COMMISSIONING OF THE LASER SYSTEM FOR SPARC PHOTOINJECTOR*

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Abstract

In this paper we report the commissioning of the SPARC photoinjector laser system. In the high brightness photoinjector the quality of the electron beam is directly related to the features of the laser pulse. In fact the temporal pulse shape, the temporization and the transverse distribution of the electron beam is determined by the incoming laser pulse. The SPARC laser system is based on an amplified Ti:Sapphire active medium and the pulse shape is imposed by a programmable acousto-optics dispersive filter. The transfer-line has been designed to reduce the angular jitter and to preserve to the cathode the temporal and spatial features of the laser pulse. The laser system has been integrated with the accelerator apparatus. The diagnostics and the control system has been completed. We present the measured performances and the simulations we carried out.

INTRODUCTION

Specs on SPARC laser system were fixed within the phase of the machine design [1, 2]. The goal is to provide photo-injector (RF-gun) with a proper laser pulse of the order of 10 ps, able to generate an electron beam with a normalized transverse emittance less than 2 mm·mrad and a current of 100 A. We currently use a monocristalline Cu cathode with a quantum efficiency (QE) of $2 \cdot 10^{-4}$ at 120 MV/m [2] therefore it is required about 50 μJ to extract 1 nC at the operating phase. Challenging requests are made on laser temporal pulse profile (flat top pulse with 1 ps rise time and ripples limited to 30%) to minimize the e-beam emittance; a pulse shaping activity is in progress and some results have been presented [3, 4]. The SPARC laser is a $10Hz$ TW system produced by $Coherent$.

The laser system [1] is composed by a Ti:Sa oscillator that generates $100\ fs$ pulses with a repetition rate (r.r.) of $79.3\ MHz$ and an energy of 10 nJ. An acousto-optic programmable dispersive filter called “DAZZLER” [5], used to modify the spectral amplitude and phase is placed between the oscillator and the amplifier to obtain the target temporal profile in the UV. The regenerative and two multipass amplifiers delivers pulses with bandwidth of at 10 nm FWHM $\lambda = 800\ nm$ with energy of $\sim 50\ mJ$ and divergence less than 1 mrad.

The amplified pulses go to the third harmonic generator (THG) where UV pulses with an energy up to $\sim 4\ mJ$ are produced. The THG is characterized by two type-I BBO (Beta Barium Borate) crystals of $0.5\ mm$ and $0.3\ mm$ thickness used to produce respectively the second and third harmonics. The crystal lengths have been chosen to allocate enough bandwidth to preserve the pulse shape and, at the same time, to guarantee good efficiency. The efficiency of the first conversion is about 50% and the overall conversion efficiency is more than 10%.

After the THG the pulse is sent to a pair of 4300 g/mm UV parallel gratings, that forms a negative group velocity dispersion two passes stretcher. Varying the distance L between the gratings it is possible to obtain the output pulse length $\tau[ps] = \tau_0 + 0.44 \cdot L[cm] \cdot \Delta\lambda[nm]$, where τ_0 is the UV input pulse duration and $\Delta\lambda$ is its spectral width. The energy efficiency of the UV stretcher is about 30% producing a energy up to $1.5mJ$ with an amplitude jitter of $5\%_{RMS}$.

To characterize the pulse time profile a multishot cross-correlator with $200fs$ resolution was built. The diagnostics uses part of the sub-ps IR pulse to cross-correlate the UV pulse and generating the frequency difference at $400nm$. According with the theory and experimental measurements, when a large chirp is imposed, such as for our the UV stretcher, the pulse spectrum allows the direct reconstruction of the time intensity distribution [3]. For the spectral measurements in the UV it has been designed a spectrometer using a UV grating with 4350 g/mm and a converging lens to focus the different wavelength on a ccd camera. This diagnostic proved a the resolution of 0.02 nm.

OPTICAL TRANSFER LINE TO THE CATHODE

The gun is placed several meters far away the laser room. At the laser exit it is mounted an iris to select the most uniform part of the beam. A $4f$ imaging system is used to bring the laser to the gun table and to reduce the effect of laser angular jitter, after a telescope is employed to change the laser spot diameter. Before the gun window is placed a reflective diffraction grating to compensate the effects of the grazing incidence on the cathode. The last mirror is motorized to align the beam at the center of the cathode with a resolution of 1 μm. Before the gun port a thin beam splitter reflects a small part of the laser beam to a Ce:YAG crystal virtual cathode.

The grating is needed because the gun layout foresees a laser incidence on the cathode at 72° [1]. This layout benefits from the removal of launch optics from the electron beamline and of an enhanced the QE of the cathode.

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However, the grazing incidence also introduces two well-known distortions in the laser pulse: (i) the original circular beam becomes elliptical and (ii) the laser amplitude front is tilted respect to the cathode plane and therefore the photons time of arrival depends of the transverse coordinate. This effects induce a strong distortion on the distribution of emitted electron respect to the ideal cylindrical shape. While for the first distortion the use of an anamorphic can easily yield a pulse the desired ellipticity, the correction of the time-slew is more problematic. The commonly accepted solution of using a grating to "crab" the beam [6] is in practice an open issue, especially when considering the fact that a large bandwidth is needed for the optimal pulse shape. The amount of time of arrival difference Δt across the beam x can be simply derived using Eq. (2):

$$\Delta t(x) = \frac{x}{2}\left(\sin(\theta_i) + \sin(\theta_d)\right) \quad (1)$$

here θ_i and θ_d are the input and the diffracted angle respectively. The grating acts also as a anamorphic system producing an elliptical diffracted beam given by:

$$e = \frac{a}{b} = \frac{cos(\theta_d)}{cos(\theta_i)} \quad (2)$$

where a is and b are the input and the output beam dimension. To obtain simultaneously the conditions $\Delta t(x) = 0$ and and a circular beam at the cathode, it was adopted a grating parallel to the cathode with $3600 grooves/mm$ which has the characteristics that when $\theta_i = 0°$, the diffracted radiation, for $266nm$, comes out at $\theta_d = 72°$. Because the grating is a highly dispersive optical element by design, the unavoidable chromatic dispersion complicates the launch optical set-up. In our case the angular dispersion is quite large: $\partial\beta/\partial\lambda = 12\ mrad$.

To balance the dispersion a lens with focal length $f_0 = 50cm$ is placed at $2f_0$ after the grating and $2f_0$ from the cathode. This lens recombines the dispersed wavelengths on the cathode where the circular laser spot is obtained.

To observe the grating induced front tilt, we performed a series of measurements with a streak camera Hamamatsu model 1360, which has $\sim$ 2 ps resolution. Since the available optics of the streak camera are not optimized for UV radiation we analyzed the time slew introduced by a grating across the IR pulse before the THG.

For the measurements we used a 1200 lines/mm grating to scale the grooves density to the case of 800 nm central wavelength pulse, maintaining unchanged θ_i and θ_d. We introduced also a lens between the grating and the streak camera slits. In this way we imaged on the camera the grating plane.

The streak images, in the cases of sub-ps and 5 ps laser input pulse are shown in Fig. 1. The measurement of the length of the laser pulse when the beam is fully compressed is limited by the streak camera resolution as it was obtained by autocorrelation technique that the pulse length in this case is $<$ 200 fs. In order to decrease the aberrations introduced by the streak camera that occur when the beam transverse size is large compared to the entrance slit, we selected an horizontal slice of the beam of width 4 mm.

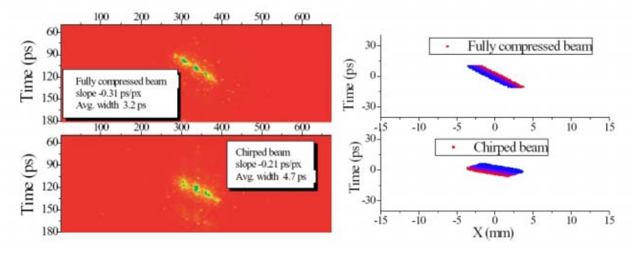

Figure 1: On the right streak images, time of arrival vs transverse position, of a sub-ps (a) and a 5 ps (b) IR pulse after the grating. On the right are reported the corresponding results obtained with the ZEMAX simulations.

From the streak images reported it is evident the amplitude front tilt imparted on the beam, especially in the case of the short pulse. To completely understand the measurements we used the optical design simulation code ZEMAX [7]. We developed a macro function that keeps track of the optical path length and by tracing a large number of rays reconstructs the three dimensional distribution of the photons at any given surface, be it the entrance slit of the streak camera. The agreement between measurements and simulations reported in Fig. 1 is quite good. For the proposed optical set up at the photocathode, the simulations indicate a minor time distortion for the different frequencies (less than $250fs$ for $\Delta\lambda = 1.4nm$).

To prove the effectiveness of the designed optical set-up we used a 2 mm diameter, sub-ps laser pulse to illuminate the cathode. The presence of a front tilt would lengthen up to 4 ps the effective width of the e-beam. We measured downstream the gun the e-beam duration, using the ps streak camera and a Cerenkov radiator [8]. In the low charge limit, the pulse length turns out to be close to 2 ps, that is the resolution of the streak. We can infer therefore that the time slew compensation is achieved in the ps range.

The main drawback of the proposed set-up is that the compensation is achieved only for a well defined position of the lens. Misalignment of about $1cm$ introduces pulse distortion and significant optical path difference between the wavelengths of $1.5ps$. In the set-up proposed, the grating generate two diffracted orders, and therefore only 35% of the input energy is useful to illuminate the cathode. Even though, the laser energy on the cathode is large enough to produce the target beam charge 1 nC.

LASER TO RF SYNCHRONIZATION MEASUREMENTS

A precise synchronization between the photocathode drive laser and the accelerating wave is necessary to have a fixed and stable time-of-arrival of the photons on the cathode with respect of the phase of the 2856 MHz RF accelerating field. This condition is very important to guarantee the stability and the shot-to-shot reproducibility of crucial beam parameters as the beam charge, energy, emittance and energy spread and to ensure a proper matching condition in the accelerator. From beam dynamics simulations [9], a variation over $\pm 4^\circ$ of RF (about ± 4 ps) of the laser-to-gun phase, in ideal conditions, increases the output rms projected normalized emittance of about 20%. From these results it has been concluded that a tolerance of ± 2 ps around the optimal phase is acceptable in order to limit the emittance growth to less than 10%. The issue of timing jitter becomes even more critical when the future experiments planned at the SPARC facility are considered. For example in FEL seeding experiments, Inverse Compton Scattering experiments, or laser acceleration experiments requires sub-ps synchronization. Since the amplification process and the optical launching to the cathode introduce a negligible time jitter the synchronization has to be carried out at the level of the laser oscillator. The oscillator synchronization unit monitors continuously the laser's phase through a 2 GHz photodiode and compare the laser repetition rate and its 9^{th} harmonic with the reference signal from the S-band master clock waveform and $1/36^{th}$ divider. The laser frequency lock is achieved using three cavity length actuators in the laser head: a high frequency piezo-electric trasducer, a low frequency galvonometer driven delay line and a DC motor.

We measured the time jitter at oscillator level using well-known technique, by mixing the reference signal and with the laser pulse detected by a 25 GHz photodiode. The IF mixer employed is a custom device from Pulsar Microwave Corporation able to demodulate the signal and to provide in-phase and in-quadrature components from which we can simply calculate amplitude (absolute) and phase (relative to a reference). The observed time jitter that varied from $650fs_{rms}$ to $750fs_{rms}$. This value takes into account also the time jitter of the S-band master oscillator and the successive signal down-conversion.

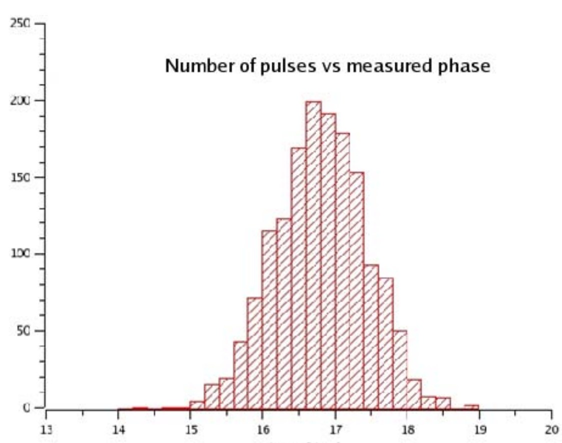

Figure 2: Statistics of the the UV laser pulse to RF reference measured phase noise.

To have information on the phase noise on the single laser UV pulse near the cathode at 10 Hz, we adopted pulse-to-pulse phase lock feedback. The measured signal comes from a cavity tuned at 2856MHz, fed by a high voltage electric pulse (with a peak of about 100V) coming out a fast photodiode illuminated by the laser pulse. This photodetector is a bi-planar vacuum photodiode with a rise time of $100ps$ operating at 1.5 kV bias voltage. The cavity grants an exponential decaying pseudo-sinusoidal signal with a duration of about 1.5μs and allows to perform a consistent relative phase measurement using the IF mixer and the a 14-bit DAQ card with sampling rate of 60 Msamples/s. As reported in Fig 2 the time jitter, recorded over few minutes, is about $630fs_{rms}$ and in general is limited to $1\ ps$. The good level of synchronization is confirmed by the stability of the SPARC e-beam parameters.

CONCLUSION

This paper reports the performances of the SPARC laser system. The laser, the diagnostic and the optical transfer line to the cathode have been presented. The experimental characterization of the front tilt introduced by a reflective diffraction grating has been reported. The results are in good agreement with simulations. The optical scheme to compensate the time slew and the ellipticity associated with the grazing incidence on the cathode have been implemented and shows a successful compensation within 1 ps in time slew. Measurement of the phase noise indicates less than 1 ps time jitter of the UV laser pulse respect to the RF system.

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