Simulation study for Self-modulation Experiment at PITZ

> Self-Modulation

> Beam matching in plasma

> Optimizing the strength of the modulation

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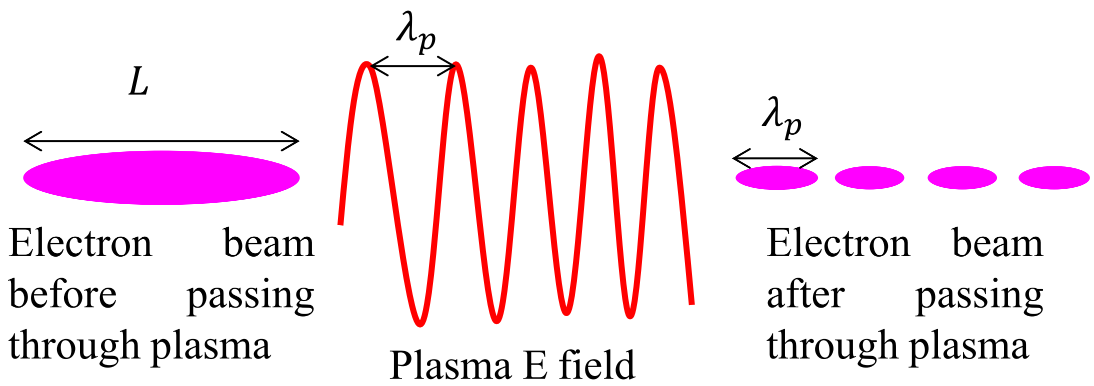
Self-modulation

A Proton driven plasma wakefield acceleration was proposed by A.Caldwell et. al. in 2009.

The CERN SPS bunch has length ~12cm (120mm).

How to generate short proton bunches?

To generate a short proton bunches a technique viz. self modulation is proposed by N. Kumar and A. Pukhov in 2010.



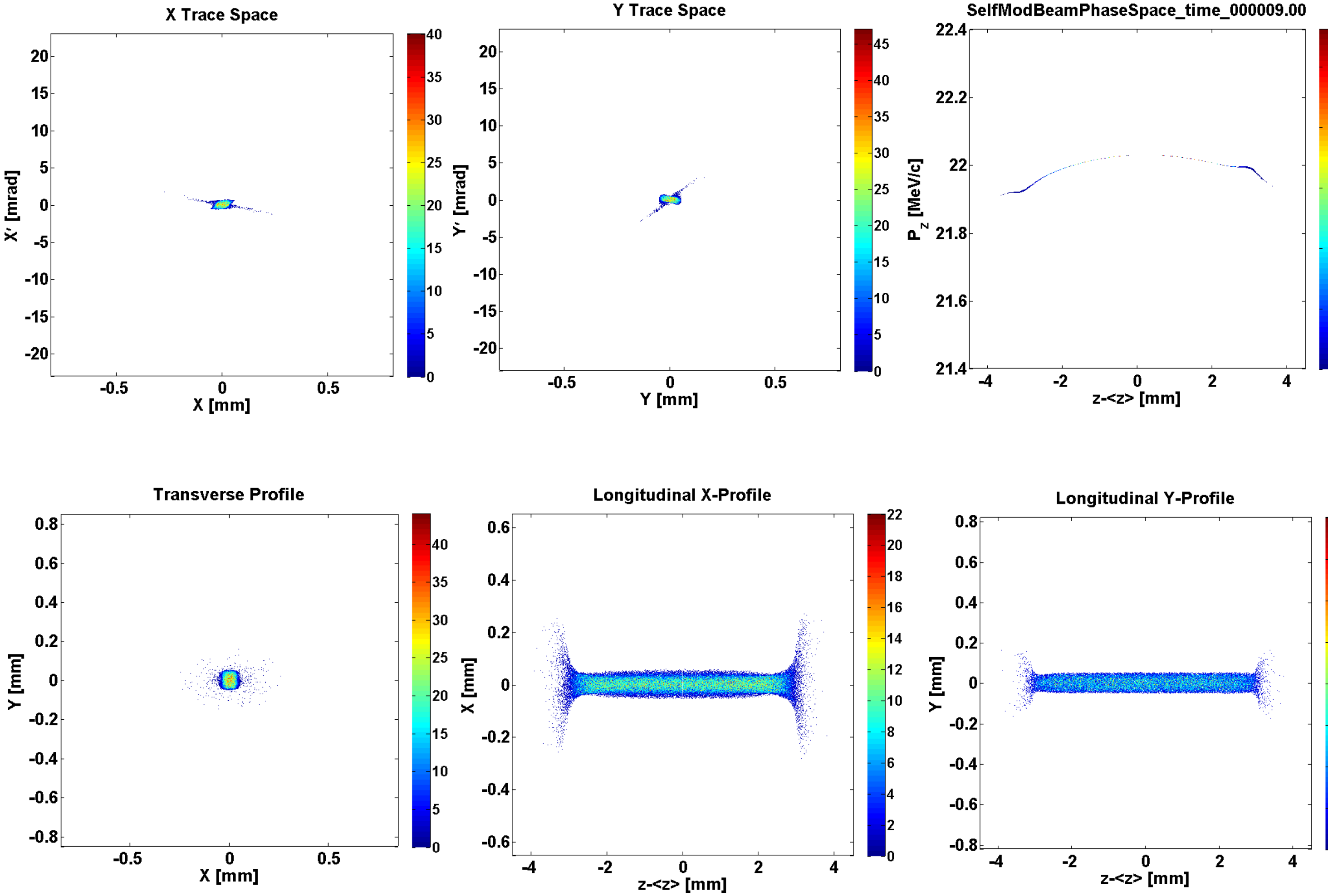
A long $(L > \lambda_p)$, relativistic particle beam propagating in an overdense plasma is subject to the self-modulation instability via transverse wakefields of plasma wave.

This principle can be applied to the long electron bunch also.

Because of its very favorable condition with electron beams, an independent experiment is proposed to set up a plasma oven in the PITZ beam line to study the self-modulation of electron beams when they passes through laser generated lithium plasma.

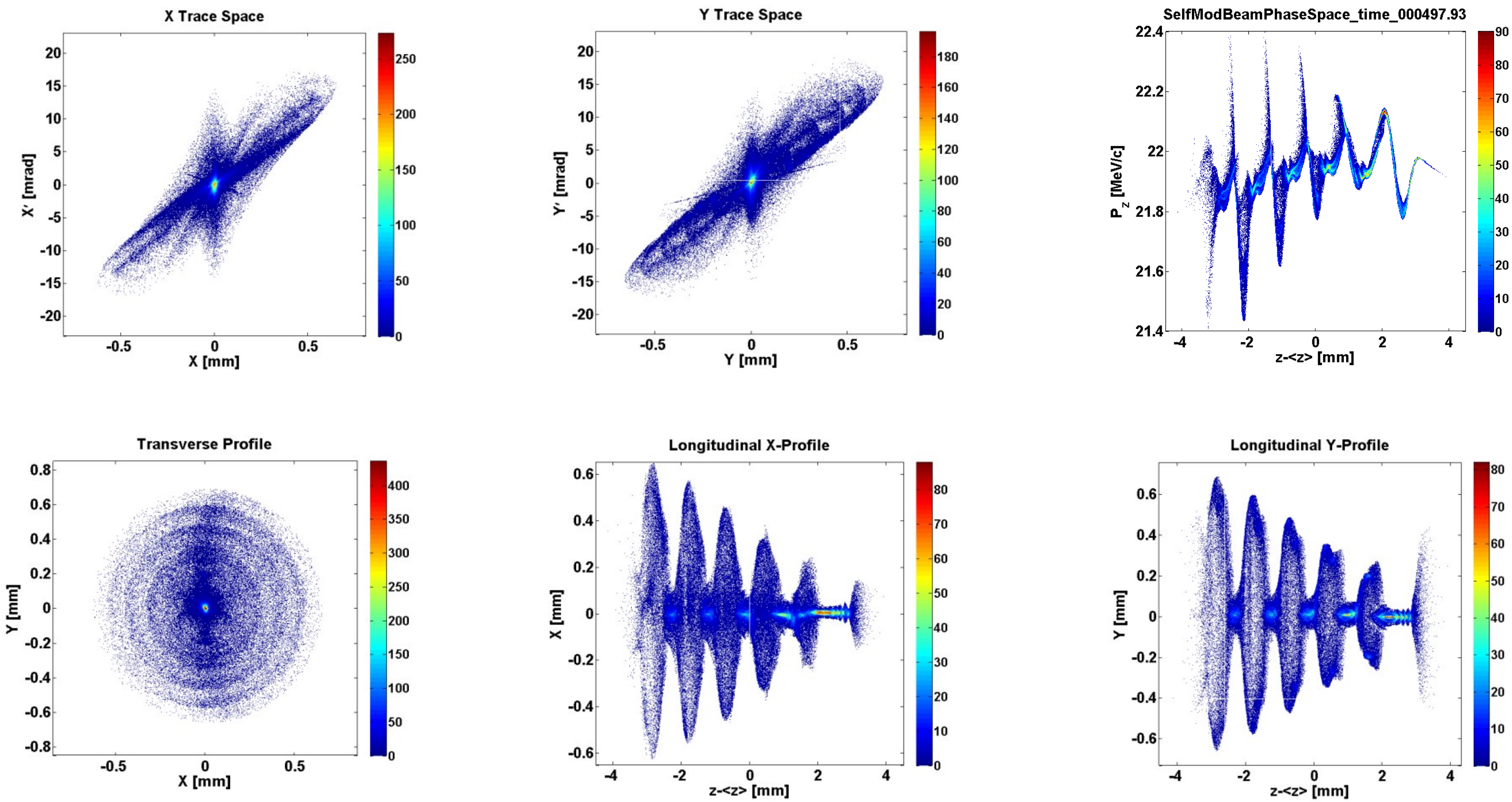
To reflect the key properties such as energy modulation in the beam via electric fields of plasma waves HiPACE simulations have been performed for the case of PITZ beam and plasma.

Beam properties before plasma



$$x' = 1.6 mrad$$
$$y' = 1.6 mrad$$
$$P_z^{mean} = 22 MeV/c$$
$$P_z^{rms} = 22 MeV/c$$
$$x_{rms} = 27 \mu m$$
$$y_{rms} = 26 \mu m$$
$$\varepsilon_x = 0.370 mm\ mrad$$
$$\varepsilon_y = 0.375 mm\ mrad$$

Beam properties after plasma



Divergence increase ~ 1 order
Modulation is observed more in the tail of beam.
Beam is compressed transversely due to strong transverse focusing force of plasma.
Different compression in x, y direction is due to asymmetrical transverse beam size.

To decrease divergence → Beam matching can be applied

Beam matching phenomena

Purpose of beam matching:

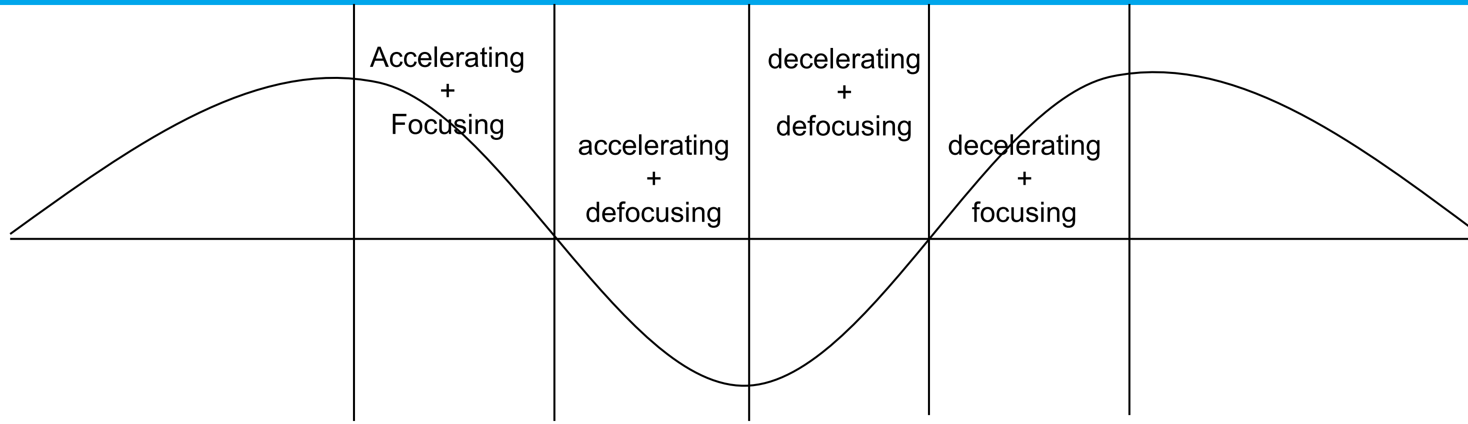
> Acceleration of the bunch of charges particles to high energies requires **synchronization** and **phase focusing**

The synchronization is achieved by matching the rf or plasma frequency with particle velocity

The Phase focusing is achieved by matching a proper phase angle between the rf-wave and the beam bunch

Prevent emittance growth

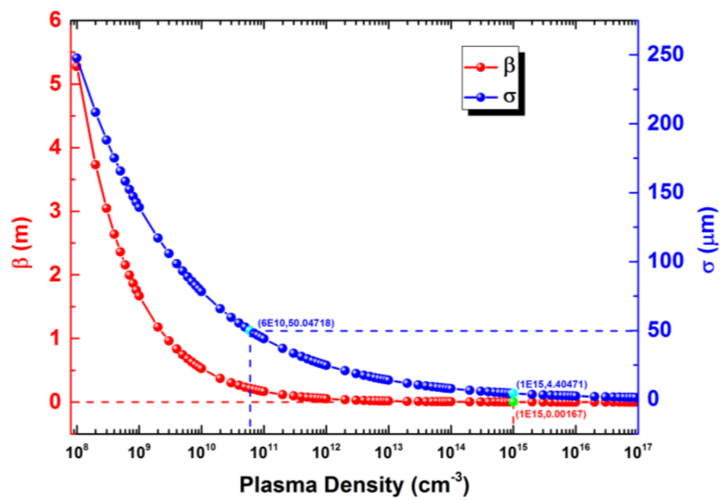
Beam matching for plasma accelerators



Beam matching for blowout regime

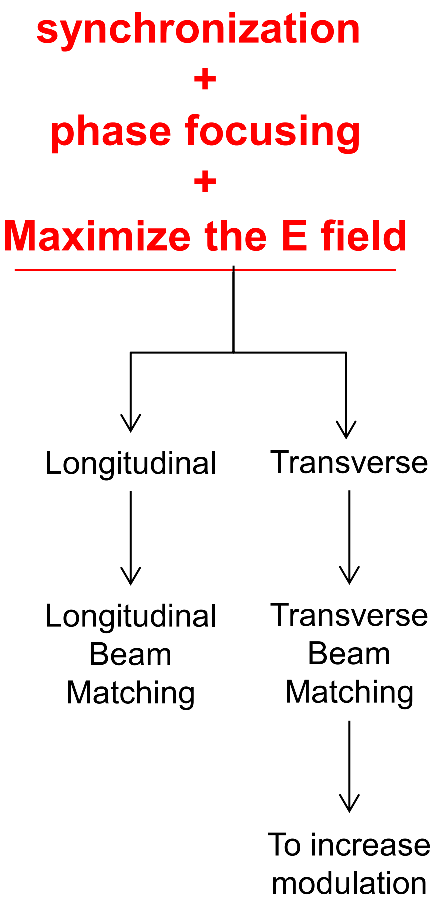
$$\beta_m \approx \frac{c}{\omega_\beta}, \gamma_m \approx \frac{c}{\omega_\beta}, \alpha_m = 0$$

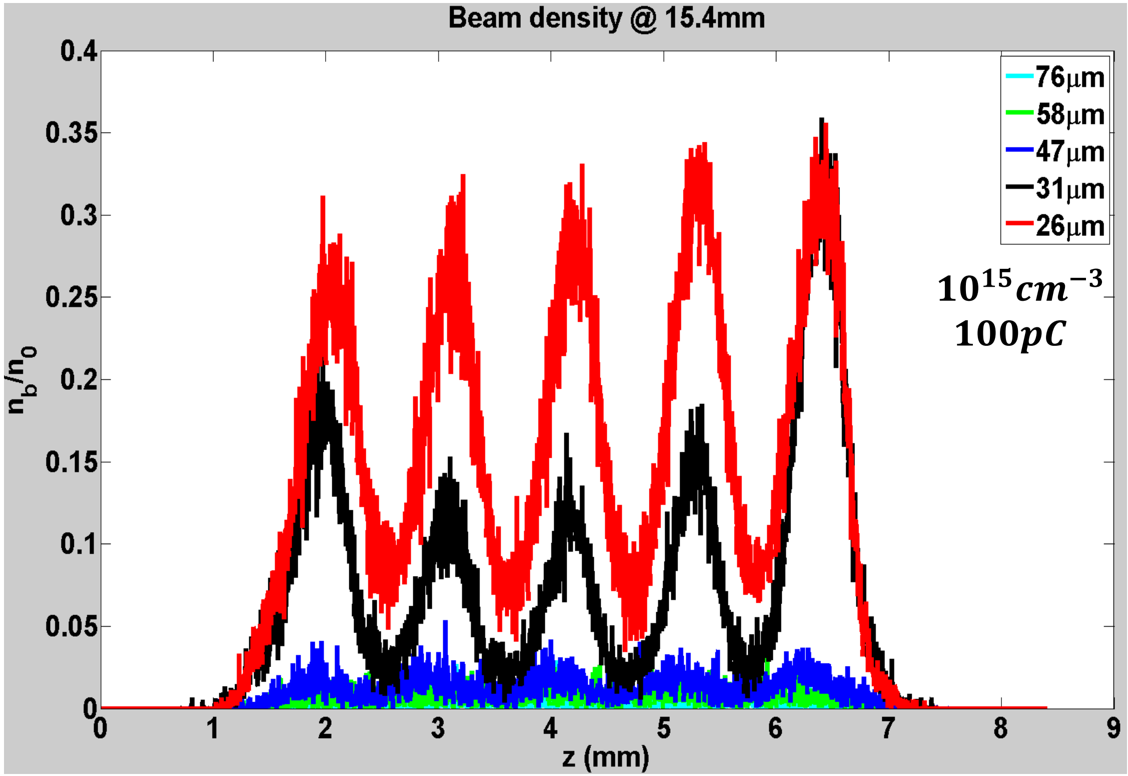
synchronization
+
phase focusing
+
Maximize the E field



- For beam matching with plasma density of $10^{15} cm^{-3}$ the twiss parameter $\beta_m(1.6\text{mm})$ and corresponding beam size $\sigma_r(4.5\mu m)$ are quite small.
- With feasible beam size $(\sim 50\mu m)$ from PITZ accelerator corresponding plasma density comes out be $6 \times 10^{10} cm^{-3}$ for matching case.
- This concludes that perfect transverse beam matching can not be achieved with "desired" beam and plasma parameters for PITZ self-modulation experiment.

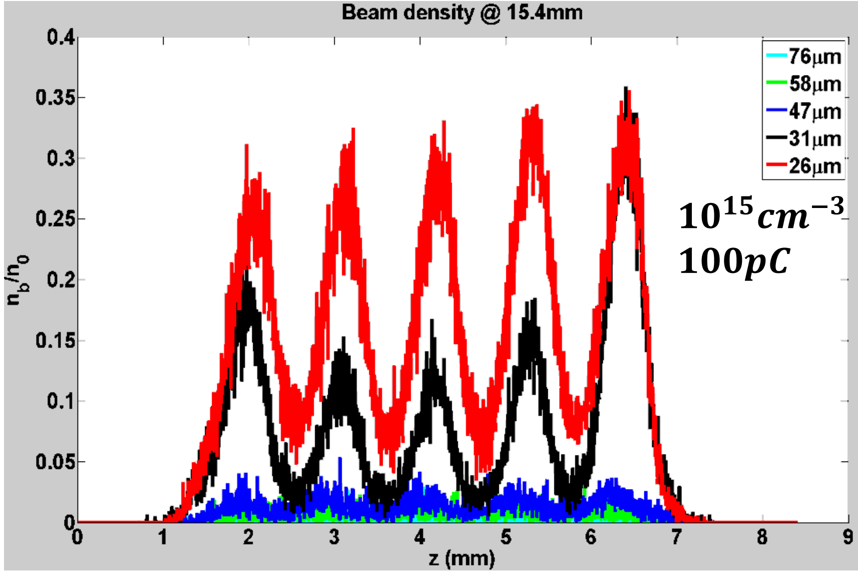
Beam matching for plasma accelerators

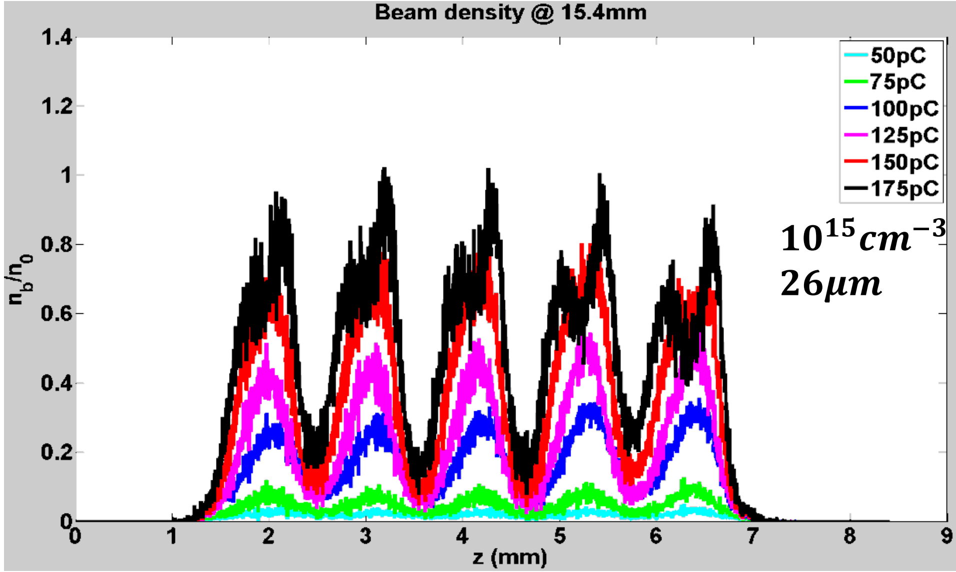


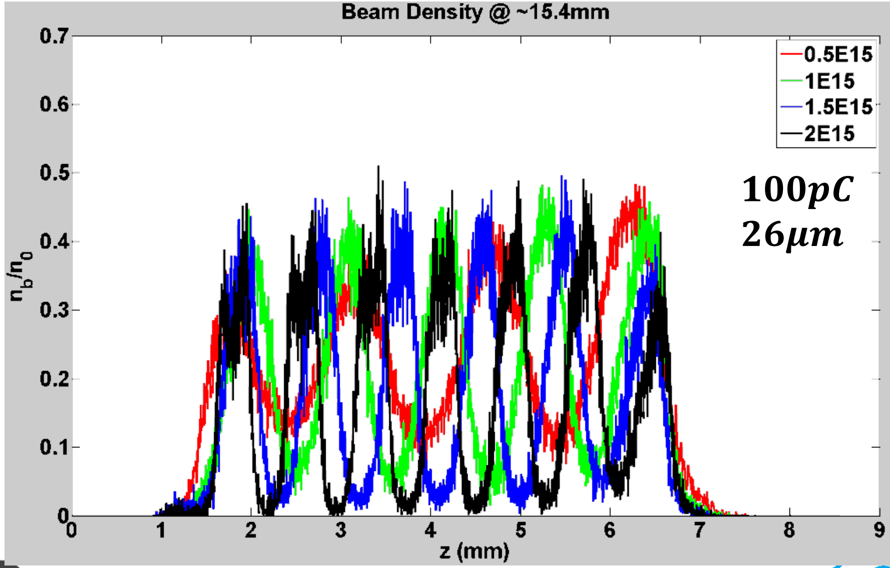


Decrease the beam size → approach to the beam matching case

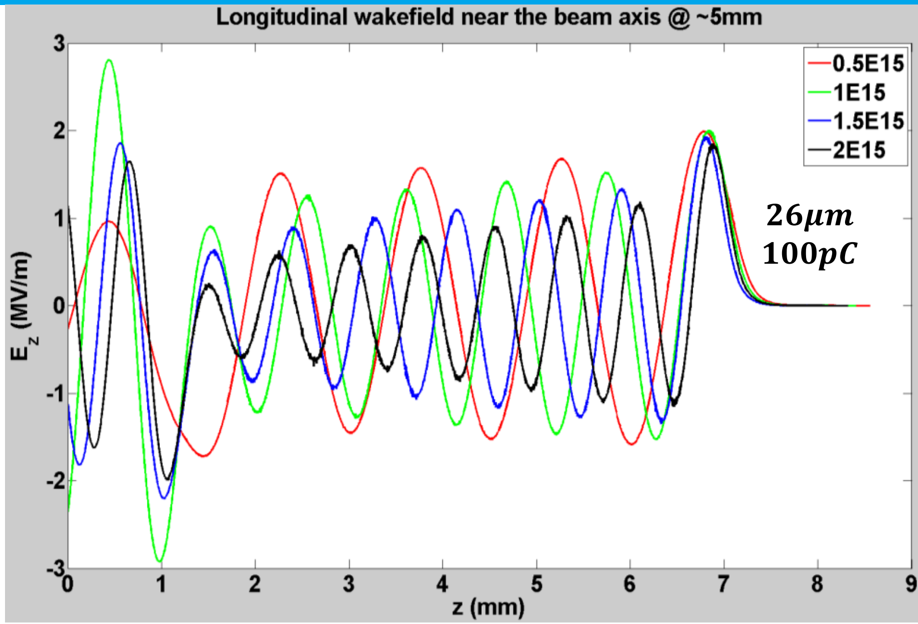
Beam density modulation

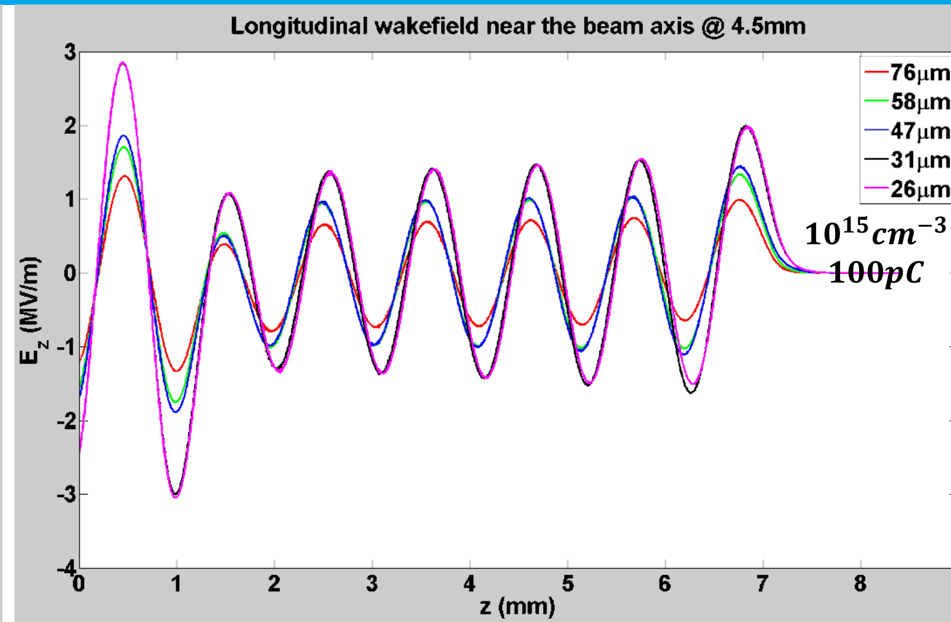






Longitudinal wakefield





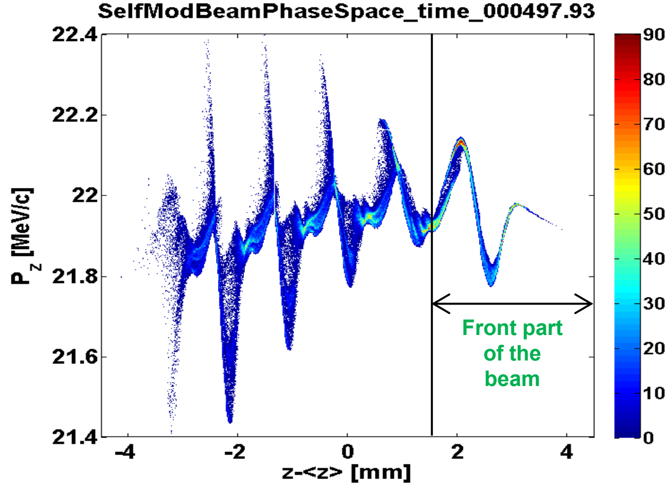
$$E_z \propto \frac{n_{b0}}{\sqrt{n_p}}.R(0)$$

$$E_{focus} \propto \frac{n_{b0}}{\sqrt{n_p}} R'(\sigma_r)$$

Where $R(0)$ is the unitless transverse component.
Both $R(0)$ and R' are increasing function of $k_p\sigma_r$.

Plasma focusing for high energy beams – P.Chen, IEEE,1986

Optimizing the strength of the modulation



Initial Beam Parameters

$P_z^{mean} = 22MeV/c$

$x_{rms} = 27\mu m$

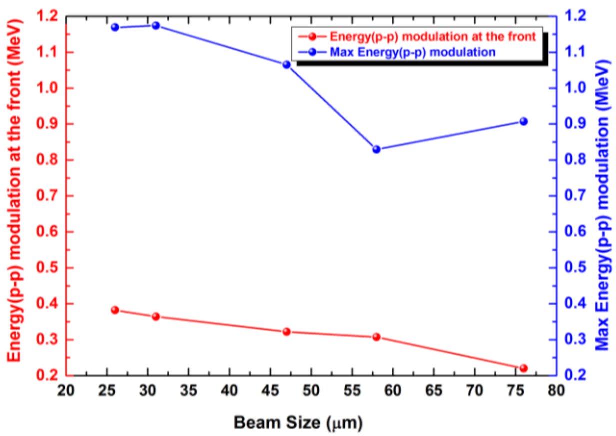
$y_{rms} = 26\mu m$

$z_{long} \approx 6mm$

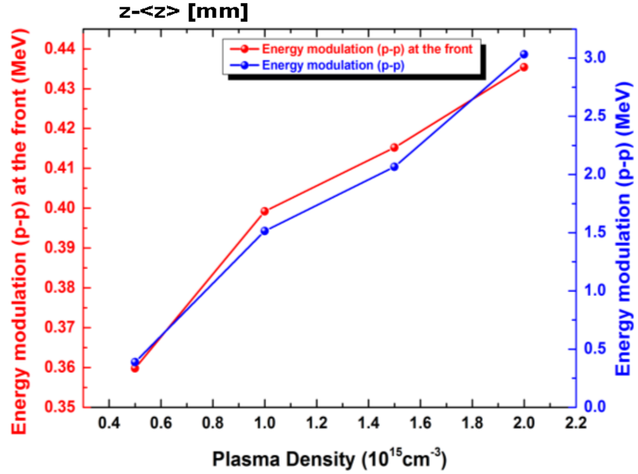
$Q = 100nC$

With Plasma Density

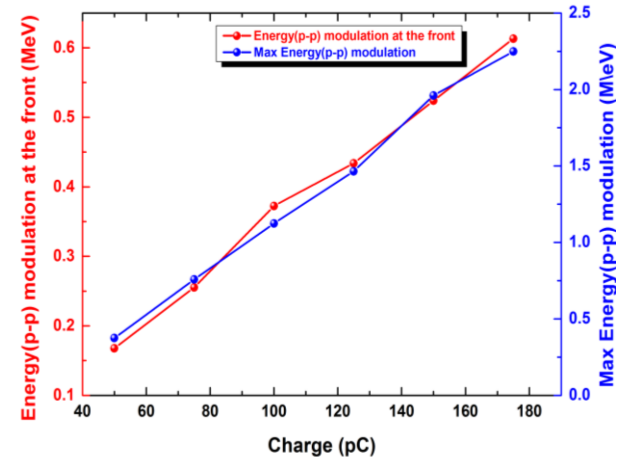
$n_e = 10^{15}cm^{-3}$



Beam size vs Energy modulation with plasma density at $10^{15}cm^{-3}$ and beam charge 100pC



Plasma density vs Energy modulation with beam size fix at $\sim 26\mu m$ and beam charge100pC



Beam Charge vs Energy modulation with plasma density $10^{15}cm^{-3}$ and beam size $\sim 26\mu m$

Summary

- Simulations were performed by varying the different parameters and it shows that decreasing beam size and increasing plasma density and beam charge contribute to increase in the modulation of beam energy.
- Study of beam matching reveals that decreasing beam size will help to increase the energy modulation however such a small beam is hard to achieve for desired plasma parameters.

Thank you

Beam Charge variation