HiPACE simulation with ASTRA and model beam

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13 Mar 2014

Outline

- Motivation
- Self-modulation
- HiPACE code – Input and Output
- OSIRIS and HiPACE comparison
- HiPACE simulation of ASTRA beam
- Conclusion

Motivation

A Proton driven plasma wakefield acceleration was proposed by A.Caldwell et. al. in 2009 .
Generating short proton beams is challenging. The CERN SPS bunch has length ~12cm.

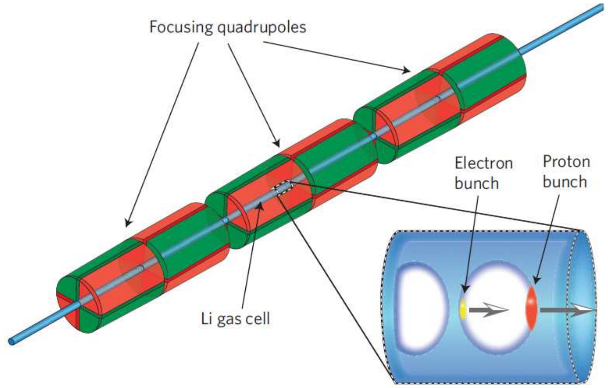
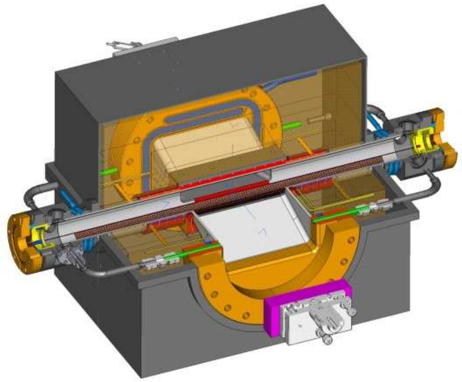


Figure 1 | A schematic description of a section of the plasma-wakefield-accelerating structure. A thin tube containing Li gas is surrounded by quadrupole magnets with alternating polarity. The magnification shows the plasma bubble created by the proton bunch (red). The electron bunch (yellow) undergoing acceleration is located at the back of the bubble. Note that the dimensions are not to scale.

To generate a short proton bunches a technique viz. self modulation is proposed by N. Kumar and A. Pukhov in 2010.
If a particle bunch travelling through plasma is long in comparison to the plasma wavelength then it can be self-modulated, splitting itself into short bunches.

Before proceeding further with proton bunches a test bed experiment with electron bunches was proposed by Schroeder and Grüner in 2011.
Because of its very favorable condition with electron beams, an 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.

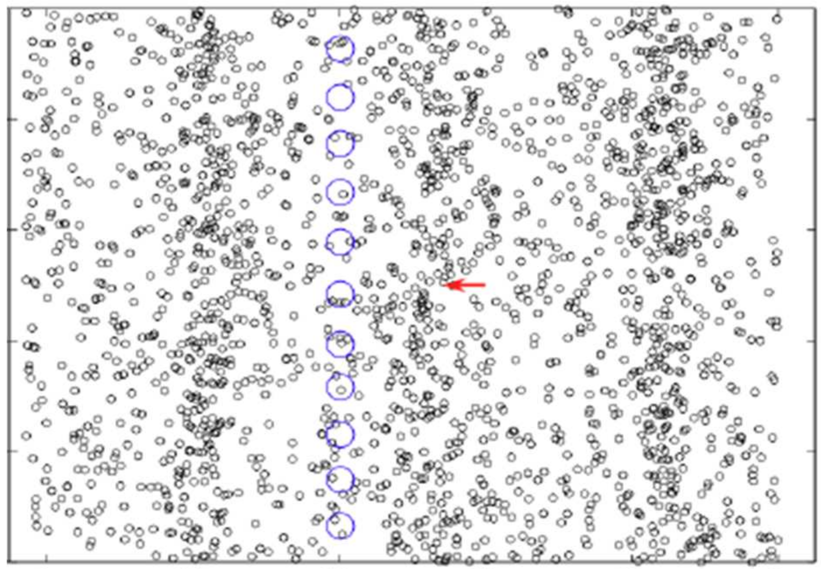


Plasma oven

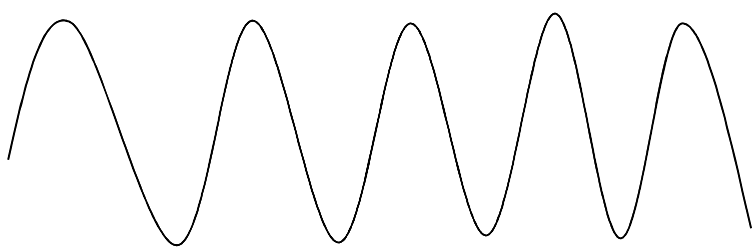
To reflect the key properties such as energy modulation in the beam via longitudinal electric field of plasma waves some simulations were required.
HiPACE simulation were performed for the case of PITZ beam and plasma.

Self-modulation

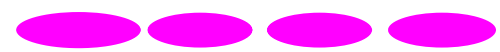
Simply speaking if a particle bunch travelling through plasma is long in comparison to the plasma wavelength then it can get self-modulated, splitting itself into short bunches.



Electron beam before passing through plasma

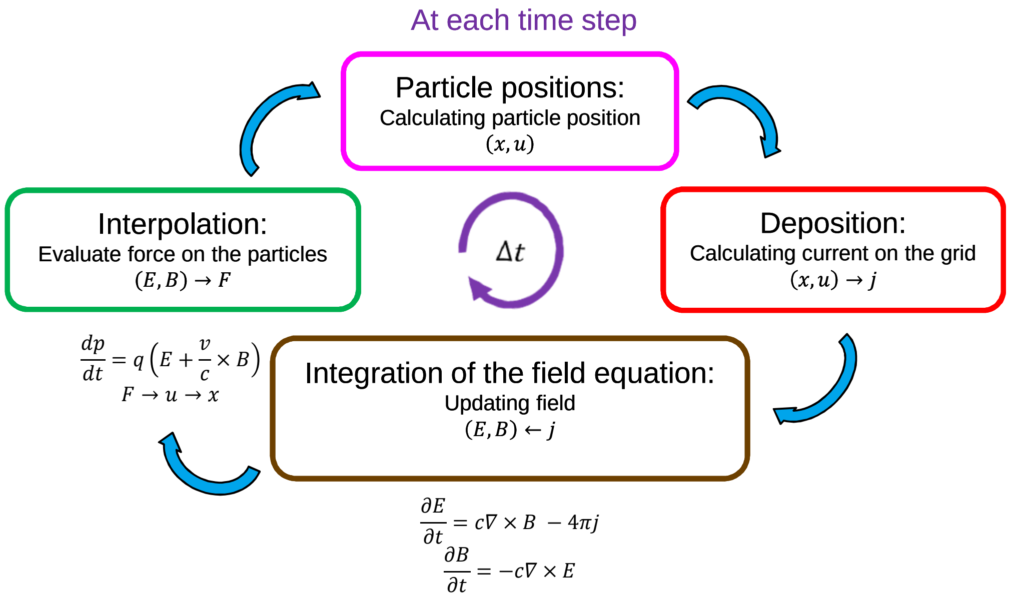


Plasma



Electron beam after passing through plasma

HiPACE - Algorithm of the code



- **Quasi-static or frozen field approximation converts Maxwell's equations into electrostatic equations**

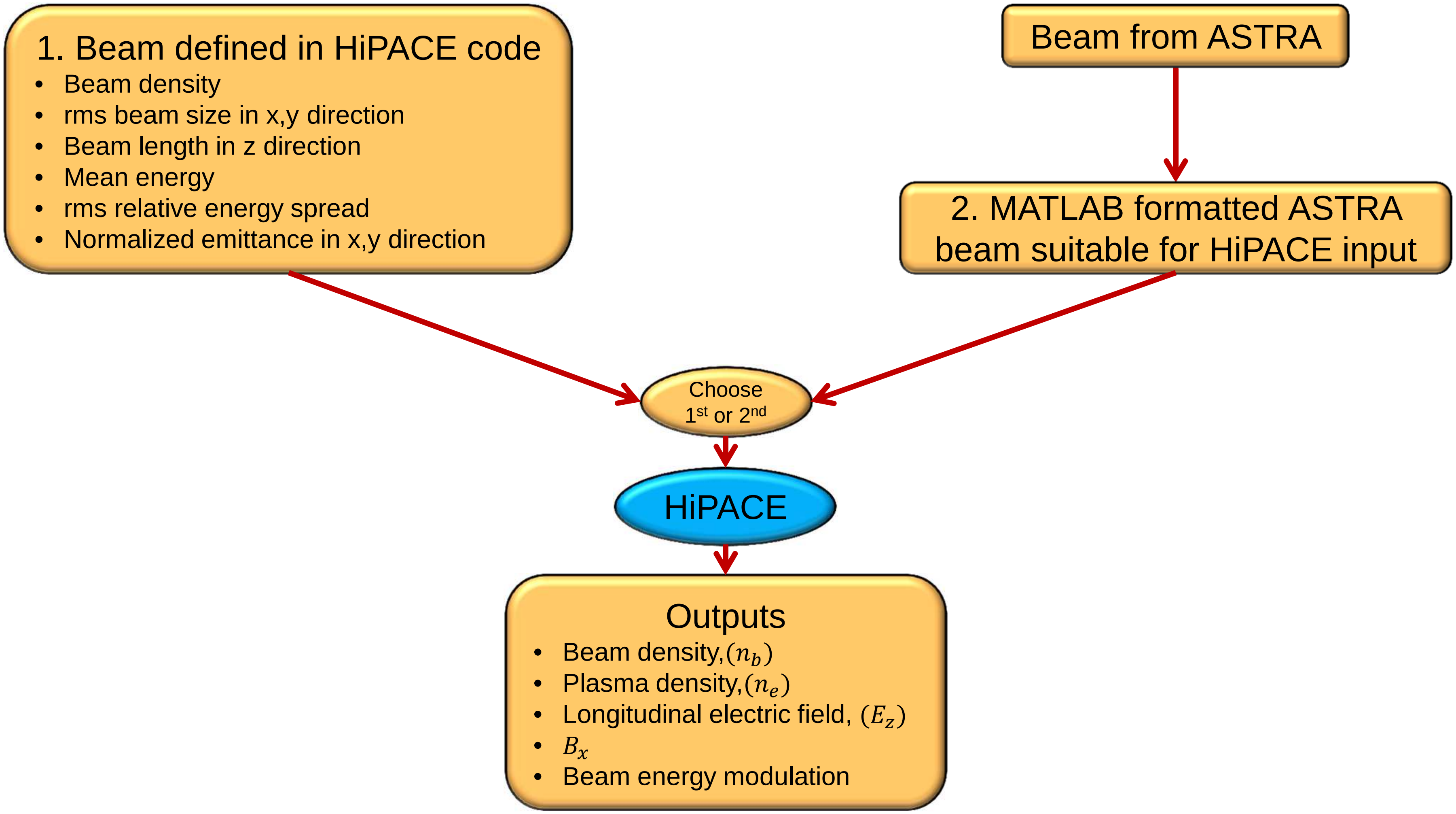
Maxwell equations in Lorentz gauge	*Transforming to co-moving frame*	*Quasi-static approximation*	*Reduced Maxwell equations*
$\left(\frac{\partial^2}{c^2\partial t^2} - \frac{\partial^2}{z^2}\right)\hat{A} = \frac{4\pi}{c} j$ $\left(\frac{\partial^2}{c^2\partial t^2} - \frac{\partial^2}{z^2}\right)\varphi = 4\pi\rho$	$\zeta = z - ct \longrightarrow \frac{\partial}{\partial t} = \left(\frac{\partial}{\partial \tau} - c\frac{\partial}{\partial \zeta}\right)$ $t = \tau \quad \frac{\partial}{\partial z} = \frac{\partial}{\partial \zeta}$	$\frac{\partial}{c\partial \tau} \ll \frac{\partial}{\partial \zeta}$ $\longrightarrow$	$-\nabla^2\hat{A} = \frac{4\pi}{c} j$ $-\nabla^2\varphi = 4\pi\rho$

❑ Solving these reduced equation saves the time.

❑ Quasi-static codes are already tested and shows good resembles with full PIC codes.*

*C.Huang et.al. doi:10.1088/1742-6596/46/1/026

HiPACE code – Input and Output



Courtesy Timon Mehrling, DESY

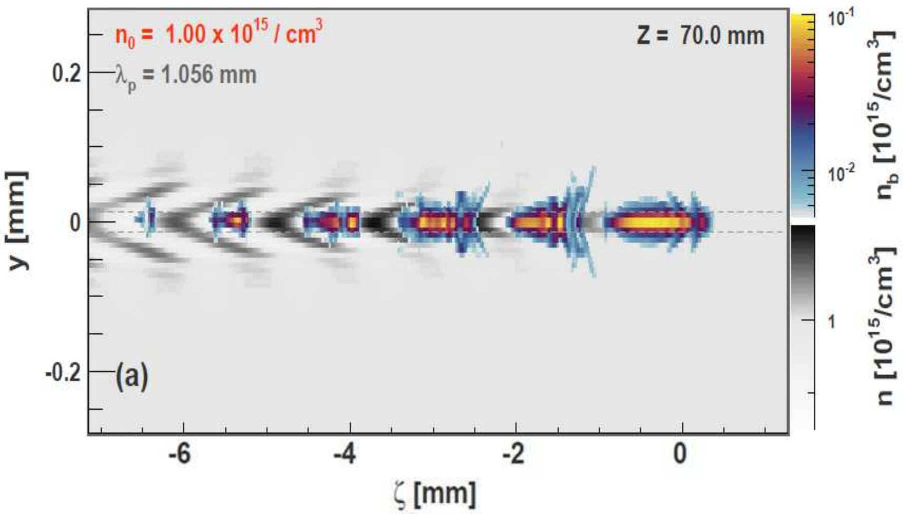
OSIRIS Beam Parameters

Beam parameters	Setup
Total charge, pC	100
Horizontal rms beam size, µm	42.0
Vertical rms beam size, µm	42.0
Bunch length in FWHM, mm	5.93
Average kinetic energy, MeV	21.5
Peak slice current, A	5.3
Horizontal rms emittance, mm mrad	0.372
Vertical rms emittance, mm mrad	0.372
Peak beam density, 10^13 e / cm^3	1.9

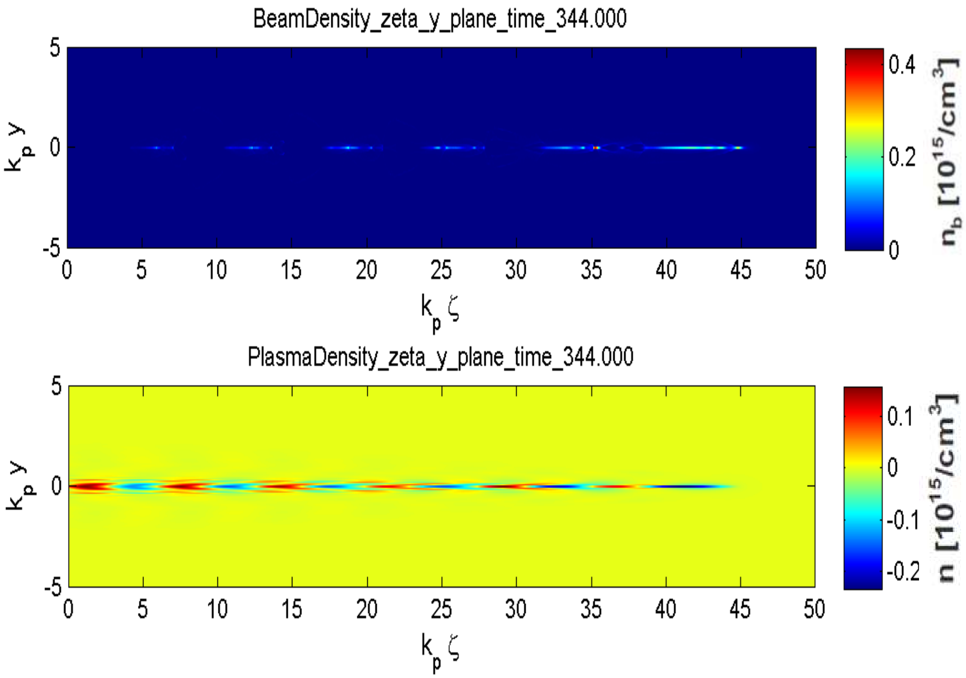
OSIRIS → SI units
HiPACE → Normalized units ($k_p\zeta$ and $^1/_{\omega_p}$)
ASTRA → SI units

Results – Beam and Plasma Density

Comparison between 3D full PIC code OSIRIS and Quasi static HiPACE code.



OSIRIS



HiPACE

Axis transformation $n_o = 10^{15} cm^{-3} \longrightarrow \lambda_p = 1mm \longrightarrow k_p = {}^{2\pi}/_{\lambda_p} = 2\pi \times 10^3 m^{-1}$

Osiris box dimension in units of $k_p\zeta$ $\quad 8(mm) = 2\pi \times 10^3 \times 8 \times 10^{-3} = 50.26 k_p\zeta$

Results - longitudinal electric field

OSIRIS

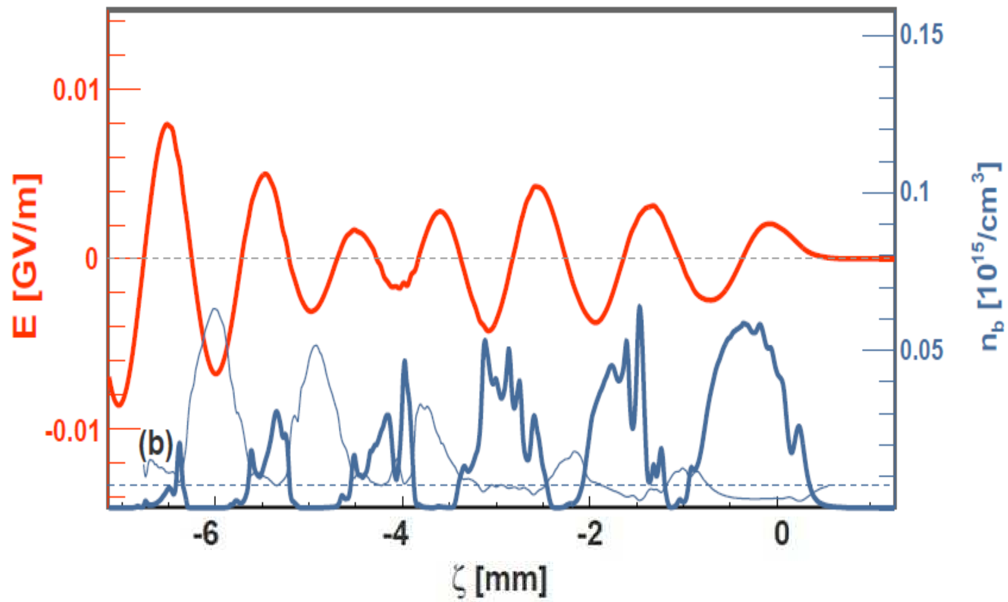


Figure 1: OSIRIS plot shows longitudinal electric field on axis (thick red line), the beam density distribution on axis (thick blue line) and the instability growth (slim blue line).

Figure 2: HiPACE plot shows normalized longitudinal electric field.

Figure 3: HiPACE plot shows normalized beam density

HiPACE

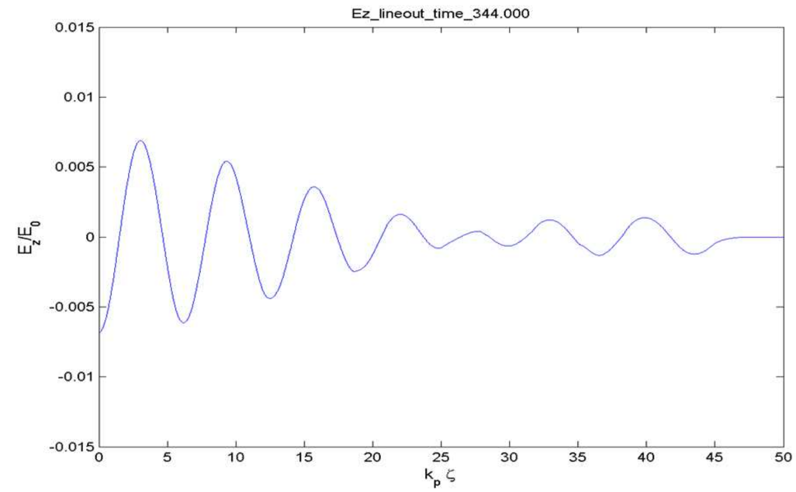


Figure 2

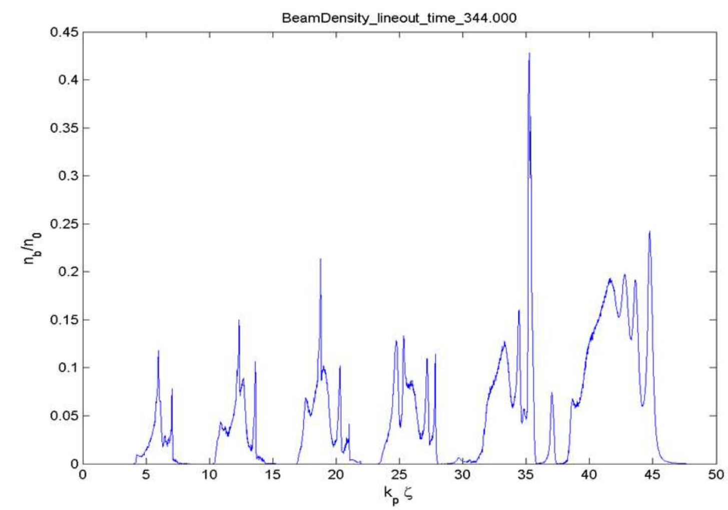


Figure 3

Results - Energy modulation

OSIRIS

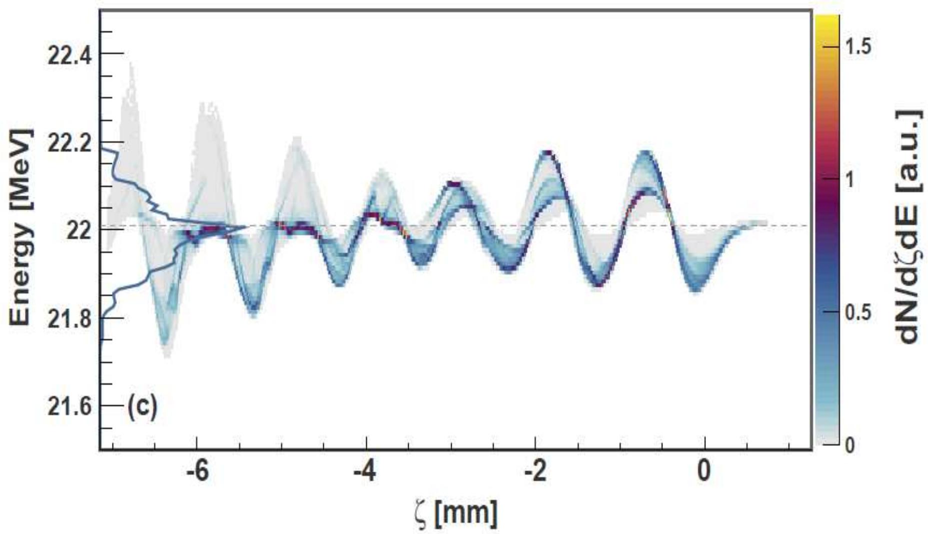


Figure 1. OSIRIS plot shows energy distribution of the beam electrons as a function of ζ.

HiPACE

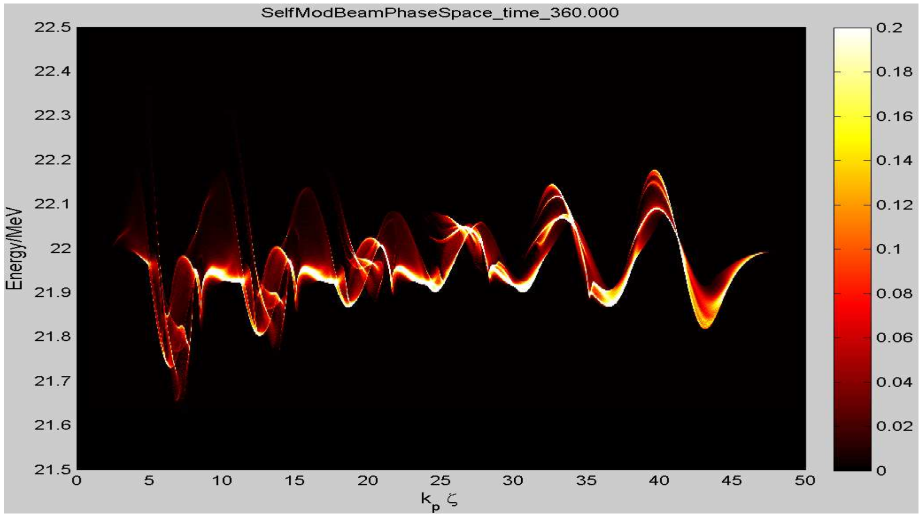


Figure 2. HiPACE plot shows energy distribution of the beam electrons as a function of $k_p\zeta$.

Initial parameters

- When loading the beam phase space from an ASTRA file to HiPACE, the aim usually is to have exactly the same 6D phase-space distribution as in the ASTRA simulation.
- However present simulation were done for zero beam energy spread.

Main Parameters	Details
Plasma Density	$10^{15} cm^{-3}$
Beam charge	0.1 nC
Beam energy spread	Defined by ASTRA
Beam length	~6mm
Plasma length	60mm

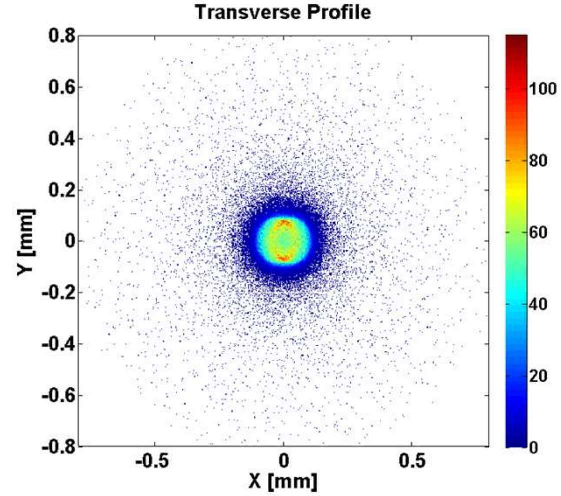
(Plasma Density) → $\lambda_p = 1mm$

- The other parameters (like Beam density, rms beam size in x,y direction, beam length etc.) are also imported from the ASTRA file.

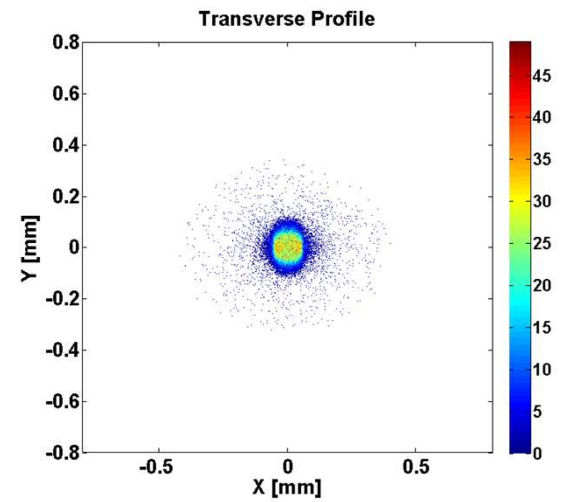
Beam Parameters

Two simulation were performed to see the effect of different beam size.

Beam parameters	Setup (1)	Setup (2)
Total charge, pC	100	100
X rms beam size, µm	75.0	47.0
Y rms beam size, µm	79.0	47.0
Z rms, mm	1.7	1.7
Average Momentum, MeV/c	22.0	22.0
Momentum Spread, keV/c	24.45	24.96
ϵ_x, mm mrad	0.352	0.366
ϵ_y, mm mrad	0.352	0.379
Number of particles	200,000	200,000



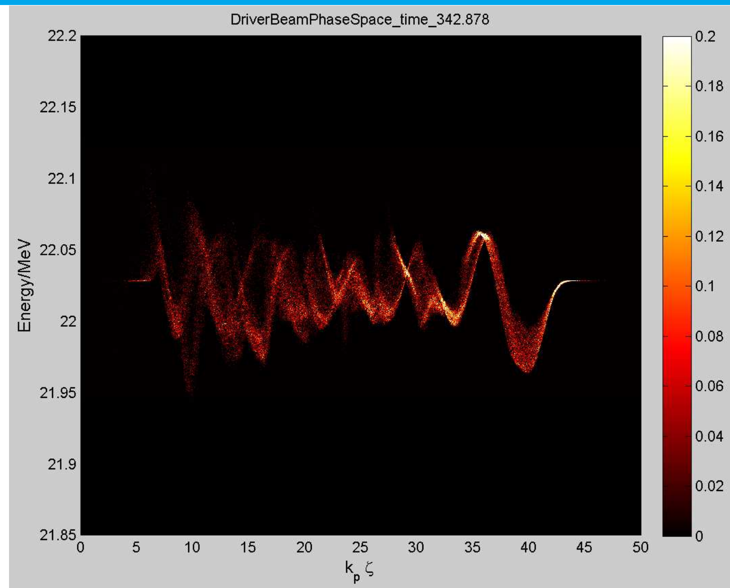
(1)

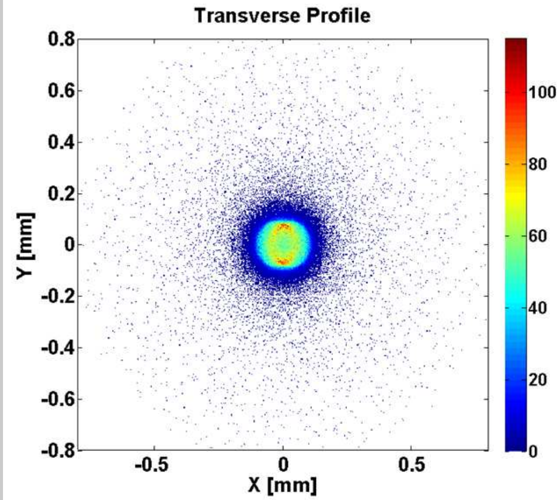


(2)

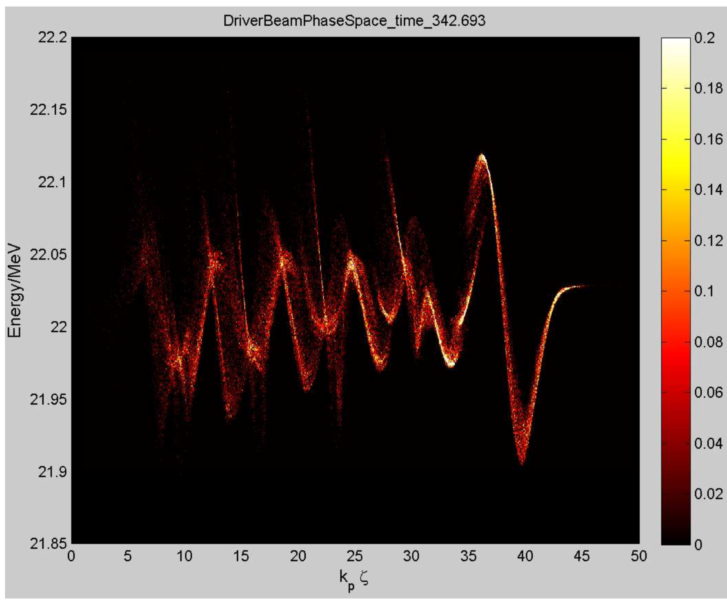
Results - Energy modulation

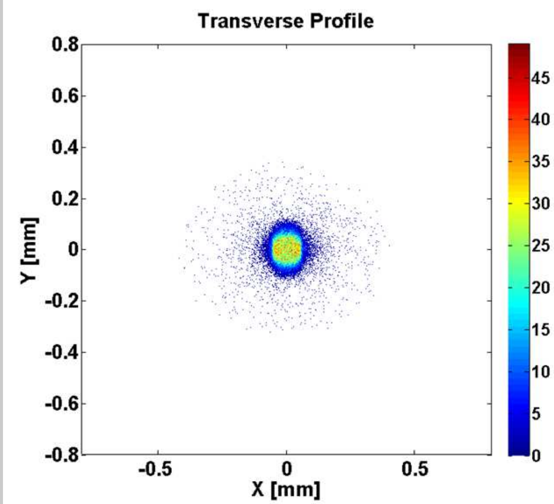
(1)





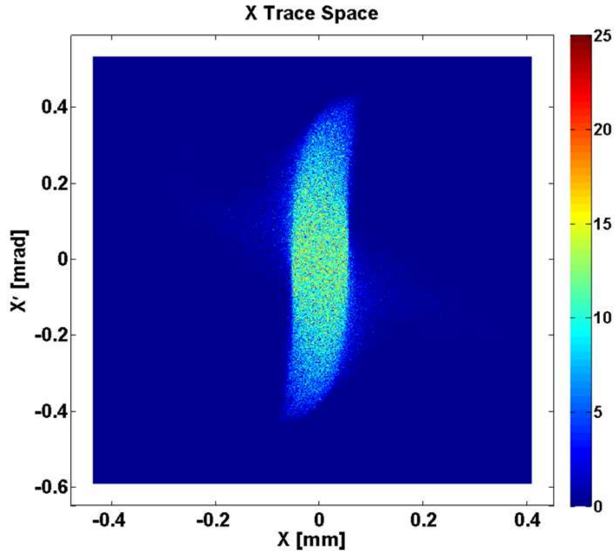
(2)

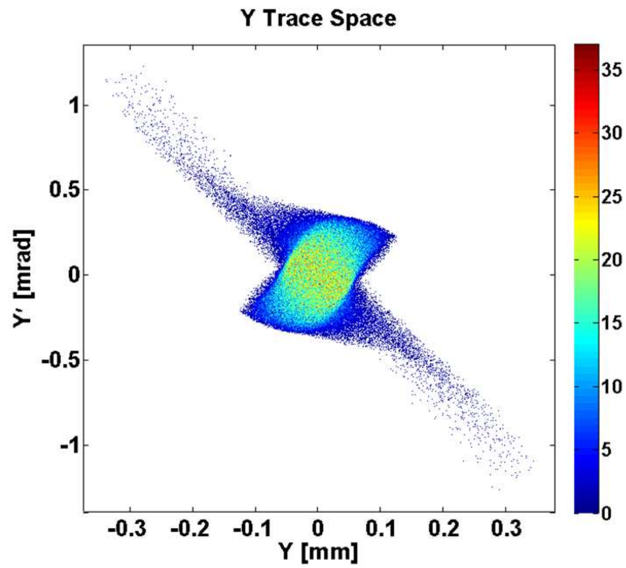


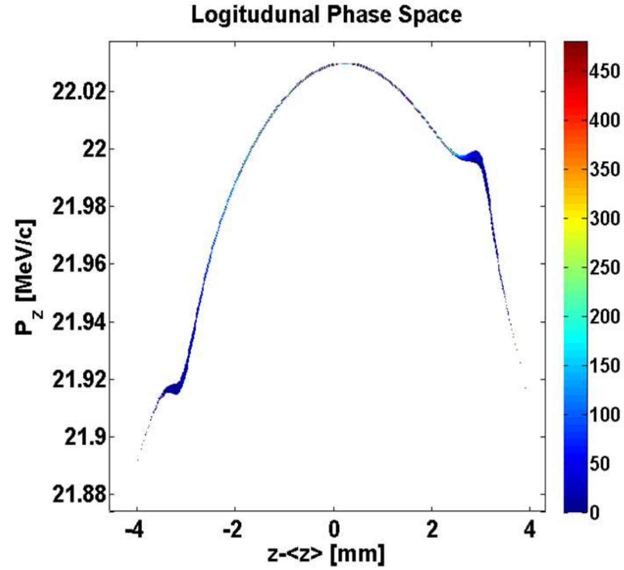


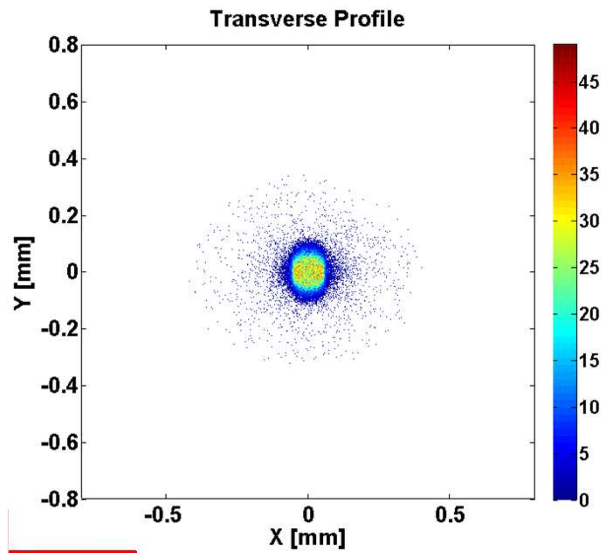
Parameters of Setup (2)

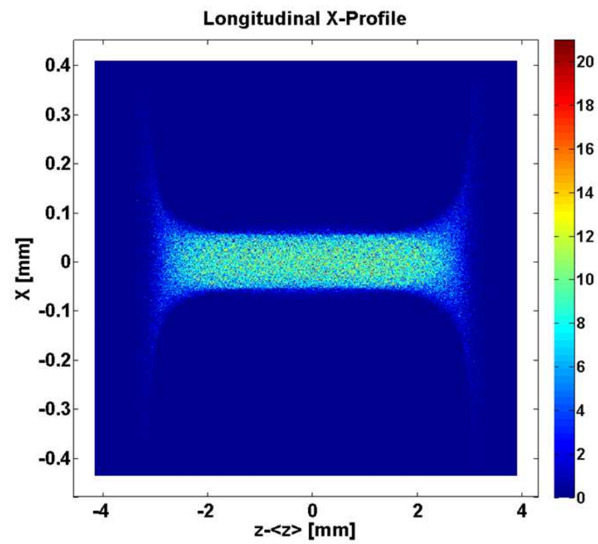
ASTRA Input

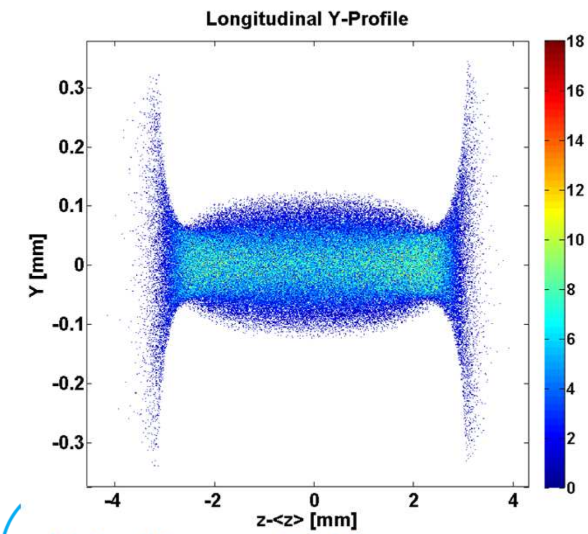




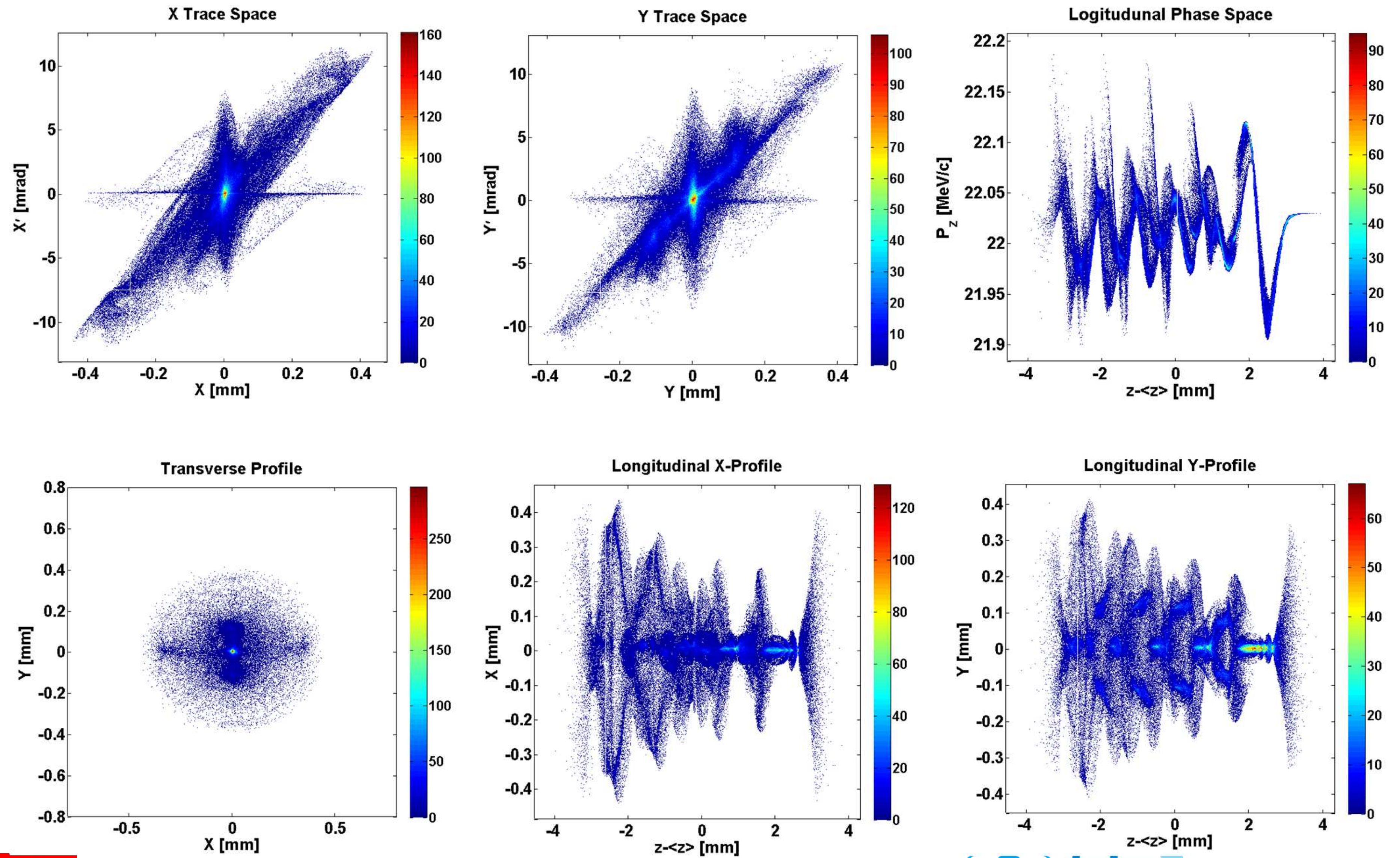








Results - HiPACE to ASTRA Beam Transport



Conclusion

- Beams can be initialized in HiPACE before or in the plasma from results of tracking codes (ASTRA) or full PIC codes (e.g. OSIRIS).
- The output from HiPACE shows quit resemblance with OSIRIS.
- Energy modulation in HiPACE shows good resemblance with previous simulations of full PIC code OSIRIS.
- However, energy modulation observed with ASTRA is almost half the modulation observed in OSIRIS.
- Decreasing the beam size shows large modulation in beam energy.
- Increment of beam charge and number of particles may increase the longitudinal electric field and energy modulation.

Difficulties

- Simulation run time is suspicious.
- Decreasing the number of particles in model beam produces noisy output.

Thank you