Numerical Study of the self-modulation process in PWFA

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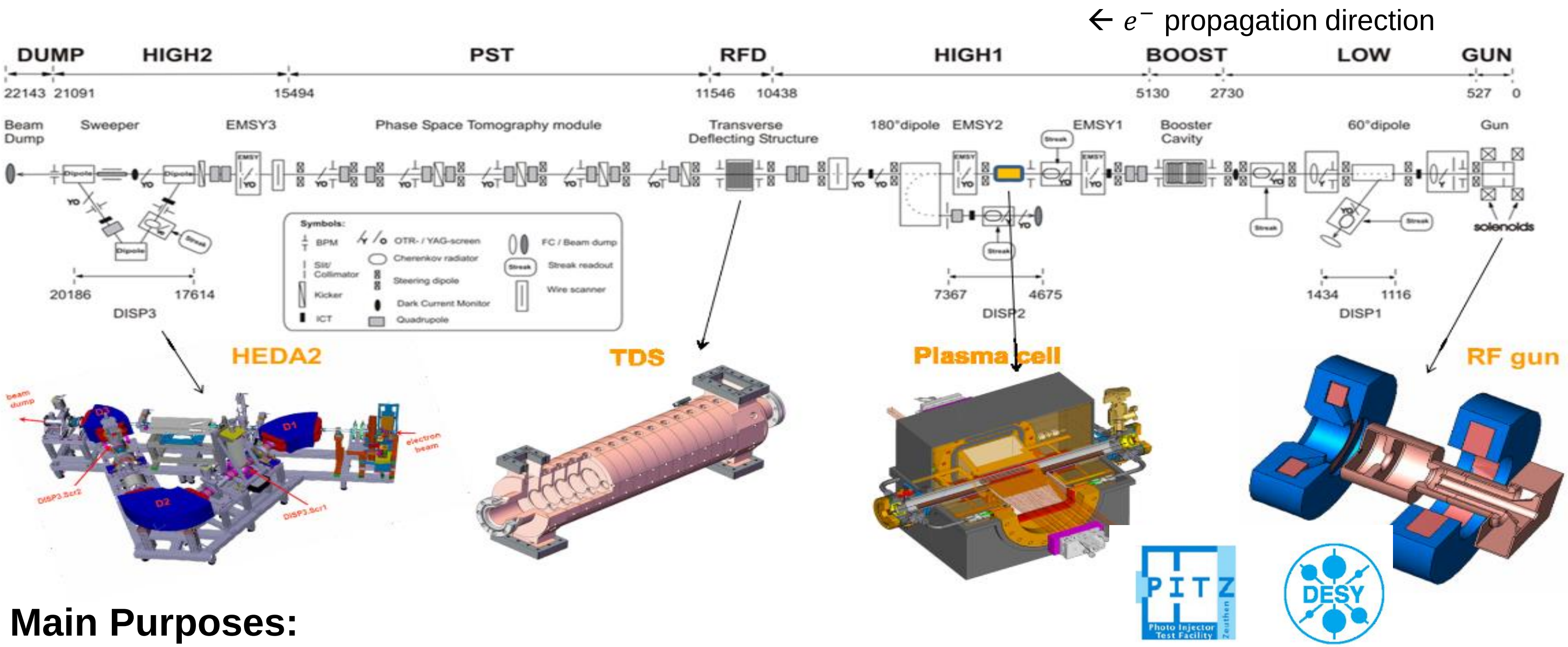
Content

- Introduction
- Code convergence
- Transverse compression
- Macro bunch train destruction

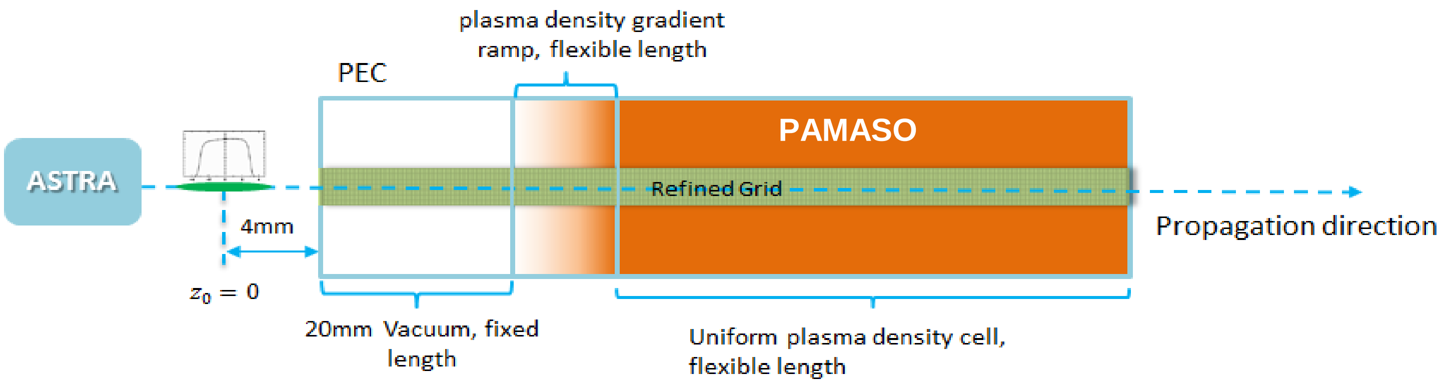
Introduction: SMPWA experiment at PITZ



Main Purposes:

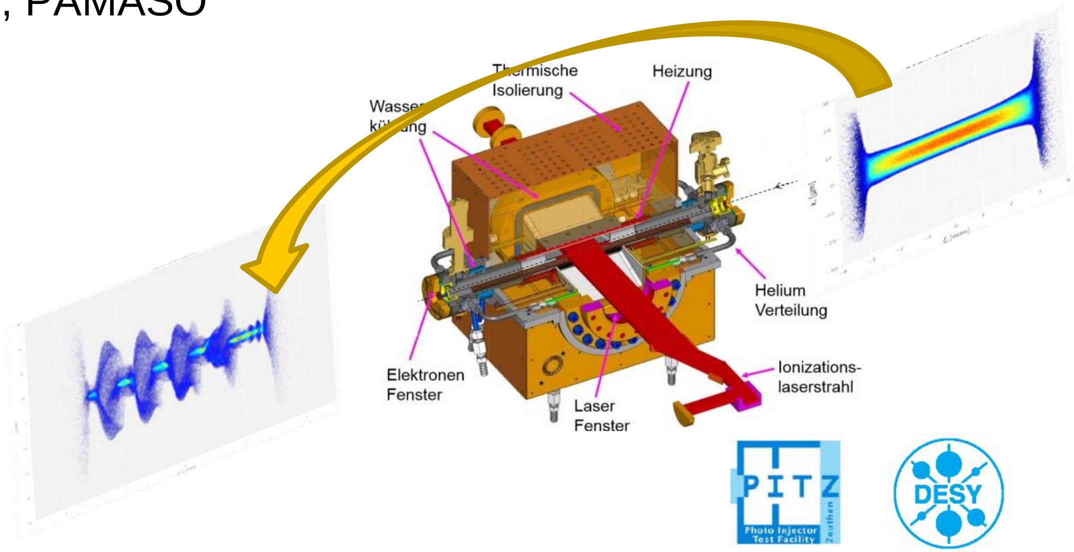
- Demonstrate the principle of self-modulation of long electron bunches in plasma
- Study the underlying physics of plasma-electron interaction, such as dephasing, hosing-instability, etc.
- To gain insight into the experiment conditions for the proposed AWAKE project at CERN, such as the beam matching,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

Introduction: SMPWA Simulation schema



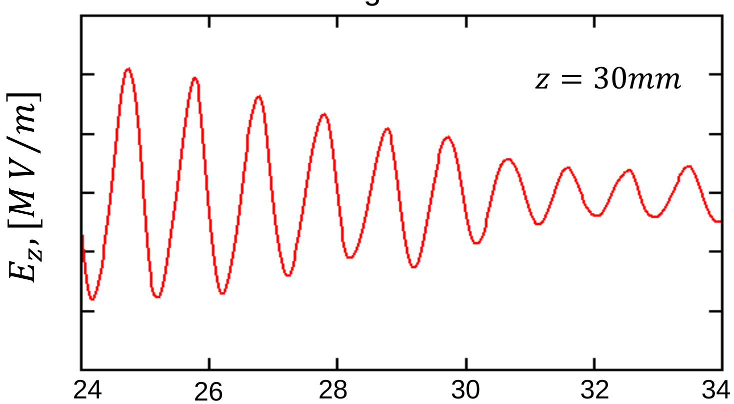
- With PITZ configuration
- ASTRA code and fully 3D PIC code, PAMASO

Parameters	Value
Plasma density	$n_{p0} = 1 \times 10^{15} cm^{-3}$
Longitudinal beam size(FWHM)	$L_b = 6mm,$ $(RMS\ \sigma_z = 1.7mm)$
Energy of the beam	$KE = 22MeV \rightarrow \gamma \approx 42$
Charge per bunch	$100pC$
Simulation windows	$k_p \Delta x = 0.1, k_p \Delta z = 0.4$

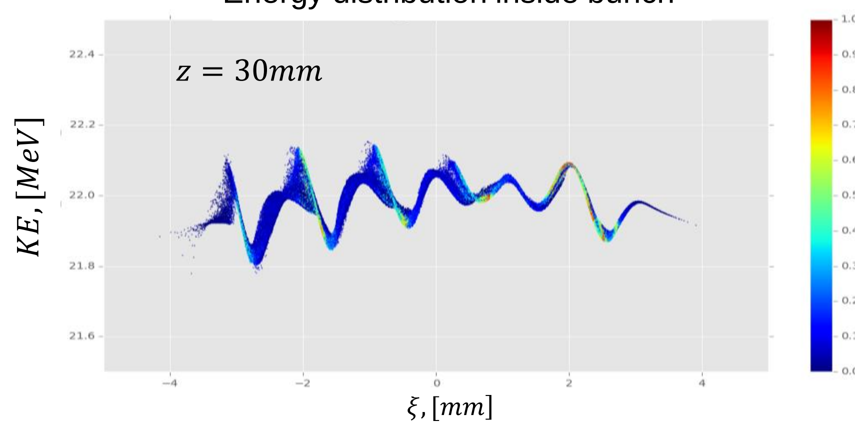


Longitudinal Wakefield Generation

On-axis excited longitudinal electric field



Energy distribution inside bunch



Transverse Wakefield Generation

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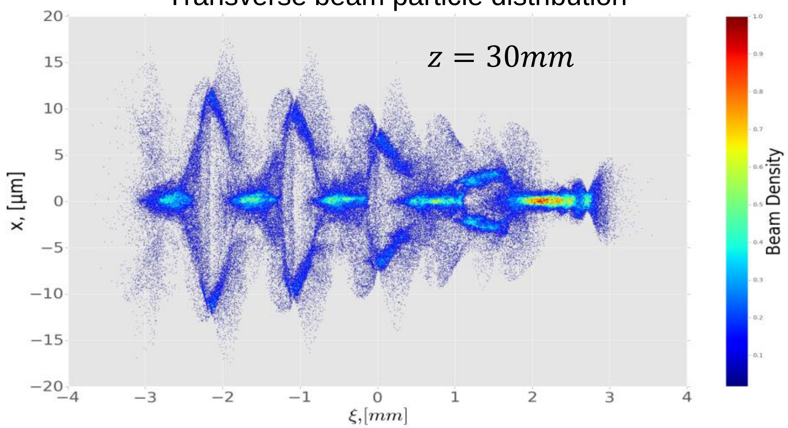
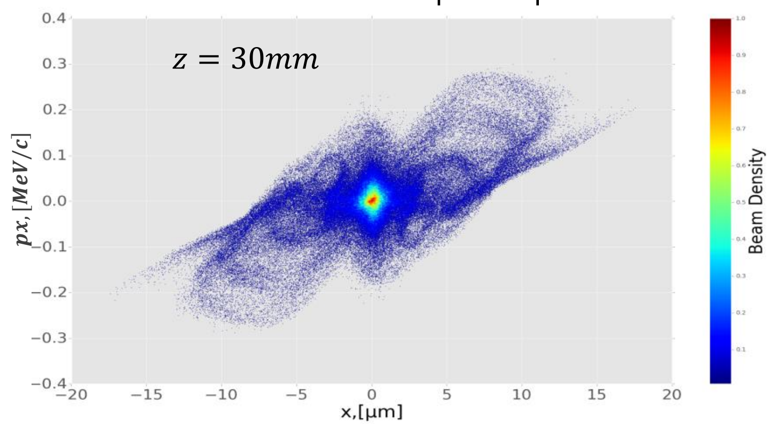
Transverse beam particle distribution

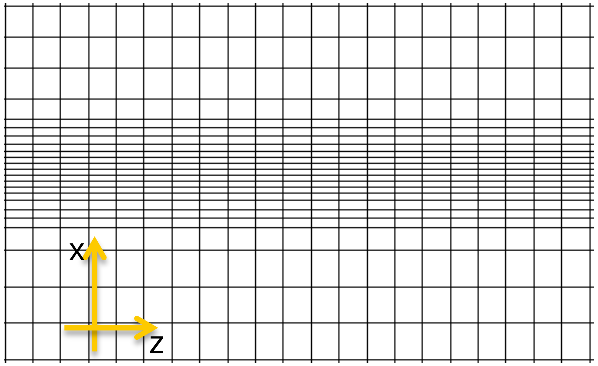


Transverse beam phase space

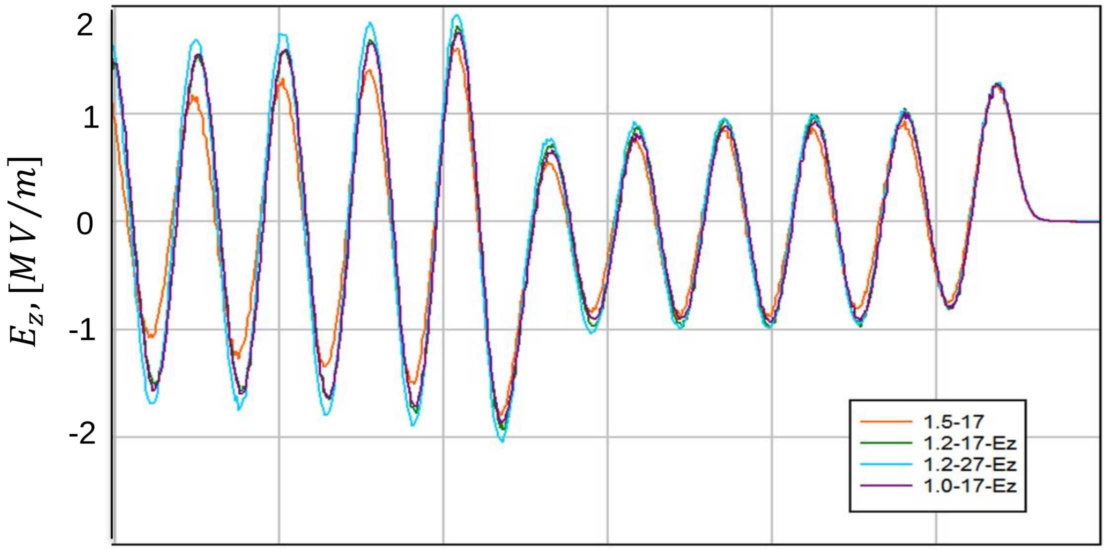


Code Convergence

- Optimize the numerical parameters for efficiency and reliability.
- Concerned parameters: grid size, particle size, plasma particle distribution, solver order.



Grid layout:
- Longitudinal uniform
- Transverse exponentially increased

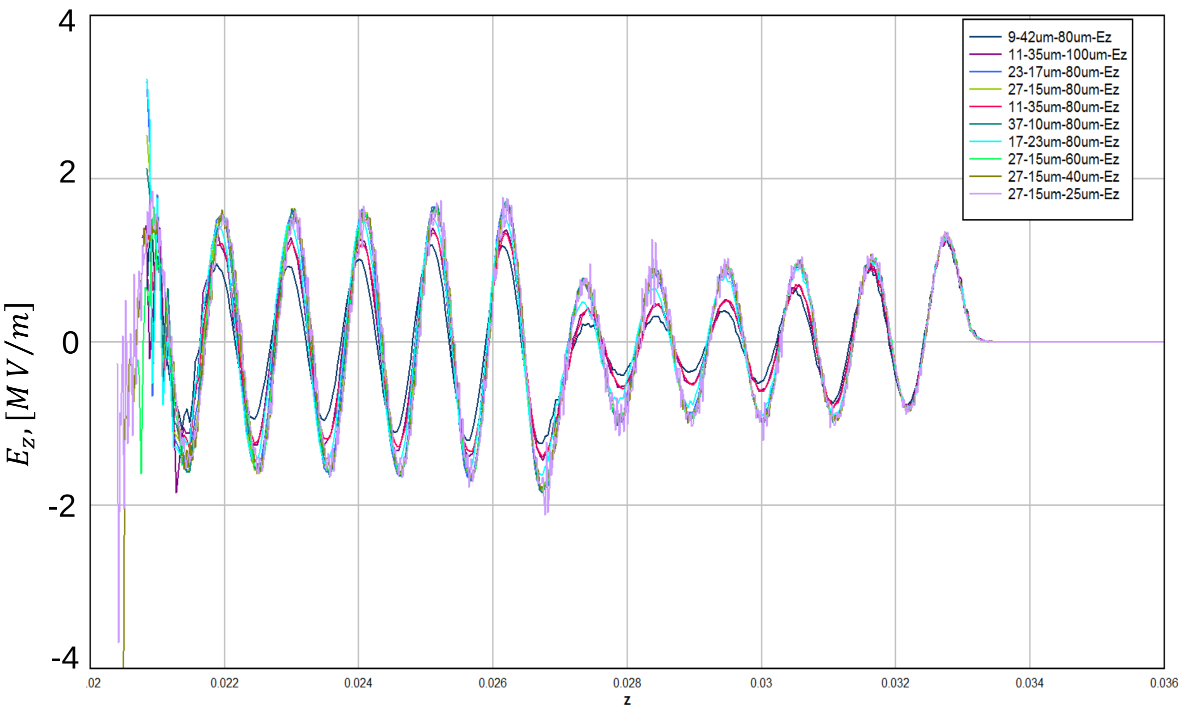


Value of rate	Minimum Tran. grid
1.5	17um
1.2	17um
	10um
1.0	17um

- Increase rate of grid <= 1.2

Code Convergence

- Longitudinal on-axis electric field at z=30mm for the solver order 4.



<table>
<tr><th>Minimum trans. Grid, [um]</th><th>Minimum longi. Grid ,[um]</th></tr>
<tr><td>10</td><td>80</td></tr>
<tr><td rowspan="5">15</td><td>80</td></tr>
<tr><td>60</td></tr>
<tr><td>40</td></tr>
<tr><td>25</td></tr>
<tr><td>17</td><td>80</td></tr>
<tr><td>23</td><td>80</td></tr>
<tr><td>35</td><td>100</td></tr>
<tr><td>42</td><td>80</td></tr>
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- Minimum transverse grid space<=17um
- Too small value gives much noise.

Code Convergence

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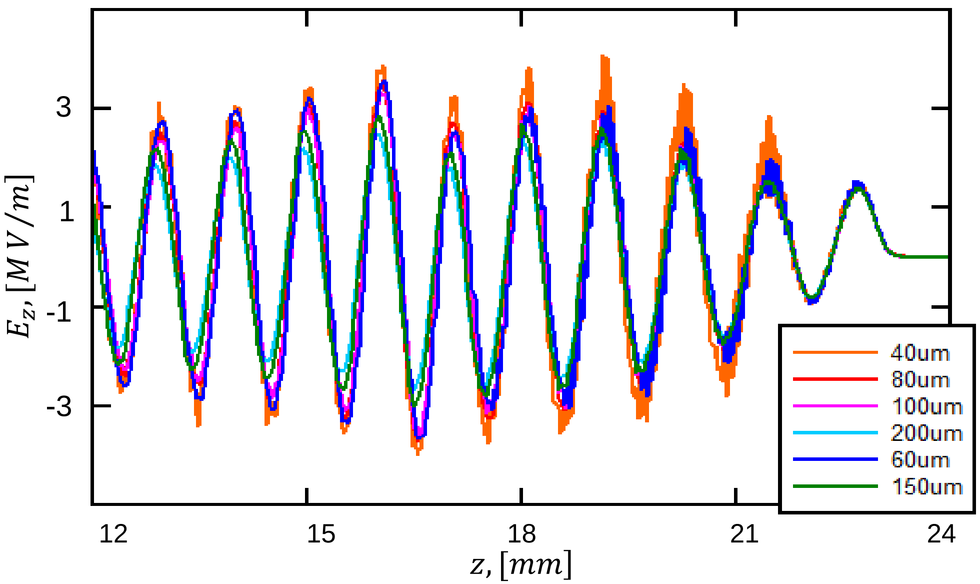
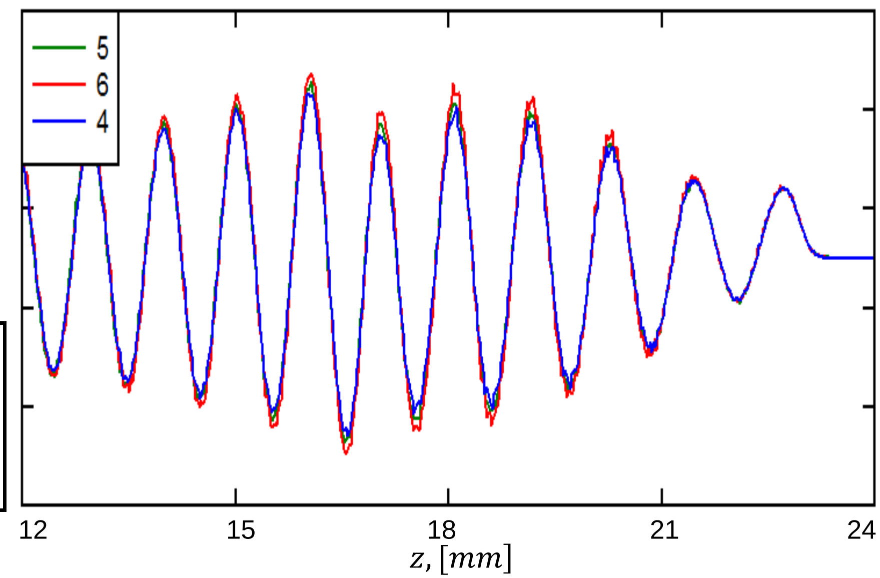
Longitudinal grid size



nppx



- The longitudinal grid size should less than 100um.
- Too small longitudinal size gives much noise.

- nppx: number of plasma particles per grid cell for the uniform plasma distribution, together with the grid solution determines the total number of numerical plasma particles.
- Large number does not give much difference, but requires much more computation time.

Code Convergence

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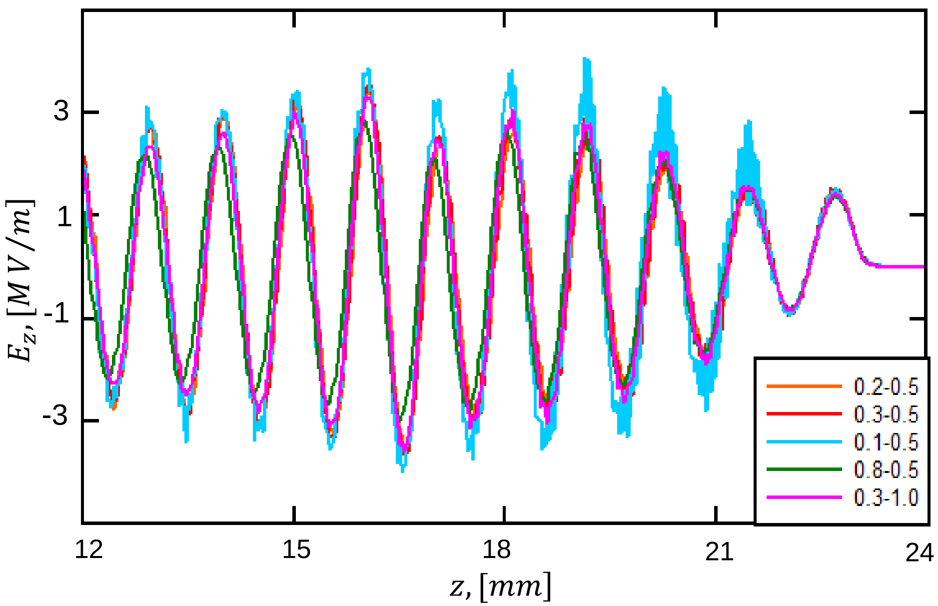
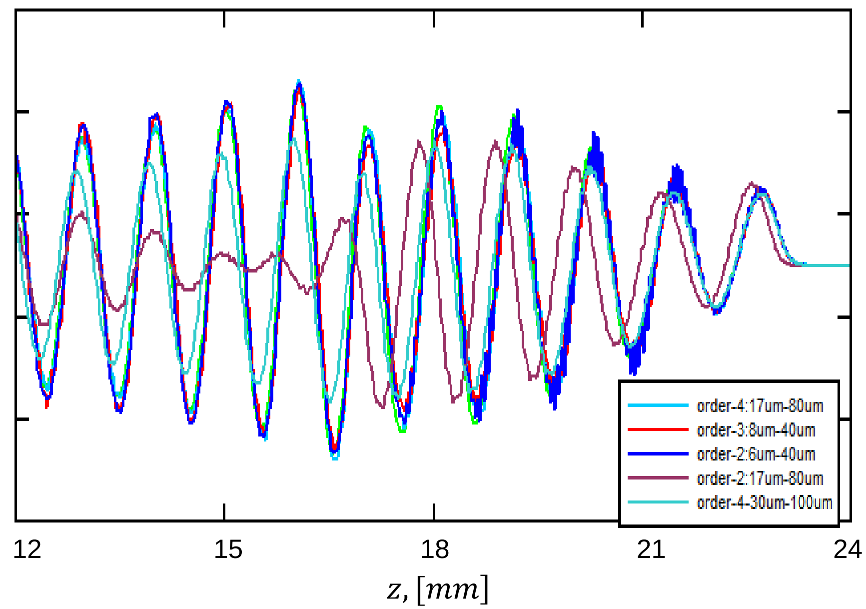
Particle size



Solver order



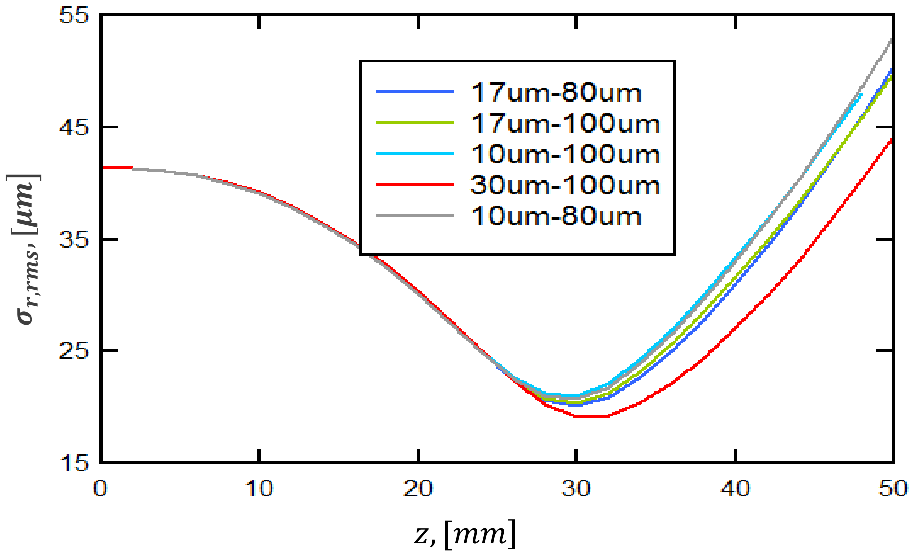
- Particle size is related to the grid size with the rate in each direction:

$$\sigma_{x,y,z,particle} = \eta_{x,y,z}\sigma_{grid}$$

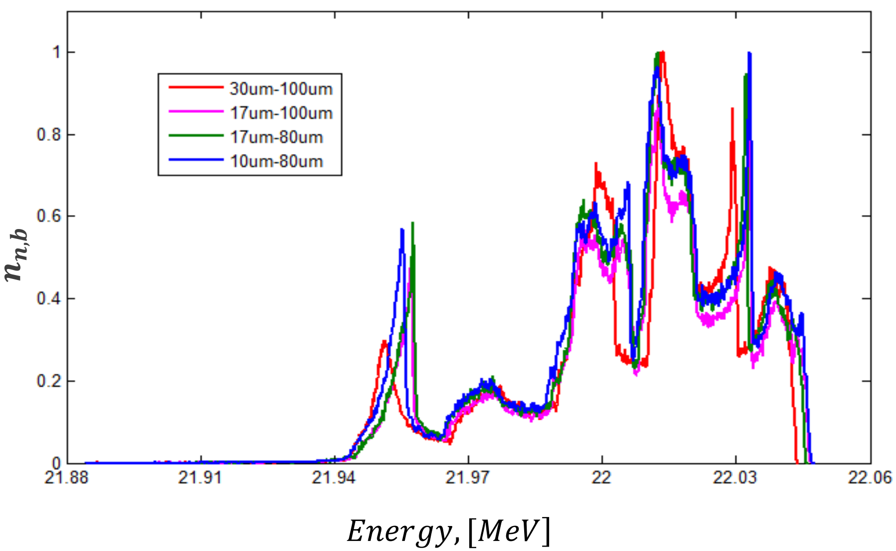
- Lower order requires much more refined grid solutions, then leads to much long computation time and noise.

Code Convergence

Beam envelope



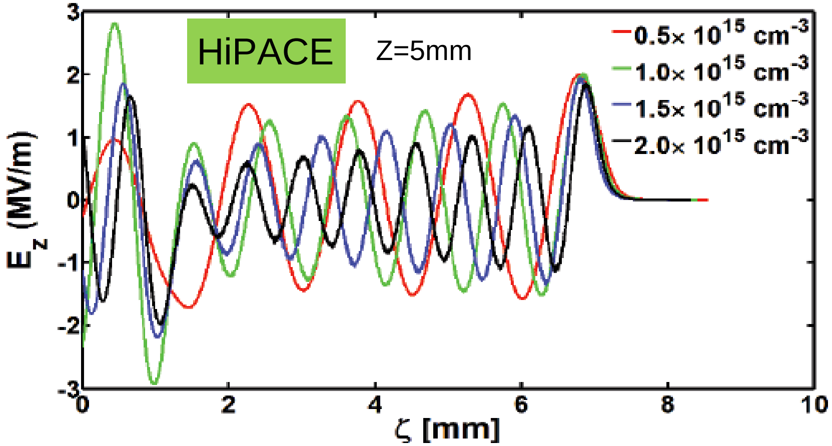
Energy Spectra at z=20mm

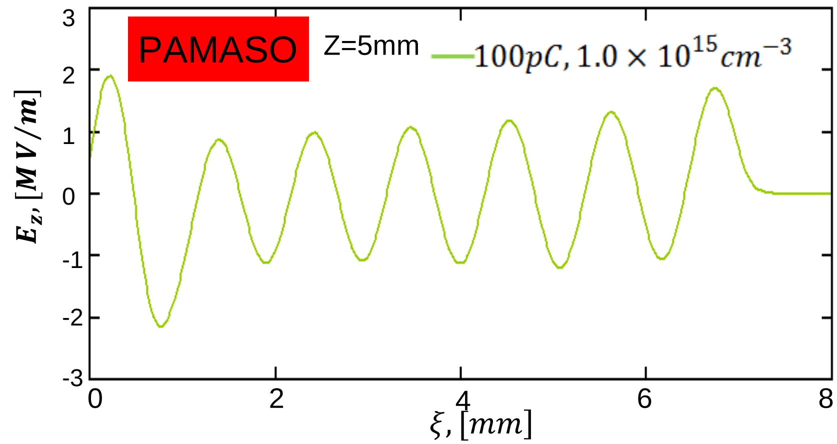


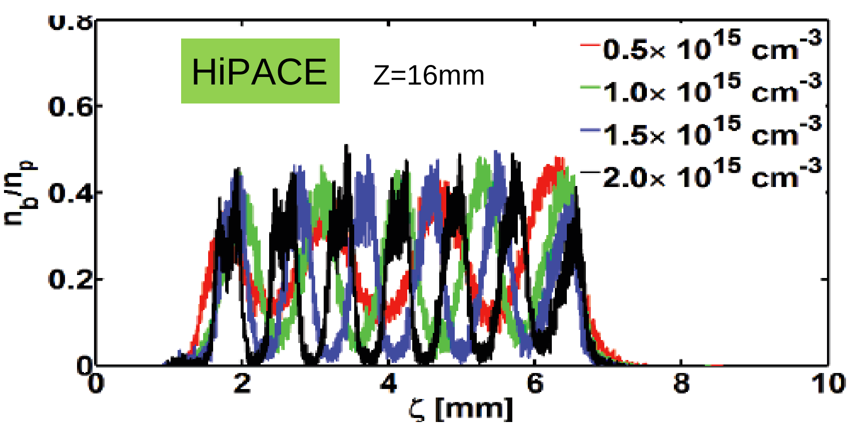
- Beam envelope evolution is more sensitive to the transverse grid size which should at least be less than 17um.
- 17um-80um grid solution is good for energy modulation.

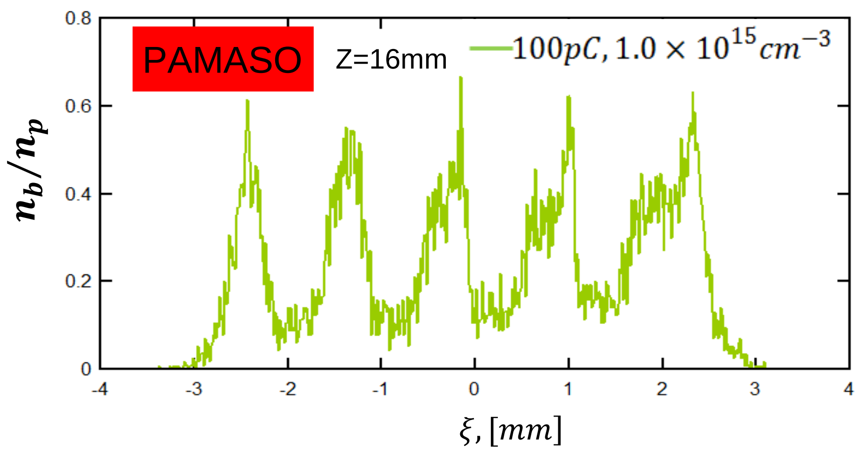
Comparison with HiPACE

- Simulation solution: grid,trans.=17um, longi.=80um,trans.rate =1.2; order=4;nppx=4; particle size, trans.=0.3, longi.=0.5. See the green curve in each picture.



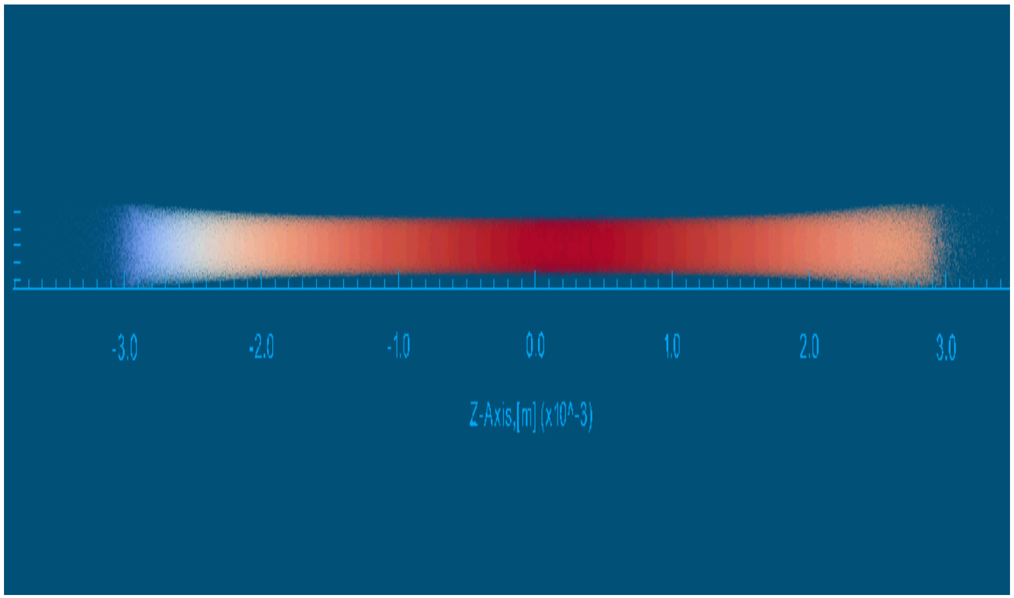






- G. Pathak, et al., WEPWA005, IPAC 2015

Transverse Compression



- The bunch is transversely comp -ressed in the early propagation stage.
- Energy modulation maintains during compression process.
- Radius modulation is mitigated during this process.

Ratio of the excited transverse potential and the kinetic energy of beam particles:

$$R_{TC} = W_f / KE_{tr} \propto m_e c^2 \frac{n_b}{n_p} \frac{\Delta\sigma_r^2}{\varepsilon^2} \frac{1}{W_b}$$

Notice, the smaller R_{TC}, the weaker compression strength.

Transverse Compression: Simulation Results

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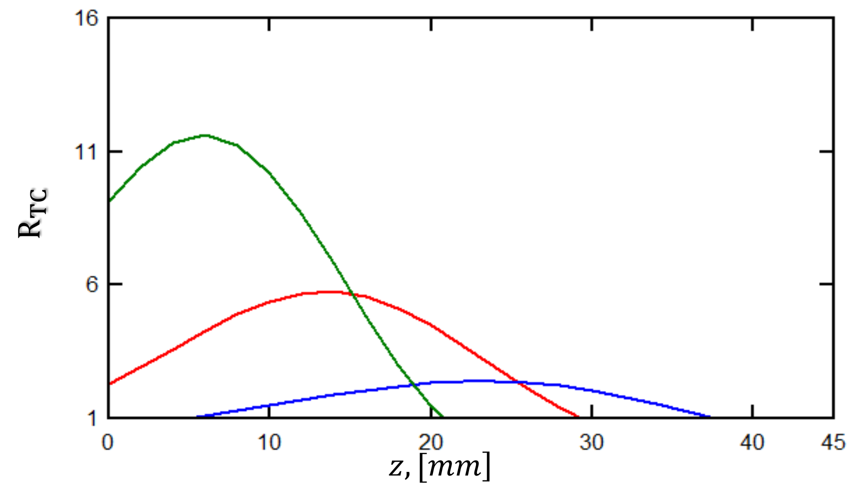
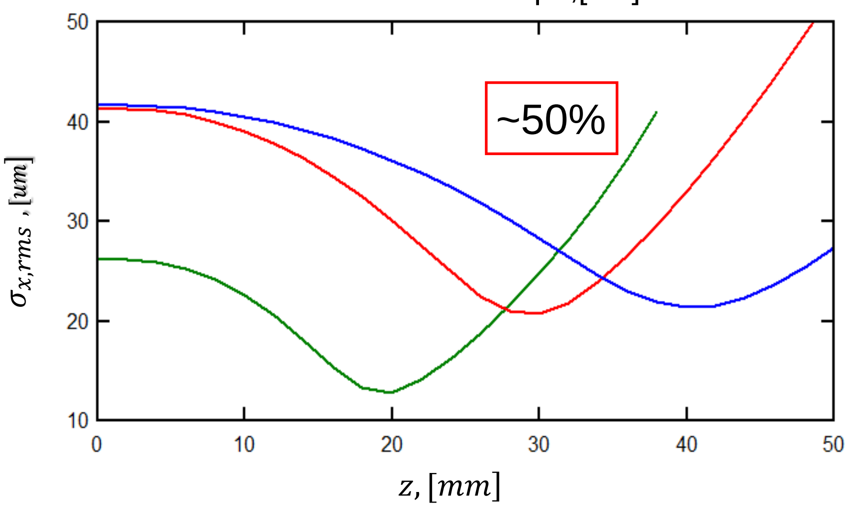
Configurations

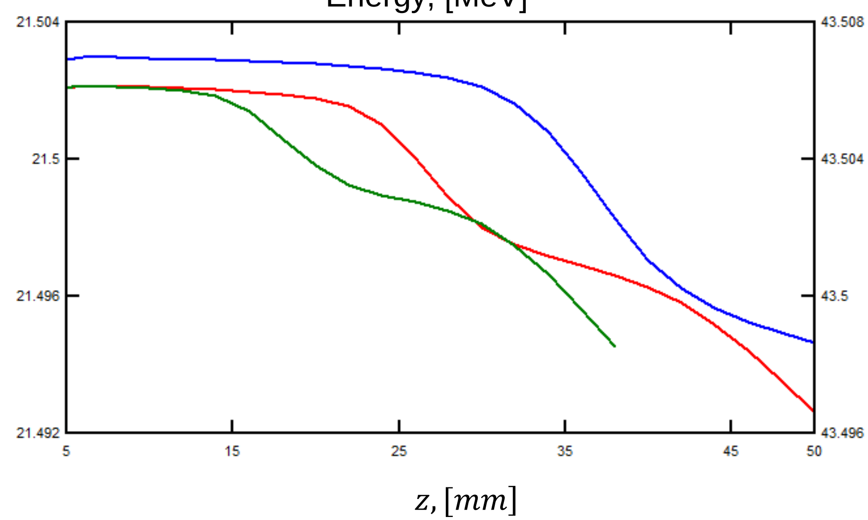
	$\sigma_x, [\mu m]$	$E, [MeV]$	Color
1	42	21.5	red
2	42	43.5	blue
3	27	21.5	green



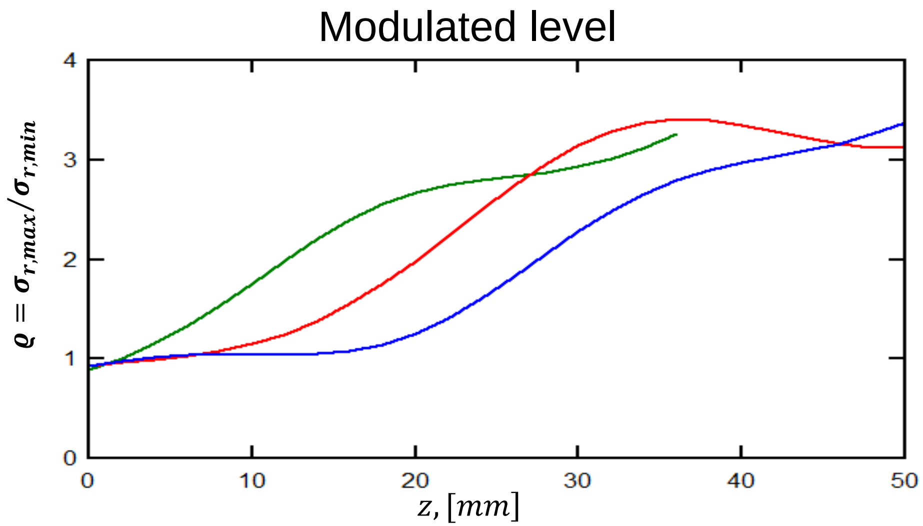
Beam envelope,[um]



Energy, [MeV]



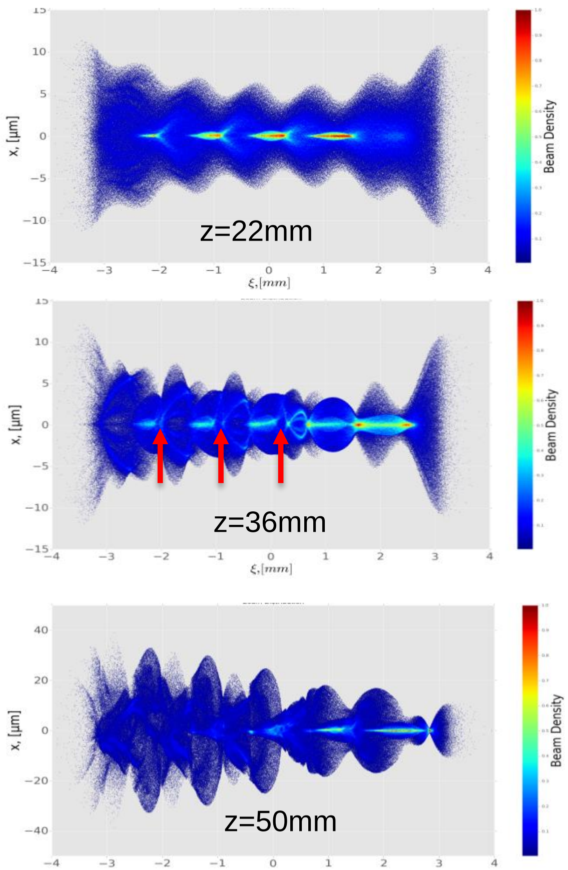
Quick Summary

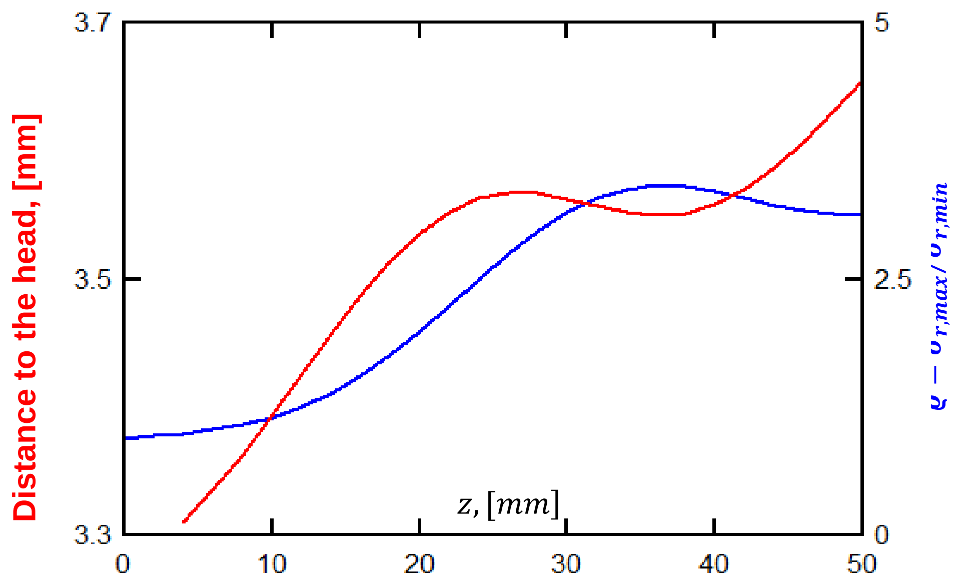


1. The transverse compression occurs in the early propagation stage, caused by the competition of transverse kinetic energy of beam particles and excited transverse potential well. The beam is compressed by 50%. That means the compression ratio is independent on the initial beam energy and transverse beam size.
2. Larger incident energy bunch has a weaker compression strength in the early stage, then a longer compression duration, and also a lower SMI grow.
3. Smaller initial transverse beam size leads to faster compression, and high SMI growth afterwards.

Macro Bunch Destruction

- Plasma wave slow down in the linear regime →Dephasing destroy the bunch train?





Red curve shows the relative position of the 4th ($\xi_0 \approx 3.3mm$) minima of on-axis E_z inside the bunch.
Blue curve shows the modulation ratio inside the bunch.

$$\beta_{ph} \approx 1 - \frac{\sqrt[3]{4}}{3\sqrt{3}\omega_p}\Gamma$$

A. Pukhov, et al., PRL 107,145003(2011)

Summary

- Simulation scheme agrees with the PITZ experiment
- The code shows good convergence with relative cheap configuration for high order.
- Simulation results for the early stage agrees well with that from HiPACE.
- Transverse compression in the early propagation stage mitigates the growth of SMI.
- Macro-bunch train destruction is observed and simulation for longer propagation will be considered.

Thank you for your attention!