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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

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travel over many turns (namely > 10^{10}) so their phase space quality must be very carefully preserved to avoid instabilities 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].

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 $4.5 MeV$, 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 [13]. 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 [14, 15]: 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 [16, 17]. 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 [18] and Elegant [19] coupled with the AI-based optimizer GIOTTO [20]. 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

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. The Compton emission has been simulated using the MonteCarlo code CAIN [21] using 2.7 mJ laser energy at 1030 nm wavelength. Two color radiation, widely required by imaging applications, can be obtained by using two different laser pulses impinging on the same electron beam at different angles, thus exciting different frequencies [22]. The potentialities of such source can be improved by using different polarizations of the initial laser pulses or by producing a temporal sequence of two X-Ray pulses with different colors. To produce the dual-color beam we need two Fabry-Pérot cavities oriented differently. An electron beam at 43 MeV can produce two colors at 31.8 and 34 keV, surrounding the iodine K-edge (33.17 keV), colliding with the laser at angles 7° and 30° shown in Fig. 2, radiation parameters presented in Table 2 . The two cavities have the same geometry and are formed by 4 mirrors, 2 curved-/2 flat, in the near-confocal configuration [23]. With a finesse of about 5000 it is possible to reach a power of about 200 kW by entering with 100 W. The other zero dispersion re-

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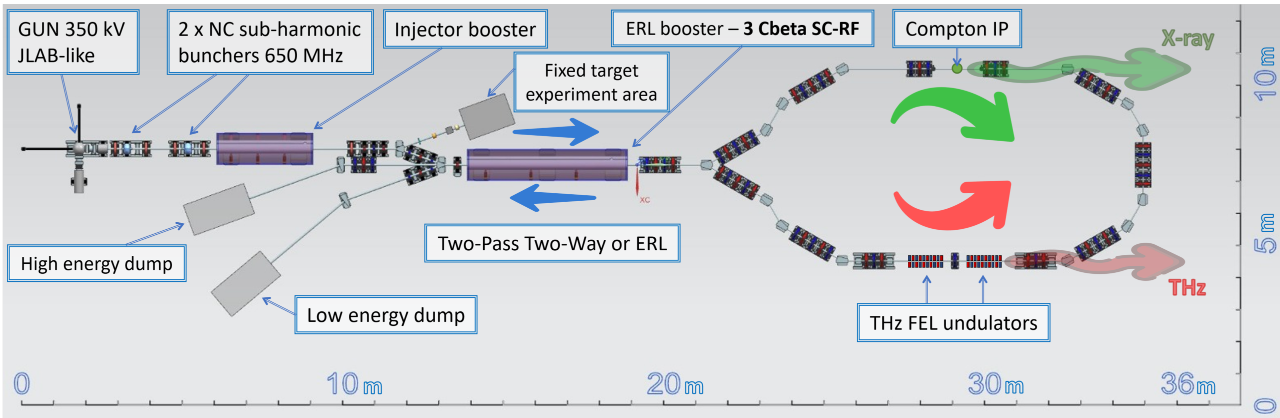

Figure 1: BriXSinO general layout. From left: injector with DC gun, bunchers and radiofrequency cavities. Low-energy (LE) dogleg with quadrupoles in red and dipoles in green. Two-way (or ERL zone) SC linac that can be operated in the two-pass two-way acceleration or ERL mode. High-energy (HE) dogleg. 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).

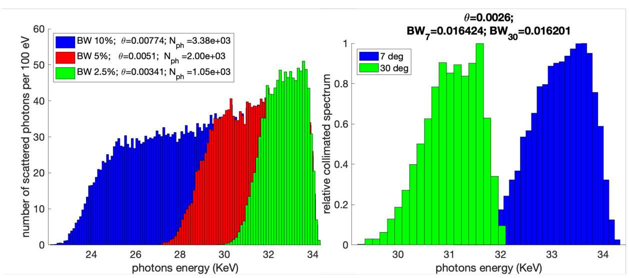

Figure 2: Right: Spectrum of the X-ray: distribution of the scattered photon number as a function of the photon energy for different bandwidth values. Left: Spectrum of the two color X radiation vs photon energy.

Table 2: Radiation parameters, (1) $1/(m^3 \mathrm{bw}\%)$

γ-ray Parameter	1	2
Mean photon energy(keV)	32.68	29.34
Bandwidth rms [keV]	0.8	2.9
Collimation angle (mrad)	3.35	7.7
Nominal photons per shot	10^4	10^4
Collimated photons per shot	10^3	3×10^3
Rms size(μm)	47	37
Rms divergence (mrad)	2.3	4.8
Pulse length (ps)	3.26	3.26
Peak brilliance (*) ($\times 10^{13}$)	3	0.6

gion of the arc is occupied by undulators and Thz cavity of the Free-electron Laser Oscillator TerRa [24]. The two undulator sections have 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. The code GENESIS 1.3 [25] has been used, coupled to a tool for the radiation round trip transport taking into account the details of the whole optical line [8], to evaluate the radiation power. Using an electron beam energy E= 40 MeV, the undulators both tuned at λ = 20 µm, mirror loss of 1.5%, extraction at 4%, energy jitters of 0.3%, pointing instability of 100 µm, intra-cavity energy level of one-few hundreds μJ, leading to 3-17 μJ of extra-cavity energy and 0.15-0.7 kW of output average power can be obtained. The radiation parameters are summarized in Table 2. Tuning the two undulator modules at different wavelengths enables the generation of two THz color [26]. The intra-cavity energy reaches levels of 50-500 μJ, delivering therefore to the users 1-100 μJ (0.06-1 kW of average power in each color). The THz radiation is then delivered to users Table 3.

Table 3: Characteristics of the radiation at λ = 20 µm and λ = 35 µm. IC: intra-cavity, EC: extra-cavity. Mirror Losses= 2 × 1.5%. Extraction 4%. Repetition rate= 46.4 MHz

Wavelength(µm) **Undulator length (m)**	**20** **1.75**	**20** **4**	**35** **1.75**	**35** **4**
Single shot IC energy(µJ)	84	420	250	420
Single shot EC energy(µJ)	3.35	16.8	10.	16.8
Average power(kW)	0.15	0.78	0.47	1.16
Bandwidth (%)	0.65	2.5	1.85	4.2
Size(mm)	2	2.6	2.4	2.8
Divergence(mrad)	2.8	4	4.2	5
Pulse rms length (μm)	635	830	749	1000

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