SPECTRAL CHARACTERIZATION OF THE FERMI PULSES IN THE PRESENCE OF ELECTRON-BEAM PHASE-SPACE MODULATIONS*

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Abstract

As a seeded FEL based on a single stage HGHG configuration, FERMI's FEL-1 has produced very narrow bandwidth FEL pulses in the XUV wavelength region relative to those typical of SASE devices. This important feature of seeded FELs relies however upon the capability to produce high quality electron beams with clean longitudinal phase spaces. As has been predicted previously, the FEL output spectra can be modified from a simple, nearly transform-limited single spike by modulation and distortions of the longitudinal phase space of the electron beam. In this work we report a study of the FEL spectra recorded at FERMI for various situations showing the effects of phase-space modulation on the FEL properties.

INTRODUCTION

FERMI@Elettra [1] is a free electron laser user facility recently built in Trieste, Italy. Based on two FEL lines that uses the electron beam produced by a common accelerator, FERMI@Elettra covers the spectral range from ~80 nm down to 4 nm. Both FELs rely upon a seeding scheme that allows FERMI to improve the quality of the longitudinal coherence of FEL pulses with respect to existing SASE FELs covering the same spectral range. For both FELs the seeding is done with an external laser in the UV and harmonic conversion is used to reach the desired FEL wavelength. The first FEL (FEL-1), covering the spectral range from 80 to 20 nm, is based on the high gain harmonic generation (HGHG) [2] and has been already operated since end 2010 [3]. The second FEL (FEL-2) requires a two stage HGHG configuration to reach wavelengths as short as 4 nm. The first stage of FEL-2 has been already operated [4] while the second stage will be commissioned late this year.

The capability of seeded harmonic generation to produce highly coherent FEL pulses has been previously demonstrated [2,5]. However it is known that this desirable feature depends on the quality of the electron beam and that distortion of the phase space of the electron beam may lead to significant deterioration of the longitudinal coherence of the FEL pulses.

Over the past two years as we have operated FEL-1, several new accelerator components have become available that have allowed us to vary the FERMI electron beam parameters. In this work we report how various electron beam properties appear to affect the FEL spectra, in particular at 32-nm output wavelength (the 8th harmonic of the seed laser).

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HGHG AT FERMI

An HGHG or a coherent harmonic generation (CHG) FEL can be divided into three parts, the modulator, the bunching section and the radiator (see Fig. 1).

In the modulator the electron beam is in resonance with the electromagnetic wave of the external seed laser. Due to the interaction with the seed laser the electron beam become energy modulated with a periodicity equal to the seed wavelength. At FERMI the magnetic period of the modulator is 100 mm and the seed laser is typically operated at 260 nm with a pulse length of about 150 fs (FWHM).

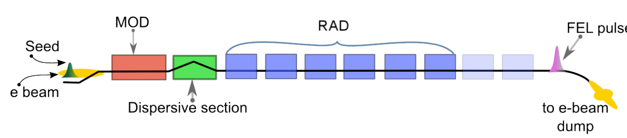

Figure 1: Layout of the undulator system of FERMI FEL-1 used for this work.

The energy modulation is then converted into density modulation when the electron beam passes through the dispersive section where higher-energy electrons follow a shorter path than lower energy electrons. Density modulation is created at the seed laser wavelength and also at higher harmonics. Typical values for the strength of the dispersive section correspond to an R56 in the range between 50 and 90 μm. In addition to producing bunching, if the electron beam has an energy chirp, the chicane acts also as a bunch compressor for the electron beam, as a result of the bunch compression also the wavelength periodicity is changed.

The magnetic strength of the final radiator is set so that the electron beam is at resonance with the desired harmonic of the seed laser. As a consequence of their

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input bunching, the electrons immediately emit coherently. In HGHG mode, the further FEL interaction inside the radiator of the electron beam with the produced coherent radiation lead to an increase of the bunching and a rapid strength increase of the coherent radiation. The FERMI FEL-1 radiator (RAD) is composed of 6 undulators , each 2.4 meter long, with a period of 55 mm.

FERMI Parameters

In the present experiments FERMI uses electron beams accelerated by a normal conducting linear accelerator to a final energy of about 1.2 GeV. Electron bunches have a charge varying from about 350 pC to 500 pC depending on the configuration studied. In all cases reported here only the first (BC1) of the two bunch-compressor chicanes present in the FERMI accelerator layout is used. The x-band linearizer and laser heater have been available since spring 2012 and have been used only for the last of the configurations ("**C**") studied in this work.

Table 1: Electron Beam Parameters

Configuration	**A**	**B**	**C**
Peak current (A)	~300	~350	~500
Charge (pC)	350	450	500

In order to study the effects of the electron beam phase space upon the spectral properties of the FEL pulses, we focus on three different configurations whose electron beam parameters are summarized in Table 1.

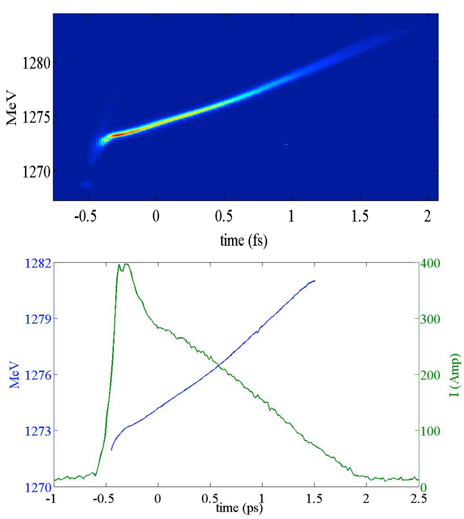

Figure 2: Typical longitudinal phase space (upper plot) and current (lower plot, green) and energy (blue) profiles of the electron beam used in configuration **A**. The head of the bunch is on the left.

Configuration **A** and **B** are the ones that have been used for the first period of commissioning of FEL-1 when x-band and laser heater where not available. In these configurations the compression of the electron beam cannot be optimized to produce a flat current profile. Configuration **B** has a somewhat higher charge than **A** in order to slightly increase the peak current. A typical phase space of the electron beam measured at the end of the accelerator is reported in Fig. 2. In these two configurations the longitudinal phase space has both a significant linear energy chirp and a current ramp with a spike at the head [6]. The seed laser, whose duration is much shorter than the electron beam, is generally placed in the region between 0 and 500 fs (Fig.2) where the electron beam properties are most conducive to good FEL output.

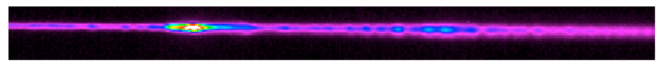
Figure 3: Electron beam spectrum measured in the beam dump after the undulator for the configuration **B**.

For configuration **B** the electron beam properties and phase space are very similar to the one of **A** shown in Figure 2. The main difference is that for configuration **B** the electron beam spectrum measured in the beam dump after the undulators shows strong evidence of modulation suggesting that microbunching instabilities along the accelerator start have affected the electron beam.

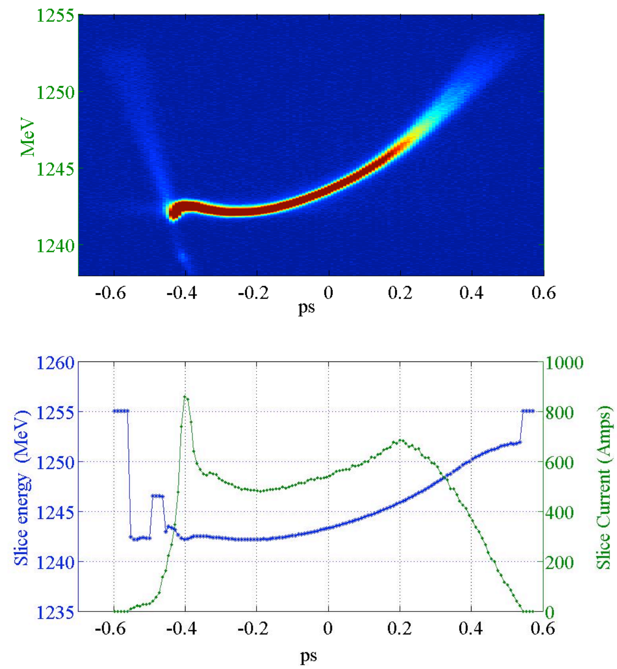

Figure 4: Typical phase space (a) and current (b, green) and energy (b, blue) profiles of the electron beam used in configuration **C**.

When the x-band and the laser heater became available in spring 2012, it was possible to change the compression scheme to take advantage of a linearized phase space at BC1. This allowed both increasing the compression factor and the beam charge. In configuration **C** the beam charge is increased to 500 pC. Setting the RF phase of the linac upstream BC1 at 28 degrees off crest, the beam is longitudinally compressed by a factor 10. The x-band is set to the decelerating crest in order to compensate the RF curvature and laser heater is set to the minimum value

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that suppresses microbunching instabilities [7]. With this configuration the typical beam has a peak current of about 500A that is almost constant over the main part of the beam. On the other hand the higher peak current of the electron beam enhances wake-field effects in the second part of the accelerator. As a result the longitudinal phase space of the electron beam at the entrance of the undulator has a significant quadratic chirp (Figure 4) [6].

SEEDED FEL SPECTRA

From the first period of operation of the FERMI FEL it has been immediately evident the benefit of seeding on the spectral properties of produced FEL pulses. Operation of FERMI in the **A** configuration produced FEL pulses characterized by narrow and very stable spectra [3].

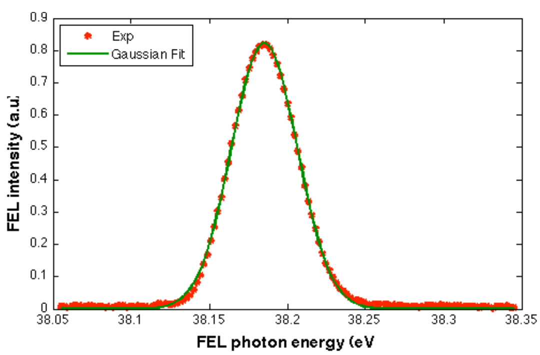

Figure 5: Typical single shot spectra measured for FERMI FEL-1 at 32 nm with the accelerator operated in the **A** configuration.

FEL spectra measured in these conditions generally are very well fit by a single mode Gaussian (Fig. 5). At 32 nm we measured typical bandwidth values of ~22 meV (rms) that, as expected from theory, are slightly larger than the seed-laser bandwidth of 14 meV.

Operating in the **A** configuration FEL spectra are extremely stable. Measured relative fluctuations of the central FEL wavelength at 32 nm are of the order of 3e-5 (rms).

The first evidence of degradation of spectral properties related to the deterioration of the electron beam quality occured in configuration **B** while trying to increase the FEL flux by increasing the electron beam charge.

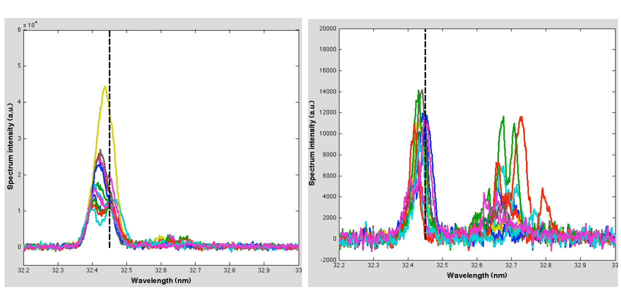

Figure 6: Series of spectra acquired in the FEL at 32nm in configuration **B** for two different timings of the external seed laser. Left: Seeding timed toward the tail of the spike. Right: Seeding moved closer to the spike.

The energy and density modulations produced by the microbunching instability and visible on the electron beam (cf. Fig. 3) can produce significant phase variations of the electromagnetic field within the FEL pulse. These variations both can broaden the central line (Fig 6-a) and/or even create new satellite lines at quite different wavelengths in the FEL spectrum (Fig. 6-b). The effects on the FEL spectra depend on the strength and period of the modulations of the electron beam that, in the case reported here, can vary along the bunch due to the non constant current profile. Microbunching instability growth is indeed expected to be stronger near the head of the bunch due to its high current spike (figure 6-b), while a smaller growth is expected near the lower current tail (figure 6-a). For this reason the FEL spectral properties in the **B** configuration will strongly depend upon the relative timing of the seed laser. Placing the seed laser toward the tail results in a stable, single mode spectrum but since the electron beam current is small, the FEL intensity is also small. By timing the seeding closer to the head of the bunch, the FEL intensity can be increased significantly but the spectra become more noisy and unstable.

If the electron beam current is further increased by using the x-band linearizer together with greater compression in BC1 and use of the laser heater (i.e., configuration **C**) we have found it possible to suppress microbunching and avoid fast energy modulations.

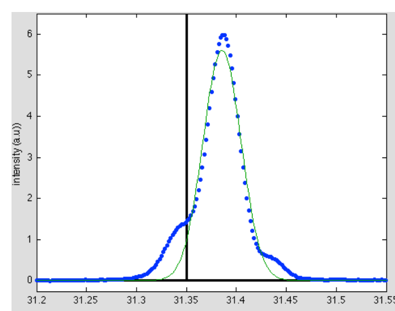

Figure 7: Single shot measurement of the FEL spectra at ~32nm using the **C** configuration for the electron beam.

In this configuration it has been possible to increase the FEL flux by more than a factor 5 with respect to what was typically obtained for configuration **A**. The FEL spectrum, however, is affected by the residual quadratic chirp in the electron beam energy. This relatively gentle variation, which occurs over a significantly longer scale compared with that of case **B,** leads to a general broadening of the spectrum to 29 meV (rms) (Fig. 7) but not multiple spikes. The main peak of the spectrum is still well fit by a simple Gaussian curve, and the bulk of the broadening is associated by appearance of shoulders on each side of the mean peak.

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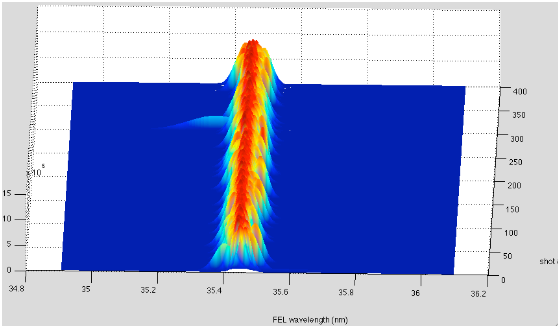

Figure 8: Series of 400 consecutive spectra of the FEL at 32 nm with the **C** configuration for electron beam.

In addition to spectral broadening, the use of higher compression and x-band linearization in configuration **C** also partially degrades the shot-to-shot stability of the central FEL wavelength as displayed in Fig. 8. Analysis of this data shows a normalized fluctuation level for the central wavelength of about 5e-4, a factor 10 larger than measured for configuration **A**. Although this value is significantly below the FEL bandwidth, ongoing studies are trying to mitigate this effect by producing a flatter longitudinal phase space for the compressed electron beam.

CONCLUSIONS

We reported experimental results obtained at FERMI FEL-1 operated at about 30 nm that show the effects of the electron beam phase space modulation on the spectral quality of the FEL pulses.

REFERENCES

[1] C.J. Bocchetta *et al.*, "*FERMI@Elettra FEL Conceptual Design Report*", Sincrotrone Trieste, Trieste (2007); E. Allaria, C. Callegari, D. Cocco, W. M. Fawley, M. Kiskinova, C. Masciovecchio and F. Parmigiani, "*The FERMI@Elettra free-electron-laser source for coherent x-ray physics: photon properties, beam transport system and applications*" New J. Phys. **12**, 075002 (2010).

[2] L.H. Yu *et al.*, Science **289**, 932-934 (2000).

[3] E. Allaria *et al.*, "*Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet*" to be publ. in Nat. Photon.

[4] L. Giannessi, "New lasing status report", this conference.

[5] L.H. Yu et al. "*First Ultraviolet High-Gain Harmonic-Generation Free-Electron Laser*", Phys. Rev. Lett. **91**, 074801 (2003); G. De Ninno *et al.*, "*Generation of ultrashort coherent vacuum ultraviolet pulses using electron storage rings: A new bright light source for experiments*", Phys. Rev. Lett. **101**, 053902 (2008); M. Labat, *et al.*, "*Coherent Harmonic Generation experiments on UVSOR-II storage ring*", Nuclear Instruments and Methods in Physics Research, Section A **593**, 1-5 (2008). D. Xiang *et al.*, "*Demonstration of the Echo-Enabled Harmonic Generation Technique for Short-Wavelength Seeded Free Electron Lasers*", Phys. Rev. Lett. **105**, 114801 (2010); C. Feng *et al.*, "*Measurement of the average local energy spread of electron beam via coherent harmonic generation*", Phys. Rev. ST Accel. Beams **14**, 090701 (2011); N. Čutić, *et al.*, "*Vacuum ultraviolet circularly polarized coherent femtosecond pulses from laser seeded relativistic electrons*", Phys. Rev. Special Topics - Accelerators and Beams **14**, 030706 (2011); M. Labat, *et al.*, "*High-Gain Harmonic-Generation Free-Electron Laser Seeded by Harmonics Generated in Gas*", Phys. Rev. Lett. **107**, 224801 (2011).

[6] G. Penco et. al., "Time-Sliced Emittance and Energy Spread Measurements at FERMI@Elettra", WEPD20 this conference.

[7] S. Spampinati *et al.*, "*Commissioning of the FERMI@ELETTRA Laser Heater*" MOPD58 this conference.

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