

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 a detailed analysis of the beam matching with the linac in order to confirm the theoretical prediction of emittance compensation based on the “invariant envelope” matching, 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.

INTRODUCTION

Soon after a long machine shut down in autumn 2008, due to a water leak in the gun RF circulator that required the complete replacement of the circulator and a contemporary installation of a new copper cathode, the SPARC experimental program restarted in January 2009 with two main goals: 1) characterisation of the spontaneous and stimulated radiation in the undulators and 2) demonstration of the “velocity bunching” technique in the linac with emittance compensation.

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 [2,3].

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 $K_{\max} \sim 2.2$.

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.

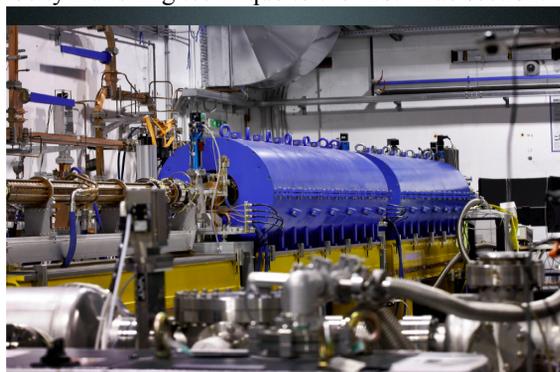


Figure 1: Picture of the SPARC photoinjector showing the 3 accelerating structures with 2 long solenoids.



Figure 2: Photo of the SPARC undulator sequence.

SPARC INJECTOR COMMISSIONING

An unsatisfactory emission uniformity, probably due to RF break downs in the gun that irreversibly damaged the cathode surface, limited our slice emittance at 1 μm for a 300 pC beam. To prevent additional damages to the cathode surface we decided to operate at a low gradient in the gun, 100 MV/m peak field, and hence with a lower charge than the nominal 1 nC. Nevertheless a stable and reproducible beam has been transported up to the undulator entrance, in order to test all diagnostic systems and to perform the careful beam based alignment of the quadrupoles required to match properly the beam to the undulators. In this stage of commissioning we have been operating with a laser pulse with Gaussian longitudinal profile, 6-8 ps FWHM long. The bunch charge was in the range of 200 - 300 pC resulting in a peak current around 35 A. The beam has been accelerated up to 150 MeV with an energy spread of 0.1% and an energy stability better than 0.1%. At the linac exit the rms emittance has been measured by a quadrupole scan and the bunch length, slice emittance and slice energy spread have been measured downstream of a high resolution RF deflector [4]. The typical measured rms emittance was around 2 μm in both planes for a 250 pC bunch. In Fig. 3 the beam current profile together with the slice energy and slice energy spread are shown. As reported in the next section, these electron beam parameters have been sufficient for the preliminary characterisation of the spontaneous and stimulated radiation in the undulators.

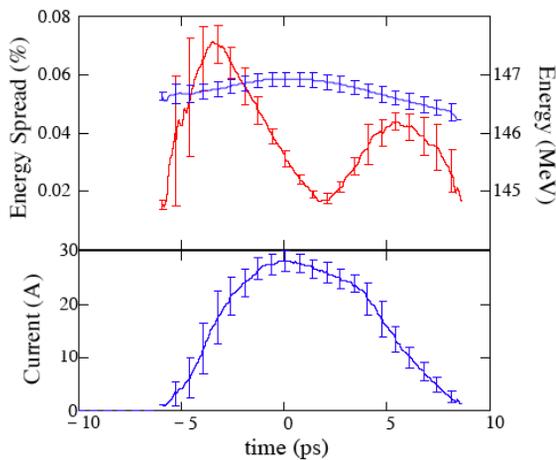


Figure 3: Measured electron beam slice parameters: slice energy (red) and slice energy spread (blue) in the upper plot, current profile in the lower plot.

FIRST SASE EXPERIMENTS

The first clear signature of coherent radiation at SPARC has been observed at 500 nm on February 17th, 2009. In between each of the 6 undulator modules shown in Fig. 2, a 36 cm drift hosts quadrupoles for horizontal focusing and radiation diagnostic stations. Each station is equipped with actuators allowing the insertion of

Alumina screens and Aluminum mirrors to extract 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. A focusing lens ($f=14\text{cm}$) positioned at a distance f from the entrance slit selects the angular acceptance of the detector. With a slit opening of 800 μm all the radiation is collected and the integrated spectrum provides the information on the pulse energy.

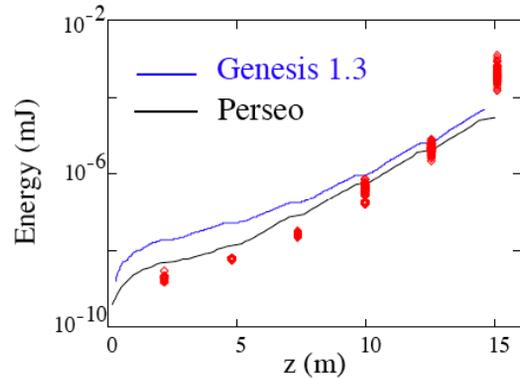


Figure 4: Pulse energy measured at the undulator intrasections. The continuous line show simulations obtained with Genesis 1.3 (blue) and Perseo (black).

The evolution of the pulse energy as a function of the position in the undulator sequence is obtained turning off the FEL interaction by progressively detuning the gap of the undulators. The measured pulse energy is shown in Fig. 4. Each of the data points corresponding to the first three undulator sections (up to $z \sim 7\text{m}$) are the result of an integration over multiple shots (1800 shots). The data corresponding to the 4th, 5th and 6th undulators are instead single shot measurements. We have observed an amplification factor of about 10^6 and the observed gain length was $\sim 1\text{ m}$. Saturation is expected in these conditions at a pulse energy $\sim 300\mu\text{J}$.

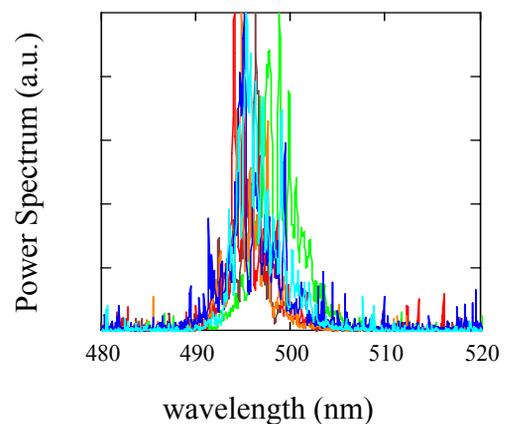


Figure 5: Single shot spectra at the end of the undulator sequence

The pulse energy is compared to simulations obtained with Genesis 1.3 [5] (blue) and Perseo [6] (black) codes. The beam parameters considered for the simulations are the measured longitudinal and transverse phase spaces discussed in the previous section and reported in Fig. 3. In Fig. 5 typical SASE single shot spectra after the sixth undulator are shown. The spectral narrowing associated with the FEL amplification is evident in Fig. 6, where the behaviour of the spectral width versus the position in the undulator sequence is shown.

A more detailed analysis of the data is currently in progress and will be the subject of forthcoming publications.

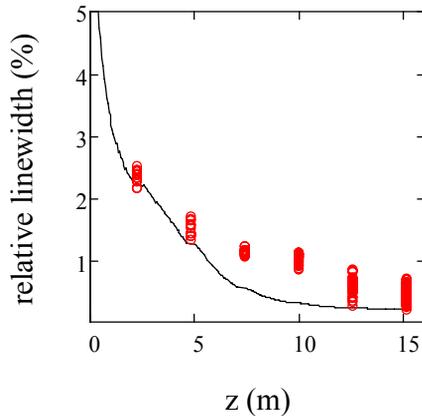


Figure 6: Measured Spectral width versus z . The continuous line is the result of a Perseo simulation.

VELOCITY BUNCHING EXPERIMENTS

Some preliminary tests of beam dynamics in the Velocity Bunching (VB) regime [7] have been also performed. Figure 7 shows the measured rms bunch length versus the injection phase in the first travelling wave structure, operating at 20 MV/m accelerating field on crest.

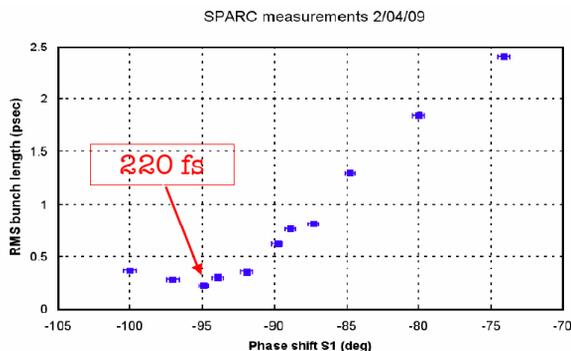


Figure 7: Measured rms bunch length of a 300 pC beam versus the phase of the first travelling wave structure.

The effectiveness of the longitudinal RF focusing provided by the first TW structure when the beam is injected far off crest is clearly visible. An initially 3.55 ps long bunch is compressed down to 220 fs with a maximum compression ratio close to a factor 14. The last

two measurements also show the over-compression effect when the phase setting exceeds -95 deg.

The main concern with the Velocity Bunching techniques was the possibility to compensate the emittance degradation induced by space charge effects during compression. A systematic study at different injection phases is still in progress. But a remarkable and promising result has been obtained with a detailed study of one case, with compression ratio 3. In Table 1 the measured beam parameters are reported. The second column contains the measured data of the uncompressed beam (on crest acceleration) for comparison. As shown in the table a successful compensation of the emittance degradation during compression was possible. This goal has been achieved with a careful tuning of the long solenoids installed around the linac. The lowest achieved emittances have been $\epsilon_{nx} = 1.7 \mu\text{m}$ and $\epsilon_{ny} = 1.4 \mu\text{m}$ (to be compared with $\epsilon_{nx} = 4.3 \mu\text{m}$ and $\epsilon_{ny} = 6.1 \mu\text{m}$ with solenoids off, marked with * in the table). With a peak current of 120 A this bunch has the highest beam brightness so far obtained with the SPARC injector.

Table 1: Measured Beam Parameters

	No Comp.	Comp. ratio 3
Injection phase [deg]	0	-85
Bunch Charge [pC]	300	300
Beam Energy [MeV]	140	100
Energy spread [%]	0.11	1.0
Rms Length [ps]	3.25±0.16	1.03±0.1
ϵ_{nx} [μm]	2.33 ±0.11	1.74±0.05 4.33 ±0.84 *
ϵ_{ny} [μm]	1.30 ±0.05	1.44 ±0.03 6.06 ±0.4 *

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