

# DESIGN CONSIDERATIONS FOR PERMANENT MAGNETIC QUADRUPOLE TRIPLET FOR MATCHING INTO LASER DRIVEN WAKE FIELD ACCELERATION EXPERIMENT AT SINBAD

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## Abstract

SINBAD (Short and INnovative Bunches and Accelerators at DESY) facility aims to produce ultrashort bunches (sub-fs) at ~100 MeV, suitable for injection into novel accelerators e.g. dielectric Laser acceleration (DLA) and Laser Driven Wakefield acceleration (LWFA). The LWFA experiment demands  $\beta$  functions to be of the order of 1 mm to reduce energy spreads and emittance growth from nonlinearities. Matching such a space charge dominated beam to such constraints with conventional electromagnets is challenging. A Permanent Magnetic Quadrupole (PMQ) triplet is one promising focusing strategy. In this paper, we investigate the performance of a PMQ triplet to fit the requirements of the electron beam properties in a plasma cell and discuss the realizable phase spaces for the LWFA experiment planned at SINBAD.

## INTRODUCTION

Laser Wake Field Acceleration (LWFA) offers the possibility of compact accelerators as a plasma wave provides accelerating gradients several orders of magnitude higher than in conventional accelerators and has made significant progress in the past few years [1-3]. The external injection experiment planned at ARES (Accelerator Research Experiment at SINBAD) aims to continue towards stable LWFA by combining the reproducible conventional RF-based accelerator technology, with high-power plasma wake field dynamics [4]. The RF-based technology allows the manipulation of phase spaces of the electron bunches entering the plasma hence providing better control and optimization of the plasma experiment.

SINBAD, acronym for Short Innovative Bunches and Accelerators at DESY, is a dedicated accelerator R&D facility currently under construction at DESY for research

and development on ultrashort electron bunches and novel acceleration techniques [5-7]. The ARES Linac [8] is based on conventional S-band accelerator technology to provide ultra-short (FWHM, length  $\leq 1$  fs-few fs) high brightness electron beams for injection into novel accelerators. ARES will support various bunch compression techniques [9, 10] allowing to produce beams with different phase space shapes suitable for injection into novel accelerators. Experimental preparation is underway for dielectric laser acceleration (DLA) and studies are being continued for Laser Wakefield Acceleration (LWFA) [11, 12]. The conditioning of the 5 MeV RF gun of the ARES is in progress [13, 14], while the main Linac is planned to be commissioned in summer 2019. In this paper we present the design, constraints and numerical studies done for the Permanent Magnetic Quadrupole (PMQ) triplet for matching into LWFA with external injection experiment planned at SINBAD.

## REQUIREMENTS OF THE MATCHING BEAMLINE

### ARES Layout

A schematic overview of the ARES Linac with LWFA acceleration experiment is shown in Fig. 1. ARES Linac consists of a 5 MeV RF gun followed by two travelling wave structures, with space reserved for a 3rd travelling wave structure for a future energy upgrade. This is followed by a matching section into the magnetic bunch compressor (BC). The BC compresses the beam to achieve sub-fs bunches [15, 16]. The BC is followed by a drift space to account for the laser beamline, diagnostics, vacuum installation and matching optics for the plasma cell.

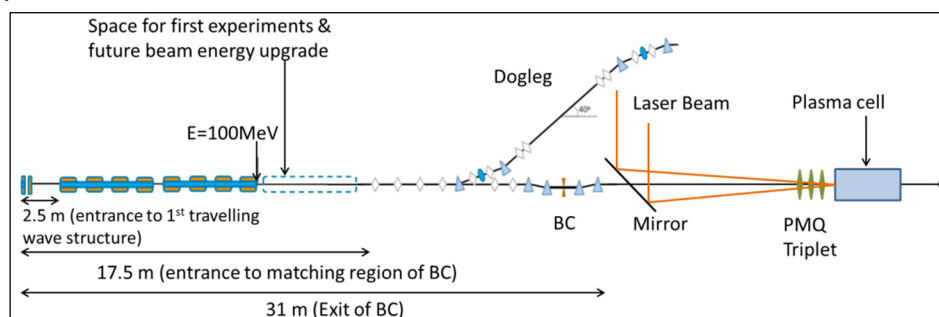


Figure 1: Schematic of ARES Linac with Bunch Compressor and matching section into LWFA

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## Laser Beamline

In the external injection LWFA experiment, the laser and electron beam are co-linearly injected into a plasma channel, which introduces strict constraints on both transverse and longitudinal dimensions of the design of the PMQ focusing system. These technical design constraints are explained in detail in the following discussion.

Due to strong space charge forces from the highly compressed beam, a long transfer beam line should be avoided between the BC and plasma cell. However, the distance between the exit of BC and the plasma is  $\sim 3.3$  m to account for the space required for diagnostics, vacuum, and to focus the laser beam. The schematic of the laser beam is shown in Fig. 2. The mirror is housed in a 10 cm beam pipe. The beam pipe size is chosen to accommodate the mirror dimensions required for focusing the 60 TW high power laser. A hole in the mirror allows the electron beam to pass through, and co-linearly to the laser beam, enters the plasma cell. At the focal point, the laser beam has a diameter (FWHM) of  $53.2 \mu\text{m}$ . This laser beam also has to pass through the PMQ. Hence the inner diameter of PMQ has to be larger than the laser spot size. As it is evident from Fig. 2, at a distance of 0.5 m before the focal point, the laser beam has a diameter of approximately 10 mm. The laser parameters and the laser beam line design dictates the limits for the physical dimensions of the PMQ inner and outer radii, length and also set constraints to the positions of the focusing magnets.

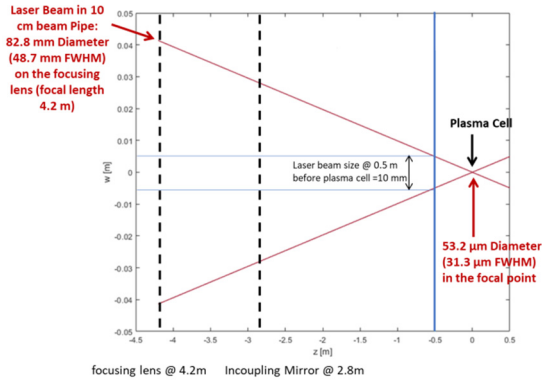


Figure 2: Evolution of the laser beam along the direction of beam propagation. The origin here is set at the focal point of the laser which is the entrance position of plasma cell. A Gaussian laser beam is assumed.

## Permenant Magnetic Quadrupole Triplet

LWFA demands a highly focused symmetric beam with mm-scale beta functions [12, 17]. A 100 MeV electron beam is planned to be injected into the LWFA experiment at SINBAD. If the beam is not properly matched, it will undergo betatron oscillations which can result in considerable projected emittance growth [18].

A Halbach type PMQ is one promising scheme used as a final focus system and provides high gradients for strong focusing required for LWFA. In a Halbach type PMQ, the quadrupole field profile is produced by

segmenting the magnet into geometrically identical pieces with a continuously varying magnetization for each piece with azimuthal angle  $\phi$ . This geometry augments the field in one direction and cancels the field in others, hence resulting in nearly ideal quadrupole field profile. A high remnant field,  $B_r$  permanent magnetic material is used for manufacturing of PMQs. One example is NdFeB, which has a remnant magnetic field of 1.22 T. The achievable field Gradient for such geometry is a function of magnet inner and outer radii and can be approximated by an analytical formula given in Eq. 1 [19, 20].

$$B' = 2B_r \left( \frac{1}{r_i} - \frac{1}{r_o} \right) \quad (1)$$

In the following section we present the result of the simulations to explore the possibility of use of PMQ triplet for focusing the space charge dominated electron beam. A similar system has also been adopted at UCLA [19] for their Inverse Compton Scattering experiment.

## SIMULATION RESULTS

In a separate study, the beam distributions at the exit of the BC were obtained by start to end simulations of the LINAC [10]. The optics upstream of the BC along with the BC dipole strengths can be tuned to obtain distributions with varying bunch length and twiss parameters at the exit of the BC. The beam parameters of 100 MeV electron beam of varying bunch lengths at the exit of bunch compressor and its evolution over a drift length of 3.3 m, without any focusing elements is shown in Fig 3. The beam is highly influenced by SC effects. The transverse SC will cause the emittance growth and longitudinal SC will result in an increased energy spread. The increase in bunch length over a drift of length  $L$ , assuming a constant energy chirp  $h$ , can be approximated by Eq 2.

$$\sigma_z \approx e^{Lh/\gamma^2} \cdot \sigma_{z,0} \quad (2)$$

Where  $\gamma$  is the Lorentz factor and  $\sigma_{z,0}$  is the initial bunch length at the start of the drift space, which in our case corresponds to exit of BC. The energy chirp is introduced during the off-crest acceleration and magnetic compression of the beam. It is already known from previous studies [21] that emittance grows with increase in initial beta function while both bunch length and energy spread increases as the initial beta function decreases. A working point of the ARES Linac producing beam distribution having bunch length of  $0.24 \mu\text{m}$  corresponding to 0.79 fs (at the exit of BC) was chosen for design studies of PMQ setup. The parameters for this working point are suitable for injection into LWFA. The parameters at the exit of BC are listed in Table 1. It is also very critical to control the growth of the energy spread to avoid the chromatic aberration introduced by the PMQ triplet.

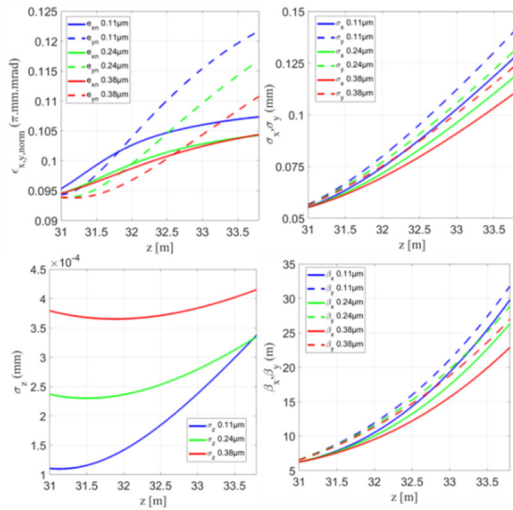


Figure 3: Evolution of the beam parameters from the exit of the bunch compressor at 31 m up to the plasma entrance without any focusing element for 3 different working points marked with different colors in the plot.

The beam dynamics simulations from the exit of BC until the plasma entrance was carried out first in Elegant (without the SC) [22] and then in ASTRA [23] to optimize and study the effects of SC. The first results of the matched beta functions are shown in Fig.4 and the matched beam parameters at the plasma entrance are given in Table 1. Here we use PMQ triplet with length of 20 mm and having strength of 400, 800 and 820  $m^{-2}$  respectively. However the matched parameters are larger than the requirements. We are aware that the requirements of matched beta functions can also be relaxed by using a ramp of plasma density. In the future we plan to refine the optimization of the matching by using the numerical optimizer LinacOpt. [24].

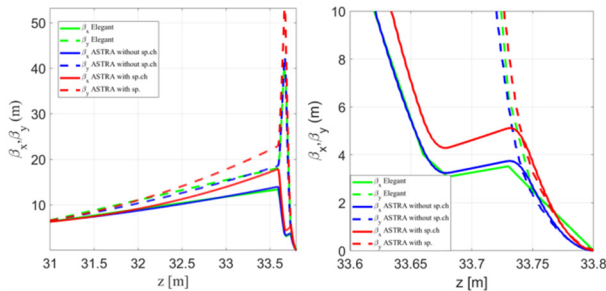


Figure 4: Matched beta function with and without SC. The right figure shows the change of scale to zoom in on beta functions.

Since the maximum achievable gradient of a PMQ strongly depends on the diameters of the quadrupole, 3D modelling and numerical analysis of Halbach PMQ was done in CST [25] to see the effect of finite length and inner and outer radii and to set the limits on maximum achievable gradients for PMQ design optimization. The segmentation of PMQ in a number of sections may also have an effect in diminishing the gradient of PMQ. Figure 5 gives the numerical analysis of 16 piece Halbach geometry, with inner radius of 5 mm, outer radius of 12.5 mm and length of 30 mm. The theoretically achievable

gradient is 292 T/m while CST simulations give a gradient of 275 T/m. This corresponds to decrease in gradient of around 6% of the theoretically predicted value.

Table 1: Beam Parameters Simulated by ASTRA

Beam Parameters	At the BC exit	At the Plasma Entrance	
		with SC	Goal
Energy (MeV)	99.25	99.25	100
Bunch Charge (pC)	0.79	0.79	0.75
$\epsilon_{nx}/\epsilon_{ny}$ (pi.mm.mrad)	0.094/0.094	0.1/0.1	0.11/0.1
$\beta_x/\beta_y$ (mm)	6.29/6.29	4.6/3.5	1.1 /1.1
$\alpha_x/\alpha_y$	-1.0/-1.6	2.5/5.4	-0.21/0.24
$\sigma_x/\sigma_y$ ( $\mu m$ )	55/55	0.8/1	0.8/0.8
$\Delta E/E$ (%)	0.0014	0.0014	0.0017

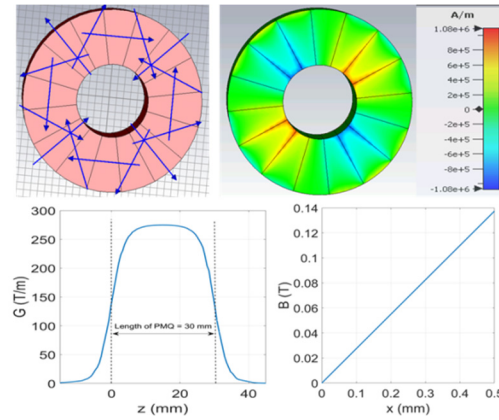


Figure 5: CST simulations of PMQ. Top figure shows the direction of magnetization and the corresponding field density plot. The bottom figure gives the maximum achievable gradient and field amplitude

## CONCLUSION AND OUTLOOK

We have presented the design constraints and first study of the PMQ triplet for use as final focus system for LWFA experiment planned at ARES. The design needs to be further optimized and then bench marked for different working points of ARES before going into the technical design phase. The initial results look promising for achieving the strict demands of the LWFA experiment. The fine tuning of the matched beam parameters can also be done by using the slope of Longitudinal Plasma field profile. Once the design is finalized, the tolerance studies will be done for PMQ geometric parameters and alignment as well as the effects of temperature and radiations needs to be investigated, especially in the case of external injection, when the laser is propagating with the electron beam through the PMQ's.



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