DESIGN STUDY FOR ADVANCED ACCELERATION EXPERIMENTS AND MONOCHROMATIC X-RAY PRODUCTION @ SPARC

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Abstract

We present a design study for an upgrade of the SPARC photo-injector system, whose main aim is the construction of an advanced beam test facility for conducting experiments on high gradient plasma acceleration and for the generation of monochromatic X-ray beams to be used for applications like advanced medical diagnostics and condensed matter physics studies. Main components of the proposed plan of upgrade are: an additional beam line with interaction regions for synchronized high brightness electron and high intensity photon beams (co-propagating in plasmas or counter-propagating in vacuum) and the upgrade of the SPARC Ti:Sa laser system to reach pulse energies in excess of 1 J. Results of numerical simulations modelling the beam dynamics of ultra-short bunch production, based on a slit-selection technique combined with double RF deflection, are presented. Calculations of the monochromatic X-ray beam angular and frequency spectra, generated via Thomson back-scattering of the SPARC electron beam with the counter-propagating laser beam, are also presented. X-ray energies are tunable in the range 20 to 500 keV, with pulse duration from sub-ps to 20 ps. The proposed time schedule for this initiative, tightly correlated with the progress of the SPARC project, is finally shown.

INTRODUCTION

The SPARC photo-injector under installation at INFN-LNF will provide an ultra-bright electron beam at 150 MeV kinetic energy for the investigation of a SASE-FEL experiment, as extensively described elsewhere [1]. The beam is expected to be delivered in bunches of up to 1.1 nC of charge, rms normalized projected emittance smaller than 2 mm·mrad, rms energy spread smaller than 0.2 % with rms bunch length of about 2-3 ps (uncompressed beam). The electron bunches will exit the photo-injector with 1 ps time jitter w.r.t. laser pulses: these are produced by a synchronized mode-locked Ti:Sa laser system delivering 20 mJ pulses in the IR (800 nm) at 10 Hz repetition rate, which are converted to UV (266 nm) to drive the electron beam production by hitting a photocathode located inside a RF gun. The foreseen availability of a bright electron beam and an intense synchronized laser is an ideal combination to pursue experiments by exploiting the interaction of the two beams (electrons and photons) either co-propagating or colliding them. High gradient plasma acceleration or mono-chromatic bright X-ray beam production in Thomson sources are noticeable examples of these beam interactions. For both of them a TW peak power laser beam and ultra-short (sub-ps) electron bunches are required. An upgrade of SPARC aimed at addressing these issues must conceive the development of 3 key components: the laser must be further amplified to reach the level of a few Joule of energy per pulse, the photo-injector has to be provided with an additional transport beam line to serve the interaction region, a dedicated diagnostic and control system has to be developed to operate the beam interaction efficiently. The Ti:Sa SPARC laser system will be installed starting this fall: it will comprise a diode-pumped 150 fs oscillator, a solid-state pumped regenerative amplifier (2 mJ) and a flash-pumped multi-pass amplifier (20 mJ). We foresee to upgrade the laser in two steps: a first multi-pass amplifier to reach the level of 200 mJ energy per pulse with in air compressor down to 100-200 fs pulse length, and a second multi-pass amplifying stage, to reach the 1-3 J energy per pulse, equipped with in vacuum compressor to hold the 10-30 TW peak power delivered at this final stage. Since the specified time jitter for the SPARC laser system is smaller than 1 ps (with 0.5 being the desired value), we can foresee to achieve the correct space-time overlap of the colliding electron and laser pulses in the final focus region of the Thomson source for mono-chromatic X-ray production as far as the electron bunch is

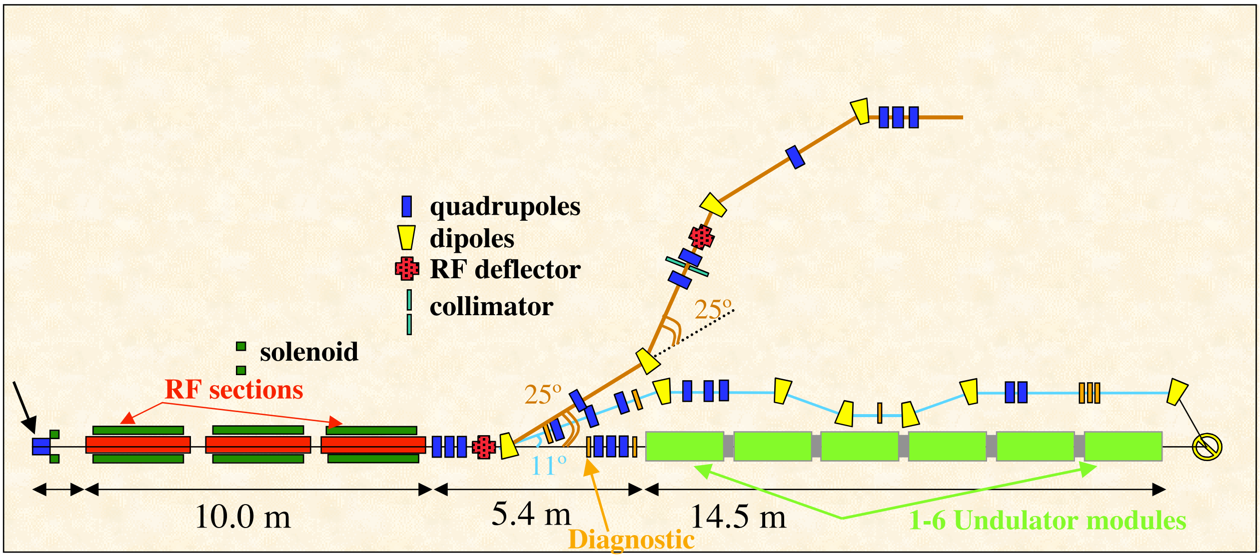

Figure 1: Lay-out of SPARC photo-injector and SASE-FEL experiment with additional double dog-leg beam line

the standard uncompressed beam delivered by the SPARC photo-injector (2-6 ps rms bunch length). For the interaction of ultra-short pulses (rms length smaller than 0.5 ps) we need to improve the synchronization level between the two beams. The anticipated beams that we aim to deliver with the SPARC advanced beam facility are listed in Table 1, which contains the main beam parameters of interest, like bunch charge, kinetic energy, rms bunch length, normalized transverse emittance and energy spread (numbers in bold mark the most critical beam parameter for the specific application). The FEL-SASE application requires a very small emittance beam with peak current in excess of 100 A (hence the 1 nC bunch charge at a few ps rms bunch length), the plasma acceleration experiment (exploited by sending the laser into a gas jet to drive a plasma wave in a synchronized fashion to the ultra-short electron bunch injected in phase into the plasma wave for further acceleration) needs ultra-short bunches, while the Thomson source needs very small energy spread beams to avoid chromatic aberrations in the final focus system where the beam is focused down to sub-10 μm spot sizes to collide with the laser beam.

Application	Q (nC)	T (MeV)	σ_t (ps)	ε_n (μm)	σ_γ/γ (%)
FEL-SASE	1	150	3	**2**	0.1
Plasma-Acc.	0.025	100	**0.025**	0.1	0.2
X-Thomson	1	**30**-150	6-3	2	**0.05**-0.2

Table 1: anticipated beams @ SPARC

TRANSPORT BEAM LINE

The lay-out of the SPARC photo-injector with additional transport beam line is plotted in Fig.1: the 3 linac sections, embedded in solenoids, launch the beam through a triplet, followed by the first RF deflector, a double bend dog-leg containing a beam collimator (a slit in the beam vertical plane) and the second RF deflector, taking the beam into a final quadrupole triplet to apply final focusing in the interaction region. While the beam for the Thomson source is transported unchanged through the dog-leg, the ultra-short bunch is produced by properly selecting a thin slice (25 μm) of the SASE-FEL beam produced at 150 MeV by the SPARC photo-injector. The slice selection is accomplished as follows: the first RF deflector induces a correlation between vertical position of each bunch slice at the slit position (located at the symmetric plane of the double dog-leg) and its longitudinal coordinate within the bunch, the slit clips a specific slice, finally the second RF deflector removes the time-z correlation imparted by the first deflector. It should be noticed that this technique is somewhat similar to the one proposed[2] for LCLS with the aim to generate fs long electron bunches, but it differs from that in the use of RF deflectors, which remove the need of correlated energy spread (energy vs. slice position within the bunch).

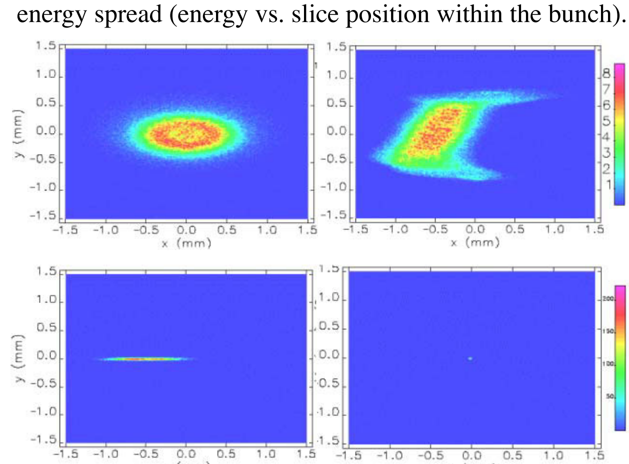

Fig. 2: beam distribution in (x,y) along the beam line

The beam density distribution in the transverse (x,y) plane is plotted in Fig.2, at 4 different positions along the beam line, *i.e.* at the photo-injector exit (upper left diagram), after the first RF deflector (upper right), after the slit (lower left) and after the second RF deflector and the final focusing triplet: the focal spot sizes are 7 and 2 μm (in x and y respectively) while the bunch rms length is 25 μm (25 pC of bunch charge selected through the slit, simulations performed with PARMELA and ELEGANT). The longitudinal phase spaces are shown in Fig.3.

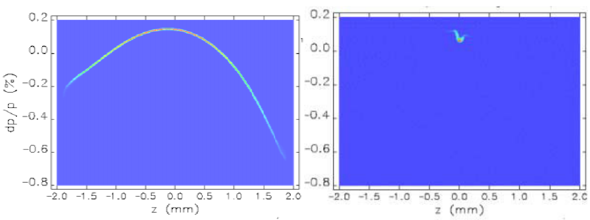

Fig. 3: beam distribution in (δz,δp/p) before and after the double dog-leg with 2 RF deflectors and slit

THOMSON SOURCE

The collision of a relativistic electron beam and a powerful laser gives rise to X-ray photons generated via the Thomson back-scattering effect (when the energy of the emitted photon is much smaller than the electron rest mass energy, *i.e.* recoil effects are negligible). The energy w_x of the emitted X-ray photon is given by $w_x = w_{las}\left(1-\beta\cos\alpha_l / 1-\beta\cos\vartheta_{ob}\right)$, where w_{las} is the laser photon energy (1.5 eV for our case), α_l is the colliding angle and ϑ_{ob} the observation angle. Head-on collisions ($\alpha_l = \pi$) observed on axis ($\vartheta_{ob} = 0$) give rise to X-ray photons of energy $w_x = 4\gamma^2 w_{las}$. A relevant range of energy is around 20 keV, in particular for advanced clinical diagnostics applications. Applying head-on collisions, which maximize the X-ray beam flux, it turns out that the electron beam energy must be 30 MeV, much smaller than the nominal SPARC value for which the photo-injector has been designed. Therefore, we had to derive a different operating point for the photo-injector, based on the launch of a longer bunch at the photo-cathode (30 ps laser pulse length, 1 nC, cathode spot size 0.6 mm) at lower phases, which generates a 20 ps electron bunch at the gun exit due to a weak bunching effect in the gun. The beam is accelerated by the first linac section up to 30 MeV, the second linac section is run at zero phase to remove the correlated energy spread while the third section is turned off. The combined effects of longitudinal wake-fields and a 4^{th} harmonic X-band cavity are used to correct the longitudinal emittance by removing the RF curvature, thus achieving a final rms energy spread lower than 0.05%. The transverse and longitudinal beam dynamics through the photo-injector are shown in Fig. 4 and Fig.5, respectively (simulations performed with ASTRA). A final lens focuses down the 30 MeV beam to a 10 μm spot size at the collision point.

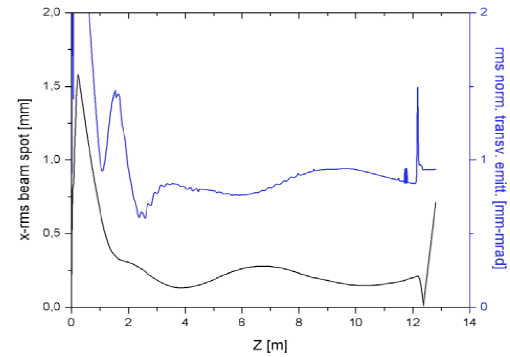

Fig. 4: 30 MeV beam for Thomson source: transv. dyn.

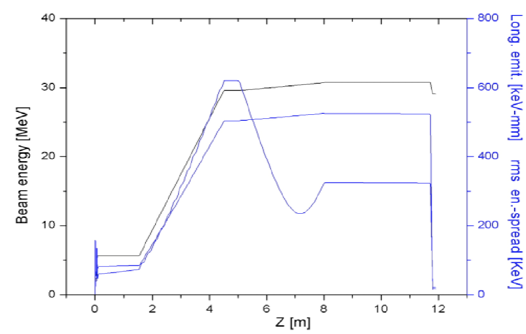

Fig. 5: 30 MeV beam for Thomson source: longit. dyn.

The estimated energy spectrum of the X-ray beam generated by colliding the electron beam with a 3 J laser pulse, 3 ps long and focused down to a spot size of 20 μm, is shown in Fig. 6. $2\cdot 10^8$ X-ray photons per collision are produced with 5% rms energy spread within a solid angle defined by $\vartheta_{ob} = \pm 6\ mrad$.

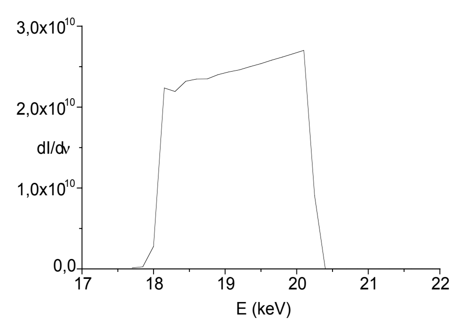

Fig. 6: X-ray beam energy spectrum

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[1] D. Alesini et al., “Status of the SPARC Project”, this conference, see also D. Alesini et al., in publication on *NIM-A* 21566

[2] P. Emma et al., *Phys. Rev. Lett.* **92**, 074801-4.