

PROGRESS WITH THE FERMI LASER HEATER COMMISSIONING*

Simone Spampinati[#], Giovanni DeNinno, Sincrotrone Trieste, Italy &
University of Nova Gorica, Nova Gorica, Slovenia

Enrico Allaria, Davide Castronovo, Miltcho B. Danailov,

Alexander Demidovich, Simone Di Mitri, Bruno Diviacco, William M. Fawley, Lars Froelich,
Giuseppe Penco, Carlo Spezzani, Mauro Trovò, Sincrotrone Trieste, Italy

Massimo Dal Forno, Eugenio Ferrari, Sincrotrone Trieste, Italy, University of Trieste, Trieste, Italy
Luca Giannessi, ENEA C.R. Frascati, Frascati (Roma) Italy, Sincrotrone Trieste, Italy

Abstract

FERMI@ELETTRA is a seeded free electron laser facility composed by one linac and two FEL lines named FEL-1 and FEL-2. FEL-1 works in HGHG configuration, while FEL-2 is a HGHG cascade implementing "fresh bunch" injection into the second stage. Performance of FEL-1 and FEL-2 lines have benefited from the use of the laser heater system, which is located right after the injector, at 100 MeV beam energy. Proper tuning of the laser heater parameters has allowed control of the microbunching instability, which is otherwise expected to degrade the high brightness electron beam quality sufficiently to reduce the FEL power. The laser heater was commissioned one year ago and positive effects upon microbunching. In this work we presents further measurements of microbunching suppression in two compressors scheme showing directly the reduction of the beam slice energy spread due to laser heater action. We present measurements showing the impact of the laser heater on FEL2.

INTRODUCTION

FERMI@ELETTRA [1] is a user facility based on two seeded FELs in the VUV (FEL-1 [2]) and soft x-ray (FEL-2 [3]) wavelength regimes. Both FEL lines are driven by a high brightness electron beam produced by the same linac [4]. The very bright electron beam required to drive VUV and X-ray FELs is susceptible to a microbunching instability [5] that produces short wavelength ($\sim 1\text{-}5\mu\text{m}$) energy and current modulations [6]. These can both degrade the FEL spectrum and reduce the power by increasing the slice energy spread. This collective instability takes place as linacs for FEL light sources are equipped with bunch compressors designed to increase the peak current to the level required for photon production. Microbunching instability is presumed to start at the photoinjector exit growing from a pure density and/or energy modulation caused by shot noise and/or unwanted modulations in the photoinjector laser temporal profile. As the electron beam travels along the linac to reach the first bunch compressor (BC1), the density modulation leads to an energy modulation via longitudinal space charge. The resultant energy

modulations are then transformed into higher density modulations by the bunch compressor. The increased current non-uniformity leads to further energy modulations along the rest of the linac. Coherent synchrotron radiation in the bunch compressor can further enhance these energy and density modulations [7,8]. The density modulation produced in the first bunch compressor is the source of further energy modulation along the linac and can eventually be amplified by the presence of other compressors. The final slice energy spread is increased and can reduce the FEL performance. A laser heater has been proposed to control these degradations [9,10]. This device can add a small controlled amount of incoherent energy spread to the beam and reduce microbunching instability growth via Landau damping in the bunch compressors. The capability of a laser heater to increase beam brightness has been demonstrated at LCLS where a reduction of the FEL gain length and an increase of the photon flux were observed [11]. The reduction of the final slice energy spread has however not been observed directly. To control microbunching instability in FERMI we have installed a laser heater between the photoinjector and the linac [4]. The FERMI laser heater was commissioned one year ago and positive effects upon microbunching instabilities, reduction of density and energy modulation, and FEL-1 performance was soon observed and reported in [12]. In this work we report further measurements demonstrating the reduction of the beam energy spread resulting to the action of the laser heater and his positive impact on FEL-2.

LINAC LAYOUT

Figure 1 shows the layout of the accelerator that produce the electron beam for FERMI [4].

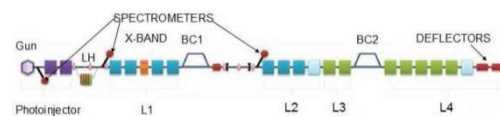


Figure 1: Layout of the electron beam accelerator of FERMI@ELETTRA.

Electrons are generated in the Gun and then pre-accelerated in the photo injector that includes two booster cavities. The first linac section (L1) accelerates the beam and produce the chirp needed for bunch compression in BC1. L1 includes a higher harmonic RF cavity used to

*Work supported in part by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3
[#]simone.spampinati@cockerfauk actually at Liverpool University, Liverpool, Uk and Cockcroft Institute Daresbury, Warrington, Uk

linearize the compression process. A second bunch compressor, BC2, is placed after other 5 cavities (in L2 and L3). Other 5 cavities (in L4) bring the beam to the final energy of 1.2-1.5 GeV. A transfer line connects the photoinjector to the linac. This transfer line hosts the laser heater (LH) and an energy spectrometer. The FERMI LH [12] consists of a short, planar polarized undulator located in a magnetic chicane through which an external laser pulse enters to longitudinally modulate the electron beam. The interaction within the undulator produces an energy modulation of the electron beam on the scale of the laser wavelength. The last half of the chicane time-smears the energy modulation leaving an effective incoherent energy spread increase. Another transfer line follows the first bunch compressor and is equipped with a vertical rf deflecting cavity [13,14] and a spectrometer that permits to characterize the longitudinal phase space of the heated and compressed beam [15]. A third diagnostic section, equipped with two deflectors [16] and a spectrometer, is placed at the linac end before the system bringing the beam to the undulator line. These two diagnostic sections are described in [15].

MICROBUNCHIN SUPPRESSION

The total compression factor needed to reach the peak current specified for FEL operation can be reached by means of BC1 only or by the combined action of BC1 and BC2. Numerical studies have enlighten that the single compression scheme is more effective in reducing the microbunching instability and allows one to obtain a lower slice energy spread respect to the double compressor configuration [17,18]. So far, FERMI user operation and the most of the commissioning have been performed running the linac with only one compressor. Attempts to run the linac with both bunch compressors resulted every time in a reduction of the FEL flux, confirming indirectly an increase of the slice energy spread. Even the initial commissioning of the laser heater was performed in the single bunch compressor configuration [12]. In that condition a cleaning of the phase space with an increasing of FEL brightness was observed. However, it was not possible to measure directly a reduction of the slice energy spread probably due to the finite experimental resolution. During the last year some commissioning time was devoted to the optimization of the double compression scheme. We report here the measurements of the final slice energy spread performed in the diagnostic section at the end of the linac when both compressor are used to produce a total compressor factor of 6-7 Beam charge was 500 pC. The final beam energy in the reported experiments is 1.21 GeV. Figure 2 shows the beam longitudinal phase space for three different settings of the laser heater. Figure 2a shows the beam phase space for an heating of 5 keV rms while the phase spaces shown in fig 2b and 2c are obtained for a beam heating of 10.5keV rms and of 42 keV. The heating occurs at a beam energy of 100MeV.

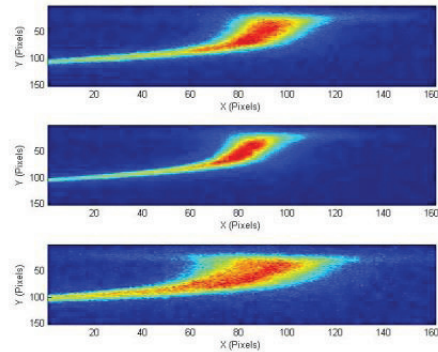


Figure 2: Beam longitudinal phase space at linac's end for three settings of the laser heater. 2a: 5 keV rms. 2b: 10.5keV rms. 2c: 42 keV.

Figure 3 shows the minimum slice energy spread as function of the energy spread added by the heater in the double compressor configuration. Each energy spread value is the mean of seven measurements. Energy spread is derived by the second moment of an ad hoc fitting function [19] built on the basis of the “Super Gaussian” function described in [20]. The expected spectrometer dispersion and resolution are 1.73m and ~50keV. An additional contribution of 50 keV to the measured energy spread is expected by the deflector while the CCD pixel dimension is equivalent to 20 keV. We suppose that these independent contributions to the measurement can be added in quadrature to give the measurement resolution. Thus, we subtract in quadrature a total of 75 keV from the measured energy spread to produce the value shown in fig 3.

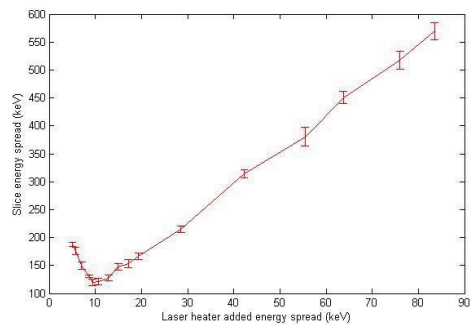


Figure 3: Slice energy spread as function of the energy spread added by the heater.

Reduction of the slice energy spread, as results of microbunching suppression by laser heater, is evident in the low heating part of the curve. Microbunching is suppressed for an optimum slice energy spread added by the heater corresponding to about 10 keV. The slice energy spread, corresponding to this value of the energy heating, is ~119KeV. A further increase of the heating results in more final energy spread due to beam compression and phase space conservation. The measurements taken at high value of added slice energy

spread are less affected by the measurement errors and by the initial beam energy spread. The measured energy spread, at high value of beam heating, is the results of the beam compression of the heated beam. From the last six points appearing in fig 3 it is possible to derive a compression factor of about 7. This is in good agreement with the bunch's peak current measured at the linac's end (~400A). From Fig.3, we can state that microbunching instability in the LINAC is well controlled by a beam heating of 10 keV.

IMPACT ON FEL 2

FEL-2 is a two stage cascade of HGHG working according the fresh bunch technique [21,22]. The electron beam interacts with the seed laser in the first modulator and it gains a spatial energy modulation at the laser wavelength. The energy modulation is converted in density modulation, at the harmonic of the laser wavelength, in the first dispersive section. FEL light is produced in the first radiator composed by two undulator that are tuned on a selected harmonic of the seed. This first HGHG stage is followed by one other in which the light pulse produce in the first radiator is used to modulate the electron beam in the second modulator. The electron beam is delayed, by a magnetic chicane, respect to the FEL pulse before to enter in the modulator. In this way, the entire HGHG process of the second stage happens in a fresh part of the bunch.

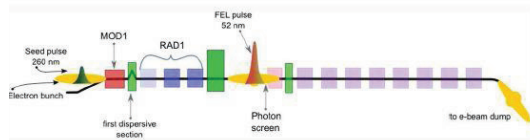


Figure 4: Schematic of the FERMI FEL-2 undulatorline

For further details on FEL2 see [3,23]. Fig 5 shows the pulse energy of the first and of the second radiator as a function of the laser heater energy. The first radiator and the second modulator are tuned on the 8th harmonic of the seed laser while the second radiator is tuned on the 4th harmonic of the first stage. The final wavelength is 8 nm. All the undulator except the first modulator are in circular polarization for maximum efficiency of photon-electron coupling. The three subplots refer to three different values of the R56 of the second dispersive section: 6, 12 and 16 μ m from the top to the bottom. The blue curve is the energy of the FEL pulse coming from the first radiator measured with a ionization gas chamber. The red curve is the energy of the FEL-2 measured with a diode [3].

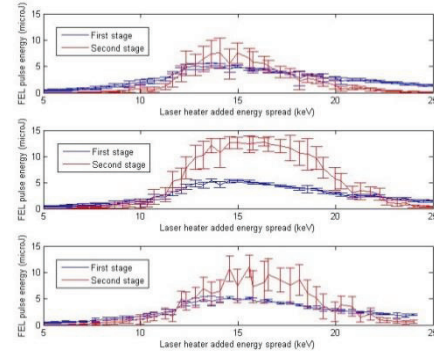


Figure 5: Schematic of the FERMI FEL-2 undulatorline

There is a clear impact of the laser heater action on the performance of FEL-2. An heating of 15 keV rms at 100 MeV produces an increase of about two orders of magnitude in the photon flux of FEL-2 respect to the case in which there is no heating, in all the three cases considered. From the plots it is possible to see even a correlation between the FEL flux produced by the second radiator and the intensity of the pulse coming from the first radiator used as a seed in the second modulator. We can guess that the impact of the laser heater of the FEL-2 performance come from the maximization of the “seed” in the second stage, from an optimization of the bunching in the second dispersive section and from the minimization of the gain length in the second radiator as a result of the reduction of the beam slice energy spread.

Actually, the first radiator, composed by two undulator modules, is quiet short so that a very high brightness of the electron beam is requested to bring the seed power to the level requested in the second stage. For this reason, the optimization of the laser heater is so important for FEL-2. We see that the pulse energy of FEL-2 is maximized for a beam heating of ~15 keV while the beam energy spread at the end of the linac is minimized by an heating of ~10keV. Further beam heating could be required to control the microbunching in the Spreader [24] and this could justified the required heating to optimize FEL performances. For a beam heating of ~15 keV the beam energy spread is ~150 keV (fig 3) and it is still well below the value of ~200 keV measured without heating. The energy spread of the unperturbed beam has a Gaussian shape while the beam energy distribution of the heated beam has a peculiar parabolic shape [10]. The energy distribution of the heated beam is more suited for HGHG process respect to the Gaussian one [25]. This could explain why a moderate reduction of the energy spread produces a great increase of the FEL power.

CONCLUSIONS

The FERMI laser heater was commissioned one year ago and positive effects upon microbunching instabilities, reduction of density and energy modulation, and FEL-1

performance was soon observed and reported in [12]. In this work we have reported further measurements demonstrating directly, for the first time, the reduction of the beam energy spread resulting from the action of the laser heater. We have collected evidence of the positive impact of the laser heater on FEL-2. We can compare these two sets of measurements to link the increasing of the FEL photon flux to the reduction of the beam slice energy spread.

REFERENCES

- [1] E. Allaria, C. Callegari, D. Cocco, W. M. Fawley, M. Kiskinova, C. Masciovecchio and F. Parmigiani, *New J. Phys.* 12, 075002 (2010).
- [2] E. Allaria et al., *Nature Photon.* 6, 693 (2012).
- [3] E. Allaria et al., to be published on *nature photonics*
- [4] C. J. Bocchetta et al., “Conceptual Design Report for the FERMI@Elettra project”, ST/F-TN-07/12 (2007).
- [5] E.L. Saldin, E.A. Schneidmiller, M-V. Yurkov, *Nucl. Instrum. Methods Phys. Res., Sect. A*, 409,1 (2002).
- [6] S. Di Mitri et al, *Nucl. Instrum. Methods Phys. Res., Sect.A*, 608,19 (2009).
- [7] S. Heifets, G. Stupakov and S. Krinsky, *Phys. Rev. ST Accel. Beams*, 5,064401 (2002).
- [8] S. Heifets, G. Stupakov, *Phys. Rev. ST Accel. Beams*, 5,054402 (2002).
- [9] E.L. Saldin, E.A. Schneidmiller, M-V. Yurkov, *TESLA FEL tech notes 2003-02* (2003). E.L.Saldin, E.A.Schneidmiller, M-V.Yurkov, *Nucl. Instrum. Methods Phys. Res., Sect.A*, 328, 355 (2004).
- [10] Z. Huang et. al., *Phys. Rv. STAB*, 7, 074401 (2004).
- [11] Z. Huang et. al., *Phys. Rv. STAB*, 12, 020703 (2010).
- [12] S. Spampinati et al., *Proceedings of the 2012 FEL Conference, MOPD58* (2012).
- [13] G.A. Loew, O.H. Altenmueller, *SLAC, PUB-135*, August 1965
- [14] M.Petronio, PhD Thesis. Trieste (2011)
- [15] M. Dal Forno et al., *Proceedings of the 2013 IPAC Conference, WEPD20* (2013).
- [16] G. Penco et al., *Proceedings of the 2012 FEL Conference, WEPD20* (2012).
- [17] M. Venturini, *PRST-AB*, 10, 104401 (2007).
- [18] S. Di Mitri et al., *Proceedings of the 2010 FEL Conference, THPB03*(2012).
- [19] G. Penco et al. *JINST* 8, 05015 (2013)
- [20] F.-J. Decker, Report No. SLAC-PUB 6684, 1994
- [21] L. H. Yu, *Phys. Rev. A* 44, 5178–5193 (1991)
- [22] I. Ben-Zvi, K. M. Yang, L. H. Yu, *NIM A* 318 (1992), p.726-729
- [23] E. Allaria et al., *FEL2013*
- [24] M. Venturini, A. Zholents, *NIM A* 593, 53 (2008)
- [25] E. Ferrari et al., *FEL2013*