EXPERIMENTAL RESULTS WITH THE SPARC EMITTANCE-METER*

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Abstract

The SPARC project foresees the realization of a high brightness photo-injector to produce a 150-200 MeV electron beam to drive a SASE-FEL in the visible light. As a first stage of the commissioning a complete characterization of the photoinjector has been accomplished with a detailed study of the emittance compensation process downstream the gun-solenoid system with a novel beam diagnostic device, called emittance meter. In this paper we report the results obtained so far including the first experimental observation of the double emittance minimum effect on which is based the optimised matching with the SPARC linac.

INTRODUCTION

The SPARC project comprises an R&D photo-injector facility devoted to the production of high brightness electron beams to drive a SASE-FEL experiment in the visible light. The high beam quality produced by SPARC will also allow investigations into the physics of ultra-short beams, plasma wave-based acceleration, and production of X-ray Compton back-scattering. Moreover SPARC is the injector prototype of the recently approved SPARX project, that foresees the construction in the Frascati area of a new high brightness electron linac for producing SASE-FEL radiation in the range of 10-1 nm wavelength. The first phase of the SPARC project, that is now concluded, consists in characterizing the electron beam out of the photoinjector, a 1.6 cell S-band RF gun, at low energy (5.6 MeV with 120 MV/m peak field on the cathode), before the installation of the 3 S-band accelerating sections, which will boost the beam energy up to 150-200 MeV. In order to study the first few meters of beam propagation where space charge effects and plasma oscillations dominate the electron dynamics, a new sophisticated diagnostic tool has been installed and commissioned: the movable emittance-meter [1]. This device has allowed measuring the evolution of beam sizes, energy spread, rms transverse emittances and transverse phase space at different locations along the beamline. The experimental layout of the first phase of the project is shown in Fig. 1.

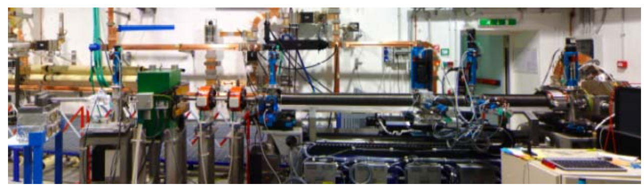

Figure 1: Picture of the SPARC photoinjector showing the RF gun with its solenoid (right end) the emittance meter (centre), the energy spectrometer and the beam dump (left end).

THE LASER SYSTEM

The SPARC laser is a 10 Hz TW system produced by Coherent [2]. It is composed by a Ti:Sa oscillator generating 100 fs pulses with a repetition rate of 79.3 MHz and an energy of 10 nJ. An acousto-optic programmable dispersive filter called "DAZZLER" used to modify the spectral amplitude and phase function, is placed between the oscillator and the amplifier to obtain the target temporal profile. After the amplification process the system delivers pulses at λ=800 nm with energy of about 50 mJ and a repetition rate of 10 Hz. At the output of the amplifier the IR pulses go to a third harmonic generator, where UV pulses with an energy of up to 4 mJ are produced. At the end of the laser chain there is a grating stretcher based on a pair of 4350 groove/mm UV reflecting gratings that is used to stretch the pulses temporally up to 8–12 ps and to reduce the pulse rise time. The optical transfer line to the cathode has been designed to increase the pointing stability, easily change the spot dimension and provide a normal incidence on the cathode surface. In combination with a quite high Quantum Efficiency (QE) up to 10^{-4} of the copper photocathode, obtained after a dedicated laser cleaning, the nominal electron beam parameters have been obtained with 50 μJ laser pulse energy at 120 MV/m peak field on the cathode.

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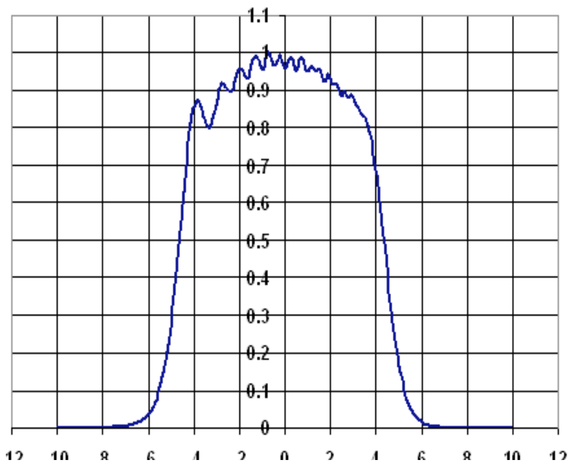

Figure 2: "Flat top" temporal laser pulse shape with 8.9 ps FWHM and 2.6 ps rise time.

A flat top laser pulse, retrieved from the spectral measurement, is shown in Fig. 2 and in Fig. 3 the corresponding emittance measurements. Additional work is under way to make this result more stable and improve also the uniformity of the transverse distribution.

THE EMITTANCE METER

In order to perform beam quality measurements at different locations along the beam line, a dedicated movable emittance measurement device, the emittance-meter, has been developed, see Fig. 1. This device allowed measurements of beam parameters in the range 1000 mm to 2100 mm from the cathode location, the so called Z-scan. The technique of measuring beam emittance and phase space distributions in the horizontal and vertical planes, makes use of a double system of horizontal and vertical slit masks. Each mask consists of a slit array (7 slits, 50 μm width spaced of 500 μm, 2 mm thick) and two single slits, 50 and 100 μm width). The beamlets emerging from the slit-mask are measured by means of a downstream Ce:YAG radiator. Images are acquired using digital CCD cameras (Basler 311f) equipped with simple 105 mm "macro" type objectives from SIGMA. The magnification used of about 0.66 gives a calibration near to 15 μm per pixel and a field of view of the screen around 9.6 x 7.2 mm. The resolution in the beam divergency is 100 μrad. Using a large number of samples (13 moving the single slit over the beam) it's possible to reconstruct the beam transverse phase space and follow its evolution along the beam line.

EXPERIMENTAL RESULTS

Measurements of emittance evolution along the photoinjector were the main goal of the first SPARC commissioning phase. Several runs were dedicated to compare of the dynamics of the beam under different conditions: moving the injection phase, changing the solenoid strength, and varying the longitudinal profile of the laser. The design goal in terms of peak current (92 A with 0.8 nC) and emittance (1.6 μm), corresponding to a peak brightness of 7 $x10^{13}$ A/m^2, has been successfully achieved with a UV "flat top" laser pulse illuminating the cathode, see Fig. 2 and Fig. 3.

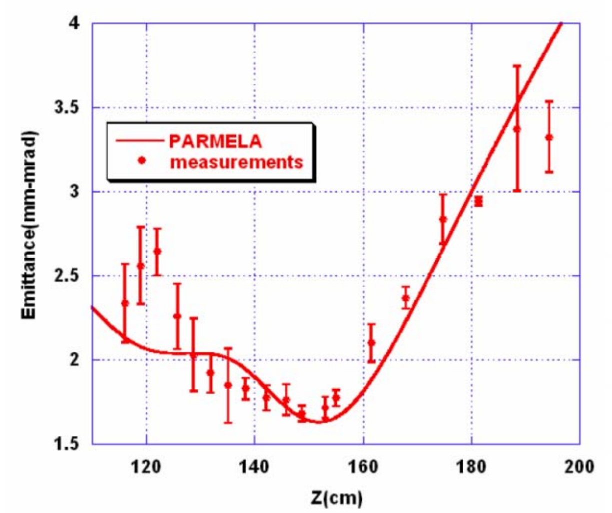

Figure 3: Emittance evolution, "flat top" case, measurements and PARMELA simulations

Of particular interest we found the comparison between a "flat top" longitudinal pulse with 85 A current 8.5 ps long, 2.5 ps rise time, and a Gaussian beam with the same FWHM length and current, as shown in Fig. 4. Superimposed in the figure are the results of PARMELA simulations using actual beam parameters, such as laser pulse length, beam size, launch phase, [3]. The results obtained confirm [4] the improved performances of the "flat top" charge distribution versus the Gaussian profile. Another important result is the first experimental observation of the double emittance minimum in the drift downstream the RF gun, in agreement to what expected from our theoretical model and numerical simulations.

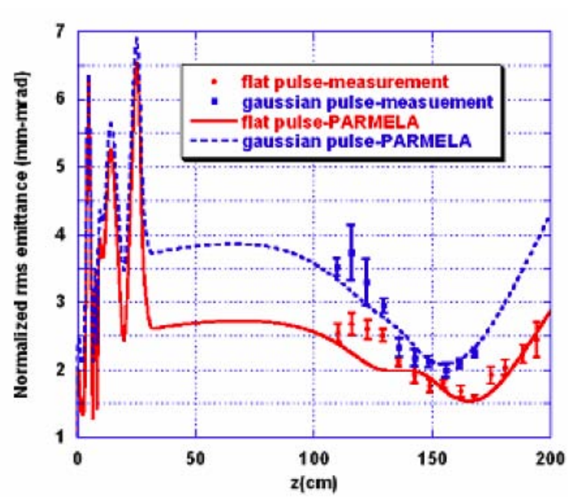

Figure 4 : Emittance evoution of Gaussian and "flat top" beams. Measurements and PARMELA simulations.

The optimized matching with the SPARC linac, will be based on this peculiar space charge regime acting in the flat top pulse mode [5] which foresees a matching to the invariant envelope in the Linac sections assuring the

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minimum emittance at the Linac exit [6]. Emittance oscillations of this kind have been explained as produced by a beating between head and tail plasma frequencies caused by correlated chromatic effects in the solenoid [7, 8]. We have obtained a direct evidence of this type of oscillation working with short laser rise time (1.5 ps) and moving the injection phase behind the maximum energy gain phase, thus inducing a higher energy spread in the beam, even if the minimum achievable emittance is larger in this case.

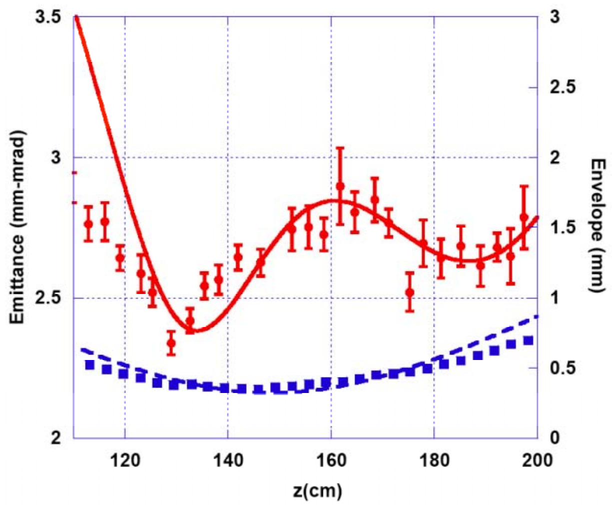

Figure 5: Envelope and Emittance downstream the RF gun of a "flat top" bunch.

The typical cross shape, shown by simulations in the transverse phase space of a flat top distribution at its relative emittance maximum, is also visible when reconstructed from beam measurements as reported in Fig. 6. In this case the head and tail of the bunch experience a different focal length when passing through the solenoid, caused by the space charge correlated energy spread that is strongly enhanced at the bunch ends.

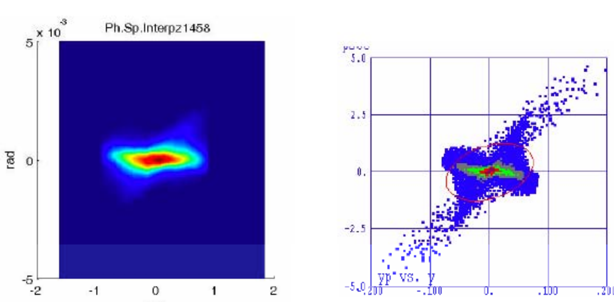

Figure 6: Transverse phase space at z=150 cm. Same beam of fig. 5

Under laminar conditions, i.e. when the solenoid field is not too high to cause cross-over, the space charge dominated waist is reached at different positions by the head and the tail slices of the bunch, so that when the bunch tail is already diverging the bunch head is still converging. In the Gaussian pulse case this cross shape in phase space is weaker since the slice current at the bunch "ends" is smaller. In particular, the bunch tails actually go through a cross-over, which prevents them from correctly undergoing the emittance correction process: this bifurcation is irreversible, leaving a part of the beam propagating as a split beam.

In Fig. 7 are shown the results of emittance versus solenoid magnetic field measurements at a fixed position (z=150 cm) for the same beam. The agreement with simulation is satisfactory when charge fluctuations of 6 % are taken in to account, a reasonable assumption in such a time consuming measurement. Notice that the emittance oscillation is visible also in this case. By increasing the solenoid field in fact the emittance oscillation tends to occur closer to the cathode. Thus, exploring the emittance at a fixed location by varying the B field, is equivalent to a continuous shift from different Z-scan curves.

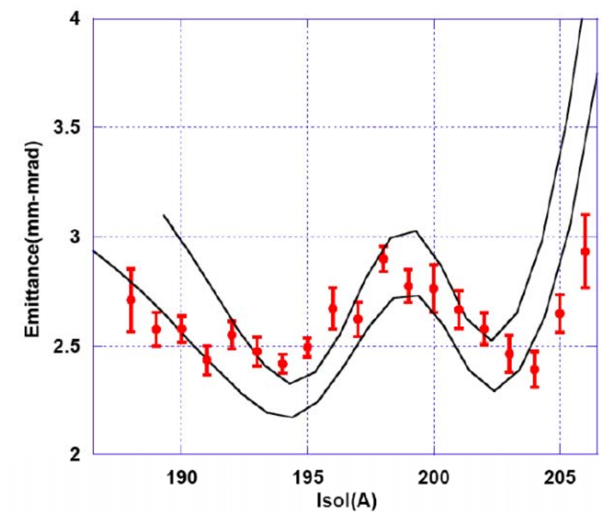

Figure 7: Emittance versus solenoid magnetic field at a fixed position (z=150 cm). Same beam of fig. 5. Simulations with charge fluctuations of 6 % are shown.

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