Multi-objective optimization of the matching beamline for external injection into a laser-driven plasma accelerator

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Abstract. Accelerators based on laser plasma wakefield acceleration are of great interest for a new generation of compact machines. External injection of an electron beam from an RF injector into a plasma accelerating stage has the advantage that a well-controlled and fully characterized beam can be used. The matching of the electron bunches into an accelerating plasma wakefield places high demands on the electron beam quality. The electron beam size must be extremely small to match the field structure inside the plasma wake. The short period of the accelerating field in the plasma requires a bunch length in the (sub-)fs range. These electron beam properties result in a high electron density and strongly space charge dominated bunches. The beamline upstream of the plasma must be able to control the significant effect of space charge on the bunch and to transversely match the beam to the focusing fields of the plasma. Further constraints to the beamline design are given by the in-coupling of the high-power drive laser and the implementation of diagnostic tools. Choosing suitable settings for the beamline elements in order to match the beam thus poses a great challenge. Using multi-objective optimization, suitable settings for the beamline elements can be extracted from Pareto optimum solutions. The development of a universal multi-objective optimization algorithm for beamline matching as well as first optimization results are presented.

1. Motivation

SINBAD [1] is a dedicated R&D facility at DESY Hamburg. It will provide a test bed for advanced acceleration techniques such as laser-driven plasma wakefield acceleration (LWFA), dielectric laser acceleration (DLA) and THz-driven acceleration, in independent experiments. ARES [2] is a conventional linear RF accelerator at SINBAD with a target energy of 100-155 MeV that is currently in the construction and commissioning phase. The facility will generate remarkably short, high-brightness electron bunches with excellent arrival-time stability which can be used for LWFA scheme with external injection. Figure 1 illustrates the planned layout of the ARES linac at SINBAD.
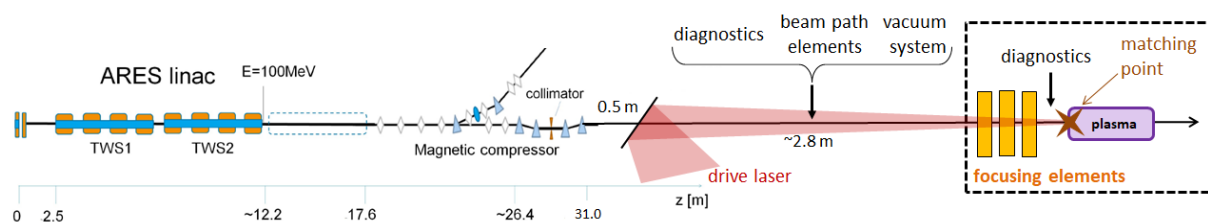
**Figure 1.** Layout of the ARES linac at SINBAD.

The last beamline section upstream the plasma is the matching area where the electron beam is fully characterized and afterwards matched into the plasma. The matching beamline at ARES is currently in the design phase. The matching of the electron bunches to the accelerating and focusing fields of the plasma poses challenges regarding the electron beam quality at the plasma entrance and the timing between the electron bunch and the laser pulse. The required beam properties are mainly defined by the field structure inside the plasma wake excited by the drive laser.

In plasma-based accelerators to control the relative energy spread growth during the acceleration process, the injected electron beam should occupy a small fraction of the plasma wave (i.e. bunch length of one to few fs for plasma density $n_e = 10^{17}\,\mathrm{cm}^{-3}$). At ARES a bunch compressor (BC) including a collimator together with the method of velocity bunching allows the generation of fs to sub-fs-scale bunches. Additionally, transverse matching of injected beams to the plasma is needed for beam emittance growth control [3,4,5]. The matched β-function of the electron beam at the beginning of the region of uniform plasma density (defined as plasma entrance) must be of sub-millimeter size for $n_e = 10^{17}\,\mathrm{cm}^{-3}$. Strong transverse focusing elements are therefore required to externally match the beam into the plasma. However, because of the ultrashort bunch length and resulting space charge (SC) forces, its focusing is limited to β-functions at the plasma entrance of more than one magnitude larger than the matched value. Proper shaping of the longitudinal plasma density profile (up-ramp) is hence needed to further match the beam in its transverse properties to the plasma [6,7].

The suitability of different focusing systems, such as a permanent quadrupole triplet, an electromagnetic quadrupole triplet and doublet, combinations of permanent and electromagnetic quadrupoles as well as active and passive plasma lenses will be studied during the design phase of the matching area. Furthermore, the design of the matching beamline includes the task of finding a stable parameter set for the focusing elements. An additional challenge is to keep the bunch length short from the exit of the BC through the drift section in the matching area. Such a control of the compact longitudinal phase space requires a study of SC effects on the bunch along the matching beamline.

The particle distribution at the BC exit, which was obtained from IMPACT-T simulations [8], was tracked along a 3.5 m drift to analyze the impact of SC effects. These simulation results achieved with the particle tracking program ASTRA [9] are summarized in figure 2 (a) and (b). Strong SC effects in the low-energy, compact bunch mode (100 MeV, 0.79 fs) together with an energy chirp lead to an increase of the bunch length. A growth of the electron beam size by a factor of two along the drift also indicates SC effects in the transverse plane. As a consequence, any optimization tool, which is considered for theoretical studies and simulations of the matching area, must include SC calculations.
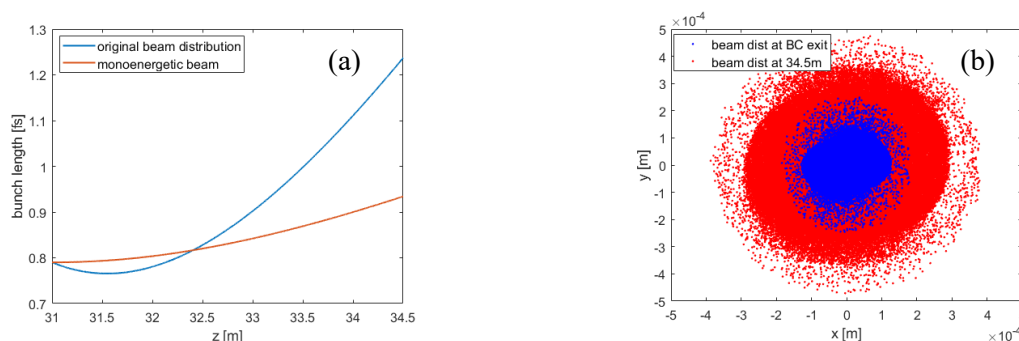
Figure 2. (a) Drift of the electron beam distribution [blue = original distribution; orange = monoenergetic beam] from the BC exit up to 3.5 m (Astra tracking). The bunch length is increased due to space charge and an energy chirp.
(b) Growth of the transverse spot size over the drift due to space charge.

Most available open source particle tracking programs include a matching feature that allows a user to evaluate a stable setting for a focusing system, such as the matching setup for external injection. However, since no matching tool with SC calculations, that fulfills the mentioned requirements, is available, a new optimizer was developed.

2. Multi-objective optimization and optimizer setup

A multi-objective optimization is used for the matching tool. This method allows for the optimization of a number of conflicting objectives simultaneously, while all limiting variables and constraints are considered.

The developed program is based on SPEA2 (Strength Pareto Evolutionary Algorithm) [10], a popular multi-objective genetic algorithm. The optimizer is implemented in a MATLAB script using the particle tracking program ASTRA for beamline simulations [11]. For the purpose of electron beam matching two objectives are minimized at the plasma entrance simultaneously: the combined β-function $\beta = \sqrt{\beta_x^2 + \beta_y^2}$, defined by the horizontal and vertical β-functions β_x, β_y, and the bunch length σ_t. The objectives depend on decision variables that are given by the parameters of the focusing system, such as position, focusing strength or length of the individual components. The physical limits of the decision variables, design limitations from the diagnostics and the in-coupling of the high-power laser as well as the position of the plasma cell represent the constraints for the optimization process.

Figure 3 illustrates the optimization procedure. As a first step the program initializes a start population consisting of a defined number of random settings for the selected focusing system. Afterwards, particle tracking in the matching beamline, which is carried out with ASTRA, evaluates the corresponding beam parameters at the plasma entrance. The selector chooses the best settings out of the population based on a dominance criterion. Comparing all settings in the population with each other, setting i dominates setting j if setting i is not worse in both objectives and better in at least one objective than setting j. Therefore, following the dominance criterion the optimizer considers only settings for the focusing system that gives the smallest β-functions and shortest bunch lengths for the electron beam. The best settings are modified and the corresponding beam parameters are calculated with ASTRA again. A new population is built consisting of the best settings of the last iteration and the new offspring solutions. Now, the selection process is repeated. The iterative process stops, when a maximum, pre-defined number of iterations is achieved or the electron beam parameters that were selected as objectives in the optimization cannot be further improved. In the latter case, the population represents the Pareto optimum for the given optimization problem.
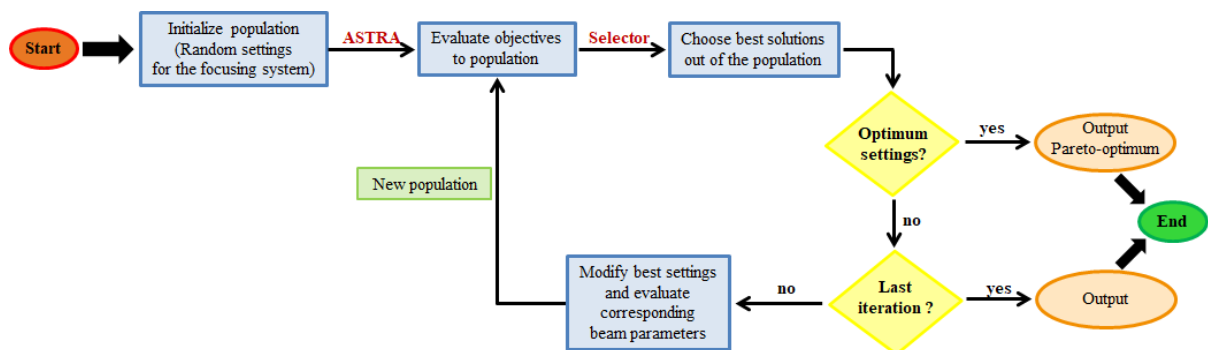
Figure 3. Flow chart of the optimization procedure implemented in the developed matching tool.

Figure 4 shows the evolution of an initially random population (left) towards the Pareto optimum front (right) in 70 iterations. The computational run time of the shown example was 12 hours on a node with 40 CPUs running 40 ASTRA trackings in parallel. Here, a permanent quadrupole (PMQ) triplet is optimized for electron beam matching. Each point in the plots represents one complete parameter setting for a PMQ triplet, including positions, lengths and focusing strengths for all three permanent quadrupoles. Beside these optimum settings the Pareto optimum front provides the physical limits of the matching area in terms of the minimum of the combined β-function and the shortest bunch length that can be achieved using the suggested focusing system.
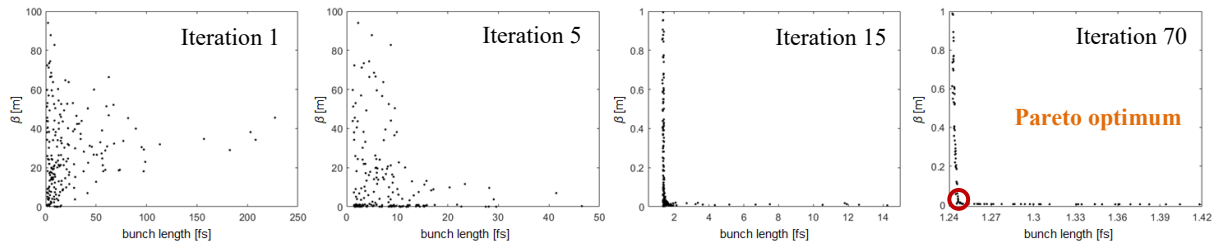
Figure 4. Evolution of an initial population towards the minimum of the combined β-function and the bunch length calculated in an evolutionary approach with a multi-objective genetic algorithm.

3. First optimization results for the electron beam matching into plasma at SINBAD-ARES

### 3.1. Optimized setting for a PMQ triplet as a matching system

One setting for the focusing system can be chosen out of the Pareto optimum curve. The electron beam dynamics are analyzed and the setting can be later used in the design, setup and commissioning phase of the matching area. In this section this is done for one PMQ triplet configuration shown in figure 4 (marked in red). A 100 MeV electron bunch with a charge of 0.78 pC is matched to the plasma in this case. Table 1 summarizes the positions, lengths and focusing strengths of the permanent magnets evaluated by the developed matching tool. All values are within feasible limits for available permanent magnets.

Table 1. One setting for the PMQ triplet selected from the Pareto optimum curve.

	Position [m]	Length [m]	Focusing strength [T/m]
Permanent quad 1	34.06	0.03	102.97
Permanent quad 2	34.14	0.04	-117.72
Permanent quad 3	34.25	0.05	160.47

Using these settings the electron beam can be matched to the plasma wakefield with a β-function at the waist of around 2.0 mm and a bunch length of 1.4 fs. An overview of all beam parameters at the plasma entrance is given in table 3 (see central column).

Figure 5 summarizes the evolution of the transverse and longitudinal beam parameters from the BC exit to the plasma entrance. The electron beam is strongly focused in the transverse plane by the three permanent quadrupoles (see figure 5(a)). The matched β-functions are strongly asymmetric in the transverse plane at the optimization point (34.28 m) where the plasma entrance will be placed. Further, a significant variation between the transverse normalized emittances can be observed (see figure 5(b)). The bunch length increases between 31 m (BC exit) and 34 m (position of the first quadrupole) due to SC and an energy chirp (see figure 5(c)), which was imprinted on the bunch to decrease the bunch length in the BC. The reason for the significant increase of the bunch length behind the focusing structure can be explained with the strong SC effects acting on the short and transversely compact bunch.
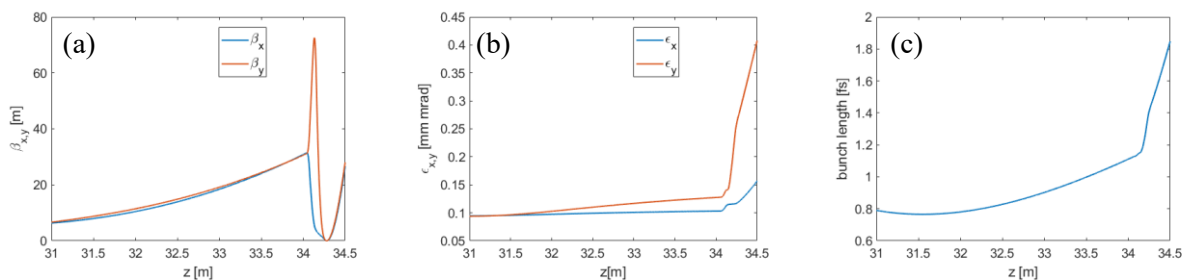
Figure 5. Evolution of the β-functions $\beta_{x,y}$ (a), the transverse emittances $\varepsilon_{x,y}$ (b) and the bunch length along the drift of the matching area and through the focusing system of three PMQs.

*3.2. Evaluation of the selected setting in a plasma simulation*
In order to evaluate the quality of the found PMQ settings the matched electron beam is tested in plasma simulations [9]. The 3D start-to-end simulations have been carried out with the spectral quasi-cylindrical PIC code FBPIC [12].

The laser parameters used in the simulations correspond to the design parameters of the ANGUS laser system [13]. The temporal and transverse profile of the IR laser pulse (λ_l=800 nm) is Gaussian. A pulse length of 25 fs (FWHM), a waist radius of 42.5 μm and a laser strength of a_0= 1.8 are considered. The plasma cell consists of a 9.5 cm long acceleration region surrounded by 0.7 cm long up- and down ramps following the shape of an exponential function. The laser pulse and the electron beam are injected collinearly into a plasma channel with a radially parabolic density profile and the on-axis plasma density of $n_o = 1 \cdot 10^{17} \text{cm}^{-3}$. A third order particle shape function was applied for the plasma with one particle per cell in z-direction, two particles in r-direction and four particles along θ-direction. Two azimuthal modes were used.

Table 2 displays the electron beam parameters at the plasma entrance and exit while figure 6 shows the horizontal and vertical phase spaces after acceleration and extraction from the plasma target.

Table 2. Electron beam parameters at the plasma entrance and exit calculated for the chosen setting for the PMQ triplet.

Beam parameters	at the plasma entrance	at the plasma exit
q_b [pC]	0.78	0.78
E [MeV]	99.2	1064.2
σ_z [fs]	1.46	1.61
$\beta_{x,y}$ [mm]	2.6 / 1.2	31.6 / 27.3
$\varepsilon_{x,y}$ [mm mrad]	0.12 / 0.28	0.12 / 0.45
$\sigma_{x,y}$ [μm]	1.27 / 1.30	1.34 / 2.40
$\alpha_{x,y}$	0.94 / 0.05	-4.21/-3.67
σ_E [%]	0.32	0.70
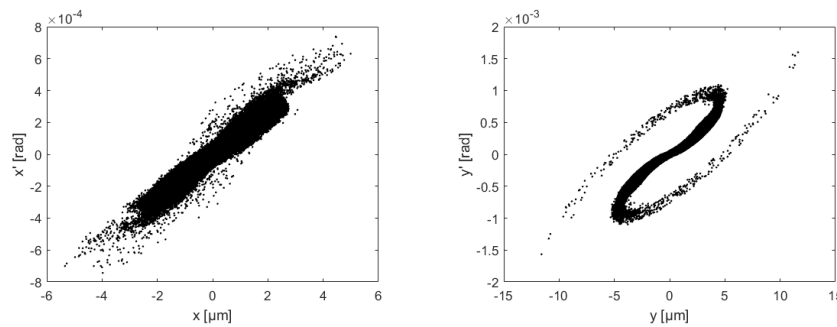
Figure 6. Horizontal and vertical phase space of the accelerated electron beam after its extraction from the plasma target.

The 100 MeV beam is successfully accelerated to an energy of 1 GeV in the plasma cell. The chosen injection phase allows beam acceleration and focusing at the same time. No particles are trapped in the defocusing area which leads to a capture efficiency of 100%. The use of a short plasma up-ramp at the beginning of the plasma allows the transverse beam size to be further decreased to a value close to the matched one. This leads to a preserved emittance in the horizontal plane. Due to the transverse asymmetry of the beam, the plasma up-ramp is only able to control the emittance growth in x-plane. The non-linear shape in the vertical phase space arises from a decoherence of particle betatron oscillations and beam envelope oscillations which occur because the beam is not perfectly matched to the plasma due to the asymmetry. Further plasma simulations confirmed that a more transversely

symmetric beam with a difference in the horizontal and vertical β-functions of less than 10%, a small difference in the horizontal and vertical α-functions and convergence in both planes ($\alpha_{x,y} > 0$) are required. Additionally, the comparatively long initial bunch length of the low charge beam causes an increase of the relative energy spread of 0.4% during the acceleration process. The beam-loading effect is not compensated for the considered laser-plasma configuration due to too low bunch peak current. An input bunch length below 1 fs for low bunch charges will allow the bunch peak current to be increased. This in turn will enable the beam-loading compensation effect to be used for control of the energy spread growth [8].

Nevertheless, since there is no beam path element after the BC that allows to decrease the bunch length again, the longitudinal phase space can only be limited by reducing the SC effects on the bunch. This is achieved with a less compact transverse phase space and a larger β-function at the BC exit.

3.3 Improved optimization results

The optimization of the matching beamline is repeated with a new beam distribution that provides an increased β-function of $\beta_{x,y}$=15 m instead of 6 m at the BC exit. Due to reduced SC forces a bunch length of 0.79 fs is achieved at the plasma matching point that leads to a 1 kA maximized peak current. Figure 7 provides the comparison of the Pareto optimum fronts for an initial β-function of 6 m (black curve) and 15 m (red curve). The impact of an enlarged transverse phase space on the minimum achievable bunch length is obvious. The corresponding improved beam parameters at the plasma entrance are summarized in table 3. Analysing the evolution of the phase spaces in figure 8 (a)-(c) a moderate increase in the bunch length over the drift space can be observed. Due to reduced SC effects, the lengthening of the bunch is mainly caused by the energy chirp and therefore unavoidable.

Furthermore, an additional constraint in the tool, which was added recently, optimizes the matching to produce a transversely symmetric beam. This fact can be observed in the evolution curves of the β-functions and the transverse emittances in figure 8(a) and 8(b).
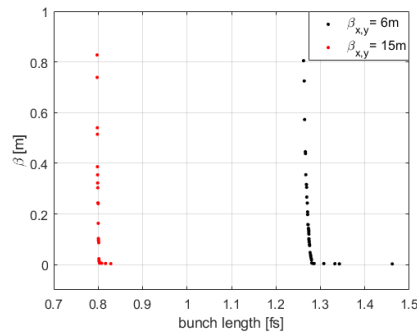
Figure 7. Pareto optimum fronts for beam distributions with an initial β-value of 6 m (black) and 15 m (red).

Table 3. Electron beam parameters at the plasma entrance for the new beam distribution with β=15 m at the BC exit.

q_b [pC]	0.78
σ_z [fs]	0.79
$\beta_{x,y}$ [mm]	13.0 / 13.0
$\varepsilon_{x,y}$ [mm mrad]	0.14 / 0.16
$\sigma_{x,y}$ [μm]	2.5 / 3.3
$\alpha_{x,y}$	1.21 / 1.01
σ_E [%]	0.4
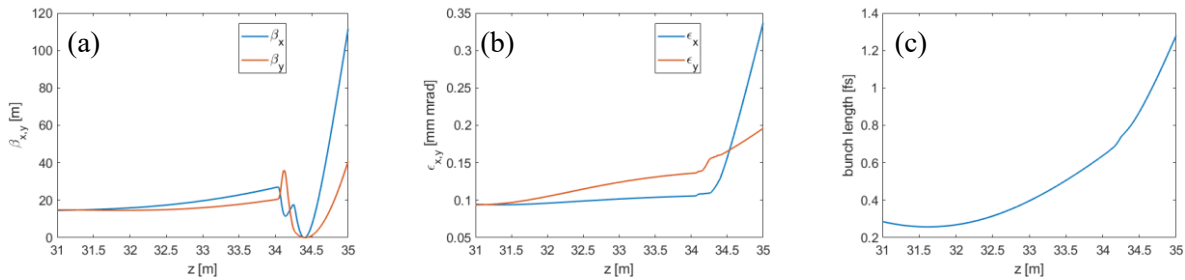
Figure 8. Evolution of the β-functions $\beta_{x,y}$ (a), the transverse emittances $\varepsilon_{x,y}$ (b) and the bunch length along the drift of the matching area and through the focusing system of three permanent quadrupoles. The initial β-function at the BC exit is 15 m.

4. Summary and Outlook

This paper presents a newly developed optimization tool based on a multi-objective genetic algorithm. The program finds stable settings for a focusing system to transversally match an electron beam into a plasma accelerator. As another advantage, it allows to map out the physical limits of the matching area and the focusing system. The analysis of the optimized settings for the chosen focusing system provides a detailed study of the beam dynamics in the matching area. Since the calculation of the electron beam parameters is done with a standard particle tracking tool, different focusing strategies can be tested and optimized with the introduced optimizer. This flexibility is given as long as the focusing elements can be implemented in the beamline setup in the tracking program. Using ASTRA, permanent and electromagnetic quadrupoles as well as active plasma lenses can be studied. This paper presents the first optimization results for a PMQ triplet. Recently, the developed optimization tool was able to find a way to successfully match the beam at the start of the plasma up-ramp using an electromagnetic quadrupole doublet. Currently, an active plasma lens is added to the particle tracking input file in order to enable the study of this third focusing strategy.

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