ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOXD2

ELETTRA 2.0 – ITALY's LIGHTSOURCE FOR SCIENCE AND OUTREACH

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Abstract

An overview of the project status of the future Italian 2.4 GeV 4th generation light source Elettra 2.0 that will replace the existing 3rd generation light source Elettra is presented, including challenges and perspectives in the design and construction of such light sources. Elettra 2.0 will be the ultra-low emittance light source that will provide ultra-high brilliance and coherence and at the same time also aims to provide very short pulses for time resolved experiments. The discussion includes the technical challenges requiring specific R&D studies, for example on injection schemes, high performance magnets, vacuum, diagnostics for stability, feed-backs, harmonic cavities, etc. The upgrade also addresses on the request from the established user community to minimize the duration of beam-time interruption, imposing the need of a careful organization and planning of all the phases of the project, from the removal of the old machine to the installation and successful commissioning of the new one.

INTRODUCTION

Located on the outskirts of Trieste, Italy, Elettra operates for users since 1994 being the first third generation light source for soft X-rays in Europe. During those 29 years, many improvements were made in order to keep the machine updated and therefore competitive with the other more recent and modern light sources already designed to operate in top-up. Following the successful set in operation of the full energy injector in 2008, after 14 years of energy ramping, Elettra established top-up operations [1] in spring 2010, although not originally designed for it. Operating in top-up proved to be, and still is, very beneficial for the machine [2]. A passive superconducting third harmonic cavity (3HC) lenghens the bunch by a factor of three for stability and lifetime.

Elettra operates 24 hours/day, seven days a week delivering more than 5000 hours/year of synchrotron light from infrared (IR) to hard x-rays to 28 beam lines. Ten of them are served by bending magnets. Two beam-lines use light from a superconducting 49-pole, 64-mm period, 3.5 T wiggler.

Many types of insertion devices are installed such as planar, polarizing, superconducting including canted APPLE II type undulators occupying all the eleven available long straights while also one dispersive short straight is used accomodating a short, 1 m long double APU (Adjustable Phase Undulator) insertion device serving the TwinMic beam line. Aditionally another APU of variable polarization of 132 mm period will serve the new MOST beam line (optimized for energies from 10 to 2000 eV) for energies between 10-200 eV.

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The present machine consists of a 100-MeV linac, a 2.5 GeV booster and a 2.0/2.4 GeV storage ring with emittance of 7/10 nm-rad. For about 75% of user-dedicated time Elettra operates at 2 GeV while for the remaining 25% it operates at 2.4 GeV, being the only facility to operate at two energies (both in top-up). The main operating modes are multi-bunch with a dark gap of 42 ns and hybrid i.e. multi-bunch with one (for time resolved experiments) or two single bunches (distant 40 ns in a dark gap of 120 ns for pump and probe experiments). In 2022, hybrid mode user beam time amounted to 30 % of the total user beam time. The operating intensities are 310 mA at 2 GeV and 160 mA at 2.4 GeV with 5 mA single bunch(es) added when in hybrid mode.

The total availability, i.e. including the power outages, is 97% and the Mean Time between Failures (MTBF) is higher than 80 hours. The top-up availability to the total user scheduled time for 2022 was 99 %.

Elettra is a user facility attracting more than 1000 experimental proposals per year from more than 50 countries. In order to keep the light source competitive for synchrotron research and enable new science and new technology developments, a diffraction limited storage ring Elettra 2.0 will replace Elettra.

ELETTRA 2.0: MACHINE OVERVIEW

Since 2014 discussions with beamline responsibles, users and partners took place in order to define the requirements of the new machine described in a series of papers [3-11] resulting to a preliminary but otherwise complete Conceptual Design Report (CDR) [8]. Since 2017 a series of workshops with the users and partners established some new and final requirements. Thus, it has been decided to operate mainly at 2.4 GeV while letting open the possibility to operate for some time and for a limited percentage of user time also at 2 GeV in order to allow some time to the partners to upgrade their beam lines. It has also been requested to let open the possibility of creating short pulses as small as 0.5-1 ps (fwhm) for time resolved experiments using vertically deflecting (crab) cavities that are planned to be installed in section 2 of the ring. All other long straight sections will be occupied by insertion devices with the exception of the injection straight. It was also requested to increase the intensity to 400 mA, the available slots for insertion devices and to install 3 super-bends and 3 in vacuum undulators. The constraints were to keep the same circumference, to keep the present injection scheme and to minimize the dark time to 18 months.

The Elettra 2.0 project was approved by the Italian Government in 2017 and definitely confirmed in 2019. According to the current schedule the new machine will start serving the users in January of 2027. Since some of

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the original requirements, as appeared in the CDR, have changed (for example increase of the operation energy from 2 to 2.4 GeV) based on the new revised requirements an enhanced version of our S6BA (symmetric six bend achromat) was produced namely S6BA-E (symmetric six bend achromat-enhanced), see Fig.1, by using longitudinal gradient (LG) dipoles (Fig. 2) and reverse bends. Thus the optics is not purely of multi-bend type but is also using dispersion minimizers to further reduce the emittance. With that we were able to achieve a factor of 47 in emittance reduction compared to the present machine emittance, that can produce up to 3 orders of magnitude brilliance increase and at the same time a factor of 60 higher coherence at 1keV. A new Technical Design Report (TDR) was produced and is available since June 2021 [12].

SCIENCE DRIVERS

The increase in brightness of almost 3 orders of magnitude and coherence of about 60 times will have a strong impact on pushing the lateral resolution down to a few nm scale range, since in all experiments using focusing optics this translates directly into an increase in focal flux density. This also opens the possibility of performing all types of spectroscopies with nano-sized photon beams (e.g., nano-PES, nano-ARPES) approaching the X-ray imaging spatial resolution of a few nm. Complemented with nano-scale IR and VUV microscopy, will allow unprecedented investigations of structure and dynamics in three and four dimensions with variable probing depths.

The high coherence of the source (per square nanometre comparable with the present one per square micrometre) will open unique opportunities for coherence-hungry methods. Coherent Diffraction Imaging (CDI) with chemical specificity, its scanning mode ptychography and closely related X-ray photon correlation spectroscopy (XPCS) will approach the wavelength-limited spatial resolution with chemical specificity and improved temporal resolution. In such experiments information can be obtained about (i) the size and shape of the individual mesoscopic constituents of the overall sample structure; (ii) the local coordination environment of different types of atoms in sub-units on the surface, at the interface or in the bulk; (iii) the interactions or real-time changes in the structure and chemical state of the constituent units.

Increasing the brightness and coherence will also have a direct impact on the achievable temporal resolution for exploiting processes in real time of material fabrication and functioning. All spectroscopic, ‘classical’ diffraction and scattering methods with gain from the brightness, whereas in the case of e.g. XPCS, the major gain will derive from the coherence, since the time resolution - proportional to the square of the coherent flux – will be limited only by the electron bunch length (~ 50 ps FWHM including the effect of the bunch lengthening from the 3HC) at 400 mA intensity.

It should also be noted that although the 21st century has seen major developments in the area of high-harmonic generation (HHG) and X-ray free-electron laser (XFEL) sources, DLSRs remain indispensable. This derives not only from capacity considerations - i.e., the limited number of beamlines that HHG and XFEL sources can serve as compared to DLSRs - but also from quality considerations. Using diffraction-limited storage rings is not only complementary, but also absolutely necessary because of the significantly higher repetition rate (>100 MHz) available at DLSRs as compared to the present HHG and FELs, together with the higher stability in intensity, wavelength and bandpass from pulse to pulse. The high average flux distributed over many electron bunches is highly beneficial for photon- and coherence-hungry techniques allowing a better handling of undesired effects in experiments due to a high ionization rate, for example space-charge problems in electron detection and radiation-induced sample damage, problems that cannot be overcome using the full power of FEL pulses.

Chemical, biological and physical processes are dynamic; thus, researchers must monitor their activity at multiple time scales. Picosecond dynamics is of paramount importance in biological, organic and inorganic processes and condensed matter systems. There is therefore a compelling argument to develop synchrotron sources complementary to FELs, producing picosecond electron bunches that will have advantages such as wide and continuous tunability, polarization control, MHz repetition rate and higher photon flux compared to slicing.

The installation of crab cavities (although not in the main path of the project) can produce a subset of tilted short bunches with FWHM in the single picosecond range (see Fig. 7) while letting the untitled bunches to have a total intensity of 400 mA.

MACHINE CHARACTERISTICS

The enhanced symmetric six bend achromat (S6BA-E) lattice (Fig. 1) has a total length equal to that of the present Elettra, i.e. 259.2 m and is made of 24 symmetric arcs , 12 long straights and 12 short straights sections, it has a 12-fold symmetry. 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) (Fig. 2)
- 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/m^2) (4 with correctors, 2 harmonic with correctors and 2 with skew quadrupole coils)
- 1 combined multipole (octupoles with corrector coils)
- 1 combined multipole (octupole with quadrupole coils)
- 1 pure corrector

The working point is (33.25, 9.2-9.4) and the natural normalized chromaticity (-71, -68) corrected to +2 for both planes. The two arcs are separated in the middle by a short straight section of 1.26 m free space for installing the rf

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cavities, equipment or short undulators or wigglers while the free useful space of the long straights connecting the sections is 4.85 m long for installing insertion devices.

The length of the long and short straight sections can be modified without affecting the optical functions and with that choice of lengths the transverse position of the Elettra 2.0 beam lines on the long straight sections compared to the ones in the present Elettra is coincident.

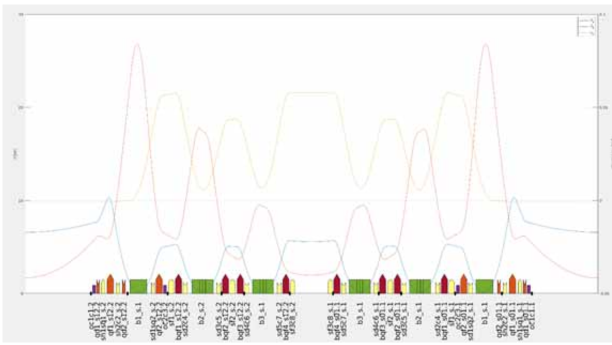

Figure 1: Elettra 2.0 S6BA-E lattice.

The total number of magnets is 552 with 192 corrector coils and 171 BPMs. For the fast correction (fast orbit feedback) 72 additional coils (6 per achromat) will be used.

The magnets [13] are specially designed and in the dipoles and quadrupoles the coils do not protrude. They will be powered independently, measured on site [14] and are mostly water cooled.

The bare emittance is 212 nm-rad (149 pm-rad at 2 GeV) at 1% coupling i.e. a factor of 50 reduction from the present machine and will increase the brilliance up to 2-3 orders of magnitude at 10 keV or above and about 36 times at 1 keV compared to that of the present machine. Also, the coherence level will be increased by a factor of 60 at 1 keV. The twiss functions of the lattice are shown in Fig. 1.

At full coupling, the emittances become respectively 100 and 70 pm-rad however there is no need or request to operate at full coupling.

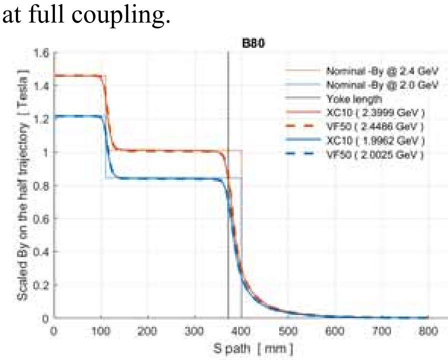

Figure 2: LG half-dipole magnet profile.

Another interesting point of the lattice is that, due to its low momentum compaction of 1.3e-4, it can naturally provide a short stable electron bunch below 14 ps (fwhm) for 100 mA total current and acceptable lifetime of 12 h, but that mode doesn't satisfy user needs for the high intensity of 400 mA.

MACHINE PHYSICS DETAILS

The dynamic aperture (DA) including all (errors, chambers, ids) is about ±6 mm horizontally and ±2 mm vertically permitting off axis injection and at the same time permitting the tilted bunches (in case of installing crab cavities) having a vertical projection of ±1.2 mm. Simulations have shown that efficient orbit corrections are achieved with < 1 mrad kick of the correction coils. The effects of the insertion devices on the beam dynamics has been studied using kick maps [15]. The analysis shows that the dynamic aperture (Fig. 3) can be recovered by a small adjustment of the horizontal tune.

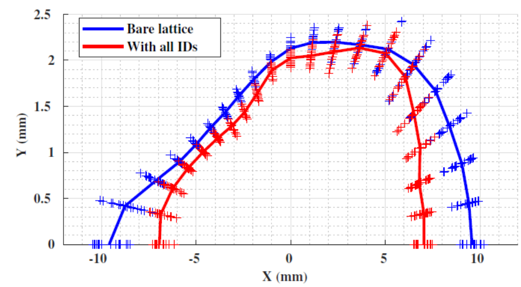

Figure 3: Dynamic aperture with IDs and errors.

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 vacuum chamber will be rhomboidal with 17x27 mm internal dimensions mainly made of copper with some parts in aluminum (long straights) and also stainless steel (dipole chambers). Most parts of the chamber will be covered with 500 nm NEG [16]. The impedance budget is comparable to that of the present 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 has -0.6 kHz/mA).

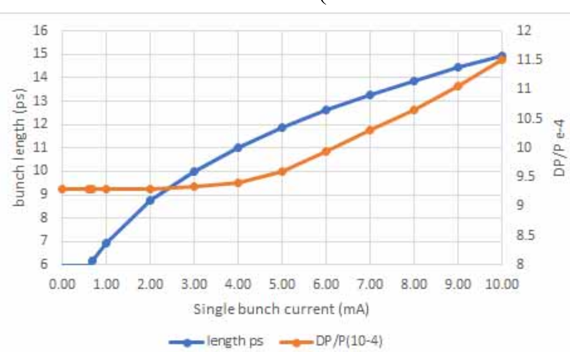

Figure 4: Bunch length and energy spread versus single bunch current.

The single bunch microwave threshold is about 3.5 mA as can be seen (Fig. 4) and the TMC (Transverse Mode Coupling threshold) about 5.5 mA. More acurate analysis for both impedances and instabilitiy thresholds is going on using different simulation programs [17-19]

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The total longitudinal loss factor is 20.2 V/pC giving a parasitic power loss at about 7 kW when the effect of the third harmonic cavity is included.

The average Touschek lifetime including errors and all is about 5 h with 1 mA/bunch, 2 MV total rf voltage and 3% coupling while including the effect of S-3HC it becomes 15 h assuming a factor of three bunch lenghtening. For an exact study of the transient beam loading effects a code has been developed [20] and calibrated on the present machine. The results confirm the factor of three bunch lenghtening at 400 mA.

FURTHER MACHINE DETAILS

The 3-D detailed design including all insertion devices and front ends is almost completed and only minor modifications are allowed. In Fig. 5 the view of an arc is shown together with the girder configuration.

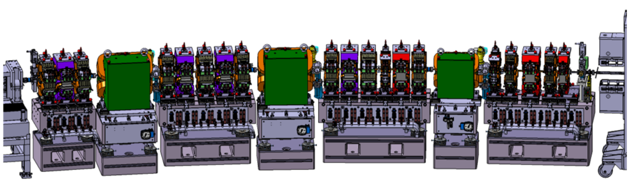

Figure 5: Elettra 2.0 arc view.

All parts of the machine are defined. All types of magnets have been specified, designed and are ordered (multipoles) or in the call for tender phase (dipoles). In the dipole and quadrupole design the coils do not protrude i.e. the useful space between magnets is not reduced by the coils since anyway the intermagnet distance varies between 50 to 130 mm.

The power supplies [21] are reduced into 3 families for redudancy and simplicity:

- A: 300 A unipolar units: 80 units (including spares), COTS (commercial of the shelf),
- B: 100 A unipolar units: 500 including spares, in-house design + COTS power part,
- C: 20 A bipolar units: 480 including spares, in-house design and special unipolar/bipolar units: 250+ units, in-house controller, Dipole B80 Trim coil, fast feedback correctors.

Prototypes for vacuum chambers, girders and many other parts are ordered expecting calls for tender in the second half of 2023 and first half of 2024 while studies on the photons absorbetrs continue [22]. Each section will have 8 girders consisting of granite slabs long from 1.2 to 1.5 m, 0.6 m large and 0.3 m thick. A mock up of a multipole section is constructed and the eigen-frequencies are analysed both experimentaly and using simulatations, finding the frequency of 44 Hz as being the closest to 50 Hz [23]. Prototyping is ongoing as well as discussions with potential manufacturers. Front-ends are defined.

Since the same injector consisting of a 100 MeV linac 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 [24, 25]. 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 present machine i.e. 4 kicker and 2+1 septa , the third septum, missing from the present machine, will be a very thin one allowing a beam separation of 4 mm. For the same reason the injection will be performed using the emittance swap techinque. The option of aperture sharing however is kept open.

A very performing BPM system (both hardware and software) is required that can detect 5% oscillations of the beam size i.e. resolution of 100 nm [26, 27]. The limit of 5% on the beam size has been defined upon discussing with the most demanding new coherent defraction beam line.

For the RF system [28], the four Elettra 500 MHz rf cavities presently in operation 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). Three SSAs have been already installed and in operation while the fourth one will be installed by the end of 2023 while for the low-level rf, a digital system will be implemented.

BEAM LINES, IDS AND SHORT PULSES

The present Elettra evolved during 29 years to 28 beamlines of which 19 are served from a large variety of insertion devices like planar, APPLE II, (both AGU and APU), superconducting, electromagnetic.

Elettra 2.0 will serve 32 beamlines, and intends to upgrade many of the already existing ones. In general 9 beamlines will keep their present position, 7 beamlines will stay in the same sector, 6 beamlines or end stations will be moved to a different sector, 8 beam lines will be removed and 10 will be new. The upgrade plan for the beam lines is divided into three phases. The first fase lasts until the start of the dark period (July 2025), the second phase is during the dark period (July 2025 to Oct 2026) and the third phase starts in 2027 until 2030. Among the new beamlines, four will be a coherent diffraction imaging (CDI) and three new micro-spot beam lines that the present machine cannot support, namely the µXRD, µXRF and HB-SAXS.

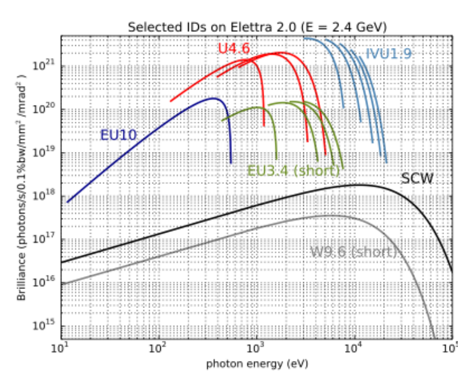

Figure 6: Old and new IDs brilliance.

To meet the requested performance, in-vacuum undulators (IVU) of 5 mm aperture will be used. Simulations show that IVUs with k_{max}=2 and 20 mm period at 2.4 GeV will provide the 7th, 9th, 11th and 13th harmonics with the required flux of 10^{14} ph/s/0.1%bw on

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the sample and energy range, while the brilliance is > 10^{21} ph/s/mm^2/mrad^2/0.1% BW (Fig. 6) at 10 keV.

We intend to reuse some already existing IDs including the super conducting 3.5 T wiggler. Also short IDs i.e. 2 mini wigglers and 3 undulators will be installed in the short straight sections. A prototype of the mini wiggler has been already constructed [29].

The hard X-ray imaging (life and material science) requires 10^{13} ph/s at 50 keV while the absorption x-ray fluorescence requires the same flux at 35 keV, and can be satisfied using three super-bends (SB) [30] of peak field at 6 T. When all insertion devices and SBs are included the emittance at 2.4 GeV reads 219 pm-rad and the energy loss due to radiation is 620 keV which for 400 mA translates to 248 kW power lost to radiation. Moving any ID field from zero to maximum changes the beam dimension by less than 1%.

In order to define well the needed radiation shileding for the beam lines, beam loss scenarios are included in the radiation (Bremsstrahlung) analysis.

Considering the short pulse option, the use of crab cavities will allow both long pulses at 400 mA for the majority of the users plus short photon pulses of few tilted bunches for the beamlines that request time resolved capability [31].

In Fig. 7 the shortest photon pulse duration and single pulse relative flux are summarized, for 10 keV photon energy. DR and IM mean drift optics and imaging optics respectively. For many beamlines the pulse durations is ≤ 3.5 ps fwhm. The minimum slit half-aperture is 5 µm in drift mode and 2 µm in imaging mode.

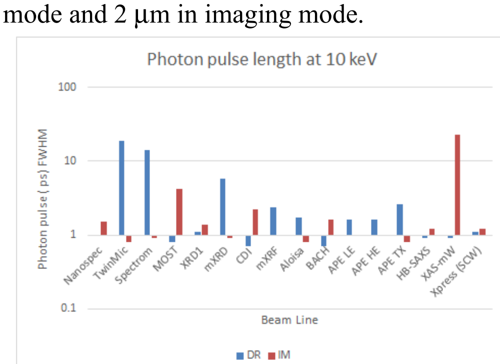

Figure 7: Pulse length at each beamline.

ENERGY SUSTAINABILITY

Elettra 2.0 will consume about 20-30 % less energy than the 3.8 MW of the present machine. Future measures to reduce the CO_2 footprint include getting energy from renewable sources (already looking for implementing a photovoltaic plant) and also reducing consumption by using permanent magnets (a task that initially is impossible due to the requirement of 2 operating energies) However when Elettra will operate only at 2.4 GeV we intend to replace the long gradient dipoles with permanent ones. The European project VADER (being the task 7.3 within I. FAST having as partners Elettra, CERN, KYMA and CIEMAT) has being created for that reason. The intent is to replace the magnets shown in Fig. 2 with permanent dipoles of a parabolic distribution field, this way a further emittance reduction of about 60% can be achieved i.e. 100 pm-rad at 2.4 GeV [32].

PROJECT MANAGEMENT

The project is structured as shown in Fig. 8 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 beamlines will replace the old ones [33, 34]. Special care is taken to provide spaces for the storage of the old machine and spaces for the assembly of the new machine and beamlines.

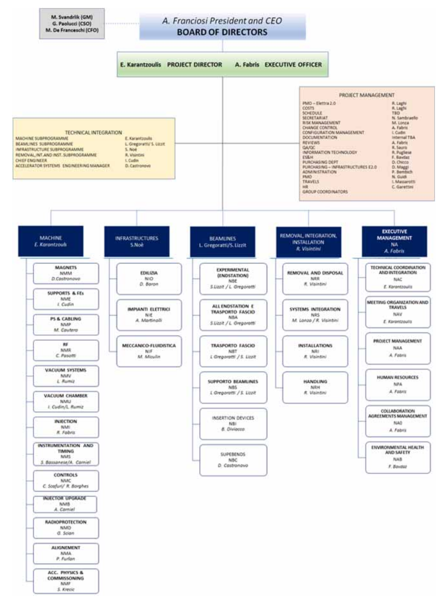

Figure 8: Elettra 2.0 WBS

The general schedule of the project is shown in the next Fig. 9 where a dark time of about 18 months is considered. The definition of the dark time duration has been agreed with the beamline scientists. Elettra will stop running in July 2025 and Elettra 2.0 will start giving light to the users in January 2027. However, it may be that in case of having already acceptable stored beam some "friendly" beam lines will start commissioning already in November 2026.

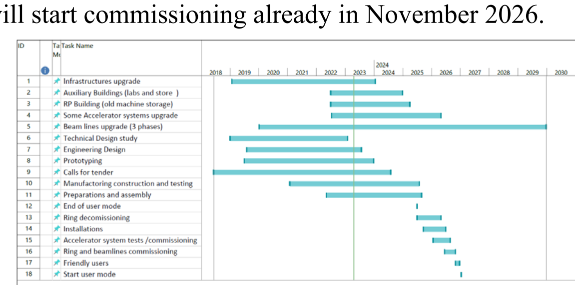

Figure 9: General schedule.

ACKNOWLEDGEMENTS

The author wish to thank the colleagues of Elettra and the community of our users for the information and support to the project. Special thanks to A. Fabris for reading and commenting the document.

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