Optimization of a high brightness photoinjector for a seeded FEL facility

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ABSTRACT: The FERMI@Elettra project is a seeded free electron laser (FEL) source, based on the High Gain Harmonic Generation (HGHG) scheme. It is designed to supply photons in a spectral range from 65 to 20 nm with the first undulator line (FEL-1) and from 20 nm to 4 nm with the second undulator line (FEL-2).

After a first period of commissioning of the electron beam up to 100 MeV at low charge, started in August 2009, several phases of installations and beam commissioning periods have been alternated through the 2010. On December 2010 the first FEL light in the FEL-1 line was obtained at 65 nm and 43 nm by adopting as an initial seed the third harmonic of a TiSa laser. The complete optimization and commissioning of the photo-injector has been carried on in parallel with the Linac and FEL commissioning, from a conservative set-up to the final designed configuration. This paper reports the electron beam characterization in the injector area, the comparison with the theoretical expectations and the experimental process which resulted in a high brightness electron beam. This beam was optimized to be compressed and then transported through the undulators of FEL-1 where intense photons ranging from 65 nm to 20 nm were generated [1, 2].

KEYWORDS: Beam Optics; Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics)

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1 Introduction

Free electron lasers (FELs) at short wavelength are powerful sources enabling new kinds of experiments that are not possible with third generation light sources [3]. These lasers strongly rely on the capability of producing very high quality and bright electron beams in order to sustain the FEL process [4]. This is true both for FELs based on the Self Amplification of Spontaneous Emission scheme (SASE) [5, 6] and for those based on the High Gain Harmonic Generation (HGHG) scheme [7] as FERMI. The 6-D brightness of an electron beam at the end of the linac is strongly determined by the photoinjector beam quality. The main goal of the photoinjector optimization is to minimize the transversal beam emittance, that should be preserved during the linac transport and in the longitudinal compression. Actually improvements in transverse emittance along the linac at best are possible, but at the expense of the longitudinal emittance (for more details on the “Transverse-to-longitudinal emittance exchange” method, we refer to [8, 9]). The longitudinal emittance has to be very small especially in the HGHG scheme, because a low slice energy spread is required to sustain the FEL process at high harmonics of the seed laser [7, 10]. Specifically the FERMI FEL requires at the undulators entrance an electron bunch with a peak current of 750 A over a bunch length of 600 fs. A slice emittance below 1.0 \( \mu \text{m} \) and an uncorrelated energy spread smaller than 150 keV are also demanded [11]. A 600 fs long bunch was required in the Conceptual Design Report [12] to guarantee a good temporal overlapping between the \( \sim 100 \text{ fs} \) long seed laser and the electron bunch, which was expected to have a time jitter of about 150 fs (rms). To meet the 750 A and 600 fs requirement with a reasonable safety margin, the bunch charge extracted at the
Table 1. Photoinjector beam operation comparison between FERMI and several FEL machines, including FLASH, LCLS, PSI, SPARC and the X-FEL test facility of PITZ. $E_{\text{gun}}$, $E_{\text{inj}}$, $\Delta t_{\text{laser}}$, $\sigma_{\text{bunch}}$, $\varepsilon_{\text{proj}}$, $I_{\text{peak, inj}}$ and $I_{\text{peak, und}}$ are respectively the beam energy at the gun exit, the beam energy at the injector end, the drive laser temporal duration, the rms bunch length, the projected normalized emittance and the peak current at the injector and at the undulators. The transverse shape of the drive laser pulse is a flat-top for all the photoinjectors, but FERMI and LCLS (nominal operational beam) that use a truncated Gaussian shape. Last line refers to the peak current at the undulators entrance.

| Parameter | FERMI | FLASH | LCLS | PSI | SPARC | PITZ |
|-----------|-------|-------|------|-----|-------|------|
| $Q$ (pC)  | 500   | 1000  | 250  | 200 | 400   | 1000-500-250-100 |
| $E_{\text{gun}}$ (MeV) | 5.0   | 4.7   | 5.2  | 7.1 | 5.6   | 7   |
| $E_{\text{inj}}$ (MeV) | 98    | 127   | 135  | 250 | 150   | 25 |
| Laser spot size radius (mm) | 0.6$^a$ | 1.0   | 0.6$^a$ | 0.53 | 0.45  | 0.38-0.26-0.21-0.1 |
| $\Delta t_{\text{laser}}$ (FWHM in ps) | 3.5   | 20    | 6.5  | 10  | 6-8   | 21-23 |
| $\sigma_{\text{bunch}}$ (ps) | 2.8   | 4.4   | 2.5  | 2.4 | 2.6   | 8.5-9.5 |
| $\varepsilon_{\text{proj}}$ (mm mrad) | 0.65  | 1.9$^b$ | 0.7  | 0.44 | 2.5-2.9 | 0.7-0.64-0.32-0.21 |
| $I_{\text{peak, inj}}$ (A) | 60    | 65    | 30   | 24  | 53    | 40-20-10-4 |
| $I_{\text{peak, und}}$ (kA) | 0.75  | 1-2   | 2.5-3.5 | 2.7 | 0.11$^c$ | - |

$^a$ Truncated Gaussian profile.
$^b$ It is calculated over 100% of the bunch charge and it decreases to 1.1 µm if taken the 90% of the bunch charge.
$^c$ Obtained by implementing the velocity bunching scheme.

cathode was required to be 800 pC. However, as shown in section 3, we have actually measured an electron time jitter at the injector exit below 100 fs rms, due to the very low time jitter of the photoinjector drive laser (PIL). After the longitudinal magnetic compression, the bunch timing jitter is further reduced to a level of about 40-50 fs rms [13]. This has allowed us to relax the requirement on the length of the good part of the beam that can be used by the FEL and consequently reduce the required extracted charge to 500 pC to obtain the desired peak current.

The FERMI layout was conceived with the intent to limit the compression in the magnetic chicanes to no more than a factor of about 10-15 in order to constrain the slice energy spread enhancement. Consequently, to reach the design current of 750 A, the electron bunch at the injector exit can not be too long. There are multiples reasons that induced us not to consider longer bunches and high longitudinal compression. First, high compression could be obtained with an increase of the $R_{56}$ term of the chicane but this would enhance the effects of the coherent synchrotron radiation that has deleterious consequences on the uncorrelated energy spread. Second, an alternative might be increasing the beam linear energy chirp before the magnetic chicane to few percent level, but this would translate into demanding requirements concerning the magnetic field uniformity of the chicane dipoles, whose chromatic aberrations would drastically affect the beam quality. Finally, a high charge, long bunch at low energy is more sensitive to microbunching instabilities driven by longitudinal space charge forces, which induce energy modulations increasing again the uncorrelated energy spread. Despite the FERMI peak current and brightness at the first glance not appearing to be highly challenging, the simultaneous requirement at the undulators of low longitudinal and transverse emittance, and a nearly constant $\sim kA$ current over a few hundreds of fs is in fact quite demanding. In table 1 we compare the present beam operational parameters of
the FERMI photoinjector with those of other FEL photoinjectors, including LCLS at SLAC [14], PSI [15], FLASH [16, 17], SPARC [18, 19], and the X-FEL Photo Injector Test facility at DESY, Zeuthen site (PITZ) [20, 21]. At PITZ they have studied several bunch charge configurations, including the 500 pC regime of interest to FERMI. However, they use a much longer drive laser pulse and thus produce a smaller output current that would require much higher compression to meet our requirements. The FLASH and SPARC injectors are operating respectively at 1 nC and 400 pC with a peak current comparable to the FERMI injector, but with larger beam transverse emittance. Despite LCLS having demonstrated the feasibility of injector operation in the nC regime with low emittance beams, they have chosen to reduce the bunch charge at 250 pC for routine operations (and recently at 150 pC), desiring lower transverse emittance and the consequent higher FEL gain.

Therefore at present, the FERMI injector has been run to provide an electron beam with a state of the art brightness obtained by the best performing injectors but moreover at the highest peak current per bunch.

This paper is organized as follows. Section 2 describes the photoinjector layout. The photoinjector comprises a high-gradient S-band photo-cathode RF gun, the photocathode gun drive laser, the first two accelerating sections to boost the electrons up to 100 MeV, the controls and the suite of diagnostics. The photoinjector drive laser system is presented in section 3. Particular attention is given to the pulse shaping features, which permit us to test several transverse distributions, and to vary the temporal shape and pulse length from 3 to 12 ps. FERMI has adopted a short drive laser pulse ($\sigma_t \sim 1.7\text{ps}$) to extract the nominal 500 pC bunch, which is lengthened up to 2.8 ps (rms) after one meter drift by the strong longitudinal space charge forces. We have found that the choice of such a short pulse laser leads to a better uniformity in its temporal profile. Section 4 is devoted to the RF gun operation and performance. In particular we describe a novel experimental technique to restore the degraded cathode quantum efficiency (Q.E.) based on "ozone cleaning processing", applied for the first time on a metallic cathode and with successful results. The electron beam characterization at the injector exit in terms of projected emittance together with our particular experimental methodology, is presented in section 5. Section 6 presents the optimization process that obtained 500 pC bunches with a projected emittance of about 0.65 mm mrad; these have been used to produce intense ($\sim 100 \mu J$) FEL pulses from 52 nm to 20 nm [1]. Slice emittance measurements performed by using a RF deflecting cavity is finally presented in section 7.

2 Injector layout

The FERMI injector’s major components are shown in figure 1. The FERMI electron source is a metallic photocathode (polycrystalline copper) illuminated by an intense (hundreds of microjoules per pulse) UV laser at about 260 nm, whose pulse shape is chosen to optimize the final e-beam quality. The photocathode also serves as the conducting back plane of the half cell of the installed BNL/SLAC/UCLA type gun [22]. External solenoid magnets are integral to the RF gun operation. A multiple pancake, emittance compensating solenoid provides focusing to help transport the beam from the gun exit to the entrance of the booster linac structures.

After the gun, the electron beam enters a compact beamline that contains the instrumentation for the low energy beam diagnostics and trajectory correction, and the vacuum instrumentation for the entire front-end section. Two dipole trim magnets allow correcting both beam offset and
Figure 1. The FERMI@Elettra FEL photoinjector is mainly composed of the RF Gun and solenoid(g), a current monitor (cm), two Spectrometers (b) at 5 MeV and at 100 MeV, two S-band traveling wave RF sections (rf), seven quadrupoles (q), ten multi-screens station (s), and the laser heater (lh).

angle. Two vacuum crosses support retractable beam profile image screens, a charge-measuring Faraday cup and horizontal and/or vertical slits. An inductive toroid is placed near the gun exit for non-destructive bunch charge measurements. A six-way cross in the beamline allows for on-axis injection of the photocathode drive laser pulse, vacuum pumping and measurement. Finally a 60-degree spectrometer magnet allows one to measure beam energy and energy spread.

The two booster traveling wave S-band structures, comprising the first L0 linac, accelerate the electron beam to 100 MeV. They are composed of 93 identical on-axis iris-coupled cells, resonating at 2.998 GHz. The two end cells are used to couple RF power into and out of the structure. They operate in the $2\pi/3$ mode, and provide peak accelerating gradients of about 15 MV/m, for a total maximum energy gain of about 45 MeV. After the accelerating sections, four quadrupoles and four multi-screen stations are used to match the photoinjector optics to the downstream linac lattice. Two additional quadrupoles between the two RF sections help to rapidly converge the beam to the downstream design optics. A magnetic spectrometer after the two booster sections permits characterization of the beam in terms of energy and energy spread.

A laser heater system (“lh” in figure 1) to damp microbunching instabilities is installed in the matching area. This paper does not report on the laser heater commissioning successfully achieved in 2012 and we refer readers to [23] for more details.

Ten multi-screen systems are installed along the injector beam-line. They are equipped with 1 $\mu$m-thick Optical Transition Radiation (OTR) and 100 $\mu$m-thick Yttrium Aluminum Garnet (YAG) targets. Both targets are mounted at an horizontal angle of 45 deg with respect to the beam propagation direction. They are viewed by a digital 8-bit CCD (Basler SCA 780-54gm) at 90 deg with respect to the beam propagation direction to minimize radiation damage hazard and at 0.45 m from the targets. The camera has remote controllable gain (from 0 to 25.4 dB) and exposure time with gigabit Ethernet interface. It is equipped with a Sigma105 macro-lens, which is used typically with $f/8$, as a good compromise between the amount of light collected on the camera sensor, depth of field and image blurring from lens diffraction effects. The light intensity on the CCD sensor can be controlled with a continuous metallic neutral density variable filter with attenuation up to a factor 10000 (Thorlabs NDC-100C-4).

At low energy ($\approx 5 MeV$) the OTR intensity is too feeble and only YAG screens have been installed to routinely investigate the beam envelope evolution outside the gun. At 100 MeV both OTR and YAG targets are available. Providing a precise value of the resolution power of the OTR
Table 2. OTR resolution estimation, taking the whole OTR signal $\sigma_{x,nat,pol}$ and taking the linear polarized light orthogonal to the measured plane $\sigma_{x,vert,pol}$.

| $\lambda = 700 \text{ nm}$ | $\lambda = 400 \text{ nm}$ |
|---------------------------|---------------------------|
| $\sigma_t$ | $\sigma_{x,vert,pol}$ | $\sigma_{x,nat,pol}$ | $\sigma_{x,vert,pol}$ | $\sigma_{x,nat,pol}$ |
| 70 $\mu$m | 73.0 $\mu$m | 75.5 $\mu$m | 71.5 $\mu$m | 72.8 $\mu$m |
| 100 $\mu$m | 102.7 $\mu$m | 105.1 $\mu$m | 101.4 $\mu$m | 102.6 $\mu$m |

and YAG is beyond the scope of this paper. Nevertheless we have estimated the minimum spot size that we could detect with these two targets. We assumed a beam with a Gaussian transversal profile with an rms spot size of $\sigma_t$. The measured rms spot size may be expressed as $\sigma^2_{meas} = \sigma_t^2 + \sigma_{res}^2$, where $\sigma_{res}$ is the contribution due to the resolution of the system. Calculations of a propagation of a Gaussian beam through a 100 $\mu$m YAG at 45deg show that the screen thickness is the main contributor to the beam size resolution $\sigma_{res}$ with 41 $\mu$m. To this value we have to add in quadrature some minor contributions. The effective pixels size due to magnification is of 19.2 $\mu$m, leading to an estimated contribution of 4.8 $\mu$m. The diffraction of the lens leads to a contribution of 7.8 $\mu$m. The chromatic aberrations, the multiple coulomb scattering and bremsstrahlung effects give a contribution of the order of the micron or less and in this case are neglected. The depth of field is much larger than the typical transverse beam spot size, which ranges from 70 to 200 $\mu$m, so its contribution is also neglected. Finally we have not seen noticeable saturation effects due to charge density, which is in our case of 0.01 $\text{pC}/\mu\text{m}^2$. This is below the limit of 0.07 $\text{pC}/\mu\text{m}^2$ at 66 MeV reported in [24]. We can therefore estimate, for the YAG:Ce target a total $\sigma_{res} \approx 45 \mu$m.

Concerning the OTR screens, the resolution is essentially governed by the diffraction of the OTR source as stated by Artru in [25]. We have estimated the effect of the OTR polarization on the transverse beam spot size measurement, considering the point spread function (PSF) of the OTR. By using the formalism described in [25], we have calculated the rms beam spot size considering the convolution of the electron beam Gaussian transverse profile with the horizontal projection of the natural polarization of the OTR-PSF ($\sigma_{x,nat,pol}$) and with the horizontal projection of the vertical polarization of the OTR-PSF ($\sigma_{x,vert,pol}$). Table 2 shows the results for two rms beam spot size (70 $\mu$m and 100 $\mu$m) and for two optical wavelengths (400 nm and 700 nm), since the OTR is a broadband source.

The results of the table 2 demonstrated that the theoretical discrepancy between the real rms beam spot size and the measured one obtained by taking all the OTR signal is in the worst case about 7% and it decreases when the beam spot size increases. We can therefore consider that in the OTR case $\sigma_{res} \approx 20 - 25 \mu$m. In virtue of the higher resolution, OTR screens have routinely been used for the transverse emittance measurements in the photoinjector, as described in section 5. The measured transverse emittance results to be slightly overestimated due to the OTR $\sigma_{res}$ by about 3-4%.

3 Drive laser

The laser system delivering the UV pulses for extracting the electron bunch must meet a number of requirements. Special attention has been paid to the design of all subsystems involved in the generation and delivery of the laser light, namely the main laser, harmonic conversion and UV
shaping, vacuum beam transport and insertion into the gun, as well as pulse/beam control and diagnostics. As has already been discussed in earlier papers [26, 27], a suitable, mature and reliable laser technology that can meet all the PIL parameters requested for the copper photocathode, is the one based on Ti:Sapphire as an active material and a regenerative amplifier/multi-pass chirped-pulse amplifier design. The amplifier system used at FERMI is a custom system constructed by Coherent Inc. It can generate more than 15 mJ in the infrared (783 nm), with the use of entirely CW diode pumping technology. The latter is the base for the very good UV energy stability obtained, experimentally at FERMI typically better than 0.8% RMS. The conversion to third harmonic (261 nm) light is performed by a in-house designed THG system based on a “time-plate” design [27], with a conversion efficiency of about 12%. The maximum UV energy that can be delivered to the photocathode in a 10 ps (FWHM) long pulse is about 0.5 mJ, which is sufficient to produce a bunch of 1 nC charge. At present the laser energy needed to extract the actual nominal bunch charge of 500 pC is below 150 \( \mu \text{J} \).

One of the main features of our laser system is the implementation of a temporal shaping setup providing the possibility of varying the electron beam pulse duration in the 3-12 ps (FWHM) range and to optimize the pulse shape (Gaussian, super-Gaussian or increasing ramp) design [28]. The time shaper is a 4-f type setup based on high efficiency transmission gratings and a deformable mirror placed after the harmonic conversion. The deformable mirror incorporates 20 piezo actuators acting on the back surface of a dielectric mirror and imprints a phase modulation on the dispersed UV pulse, while the amplitude modulation is done by knife-edge filtering of the wings of the spectrum in front of the mirror. In figure 2 we show cross-correlation traces of typical pulses, including flat-top of two different durations (5 ps (fwhm) and 10 ps (fwhm)), Gaussian profile and an increasing ramp.

The latter is the shape requested for optimum operation of FERMI at high charge (800 pC) as described in [29]. The use of the deformable mirror allows adjusting the exact slope of the
ramp in order to linearize longitudinal wakefields effects in the linac and consequently flattening the electrons longitudinal phase space for optimizing the FEL performance. However, at present, FERMI injector has been operating at a lower charge (500 pC) and experimental characterization of the projected emittance as a function of temporal duration of the drive laser has revealed that is preferable to function with a short laser pulse, of about 4 ps FWHM (i.e. \(\sim 1.7\) ps rms). Moreover, this choice helps reduce the requirement on the longitudinal flatness, which should be less than 5\% (rms) according to the FERMI design [12]. As mentioned in the Introduction the generated electron beam of 500 pC evolves very rapidly under the longitudinal space charge forces, reaching after one meter drift a bunch length of about 2.8 ps (rms).

The transverse profile of the UV beam reaching the photocathode is requested to have a truncated Gaussian or top-hat shape in order to efficiently produce a low emittance electron beam. The FERMI PIL laser system has two modalities for obtaining these profiles. The one that has been mostly used so far delivers a truncated Gaussian beam and is based on a hard aperture (with 12 different remotely exchangeable diameters), intercepting the beam at the exit of the time shaping part. The aperture is then imaged onto the photocathode by the beam transport system with a proper de-magnification. A typical spot is shown on figure 3 on the left. As an alternative, an aspheric beam shaper is inserted for generating a flat-top UV beam (see figure 3 on the right).

In order to characterize quantitatively the drive laser transverse profile quality, analyses of the angular and radial power distribution has been routinely performed. This has allowed comparing different transverse profile shapes and checking the evolution of the drive laser quality day by day. Figure 4 shows an example of a virtual cathode image (inset picture) and its angular and radial distribution analysis. In a perfect transverse flat-top case, the angular and radial distribution (up to the maximum radius) should be uniform, while in this case the angular power rms (\(\sigma_{\text{ang}}\)) is about 19\%, and the radial power rms (\(\sigma_{\text{rad}}\)) is 23\%.

Defining the quality factor \(\Xi\) as

\[
\Xi = \sqrt{\frac{(1 - \sigma_{\text{ang}})^2 + (1 - \sigma_{\text{rad}})^2}{2}};
\]

a perfect uniform beam \(\Xi = 1\). For the example in figure 4, \(\Xi = 0.79\), i.e. 79\%. Typically the PIL transverse \(\Xi\) factor ranges from 0.75 to 0.90. Even if a complete analysis, as already treated in [30,
was not carried on, we experimentally verified that the beam emittance is more influenced by angular anisotropies (e.g. "holes" or "hills"), than radial non-uniformity. Moreover a slightly lower density of electrons at higher radius mitigates radial space charge forces, helping the emittance compensation process especially for high charge bunches. Beginning in the middle of 2011 we have routinely adopted a transverse truncated gaussian distribution (total radius = 0.65 mm) which produces better transverse emittance beams. A recently published analytical and experimental investigation on the impact of the spatial laser distribution on the beam emittance confirms our empirical results \[32\].

The beam transport from the laser table to the beam insertion breadboard close to the gun is in low vacuum and incorporates relay imaging allowing a very high pointing stability (better than 4 µm RMS over 8 hours). The breadboard that contains the virtual cathode CCD and other diagnostics is not in vacuum. An important feature of the FERMI gun design, compared to standard designs, is that the last folding mirror sending the beam to the cathode is outside the gun vacuum, allowing use of a multilayer dielectric mirror which has a higher damage threshold than metallic mirrors. In the first commissioning run, the synchronization of the photoinjector laser to the FERMI timing was performed by using the commercial RF-phase detection based locking electronics supplied by Coherent, with a typical timing jitter of about 150 fs RMS (10Hz-10MHz). In order to improve the performance, especially in terms of slow timing drifts, the PIL synchronization system has been upgraded to balanced optical cross-correlator based version. At present this system gives better than 100 fs rms jitter and cancels the timing drifts of the laser oscillator.

Figure 5 shows the electron bunch arrival time jitter measured with the bunch arrival monitor \[33\], located after the first magnetic chicane at 300 MeV. During these measurements, the chicane was set straight and all the accelerating RF sections were set on crest. In this condition the electron beam time jitter is mainly due to the difference between the drive laser time jitter and
Figure 5. Bunch arrival time jitter measured at 300 MeV with a bunch arrival monitor system, based on a 4-electrode (open coax-line type) pick up. Each point corresponds to the rms time jitter measured over ten consecutive bunches. The red line is the mean value (86 fs) calculated over 50 consecutive measurements.

Table 3. Gun cavity parameters at 22.9 °C in air.

| Parameter        | Measured Value |
|------------------|----------------|
| π mode f         | 2997.92 MHz    |
| 0 mode f         | 2983.30 MHz    |
| $Q_0$            | 11900          |
| Field balance    | 0.99           |
| $S_{11}$         | -15.9 dB       |
| Coupling         | 1.38           |
| Filling time     | 520 ns         |
| Input power for 120 MV/m | 10.3 MW |

the gun RF phase jitter. A time jitter of $86 \pm 22$ fs has been measured, well below the design requirement of 350 fs [12].

4 The photocathode RF gun

The 1.6-cell RF gun cavity parameters are listed in table 3. One of the requirements for a photoinjector dedicated to a scientific user facility such as FERMI is reliability and constant quality of the generated electron beam. This led us to chose the proved BNL/SLAC/UCLA gun design. The 1.6 cell normal conductive RF gun for FERMI was built by the Particle Beam Physics Laboratory at UCLA [22]. The gun cavity dimensions were carefully designed in order to control the resonant frequency and to allow the absence of the full cell tuner penetrations: this shrewdness has been
adopted to reduce the arcing risk. The final tuning can be performed by cathode deformation and also temperature control. The optimization of the RF gun cavity shape led to a frequency separation of the $0$-mode from the $\pi$-mode greater than 14 MHz. This minimizes the beam energy spread at the gun solenoid and downstream optical aberrations.

Measurements of the mean energy and energy spread of the bunch versus the RF gun phase have been performed at the gun spectrometer with results being shown in figure 6. A minimum energy spread of 9 keV (rms) is obtained when the RF phase is set -22 deg off the zero charge extraction, for a 350 pC, 2.4 ps (rms) long bunch.

We have estimated the increase in the projected emittance produced by the chromatic effects of the solenoid, using the following expression [34]:

$$\epsilon_{\text{n,chrom.}} = \beta \gamma \sigma_x^2 K (\sin(KL) + (KL) \cos(KL)) \frac{\sigma_E}{E}$$

(4.1)

where $\beta \gamma$ is the Lorentz factor, $\sigma_x$ is the beam size at the solenoid, $\sigma_E$ is the rms energy spread, and $E$ is the beam energy. We have considered the solenoid focal length definition: $1/f_{\text{sol}} = K \sin(KL)$, where $L$ is the solenoid magnetic length, that in our case is 0.142 m. Assuming a rms spot size of 1 mm at the solenoid, an energy spread of 9 keV at the gun exit, a beam energy of 4.7 MeV and the nominal value of $K = 7.7$ we estimate a projected emittance increment of about 0.2 mm mrad.

For the FERMI injector, the gun solenoid comprises four coils, each of which could be supplied independently. However we have used the same configuration adopted in the SPARC photoinjector [19]: the current in the first two coils has the opposite sign relative to the current in the third and fourth coils, so the Larmor rotation angle is compensated when the beam passes through the solenoid. This is useful in the drive laser pointing alignment system on the cathode because there is a full correspondence between the laser and the electron beam movements when varying the solenoid strength. As a consequence, it is necessary to increase the power supply current of the solenoid by about 15% to obtain the same integral field, i.e., the same focusing strength. Supplying the four coils with the same current, the chromatic contribution to the projected emittance is slightly decreased to 0.18 mm mrad.

For the 350 pC operation the best emittance has been obtained setting the gun RF phase at the minimum energy spread, that occurs at -22 deg off that corresponding to zero crossing of the RF field. On the contrary, when operating at higher charge, we found that it is preferable to slightly adjust the gun RF phase to increase the beam energy, i.e., the accelerating gradient, in order to counter the defocusing effect of the stronger transverse space charge forces. For the nominal 500 pC the best emittance is obtained when the gun RF phase is at -30 deg.

### 4.1 Schottky scans

In machine operation, the relative phasing between the gun RF field and the laser arrival time on the cathode has to be maintained and reestablished at any start-up. It is important to reproduce the nominal RF phase during operation to maintain the best emittance and especially to keep the electron beam matched to the nominal machine optics.

The phasing is established by running a "Schottky scan" [36]. This varies the accelerating field phase while measuring the extracted bunch charge by means of the first current monitor placed at 0.6 m from the cathode. In order to calibrate the RF phase shifter and to be able to set the nominal
value, we routinely compare the measured curves with the simulated one. The Astra program [35] can model the charge extraction and acceleration up to the gun exit taking into account the Schottky effect and the space charge limitation effect as well as the field reversion that accelerates electrons back towards the cathode. In this way the whole (the 360 deg cycle) measured curve could be reconstructed for different operating conditions. After selecting the simulated curve corresponding to the operation set of gun and laser parameters, such as accelerating field amplitude, laser pulse duration and transverse size and beam energy, by using a developed software tool we find the phase offset to calibrate the phase shifter with respect to the zero crossing of the RF field on the cathode.

Figure 7 shows three experimental phase scans, relative to three different operation modes and the corresponding simulated curves we used to find the zero crossing. The horizontal axes displays the phase between the RF field and the laser which is defined so that the zero occurs when the laser pulse centroid hits the cathode in coincidence with the zero crossing of the RF field. Similarly the $-90$ deg corresponds to the maximum accelerating electrical field on the cathode. When increasing the extracted charge, as for the high charge case (red line), the space charge forces dominate on the photoemission process and the charge increment has a higher slope than the similar case with lower charge (blue line). In order to well reproduce this effect at high charge, in the ASTRA simulations the contribution coming from the linear dependence on the electric field, modeling the space charge limitation, has to be increased.

4.2 The cathode efficiency

The cathode efficiency relative to the UV laser parameters is evaluated by measuring the bunch charge extracted versus the laser pulse energy. The linear slope of the data curve, typical of the single photon process, quantifies the system quantum efficiency (Q.E.). Figure 8 shows the initial (September 2009) performance of the gun. The extraction limit due to the space charge is clearly
Figure 7. Three measured charge versus phase behaviors with the relative simulated curves. In all three cases the maximum accelerating electric field is 100 MV/m and the laser transverse distribution is a truncated Gaussian with a full radius of 0.65 mm in the low charge case and 0.60 mm in the other two cases. The laser temporal distribution is a flat-top with a FWHM of 5 ps (see black profile in figure 2) in the low charge case and a short Gaussian with a sigma of 1.7 ps (see green profile in figure 2) in the other two cases. The laser pulse energy for each case is reported in the legend.

visible in the roll-over of the data from the linear dependence. Fitting the linear part, the Q.E. is estimated equal to $7.5 \times 10^{-5}$. During the first commissioning months (Sept.-Nov. ’09), a Q.E. degradation was observed with a drop down to few $10^{-6}$; moreover, the charge curve moves from a linear dependence from the laser energy to a quadratic one. The possible explanation of the effect is that some material with the work function higher than the laser photon energy ($4.73\,eV$) has been deposited on the Cu cathode surface and therefore the photoemission is affected by two photons processes. This idea is supported also by the fact that the vacuum level in the system was not optimum (about $7 \times 10^{-9}\,\text{mbar}$) at that time.

During the shut-down between November ‘09 and February ‘10, we performed an ozone cleaning procedure. This technique, standard for semiconductor surfaces [37], has been applied on a metallic cathode for the first time. It consists in venting the gun cavity with oxygen and in illuminating the cathode for few hours with a mercury lamp. After a UV light exposure that assists the ozone cleaning, the system is pumped down and baked out. When the beam commissioning started again in February 2010, the Q.E. was restored. Figure 9 compares the charge extracted before and after the cleaning. After mapping the Q.E. on the cathode by scanning the surface with a small laser spot probe (about $200\,\mu\text{m}$ rms size), we observed that the degradation is stronger in the cathode center, which is the interaction area with the laser. Figure 10 shows the comparison between the Q.E. map of October ‘09 and that one of February ‘10. The central degradation is
Figure 8. The measured charge versus the laser pulse energy; phase set at -35 deg from the zero crossing.

Figure 9. Comparison of the charge vs. the laser pulse energy before (red solid line) and after (green dashed line) the ozone cleaning. Phase set at -30 deg from the zero crossing.

almost completely removed and the Q.E. variation over the surface is restricted to few $10^{-6}$.

During 2010, the Q.E. was monitored, revealing another quantitative decrease. Figure 11
Figure 10. Q.E. map before (on the left) and after (on the right) the ozone gas treatment.

Figure 11. The various measurements of the charge vs. the laser pulse energy during the first 3 months of 2010. On the top-right side the Q.E. trend.

shows how the charge extracted versus the laser energy curves changes by the time and on the right-top side the estimated Q.E. is plotted. The efficiency again dropped to a few $10^{-6}$. During the following shut-down the ozone treatment was successfully repeated. Since then, this procedure was routinely implemented during each shut-down. After months of operation, the vacuum in the gun cavity and in the diagnostic beamline improved, decreasing in operation pressure of $5 \cdot 10^{-10}$ mbar. The cathode preserves the Q.E. over a run time span, suffering only a smaller degradation. Fig-
Figure 12. Collection of Schottky scans over the entire year 2011. The data are in Q.E., i.e. the charge is normalized over the laser energy.

Figure 12 shows the Schottky scans collected over the entire year 2011. The good effect of the cleaning performed in April and in July is quite noticeable.

5 Emittance measurements

As shown in figure 1, four quadrupoles and four multi-screens stations are installed after the L0 linac sections, constituting the "optics matching area" [38]. In this zone projected emittance and Twiss parameters measurements have been routinely performed during the commissioning. In the optimization process, the first goal is finding the proper settings of the RF gun phase and intensity of the solenoid field to compensate the normalized projected emittance evolution from the cathode to 100 MeV energy, the region where the space charge forces dominate [39, 40]. This area is devoted to optically match the electron beam coming out from the photo-injector with the linac predefined lattice. Beam position monitors (BPMs) and correctors are installed after the gun, in between the two accelerating sections and in the matching area, allow us to steer the beam close to the L0 linac electromagnetic axis and to the quadrupoles’ magnetic axis. Two screens encompass the laser heater chicane that contains an undulator for heating of the electron beam. Both simulations and experimental tests demonstrated that the small bending angle does not perturb the lattice optics more than a few percent and do not affect the beam’s projected emittance. The fourth quadrupole lies after the L0 linac and the subsequent third screen, where the nominal optics have a beam waist, are used to measure the transverse emittance and the optics parameters with the quadrupole scan technique. We typically acquire five or more images at each of ∼10 quadrupole strength values. As anticipated, the OTR screen gives highest resolution.

Determining the beam size is the critical step in the measurement process. Shot-to-shot image processing has been implemented directly in the digital CCD camera server [41] and the beam
size could be obtained with different approaches. Readers are addressed to reference \[41\] for a more detailed description of the CCD server. It is possible to select manually a Region of Interest (ROI) or enable an automatic ROI option which finds the best square area containing the beam spot shot-to-shot. A background subtraction option is also implemented. The advantage of using a shot-to-shot image processing is straightforward: by driving the quadrupole scan synchronously with the acquisition of the screen image, it is possible to obtain a good estimation of the projected emittance in about 50 shots, which at the present 10 Hz repetition rate of FERMI corresponds to 5 seconds. In the future, when the linac will be switched into 50 Hz operation, the beam emittance could be measured in “a quasi-real time” mode.

Different approaches to compute the beam size have been implemented either for shot-to-shot image processing or for off-line analysis. One option consists in computing the raw rms over the entire profile or over a fractional area-integrated projection cut. We typically use 5% but we have applied larger cutting to investigate the contribution of halo particles and to separate them from the bunch core. Another method consists of fitting the image projection with a classical Gaussian or with an Asymmetric Gaussian. We have also implemented an "ad hoc" fitting function that we call "confi", built on the basis of the well-known Super Gaussian function \[42\], adding a fitting parameter to evaluate the asymmetry in the profile:

\[
Y = K \cdot \exp \left( \frac{|x - \mu|^{a+b \cdot \text{sign}(x-\mu)}}{g + d \cdot \text{sign}(x-\mu)} \right)
\]

\[
K = \frac{1}{(g + d)^{\frac{1}{2(a+b)}} \Gamma \left(1 + \frac{1}{a+b}\right) - (g - d)^{\frac{1}{2(a+b)}} \Gamma \left(1 + \frac{1}{a-b}\right)}
\]

(5.1)

where K is the normalized constant, \( \Gamma \) is the mathematical gamma function and \( \mu \), \( a \), \( b \), \( g \) and \( d \) are fitting parameters. When \( a = 2 \) and \( b = 0 \), the function is a standard Gaussian with symmetric standard deviation for the left and right tail. The second moment of the "confi" distribution has an analytical expression that we use for measuring the beam size. In case of strongly non-Gaussian profiles, the "confi" function allows fitting the whole projected beam size without cutting the drawn out tails, providing a 100% charge emittance estimation. Figure 13 shows an example of not perfect Gaussian profile, acquired during a quadrupole scan. One can observe a left tail due to transverse wakefields that were not completely compensated, inducing a longitudinal "banana shape" that translated into a larger beam size projection at the screen.

The rms beam spot sizes, measured scanning the quadrupole strength, are used for computing the projected emittance and the "Courant-Snyder" parameters, following the experimental method well described in [43]. We acquired several images for each strength of the quadrupole and the statistical standard deviation of the measured rms beam size is used as weighting factor in the least-square fitting used for determining the "Courant-Snyder" parameters. The statistical error over the beam size provides the main contribution in the error propagation to the "Courant-Snyder" parameters and to the emittance evaluation. Figure 14 shows an example of quadrupole scan measurement output relative to a 500 pC - 2.8 ps (rms) electron bunch, performed after optimizing the solenoid (**B_{peak} = 0.239 T**) and the RF gun phase (−30 deg from the zero charge extraction) and after matching the optics with respect to the nominal lattice. The quadratic beam size obtained in this case with a 5% charge cut in the post-processing, is plotted versus the focusing strength of the
quadrupole ($KL$) on the right graphs. "Courant-Snyder" parameters and beam normalized transverse emittance provided by the aforementioned processing are reported directly on the picture.

In order to graphically estimate the operational efficiency we compare in the left plots the ellipse obtained with the nominal optics (dashed blue line) with the experimental ellipse reconstructed with the measured parameters (black continuous line). Since both ellipses are plotted in the normalized phase space $(x\sqrt{\beta}, \alpha x + \beta x')\sqrt{\beta}$, they are circles with radius equal to the square root of the geometric emittance. Using the lattice model, we backtrack the beam size measured for each quadrupole strength and its divergence inferred from the measured optics parameters up to the entrance of the forth quadrupole. Results are then plotted in the normalized phase space as straight lines, which should ideally intercept the measured ellipse at their tangent points, providing in addition a measure of the phase space coverage obtained with the quadrupole scan. Considering the high charge density, the results in terms of projected emittance (0.64 $\mu m$ in x and 0.58 $\mu m$ in y) are close to the best we have obtained; the rms error is only a few percent. Even the optics parameters errors are of the same order of magnitude and these results are quite repeatable over few minutes. Comparison with tracking code simulations are reported in the next section.

Slightly different results are obtained when applying a different fitting method to the screen raw image data to get the rms beam size. Figure 15 shows the projected emittance measurements of the optimized electron bunch (500 pC-2.8 ps ) obtained with a “confi” fitting, with a Gaussian fitting, and by calculating the raw rms over a variable area-integrated projection cut (fractional charge). The error bars corresponds to the statistical error propagated to the emittance measurements obtained with the aforementioned method. The “confi” processing output is very close to what is obtained considering 100% of the bunch charge, including halo particles. On the other
Figure 14. Square of the beam size ($\sigma^2$) in horizontal (on the top) and vertical (at the bottom) plane as a function of the quadrupole strength ($KL$), where $L$ is its magnetic length. On the left: measured (black continuous line) and nominal (dashed blue line) ellipse in the normalized phase space and lines representing the measured beam size at each quadrupole setting backtracked to the reference point.

hand, the Gaussian fitting provides a projected emittance of 0.67 (horizontal) and 0.59 (vertical) mm mrad, very close to the values obtained cutting the 5% of the total charge. We therefore conclude that performing a Gaussian fitting is equivalent to consider an effective bunch core, neglecting in an indirect way the halo particles contribution to the projected emittance. Figure 15 also displays the expected emittance trend evaluated by simulating the optimum case with the tracking code GPT [44]. Experimental measurements are in good agreement with the simulation results and
suggest that the optimized FERMI injector provides a very bright bunch core. In fact, a halo charge of \( \sim 100 \) pC is responsible for the 70% of the whole projected emittance; the central core of about 400 pC has a projected emittance of about 0.3 mm mrad, as predicted by simulations.

6 Electron beam optimization

In the injector beam optimization process, we initially (2009) operated in a very relaxed configuration (short bunch and low charge). We then progressively increased the bunch charge from 250 pC to 500 pC, preserving the transverse projected emittance well below 1.0 mm mrad, as summarized in table 4. When increasing the charge, the transverse wakefields effects in the first two accelerating sections (L0 linac) became more important. This required an optimization of the trajectory in the L0 linac that improved the beam transverse projected emittance at the end of the injector.

To optimize the projected emittance after the first L0 linac, it is necessary to find the proper settings of the RF gun and of the solenoid \([39]\). For a 500 pC bunch we experimentally obtained the best projected emittance when the RF phase was set at -30 deg off the zero charge extraction phase. Concerning the solenoid field setting, this could need some adjustment week by week due to slightly differences in the drive laser transverse profile. In figure 16 we plot an example of the measured projected emittance (in x and y) as a function of the gun solenoid peak field, compared with GPT tracking code simulations \([44]\). In order to better compare the simulation
Table 4. Improvements in the electron beam brightness at the injector exit.

| Time Period    | Charge [pC] | Bunch Length (RMS) [ps] | $\varepsilon_{xy, proj}$ [mm mrad] |
|----------------|-------------|-------------------------|-----------------------------------|
| December 2009  | 250         | 2.1                     | 0.90                              |
| March 2010     | 350         | 2.4                     | 0.95                              |
| September 2010 | 350         | 2.4                     | 0.85                              |
| April 2011     | 450         | 2.6                     | 1.0                               |
| September 2011 | 450         | 2.6                     | 0.80                              |
| October 2011   | 350         | 2.4                     | 0.50                              |
| February 2012  | 500         | 2.8                     | 0.75                              |
| April 2012     | 500         | 2.8                     | 0.65                              |

results with the experimental data, we calculated the predicted rms normalized emittance for the whole (100%) simulation particles ($\varepsilon_n$) and for the inner 95% core ($\varepsilon_{n,95\%}$). The experimental data were processed executing the 5% charge cutting described above. The measured $\varepsilon_x$ and $\varepsilon_y$ behaviors versus the solenoid current shows a trade off between the trend of the theoretical $\varepsilon_n$ and $\varepsilon_{n,95\%}$. In the experiment the solenoid setting corresponding to the minimum projected emittance value in the horizontal plane is not perfectly coincident with the minimum value obtained in the vertical plane, even if both are very close to the expected values. A possible reason for this is that asymmetries between the two planes of the drive laser transverse profile or in the quantum efficiency of the cathode surface eventually translate into a transverse anisotropic electrons distribution. In the optics matching procedure, we are able to use the four quadrupoles after the L0 linac with two quadrupoles installed in between the two sections. These two quadrupoles act on the beam at about 50 MeV, where the space charge forces are not negligible, so they play a role in the emittance compensation process. For the ideal case of perfect symmetric transverse distribution at the cathode, these two quadrupoles should have the same strength but opposite signs. In the real machine optimization, we have been iterating the optics measurements and the matching procedures in order to converge to values that partially balance the cathode emission asymmetries. For the data reported in figure 16, the two quadrupoles settings have a 10% difference in absolute value, while in the simulation the quadrupoles are switched off, indicating there are asymmetries upstream experimentally.

7 Slice emittance measurement

In order to measure the time-sliced emittance of the electron bunch coming from the injector, we have used a multi-purpose diagnostics station installed downstream of the first magnetic chicane (BC1) [45]. This station included a RF deflecting cavity [46], three multi-screens, a bunch length monitor based on the detection of the edge radiation coming from the last BC1 dipole magnet, a ceramic gap and a bunch arrival time monitor. For these measurements, the BC1 chicane is set to zero angle.

The experimental method to measure the time-sliced emittance is also in this case based on the quadrupole scan technique described in the previous section. The beam is vertically stretched by the RF deflecting cavity before passing, after a couple of meters, through the quadrupole used for the
measurements of the horizontal slice emittance. The diagnostic screen is about 6.8 m downstream of the quadrupole. Figure 17 shows that the typical beam spot has a vertical dimension of few mm. When the deflecting cavity is switched off, the beam spot dimension is about 200 \( \mu m \) (rms). Therefore the perturbation by the non-zero transverse emittance could be neglected which allowed us to slice the streaked beam trace in several portions. The measured horizontal emittance of ten time-slices are plotted on the right of figure 17 for a 500 pC electron bunch. The behavior of the slice emittance in the bunch core reflects the slice current profile: a maximum value of about 0.65 \( \mu m \) is in correspondence of the 60 A peak current slice. If we neglect the tails of the electron bunch and consider the 80% core, the average time-sliced horizontal emittance is 0.55 \( \mu m \) with a standard deviation of 0.08 \( \mu m \).

8 Conclusion

In this paper we demonstrate that the FERMI photoinjector successfully provides high brightness electron beams with projected and slice emittances ranging from 0.50 to 0.65 \( \mu m \) at high peak current. The achieved peak current allowed to relax the compression in the magnetic chicanes and consequently constrain the slice energy spread enhancement and reduce the microbunching instability growth. The FERMI photoinjector has been routinely running to produce electron bunches which are sent into the undulators beam-lines, allowing seeded FEL operation down to wavelengths below 10nm \[47\].
Figure 17. On the left: beam spot at the YAG screen after activating the RF deflecting cavity powered by 3 MW; On the right: time-sliced horizontal emittance (blue circle points) and time-sliced current (dashed red line) measurement results for a 500 pC bunch.

We have also presented a novel experimental technique that we applied to restore the degraded cathode Q.E. based on ozone cleaning processing. This procedure has allowed extraction of high-charge beams without efficiency degradation over long periods of time and has enabled keeping the reliability and reproducibility of the machine at a high level.

Acknowledgments

The FERMI injector commissioning was carried on by a tightly collaborative effort shared by physics team, laser, control, diagnostic and linac groups. We give special thanks to Simone Di Mitri for the optics matching procedure, Giovanni De Ninno, Simone Spampinati and Lars Froehlich for their support in the beam measurements and to Massimo Cornacchia and William Fawley for interesting discussions on the experimental results. This work was supported in part by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP-6AWK3.

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