Injector design for the MariX-FEL project

L. Faillace, A. Bacci, A. Bosotti, S. Cialdi, I. Drebot, P. Michelato, L. Monaco, V. Petrillo, M. Rossetti Conti,
R. Paparella, A.R. Rossi, D. Sertore and L. Serafini, INFN-Milan and LASA, Milan, Italy.

Abstract

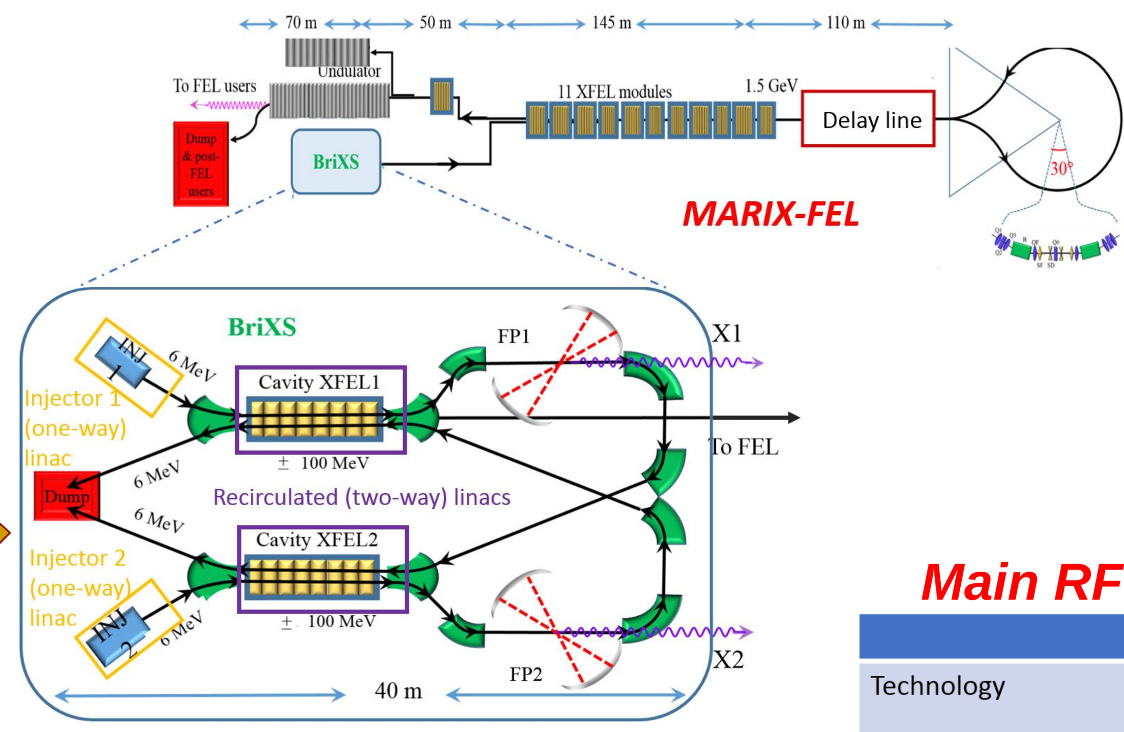
The MariX project (Multi-disciplinary Advanced Infra-structure for Research with X-rays) is a free electron laser (FEL) light source proposed by the INFN-Milan. It will produce highly coherent X-rays, in the range 0.2-8 keV, with ultra-short pulses (10-50 fs) and a repetition rate up to 1MHz. At the same time, MariX will host a compact monochromatic X-ray source, called BriXS, by using an inverse-Compton scattering scheme, with energies up to 180 keV and a repetition rate of 100 MHz (continuous-wave CW operation) that will generate fluxes up to 10^{13} photons per second.

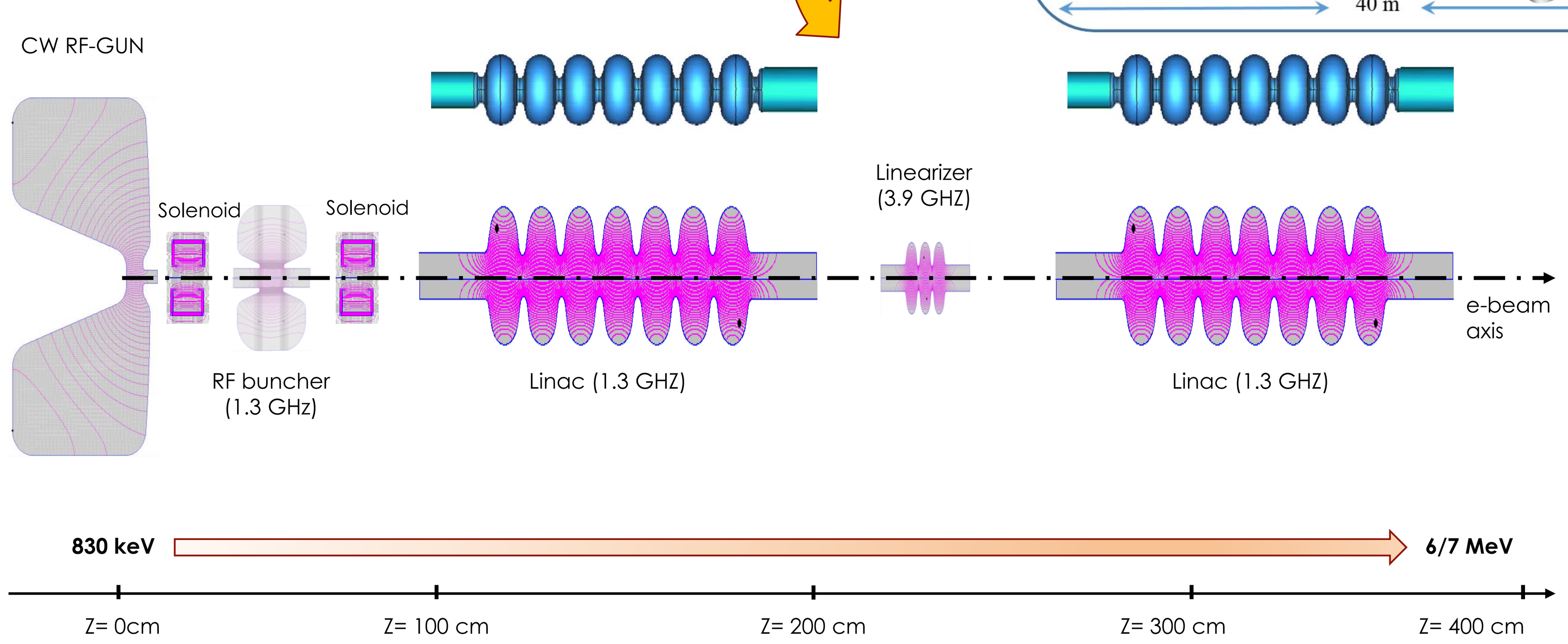
In this paper, the Radio-Frequency (RF) and beam dynamics designs of the electron injector for the MariX-FEL project are presented. The choice of the main devices, such as the electron gun and the accelerating linear accelerators, as well as the main parameters for CW operation are discussed in details.

Injector Layout

Two twin injectors are present in BriXS. The injector layout of the BriXS/MariX common acceleration beamline is composed of the following accelerating and focusing elements:

1. The CW RF gun (Apex-I like);
2. Two focusing solenoids;
3. One RF buncher;
4. Two linear accelerators (linacs);
5. One RF linearizing RF cavity.





- **Photo-injector Main Requirements**
  - High Average beam current (>20mA for the Compton)
  - High QE (>0.5%)
  - Low emittance (<0.5μm for the FEL)
- **Current Technologies**
  - CW DC-Gun (<500kV)
  - CW RF Gun (operating at sub-harmonic,<187MHz)
  - Superconducting RF (SRF) multi-cell gun

Main RF Parameters

	CW RF-Gun	Buncher	Linac I	Linearizer	Linac II
Technology	Normal Conducting	Normal Conducting	Super Conducting	Super Conducting	Super Conducting
Frequency (MHz)	187	1300	1300	3900	1300
Effective Shunt Impedance per unit length (Ω/m)	162.5E6	37.5E6	2.0E13	3.46E13	2.0E13
Effective Shunt Impedance (Ω)	6.5E6	17E6	1.61E13	6.91E12	1.61E13
Quality Factor Q_0	30880	25000	2.0E10	3.46E10	2.0E10
Accelerating Voltage V_{acc} (MV)	0.83	0.35	3.26	1.2	3.8
Gap Length (cm)	4	16	100	20	100
Accelerating Gradient E_{acc} (MV/m)	20.75	2.1875	3.83	6	4.47
Injection Phase *inj* (°)	-3.8	-80.1	11.05	-156.5	22.7
Energy Gain (MeV) [$=V_{acc}\cos(inj)$]	0.83	0.06	3.2	-1.1	3.5
Cavity wall dissipation power (W), beam OFF	87500	7200	0.64	0.37	0.76
Total RF power (W), beam ON	102500	~7200	64000	22000	70000
RF power supply	>100kW CW Triode	<10kW CW IOT	100kW CW Klystron	<30kW CW IOT	100kW CW Klystron

Comparison of different types of e-guns

CW DC-Gun	CW RF-Gun	SRF multi-cell gun
DC Voltage (<500 kV, Cornell)	Low frequency (187 MHz, APEX)	High Frequency (1.3GHz, bERLinPRO)
Gradient at cathode is limited (E_{peak}=6MV/m)	Gradient at cathode is higher (E_{peak}=20MV/m)	Gradient at cathode is higher (E_{peak}=30MV/m)
Multipacting, ion-back-bombardment and dark current are under control.	Multipacting, ion-back-bombardment and dark current are under control.	• Multipacting, ion-back-bombardment and dark current need to be under control. • Implications due to high QE cathode/ SRF cavity interface → impact on cavity performance
Lower output energy (300keV) → Higher space-charge	Higher output energy (800keV) but possible upgrade to multi-cell (APEX-II, >2MeV) → Lower space-charge	Higher output energy (up to 2.3MeV) → Lower space-charge
• 0.4/0.6 μm emittance@100/300 pC (@injector exit <9MeV) • Stable operation at high average current (>100mA, laser reprate 1.3GHz)	• 0.4/0.6 μm emittance @100/300 pC (@injector exit <9MeV) • Operation at low average current (<1mA limited by their laser reprate at 1MHz)	Prediction: 100mA, 1mm-mrad

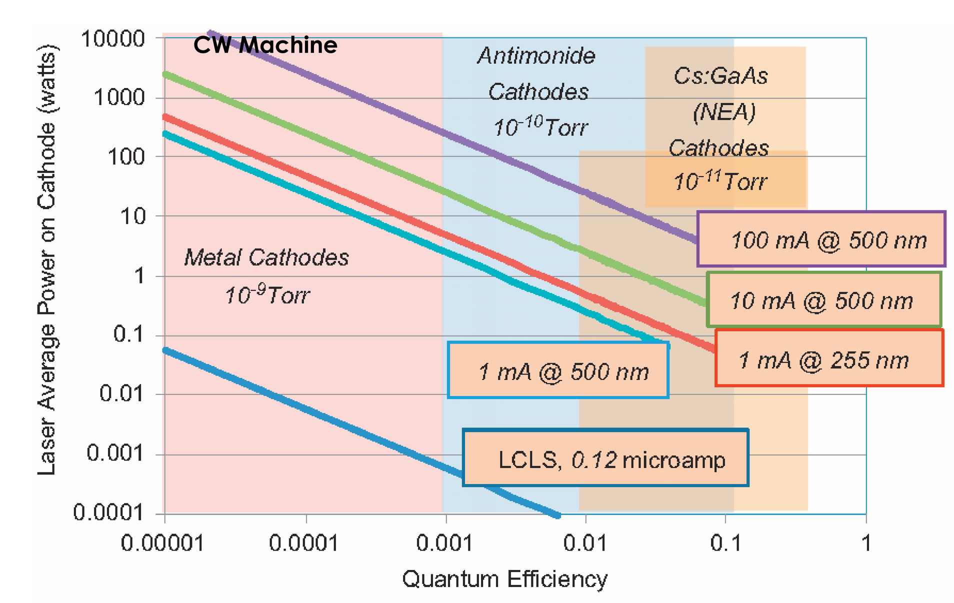
- Extensive beam dynamics simulations were performed by using ASTRA, GIOTTO and PARMELA.
- As a result, the APEX Gun offers more flexibility in terms of beam handling, i.e. matching and transport through the magnetic devices and accelerating cavities.
- Moreover, it permits higher density beam current extraction from the cathode which results in lower intrinsic emittance for the same charge and laser pulse width due to higher accelerating field.

Cathode and Laser Parameters

- Semiconductor photocathodes have higher Quantum Efficiency (QE) than metallic ones;
- Their sensitivity to gas exposition requires UHV conditions.
- Requirements inside an electron Gun:

1. QE uniformity
2. Low dark current
3. Long operative lifetime
4. Stable operation along the train
5. Fast response time

$$QE = 1240\,\frac{\langle I\rangle(Amperes)}{P_{laser}(watts)\times\lambda(nm)}$$



- High QE photocathodes (like Cs_2Te) have typical QE ≥ 10 % (fresh cathode, λ = 254 nm), good spatial uniformity and high robustness. UHV condition needed. @LASA (INFN-MI)
- With λ = 262 nm (E_{ph} = 4.7 eV), with a conservative value of QE = 0.5 % (Cs_2Te) to produce 200 pC → Laser Pulse Energy = 19.1 nJ corresponding to Laser Power = 19.1 W (at 100 MHz)

$$\varepsilon_{th,min} = \sqrt{\frac{Q}{12\pi\varepsilon_0 mc^2}\,\frac{\hbar\omega-\phi}{E_{rf}}}$$

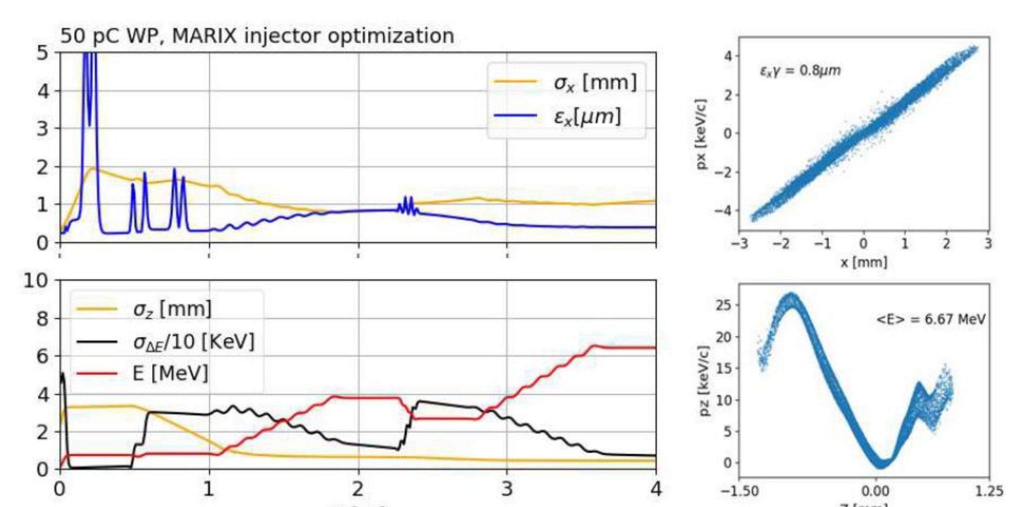
material	Eg + Ea (or ϕ)	λ laser	ε_{th} (Formula)	ε_{th} (Exp.)	QE (%)
Cs_2Te	3.5	264 nm	0.9	0.5 ± 0.1	10
K_2CsSb	2.1	543 nm	0.4	0.36 ± 0.04	5
Cu	4.6	250 nm	0.5	1.0 ± 0.1	$1.4\ 10^{-2}$

Beam Dynamics

- Electron source: RF (186MHz) CW RF photo-Gun working at 20MV/m peak electric field;
- A single coil short solenoid (at 20 cm from the cathode) controls both the beam envelope and the beam emittance (space charge regime);
- A normal-conducting 1:3 GHz single RF cell buncher (53 cm downstream the cathode) correlates the electron energy with their positions → ballistic bunching into a 90 cm long drift between the buncher itself and the first linear accelerating cavity (Linac).
- A second solenoid similar to the first one is also dedicated to envelope and emittance control;
- A 7-cell, 1.3 GHz SC Linac brings the beam energy up to 3.8 MeV;
- A 3.9 GHz three-cell SC cavity (third harmonic linearizer, at 2.2 m downstream the cathode), is used to pre-correct the RF curvature and the bunch current profile via a mild deceleration of about 1MeV;
- A second 7-cell accelerating cavity, downstream the linearizer, brings the beam energy at about 6.5 MeV;
- The injector exit energy is chosen to be lower than the photonuclear neutron production threshold (about 7MeV for heavy metals) and it is also the dump energy.

Q=50 pC
σ_x=200μm
Bunch length ~40ps (18.7°)

Input beam



Q=200 pC
σ_x=420μm
Bunch length ~48ps (22.5°)