RECENT RESULTS OF THE SPARC FEL EXPERIMENTS

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Abstract

The SPARC project foresees the realization of a free electron laser operating at 500 nm driven by a high brightness photo-injector at a beam energy of 150-200 MeV. The SPARC photoinjector is also the test and training facility for the recently approved VUV/soft X-ray FEL project named SPARX [1]. The second stage of the commissioning, that is currently underway, foresees the demonstration of the "velocity bunching" technique in the linac and the characterisation of the spontaneous and stimulated radiation in the SPARC undulators. In this paper we report the experimental results obtained so far with the self amplified spontaneous emission (SASE) FEL [2-6] and the near future plan.

INTRODUCTION

Commissioning of the SPARC FEL initiated in autumn 2008 with the following main goals: 1) transport the beam through the vacuum chamber up to the beam dump consistently with the matching condition in the undulators 2) characterisation of the spontaneous and stimulated radiation in the undulators and 3) demonstration of "velocity bunching" technique in the linac with emittance compensation. All these steps were carried out during winter 2009, with the first SASE FEL spectra obtained on February 17th [7] and beam compression via velocity bunching with emittance compensation demonstrated in April 2009 [8]. In July 2009 a substantial increase of the extracted radiation from the FEL source was obtained with a longitudinally flat top e-beam by increasing the bunch charge and by anticipating the phase in the gun to reduce the debunching in the first stage of acceleration.

The present layout of the injector is shown in Fig. 1. The first two accelerating structures are surrounded by two long solenoids providing the additional focusing (with a maximum field of 0.18 T) required to match the beam envelope to the linac, according to the invariant envelope conditions [9,10].

In Fig. 2 a picture of SPARC taken from the undulator end is shown. The undulator, realized by *ACCEL Gmbh*, is made of six permanent magnet sections with 2.8 cm period, 25 to 6 mm variable gap with maximum undulator parameter K_{max}~2.2.

In the next sections we will discuss the injector performances, the first observation of the Self Amplified Spontaneous Emission (SASE) at 500 nm in the SPARC FEL and the preliminary results obtained applying the Velocity Bunching technique to the first linac section.

SPARC INJECTOR COMMISSIONING

An unsatisfactory emission uniformity, probably due to RF break downs in the gun that irreversibly damaged the cathode surface or to a damage of the in vacuum mirror delivering the laser light to the cathode itself, limits the brightness of the SPARC photoinjector. In order to reduce to a minimum the radiofrequency (RF) discharge rate, the gun is operated at a gradient of about 105 MV/m.

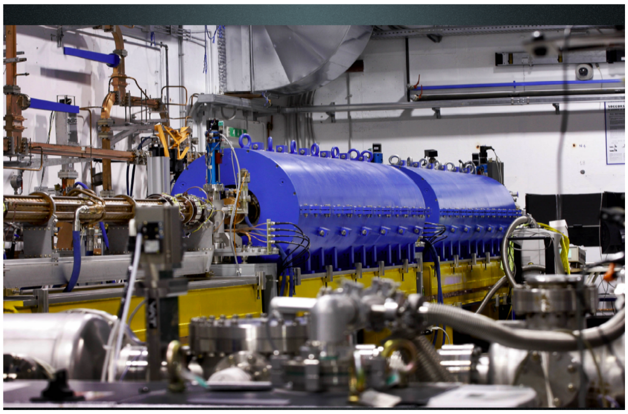

Figure 1: Picture of the SPARC photoinjector showing the 3 accelerating structures with 2 long solenoids.

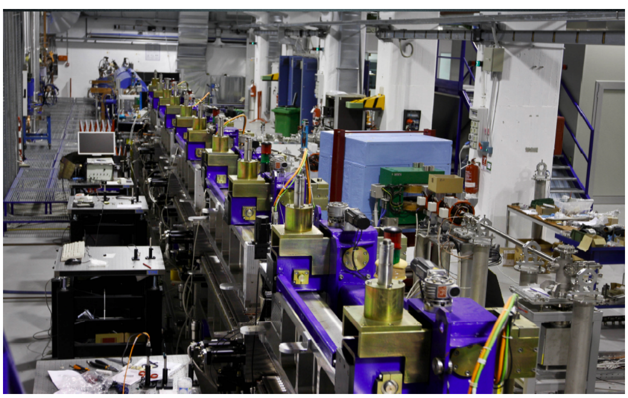

Figure 2: Picture of the SPARC undulator sequence.

The beam has been transported up to the undulator entrance and the longitudinal phase space is measured with an rf-deflector introducing a linear correlation between the arrival time and the vertical position on the screen monitor. The analysed phase space image provided the information on the local current, energy and energy spread [11]. In this stage of commissioning we have been operating with a laser pulse with flat-top longitudinal profile, 6-8 ps FWHM long. The bunch charge was in the range of 200 - 450 pC resulting in a peak current between 30 and 55 A. The beam has been accelerated up to 150 MeV with an energy spread of 0.2% and an energy stability better than 0.1%. At the linac exit the rms emittance has been measured by quadrupole scan and the bunch length, slice emittance and slice energy spread have been measured downstream of the high resolution RF deflector [11]. In Fig.3 the beam energy (blue) and the beam energy spread (red) as a function of the position along the microbunch is shown. In Fig. 4 the "slice" beam current is shown. In this condition the maximum current is about 53A and the rms bunch length is 2.65ps.

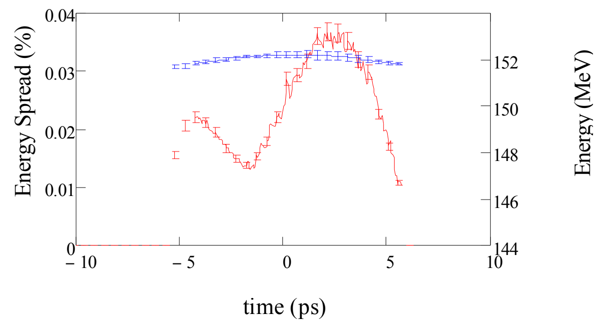

Figure 3: Beam energy (blue) and the beam energy spread (red) as a function of the position along the microbunch.

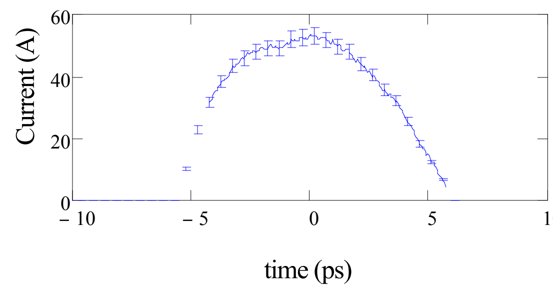

Figure 4: Beam current as a function of the position along the microbunch.

The transverse emittance measured with the quadrupole scan is 2.9 (2.5) mm-mrad in the vertical (horizontal) plane. As reported in the next section in these conditions the beam has been injected in the undulator for FEL amplification.

SASE EXPERIMENTS

A layout of the SPARC undulator is shown in Fig. 5. The undulator is composed by six independent modules. The gap between the modules host quadrupoles for horizontal focusing and radiation diagnostic stations.

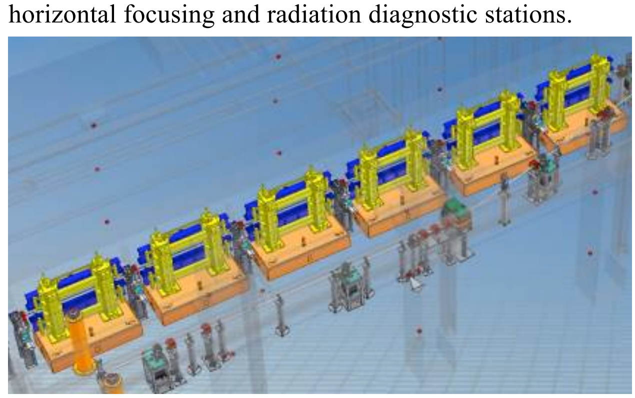

Figure 5: Layout of the SPARC undulator.

Each station is equipped with actuators allowing the insertion of alumina screens and aluminum mirrors to extract the radiation. Two CCD cameras per diagnostic chamber are available to monitor the electron beam orbit and the radiation. At the end of the undulator sequence, an in-vacuum spectrometer built by the LUXOR Laboratory (Padova) is installed. The instrument is a 1 m long normal incidence spectrometer with a Princeton UV grade CCD camera allowing the detection of spectra both in single shot and in the integrated mode in the spectral range 40 – 570 nm. The CCD camera is calibrated and the signal permits the reconstruction of the total energy per pulse at the end of the FEL.

The first clear signature of coherent radiation was observed at 500 nm on February 17th, 2009. In July 2009 the higher accelerated charge and the higher peak current available at the undulator allowed to increase the radiation intensity by about two orders of magnitude.

A typical image of the spectrum at the end of the six undulator sections is shown in Fig. 6. The vertical axis indicates the position on the vertical entrance slit of the spectrometer. The horizontal axis corresponds to wavelengths in a window of 43nm of width and centred at 500nm. The FEL spectrum is centred at about 492nm. The instrument resolves the spiky nature of the SASE radiation.

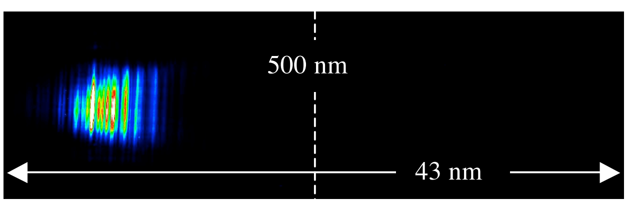

Figure 6: SPARC spectrum with 6 sections closed. The window is centred at 500 nm and the window full width is 43 nm.

The evolution of the pulse energy as a function of the position in the undulator sequence is obtained by turning off the FEL interaction by progressively opening the gap of the undulators. The measured pulse energy is shown in Fig. 7. Each of the data points corresponds to a single shot spectrum. The error bars are related to the uncertainty in the spectrometer calibration and transmission through the spectrometer slit and vacuum chamber. We have observed an amplification factor of about 10^7 and the observed gain length was ~0.7m. Saturation is expected in these conditions at a pulse energy ~0.2-0.3mJ. The maximum energy in Fig. 7 was about 0.01mJ. With all the undulators set at resonance spectra at the third harmonic wavelength have been acquired. The sequences *2009.07.24 1H* (blue) and *2009.07.24 3H* (purple) represent the measured data on the fundamental and third harmonic respectively. The sequence 2009.07.24 1H o. represents the result of an optimization of the delivered energy varying the rf injection phase of the gun and of the three linac sections. The continuous lines represent simulations with Perseo[12] and Genesis 1.3 [13]. The third harmonic simulation is obtained with Perseo. Simulations have been obtained assuming a beam with the longitudinal phase space corresponding to the measured data in figures 3 and 4, and with transverse emittances given by the quadrupole scan measurement (2.5/2.9 mm-mrad). Even though not included in the figure, similar results are provided by different numerical and analytical tools, like Prometeo [14] and Parsifel [15].

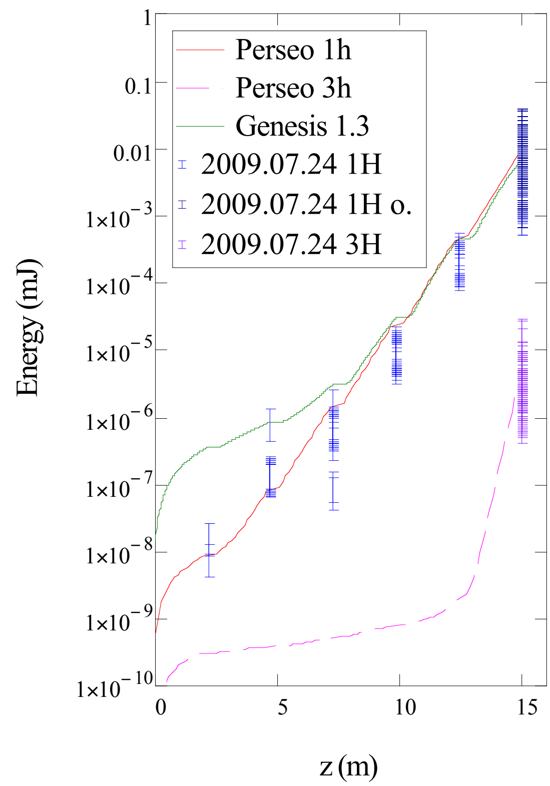

Figure 7: Pulse energy vs. longitudinal position in the undulator. The sequences 2009.07.24 1H and 2009.07.24 1H o. (blue) and 2009.07.24 3H (purple) represent the measured data on the fundamental and third harmonic respectively. The continuous lines represent simulations with Perseo (1st harmonic, red and 3rd harmonic, purple) and Genesis 1.3 (green).

In Fig. 8 we have shown the behaviour of the radiation linewidth as a function of the longitudinal position in the undulator. The continuous lines represent simulation data obtained with Perseo (black) and Genesis 1.3 (blue). The agreement with the simulations is fairly good. Perseo (as Prometeo) is a one dimensional code assuming a single mode matched to the e-beam, and provides a slightly underestimated linewidth. Genesis 1.3, which is a three dimensional code, calculates the spectrum as it is given by the field at the coordinate z, propagated in the far field. This operation is affected by the Rayleigh range oscillations induced by the gain variations at the undulator gaps and is spatially filtered by the transverse mesh where the field is represented. The measured spectra are acquired at the end of the undulator line, about two meters after the last undulator. The geometry of the vacuum chamber and the transport line to the spectrometer selects the low divergence part of the radiation field affecting both the measured energy and linewidth.

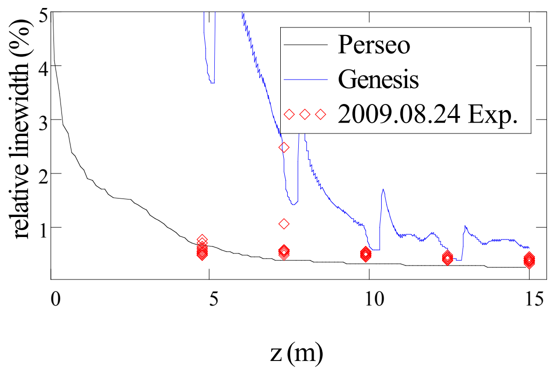

Figure 8: Linewidh of the FEL radiation as a function of the longitudinal position in the undulator. The continuous lines represent simulation data obtained with Perseo (black) and Genesis 1.3 (blue).

EXPERIMENTAL PROGRAMME FOR THE NEAR FUTURE

The SPARC FEL can be operated in both SASE and seeded modes. One of the future experiments at SPARC, is to study and test the amplification and the FEL harmonic generation process of an input seed signal obtained as higher order harmonics generated in gases [16] and compare it with the single spike operation described in [17] and [18]. The main components of the seed source consist in a second laser amplification chain operating in parallel to the photo-injector laser system, in a chamber devoted to the generation of high harmonics in gas, which has been realized at CEA [19], and finally in the hardware required for injecting the radiation generated in the chamber, in the electron transfer line connecting the SPARC linac with the SPARC undulator. A chicane deflecting the e-beam from the linac axis and a periscope allowing the injection of the harmonic beam have been realized for this purpose. The experiment setup for seeded FEL experiments is ready, the reader is addressed to ref. [20-21] for more details.

A number of beam experiments will be also performed taking advantage of the velocity bunching technique developed at SPARC, as reported in the following.

Additional SASE investigations are foreseen by injecting a progressively shorter bunch in the undulator chain. A transition of the radiation spectrum from the multi-spike to the single spike regime is expected [5-17] when a sub-picosecond long bunch corresponding to a few SASE cooperation lengths [5] is injected in the undulators. The measurement of the properties of the electron beam, the determination of shape and spectrum of the radiation pulse and the validation of the single spike scaling laws will be analysed in order to foresee future operations at shorter wavelength with SPARX. In collaboration with UCLA a dedicated FROG system [22] will be soon installed at the undulators exit in order to measure the temporal profile of the emitted radiation.

A dedicated beamline for a THz radiation source driven by sub-picosecond long bunch produced with the velocity bunching is also under commissioning at SPARC. The form factor of the recently measured compressed beam (charge of 200 pC) is shown in the upper plot of Fig. 9, together with the one obtained from a simulation. A more advanced experiment is foreseen with a comb beam (a train of few sub-picosecond electron pulses at THz repetition rate) leading to a narrower spectrum of the THz radiation [23].

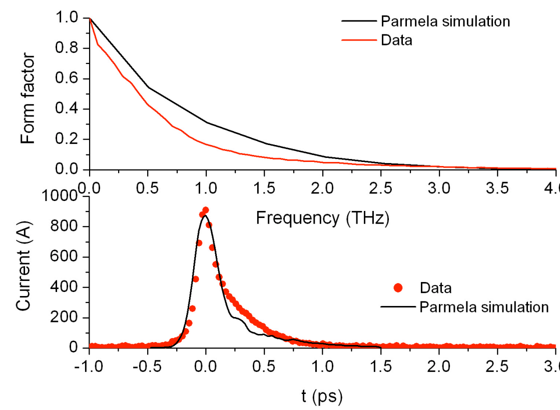

Figure 9: Form factor of the measured compressed beam compared to the simulated one (upper) and corresponding longitudinal beam distribution (lower).

Careful attention has been devoted in the last years to the effects of high frequency modulation of the bunch current, leading to enhanced COTR radiation [24] or even to a seed for microbunching in a SASE FEL [25]. HOMDYN simulations of the electron emission process including the electron beam-laser interaction near the cathode [26] show that a longitudinal charge modulation occurs on the scale of the laser wavelength, in case of laser oblique incidence on the cathode, driven by the longitudinal component of the laser field. Preliminary simulations up to the photoinjector exit show that charge modulation is partially conserved which may produce enhanced microbunching at shorter modulation wavelength when the beam is further compressed. In Fig. 10 and 11 the charge modulation is shown right after the electron emission and at the gun exit. A dedicated experiment will be soon performed at SPARC with a minor modification of the cathode driving laser system: the laser IR light will be transported up to the cathode with oblique incidence (working as a modulator) and superimposed to the normally incident UV light. The induced energy spread of the extracted electron beam and the OTR radiation signals will be compared with the IR light on and off.

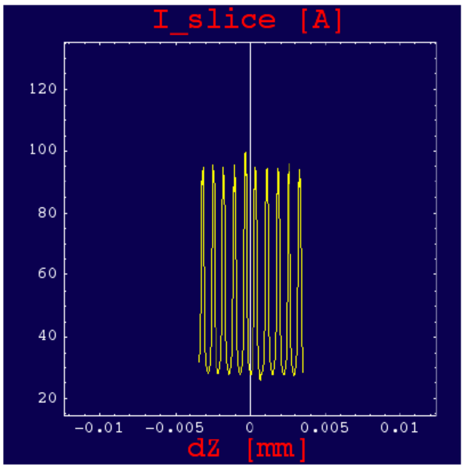

Figure 10: Modulation induced on a 100 pC 1 ps long bunch right after the interaction with a IR laser pulse with grazing incidence (75^{o}) on the cathode, superimposed to the UV pulse. Only central part of the bunch is shown.

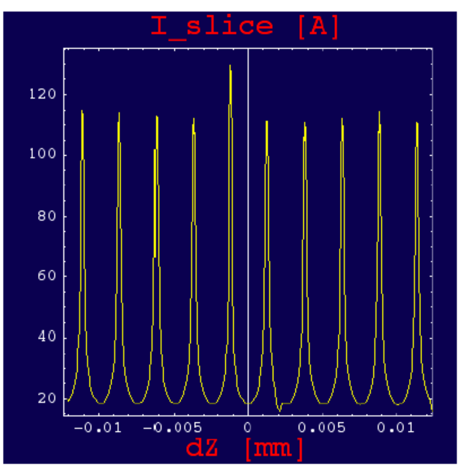

Figure 11: Modulation remaining at the gun exit. Same bunch of Fig. 10.

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