New approach to space charge dominated beamline design

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This paper presents a new approach to space charge dominated beamline design using an artificial intelligence (AI)-based optimization code named GIOTTO. The code incorporates advanced algorithms for multiobjective genetic optimizations in particle accelerators, allowing efficient exploration of the parameter space and improved beam quality. The study demonstrates the application of GIOTTO in the design of a high-brightness injector for an Energy Recovery Linac (ERL) called BriXSinO. The optimized injector features a low energy (4.5 MeV) and relatively high bunch charge (100 pC) operation. The results show promising beam parameters comparable to other ERL projects. Furthermore, the paper introduces innovative techniques, including bunches back-rotation the use of Lorentzian distributions in the fitness function. The approach successfully achieves dispersion closure in a space charge dominated dogleg. Overall, this work contributes to the advancement of accelerator science, offering a powerful methodology for beamline design and optimization. The new techniques and methodologies introduced have the potential to enhance the performance and stability of particle accelerators in various applications.

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I. INTRODUCTION

Accelerators, serving as essential tools for diverse applications worldwide, have experienced a proliferation of design variations and optimization strategies over the past century. From high-energy light sources with substantial peak and average currents to low-energy, high repetition rate machines, each application requires unique accelerator design approaches and careful performance optimization.

One of the primary challenges in beam dynamics (BD) is effectively controlling space charge effects, which significantly impact the final beam quality. These effects are particularly prominent during the initial stages of the beam's life when the particles energy is low; however, they can also reappear at higher energy levels if the charge density is amplified. Managing beam parameters in such situations becomes complex due to the nonlinear correlations introduced by the presence of space charge.

On the other hand, recent advancements in accelerators design, coupled with progress in computing capabilities, opened up a new era of optimization techniques and methodologies for online tuning and for offline machine design. Particle tracking programs, artificial intelligence (AI), and multiobjective optimizations are now considered essential tools that accelerator scientists should master to explore the full potential of accelerator systems. These optimization tools must be capable of easily adapting to different types of lattices and efficiently simulating a wide range of effects underlying the main beam dynamics challenges.

In this article, we illustrate the enhancements we have made to a tool called GIOTTO [1], a genetic algorithm (GA) specifically tailored for lattice design. We apply GIOTTO to develop a low-energy, high-brightness injector for an Energy Recovery Linac (ERL) based machine called BriXSinO [2–4], developed at INFN research institute.

Many facilities projects are increasingly considering ERLs as a reliable solution [5], as this technology not only significantly increases sustainability but also enables enhanced accelerator performance. For example, evaluations have demonstrated that an ERL-based high-energy e^+e^- collider can rely on higher luminosity and energy at the center of mass. Additionally, light sources can achieve significantly higher average beam currents and, consequently, higher radiation flux [6–11].

ERL injectors have two key features: the need to inject a low-energy beam into the linac to minimize wasted beam power, and the requirement for a merger at the lattice's end, enabling injection into a higher-energy recirculating line.

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Traversing a low-energy dispersive line introduces the challenge of compensating for longitudinal space charge effects on beam optics to preserve the achromaticity of the line, thus avoiding dispersion leakage from the merger. GIOTTO is employed to optimize several main beam parameters at the injector output, with particular attention to transverse emittance and energy spread.

Addressing this specific issue, we aim to demonstrate the suitability of GAs, particularly GIOTTO, for optimizing complex working points in beamlines dominated by space charge effects. As evidence of this, we cite here some recent applications of GIOTTO, where it has been employed to address various challenges. These include designing transfer lines and matching for plasma-based free electron lasers in EuPRAXIA@SPARC_LAB [12,13], positron capture in the FCC-ee injector [14], investigating innovative acceleration and compression techniques in traveling wave cavities [15], and optimizing combed beams dynamics for beam-driven plasma acceleration [16] for EuPRAXIA@SPARC_LAB, among numerous others.

II. OPTIMIZATION METHODOLOGY

Beam dynamics simulations within a gun are always nontrivial due to the intense space charge forces present, especially during the initial moments of beam acceleration. In the case studied here the whole injector beamline together with the dispersive path downstream are affected by space charge forces. For this reason, the simulations reported in this paper have been performed with ASTRA (A Space charge TRacking Algorithm) [17]. Astra is an optimal code to simulate the effects of Coulomb forces, based on two main solvers: a 2D-cylindrical and/or full-3D particle-in-cell (PIC) model.

The beamline optimizations have been instead carried out with GIOTTO (genetic interface for optimizing tracking with optics) [1], a code based on a GA developed and improved in the last two decades. GAs are a class of artificial intelligence (AI) particularly well-suited to handle complex problems in which variables are strongly correlated in a nonlinear way, as is the case in beam electrodynamics [18]. GIOTTO is used here to drive Astra in multiobjective optimizations of beamlines, similar to a MOGA (multiobjective genetic algorithm).

When discussing MOGA, confusion may arise, primarily due to the widespread success of a certain class of MOGA [19]. This class aims to extensively explore the space of possible solutions by scanning multiple search directions to construct the set of Pareto optimal solutions. However, this exploration methodology is much more computationally and time-intensive.

Our typical approach to optimizing multiple objectives is different, involving appropriately shaping the fitness function (FF) by tuning its weights. This imposes a specific search direction in the solution space. This direction can be modified during the optimization process, enabling GIOTTO to identify one of the points within the set of Pareto optimal solutions.

The optimization process involved the tuning of several different beamline knobs, including the velocity bunching (VB) compression technique [20] with the ballistic one and the energy spread compensation. Additionally, the cavities focusing effect was considered by adjusting injection phases and acceleration cavity gradients.

A. Fitness function shaping

GIOTTO has experienced significant development in recent years, enabling it to handle wider solution space explorations. For example, it can now design matching lines from scratch [12].

Choosing the correct shape of the objective functions that are summed together to compose the FF allows driving optimizations in a very wide solutions space. This has played a key role in the recent results obtained with GIOTTO [21,22], as well as those presented in this paper.

Indeed, the optimizations performed are multiobjective and were aimed at minimizing the normalized transverse beam emittance ($\varepsilon_{n,x-y}$), the relative energy spread (σ_E/E), the bunch length (σ_z), and several brand new dispersion parameters (η_{x-y} and η'_{x-y}) described below in eq. (4). In particular, the FF returns the idoneity score I_d of a proposed solution, a score that ideally have to be maximized. The FF is defined as a summation of N Lorentzians:

$$I_d = \sum_{i=1}^{N} A_i \frac{B_i^2}{B_i^2 + (x_{Ti} - x_{Fi})^2}. \tag{1}$$

Lorentzian functions are used to determine the priority with which each objective parameter outputted by the simulation (x_{Fi}) is optimized (i.e., brought close to its target value x_{Ti}). The weight coefficients A_i define the maximum score that is assigned when the target value is reached, while B_i represents the sensitivity of the function on the parameter. This is a consequence of the local function slope and acts on the individual target priority.

The A_i and B_i coefficients are typically chosen to select an exploration direction in the solutions space and to ensure a balanced optimization process that does not favor certain parameters over others. This approach promotes convergence to solutions that effectively optimize all the desired parameters, rather than a subset of them.

Ideally, the user should be able to intervene in the optimization process by adjusting the FF. This allows for a gradual convergence of all desired parameters while still maintaining a balance through the tuning of the A_i and B_i coefficients.

B. Optimization of dispersion with space charge

The tracking code used in this study, Astra, describes particle coordinates using a laboratory Cartesian reference system, where z is the longitudinal coordinate, x is the horizontal, and y is the vertical one. This reference system is specifically designed for linear tracking. Other codes dealing with circular orbits [23], typically used for ring machines, use s instead of z, where s is the longitudinal orbit pointing to the local beam velocity direction. As a consequence, when a bunch undergoes a rotation (e.g., passing through dipole fields), the Astra computed beam parameters are affected by the rotation itself.

Let us consider the longitudinal and horizontal rms bunch size (σ_z and σ_x) of a cigarlike bunch deflected by a horizontal magnetic dipole at some angle θ_x (ignoring any dispersive effects). When using a code with a coordinate system that rotates with the beam trajectory, σ_z and σ_x do not change. On the other hand, as mentioned above, a code working with the laboratory system will compute relevant changes in the σ values, both in beam sizes and momenta (see Fig. 1), or relative parameters, such as the beam emittance.

We overcame this limitation by equipping GIOTTO with a functionality that rotates back bunches at user-defined beamline positions. This allows the beam to be postprocessed. The bunch rotation angle is computed using:

$$\theta_x = \arctan\left(\frac{\langle p_x\rangle}{\langle p_z\rangle}\right), \tag{2}$$

where the $\langle\cdot\rangle$ indicates the mean of a variable. The average values of the beam positions and momenta are calculated and subtracted from the particle coordinates.

The 3D rotation matrix around the y-axis for an angle $\theta = -\theta_x$ [in Eq. (3)] is then applied to the vectors of momenta $(p_x, p_y, p_z)^T$ and positions $(x, y, z)^T$ of each particle; i.e., it is applied as a counterrotation

$$R_y \equiv \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} = \begin{bmatrix} \cos\theta_x & 0 & \sin\theta_x \\ 0 & 1 & 0 \\ -\sin\theta_x & 0 & \cos\theta_x \end{bmatrix}. \tag{3}$$

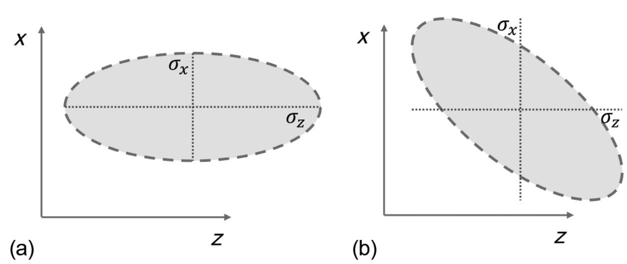

FIG. 1. The figure shows the quantities σ_z and σ_x computed with respect to a static coordinate system before (a) and after (b) a cigarlike beam is deflected (and rotated) by a dipole. It is observed that the measured dimensions are not conserved in the process.

The vectors of the average momenta are also transformed from the matrix: $(\langle p_x\rangle', \langle p_y\rangle', \langle p_z\rangle')^T = R_y \cdot (\langle p_x\rangle, \langle p_y\rangle, \langle p_z\rangle)^T$, and the resulting vector is then added back to the vectors of particle momenta. The primed symbol is introduced to identify the transformed average values after the rotation of the bunch distribution. The average positions vector is instead summed with the particle position vectors without being rotated, to leave the positions of the center of the bunch unchanged.

Using this method to calculate beam parameters in oblique lines, such as those found after a double bend achromat (DBA) or on lines that are not coaxial with the gun axis, allows for detailed simulations of beam transport using Astra. Subsequently, the results can be post-processed with GIOTTO. It enables the derivation of both horizontal and longitudinal parameters in relation to the direction of beam propagation, while circumventing the effects of rotation that may otherwise distort the results when changes in the axis of propagation are introduced. Consequently, it becomes feasible to reconstruct the bunch-associated Twiss parameters along the beamline, promoting a more accurate understanding of the beam dynamics. Finally, this approach allows for simulating beam paths characterized by larger total deflection angles, such as the 120° DBA in [24], using Astra and optimizing them in GIOTTO.

Once the rotation is applied, the dispersion of the particle distribution is evaluated as:

$$\eta_x = \frac{\langle x \cdot p_r\rangle}{\sigma^2_{p_r}}, \qquad \eta'_x = \frac{\langle x' \cdot p_r\rangle}{\sigma^2_{p_r}}, \tag{4}$$

where $x' = \frac{p_x}{p_z}$ represents the horizontal slope of the particle trajectory, and $\sigma^2_{p_r}$ is the squared value of the standard deviation of the relative total momentum spread: $p_r = \frac{p - \langle p\rangle}{\langle p\rangle}$, with $p = \sqrt{p_x^2 + p_y^2 + p_z^2}$.

This particular system for calculating the dispersion can be used to monitor the behavior along a dogleg or more generally, an achromatic cell during a run of Astra. It can also be used to optimize and cancel the dispersion at the output of these lines [24]. Indeed, it is well known that leaking dispersion from achromatic cells introduces a beam tilt similar to that shown in Fig. 1 [25].

A further capability added to GIOTTO is that now it is possible to optimize key beam properties simultaneously at different beamline positions. For example, the dispersion cancellation after a dogleg setting $\eta_x = 0$ and $\eta'_x = 0$, and the emittance downstream the line. This new feature of GIOTTO will have further important applications, such as reproducing experimental data measured at different positions of a beamline.

III. INJECTOR DESIGN CRITERIA

The most recent version of GIOTTO has been developed specifically for the design of the BriXSinO injector.

BriXSinO aims to address important challenges related to the study of peculiar acceleration working schemes, such as the double acceleration into a standing wave (SW) rf superconducting (SC) linac (named the two pass two way scheme [22,26,27]) and the ERL mode with an average current of up to 5 mA. The injector's maximum repetition rate is 92.9 MHz, which is one fourteenth of the rf fundamental frequency of 1.3 GHz.

BriXSinO's test facility will investigate two domains: one where maximum efficiency in accelerating a high-power electron beam is pursued and one where high-flux coherent radiation beams (in the THz spectral range and in x-rays) are made available for medical applications and applied research in general. Moreover, a project was recently funded by INFN, named High Brightness Beams Test Facility (HB_2TF) [28], with the aim of developing the first part of an injector (up to the booster) inspired by this design at the INFN LASA laboratory.

The BriXSinO injector, as sketched in Fig. 2, is based on well-consolidated technologies. Its peculiarity is injecting into an ERL with a low energy compared to other main worldwide projects; e.g., CBETA (Cornell) [29] and bERLinPro (HZB) [30], which inject at 8 and 6.5 MeV, respectively, with a bunch charge of 77 pC. In this matter, we are presenting a study for injecting at 4.5 MeV with a charge of 100 pC.

Because of the high repetition rate, we chose a dc-gun capable of working in CW, referring to the 250 kV JAEA gun [31] whose design is solid. The beam extraction will be driven by a Ytterbium laser illuminating a Cs_2Te photo-cathode.

Following Fig. 2, downstream of the gun, there is the emittance compensation solenoid. Its position is very important to minimize the emittance; the closer the solenoid is to the cathode, the more effective the compensation is [31]. The solenoid is followed by two normal conducting (NC) rf bunchers operating at 650 MHz. The subharmonic frequency of 650 MHz was chosen for beam dynamics reasons, rather than using the main machine frequency of 1.3 GHz. A longer rf bucket (i.e., 650 MHz vs 1.3 GHz) guarantees a more linear accelerating field with relevant benefits for longitudinal beam compression, considering both the velocity bunching (VB) [20,32] and ballistic bunching. The VB exploits the rf longitudinal strength on the bunch ([33], Ch. 5) during its slippage on the acceleration wave, while the ballistic bunching occurs in the drift downstream of an rf cavity, exploiting a proper correlation in the beam's longitudinal phase space. Both the rf longitudinal strength and the proper beam longitudinal phase space correlation are controlled by the buncher injection phase. Thanks to the longer rf bucket, there is also a benefit in reducing the energy spread due to the less pronounced rf curvature. The two bunchers are sized in relation to the beams' entering energies, and electromagnetic and mechanical studies are being done at the INFN LASA laboratory for HB_2TF, the project cited above.

Downstream of the bunchers, the beam energy of ≈4.5 MeV is reached with three 1.3 GHz two-cells SC cavities enclosed in a dedicated cryomodule (the injector booster [34]).

Downstream of the injector booster, there is a solenoid and a quadrupole matching triplet that prepare the beam to enter into a dogleg, the design of which is nontrivial due to the space-charge effects.

In ERLs, these doglegs are typically named mergers, as their purpose is to join two copropagating beams with different kinetic energy. In the case of BriXSinO, the beams are counterpropagating, but the beam dynamics issues remain the same. The internal forces in the electron bunches have the effect of remodulating the particle momenta inside the open dispersion regions, and the beam transport becomes no longer achromatic. Open dispersion regions are where, along the beamline, particle transverse momenta and transverse positions are strongly correlated with their energy [see Eq. (4)]. This is an inevitable byproduct of the propagation inside mergers and other common dispersive paths (doglegs, multibend achromats, magnetic chicanes). This effect is analogous to what happens in the presence of coherent synchrotron radiation (CSR) emission in magnetic compressors or arc compressors [35]. The consequences include dispersion leakage, leading to increased beam emittance, as well as betatron kicks in dipoles and beam tilts in the $x - z$ and $p_x - z$ planes [25]. Dispersion leakage refers to residual dispersion remaining in particle bunches due to internal collective effects.

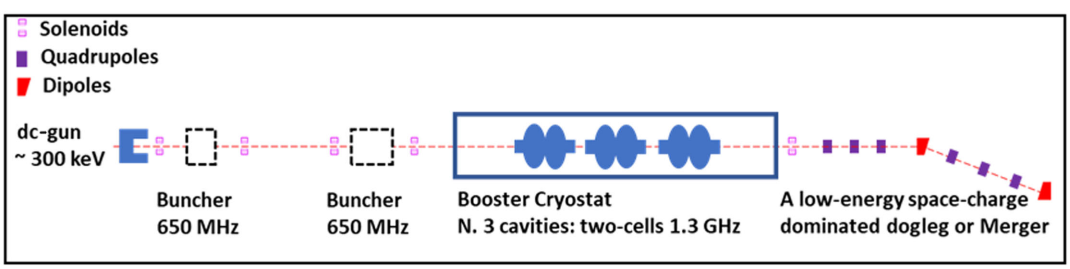

FIG. 2. Injector blocks schema sketch: The dc-gun, the two sub harmonic bunchers, the cryostat booster carrying three two-cells rf cavities and the low energy dogleg. The different length of the two bunchers is because of the different phase velocity.

IV. BD OPTIMIZATIONS AND SIMULATIONS

The simulations presented in this section refer to a BriXSinO operating mode with a bunch charge of 100 pC, considering a repetition rate of approximately 46 MHz (half of the maximum one) to keep the beam average current below 5 mA (see Sec. III). A bunch charge of 100 pC is relatively high and allows us to test space charge effects on beam dynamics (BD) while still being within the range typically used for inverse Compton scattering (ICS) or FEL sources.

All simulations were performed taking into account the effects of space charge in the beamline, starting from the cathode, where mirror charges are considered. The space charge fields are computed with a cylindrical symmetry mesh up to the first dipole; after that, the mesh switches to a full 3D Cartesian one. We chose to work with 20,000 macroparticles per bunch, which is a high enough value for accurate bunch modeling without causing excessive computation overhead.

Our optimization campaign proceeded as follows: initially, we optimized the BD of the injector up to the entry point of the dogleg. Subsequently, we optimized the BD within the dogleg, taking into account beam dispersion. For completeness, it is essential to note that the optimization of the dispersive path was carried out by integrating a retuning process for the entire line, up to the cathode. This approach allowed us to achieve a more comprehensive solution.

A. BD injector optimization up to the dogleg

The BD solution for the injector (up to the dogleg entrance) resulting from the GIOTTO optimizations is presented in Fig. 3, showing the main beam parameters' behaviors. It is worth noting that some spikes in the normalized transverse emittance ($\varepsilon_{n,x}$) are visible in Fig. 3. These spikes correspond to the solenoids and are due to the azimuthal acceleration of the particles in the entrance fringing field, which is then completely removed by the exit fringing field [36]. At the center of the solenoid, a special Astra built-in algorithm cancels out the azimuthal contribution to the emittance. Other spikes are visible corresponding to the cavities (both bunchers and booster cavities), due to the typical rf focusing effect that contributes to the transverse beam dynamics in the cavities. As shown, this contribution is damped as the beam energy increases, and the most noticeable spike comes from the first buncher.

The optimization process involves the following key steps: (i) Electron bunch generation using a laser-driven dc gun with specific pulse shaping characteristics. (ii) Placement of a solenoid downstream from the gun for emittance compensation and envelope control. (iii) Implementation of the first subharmonic buncher to focus the envelope, chirp the longitudinal phase space, and accelerate the bunch. (iv) A relatively long drift section with additional solenoids to maintain transverse envelope control during ballistic bunching and reach the first relative emittance minimum. (v) Introduction of the second subharmonic buncher to continue envelope focusing, maintain phase space chirp, and accelerate the beam. (vi) Another drift section where the emittance oscillation reaches a relative minimum before injection into the injector booster. (vii) Utilization of the injector booster with multiple cavities for further compression and acceleration of the beam exploiting the VB technique, aided by *ad hoc* injection phases to compensate for beam energy spread. (viii) Final drift before injection into the dogleg, resulting in optimal and stable beam parameters.

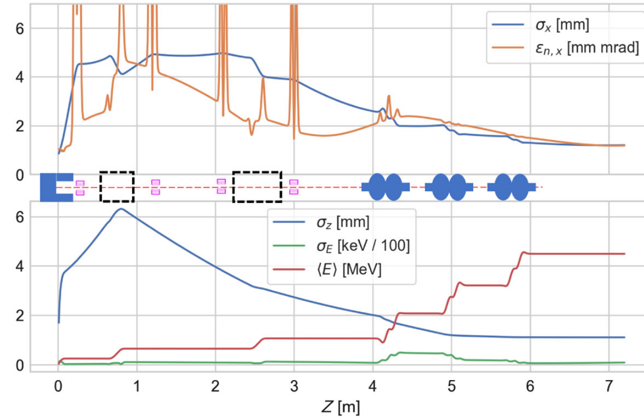

FIG. 3. The upper plot shows the normalized emittance (in orange) and the transverse envelope (in blue) for a cylindrical symmetry beam. Additionally, the main active elements are shown to help the reader see their effects on the beam dynamics. The lower plot shows three curves: the energy gain (in red), the bunch length (in blue), and the energy spread (in green).

The entire optimization process for this line involved modifying 11 parameters (referred to as genes in GA terminology) to refine the beam parameters at the dogleg entrance.

Here, the fitness function had three specific objectives, each represented by a Lorentzian-shaped objective function (see Sec. II A): achieving a 1 mm bunch length, 700 μm transverse dimensions, and minimizing emittance with a target set at 0. By allowing competing parameters to find the optimal balance (excessive compression could affect emittance through space charge), the desired outcome was attained. To ensure a greater emphasis on emittance while balancing the competing factors influenced by space charge, we set the Lorentzian height parameters to 2 for emittance and 1 for longitudinal and transverse dimensions.

To promote high genetic variability and achieve a broader exploration of the solution space, we kept the widths of the target functions considerably wide.

The bunch parameters obtained at the exit of the booster are as follows: normalized transverse emittance $\varepsilon_{n,x-y}$ of 1.2 mm-rad, transverse envelope σ_{x-y} of 1.2 mm, longitudinal envelope σ_z of 1.1 mm, beam energy E of 4.5 MeV, and rms energy spread σ_E of 8.9 keV.

As evident, the target parameters in this scenario are not set to the expected outcome values, but rather as minimum values that we consider acceptable within the desired equilibrium range. By working with Lorentzian functions, we are aware that GIOTTO will strive to optimally approach these target parameters while respecting the imposed equilibrium by the weights.

B. The low energy dogleg/merger

Previous studies (e.g., [37,38]) reporting space charge effects in ERL mergers show how it is necessary to avoid strong beam focusing along the dispersive line to prevent emittance degradation [25,39]. *Ad hoc* dipole line configurations can be used to overcome these effects; for example, the one named "zigzag" schema [37,38]. The merger line we use is a classic dogleg configuration: two dipoles ($\theta_{\mathrm{bend}} = 20$ deg and $\rho = 0.28$ m) and three quadrupoles ($L = 0.1$ m). In this section, we report how space charge effects can be perfectly compensated by an appropriate beamline setting using a code like GIOTTO, both closing the dispersion and compensating the emittance in a space-charge-dominated dispersive beamline.

For the effective optimization of the injector's BD with the addition of the merger, it is essential to extend GIOTTO's influence to the previously optimized beamline elements. The dogleg necessitates proper matching of the beam's transverse parameters to ensure achromatic transport, which can be adjusted using the three quadrupoles preceding the first bending element, along with the four solenoids and the rf focusing in the line.

Furthermore, achieving minimal optic imbalances caused by space charge in the dispersive region requires optimizing the phase of all four injector cavities. Lastly, it is crucial to apply optimization to the transverse optics

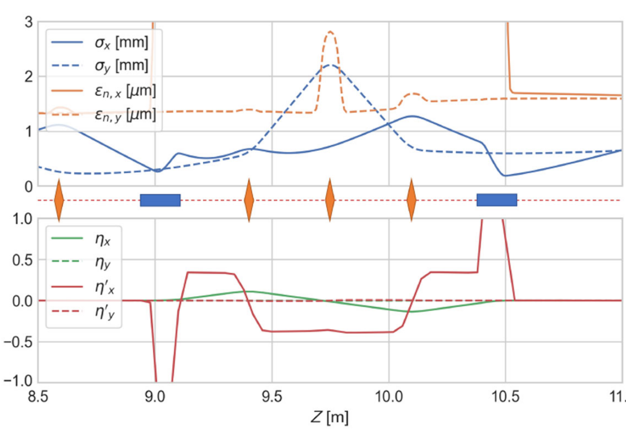

FIG. 4. Beam tracking inside the dogleg. The upper plot shows the beam envelopes and the beam normalized emittance. The lower plot shows the vertical and horizontal dispersion (η), together with the first derivative of dispersion (η'). Between the two plots, the magnetic elements of the line are shown, dipoles in blue and quadrupoles in orange.

TABLE I. Main bunch parameters at the injector exit.

Parameter	Value
$\varepsilon_{n,x-y}$	1.60, 1.65 mm-mrad
σ_{x-y}	0.65, 0.65 mm
σ_z	2.0 mm
E	4.5 MeV
σ_E	26.0 keV

during transport within the dogleg to adequately close the dispersion.

A total of 15 beamline parameters were varied to obtain the optimal solution, enlarging the solution space. However, GA's exploration capabilities are known to scale well with the number of dimensions. Previously optimized elements (in Sec. IV A) were adjusted within a narrower range to maintain established dynamics while allowing for fine-tuning.

The fitness function comprises eight different target functions, all set at 0, organized as follows: two for minimizing the normalized emittance $\varepsilon_{n,x-y}$ on the two transverse planes, and two for minimizing the horizontal dispersion parameters η_x and η'_x at three consecutive downstream points, each 20 cm apart from the other. This approach accelerates identifying stable optical solutions and selects an initial subset of solutions to evolve. Since the optimization objectives are not in competition but rather synergistic, prioritization balancing was not necessary, and all Lorentzian heights were set to 1.

In Fig. 4, the BD solution resulting from the final optimization for the dogleg is shown, while in Table I, the resulting relative main beam parameters are reported.

As visible in Fig. 4, the dispersion is perfectly closed on both planes ($\eta = 0$ and $\eta' = 0$), and there is a small emittance increase of about 0.3 mm-mrad in the x and y planes, which is due to a mild chromatic effect in the last two quadrupoles. This emittance increase is acceptable, considering the capability to inject into the ERL with a lower energy.

The doubled bunch length from 1.0 to 2.0 mm (rms), visible by comparing Table I with the parameters reported in Sec. A, is not a concern for two reasons: the lower peak current of about 8 A is acceptable, and downstream the ERL, the beam can be further compressed, taking advantage of a higher beam energy. Also, the energy spread is increased from 8.9 to 26.0 keV, but it is still a very low value acceptable for our applications. It is worth noting in Fig. 4 how GIOTTO restores a quasi-cylindrical beam on the transverse plane at the end of the dispersive path.

V. CONCLUSION

In this work, we present the new features we have developed for GIOTTO [1], an AI code capable of guiding the Astra tracking code in multiobjective genetic optimizations of beam dynamics in the presence of space charge.

To demonstrate the capabilities of our code, we apply this latest version to the design of a low-energy high-brightness injector for an ERL named BriXSinO and the closure of beam dispersion during space charge dominated transport in its dogleg.

The main new features of GIOTTO presented and used in this work are as follows: (i) Bunches back-rotation (Sec. II B) management, a feature that makes Astra [17] usable for designing dispersive lines furthermore in presence of space charge. (ii) Description of the fitness function based on Lorentzian distributions that is a very smart way to cope with multiobjective optimizations, even when starting the design from scratch. (iii) The ability to simultaneously optimize beam parameters at different points along the line.

The beam parameters obtained in this 4.5 MeV injector delivering 100 pC bunches show promising results when compared to those of other worldwide ERL projects such as CBETA (Cornell) [29] and bERLinPro (HZB) [5]. In these facilities, working points with 77 pC bunch charge have been studied, featuring injection energies of 8 and 6.5 MeV, respectively. It is well known how space-charge effects introduce nonlinear emittance degradation and further, how the beam average energy damps the space-charge forces, respectively, with a factor of $\frac{1}{\gamma^3}$ and $\frac{1}{\gamma^4}$ [40].

Despite the potentially detrimental effects of space charge due to high bunch charge and low operating energy, we successfully designed a high-performance injector using GIOTTO. This AI tool effectively balances multiple advanced beam dynamics techniques, e.g., cigarlike distributions and the velocity bunching (VB) technique [20], in the design of high-brightness beamlines and preserves performance even in critical sections where dispersion is open. The VB used in the bunchers is a new solution that permits to work simultaneously on the bunch compression and its acceleration; new is also the use of two bunchers instead of one, both with an *ad hoc* λ_{cell} for better control of the beam phase slippage (vs the accelerating wave) and the VB itself. By introducing these elements, we aim to enrich the existing solutions in beam dynamics and contribute to the progressive evolution of accelerator science.

It is worth noting that with these new enhancements in GIOTTO, Astra gains the capability to accurately assess dispersion effects, providing users with a better understanding and capability to control the evolution of these phenomena in the studied beamlines, even in the presence of space charge. Coupling this to an advanced optimizer was the key to avoid the use of peculiar dispersive path shapes [37,38] by properly tuning all active optics of a standard dogleg.

In the future, we intend to extend this optimization method to real machines. Nowadays, there are different examples of A.I. codes implemented on Control Systems (CS) of worldwide facilities [41,42]. In the case of BriXSinO, our approach will be to pre-set the working points by hand and then refine them with a feedback procedure based on GIOTTO (at CS level) and on diagnostics at the dogleg exit. Moreover, we are concluding the upgrade of the STAR linac [43] and we plan to implement GIOTTO on its CS to enhance the machine performance.

This research has the potential to extend GIOTTO utility to accelerator control systems, facilitating real-time feedback, corrections, and optimization. Such implementations could enhance the operational performance and stability of accelerators across various applications.

In conclusion, this paper presents significant advancements in beamline design by optimizing low-energy, high-brightness electron beams for enhanced energy recovery. By introducing innovative techniques and methodologies, we aim to propel accelerator science forward and contribute to the development of cutting-edge accelerators with enhanced performance and versatility for scientific and industrial applications.

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