STATUS OF THE SEEDING EXPERIMENT AT SPARC

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Abstract

Sources based on high order harmonics generated in gas with high power Ti:Sa lasers pulses represent promising candidates as seed for free electron laser (FEL) amplifiers for several reasons, as spatial and temporal coherence and wavelength tunability. We describe the research work plan under implementation at the SPARC FEL facility (Sorgente Pulsata e Amplificata di Radiazione Coerente, Italy) [1] in the framework of the EUROFEL programme. The main goal of the collaboration is to study and test the amplification and the FEL harmonic generation process of an input seed signal obtained as higher order harmonics generated both in crystal (400nm and 266 nm) and in gas (266nm, 160nm, 114nm) from a high intensity Ti:Sa laser.

INTRODUCTION

During the last years, new schemes other than the Self Amplified Spontaneous Emission (SASE) have been proposed for reaching very short wavelengths in systems based on Free Electron Laser (FEL) [2,3,4,5], where the main goal is to design relatively compact and fully temporally coherent sources. Seeded FEL amplifier operation in combination with harmonic generation has been demonstrated experimentally in Brookhaven [4]. In this arrangement, an external laser source is seeded into a modulator, i.e. an undulator where a periodic energy modulation with the periodicity of the seed wavelength is induced in the longitudinal electron beam phase space. The successive beam evolution in a dispersive section induces the conversion of the energy modulation into a density modulation and consistent emission of radiation at higher order harmonics with longitudinal and transverse coherence reproducing those of the laser seed is obtained in a radiator undulator. The idea of seeding or self-seeding an FEL amplifier and then using the induced energy/phase modulation in order to produce radiation at the harmonics of the fundamental in a cascaded FEL configuration plays a significant role in many of the existing or proposed FEL projects [6,7,8,9,10,11,12].

At the same time important progresses in the field of strong laser-matter interaction have been made, leading to the generation of high-order harmonics of intense laser pulses in gases. This technique is being well controlled and the generation of radiation with reasonable energy per pulse down to 10 nm [13] has been demonstrated. An intense tunable source as the High-order Harmonics of a Ti:Sa laser generated in a Gas (HHG), represents a good candidate to feed a FEL amplifier cascade with the final operating wavelength down to the water window range [14].

With these driving motivations a test experiment consisting in seeding the HHG harmonics in the SPARC FEL amplifier has been proposed and is under implementation [15]. This experiment has many associated outcomes and possibilities:

- Study of the problems related to the injection of an external radiation seed in a single pass FEL. Analysis of the coupling efficiency of the e-beam – seed pulse in terms of the input parameters.
- The e-beam shot noise suppression induced by the coherent seed at different wavelengths can be studied. A comparison with simulation data will allow code validation for extrapolation of the simulation data to lower wavelengths.
- The evolution of phase/amplitude perturbations of a smooth pulse can be analysed in different conditions of gain saturation and slippage. Strongly non-linear regime of FEL operation can be induced and experimentally verified.
- The above analysis can be extended to the harmonics produced in SPARC. The seeding in the present SPARC configuration is possible at 266, 160, 114 and 88 nm. At the shortest wavelength the FEL is

operated exploiting the gain on higher order harmonics.

- The SPARC variable gap undulator can be operated at different resonant frequencies, thus allowing tests of cascaded FEL configurations. The fresh bunch injection technique [16], which has been considered as a mean to overcome the e-beam heating which inhibits the gain process in a multiple stage FEL cascade can be also tested.
- An experimental test of super-radiant FEL cascade [17] can be implemented, and the properties of a Super-radiant pulse in a cascaded FEL can be experimentally studied.

EXPERIMENT LAYOUT

The experiment is based on the installation of an additional laser amplifier and a gas jet interaction chamber devoted to the amplification and conversion to higher order harmonics respectively, of a short laser pulse extracted from the same oscillator driving the electron gun. A layout of the SPARC FEL with the seeding injection line is shown in Figure 1.

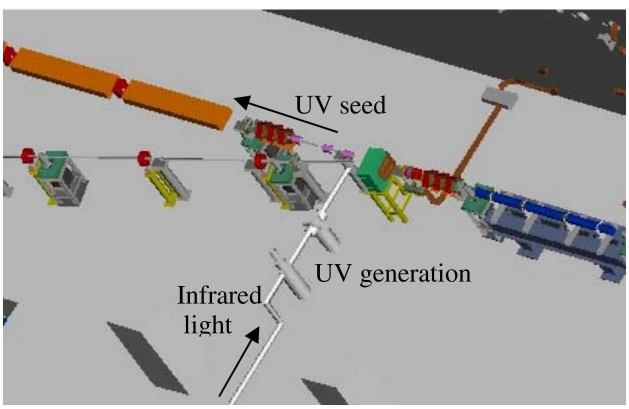

Figure 1: Seeded SPARC FEL general layout.

The UV pulse is then injected into the SPARC undulator by means of a periscope and a magnetic chicane deflecting the e-beam from the straight path. High-order odd harmonics of the Ti:Sa laser may be generated in gas, at the wavelengths 266, 160, 114 and 88 nm. In Fig. 2 it is shown the dependence of the wavelength with the undulator K parameter in the gap range allowed by the SPARC undulator, by assuming that the SPARC e-beam energy may be varied in the range 150-200 MeV. Seeding is foreseen at the starting wavelength of 400 nm, the second harmonic of Ti:Sa generated in crystal. The resonance condition is fulfilled in this case at a beam energy of about 170 MeV. At 200 MeV the resonance condition corresponding to the gas generated odd harmonics of the Ti:Sa (266 – 160 and 114 nm) may be reached by varying the undulator gap. The wavelength of 88 nm may be reached by tuning the undulator at the gap corresponding to the resonance at 266 nm and by seeding at the third harmonic of the FEL. The SPARC configuration is monitored by diagnostic stations located in between the six undulator segments, which provide the possibility to follow the dynamics of the FEL pulse propagation in different regimes, from the shot noise dominated regime, to the exponential growth and the saturation regime.

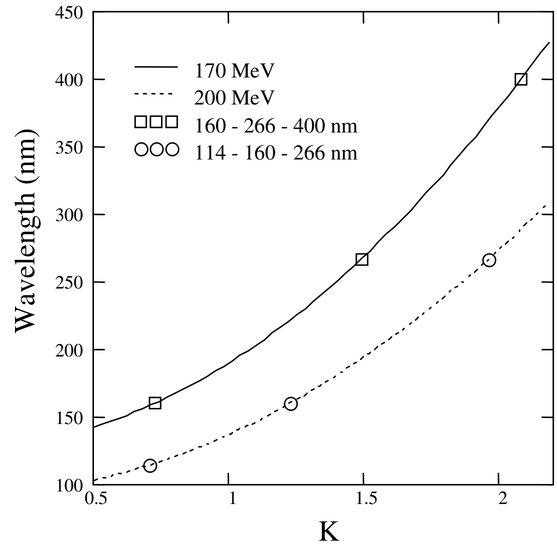

Figure 2: Seeded SPARC FEL operation wavelengths.

SEEDED FEL DYNAMICS

An analysis of the seeded SPARC FEL characteristics has been performed with the code GENESIS 1.3 [18]. This code assumes a TEM_{00} Gaussian mode as input seed and solves the equations for the motion of the electrons and the evolution of the field in the undulator.

What we observed is that the optical injection scheme does not critically influence the performances of the FEL amplifier, because when the exponential gain regime begins, the gain guiding of the electromagnetic power determines the equilibrium radiation beam size (Figure 3). For this reason the optimum point for the injection parameters consist in maximizing the intensity of the radiation in the first few gain lengths.

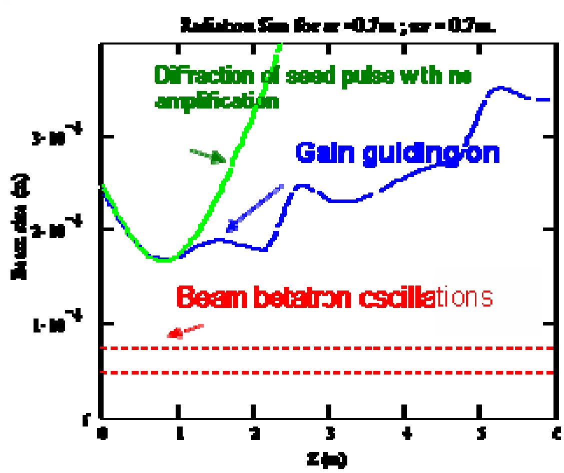

Figure 3: Beam size of the seeded FEL (blue) vs the longitudinal coordinate. Beam size in absence of gain (green). E-beam size (dashed red, max-min).

A summary of the simulations done at the different wavelengths is shown in Table 1.

Table 1: Seeded SPARC simulation parameters. The saturation length has been calculated assuming 10^5W input seed at all the wavelengths.

λ (nm)	K	Energy (MeV)	Gain length	Sat. length	Sat. power
400	2.17	170	0.51 m	6.5 m	50 W
266	1.96	200	0.59 m	7.25 m	200 W
160	1.22	200	0.96 m	12 m	7.5 kW
114	0.7	200	1.3 m	15 m	100 kW

HHG GENERATION

Different criteria are taken into account for the design of the HHG generation chamber, such as the performances of the high harmonics in gases, the vacuum needs, the resistance of the optics in the transport line, the geometrical constraints due to the accelerator and the building. The system is composed by three separated chambers, the generation of harmonics in gas occurs in the first chamber, frequency selection in the second chamber and VUV beam matching for its overlap with the electron beam takes place in the third chamber. A final vertical periscope is used to align the VUV beam in the undulator.

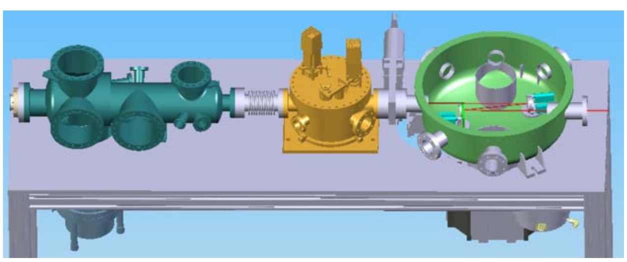

Figure 4: CATIA view of the three chambers for harmonic generation, filtering and mode matching to the undulator.

The energy requirement for the generation of harmonics in gas for the SPARC experiment can be fulfilled with a Ti:Sa regenerative amplifier. This class of amplifiers may deliver up to 2.5 mJ per pulse with a good transverse mode profile. The expected pulse duration is the same generated by the master oscillator driving the photocathode, before the pulse shaping procedure, which is 100 fs.

Table 2: Energy per pulse at the first harmonics

λ (nm)	Energy (nJ)	Peak Power (kW)
266	>50	>470
160	>5	>47
114	>0.5	>4.7
88	>0.5	>4.7

The optimized laser waist size for high order harmonic generation in the gas jet is about 100μm, which is obtained after focusing with a focal length of 2 m. The expected energy per pulse at the first harmonics is listed in Table 2.

BEAM DYNAMICS

Magnetic chicane

The transfer line from the SPARC linac exit to the undulator entrance, sketched in Fig. 5, is a 5.75 m long line including two triplets of quadrupoles, used for matching the beam parameters at the exit of the linac to those of the undulator beamline. The line includes an RF-deflector placed at the exit of the first triplet for the measure of bunch length and slice beam parameters. The RF-deflector is followed by a bending magnet that will be used to deviate the beam towards the dogleg line (upper beam line in Fig. 5) used for beam compression studies.

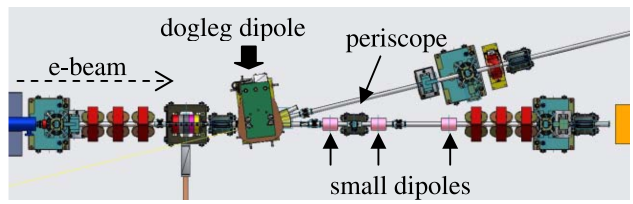

Figure 5: Layout of the SPARC transfer line

The original layout of the transfer line has been modified in order allow the electron beam to perform a small "orbit chicane" and avoid interaction with the photon beam injected at the periscope, and ensuring superposition at the undulator entrance. The required orbit bump is from 5 to 10 mm at the periscope location. The best solution is a four correctors scheme, which allows for having beam displacement and no angle at the desired injection location. Since the design of the transfer line has been already optimized for the SPARC working points at 155 and 200 MeV electron energies, the best solution was to use as first bump corrector the first dipole of the dogleg (black big arrow in Fig. 5). This solution allows to save space and to reduce at the same time the required corrector strengths. The flag and bellows positions, originally placed at the midpoint between the dipole and the second quadrupole triplet, had to be changed in order to accommodate the other three dipole magnets (indicated by small arrows in Fig.5). According to the magnets positions, the required bump can be obtained with angles respectively of 7 and 14 mrad.

Dynamics in the chicane

The space charge effects associated to the magnetic chicane on the e-beam quality at the undulator entrance has been calculated with PARMELA [19] and TREDI [20]. Due to the large aperture of the short dipole magnets of the chicane an accurate modelling of the magnetic fields of all the magnetic elements placed in the beamline based on 3D maps retrieved by RADIA[21] code was preferred to the usual approach based on the hard edge model. In particular the maps of the single elements (quadrupole and dipole) on a grid x,y,z have been computed by RADIA. The computations, that include the effect of beam space charge, were done for two beam energies, 155 and 200 MeV and two beam offsets, 5 and 10 mm. The chicane magnetic fields is set in order to get the desired beam deflection and simultaneously to control the e-beam centroid position and angle at the undulator entrance that must be kept within the prescribed tolerances (respectively 100 μm and 50 μrad). In figure 6 the x-z trajectory and the *By* magnetic fields of the chicane for a bump of 10 mm at an energy of 200 MeV is shown: the magnetic field on the first dipole is set to ~400 gauss in order to get the necessary deflecting angle of 7.14 mrad while the magnetic fields of the inner dipoles must be equal (~800 gauss) in order to get a null angle in the middle while a magnetic field of opposite sign on the fourth dipole (in first approximation equal to the magnetic fields of dipoles 2 and 3) reports the beam on the axis. The resulting evolution of the centroid angle and position is shown.

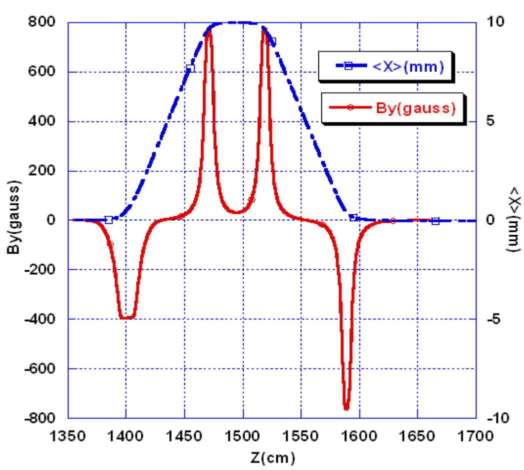

Figure 6: x-z trajectory and the By magnetic fields of the chicane for a bump of 10 mm at an energy of 200 MeV

PARMELA gives, for a bump of 10 mm at 155 MeV, an emittance growth of ~3% in the bending plane due to a residual dispersion given by the combined effect of the space charge and the motion in the bending magnets. This emittance growth decreases to ~0.7 % for a bump of 10 mm at 200 MeV. The results given by TREDI including CSR effects are similar. These results show that the injection scheme based on the use of a chicane in the SPARC transfer line for the seeding experiment does not give problems in terms of beam emittance and phase space matching at the entrance of the undulator.

Wake fields

The magnetic chicane deflects the electron trajectory of a distance comprised between 5 and 10 mm from the undulator axis. The effects of the interaction of this beam with the last mirror inserted in the straight path has been analysed. The mirror is modelled as a conducting block 6 mm large and 20 mm long. The wake potential induced by the SPARC beam x-z trajectory has been estimated according to the diffraction theory [22], with the ABCI code and including the effects of the asymmetries due to the vacuum chamber with the code MAFIA. In the latter case the maximum loss factor is ≈ 2V/pC. These results show that the wake field effects on the beam dynamics can be neglected.

ACKNOWLEDGMENTS

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