Optimization of the arc compressor performance in the MariX free electron laser

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Abstract. The MariX FEL is a compact GeV-class X-ray source exploiting a two-pass two-way acceleration in a Super-Conducting linac operated in continuous wave mode. A key component of this peculiar machine layout is the Bubble Arc Compressor (BAC), a 300 m long beamline consisting of 14 "Double Bend Achromat" cells and a bidirectional quadrupole focusing channel, which allows the beam to make a U-turn while it is being compressed to greatly increase its brightness and peak current.
In this paper we present the performance of the BAC of MariX and the solutions we adopted to solve the main issues that the beam dynamics encounters in a line of this kind. We show the beam dynamics in the BAC matching line which is designed to operate on beams propagating in both directions, considering the anti-symmetric quadrupole focusing behavior. We study the Coherent Synchrotron Radiation (CSR) emission in the BAC showing a scheme that preserves the low emittance granting also a linear compression in presence of strong CSR effects. Lastly, we present a strategy to correct the residual dispersion-based beam tilt that is introduced by the CSR kick and would otherwise spoil the FEL emission. Further, the projected emittance is minimized cancelling the dispersive contributions.

1. Introduction

Electron beam dynamics studies in arc compressors have been performed in the last two decades mainly in the context of compact Free Electron Lasers (FELs) designs [1] based often on energy-recovery linacs [2, 3, 4, 5], and, more recently, on a two-pass two-way linac [6, 7, 8].
The ACs lattice is based on a series of achromatic cells, specifically Double Bend Achromats (DBAs) or Multi Bend Achromats. The use of arcs as bunch compressors allows to correct cell by cell the effects of the chromatic aberrations and the betatron kicks that are induced by the emission of Coherent Synchrotron Radiation (CSR) in the bending magnets [9, 10].
MariX FEL [11, 12] exploits a new type of arc compressor, called Bubble Arc Compressor (BAC) because of its characteristic shape. This peculiar device is used to increase the peak current of the bunches, up to 100 multiplication factor, while they are U-turned and re-injected in a Continuous Wave (CW) Standing Wave (SW) cryogenic linac booster to double the beam energy gain. The scheme based on the double acceleration in the booster plus the compression and the U-turn in the BAC is the so called two-pass two-way (2P2W) scheme [8].
The beam dynamics of MariX [7] is performed exploiting three different techniques for the
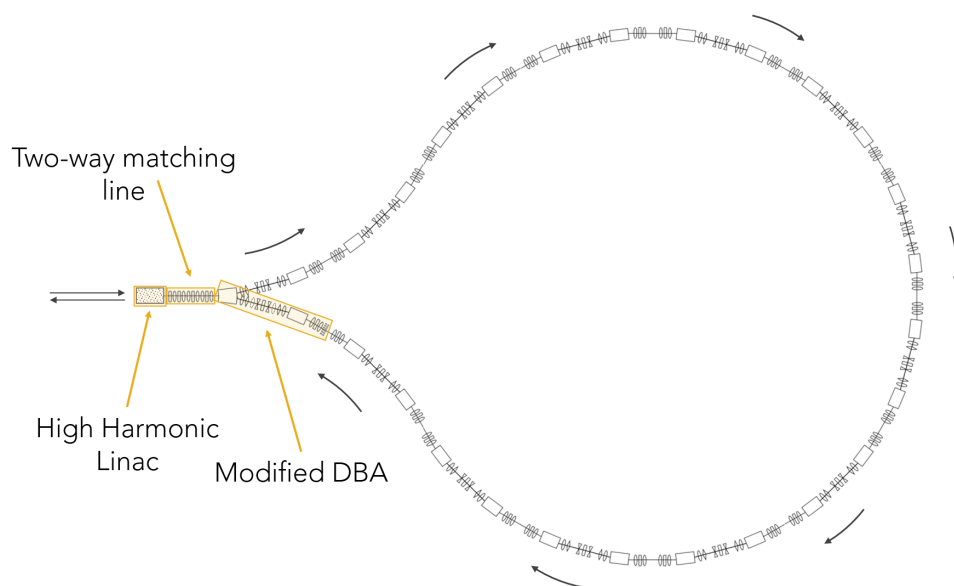
compensation of the effects due to CSR emission in the last phases of compression in the BAC: the innovative use of an high harmonic cavity where the beam is injected in crest, the current profile shaping that is performed in the injector (see ref. [13]) and the optical compensation of the dispersion-based beam tilt acquired at maximum compression as in [14].

This paper is organized as follows: section 2 will introduce the BAC design criteria. In section 3 we will describe how the bi-directional matching line of the BAC have been designed with for the purpose of carrying out a dual beam dynamics which depends on the propagation direction. In section 4 I will describe the strategies adopted to compensate the longitudinal phase space (LPS) distortion induced by CSR. Finally, in section 5 we will show how the betatron kick that takes place in the bending magnets of the last DBA (that could lead to a breaking of the achromaticity of the line) is compensated preventing a dispersion leak that would spoil the FEL emission.

2. The BAC Section

In this paper we will consider as "BAC section" a line longer than 320 m with two-folded geometry (shown in Fig. 1), this section can be divided in 3 subsections considering their purpose.

Figure 1. Scheme of the BAC section of the MariX FEL. The beam is accelerated in the HHL, injected in the two-way matching line, compressed and U-turned in the 14 DBAs composing the BAC, re-injected and collimated in the matching line and accelerated a second time in the HHL.

The first of these subsections is the High Harmonic Linac (HHL), a two-way line composed by a 3.9 GHz TESLA cavity used to accelerate the electron bunches. The effect on a bunch travelling this element for the first time is an increase of the LPS curvature given by the RF. While this is often an unwanted effect, in MariX we exploit it to pre-compensate the curvature (of opposite sign) that is introduced by the CSR emission in the arc. This is possible thanks to the peculiar current profile distribution inherited from the injector beam dynamics (further information can be found in [11]). The second passage introduces a negligible curvature effect thanks to the reduced beam length that is compressed in the arc.

The second subsection is the dual purpose two-way matching line, a 13 m long lattice composed by 10 quadrupoles that is used to match the beam to the BAC during its first passage and to

collimate the beam coming back from the BAC by reducing its divergence. This second task is important because after few tens of meters the beam will be focused by a superconducting solenoid that can introduce an emittance degradation by chromatic effects proportional to the transverse rms size squared.

Lastly, the third subsection is the BAC, ~ 300 m long and composed by 14 DBA cells (a scheme of the DBA cell is shown in Fig. 2). A number of 4 DBA cells are used to bend the beam to the left and 10 to the right, the geometry of these two variants is vertically flipped and the beam dynamics is easily obtained inverting the dipole and sextupole fields and keeping the quadrupole fields values. The 14th DBA have been modified to compensate the CSR betatron kick effects on chromaticity by adding 2 steering magnets at its beginning and 2 quadrupoles in the dispersed region. A summary of the DBAs main parameters is shown in Table 1 and fig. 2.

All the simulations and the optimizations of the BAC section have been performed with elegant code [15] considering a 50 pC electron beam by using 10^6 macroparticles at an energy of 1.5 - 1.6 GeV.

Figure 2. Scheme of a right turning DBA. Black parts are present in all the DBAs, the golden parts are the elements present only in the 14th DBA that controls the dispersion leak, the final three dots represent the remaining 7 quadrupoles of the the matching line.

Parameter	Unit	1st - 13th DBA	14th DBA
Cell length	m	$\simeq 21.8$	$\simeq 21.8$
Dipole bending angle	deg	15	15
Dipole length	m	1.4	1.4
R_{56} per DBA cell	mm	35	35
# dipoles per DBA		2	2
# steerings per DBA		0	2
# quadrupoles per DBA		9	11
# sextupoles per DBA		6	6

Table 1. DBAs and main parameters.

3. Two-way matching line

The two tasks performed by the two-way matching line of MariX (matching to the BAC and collimation of the back-travelling beam) require to match 6 beam parameters at least. Indeed, the line have to match 4 Twiss parameters during the first pass through the line and 2 rms values of the transverse divergence during the second pass (see the parameters in table 2).

The design from scratch of matching lines addressing one of the two tasks could be easily performed like in [16] by an optimization code, but addressing both the tasks together requires coding an ad-hoc optimizer. We therefore chose to use the optimizer of elegant code speeding-up the optimization process.

The peculiarity of this matching line is that it is travelled in both the directions and this makes the beam dynamics more complicated. Indeed, a bunch being focused by a quadrupole at the first passage will be defocused by the same quadrupole when coming back with opposite direction.
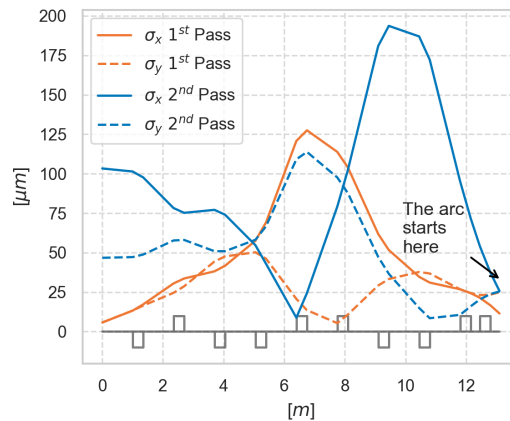
The optimization of this peculiar beam dynamics requires to optimize the first beam passage finding the proper values of the quadrupoles focusing strengths, then to change the sign of those values to optimize the collimation of the back-travelling beam and to continue the alternation of the passages of these two competing processes searching a common solution.

This optimization strategy has been performed initially with a line of 6 quadrupoles and shown to suffer of stagnation due to the competitive nature of the two optimization processes. We solved this problem increasing the number of quadrupoles up to 10 and dedicating some of them (those of even numbers counting them starting from the BAC) in matching to the BAC and the others (the odd ones) in collimating the beam. After that, we iterated the optimizations in a loop until the convergence to a common solution was reached, the final results are shown in Table 2.

In fig. 3 we show the beam envelopes while travelling the line in both the directions.

Passage	Par.	Final val.	Unit
1st pass	α_x	3.18	
1st pass	β_x	2.15	m
1st pass	α_y	-2.21	
1st pass	β_y	10.02	m
2nd pass	$\sigma_{x'}$	2.02×10^{-6}	rad
2nd pass	$\sigma_{y'}$	1.19×10^{-6}	rad

Table 2. Parameters obtained for the dual matching of the beam in the MariX two-way matching line

Figure 3. Tracking of the beam transverse envelopes: during the matching to the BAC (first pass travelling from left to right, orange color); during the collimation phase (line travelled backward second pass, blue color).
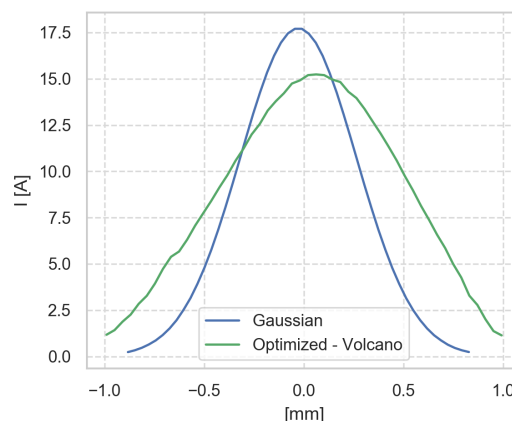
4. Compensation of CSR effects on the LPS

The BAC is used to compress properly chirped electron bunches thanks to the non-zero R_{56} element of the associated transfer matrix. This compression process is the analogue of the one

that takes place in magnetic chicanes and suffers from the same issues; in particular the high power emission of CSR that takes place when the length of the beam becomes comparable with the wavelength of the emitted radiation. This mainly happens in the last DBA where it is emitted more than 60% of the total emitted power by synchrotron radiation.

The particles emitting CSR experience a strong recoil losing kinetic energy, since this effect is collective a relevant shape distortion of the most dense regions of the LPS can be noted.

The initial beam current profile has been shaped in order to better mitigate the effect of this phenomenon: after some tests we chose to adopt a distribution similar to an isosceles triangle blunt at the vertex, called volcano shape (shown in fig. 4).

Figure 4. Comparison between the current profiles of the optimised bunch showing less CSR emission (the volcano shape, in green) and a Gaussian beam (in blue)
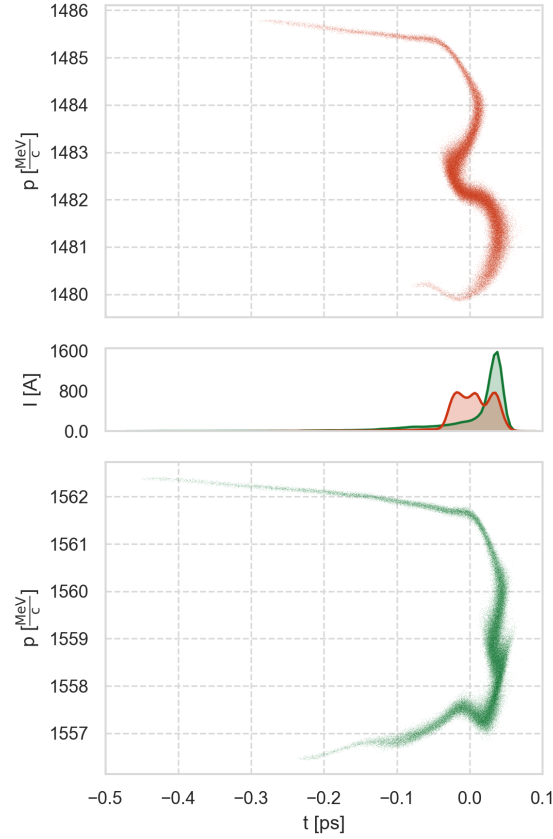
The volcano shaped distribution shown a better behaviour respect to the Gaussian distributions tested before. This difference can be explained considering that elegant code evaluates the CSR emission making use of the 1-D model developed by Saldin ([17, 18]). This model depends not only on the current value of the beam slices but also on the local derivative of the current profile, i.e. the profile slope. The Saldin model has been shown to be a conservative respect to the 3-D models when the Derbenev criterion is met (as in our case) [18]. The difference in the current profile slopes is shown in fig. 4.

The region of the beam experiencing the strongest LPS distortion is the central one, which shows the highest current value. We compensated the effect of this distortion (that shows up as an increased convexity in the central region of the beam) injecting the beam in the HHL in accelerating phase to increase the concavity (via RF-curvature) of the LPS in oreder to pre-compensate the CSR induced recoil. As a result, the LPS after the BAC appears corrected showing a much higher peak current (see fig. 5, note that the energy of the compensated beam is increased by the HHL).

5. Betatron kick compensation

The CSR has two other effects on the beam that are visible in the transverse distribution of the particles. These effects are responsible for a beam emittance increase and for a strong reduction of the FEL efficiency.

The first one is a betatron kick in the horizontal direction (x axis) due to the energy loss of groups of particles in the bending magnet that is translated in a small difference of bending angle. This effect is measurable in an increase of the horizontal beam centroid displacement ($\langle x \rangle$) and horizontal slope of the trajectory ($\langle x' \rangle$, where for a single particle $x' = \frac{p_x}{p_z}$) at the end

Figure 5. LPS obtained at the BAC exit. Top, in red the distribution obtained turning off the HHL. Bottom, in green the case where the CSR effect is pre-compensated by the acceleration in HHL. Middle, a comparison between the current profiles.

of the line.

The second effect is a beam tilt in the z-x plane, it is due to the dispersion leak after the DBA that is induced both by the energy loss of the CSR emitting particles and by the energy re-modulation of the head particles that interact with the CSR wake-field.

It is shown in [14] that the leaking dispersion η_x for a chirped beam (where $|\langle z \cdot p_r \rangle| \gg 0$) leads to a peculiar beam tilt $\mu_x \approx \frac{\langle z \cdot p_r \rangle}{\langle z^2 \rangle} \eta_x$ with $p_r = \frac{p - \langle p \rangle}{\langle p \rangle}$. The presence of the beam tilt leads to a decrease of the FEL emission performance due to the reduction of the overlap between the electron bunches and the FEL radiation field in the undulators. We estimate intensity of this effect with the quantities $s_{16} = \langle x \cdot p_r \rangle$, $s_{26} = \langle x' \cdot p_r \rangle$ that then were used to minimize the beam tilt.

	$\langle x \rangle$	$\langle x' \rangle$	$s_{1,6}$	$s_{2,6}$	$\varepsilon_{n,x}$
Before opt.	13.8 μm	28.46 μrad	-21.56 nm	25.34 nrad	1.00 mm mrad
Optimized	-5.44 μm	-5.14 μrad	0.24 nm	0.54 nrad	0.70 mm mrad

Table 3. Dispersion effects reduction as result of the optimization process.

In particular, we modified the last DBA layout adding two steering magnets at its beginning to center back the centroid on axis and two quadrupoles in the area where the dispersion is open

to correct the beam tilt (golden parts in fig. 2). As result of the optimization of those elements we centered back the beam on axis and reduced the normalized emittance by 30% (see Table 3).

6. Conclusion

In the context of the design study of the MariX FEL a bubble shaped arc compressor has been introduced exploiting the new two-pass two-way scheme [8] to increase the sustainability of the MariX facility. During the design phase of the MariX FEL BAC we solved three main beam dynamics issues: to design a two-pass two-way matching line, to compensate for the effects of CSR emission in beam LPS and to correct the chromatism induced by the CSR emission in the last DBA.

In order to overcome each of these problems we adopted specific design solutions and optimization strategies. In particular, we shown that it is possible to find solutions that grants a dual matching depending on the propagation direction by increasing the number of quadrupoles adopted in the matching line and by separating those in two groups in the optimization phase. Moreover, acceleration in 3rd harmonic and a peculiar current profile shaping can be exploited to reduce the effect of the CSR on the final peak current. Finally, we shown that the CSR based dispersion leak and the consequent beam tilt can be avoided modifying the last BAC DBA by adding two quadrupoles and two steering magnets minimizing the emittance dilution.

Despite the goodness of the results presented in this paper, further studies on the robustness of these solutions have to be carried out keeping into consideration beam jitters; Those studies will be addressed in the context of a future technical design study of the MariX FEL.

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