FERMI @ ELETTRA – A SEEDED HARMONIC CASCADE FEL FOR EUV AND SOFT X-RAYS

C. Bocchetta, D. Bulfone, P. Craievich, M. B. Danailov, G. D'Auria, G. DeNinno, S. Di Mitri, B. Diviacco, M. Ferianis, A. Gomezel, F. Iazzourene, E. Karantzoulis, F. Parmigiani, G. Penco, M. Trovo, Sincrotrone Trieste, Trieste, Italy
J. Corlett, W. Fawley, S. Lidia, G. Penn, A. Ratti, J. Staples, R. Wilcox, A. Zholents, LBNL, Berkeley, CA, USA
W. Graves, F. O. Ilday, F. Kaertner, D. Wang, T. Zwart, MIT, Cambridge, MA, USA
M. Cornacchia, P. Emma, Z. Huang, J. Wu, SLAC, Stanford, CA, USA

Abstract

We describe the machine layout and major performance parameters for the FERMI FEL project funded for construction at Sincrotrone Trieste, Italy, within the next five years. The project will be the first user facility based on seeded harmonic cascade FEL's, providing controlled, high peak-power pulses. With a high-brightness rf photocathode gun, and using the existing 1.2 GeV S-band linac, the facility will provide tunable output over a range from ~100 nm to ~10 nm, with pulse duration from 40 fs to ~ 1ps, peak power ~GW, and with fully variable output polarization. Initially, two FEL cascades are planned; a single-stage harmonic generation to operate > 40 nm, and a two-stage cascade operating from ~40 nm to ~10 nm or shorter wavelength. The output is spatially and temporally coherent, with peak power in the GW range. Lasers provide modulation to the electron beam, as well as driving the photocathode and other systems, and the facility will integrate laser systems with the accelerator infrastructure, including a state-of-the-art optical timing system providing synchronization of rf signals, lasers, and x-ray pulses. Major systems and overall facility layout are described, and key performance parameters summarized.

OVERVIEW OF THE FACILITY

The FERMI @ Elettra facility will make use of the existing GeV linac at Sincrotrone Elettra, which will become available for dedicated FEL applications following the completion of construction of a new injector booster complex for the storage ring. With a new rf photocathode injector, and some additional accelerating sections, this linac will be capable of providing high brightness bunches at 1.2 GeV and up to 50 Hz repetition rates. Figure 1 shows a preliminary CAD drawing of the proposed facility, with the linac-based FEL facility adjacent to the Elettra storage ring building.

To accommodate the new rf photocathode gun, the tunnel which houses the existing linac and thermionic gun will be extended upstream. This will be a relatively minor investment in additional excavation and will take advantage of the present roadway cutting, already at the level of the linac and extending backward several meters.

An S-band rf photocathode gun, with spatial and temporal control of the photocathode laser system, will provide high brightness electron bunches at up to 50 Hz rate. Flexibility in bunch parameters will be incorporated into the systems design. Accelerating sections raise the beam energy to ~100 MeV at the exit of the injector.

A laser heater system following the injector system will provide control of the uncorrelated energy spread in the beam and minimize potential impact of the microbunching instability. The laser heater also allows opportunity for implementing useful diagnostics systems.

Two magnetic bunch compressors are planned, inserted at 230 MeV and at 650 MeV. The final energy of the beam, 1.2 GeV, is determined by the accelerator section maximum gradient, available RF power including overhead and de-rating for reliable operations, and off-crest operation for control of energy chirp.

The linac is installed in a tunnel about 5 m below ground level, and the new facility will include a transport line to take the beam up to an undulator hall at or near the surface. This vertical ramp allows inclusion of useful diagnostics, and is carefully designed to minimize perturbations to the beam quality.

In the undulator hall, the electron beam may be directed to the longer-wavelength FEL (FEL-I) by a transport line which introduces a horizontal offset to the beam, or to the short-wavelength FEL (FEL-II) in a direct line to avoid perturbation to beam quality due to CSR in bend magnets.

A timing system based on transmission of optical signals over a highly stabilized fiber optic system will distribute timing signals throughout the facility. This provides synchronization of the photocathode laser to the RF gun phase, stabilized drive signals to RF systems in the facility, and synchronization of the FEL seed laser with the arrival time of the electron beam.

The seeded FEL process occurs in one stage of harmonic generation for FEL-I, and in a two-stage cascade for FEL-II. For FEL-II, both a fresh-bunch approach and a whole-bunch seeding technique are being developed. The x-ray pulse duration is determined by the seed laser, and both short-pulse (~40-100 fs) and long pulse (~0.5-1.0 ps) schemes are under development.

The photon beams from the FELs are transported in beamlines to hutches an adjoining downstream experimental hall. The electron beams are dumped following the final radiating undulator. Laser systems in the experimental area are synchronized to the FEL output using the stabilized optical timing system distributed around the facility.

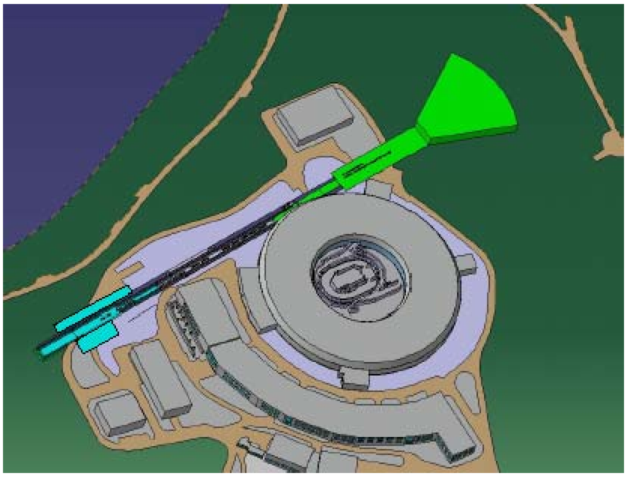

Figure 1: The FERMI FEL facility shown adjacent to the existing synchrotron radiation source Elettra.

Figure 2 shows the machine layout with various sections identified; INJ – injector, L1-L4 – linac sections, BC1,2 - bunch compressors, MTC1,2 – matching section, RAMP – vertical transport line, SPRD – beam spreader section, FEL1,2 – FEL's.

INJECTOR

The injector major systems are; photocathode laser, RF gun, booster linacs, emittance compensation solenoids, and laser heater. A diagnostics beamline will be incorporated in a branch line following the RF gun, to allow analysis of the beam phase space at the exit of the gun. A high quality electron source is essential to meet the requirements for photon production in the FERMI @ Elettra FEL. Two different bunch charge regimes have been explored; low (few hundreds of pC) and high (~1nC). In the first case, the limited charge extracted from the photocathode allows production of a relatively short bunch and to compress it at higher energies down to a few hundreds of fs, attaining a high peak current bunch with a very low slice emittance. The second case is optimized for the possibility to produce a longer bunch required for the harmonic cascade (FEL-II). Details of the injector design are presented in [1].

Photocathode laser

The photocathode laser must produce up to 1 nC of charge, and requires UV pulses with energy in the few hundred μJ range to produce low thermal emittance from a copper cathode with quantum efficiency ~10^{-5}. Taking into account the losses associated with temporal and spatial shaping systems, the harmonic conversion, and the need of a relatively large bandwidth to support a pulse with <1 ps risetime, we choose a Ti:sapphire system with >15 mJ in the infrared. Effects of intensity modulation of the laser in driving longitudinal space charge fluctuations are discussed in [2].

RF photocathode gun

The difference between 'European' S-band and 'U.S.' S-band frequencies makes it difficult to take an established S-band gun design and apply it directly to the FERMI @ Elettra project, however existing designs may be scaled to the required frequency. Operating at up to 50Hz pulse rate sets demands on the thermal control of the gun, however there are designs, such as the LCLS gun, that operate at similar high repetition rate. An attractive choice for the electron gun is the SLAC/BNL/UCLA 1.6 cell s-band gun III, based upon the demonstrated high performance of this design and its descendants. Gun design is discussed in more detail in [1].

Booster linac

Two sections of traveling wave structure provide ~100 MeV total energy to the beam in the injector. These sections work in 2/3π mode with on-axis coupling, have relatively weak wakefields, and have solenoidal windings for focusing. Effects of wakefields are discussed in [3,4].

Laser heater

At the end of the injector a "laser heater" is used to induce controlled rapid energy modulation in the bunch and effectively 'heat-up' the beam. A laser pulse interacts with the e-beam in a short undulator inserted in a chicane. The laser heater is required to provide Landau damping of microbunching instabilities in the beam, as described in [2,3]. The device will have a secondary and important function as an electron beam diagnostics tool, described in [5]. The required laser pulse peak power is moderate (below 10 MW in a pulse duration of a few ps) and infrared wavelength can be used, from the photoinjector laser or from the fiber-optic timing system master oscillator.

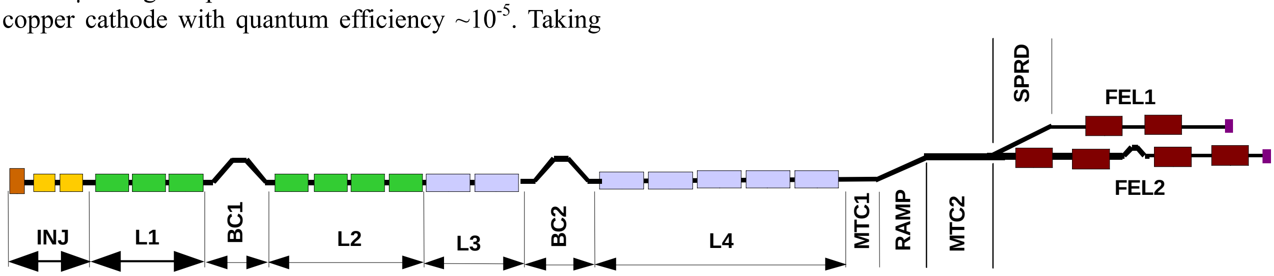

Figure 2: FERMI @ Elettra machine layout showing major sections

MAIN LINAC

Three types of accelerating sections are used in the linac, color-coded in Figure 2. Injector sections (see above) are yellow. Seven CERN-type sections (green color in Figure 2) are used before and after the first chicane. Like the injector sections, these are traveling wave (TW) structures operating in $2\pi/3$ mode and with on- axis coupling between cells. Seven Elettra-sections (blue color in Figure 2) form the high-energy portion of the linac. These final sections are backward traveling wave (BTW) structures that are coupled magnetically, operate in $3\pi/4$ mode, and provide high shunt impedance.

To meet the stringent requirements of the project the present RF systems will be completely revised and upgraded. Stabilized modulators and feedback around the RF stations will be employed to meet phase and amplitude stability requirements, and RF systems will be integrated with the stabilized timing system, as reported in [6].

Accelerating structures and wakefields

The magnetic coupling of the BTW structures demands a small iris radius compared to on-axis coupled structures, and for this reason the BTW structure wakefields are stronger than for the TW structures. We find both longitudinal and transverse wakefield effects are controllable, and a study of the emittance growth under the combined influence of the short-range transverse wakefields, injection offset, initial emittance and misaligned accelerating sections is reported in [4]. Details of overall accelerator optimization studies ("start-to-end") are described in [3].

Bunch compressors

The bunch compression uses a 'standard' technique of two chicanes of rectangular dipoles. The off-crest acceleration of the electron beam in the linac sections generates a correlated energy spread which is used with the energy-path length correlation given by the chicanes' optics to provide a compression in bunch length. The beam length is compressed by a factor of between 8 and 11 depending on details of the operating mode, and flexibility to adjust each compressor is incorporated into the design. The main challenge in the design of the compressors is to minimize the interaction between the coherent synchrotron radiation (CSR) and the longitudinal space charge (LSC), since this is the cause of the microbunching instability and the main factor degrading the beam quality. A laser heater is installed in the injector to suppress the instability.

VERTICAL RAMP

The lattice of the vertical ramp is designed such that the first two bending magnets and the last two bending magnets are separated by $-I$ transport matrixes in both x and y planes, *i.e* π betatron phase advance. A FODO lattice consisting of two doublets is used for this purpose. This constrains the dispersion function between the pairs of magnets and mitigates the emittance excitation due to CSR effects. The lattice in the middle section between magnet pairs is also a FODO structure, with π phase advance in both planes in the high-beta case and 3π phase advance in the low-beta case. The $-I$ transport matrix in the middle section is important for a compensation of the emittance excitation due to CSR effects.

FEL'S

The FEL configuration relies on a Low-Gain-Harmonic-Generation (LGHG) scheme, similar to HGHG [7,8]. In the LGHG configuration, the use of high radiation power in the modulator(s) produces micro-bunching in the low-gain regime (no self-modulation), and permits relatively short undulator lengths. Figure 3 shows the principle, as employed in FEL-I. The modulating undulators are of planar design, and only the final radiating undulator is an APPLE-type design to allow control of the output polarization.

In the case of FEL-II, a delay chicane is placed following the radiator of the first optical klystron. This ensures that a "virgin" electron-beam portion, whose electrons instantaneous energy spread has not been increased by FEL interaction in the upstream undulators, is brought into temporal synchronism with the radiation pulse. Simulations are reported in [9].

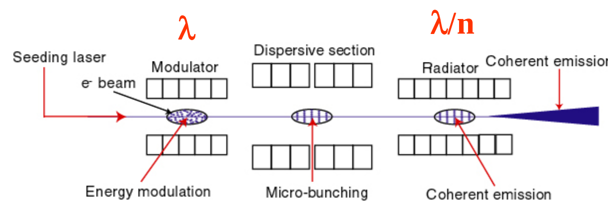

Figure 3: The principle of harmonic generation

FEL seed laser

The main requirement for this laser is to deliver sufficiently high peak power (~100 MW), at wavelengths tunable in the range 240-360 nm. Other parameters of the seed laser pulses are: Gaussian profiles, pulse duration in the range 0.2- 1 ps, high stability of the pulse energy, high stability of the central wavelength, spot size 200-300 µm.

The requirement for such a broad UV tuning can be met by using parametric amplification in the visible or near infrared, followed by harmonic generation. In addition, the high UV pulse energy needed (100 µJ range with 1 ps pulses) imposes that the energy of the pulses that will pump the parametric amplifier should be ~15 mJ.

TIMING AND SYNCHRONIZATION SYSTEMS

The timing system will play a crucial role in achieving the expected performance of the FERMI @ Elettra FELs due to the sub-ps electron bunch length and the expanded use of fs-lasers as key components. The timing system intended for a user facility that is operated on a 24-h, 7-d basis, must be stable and reliable. The fundamental components of the system are an optical reference oscillator, the fiber optic stabilized links, and the local optical to electrical converters, needed for the RF plant synchronization. Using commercial 1550 nm components, jitter at the level of 10 fs is expected between remote laser systems. Concepts are discussed in [10,11,12].

INSTRUMENTATION

The successful implementation of FEL schemes calls for precise knowledge of electron beam properties. Measurements of each of its 6 phase space dimensions will be employed, including position and momentum in both transverse planes, beam energy, bunch length, and total charge. At a minimum the first and second moments in each dimension will be measured, the detailed electron distribution in each dimension as well as the correlations between dimensions. Electron beam diagnostics are reported in [13]. Methods to measure time-dependent beam quantities with sub-ps resolution are being investigated, including diagnostics in the laser heater [5].

ACCELERATOR AND FEL MODELING

Design studies are in progress to model the FERMI @ Elettra FEL from start-to-end. Two operational scenarios are under development – for a short-pulse (40-100 fs) at the FEL and for a long-pulse (0.5-0.8 ps) at the FEL.

The injector systems have been modeled and optimized as reported in [1], and the output of the injector models is used as input for the rest of the machine. Optimization of all accelerator components downstream of the gun, aimed at achieving high peak current, low energy spread and low emittance electron beam necessary for the FEL, has been performed in simulations including effects of space charge, coherent synchrotron radiation, and wakefields as reported in [3]. Major parameters are shown in Table 1.

The longitudinal beam phase space is affected by nonlinearities from space charge at low energy, rf curvature, longitudinal wakefields and second order (chromatic) optics in the chicanes. The optimization process combines these effects in such a way to linearise as much as possible the longitudinal phase space. Very effective minimization of the emittance growth from transverse wakefields may be achieved by use of a pair of correctors in the linac. Simulations demonstrate the transverse wakefields are manageable, with negligible emittance growth after the corrections.

Using the electron beam properties determined by the accelerator optimization (start-to-end) studies, the FEL performance has been studied in simulations [9]. Free parameters are power of the input seed, the lengths of the individual modulator and radiator undulators, the strengths (i.e. the R56's) of the dispersive sections, the choice of the actual harmonic numbers to reach a given wavelength. Major parameters are shown in Table 1.

Table 1. Major parameters for the FERMI @ Elettra FEL

Parameter	**FEL-I**	**FEL-II**
Wavelength (nm)	100 - 40	40 - 10
Output power (GW)	2+	1+
Pulse duration (fs)	100-800	100-800
Bunch charge (nC)	0.33 - 1.0	
Usable bunch length (fs)	200 - 800	
Energy spread (uncorrelated)	1×10^{-4}	
Emitance, slice (mm-mrad)	1.2	

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