LONGITUDINAL DIAGNOSTIC FOR SINGLE-SPIKE SASE FEL OPERATION

G. Marcus*, G. Andonian, A. Fukasawa, S. Reiche, J. B. Rosenzweig
UCLA, Los Angeles, USA

L. Giannessi
ENEA-Frascati, ITALY

M. Ferrario, L. Palumbo
INFN-LNF, Frascati, ITALY

Abstract

The possibility of ultra-short beam, very low charge, short wavelength Free Electron Lasers (FEL) at Sorgente Pulsata Auto-amplificata di Radiazione Coerente (SPARC) has been recently investigated. This paper explores the development of a longitudinal diagnostic that will provide the capability to characterize the short wavelength radiation based on the Frequency Resolved Optical Gating (FROG) technique. The paper includes studies of pulses simulated for the SPARC case using GENESIS and reconstructed using the FROG algorithm as well as proposed experimental layouts for the device.

INTRODUCTION

Recently, a broad user community has begun to realize the potential applications of FEL's as robust and varied light sources [1]. Some fields include the biological sciences, biomedical sciences and material sciences where the full gamut of FEL characteristics are employed. Full pulse characterization, however, including amplitude and pulse length, as well as full phase information, which is required for many experiments, has been somewhat difficult to acquire. Pulse amplitude information can be obtained through an autocorrelation, but the phase information has remained somewhat illusive due to the nature of the autocorrelation signal and the one-dimensional phase retrieval problem. Past experiments have succeeded in obtaining the phase information using a process called Frequency Resolved Optical Gating [2]. Some FROG geometries, however, were somewhat complex and operated only for small bandwidth. This paper explores the possibility of implementing a new geometry based on the Transient-Grating (TG) nonlinear interaction [3]. It has the advantage of minimal alignment degrees of freedom and the range of operation extends from the UV to the IR. The design of such a geometry is studied with start to end simulations of low charge, ultra-short pulses where the wavelength of radiation is 400 nm and 800 nm at SPARC, which have been simulated using GENESIS and reconstructed using Femtosoft Technologies FROG software [4]. Initial tests of the apparatus are proposed at the Visable-Infrared SASE Amplifier (VISA) FEL at BNL [5].

* gmarcus@physics.ucla.edu

FROG

The FROG technique involves using a nonlinear optical process to obtain an autocorrelation signal, which is then spectrally resolved to yield a spectrogram, or FROG trace [6]. A FROG trace is a two-dimensional plot of the signal spectrum vs. time delay. The phase information is stored within this trace and is retrieved using inversion algorithms found in commercial software. Previous experiments used to characterize FEL pulses have utilized multishot geometries [2]. This technique works well for conventional lasers because the shot to shot variability within the pulse is extremely small. However, FEL pulses are dependent upon the free electron bunches which create them and are somewhat less reliable in their shot to shot characteristics than their conventional laser counterparts. Therefore, single-shot methods are preferred to characterize the FEL pulse on a shot to shot basis and to quantify the variations between pulses.

Many experiments using conventional lasers often employ a rather robust and very simple FROG apparatus called GRating-Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields (GRENOUILLE) [6]. This particular geometry uses a thick Second Harmonic Generation (SHG) crystal as the nonlinear medium, which provides the autocorrelation signal and acts as a spectrometer. This is possible because SHG crystals have small phase-matching bandwidths. Therefore, certain wavelengths will be phase matched at particular angles from the optic axis within the crystal. Providing a large enough incidence angle allows the crystal to spectrally resolve the pulse. The SPARC FEL, however, will be capable of operating with wavelengths ranging from the UV to the IR. This bandwidth is far to large for a single SHG crystal. Also, the lower wavelength limit for SHG crystal operation does not extend into the UV [7]. For these reasons the GRENOUILLE geometry is not a suitable choice for a FROG device at SPARC. A new FROG geometry, there-

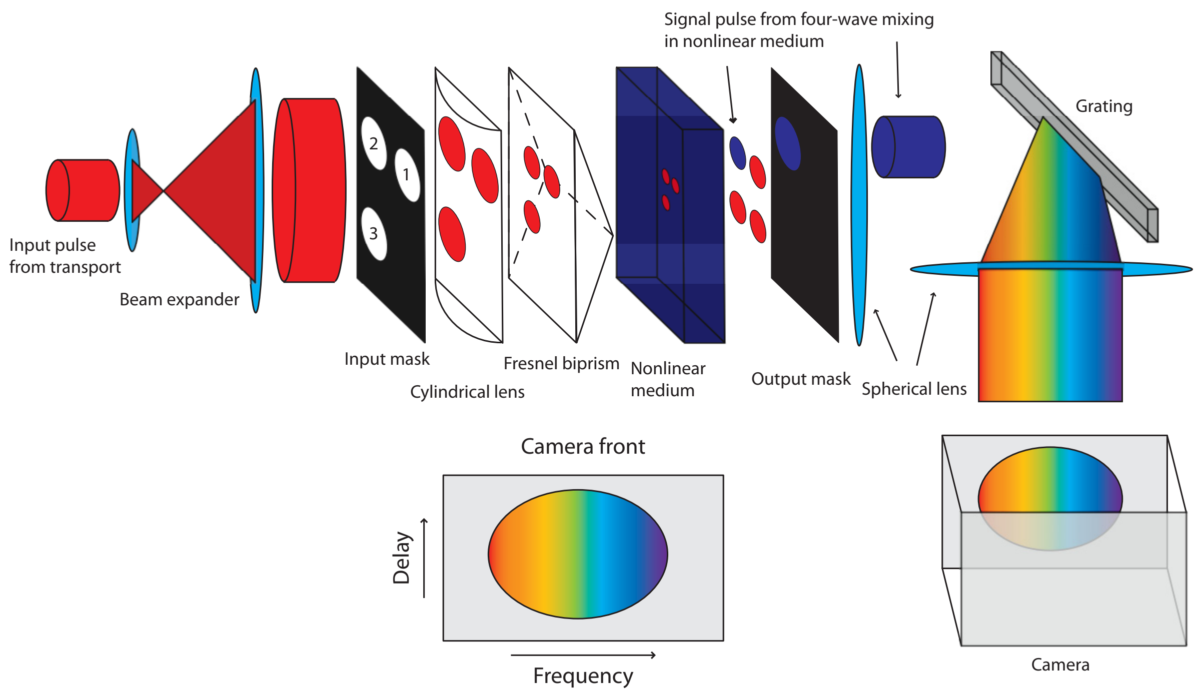

Figure 1: Transient-grating FROG geometry proposed for SPARC FEL as described in Ref. [3]

fore, must be developed utilizing a different nonlinear process to create the autocorrelation signal.

FROG Geometry

The geometry proposed by Dongjoo Lee *et al.* (Fig. 1), operates on a single shot basis and boasts a minimum number of alignment degrees of freedom among its many advantages, much like GRENOUILLE. First, the pulse obtained from the transport is expanded to a relatively large diameter and passed through a mask to split it into three beams. These beams then pass through a cylindrical lens, which brings each pulse to a line focus within the nonlinear medium. Before reaching the medium the beams pass through a fresnel bi-prism, which serves to cross interfering beams at a relatively large angle. Crossing the beams at an angle maps a relative delay along one of the beam's transverse dimensions, here along the vertical axis. Thus, this particular geometry operates on a single shot basis and does not require any additional delay lines. A major advantage of the bi-prism is that it is automatically aligned in space and time. The interaction of the three beams within the crystal generates an autocorrelation signal, which is selected by the output mask. The signal is then spectrally resolved by passing it through a homemade spectrometer consisting of a collimating lens, diffraction grating and focusing lens. Imaging the spectrally resolved signal pulse along the horizontal transverse dimension into a camera yields a FROG trace.

Nonlinear Interaction

The process that creates the autocorrelation signal within the nonlinear medium is a Transient-Grating nonlinear interaction termed Degenerate Four-Wave Mixing (DFWM) [8]. DFWM can be analyzed using a grating picture. The top two beams (beam 1 and beam 2) in Fig. 1 interfere and form a grating within the nonlinear medium. Bragg diffraction of the bottom beam from this grating produces a signal beam with wave-vector

$$\vec{k}_{sig} = \vec{k}_1 - \vec{k}_2 + \vec{k}_3 \tag{1}$$

as shown in Fig. 2

This process may also be described through the use of a nonlinear polarization. The three beams from Fig. 1 induce a nonlinear polarization (P^{NL}) with a term [8]

$$P^{(NL)} = \varepsilon_o \chi^{(3)} \mathscr{E}^3 \tag{2}$$

Here, ε_o is the electric permittivity of free space, $\chi^{(3)}$ is the third-order susceptibility of the nonlinear medium, and $\mathscr{E}$ is the total electric field

$$\mathscr{E}(\vec{r}, t) = \sum_{i=1}^{3} E_i(\vec{r}, t) \tag{3}$$

where E_i is an individual beam electric field given by

$$E_i(r,t) = \frac{1}{2} A_i(z) e^{i(\vec{k}_i \cdot \vec{r} - \omega_i t)} + c.c. \tag{4}$$

and A_i is the electric field amplitude. The nonlinear polarization that results is

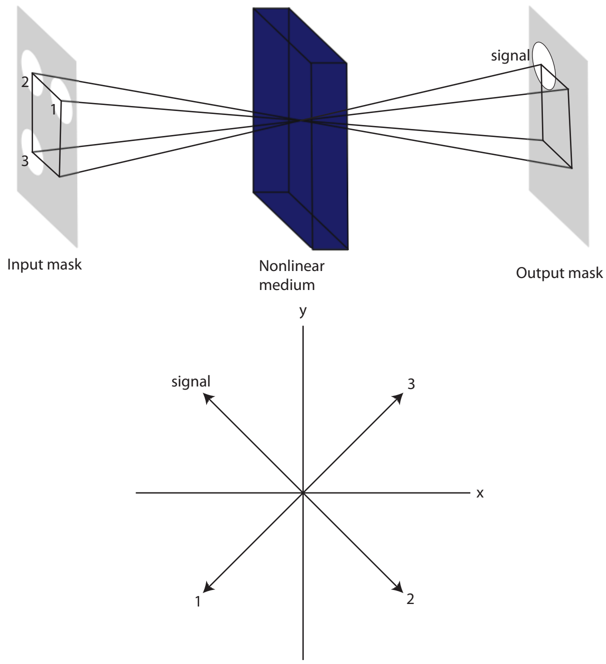

Figure 2: Above: Diagram showing the interaction of three input beams within the nonlinear medium and the resulting signal field selected by the output mask. Below: $\vec{k}_i$ vectors ($i = 1, 2, 3, sig$) in the transverse plane associated with the interacting input beams resulting in the signal beam. The result of the interaction is a signal beam with wavevector $\vec{k}_{sig} = \vec{k}_1 - \vec{k}_2 + \vec{k}_3$.

$$
\begin{aligned}
P^{NL}(\omega) &= \frac{\varepsilon_o}{2}\chi^{(3)}A_1 A_2^{\star} A_3 e^{i(\omega t + \vec{k}_p \cdot \vec{r})} + c.c && (5)\\
\omega &= \omega_1 - \omega_2 + \omega_3 && (6)\\
\vec{k}_p &= \vec{k}_1 - \vec{k}_2 + \vec{k}_3 && (7)
\end{aligned}
$$

Here, $\vec{k}_p$ is the polarization wave vector.

Because $\vec{k}_p = \vec{k}_{sig}$ the polarization has a constant phase related to that of the diffracted wave. Therefore, P^{NL} and E_{sig} are automatically phase matched. The TG nonlinear process is not limited by the phase matching bandwidth that SHG is. Also, since all three beams are of the same frequency the signal wave and polarization also propagate with the input frequency. These are advantages utilized in this customized TG FROG geometry [9].

SIMULATION

Start to end simulations of low charge, ultra-short beam pulses lasing at 400 nm and 800 nm at the SPARC facility were investigated. Beam creation and propagation were simulated using PARMELA and ELEGANT while FEL operation was simulated using GENESIS. Experimental FROG traces were also generated and analyzed using Femtosoft Technologies FROG software. The FROG trace generated by GENESIS as well as its reconstruction for the 800 nm simulation are pictured in Fig. 3. Notice the good agreement between the original trace and its reconstruction.

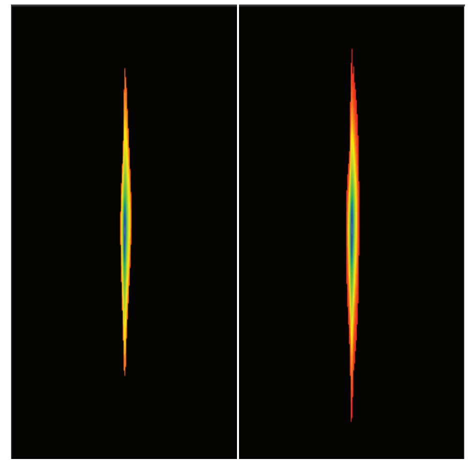

Figure 3: FROG trace from simulation (left) and its reconstruction (right) for the 800 nm case at SPARC. The FROG error for the 512×512 trace was 0.14%.

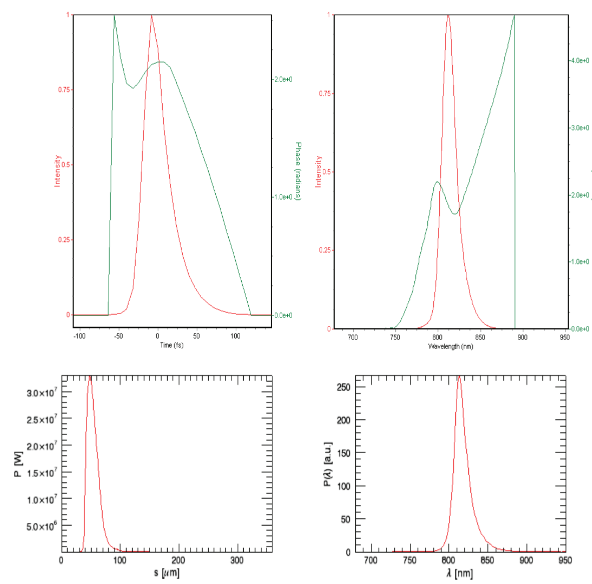

Figure 4: Above: plots of the reconstructed temporal intensity and phase (left) and the spectral intensity and phase (right). Below: corresponding plots generated by GENESIS simulations.

Fig. 4 shows both the temporal and the spectral reconstructed intensities and phases as well as their corresponding GENESIS plots for the 800 nm simulation. Note the agreement between the reconstructed images and their GENESIS counterparts for both the pulse and spectral shapes.

Similar simulations were also done for the case of lasing at 400 nm. The FROG trace generated by GENESIS as well as its reconstruction for this case can be seen in Fig. 5. Again, there is agreement between the original trace and its reconstruction. The retrieved spectrum as well as the phase can be seen in Fig. 6

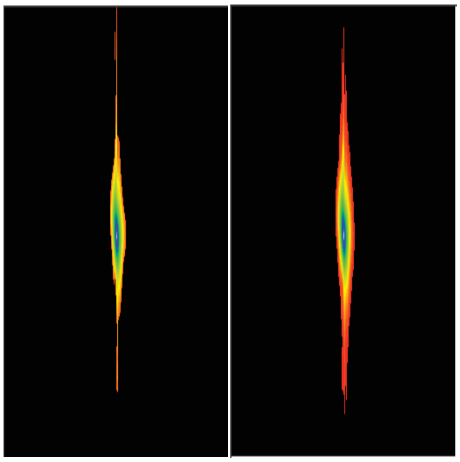

Figure 5: FROG trace from simulation (left) and its reconstruction (right) for the 400 nm case at SPARC. The FROG error for the 512×512 trace was 0.11%

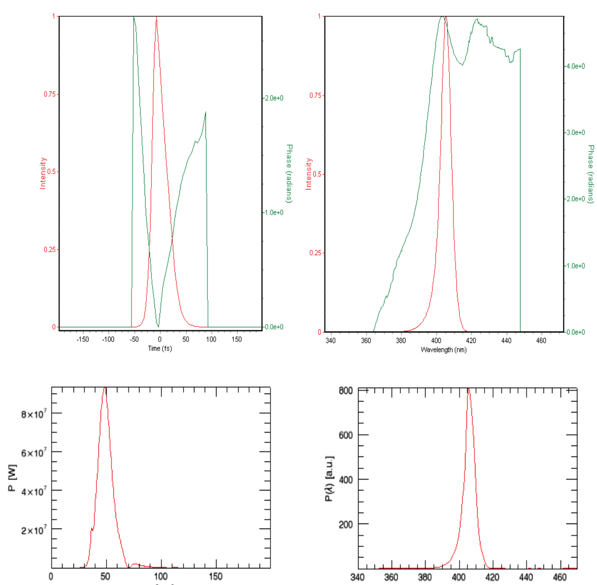

Figure 6: Above: plots are the reconstructed temporal intensity and phase (left) and the spectral intensity and phase (right). Below: corresponding plots generated by GENESIS simulations.

This figure shows both the temporal and the spectral reconstructed intensities and phases as well as their corresponding GENESIS plots for the 400 nm simulation. As in the case for the 800 nm simulation the agreement between the reconstructed images and their GENESIS counterparts for both the pulse and spectral shapes is apparent. For both the 400 nm and 800 nm simulations pulse lengths, amplitudes and full phase information was extracted.

CONCLUSION

A relatively simple, broadband TG FROG device designed by Lee et al. will be the most efficient and effective way to characterize FEL pulses at the SPARC facility. The device's ability to operate for a broad range of wavelengths with minimal alignment offers an attractive alternative to the popular GRENOUILLE apparatus, which is undesirable because SHG only operates for a limited bandwidth. Because the TG FROG beam geometry has the ability to operate in both the UV and the IR without requiring the change of any optical components, it is especially suited to function at two wavelengths of special interest, namely 400 nm and 800 nm. Start to end simulations using PARMELA, ELEGANT and GENESIS were done for both of these wavelengths at SPARC. FROG traces were obtained and reconstructed using Femtosoft Technologies software. The agreement between the initial trace and its reconstruction is clearly evident for both wavelengths. Also, the reconstructed spectral and temporal intensities matched well with the corresponding GENESIS plots. Relevant information about the pulse, including the spectral phase information, was retrieved and full pulse characterization was obtained.

The VISA FEL offers an attractive location at which to test the apparatus because the wavelength of operation as well as nonlinear harmonics are close to those of interest at SPARC. The current wavelength of SASE operation is 845 nm with the second and third nonlinear harmonics at 423 nm and 281 nm respectively [10]. Seeded operation is also planned at a wavelength of 1064 nm [11]. These wavelengths would allow testing of the full spectral range provided by the TG FROG device.

REFERENCES

[1] G. S. Edwards, *et al.*, Photochem. and Photobio. **81**, 711 (2005)

[2] B. A. Richman, *et al.*, Opt. Lett., **22(10)**, 721 (1997)

[3] Dongjoo Lee, *et al.*, Opt. Exp. **15(2)**, 760 (2007)

[4] Femtosoft Technologies, `http://www.femtosoft.biz/`.

[5] A. Murokh, *et al.*, Phys. Rev. E **67** 066501 (2003)

[6] R. Trebino. *Frequency-Resolved Optical Gating*, Kluwer Academic Publishers (2000)

[7] V. G. Dmitriev, *et al.*, *Handbook of Nonlinear Optical Crystals*, Springer-Verlag Publishers (1997)

[8] H. J. Eichler, *et al.*, *Laser-Induced Dynamic Gratings*, Springer-Verlag Publishers, (1986)

[9] John N. Sweetser, *et al.*, Opt. Lett. **22(8)**, 519 (1997)

[10] A. Tremaine, *et al.*, Phys. Rev. Lett., **88**, 204801 (2002)

[11] M. Dunning, *et al.*, *Proceedings of the 2007 Particle Accelerator Conference*, 1257, (2007)