Gas Density Measurement for Self-modulation Eperiment at PITZ

> Self-Modulation

> Methods of gas density measurement

> Progress in gas density measurement

> Summary

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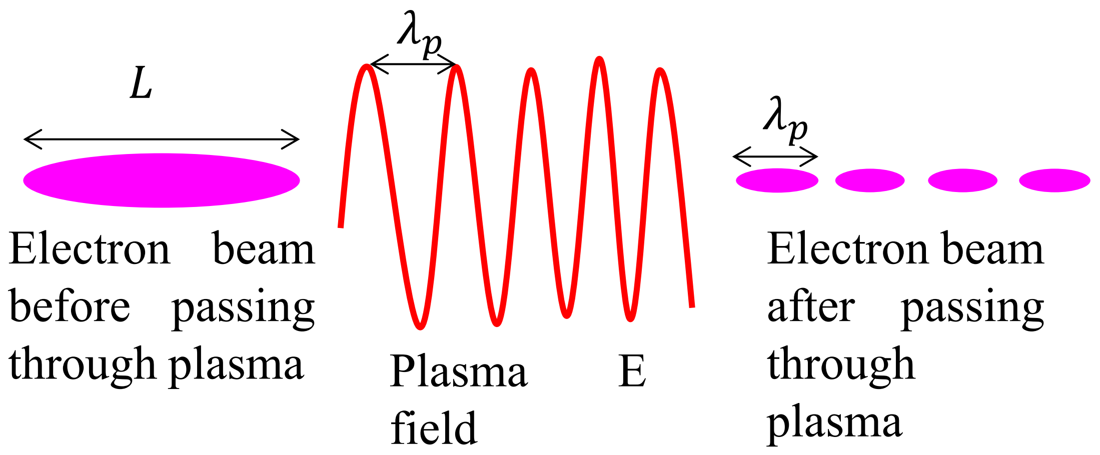
Self-modulation

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

The CERN SPS bunch has length ~12cm (120mm), but short (<1mm) bunches are needed for efficient acceleration.

How to generate short proton bunches?

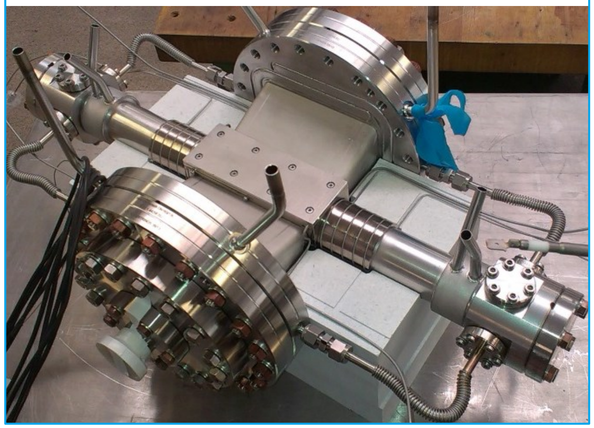
To generate short proton bunches a technique viz. self modulation was proposed by N. Kumar and A. Pukhov in 2010.

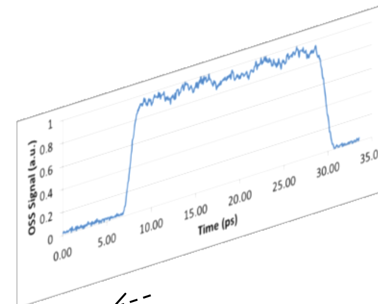


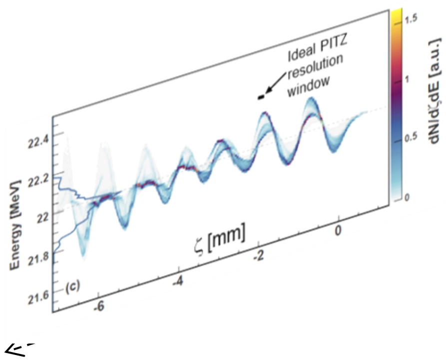
A long $(L > \lambda_p)$, relativistic particle beam propagating in an overdense plasma is subject to the self-modulation instability via transverse wakefields of a plasma wave.

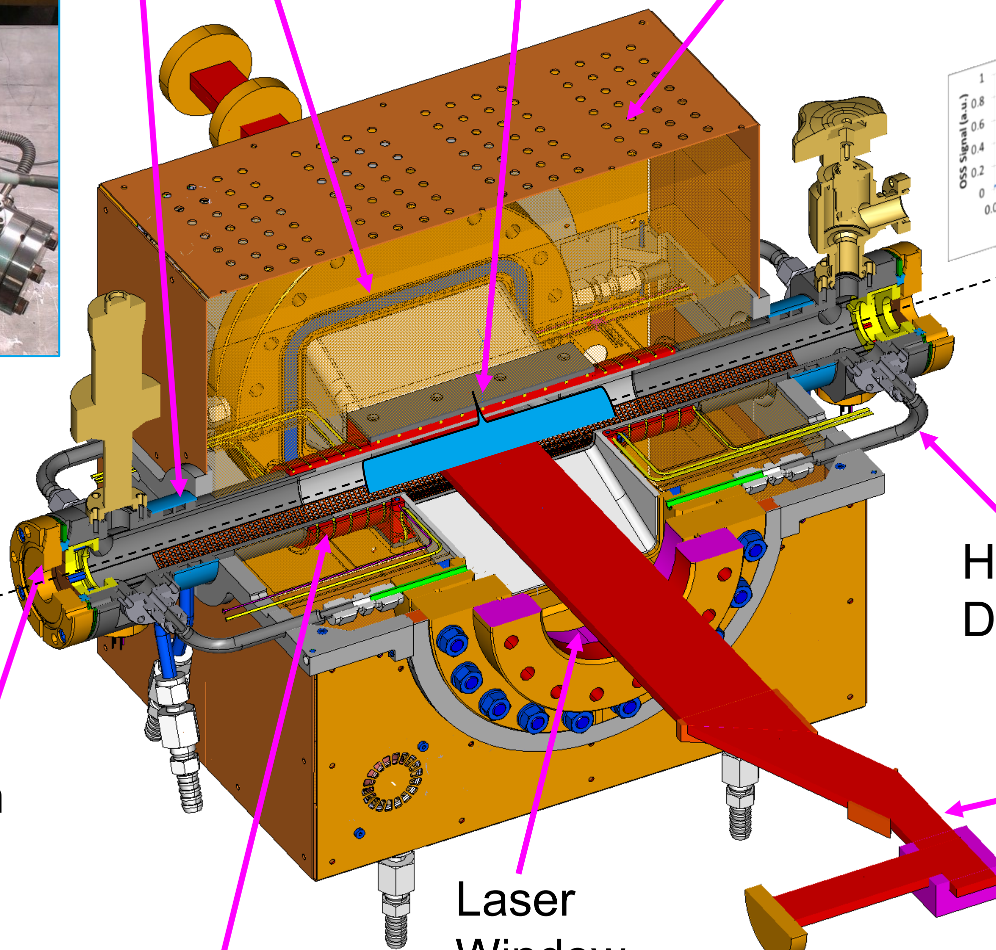
Self-modulation at PITZ

Fabricated Cell





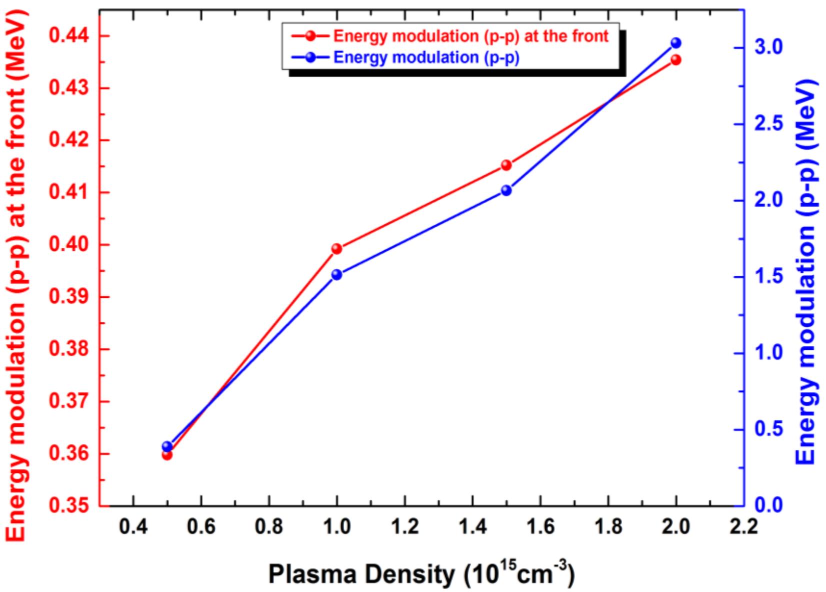




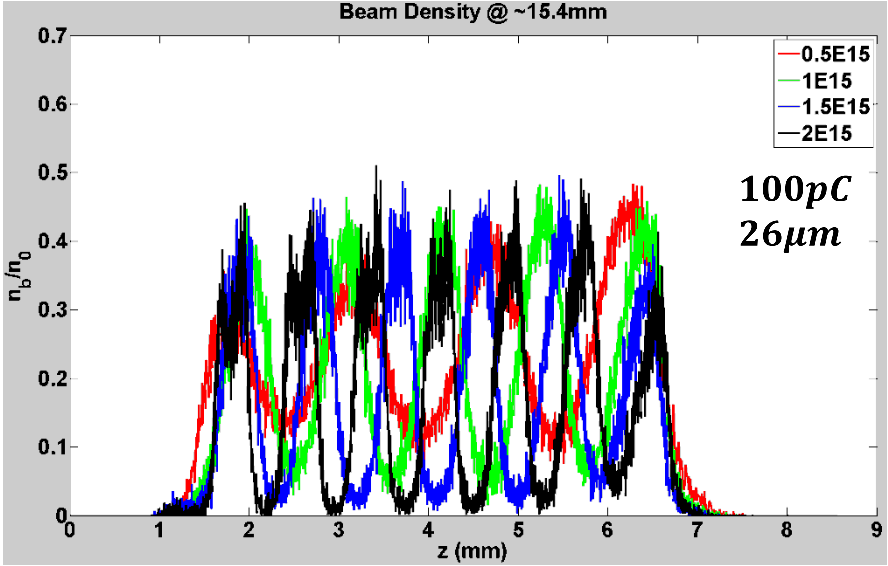
Design:
Gerald Koss

Effect of Plasma Density Variation

$$\lambda_p = 1mm\sqrt{\frac{10^{15}cm^{-3}}{n_p}}, \lambda_p(mm) = \begin{cases} 1.414 & for 0.5 \times 10^{15}cm^{-3} \\ 1 & for\ 10^{15}cm^{-3} \\ 0.816 & for 1.5 \times 10^{15}cm^{-3} \end{cases}$$



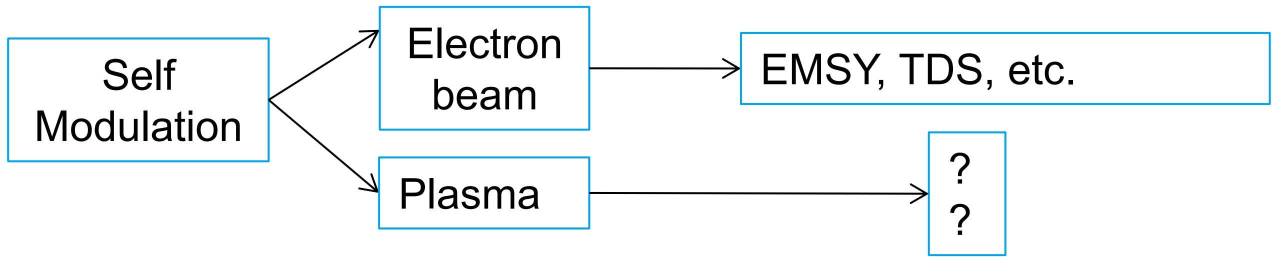
Plasma density vs Energy modulation with beam size fix at $\sim 26\mu m$ and beam charge 100pC



Bea density modulation with beam size fix at $\sim 26\mu m$ and beam charge100pC

Methods of Density Measurement

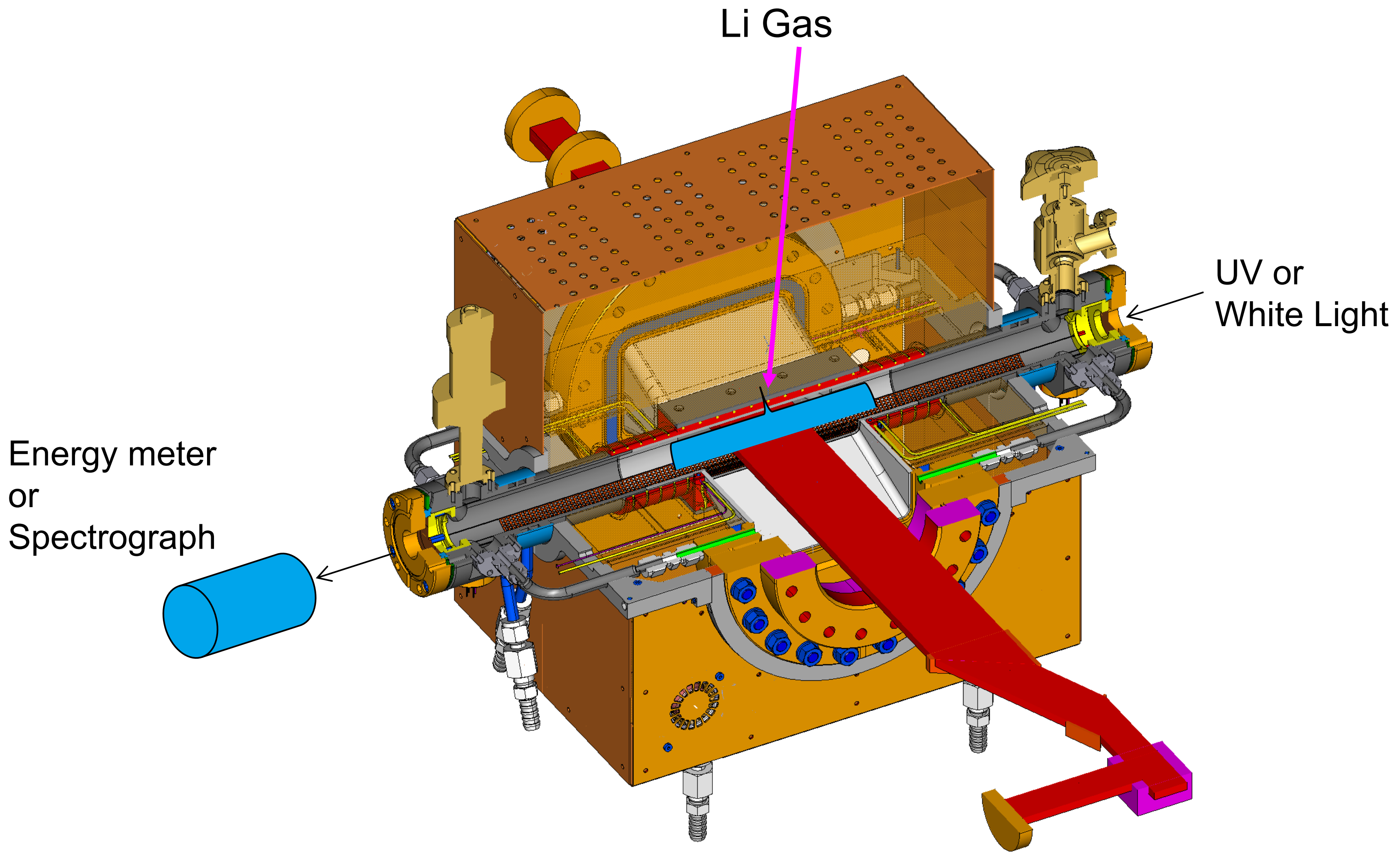
1) Plasma:



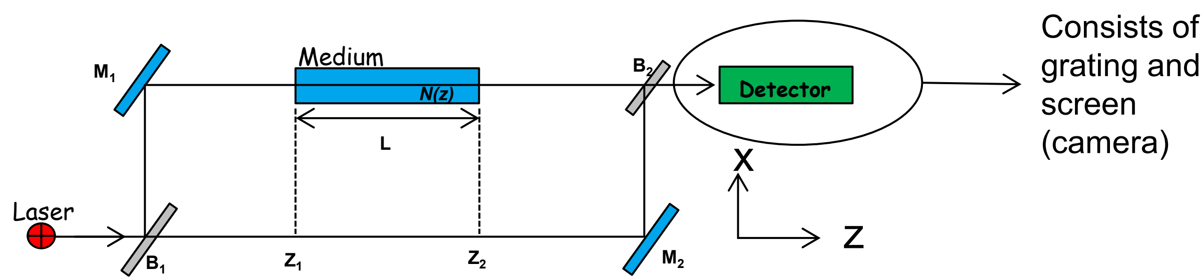
2) Gas:

Measurement	Principle	Density relation
UV absorption	A low energy laser pulse will be sent to the gas. The absorption will be recorded at the end.	$n_0 L = -\frac{1}{\sigma}\ln(\frac{E_{transmitted}}{E_{incident}})$
White light absorption	Strong transition of Li first excited state to second leads to determine the density.	Absorption coefficient $\gamma(\omega) \propto n_0$
Hook Method	Hooks formed at white light interference pattern are related to gas density.	$n_0 L \propto \Delta^2$ $\Delta = hook\ distance$

UV and White Light Absorption



Hook method for gas density measurement



Hook method: Mach-Zehnder interferometer

Hook Method: The grating disperses the fringes with different wavelengths λ_i in different x-directions. Because of the wavelength-dependent refractive index $n(\lambda)$ of the atomic vapor the fringe shift follows a dispersion curve in the vicinity of the absorption spectral line. The dispersed fringes look like hooks around an absorption line, which gave this technique the name hook method (Fig. 1).

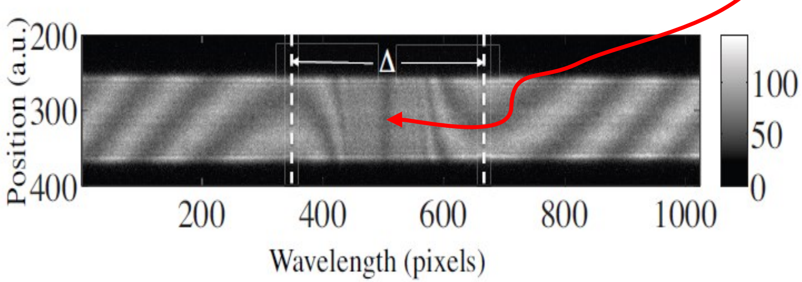


Fig. 1: Hook interferogram (current figure is for Rubidium vapor, courtesy: E. Öz, IPAC 2014)

$$n_e \propto \Delta^2$$

Calibration of diffraction grating for hook method

Used for calibration of the diffraction grating:

1) Two lasers of slightly different wavelengths λ_1 and λ_2.
2) Screen (camera).

Diffraction equation:

$$d \sin\theta = m\lambda$$

d: grooves spacing in the grating
θ: angle of diffraction for a particular λ
m:order of diffraction

$$\theta = \sin^{-1}\left(\frac{\lambda_{\mu m}}{1.66}\right)$$

$m = 1, d = 1.66\ \mu m$

Angle of diffraction for the two lasers: θ_1 and θ_2

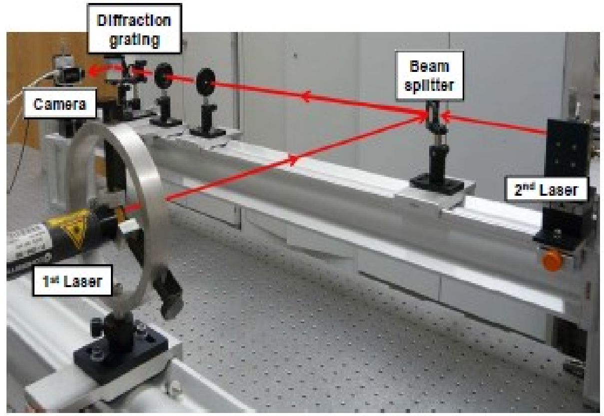
Distance between grating and screen: x

Difference between first order diffraction for both wavelengths:

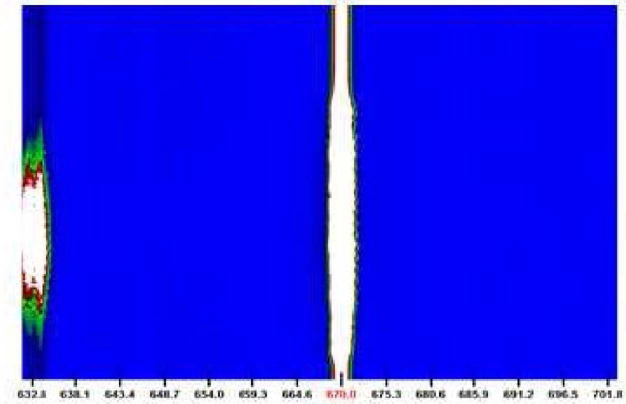
$$\Delta y = x(\tan\theta_1 - \tan\theta_2)$$

and hence

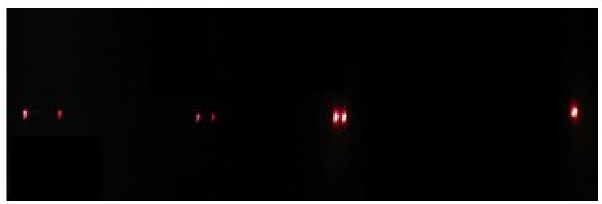
$$\Delta y = \lambda_1 - \lambda_2$$



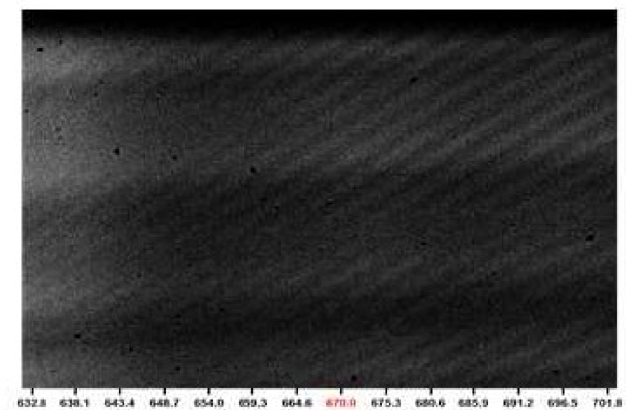
Calibration setup for diffraction grating



First order diffraction for the 670nm and 632.8nm



Diffraction pattern for the 670 nm and 632.8 nm. From right to left 0th, 1st, 2nd ... order diffraction pattern. 0th order diffraction overlaps for both lasers because it is just a reflection from grating.



Wavelength distribution of white light interference

The calibration achieved by this method is 0.05 nm/pixel or 11.34 nm/mm

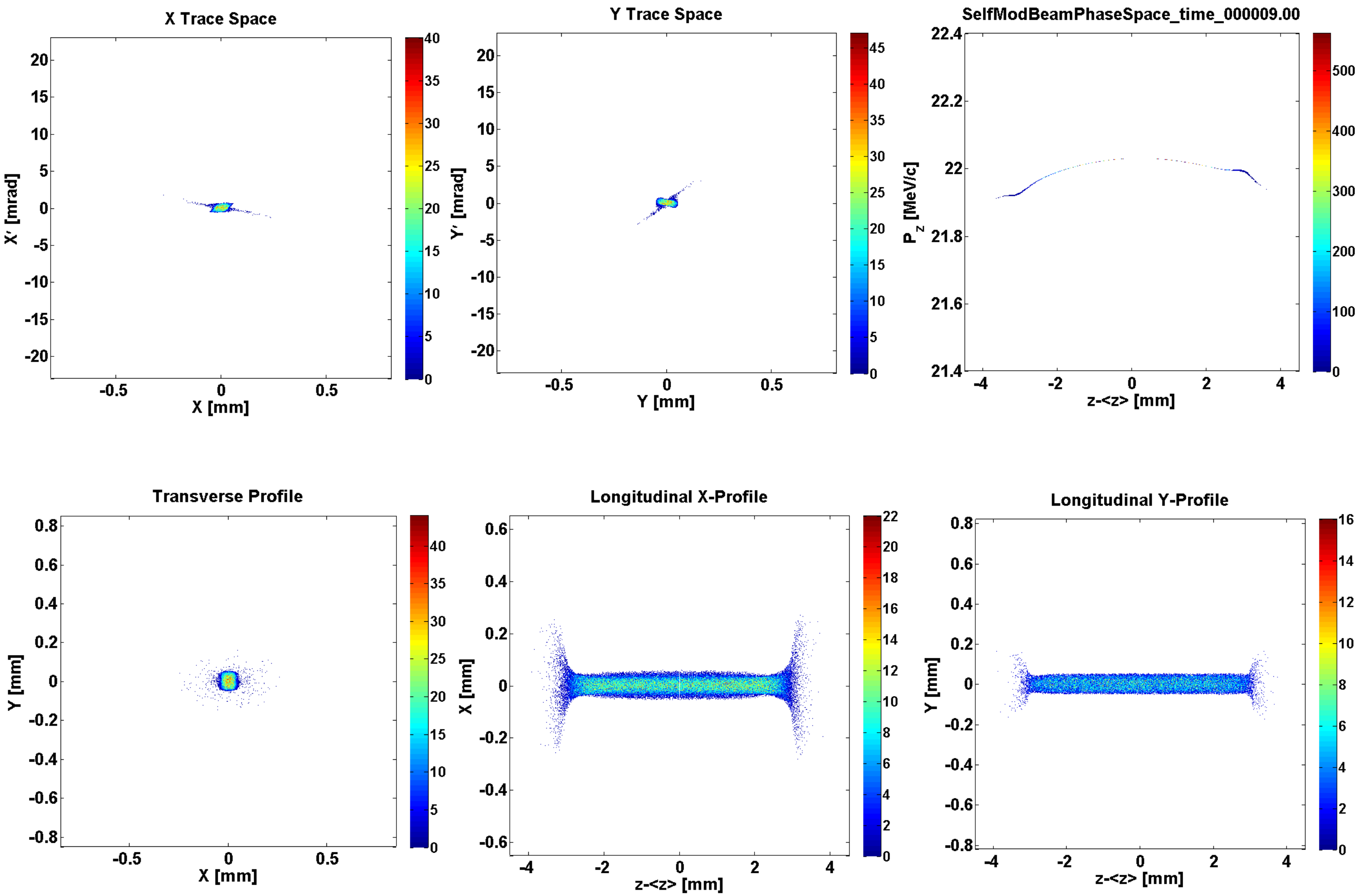
Summary

- Lithium gas density for PITZ plasma experiment will be measured with Hook method.
- Calibration has been done for diffraction grating using two lasers and it comes out to be 0.05 nm/pixel or 11.34 nm/mm.
- Expected gas density: $\sim 10^{15} cm^{-3}$ - can be measured with this method.
- Plasma density will be measured by different methods as well.

Thank you

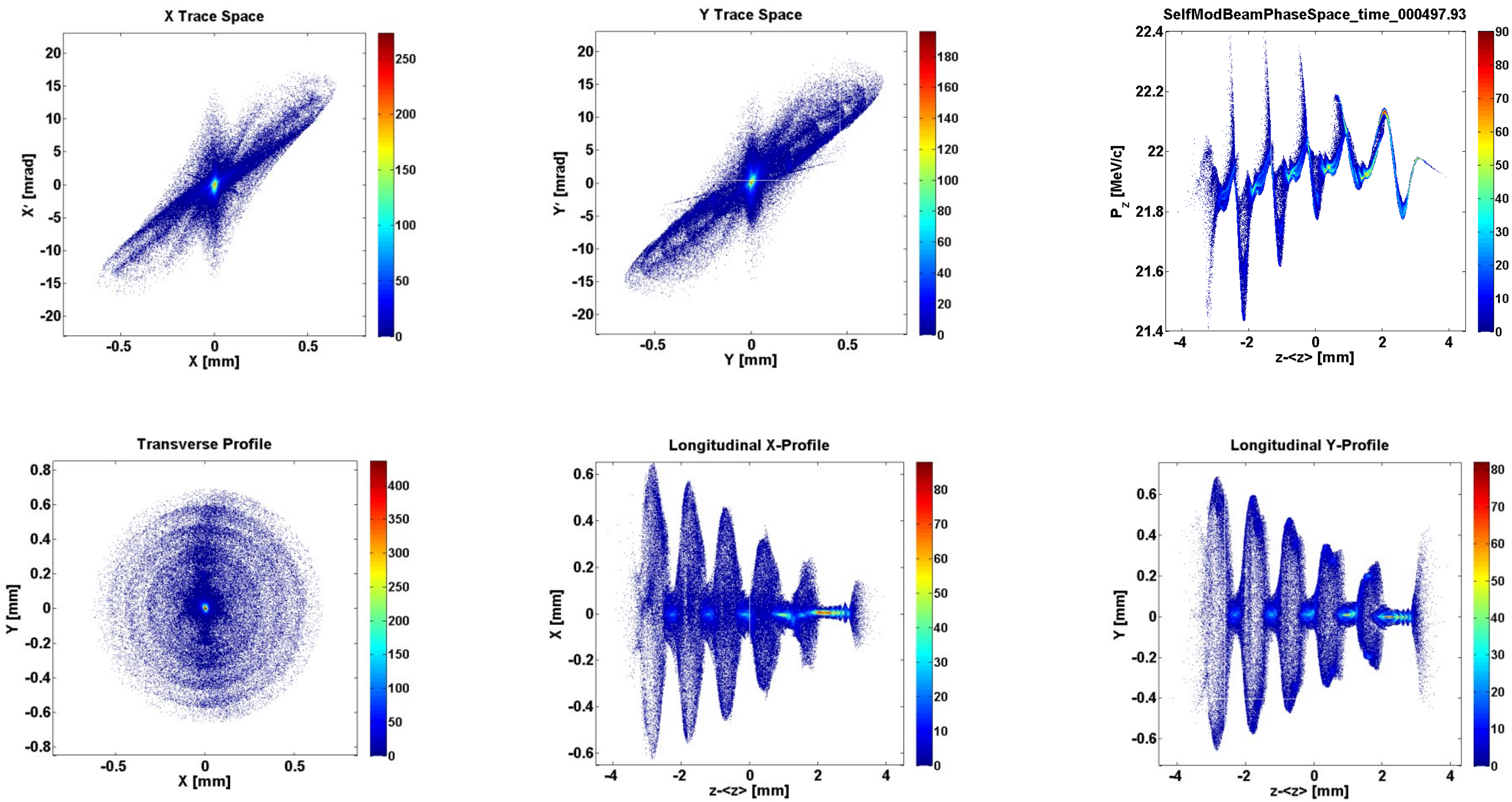
Back up for simulations

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:

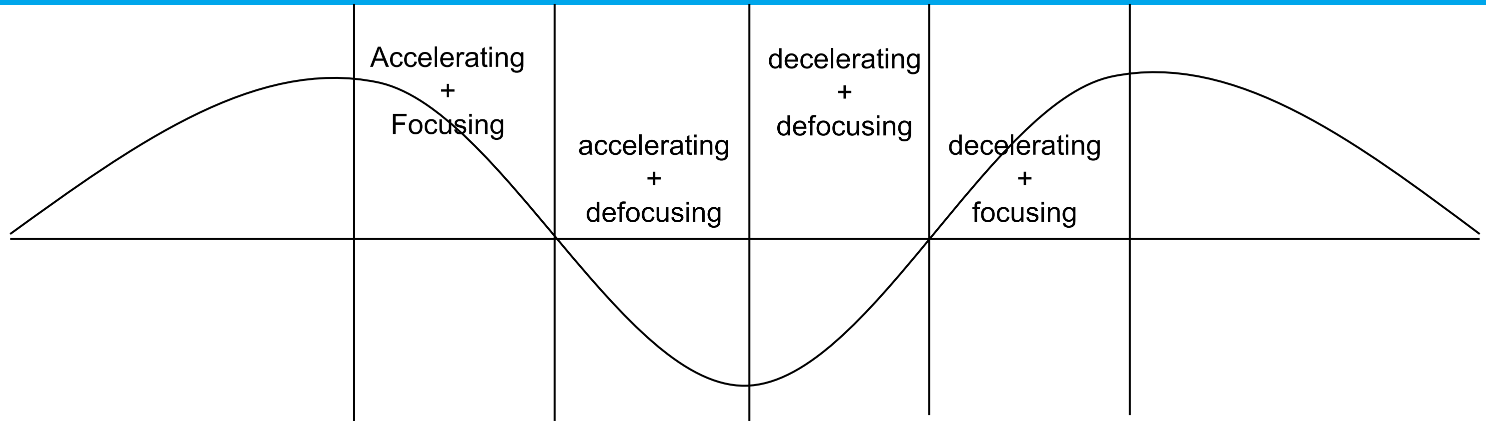
> Acceleration of the bunch of charges particles to high energies requires
> **synchronization** and **phase focusing**

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

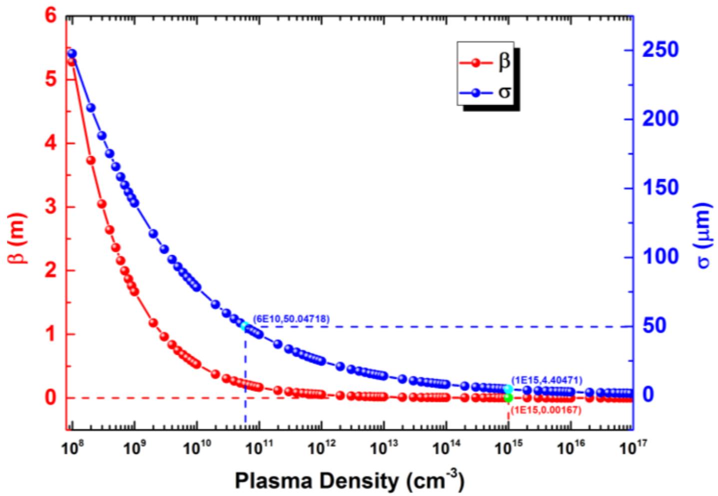
Prevent emittance growth

Beam matching for plasma accelerators



Beam matching for blowout regime

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



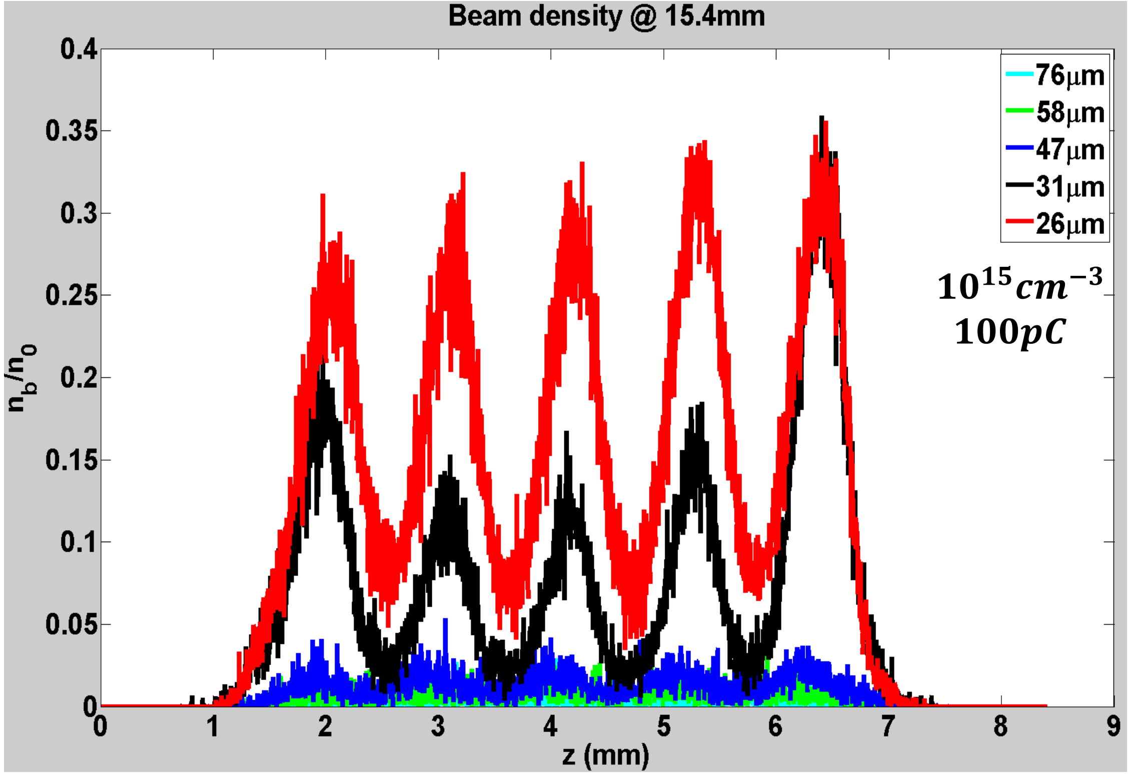
synchronization
+
phase focusing
+
Maximize the E field

- 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

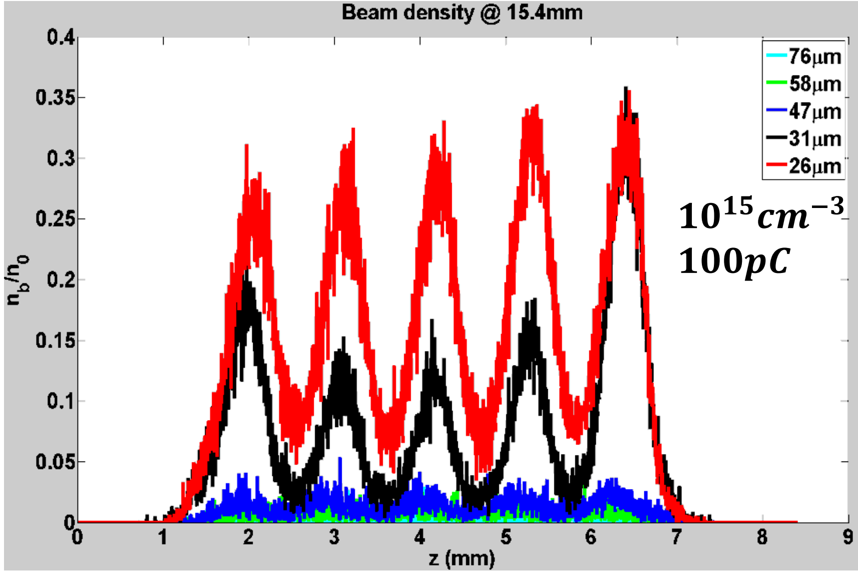
synchronization
+
phase focusing
+
Maximize the E field

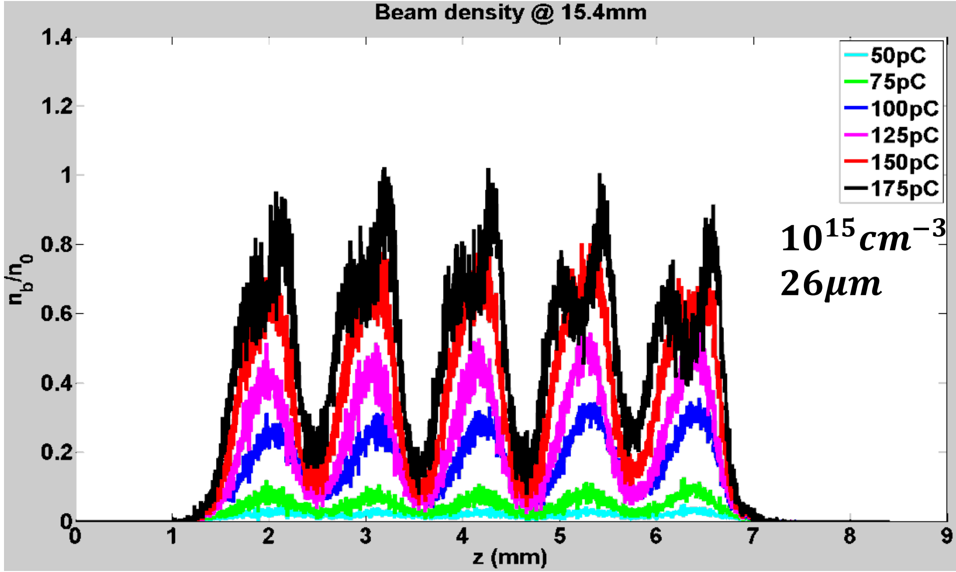
- Longitudinal → Longitudinal Beam Matching
- Transverse → Transverse Beam Matching → To increase modulation

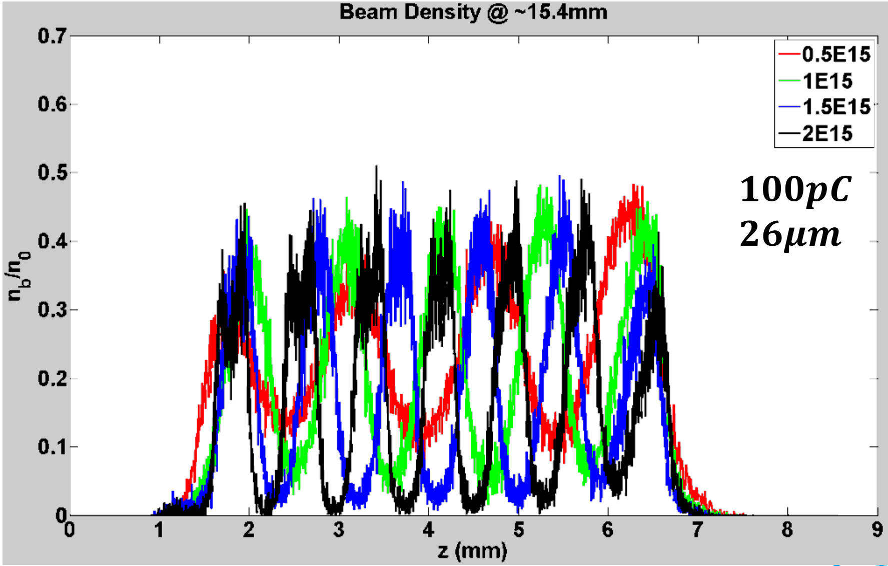


Decrease the beam size → approach to the beam matching case

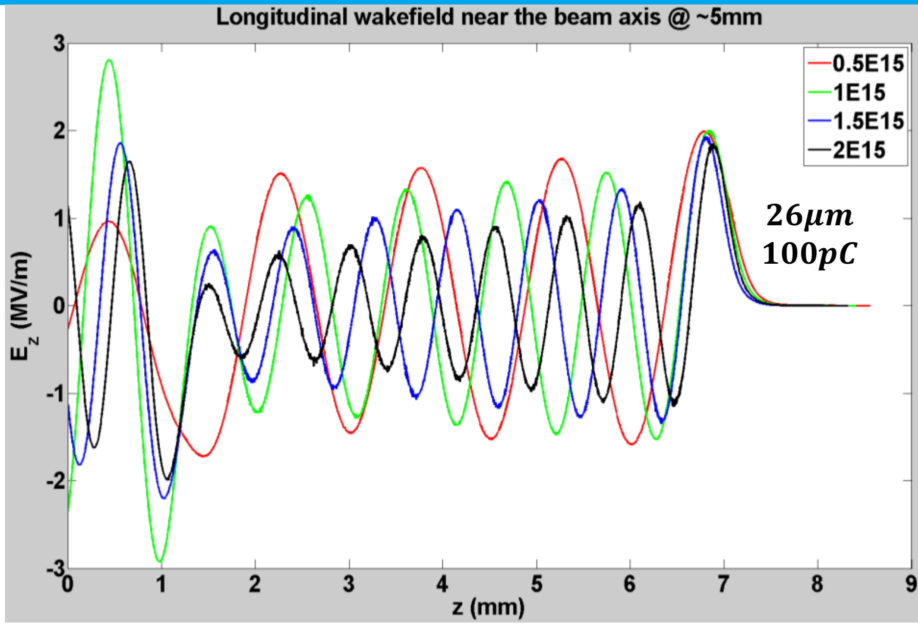
Beam density modulation

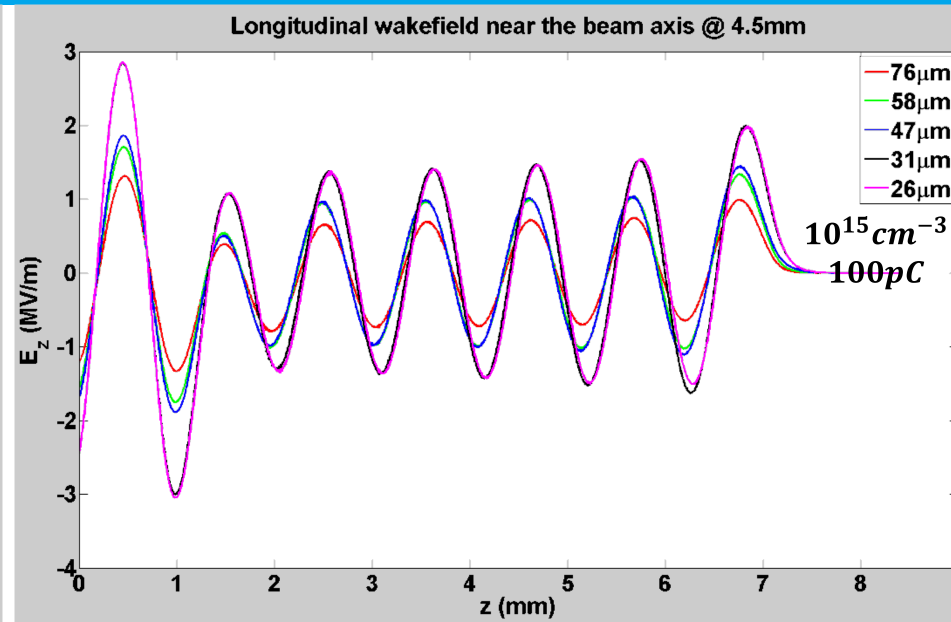






Longitudinal wakefield





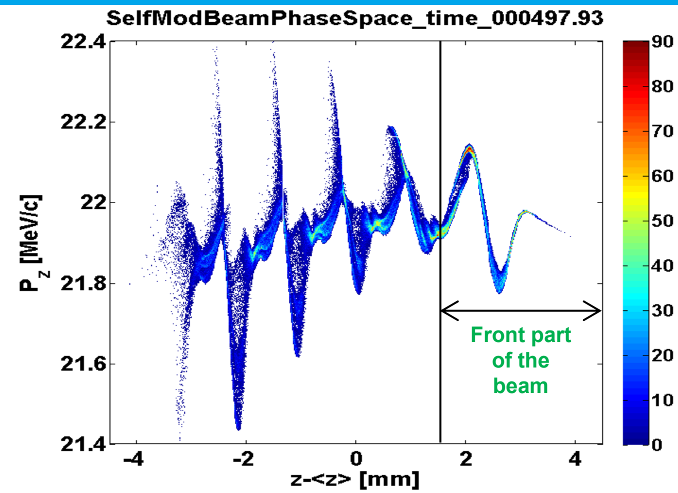
$$E_z \propto \frac{n_{b0}}{\sqrt{n_p}}.R(0)$$

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

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

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

$x_{rms} = 27\mu m$

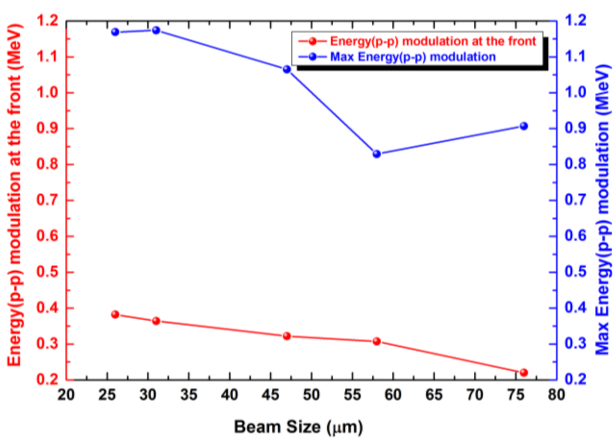
$y_{rms} = 26\mu m$

$z_{long} \approx 6mm$

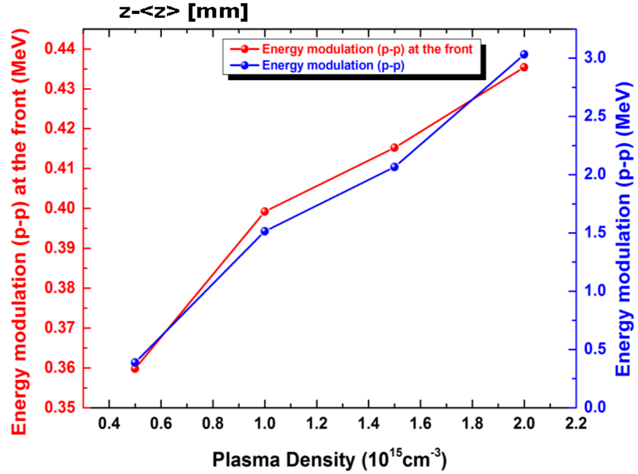
$Q = 100nC$

With Plasma Density

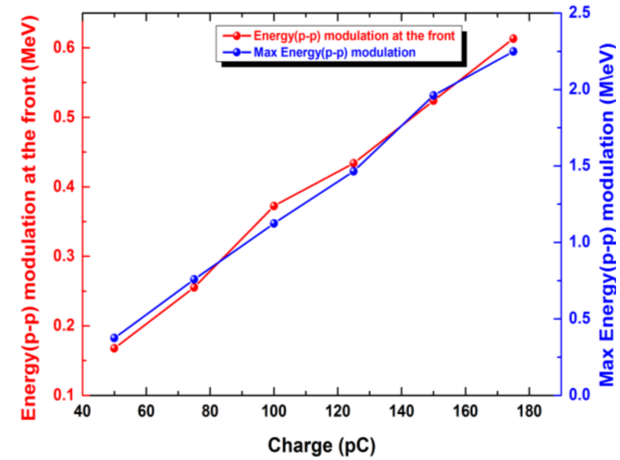
$n_e = 10^{15}cm^{-3}$



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 $\sim 26\mu m$