Numerical Models for the Investigation of Charged Particle Motion

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Content

- Motivation
- Symplectic Integrator
- Space-charge (PIC)
- Collective phenomena

Motivation

- Tracking Programs – 6D
  - paraxial Approximation
  - higher order maps
  - time integration – example

- PIC-Methods -> efficiency, parallelism
- Binary collisions -> plasma simulations
- Secondary particles -> electron clouds

Particle motion

- Particle motion – time evolution

$$\dot{z} = \{z, H\}$$

$$\{f, g\} = \sum_{i=1}^{N} \left[\frac{\partial f}{\partial q_i} \frac{\partial g}{\partial p_i} - \frac{\partial f}{\partial p_i} \frac{\partial g}{\partial q_i} \right]$$

- Formal

$$\dot{z} = D_H z$$

$$z(\tau) = \exp(\tau \cdot D_H) \cdot z(0)$$

- Conservation of two-form(bilinear form) $dp \wedge dq$

= symplectomorphismus (isomorphismus of Symplectic manifolds)

Numerical

- Formal

$$\dot{z} = D_H z$$

Looking for numerical scheme (operator D_H , symplectic integrator that also conserves two-form) => matrix

$$M^T \Omega M = \Omega$$

$$\Omega = \begin{bmatrix} 0 & I_n \\ -I_n & 0 \end{bmatrix}$$

- Example

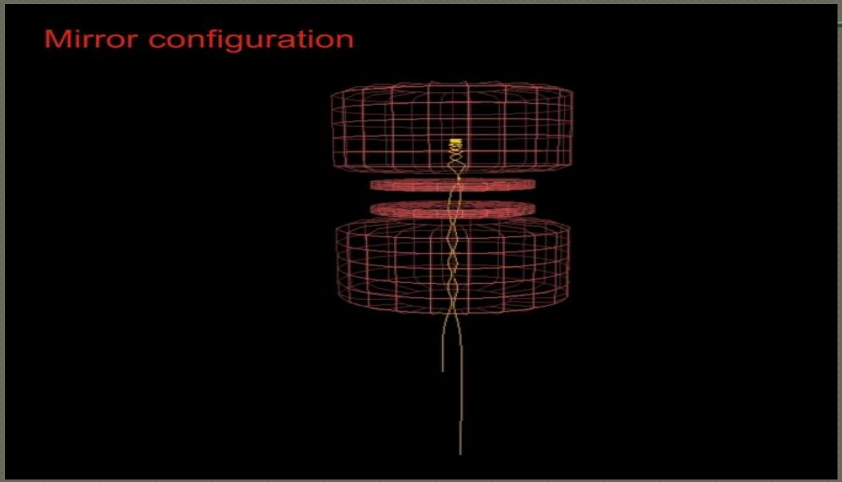
$$H(p,q) = T(p) + V(q)$$

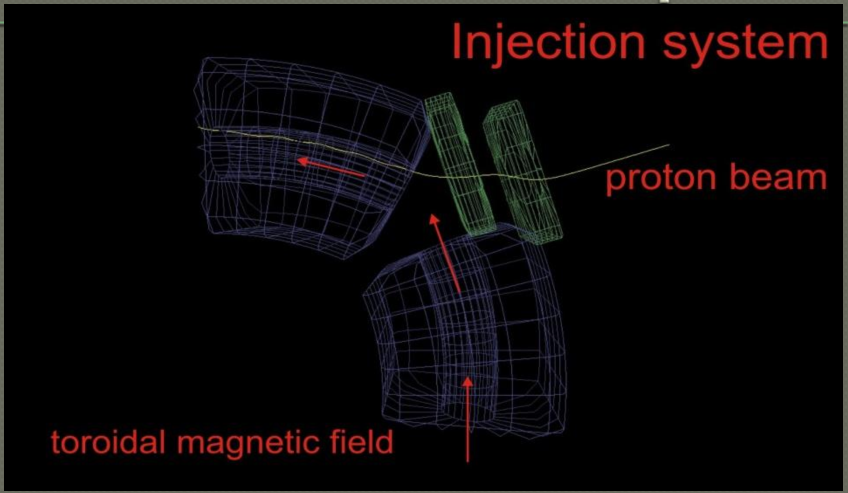
$$\frac{\vec{p}^{\,i+1} - \vec{p}^{\,i}}{dt} = qE^i + q\frac{\vec{p}^{\,i} + \vec{p}^{\,i+1}}{2m} \times B^i$$

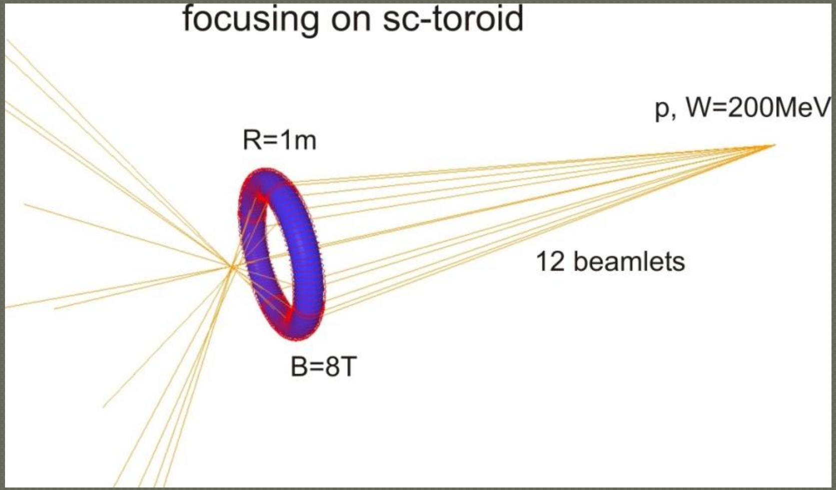
$$\frac{\vec{q}^{\,i+1} - \vec{q}^{\,i}}{dt} = \frac{\vec{p}^{\,i+1} + \vec{p}^{\,i}}{2m}$$

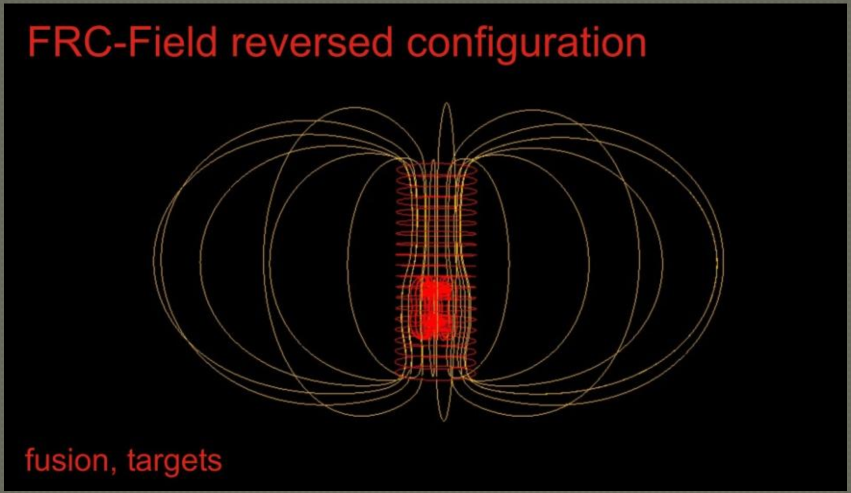
- Explicit and Implicit schemes

Examples

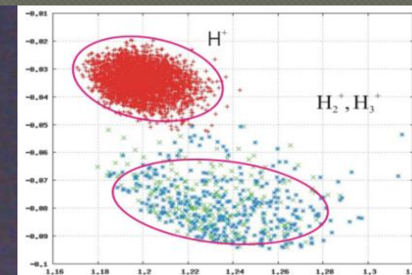

Mirror configuration


Injection system
proton beam
toroidal magnetic field

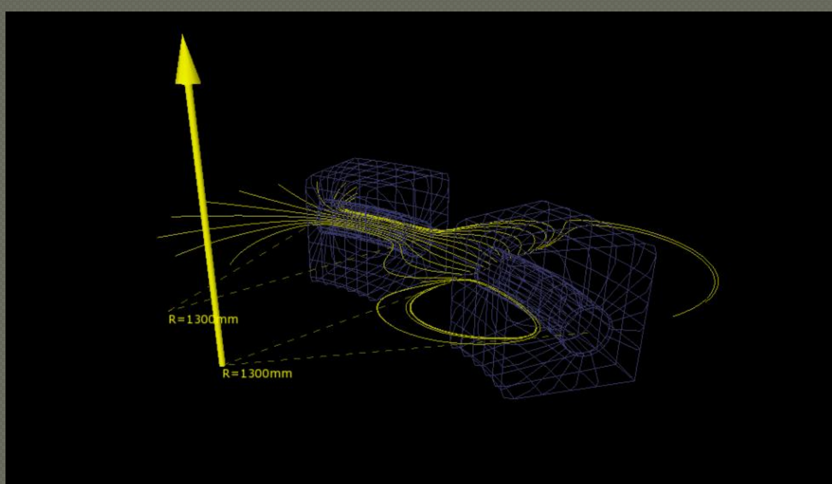

focusing on sc-toroid
p, W=200MeV
R=1m
12 beamlets
B=8T

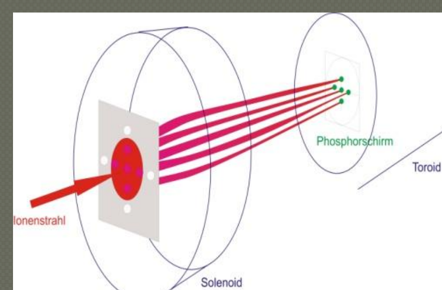

FRC-Field reversed configuration
fusion, targets

Toroidal beam transport



- Low energy (10keV) composited ion beam
- The separation between species due to curvature drift possible over long path length
- Separation due to phase difference in Larmor gyration

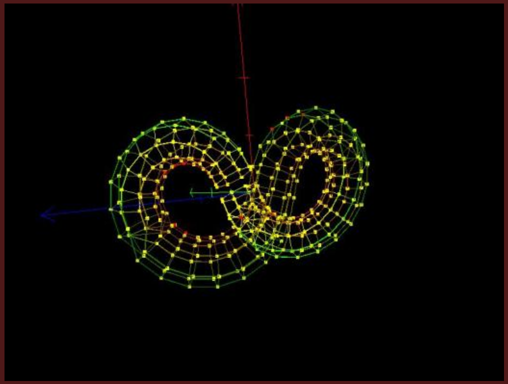




Collective phenomena

- Multispecies – Beam collimation
- Secondary electrons – -> electron clouds
- Two stream instability
- NNP
- Beam plasma interaction

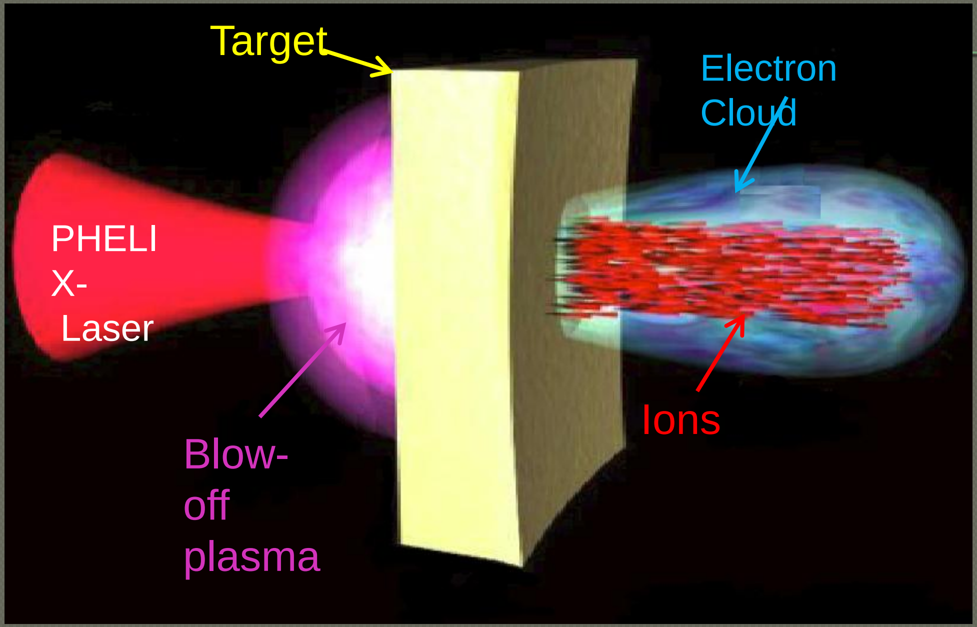
- Particle in cell Method

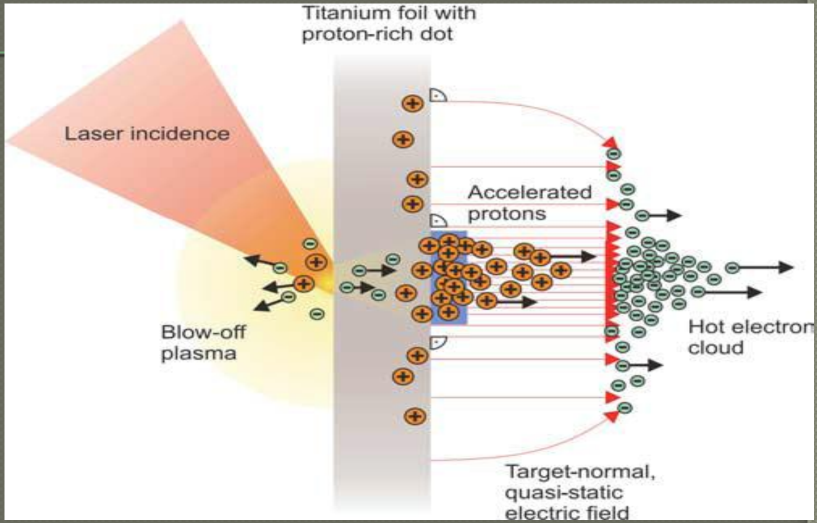


- Important

  - computation step dt
  - mesh size

Project LIGHT



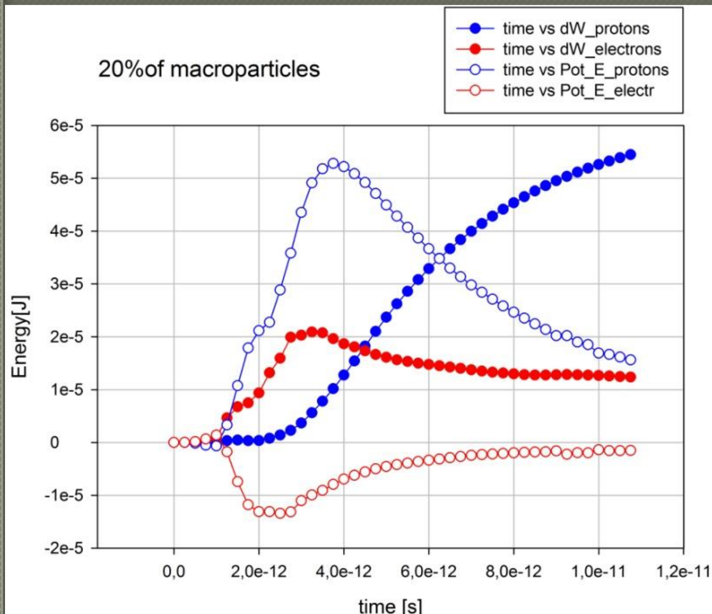


H. Schwoerer et al., Nature **439**, 26.

Target Normal Sheath Acceleration (TNSA)

-Focusing (Pulsed Solenoid ~ 18T)
-Injection and Post-acceleration in CH-Structure

Simulation – Protons&Electrons



dt=25fs

R=30μm, L=22μm

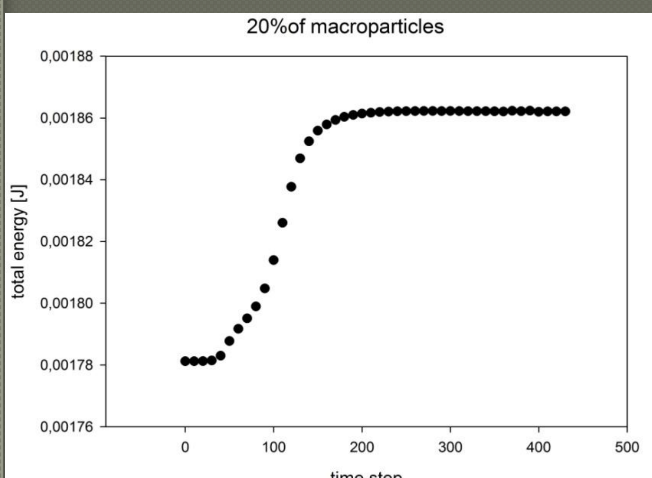
Protons W=10MeV

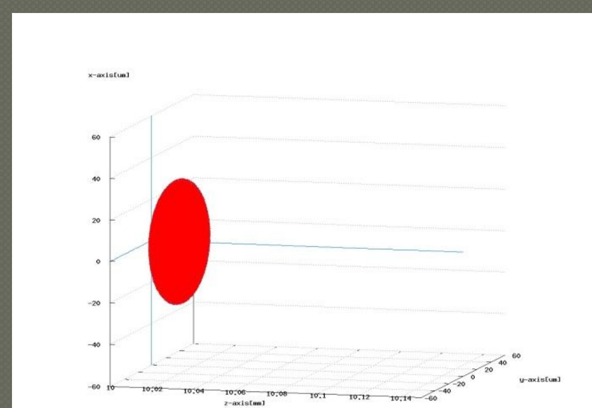
Electrons W=5.5keV

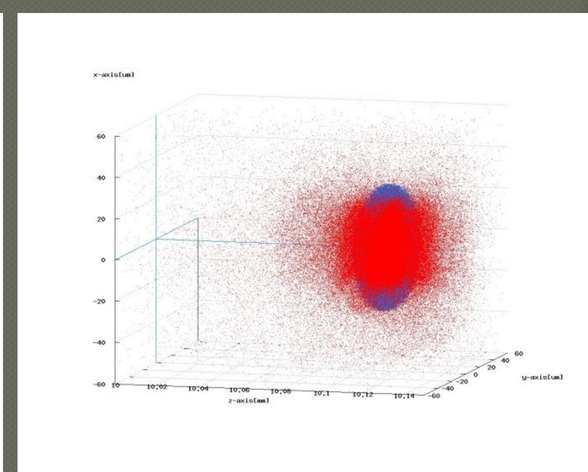
Particles/1 Macroparticle=4444 =>4.5Mio Macroparticles

Mesh:

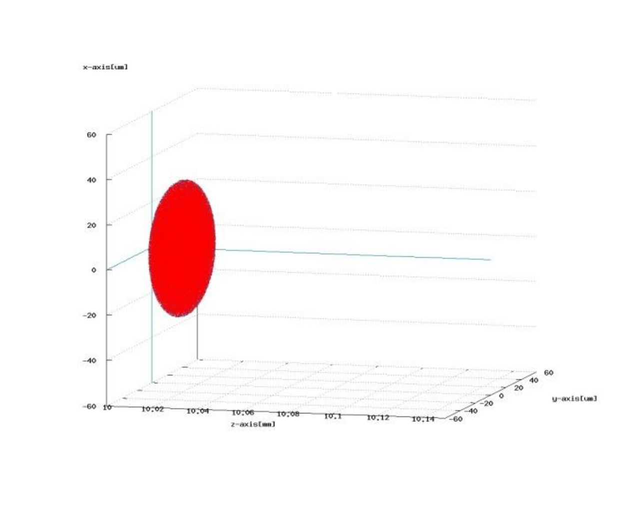
- dr=6μm
- dφ=0.2rad
- dz=2μm

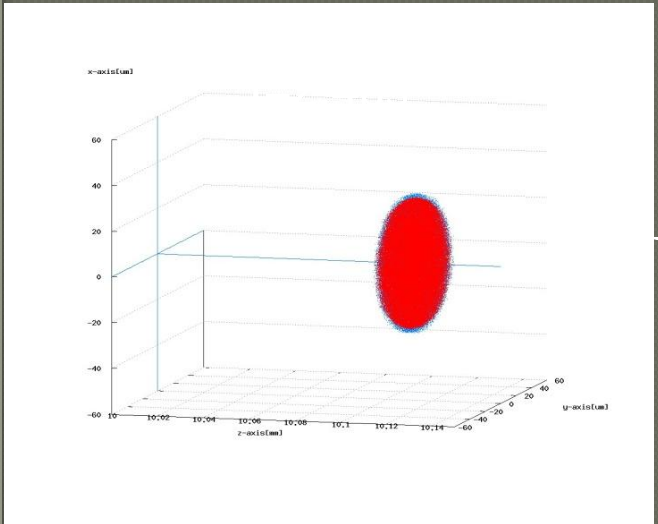






Simulation - Improvements





dt=5fs

R=30μm, L=22μm

Protons W=10MeV

Electrons W=5.5keV

Particles/1 Macroparticle=4444 =>4.5Mio Macroparticles

Mesh:

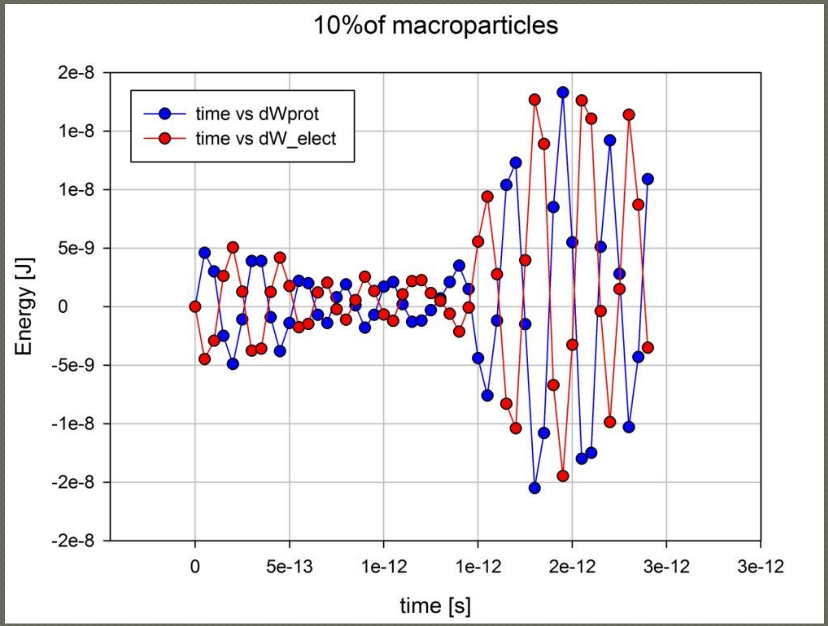
- dr=6μm
- dϕ=0.2rad
- dz=2μm

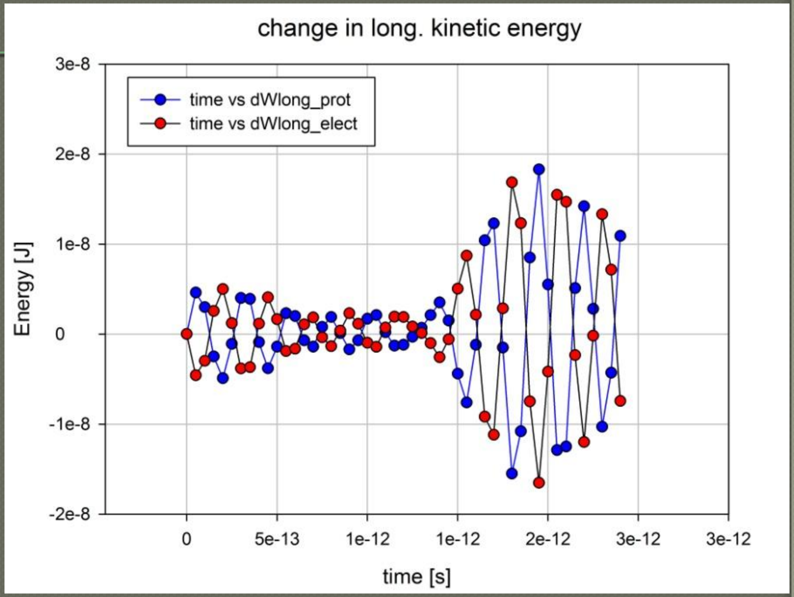
Less separation

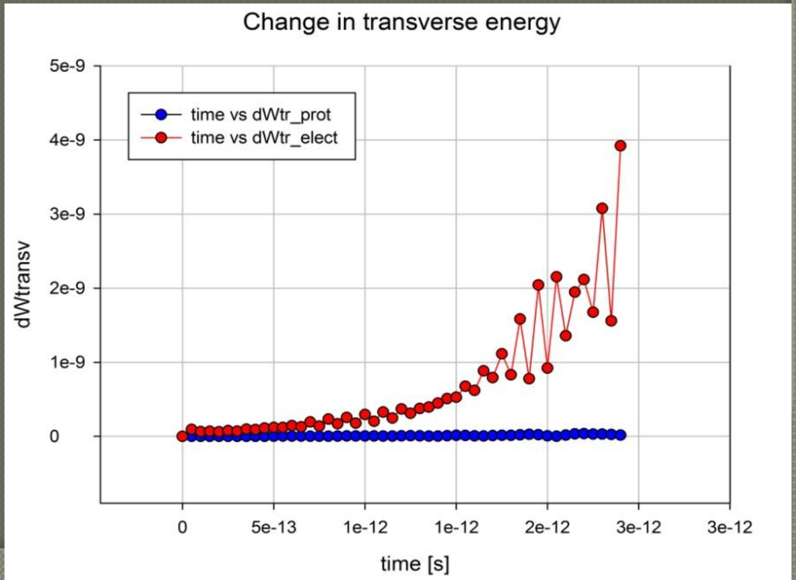
Lower electric fields and potential

LASIN – Kinetic Energy

Plasma oscillation longitudinally
Along magnetic field







Due to the higher magnetic field in propagation direction
Redistribution of longitudinal momentum
To the transverse direction

LASIN - Energy

Ratio – variation of total energy/energy (~ 1e-5 @ 3ps)

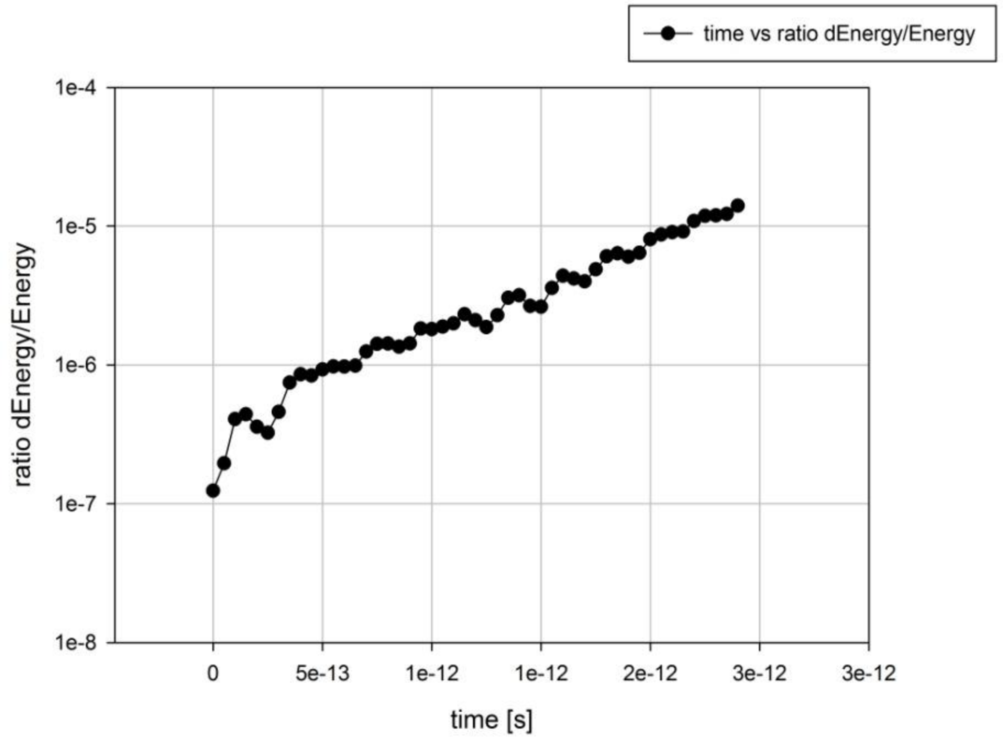
-Less comparing with previous case 6%
-Due to the variation of magnetic field ?

-Using different type of integrators

-Longer simulation needed

-Cyclotron frequency ->characteristic time τ_c=6e-12s
-Plasma frequency -> characteristic time τ= 3.5e-13s

-Debye length λ_D=0.2μm



New strategy -> finer mesh
dual mesh

Outlook

- Dynamic in strong magnetic field (Solenoids, Toroids & Fringing fields+ magnetic coupling)
- Collective phenomena (Gabor Lens, electrons&ions)
- Correction coils
- Space-charge effects & Aberrations
- Experience -> Development of efficient simulation and design tools for Accelerators