FERMI SEEDED FEL PROGRESS REPORT

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Abstract

FERMI, the seeded Free Electron Laser (FEL) located at the Elettra laboratory in Trieste, Italy, welcomed in December 2012 the first external users on the FEL-1 line. This line is based on a single stage of High Gain Harmonic Generation (HGHG), seeded by a UV laser, and covers wavelengths between 80 and 20 nm. The photon energy reached more than 300 μJ. The second FEL line, FEL-2, covering the lower wavelength range between 20 and 4 nm thanks to a double stage cascaded HGHG scheme, has generated its first coherent photons in October 2012. The latter is the first experimental demonstration of a seeded free electron laser configured as a two-stage cascade operating in the "fresh bunch injection" mode, where the second stage is seeded by the light produced by the first stage. This paper describes the status of the operation and user experiments with FEL-1 and reports about the progress in the commissioning of FEL-2.

INTRODUCTION

FERMI@Elettra is the fourth generation light source facility at Elettra –Sincrotrone Trieste, Italy. The FEL will produce photons in the ultraviolet and soft X-ray range, between 15 eV and 310 eV. The scientific case, based on three experimental programs, namely *Diffraction and Projection Imaging* (DiProI), *Elastic and Inelastic Scattering* (EIS), *Low Density Matter* (LDM), calls for high peak brightness, fully coherent, narrow and stable bandwidth photon pulses, wavelength tunability and variable polarization [1].

Two FEL lines cover the foreseen wavelength range. FEL-1, based on a High Gain Harmonic Generation (HGHG) single stage source seeded by an external UV laser (~ 260 nm), covers the range from 80 to 20 nm [2]. To get down to 4 nm still starting from an external seed laser in the UV range, a double stage HGHG cascade is adopted for FEL-2. A delay line permits to improve the FEL performance by using the *fresh part* of the electron bunch in the second stage of the cascade (see [1] and references therein).

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The maximum electron beam energies required for FEL-1 and FEL-2 are respectively 1.2 and 1.5 GeV. The accelerator is a normal conducting linac, working at 3 GHz RF frequency and 10 Hz repetition rate. Upgrade to 50 Hz of the entire facility is currently ongoing. A high brightness electron beam is generated by a photocathode RF gun. Two stages of magnetic compression are used to get extremely short electron bunches (less than 1 ps) with high peak current. A 4th harmonic system provides the longitudinal phase space linearization needed to optimize the compression process. At high compression factors micro-bunching instabilities are predicted; to cure them, a laser heater is used to increase in a controlled way the incoherent energy spread of the electron beam.

Each stage of the two FEL lines is made up of a modulator, where the electron beam is seeded by an external laser, a dispersive bunching section, and the radiator, where the interaction between the electron beam and the emitted coherent radiation produces the exponential growth of the FEL intensity. Both for FEL-1 and FEL-2 the final radiator is made of six APPLE-II undulators, with magnetic periods of 55 and 35 mm respectively, that provide full control of the polarization of the FEL radiation. The variable gap allows changing the wavelength of the emitted radiation.

FACILITY ACHIEVEMENTS

After that first evidence of Coherent Harmonic Generation (CHG) was observed at the end of 2010, in 2011 the facility performance was gradually optimized until exponential growth of the FEL radiation was detected [3]. Further optimization studies and commissioning activities have been carried out during the following months and in 2012 [4, 5], leading to the completion of FEL-1 commissioning [2] and first external users operation [6]. At the same time, commissioning of FEL-2 first stage of HGHG was accomplished in May 2012 [5]. In October 2012, FEL-2 commissioning was extended to the second stage of HGHG [7], reaching fundamental wavelengths as short as 10.8. The energy per pulse was estimated to be at 10 μJ level. Table 1 summarizes the present FERMI performance parameters.

Table 1: Present FEL-1 and FEL-2 Parameters

Parameter	**FEL-1**	**FEL-2**
Electron bunch energy	1.2 GeV	1.0 – 1.2 GeV
Bunch charge	500 pC	500 pC
Bunch Peak current	400 – 600 A	300 - 500 A
Wavelength	80 – 20 nm	20 – 10.8 nm
Energy per pulse*	90 to 400 μJ	up 100 μJ
Photons per pulse**	10^{13} @ 20 nm 10^{14} @ 52 nm	10^{11} @ 10.8 nm
Relative bandwidth	$\sim 10^{-4}$	$< 10^{-3}$
Intensity stability, rms	~10%	~50%
Central wavelength stability, rms	$\sim 10^{-4}$	to be measured
Bandwidth stability	< 3%	to be measured
Repetition Rate	10 Hz	10 Hz

** average, depending on wavelength and spectral purity*
*** max achieved*

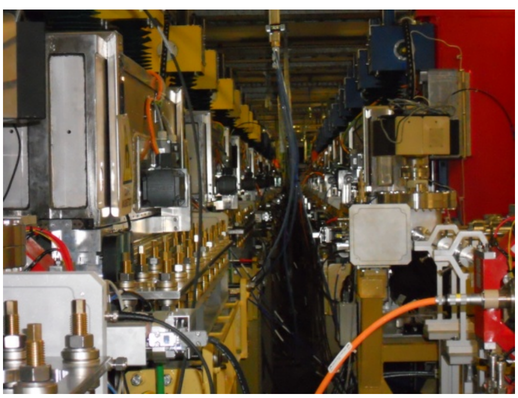

Figure 1: Undulator line of FEL-1 (left) and FEL-2.

FEL-1 PERFORMANCE

Improvement of the electron beam brightness and stability, optimization of the undulator line parameters and remote control of the seed laser characteristics eventually led FEL-1 to match its design goal parameters (wavelength range, intensity, spectral bandwidth, stability, see Table 1) and to provide a reliable users operation. Flatness of the longitudinal phase space with a peak current between 400 A and 600 A was achieved with one-stage time-compression of the initial 500pC electron bunch. An X-band cavity at low energy allows the compression factor tuning while ensuring uniformity of the beam parameters along the bunch [8]. Laser heater system was fully commissioned to counteract microbunching instability, which would otherwise spoil FEL gain and longitudinal coherence [9]. Control of the effects of the linac impedance [10] and coherent synchrotron radiation emission [11] led to final relative energy spread below 0.1% and transverse normalized emittances of 1.5 mm mrad. Optics matching in the undulator line and adjustment of the trajectory in the undulator turned out to improve the very initial FEL performance. At the end, Gaussian mode, transverse coherence [12] and spectral purity at few 100s μJ per pulse were achieved over the entire wavelength range 20–80 nm. Remote control of undulator gap and phases, of seed laser intensity, timing and central wavelength in the range 230–260 nm brought to full control of FEL-1 fundamental wavelength and polarization; polarization switching typically required few minutes. Continuous wavelength tuning was allowed by a seed laser Optical Parametric Amplifier. Experiments were carried out with linear horizontal, vertical and circular polarization, including fast switching from one to the other. Once FEL performance is optimized for one wavelength [13], that is with narrow bandwidth, excellent central wavelength and intensity stabilities (see Table 1), similarly good performance was easily achieved at other wavelengths and polarizations. Success of FEL-1 operation was finally ensured by the strict collaboration between the team working on the accelerator, on the photon diagnostic and transport, and on the experimental stations. An innovative and complex system for x-ray spatial and spectral characterization allowed the FEL pulses to be imaged along the 100 m long line from the source point in the undulator to the experimental vacuum chamber. Non-invasive measurements of the FEL spectrum and vertical projection were used for on-line characterization and survey of the FEL pulse quality. Kirkpatrick-Baez mirror systems were used to focus the FEL spot size down to 10μm x 10μm [14].

FEL-2 PERFORMANCE

FEL-2 commissioning started in February 2012. In few shifts it was possible to get transport rates close to 100 % along the FEL-2 line, hence all undulators were installed during April 2012. Commissioning of FEL-2 first stage was successfully accomplished in May 2012. October 2012 and March 2013 were devoted to the commissioning of the second stage. After evidence of the coherent harmonic generation from the first stage (planar modulator plus two APPLE-II type undulators), in September 2012 the installation of the photon front-end of FEL-2 was completed, which merges with the FEL-1 line at the spectrometer. It included the presence of dedicated filters (Zr and Pd) which were necessary to discriminate between the contributions coming from the two stages of FEL-2. In particular they isolated the photons generated by the second stage, giving the possibility to measure their intensity independently from those coming from the first stage (measured by gas monitor detectors). During the October run the HGHG double cascade was fully commissioned, including the FEL optimization by using the fresh part of the bunch, at 14 nm (wavelength compatible with 1.0 GeV electron beam energy). In March 2013 the energy was set to 1.2 GeV and

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wavelength as short as 5.4 nm was observed, even if at low intensity [7].

MAIN USER ACTIVITIES

FEL wavelength tuning was used from LDM for photo-ionization experiments on atoms, molecules, and clusters, and, particular, to measure resonant absorption line of the He *1s-4p* transition at 52.2 nm in LDM, as shown in [6]. This work also reports the activity of EIS and DiProI scan of the $M_{4,5}$ absorption edge of Ge (~29.5 eV) in the wavelength region 30–60 nm.

Ultrafast absorption spectroscopy and FEL self-reflection measurements have been successfully carried out on Ti samples at the EIS-TIMEX end-station. Effective wavelength tunability of the machine has been demonstrated in a wide spectral range between 30nm and 65nm.

High degree of transverse coherence, along with a good focussing spot on the sample, allowed the DiProI team to successfully perform single shot Coherent Diffraction Imaging experiment. The experiments performed at DiProI were also focused on studies of magnetic dynamics in thin films, triggered by pump with the seed laser. The great advantages of FERMI for such studies are the circular polarization of the FEL coherent radiation and the use of the seed laser, naturally synchronized with the probe femtosecond FEL pulses. Another study explored transient states of Ti thin layer grating structures, interacting with very intense XUV FEL pulses tuned to the Ti M edge. This was a proof-of-principle experiment exploring a novel two color FEL scheme, which is possible with seeded-FERMI. The pump and probe FEL pulses, with controlled wavelength, intensity ratio and time delay, were generated by seeding the electron bunch with two laser pulses. Changes in Ti electronic structure, occurring at high pump-FEL fluences, were detected following the changes of the diffraction pattern from the grating [15].

An important condition to perform time-resolved user experiments with FERMI was the delivery to the end stations of synchronized infrared pulses for pump-probe measurements. Taking advantage of the inherent to the seeded FEL operation synchronization of the emitted FEL pulses to the seed laser pulses, one part of the IR pulses generated by the seed laser system was transported to the FERMI experimental hall. Given the rather long beam transport length (150 m), advanced optical and mechanical design in combination with high performance feedback loops have been implemented in order to preserve low timing jitter and high pointing stability. The results of the first user experiments in February/March 2013 indicated that this goal has been reached: a timing jitter smaller than 25 fs RMS and negligible slow timing drifts have been observed.

FUTURE PLANS

In Spring 2013 the linac energy will increase to 1.5 GeV, by full activation of the SLED cavities, in order to reach 4 nm, i.e. the lower wavelength limit for FEL-2. The repetition rate of the facility will also be upgraded at the same time from 10 Hz up to 50 Hz upon the installation of the new photocathode gun and the completion of the upgrade program of the linac modulators. An intense development program of the beamlines is also ongoing, including, among others, the construction of the second EIS beamline, TIMER. Finally, the installation and commissioning of a split and delay line devoted to auto-correlation and FEL pump – FEL probe experiments is ongoing. This instrument, performing a wavefront splitting of the incoming FEL pulse, will be capable of introducing a controllable delay (-2–30ps) between the recombined two parts of the initial pulse, independently from its wavelength.

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