

ELETTRA 2.0 - THE NEW FRONTIER OF SYNCHROTRON RADIATION

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Abstract

With the definitive shutdown of Elettra on July 2, 2025, a new chapter opens for scientific and technological research in Trieste. After thirty-two years of activity with excellent results, Elettra, Italy's 3rd generation light source is handing over the baton to Elettra 2.0, a fourth-generation light source based on an ultra-low emittance and high transverse coherence storage ring, designed to address the challenges of contemporary science. From advanced materials science to biology and medical applications, the new facility will provide researchers with access to vastly enhanced high-resolution three-dimensional imaging, ultra-high-resolution spectroscopies (such as XAS, XPS, and RIXS) and time-resolved techniques on the picosecond scale. In the paper the project is presented including information on the old machine removal, the present installation progress as well as the future plans on short pulses and energy sustainability.

INTRODUCTION AND OVERVIEW

Elettra 2.0 features several critical technological advancements that distinguish it from its predecessor:

1. **Storage Ring Upgrade:** The core of the Elettra 2.0 project is the replacement of the existing storage ring with a new low-emittance ring [1-7]. This will significantly reduce the present beam emittance by a factor of 50, resulting in a photon source with much higher brilliance and coherence. The storage ring will also include initially one (with the possibility of another one later), superconducting dipole [8] with 6 T peak field for hard X-ray imaging for the new SYRMEP-LS beamline (life and material science enabling *in vitro* imaging for high resolution morphological studies and clinical application to humans) giving 2×10^{13} ph/s at 60 keV and extending the photon energy to 140 keV at lower flux, about 10^{11} ph/s.

The design is compatible with providing in the future simultaneously short pulses as short as 0.5 ps (FWHM) using superconducting deflecting RF cavities for time-resolved experiments requiring high repetition rate and standard single bunch charge, while preserving the transverse coherence

2. **Beamline Enhancements:** Elettra 2.0 will introduce 10 new beamlines to fully exploit the features of the upgraded storage ring and upgrade many of the existing ones while 8 old ones are removed. The total number of the beamlines are increased to 32 (from 28 of the old machine) whereas a clear shift towards tender and hard x-rays has been decided. New beamlines will include several ones specifically designed for enhanced capabilities in X-ray

absorption spectroscopy, photoemission spectroscopy, high-resolution diffraction, coherent diffraction imaging and time-resolved experiments resulting in an enhanced ability to capture ultrafast processes opening thus new possibilities in studying dynamic systems such as chemical reactions and phase transitions in materials.

The new capabilities of Elettra 2.0 will enable research in several scientific and industrial fields like nanotechnology and materials science, quantum materials and pharmaceuticals and health sciences.

The Elettra 2.0 upgrade follows a well-defined project schedule, with several major milestones:

Decommissioning of the old storage ring and installation of the New Storage Ring [9]: This phase began in July 2025 and completed in January 2026 including the complete removal of the old machine that has been stored in a dedicated prefabricate building for radioprotection measurements. The tunnel and service area are refurbished to be ready for the new machine installation. The decommissioning did not include the injectors (100 MeV linac and 2.5 GeV booster and transfer lines) that are refurbished and will be reused. The new storage ring installation started in April 2026, with completion expected by December 2026.

Beam Commissioning and User-mode Operations: Commissioning with beam is scheduled to start in January 2027. In the first trimester of 2027, the new ring and an initial set of 15 beamlines are programmed to be operational and available to researchers whereas all 32 beam lines will be gradually available until the end of the project in 2029.

The project also includes many infrastructural works like renewing the air-condition and cooling systems as well as the electricity plant on site and other, mainly maintenance, works.

MACHINE DESCRIPTION

The enhanced symmetric six bend achromat (S6BA-E) lattice (Fig. 1) has been uniquely designed to meet all experiment / user requirements. The new ring has the same circumference as before, i.e. 259.2 m and consists of 24 symmetric arcs rendering a 12-fold symmetry, producing 12 long straights and 12 short straights sections. Each arc consists of 3-unit cells of the TME (theoretical minimum emittance) type i.e. :

- 3 dipoles, of which one at 0.8 T with vertical field gradient and two with combined transverse (< 22 T/m), and longitudinal gradient (1 and 1.46 T)
- 7 quadrupoles (< 50 T/m) four of which are shifted at 5.16 mm to give the required reverse-bend angle of -0.4 deg each
- 10 combined sextupoles (< 4500 T/m²) (4 with correctors, 2 harmonic with correctors and 2 with skew quadrupole coils)

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- 1 combined multipole (octupoles with corrector coils)
- 1 combined multipole (octupole with quadrupole coils)
- 1 pure corrector
- 3 correctors coils for fast orbit correction, cut-off at 6 kHz

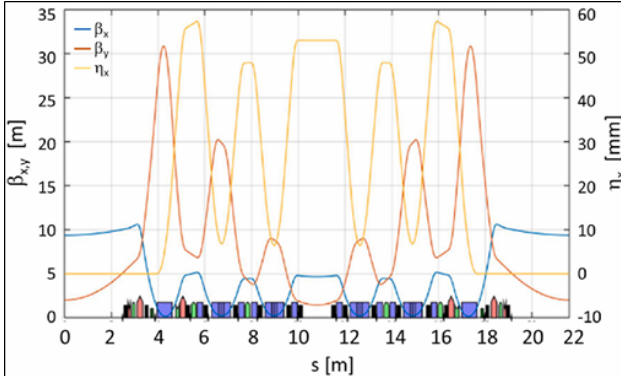


Figure 1: Elettra 2.0 S6BA-E lattice (phase 1).

The two arcs are separated in the middle by a short straight section of 1.26 m free space. Of those twelve spaces 4 will be used for installing the 4 rf cavities, 3 will be used for instrumentation and 5 for installing 3 short fixed gap undulators and 2 1.8 T wigglers. The free useful space of the long straights sections is 4.85 m long and it is dedicated to insertion devices (IDs) and to the feedbacks.

The total number of magnets is 552 with 192 correctors of which 168 are based on multipole coils embedded in the sextupoles and 24 independent correctors on each side of the long straights. For the fast correction (fast orbit feedback at 5.5 kHz) 72 additional coils (6 per achromat) will be used. For the orbit control there are 14 BPMs (Beam Position Monitors)/ achromat for a total of 168 with additional 4 BPMs for other uses. All electronics are delivered as well as the feed-throughs [10].

The magnets [11] are specially designed with no protruding coils in the dipoles and quadrupoles, are independently powered and mostly water cooled. All magnets are delivered, measured on site [12] and are installed on their girders (Fig. 2). There are 8 granite girders for the multipoles and 6 for the dipoles per achromat for a total of 168 girders. Also the machine basements are made of granites.

The vacuum chamber is rhomboidal with 17x27 mm internal dimensions. It is mainly made out of copper with some parts in aluminum (long straights) and also stainless steel (chambers in the dipoles). Most parts of the chamber are covered with 250 nm NEG (Non-Evaporable Getter) on the average [13].

The power supplies [14] are reduced into 3 families for redundancy and simplicity. There are 74 unipolar 300 A for the dipoles, 504 bipolar 100 A for the multipoles and 676 bipolar 25 A for the correctors. All types of power supplies are delivered and ready for installation.

The same injector, consisting of a 100 MeV linac, a 2.5 GeV booster and a booster to storage ring transfer line, will be used also in Elettra 2.0. An injector upgrade program is running [15]. Due to the large dimensions of the beam coming from the booster (140 nm rad at 2.4 GeV) no pulsed multipole can be employed and the injection scheme will be similar to the previous machine, i.e. off-axis injection with a beam separation of 4 mm. The injection will be performed using the emittance swap technique having an efficiency $\geq 97\%$.

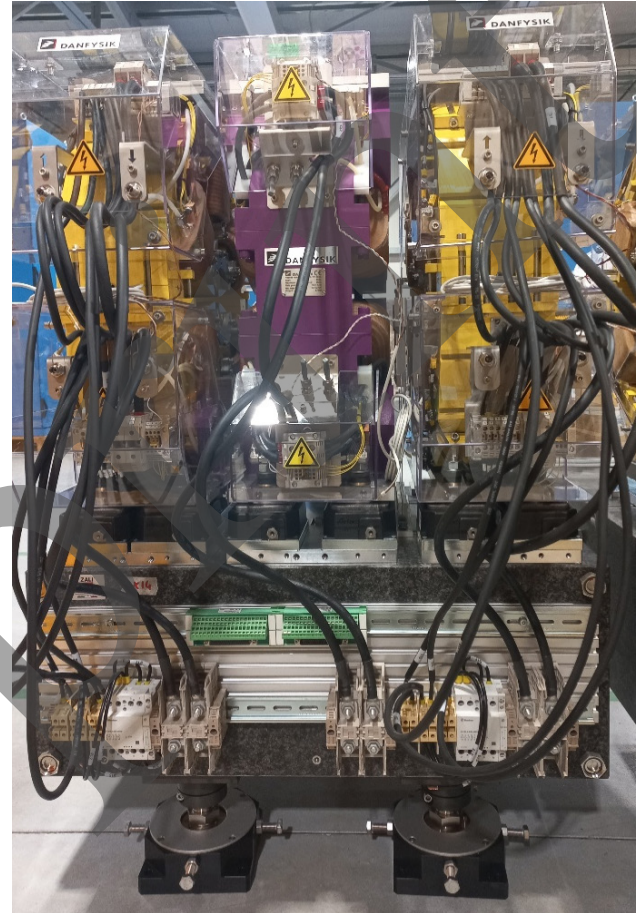


Figure 2: One quadrupole and 2 sextupoles on a girder.

For the RF system [16-17], the four Elettra 500 MHz RF cavities will be re-used. Each cavity will be installed in a short straight section and each one will be powered by a 130 kW solid state amplifier (SSA). All SSAs are already installed and already operated with the previous machine. It is planned to replace the cavities with HOM-less ones in the near future.

SOME MACHINE PHYSICS DETAILS

The commissioning will start with phase 1 optics (Fig. 1) with working point (32.30, 9.16), this optic has a rather large horizontal beta function in the long straights of 9.5 m while in the phase 2 optics to be used later in operations this beta will be reduced to 6.3 m (33% reduction) with a working point (33.30, 9.16). The natural normalized chromaticity (-71, -68) is corrected to +2 for both planes. The dynamic aperture (DA) including all (errors,

chambers, IDs) is about ± 6 mm horizontally and ± 2 mm vertically permitting off axis injection [18-19] and at the same time permitting the tilted bunches (in case of installing crab cavities) having a vertical projection of ± 1.2 mm.

A passive superconductive third harmonic cavity (S-3HC) lengthens the bunch for stability and lifetime. The intra-beam scattering without the effect of the S-3HC at 400 mA will increase the emittance from 212 to 275 pm-rad (30% increase) while, including the effect of the S-3HC, the emittance will increase to 235 pm-rad (11% increase).

The impedance budget is comparable to that of the previous machine, being about 0.85 Ohm longitudinal (about 0.24 Ohm effective) and 564 kOhm/m transverse giving a tune shift of about -0.8 kHz/mA (Elettra had -0.6 kHz/mA).

The single bunch microwave threshold is about 2.5 mA when CSR (Coherent Synchrotron Radiation) is included and the TMC (Transverse Mode Coupling threshold) results at about 4 mA. Detailed studies have been performed and still are ongoing for exact impedance estimations and instability thresholds using different simulation programs [20-22].

The total longitudinal loss factor when the effect of the third harmonic cavity is included, is 13.5 V/pC giving a parasitic power loss of 4.7 kW at 400 mA.

The average Touschek lifetime, including errors and all, is about 4 h with 1 mA/bunch, 2 MV total rf voltage and 5% coupling, while including the effect of S-3HC it becomes 12 h for a factor of three bunch lengthening resulting from an exact study of the transient beam loading effects [23], using a code developed and calibrated on the previous machine.

FURTHER DETAILS

The 3-D detailed design including all insertion devices and front ends is completed and frozen. In Fig. 3 the view of an achromat is shown together with the girder configuration [24].



Figure 3: 3D view of an achromat with IDs (long and short) and a rf cavity and a front end.

Elettra 2.0 will serve up to 32 beamlines. Amongst the new beamlines, except the SYRMEP-LS there is a coherent diffraction imaging (CDI) and three new micro-spot beam lines that the previous machine could not support.

To meet the requested performance, in-vacuum undulators (IVU) of 5 mm aperture will be installed and provide the 7th, 9th, 11th and 13th harmonics with the required flux of 10^{14} ph/s/0.1%bw on the sample and

energy range, while the brilliance is $> 10^{21}$ ph/s/mm²/mrad²/0.1% BW (Fig. 4) at 10 keV.

Some already existing IDs including the superconducting 3.5 T wiggler will be reused. Also short IDs i.e. 2 mini wigglers and 3 undulators being already in production will be installed in the short straight sections [25-26].

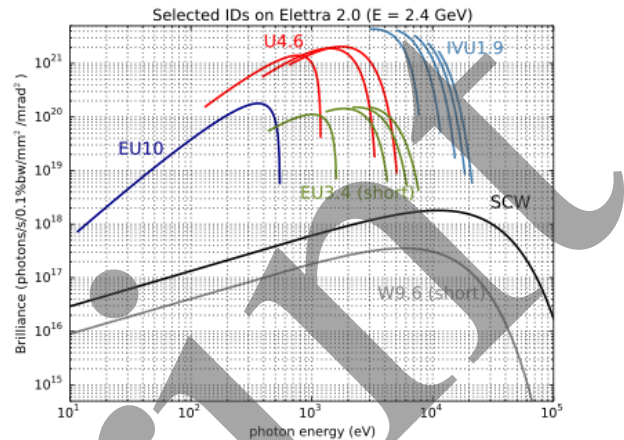


Figure 4: Old and new IDs brilliance.

Regarding the short pulse option, the use of crab cavities will allow both long pulses at 400 mA for the majority of the beamlines plus a short photon pulse from a tilted 2 mA bunch for the beamline(s) that request time resolved capability [27-28]. Depending upon the position of the beam line along the ring circumference the effective tilted bunch can give photon pulses between 0.5 to 10 ps FWHM.

The project organization is well structured and is divided mainly into 5 areas dedicated to machine, beam lines, infrastructures, executive management and removal and installations, the latter being an area of particular importance due to the fact that the new machine and most beamlines will replace the old ones. Already two temporary buildings are constructed: one that already stores the old machine components and the other one providing space for the assembly of the new machine and beamlines. A very detailed scheduling of all activities has been developed including detailed activities for the removal and installation works.

Elettra 2.0 will consume about 20 % less energy than the previous machine. Future measures to reduce the CO₂ footprint include getting energy from renewable sources (already a financed project runs for implementing a photovoltaic plant) and also reducing consumption by using permanent magnets (a task that initially is impossible due to the requirement for two operating energies for some years).

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