# SEEDING OF SPARC-FEL WITH A TUNABLE FIBRE-BASED SOURCE

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*Abstract*

Instead of seeding a free electron laser in the UV-VUV with a frequency doubled or tripled laser or high order harmonics, here we investigate and present the first results on seeding the SPARC-FEL with a fibre-based tunable ultraviolet source. The seed generation system consists of a kagome hollow-core photonic crystal fibre (HC-PCF) filled with noble gas. Diffraction-limited DUV pulses of > 50 nJ and fs-duration which are continuously tunable from below 200 nm to above 300 nm are generated. The process is based on soliton-effect self-compression of the pump pulse down to a few optical cycles, accompanied by the emission of a resonant dispersive wave in the DUV spectral region. The quality of the compression highly depends strongly on the pump pulse duration, and ideally, pulses < 60 fs should be used. Our experimental set-up and associated GENESIS simulations enable us to study the utility of the seed tunability, and the influence of the seed quality, on the performance of the SPARC-FEL in the 200-300 nm range.

Single-pass free-electron lasers (FELs) can be used to generate powerful short pulses at very short wavelengths. Moreover, when seeded with an appropriate pulse, the overall properties of the FEL are greatly enhanced because the temporal coherence of the seed is transferred onto the FEL output wavelength [1,2]. Pulse-to-pulse fluctuations usually present when the FEL runs in the self-amplification spontaneous-emission (SASE) regime are also reduced. In addition, in a seeded configuration, the required length of the undulator is shorter than a SASE configuration. This is an advantage when striving for a more compact source. For short wavelength FELs, seeding sources include harmonics in gas [3] or harmonics of a mode-locked Ti:sapphire (Ti:Sa) laser [4]. Here we propose a recently developed ultra-compact deep-UV laser source. This tunable source consists of a HC-PCF filled with Argon, and pumped with fs-pulses. For the conversion from the pump to the UV to be efficient, the input pulse duration should not be too long (typically < 40 fs) and for this reason it is important to adapt our device to seed the SPARC-FEL [5]. Calculations using GENESIS show possible amplification.

In HC-PCFs, light propagates in an effectively diffraction-free manner, and can then interact efficiently with any material filling the core region. Furthermore, the very broad transmission window and the ultra-low dispersion of a kagome-lattice HC-PCf make it a unique tool for controlling nonlinear effects and especially spectral broadening [6,7]. Under appropriate conditions, an input pulse can experience soliton effects and be self-compress down to a few cycles, at which point it emits a resonant dispersive wave at a phase-matched wavelength in the UV spectral range [7,8]. The ultra-low dispersion of the fibre can be tuned through the gas pressure. Varying the filling pressure allows the tuning of the phase-matching conditions [9], and therefore the wavelength of the generated band. Tunability from < 200 nm to 320 nm with argon-filled fibre is possible (Fig.1d). More important, the UV band emerges in a single-lobed mode. To generated UV-light efficiently, we used ~20 cm of kagome HC-PCF sealed between two gas-cells (Fig.1). The fibre has a ~28 µm core diameter and low transmission loss (~1.1 dB/m at 800 nm) from 700 nm to 1.2 µm and the pressure of argon can be continuously adjusted up to 20 bar. Pumped with a 30 fs long pulse from an amplified Ti:Sa laser system, we measured a conversion efficiency of more than 8% from the pump wavelength to the UV [7].

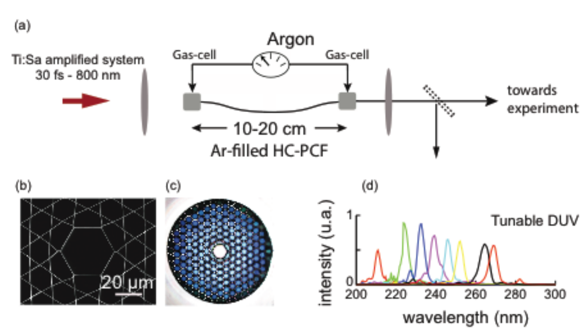


Figure 1: (a) Experimental set-up for the generation of tunable UV light. (b) A scanning electron micrograph and (c) an optical microscograph of the kagomé-fibre. (d) Tunable UV generated with various combinations of pressure/input power. Each colour corresponds to a different spectrum.

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The process can be explained by numerically solving the generalised nonlinear Schrödinger equation, which models the propagation of the input pulse along the fibre:

$$\frac{\partial A}{\partial z} = i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial t}\right)|A|^2 A + \mathfrak{F}^{-1}\left\{\left[i\left(\beta-\frac{\omega-\omega_0}{v}\right)-\frac{\alpha}{2}\right]A(\omega)\right\} \quad (1)$$

where $A$ is the complex envelope of the optical field, $t$ is the time in a reference frame moving at the group velocity $v$ of the input pulse, $\alpha$ is the wavelength-dependent loss, $\beta$ is the axial wavevector and $\mathfrak{F}^{-1}$ is the inverse Fourier transform and $\omega_0$ is the central frequency of the input pulse. The nonlinear contribution of the gas is $\gamma = n_2\omega_0/(cA_{\text{eff}})$, where $n_2$ is the nonlinear refractive index, $c$ the speed of light in vacuum and $A_{\text{eff}}$ the effective area of the core and $\omega_0$ the angular frequency of the pump. In our case, the core diameter was 28 µm and $\gamma \simeq 2.2\times10^{-6}$ $\text{W}^{-1}\text{m}^{-1}$ at 10 bar of argon. Propagation of a 1.5 µJ, 30 fs pulse at 800 nm in this fibre filled with 10 bar of argon is presented in Fig. 2.

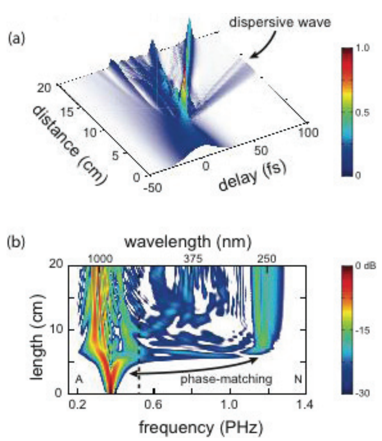


Figure 2: Temporal and spectral evolution of a 1.5 µJ 30 fs Gaussian pulse propagating inside 20 cm of kagome-fibre filled with 10 bar of argon gas. The dispersive wave is generated after ~ 6 cm.

Initially the pulse undergoes soliton-like compression (in the time domain) due to self-phase modulation induced by the Kerr-nonlinearity and the very low anomalous dispersion of the waveguide ($\beta_2$=−0.3 ps$^2$/km at the pump wavelength). The shock derivative term causes the spectrum to extend asymmetrically into the UV region. In the second stage the compressed pulse radiates resonant dispersive waves into the UV region. In the reference frame of the soliton, the phase-matching condition between the soliton and the emitted wave is given by

$$\beta_{\text{disp.}}(\omega) = \beta_{\text{sol.}}(\omega) \quad (2)$$

where the wavevector of the soliton is $\beta_{\text{sol}} = \gamma P_0/2$, $P_0$ being the peak power of the soliton at the point of emission [10]. Since the dispersion of the filled-fibre depends strongly on the gas pressure, the phase-matching condition and consequently the wavelength of the generated UV are tunable by varying the pressure. When generated, the radiation quickly separates from the residual pump due to strong group velocity walk-off (Fig. 2a). From the simulations we estimate that the UV pulse duration immediately after its generation is ~10 fs. A crucial point in this process is the initial compression of the soliton. The compression factor ($F_c$) as well as the length required to reach the maximum compression ($L_{\text{fiss}}$) are directly related to the soliton order N by [8]

$$F_c \sim 4.6\,N\,, \quad L_{\text{fiss}} \sim \frac{L_D}{N} \quad (3)$$

where $L_D = t_0^2/|\beta_2|$ is the dispersion length, $t_0$ is the input pulse duration. The soliton order is given by $N^2 = \gamma P L_D$. Unfortunately, the quality of the compression is $\propto N^{-1}$, the quality of the generated band is then strongly affected by N: the longer the pulse duration, the less clean is the emerging UV band (Fig.3).

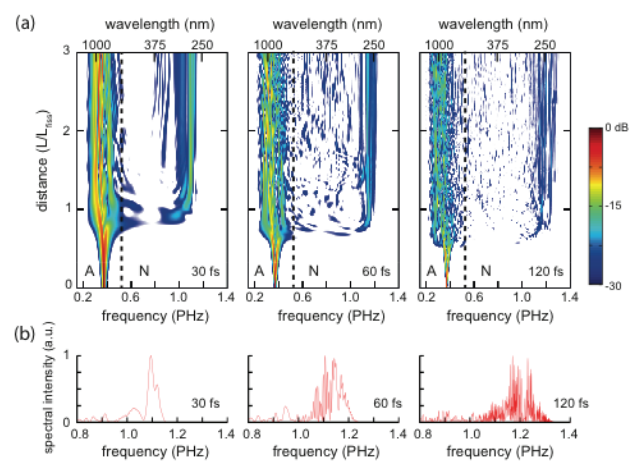


Figure 3: Influence of the input pulse duration with $t_0$/N=0.2. Spectrum of the UV band is dramatically degraded as the input pulse duration increases.

In the case of the SPARC-FEL, harmonics are generated with an amplified Ti:Sa with 160 fs long pulses. To use the fibre-base UV-source, it is important to include an extra stage in order to compress these pulses down to 20-30 fs. The compression stage at the output of the amplified Ti:Sa prior the UV generation scheme (fig. 4) consists of 2 cm of 37 µm core diameter kagome HC-PCF filled with 20 bar of krypton. Under such conditions, the input pulse propagates in the normal dispersion regime and experiences both temporal and spectral broadening. The linear chirp of the pulse is then compensated using a



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pair of chirped mirrors and the pulse is compressed down to ~ 25 fs, sufficient for the generation of UV.

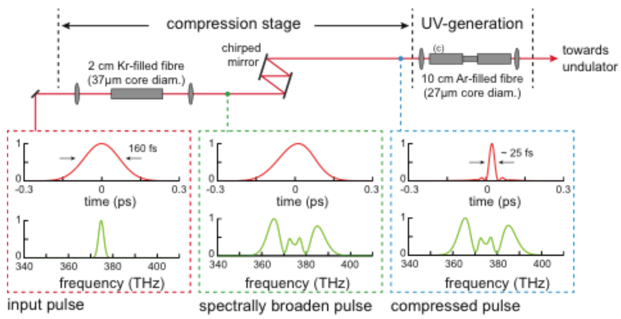


Figure 4: Two stage set-up. The compression stage consists of 2 cm of Kr-filled kagome fibre with 37 µm core diameter followed by a pair of chirped mirrors. Graphs are simulated from a perfect sech-pulse at the input of the compression scheme.

To explore the potential of this new source for seeding a FEL, we used the GENESIS code [11] with parameters corresponding to the SPARC-FEL. Table 1 presents the different parameters used in the simulations, for seed pulses at 275 nm.

Table 1: Parameters Used for GENESIS Simulation in the Case of Seeding of the SPARC-FEL

| | |
|---|---|
| **E-beam** | |
| Energy | 176 MeV |
| Current | 50 A |
| Emittance | 1.0 π.mm.rad |
| Energy spread | $10^{-4}$ |
| **Undulator** | |
| Period | 28 mm |
| Nb. periods/section | 77 |
| Nb. of sections | 6 |
| Deflexion parameter | K = 0 to 3.4 |
| **Seeding pulse** | |
| Wavelength | 275 nm |
| Energy/pulse | <100 nJ |
| Pulse duration | 10 fs |
| Peak Power | 10 MW |

Fig. 5 shows the main results of the GENESIS simulations. Seeding at 275 nm with an input pulse of 10 fs-FWHM duration and 10 MW peak power (Fig. 5a), leads to amplification in the FEL by one order of magnitude. However, the seed rapidly slips over the electron bunch and the power then grows at the rear of the pulse. This leads to a significant temporal broadening of the input pulse. The spectrum is significantly narrowed by the FEL bandwidth and shows small ripples on the edged of the main spectral peak.

In summary, we proposed here a new source of tunable UV for seeding FELs. The source generates deep-UV

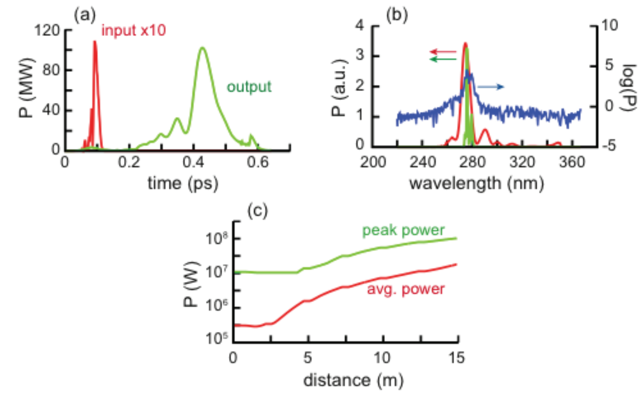


Figure 5: Simulations using the Genesis code with parameters given in Table 1.

light, widely tunable by varying the gas-pressure in an argon-filled kagome-lattice HC-PCF. The UV is always generated in the fundamental mode and conversion efficiencies of up to 8% have been measured. The set-up is extremely compact and could be integrated into an existing FEL, providing access to continuously-tunable seed light from < 200 to 320 nm. Simulations on the SPARC-FEL show amplification for a typical achievable wavelength of 275 nm.

A European grant (CENILS) has recently been accepted with the aim of implementing this fibre-based source at FERMI@Elettra, in Trieste.

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