FERMI@ELETTRA STATUS REPORT

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Abstract

The FERMI@Elettra seeded Free Electron Laser (FEL) is based on two separate FEL lines, FEL-1 and FEL-2. FEL-1 is a single stage cascaded FEL delivering light in the 65-20nm wavelength range, while FEL-2 is a double stage cascaded FEL where the additional stage extends the frequency up-conversion process to the spectral range of 20-4nm.

The FEL-1 beam line has been in operation since the end of 2010, with user experiments carried on in 2011-2013 and user beam time allocated until the first half of 2014. Fermi FEL-2 is the a seeded FEL operating with a double stage cascade in the "fresh bunch injection" mode [1]. The two stages are two high gain harmonic generation FELs where the first stage is seeded by the 3rd harmonic of a Ti:Sa laser system, which is up converted to the 4th-12th harmonic. The output of the first stage is then used to seed the second stage. A final wavelength of 10.8 nm was obtained (the 24th harmonic of the seed wavelength) during the first commissioning in October 2012. The experiment demonstrated that the FEL is capable of producing single mode narrow bandwidth pulses with energy of several tens of microjoules. The commissioning of FEL-2 continued in March and June 2013, where the wavelength of operation was extended down to 4nm and below, demonstrating that an externally seeded FEL is capable of reaching the soft X-ray range of the spectrum.

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INTRODUCTION

FERMI@Elettra free electron laser (FEL) is a fourth generation light source at the research centre Elettra – Sincrotrone Trieste, Italy that functions as a user facility producing photons in the ultraviolet and soft X-ray wavelength regions. 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 stable, high peak brightness, nearly fully coherent (both transversely and longitudinally), narrow bandwidth photon pulses, together with wavelength tunability and variable polarization [2-4].

FERMI is driven by a single-bunch, S-band high brightness electron linac. The linac is presently capable of reaching a final energy up to 1.4 GeV, in conditions of FEL operation (*i.e.*, including energy losses due to the required off crest operation of two linac sections for compression and the X-band cavity for phase space linearization). The linac energy was increased from the previously available 1.2 GeV by an extensive RF conditioning plan program during May 2013. At the same time the machine repetition rate was increased to 50 Hz, with the linac has operating at this rate during all the conditioning of the RF plants. However, the rep rate was reduced back to 10 Hz for the FEL commissioning shifts, in order both to increase the linac reliability for the FEL operation at the higher energy, and to reduce the (expected) cathode aging that was observed on the new 50 Hz gun, delivered by Radia Beam and installed during the winter 2013. In the future the linac energy will be extended further to 1.5 GeV in order to increase the FEL gain in the shortest wavelenght range (at and below 5 nm).

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Two separate undulator lines cover different parts of the total wavelength range. FEL-1, based on a single stage, High Gain Harmonic Generation (HGHG) configuration seeded by an external UV laser (THG from Ti:Sa at 260 nm or tunable OPA in the range 260-230nm [5]), covers the range from 65 to 20 nm. To access the 20 to 4 nm region, while still starting from an external seed laser in the UV range, we adopted a two stage, harmonic upshift cascade for FEL-2. A delay line chicane between the two stages improves the FEL performance by using a *fresh part* of the electron bunch in the second stage of the cascade [1].

STATUS OF FEL-1

The FEL-1 beam line began operation in late 2010, with user experiments starting in 2011. More than 70 user experiments from the first two calls for external proposals will be carried on in the 2013 to mid 2014 time frame. Typical achieved FEL-1 performance parameters are listed in Table 1.

Table 1: Present FEL-1 Parameters

Parameter	**FEL-1**
Electron bunch energy	1.2 GeV
Bunch charge	500 pC
Bunch peak current	400 – 600 A
Wavelength*	(100) 65 – 20 nm
Energy per pulse**	90 to 320 mJ
Photons per pulse***	10^{13} @ 20 nm 10^{14} @ 52 nm
Relative bandwidth, rms	~10^{-4}
Intensity stability, rms	15%
Central wavelength stability, rms	~10^{-4}
Bandwidth stability	< 3%
Repetition Rate	10 Hz

* *lowering the beam energy and implementing a specific setup for the tunable OPA laser driving the FEL modulation, should ensure operation in the extended wavelength range 100-20nm.*

** *average, depending on wavelength*

*** *max achieved*

The FEL characteristics can be adjusted to the user experimental needs in numerous ways, e.g., by optimizing the source for pulse energy or spectral purity, and/or by exploiting the flexibility associated with the use of the input seed. One particular important feature is the generation of a sequence of multiple pulses, for pump and probe experiments [6,7]. Such pulses from short wavelength FEL sources open new frontiers in ultrafast science, allowing one to probe electronic transitions from core levels, with the extension to the short wavelength range of techniques in use in optical lasers. In SASE FELs, the LCLS group has recently reported the generation of a pair of temporally and spectrally separate soft X-ray FEL pulses via a double undulator scheme [8]. Similar studies are ongoing at SPARC [9,10], where two distinct electron bunches at different energies generate independent pulses of FEL radiation.

There are different processes that can lead to the generation of multiple pulses in a seeded FEL. The simplest and more straightforward way is that of seeding the FEL with two independent seed pulses separated in time [11]. If the e-beam characteristics at the temporal positions corresponding to where the two seed pulses are placed are good enough, two independent FEL pulses will be emitted. This requires that the seed radiation spectrum be contained within the gain bandwidth of the FEL amplifier and that the electron bunch length be sufficient long to accommodate both two seed pulses. In addition the amplification process should not enter into a deep saturation regime in order to keep the output radiation properties (spectrum, duration, arrival time) tightly correlated to those of the input seed laser pulse. For FERMI, two seed pulses are focused in the modulator stage of FEL-1 and interact with a mildly compressed, 750-*fs* long electron bunch, for which particular care was devoted to preserve the uniformity of the electron beam properties. The FEL generates two VUV pulses whose time separation is strictly correlated to the separation of the seed pulses [6]. This techniques can easily be extended to generate pump-probe pulses with similar wavelength separation in the whole presently available FERMI FEL-1 range (20-65 nm) while the minimum time delay can be decreased to about 150 fs for the existing seed laser pulse length.

Shorter pulse delays can be obtained by adopting a second scheme where the FEL is seeded with a single, frequency-chirped pulse, and a deterministic spectro-temporal pulse-splitting occurs in the deep saturation regime of the FEL. In this configuration, the FEL is seeded by a powerful laser pulse that carries a significant frequency chirp. As an effect of saturation at the position of the seed peak power, the output FEL radiation is split in two pulses, separated in time and having different central wavelengths [12-14].

About 30% of the beam time of the second call for proposals on FEL-1 have been allocated for pump and probe experiments where these two techniques can be applied.

COMMISSIONING OF FEL-2

A detailed overview of the FERMI FEL-2 commissioning results is provided in these proceedings [15] and in ref.[16]. Therefore we provide here only a summary of the present status of this second FERMI FEL. The schematic layout of FEL-2 undulator line is shown in Fig.1. Undulators were installed during April 2012. Commissioning of the first stage of the cascaded HGHG scheme was accomplished by late October 2012 [17].

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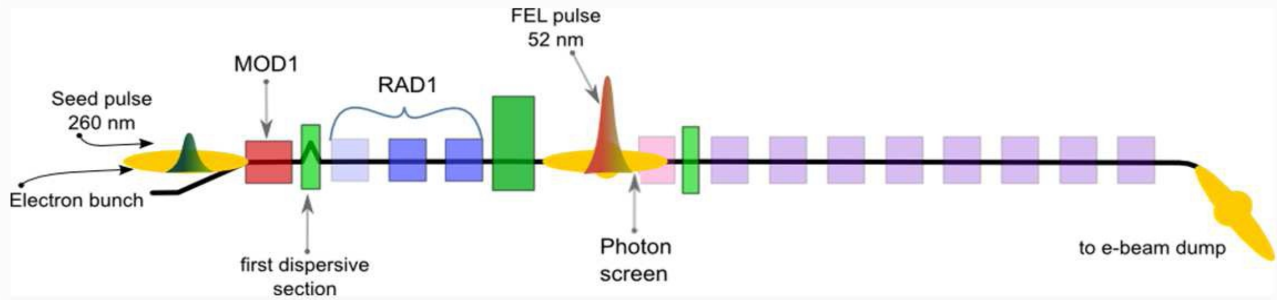

Figure 1. Schematic of FERMI FEL-2 undulator line.

In order to attain the required synchronization between the electrons and the seed laser, a similar procedure to that used for FEL-1 commissioning [3] was followed. Transverse spatial overlap between electrons and the seed laser was ensured by aligning electrons and photons on two diagnostic screens placed before and after the modulator (MOD1). With the undulator resonance tuned at the seed laser wavelength, the electrons energy distribution appeared to be modified according spectrometer measurements at the beam dump [18]. The electrons and seed laser spatial and temporal overlap led to the detection of coherent signal on the photon screens downstream the first stage radiators, tuned to the 5th harmonic of the seed laser. This coherent emission was used as a probe for an alignment check of a number of diagnostic stations placed in between the second stage radiators. Finally, the FEL photon beam became visible on the screen at the entrance of the experimental hall, 55m away from the emitting radiators.

Commissioning of the entire FEL-2 line was accomplished with main electron beam parameters listed in Table 2 (the FEL measurements correspond to an electron beam energy of 1.0 GeV).

The external seed laser was the third harmonic of a Titanium:Sapphire laser with a duration of ~180 fs (FWHM) and up to 20 μJ energy per pulse. Its transverse size in the modulator was made larger than the electron beam size to ensure as uniform as possible the electron beam energy modulation.

FEL-2's first stage is followed by a magnetic chicane that delays the electron bunch respect to the co-propagating photon pulse. Typical time delays are in the range 100 – 300 fs; the corresponding momentum compaction destroys nearly all residual bunching from the first stage,. The second stage with its 6 radiator segments acts in a true HGHG regime, with the FEL power growing exponentially along the second half of the undulator line.

FEL-2 output spectrum is dominated by the coherent radiation emitted from the first stage, at the n^{th} harmonic of the seed laser wavelength, and by radiation emitted from the second stage, at the m^{th} harmonic of the first stage. These two spectral components approximately overlap both in time and space. Their energy per pulse and spectrum was measured by two independent systems, on a shot-by-shot basis.

Table 2: FEL-2 Parameters

Parameter	FEL-2
Electron bunch energy	1.0 – 1.38 GeV
Bunch charge	500 pC
Bunch Peak current	300 - 500 A
Wavelength	20 – 4 nm
Energy per pulse*	up to 100 μJ
Photons per pulse**	10^{12} @ 8.3 nm
Relative bandwidth	< 10^{-3}
Intensity stability, rms	~50%
Central wavelength stability, rms	~ 10^{-4}
Bandwidth stability	~ 10%
Repetition Rate	10 Hz

** average, depending on wavelength (100uJ achieved at 10.8nm)*
*** max achieved*

Commissioning of FEL-2 in fresh bunch mode was accomplished by investigating several harmonic transitions, in both stages. As an example, the second stage was tuned at harmonic number m = 2, 3, 4 or 6, depending on the harmonic number in the first stage, to eventually reach the 18^{th} and the 24^{th} harmonic of the seed laser. A first campaign of studies was carried out at 1.0 GeV to reach 10.8 nm fundamental wavelength. Later, the beam energy was increased to 1.2 GeV to access to shorter wavelengths, such as n = 8, m = 6 corresponding to the 48^{th} harmonic of the seed laser, namely 5 nm. Finally the linac beam energy of 1.5 GeV was reached, with all the RF klystron phases set to accelerate the beam on crest. This corresponded to about

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1.4 GeV for an electron beam compressed with the X-band phase space linearization cavity on line, optimized for FEL operation. In this condition FEL spectra at the wavelength of 4.09 nm of central wavelength and a pulse energy of the order of 1 uJ were measured. These measurements revealed good spectral stability. Purity of the second stage spectra was sensitive to the initial seed laser power. During optimization of the entire system, the first stage output energy was set at few μJ level.

Commissioning in the near future will continue with the conditioning of the accelerating structures to allow the increase of the electron beam energy up to 1.5 GeV in FEL operating condition mode and multi-microjoules pulse energy output below the carbon K-edge at 4.3 nm.

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