STATUS OF SPARX PROJECT

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Abstract

Driven by the large interest that 4[th] generation light sources, *i.e.* X-ray SASE FELs, have raised world-wide in the synchrotron light scientific community, as well as in the particle accelerator community, and following the solicitations arising from several Italian national research institutions, the Italian Government launched in 2001 a long-term initiative devoted to the realization in Italy of a coherent X-ray source.

In March 2002 a proposal, born from a collaboration among ENEA, INFN, CNR, Università di Roma “Tor Vergata”, and INFM was strategically oriented to explore both the feasibility of a ultra-brilliant photo-injector and to perform a SASE-FEL experiments based on the **SPARC Test Facility**. In 2004 the scientific program was enriched with a seeding and velocity bunching experiments, and new diagnostics devices, by means of EUROFEL, Design Study Project funded by 7[th] Framework Programme of EC. The SPARC Test Facility is now at the end of its installation; a robust beam physics experiments program has demonstrated the achievement of the nominal parameter of the electron photo-injector downstream the gun [2]. The experimental program will continue in the next months with the full characterization of the electron beam at 150 MeV which includes slice emittance and velocity bunching measurements [3]. The **SPARX** (Sorgente Pulsata Autoamplificata di Radiazione X) **FEL** is devoted to the realization of SASE radiation source operating with Seeding and Harmonic Generation schemes. It will cover the spectral bandwidth from 0.6 nm to 40 nm, with a temporal resolution in the range 1 fs -100 fs. The source is complementary to the Fermi-FEL Facility in costruction at Elettra Trieste and to the European X-FEL in Hamburg, and will offer a powerful tool unique in its characteristics and helpful for a number of applications in basic science and technology: time resolved X-ray diffraction with pump and probe experiments, nanolithography processes, biological proteins, nano-particles and clusters, coherent diffraction and holographic X-ray techniques, nano-imaging. The initiative, which got the first fundings from the Ministry of Research MIUR and from the Regione Lazio, foresees a construction of a user facility inside the Tor Vergata campus by a collaboration among CNR, ENEA, INFN and the Università di Tor Vergata itself. The above institutions will collaborate through the SPARX-FEL Consortium which will construct and operate the facility. SPARX-FEL is also participating at the preparatory phase of the IRUVX-FEL Consortium, which gathers, the major national FEL facilities in Europe.

SPARX LAYOUT

The SPARX accelerator is meant to be realized in two phases providing a radiation wavelength in the following ranges: λ_r≈40nm-10 nm, λ_r≈15-nm-3 nm, λ_r≈4nm-1.2nm, λ_r≈1.2nm-0.6nm, at different electron beam energies around 0.8 GeV, 1.2 GeV, 1.5 GeV, and 2.4 GeV.

To reach SASE saturation in reasonable length undulators a peak current I_{pk} ≈1÷2.5 kA is needed at the two energies. The required final beam energy spread is 0.1% in both cases and the nominal machine is designed to operate at a repetition rate of 100 Hz. The main parameter list are reported in Table 1 where the nominal beam energy, rms bunch length σ_z and rms energy spread σ_δ are indicated.

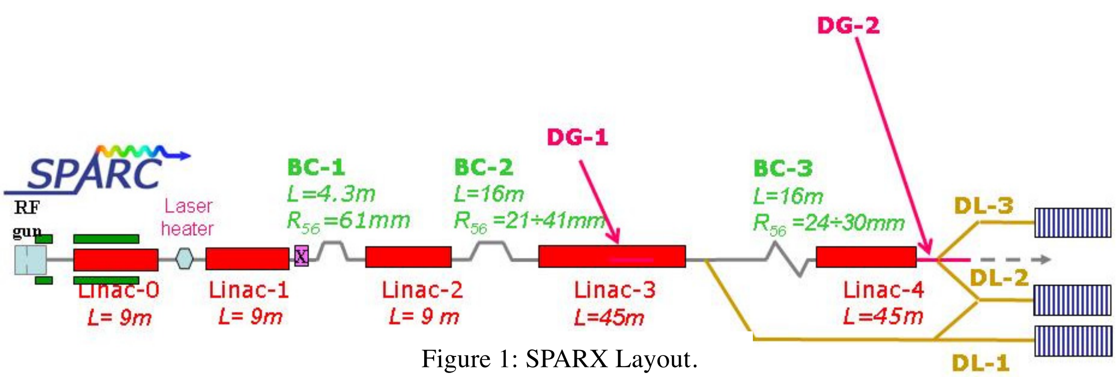

Figure 1: SPARX Layout.

Table 1: Electron beam main parameter list

Energy(GeV)	E	1.5	2.4
Peak current (kA)	I_{pk}	1.	2.5
Normalized transverse emittance slice	ε_n	1	1
Correlated energy spread (%)	σ_δ	0.1	0.1
Radiation wavelength (nm)	λ_r	13÷3	3÷1.5

Table 2: Radiation wavelengths

	Units	U1 0.8 - 1.2 GeV	U2 1.2 – 1.5 GeV	U2 2.4GeV	U3 2.4GeV
Wavelength	nm	40 – 10	15 – 3.0	4 - 1.2	1.2 – 0.6

SPARX ACCELERATOR

A schematic drawing of the accelerator is shown in Fig. 1. The SPARX accelerator and is made of S-band type sections at frf=2.856 GHz andEacc= 23.5MV/m. The first part Linac-0 (See Fig.1) is composed of three 3m long accelerating sections: it consists of SPARC photoinjector already developed and in operation at LNF-INFN. A diagnostic section, following the transport line provides energy and beam emittance measurements. A laser heater chicane is included in the scheme in order to rise the uncorrelated beam energy spread. The second Linac-1 includes three accelerating sections rises the beam energy up to ≈ 350 MeV before the first magnetic compressor BC-1; a short X-band section is also provided to linearize the beam longitudinal phase space before the bunch compression. The BC-1 magnetic chicane, with R56≈ 61mm, will bring the peak current up to 350÷400 A. The BC-1 magnets are foreseen to be switched off when the beam current from the photoinjector is Ipk ≥ 300A, i.e. when the velocity bunching technique is adopted in the photoinjector system and the magnetic compression occurs in BC-2-3 only. The RF-compression technique is presently under test at the SPARC facility at LNF, and will be definitively adopted in the SPARX design only after successful experimental proof.

The Linac-2 is composed of five accelerating sections it brings the beam energy up to 500 MeV and the projected energy spread up to $\sigma_d \approx 0.7$ %. The BC-2 magnetic chicane with an $R_{56}\approx$ 24 mm compresses the bunch length up to a peak current of 1 kA and the Linac-3 (fifteen sections) increases the beam energy up to 1.5 GeV, bringing the projected beam energy spread down to $\sigma_\delta\approx 0.1\%$. The DL1-2 doglegs are a four-six dipole bypass beamline with $R_{56}=0$ that extracts the 1.5 GeV beam and deliver it to the low-medium energy undulator entrance. A diagnostic section DG-1 is provided downstream the Linac-3 which injects an energy chirped 1.5 GeV beam in the BC-3 s-shaped magnetic chicane, $R_{56}\approx$ 24 mm, that performs the final compression on the electron beam rising the bunch current up to Ipk ≈ 2.5 kA. Finally Linac-4 accelerates the electrons up to 2.4 GeV (with a maximum energy of 2.6 GeV) and the high energy DL-2 dogleg delivers the beam to the medium-high energy undulator.

FEL AND UNDULATOR SYSTEMS

To achieve a high level of FEL output commensurate with user requirements over a large range of X-ray energies from 40eV to 2keV, the family of SPARX undulators will be able to run in multiple configurations.

The fundamental architectures of the SPARX system are SASE operation: The simplest and most common FEL architecture is self-amplified spontaneous emission (SASE) in which the radiation starts from shot noise of the electron beam and grows up as the bean passes through the undulator the undulator. This process produces short wavelengths without the requirement of an external master oscillator source. The SASE output has with high peak power and a high degree of transverse coherence. However, the temporal coherence of the generated pulses are only partial and the intensity fluctuations are important. Several schemes are under investigations:

1) SASE operation with the option of harmonic up-conversion: If the SASE amplifier is interrupted when the bunching is maximum – at roughly 80% of saturation – the bunched beam will contain large Fourier components of the current at the harmonics of the SASE fundamental frequency. If this bunched beam is immediately injected into a radiator (undulator) that is tuned to the harmonic the beam will emit strong, coherent synchrotron radiation at the harmonic.

2) Seeded, single-step High Gain Harmonic Generation (HGHG). One new scheme for single pass FEL is High Gain Harmonic Generation (HGHG). This proven approach is more compact and can produce a XUV radiation with the same properties of SASE radiation but with fully temporally coherent pulses and small energy fluctuations. In this configuration, an external laser source is injected as a seed into a first undulator where an energy modulation is imposed on the electron beam by its interaction with the laser. This energy modulation is converted into a spatial density modulation as the electron beam crosses a dispersive section. The microbunched electron beam coherently emits at the nth harmonic of the laser fundamental frequency. The tuning of the undulator radiator selects the amplified harmonic. The properties of the output radiation are determined by the seed laser, which can have a high degree of temporal coherence. Seeded FEL amplifier operation in combination with harmonic generation has been

demonstrated experimentally at both mid-infrared and VUV wavelengths. A complication of using a seeded architecture is that the electron beam energy, which sets the central wavelength of the gain-bandwidth, must be stabilized to well within the gain bandwidth of the FEL process. That is, the energy should be stable on a pulse-to-pulse basis to ~r/3.

3) HHG plus HGHG: an alternate way to reach shorter wavelengths is to use a seed laser in operating in VUV the domain. Developments in femtosecond laser technology are making possible new, coherent, short wavelength sources. One such source, called High-Order Harmonics Generation (HHG), is based on the interaction between the laser beam and a gas target. Fraction of a microjoule energies can be obtained at wavelengths down to 25 nm. The HHG could be used as seed to inject an undulator, either in the amplifier or in the HGHG configuration to extend the operating wavelength of FELs down to sub nm. A critical question is whether the intensity and phase stability of the HHG harmonics at short wavelength is sufficient for the FEL output to satisfy the stability requirements of users. Such questions will be investigated on SPARC configuration to quantify issues related to the injection of an external radiation seed in a single pass FEL and the analysis of the coupling efficiency of the electron and photon beams in terms of the input parameters.

4) Multi-stage HGHG cascade: In the multiple step harmonic cascade the radiation output from the first radiator is used as a high power seed to be injected into a downstream modulator-radiator section. Physics limitations of this approach will be investigated in experiments at SPARC.

5) Multi-bunch regenerative amplifier either self-seeded or externally seeded: In EUV FELs driven by bunch trains from a linac with peak currents in the range of ~100 A and with an emittance in the range of 1- 2 π mm-mrad, a 10 -15 m undulator can produce an overall gain of 20 –30% even in a four mirror resonator. Such a multi-pass, self-seeded Regenerative Amplifier FEL (RAFEL) has been tested at infra-red wavelengths by at Los Alamos. The Los Alamos experiment, consisting of a simple ring resonator with two imaging paraboloids and two annular mirrors had a radiation out-coupling ~50 % of the generated radiation. This configuration allowed the RAFEL to come to saturation after few passes through the undulator. The SPARX linac is suited for the generation of train of pulses within the same RF macropulse, to be delivered to multiple undulator beamlines in order to simultaneously serve a larger number of users. As suitable multi-layer mirrors are available in the EUV, a RAFEL may be consitent with the SPARX linac operation in a multi-bunch mode with a pulse spacing of several ns. A second injector optimized to deliver longer train of pulses could be implemented as a second option. This would allow a substantial increase of the laser repetition rate and would make particularly interesting the regenerative amplifier scheme.

6) Single Spike operation: An ultra-short beam, with very small charge, may have very high brightness, and thus may efficiently drive the SPARX FELs producing ultrashort radiation pulses. We have therefore investigated the creation, through initial velocity bunching at low energy and subsequent chicane bunching, of ultra-low-charge -1pC - beams of sufficient quality to support strong FEL gain. These beams can drive the FEL in single (or few) spike mode; one may therefore obtain SASE sources with improved coherence X-rays that are both quite stable and have pulse lengths at the femtosecond scale.

	Units	**1.2 – 1.5 GeV**	**2.4GeV**
Wavelength	nm	15 – 3	4 – 0.6
Peak power	GW	2-9	3-20
Average power	W	0.1-0.2	0.03-0.1
Photon beam size (FWHM)	*mm*	100	-
Photon beam divergence (FWHM)	*m*rad	20	-
Bandwidth (FWHM)	%	0.2-0.1	0.15-0.1
Pulse duration (FWHM)	fs	250	70-30
Repetition rate	Hz	100-50	100-50
Number of photons per pulse	#	$1.5\text{-}8.5 \times 10^{13}$	5×10^{12}

REFERENCES

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