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BRIXSINO HIGH-FLUX DUAL X-RAY AND THZ RADIATION SOURCE BASED ON ENERGY RECOVERY LINACS

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Abstract

We present the conceptual design of a compact light source named BriXSinO. BriXSinO was born as demonstrator of the Marix project, but it is also a dual high flux radiation source Inverse Compton Source (ICS) of X-ray and Free-Electron Laser of THz spectral range radiation conceived for medical applications and general applied research. The accelerator is a push-pull CW-SC Energy Recovery Linac (ERL) based on superconducting cavities technology and allows to sustain MW-class beam power with almost just one hundred kW active power dissipation/consumption. ICS line produces 33 keV monochromatic X-Rays via Compton scattering of the electron beam with a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz. The THz FEL oscillator is based on an undulator imbedded in optical cavity and generates THz wavelengths from 15 to 50 micron.

INTRODUCTION

The increasing requests of complete autonomy of Research Infrastructures drive the research communities at developing sustainable accelerators for the frontiers of the High Energy Physics (HEP) and of the future applied researches. Energy Recovery Linacs (ERLs) [1] promise to be a keystone for future sustainable accelerators, providing a reasonable balancing between use of the beam and beam power waste/dissipation which is attractive not only to users oriented to radiation experiments, i.e. Free Electron Lasers (FEL), Inverse Compton Scattering (ICS), and synchrotron radiation, but also in the HEP scenario, as discussed in Ref. [2]. The main perspectives of ERLs include: to provide nearly linac quality/brightness beam at nearly storage ring beam powers, to mitigate intractable environmental/safety concerns since the beam can be dumped at low energy, to consider high power applications than would otherwise be unaffordable, looking at GW class beams. Main ERL paradigms worldwide are BNL-ERL [3] and CBETA [4]. The facility presented here, named BriXSinO [5], is inspired, on reduced scale, by the same philosophy of other more ambitious projects grown up around the MariX concept [6–11]. A newly conceived scheme of ERL with counter-propagating beams is proposed in BriXSinO: 5 mA of average electron beam current in CW mode with a time structure organized in a regular repetition rate up to 100 MHz, i.e. bunch spacing 10 ns. It is similar in parameters and dimensions to a storage ring, with the very much larger recovery of the 225 kW beam power (>90%). Moreover, the electron bunches in BriXSinO travel through the full orbit back-and-forth just one time, while, conversely, in a storage ring must electrons travel over many turns (namely $> 10^{10}$) so their phase space quality must be very carefully preserved to avoid instabilities

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that may seriously impact the storage ring life-time.
Its unique features will enable at LASA new promising synergies between fundamental physics oriented research and high social impact applications.
It will act as test facility for fundamental questions and strategies of Dynamics and Energetic and it will work as user facility by providing large quality THz and X-rays emission from its high brightness accelerated electron beam, enabling important and advanced applications [12].

After delivery of BriXSinO's TDR to INFN Executive Board, a review and discussion about the project approval and funding has been initiated among the project team, the INFN Executive Board, and two INFN Committees - INFN Acceleratori and the Machine Advisory Committee. In December 2022 INFN Exec. Board decided to allocate the funds (about 2 M€) necessary to the construction, at the LASA Laboratory, of an underground bunker compatible to BriXSinO's machine requirements, as illustrated in the TDR [5].

Very recently a final review took place in order to finalize the decision about project approval: a consensus was reached with INFN Exec. Board to spread the construction of BriXSinO into 4 phases: i) development and construciont of the electron photo-Gun and bunchers, up to an energy of about 1 MeV, with full control/diagnostics/laser system operational during the next 2 years - (this phase is already approved and funded under the experiment HB2TF [13]) ii) construction of the full injector with merging line and fixed target exeprimental area - up to 10 MeV and up to 5 mA iii) construction of the main Linac with complete cryomodule in order to achieve a final energy up to 50 MeV iv) re-design and development of a compact recirculation arc in order to carry out the ERL (and two-way acceleration) experimental program

A possible scenario comprises the approval/funding of the first three phases in next years, with a successive negotiation concerning phase 4 and its effective configuration, oriented to ERL and high brightness beam physics. We are awaiting for a formal approval that is expected soon.

BRIXSINO STRUCTURE AND PARAMETERS

Fig. 1 shows a schematic layout of BriXSinO. From the left side, the injector generates electron bunches through a DC gun. Downstream the gun, the bunches are first compressed with two RF sub harmonic bunchers (650 MHz), then boosted by three 2-cell SC cavities at the energy of about 4.5MeV, and finally injected into the ERL superconducting Module through a low energy dogleg. In the middle region, the ERL Superconducting Modules (and/or two-way linac) are present [14]. At the right end there is the arc, designed in such a way to bring back the beam to the Superconducting modules. The arc lattice is constituted by 7 DBA (Double Bend Achromat). In the straight parts, it will host two experimental areas devoted to ICS and THz FEL without any additional magnetic elements. BriXSinO's beams travel the cavity sequence twice, back and forth, and return to the linac after having crossed the arc in different phase conditions. BriXSinO can therefore operates in two different working modes: the first is the ERL working mode: an ad hoc path length adjustment system synchronizes the coming back beam with the decelerating RF wave crest: the electron beam is decelerated giving up its energy to the cavity radiofrequency. The second working mode is the two-pass two-way acceleration mode, fundamental for operation a la MariX [15, 16]: the beam crosses twice the linac, first in the forward and then in the backward direction, experimenting in both cases the accelerating field crest. The beam is re-injected in the linac by the arc transport line, where the beam can be also compressed avoiding emittance dilution [17, 18]. This novel working mode, that will be tested in BriXSinO for the first time, permits to save precious space while improving the efficiency by doubling the energy exchange in the linac. All start-to-end beam dynamics simulations have been done by using the codes ASTRA [19] and Elegant [20] coupled with the AI-based optimizer GIOTTO [21]. A list of BriXSinO's electron beam characteristics, summarized in Table 1, emphasizes different cases of operations, the application to drive ICS at very large photon flux (10^{12} photons/s) (Table 1, second column) and a kW-class THz FEL (Table 1, third column). The availability of such a high intensity beam (50 kW) enables both experiments of flash therapy tests using electrons, with a capability to irradiate samples with a delivered total charge in a 200 ms time interval up to 1 mC, as well as converting the electron beam into bremsstrahlung photons with energy peaked at 7-8 MeV at an impressive flux of 10^{16} photons/s (i.e. up to 30 kW X-Ray beam).

Table 1: BriXSinO's electron beam main parameters: Electron beam parameters at Compton Interaction Point for I.C.S., and at THz FEL *Maximum (CW, ca. 92.86–0.9286 MHz,**after ERL

Parameter	**ICS**	**FEL**
Energy (MeV)	22 - 45	22 - 45
Bunch charge (pC)	50 - 200	50 -100
Repetition rate (GHz)*	< 0.9286	<0.4643
Average Current (mA)	< 5	5
Peak Current (A)	-	8-12
Nominal beam power (kW)	< 225	<225
Beam energy @ dump (MeV)	4.5	4.5
Beam power @ dump** (kW)	< 22.5	22.5
Bunch length (rms, mm)	2.2	< 1
$\epsilon_{n,x,y}$ (mm mrad)	1 – 3	1 -3
Slice Emittance (mm mrad)	-	1.2-1.7
Energy spread (rms, %)	0.5 – 1.5	0.1
Slice Energy spread (%)	-	0.05
Focal spot size (rms, μm)	30 - 60	100
Bunch separation (ns)	10 – 1000	10-20
Beam energy fluctuation (rms,%)	< 0.1	<0.01
Time arrival jitter (fs)	< 150.	< 50
Pointing jitter (μm)	10.	20

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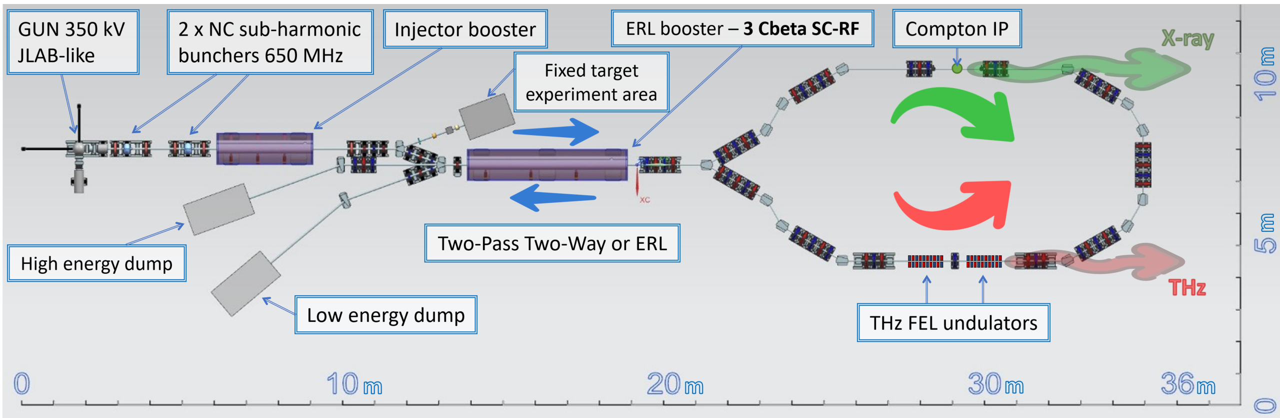

Figure 1: BriXSinO general layout. From left: injector with DC gun, bunchers and radiofrequency cavities. Low-energy (LE) dogleg with quadrupoles in red and dipoles in green. Two-way (or ERL zone) SC linac that can be operated in the two-pass two-way acceleration or ERL mode. High-energy (HE) dogleg. Recirculating loop (Arc), made by Double Bend Achromats (DBA), hosting the light sources and bringing back the beam to the two-way zone. On left branch of the arc: Fabry-Peròt (FP) cavity with Inverse Compton Scattering (ICS) source. On right branch of he arc: Free-Electron Laser (FEL).

RADIATION SOURCES DRIVEN BY BRIXSINO ELECTRON BEAM

BriXSinO will host in the zero dispersion zones of the arc two radiation sources: an Inverse Compton Source (ICS), named Sors and one THz Free-Electron Laser Oscillator, named TerRa.

The Compton photon energy can be tuned from 16 keV to 45 keV by varying the electron energy from 30 to 50 MeV with possibility to produce two X-Ray pulses with different colors [22, 23].

The FEL oscillator TerRa [24] is composed by two undulator sections with variable gaps, linear polarization, peak magnetic field of about 1 T, periods of 4.5 and 3.5 cm respectively and length of 1.75 m. The optical cavity embedding the undulators is composed by metal-coated (gold on copper) mirrors with a total reflectivity of the order of 97% , with length is L_c = 12.92 m and round trip of 25.84 m. Using an electron beam energy E= 40 MeV, mirror loss of 1.5%, energy jitters of 0.3%, pointing instability of 100 µm, 3-17 μJ of extra-cavity energy and 0.15-0.7 kW of output average power at λ = 20 µm can be obtained. Tuning the two undulator modules at different wavelengths enables the generation of two THz color [25].

THE ONGOING ACTIVITIES

Currently progress is expressed in the following activities: HB2TF (High Brightness Beams Test Facility), HOMEN (High Order Mode Evolution based on Energy budget) and Non-destructive definition of emittance by AI Machine Learning.

HB2TF [13] is a facility to develop and test advancements in accelerator physics, particularly in the areas of high-current CW electron beams and high-brightness electron beam sources as injector for BriXSinO. The facility will include a high-performance laser-driven DC Gun and a normal conducting RF buncher-acceleration section, which will provide a nearly 1 MeV 5 mA CW electron beam. In addition, the proposal includes the engineering design of a Superconducting RF booster linac to increase electron energies up to 5-10 MeV while maintaining a beam current up to 2.5 mA. The project aims to pool the expertise and resources of research groups at the INFN-LASA laboratory, as well as other INFN sites and foreign labs, to develop a world-class facility for advancing accelerator physics.

HOMEN is a numerical and theoretical model that addresses the effects of HOMs on beam quality and stability in SC cavities back and forth in CW operation [14, 26]. This is done by solving for each monopole mode three coupled differential equations, describing the variation of stored energy, mode oscillation amplitude and bunch energy gain respectively.

Non-destructive emittance definition using AI machine learning is the new project [27], which presents a model for reconstructing beam emittance from the spectrum of Compton scattered photons. By using machine learning to analyze the energy spectrum of the photons produced in the scattering process, information about the transverse momentum of the initial electron bunch can be obtained. The work includes theory, model implementation, and simulations demonstrating how beam emittance can be estimated from the radiation spectrum.

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