ACTIVITIES ON HIGH BRIGHTNESS PHOTO-INJECTORS AT THE FRASCATI LABORATORIES, ITALY

R. Boni, D. Alesini, M. Bellaveglia, C. Biscari, M. Boscolo, M. Castellano, E. Chiadroni, A. Clozza, L. Cultrera, G. Di Pirro, A. Drago, A. Esposito, M. Ferrario, L. Ficcadenti, D. Filippetto, V. Fusco, A. Gallo, G. Gatti, A. Ghigo, B. Marchetti, A. Marinelli, C. Marrelli, M. Migliorati, A. Mostacci, E. Pace, L. Palumbo, L. Pellegrino, R. Ricci, U. Rotundo, C. Sanelli, M. Serio, F. Sgamma, B. Spataro, F. Tazzioli, S. Tomassini, C. Vaccarezza, M. Vescovi, C. Vicario,
INFN-LNF, Frascati, RM, Italy
F. Ciocci, G. Dattoli, A. Dipace, A. Doria, M. Del Franco, G. P. Gallerano, L. Giannessi, E. Giovenale, G. Orlandi, S. Pagnutti, A. Petralia, M. Quattromini, A. Lo Bue, C. Ronsivalle, P. Rossi, E. Sabia, I. Spassovsky, V. Surrenti,
ENEA C.R. Frascati, RM, Italy
A. Bacci, I. Boscolo, F.Broggi, F. Castelli, S. Cialdi, C. De Martinis, D. Giove, C. Maroli, V. Petrillo, A.R. Rossi, L. Serafini, INFN-Mi, Milano, Italy
M. Mattioli, M. Petrarca, M. Serluca, INFN-Roma I, Roma, Italy
L. Catani, A. Cianchi, INFN-Roma II, RM, Italy
J. Rosenzweig, UCLA, Los Angeles, CA, USA
M. E. Couprie, SOLEIL, Gif-sur-Yvette, France
M. Bougeard, B. Carré, D. Garzella, M. Labat, G. Lambert, H. Merdji, P. Salières, O. Tchebakoff, CEA Saclay, DSM/DRECAM, France.
J. Rossbach, Hamburg University and DESY

Abstract

An intense activity on high brightness photo-injectors for SASE-FEL experiments and facilities, is being carried out, since 2003, in the Research Site of the INFN Frascati Laboratory, Rome, in collaboration with CNR and ENEA. SPARC is the 150 MeV photo-injector, in advanced phase of commissioning at LNF. The electron beam, which drives a 530 nm FEL experiment, is being characterized in terms of emittance, energy spread, peak current. The matching with the linac confirmed the theoretical prediction of emittance compensation based on the "invariant envelope" matching. The demonstration of the "velocity bunching" technique is in progress too. The SPARC photo-injector is the test facility for the soft-X FEL project named SPARX [1], that is based on the generation of ultra high peak brightness electron beams at the energies of 1.2 and 2.4 GeV generating radiation in the 1.5-13 nm range. SPARX will be realized in the Tor-Vergata University campus. In this paper we report the experimental results obtained so far with SPARC and the design status of the SPARX project.

THE SPARC TEST FACILITY

The INFN Frascati Laboratory (LNF) and the ENEA Frascati Research Center (CRF) are involved since 2003 in the development and the commissioning of the S-band photo-injector SPARC, aimed to generate high brilliance electron beams to drive SASE-FEL experiments in the visible and UV region, with a laser-seeding process. Moreover, SPARC will be the pre-injector of SPARX, the new high brightness electron linac to generate SASE-FEL radiation in the 40 to 0.6 nm wavelength range, that will be built in the campus of the Tor-Vergata (TV) Rome University, 4 km airline from LNF.

The SPARC research program is scheduled in two phases. The first one is concluded and consisted in characterizing the electron beam, photo-emitted at 5.6 MeV by the cathode of a S-band RF gun, illuminated by Ti-Sa Laser beam pulses [2]. The results of the first commissioning phase are reported in [3]. The second phase, still in progress, foresees a detailed analysis of the beam matching with the linac to confirm the emittance compensation theory, based on the "invariant envelope" matching [4] and to verify the emittance compensation with the "velocity bunching" (VB) experiment [5]. SASE and SEEDING experiments are also foreseen by the end of 2008. SPARC will also allow to study ultra-short beams physics, plasma wave-based acceleration, and to generate advanced X-ray beams via Compton back-scattering.

SPARC COMMISSIONING

The installation of the whole machine, including six permanent magnet (pm) undulators and the by-pass diagnostic channel was completed after disassembling the emittance-meter in January 2007. Three S-band sections [6] have been power conditioned in short time and operate at 20-20-10 MV/m respectively, providing a final beam energy of 150 MeV. Digital based, low level RF (LLRF) controls [7] allow to monitor, synchronize and stabilize the accelerating section RF fields and the phase of the laser pulses on the photocathode. The beam energy stability achieved is less than 0.1%. Two solenoids with 0.18 T field, are wrapped around the first two accelerating sections, to provide additional focusing for matching the beam envelope with the linac.

The possibility to vary independently the input power to each RF section was foreseen by means of “in-vacuum” waveguide variable attenuators. This option would have allowed to operate the photo-injector in very flexible way. Unfortunately, the manufacturer, (the German company *AFT*) failed in developing such high power devices that discharged at a power level (≈ 20 MWpeak) much lower than the design one (≈ 60 MWp).

To estimate bunch length, long. phase-space and slice-emittance an RF deflector (RFD) is installed on the beam-line downstream the last RF section [8].

Six 1.2 m long undulators, manufactured by *ACCEL Gmbh* [9] and made of a pm section with 28 mm period, 6÷30 mm variable gap and k = 1.4, are aligned on the beam line. A drift space of 360 mm between each unit, hosts quadrupoles for horizontal focusing and radiation diagnostic boxes. The undulator vacuum chamber consists of a 20x10 mm rectangular copper guide.

The gun emitted beam was initially fully characterized with the emittance-meter [10]. Then, after the installation conclusion, bunches of 200÷700 pC, with photo-cathode QE of 10^{-5} and gaussian laser pulses 6÷8 ps FWHM long, have been accelerated up to 150 MeV with an energy spread of 0.1%. An unexpected degradation of the cathode QE, prevented us to achieve the nominal bunch charge of 1 nC. Main beam parameters like the rms spot-size and emittance [11], bunch charge, length and slice-emittance have been measured and compared with the simulations [12]. The emittance was measured at 500 pC and 8.5 psec FWHM Gaussian pulse. The best projected value is below 2 mm-mrad in both planes, in good agreement with the simulations. Optimal envelope matching conditions have not yet been achieved, but more improvements in beam quality are expected [12]. A preliminary measurement of slice emittance has been also performed, see Fig. 1. The bunch charge was 300 pC, 5.3 FHWM bunch length, at 145 MeV. The result is consistent with the projected emittance value. More details are reported in [8].

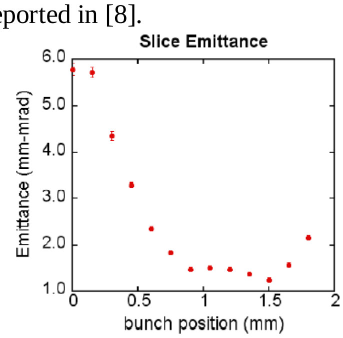

Figure 1: Slice emittance measurements. The slice length has been set to 150 μ i.e. about 0.5 ps.

Initial tests of beam longitudinal dynamics in the VB regime are shown in Fig. 2. The compression factor for 250 pC beam vs the phase of the first RF section is given. A bunch length reduction from 5 to 2.5 psec have been obtained, for ΔΦ = 20 degrees.

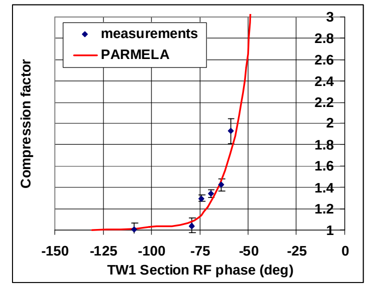

Figure 2: First velocity bunching: compression factor. Comparison between measurements and simulations.

The RFD together with a spectrometer dipole allows to obtain an image of the longitudinal phase space on a downstream screen as shown in Fig. 3.

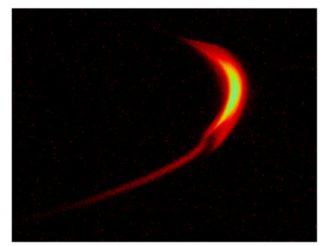

Figure 3: Imaging of long. phase space with the RFD. Beam energy: hor. axis; beam phase vert. axis.

THE FREE ELECTRON LASER

The FEL will operate in SASE mode at a wavelength of about 500 nm with an expected saturation length of about 10-12 m. Shorter saturation length may be obtained in short e-pulse mode, where VB allows to test the single spike operation [14]. The flexibility offered by the variable gap configuration of the SPARC undulators and the natural synchronization of the electron beam with the laser driving the photoinjector, makes the SPARC layout particularly suited for a number of experiments where the FEL amplifier is seeded by an external laser source. The seed laser is driven by the same oscillator initiating the laser cascade which is used to run the photocathode and consists in a regenerative amplifier delivering 2.5mJ at 800 nm with a pulse duration shorter than 120 fs.

Different schemes of non-linear harmonic generation are then implemented to generate the shorter wavelength radiation for seeding the FEL. Second and third harmonic generation in LBO crystals will provide the powerful pulses required to reach saturation and study the non-linear pulse propagation in FELs and FEL cascades in superradiant regime, at 400 nm and 266 nm [17,18]. The other method considered for the frequency up-conversion of the Ti:Sa fundamental wavelength, is based on the non-linear higher order harmonics generation of the Ti:Sa laser in a gas-cell [19,20]. Injection is obtained with a chicane deflecting the beam from the linac axis and a periscope allowing the injection of the harmonic beam. The system has been aligned, with the laser and the injection periscope, and commissioned. A preliminary test was concluded with the observation of the third harmonic of the Ti:Sa beam with a CCD camera, shown in Fig. 4.

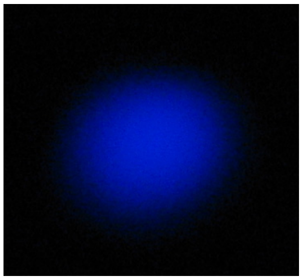

Figure 4: Spot of the UV radiation at the detection screen.

THE SPARX PROJECT

The SPARX project is the natural continuation of the activity, undertook at LNF, on high brilliance photo-injectors. Supported by the Italian Minister of Reasearch (MIUR) and by the local government Regione Lazio, the project gathers the scientific know-how of three Italian research institutions, CNR, ENEA and INFN, together with the TV-University. SPARX will be an evolutionary project aiming to generate X-FEL radiation from 40 to 0.6 nm. It will be developed in two phases, corresponding to 1.5 GeV and 2.4 GeV, and realized on the grounds of the TV-University, not far from the LNF. SPARX, a user facility for applications in basic science and technology, will be housed in 2 underground 400 m. long overlaying tunnels. Construction and commissioning of the SPARX complex are planned in a 5 years schedule starting from the summer 2009. The 2008 is being dedicated to prepare a Technical Design Report that will be submitted to the funding authorities. The machine is a room-temperature S-band linac, with a 150 MeV SPARC-like pre-injector, followed by successive linac stages and undulator lines, as shown in Fig. 5, which also shows the RF layout consisting of '8+7' 60 MW klystron stations, each feeding three accelerating sections via SLED-type energy compressors. A travelling-wave 11.424 GHz accelerating structure, supplied by a 50 MW peak klystron, provides to linearize the beam longitudinal phase-space [x].

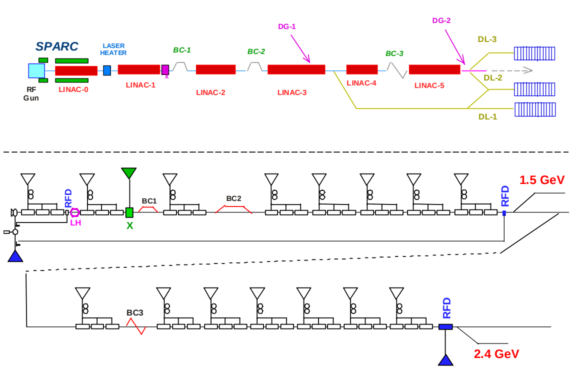

Figure 5: Layout and RF system of SPARX.

To keep the SASE saturation length within a reasonable value, magnetic bunch compressors (BC), between the linac stages, will be used to increase the bunch peak currents to 1÷2.5 kA at 1.5÷2.4 GeV respectively. A laser heater chicane [16] is also foreseen, after the pre-injector, to suppress microbunching instability generated by BC's.

Several operating schemes are being considered for SPARX [17]:

1) SASE operation with harmonic up-conversion;
2) Seeded, single step High Gain Harmonic Generation (HGHG), that is a new scheme for single pass FEL, more compact and capable of generating XUV radiation with better coherence and smaller energy fluctuations;
3) HHG + HGHG: an alternate way to get shorter wavelengths is to use a seed laser operating in VUV domain;
4) Multi stage HGHG cascade, in which the radiation from the first undulator is used as high-power seed for the successive stages;
5) Multi-bunch regenerative amplifier, either self-seeded or externally seeded, in a mirror resonator;. SPARX will be suited to accelerate multi-bunch trains at 357 MHz
6) Single spike operation with ultra-short, small charge beams that may have very high brightness and can drive the SPARX FEL producing ultra-short radiation pulses.

The SPARX Technical Design Report will be presented to the supporting Institutions within 2008. The civil works in the TV campus should start by the spring 2009 and the major contract procurements by the autumn 2009.

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