COMMISSIONING AND INITIAL OPERATION OF FERMI@ELETTRA*

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Abstract

This article describes the design goals of FERMI@Elettra, reports on the goals achieved so far and shows how the facility development has been driven by the new research frontier of ultra-fast, extreme ultra-violet and soft X-ray science. The commissioning phases and first experience with user pilot experiments are presented and discussed.

OVERVIEW OF THE FACILITY

FERMI@Elettra [1] is a linac-based 4th generation light source that is an externally seeded Free Electron Laser (FEL) in the extreme ultra-violet and soft X-rays. The facility [2] is hosted in three main buildings, close to the Elettra storage ring. Figure 1 shows from the top-right to bottom-left corner, the 200 m long Linac building, the 100 m long Undulator Hall (UH) ending with the 50 m long Experimental Hall (EH). A fourth building hosts the technological plants. Civil works were carried out in different phases, in the period 2007–2010. Particular care was taken in planning the excavation activities, resorting in particular to low-vibration techniques in order to minimize any disturbance to the regular operation of Elettra. The main construction phase, devoted to the UH, EH and to the technological plants, started in 2009. Beneficial occupancy was handed over at the end of September 2010. Early co-occupancy allowed the installation of machine sections in parallel to the construction of buildings and plants. Figure 2 sketches the electron and photon beam delivery system. Main project parameters are listed in Table 1.

Figure 1: FERMI@Elettra, next to the Elettra storage ring.

Table 1: FERMI@Elettra Main Parameters. In bold, we report the design goals achieved (measured) to date.

Parameter	FEL-1	FEL-2
Output λ (fundamental)	100-**20** nm	20-4 nm
Peak Power	**0.5** – 5 GW	> 0.3 GW
Repetition Rate	**10** Hz	50 Hz
e^- Energy	**1.2** GeV	1.5 GeV
Peak Current	**200** - 800 A	800 A
Bunch Length (fwhm)	**0.7 – 1.2** ps	1.2 ps
Slice Norm. Emittance	**1.5** – 3 mm mrad	1 mm mrad
Slice Energy Spread	0.20 MeV	0.15 MeV

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The normal-conducting 3 GHz linac is equipped with 14 radio-frequency (RF) transmitters, rated at 45 MW peak power, which feed 16 accelerating sections, plus the photocathode Gun and 3 RF deflectors (presently, only one of these is installed for diagnostic purposes at low energy). Seven accelerating structures are fed in couple with a single transmitter; other seven are fed via a SLED cavity with a single transmitter. The nominal operation energy is 1.2 GeV for the first FEL line, FEL-1, and 1.5 GeV for the second one, FEL-2. Space for two additional ~3.5 m long accelerating structures is also available in the main linac. Repetition rate is presently 10 Hz and will be upgraded to 50 Hz in 2012. A "laser heater" undulator is installed at 100 MeV to cure microbunching instability (i.e., see [3] and references in [4]). Two identical, symmetric (4-dipole) magnetic chicanes for bunch length compression are installed at 350 MeV and 700 MeV. They are movable in the bending plane to allow continuously tunable bunch length compression. Diagnostics is also inside the chicane and moving with it. The in-house design was based on that of LCLS [5] at SLAC, but with some improvements on the magnet field quality and mechanical control. The nominal total compression factor is 11 that is an expected compressed bunch length of 0.7 ps (FWHM). In Autumn 2011 a harmonic cavity at 12 GHz (X-band) will be set into operation for linear time compression.

A transfer line transports the electrons from the end of the linac to the undulators. The transfer line is about 30 m long and allows switching between the two FEL lines, FEL-1 and FEL-2; it further includes collimation devices, diagnostic facilities and the seed laser insertion point. The adopted High Gain Harmonic Generation (HGHG) FEL scheme [6–8] sets the specifications for the seed laser, which has to be tunable down to 200 nm, with a peak power above 100 MW over the entire tunability range [9]. Synchronization on the fs time scale between the seed laser and the electron beam, as well as along the whole facility, is provided by an all optical timing distribution system [10].

The FEL-1 line consists of a planar undulator ("modulator") and six APPLE-II type undulators ("radiators"). The FEL-2 line runs parallel to the FEL-1 line and 1 m apart from it. A HGHG double-cascade scheme is adopted for FEL-2, which consists of a first stage with 1 modulator and 2 radiators followed by a second stage with 1 modulator and 6 radiators. The radiator permanent magnets periodicity is lower than in FEL-1, all other specifications are similar [1]. The out-of-vacuum undulator design has been carried out at the Elettra laboratory. Our laboratory also participates in KYMA, a spin-off company that has been in charge of manufacturing the undulators. The use of APPLE-II type undulators allows control of the FEL polarization that can be varied from linear to circular [11]. The wavelength of the FEL radiation can be varied thanks to the variable undulator gap (the low gap Aluminum vacuum chamber has 7 mm internal height). Fast wavelength tunability and variable polarization make FERMI a unique source for research programs aiming to investigate processes in sub-ps time scale.

At the end of the two FELs, the electrons are recombined and dumped to a common beam dump, while the photons are transported to the different experimental stations, first via Photon Analysis, Delivery and Reduction System (PADReS) [12] and then via dedicated beamlines. Three experimental programs are foreseen, namely Diffraction and Projection Imaging (DiProI), Low Density Matter (LDM) and Elastic and Inelastic Scattering (EIS), for a total of 4 beamlines, since EIS comprises two stations: TIMEX, already installed, and TIMER, whose installation is foreseen in 2012.

STRATEGY OF THE PROJECT

Commissioning of FERMI has been planned in a way to produce FEL output as early as possible with features matching the minimum internal users requirements for preliminary experiments. This strategy has implied:

- the lack of a test facility;
- an aggressive although plausible schedule for the commissioning and initial operation;
- simultaneous phases of installation and commissioning, allowed by a physical separation of different machine parts in the linac tunnel;
- intense 24 hours/day runs of commissioning alternated to 4 periods/year of machine shut down.

In spite of the challenging plan, all main deadlines have been respected, such as for the completion of civil engineering and installation (October 2010), RF conditioning and FEL-1 commissioning (end of 2010), first seeded lasing with coherent harmonic generation (13 December 2010) and FEL-1 operation with internal users (June 2011).

COMMISSIONING STATUS REPORT

All most relevant articles about the FERMI commissioning until July 2011 are in [13–17]. A short schedule of the accelerator and FEL-1 commissioning is reported in the following.

- Photoinjector (PI) laser and Gun have been commissioned in 2.5 months, starting in September 2009 (first photo-electrons were extracted at MAX-lab in 2008).
- The whole linac and first magnetic bunch length compressor (BC1) have been commissioned in 2010 in 3.5 months.
- The high energy transfer line to the Main Beam Dump has been commissioned in 2010 in 1.5 months.
- After installation of the FEL-1 undulators, first coherent X-rays have been produced on 13 December 2010, within 9 months after the linac warm up. The coherent emission produced with 6 radiators tuned at 43 nm fundamental wavelength exceeded the spontaneous emission.
- All essential components of the X-ray diagnostic area and transport system have been commissioned in 2011 in 2 months.

- True FEL exponential gain, polarization control and wavelength tunability has been achieved in 2011 in 1.5 months.
- Commissioning of the three experimental beam lines in the wavelength range 32.5–65 nm has been accomplished in 1.5 months. First user tests have thus been done 5 months after the very first coherent output.

ACCELERATOR COMMISSIONING

Main Components

The previously existing Elettra linac has been upgraded with a PI. Silica aerogels are used to measure the transversal and longitudinal profile of the electron bunch taking advantage of Cherenkov effect (the emitted light is transported and focused to an ultrafast streak camera). The PI is routinely providing a 1 mm mrad normalized emittance at 100 MeV for a 450 pC, 6 ps (FWHM) long bunch. In the main linac, the remarkable accelerating gradient of 27 MV/m has been reached that is confirming the specified 1.5 GeV final energy for FEL-2. So far, we have been routinely running FEL-1 at the energy of 1.2 GeV with a one-stage bunch length compression factor not larger than 6.

Commissioning in the photon transport area has been carried out by means of an on-line spectrometer [18], gas monitor detectors and photon Beam Position Monitors (BPMs), and off-line diagnostics such as a photo-diode with Aluminum filter for direct measurements of the FEL pulse energy, screens and slits to measure the FEL transverse coherence. Active mirrors in Kirkpartick-Baez (KB) configuration for μm level focusing on the experimental sample are in schedule.

Commissioning of the facility has obviously involved many other systems, such as the Tango-based control system [19] which incorporates a real-time framework and allows on-line control of the accelerator with an external tracking code as well as the development of Tango-interfaced MATLAB scripts. In order to achieve the milestones reported in the previous section, particular cure has been taken to design and develop electron diagnostics such as an electro-optical sampling station in front of the undulators for time-resolved measurements, bunch arrival monitors for time jitter measurements, 2 μm resolution RF cavity BPMs and screen systems, both for electrons and X-rays, in between the undulator segments. To operate the accelerator under real-time safety condition, the machine protection system includes Cherenkov fiber beam loss monitors, on-line dosimeters and ionization chambers [20].

Cathode Cleaning

Ozone cleaning of the Gun cavity is routinely performed at the beginning of each run. In fact, after a few months of 24h machine operation we usually observe a degradation of the quantum efficiency, which is restored by filling the whole Gun cavity with Oxygen and illuminating it with a UV lamp. Thus, Ozone is created that absorbs the impurities fixed on the internal Gun surface as well as on the cathode. Then, everything is removed by venting the cavity. We generally measure quantum efficiency above the 10^{-5} level.

Electron Beam Diagnostics

The electron beam is fully characterized with the diagnostics station located downstream of the first compressor. The arrival time jitter has been measured to be around 70 fs, which is well below the design tolerance. Since it is expected to be dominated by the PI laser time jitter and the RF peak voltage and phase jitter, we deduce that all these systems are within specifications.

The absolute measurement of the bunch length, with and without compression, is done with the RF vertical deflector that stretches the beam in the vertical plane. The spot dimension is proportional to the bunch duration and in this way we can control the effective compression factor. From this image, we can also reconstruct the longitudinal charge distribution. The vertical deflection associated to the horizontal spectrometer allows us to reconstruct the longitudinal phase space. Due to the limited resolution of this system, the slice energy spread has been estimated to be less than 35 keV rms. The horizontal slice emittance has been measured below the 1 mm mrad threshold by deflecting vertically the bunch and scanning the horizontal beam size with an upstream quadrupole magnet. The measurement confirms our PI model.

External Seeding

The transverse overlap of electrons and photons is made by aligning the electron beam on the RF BPMs at the entrance of the undulator line, on the reference trajectory. The electrons and the seed laser are displayed on two Yttrium Aluminum Garnet (YAG) targets across the modulator. The seed is aligned onto the electron beam with remotely controlled steering mirrors using stepper motors for the coarse positioning and piezo tip-tilt for the fine one. The coarse temporal overlap of the seed pulse and the bunch is monitored through an Al foil that reflects the laser out and, at the same time, makes the electrons generating OTR. The laser and the OTR signals are detected with a fast photodiode, read by an oscilloscope. A delay line on the seed laser path is used for fine tuning of the seed pulse in time.

We use the last YAG screen of the main beam dump line to optimize the seeding process. This screen is in a high dispersion area. The horizontal axis is therefore proportional to the particle energy. At the same time, when the electron bunch is compressed, it has a residual energy chirp so that the horizontal axis of the screen is also proportional to the longitudinal coordinate along the bunch, with higher current at lower energies. Accordingly, when traveling along the line, the electrons that are modulated in energy by the seed laser are moved away from their initial position along the bunch: they are actually moved at the edges of the overlap area that appears at the screen as charge depletion. Looking to this hole, we can visualize the time-overlap of seed and electrons. The maximum FEL intensity is usually obtained when the seed laser is at an intermediate position along the bunch, not really in the very high current region. We could state that the intermediate position corresponds to an effective optimum condition for the FEL resonance, in terms of peak current and electrons energy.

SEEDED FEL COMMISSIONING

The FEL-1 performance improved gradually in 2011, as shown in Figure 3. At 43 nm, the measured photon flux increased from less than 1×10^{9} photons per pulse in December 2010 to more than 1×10^{13} photons per pulse in July 2011. We have measured similar flux intensities at 52 nm and 32.5 nm. Most importantly, we could also reach the design lower wavelength limit of FEL-1: 20 nm, where the photon flux achieved was more than 1×10^{12} photons per pulse.

While the benefit of using external seeding in terms of bandwidth and photon energy stability was evident since the very first days of FEL operation, with a typical $\Delta\lambda/\lambda$ of 1×10^{-3} (FWHM), other important advantages have only recently been demonstrated when the bunch charge has been increased from 250 to 450 pC. In December 2010 the FEL flux was optimized with the lower charge in terms of seeding power and strength of the dispersive line. We measured a quadratic FEL gain along the radiators whose regime of emission is usually named as coherent harmonic generation. By increasing the charge with very minor changes in the accelerator and upon optimizing the FEL on the TEM_{00} Gaussian mode, we obtained clear evidence of true FEL exponential gain. FEL simulation based on the experimental beam parameters agrees well with the experimental result. The gain length at this stage is 3.5 m. Once FEL operation is optimized, its stability is quite good over a few hours: the central wavelength jitter is below 10^{-4}, the spectral bandwidth stability is below the 3% level and the intensity jitter is about 10%.

INITIAL OPERATION OF FEL-1

FEL light was provided already in March-April 2011 to the experimental stations for beamlines and end-stations commissioning. During that period, to address an LDM requirement the FEL polarization was varied for the first time from linear to circular. In July, all three experimental stations were tested with photons. The wavelength tunability of FERMI FEL has been experimentally demonstrated, during the LDM beam time. In such experimental run, a small change of the fundamental harmonic of the FEL radiation around 52 nm has been achieved by varying the seeding laser wavelength by approximately 1 nm, corresponding to 0.4% variation of the FEL wavelength.

Due to delay in installing user-dedicated focusing mirrors, first coherent diffraction imaging tests with DiProI were carried out using a 20 μm pin-hole for tailoring the FEL pulses and illuminating the test specimens, pinholes of different sizes and a periodic array sample. The obtained diffraction patterns confirmed the excellent transverse and longitudinal coherence of the FEL pulses.

OUTLOOK AND LESSONS LEARNED

In spite of the success and important milestones achieved so far, the accelerator and the beamlines are not yet in their final configurations. Commissioning of the second compressor, X-band, Laser Heater, FEL2, 50Hz operation, all these new tools require much work and time. In addition to this, some other smaller issues have to be faced in terms of electron beam quality such as projected emittance growth along the linac due to single bunch transverse wake field instability, optimization of the feedback loops and optics matching of the electron beam into the FEL undulators. They are not limiting the FEL performance right now but are expected to do at shorter wavelengths (FEL-2). The installation and commissioning of the focusing optics for providing well focused μm-sized illumination spots and implementation of split-delay lines for opening the possibility for time-resolved experiments are the priorities that will be completed before the end of 2011.

Finally, we would like to highlight three aspects of our commissioning experience. First, there was no need to optimize the SASE [21, 22] mode to optimize the HGHG output. The seeding was achieved at the first try. Second, because of the very aggressive commissioning plan, the FEL was finally obtained in a relatively short period of time, but we have now a machine that is still under development. This implies our commissioning is a compromise between testing subsystems, physics studies and preparation of FEL for users. The facility allows us to increase the charge by 40% with only minor changes to the settings. Doing this, the FEL gain increases accordingly.We interpret this result as a demonstration of robust machine design and a large machine acceptance in the beam parameter space.

Next year will be focused on FEL-2, whose final aim is producing first 10 nm and later on 4 nm fundamental wavelength with the two-stage HGHG. The 3 nm wavelength could in principle be obtained by rising up the linac energy to 1.8 GeV or implementing direct seeding at 30 nm. The 1.5 nm is on the horizon, possibly obtained in a few years with direct seeding or other FEL schemes. Analytical models and simulation results show that this picture is feasible for FERMI with the available technology and know-how.

CONCLUSION

FERMI@Elettra FEL-1 commissioning is at a fairly advanced stage and we expect to attain the full design performance of FEL-1 by the end of 2011. First operation with internal users has already started. Commissioning of FEL-2 will start in 2012, in parallel to the user experiment program that will be launched on FEL-1.

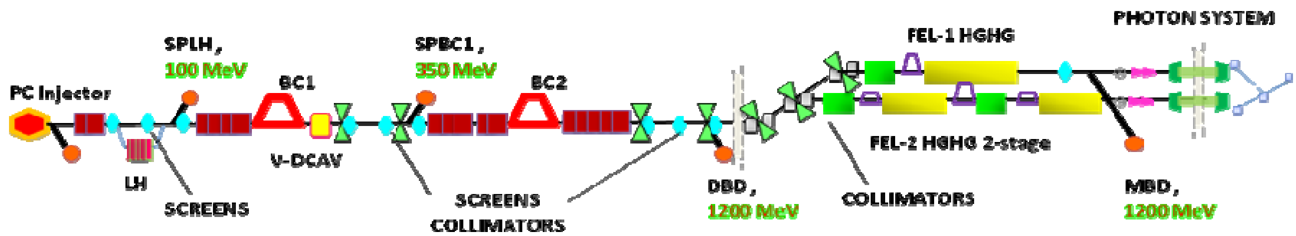

Figure 2: FERMI layout, from the Gun to the photon transport system (conceptual).

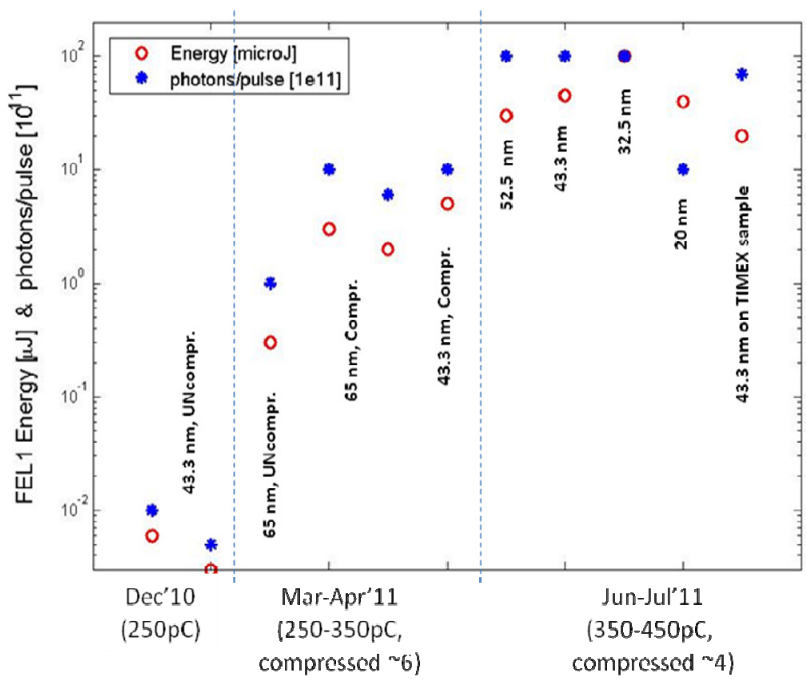

Figure 3: FEL-1 energy and photons per pulse during commissioning from December 2010 to July 2011.

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