

# Design considerations for permanent magnetic quadrupole triplet for matching into laser driven wake field acceleration experiment at SINBAD

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**Abstract.** The ARES (Accelerator Research experiment at SINBAD) Linac at SINBAD (Short and INnovative Bunches and Accelerators at DESY) facility at DESY aims to produce high brightness ultrashort electron bunches (sub fs to few fs) at around 100 MeV, suitable for injection into novel accelerators e.g. dielectric Laser acceleration (DLA) and Laser Driven Wakefield acceleration (LWFA). The external injection experiment planned at ARES aims for stable LWFA by combining the reproducible conventional RF-based accelerator technology, with high-power plasma wakefield dynamics. The LWFA experiment demands Twiss parameter  $\beta$  to be of the order of few mm, in order to avoid emittance growth because of high accelerating gradient in the plasma. The ARES Linac is capable of producing ultra-short bunches at around 100-150 MeV, so the effect of space charge is significantly high. To match such a space charge dominated beam, strong transverse focusing is required. A Permanent Magnetic Quadrupole (PMQ) triplet is one promising focusing strategy. In this paper, we report the technical design constraints and findings for stable settings for PMQ triplet to match the requirements of the electron beam properties and study of phase spaces for final focus into LWFA experiment.

## 1. Introduction

Laser Wake Field Acceleration (LWFA) provides accelerating gradient several orders of magnitude higher than conventional accelerators and hence offers the possibility of compact accelerators. LWFA has been a subject of extensive study with significant progress in the past few years [1-4]. The external injection LWFA experiment planned at ARES (Accelerator Research Experiment at SINBAD) will be an important step towards stable LWFA as it combines the reproducible conventional RF-based accelerator technology, with high-power plasma wake field dynamics [5]. The RF-based technology allows the manipulation of phase spaces of the electron bunches entering the plasma hence providing better control and quality as well as optimization of the plasma experiment.

SINBAD, acronym for Short INnovative Bunches and Accelerators at DESY, is an accelerator R&D facility currently under construction at DESY, Hamburg site. SINBAD is dedicated for research and development on ultrashort electron bunches and novel acceleration techniques [6-8]. It will also serve as test bench for novel diagnostic devices [9]. The ARES Linac [10], based on conventional S-band technology, is a photo injector at SINBAD to provide ultra-short (FWHM, length  $\leq 1$  fs-few fs)



high brightness electron beams for injection into novel accelerators. The use of conventional photo injector for producing electron bunches to inject into novel accelerators has several advantages. On one hand, conventional S-band RF technology of ARES allows to produce stable and reproducible electron bunches, and on the other hand, allows the production of high brightness e-bunches with bunch length of the order of fs/sub-fs. At ARES, the target value of the arrival time jitter is around 10 fs rms [11]. Short bunches fit into very compact novel accelerators, with short accelerating field wavelength. Hence such bunches constitute excellent probes to measure energy gain and the quality of the acceleration. The beam quality in novel accelerators depends on the detailed parameters and quality of the injected beam e.g. bunch shape, bunch length, emittance, arrival time stability, energy etc. Hence, ARES provides the option of flexible widely tunable Working Points (WP) and bunch shapes for novel accelerator R&D. ARES has the capability to produce ultrashort bunches using different bunch compression techniques [12-13]. Dielectric Laser Acceleration (DLA) experiment preparations are ongoing and studies are being continued for a LWFA experiment [14-15]. Currently, the conditioning and commissioning of 5 MeV RF gun and Linac cavities of the ARES is in progress [16-18]. In this paper we present the experimental design constraints and numerical studies done for a final focus system consisting of Permanent Magnetic Quadrupole (PMQ) triplet for matching into LWFA with external injection experiment planned at SINBAD

## 2. Constraints and Requirements of the Matching Beamline

In this section, the layout of the ARES Linac is explained and requirements and space constraints of the matching beamline are discussed.

### 2.1. ARES Layout

A schematic overview of the ARES Linac with LWFA experiment is shown in figure 1 and main beam parameters are summarized in table 1. The ARES Linac consists of a 5 MeV RF gun followed by two travelling wave structures (TWS), with space reserved for a 3rd travelling wave structure for future energy upgrade. This space will be initially used for DLA experiment and then a 3<sup>rd</sup> travelling wave structure will be installed. The DLA experiment will then be moved to the dogleg area. This is followed by a matching section into magnetic Bunch Compressor (BC). The BC compresses the beam to achieve sub-fs bunches [19]. The BC is followed by a drift space to account for the laser beamline, diagnostics, vacuum installation followed by the matching optics for the plasma cell for LWFA experiment.

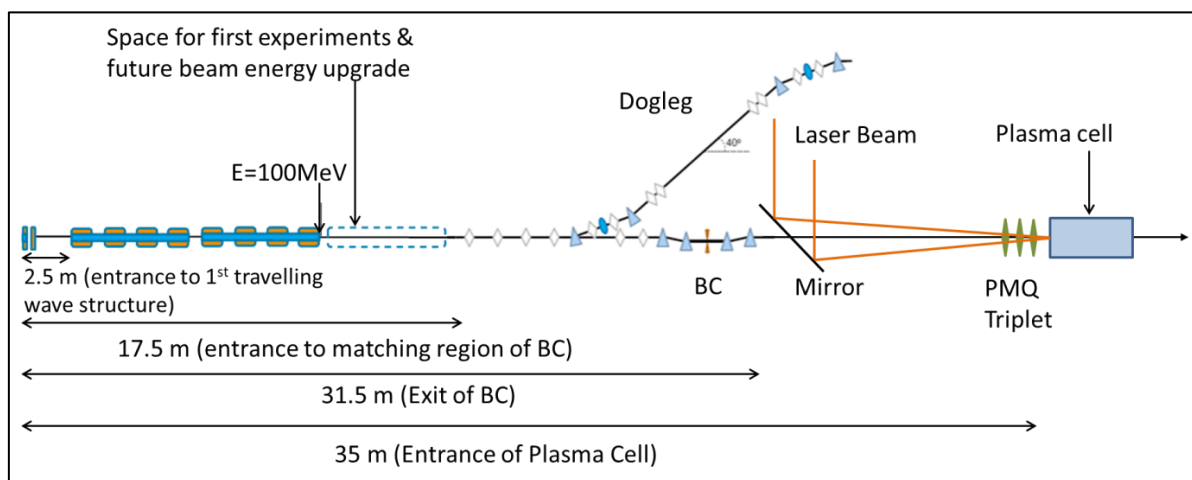


Figure 1: Schematic of ARES Linac with Bunch Compressor and matching section into LWFA

**Table 1.** Achievable Beam parameters for ARES Linac.

Parameters	Values
RF Frequency	2.998 GHz
Rep rate	10-50 Hz
Beam Energy (using 2 TWS structures)	100 MeV (155 MeV on crest)
Upgraded Beam Energy (using 3 TWS structures)	150 MeV (230 MeV on crest)
Bunch charge	0.5-30 pC
Bunch length	Sub fs to few fs
Arrival time jitter stability	~ 10fs to few tens of fs

## 2.2. Laser beamline Layout

In the external injection LWFA experiment, the laser and electron beam are collinearly injected into a plasma channel, which introduces strict constraints on both transverse and longitudinal dimensions for the design of the final focusing system. These space-constraints are one of the key factors for choosing PMQ triplet as final focusing system, as they are compact and provide gradient high enough to fulfill the demands of LWFA. These technical design constraints are explained in detail in the following paragraph.

The schematic of the laser beam is shown in figure 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 125 TW high power laser. A hole in the mirror allows the electron beam to pass through, and collinearly to the laser beam, it enters the plasma cell. At the focal point, the laser beam has a diameter (FWHM) of 53.2  $\mu\text{m}$ . For the external injection experiment, the laser beam also has to pass through the PMQ triplet to reach the plasma cell. Hence the inner diameter of PMQ should be larger than the laser spot size with allowance for the pointing jitter. The laser parameters and the laser beam line design dictates the limits for the physical dimensions of the PMQ inner and outer radii, length of the total triplet and also set constraints to the positions of the focusing magnets. Due to strong space charge forces characterizing the highly compressed beam, there is the need to minimize the drift space between the BC and plasma cell. However, the distance between the exit of BC and the entrance of plasma cell is  $\sim 3.3$  m to account for the space required for diagnostics, vacuum, and to focus the laser beam.

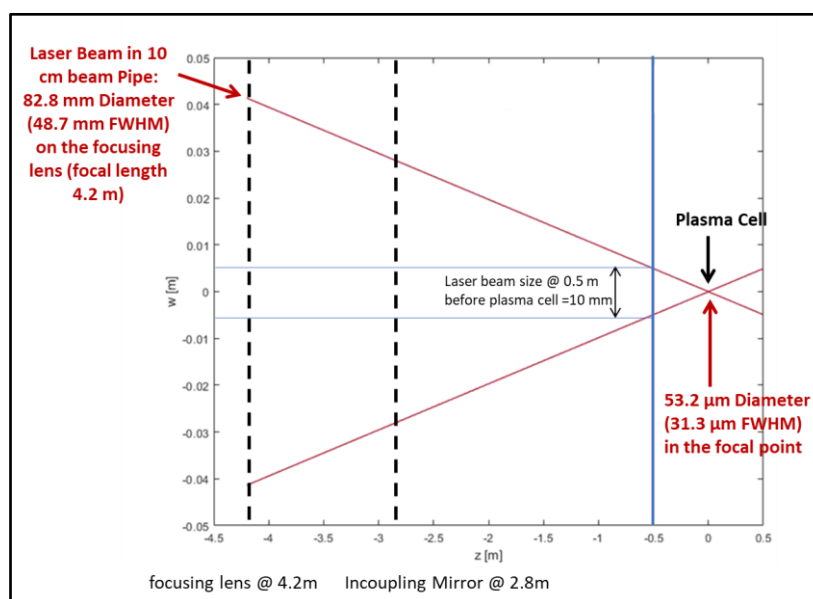


Figure 2: Evolution of the laser beam along the direction of beam propagation. The origin here is set at the focal point of the laser which is the entrance position of plasma cell. A Gaussian laser beam is assumed.

### 3. Simulations for beam matching

In this section, the results for the electron beam matching studies are presented. LWFA experiment requires a highly focused and symmetric beam with mm-scale beta functions [15,20]. A 100-200 MeV electron beam is planned to be injected into LWFA experiment at SINBAD. If the beam is not properly matched, it will undergo betatron oscillations which can result in significant projected emittance growth [21].

A Halbach type PMQ triplet is one promising scheme used as a final focus system and provides high gradients for strong focusing required for LWFA to reach mm-scale  $\beta_{x,y}$ . In this section, the result of the matching studies to explore the possibility of using a PMQ triplet for focusing the space charge dominated electron beam is presented. A similar system has also been adopted at UCLA [22] for their Inverse Compton Scattering experiment.

#### 3.1. Beam after BC

The beam distribution at the end of the Linac and the exit of BC were obtained by a start to end simulations of ARES Linac and have been discussed in detail in [19]. The different working points of ARES with varying beam parameters can be realized by tuning the optics upstream of BC along with the dipoles of BC. The WP with smallest arrival time jitter  $\sim 10$  fs rms with sub fs bunch length aims to serve as probe particles for LWFA experiment since amplitude of accelerating field gradients is also of the order of few  $\mu\text{m}$ . In the following paragraph we will discuss the matching studies and results for this WP of the ARES Linac. Also results for matching studies at higher energies using the third travelling wave structure for the same WP will be compared and discussed.

The parameters at the exit of BC for WP are listed in table 2 and their evolution over a drift length of 3.3 m, without any focusing elements, is shown in figure 3. The first column of table 1 corresponds to beam parameters with 2 travelling wave structures and second column shows beam parameters with 3 travelling wave structures simulated with respect to ARES energy upgrade studies.

**Table 2.** Beam Parameters at the BC exit with 2 and 3 TWS structures.

Parameter	WP_2 TWS structures	WP_3 TWS structures
Bunch Charge (pC)	0.8	0.8
Bunch length rms (fs)	0.42	0.20
$\varepsilon_{nx} / \varepsilon_{ny}$ (pi.mm.mrad)	0.11/0.095	0.10/0.098
$\beta_x / \beta_y$ (mm)	9.24e3/8.21e3	16.60e3/52.65 e3
$\alpha_x / \alpha_y$	-2.55/-2.81	-4.2/3.5
$\sigma_x / \sigma_y$ ( $\mu\text{m}$ )	71.8/63.1	67.21/114.79
RMS energy spread (%)	0.13	0.12
Peak Current (kA)	1	4

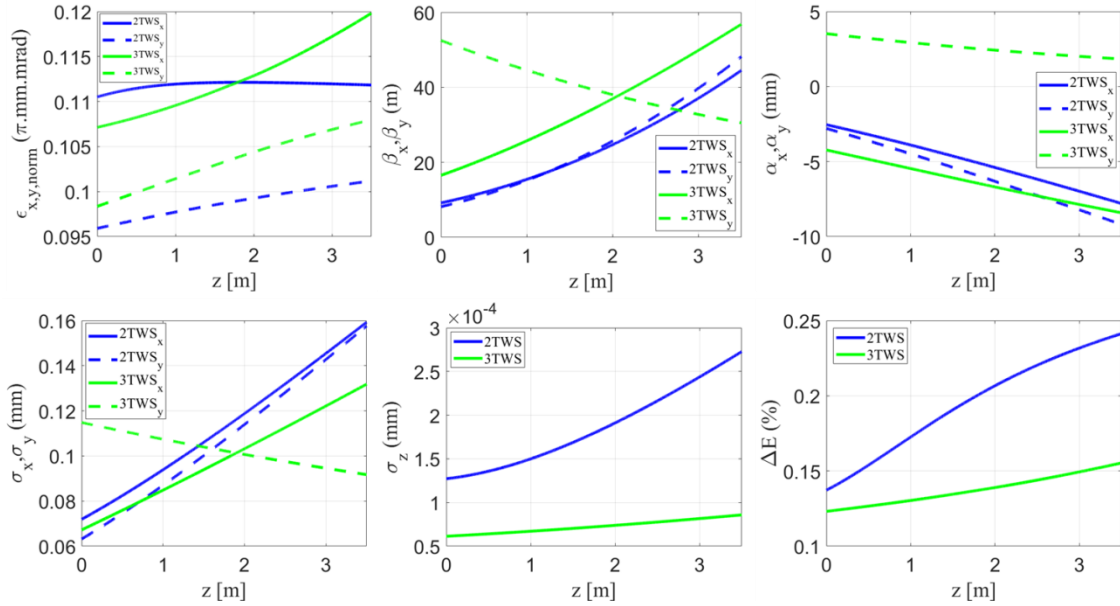


Figure 3: Evolution of electron beam for WP over drift space without any focusing element.

The beam is highly influenced by SC effects as can be seen in figure 3. The transverse SC will cause the emittance growth and longitudinal SC will result in an increased energy spread. The increase in bunch length  $\sigma_z$  over a drift of length  $L$ , assuming a constant energy chirp  $h$ , can be approximated by equation (1).

$$\sigma_z \approx e^{Lh/\gamma^2} \cdot \sigma_{z,0} \quad (1)$$

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 has been already observed in previous studies [23] that the emittance increases with a higher initial beta function, whereas both the bunch length and energy spread decrease. These WP's have been simulated keeping bunch length and energy spread appropriate for LWFA.

### 3.2. Matching requirements and Optimization for Matching Beamline

The beam dynamics simulation for the matching beamline after the BC was done using Elegant and then ASTRA [24-25] to optimize and include the effects of 3D SC, since there is very strong effects of SC for this energy regime. The matching requirements depends on the focusing strength of the plasma channel [26]. For our LWFA experiment, the matched twiss parameter  $\beta_{x,y} \sim 1$  mm for a step function of longitudinal plasma density profile and was relaxed upto few mm by proper shaping of the longitudinal plasma density profile (upramps). The detailed parameters for plasma profiles is a part of separate study and are discussed in [15,20]. The optimization parameters for the PMQ triplet were the length and strength of the quadrupoles, as well as the distances between them. Based on the laser beamline layout, as shown in figure 2, the constraints for final focus system were the inner and outer radii, and the focal length. The minimum focal length required for our system was to at least 10 cm to account for diagnostic screens for laser and electron beam between the last magnet of triplet and the plasma cell. The matched beam parameters for WP with 2 and 3 travelling wave structures are listed in table 3 and the corresponding phase spaces are shown in figure 4.

The third travelling wave structures helps in mitigating the effects of SC over the long drift and allows transporting much higher peak current for the same amount of bunch charge. The 3<sup>rd</sup> TWS structure also gives a high tuning range of beam parameters in terms of bunch length and lower energy spread. The lower energy spread is desirable to show stable LWFA with excellent beam quality. Also under the transnational access program of ARIES [6,27], a certain fraction of ARES beam time will be

available to user community for other experiments and the ARES energy upgrade with third TWS structure enables to produce broader spectrum of parameters which have a wide range of applications in other fields as well [28].

**Table 3.** Beam Parameters at the Entrance of plasma Cell.

	2 TWS	3 TWS
Bunch Charge (pC)	0.8	0.8
Bunch length rms (fs)	0.89	0.27
$\epsilon_{nx} / \epsilon_{ny}$ (pi.mm.mrad)	0.114/0.118	0.110/0.117
$\beta_x / \beta_y$ (mm)	7.5/7.5	3.3/3.4
$\alpha_x / \alpha_y$	-0.40/-0.22	-0.6/0.4
$\sigma_x / \sigma_y$ ( $\mu\text{m}$ )	2.09/2.13	0.97/1.0
RMS energy spread (%)	0.28	0.16
Peak Current (kA)	$\sim 0.35$	$\sim 2$

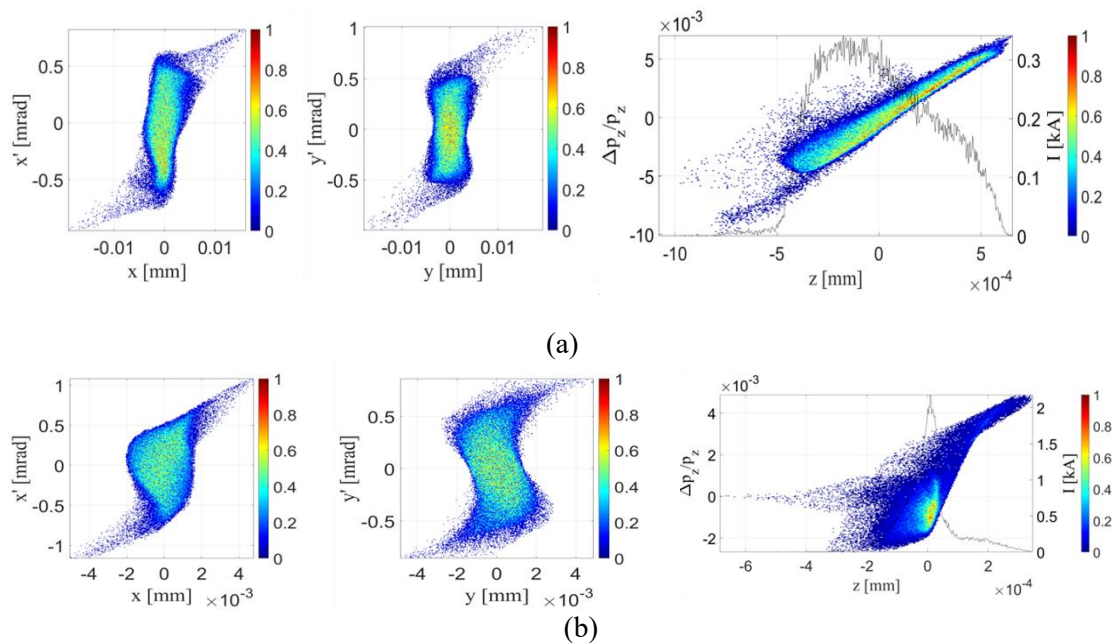


Figure 4: Transverse and Longitudinal Phase spaces of the matched beam at the entrance of plasma cell with (a) two TWS (b) 3 TWS. The colour bar shows normalized number density

#### 4. Numerical Analysis of a Halbach type PMQ

In a Halbach type PMQ [29], the magnet is segmented into geometrically identical pieces with a continuously varying magnetization for each piece with azimuthal angle  $\varphi$ . 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 at room temperature. The achievable field gradient  $B'$  for such geometry is a function of inner and outer radii of the magnet and can be approximated by an analytical formula given in equation (2) [29].

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

Since the maximum achievable gradient of a PMQ strongly depends on the diameters of the quadrupole, 3D modelling and numerical analysis of a Halbach PMQ was done in CST [30] 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 the PMQ in a number of sections may also have an effect on 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. These parameters of the quadrupoles were derived from optimization as explained in the previous section. The theoretically achievable gradient is 292 T/m while CST simulations gives a gradient of 275 T/m. This corresponds to decrease in gradient of around 6% of the theoretically predicted value.

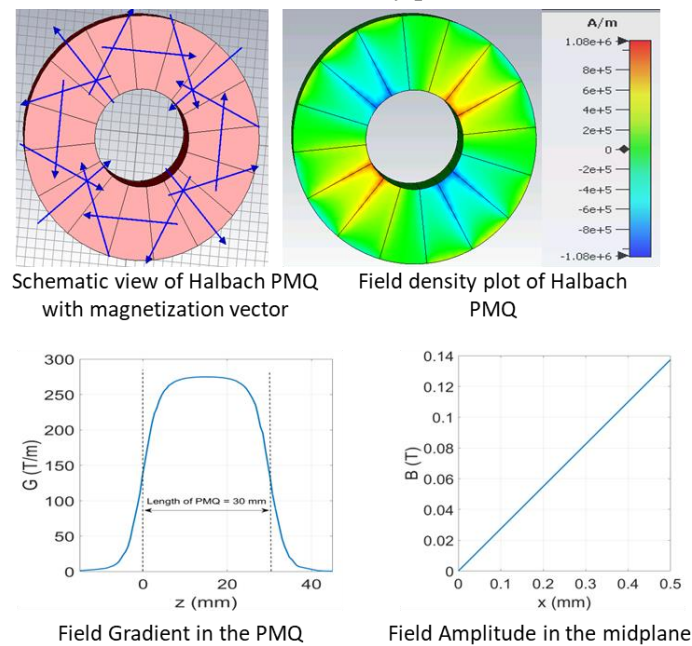


Figure 5: CST simulations of PMQ. Top figure shows the direction of magnetization and the corresponding field density plot. The bottom figure gives the maximum achievable gradient and field amplitude

## 5. Summary and Outlook

In this paper, the matching studies for focusing beam into a LWFA experiment planned at SINBAD is presented. The ARES Linac will provide a stable and reproducible electron beam for injection into novel acceleration experiments. An important feature of such acceleration schemes is the small size of the accelerating structure and hence a smaller accelerating channel in both longitudinal and transverse planes. The finite energy spread beam needs to be matched to avoid emittance growth. We have presented the matched beam parameters for LWFA experiment planned at ARES. The Transverse and Longitudinal parameters are suitable for injection into LWFA. We have also discussed the matching with an energy upgrade of the ARES Linac and how it helps to achieve smaller bunch length and hence much higher peak currents since SC effects become less dominant. Because of collinearly travelling electron and laser beam, there are strict technical and space constraints of the external injection experiment planned at ARES. The possibility of using Halbach type PMQ quadrupole triplet has been presented as one promising strategy to be used as final focus system. The numerical studies performed in CST have been shown to give good agreement with the analytical results. The initial results look promising for achieving the strict demands of the LWFA experiment. The flexibility of the current technical design for other working points of ARES needs still to be investigated before going into the technical design phase. Moreover the effect of temperature and radiations on PMQ needs to be investigated, especially in the case of external injection, when the 125 TW laser is propagating with the electron beam through the PMQ's. Since the electron beam has to pass through the hole of the

focusing mirror of the laser, the effects of wakefield on the electron beam will also be taken into account in a further study.

### Acknowledgement

Author deeply Acknowledges Klaus Floettmann, Frank Mayet, Willi Kuroпка and Farzad Jafarinia for their valuable discussion

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