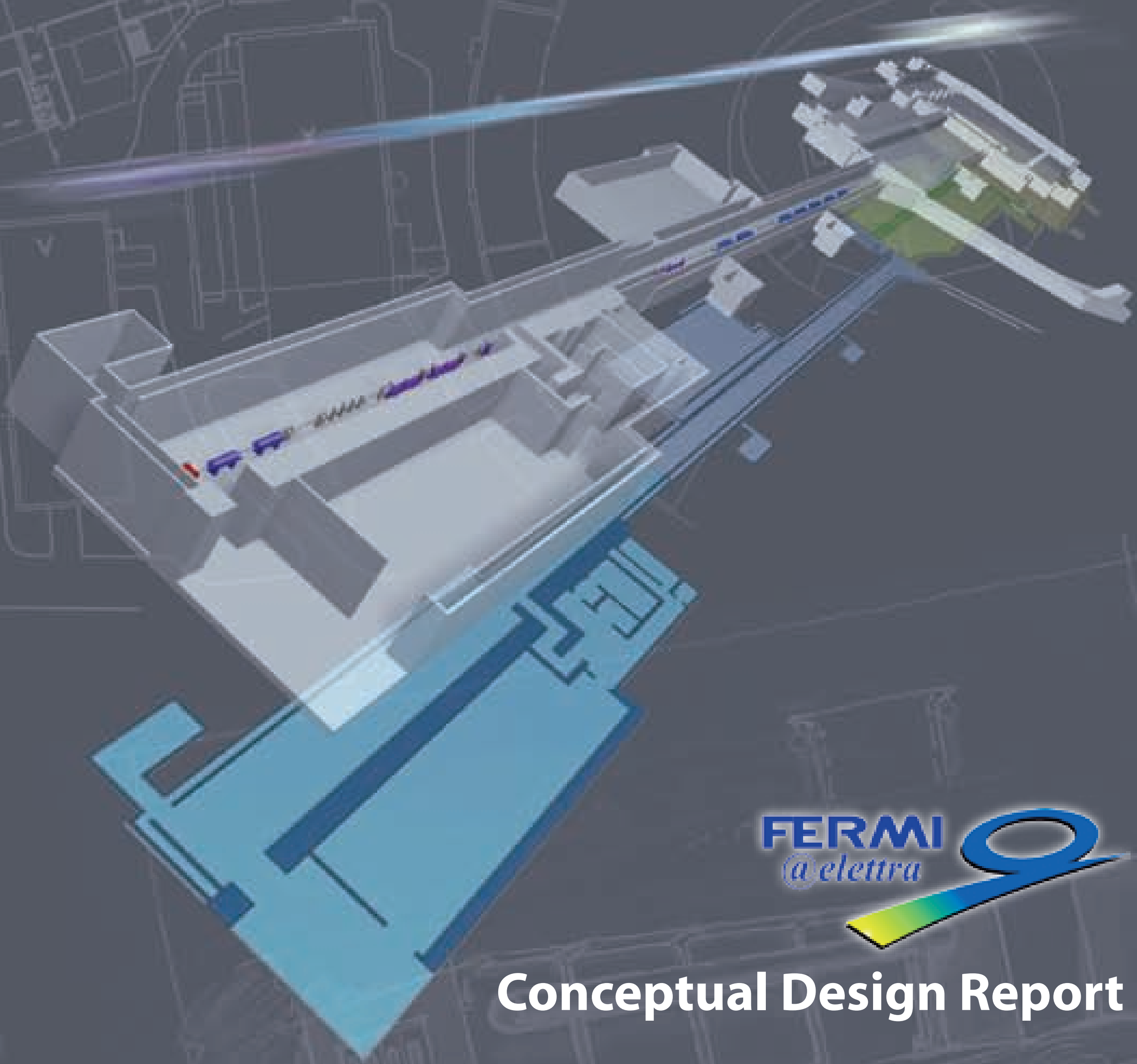

FERMI
@elettra

Conceptual Design Report


FERMI
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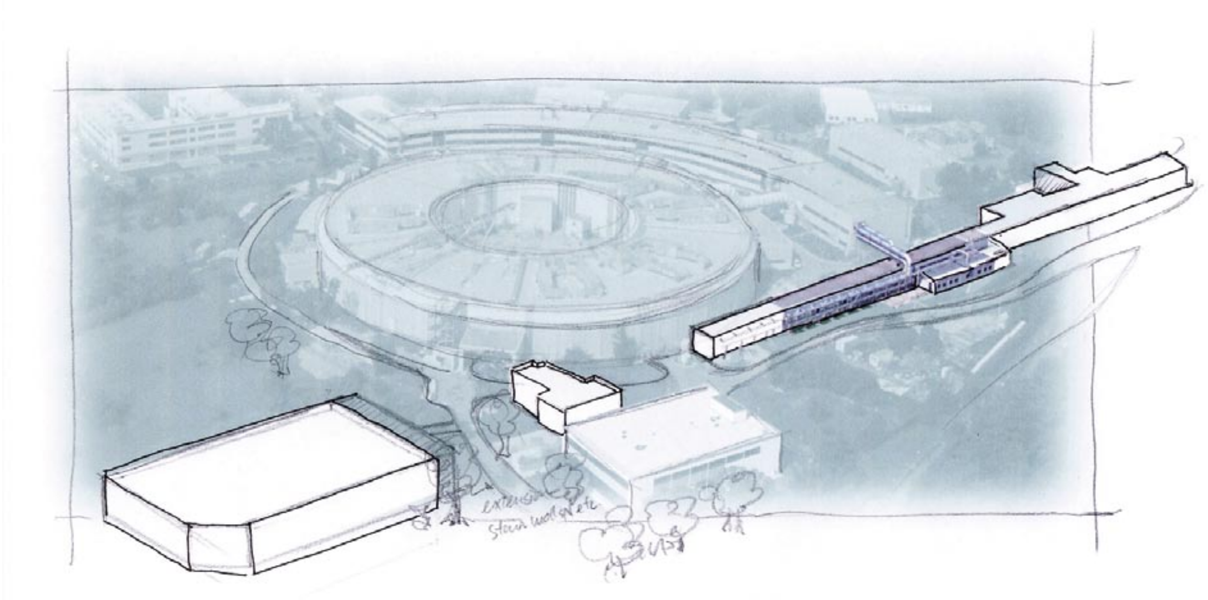

January 2007

FERMI@Elettra

Conceptual Design Report

Foreword

The Conceptual Design Report of the FERMI@Elettra Project is the result of several years of incubation, development and international collaboration.

The concept started with a first proposal presented by the Trieste team in the beginning of 2002, reinforcing an already strong interaction between EU and USA synchrotron radiation laboratories, in response to a call for proposals by the Italian Ministry of Research. The proposal has evolved into the present Report that has been written in parallel with preliminary development activities. In particular, we strongly acknowledge contributions from the design study activities of the sixth framework EU program EUROFEL and the detailed physics and technological studies carried out together with Lawrence Berkeley National Laboratory, the Massachusetts Institute of Technology and the Linac Coherent Light Source (SLAC). The gratefully acknowledged help from many other expert teams, listed in this report, also contributed to make the report a solid conceptual base for the construction of the FERMI@Elettra facility.

The Free Electron Laser (FEL) activity at Sincrotrone Trieste has always been an important research and development topic; a strong international community has in fact grown around the EU storage-ring-FEL project, EUFELE, in operation at the ELETTRA storage ring, considered to a be the precursor to FERMI.

FERMI@Elettra has always been intended as a “User Facility” and as such it has involved, from the very beginning, the user community in defining the project physics goals and therefore the fundamental machine parameters and configurations. As a result, the facility design has been based on complex and still evolving techniques, such as “seeding”, in order to ensure the high beam stability and synchronization needed for fine spectroscopy measurements.

FERMI will be an “International Open Access” Facility to serve the most advanced experiments proposed by the international user Communities. To further improve the overall service, and to ensure the best use of resources available in Europe, we have proposed, at the EU level, to develop our facility in coordination with other similar projects now in operation (FLASH, in Hamburg) or in the design and development stage (4GLS in Daresbury, BESSY-FEL in Berlin, MAX-IV in Lund, SPARX in Frascati and PSI-FEL in Villigen) and with previously existing facilities such as FELIX in Holland. The proposal is now evolving into an integrated EU facility-Consortium, IRUVX, that has been selected as one of the Facilities in the Roadmap of Research Infrastructures for Europe. The integration will, among others, offer the advantage of possibly making the various facilities cover different parameter ranges, thus helping extend the use of FEL generated Light over a much wider range of scientific fields.

The construction of FERMI has started thanks to the financial support of the Italian National and Regional Governments as well as of a project-financing supported loan from the European Investment Bank.
The first light is planned to be delivered to the users in 2009, thus translating the concepts of this CDR into practice!

Carlo Rizzuto

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Special thanks for the editing and publication of this report go to Massimo Cornacchia, Miltcho Danailov, Giovanni De Ninno, Simone Di Mitri, Bruno Diviacco, Mario Ferianis, Mario Giannini, Catherine LeCocq, Marco Lonza, Marina Nadalin, Fulvio Parmigiani, Giuseppe Penco, Giulia Quondam, Giuliana Tromba, Mauro Trovò, Carol Yen, Marco Zangrando.

Finally, the donation of seven accelerating linac section by CERN is also gratefully acknowledged.

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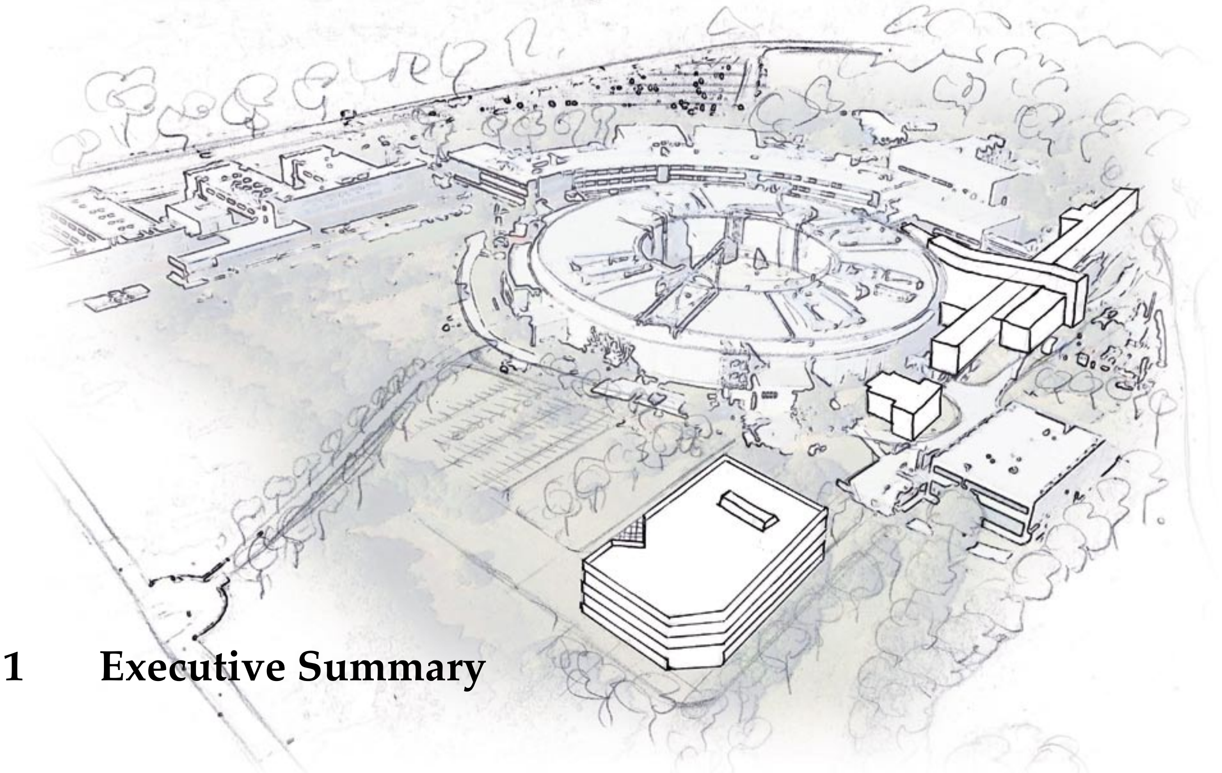

1 Executive Summary

1.1 Introduction

Synchrotron radiation is a fundamental and indispensable tool for the study of materials which encompasses a wide spectrum of sciences, technologies and applications, from life sciences to nanotechnologies, from environmental sciences and geochemistry to archaeology.

Synchrotron radiation has seen an explosive growth in its application to research and development and in the number of facilities built to serve its users, covering a large range of radiation wavelengths, extending from the infrared down to hard X-rays, in the form of radiation pulses with time duration down to the few picoseconds range. The number of facilities in operation worldwide is close to eighty, serving tens of thousands of users per year.

The main figure of merit of radiation sources is brilliance, which defines the intensity of radiation, within a given bandwidth around the desired wavelength, that can be focused unto a sample of given area. Typical brilliance values for the highest performance “third generation” light sources are around 10^{19} to 10^{21} photons/s/mm^2/mrad^2/0.1% bandwidth. Another important characteristic is the pulse duration: ultra short, sub-picosecond radiation pulses are needed to open up the new investigation field covering not only the structure of a sample but also its dynamics during irradiation.

A strong need has emerged over the last few years, for a source of radiation with extremely high brilliance, close to full coherence, a bandwidth approaching the Fourier limit and with a stable and well characterized temporal structure in the femtosecond and picosecond time domain. Such a source is the single-pass Free Electron Laser (FEL) that has the potential for producing light pulses with peak brilliance many orders of magnitude higher than that generated in present third generation sources and with sub-picosecond pulse lengths, as shown in Figure 1.1.1 [see also Chapter 3] in which the peak brightness (brilliance) and pulse duration performance of different types of X-ray sources is compared (see Table 1.1.1).

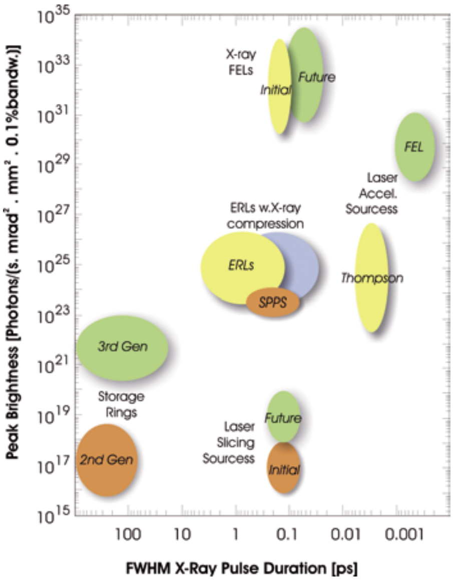

Figure 1.1.1:
Peak brightness (brilliance) versus pulse duration of various types of radiation sources.

The investigation domain opened by the new sources cover essentially all basic science fields giving access to explorations of matter in practically unexplored regimes. The scientific opportunities will in fact impact studies of a large number of disciplines ranging from materials and biomaterials sciences, nanosciences, plasma physics, molecular and cluster femto- and nano- physics and chemistry, as well as having various connections to life, environmental, astrophysical and earth sciences. As important as the immediate applications is the promise of new discoveries, studies and techniques that will emerge as this new tool is fully exploited. The potential is there to further develop technologies ranging from micro-electronics to energy. A more extensive presentation of the science case is given in Chapter 3.

The FERMI single pass FEL project at the ELETTRA Laboratory of Sincrotrone Trieste (ST) is one of the FEL based European projects, designed to become the international user facility in Italy for scientific investigations, with ultra high brilliance X-ray pulses, of ultra-fast and ultra-high resolution processes in material science and physical biosciences.

1.2 The Fermi FEL Facility

1.2.1 General Layout

The FERMI single-pass FEL facility will be driven by the present ELETTRA injector S-band linac, upgraded by the addition of seven accelerating sections[1] to bring its top energy to 1.2 GeV and of a new photoinjector, low emittance electron source. The Linac repetition rate will also be ramped up to from 10 Hz to 50 Hz. Injection into ELETTRA will be taken up by a new full energy booster synchrotron scheduled to become operational at the end of 2007 [1].

The upgraded Linac 1.2 GeV electron beam energy plus a complex of state-of-the-art undulators will allow FERMI to cover the 100-40 nm wavelength region in a first phase (FEL-1) and to reach down to 10 nm in a second, later phase (FEL-2). User experiments will be housed in the new experimental hall shown in Figure 1.2.1, located next to the ELETTRA light source [2], thus allowing for the possibility of eventually bringing ELETTRA photon beams into it to perform multi-beam experiments.

A general layout of the facility is shown in Figure 1.2.1. The accelerator and FEL complex comprises the following parts: a photoinjector and two short linac sections generating a bright, ~ 100 MeV electron beam, the main linear accelerator in which the beam is time-compressed and accelerated to ~ 1.2 GeV, the system to transport the beam to the undulators, the undulator complex generating the FEL radiation, the photon beamlines taking the radiation from the undulator to the experimental area and the experimental area itself. After leaving the undulators, while the FEL radiation is transported to the experimental areas, the electron beam is brought to a beam dump by a sequence of bending magnets. The FEL radiation transport system, designed to handle the high peak power of up to 10 GW in the sub-ps long pulse, includes a differentially pumped windowless vacuum system and low-Z material beam-line components operating at grazing incidence angles. The photon beam transport system incorporates all provisions and equipment necessary to ensure pulse length and energy resolution preservation, monochromatization, source shift compensation, beam splitting and focusing into the experimental chamber.

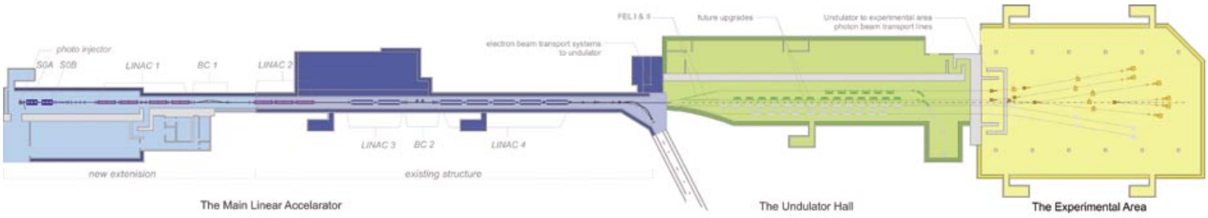

Figure 1.2.1:
FERMI General layout.

As above mentioned, the FEL facility operates two different free electron laser radiation sources, FEL-1 and FEL-2, to be realized in two phases. FEL-1, to be implemented first, is designed to operate in the time domain (short pulses) with two complementary modes: a high stability and a high intensity one.

---

[1] Courtesy of CERN

FEL-2, to be implemented in the second phase, is designed to operate with relatively long photon pulses, in the frequency domain to provide the highest energy resolution, i.e. the narrowest bandwidth.

The initial FERMI science program, by which the design choices have been guided, is structured to reach its final performance from the very start with diverse experiments and increasingly more demanding photon beam parameters (see Tables 3.1.2 through 3.1.7, Chapter 3), thus allowing high quality experiments to be performed from the very beginning of commissioning of both FEL-1 and FEL-2.

The classes of planned experiments, temporally ordered, are: single shot, high peak brightness experiments, pump-probe experiments and non-linear spectroscopy high-energy resolution experiments in both the time and the frequency domain.

The "roadmap" showing in more detail how the various stages of facility performance optimization will open up diverse experimental opportunities is shown in Figure 1.2.2.

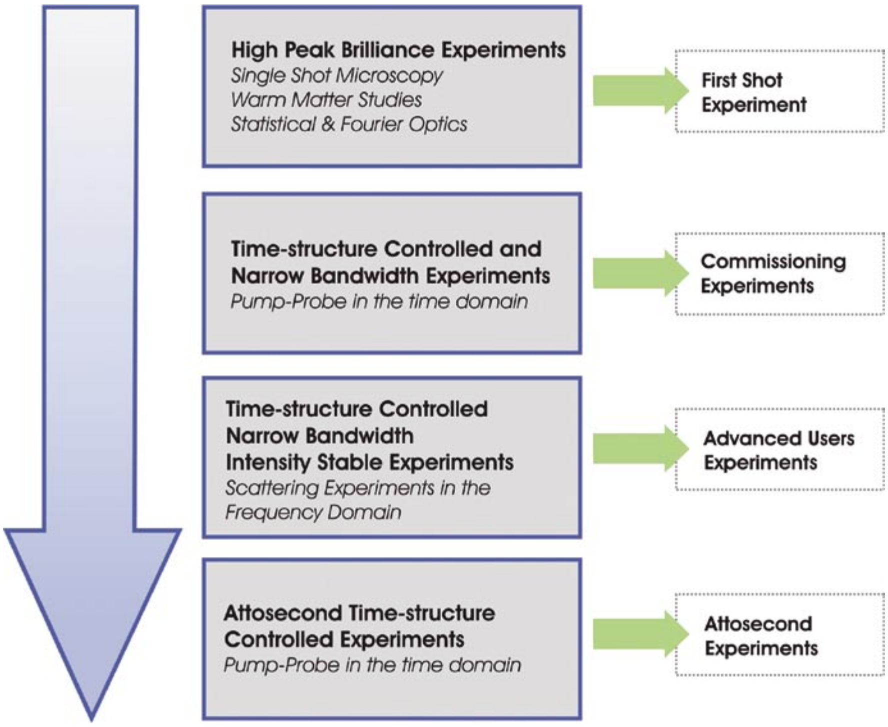

Figure 1.2.2:
Accessible experiments as the Fermi performance is gradually improved.

1.2.2 FEL Operation: Seeding Mechanism and Main FEL Parameters

The quite novel "seeding" scheme by which FEL-1 is designed to produce radiation down to 40 *nm* wavelength, is the following. An initial "seed" signal, provided by a conventional, high peak power pulsed laser operating at wavelengths in the region 240-300 nm at the electron bunches repetition frequency, is made to overlap the electron beam in a first undulator magnet called the modulator. The laser field modulates the electron bunch energy at its own frequency and the modulation is converted to bunch charge spatial modulation by passing the electrons through a dispersive section.

The frequency spectrum of the so obtained charge modulated electron bunch contains higher harmonics of the seed laser wavelength so that intense coherent FEL radiation at the frequency of one of these harmonics can be finally obtained by passing the modulated bunch through a second set of undulators (the "radiator") tuned to select and amplify the desired harmonic.

For the FEL-2 beamline to reach the shortest foreseen design wavelength of 10 nm, a second undulator stage must be added to a first stage similar to FEL-1, consisting of a modulator plus a dispersive section plus a radiator, tuned to and seeded by the first stage output radiation.

One should note that the nature of the mechanism, with an external laser driving the FEL process, is particularly suitable for pump/probe synchronization at time scales well below 1 picosecond.

FERMI's resulting main parameters, collected in Table 1.2.1, 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. Exhaustive studies have also been carried out to estimate the effect of foreseen random perturbations and jitters of the accelerator and of the FEL parameters.

Table 1.2.1: Nominal electron beam and FEL parameters.

Parameters	*Value at 40 nm*	*Value at 10 nm*	*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	2.5	0.6	GW
FEL pulse duration	200	400	fs, FWHM
# of photons/pulse	10^{14}	10^{12}	
Bandwidth	17	4	meV
Brilliance	~10^{31}	~10^{31}	ph/s/mm^2/mrad^2/0.1%BW

Another novel paramount feature of FERMI is that both FEL-1 and FEL-2 are designed to provide, at all design wavelengths, beam polarization ranging from linear-horizontal to circular to linear-vertical, continuously tunable by changing the undulator gap at constant electron beam energy.

The FEL-1 radiator and the final radiator section in FEL-2 have therefore been chosen to be of the APPLE-II, pure permanent magnet type. For the modulator a mechanically simpler configuration can be used because the input radiation seed can be linearly polarized.

The radiators for both FEL-1 and FEL-2 consist of a sequence of 6 and 10 undulator magnets respectively. Electromagnetic quadrupoles, high quality beam position monitors and quadrupole movers are installed in between magnets to correct the electron trajectory. More details on the undulators can be found in Chapter 7.

In summary, with a peak brightness in the lower energy region of the XUV spectrum that can reach values 10 orders of magnitude greater than that of third generation sources, with full transverse coherence, close to transform limited bandwidth, pulse lengths of hundreds of femtoseconds, variable polarization and tunability, the FERMI source is a powerful tool for scientific exploration.

Its coherence properties are expected to open up new perspectives for single shot imaging, allowing to study the dynamics of chemical reactions and of other time dependent phenomena. The high peak power will allow studying non-linear multi-photon processes in a regime so far never explored and enable studying dilute samples of paramount importance in atmospheric, astrophysical and environmental physics as well as in the characterization of nano-size materials. The short pulse duration will open the door to visualizing ultra-fast nuclear and electronic dynamics.

1.3 References

[1] C.J. Bocchetta et al., "*Elettra Present and Future Upgrades*", Proc PAC 2005, Knoxville, USA, cern.ch/AccelConf/p05/PAPERS/RPAE085.PDF

[2] M. Svandrlik et al., *"Elettra New Full Energy Injector Status Report Status*", Proc. EPAC 2006, Edimburgh, UK, accelconf.web.cern.ch/AccelConf/e06/papers/thpls033.pdf