists in preserving the transverse emittance and limiting the undesirable effects inducing emittance growth. At this purpose, the electron beam Courant-Snyder parameters, i.e. β and α functions, and the transverse emittance are routinely measured in strategic regions along the linac and the undulators lines, and an optimization procedure is implemented to match the optics to the lattice design. These diagnostic stations are placed after the injector (~100 MeV), after the first bunch compressor, at the end of the linac, and in front of the modulator. In this paper we focus on the 15-meter long optics diagnostic station located at the end of the linac, whose schematic layout is shown in Fig. 1.

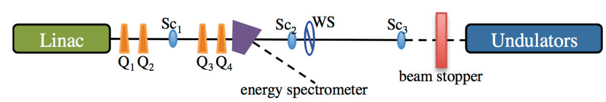

Figure 1: Diagnostic station layout at the end of the FERMI linac, including quadrupoles (Q), YAG-OTR multi-screens system (Sc) and the wire-scanner that has been installed 64 cm downstream the screen Sc_2.

THE WIRE-SCANNER PROTOTYPE AT FERMI

The nominal optics design at the end of the linac is reported in Fig. 2.

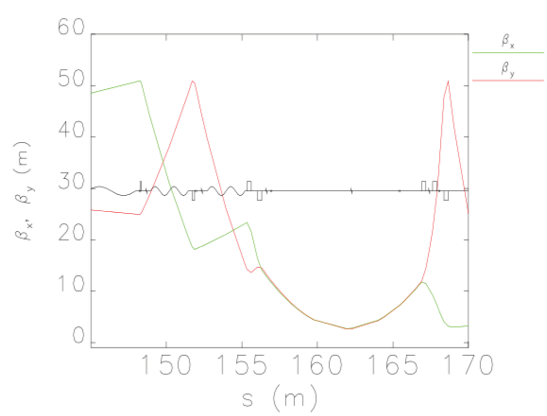

Figure 2: The horizontal and vertical β-function along the straight path at the end of the linac. The origin (s=0m) of the horizontal axis corresponds to the electron source, i.e. the photo-cathode plate.

The quadrupoles Q_3 and Q_4, see Fig. 1, are usually used only when the beam is sent into the spectrometer beam-line, to increase the measurement resolution of the longitudinal phase space [6], and are completely switched

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off when the beam is routinely driven to the undulators. As a consequence the beam evolves from the second quadrupole (Q_2) to the third screen (Sc_3) as in a simple drift, with a very small waist ($\beta x=\beta y\sim 2m$) in correspondence to the second screen Sc_2.

The beam optics functions and transverse emittance are measured by using the quadrupole scan technique [7], consisting in changing the strength of the quadrupole Q_2 and measuring the correspondent beam spot size variation on a downstream screen. The screen Sc_2 has been conceived as the most suitable at this purpose since it is just in the beam waist (for the nominal lattice).

Each FERMI screen station has the option to use an OTR or a YAG target [8]. Despite of the higher spatial resolution of the OTR, strong spurious coherent-OTR signals emitted by the shortened electron bunch affect the beam spot size measurement [9]. The laser heater system [10] is used at high intensity to suppress, as much as possible any microbunching instabilities during the optics measurements. Unfortunately, it is hard to complete suppress any spurious signals that are still present, although not distinguishable. By the other hand, the YAG is limited by its low resolution (~40µm) and could be a reliable alternative only where the beam is not strongly focused. Moreover, the FERMI linac commissioning activities have required to set the screen system with a large field of view, for the slice parameters measurements [11], and this decreases the beam spot size measurement resolution also in the case of the OTR.

For all these reasons, a wire-scanner (WS) device has been installed as close as possible to the Sc_2 in order to evaluate the beam transverse profile and make a comparison with the OTR screen.

The WS is a SwissFEL prototype composed of an in-vacuum scanning hardware and scintillator-fibers for out-vacuum detection of the beam-losses [12]. The wire-fork can be inserted 45-deg with respect to vertical axis by means of a UHV linear-feed-through motorized by a stepper-motor. Two pairs of Tungsten wires are stretched on the fork frame to scan the beam profile along the horizontal and vertical directions. The two pairs of wires have a diameter of 5 and 13 µm, respectively, to ensure a geometrical resolution in the range 1.3-3.3 µm (rms).

When the wire intercepts the electron beam, a shower of high energy primary scattered electrons and secondary particles is forward emitted at a small angle in proportion to the fraction of the beam charge that is intercepted by the wire. Scanning the wire at constant speed and detecting the beam losses allow reconstructing the single projection of the beam profile. The wire losses have been measured with three Saint Gobain Scintillator fiber BCF-20 (1mm diameter): two were placed in the linac tunnel, before the beam stopper, respectively 2.48m and 5.52m downstream the WS device, while the third one was installed in the undulator hall (at 8.40m). A forth loss monitor, a Cerenkov fiber, has been placed in the linac tunnel, at about 4.5m from the WS. All four monitors signals are digitized by a vme multichannel adc board running at 250 Msamples/sec. Real-time software acquires, processes and stores shot-by-shot the waveforms coming out from board whereas a dedicated tango server manages the communication to higher level programs.

BEAM PROFILE MEASUREMENTS

The WS stepping motor system ensures a reliable constant wire scanning velocity. Wire mechanical vibrations are completely negligible for scanning speed lower than 1 mm/s as reported in [12].

Figure 3a shows a horizontal beam profile acquired by the four beam loss monitors when scanning the 5-µm vertical wire at 0.1mm/s. Since FERMI operates at 10Hz and the wires form an absolute angle of 45-deg with respect to the insertion axis of the wire-fork, the beam profile is sampled with a step of about 7µm.

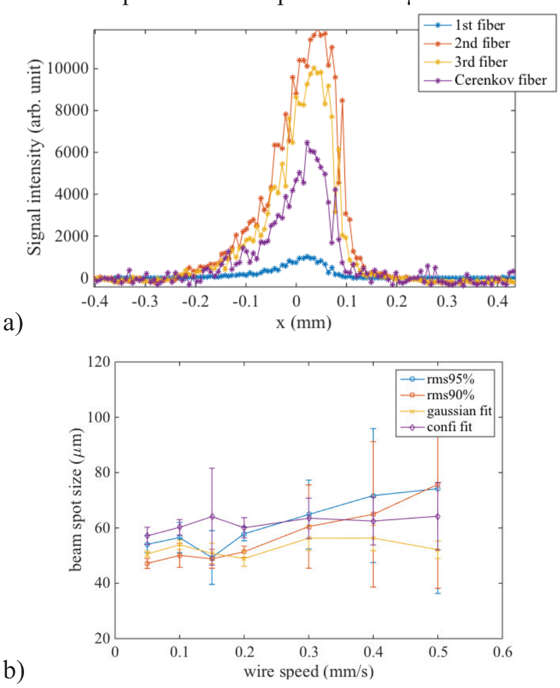

Figure 3: a) Horizontal beam profile acquired by the four monitors for the vertical 5-µm wire scanning at 0.1mm/s. b) Horizontal beam size (σ_x) versus the wire speed obtained by processing in four different ways the profile measured with the second fiber.

The second fiber is placed at the best distance from the WS to maximize the beam losses signal and it is taken as the reference for the measurement. By the way, when the beam stopper is closed, the backscattering shower saturates the fiber and only the first one could be used. The acquired profiles can be processed in different ways to estimate the beam spot size: by a Gaussian fit, or by an asymmetric Super-Gaussian function ("confi" fit [4]), or by calculating the raw rms over 90% or 95% of the whole bunch charge ("rms90%", "rms95%"). Figure 3b reports the horizontal beam size σ_x obtained with these 4 methods as a function of the 5-µm wire scanning speed (using the second fiber). The higher the speed the lower the resolution in sampling the beam profile, so one should expect the beam size tends to increase with the wire

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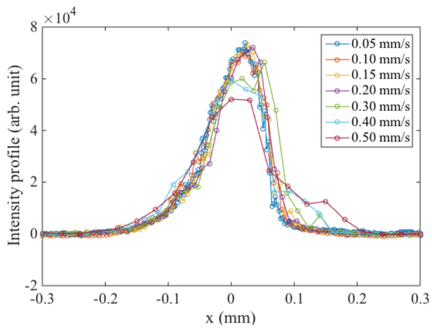
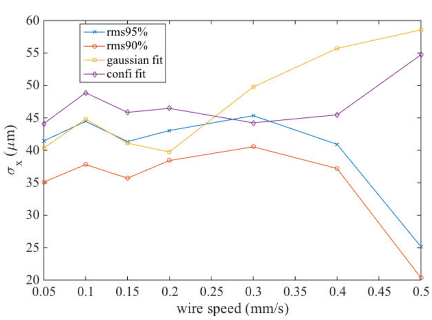
speed. This is confirmed by processing the profile with the "rms90%" and "rms95%" methods. This is less evident for the Gaussian and "confi" fits, where the edges of the bunch profiles can lead respectively to underestimate and overestimate the beam size.

The noise in the beam profile obtained in a wire scan is mainly due to the beam trajectory jitter, usually about 10-μm (rms), that leads to an overestimation of the beam size. We have chosen to process the acquired data with the "rms95%" method, that results to be the best compromise between cutting the tails, more affected by trajectory jitter, without losing too much information about the actual beam profile. In order to "wash out" the effect of the trajectory jitter, we integrated several beam profiles acquired in the same machine condition for different wire speeds (see Fig. 4a). The four aforementioned fitting methods were applied to the integrated profiles and plotted in Fig. 4b. The values of σ_x are smaller than those in Fig. 3b and almost constant for wire speed <0.2mm/s. We therefore chose to set the wire speed at 0.2mm/s and integrate the beam profiles to have a reliable beam size measurement.



a)



b)

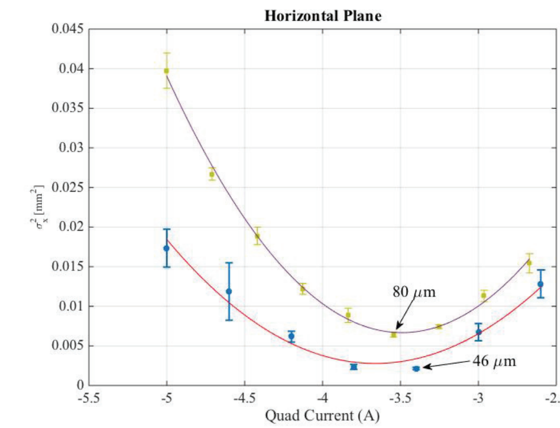
Figure 4: a) Horizontal profile integrated over six profiles acquired with the second fiber at different wire speed; b) σ_x obtained with the four methods as a function of the wire speed. At wire speed = 0.5mm/s, the measurements are not reliable due to the poor resolution in sampling the beam profile.

BEAM EMITTANCE MEASUREMENTS

As mentioned above, the optics and transverse emittance measurements are performed by means of the quadrupole scan method. During these measurements, the linac beam stopper was closed to avoid too much radiation in undulator hall. In fact, changing the quad strength completely mismatches the beam downstream, with a consequent intolerable enhancement of the beam losses in the undulators. By the other hand, a beam profile measurement with the WS system at scanning speed of about 0.2mm/s and without varying the machine optics is almost transparent for the FEL: this permits to monitor the beam transverse size on-line and in a non-invasive way.

As said above, when the beam stopper is closed it is possible to use only the first fiber. Despite its signal is almost a factor 10 less intense than the second fiber one, it is anyway three orders of magnitude larger than the background noise, and it is perfectly suitable for the FERMI beam profile measurements.

We have compared the beam size measured by the WS and by the screen Sc_2 during a quadrupole scan, and consequently the Twiss functions and the emittance obtained (see Fig. 5).



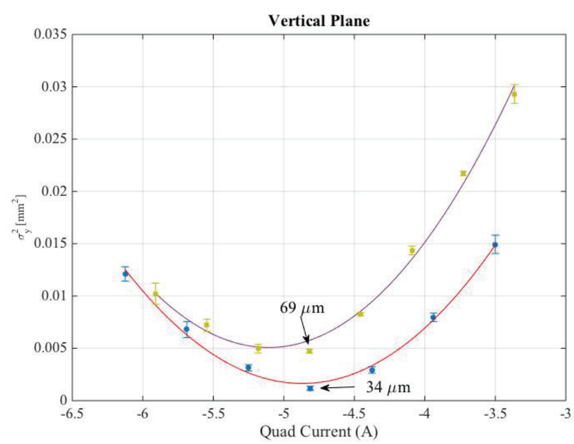


Figure 5: Horizontal (top) and Vertical (bottom) beam spot size versus the quadrupole Q_2 current measured by the WS device (blue circles data and red line) and by the Sc_2 (yellow squares data and purple line). The horizontal profile was measured with the 5-μm wire, while the vertical one with the 13-μm wire.

The beam spot on the OTR screen was filtered to clean-up the background noise and the beam sizes (σ_x and σ_y) were provided by calculating the RMS of the 90% of the total beam charge, with a two dimensional image cutting process. To be consistent, the beam profiles measured by the WS were processed with the "rms95%" method (one dimensional cutting).

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The minimum beam sizes obtained with the two devices are reported in the plots of Fig. 5: the OTR measured a beam waist that is about two times larger than the WS. Since the emittance obtained by this kind of measurement is strongly correlated to the minimum beam spot size detected, the Sc_2 provides larger value of emittance than the WS, and different Twiss functions (see Table 1). During the FERMI commissioning, the screen Sc_3 has been usually utilized for this measurement because here the β-function assumes a larger value. Table 1 lists also the results of a quadrupole scan measurement performed using Sc_3: the emittances, β and α are closer to the values measured with WS than that obtained with the screen Sc_2.

Table 1: Twiss Functions and Emittance Measured at the Quadrupole Q2 by using the WS, the OTR Sc_2 and Sc_3, before the Matching Procedure

	WS	**Sc_2**	**Sc_3**
β_x [m]	18.79±1.98	15.49±0.70	16.75±0.88
α_x	9.47±1.07	7.79±0.40	8.44±0.49
ε_x [mm mrad]	2.42±0.25	5.92±0.27	3.31±0.17
β_y [m]	18.71±0.85	11.47±0.41	16.16±1.05
α_y	-6.78±0.30	-4.23±0.12	-5.58±0.34
ε_y [mm mrad]	1.81±0.08	4.28±0.15	2.95±0.19

The values of Table 1 are used to match the beam optics to the nominal lattice, by acting on the upstream quadrupoles. The matching procedure converges fast and reliable with the WS results, while it requires several iterations with the Sc_3 ones and it does not converge at all with the Sc_2 ones. Applying the quadrupoles setting foreseen by using the WS values as input, and measuring again the optics, we obtained the results reported in Table 2.

Table 2: Twiss Functions and Emittance Measured at the Quadrupole Q_2 by using the WS and the OTR Sc_2, after the Matching Procedure

	WS	**Sc_2**
β_x [m]	17.96±1.46	13.76±0.68
α_x	10.82±0.95	8.27±0.45
ε_x [mm mrad]	1.70±0.14	6.23±0.31
β_y [m]	14.48±0.35	10.42±0.40
α_y	-5.53±0.13	-4.06±0.15
ε_y [mm mrad]	1.62±0.04	4.35±0.17

As before the matching, the Sc2 is not able to provide reliable beam spot size, so that the measured optics and emittances are completely different from the WS results. The mismatch parameter $B=1/2(\beta_0\gamma_m-2\alpha_0\alpha_m+\beta_m\gamma_0)$, where the sub-fix "0" refers to the nominal lattice and "m" to the measurements, calculated by using the WS output is 1.042 in the horizontal plane and 1.008 in the vertical one.

CONCLUSION

A SwissFEL wire-scanner prototype has been installed and successfully tested in the diagnostic area placed at the end of the FERMI linac. The experimental results confirmed the feasibility at the GeV energy scale of the WS set-up for emittance measurements and beam profile monitoring during FEL operations. It has demonstrated the capability to measure beam size of few tens of µm (rms), constituting an important improvements with respect to the current OTR screens. Optics and emittance measurements performed with the WS device have provided reliable results, making converging the optics matching procedure faster and allowing a better optics transport up to the undulator chain, with relevant benefits to the FERMI FEL performance.

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