# DOUBLE STAGE SEEDED FEL WITH FRESH BUNCH INJECTION TECHNIQUE AT FERMI*

E. Allaria[1,#], D. Castronovo[1], P. Cinquegrana[1], M.B. Danailov[1], G. D'Auria[1], A. Demidovich[1], S. Di Mitri[1], B. Diviacco[1], W.M. Fawley[1], M. Ferianis[1], L. Froehlich[1], G. Gaio[1], R. Ivanov[1], N. Mahne[1], I. Nikolov[1], G. Penco[1], L. Raimondi[1], C. Serpico[1], P. Sigalotti[1], C. Spezzani[1], M. Svandrlik[1], C. Svetina[1], M. Trovo[1], M. Veronese[1], D. Zangrando[1], Benoît Mahieu[1,2], M. Dal Forno[3,1], L. Giannessi[4,1], M. Zangrando[5,1], G. De Ninno [7,1], E. Ferrari[8,1], F. Parmigiani[8,1], D. Gauthier [7]

[1]Elettra-Sincrotrone Trieste S.C.p.A., Basovizza
[2]CEA/DSM/DRECAM/SPAM, Gif-sur-Yvette
[3]DEEI, Trieste
[4]ENEA C.R. Frascati, Frascati (Roma)
[5]IOM-CNR, Trieste
[6]PSI, Villigen PSI
[7]University of Nova Gorica, Nova Gorica
[8]Università degli Studi di Trieste, Trieste

*Abstract*

Seeding a FEL with an external coherent source has been extensively studied in the last decades as it can provide a way to enhance the radiation brightness and stability with respect to that available from SASE. An efficient scheme for seeding a VUV-soft x ray FEL uses a powerful, long wavelength external laser to induce on the electron beam coherent bunching at the harmonics of the laser wavelength [1]. When the bunching is further amplified by FEL interaction in the radiator, the scheme is called high gain harmonic generation (HGHG) [2]. The need for high power seed sources and small electron beam energy spread are at the main limits for direct extension of the HGHG scheme to short wavelengths. The fresh bunch scheme was proposed as a way to overcome these limitations [3]; the scheme foresees the FEL radiation produced by one HGHG stage as an external seed for a second HGHG stage. We report the latest results obtained at FERMI that uses the two-stage HGHG scheme for generation of FEL pulses in the soft x-ray regime. A characterization of the FEL performance in terms of power, bandwidth and stability is reported. Starting from the FERMI results we will discuss extension of the scheme toward shorter wavelengths.

## TWO STAGE HGHG AT FERMI

Operation of FERMI FEL-1 has recently shown the possibility to produce high quality FEL pulses from a single stage HGHG device down to 20nm [4]. Although some coherent emission can be generated at even shorter wavelength with a single stage cascade [5], the amount of power that can be accessed is limited by the large energy spread that is necessary to get a significant bunching at a very large harmonic of the initial seed laser. In order to efficiently produce coherent emission at wavelengths at 10 nm and shorter, a two stage HGHG scheme [3] has been implemented in FERMI's FEL-2 [6]. The layout of the FEL-2 line is sketched in Figure 1. The linear accelerator is not shown as it is the same as used for FEL-1 (see, *e.g.*, [7,8]).

The FERMI FEL-2 layout has a first undulator (MOD) where the electron beam is in resonance with the external seed laser and becomes energy modulated at the laser wavelength (260 nm). The energy modulation is then converted into spatial modulation (bunching) at the laser wavelength and harmonics when the electron beam passes through the first dispersive section (DS1) with an R56 of few tens of microns. The bunched beam emits coherent emission at the desired harmonic wavelength (*e.g.,* 32.5 nm) that is resonant in the following undulators (RAD1. In the delay line (DL) the electron beam is delayed by few hundreds of fs with respect to the FEL pulse produced. The strong dispersion of the delay line also eliminates nearly all residual bunching in the beam at 32.5 nm and harmonics. An additional undulator (MOD2) is tuned again at 32.5 nm so that the head part of the beam can interact with the FEL pulse produced on the first stage. Here the interaction produces energy modulation at 32.5 nm that is converted to coherent bunching at 32.5 nm and higher harmonics by the second dispersive section (DS2) with an R56 of few microns. The electron beam, now bunched at very short wavelengths, enters the final radiator (RAD2) that is tuned to one of the harmonics of 32.5 nm (*e.g.*, 10.8 nm). Here coherent emission is followed by FEL amplification.

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#enrico.allaria@elettra.eu

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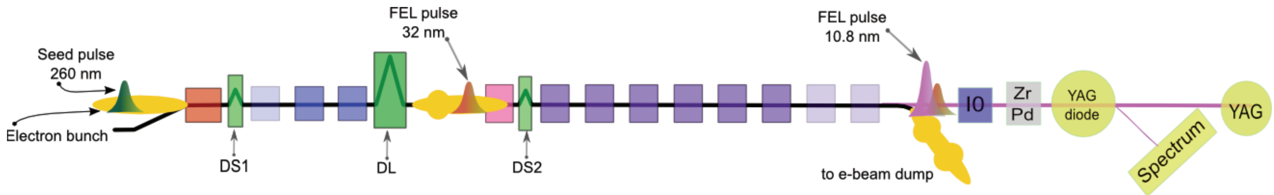

Figure 2: Layout of the undulator system of FERMI FEL-2 used for this work.

At the end of the undulator system the electron beam is sent to a beam dump while the FEL radiation goes to the diagnostic area. Diagnostics include an intensity monitor (I0), a set of filters capable of attenuate one of the two produced FEL pulses, a YAG screen with a CCD camera and a photodiode, and a spectrometer. More details about the photon diagnostic system can be found in [9].

### *The Electron Beam*

The electron beam used during the reported experiment is characterized by the parameters reported in table 1.

Table 1: Electron Beam Parameters

| **Parameter** | |
|---|---|
| Peak current (A) | ~300 |
| Charge (pC) | 500 |
| Energy (GeV) | 1.0-1.4 |
| Energy spread (keV) | 150 |
| Emittance (mm mrad) | 1 |
| Beam size (mm) | 0.15 |

Due both to the compression process and the wakefields produced by the FERMI accelerating structures, a significant quadratic chirp typically characterizes the longitudinal phase space as shown in Fig.2. Methods for reduction of the quadratic chirp have been proposed [10] and recently tested [8].

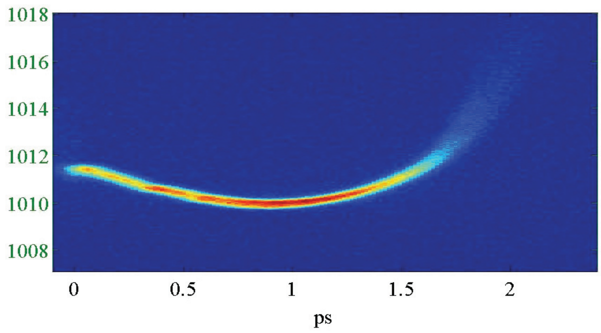

Figure 3: Typical phase space (energy vs time) of the electron beam used for the FERMI FEL-2 experiments.

## TWO STAGE HGHG RESULTS

Activity on FEL-2 started at FERMI in May 2012 [5] resulting later that year in the first evidence of coherent emission from the two stages HGHG [11]. More recent results obtained at FERMI FEL-2 and reported here show that the two stage HGHG scheme is suitable for FEL operation and user experiments in the EUV-soft x-ray spectral ranges that require highly stable and narrow bandwidth spectral properties.

Results at FERMI clearly show that the quality of the unseeded part of the electron beam is preserved in the first stage and in the delay line. Indeed, the seeding produced by the first stage radiation allows us to create strong bunching at higher harmonics that is then amplified by the FEL process (Figure 4).

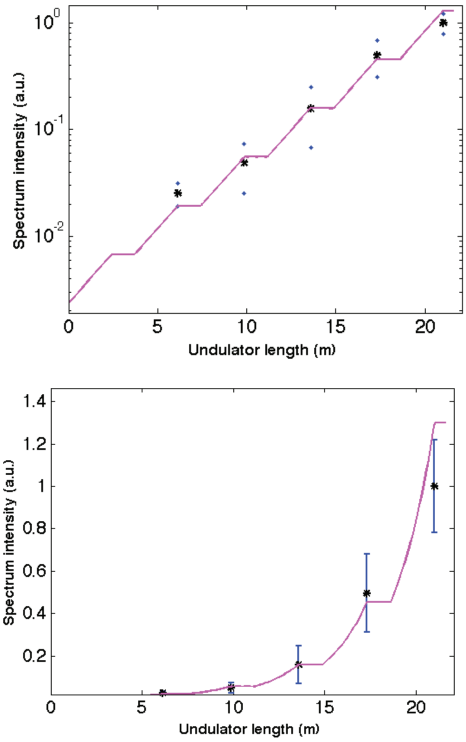

Figure 4: Experimental measurements of the FEL amplification on the second stage radiator at 10.8 nm.

The experimental data of the FEL power at various undulator lengths (dots in Fig.4) are compared with an exponential curve (magenta line in Fig.4) characterized by a gain length of 2.2 m as predicted by the Xie equations [12] using the FERMI parameters.

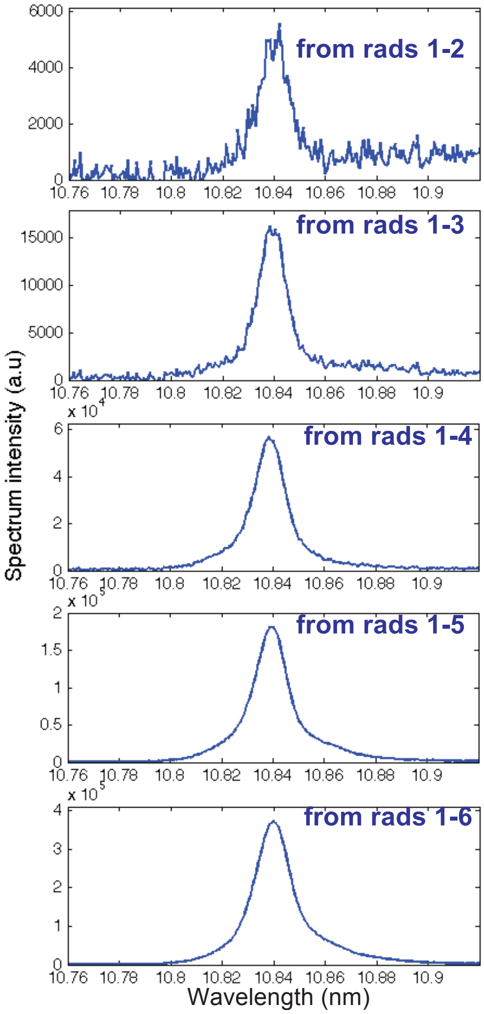

Figure 5: Spectra from the second stage for different length of the final radiator.

In addition to showing clear evidence of exponential gain, results at FERMI also show that the seeding has a strong impact on the spectral properties of the FEL from the beginning of the undulator. Figure 5 reports the spectrum acquired at FERMI for various undulator lengths. While the intensity of the spectra is increasing as the number of used undulator in RAD2 increases, the central wavelength and spectral bandwidth do not show significant changes with undulator number. Although it cannot be measured, a similar behavior is also expected for the temporal properties of the FEL pulse. This property of seeded FELs is very different from SASE where the spectrum become narrower as the FEL pulse is amplified in the undulator.

## SEEDED FEL SPECTRA

The quality and stability of the FEL spectra is an important aspect of the seeded FEL. A detailed analysis of the spectral properties of the FEL pulses produced by FERMI FEL-2 has been carried out.

Figure 6 reports the image of the FEL pulse at 5.4 nm as recorded by a CCD looking at the spectrometer output. The vertical axis shows the vertical beam size at the spectrometer while the horizontal axis for which the grating dispersion occurs shows the spectral distribution of the FEL power.

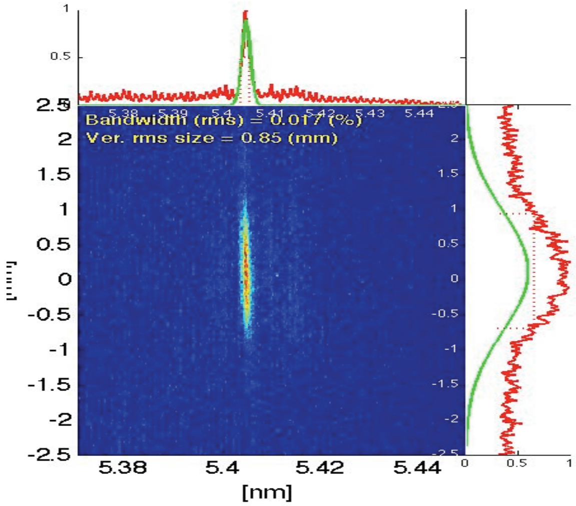

Figure 6: Single shot spectrum of FERMI FEL-2 operated at 5.4 nm.

Figure 6 clearly shows that the FEL emission occurs in a single spectral spike and the transverse profile of the FEL pulses is very close to the TEM00 Gaussian mode. The relative bandwidth measured for this case is $1.7*10^{-4}$ rms that, for Fourier limit pulse, would correspond to a temporal length of about 20 fs (FWHM). Although it has not been measured yet, 20 fs is a pulse length that is close what one could expect for an ideal HGHG at such a wavelength due to the pulse shortening occurring in the FEL process. For such a reason we are confident that when the system is properly optimized the FERMI FEL-2 can produce FEL pulses down to about 5 nm with a very high degree of longitudinal coherence.

The degree of spectral stability that is possible with FEL-2 can be inferred from the results reported in Fig.7. Here the analysis is performed on a sequence of more than 1500 shots with FEL-2 operated at 8.1 nm final wavelength.

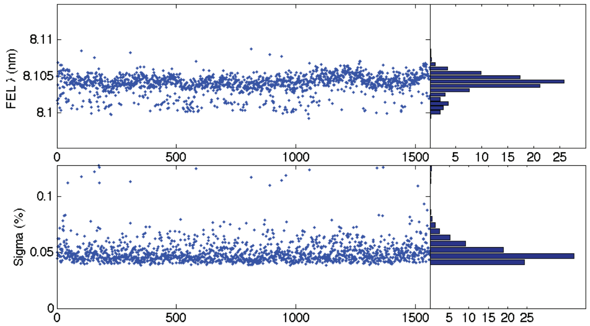

Figure 7: Statistical analysis of the FEL-2 spectra at 8.1 nm.

Results reported in Fig.7 show a very high stability of the central wavelength, i.e., a 1.6*10$^{-4}$ relative RMS fluctuation level, and an average RMS bandwidth of about 5*10$^{-4}$ that also show very low fluctuations.

## FRESH BUNCH DELAY

An important parameter in the double stage HGHG operating fresh bunch mode is the setting of the delay introduced by the delay line (DL). In case of too small a delay, the seeding in the second stage occurs in a part of the electron beam that has been already used in the first stage and thus spoiled by the FEL induced energy spread. In case of too large a delay, the second stage interaction will occur too close to the electron beam head (or even beyond) where the properties are not good enough to support reasonable FEL gain.

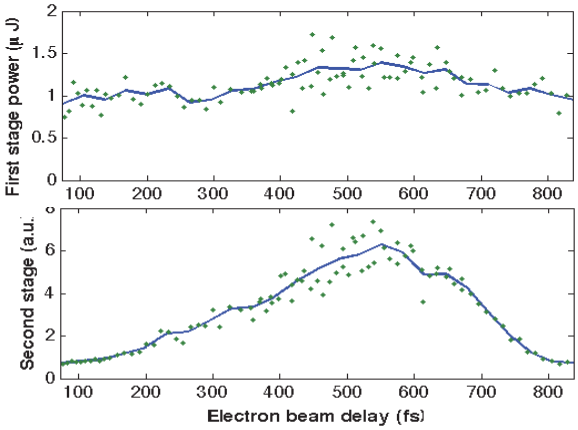

Figure 8: Energy from the first stage (upper panel) and second stage (lower panel) FEL pulses as a function of the delay introduced by the delay line.

The effect of the delay line has been studied at FERMI and the results in terms of FEL power are reported in Fig. 8.

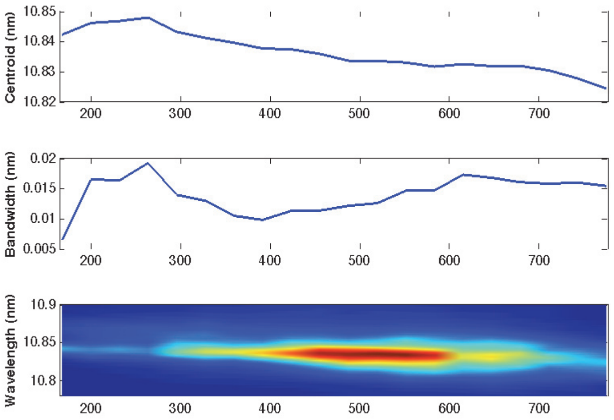

Figure 9: Spectral dependence of second stage FEL emission on the set of the delay line.

Figure 9 shows that in addition to affecting the overall FEL intensity of the second stage, the setting of the delay line also affects the spectral properties of the FEL radiation at the desired wavelength.

In the upper panel of Fig. 9 a clear dependence of the FEL wavelength vs the delay is shown. The almost linear dependence is a direct consequence of the quadratic chirp in the electron beam energy (Fig.3). In addition to the slight wavelength shift, one sees also a clear dependence of the FEL spectral bandwidth as a function of the delay (Fig.9 central and bottom panels). For short delays, the electron beam is degraded by the FEL processes in the first stage, while for large delay the second stage process occurs in a region too close to the head that is more affected by instabilities (e.g., microbunching) that locally deteriorate the phase space.

## ENERGY STABILITY

As was already shown on FEL-1, FERMI can be operated in a condition that gives very stable FEL pulses in terms of intensity to wavelengths as short as 20 nm.

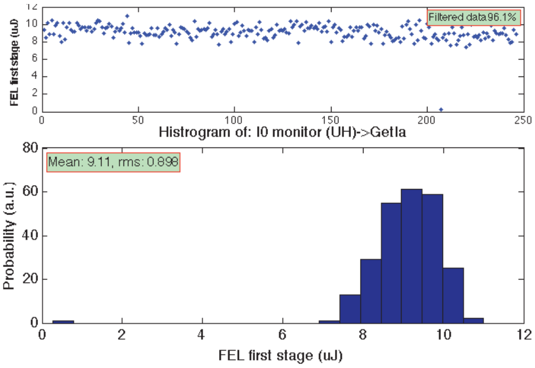

Figure 10: Evolution of the pulse energy produced by the first stage at 32.5 nm (upper panel) and histogram (bottom panel).

For FEL-2, the same level of stability with power fluctuations of the order of 10% can be achieved from the power produced by the first stage as shown in Fig. 10.

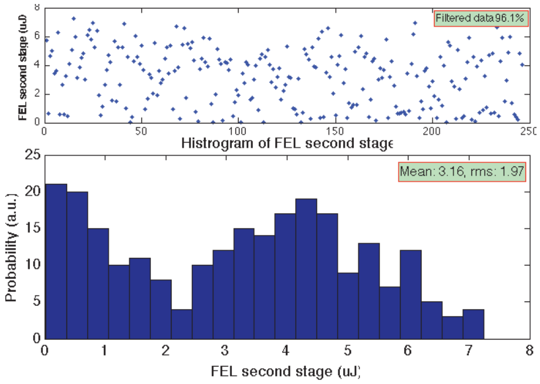

Figure 11: Evolution of the pulse energy produced by the second stage (4.7 nm) (upper panel) and histogram (bottom panel). The reported data refer to the same shots used in Fig.10.

However, the same level of stability has not been yet reached for the second stage FEL. Figure 11 reports the sequence for the FEL intensity at 4.7 nm for the same shots used in Fig.10.

As can be seen, although the system is stable enough to guarantee a reliable and stable operation of the first stage, the second stage at much shorter wavelength shows much larger fluctuations in FEL intensity.

Because the two data sets used in Fig.10 and Fig.11 were acquired simultaneously and refer to the same shots, it is possible to look for correlations between the two signals. As displayed in Fig. 12, the two signals show a clear evidence of nonlinear correlation. Moreover additional analysis not reported here indicates that both first stage and second stage FEL intensity are correlated to the electron beam energy.

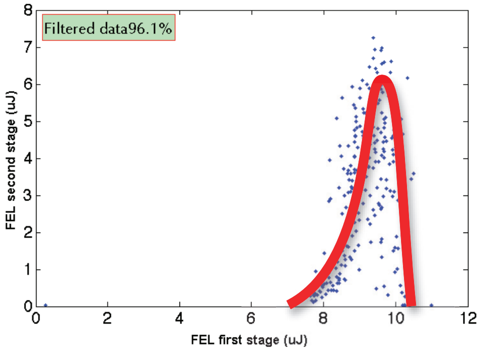

Figure 12: Correlation between the pulse energy of the first stage and the second stage. The nonlinear correlation is the results of a different sensitivity to electron beam energy for the two stages.

Our results suggest that the main reason for the larger fluctuations of the second stage FEL intensity at short wavelength are the energy jitter of the electron beam and the smaller gain bandwidth associated to the short wavelength operations.

## FERMI FEL-2 TUNING RANGE

In the last year FERMI FEL-2 has been operated with three different electron beam energies (1.0, 1.2, 1.4 GeV) allowing exploration of the spectral range from 14 nm down to about 3 nm (Fig. 13). In order to reach the very shortest wavelengths, in some cases the FEL has been operated in a way without true gain in the final radiator (in general, this is due to a low undulator strength parameter *K* for a given electron beam energy).

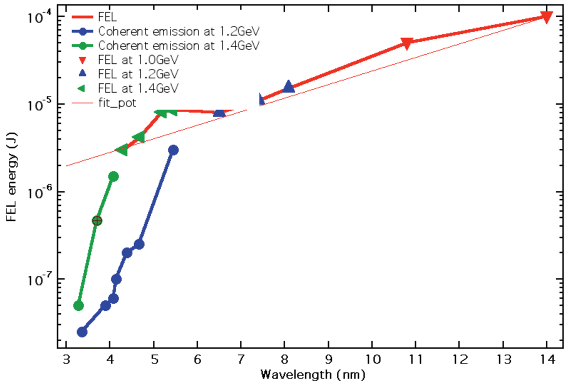

Figure 13: Summary of the achieved wavelength at FERMI FEL-2 at different electron beam energies (1.0 GeV red, 1.2 GeV blue, 1.4 GeV green) and in different regimes (FEL with triangles, coherent emission represented by circles).

## CONCLUSIONS

We report the most recent experimental results obtained at FERMI FEL-2 operated in the wavelength range of 14 to 3 nm. We have shown successful operation of a two stage HGHG cascade employing the fresh bunch technique. The scheme shows excellent spectral quality and stability but moderate stability in output pulse energy that we attribute mainly to electron beam energy jitter.

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