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# WIDE-RANGING GENETIC RESEARCH OF MATCHING LINE DESIGN FOR PLASMA ACCELERATED BEAMS WITH GIOTTO

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## *Abstract*

GIOTTO is a code based on a Genetic Algorithm, being used in the field of particles accelerators for some years [1-3]. Its main use concerns beam-dynamics optimizations for low energy linacs, or injectors, where the beam space-charge plays an important role on its dynamics. Typical optimizations regard the Velocity Bunching technique or, more generally, the emittance and energy spread minimization. Recent improvements in GIOTTO, here discussed, have added the important capability to solve problems with a wide research domain, making GIOTTO able to design a beam Transfer Line (TL) from scratch [4]. The code, taking as input the TL length and the optics elements, can define the correct lattice of the line that transports and matches the beam from the linac to the undulators of an FEL, finding the right gradients, positions and dimensions for the optics elements by exploring the parameters values in selected ranges. Further, the introduction of Twiss parameters into the fitness function makes GIOTTO a powerful tool in the design of highly different beam lines. Lastly, a new routine for the statistical analysis of parameters jitters effects on the beam is under development.

## INTRODUCION

Today many labs are strongly investing in the plasma acceleration [5], in terms of R&D. This technique promises table top machines able to drive Free Electron Lasers (FEL), Inverse Compton Sources (ICS) or other kind of technologies related to the field of particle accelerators. Furthermore, technologies like FELs [6] or ICS [7] need for very high-quality electron beams, in terms of average current, peak current, emittance, energy-spread and others beam figures of merit, which often counteract each other in the optimization process.

One of the more stressed plasma acceleration issues is related to the matching line, or Transfer Line (TL), set up, which is needed to bring the electron beam to the experimental zone; in case of ICS it is the electron-laser Interaction Point (IP), for an FEL it is the undulator. For plasma accelerated beams, the TL set up is very complex because of the beam nature itself. At the exit of the plasma stage, the beam energy spread is very high and the envelope really small, of the order of the capillary radius ($\approx 10\ \mu$m); the combination of these factors cause strong chromatic aberrations that makes blow-out the emittance. This effect is well described by the chromatic length parameter [4] id east the distance (a drift free propagation) at which the emittance increases by a factor $\sqrt{2}$.

In this proceeding we show how GIOTTO has been successfully used to solve the TL design of the project Eupraxia@SPARCLAB [8] a compact FEL driven by a plasma accelerated beam. This problem shows a wide range research domain and is a good field for the GIOTTO search ability. This Genetic Algorithm (GA) demonstrated to be able to design a TL starting from scratch. Furthermore, GIOTTO's last updates gives the possibility to set the Twiss parameters directly into the fitness function, which makes the code more user-friendly.

For the sake of completeness, in this proceeding we present another result in a wide range research problem. We show how GIOTTO could close the dispersion in the first dogleg of the BriXS project [6] satisfying two other non-trivial conditions: equal beam divergence and equal spot size on the transversal planes, which means that at the dogleg exit the cylindrical symmetry is re-established.

## WIDE RANGE SEARCH WITH GENETIC ALGORITHMS

GIOTTO [3] is an up-to-date GA, fully developed since 2007 [2]. It has been written in Fortran 90/95 and is able to perform genetic optimizations of a beamline [1, 6] and statistical analysis [9]. It is able to drive and to communicate with ASTRA [10], a tracking code that considers full-3D space charge effects.

GA are a class of stochastic optimizers with the ability to deal very well with problems in which the parameters values are correlated in a strongly nonlinear way. The beam dynamics in particle accelerators can be a problem with these characteristics. For example, when the particles energy is low, the space charge turns-on many non-linear correlations which make very difficult the machine tuning. Also at relatively high beam energy these effects can raise, as in case of strong transversal focusing or longitudinal compression factor; nowadays requested in many advanced applications.

Here we are going to show similar beam dynamics problems that are characterized by a Wide Range Search Domain (WRSD). This kind of problems do not start from known working points that need further optimizations, to cope with this kind of WRSD problems we chose the approach to start from scratch the exploration. In the specific case, how we are going to show, it means to start from the origin of the multidimensional domain [4].

We upgraded GIOTTO to face WRSD problems, which means a better deal with low values of the sub-functions

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composing the fitness function and to change the way we define the main fitness function. The new fitness function shape we introduce here (shown below) is a sum of Lorentzian functions, each one centred on the target values of the parameters that we want to optimize:

$$I = \sum_{i=1}^{n} A_i \frac{B_i^2}{B_i^2+(x_{Ti}-x_{Fi})^2} \qquad (1)$$

Where $I$ stays for idoneity score (or fitness score), $x_{Ti}$ are the target of the parameters we chose to optimize, $x_{Fi}$ are the final values of these parameters that are obtained where the tracking stops $A_i$ and $B_i$ are coefficients of the Lorentzian functions that determinate respectively height and width of the curves.

## TRANSFER LINE DESIGN

The TL studied is designed to transport the bunches from the plasma stage up to the injection in the first undulator module of the FEL. It makes use of both permanent quadrupole magnets (PMQ), able to generate stronger field gradients, and electromagnetic magnets (EMQ).

The beam must match a specific set of values of the Twiss functions at the end of the transfer line [4].

The plasma stage increases considerably the beam energy (up to 1 GeV) with the typical drawback of introducing strong transverse momenta, for this reason the chromatic length of the beam decreases from $L_C \gtrsim 10^2\ m$, before the plasma stage, to $L_C \lesssim 10^{-1}\ m$. Because of this extreme condition the chromatic aberrations contribute to increase the emittances even in drift spaces [11]. The TL must than keep under control the beam envelopes end divergences to prevent this emittance dilution.

Table 1: Target values of the parameters that are optimized in the algorithm, a Lorentzian function is assigned to each parameter.

| Target Parameter | Value |
|---|---|
| $x_{T1} = \alpha_{xT}$ | 1.48 |
| $x_{T2} = \beta_{xT}$ | 5.04 m |
| $x_{T3} = \alpha_{yT}$ | -0.65 |
| $x_{T4} = \beta_{yT}$ | 2.11 m |
| $x_{T5} = \varepsilon_{n,xT}$ | 0.42 mm mrad |
| $x_{T6} = \varepsilon_{n,yT}$ | 0.43 mm mrad |

In the case of the TL for Eupraxia@SPARCLAB we tested 4 different total lengths of the line (8 m, 5.15 m, 4 m, 3 m), and set as variables (called genes) the positions and the gradients applied to the set of quadrupoles.

The fitness function has been defined as a sum of 6 different Lorentzian functions each one centred on one of the target values shown in Table 1 (two values for the transverse normalized emittances and four for the transverse Twiss functions: $\alpha_x$, $\alpha_y$, $\beta_x$ and $\beta_y$ )

A summary of the line obtained is shown in Table 2 and Table 3, a visual comparison in Fig. 2.

A latter application of GIOTTO has been done on line C to test its capacity to contain beams with different energies (2 GeV and 0.5 GeV), to do this the magnet position were kept and a new matching was performed with the same target values in Table 1.

## A DOGLEG OPTIMIZATION

A dogleg is a dispersive path that can be used for different scopes. We are considering the easiest or classical one: i.e. an achromatic line that brings a beam from a main linear orbit to another parallel one. An achromatic dogleg, in its simplest design is made by a triplet that prepare the beam, a dipole that bends the beam opening the dispersion, three quadrupoles that work on the dispersion and control the envelopes and a final dipole that re-bends the beam on the final orbit. The free parameters, once the bending radius is fixed, are five quadrupole gradients, three for the triplet at the dogleg entrance, one for the quadrupole in the middle of the dispersive path, one for the two twin-quadrupoles that compensate the dispersion.

Here we are considering the first dogleg of the project MariX/BriXS [12], where a 6.4 MeV and 50 A peak current bunch is transported in an energy recovery accelerating machine. The complexity of this scheme is given by the space-charge and by the number of the needed objectives at the dogleg exit, which are: preservation of the transverse emittances in the dogleg, envelopes and divergences symmetric on both the transverse planes.

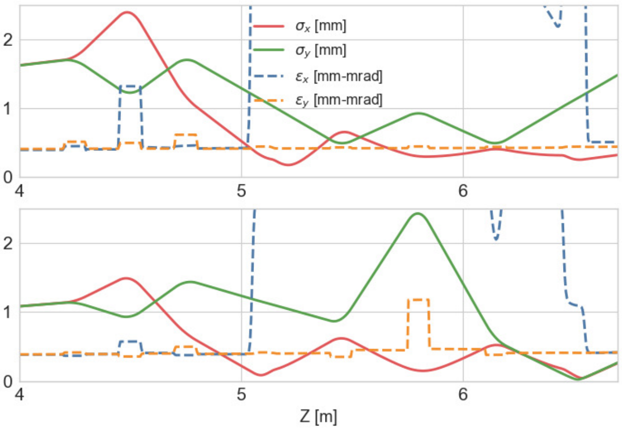

Figure 1: Solid lines, red and green, show the horizontal and vertical envelopes. Dashed lines, blue and orange, show horizontal and vertical emittances. Upper: GIOTTO dogleg optimization, like the analytical solution, where the aim was to obtain an achromatic line, preserving the emittance. Lower: GIOTTO multi objectives optimization, in terms of emittance and cylindrical beam symmetry at the dogleg exit.

The dogleg design problem involves five quadrupole gradients, and four targets: $\varepsilon_{n,x} = \varepsilon_{n,x0}$, $\varepsilon_{n,y} = \varepsilon_{n,y0}$, $\sigma_x = \sigma_y$, $\sigma_{x'} = \sigma_{y'}$. These four targets define four different subfunctions like in Eq. (1).

Figure 1 shows the comparison between two different MariX/BriXS dogleg set up. The first (upper) is a solution where the dispersion was closed, following an analytical solution and using GIOTTO for a fine tuning necessary because of the space-charge non-linear effects; the second (lower) is a GIOTTO solution for the multi objectives fitness function. The power of the GIOTTO capability in solving WRSD problems is well shown by the two images comparison.

## CONCLUSION

GIOTTO demonstrated to be a flexible code able to cope with this new class of beam dynamics problems (WRSD). In the last months this code was used to design succefully the TL of Eupraxia@SPARCLAB (Case C in Table 2 and 3), the line have also been tested to work, with a different set of focusing strengths, at double and half of the nominal energy of the machine. The dogleg of the injector of MariX/BriXS was also designed using the last version of GIOTTO.

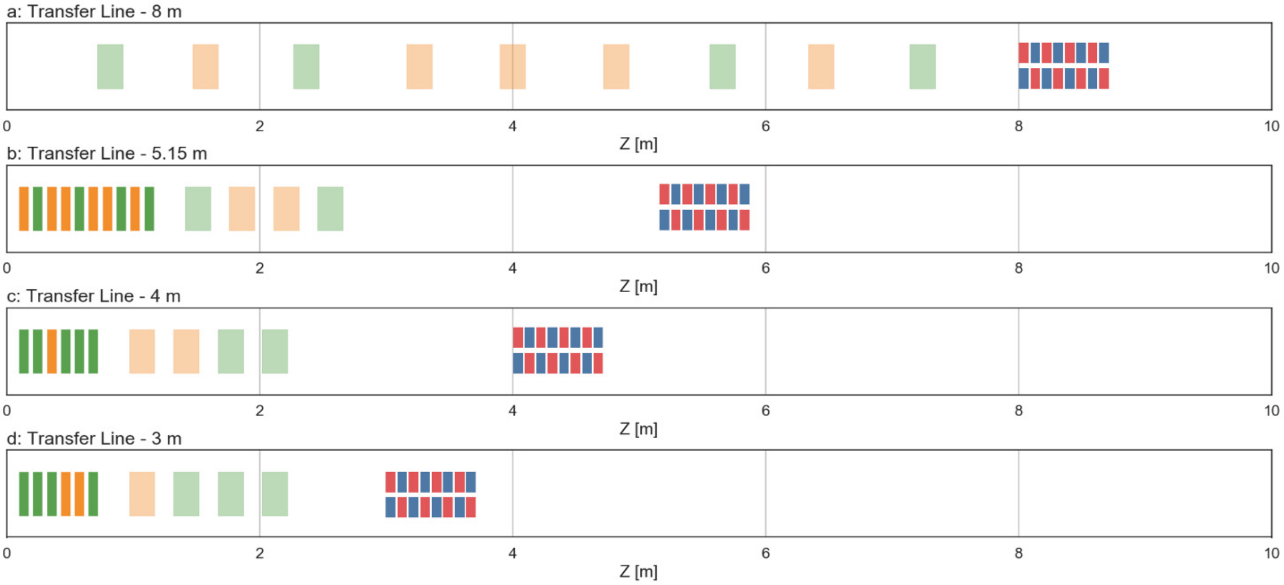

Figure 2: schematic lattice of 4 alternative TLs obtained for different line lengths (from top to bottom: 8 m, 5.15 m, 4 m, 3 m). The orange and the green elements are quadrupoles, with focusing and defocusing effect on the horizontal plane. The transparent style means that they are EMQ, the colourful style mean that they are PMQ. In red and blue is shown (not in scale) the position of the first undulator module.

Table 2: Focusing strengths of the four solutions; in bold for PMQ. The values are rounded for sake of compactness; the aim is to give an idea of their magnitude.

| Line | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Q13 | Q14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | -14 | 10 | -11 | 8.7 | 8.7 | 4.3 | -8.2 | 6.1 | -8.3 | - | - | - | - | - |
| B | **49** | **-134** | **35** | **155** | **-158** | **170** | **85** | **-47** | **78** | **-53** | -5.9 | 8.3 | 7.1 | -7.0 |
| C | **-12** | **-120** | **100** | **-6** | **-19** | **-2** | 6.7 | 0.5 | -5.2 | -4.1 | - | - | - | - |
| D | **-68** | **-21** | **-61** | **77** | **18** | **-31** | 2.1 | -3.0 | -3.8 | -4.0 | - | - | - | - |

Table 3: Magnetic Elements in the 4 Different TLs Shown in Fig. 2

| Line | Length | # EMQ | EMQ length | EMQ bore | # PMQ | PMQ length | PMQ bore |
|---|---|---|---|---|---|---|---|
| A | 8 m | 9 | 20 cm | 1 cm | | | |
| B | 5.15 m | 4 | 20 cm | 1.5 cm | 10 | 7 cm | 1cm |
| C | 4 m | 4 | 20 cm | 1.5 cm | 6 | 7 cm | 1cm |
| D | 3 m | 4 | 20 cm | 1.5 cm | 6 | 7 cm | 1cm |

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