GSRN#2312067, Vol 0, ISS 0

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The Elettra 2.0 Beamlines

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Introduction

Situated on the outskirts of Trieste, Italy, the Elettra synchrotron radiation facility has been operating for users since 1994, and was the first third-generation light source for soft X-rays in Europe. The facility comprises a 100 MeV linac, a 2.5 GeV booster synchrotron, and a storage ring operating at 2.0 or 2.4 GeV with a horizontal emittance of 7 nm-rad at 2.0 GeV and10 nm-rad at 2.4 GeV. Elettra currently is the sole facility operating at either one of two energies, depending on the users' demand, in top-up mode at both energies. A passive superconducting third harmonic cavity (3HC) extends the bunch length by a factor of three, enhancing stability and lifetime [1]. Operational modes include multi-bunch with a 42 ns dark gap and hybrid configurations involving one (for time-resolved experiments) or two single bunches (with a 40 ns separation in a dark gap of 120 ns) for pump-probe experiments.

Crucial parameters for conducting synchrotron radiation experiments with substantially improved spatial, temporal, and energy resolution include the brightness and transverse coherence of X-rays. Diffraction-limited storage rings (DLSRs), implemented through multi-bend technology, yield transversely coherent beams characterized by uniform phase, ensuring high flux and stability [2, 3]. Recent advances, such as the implementation of new insertion devices (IDs) with stronger magnetic fields and shorter periods, hold the potential to further enhance coherent flux and contribute to the expected performance of DLSR-generated photon beams.

The design of a new, more advanced source than the current Elettra began in 2014. These studies analyzed the possibility and possible cost of creating a new very low emittance storage ring, called Elettra 2.0, which could operate in the same Elettra tunnel using the current injection system, therefore minimizing infrastructure costs. A wide range of technical solutions for the lattice of the new machine was examined, from 4-bend achromat to 10-bend achromat, and the cost-performance ratio led to the choice of an enhanced 6-bend achromat type structure, which would allow reaching an emittance of 212 pm-rad, at 2.4 eV, therefore about 47 times lower than the current emittance. At the same time, energy consumption would decrease by approximately 25%.

The Elettra 2.0 project [4–6] was approved by the Italian Government in 2017, with plans for the new machine to commence serving external users in 2027. The design phase lead to a final version of Elettra 2.0 a fully transversely coherent source up to 0.5 keV-photon energy, more than doubling the total average current and increasing brightness by more than two orders of magnitude as compared to the current source, and maintaining a diversified beamline portfolio to allow experiments across a broad spectrum of photon energies, from a few tens of eV to several tens of keV, while substantially increasing the number of beamlines operating in the hard-X-ray range. In perspective, the possibility of producing picosecond-long light pulses at a MHz repetition rate across multiple beamlines simultaneously, without interference to standard multi-bunch operation is also being considered. Another important aspect of Elettra 2.0 is the high degree of transverse coherence in both the horizontal and vertical directions, projected to improve by a factor of 60 at 1 keV as compared to the current source.

The Elettra 2.0 project includes the construction of new beamlines and an extensive upgrade of most of the existing beamlines to fully exploit the high brightness and high degree of coherence offered by the new source. Over 40% of the entire investment budget is allocated to this purpose. Following this program, Elettra 2.0 is poised to host up to 32 new and upgraded beamlines, with a comprehensive list detailed in the subsequent sections of this paper.

The Elettra 2.0 storage ring lattice

Several key parameters have been taken into consideration during the design phase. Elettra 2.0 will maintain the same circumference as Elettra, at 259.2 m, and will be housed in the existing storage ring building. The positions of the source points and exit ports of the straight sections will be retained. The current injection system will be retained. The primary operating energy will be 2.4 GeV, with 2.0 GeV operation being sustained for a transitional period. The ring current will increase from 310 at 2 GeV and 160 mA at 2.4 GeV to 400 mA.

The lattice design is based on an enhanced symmetric six-bend achromat (S6BA-E) concept, incorporating longitudinal gradient (LG) dipoles and reverse bends [6]. The new ring remains 12-fold symmetric, featuring 24 symmetric arcs, including 12 dispersion-free long straight sections (each 4.85 m long) and 12 short straight sections (each 1.26 m long) with a relatively small dispersion (57 mm). The lengths of these straight sections have been carefully adjusted to ensure that the source points of the long straights coincide with those of the current machine. While the number of long straight sections mirrors that of Elettra, the increased number of short straights provides additional slots for beamlines in Elettra 2.0, optimizing the utilization of available space.

Elettra 2.0 beamline portfolio

Currently Elettra delivers synchrotron radiation ranging from the infrared to the hard X-rays to 28 beamlines. Among these, 17 operate in the VUV-soft X ray range, 9 in the hard X range, and 2 in the IR-THz range. These beamlines are equipped with versatile experimental stations implementing a variety of X-ray-based techniques, including spectroscopy, spectromicroscopy, diffraction, scattering, and lithography. Experimental tools available to Elettra users include:

- photon-in/electron-out spectroscopies: Photoelectron Spectroscopy (PES), Angle Resolved PES (ARPES), spin-resolved ARPES, and X-ray Absorption Spectroscopy (XAS), including spectromicroscopy and chemical or magnetic imaging;
- photon-in/photon-out spectroscopies: XAS, Fluorescence Spectroscopy (FS), Inelastic UV Scattering (IUVS), Raman, and Infrared (IR), including X-ray and IR microscopy.
- X-ray Diffraction (XRD) and Small Angle X-ray Scattering (SAXS).

Over half of the beamlines at Elettra have been developed and are operated in collaboration with national and international scientific institutes and agencies. In Figure 1, the full list of beamlines in operation is shown. For each beamline, the main available techniques are

Beamlines	Photon source	Photoelectron emission	Imaging	Scattering	Reflection/ Emission	Absorption	Diffraction	Lithography
TwinMic	APU		✓		✓	✓		
Nanospectroscopy	EPU	✓	✓			✓		
NanoESCA	EPU	✓	✓			✓		
ESCA Microscopy	LPU	✓	✓					
SuperESCA	LPU	✓				✓		
Spectromicroscopy	LPU	✓	✓					
VUV	LPU	✓						
CiPo	EMW	✓		✓		✓		
SAXS	W			✓			✓	
XRD1	W						✓	
Materials Science	BM	✓				✓		
SYRMEP	BM		✓					
GasPhase	LPU	✓			✓	✓		
MCX	BM						✓	
ALOISA	APU	✓				✓		
BEAR	BM	✓		✓	✓	✓		
BACH	EPU	✓		✓	✓	✓		
SISSI-Bio	BM		✓		✓	✓		
SISSI-Mat	BM		✓		✓	✓		
APE-LE	EPU	✓				✓		
APE-HE	EPU	✓				✓		
XRF	BM				✓			
DXRL	BM							✓
IUVS	F8			✓				
BaDElPh	F8	✓						
XAFS	BM					✓	✓	
XRD2	SCW						✓	
Xpress	SCW						✓	

Figure 1: Beamlines currently in operation at Elettra. Hard X-ray beamlines are denoted in black, the beamlines operating in the UV to soft X-ray range are denoted in red and the IR/THz beamlines are denoted in orange colour. For each beamline we list the main experimental techniques available to users.

indicated. The Italian Consiglio Nazionale delle Ricerche (CNR) operates nine of the existing beamlines through three CNR Institutes, the Istituto di Cristallografia (CNR-IC), the Istituto dei Materiali Nanostrutturati (CNR-ISM), and the Istituto Officina dei Materiali (CNR-IOM). Additional beamlines are operated in partnership with the Technical University of Graz (TU-Graz), the Forschungszentrum Jülich, the Charles University of Prague, the Indian Institute of Science of Bangalore (IIS), the International Atomic Energy Agency (IAEA) [7].

The eleven available long straight sections (the twelfth being used for injection) host adjustable gap linearly polarizing undulators (LPU), adjustable phase undulators (APU), a Figure 8 undulator (F8), elliptically polarizing undulators (EPU), including a canted APPLE-II type undulator in one section for the APE-LE and APE-HE beamlines, an electromagnetic wiggler (EMW), a standard wiggler (W) and a superconducting 3.5 T wiggler (SCW). A double magnet array APU has been recently installed in one short section for the TwinMic beamline. In addition, seven bending magnets (BM) of Elettra provide radiation to nine beamlines.

Several supporting laboratories offer facilities for utilizing atomic probe techniques such as Atomic Force Microscopy (AFM) and Scanning Tunneling Microscopy (STM). These laboratories also provide access to a cell culture room, a protein production facility, conventional XPS, UPS, and more.

The beamline portfolio of the new Elettra 2.0 source is designed to exploit the high brightness and high degree of coherence of the new source, increasing the number of beamlines operating in the hard-X-ray range, expanding imaging and tomography applications while ensuring that a wide array of techniques remain available in a broad photon energy range, from the IR to the hard X-rays. The aim is to anticipate the needs of the scientific and industrial communities that will utilize our facility in the future.

Upon project completion, a maximum of 32 beamlines will receive radiation from the new machine. The number of beamlines operating in the hard X-ray range will increase from 9 to 12, with most of them upgrading their photon sources with new ones, currently unavailable at Elettra. To enhance capabilities in the hard X-ray range, three superconducting bending magnets (SBM) with a peak field of 6 T will be incorporated into the ring optics. These magnets will provide hard X-rays with energies up to 140 keV (in the white beam configuration) to beamlines devoted to X-ray imaging and tomography (SYRMEP-LS and MAIA), X-ray absorption spectroscopy (XAS-SB), and diffraction under extreme conditions (Xpress-SB).

The extended X-ray energy range will allow the SYRMEP-LS beamline, dedicated to multiscale imaging and tomography for life sciences, to be employed in clinical imaging programs, including the study of human lung pathologies through phase contrast techniques. For this purpose, a dedicated patient room extending outside the experimental hall and connected with the beamline will be constructed. The MAIA beamline will complement SYRMEP-LS and focus on high-speed imaging and tomography for materials science; 4D CT will be employed to investigate dynamic processes in geomaterials, ceramics, and metallic alloys, with in situ and operando sample setups available. The XAS-SB beamline will explore new XAS science with very hard X-rays. Additional techniques such as diffraction and macro fluorescence mapping will complement the available methods. The Xpress-SB beamline will offer tools for diffraction, single crystal diffraction, and PDF characterization for samples at high pressure/high temperature, in response to the increasing demand for materials characterization under extreme conditions.

Additionally, three new beamlines will use radiation produced by in-vacuum undulators (IVU), capable of generating X-rays with energies up to 16 keV using a 5.2 mm gap. Such devices will significantly enhance the capabilities of the facility for X-ray fluorescence, protein crystallography, and SAXS applications by providing smaller photon spots, higher brightness, and an extended coherence range. New beamlines include µXRF, in collaboration with IAEA, µXRD, in collaboration with IIS, and a high-brilliance SAXS beamline (HB-SAXS), in collaboration with TU-Graz and University of Maribor. The other hard X-ray beamlines XRD1 and XAS-mW will utilize new fixed-gap wigglers positioned in the short straight sections, while a high-flux SAXS beamline (HF-SAXS), in collaboration with TU-Graz and MCX, will utilize the upgraded SCW.

The µXRF beamline in particular will feature a micron-sized spot at the sample stage, which will allow micro spot XRF/XAS, 3D XRF mapping, and full-field XANES. Scientific applications will range from environmental science to cultural heritage, and from earth and planetary to materials science. The µXRD beamline, dedicated to macromolecular crystallography, will feature a reduced beam size in the micron range, expanding MX capabilities at Elettra to the analysis of small crystals. The beamline will be a pivotal component of the Elettra 2.0 integrated structural biology platform, which will include a new cryoEM facility, developed in collaboration with CNR, and a major upgrade of the protein expression and crystallization user facility. The HB-SAXS beamline will complement the existing HF-SAXS beamline and its small spot and high brilliance will also allow coherence-based techniques such as high-energy ptychography, XPCS, and SAXS tomography.

Elettra 2.0 will also host beamlines operating in the soft to tender-X-ray range, namely the TwinMic imaging beamline, the coherent diffraction imaging beamline (CDI), BL1 for near ambient pressure XPS, and APE-TX, marking another significant upgrade to the current facility, where no such beamlines exist. These beamlines will offer X-ray imaging, ptychography, photoemission, absorption spectroscopies, XMCD, coherent diffraction, and scattering spectro-microscopy in the 0.5–6 keV energy range. The high degree of coherence provided by Elettra 2.0 in this energy range will be fully exploited by these beamlines and associated characterization tools. For example, the APE-TX beamline will broaden the facility offerings in techniques such as hard X-ray photoelectron spectroscopy, including core level and valence band analysis, and XAS/XMCD. A special end station will be dedicated to ambient pressure XAS experiments.

The new CDI beamline, that will receive the light from an undulator in a long straight section with full control of light polarization, will feature an in-vacuum scattering and nano-diffraction station fully exploiting the enhanced coherence of the beam.

The other three beamlines operating in the tender X-ray range will receive radiation from APUs. The APE-TX beamline, in particular, will exploit an elliptically polarizing APU (EP-APU) installed in one of the short straight sections available at Elettra 2.0.

Due to the comparatively low ring electron energy, generating synchrotron radiation particularly suitable for VUV and soft X-ray-based characterization techniques, more than half of the beamlines in the current facility operate in this energy range. At Elettra 2.0, operating at 2.4 GeV, the number of such beamlines will decrease from 17 to 14 and include Nanospectroscopy, NanoESCA, ESCA Microscopy, SuperESCA, BEAR, Spectromicroscopy, BaDElPh, MOST, CUBES (formerly known as Materials Science), BL1 (formerly known as ALOISA), BL2 (formerly known as BACH/VUV), APE-HE, and APE-LE. Some of the existing beamlines will be replaced by new ones, while others will be upgraded to take full advantage of the new beam features.

Various types of undulators, installed in long and short sections, providing light with different features in terms of photon range and polarization, will generate photons for most of these beamlines. Only two of the VUV and soft X-ray beamlines (BEAR and CUBES) will use standard bending magnets of Elettra 2.0 as photon sources to offer characterization tools such as photoelectron emission and absorption-based techniques. The IR-THz beamline currently present at Elettra is also expected to be maintained in the new facility. With two separate branches (SISSI bio, SISSI mat) focusing on bio and materials sciences, respectively, this beamline will use IR and THz radiation from Elettra 2.0 for MIR-FIR microscopy and nanoscopy and IR/THz condensed matter spectroscopy and imaging.

Figure 2 illustrates the beamline portfolio that will be available at Elettra 2.0 upon project completion, indicating the main available techniques and photon sources. In view of the increase in the cost of materials and energy, as well as in the inflation rate in the last few years, we should caution the reader that the time to complete the construction of the 12 new beamlines and the upgrade of the other 20 existing beamlines will depend on the available cash flow. At the time of this writing we expect, that the external user program at Elettra 2.0 will start in January 2027 with an initial set of 19 operating beamlines.

Time-resolved options at Elettra 2.0

In recent years, several beamlines at Elettra have engaged in time-resolved experiments across diverse research domains. The establishment of the FERMI free electron laser facility, has catalyzed collaborative research endeavors in this area. Elettra operates in various modes, providing different time resolution and pulse frequency for time-resolved experiments. Notably, the hybrid filling mode provides continuous filling and transient pulsed experiments with time resolution in the order of 100 ps.

Elettra 2.0 will be able to operate in the hybrid mode at 2.4 GeV, but with improved time resolution due to the characteristics of the new machine. Additionally, a novel operating mode of Elettra 2.0, involving transverse deflecting cavities (TDC) or crab cavities, is under study. This mode could deliver radiation pulses with a 0.5–5 ps FWHM pulse duration at several locations around the storage ring with repetition rates of 1 MHz. The innovative use of TDCs creates a steady-state configuration of vertically tilted bunches, providing a unique opportunity for time-resolved experiments with picosecond time resolution [8]. This mode combines the advantages of DLSR, derived from unperturbed bunches carrying the majority of the current, with the time-resolved option using tilted bunches. At the moment we are only in the process of conducting a feasibility study of TDC development, and we should emphasize that this promising option is not yet part of the Elettra 2.0 project baseline.

Conclusions

The Elettra 2.0 project was approved by the Italian Government at the end of 2017 to construct a new fourth generation synchrotron radiation source that would commence serving external users in 2027. Elettra 2.0 will be a fully transversely coherent source up to 0.5 keV-photon energy, will double the total average current, increase brightness by more than two orders of magnitude and the coherence fraction by 60 times at 1 keV, as compared to the current source.

The beamline program for Elettra 2.0 aims at maintaining a diversified beamline portfolio to allow experiments across a broad spectrum of photon energies, from a few tens of eV to several tens of keV, while substantially increasing the number of beamlines operating in the hard-X-ray range and expanding imaging and tomography applications. By rationalizing the available space in the experimental hall and optimizing the enhanced six-bend achromat lattice and exploiting the additional short straight sections on the arcs alongside the long straight sections, we will substantially increase the number of beamlines compared to the current laboratory. Construction of 12 new beamlines and major upgrades to existing ones is slated for implementation.

The enhanced coherence of Elettra 2.0 will have a profound impact on imaging, especially in techniques such as coherent diffraction imaging, ptychography, and XPCS. These methods make use of the coherent X-ray beams to create speckle diffraction patterns, enabling phase-contrast tomography for low-dose analyses of weakly absorbing bio-matter. The significant enhancement of coherence in the soft and medium-hard X-ray range at Elettra 2.0 will allow new beamlines to approach wavelength-limited spatial resolution with chemical specificity and improved temporal resolution. Concurrently, the ongoing development of more efficient and faster photon and electron detectors, coupled with new sample environments and delivery systems, will amplify efforts to fully capitalize on the opportunities offered by the new DLSR source.

The high brightness and substantially reduced horizontal beam size provided by Elettra 2.0 will benefit various spectroscopy

Beamlines	Photon source	Photoelectron emission	Imaging	Scattering	Reflection/ Emission	Absorption	Diffraction	Lithography
Nanospectroscopy	EPU	✓	✓			✓		
NanoESCA	EPU	✓	✓			✓		
TwinMic	APU		✓		✓	✓		
ESCA Microscopy	LPU	✓	✓					
SuperESCA	LPU	✓				✓		
BEAR	BM	✓		✓	✓	✓		
Spectromicroscopy	F8	✓	✓					
BaDElPh	F8	✓						
XAS-SB	SBM					✓	✓	
MAYA	SBM		✓					
MOST	EPU AP-EPU	✓		✓	✓	✓		
XRD1	mW						✓	
µXRD	IVU						✓	
CUBES	BM	✓				✓		
XAS-mW	mW				✓	✓	✓	
CDI	EPU		✓	✓			✓	
BL1 (NAP-XPS)	APU	✓				✓		
BL1 (ALOISA)	APU	✓				✓		
µXRF	IVU				✓			
Xpress-SB	SBM						✓	
BL2 (BACH)	EPU	✓		✓	✓	✓		
BL2 (VUV)	EPU	✓		✓	✓	✓		
SISSI-Bio	BM		✓		✓	✓		
SISSI-Mat	BM		✓		✓	✓		
APE-HE	EPU	✓				✓		
APE-LE	EPU	✓				✓		
DXRL	BM							✓
HB-SAXS	IVU			✓			✓	
APE-TX	AP-EPU	✓				✓		
HF-SAXS	SCW			✓			✓	
MCX	SCW						✓	
SYRMEP-LS	SBM		✓					

Figure 2: Beamlines expected to become operational at Elettra 2.0. Hard X-ray beamlines are denoted in black, beamlines operating in the UV to soft X-ray range are denoted in red, beamlines operating in the soft to tender X-rays are denoted in purple and the IR/THz beamlines are denoted in orange colour. For each beamline, we list the main experimental techniques that will be available to users.

techniques. This includes shorter acquisition times for operando characterizations, enhanced spectral resolution for precise speciation, monitoring of weak signals for photon-hungry experiments (e.g., spin-resolved ARPES, dilute or small samples), and improved spatial resolution through focusing optics, offering nano-PES, nano-ARPES, nano-XAS, nano-XRF spectroscopy, and spectro-imaging options. When the user program of the new Elettra 2.0 source will begin in January 2027, the facility will feature a set of new and upgraded beamlines, fully harnessing the increased brightness and coherence of the new light source. ■

Disclosure statement

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No potential conflict of interest was reported by the authors.

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