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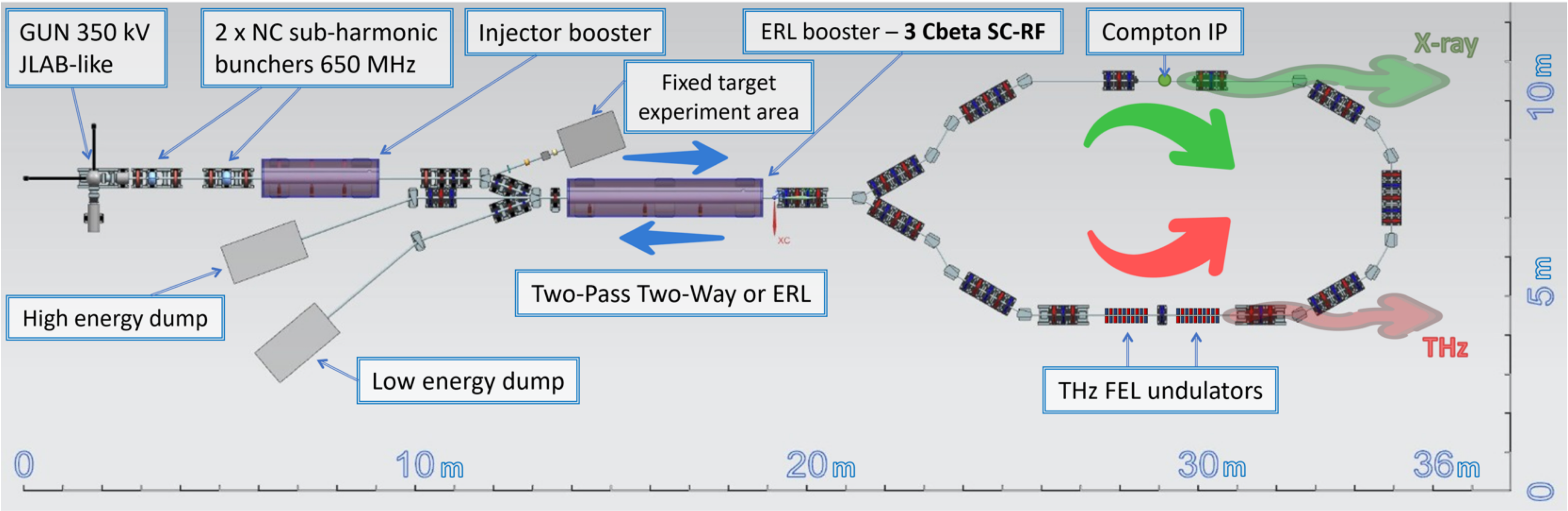
The BriXSinO proposal

Dario Giove

on behalf of the BriXSinO collaboration

ERL 2022– October 2022

The BriXSinO Proposal



BriXSinO (the acronym for **Bri**lliant source of **X**-rays based on **S**ustainable and **innO**vative accelerators) is a project for a small research infra-structure based on super-conductive accelerators with very high energy sustainability, oriented towards the frontier of high intensity in electron beams with high average power

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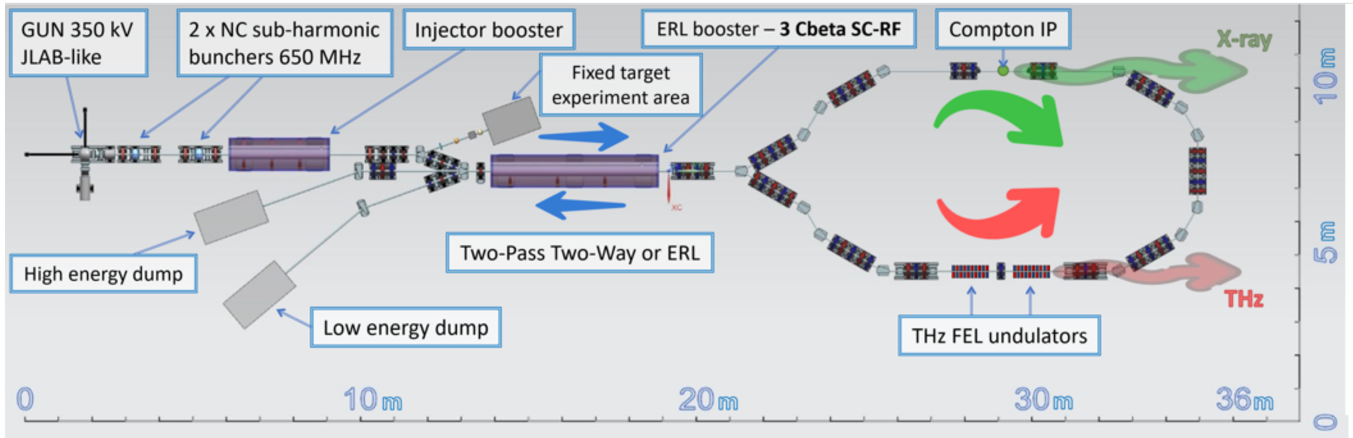
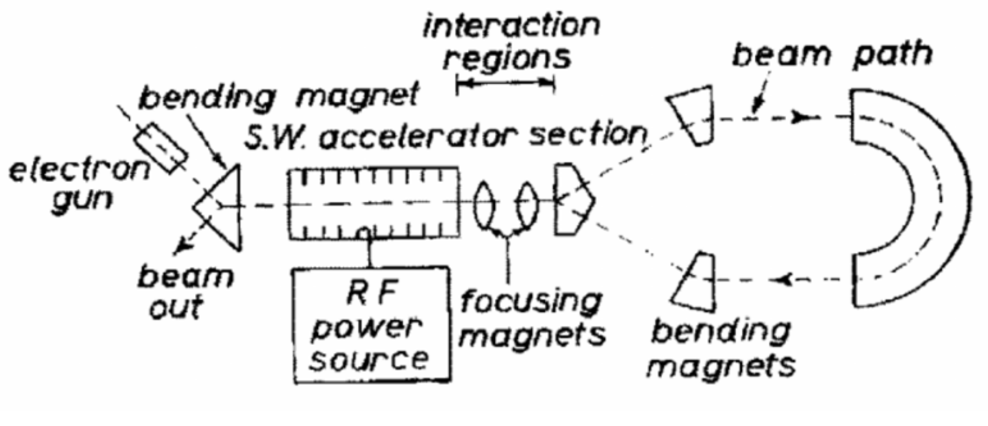
The BriXSinO Proposal





BriXSinO is a demonstrator of a new acceleration mechanism – two way in the same Linac, pursuing at the same time research of beam and machine operation in E.R.L. (Energy Recovery Linac) mode, following the original Maury Tigner's configuration of opposite way, dog-bone recirculation.

BriXSinO's mission is the demonstration of high peak and average brightness beam generation, acceleration and manipulation with large energy sustainability, as requested by the high intensity frontier.

Besides such a primary mission, that is in the mainstream of future strategies for large scale particle accelerators, **BriXSinO** will offer unique radiation beams to users of X-rays and THz, thanks to the very large expected electron beam power/brightness.

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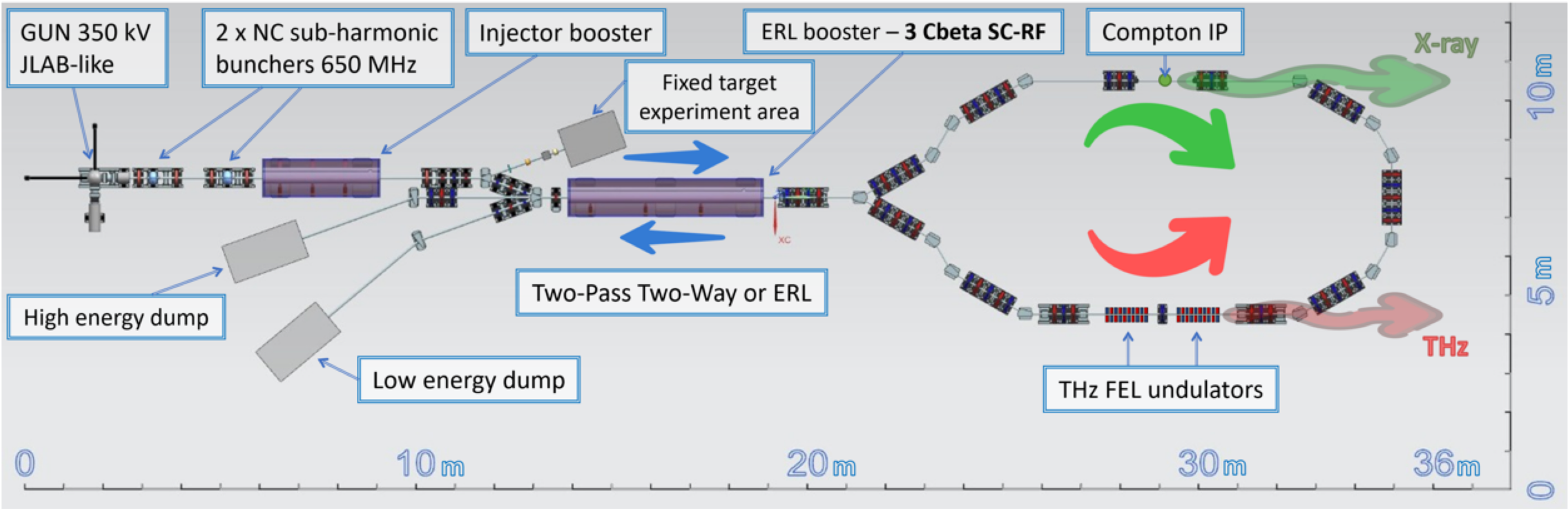

Due to constraints in the footprint available at **LASA**'s site, and budget/resources limitations typical of a demonstrator, **BriXSinO** will be restricted to modest beam energy, below 50 MeV in ERL mode, and 90 MeV in two-way mode, a minimum requirement in order to conceive a machine set-up composed of multiple accelerating sections, operated with Super-conducting CW RF cavities, within a configuration capable to effectively test two-way and E.R.L. operation modes.

Nevertheless, the beam power achieved is expected to reach up to **250 kW**, carried by **a CW 5 mA - 50 MeV electron beam**, that is **recirculated** by a proper arc-shaped beam transport line, and decelerated through the main SC Linac back down to the injector beam energy, at about 5 MeV. The challenge is to generate, accelerate, manipulate, characterize, deliver to users and recover back such a large beam power, at the same time reaching the high phase space density (*i.e.* peak brightness) requested by the **Compton source** and the **THz FEL operation**.

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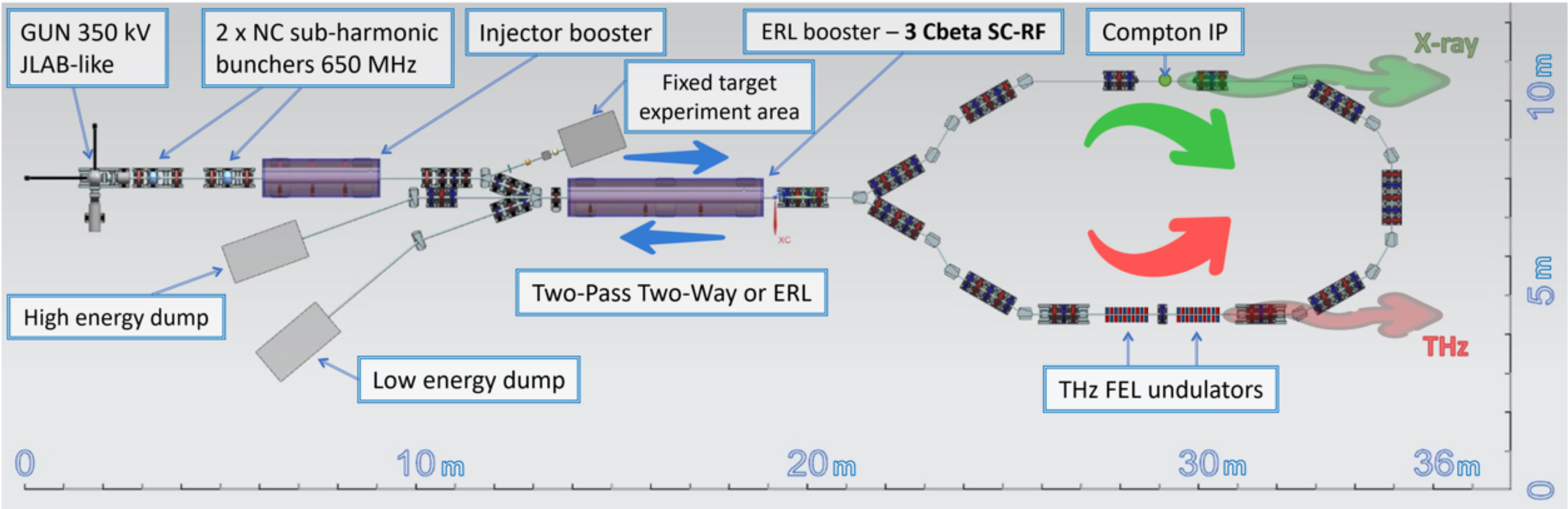

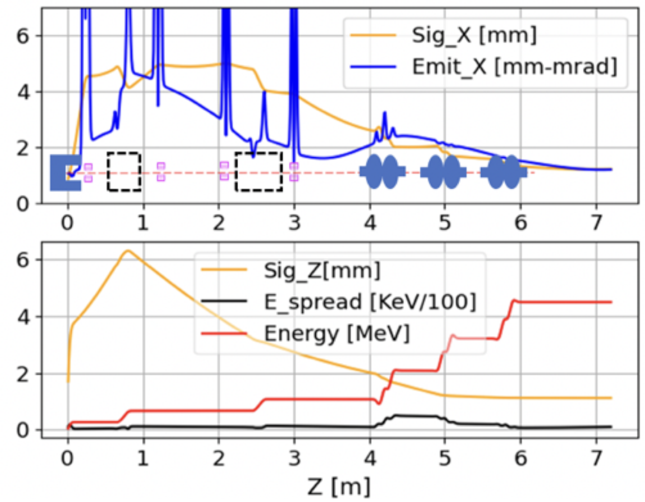

BriXSinO will reach beams with normalized transverse emittances below **1 mm·mrad**, together with **energy spreads below 0.1%**, and time and pointing stabilities typical of high brightness Linacs.

These are in fact minimum requirements on beam quality requested to drive either I.C.S. (Inverse Comtpon Scattering sources) or Free Electron Lasers (FEL): the great advantage of ERLs, compared to storage rings, is the full accessibility to beam phase space for experiments, married to beam power levels typical of storage rings, that are not achievable in standard Linacs.

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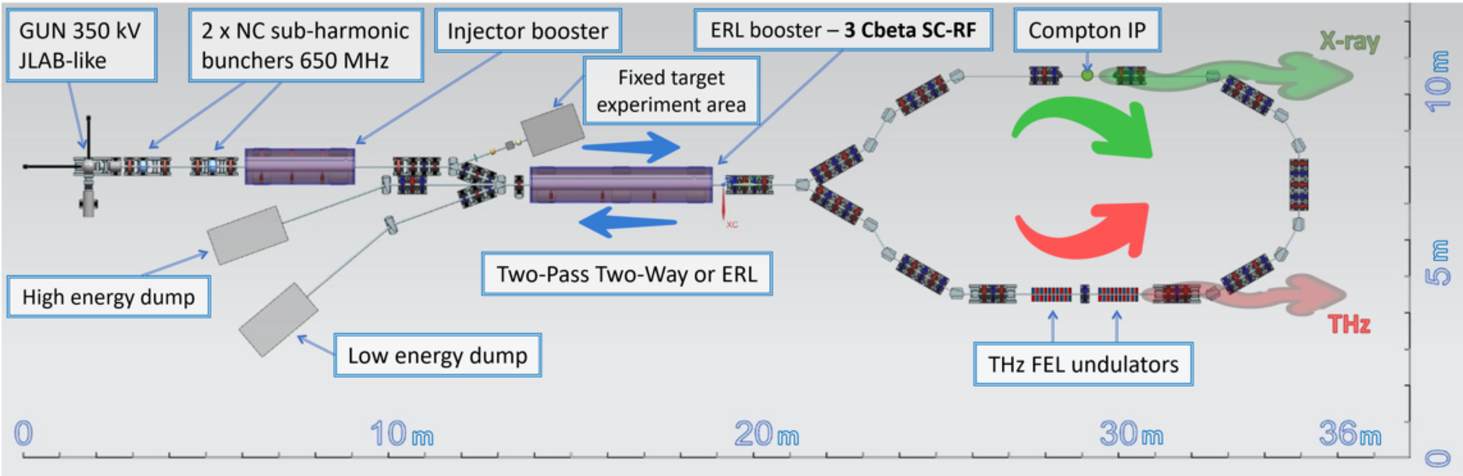
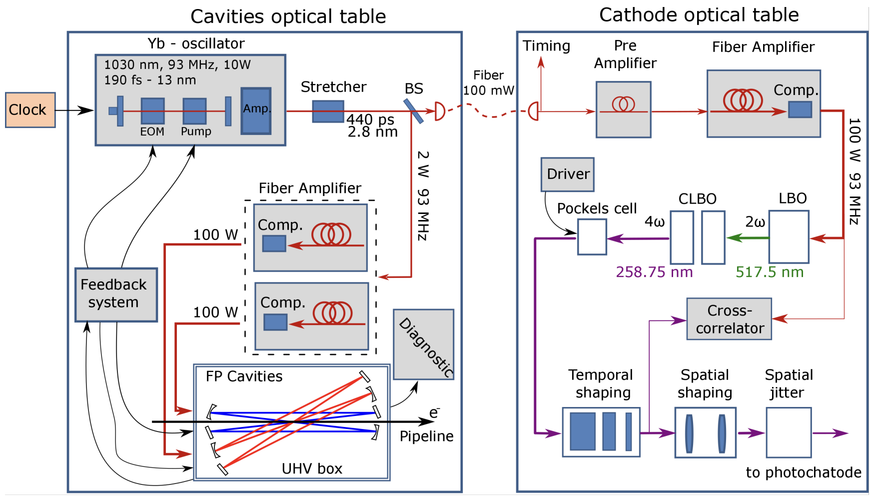
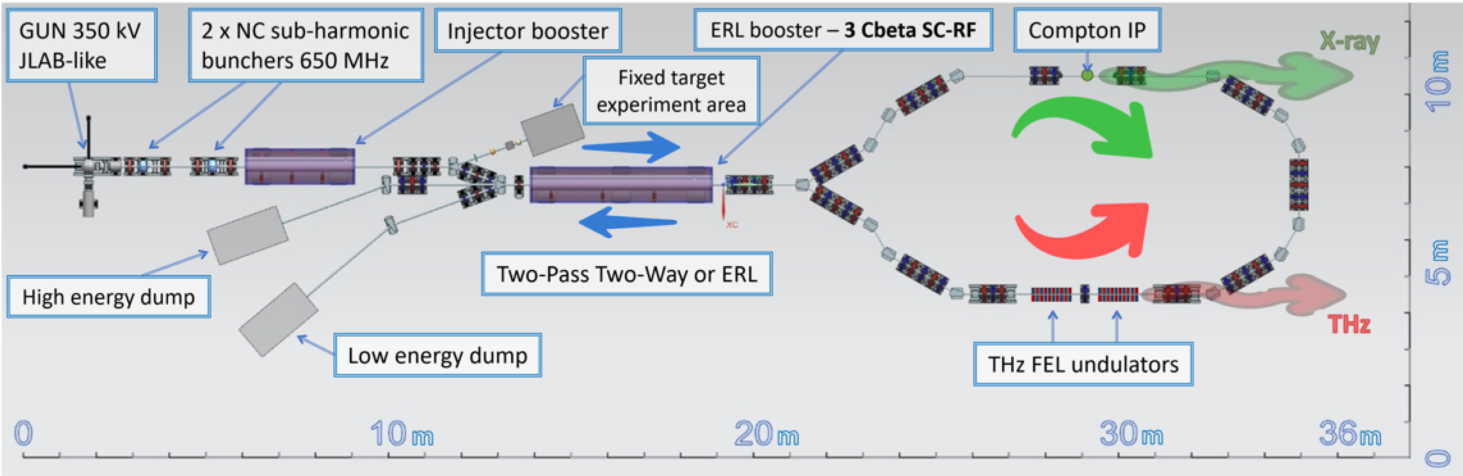


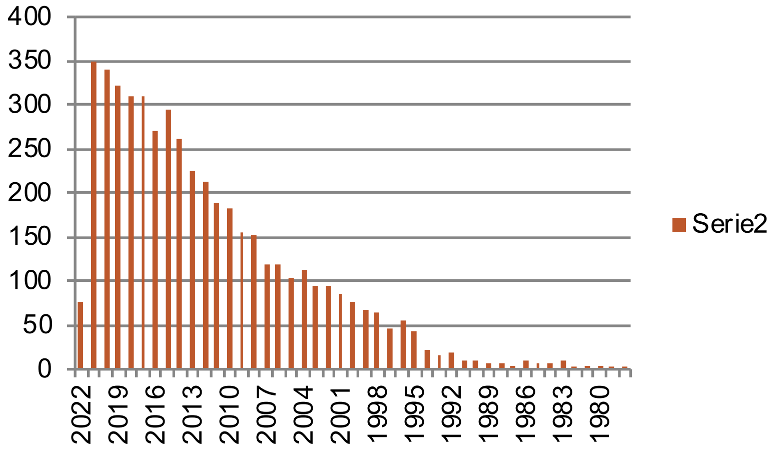


BriXSinO's electron accelerator would not reach his missions without **a photonic machine** based on a very high phase-stability laser system, capable to pump the **optical Fabry-Perot cavity** of the Compton source and, at the same time, **drive the injector photo-cathodes** with CW beams with up to **100 MHz rep rate**. An **ultra-stable kW-class fiber laser** is the core of the photonic machine, to drive the Fabry-Prot cavities **up to MW-class stored power level** and 10 mA-class electron beams delivered by photo-cathodes.

The integration between the two - electron and the photonic - machines is essential in BriXSinO.

The BriXSinO Proposal





Phase stabilities performances up to the level of the laser optical carrier will allow full synchronization of the electron beam with radiation beams delivered to users. This would allow experiments with **fully synchronized mono-chromatic X-rays** from the Compton source with **THz beams** from the Free Electron Laser oscillator.

Dual color X-rays up to 35 keV are also planned to be generated in the Compton source by a system of twin shiftable Fabry-Perot optical cavities, that was conceived, developed and succesfully tested for the first time in the context of the R&D activity associated to the preparation of this TDR. This innovative and new technique will allow two and three-dimensional breast radiography by exploiting dual-energy flashes and K-edge subtraction or speckle-based **Phase Contrast Imaging**.

Fully coherent kW-class THz beams generated by the FEL oscillator cavity will also be available, opening a new unexplored range of user experiments with imaging methods from **6 to 30 THz**

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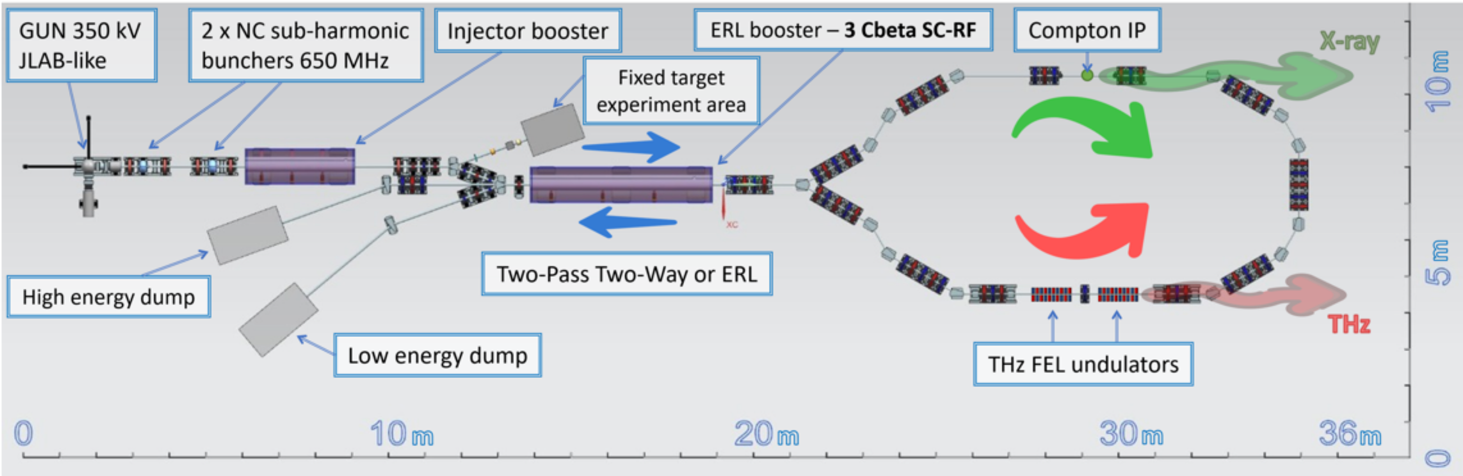
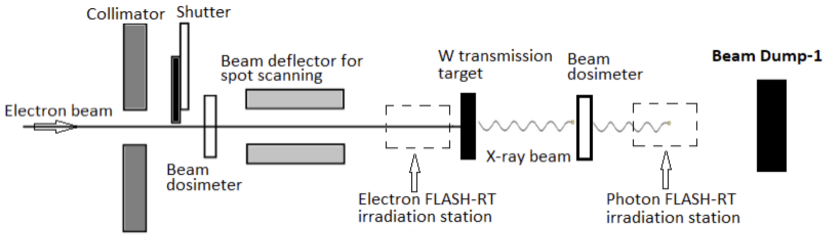
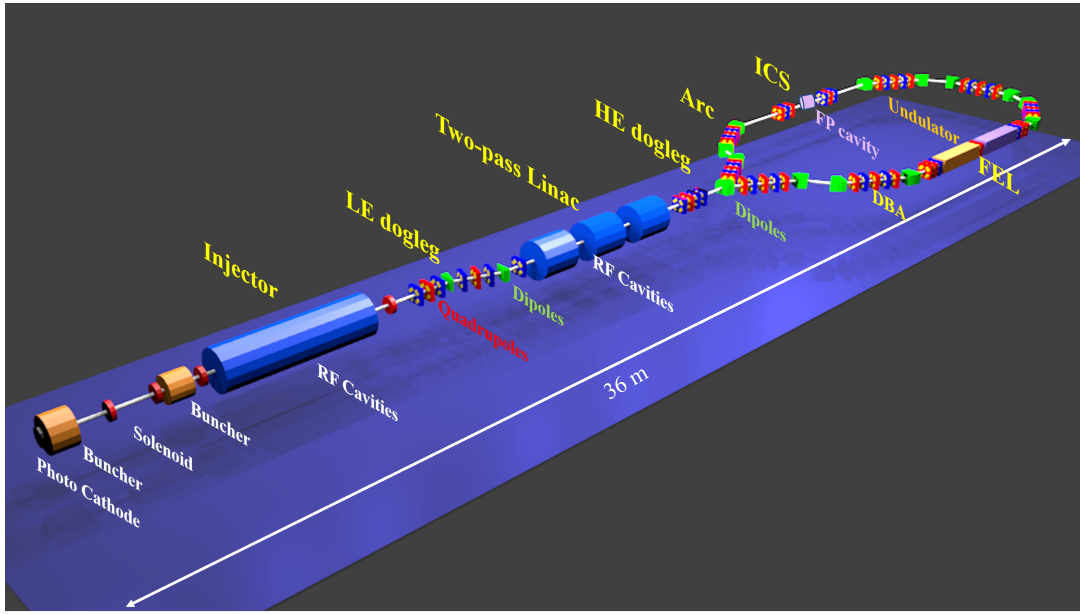




A **dedicated fixed target beam line**, carrying an intense beam of **up to 10 MeV energy and up to 2.5 mA average current**, will enable experiments in **the flash-therapy domain**, as well as **new positron source investigations** in conjunction with **Quplas** experiments and scientific case, aiming the study of positronium (Ps) interferometry to test the fundamental physical laws, with special attention **to the matter-antimatter gravitational symmetry law**.

The BriXSinO Proposal – The Injector



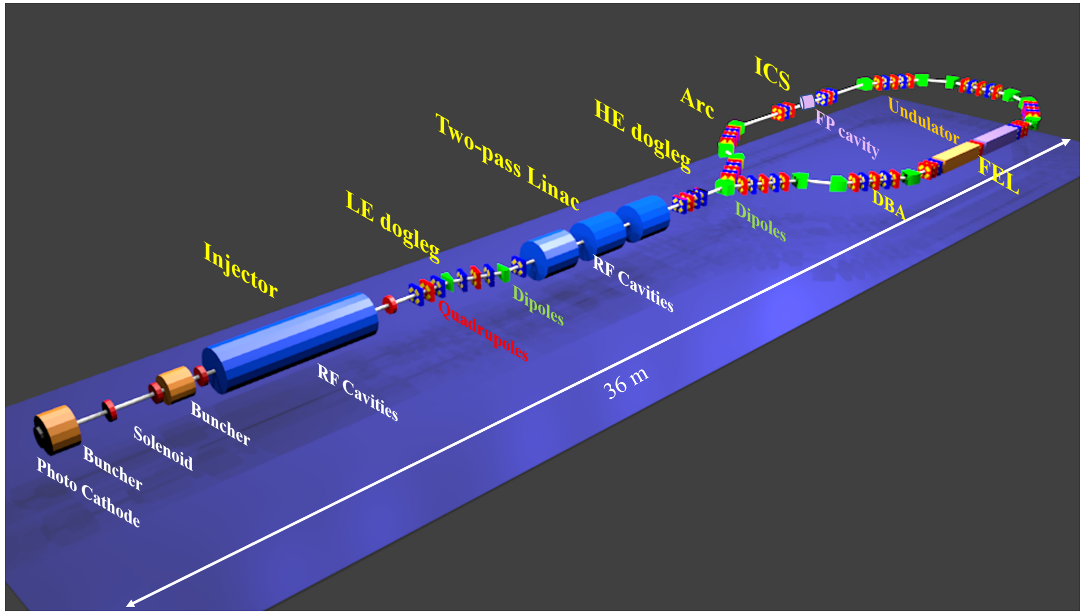
Experiment	Charge (pC)	Rep. rate (MHz)	Average current (mA)
ICS	50 - 200	0.9286 - 92.85	5
THz FEL	50 - 100	46 - 92.86	5
2-way	5	1	0.005
Fixed Target	25 - 50	<92.86	<5

The **BriXSinO injector aims to provide a high power and high brightness CW beam**. The Injector has to provide different bunch charges at different repetition rate and energies.

The Injector is composed of different elements that can be grouped into the following sections:

- The **DC gun** with focusing solenoids.
- The two 650 MHz sub-harmonic **bunchers**.
- Transport optics.
- Injector **Superconducting Booster**.
- Dogleg and **matching section** into the main ERL SC accelerating module.

The BriXSinO Proposal – The Injector



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The general layout of **the Injector** is based on **a laser-driven photoemission DC gun** running at nearly 100 MHz where the electrons are accelerated at **350 keV**.

The long bunch so generated is compressed and further accelerated in two Normal Conducting (NC) buncher cavities, operated at 650 MHz with β = 0.74 and β = 0.904 to optimize the bunching and acceleration efficiency due to the non-relativistic properties of the beam.

The electron bunch is accelerated in **a SC Booster Cryomodule** that hosts three 1.3 GHz two-cell Nb cavities operated at 2 K.

The energy **at the exit of the SC module is in the range 5-10 MeV**.

Afterwards, a transport system consisting of **a dogleg and a matching section brings** the beam into the main ERL module.

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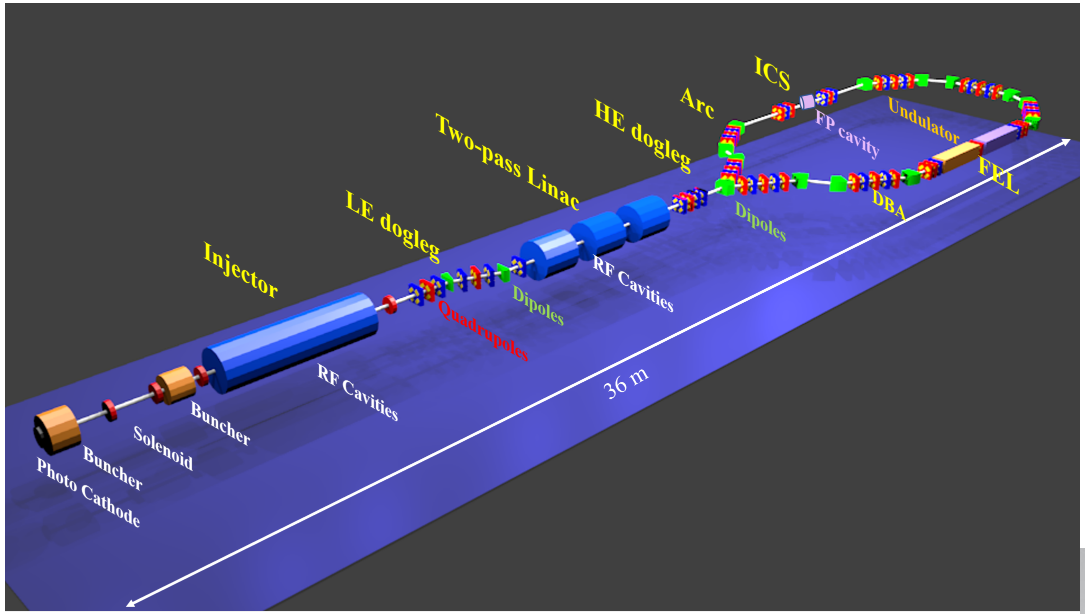
The BriXSinO Proposal – The Injector



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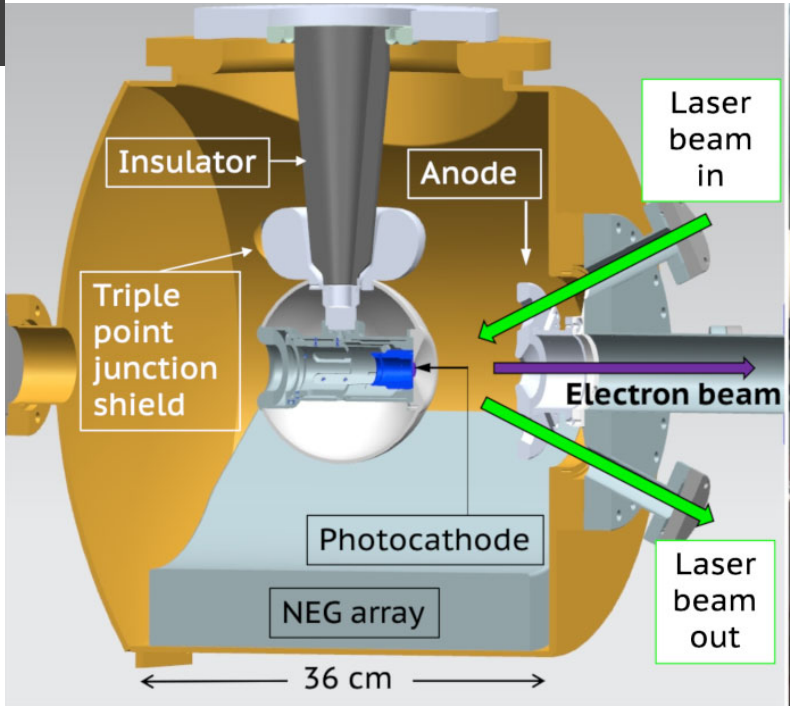
The **HV DC Gun** will be developed within the frame of an already **signed user agreement with Jlab**.

The collaboration has been in progress since a few months and is based on regular meetings and the share of technical drawings and bill of materials.



The BriXSinO Proposal – The Injector

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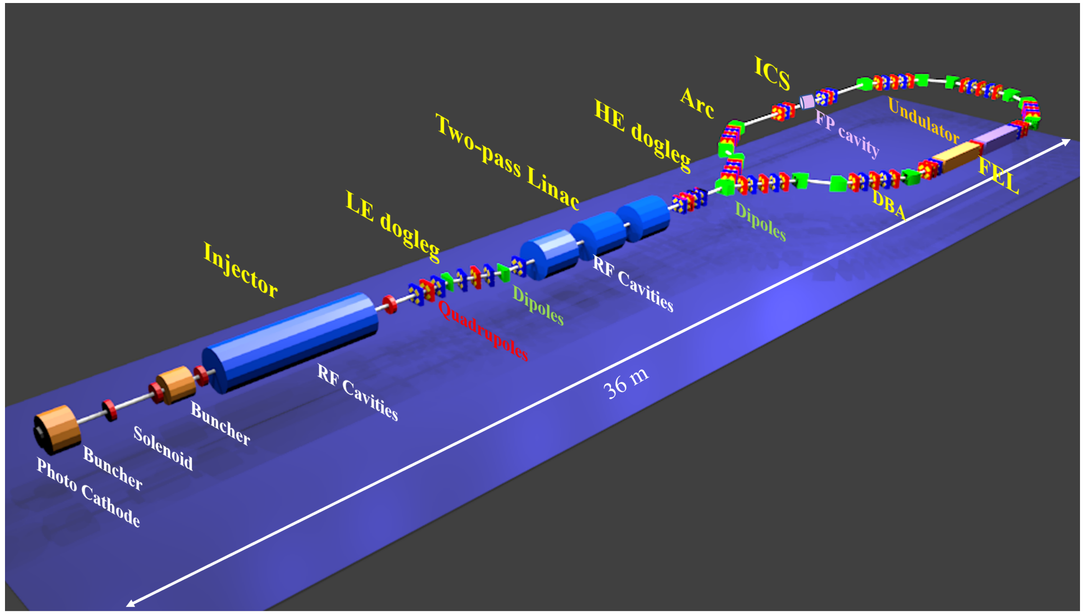

	Buncher 1	Buncher 2
Resonant frequency (π-mode) (MHz)	650	
β (v/c)	0.74	0.906
Accelerating voltage (MV)	0.45	0.424
Beam phase (°)	-30	-17
Input beam energy (MeV)	0.3	0.638
Electric field amplitude (MV/m)	3.4	
Cell per cavity	1	
Active cavity length (m)	0.171	0.209
Cavity quality factor Q_0	3.2×10^4	3.67×10^4
Nominal external quality factor Q_{ext}	3.02×10^4	3.24×10^4
R/Q (Ω)	195.7	223
Cavity geometry factor G (Ω)	211	244.4
E_{peak}/E_{acc}	3.07	3.88
B_{peak}/E_{peak} (mT/(MV/m))	0.96	0.96
B_{peak}/E_{acc} (mT/(MV/m))	2.94	3.73

The DC Gun generated electron bunches have long longitudinal profile to avoid emittance dilution but, to minimize nonlinear energy spreading due to RF waveform in the main superconducting Linac, **bunches need to be compressed to shorter length after the gun** and before entering the BriXSinO SC Booster. As the beam is still non-relativistic at this point, the simplest method of bunch compression is the velocity bunching for which we choose sub-harmonic bunching solution, employing two β < 1, 650 MHz spherical reentrant shape copper cavities. The beam energy before entering the first cavity is assumed to be 300 keV and 638 keV before entering the second.

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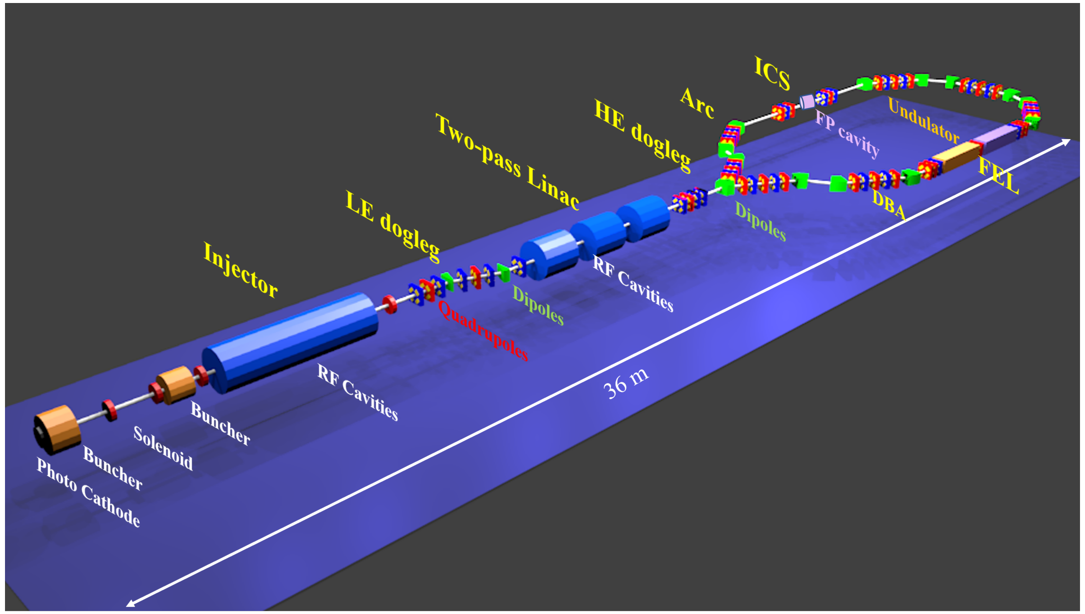
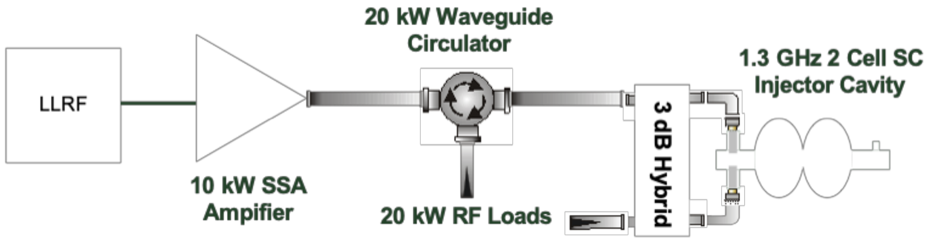
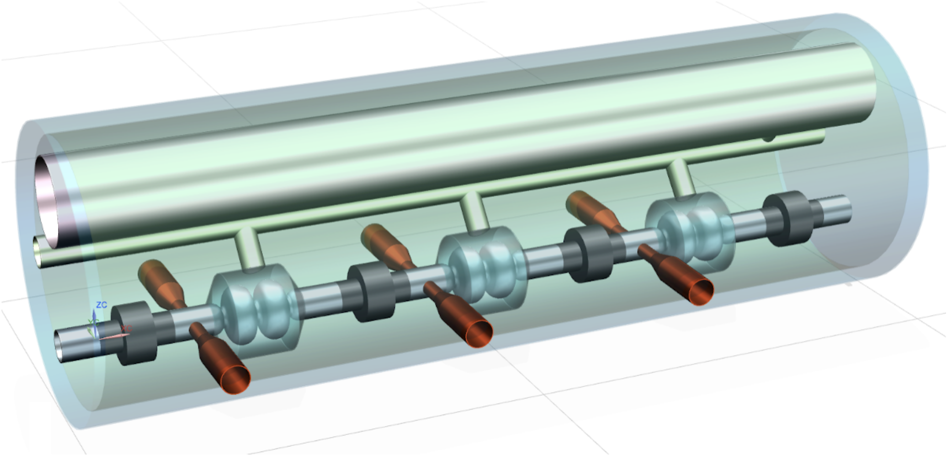
The BriXSinO Proposal – The Injector



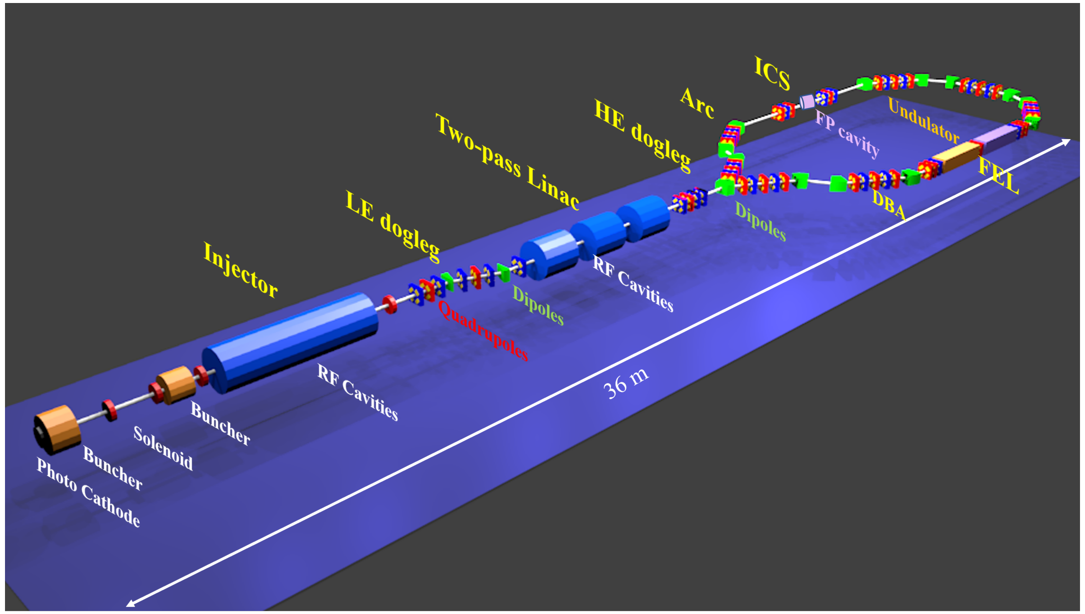
Resonant frequency (π-mode) (GHz)	1.3
Accelerating voltage (MV)	1.64
Accelerating gradient E_{acc} (MV/m)	7.5
Cells per cavity	2
R/Q (Ω)	222
Cavity geometry factor G (Ω)	261
Cavity quality factor Q_0	2×10^{10}
Nominal external quality factor Q_{ext}	1.5×10^6
Cell-to-cell coupling (%)	0.7
E_{peak}/E_{acc}	1.94
B_{peak}/E_{acc} (mT/(MV/m))	4.28
Small beam pipe diameter (mm)	78
Large beam pipe diameter (mm)	106
Inner iris diameter (mm)	70
Active cavity length (m)	0.218
Cavity length flange-to-flange (m)	0.536

The **superconducting section** of the injector complex is a cryomodule that hosts **three CBETA like 1.3 GHz 2 cell SC cavities**





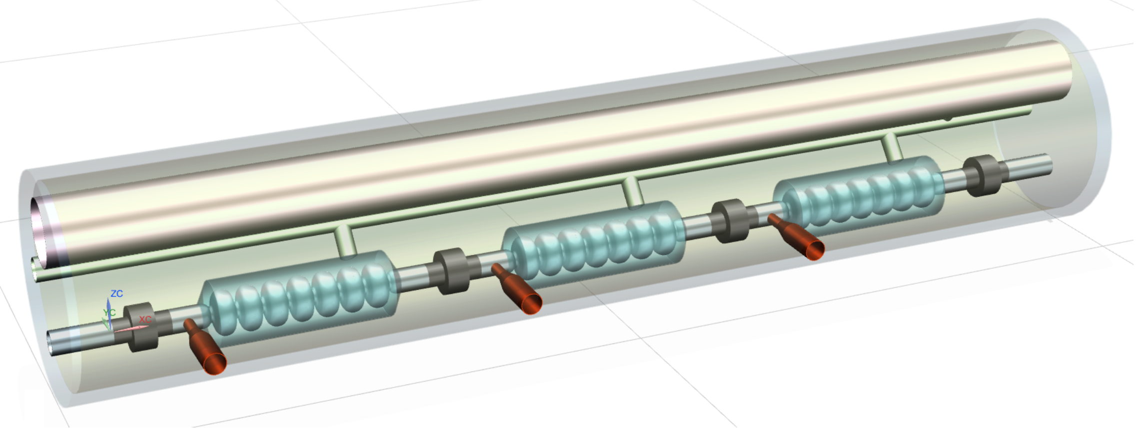
The BriXSinO Proposal – The ERL Main SC-Linac



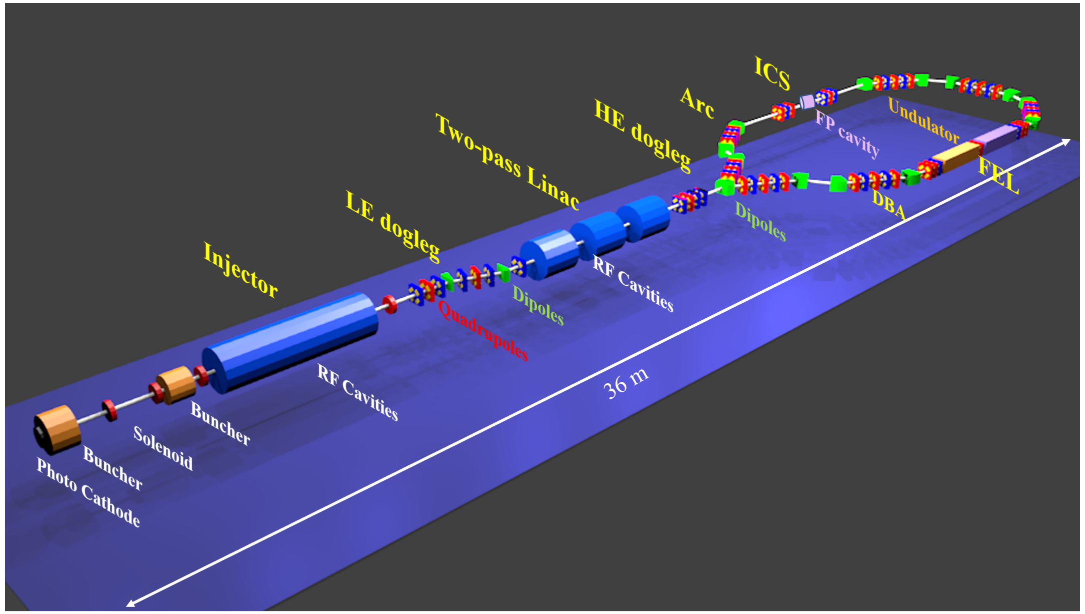
The ERL Main SC-Linac hosts **three superconducting 7-cell** cavities and has an overall length of 5 m, providing **40 MeV energy gain** to the beam.

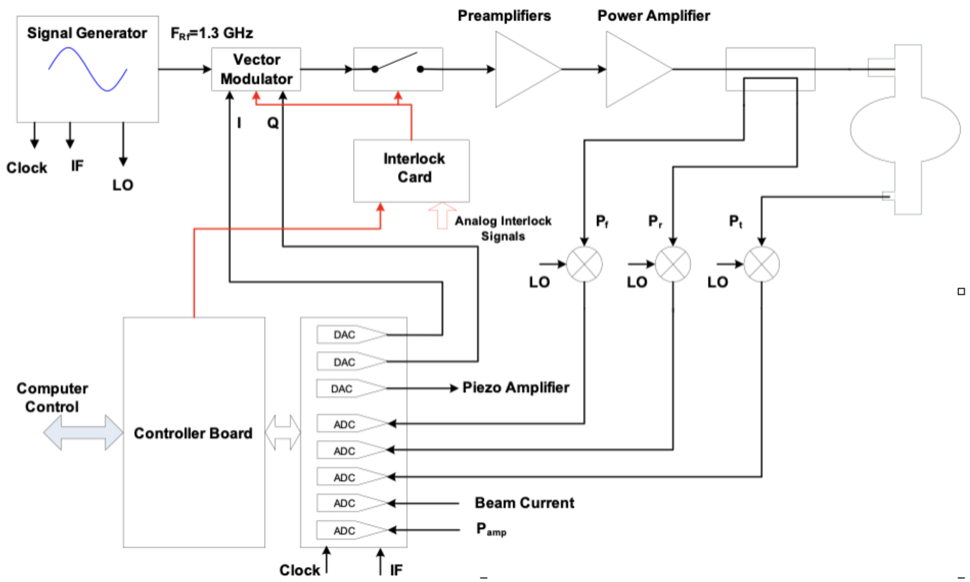
The cavity design, based on the CBETA ERL resonator, is characterized by a cell shape optimized to have a high beam-break-up (BBU) limit for the beam current. Also, with 5 mA beam current combined with the short bunch operation, an efficient damping of the Higher Order Modes (HOMs) is needed, leading to the installation of radiofrequency (RF) power absorbers between cavities.

Parameter	Value
Type of accelerating structure	Standing wave
Accelerating mode	TM_{010} π-mode
Fundamental frequency (MHz)	1300
Design gradient (MV/m)	16.5
Intrinsic quality factor Q_0	2×10^{10}
Loaded quality factor Q_{EXT}	3.25×10^7
Active length (m)	0.81
Cell to cell coupling (%)	2.2
Iris diameter (mm)	72
Beam tube diameter (mm)	110
R/Q (Ω)	774
Geometric factor G (Ω)	271
E_{peak}/E_{acc}	2.06
B_{peak}/E_{acc} (mT/MV/m)	4.196
$\Delta f/\Delta l$ (kHz/mm)	350
Lorentz force detuning constant (Hz(MV/m)^2)	1
Cavity bandwidth $\delta f = f/(2Q_{EXT})$ (Hz) HWHM	20
Total longitudinal loss factor $k_{\parallel}$ (V/pC), σ=2.2 mm	3.5



The BriXSinO Proposal – The ERL Main SC-Linac





The cryomodule design has been guided by the ILC cryomodule while necessary modifications have been made **to allow Continuous Wave (CW)** operation, with correspondingly higher dynamic cryogenic loads. All components within the cryomodule will be suspended from the Helium Gas Return Pipe (HGRP).

The **main coupler needs to provide at least about 3.6 kW CW RF to the cavity for perfect ERL operation and 20 Hz detuning operation**, but must withstand up to 10 kW CW to also allow not perfect ERL efficiency.

The BERLinPro modified TTF III power coupler is the suitable solution for our design: modifying the cooling of the coupler inner conductor, CW power capability has been raised from 5 kW to 10 kW.

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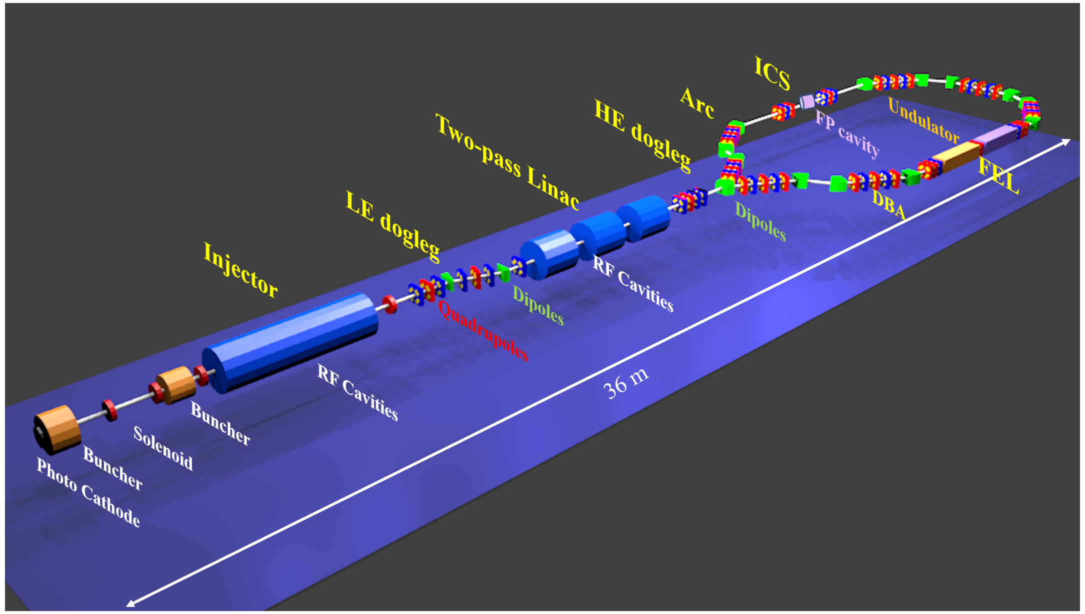
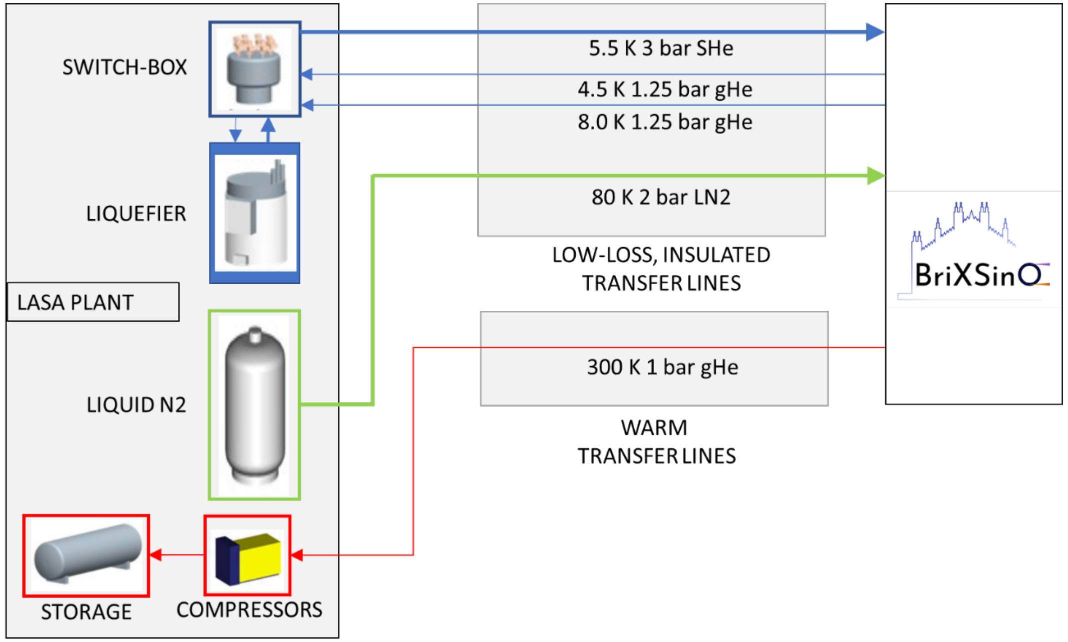
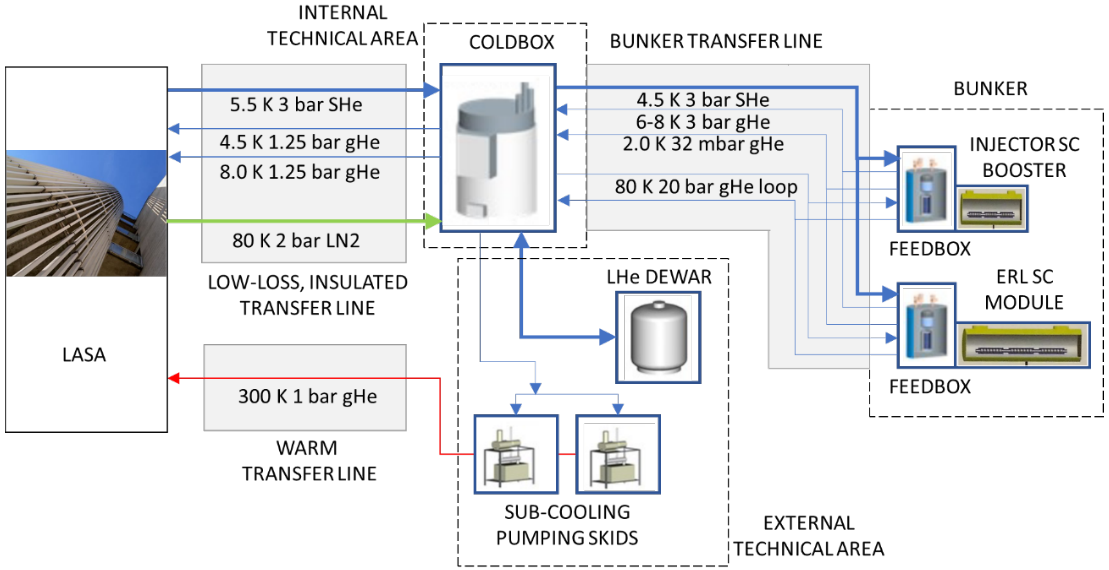
The BriXSinO Proposal – The Cryogenic Subsystem



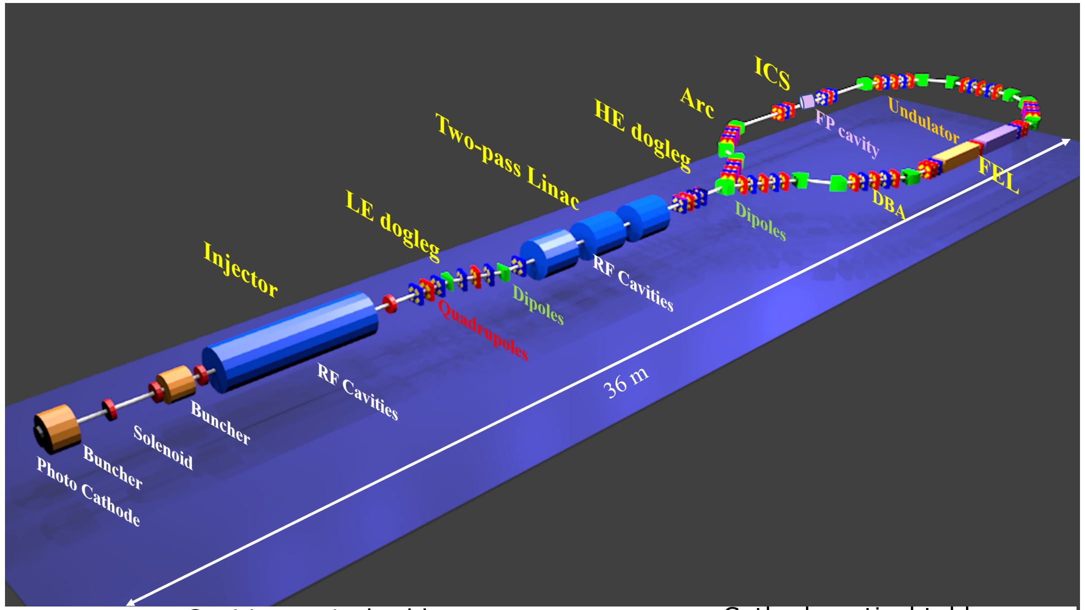


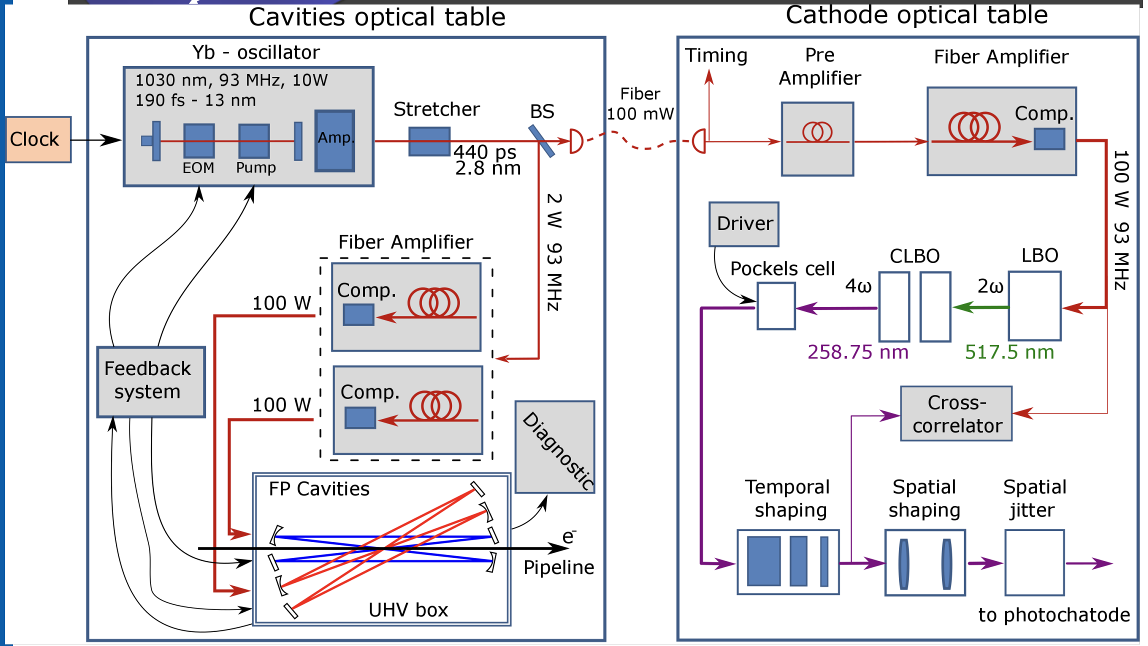


The cryogenic plant of the BriXSinO complex will integrate the central LASA cryogenic plant in order to support:

- controlled cool-down and warm-up of the two BriXSinO superconducting cavities cryomodules from room temperature or from an intermediate parking temperature stable stand-by cryogenic configurations at an intermediate temperature for the time windows in between cold run,
- sufficient cooling capacity to enable robust operation of all BriXSinO cryogenic components. The lowest end of such ranges being the superconducting resonators whose operating temperature is 2.0 K, achieved by evaporative cooling in boiling superfluid helium II at a saturated vapor pressure of 32 mbar.

The BriXSinO Proposal – The Low Phase Noise Laser System





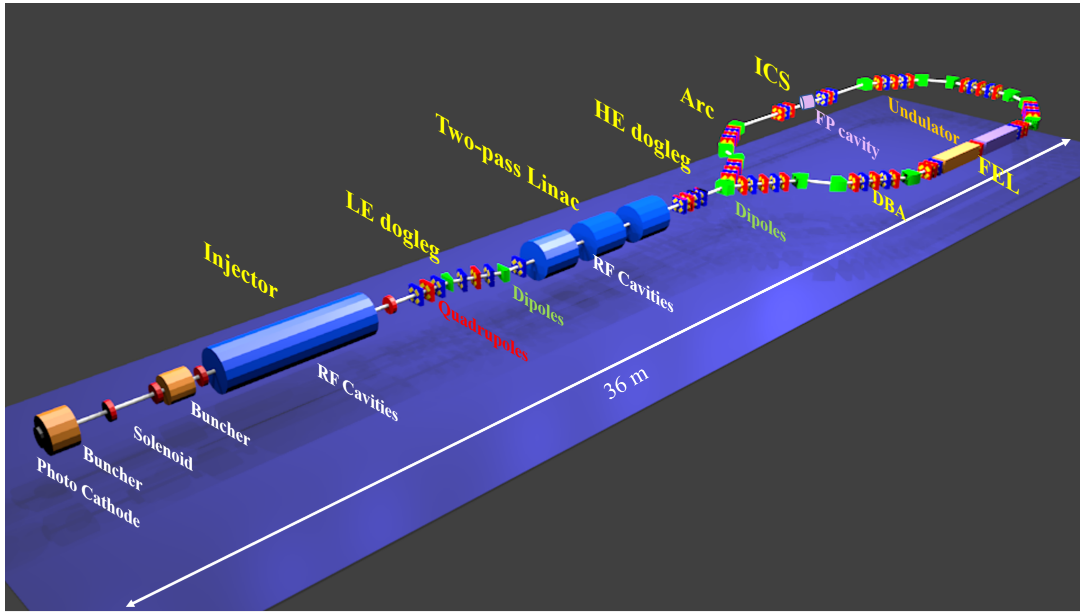
One of the fundamental elements in the BriXSinO machine is the optical system.

The aims of the optical system are both **pumping the two Fabry-Pérot (FP) cavities** of the inverse Compton scattering (ICS) X-Ray source and **exciting the photocathode** for the generation of the electron bunches.

Moreover, **the laser oscillator will be used to carry the timing reference to all other BriXSinOcomponents**.

Free spectral range (MHz)	92.587
Input power (W)	100
Finesse	5000
Gain	2800
Mode width (kHz)	18

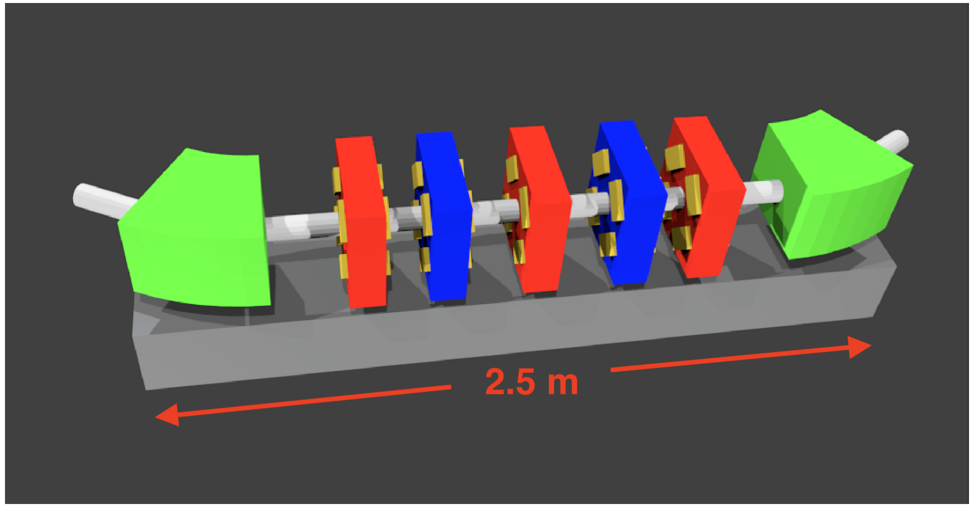
The BriXSinO Proposal – The Recirculating Loop



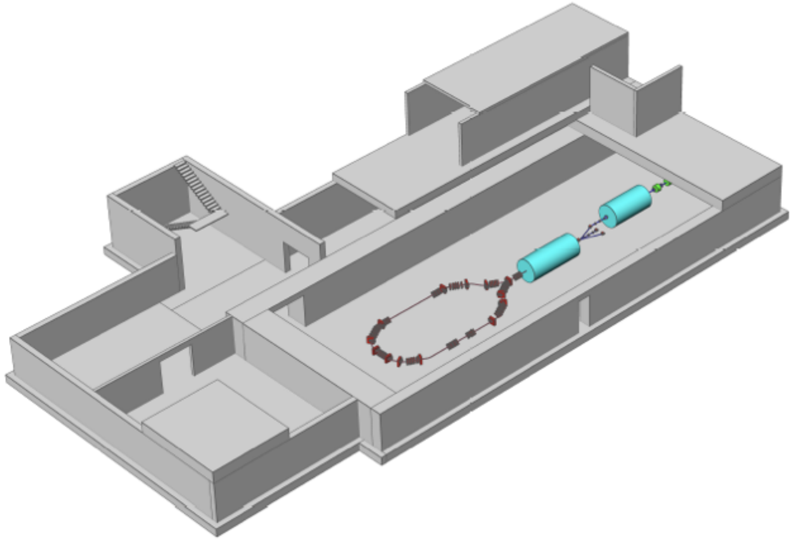
The loop is based on **a peculiar single achromatic cell design, the BriXSinO's DBA (Double Bend Achromat)**. The choice of a single repeated element within the arc brings several ad- vantages: the use of common optics and engineering solutions and fewer beam dynamics issues to deal with.

The peculiarity of this DBA is that it has quadrupole optics within the dispersed area.

This choice allows a linear arrangement of the cell elements (dipoles and quadrupoles) and therefore their installation on a single compact girder. The closed dispersion region has been reduced to a minimum compatibly with the presence of beam diagnostic stations.



The BriXSinO Proposal – The Site



BriXSinO has been conceived **to be hosted by the Laboratorio Acceleratori e Superconduttività Applicata (LASA)** located in Segrate.

The land where the LASA is located, along with the existing buildings, belongs to the Università degli Studi di Milano and is presently occupied by the Istituto Nazionale di Fisica Nucleare (INFN) and hosts several research activities connected with the construction and the operation of particles accelerators.

With the development of advanced technologies for superconductivity, cryogenics and the productions of high intensity DC and RF electromagnetic fields, **the laboratory has built unique competences that allowed contributing with innovative components to large international accelerator projects for high energy and applied physics**.

This strong background makes LASA an ideal site for the construction of an innovative research accelerator facility such as BriXSinO.

BriXSinO

BriXSinO: Reports on ongoing R&D activity

The **activities have involved** a total of **40 researchers, PhD students, technicians**, organized in Working Groups, with a regular exchange of information via group meetings and seminars.

The research and development activities on BriXSinO have included detailed **start-to-end simulations** of all aspects of the project. **Extended beam dynamics simulations** have been performed using code **ASTRA** to investigate the **optimum electron bunch size and its dependence on the laser spot size at the photocathode, the complete control of emittance and energy spread, the precision in the re-injection of the beam inside the linac**.

The code **GIOTTO** was used **to drive the scan and the statistics and to optimize the beam both in the interaction point of the ICS and at the entrance of the TeraHertz undulator**.

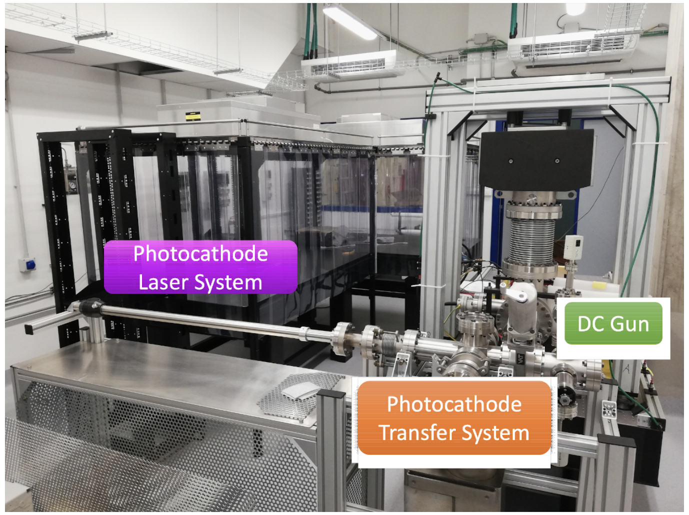
The problems connected to **the travel of the beam in the arc have also been analyzed**.

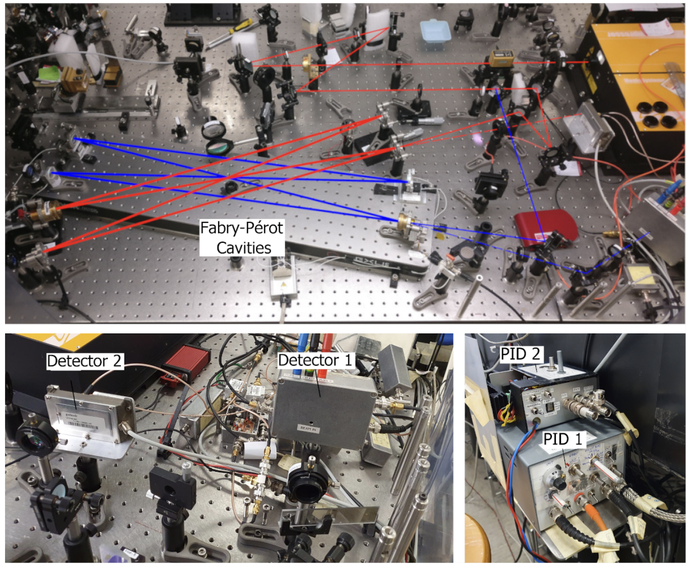
A novel numerical tool named **HOMEN**, developed ad hoc, has been devoted to the study of the effect of the high order modes in the accelerator superconductive cavities, an open problem that could affect the performances of BriXSinO and, in general, of ERLs.

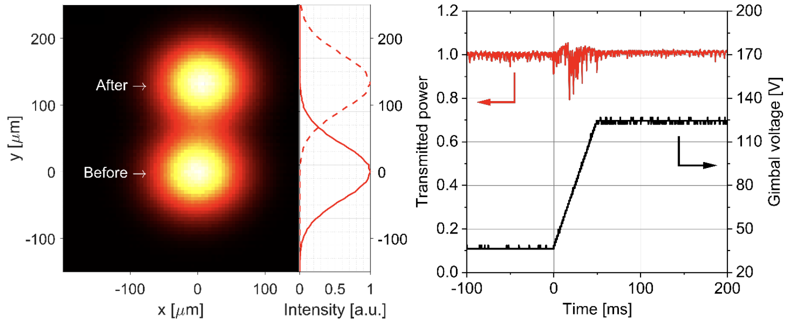
BriXSinO: Reports on ongoing R&D activity

The R&D activities are not limited only to theoretical and numerical analyses, but concern also an intense experimental program, focused on the Fabry-Pérot cavity and the photocathode.

Their main objectives are **to test the high Finesse Fabry-Pérot (FP) optical cavity, the amplification system and the lines for the RF-Guns** (harmonic + temporal and spatial shaping + spatial stabilization) and to prove **the possibility of using a Cs2Te photocathode at 100 MHz repetition rate and high average current** (mAs scale).







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Thanks !