FERMI@ELETTRA: A SEEDED FEL FACILITY FOR EUV AND SOFT X-RAYS

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Abstract

We describe the conceptual design and major performance parameters for the FERMI@Elettra Free Electron Laser (FEL) project funded for construction at Sincrotrone Trieste, Italy. This user facility complements the existing storage ring light source at Sincrotrone Trieste, and will be the first facility to be based on seeded harmonic cascade FELs. Seeded FELs provide high peak power pulses, with controlled temporal duration of the coherent output allowing tailored x-ray output for time domain explorations with short pulses of 100 fs or less, and high resolution with output bandwidths of the order of meV. The facility uses the existing 1.2 GeV S-band linac, driven by electron beam from a new high-brightness RF photocathode gun, and will provide tunable output over a range from ~100 nm to ~10 nm, and APPLE undulator radiators allow control of x-ray polarization. Initially, two FEL cascades are planned, a single-stage harmonic generation to operate over ~100 nm to ~40 nm, and a two-stage cascade operating from ~40 nm to ~10 nm or shorter wavelengh, each with spatially and temporally coherent output, and peak power in the GW range.

INTRODUCTION

The single-pass seeded FEL project FERMI@Elettra will be a User facility providing quality photons in the EUV to soft X-ray range. Photon production will be based on harmonic generation. The concept design has been studied and optimised towards a detailed engineering phase [1]. All major parameters and systems have been studied and an overview is presented here. Comprehensive studies including collective effects from space charge, coherent synchrotron radiation and wakefields as well as nonlinear dynamics from RF waveforms and bunch compressors have been performed to determine the optimum electron beam parameters for the facility. The studies have included error tolerances and beam jitter sensitivities in start-to-end computations.

The project covers the lower energy region of the XUV-X ray spectrum. With a peak brightness of more than ten orders of magnitude greater than 3rd generation sources, full transverse coherence, transform limited bandwidth, choice of pulse lengths of the order of a ps or less, variable polarization and energy tuneability, the FERMI source represents a powerful tool of scientific exploration in a large field of research. The coherence properties will provide single-shot imaging, allowing the study of chemical reactions as they happen. The high peak power will allow the study of non-linear multi-photon processes in a regime never explored before. The short time properties will allow the visualisation of ultra-short nuclear and electronic dynamics. The facility will enable the study of dilute samples of paramount importance in atmospheric, astrophysical and environmental physics, as well as in the characterization of nano-size materials. The applications extend from chemical reaction dynamics to biological systems, materials and surfaces, nano-structures and superconductors. The nature of harmonic generation schemes, with an external laser driving the FEL process, is particularly suitable for pump/probe synchronization at the ps time scale or less.

Figure 1 shows the layout of the facility. The accelerator and FEL complex is housed below ground and is composed of the following parts: (a) A photo-injector and two short linac sections, where a bright electron beam is generated and accelerated to ~100 MeV. (b) The main linear accelerator, where the electron beam is time-compressed and accelerated to a final energy of ~1.2 GeV. (c) A beam transport system to the undulators. (d) The undulator chains where the FEL radiation is generated. (e) The undulator to experimental area transport lines. (f) The experimental area. The new constructions include pushing back by ~ 80 m the linac tunnel and surface klystron gallery to make room for the photo-injector, accelerating sections and the first bunch compressor. At the downstream end, the klystron gallery is extended by ~30 m to power more accelerating sections. A FEL hall will be constructed below ground at the exit of the linac with transverse dimensions for the installation of up to four undulators side-by-side. Finally, an experimental hall, also below ground, will be constructed to house the FEL radiation transport optics and the experimental hutches. The facility will be provided with new support laboratories and office spaces.

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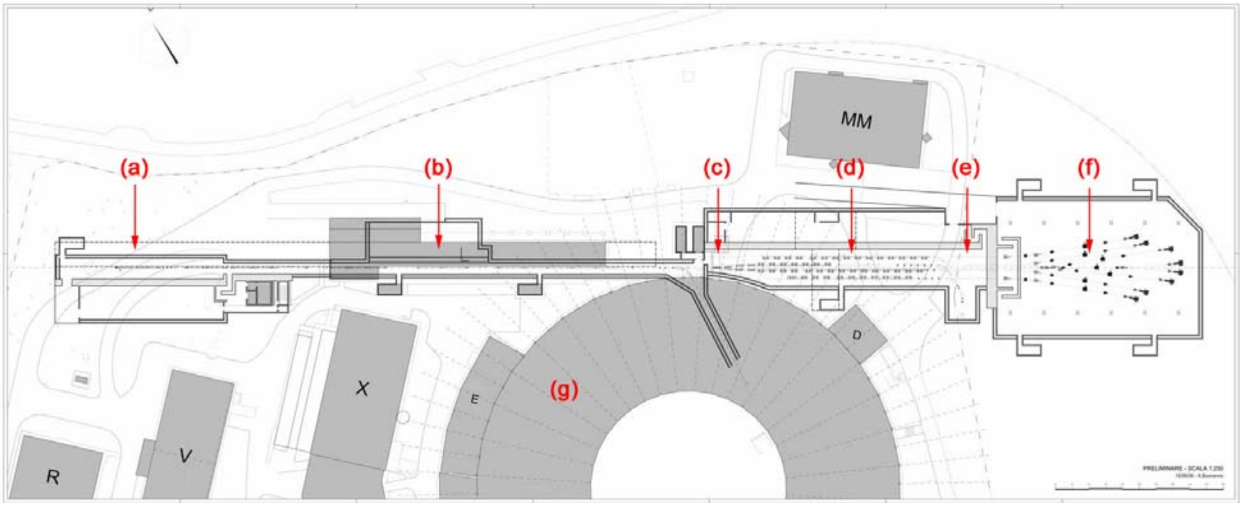

Figure 1: Schematic FERMI layout beside the ELETTRA storage ring building (g). See text for details.

THE PHOTO-INJECTOR

The photo-injector [2] is based on the proven 1.6 cell electron gun developed at BNL/SLAC/UCLA and adopted by the Linac Coherent Light Source (LCLS). The RF gun will provide a peak-accelerating gradient of 110 MV/m and an exit beam energy of around 5 MeV from a 10 MW peak input pulse (2.8 μsec). The injector will produce a 10ps long pulse with 0.8-1 nC charge and a rms normalized transverse emittance of 1.2 mm-mrad at 100 MeV. The initial repetition rate of 10 Hz will later be increased to 50 Hz following a modified gun design. The design includes a solenoid for emittance compensation, an off-axis diagnostic line and acceleration to 100 MeV with two booster S-band rf sections. These sections, named S0A and S0B, are part of the present Elettra injection system. Their on-axis, iris coupled cells resonate at 2.998 GHz in the $2\pi/3$ mode, and provide peak accelerating gradients of ~18 MV/m, for a total energy gain of ~45 MeV (with operational 10% energy margin). The booster modules include solenoid magnets to provide transverse focusing, to assist with emittance compensation, and to match the optical functions at the input to the main linac.

A laser pulse provides temporal and spatial shaping of the electron bunch. To compensate wakefield effects in the main linac sections [3], the electron bunch should ideally have a linear ramped peak current distribution at the exit of the injector rather than a flat top [4]. Studies have showed that such a profile at the start of acceleration produces a more uniform energy and current profile at the entrance to the undulators. The FERMI photo-injector addresses this novel concept by using a laser profile that has a quadratic ramp. Space charge forces subsequently transform this distribution to a linear ramped current shape at the exit of the injector, i.e. a profile where the current in the bunch increases approximately linearly with time. The photo-injector laser system [5] includes two amplifier stages, a regenerative one followed by a multipass, and reaches pulse energy of 20 mJ in the IR. Pulse shaping is done partially in the IR, by an acoustic optic dispersive filter (DAZZLER), and completed in UV in a transmission grating based stretcher or Fourier-system. Beam shaping is done either in the IR or in the UV by an aspheric shaper. A small part ~400 μJ of the IR beam is split away and transported for use by the laser heater.

Beam dynamics in the injector system have been extensively modelled from photocathode emission to the exit of the booster accelerator modules using 2D and 3D space-charge tracking codes (GPT and ASTRA). Simulations confirm that electron beam performance objectives for injection into the main linac at ~ 100 MeV are reachable. The timing and charge stability are both challenging, 0.5 ps and 1% respectively, but have been shown to be within present state of the art techniques.

ACCELERATION, COMPRESSION AND BEAM TRANSPORT

The accelerator is shown schematically in Figure 2 [6]. It consists of four linacs, two bunch compressors, a laser heater and a beam transport system (spreader) to the undulators. The function of this system is to accelerate the electron beam to the FEL energy of ~1.2 GeV and to compress the ~10 ps long pulse from the photo-injector to the final lengths and peak current. Two FEL layouts are envisaged. FEL-1 will provide photons with wavelengths in the range 100-40 nm. Depending on the experiments, electron bunch lengths of 200 fs and a peak current of 800 A or higher can be provided (in this case with shorter bunch lengths). For those experiment where small time jitter is important, and to account for a predicted jitter of up to 400 fs, an electron bunch of 600 fs ("medium bunch") has been designed. Including the inevitable inefficiency of the compression system, the obtainable peak current is ~800 A with 0.8 nC of charge from the photo-injector. FEL-2 will cover the wavelength range 40-10 nm and will make use of a ~1 ps long pulse to provide close to Fourier-transform-limited radiation and or a ~200 fs high brightness FEL radiation using the fresh-bunch technique. In both cases a “long bunch” of 1.5 ps is required from the accelerator. With 1 nC charge from the injector, the attainable peak current is ~ 500 A.

For both FELs the final energy and charge distributions correlated with the distance along the electron bunch should be as flat as possible in order not to broaden the FEL bandwidth. The aim is to produce an energy variation no greater than 1-2 x 10^{-4} along the useable part of the bunch and a peak current variation no greater than ~100 A. In transverse space, the horizontal and vertical normalized emittances at the end of the linac, 1.2 GeV, will not be greater than 1.5 mm-mrad in order to meet the desired photon throughput. This represents a ~30% increase from the photo-injector simulation results and includes a safety margin against emittance dilution effects. The emittance value of 1.5 mm-mrad is a condition of the shortest wavelength and accelerator performance is aimed at satisfying this most stringent requirement. This specification may be relaxed for longer photon wavelengths.

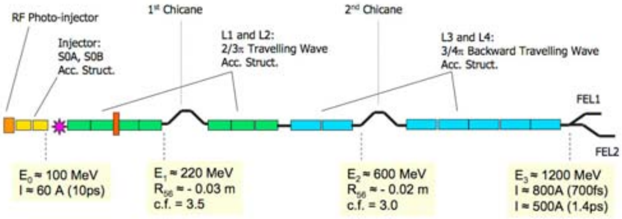

Figure 2: Schematic layout of the accelerator. The star indicates the position of the laser heater, while the red section the X-band accelerator.

At the exit of the photo-injector the electrons enter the L1 linac where they are accelerated to ~250 MeV. Acceleration occurs off-crest to provide correlated energy spread along the bunch that will compress it in the first compressor BC1. An RF structure tuned at the 4th harmonic of the main s-band sections, ie at X-band frequency, is placed half-way in L1. The function of the X-band linac is to provide the non-linear quadratic and, when operated off-crest, cubic corrections of the correlated momentum distribution along the bunch in the presence of the non-linearities of the photo-injector, the magnetic compressors and the non-linear effects of the longitudinal wakefields.

The linac structures L2 and L3 between the first and second bunch compressors accelerate the beam from ~ 250 MeV to ~650 MeV. They also provide the residual momentum chirp for the second compressor, BC2. After BC2 the beam is further accelerated to its final energy in the L4 structure. The phases of the linac after BC1 are chosen to provide the necessary momentum spread for compression and also to cancel the linear part of the longitudinal wakefields. The non-linear correlated momentum spread at the end of the linac is fine-tuned with the amplitude and phase of the X-band structure. The focusing structure of the linac is designed to minimize transverse emittance dilution due to transverse wakefields, momentum dispersion and coherent synchrotron radiation in bending magnets. Exhaustive computations with codes LiTRACK and “elegant” were performed to optimise beam parameters and to simulate expected jitter and parameter sensitivities. The computed electron distributions were further used in the FEL simulation studies.

The electron beam is transported from the end of the linac to the FELs by a FODO spreader channel. It is designed for diagnostics and parallel separation of the two FELs. The spreader has been designed to preserve electron beam emittance. This is done in two ways: by using a lattice with a small “curly-*H*” function in the magnets and by employing a scheme of self emittance compensation. Quadrupoles in the deflecting arcs, located near the positive and negative peaks of the dispersion function, are separated by a unit transfer matrix and. This allows simultaneous change of their gradients and the production of a dispersion bump localized between the quadrupoles. Control of this bump regulates R56 within the spreader allowing it to be exactly zero or any other reasonable value. It is in fact kept slightly positive in some cases to disperse the electrons in the spikes of the peak current.

THE UNDULATORS AND THE FEL PROCESS

FEL configurations are based on harmonic generation schemes seeded by an external laser. FEL-1 will utilise one stage (modulator, dispersion section and radiator) while for FEL-2 two stages will be used in a fresh part of the bunch seeding scheme. A whole bunch seeding scheme was also studied for FEL-2 and requires a larger number of undulators and a higher quality electron beam.

FEL-1 and FEL-2 are required to have continuously tuneable output polarizations at all wavelengths, ranging from linear-horizontal to circular to linear-vertical. For this reason, the FEL-1 radiator and the final radiator in FEL-2 have been chosen to have APPLE-II configurations with pure permanent magnets. For the modulator a simple, linearly-polarized configuration, is optimal both due to its simplicity and because the input radiation seed can be linearly polarized. The tuning of the wavelength will be done by changing the gap of the undulator while keeping the electron beam energy constant. The magnetic lengths of the undulators segments are 2.34 m (containing 36 periods) for the FEL-1 and 1st FEL-2 radiators and 2.40 m (48 periods) for the 2nd FEL-2 radiator. FEL-1 and 2 consist of 6 and 10 segments respectively. The intra-segment spools contain electromagnetic quadrupoles, high quality beam position monitors and quadrupole movers to steer the electron trajectory.

Theoretical and computational studies led to a selection of the accelerator and FEL parameters. An exhaustive study through start-to-end simulations, that included the use of FEL codes GENESIS and GINGER, was performed [7]. The simulations took into account perturbations in the accelerator and FEL parameters. In particular parameter sensitivity and time dependent jitter studies were carried out for both FELs. Studies of the variation of mean energy, energy spread, peak current, emittance and seed input power were done both for single and multi-parameter variations. Methods, such as undulator tapering, to reduce the sensitivity to variations, were also examined. Table 1 gives the expected performance parameters for the two FELs.

The seed laser will provide tuneable UV radiation in two pulse duration schemes: 100 fs and 1 ps. A dual pulse duration regenerative amplifier will be used. In the 100 fs case the amplifier directly pumps a travelling wave parametric amplifier (TOPAS) followed by harmonic conversion stages. In the 1 ps case this output is further amplified in a two pass stage to the 10 mJ level that then pumps a ps TOPAS. Timing and synchronization [8] of RF, laser and diagnostic systems will be guaranteed to sub 50 fs levels by an integrated system handling both CW and pulsed transmission schemes. A central clock system generating stable timing signals for the whole facility will be used. The signals will be distributed over distances exceeding 300 m by optical fibres in a star configuration. Timing information is transmitted using either RF modulated CW light mainly for the RF systems or pulsed light mainly for the laser systems.

The consequence of orbit displacements from the ideal trajectory in the undulators were simulated. The FEL process at the shortest wavelength, 10 nm, requires the straightness of the electron orbit in the undulators to be within 10 μm (rms value over the undulators length). Although this is beyond state-of-the art mechanical alignment techniques, realistic simulations show that a combination of the latter and of beam-based-alignment (tested at the Stanford Linear Collider and proposed for the LCLS) will achieve the desired performance.

Table 1: Principal FEL output parameters

Parameter	**FEL-1**	**FEL-2**
Wavelength range [nm]	100 to 40	40 to 10
Output pulse length (rms) [fs]	< 100	> 200
Bandwidth (rms) [meV]	17 (at 40 nm)	5 (at 10 nm)
Polarization	variable	Variable
Repetition rate [Hz]	50	50
Peak power [GW]	1 to >5	0.5 to 1
Harmonic peak power (% of fundamental)	~2	~0.2 (at 10 nm)
Photons per pulse	10^{14} (at 40 nm)	10^{12} (at 10 nm)
Pulse-to-pulse stability	≤ 30 %	~50 %
Pointing stability [μrad]	< 20	< 20
Virtual waist size [μm]	250 (at 40 nm)	120
Divergence (rms, intensity) [μrad]	50 (at 40 nm)	15 (at 10 nm)

PHOTON BEAM TRANSPORT AND EXPERIMENTAL AREAS

After leaving the undulators the electron beam, carrying an average power of 75 W (at 50 Hz) will be dumped into a shielding block by a sequence of bending magnets, while the FEL radiation will be transported to the experimental areas. The transport optics is designed to handle the high power density (up 10 GW) in a very short temporal interval. In order to handle the high peak photon energy density, the beam line optics operate at low grazing incidence angles with low Z-materials and the radiation intensity can be controlled by a gas absorption cell. The vacuum system is windowless with differential pumping sections. Pulse length preservation, monochromatization, energy resolution, source shift compensation, focusing in the experimental chamber and beam splitting are all included in the design of the FEL radiation transport system.

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