Injector Design for the MariX-FEL Project

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Abstract. The MariX project (Multi-disciplinary Advanced Infrastructure 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 (Bright and compact X-ray Source), 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 detail.

1. Introduction

Among all most advanced Synchrotron and FEL light sources currently proposed and/or operating worldwide, there is a strong scientific requirement for an innovative type of source that would provide 10 fs pulses of $10^8$ photons at 1-2 MHz, as discussed in detail in [1]-[3], [10]. The source proposed here, MariX (Multidisciplinary Advanced Research Infrastructure for the generation and application of X-rays) [2], 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 for research in many diverse science domains and applications. The MariX accelerator complex includes a two-pass FEL with arc compressor for high brilliance X-ray pulses and an advanced compact monochromatic X-ray source, called BriXS, which uses an inverse-Compton scattering scheme and reaches energies up to 180 keV and a repetition rate of 100 MHz (continuous-wave CW operation) with fluxes up to $10^{13}$ photons per second [8].

In this paper, we discuss the main layout including the Radio-Frequency (RF) and beam dynamics designs of the electron injector for the MariX-FEL project. 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.

2. Injector Layout

The injector layout is a dual system composed of two symmetric beam lines, fed by two independent photoinjectors, where two equal and coupled Energy Recovery Linacs (ERL) accelerate the electron beams [4][5], as shown in Figure 1. The two ERLs accelerate and decelerate the electron bunches in an
unconventional push-and-pull scheme. The injector output electron beams, with energy of 100 MeV, are either sent to the FEL, with a repetition rate of 1 MHz, and to BriXS, the Compton source, with a higher repetition rate up to 100 MHz. Because of such high repetition rates (Continuous Wave CW-mode operation), the whole machine accelerating system is mainly based on superconducting (SC) technology. There are two main reasons for choosing such a dual ERL system. First, we have the possibility of operating two Compton lines at the same time. Second, the scheme offers more stability since two independently fed RF beamlines give extra knobs in the case of a failure on one of the two.

Figure 1: Sketch of the BriXS layout: From the left side: Inj1 and Inj2: photocathodes. ERL1 and ERL2: Superconducting Linacs. FP1 and FP2: Fabri-Pérot cavities. IP1 and IP2: interaction points. X-ray1 and X-ray2: X rays beams, going towards Compton users areas.

In this paper, we will discuss only one injector line for simplicity. The injector layout is sketched in Figure 2. It is composed of the following accelerating and focusing elements: 1. The CW RF Gun for generation of high repetition rate electron bunch trains (up to 100 MHz); 2. Two solenoids for beam focusing; 3. One RF buncher for beam ballistic bunching; 4. Two linear accelerators (linacs) to energize the electrons up to 6-7 MeV; 5. One RF linearizing RF cavity for longitudinal phase-space manipulation.

The electron beams which are sent to BriXS will reach an average power of 120 kW at the exit, i.e. energy up to 6-7 MeV and average current of 20 mA, while the electron pulse train for the FEL will have an average power of about 300 W, i.e. energy up to 6-7 MeV and average current of 50 μA. The injector exit energy is kept below neutron activation in order to use a standard beam dump design.

Figure 2: Injector layout for 1 beamline, SuperFish 2D model.
All main RF parameters for the devices used in the injector and RF power supplies are listed in Table 1. The RF power required by the elements represents the major part of the RF power needed for the whole MariX machine. The main reason is due to the fact that the injector is a one-way acceleration beamline and therefore no energy recovery scheme is employed.

The CW RF-Gun and the RF Buncher are based on normal conducting (NC) technology (copper structures), 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. As for the two linacs (I and II) and the RF linearizer, where the high rep-rate beam is accelerated up to at least 6-7 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 $10^5$-$10^6$.

Table 1: Main RF Parameters.

| Technology       | CW RF-Gun | Buncher | Linac I | Linearizer | Linac II |
|------------------|-----------|---------|---------|------------|---------|
| Technology       | Normal Conducting | Normal Conducting | Super Conducting | Super Conducting | Super Conducting |
| Frequency (MHz)  | 185.714   | 1,300   | 1,300   | 3,900      | 1,300   |
| Effective Shunt Impedance ($\Omega$) | $6.5\times10^6$ | $9.9\times10^6$ | $1.61\times10^{13}$ | $6.91\times10^{12}$ | $1.61\times10^{13}$ |
| Quality Factor $Q_0$ | 30,880     | 19,100  | 2.0$\times10^{10}$ | 3.46$\times10^{10}$ | 2.0$\times10^{10}$ |
| Accelerating Voltage $V_{acc}$ (MV) | 0.75       | 0.25    | 3.26    | 1.2        | 3.8     |
| Gap Length (cm)  | 4         | 16      | 100     | 20         | 100     |
| Accelerating Gradient $E_{acc}$ (MV/m) | 18.75 ($E_{peak}=19.5$ @cathode) | 1.56    | 3.26    | 6          | 3.8     |
| Injection Phase Inj (deg) | -3.8       | -80.1   | 11.05   | -156.5     | 22.7    |
| Energy Gain (MeV) | ~ 0.75    | 0.04    | 3.2     | -1.1       | 3.5     |
| Cavity wall dissipated RF power (W) | 86,200     | 6,310   | 0.64    | 0.37       | 0.76    |
| Total Input RF Power (W) | ~ 102,000 | ~7,200  | 64,000  | 22,000     | 70,000  |
| RF Power Supply  | >100 kW   | <10 kW  | <100 kW | <30 kW     | <100 kW |

3. Comparison of different types of e-guns

Due to the high repetition of the electron bunch trains, CW electron Guns, capable to produce high average beam currents, have been considered. Some of the most promising photo-cathode Guns as the Cornell DC Gun [11]-[14], the normal conducting RF CW Apex-like Gun[15]-[17] and the bERLinPRO superconducting SRF Gun [18], [19], discussed in detail and explained in Table 2, have been therefore compared by simulations.

Here we list the main requirements for the BriXS/MariX photoinjector:
1. High Average beam current (up to 20 mA);
2. High cathode QE of few percent (>0.5% at $\lambda = 262$ nm);
3. Low emittance (<0.5 $\mu$m for the FEL).

The SRF Gun was excluded apriori, since it is a not well-established technology at the moment. On the other hand, the DC gun and the normal conducting RF gun feature lower electric peak fields at the photocathode, $\sim 4.5$ MV/m and $\sim 20$ MV/m respectively. Therefore, the output beam energy is relatively low, i.e. $\sim 400$ keV for the DC gun and 750 keV for the RF Gun. As a result, the beam dynamics characterization throughout the injector needs special attention, since emittance compensation schemes are more complicated in our present case with high bunch peak currents. Nevertheless, these guns allow for near-CW operation, as it is required by the MariX project.

For this reason, extensive beam dynamics simulations were performed by using ASTRA, GIOTTO and PARMELA. Both the DC and RF CW Guns showed similar performances, which are discussed in the next section. Nevertheless, the APEX-like Gun, with a higher cathode electric field, 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.

### Table 2: Comparison of three types of photocathode 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 ($E_{\text{peak}}=4.5$ MV/m) | Gradient at cathode is higher ($E_{\text{peak}}=20$MV/m) | Gradient at cathode is higher ($E_{\text{peak}}=30$MV/m) |
| Multipactoring and dark current are under control; laser illumination is off-center in order to avoid ion back-bombardment onto the cathode emission area. | Multipactoring, ion-back-bombardment and dark current are under control. | Multipactoring, ion-back-bombardment and dark current need to be under control. |
| Lower output energy (400 keV) $\Rightarrow$ Higher space-charge | Higher output energy (750 keV) but possible upgrade to multi-cell (APEX-II, up to 1.6 MeV) $\Rightarrow$ Lower space-charge | Higher output energy (up to 2.3MeV) $\Rightarrow$ Lower space-charge |
| $\bullet$ 0.4/0.6 $\mu$m emittance@100/300 pC (@injector exit of 9MeV) Stable operation at high average current (measured up to 75 mA, laser reprate 1.3GHz) | $\bullet$ 0.4/0.6 $\mu$m emittance @100/300 pC (@injector exit of 15 MeV) Operation at low average current (<1mA limited by their laser reprate at 1MHz) | Prediction: 100mA, 1mm-mrad |

### 4. Photocathode Choice

We discuss the choice for the photocathode that will be employed inside the CW RF-Gun. The natural choice falls upon semiconductor materials mainly for their high QE in UHV condition, allowing the reduction of the laser power needed to produce the required current, and for their small thermal emittance and their sub-picosecond response time. These materials over the last decades have shown huge improvements in beam brightness inside pulsed accelerating machines; moreover, tests have been done in last years in CW regime Gun showing promising results to satisfy the CW requirements: 1- QE
uniformity; 2- Low dark current; 3- Long operative lifetime; 4- Stable operation along the train; 5- Fast response time.

Considering a Cs$_2$Te photocathode with a really conservative value of QE = 0.5 % at $\lambda = 262$ nm (typically QE at the production $\geq$10 % at $\lambda = 254$ nm), the extraction of an average beam current of 20mA (200 pC and 100 MHz) will be obtained with a laser average power of 19.1 W. These Cs$_2$Te photocathodes, with a very good spatial uniformity, are routinely produced at the Laboratorio Aceleratori e Superconduttivita’ Applicata (LASA) in Milan under UHV condition on polished Mo plugs, due to the Mo good thermal conductivity. The LASA group at INFN-Milan proposed the development of an R&D project of a laser for the photoinjector able to produce UV pulses of the order of few tens of Watts (30 W from initial studies) from a 200 W IR laser pulse. Technical details are given in the MariX CDR report [4].

5. Beam Dynamics

The CW RF photo-Gun (APEX-like), working at 20MV/m peak electric field, was chosen for the MariX project. The RF frequency is $\sim$186 MHz (i.e. the 7th harmonic of the main accelerating frequency of 1.3 GHz). A single coil short solenoid (located 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 resulting in 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. The 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. The reason to have a linearizer at low energy is that it allows easy manipulation of the longitudinal phase space with mild deceleration fields. In particular, it allows to change the bunch current distribution. The minimization of both transverse and longitudinal emittance results into a very symmetric current distribution with a quasi-parabolic current distribution showing in this injector an ideal beam laminarity behavior along the bunch, which in turn allows an optimal transverse emittance compensation. This symmetric current distribution turned out to be beneficial also for the CSR detrimental effects in the bunch compressor [6][7]. 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.

The two simulated cases are for BriXS (beam charge $Q$=200pC, sport size $\sigma_\mathrm{r} = 0.45$ mm, thermal emittance = 0.22 $\mu$m, laser pulse length = 50ps with 1 ps rise time) and MariX (beam charge $Q$=50pC, sport size $\sigma_\mathrm{r} = 0.2$ mm, thermal emittance = 0.1 $\mu$m, laser pulse length = 40ps with 1 ps rise time). The thermal emittance values used in simulations are scaled from actual measurements conducted by the LASA group [20].

In Figure 3 (left), the beam dynamics results for the first case are shown. The final emittance value is close to 0.8 mm-mrad and the bunch envelope is $\sigma_\mathrm{r} \sim 2$mm. A spot size of 2mm for the 200 pC case is not a problem for the following transport line after the injector and before the 100 MeV ERL linac, which will bring the beam into the FP cavity. Here, a dedicated focusing system is designed for an efficient Compton interaction. The plot also shows very well compensated energy spread (in black). The bunch longitudinal compression, $\sigma_z$, is first performed by ballistic bunching then adopting the velocity bunching (VB) technique [21].

In Figure 3 (right), the beam dynamics results for the second case are shown. The final emittance value is lower and close to 0.2 mm-mrad and the bunch envelope is $\sigma_\mathrm{r} \sim 1$mm. The plot also shows very well compensated energy spread (in black).
Figure 3: Left) 200 pC case. The simulated envelope $\sigma_{x}$, emittance $\varepsilon_{x}$ and the transverse phase space (upper part); the bunch length $\sigma_{z}$, the energy spread $\sigma_{\Delta E}$, the beam energy $E$ and the longitudinal phase space (lower part). Right) 50 pC case. The simulated envelope $\sigma_{x}$, emittance $\varepsilon_{x}$ and the transverse phase space (upper part); the bunch length $\sigma_{z}$, the energy spread $\sigma_{\Delta E}$, the beam energy $E$ and the longitudinal phase space (lower part).

6. Conclusions

In this paper, we presented the electron injector scheme for the MariX FEL user facility, which has been proposed at INFN-Milan in Italy. The MariX project employs new acceleration schemes in order to offer a relatively small foot-print facility compatible with a University Campus size. The MariX accelerator complex includes two machines at the same time: a two-pass FEL, with arc compressor for high brilliance X-ray pulses and an advanced compact monochromatic inverse-Compton X-ray source called BriXS.

Here, we discussed the main layout of the electron injector, including the Radio-Frequency (RF) and beam dynamics designs. This injector will have to fulfil two operation regimes: high-average current (20 mA) for the Compton source and low average current (50uA) for the FEL source. The main parameters for CW operation were chosen to satisfy both operational regimes. This showed not an easy task since all devices have to be able to accommodate two types of electron beams with the same layout and possibly at the same time. We also showed of multi-code based start-to-end beam dynamics simulations that demonstrate the feasibility of the proposed acceleration schemes for both the Compton and the FEL sources.

Further details concerning the MariX project and the machine design can be found on the official website [4] and on the Conceptual Design Report of the machine [5].
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