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 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).

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
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

<table>
<thead>
<tr>
<th>Configuration</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current (A)</td>
<td>~300</td>
<td>~350</td>
<td>~500</td>
</tr>
<tr>
<td>Charge (pC)</td>
<td>350</td>
<td>450</td>
<td>500</td>
</tr>
</tbody>
</table>

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.

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

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.
that suppresses microbunching instabilities [7]. With this configuration the typical beam has a peak current of about 500 A 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.](image)

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 occurred 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 32 nm 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.](image)

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.

![Figure 7: Single shot measurement of the FEL spectra at ~32 nm using the C configuration for the electron beam.](image)
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 $5 \times 10^{-4}$, 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**


