Numerical Study of the Self-modulated Plasma Wakefield Acceleration

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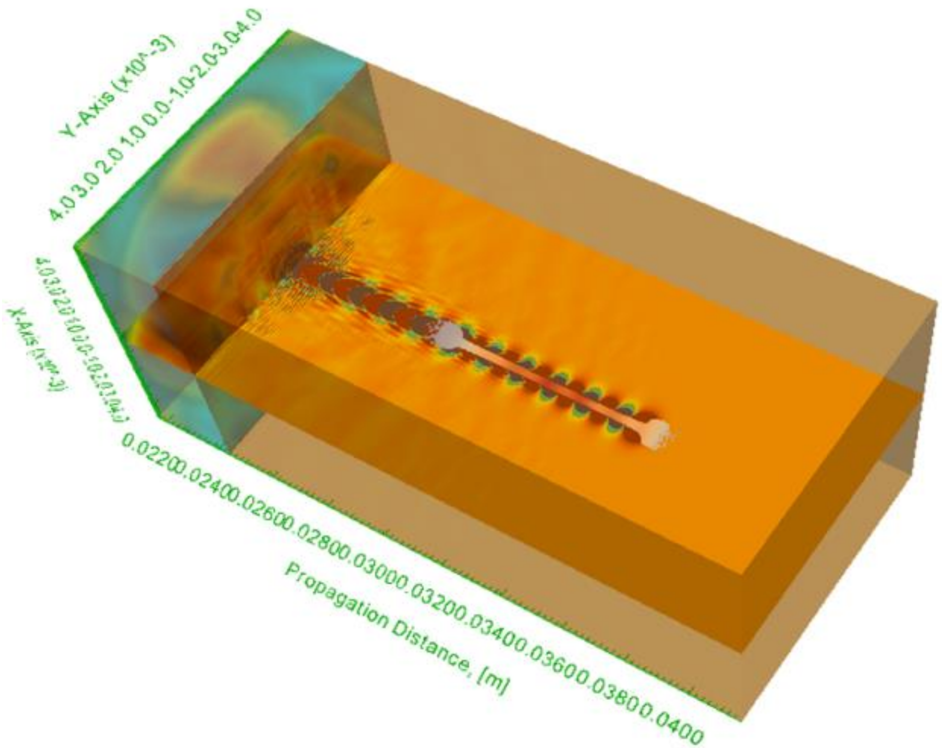
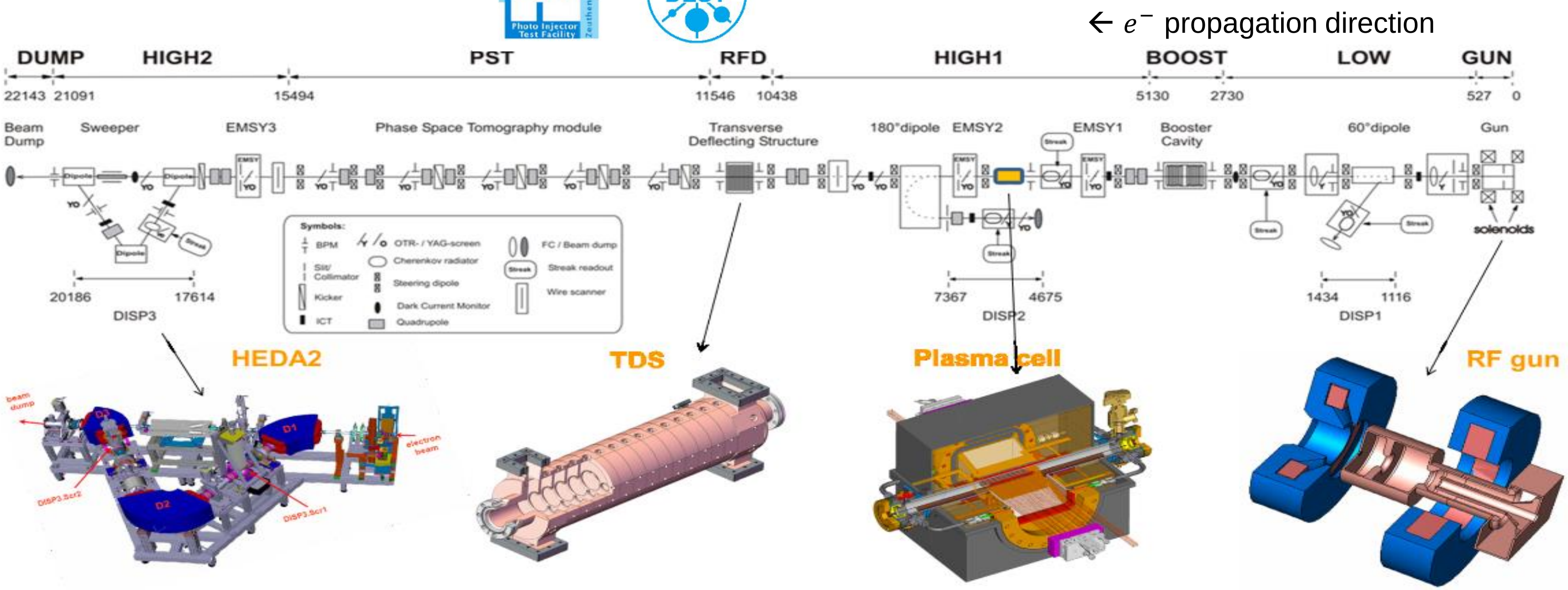
- PWFA Linear Theory
- Numerical simulations
- Benchmark
- Summary and Perspective



Introduction: SMPWA experiment at PITZ



Main Purposes:

- Demonstrate the principle of self-modulation of long electron bunches in plasma
- Study the underlying physics of plasma-electron interaction, such as dephasing, hosing-instability, etc.
- To gain insight into the experiment conditions for the proposed AWAKE project at CERN, such as the beam matching, etc.

Introduction: Simulation code – PAMASO (Particle Maxwell Solver)

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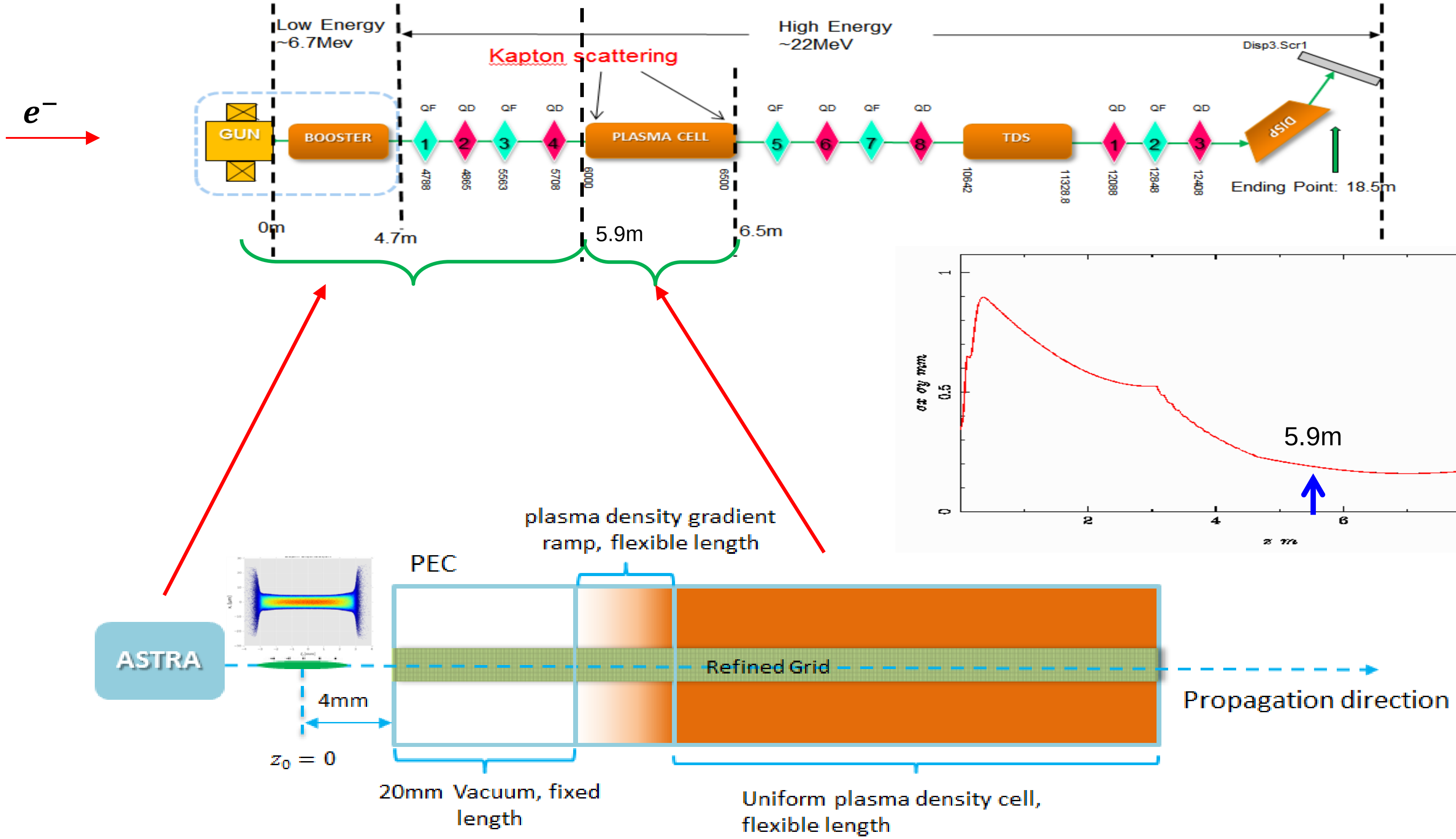
- Fully explicit 3D code→ Avoid to lose any physics
- Input beam file with the real distribution, i.e ASTRA tracing file of PITZ beam → Make the simulation close to the real experiments
- Extremely low numerical dispersion and the excellent numerical accuracy → allow to use the sparse grid → Largely reduce the simulating resource consumption to make it possible run on the desktop PC.

Code benchmark

	PAMASO	OSIRIS	HiPACE
Type of the code	PIC-High Order DG	PIC-FDTD	Paraxial-Code

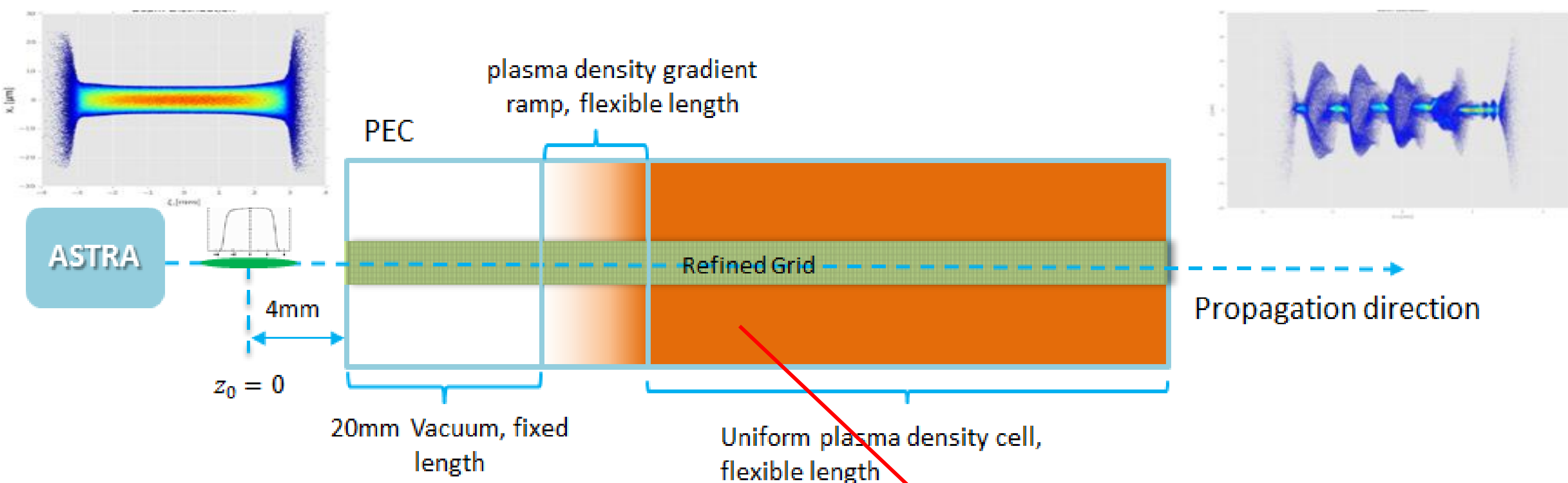
- HiPACE simulation was done by PhD. Gaurav Pathak at Zeuthen
- OSIRIS simulation was done by Dr. R. Fonseca, et al. at Hamburg

Introduction: SMPWA Simulation schema

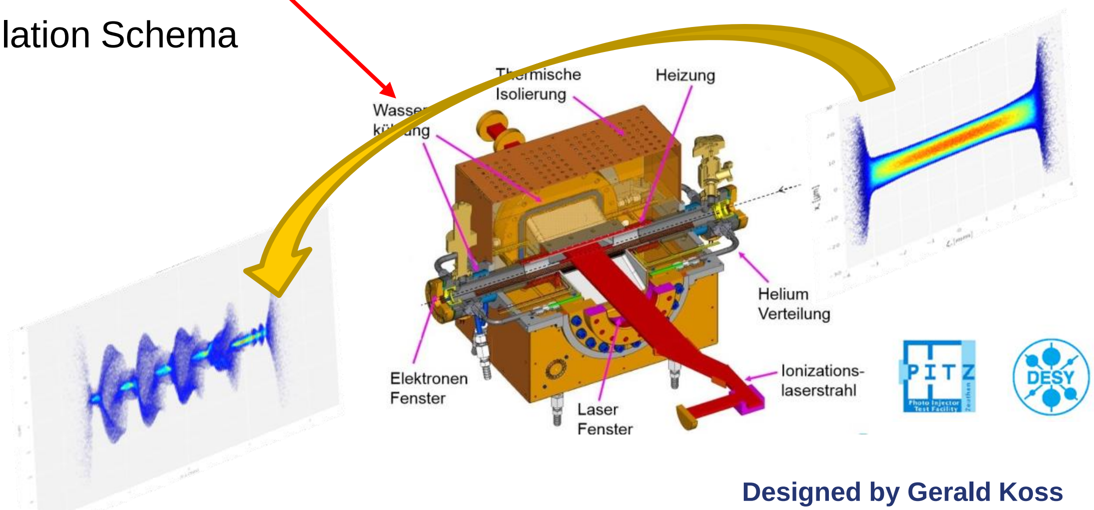


SMI Simulation Schema

Introduction: SMPWA Simulation schema



SMI Simulation Schema



Experiment condition:

- Beam pipe opening: 20mm
- Diameter of Plasma channel 1mm

Simulation window:

- $10mm \times 10mm \times 20mm$ space dimension
- Traveling along with the bunch

Designed by Gerald Koss

PWFA Linear Theory

With the following 2D linear assumptions:

- Azimuthal symmetry, $\partial/\partial_\theta = 0$
- Static plasma ions
- Cold plasma
- Beam velocity is close to the speed of light, $v_b = c$
- Negligible second order perturbation

The normalized electron plasma density perturbation is given by : $\xi = z - ct$

$$(\partial_\xi^2 + k_p^2)\delta n/n_0 = -k_p^2 n_b/n_0$$

The beam driven longitudinal and transverse wake field are given by:

$$(\nabla_\perp^2 - k_p^2) E_z/E_0 = -k_p \partial_\xi \delta n/n_0$$

$$(\nabla_\perp^2 - k_p^2)(E_r - B_\theta)/E_0 = -k_p \partial_r \delta n/n_0$$

R. Keinigs, et al. Phys. Fluid 30, 252(1987)

Parameters	Value
Plasma density	$n_p = 1 \times 10^{15} cm^{-3}$
Transverse beam size	$\sigma_{x,y} = 42\mu m$
Longitudinal beam size(FWHM)	$L_b = 6mm$, $(RMS\ \sigma_z = 1.7mm)$
Peak Beam density	$n_{b0} \sim 10^{13} cm^{-3}$
Plasma wave frequency	$\omega_p = 1.78THz$
Plasma wave number	$k_p = 5.94mm^{-1}$
Plasma wave length	$\lambda_p = 1mm$
Energy of the beam	$KE = 21.5MeV \to \gamma \approx 42$
Number of the electrons in one bunch	$N_b \sim 10^9$
Number of macro particles in one bunch	0.2 million
Length of plasma density ramp	0 mm

PWFA Linear Theory :Radius Self-Modulation

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Further, the growth rate of self modulation is given by:

$$\Gamma \approx \frac{3\sqrt{3}}{4}\omega_p\left[\frac{\alpha}{\gamma_b}\frac{|\xi|}{z}\right]^{1/3}$$

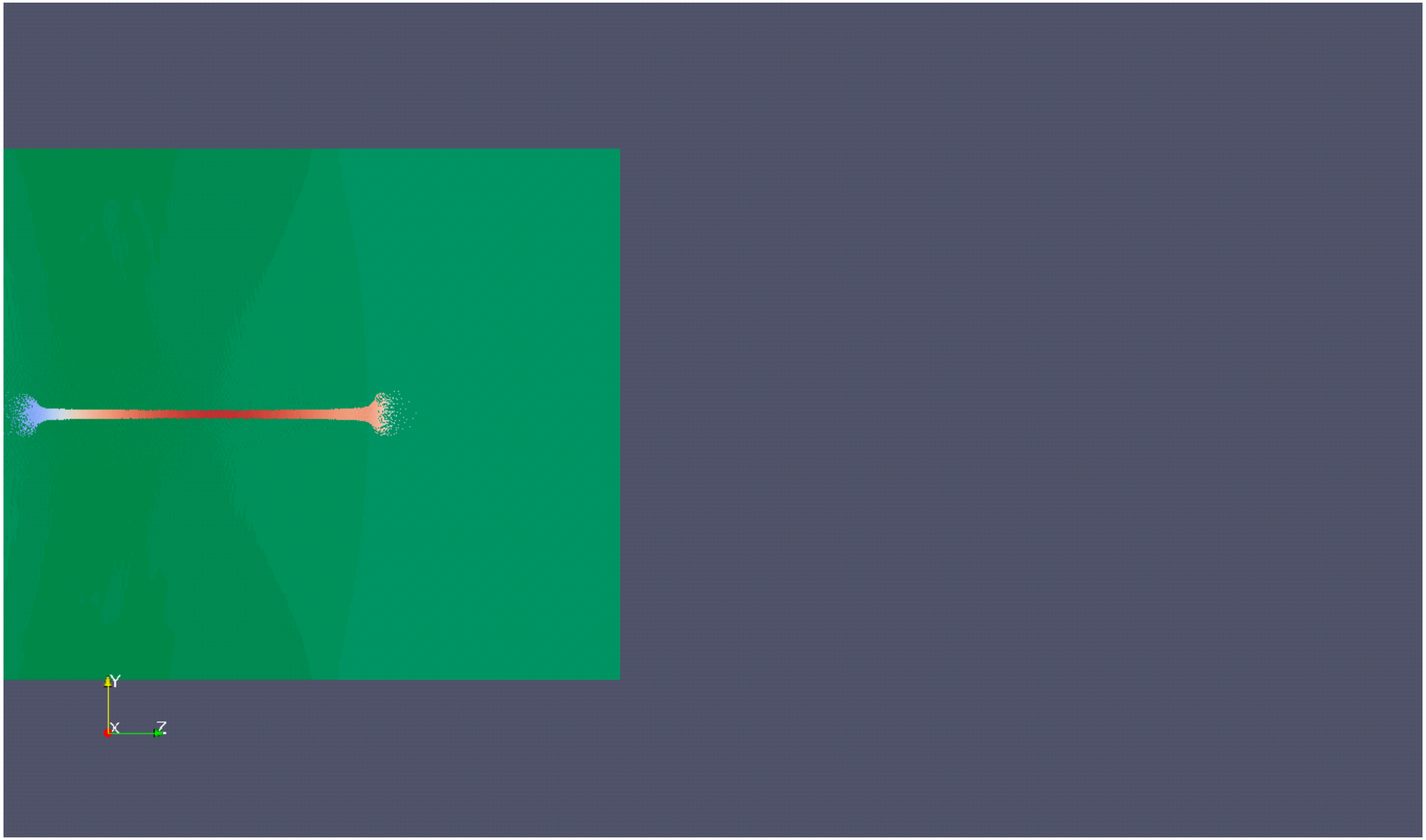
$\alpha = \frac{n_b}{n_e}$ is the ratio of beam density to plasma electron density .

Assuming a small perturbation on plasma density, the EM wave phase velocity could be given by

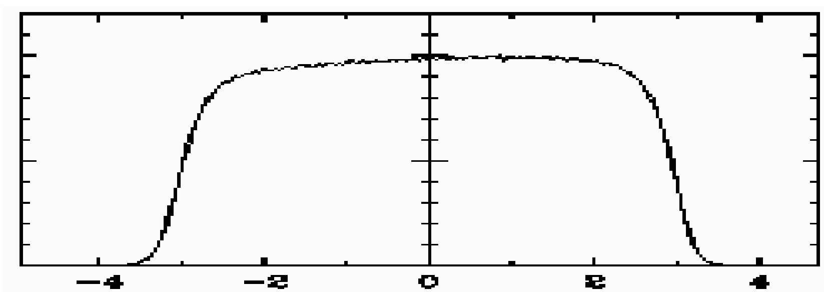
$$v_{ph} = v_b(1 - \frac{1}{2}\left(\frac{1}{2\gamma_b}\frac{\alpha}{z}\xi\right)^{1/3} \quad)$$

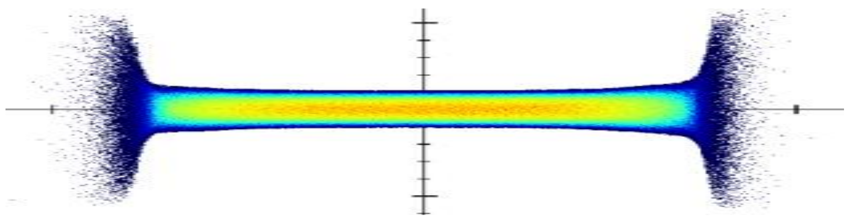
A. Pukhov at el. PRL 107,145003(2011

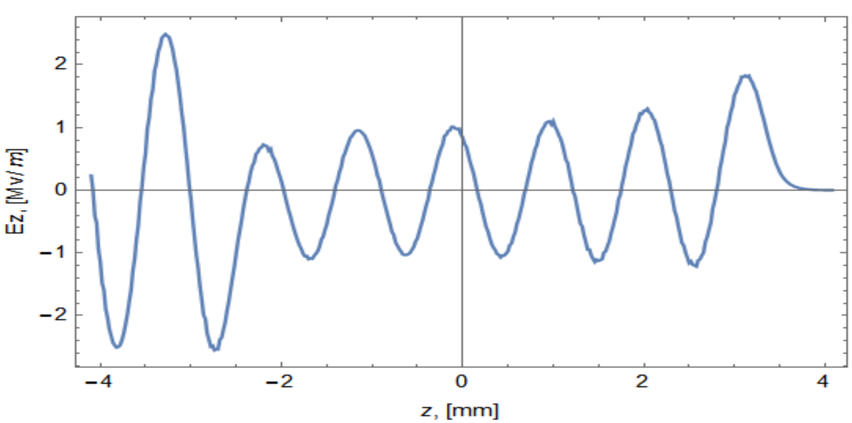
Wakefield Generation: Simulation Results, Longitudinal Wakefield



On-axis Longitudinal Electric Field







After 10mm propagation in plasma the beam density is not modulated too much and could be considered same as initial.

Engineer formula of the peak value for the flat-top is given with $k_p \sigma_r \ll 1$

$$E_z \cong$$

$$Q[nC] \cdot \left(\frac{11.28}{L_b[mm]}\right) \cdot \left(\frac{n_p[cm^{-3}]}{10^{14}}\right)^{1/2} \cdot \left(e^{\frac{n_p[cm^{-3}]}{10^{14}} \cdot (1.3 \cdot \sigma_r[mm])^2}\right) \cdot$$

$$\left(0.06 - \ln\left(\frac{n_p[cm^{-3}]}{10^{14}} \cdot (1.3 \cdot \sigma_r[mm])^2\right)\right)[MV/m]$$

$$E_{wb} = \frac{mc\omega_p}{e} \cong 3.03GeV/m$$

Excited electric field behind the bunch

$$E_z(0, \xi) \cong 2.5[MV \cdot m^{-1}] \times \sin k_p \xi$$

Energy modulation

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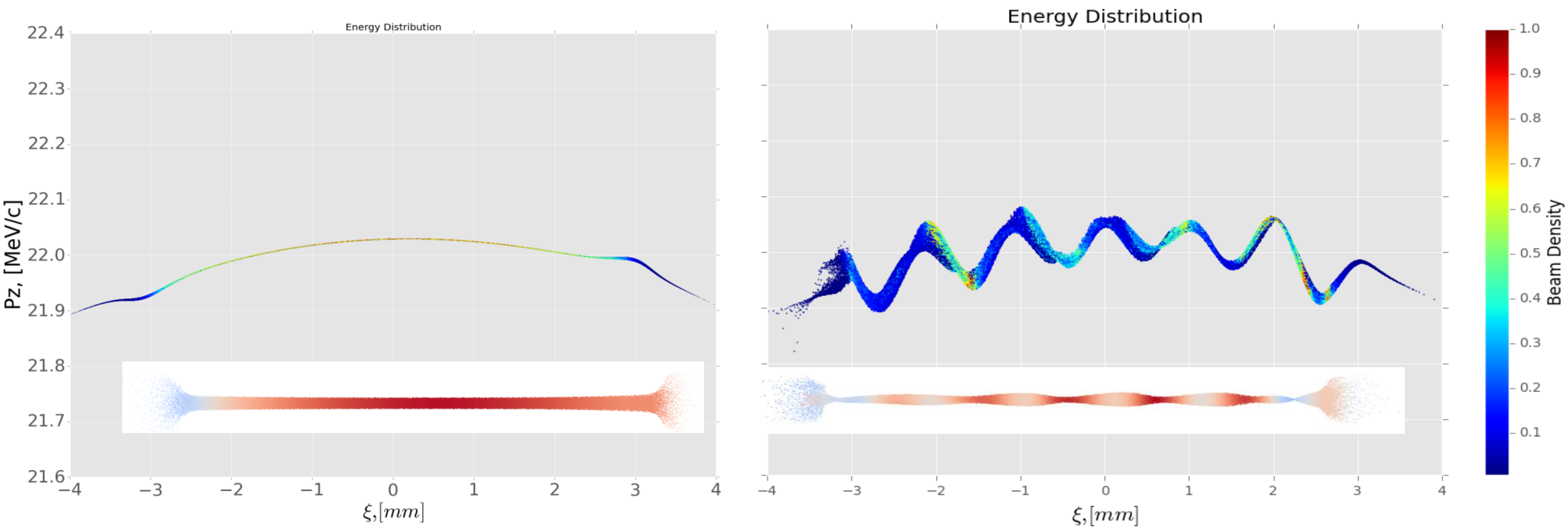
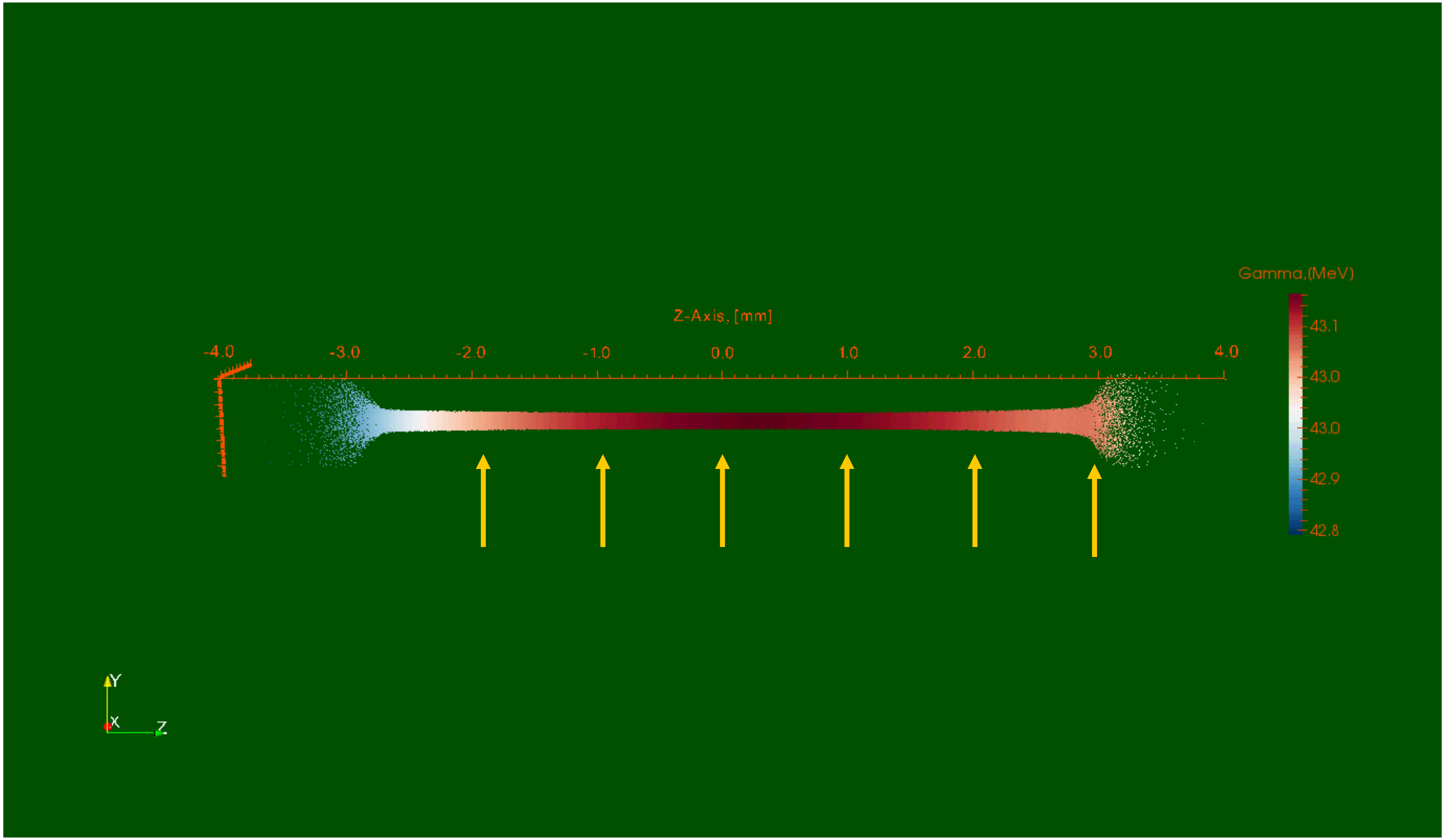


0mm in plasma

40mm in plasma

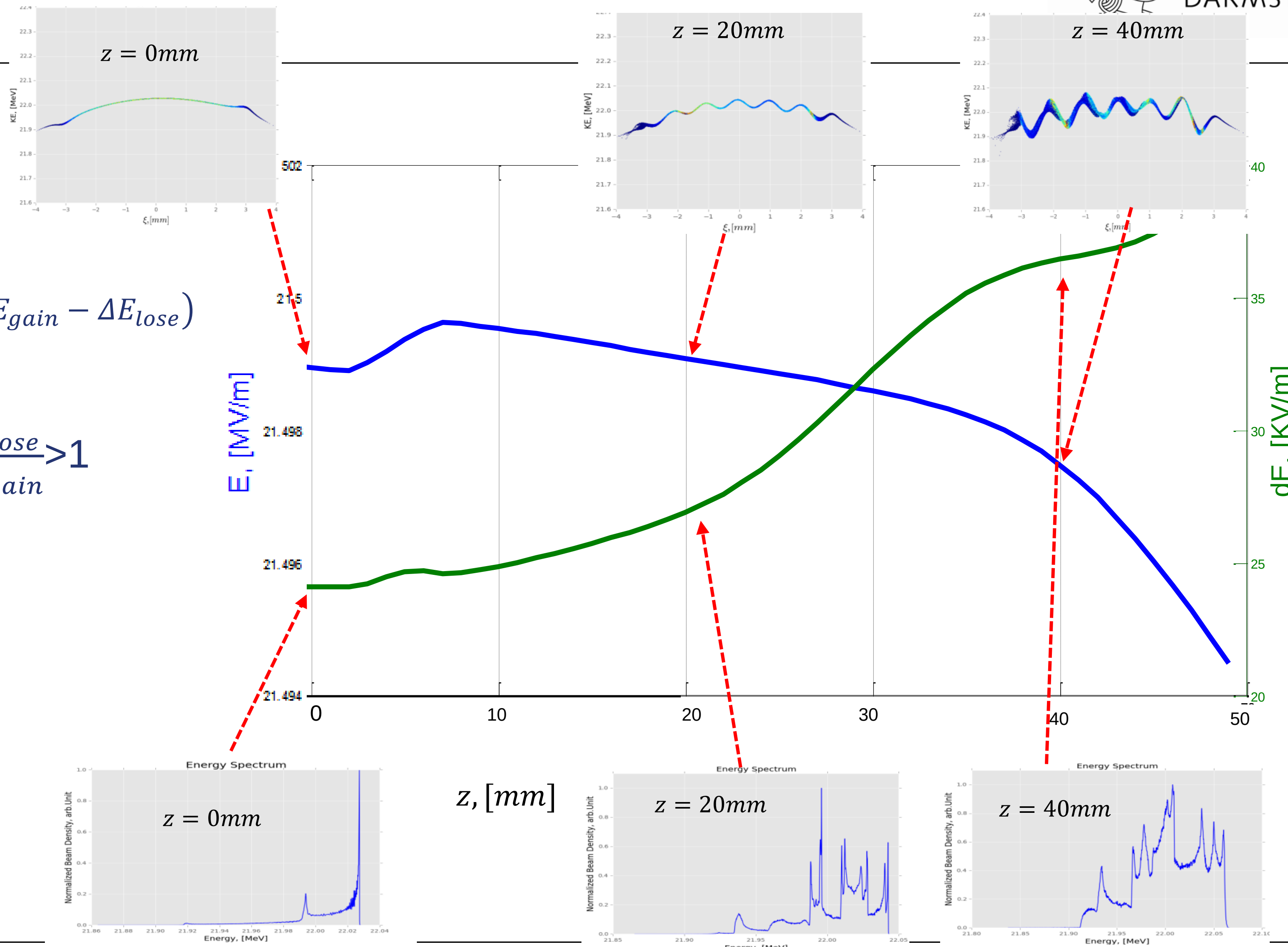
Energy modulation



Energy modulation: Energy Lose and Spread

$$E = E_0 + (\Delta E_{gain} - \Delta E_{lose})$$

$$\Delta = \frac{\Delta E_{lose}}{\Delta E_{gain}} > 1$$



Phase Slippage

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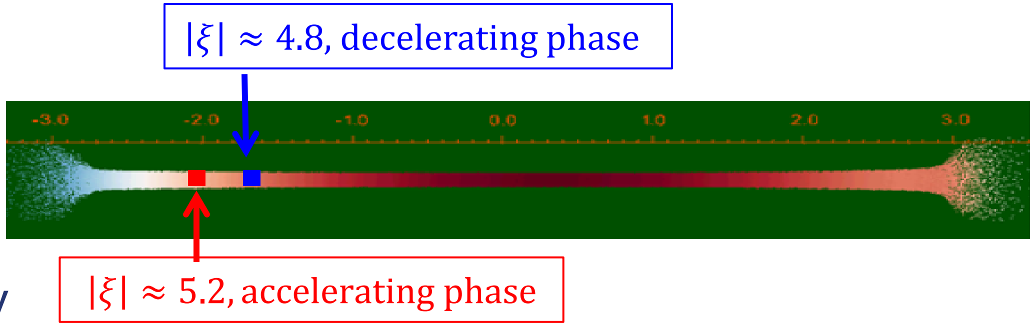
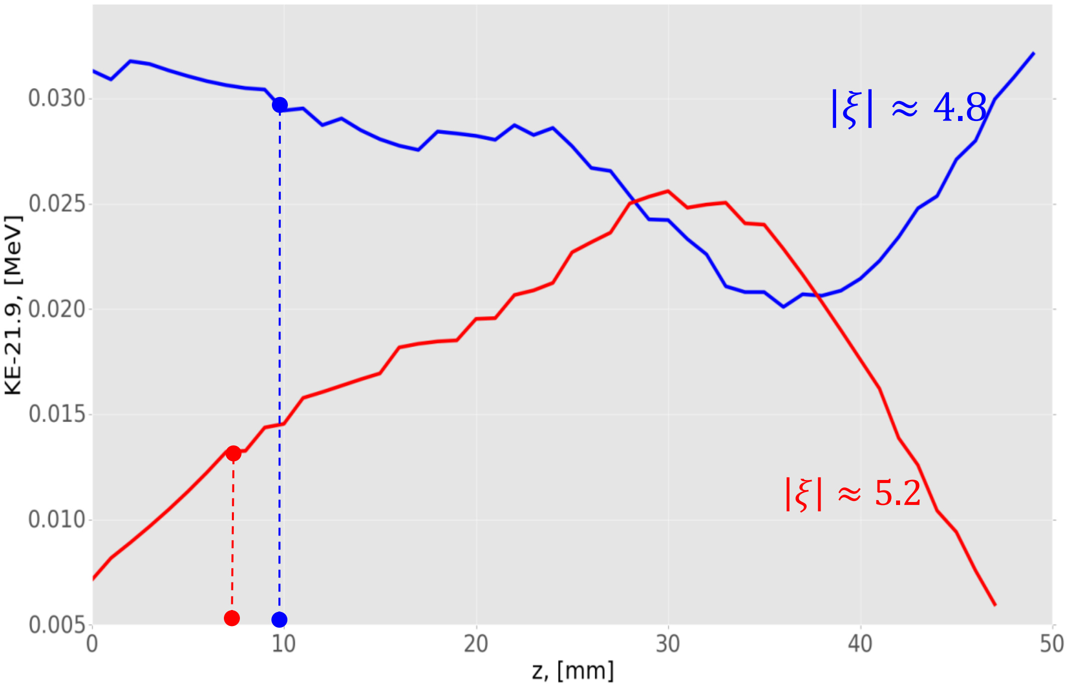
$$v_{ph} = v_b(1 - \frac{1}{2}\left(\frac{1}{2\gamma_b}\frac{\alpha}{z}\xi\right)^{1/3}$$



Dephasing length is approximately obtained by

$$\frac{\lambda}{4} = \int_0^{L_d} \frac{1}{2}\left(\frac{1}{2\gamma_b}\frac{\alpha}{z}|\xi|\right)^{1/3} dz$$



With the initial parameters:

$\gamma_b \approx 42$

$|\xi| \approx 4.8\ /5.2$

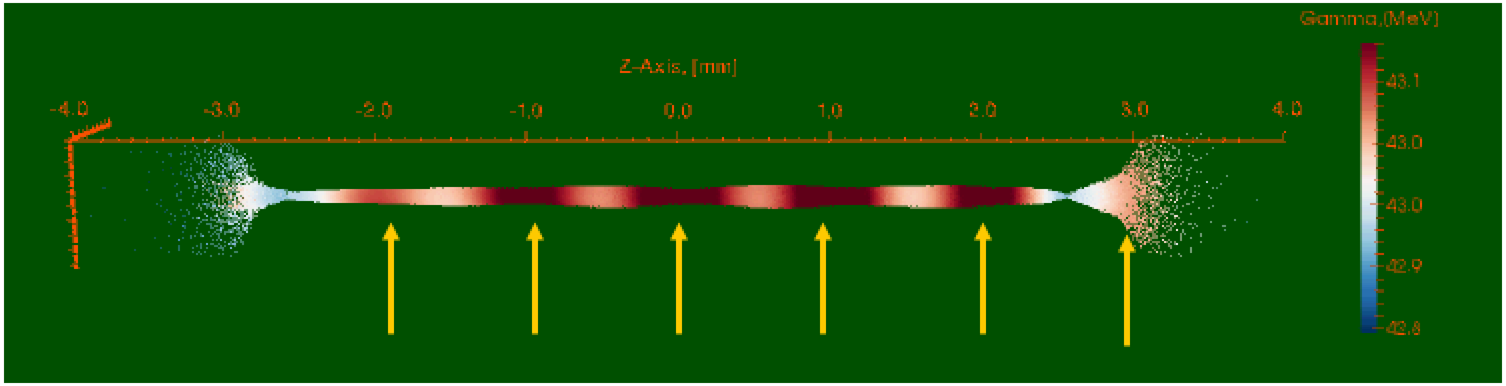
$\alpha \approx 0.015$

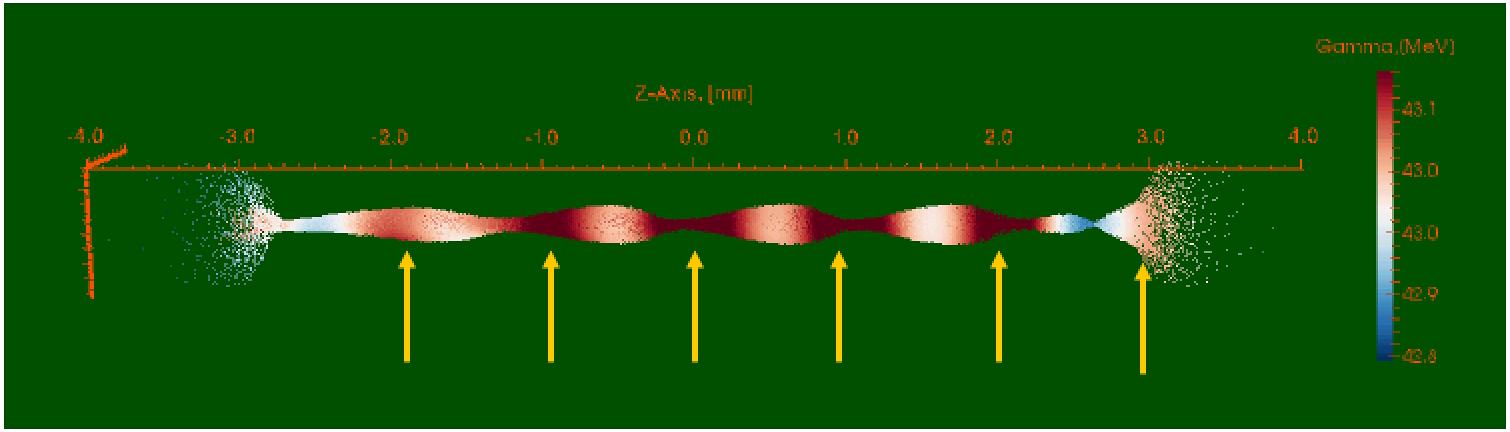
$\lambda \approx 1mm$

$L_{d,4.8} \approx 6.5mm$

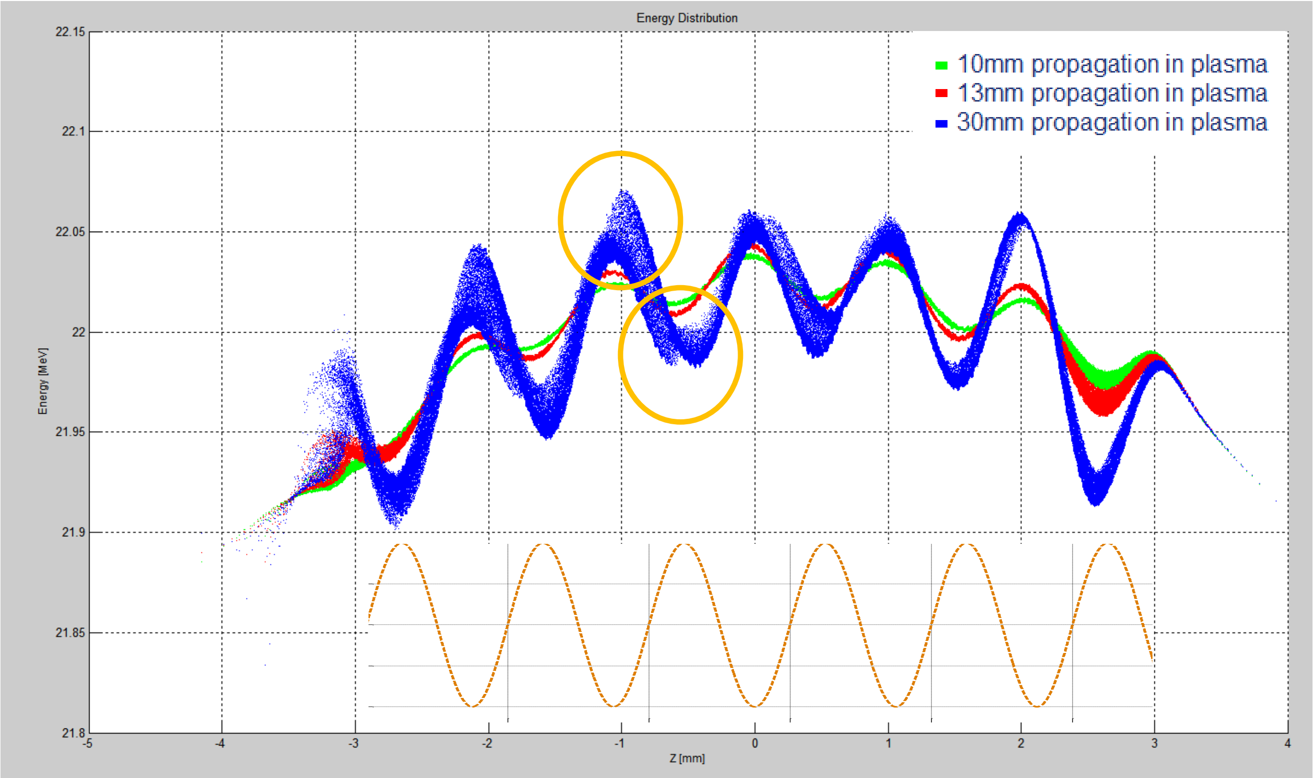
$L_{d,5.2} \approx 6mm$

Dephasing


Gamma,(MeV)
Z-Axis, [mm]
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
43.1
43.0
43.0
42.9
42.8

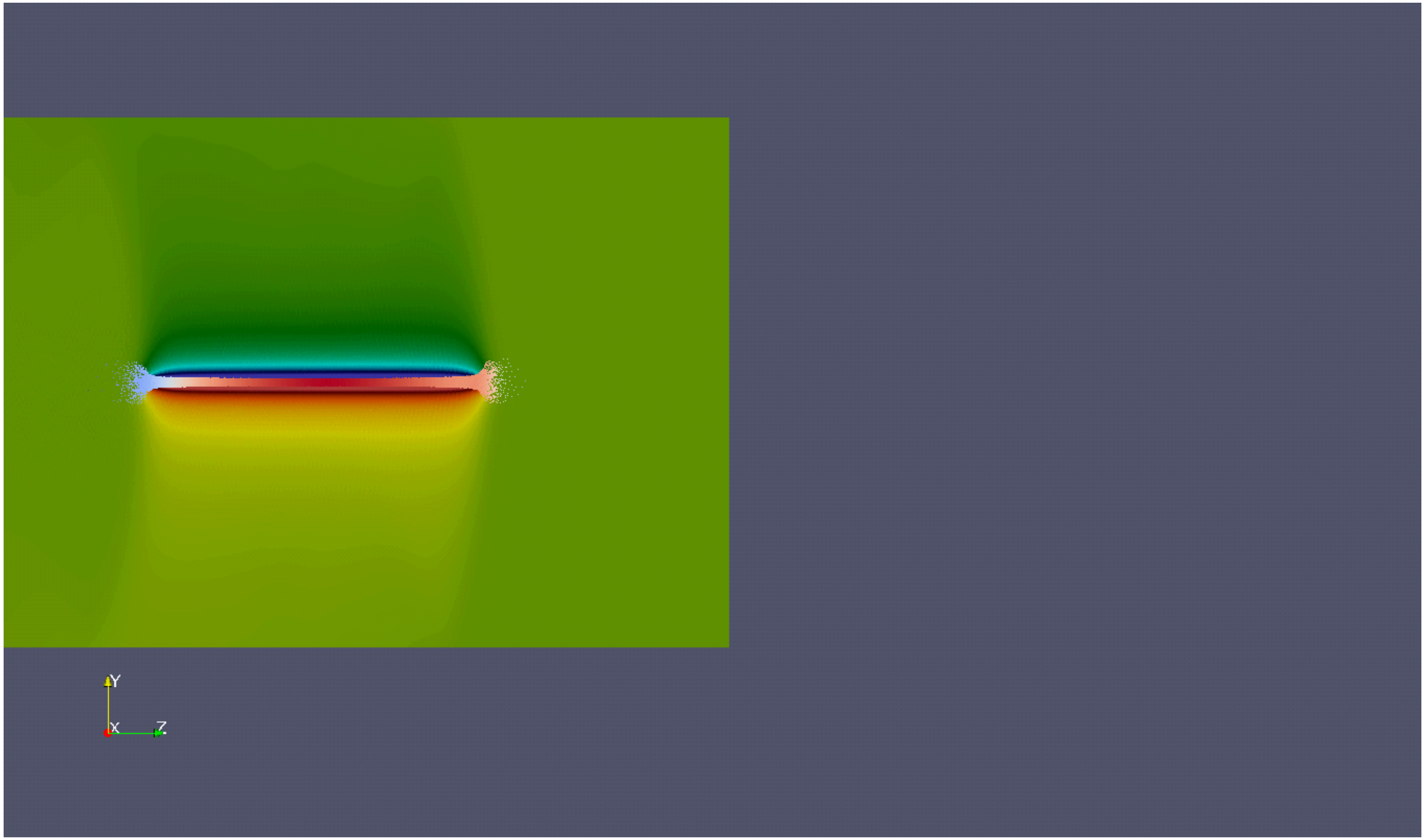

Gamma,(MeV)
Z-Axis, [mm]
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
43.1
43.0
43.0
42.9
42.8

Energy modulation: Energy Modulation and Dephasing



Energy modulation at the different position shows the characteristics of the excited wakefield.

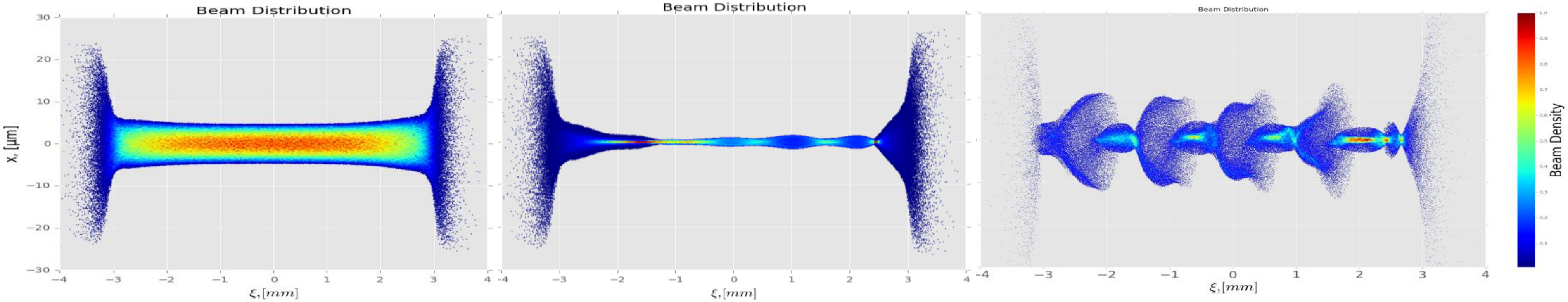
Wakefield Generation: Simulation Results, Transverse Wakefield



Radius Self-Modulation: Onset of Beam Envelop modulation

Propagation direction

Initial | 10mm | Transversely compressed | Modulated

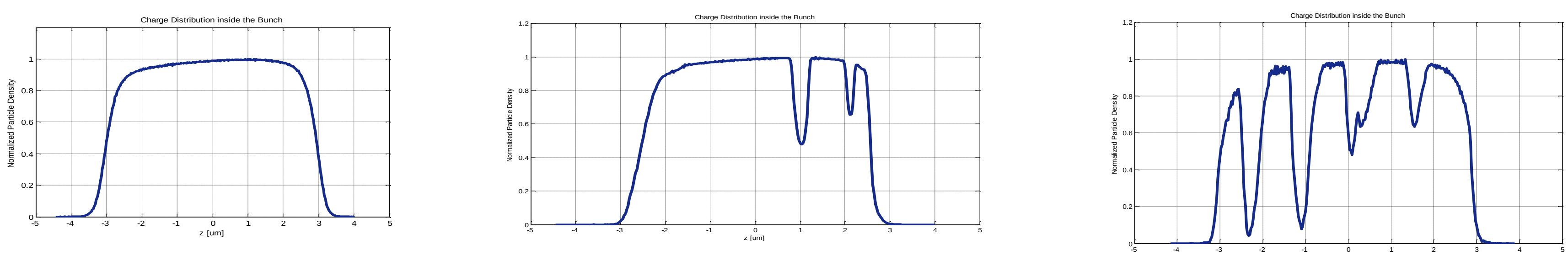


After 10mm propagation in plasma
$\alpha = 0.015$
$\alpha/z = 0.0015\ mm^{-1}$

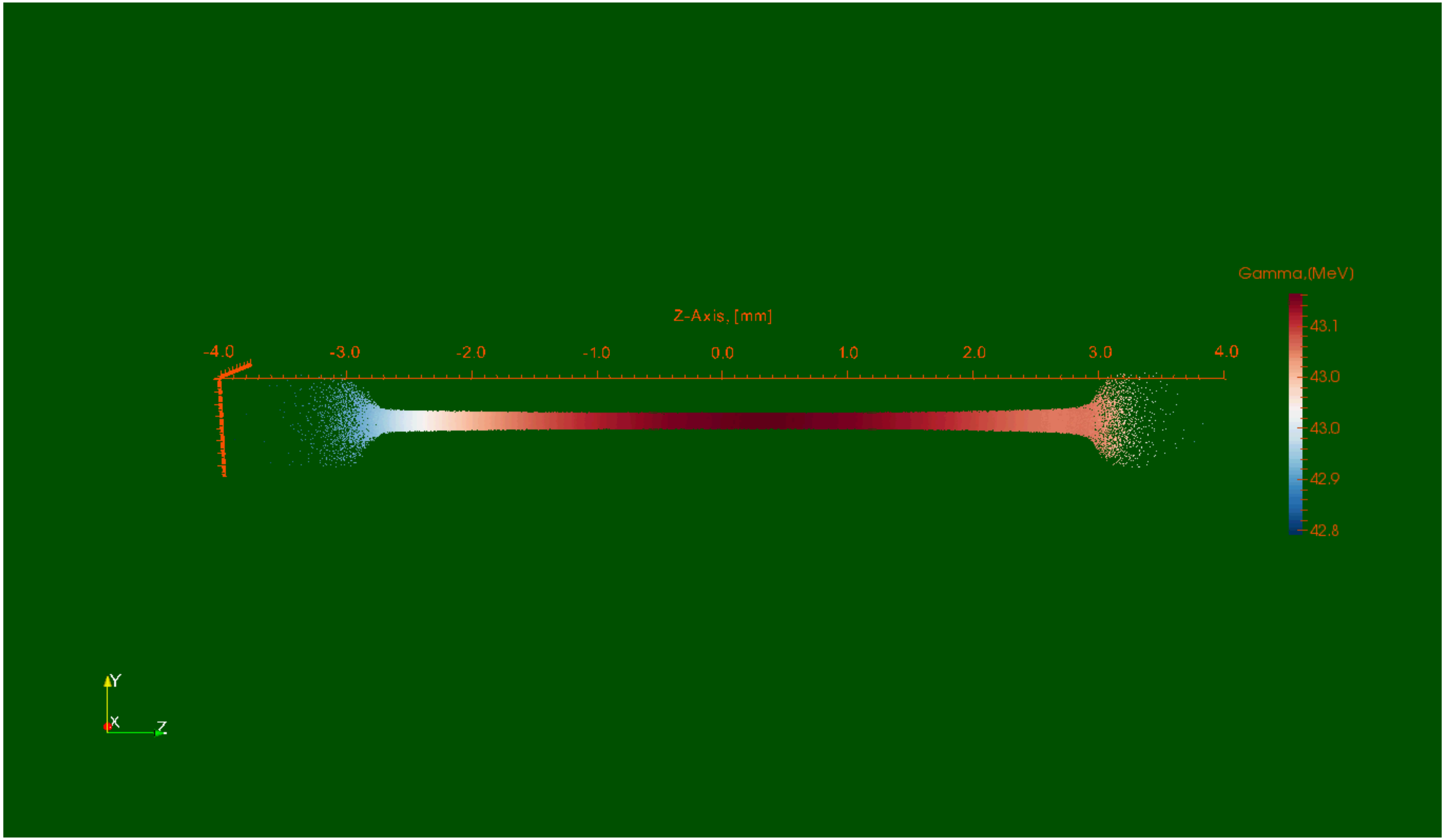
After 16mm propagation in plasma
$\alpha = 0.043$
$\alpha/z = 0.002\ mm^{-1}$

After 36mm propagation in plasma
$\alpha = 0.015$
$\alpha/z = 0.0003\ mm^{-1}$

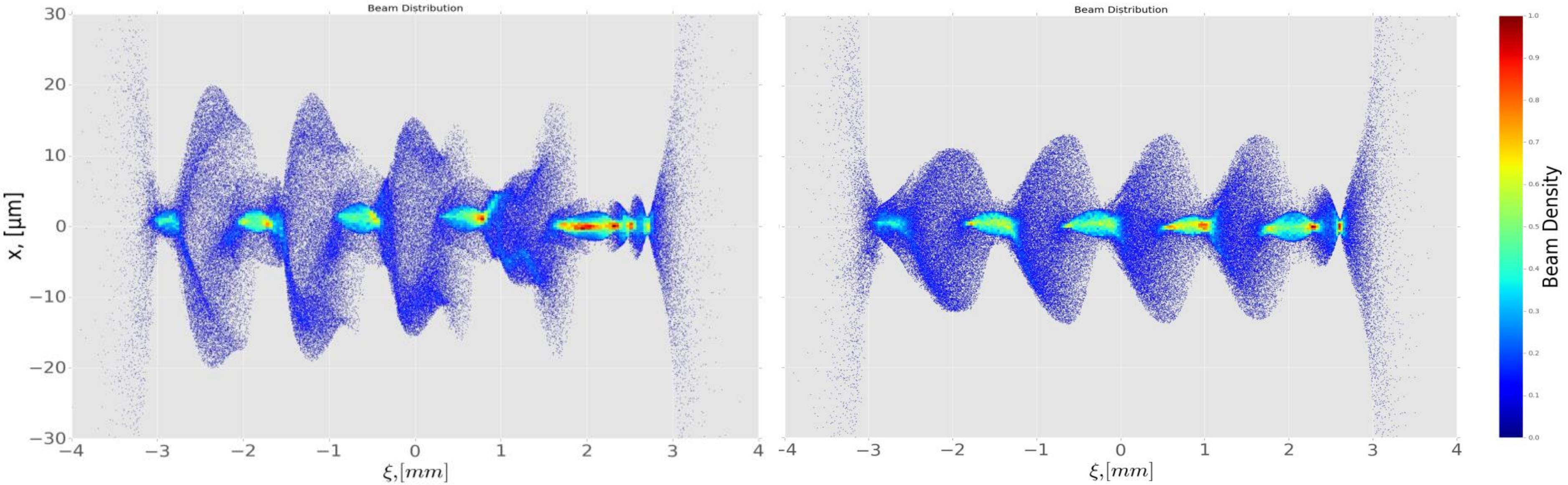
Normalized Particle density in the longitudinal direction



Radius Self-Modulation: Onset of Envelop modulation



Radius Self-Modulation: Onset of Envelop modulation

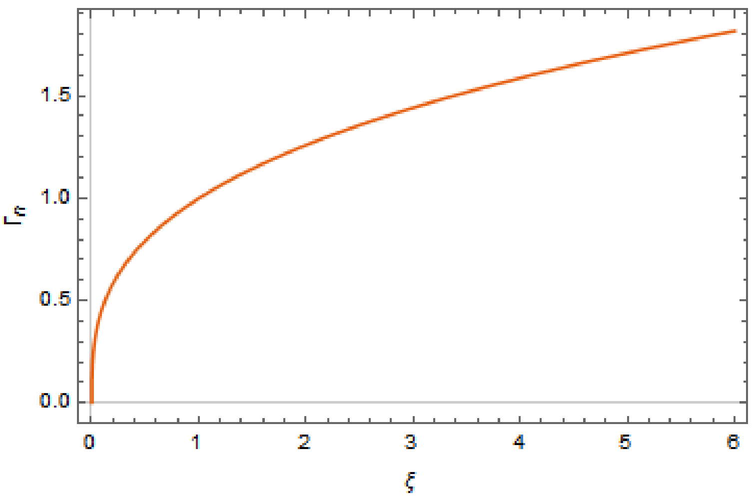


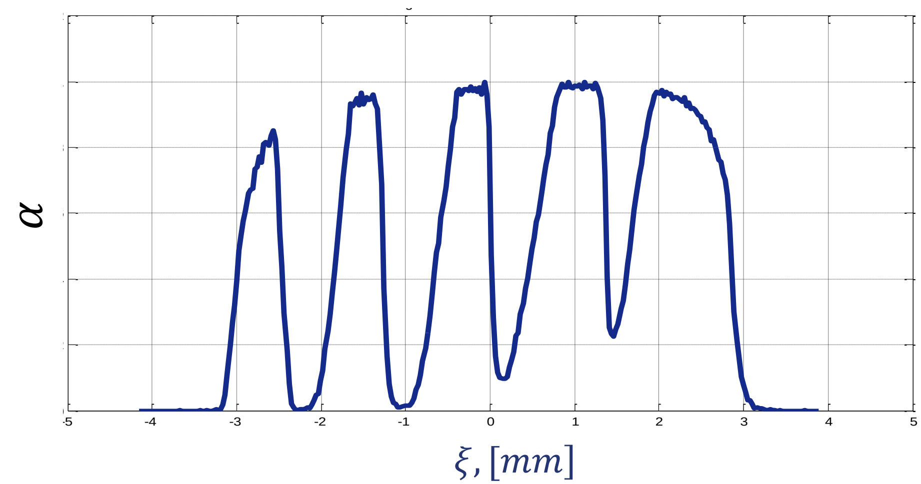
$n_b = 2.2 \times 10^{-13} cm^{-3}$

$n_b = 0.9 \times 10^{-13} cm^{-3}$

$z = 54mm$

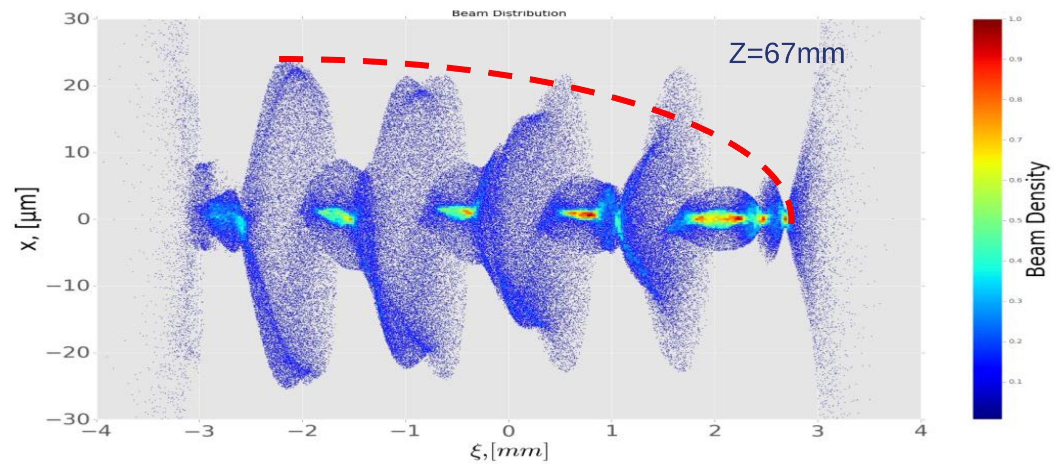
Radius Self-Modulation: Beam Envelop Modulation inside the bunch



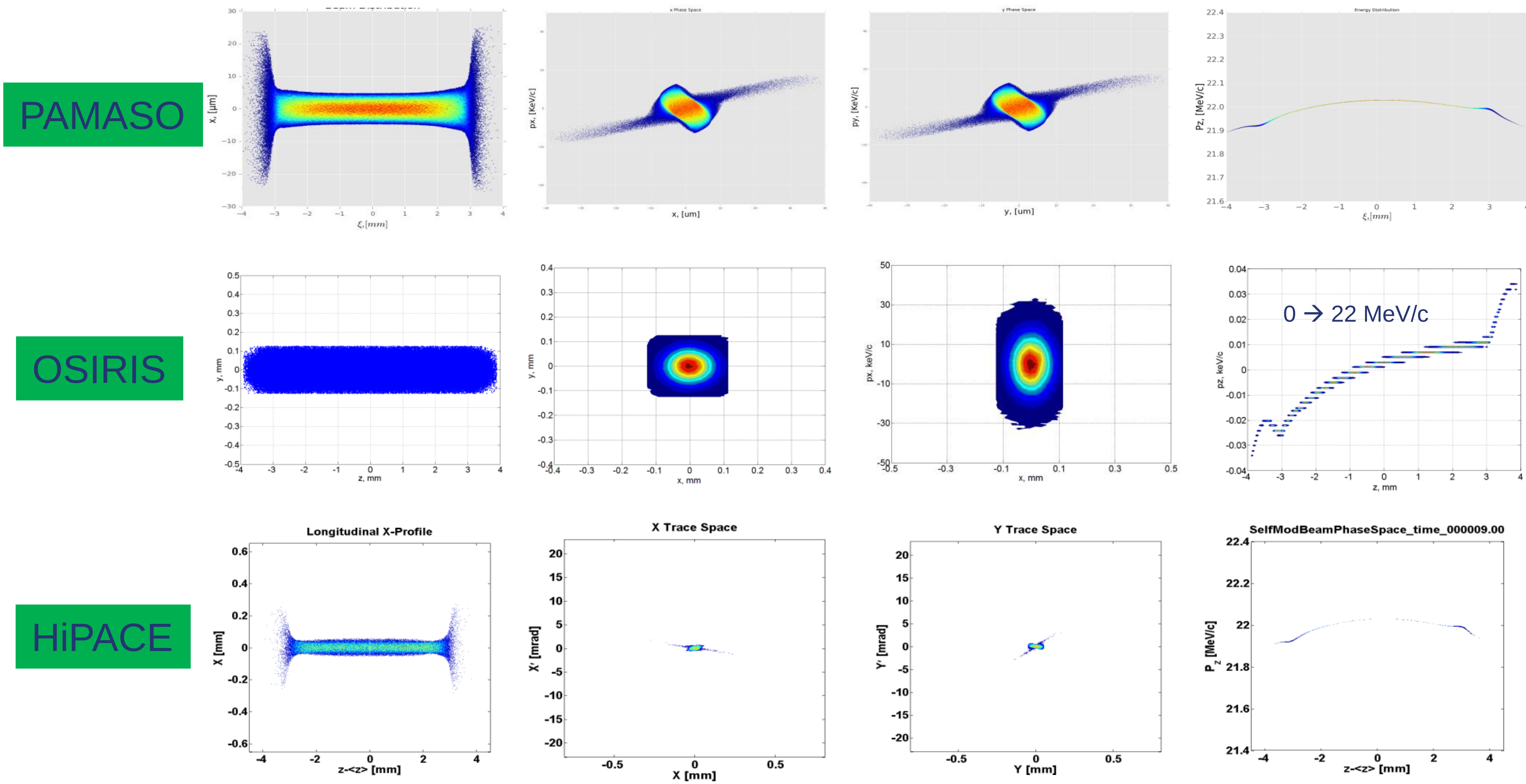


$$\Gamma \approx \frac{3\sqrt{3}}{4}\omega_p \left[\frac{1}{\gamma_b}\frac{\alpha}{z}\cdot|\xi|\right]^{1/3}$$

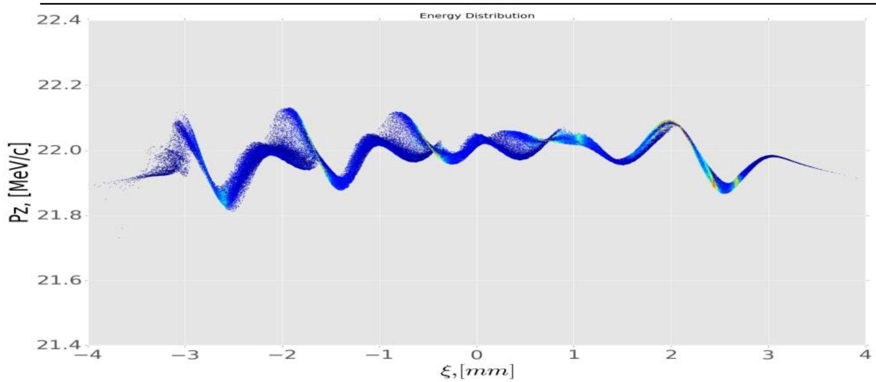
→ $\Gamma \propto (|\xi|)^{1/3}$



Code benchmark : PAMASO VS. OSIRIS VS. HiPACE

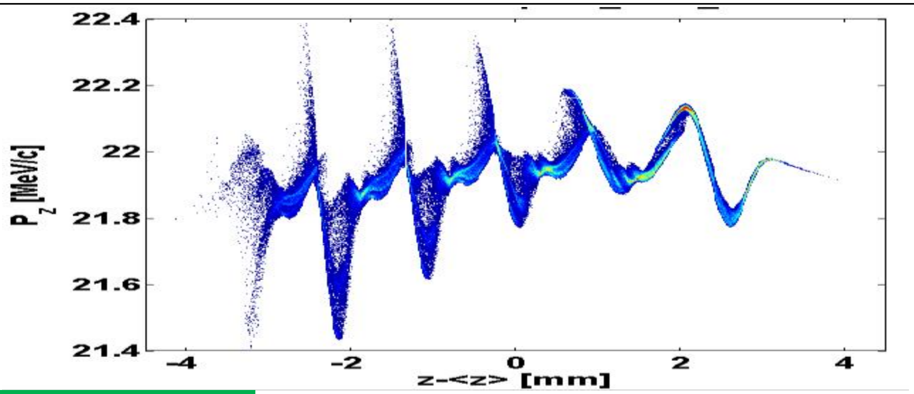


Code benchmark- Energy modulation

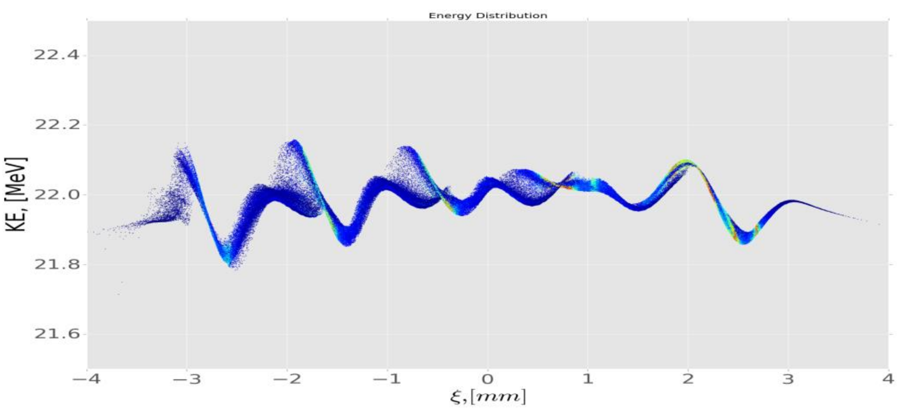


PAMASO

$z = 54mm, \sigma_{x;y} = 27\mu m$

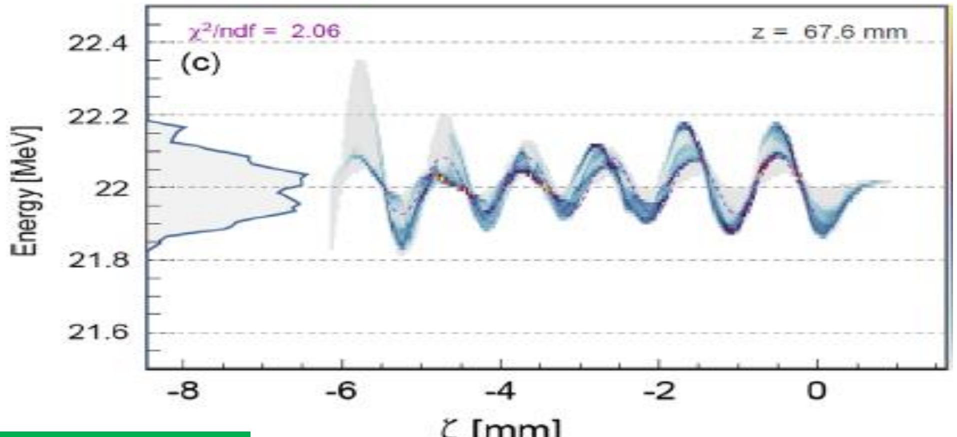


HiPACE



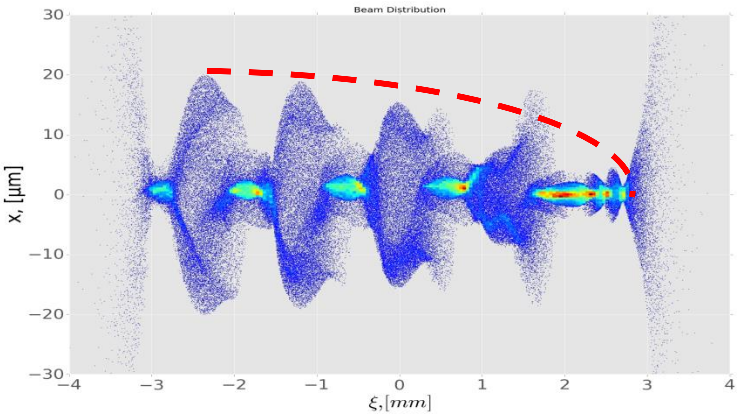
PAMASO

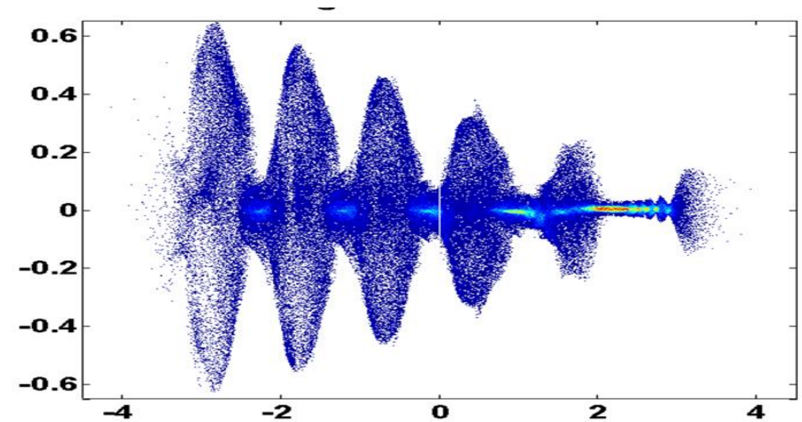
$z = 67mm, \sigma_{x;y} = 42\mu m$



OSIRIS

Code benchmark – Radius modulation

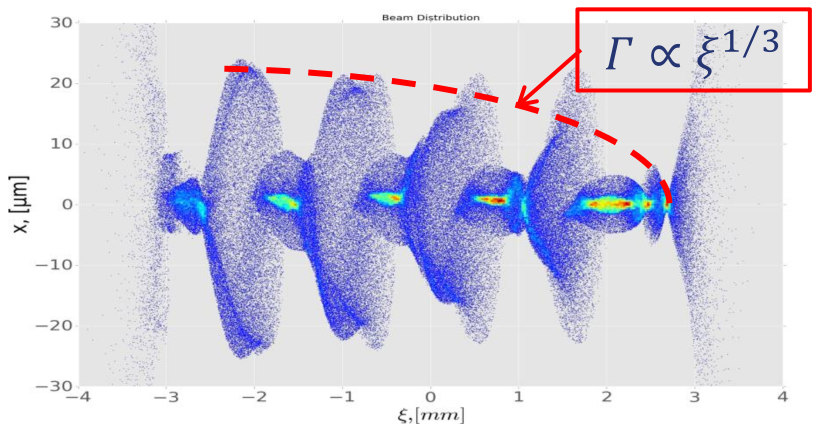


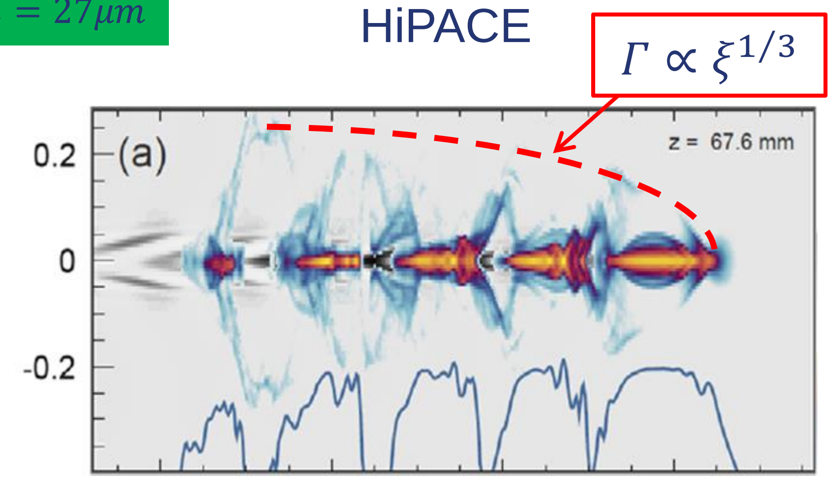


PAMASO

$z = 54mm,\ \sigma_{x;y} = 27\mu m$

HiPACE





PAMASO

$z = 67/67mm,\ \sigma_{x;y} = 42\mu m$

OSIRIS

Summary and Perspective

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Summary

- ✓ Simulate the PITZ transport line for PWFA experiment by ASTRA
- ✓ Demonstrate the capability of PAMASO code for a simulation of SMPWFA
- ✓ Preliminarily demonstrate the principle of SMI
- ✓ Benchmark the code against with OSIRIS and HiPACE

Perspective

However, a lot of works are still needed…

- Hosing instability
- Seeding of SMI
- Dephasing
- Stable propagation and beam lose
- Phase velocity evolution
- Further simulation works on the SMPWA experiment at PITZ
- …

Thank you so much for your attention!