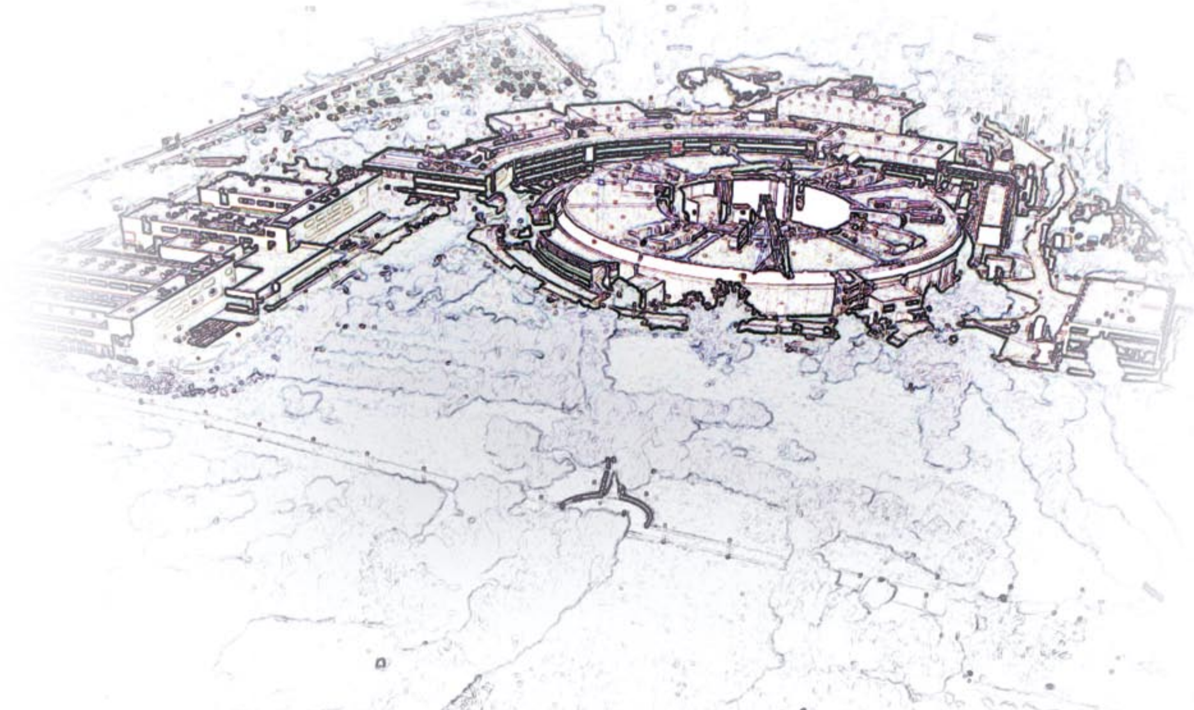


2 Overview

2.1 Introduction

The FERMI project at the ELETTRA Laboratory of Sincrotrone Trieste (ST) will be a national and international user facility for scientific investigations with high brilliance X-ray pulses of ultra-fast and ultra-high resolution processes in material science and physical biosciences. The underlying technology of the new facility is the Free-Electron-Laser (FEL) employing a master-oscillator-power-amplifier configuration with high gain harmonic cascades of wigglers. The full FERMI facility will consist of a linear accelerator plus two principal FEL beamlines in a new experimental hall in the complex environment of a multi-beamline user facility provided by the ELETTRA synchrotron light source.

The FERMI Project utilizes a 1.2 GeV linear accelerator, part of which is the current injector of the ELETTRA storage ring, and a new electron source based on photoinjector technology. In the near future, with the start of operation of the booster ring as the new ELETTRA injector, the existing linac will become available as part of a dedicated driver of the free-electron-laser. The addition of seven accelerating sections brings the linac energy to ~ 1.2 GeV. At this energy, and with state-of-the-art undulator technology, the free-electron-laser described in this report can operate in the 100-40 nm energy region in the initial phase (FEL-1) and down to 10 nm in a subsequent phase (FEL-2).

This chapter gives a broad overview of the facility and of the issues relevant to achieving the design objectives.

2.2 Principle of Operation

The FERMI project is based on the principle of high gain, harmonic generation FEL amplifier employing multiple undulators, up-shifting an initial "seed" signal in a single-pass [1,2,3]. The initial (master oscillator or seed) signal is provided by a conventional pulsed laser operating at wavelengths in the region 240-300 nm. The energy modulation induced by the interaction of the laser with the electron beam in the first undulator (the "modulator") is converted to spatial modulation by passing the beam through the magnetic field of a dispersive section. The bunching further increases the initial bunch modulation at harmonics of the seed wavelength. Thus re-bunched, the electrons emit coherent radiation in a second undulator (the "radiator") tuned at a higher harmonic corresponding to the desired FEL output. This scheme broadly describes the FEL-1 layout, down to 40 nm. To reach the shortest design wavelength of 10 nm, a second stage (modulator + dispersive section +radiator) is added to produce the FEL-2 configuration.

The choice of harmonic generation by an external seed laser is dictated by the scientific applications and the flexibility that such choice entails. As the seed laser determines the duration, bandwidth, and wavelength of the output radiation, all are tunable and controllable, covering a wide spectral range. The choice of design parameters, in fact, allows FERMI to generate FEL radiation with a wide range of characteristics tailored to match a diversity of experimental requirements, ranging from single shot, short (~100 fs), high brilliance, time-resolved experiments to ultra-fast pump-probe experiments, to high resolution (1 – 5 meV) experiments with close to transform-limited radiation on the *ps* time scale. The seed laser furthermore provides a reference signal throughout the FERMI facility (including the experimental beamlines) to facilitate the femtosecond level precision timing and synchronization of all systems.

Delivering such flexibility to serve a broad range of potential applications imposes severe requirements on the quality of the electron beam. To meet these requirements the FERMI FEL design is based on extensive studies of possible perturbations that may affect the electron beam dynamics, of means to correct them, and of parameter optimization. These studies show that the most important determinants of the quality of the FEL radiation are the quality and uniformity of the electron beam properties along the bunch (energy, energy spread, transverse emittance, electron optics, peak current, etc.), as well as the pulse-to-pulse stability of such properties.

2.3 Performance Characteristics

Table 2.3.1 lists some of the basic parameters of the electron beam and of the FEL radiation at 40 nm (FEL-1) and 10 nm (FEL-2).

Table 2.3.1: Nominal electron beam and FEL parameters.

Parameters	*Value at 40 nm*	*Value at 10 nm (fresh bunch)*	*Units*
Electron beam energy	1.2	1.2	GeV
Peak current	800	500	A
Emittance (slice)	1.5	1.5	μm, rms
Energy spread (slice)	150	150	keV
Bunch duration	700	1400	fs, FWHM
Repetition rate	10	10	Hz
FEL peak power	1 ÷ 5	0.5 ÷ 1	GW
FEL pulse duration	50 ÷ 100	100 ÷ 200	fs, FWHM
# of photons/pulse	10^{14}	10^{12}	
Bandwidth	~ 20	5	meV

2.4 Overall Layout

Figure 2.4.1 shows the layout of the facility. The accelerator and Free-Electron-Laser (FEL) complex comprise the following parts:

- A photoinjector and two short linac sections (SØA and SØB), generating a bright electron beam and accelerating it to ~ 100 MeV.
- The main linear accelerator, where the electron beam is time-compressed and accelerated to ~ 1.2 GeV.
- The electron beam transport system to the undulators.
- The undulators complex, in which the FEL radiation is generated.
- The photon beam transport lines from the undulator to the experimental area.
- The experimental area.

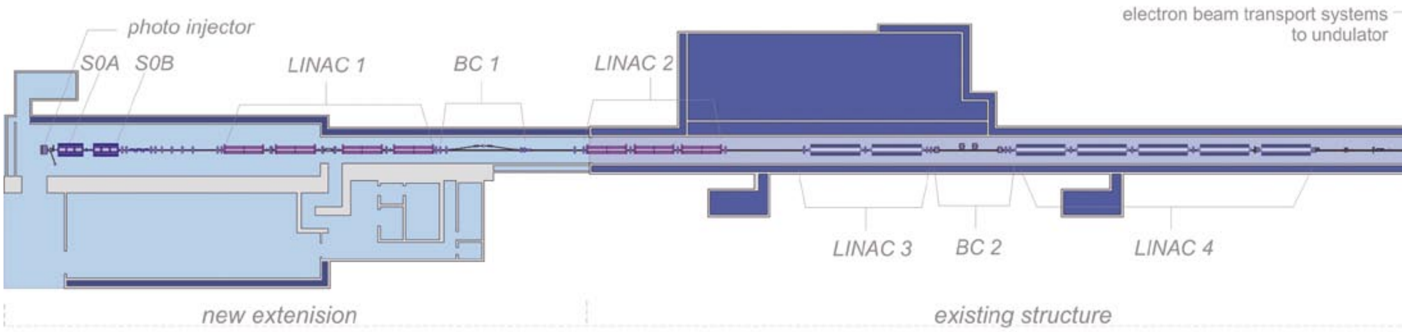
The new constructions include extending back the linac tunnel by ~ 80 m to make room for the photoinjector, new accelerating sections and the first bunch compressor. At its downstream end, the tunnel is extended by ~ 30 m to accommodate additional accelerating sections and the electron beam transfer line up to the Undulator Area. While only two lines (FEL-1 and 2) are envisaged initially, the transverse dimension of the Undulator Area allows installation of up to four undulators side-by-side. Finally, an experimental hall will house the FEL radiation beamline optics and the experimental hutches.

The following sections offer a brief overview of each major component. The reader is directed to the appropriate chapters for more detailed information and references.

2.5 The Photoinjector

The photoinjector is based on the proven 1.6 cell electron gun developed at BNL/SLAC/UCLA [4]. Given the similarities between the LCLS and FERMI photoinjector requirements, this design draws heavily on the LCLS concept to produce a 10 ps long pulse with 0.8-1 nC charge and a rms normalized transverse emittance of 1.2 mm-mrad at 100 MeV. The repetition rate is 10 Hz during the initial stage of operation, but the design allows for upgrading the photoinjector to 50 Hz. Following standard layout schemes, the design includes a solenoid for emittance compensation and acceleration to 100 MeV with two S-band rf sections. These sections, named SØA and SØB, are part of the present ELETTRA injection system.

A laser pulse provides temporal and spatial bunch shaping. The FERMI design calls for a novel temporal bunch profile in which the bunch current increases approximately linearly with time (linear ramp). Such profile at the start of acceleration produces a more uniform energy and current profile at the entrance to the undulators.



The Main Linear Accelarator

Simulations using the GPT and Astra codes indicate that the electron beam performance objectives for injection into the main linac at ~ 100 MeV are attainable. The timing and charge stability, – 0.5 ps and 1% respectively, are challenging but within present state of the art.

2.6 Acceleration, Compression and Transport to the Undulators

The function of the system is to accelerate the ~10 ps long electron bunch exiting the photoinjector to ~1.2 GeV and to compress the beam to its final duration and peak current. Two FEL layouts are envisaged in FERMI.

FEL-1 will cover the 100-40 nm energy wavelength range. Depending on the user experiments, an electron bunch length of 200 fs and a peak current of 800 A or higher can be provided ("short bunch"). For those experiments for which the timing jitter is critical, and to account for a predicted e-beam timing jitter of ~ 400 fs, the "medium bunch" design aims at a duration of 700 fs. Including the inevitable inefficiency of the compression system, the obtainable peak current is ~800 A with 0.8 nC of charge from the photoinjector.

FEL-2 covers the 40-10 nm wavelength range. This line will be developed to produce a narrow bandwidth (10 meV), close-to Fourier-transform limited radiation pulse.

Alternatively, ~200 fs long, high brightness FEL radiation pulses can be produced using the "fresh-bunch" technique. In both cases, a ~1.4 ps "long bunch" of electrons ~ is required from the electron accelerator. With a 1 nC bunch charge from the injector the attainable peak current is ~ 500 A.

In both the above cases, the 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 design values of energy and peak current variations along the useable part of the bunch are specified to be less

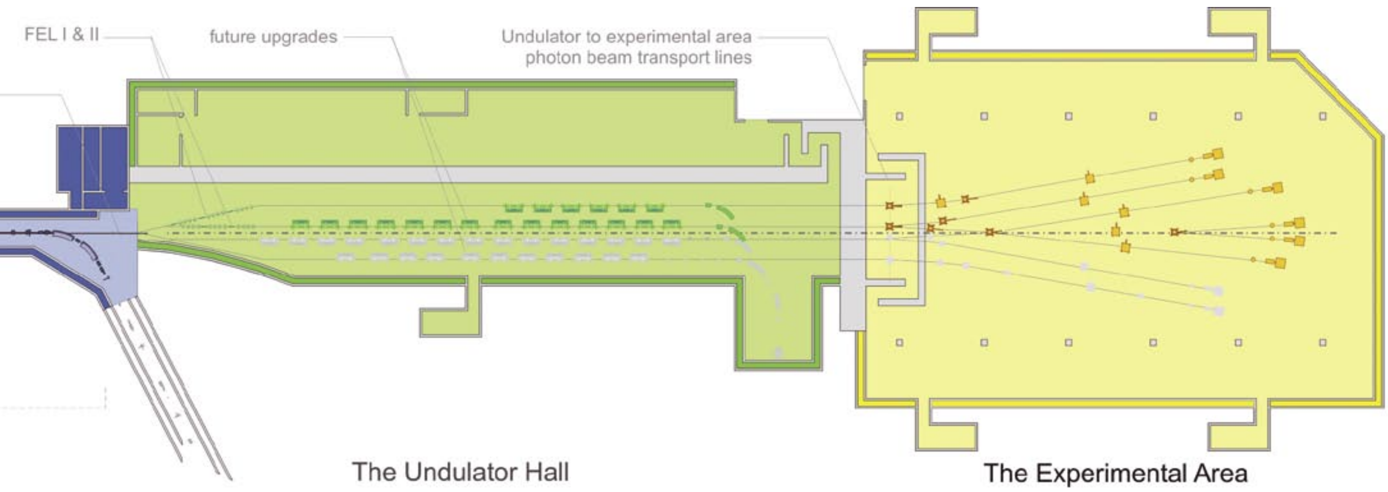


Figure 2.4.1: *Overall FERMI layout.*

than $2x10^{-4}$ and ~ 100 A respectively. The horizontal and vertical normalized emittances at the end of the linac (1.2 GeV) should not exceed 1.5 mm-mrad to meet the desired photon throughput. This value, ~ 30% higher than predicted by photoinjector simulations, includes a safety margin against emittance dilution effects. As an emittance of 1.5 mm-mrad is demanded at the shortest output wavelength, the accelerator performance is designed to satisfy this most stringent requirement. The specification could be relaxed during longer wavelength operation.

At the exit of the photoinjector, the ~ 100 MeV electrons enter the L1 linac (four C-type sections) where they are accelerated to ~ 250 MeV. Acceleration off-crest creates the correlated energy spread along the bunch needed to compress it in the first compressor, BC1. An X-band rf structure tuned at the 4th harmonic of the main (3 GHz) linac frequency is placed half-way between the four C-type sections of L1. The function of the structure is to provide the non-linear quadratic and, when operated off-crest, cubic corrections of the correlated momentum distribution along the bunch in presence of the photoinjector and the magnetic compressors non-linearities and of longitudinal wakefields.

The L2 and L3 linac structures, located between the first and second bunch compressors, accelerate the beam from ~ 250 MeV to ~ 650 MeV. They also provide the residual momentum chirp needed for the second compressor, BC2. After BC2 the beam is accelerated to its final ~1.2 GeV energy in the L4 structure. The rf phases of the linac sections following BC1 are chosen to provide the necessary momentum spread for compression and also to cancel the linear part of the longitudinal wakes. The non-linear correlated momentum spread at the end of the linac is fine-tuned by acting on the amplitude and phase of the x-band structure.

The linac focusing system is designed to minimize transverse emittance dilution due to transverse wakefields, momentum dispersion and coherent synchrotron radiation in bends.

Two transfer lines, one assigned to FEL-1 and the other to FEL-2, transport the electron beam from the linac end to the undulators. This system, called the “Spreader”, starts with two, three degree bending magnets that deflect the beam away from the linac. In the line that leads to the FEL-2 undulator, two more, three degree bend dipoles of opposite polarity bring the beam back parallel to the linac at a distance from it of 1 m. When operating the FEL-1 line, one of the afore-mentioned dipoles is switched off and the beam proceeds to a second pair of dipoles that again bend the beam parallel to the linac and displaced from it by 3 m. The two undulator lines are thus parallel and separated by 2 m. The electron optics is designed to cancel any emittance blow up due to the emission of coherent synchrotron radiation in the bends by a suitable choice of the (small) bending angles and of the phase advances between dipoles. The lattice of the spreader is flexible, and allows to switch from the configuration for photon delivery to a configuration less suitable for operation but optimized for electron beam diagnostics purposes.

2.7 The Undulators and the FEL Process

FEL-1 and FEL-2 are required to provide, at all wavelengths, continuously tunable beam polarization ranging from linear-horizontal to circular to linear-vertical. The FEL-1 radiator and the final radiator in FEL-2 have therefore been chosen to be of the APPLE-II [5], pure permanent magnets type. For the modulator a simple, linearly-polarized configuration is best, due to both its simplicity and because the input radiation seed can be linearly polarized. The wavelength will be tuned by changing the undulator gap at constant electron beam energy. The FEL-1 and FEL-2 radiators consist of 6 and 10 undulator magnets. The magnetic lengths of the individual magnets are 2.34 m (containing 36 periods) for the

FEL-1 and first FEL-2 radiators and 2.40 m (48 periods) for the second FEL-2 radiator, respectively. Electromagnetic quadrupoles, high quality beam position monitors, and quadrupole movers are installed in between magnets to correct the electron trajectory.

The accelerator and FEL parameters were defined based on theoretical studies and simulations. A cornerstone has been provided by "start-to-end" simulations, in which the electron beam is tracked from the photocathode, through the linac and all the way through the FEL process. The exhaustive studies carried out included foreseeable consequences random perturbations and jitters of accelerator and FEL parameters.

The consequences of orbit displacements from the ideal trajectory in the undulators were simulated. At the shortest design wavelength of 10 nm, the FEL process requires the straightness of the electron trajectory in the undulators to stay within 10 μm (rms value over the undulators length). While this requirement is beyond the state-of-the-art of present surveying techniques, realistic simulations show that a combination of the latter and of beam-based-alignment procedures [6] (tested at the Stanford Linear Collider and proposed for the LCLS) will achieve the desired performance.

2.8 The 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 is transported to the experimental areas. Pulse length preservation, monochromatization, energy resolution, source shift compensation, focusing into the experimental chamber and beam splitting are all included in the design of the FEL radiation transport system. It is designed to handle the high power of up to 10 GW in a sub-ps long pulse. Its differentially pumped vacuum system is windowless, the low-Z material beam line components operate at grazing incidence angles, and the radiation intensity is controlled by a gas absorption cell.

2.9 Applications of FERMI

The FERMI FEL covers the lower energy region of the XUV spectrum. With a peak brightness of about 6 orders of magnitude greater than third generation sources, full transverse coherence, (close to) transform limited bandwidth, pulse lengths of the order of a picosecond or less, variable polarization and energy tunability, the FERMI source is a powerful tool for scientific exploration in a wide spectrum of disciplines. The coherence properties will open up new perspectives for single shot imaging, allowing to study the dynamics of chemical reactions and other phenomena. The high peak power will allow studying non-linear multi-photon processes in a regime never explored before. The short pulse duration will open the door to visualizing ultra-fast nuclear and electronic dynamics. The high peak power enables studying dilute samples that are of paramount importance in atmospheric, astrophysical and environmental physics as well as in the characterization of nano-size materials.

Applications of FERMI therefore extend from chemical reaction dynamics to biological systems, materials and surfaces, nano-structures and superconductors. The nature of HGHG, with an external laser driving the FEL process, is particularly suitable for pump/probe synchronization at time scales well below 1 picosecond.

2.10 Summary

This report describes the FERMI free-electron-laser, a source unique in its capability to produce intense, tunable coherent radiation of picosecond and sub-picosecond duration in the 100 to 10 *nm* wavelength region. The strength of the design concept relies on extensive studies on the optimization and control of the primary electron beam, as well as on well-tested theory and simulations of the FEL process.

The FERMI design uses the most up-to-date, normal conducting linac technologies developed primarily at SLAC and applied to the Linac Coherent Light Source, a free-electron-laser under construction there. The FERMI design also greatly profited from the advances in knowledge and technology made by the synchrotron radiation community, and in particular, from the experience gained at ELETTRA on the technology of insertion devices, on radiation transport and on the experimental utilization of XUV and soft X-ray radiation.

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