X-RAY ICS SOURCE BASED ON MODIFIED PUSH-PULL ERLS.

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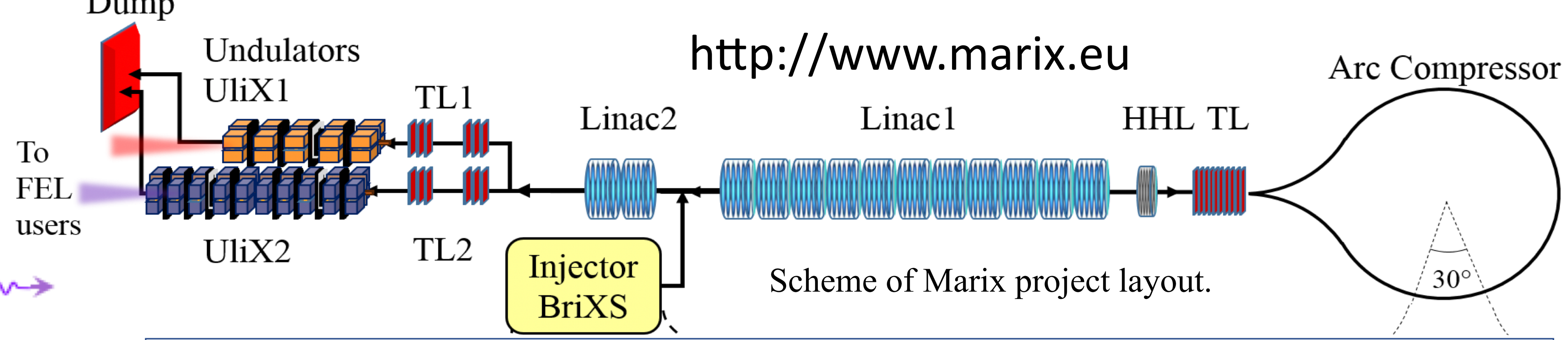


Scheme of Marix project layout.

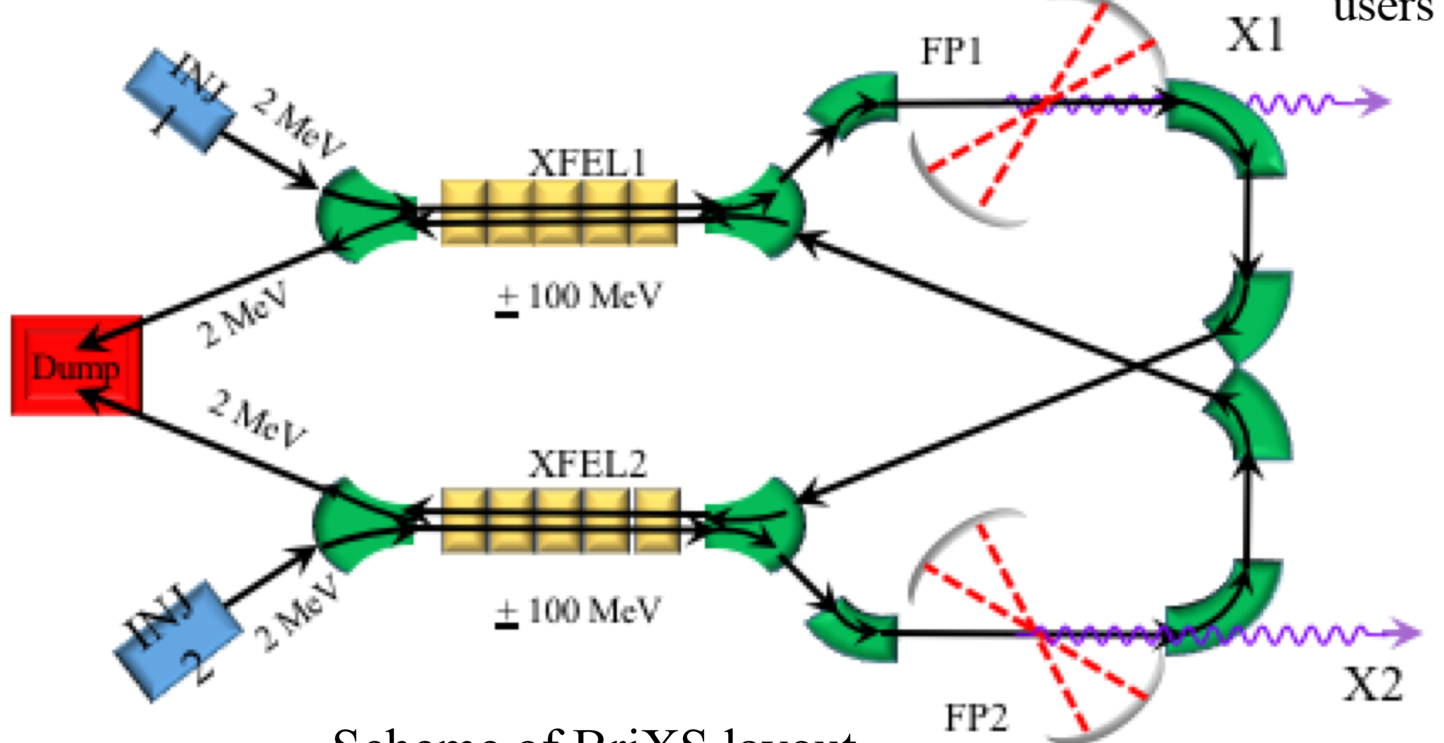
Abstract

We present the conceptual designs of BriXS and BriXSino (a minimal test-bench demonstrator of proof of principle) for a compact X-ray Source based on innovative push-pull ERLs. BriXS, the first stage of the Marix project, is a Compton X-ray source based on superconducting cavity technology with energy recirculation and on a laser system in Fabry- Pérot cavity at a repetition rate of 100 MHz, producing 20-180 keV radiation for medical applications. The energy recovery scheme based on a modified folded push-pull CW- SC twin Linac ensemble allows to sustain MW-class beam power with almost just one hundred kW active power dissipation/consumption.

INTRODUCTION

BriXS (Bright and compact X-ray Source) is a twin Compton X-ray source based on superconductive cavities technology for the electron beam with energy recirculation and on a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz, producing 20-180 keV radiation.
It has been conceived as the first acceleration stage of the X-ray FEL MariX. MariX is an X-ray FEL based on the innovative design of a two-pass two-way superconducting linear electron accelerator, equipped with an arc compressor to be operated in CW mode at 1 MHz.
The double Compton X-ray sources will operate at very high repetition rate 100 MHz, with 200 pC electron bunches that means very high average current 20 mA.
These Compton sources are designed to operate with an electron energy range of 30-100 MeV, which for a 20 mA of current means 2 MW. Such a high beam power cannot be dumped without deceleration, and together with the CW (Continuous Wave) regime, it justifies to foresee an ERL (Energy Recovery Linac) machine, like in the CBETA ERL project.
The focus on enabled applications by such an energy range and brilliance is on medical oriented research/investigations, mainly in the radio-diagnostics and radio-therapy fields [4], exploiting the unique features of monochromatic X-rays, as well as in micro-biological studies, and, within this main-stream, material studies, crystallography and museology for cultural heritage investigations. In this paper, the layout and the typical parameters of the BriXS X-ray source will be discussed.

MACHINE LAYOUT



Scheme of BriXS layout.

The BriXS layout consists of two symmetric beam lines, fed by two independent photoinjectors, where two equal and coupled Energy Recovery Linacs (ERL) accelerate the electron beams. Electron trains are extracted from the photo-cathodes Inj1 and Inj2. The two ERLs accelerate and decelerate the electron trains in an unconventional push-and-pull scheme. Bunches from Guns and travelling right away in the Figure are accelerated, those coming back from the interaction points (IPs) are decelerated during the energy recovery phase and brought simultaneously to a single beam-dump. Each Linac is therefore traversed by two counter-propagating trains of electron beams, both gaining and yielding energy. This push-and-pull coupled scheme permits to concurrently drive two Compton X-ray sources with the same degrees of freedom, in terms of energy and electron beam quality, as a Linac driven source, with the advantage that the coupled ERLs scheme, fed by two independent RF, systems is more stable. CW electron Guns, capable to produce such an average beam current, are not yet state of the art. Some of the most promising photo cathode Guns as the Cornell DC Gun and the RF-CW Apex Gun have been therefore compared by simulations. Considering the simulations results was chosen the APEX one. Partial modifications of the beam lines to host additional Compton interaction points are under study.

Electrons mean energy [MeV]	30-100
Bunch charge [pC]	100-200
Nominal normalized ϵ_{nx}, ϵ_{ny} [mm mrad]	0.6-1.5
Nominal relative energy spread σ_e %	$10^{-2} - 10^{-1}$
Focal spot size σ_x,σ_y [μm] %	19.4-23.4
Bunch length rms [μm]	400-900
Repetition rate [MHz]	100

ACCELERATOR SECTION

To provide the required 100 MeV maximum energy, we need to consider two important aspects for the selection of the accelerating structure, namely the requirement for RF operation and the effect of the induced High Order Modes on the beam quality. The choice of the BriXS accelerating structure is determined by the above considerations and by the performance already achieved in structures used in installations similar to BriXS with accelerating gradient of at least 16 MV/m..
In order to contain the overall module footprint, a solution adopting a single cryomodule hosting the required number of cavities is preferable. This would suggest to explore the opportunities offered by the six-cavities CBETA cryomodule given its demonstrated performance. However, with a 0.81 m single cavity active length, the CBETA cryomodule would yield a 77.8 MeV energy gain when operated at 16 MV/m accelerating gradient. An eight 7-cells cavities geometry CBETA cryomodule appears to be needed to fulfill the energy gain requirements for BriXS. It is clear that, while the CBETA cryomodule remains a reference design, dedicated developments are needed for the current project.
Dealing with the cryogenics losses we need to include the dynamic losses as well as the HOM power. The cryogenic dynamic losses per single cavity, based on the previous parameter set, are expected to be 9.3 W. For the HOM power, in the non-resonant monopole case, the CBETA cavity has a longitudinal loss factor of 14.7 V/pC. Based on this parameter, the estimated loss power is 117 W per cavity. This value can be reasonably handled by a CBETA-like solution for the HOM absorber made of SiC material and with a cooling jacket held at 80 K. It is then clear that, if we opt to start from a proofed and operating cavity and cryomodule design, the CBETA layout guarantees these points and allows a smaller total length with respect to a solution like ERL(KEK). It is worth noting that modifications of the original CBETA design are necessary to reach the requested 100 MeV energy gain by implementing an 8 cavities per module structure.

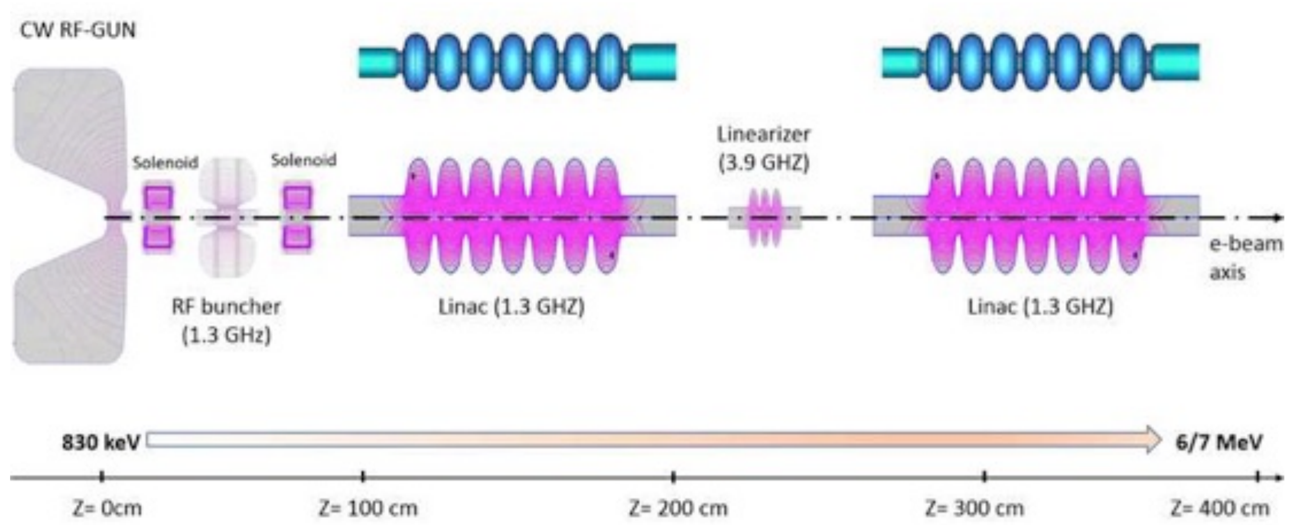
On the cavity side, we should keep in mind that the 2×10^{10} unloaded quality factor is achieved by operating the cavity at 1.8 K, while we are now aiming at operating BriXS at 2.0 K. While the CBETA cavity has shown to reach our specification also at 2.0 K, we are now considering to introduce an Electro Polishing process in the cavity treatment procedure (well established in the XFEL production). This will help achieving BriXS higher Q_0 values and will give us more confidence in reaching the design unloaded Q value.

Table 1. BriXS cavity operational parameters.

Parameter	Value
Accelerating structure	Standing Wave
Accelerating mode	$TM_{0,1,0}$ π
Fundamental frequency [GHz]	1.3
Energy gain per cavity [MeV]	12.5
Accelerating gradient E_{acc} [MV/m]	15.6
Intrinsic quality factor Q_0	2×10^{10}
Loaded quality factor Q_{load}	3.25×10^7
Cavity half bandwidth at Q_{load} [Hz]	20
Operating temperature [K]	1.8 (2.0)
Number of cells	7
Active length [m]	0.810
R/Q (fundamental mode) [Ohm]	774
RF power per cavity [kW]	2.85
Dynamic cryogenic losses per cavity [W]	9.3
HOM cryogenic losses per cavity [W]	117
Cavity total longitudinal loss factor for σ = 0.6 mm [V/pC]	14.7
Q [pC]	200.0
f_{bunch} [MHz]	100
Average current [mA]	20

INJECTOR

Two twin injectors are present in BriXS. The injector layout of the BriXS/MariX common acceleration beam-line, is composed of the following accelerating and focusing elements: 1. The CW RF Gun; 2. Two focusing solenoids; 3. One RF buncher; 4. Two linear accelerators; 5. One RF linearizing cavity. Being two identical beamlines, we show and discuss only one from here on for simplicity. The RF power source for each component of the BriXS injector operates in CW, since the high repetition rate (100 MHz) electron beam reaches an average power of 120 kW at the exit, i.e. energy up to 6 MeV and average current of 20 mA. Therefore, the choice of the RF system is based on the maximum average RF power that can be handled by the RF devices. The CW RF-Gun and the RF Buncher are based on normal conducting (NC) technology, since the RF power dissipated inside the cavities, required to accelerate and to bunch the electron beam with an energy of about 800 keV at the beginning, can be still handled by using standard water-cooling systems. The APEX Gun has already shown operation at about 87 kW of average dissipated RF power with the possibility to operate even up to 100 kW . As for the two linacs and the RF linearizer, where the high rep-rate beam is accelerated up to at least 6 MeV, we have decided to use superconducting (SC) technology since standard copper structures are not able to dissipate the high average RF power that would be required. Indeed, the cavity wall power consumption inside a SC structure is lower than a NC one by a factor of $10^5 - 10^6$.

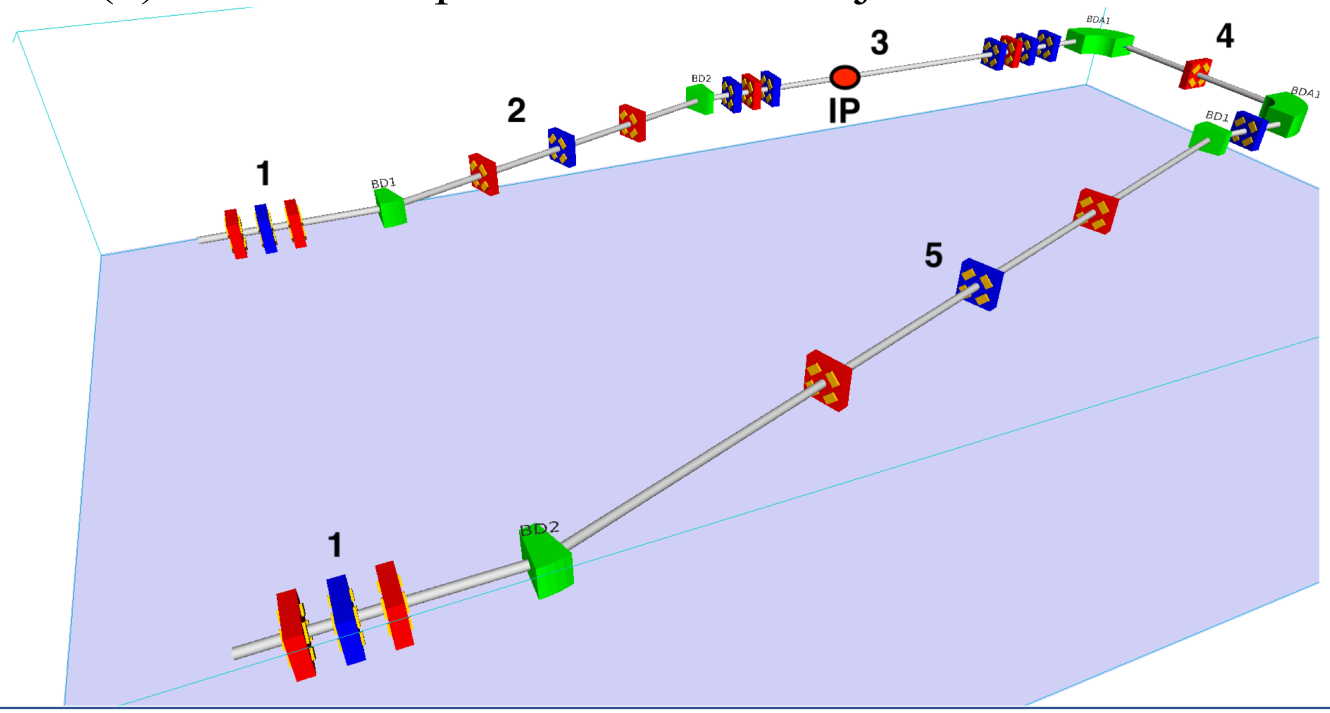


ELECTRON BEAM LINES

Each branch of the two BriXs beam lines includes the following sections:

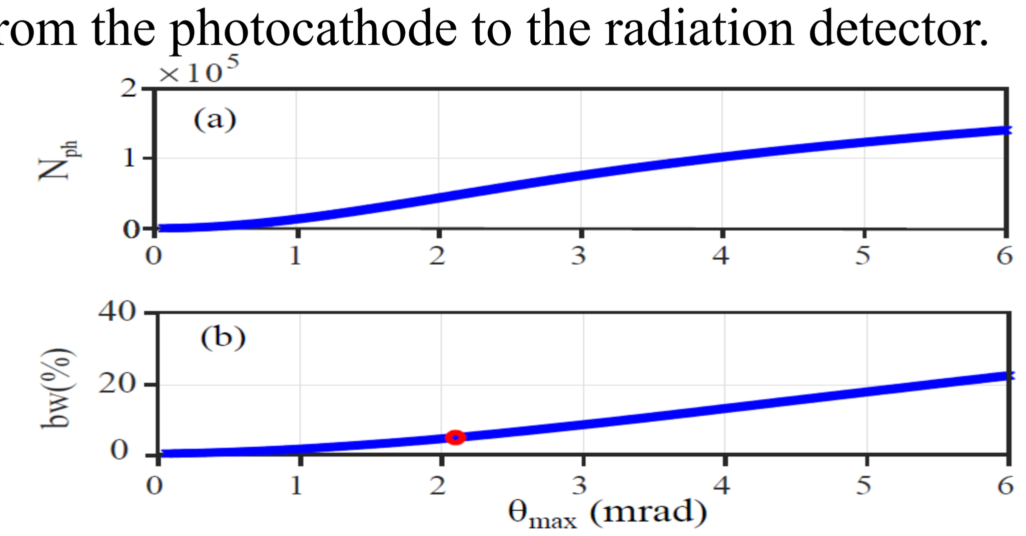
1. a quadrupole triplet, located downstream the SC Linac ERL1, matches the beam to the first chicane and allows for quadrupole-scan emittance diagnostic; electron bunches travel through these elements in both directions, outgoing from the accelerator or backwards from the specular path;
2. a dog-leg chicane, composed of two 20° dipoles and three quadrupole lenses closing the chicane dispersion, transports the beam to the IP line;
3. the IP region includes two strong focusing triplets, symmetrically installed w.r.t. the IP, and the about 1 m long Fabri-Pérot Optical Cavity. This section has identity transport matrix, so different focusing settings at IP can be adopted without affecting the magnetic elements downstream.
4. a double bend achromat (*DBA*) section with two 90° dipoles and three quadrupoles deflects the beam by 180° and closes the dispersion at its end;
5. a long dog-leg chicane with two 20° dipoles translates the beam to the second SC Linac; the triplets provide control of the clearance between the first quads to avoid interference at the X-cross of the two beam lines;

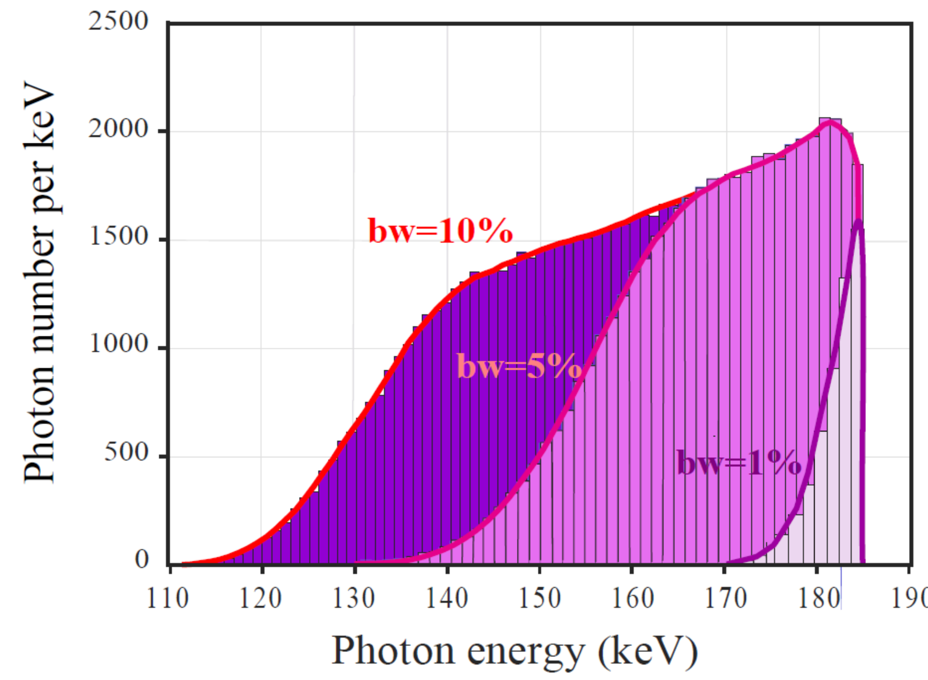
Each of the electron beam lines has been designed so that the dispersion is closed at the IP region, at the exit of the DBA (4), where a diagnostic station will be installed, and at the exit of the second chicane (5) in order to optimize the beam injection in the ERL.

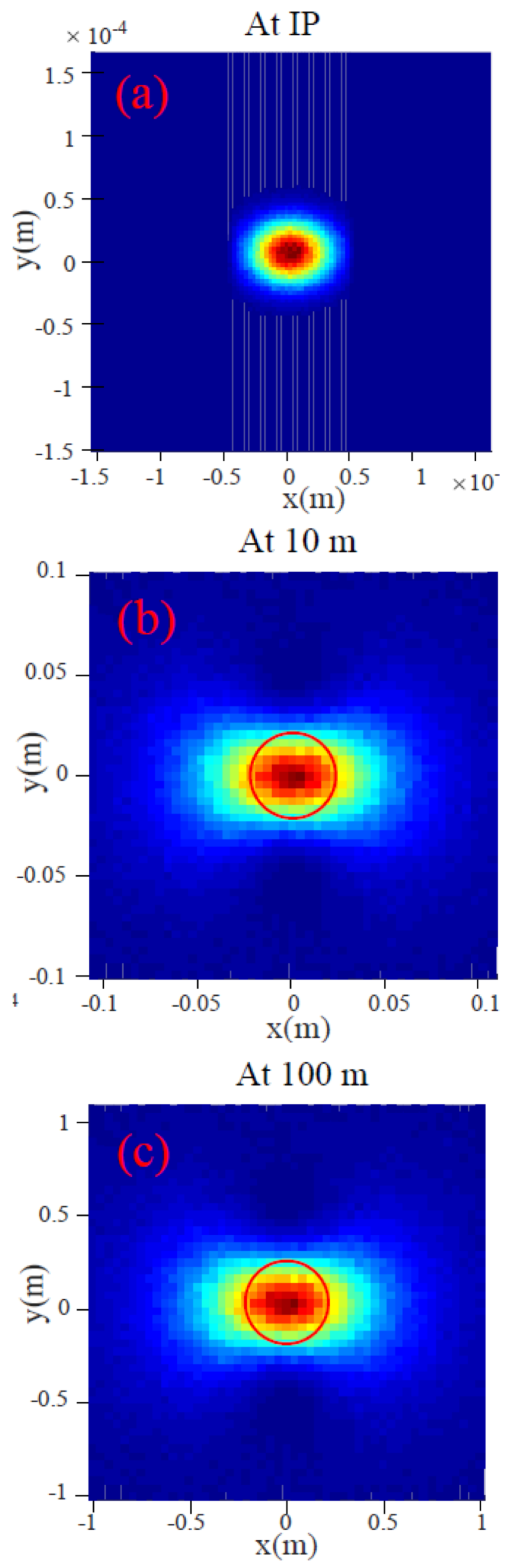


EXPECTED PERFORMANCE

The working point is the result of a full start-to-end simulation along all the BriXs electron beam line, from the photocathode to the radiation detector.







Electron Beam Parameters			
Electrons mean energy (MeV)	100		
Bunch charge (pC)	200		
Normalized emittance $\epsilon_{nx}, \epsilon_{ny}$ (emitt)	1.2, 1.2		
Relative energy spread σ_E/E	1.6×10^{-2}		
Bunch length rms (μm)	440		
Focal spot size σ_x, σ_y (μm)	19.4, 23.4		
Repetition rate (MHz)	100		
Laser Parameters			
Laser pulse energy (mJ)	7.5		
Laser wavelength (nm)	1030		
Laser pulse length (ps)	2		
Laser focal spot size w_{0x} (μm)	40		
Laser focal spot size w_{0y} (μm)	80		
Collision angle (deg)	7		
γ-ray Photon Beam Parameters			
Relative bandwidth rms %	1	5	10
Absolute bandwidth rms (keV)	1.98	8.66	16.01
Absolute bandwidth FWHM (keV)	3.51	22.7	47.67
Collimation angle θ_{max} (mrad)	0.6	2.08	3.3
Peak photon energy (keV)	183.4	182.4	180.4
Mean photon energy (keV)	181.0	170.4	158.7
Photon number per shot N_{Tot}	2.5×10^5		
Photon number per shot after collimation N_{ph}	5×10^3	4.7×10^4	8.4×10^4
Source rms size $\sigma_{\gamma x}, \sigma_{\gamma y}$ at IP (μm)	19.6, 16.7		
Source rms divergence $\sigma_{\gamma X'}, \sigma_{\gamma Y'}$ (μrad)	0.3, 0.3	1.0, 1.0	1.6, 1.3
Source rms divergence θ_{rms} (μrad)	0.42	1.41	2.08
Spot Size at 10 m (mm)	3.0, 3.0	10.5, 9.44	16.3, 13.0
Rad. pulse length $\sigma_{\gamma z}$ (ps)	1.35		

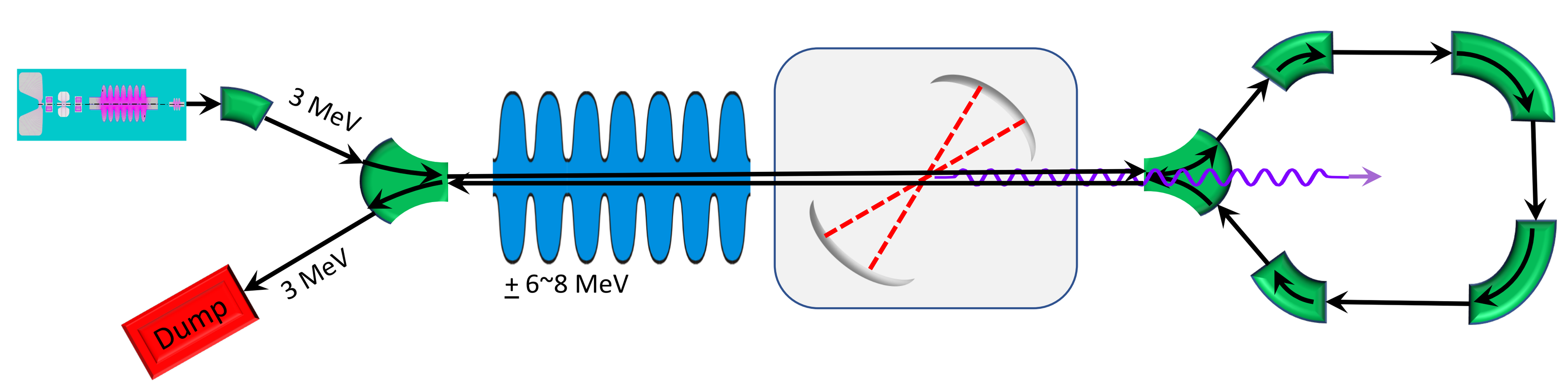
BriXSino, as a reduced scale demonstrator of the modified push-pull folded ERL scheme.

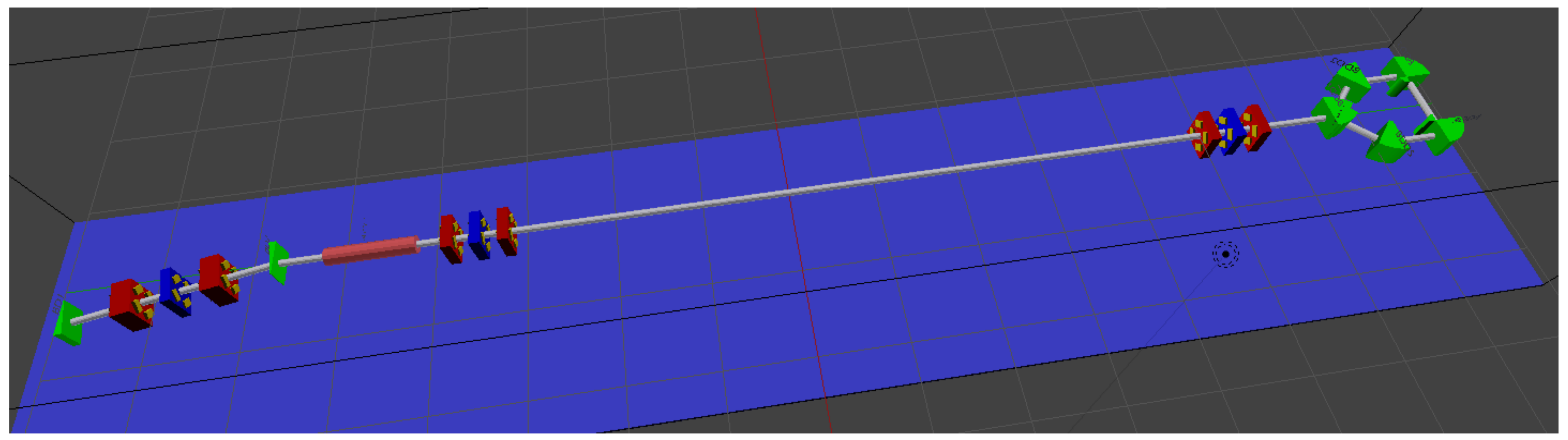
The specific goal of this demonstrator compact machine is to investigate RF mode stability issues in the CW energy recovery operating mode at high average current and very high repetition rate for the electron beam (up to 100 MHz), and related impacts on the electron beam quality (emittance, energy spread) due to beam break-up effects and beam loading.

The main issues to be addressed by the test-bench demonstrator BriXSino include:

a) Achievement of electron beam quality (emittance, energy spread), as requested by an optimal luminosity in the ICS.
b) Stability of RF, phasing and timing of beam energy recovery in the folded push-pull ERL scheme.
c) Photo-cathodes and RF-Gun capabilities to generate 100 MHz electron beams.
d) Beam quality preservation with and without ERL (beam-breakup, beam loading).
e) Options of two-color ICS generation.
f) Radio-protection evaluation with deaccelerated beam after energy recovery.

BriXsinO





CONCLUSION

In this paper the conceptual design of the compact X-ray Source BriXS (Bright and compact X-ray Source) is presented. BriXS , the first stage of Marix project, is a Compton X-ray source based on superconducting cavities technology for the electron beam with energy recirculation and on a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz, producing 20-180 keV radiation for medical applications. An energy recovery scheme based on a modified folded push-pull CW-SC twin Linac ensemble allows to sustain MW-class beam power with almost just one hundred kW active power dissipation/consumption. $5 \times 10^4 - 10^5$ collimated photons per shot in a bandwidth of 5 − 10% are produced with 10^8 repetition rate for a total amount of more than 10^{13} photons per second, a performance comparable to the most advanced X-rays sources. A further option is the production of two color radiation for imagine application.