

# FERMI@ELETTRA: 100 NM - 10 NM SINGLE PASS FEL USER FACILITY

R.J. Bakker, C.J. Bocchetta, P. Craievich, M. Danailov, G. D'Auria, G. De Ninno, S. Di Mitri,  
 B. Diviaco, G. Pangon, L. Rumiz, L. Tosi, V. Verzilov, D. Zangrando  
 Sincrotrone Trieste, SS 14 - km 163,5 in AREA Science Park, 34012 Basovizza, Trieste ITALY

## Abstract

The FERMI@ELETTRA project is an initiative from ELETTRA, INFN and other Italian institutes, to construct a single-pass FEL user-facility for the wavelength range from 100 nm (12 eV) to 10 nm (124 eV), to be located next to the third-generation synchrotron radiation facility ELETTRA in Trieste, Italy. The project is concentrated around the existing 1.2-GeV S-band linac, i.e., the injector for the storage ring. Normally the linac operates approximately 2 hours per day. The remaining time is available for the construction and operation of an FEL but modifications and operation must be planned such that operation of the storage ring can be guaranteed until the completion of a new full-energy injector (2006).

A request for funding has been granted. In anticipation of the arrival of money, the project now evolves from a conceptional design stage towards a technical design and the actual implementation. Key issues are: incorporation of the free-electron laser in the infrastructure of the Sincrotrone Trieste, adjustments of the linac to facilitate FEL operation, required additional civil engineering, undulator design, FEL seeding options, and beamline design.

## INTRODUCTION

FERMI@ELETTRA involves the construction of a single-pass FEL user-facility for the spectral range of 100 nm (12 eV) to 10 nm (124 eV) with two undulator beamlines: 100 nm to 40 nm and 40 nm to 10 nm, respectively. The laser will be driven by the existing 1.2-GeV linac. During the start-up of the project (until 2007) the linac will be used both as an FEL driver and as injector for the ELETTRA storage ring. Hence, the linac configuration will be modified such that it will allow for fast switching between the two modes of operation.

The capabilities and specifications have been defined in close collaboration with potential users [1]. The most important machine properties are:

- High-power short optical pulses (~100 fs) with a high pulse-to-pulse reproducibility, time-synchronized to external laser sources.
- APPLE II type undulators to enable flexible tuning of both the wavelength and the polarization.
- Implementation seeding schemes for further stabilization and tuning of the FEL process.
- Advanced feedback and feed-forward systems to improve the stability.
- An as high as possible repetition rate, compatible with normal-conducting accelerator technology.

In this paper we present the present status of the design as well as its expected performance.

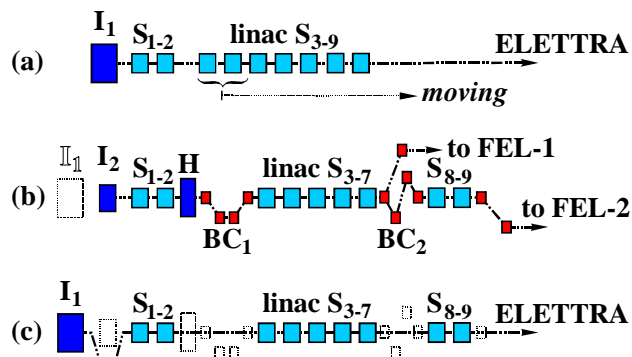


Figure 1: Schematic of the present linac configuration (a), the modified infra-structure to drive the FELs (b), and the new layout for injection into the storage ring (c). Non-operational elements are marked with dashed lines. The labels are: I – injector, S – linac sections, H – harmonic RF cavities, and BC – magnetic bunch compressors, respectively. See text for details on the configuration.

## LAYOUT

### LINAC Modifications

Figure 1. depicts a schematic representation of the linac modifications starting from the present situation (a). The most essential steps involve:

- Replacement of the existing electron beam source ( $I_1$ ) with a RF photo-cathode gun ( $I_2$ ) [2].
- An upgrade of the RF modulators to: (1) increase the repetition rate from 10 Hz to 50 Hz and (2) improve the stability. The repetition rate of 50 Hz is compatible with the presently operational klystrons (TH2132A) at the Sincrotrone Trieste.
- Moving of two accelerator modules down-stream to create sufficient space for a harmonic X-band cavity and two magnetic bunch compressors, to increase the peak current up to 2.5 kA.
- Upgrade of the electron beam diagnostics in combination with advanced feedback and feed-forward systems to stabilize the energy, orbit and duration of the electron bunches.

FEL-1 has been designed for a fixed target energy of 700 MeV. The electron beam will be extracted at the position of the second bunch-compressor, see Figure 1b. The wavelength of this FEL will be tuned through gap-variation of permanent magnet undulators. FEL-2 will use the full linac infrastructure of the Sincrotrone Trieste. The wavelength will be tuned both through the beam energy gain in the last two modules and through gap variation of permanent magnet undulators. Table 1 summarizes the parameters. Note that for FEL-2 the two down-stream

accelerator modules may operate in accelerating or decelerating mode.

For ELETTRA, it is also important that the linac can serve as an injector for the storage ring until a new full-energy injector will take over this task. For this we intend to move the existing injector ( $I_1$ ) backwards and provide space for a chicane, which bypasses the new injector ( $I_2$ ), see Figure 1c. In this mode the linac is generally tuned to an exit energy of 900 MeV.

Table 1: Electron beam target parameters.

	FEL-1		FEL-2		
Wavelength target	100	40	40	10	nm
	10	31	25	124	eV
Beam energy	0.70		0.55 1.00		GeV
Bunch charge	1.0		1.0		nC
Peak current	0.8		2.5		kA
Bunch duration ( $\sigma_T$ )	500		160		fs
Energy spread ( $\sigma_e$ )	0.7		1.0		MeV
Emittance ( $\epsilon_n$ )	1.5		1.5		$10^{-6}$ m
Repetition rate	50		50		Hz

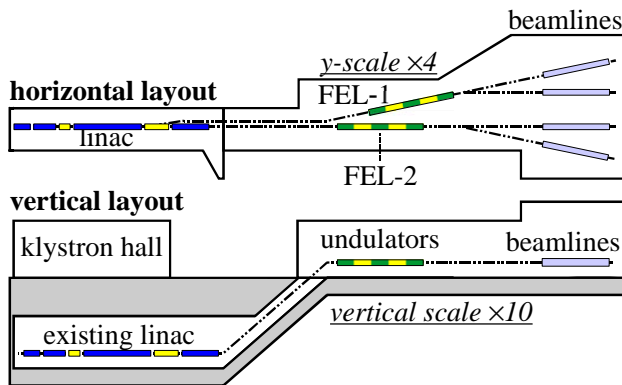


Figure 2: Details of the infrastructure. The electron beam is transported to the surface into an undulator hall. The downstream experimental user area is located sufficiently far from the undulator sections to permit sufficient radiation shielding and manipulation of the photon beam.

### Civil Engineering

The existing linac tunnel is adequate to house the linac, including the required modifications. Additional space is needed for the undulator section and the experimental hall. For practical reasons the electron beam will be transported up to a green-field area on the surface where a new undulator hall and experimental area needs to be constructed. Figure 2. gives an overview. Note that the vertical ramp is designed sufficiently shallow (5 deg) to avoid degradation of the electron beam quality due to effects like coherent synchrotron radiation.

### Undulator Section

For technical and economic reasons, the undulator will consist of sections of approximately 2.5 m, separated by 0.75 m for diagnostics and quadrupoles for refocusing of the electron beam by means of a FODO lattice. Planar

type undulators will be used in the upstream areas where mainly the electron-bunching process is important. APPLE II type of undulators will be used to produce the final radiation and enable full control by the user over the polarization of the photon-beam.

To optimize the stability and flexibility of the system, as well as the spectral properties radiated output, we aim for a laser-seeded mode of operation, i.e., so-called High Gain Harmonics Generation (HGHH) [3]. Compared to startup from noise or a SASE mode of operation the advantages are: (1) improvement of the spectral purity, tunability of the pulse duration through the seed laser, and (3) locking the temporal jitter of the FEL to the seed laser. The source will be a frequency up-converted Ti:Sa laser in combination with an Optical Parametric Oscillator to enable wavelength tunability of the seed. For FEL-1 a single stage HGHH is sufficient, see Figure 3-top. We note that the design of this system is such that it may also switch back to a SASE mode by opening the gap of the modulator.

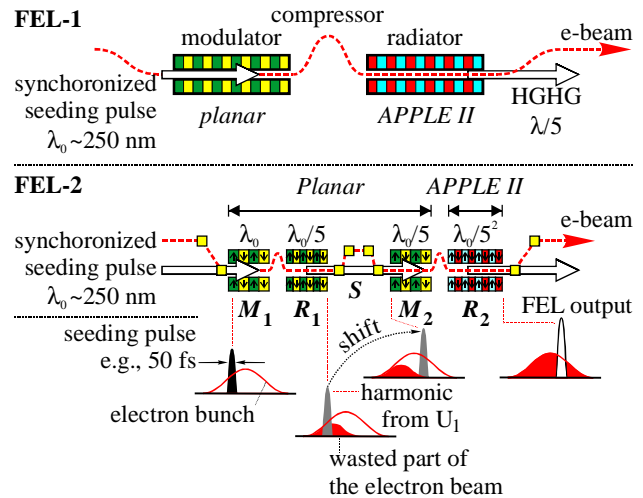


Figure 3: Set-up of FEL-1 (top) and FEL-2 (bottom). FEL-1 is based on a single-stage HGHH mode of operation. For FEL-2 it is planned to use a fresh-bunch 2-stage cascaded HGHH scheme. See text for details.

The design of FEL-2 is based on a fresh-bunch 2-stage cascaded HGHH scheme [4], see Figure 3-bottom. In the example the seed laser modulates the electron beam at a wavelength of 250 nm in modulator  $M_1$ . The output of  $U_1$  is enhanced by tuning this undulator to the 5<sup>th</sup> harmonic. The radiation of  $U_1$  (50 nm) is then used as seed for a 2<sup>nd</sup> HGHH scheme. A small chicane  $S$  is used to shift the radiation produced by  $R_1$  relative to the electron bunch in such a way that the first HGHH step interacts and spoils the tail of the electron bunch. The HGHH step then acts on the (unspoiled) head of the bunch. The final undulator stage  $R_2$  will be of the APPLE II type to enable tuning of the polarization.

### Beamlines

A general layout for each undulator line is depicted in Figure 4. Part of the FEL radiation will be diverted to a

diagnostic station to allow single-shot monitoring of the power, pulse-profile and spectrum. Users may get access to the direct beam or focused beam, possibly in combination with a monochromator to filter out undesired parts of the spectrum. A concern is the power-density of the produced radiation. The design foresees sufficient free space (up to 70 m) after the end of the undulator to allow for beam blow-up through diffraction.

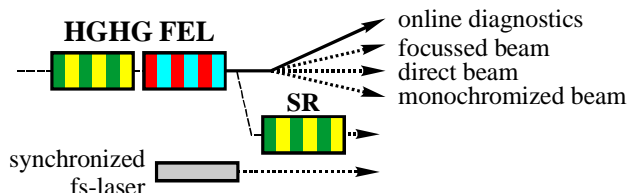


Figure 4: Sources of radiation: the FEL on top in series with an auxiliary undulator for spontaneous incoherent synchrotron radiation (SR) and time-synchronized fs lasers.

To facilitate two-color pump-probe experiments, an auxiliary undulator will be positioned downstream of the FEL to produce synchrotron radiation, which is naturally synchronized to the FEL. In addition it is foreseen to synchronize additional fs-lasers to the seed laser of the HGFG process.

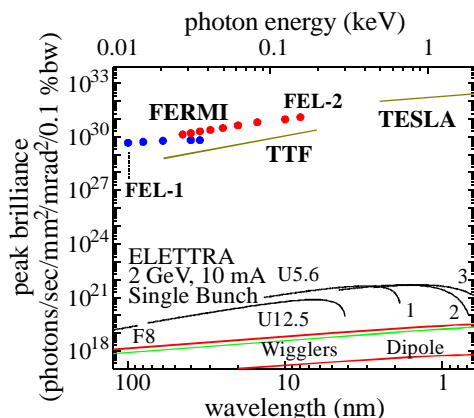


Figure 5: Peak performance estimates (brilliance) of FERMI compared to ELETTRA beamlines, TTF and TESLA.

## PERFORMANCE

The expected performances, based on the electron beam parameters presented in Table 1, are estimated by analytical formulas [5]. More rigorous results are based on start-to-end (S2E) calculations, i.e., particle tracking simulations where the codes ASTRA [6], ELEGANT [7] and GENESIS 3D [8] are successively used to simulate the performance of the injector, the linac and bunch compressor sections, and the undulator sections, respectively. For reference the performance estimates presented in Figure 5 [5], Figure 6 [9], and Table 2 [5] assume startup from noise (SASE). This reference is used rather than the foreseen HGFG mode as the latter is sensitive to fine-tuning of the electron beam parameters,

specifically energy-spread. More calculations are still needed to setup a reference in the case in this mode of operation. Preliminary calculations indicate a slight decrease of the peak power (up to one order of magnitude for FEL-2) while the spectral width reduces to a single spike, see Figure 6. The pulse duration and hence, photons per pulse are directly linked to the duration of the seed laser pulse. The spot-size and divergence are similar in both modes of operation.

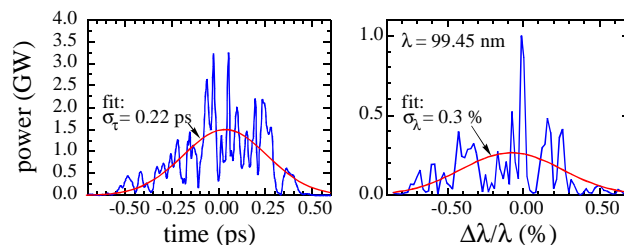


Figure 6: Pulse profile (left) and spectrum (right) obtained from an S2E calculation in SASE mode for the initial wavelength target of FEL-1.

Table 2: Specifications for the three beamlines in the case of a non-seeded FEL.

	FEL 1		FEL 2		
Wavelength	100	40	40	10	nm
Target	10	31	25	124	eV
Undulator period	52		36.6		mm
FODO period	6.7		6.6		m
Average $\beta$ -func.	8.5		8.5		m
Raleigh length	2	4	21	45	m
Peak power	2	2	2	4	GW
Peak flux	9	2	2	2	$\times 10^{26}/s$
Peak brilliance	0.3	0.6	1	7	$\times 10^{30\#}$
Photons/bunch	55	14	9	4	$\times 10^{13}$
Pulse energy	1	0.7	0.4	0.7	mJ

# photons/sec/mm<sup>2</sup>/mrad<sup>2</sup>/0.1 %  $\Delta\lambda/\lambda$

## REFERENCES

- [1] FERMI@ELETTRA, Preliminary Conceptual Design Report, Sincrotrone Trieste, Feb., 2002
- [2] Photo-injector study for the ELETTRA linac FEL, V.A. Verzilov et al., to be published in Nucl. Instr. Meth. in Physics Research A (NIM-A).
- [3] L.H. Yu et al., Phys. Rev. Lett. **91**, 74801 (2003).
- [4] W.M. Fawley et al., Nucl. Instr. Meth. in Physics Research A (NIM), **A507**, 396 (2003).
- [5] Ming Xie, Nucl. Instr. Meth. in Physics Research A (NIM), **A445**, 59 (2000).
- [6] K. Flötman, ASTRA, A space Charge Tracking Algorithm, <http://www.desy.de/~mpyflo>
- [7] M. Borland, <http://www.aps.anl.gov/asd/oag/software.shtml>
- [8] S. Reiche, <http://corona.physics.ucla.edu/~reiche/>
- [9] Start-to-end simulations for the FERMI project, S. Di Mitri et al., to be published in Nucl. Instr. Meth. in Physics Research A (NIM-A).