STATUS OF THE SPARX-FEL PROJECT*

L.Palumbo, Università di Roma La Sapienza and INFNF-LNF, Frascati, Italy,
On behalf of SPARX Collaboration [1]

Abstract

The SPARX-FEL project aims at producing ultra high peak brightness electron beams in the 1.5 - 2.4 GeV range with the goal of generating FEL radiation in the 0.6-40 nm range. The construction is planned in two steps, starting with a 1.5 GeV Linac. The project layout includes both RF-compression and magnetic chicane techniques, in order to provide the suitable electron beam to each one of three undulator systems which will generate VUV-EUV, Soft X-Rays and Hard X-rays radiation respectively This will be distributed in dedicated beamlines suitable for 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 project was funded by the Italian Department of Research, MIUR, and by the local regional government, Regione Lazio; the associated test-facility, SPARC, located at LNF, has been successfully commissioned: the SPARX-FEL project foresees the construction of a user facility inside the Tor Vergata campus by collaboration among CNR, ENEA, INFN and the Università di Tor Vergata itself.

THE SPARX PROJECT

The SPARX (Sorgente Pulsata Autoamplificata di Radiazione X) FEL covers a radiation region complementary to those of other existing or in construction facilities, such as FLASH ($4<\lambda<40$ nm), FERMI ($10<\lambda<100$ nm), X-FEL ($0.1<\lambda<1.6$ nm), LCLS ($0.15<\lambda<1.5$ nm), and will produce, with special magnets, radiation up to the THz region. The project is planned as a research infrastructure in Tor Vergata University campus, an area about 1.5 km long, that does not limit the expansibility of the facility for future upgrades. The project "dimensions" are: Accelerator tunnels ~300 m, Experimental hall ~ 60 m, Undulator hall ~85 m, in Fig. 1

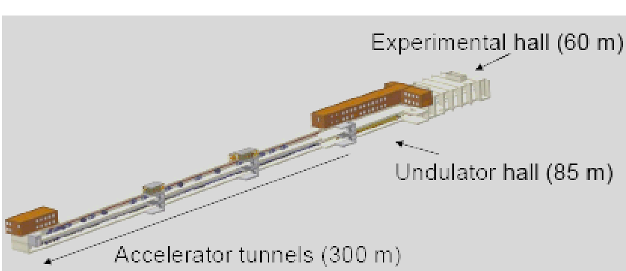

Figure 1: The SPARX surface buildings and the LINAC tunnel design.

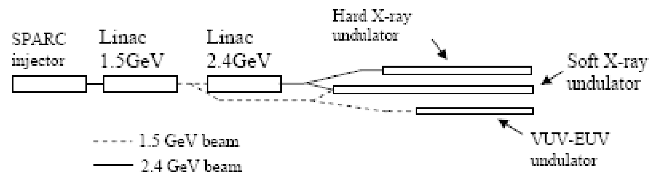

Figure 2: Layout of SPARX.

the SPARX surface buildings and the LINAC tunnel are shown.

By the end of 2008 the Technical Design Report has been completed [1] and it foresees an evolutionary project with two additional steps to the already completed SPARC test facility [2]. The main goal is to achieve in the first harmonic the VUV and soft X-Rays spectrum, tuning the machine from 5-6 Å to 30-40 nm. In this way the facility easily covers in its first harmonic the water window spectral region (ranging from 2.3 to 4.4 nm).

The subnanometer FEL emission (5-6 Å) is quite suitable for molecular structure studies and it can be further extended down to 1 Å with the use of third and fifth harmonics. To this end, in order to operate with high flexibility and energy tunability of the electron beam, the electron LINAC has been designed with a maximum energy of 2.64 GeV. This is reached by means of a 150 MeV SPARC-like photoinjector [3] followed by a first LINAC, bringing the operating energy up to 1.5 GeV (which allows to enter the water window region) and the second LINAC for an optimized operating energy of 2.4 GeV (maximum energy is 2.64 GeV) necessary for reaching the subnanometer region. The electron beam, which can be extracted at 1.5 GeV and at 2.4 GeV, feeds three parallel undulators (see Figure 2).

Two beamlines are provided for each undulator source in order to maximize the users' accessibility. The beamlines, optimized for high photon energy resolution and for short-pulse handling, have been designed for the following energy ranges:

- VUV-EUV beamline: 30 -124 eV (10 -40 nm)EUV
- Soft X-ray beamline: 88.6 – 1240 eV (1 - 14 nm)
- Soft-X-ray beamline: 1280 eV – 2000 eV (0.6 – 1 nm)

In order to reach SASE saturation in undulators of reasonable length, a peak current $I_{pk}=1\div2.5$ kA is needed for lower and higher energies respectively. The required final beam energy spread is 0.1% in each case and the machine is designed to operate at a repetition rate of 100 Hz. The main parameter list is reported in Table 1 and Table 2.

Table 1: Electron Beam Parameter List

Energy	(GeV)	E	1÷1.5	2.4
Peak current	(kA)	I_{pk}	1	2.5
Normalized transverse emittance slice	(μm)	ε_n	0.1	1
Correlated energy spread	(%)	$\sigma\delta$	0.1	0.1
Photon Radiation wavelength	(nm)	λ_r	40÷3	3÷0.6

Table 2: Radiation Parameters of the FEL Sources

	Units	*U1*	*U2*	*U2*	*U3*
Electron Beam energy	GeV	0.96-1.5	0.96-1.5	1.9-2.4	1.9-2.4
Wavelength	nm	40-10	15-4	4-1.2	1.2-0.6
Photon energy	eV	30-120	80-300	300-1000	1000-2000
Peak power	GW	1.7-3.4	~2	3-20	0.8@2G.4GeV
Average power	W	-	0.1-0.2	0.03-0.1	-
Photon beam size (FWHM)	μm	~140	~150	~130	~120
Photon beam divergence (FWM)	μrad	33	25	19	17
Bandwidth (FWHM)	%	0.2	0.2-0.1	0.15-0.1	0.09@2.4GeV
Pulse duration (FWHM)	Fs	200	30-250	70-30	70-80
Repetition rate	Hz	100-50	100-50	100-50	100-50
Number of photons per pulse	#	1.0×10^{14}	$1.5\text{-}8.5\times10^{13}$	5.0×10^{12}	$0.5\text{-}1.5\times10^{12}$
Peak brilliance*		$\approx10^{28}$		$\approx10^{27}$	
Average brilliance		$\approx10^{20}$		$\approx10^{19}$	

*standard units: *Number of photons (sec·mrad^2·mm^{2}0.1% BW) Mean values have been considered for the different cases.*

THE ACCELERATOR LAYOUT

The SPARX accelerator (Fig. 3) is made of S-band type accelerating sections at f_{rf}=2.856 GHz and Eacc= 23.5MV/m. The first part Linac-0 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 raise the uncorrelated beam energy spread. The second Linac-1 includes three accelerating sections and it 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 R_{56}≈ 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 σ_δ ≈ 0.7 %. The BC-2 magnetic chicane with an R56≈ 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 σ_δ ≈ 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 energy chirped 1.5 GeV beam in the BC-3 s-shaped magnetic chicane, R56≈ 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.

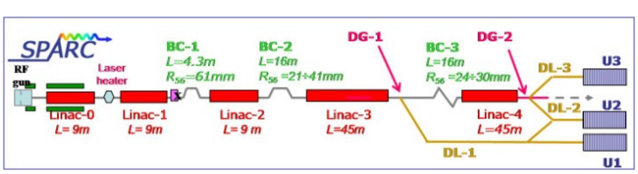

Figure 3: SPARX accelerator layout.

FEL AND UNDULATOR SYSTEMS

To achieve high power FEL output over a large range of X-ray energies from 40 eV to 2 keV, a family of SPARX undulators has been designed to be able to run in multiple configurations. The fundamental architectures of the SPARX system are: **1)** SASE operation with option of harmonic up-conversion, **2)** Seeded, single-step High Gain Harmonic Generation (HGHG), **3)** HHG plus HGHG, **4)** Multi-stage HGHG cascade, **5)** Multi-stage regenerative amplifier either self-seeded or externally

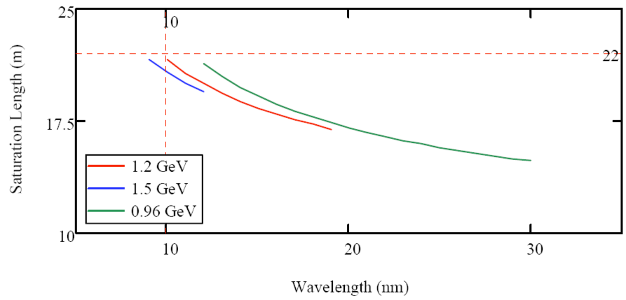

Figure 4: Saturation length vs. wavelength at different seeded, **6)** Single spike operation. The SPARX linear electron beam energies.

accelerator is configured to provide the beam at energies ranging between 0.96 GeV and 2.64 GeV. The large range planned for the soft x-ray beamline is made possible by allowing the line to be fed with the electron beam coming from either the low or high energy exits. The electron beam energy may be varied over the range from 0.96 GeV to 1.5 GeV at the "low" energy exit and over the range from 1.70 GeV –2.64 GeV at the LINAC exit. The expected beam parameters depend on the specific conditions of operation – i.e. energy, charge and pulse duration – which may be varied according to the specific needs of the users.

VUV-EUV Beamline (40-124 eV)

The VUV-EUV undulator beamline is composed by 11 permanent magnet undulators in the Halbach configuration, with the parameters listed in Table 3. The lowest photon energy of 40eV is obtained with an undulator period of 34 mm.

Table 3: VUV Undulator Parameter list

Period	(mm)	34
Min. Gap	(mm)	8.1
K (min-max)		3.3-0.3
Periods/segment		65
# of segments		11

The saturation length depends on the emittances and energy spread of the electron beam; based on the modified Xie/DOP models, and assuming that the beam has the reference parameters of 1kA, 1 mm-mrad transverse emittances, and 2x10-4 relative energy spread, we have estimated the dependence of the saturation length as a function of the wavelength at different beam energies. See Fig. 4.

EUV-Soft X-Ray Beamline

The photon energy range required from the EUV-Soft X-Ray beamline spans from 88.5 eV (14 nm) to 1.24 keV (1 nm). Despite the fact that the EUV-Soft X-ray beamline may be fed with both the high energy and the low energy electron beams, even exploiting the full beam energy variation available from SPARX, the simple energy tuning is not sufficient to ensure such a wide range, obtaining the wavelength variation by gap and energy tuning. The optimization is possible considering the alternative undulator configuration with the same overall magnetic length, but composed of three different segments. The segments are characterized by an undulator period that decreases toward the end of the structure. The scheme considered is shown in Fig. 4

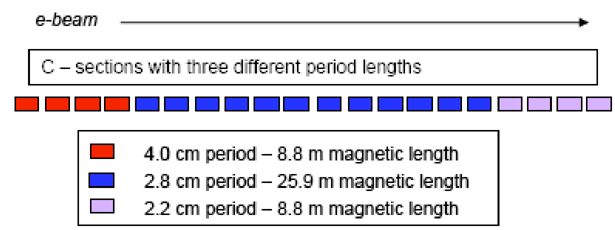

Fig. 3: Multi-period undulator scheme (C) including four sections with a larger period matching the resonance at the 27th harmonic of the Ti:Sa (29.6 nm).

The Hard X-Ray Undulator Beamline

This beamline is designed to cover the hard X-ray photon energy range at SPARX with maximum photon energy of 2keV (0.62nm). The production of hard X-ray photons using conventional undulator technology, in which the remnant magnetic field is ~1.2-1.3T, requires relatively long period lengths to yield a sufficiently large K parameter. This implies relatively high beam energy and a long undulator structure. The HE beam nominal energy is 2.4GeV (with an upper limit of 2.64 Gev due to RF constraints). The requirement on the spectral range suggests that: **a)** the undulator must be optimized for the shortest wavelength tuning the beam energy instead of the undulator strength, **b)** the undulator must be in vacuum, to maximize the undulator field vs. gap, **c)** high field technology must be implemented to maximize the remanent field. In Table 4 the parameters are listed.

Period	(mm)	1.5
Undulator length	(m)	2.7
# Periods		180
Gap	(mm)	5
K		1.283
Remanent field (effective)	(T)	1.45
# undulator sections		11

REFERENCES

[1] www.sparx-fel.it, SPARX-TDR-Team.
[2] www.lnf.infn.it/acceleratori/sparc/.
[3] M. Ferrario, *et al*, or EPAC08 or this conference.