DESIGN STUDIES FOR PERMENANT MAGNETIC QUADRUPOLE TRIPLET FOR MATCHING INTO LASER DRIVEN WAKE FIELD ACCELERATION EXPERIMENT WITH EXTERNAL INJECTION AT SINBAD

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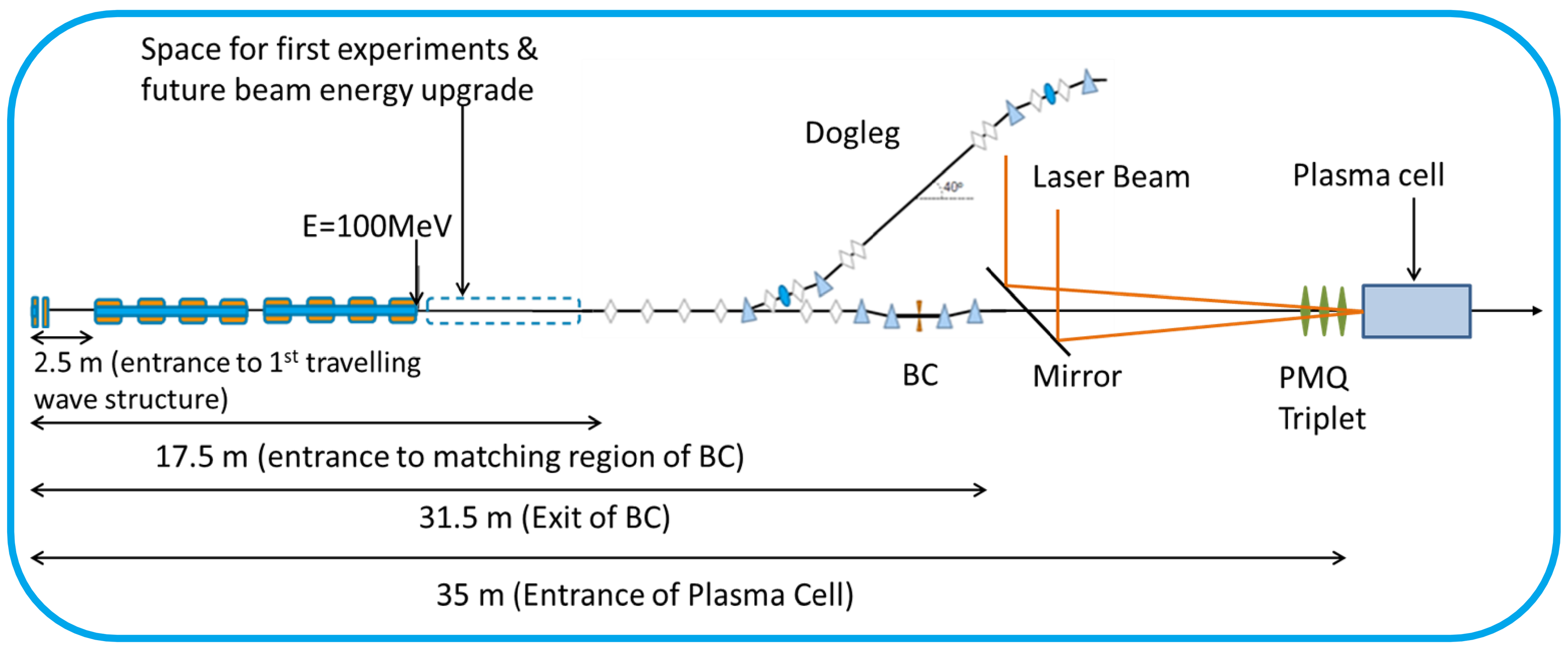
SINBAD: Short INnovative Bunches and Accelerators at DESY
ARES: Accelerator Research Experiment at SINBAD

ARES LINAC

- A conventional S-band photo injector → **ultra-short (FWHM, length <=1 fs-few fs) high brightness electron beam**
- Injection into novel accelerators: DLA, LWFA, THz driven accelerators
- Allows manipulation of the beam → **different bunch length compression techniques**
- Serve as → **testbed for technology development**
- Energy: 100-150 MeV, Charge: 0.5-20 pC (up to 1nC), $\varepsilon_{x,y}$ < 0.5 mm*mrad, Arrival time jitter stability < 10 fs RMS
- The conditioning of 5 MeV RF gun and TW structures → in progress



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

Why a "conventional" photo-injector?

- Conventional RF technology → **a stable and reproducible e-bunch**
- The quality of the acceleration in novel accelerators depends on the quality of the injected beam (e.g. bunch length, emittance, arrival time stability, energy) → **flexible widely tunable Working Points**
- Well known beam dynamics codes have not yet been benchmarked with experiments in this special beam parameter range → **extending our understanding of beam dynamics**
- Characterization of ultra-short (~fs), low charge (~sub-pC) bunches is challenging → **test novel diagnostics devices**

Motivation for External Injection

- Stable LWFA: As it combines the reproducible conventional RF-based accelerator technology, with high-power plasma wake field dynamics
- The RF-based technology allows the manipulation of phase spaces of the electron bunches entering the plasma
- Better control and optimization of the plasma experiment

Matching Requirements of LWFA with External Injection

- LWFA demands a highly focused symmetric beam with mm-scale beta functions [1]
- Non-matched: betatron oscillations → considerable projected emittance growth
- A Halbach type Permanent Magnetic Quadrupole (PMQ) as final focus system [2,3]
- Provides high gradients for strong focusing required for LWFA.
- The quadrupole field profile produced by segmenting the magnet into geometrically identical pieces with a continuously varying magnetization for each piece with azimuthal angle φ.

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

Design Constraints for PMQ Triplet

- Collinearly injected laser and electron beam into the plasma channel.
- Strict constraints on both transverse and longitudinal dimensions for the design of PMQ focusing system.
- Compressed beam→ Strong space charge force→ Longer drift should be avoided
- Drift ~3.5 m: space required for diagnostics, vacuum equipment and focusing mirror of the laser.
- The beam pipe size is chosen to accommodate the laser and mirror dimensions required for focusing the 100 TW high power laser.
- A hole in the mirror allows the electron beam to pass through, and collinearly to the laser beam, enters the plasma cell.
- At the focal point, the laser beam has a diameter (FWHM) of 53.2 µm.
- Laser beam also has to pass through the PMQ. Inner diameter of PMQ should be larger than the laser spot size.

Optimization of ARES WP1

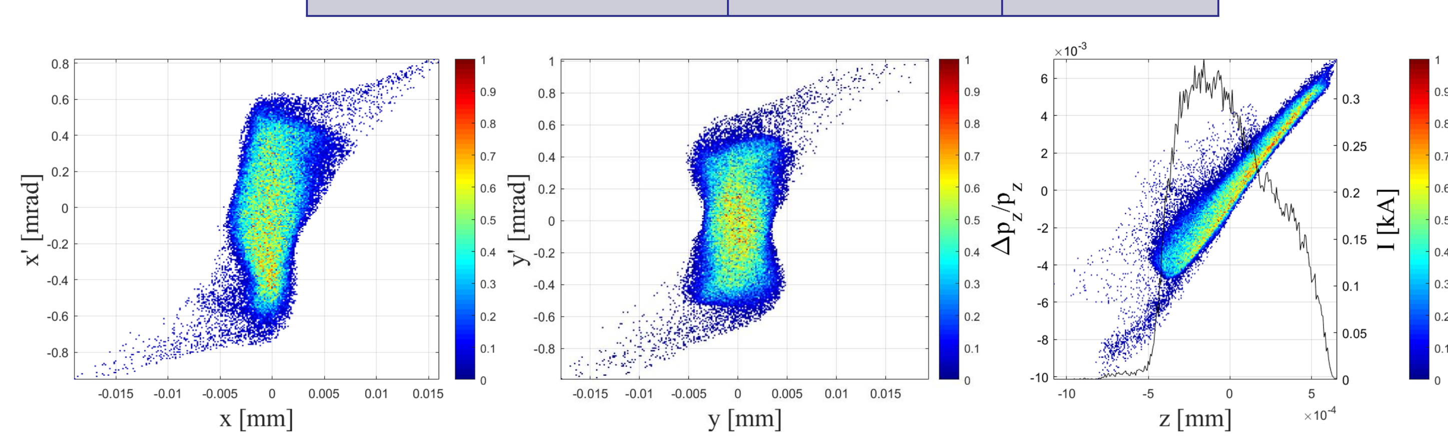
- WP1: sub fs bunch with smallest arrival time jitter with pure magnetic compression
- As probes with good time resolution for LWFA, DLA
- Short bunches are extremely space charge dominated
- With ARES energy upgrade, using 3rd TW structure, space charge is considerably reduced and hence much higher peak current can be delivered to plasma cell.
- 3rd TW structure gives a wide spectrum of tunability of WP's for various applications.

Beam Parameters with 2 TW structures

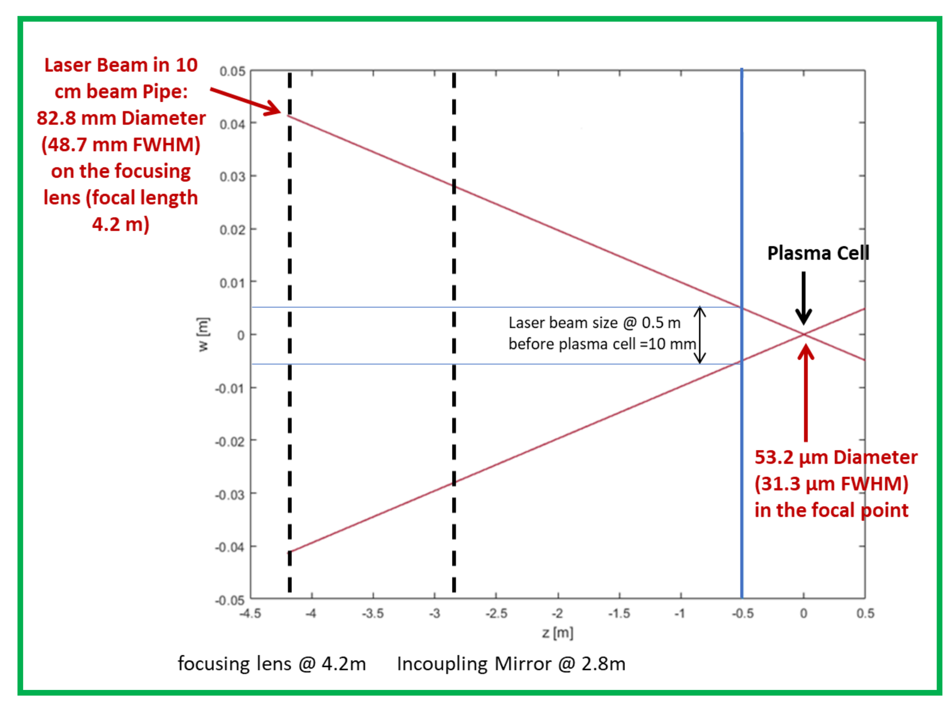
Parameter	At BC exit	At plasma entrance
Beam Energy (MeV)	100	100
Bunch Charge (pC)	0.79	0.79
Bunch length rms (fs)	0.42	0.89
$\varepsilon_{nx}/\varepsilon_{ny}$ (pi.mm.mrad)	0.11/0.095	0.114/0.118
β_x/β_y (mm)	9.24e3/8.21e3	7.57/7.58
α_x/α_y	-2.55/-2.81	-0.40/-0.22
σ_x/σ_y (µm)	71.8/63.1	2.09/2.13
RMS energy spread (%)	0.13	0.28
Peak Current rms (kA)	0.53	0.25

Beam Parameters with 3 TW structures

Parameter	At BC exit	At plasma entrance
Beam Energy (MeV)	200	200
Bunch Charge (pC)	0.80	0.80
Bunch length rms (fs)	0.20	0.27
$\varepsilon_{nx}/\varepsilon_{ny}$ (pi.mm.mrad)	0.10/0.098	0.110/0.117
β_x/β_y (mm)	16.6e3/52.65e3	3.3/3.4
α_x/α_y	-4.2/3.5	-0.6/0.4
σ_x/σ_y (µm)	67.21/114.79	0.97/1.0
RMS energy spread (%)	0.122	0.16
Peak Current rms (kA)	1.12	0.73

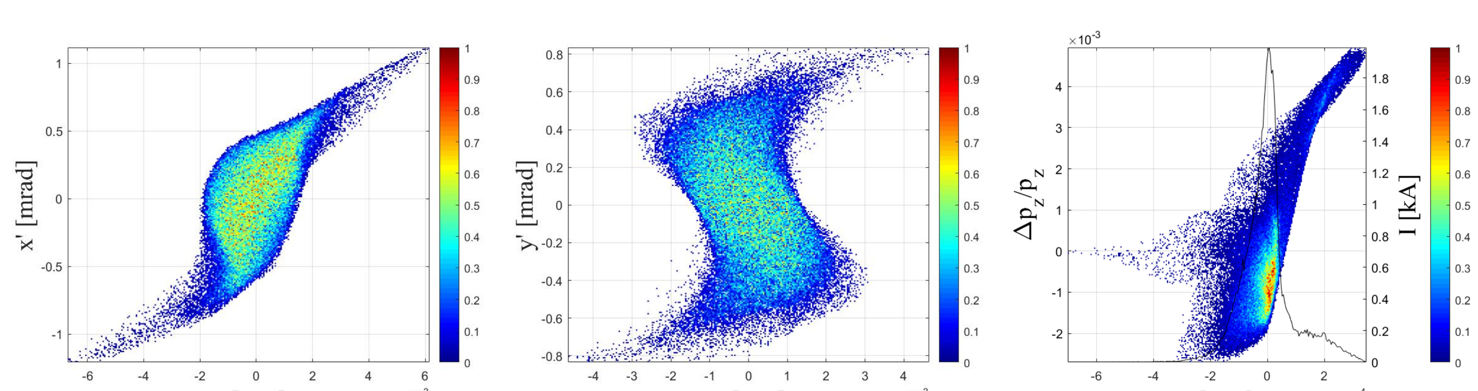


Longitudinal and Transverse phase spaces for with 2 TW structures



Evolution of the laser and electron 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.

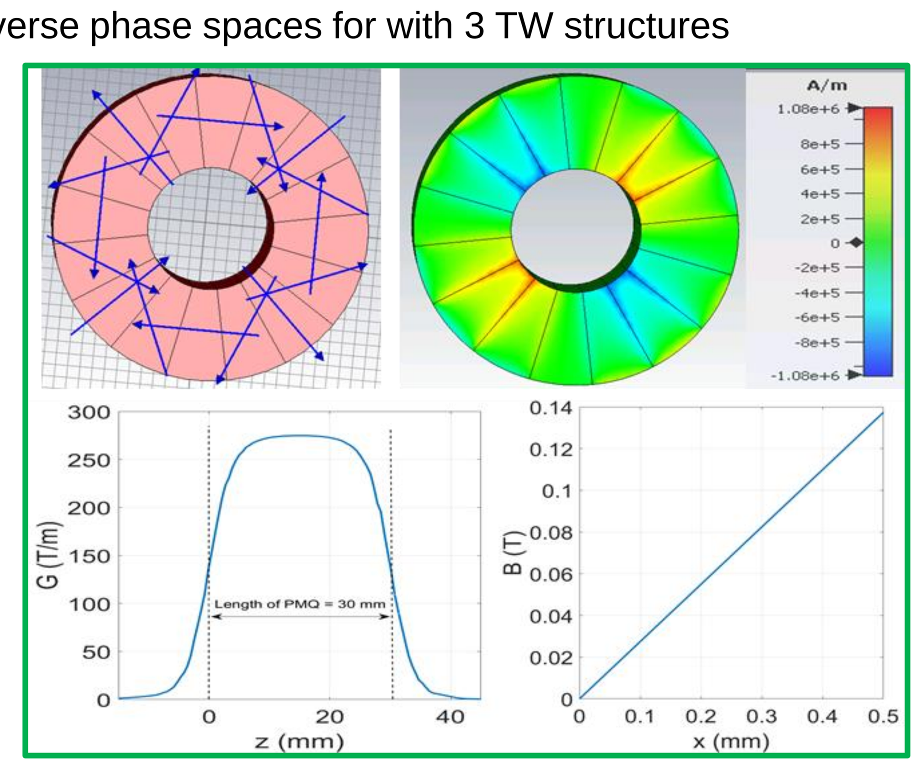
PMQ settings
l=0.045, 0.035, 0.04 m
k =54, -188, 184 m^{-2}
Focal length: 0.14 m



Longitudinal and Transverse phase spaces for with 3 TW structures

3D modelling and numerical analysis of Halbach PMQ in CST

- For PMQ design optimization to see the effect of
  - finite length
  - inner and outer radii
  - set the limits on maximum achievable gradients
- The segmentation of PMQ in a number of sections may also have an effect in the gradient of PMQ.
- 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 gives a gradient of 275 T/m: a difference of 6%



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

- Presented the design constraints and study of the PMQ triplet for use as final focus system for LWFA experiment planned at ARES.
- The studies for higher beam injection energy for one of the WP are presented.
- Wide spectrum of WP's (charge, energy) with ARES possible for various experiments.
- The initial results look promising for achieving the strict demands of the LWFA experiment.
- The fine tuning of the requirements of the matched beam parameters can by using the slope of Longitudinal Plasma field profile.
- The tolerance studies will be done for PMQ geometric parameters and alignment.
- The effects of temperature and radiations also needs to be investigated, especially in the case of external injection, when the laser is propagating with the electron beam through the PMQ's.
- Effects of CSR and wake fields (beam passing through the mirror) will also be taken into account.

References
[1] E. N. Svystun et al, in Proc. 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, THPGW023.
[2] J. K. Lim et. al, Phys. Rev. STAB 8, 072401, 2005.
[3] F. H. O, G. Andonian, and J. B. Rosenzweig, in Proc. 1st Int. Particle Accelerator Conf. (IPAC'10), Kyoto, Japan, May 2010, paper WEPE077.