# Proton Driven Plasma Wakefield Accelerator

FNAL 27-10-2009

# Lasers: Centimeters instead of Kilometers ?

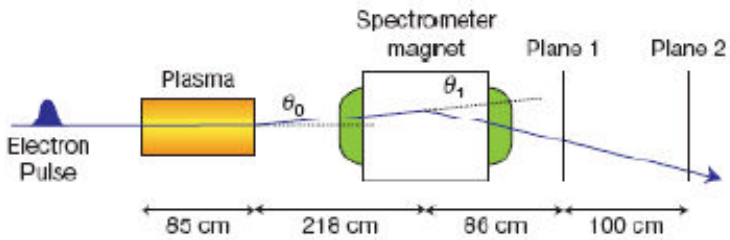
If we take a Petawatt laser pulse, $I=10^{21}$ W/cm$^2$
then the electric field is as high as $E=10^{14}$ eV/m=100 TeV/m

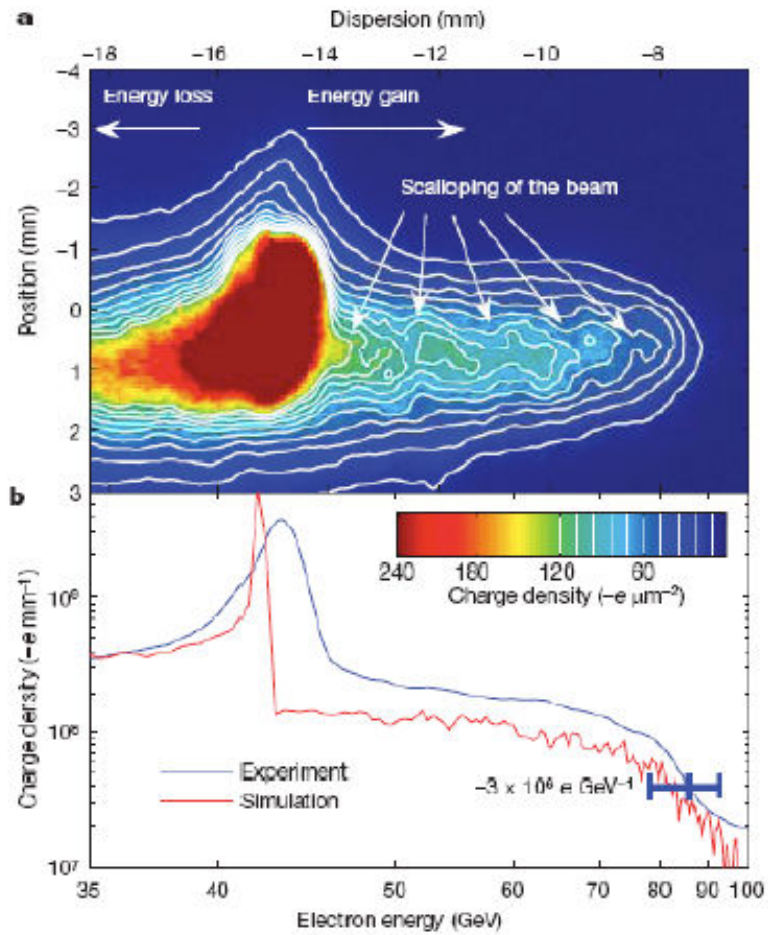
Unfortunately, it is not possible to use these fields directly since the fields are transverse and oscillating

Solution:
Use the laser to excite a plasma wave. The plasma wave can then produce strong longitudinal electric fields; i.e., the plasma acts as a transformer.
*T. Tajima and J.M. Dawson, Phys. Rev. Lett. 43 (4) (1979) 267-270.*

But – Acceleration is *DEPLETION-LIMITED*
i.e., the lasers do not have enough energy to accelerate a bunch of particles to very high energies

# Highlight: latest SLAC/UCLA/USC results
(Nature 2007)




SLAC beam
- 42 GeV
- 3 nC @ 10 Hz
- focused to 10 μm spot size
- compressed to 50 fs

- Some electrons double their energy: from 42 to > 80 GeV
- E=50 GV/m over 0.8 meters

Jérôme Faure

Transformer ratio limits maximum energy gain of trailing bunch (E field is slowing down drive bunch while accelerating trailing bunch)

$$R = \frac{E_{\max}^{\text{trail}}}{E_{\max}^{\text{drive}}} \leq 2 - \frac{N_{\text{trail}}}{N_{\text{drive}}}$$

See e.g. SLAC-PUB-3374, R.D. Ruth et al.

(for longitudinally symmetric bunches).

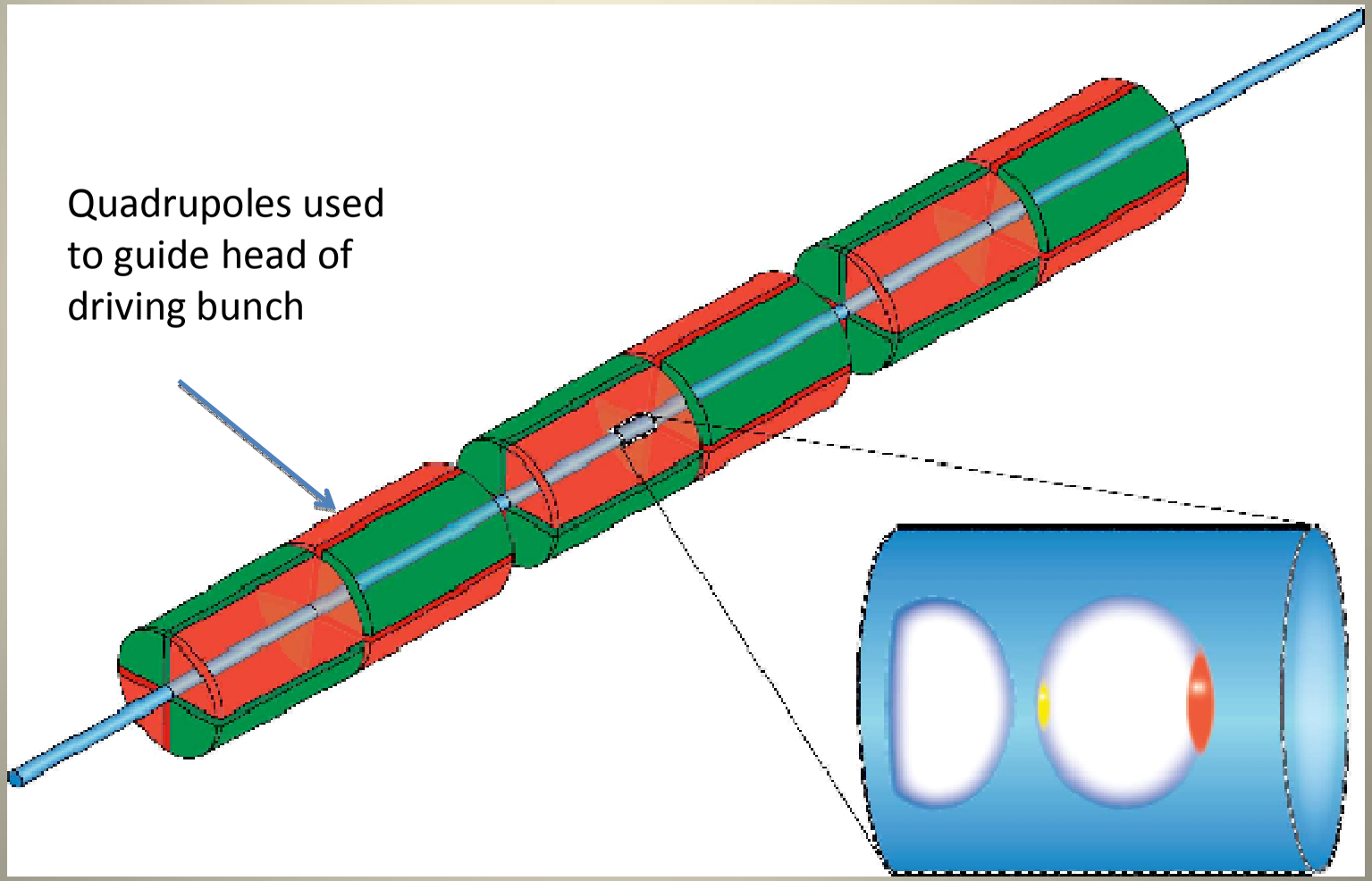
Here E is electric field strength

This means many stages required to produce a 1TeV electron beam from known electron beams (SLAC has 45 GeV)

**Proton beams of 1TeV exist today - so, why not drive plasma with a proton beam ?**

# Simulation study

Allen Caldwell, Konstantin Lotov, Alexander Pukhov, Frank Simon *Nature Physics* ***5, 363 - 367 (2009)***



Issues with a Proton Driven PWA:

- Small beam dimensions required

Can such small beams be achieved with protons ? Typical proton bunches in high energy accelerators have rms length >20 cm

- Phase slippage because protons heavy (move more slowly than electrons)

Few hundred meters possible but depends on plasma wavelength

Issues with a Proton Driven PWA continued:

- Longitudinal growth of driving bunch due to energy spread

Large momentum spread is allowed !

Issues - continued

- Proton interactions

Only small fraction of protons will interact in plasma cell

Biggest issue identified so far is proton bunch length.

Need large energies to avoid phase slippage because protons are heavy.

Large momentum spread is allowed.

# Simulation

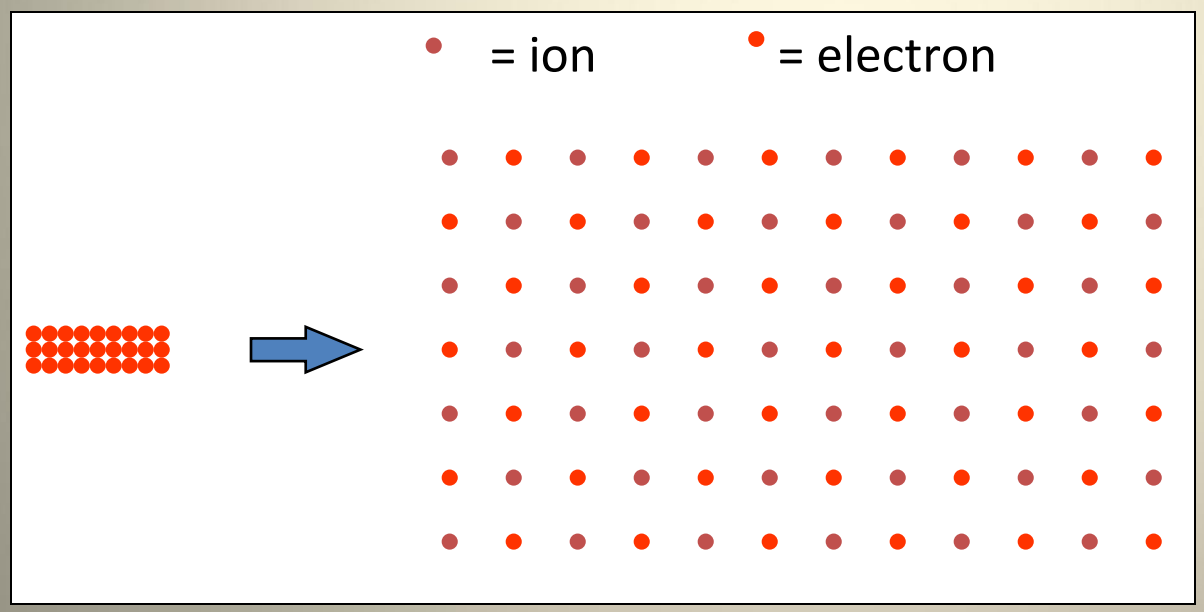
Table 1: Table of parameters for the simulation.

| Parameter | Symbol | Value | Units |
|---|---|---|---|
| Protons in Drive Bunch | $N_p$ | $10^{11}$ | |
| Proton energy | $E_p$ | 1 | TeV |
| Initial Proton momentum spread | $\sigma_{p,i}$ | 0.1 | |
| Initial Proton longitudinal spread | $\sigma_z$ | 100 | mm |
| Initial Proton bunch angular spread | $\sigma_\theta$ | 0.03 | mrad |
| Initial Proton bunch transverse size | $\sigma_{x,y}$ | 0.1 | mm |
| Electrons injected in witness bunch | $N_e$ | $1.0 \times 10^{10}$ | |
| Energy of electrons in witness bunch | $E_e$ | 10 | GeV |
| free electron density | $n_p$ | $6 \times 10^{14}$ | $cm^{-3}$ |
| Plasma wavelength | $\lambda_p$ | 2.37 | mm |
| Magnetic field gradient | | 1000 | T/m |
| Magnet length | | 0.7 | m |

# (Electron) Beam Driven Plasma Wakefield Acceleration

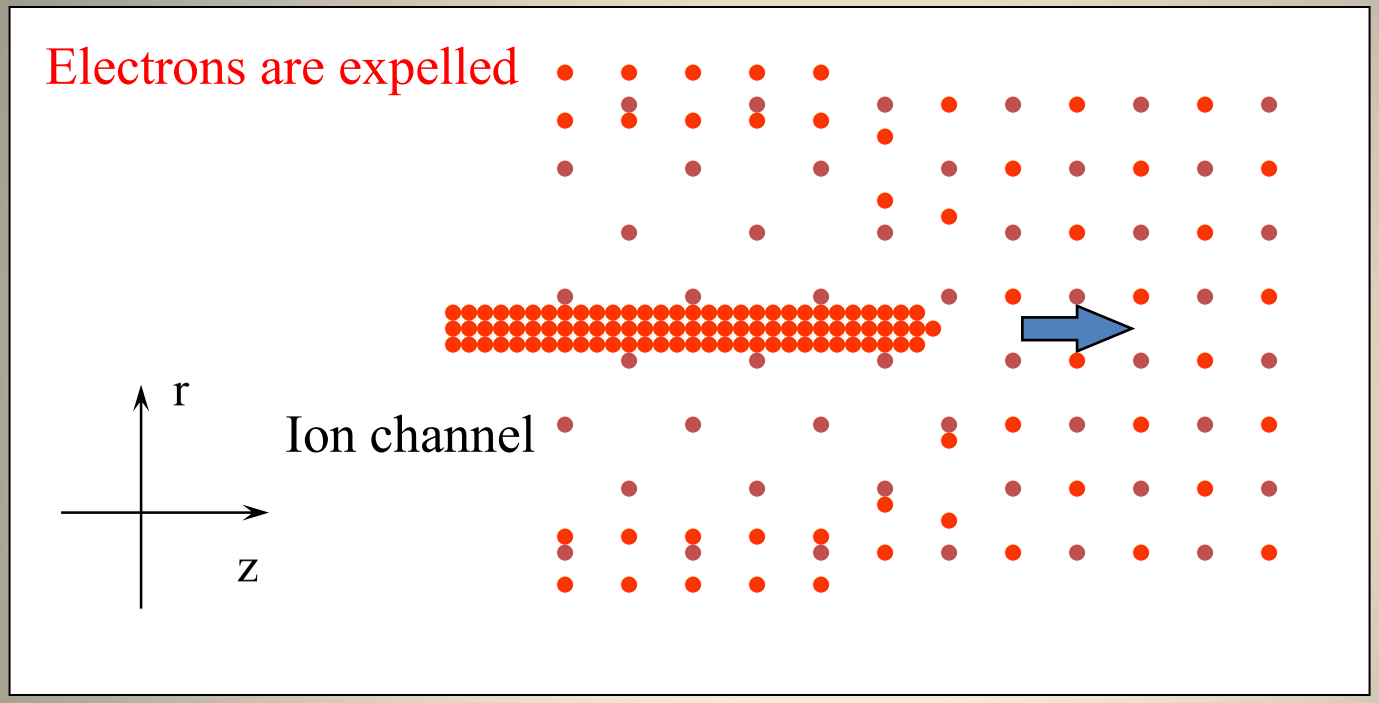
I) Generate homogeneous plasma channel:

II) Send dense electron beam towards plasma:




Beam density $n_b$
> Gas density $n_0$

III) Excite plasma wakefields:

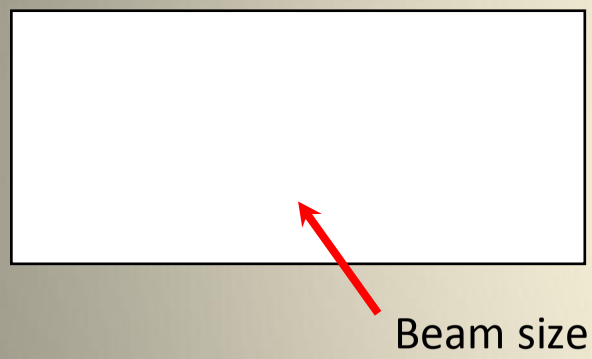


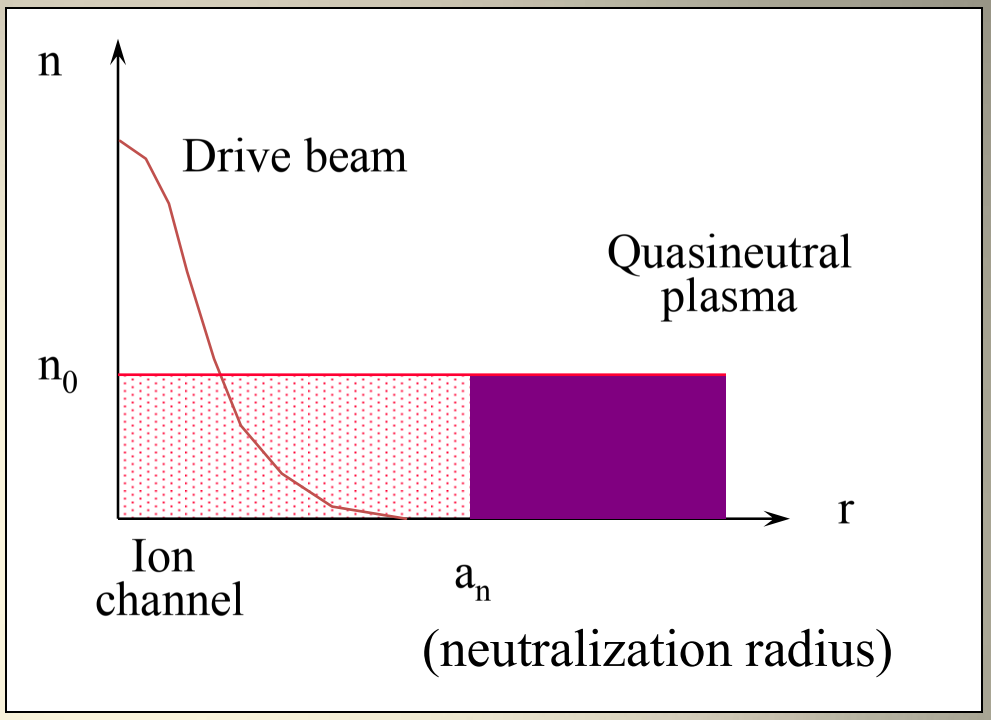

Space charge force of beam ejects all plasma electrons promptly along radial trajectories

Pure ion channel is left: Ion-focused regime, underdense plasma

## Equilibrium condition:

**Ion charge neutralizes beam charge:**




SLC:
$n_b/n_0 = 10$

Beam and plasma densities determine most characteristics of plasma wakefields!

Electron motion solved with ...

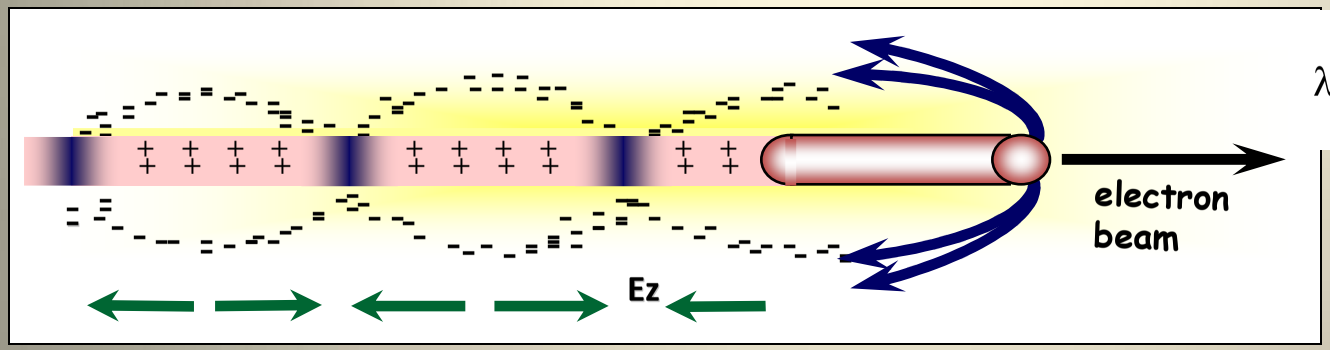
**driving force:**

Space charge of drive beam displaces plasma electrons.

**restoring force:**

Plasma ions exert restoring force

**Space charge oscillations (Harmonic oscillator)**




$$\lambda_p \approx 1\,\mathrm{mm} \cdot \sqrt{\frac{10^{15}\,\mathrm{cm}^{-3}}{n_0}}$$

Longitudinal fields can accelerate and decelerate!

Plasma ions move relatively little → Constant focusing gradient

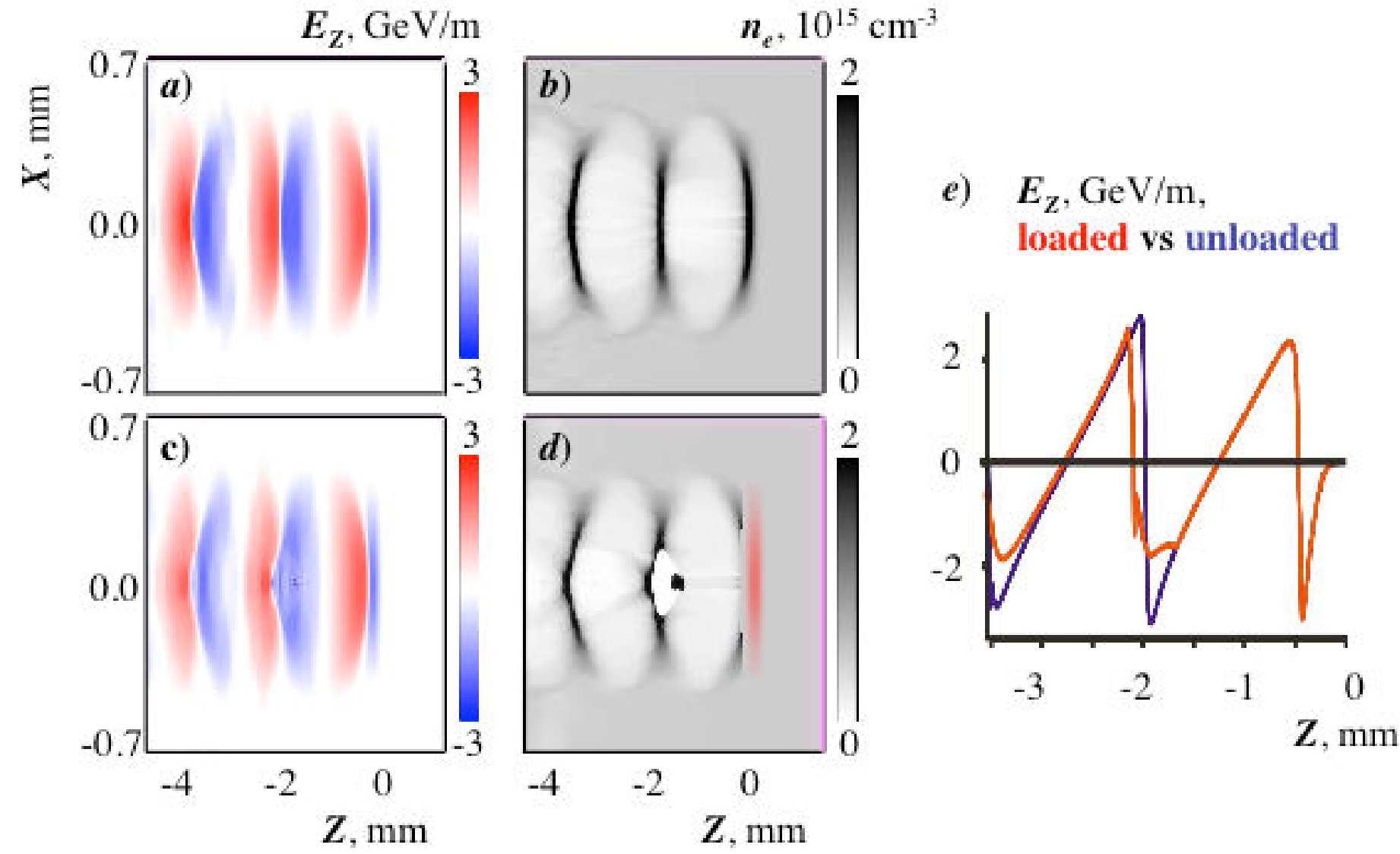
$$\beta = \sqrt{2\gamma} \cdot \frac{c}{\omega_p}$$

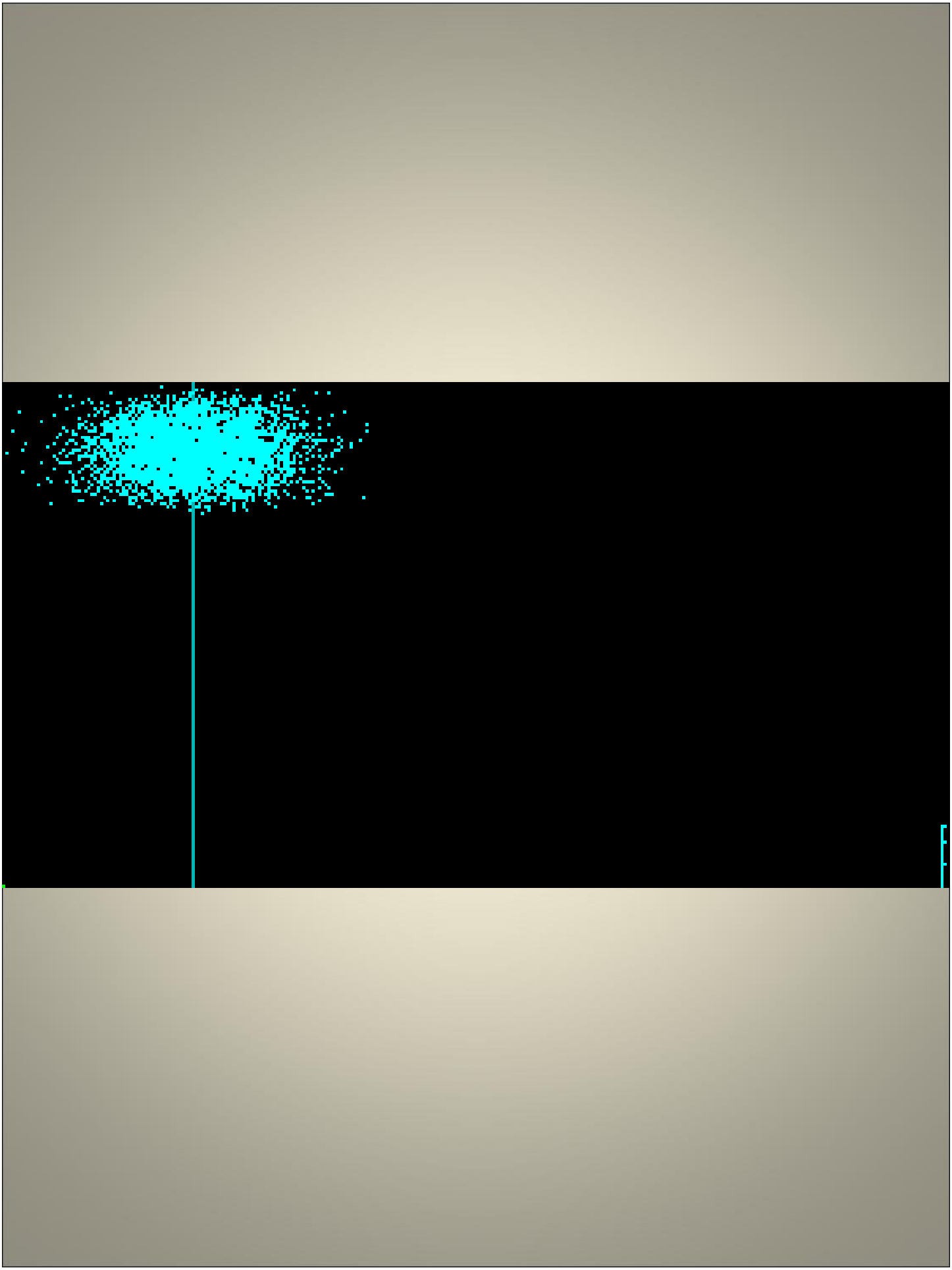
**Plasma "structures" are also super-strong "quadrupoles"!**

**(many thousand T/m)**

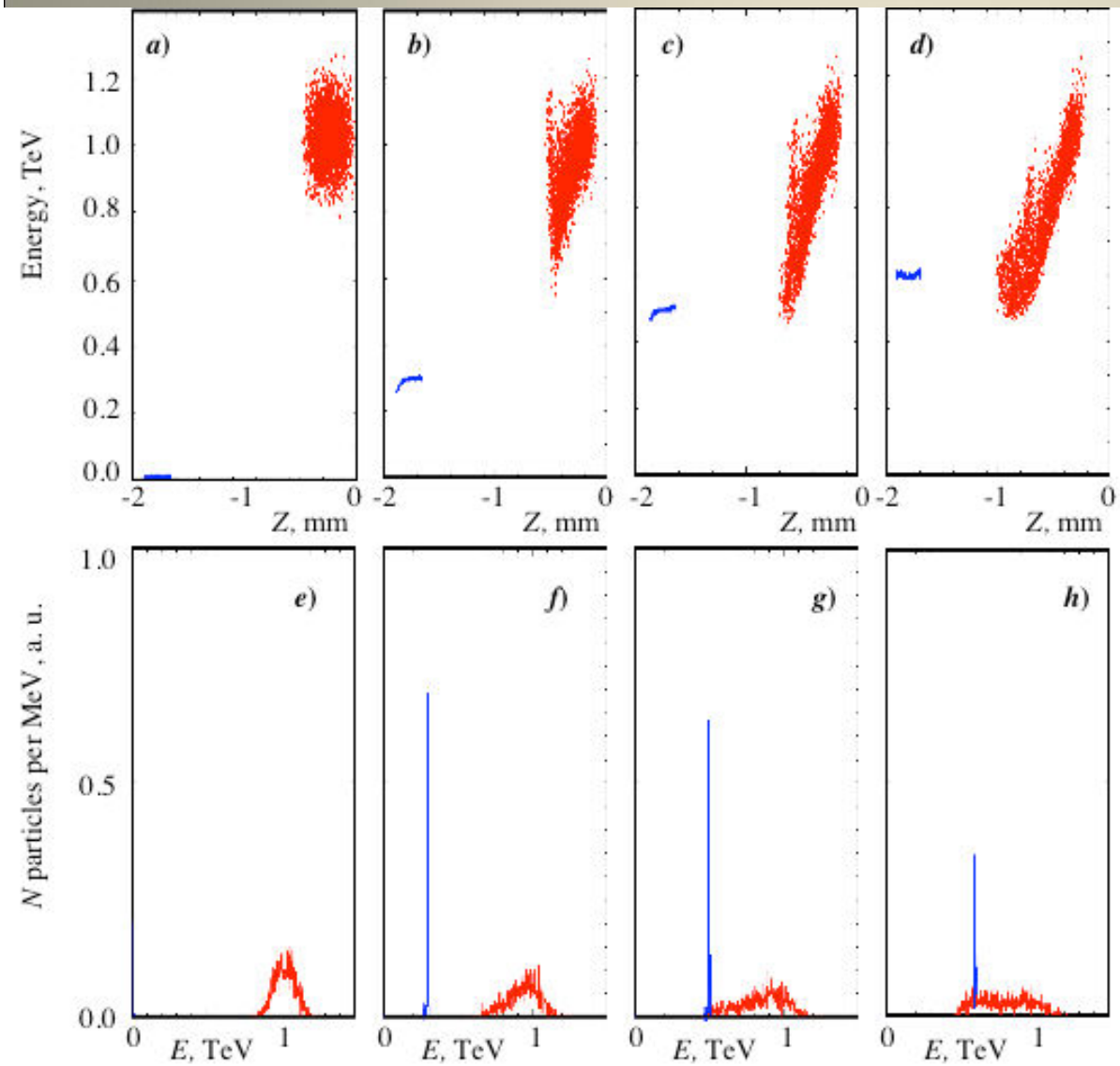
*... need to handle acceleration and focusing!*

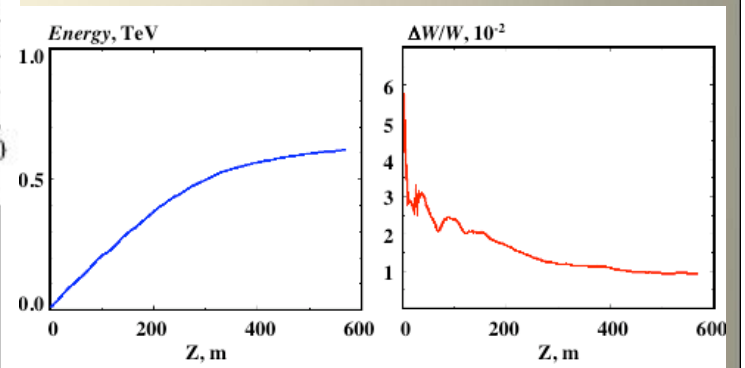
# Fields


$E_Z$, GeV/m
$n_e$, $10^{15}$ cm$^{-3}$
X, mm
0.7
0.0
-0.7
a)
b)
c)
d)
3
-3
2
0
-4
-2
0
Z, mm
e)
$E_Z$, GeV/m,
loaded vs unloaded
2
0
-2
-3
-2
-1
0
Z, mm



# Results

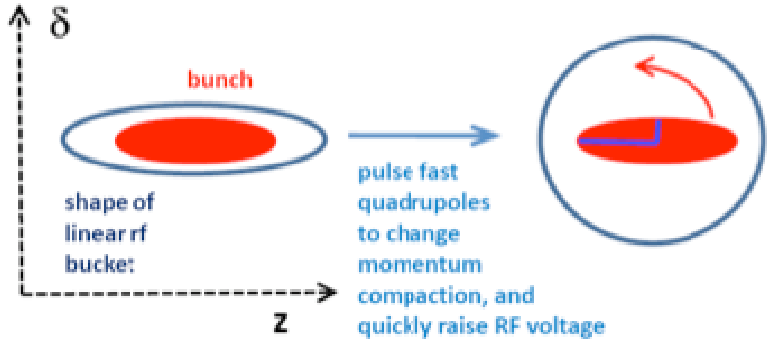

a)
b)
c)
d)
Energy, TeV
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-2
-1
0
Z, mm
e)
f)
g)
h)
N particles per MeV, a. u.
1.0
0.5
0.0
0
E, TeV
1


Energy, TeV
1.0
0.5
0.0
0
200
400
600
Z, m
ΔW/W, 10⁻²
6
5
4
3
2
1

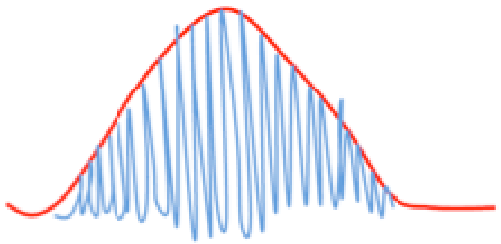
# Bunch Compression

Producing a short proton bunch is critical. Different ideas are under investigation.

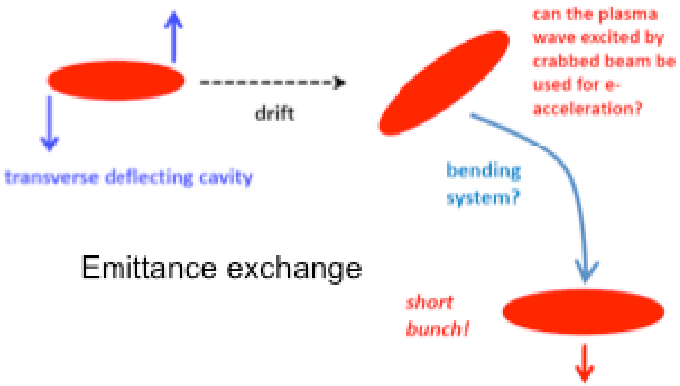
## Short proton bunch production




Schematics of fast bunch rotation in storage ring



Nanochopper gets the microbunch

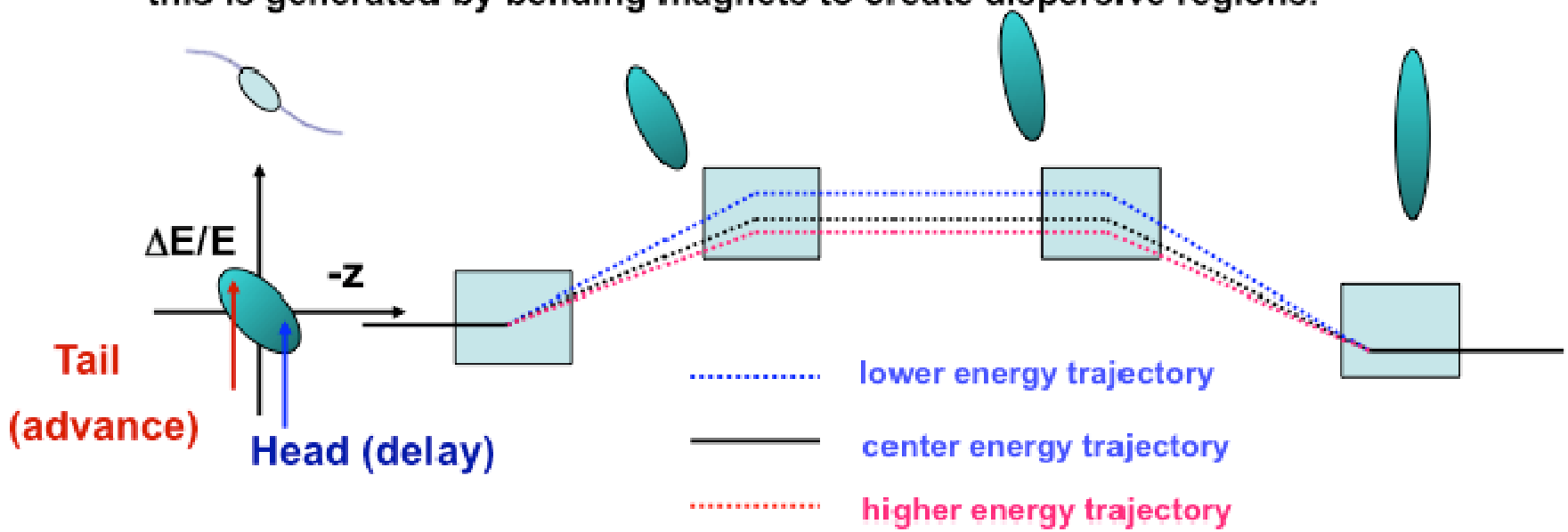



Emittance exchange

F. Zimmermann

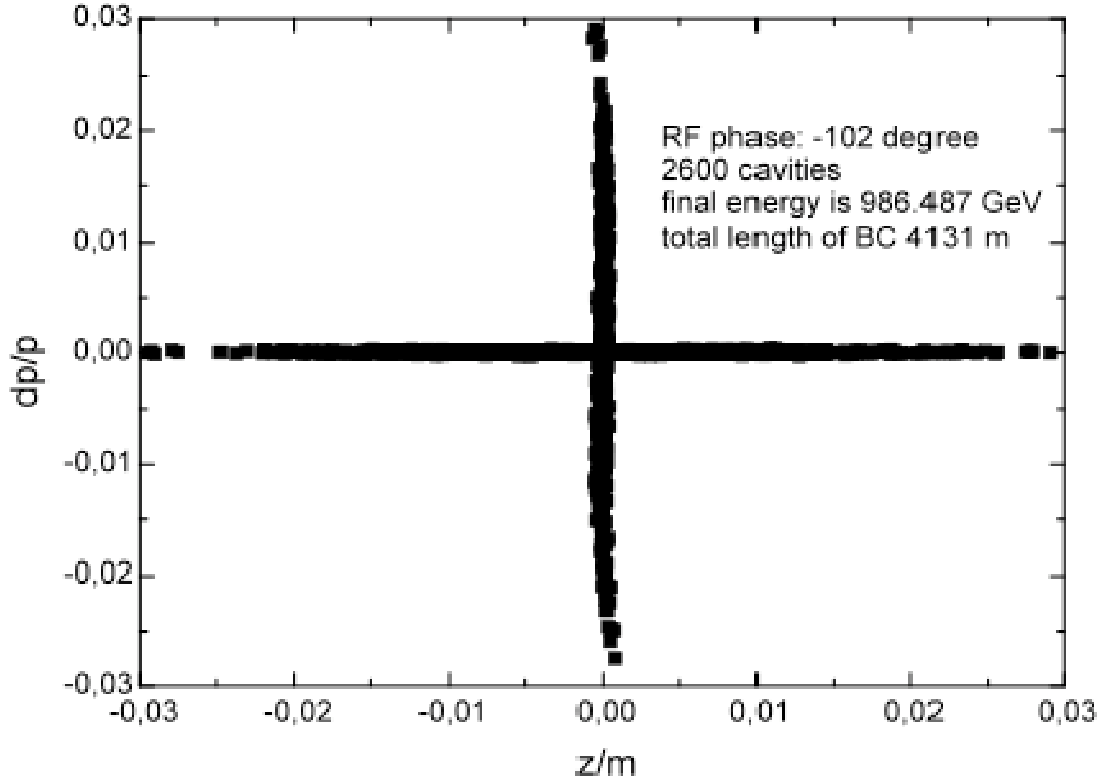
# Magnetic bunch compression (BC)

- **Beam compression can be achieved:**
  - (1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage
  - (2) and passing beam through a region where path length is energy dependent: this is generated by bending magnets to create dispersive regions.



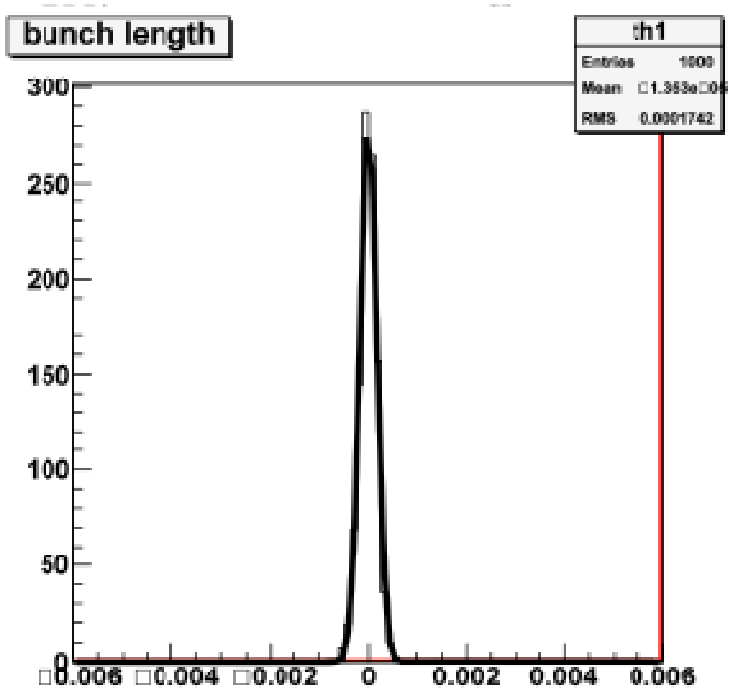

- **To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.**

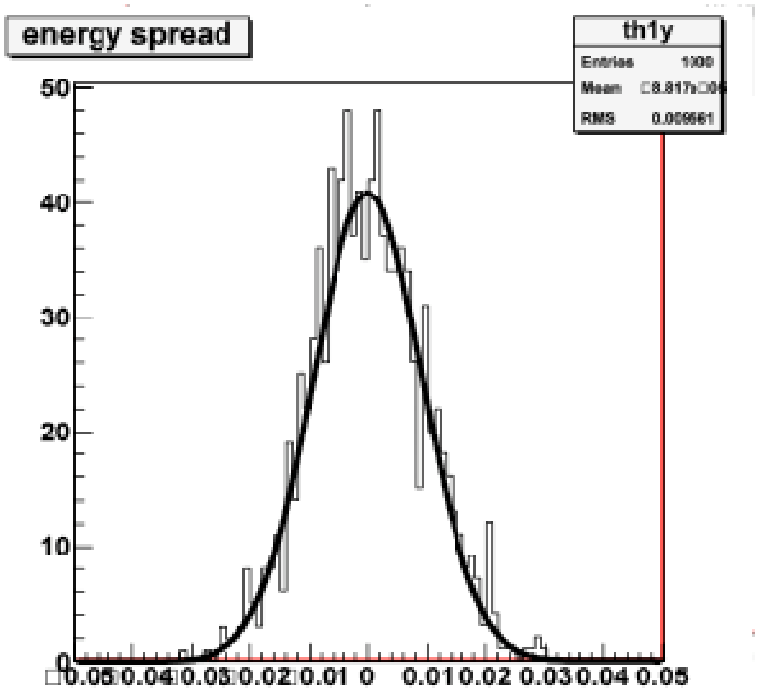
# Phase space of beam




See A. Caldwell, G. Xia et al., Preliminary study of proton driven plasma wakefield acceleration, Proceedings of PAC09, May 3-8, 2009, Vancouver, Canada

# Bunch length & energy spread




Fitting data show that the bunch length of 165 micron and the relative energy spread of 9e-3 can be achieved. Futher optimization is onging.

# Demonstration experiment

- Test validity of simulation codes

- Gain experience with experimental techniques
    - producing uniform plasma
    - monitoring plasma
    - characterizing beam
    - measuring E fields directly
    - …

- Demonstrate acceleration with proton driven plasma

# Demonstration experiment – possible sequence

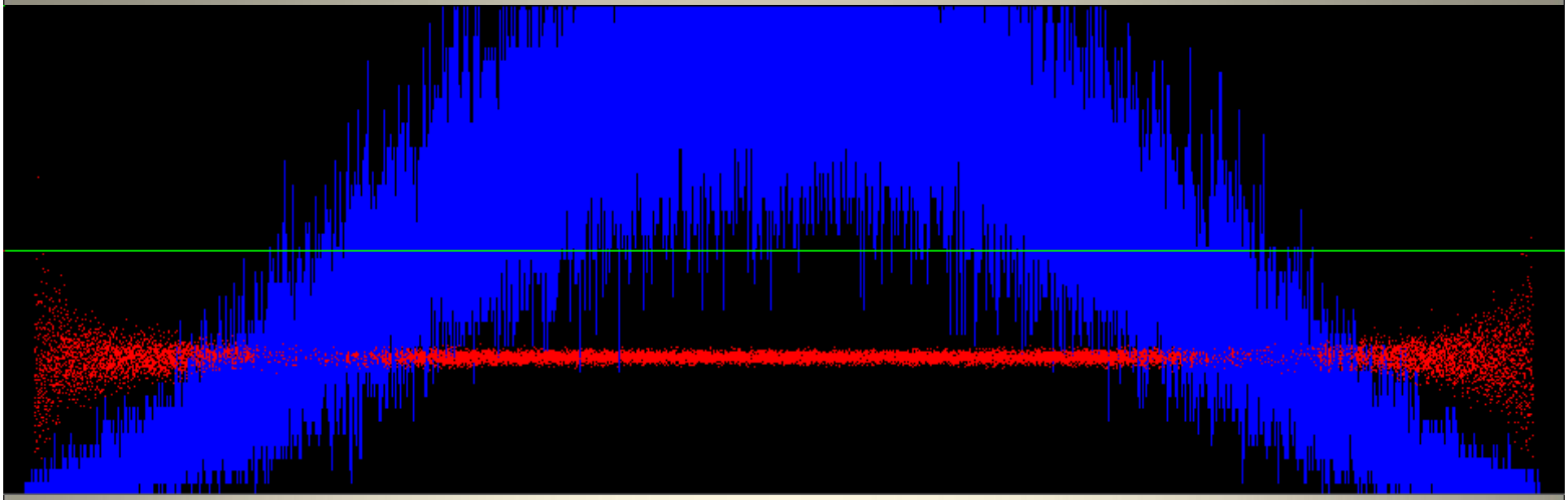
1. Plasma cell + diagnostics: expect to see modulation of proton bunch by plasma

2. Plasma cell + laser: seed the modulation to add reproducibility

3. Plasma cell + bunch compression: generation of stronger fields, demonstration of scaling principles

4. Plasma cell + bunch compression + electron injection: demonstration of electron acceleration

# Modulation



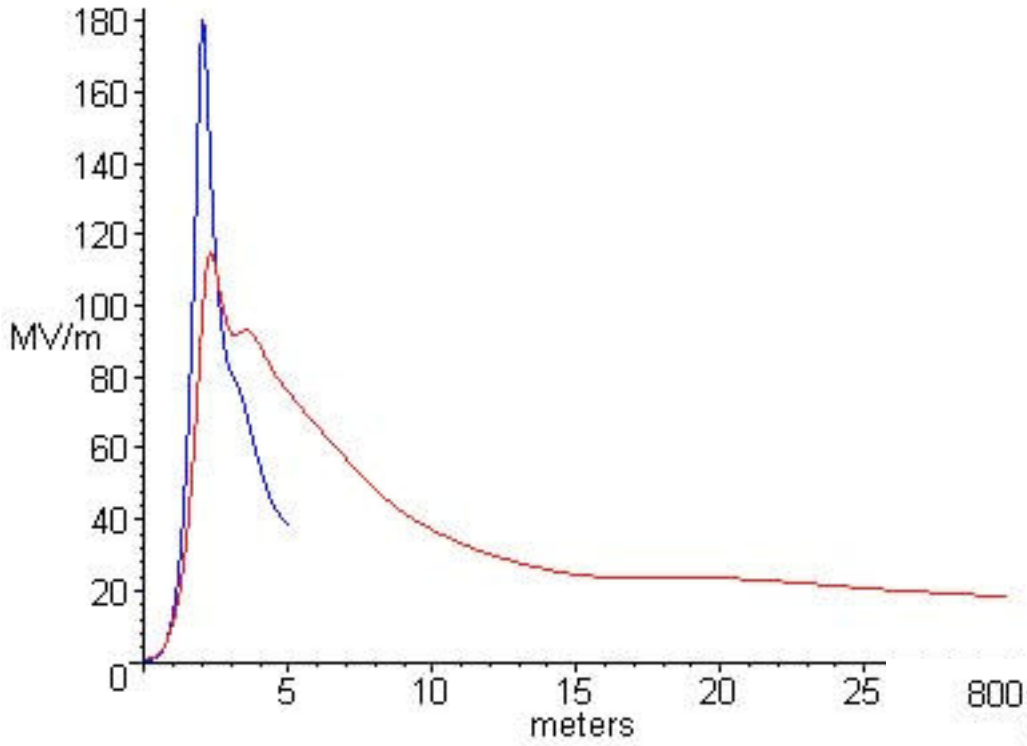
- (green) field Ez at the distance $\sigma_r$ from axis, scale +-200 MV/m
- (blue) beam density at the distance $\sigma_r$ from axis, axis: 0 - 8e-4 of plasma density
- (red) beam radius, 0 - 1.4 mm
- (grey) energy stored in the plasma, arb. units

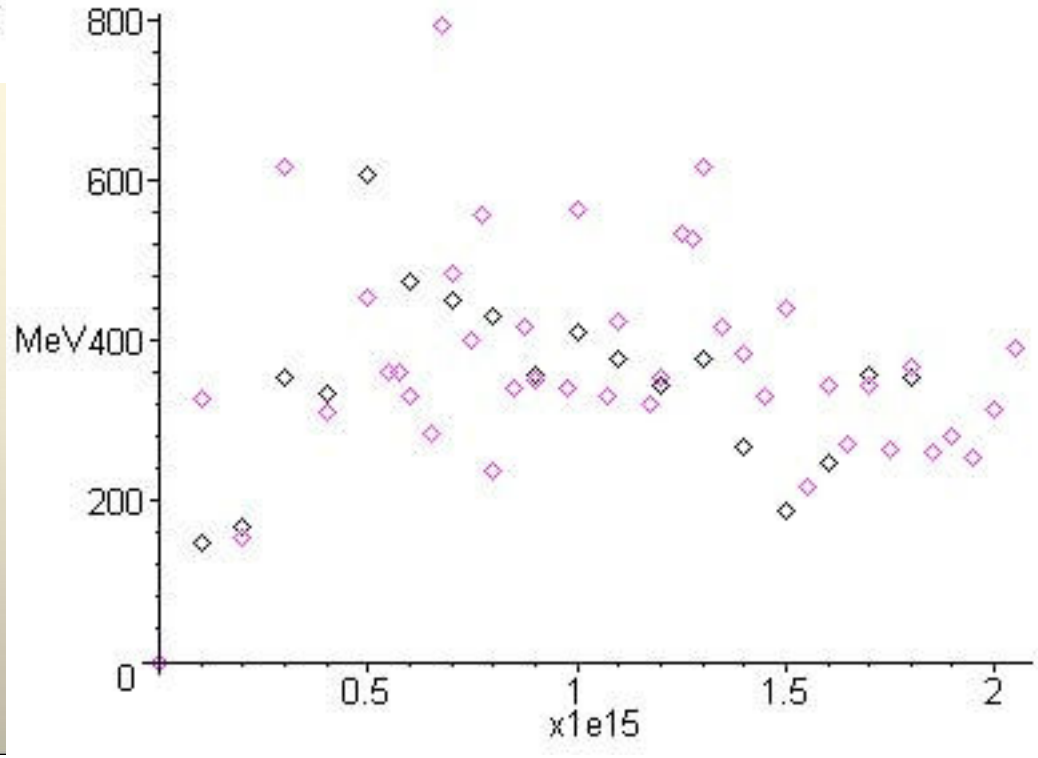
Simulation by K. Lotov (Novosibirsk) for 24 GeV PS beam, no compression

# Modulation

23.5 GeV 24.5 GeV

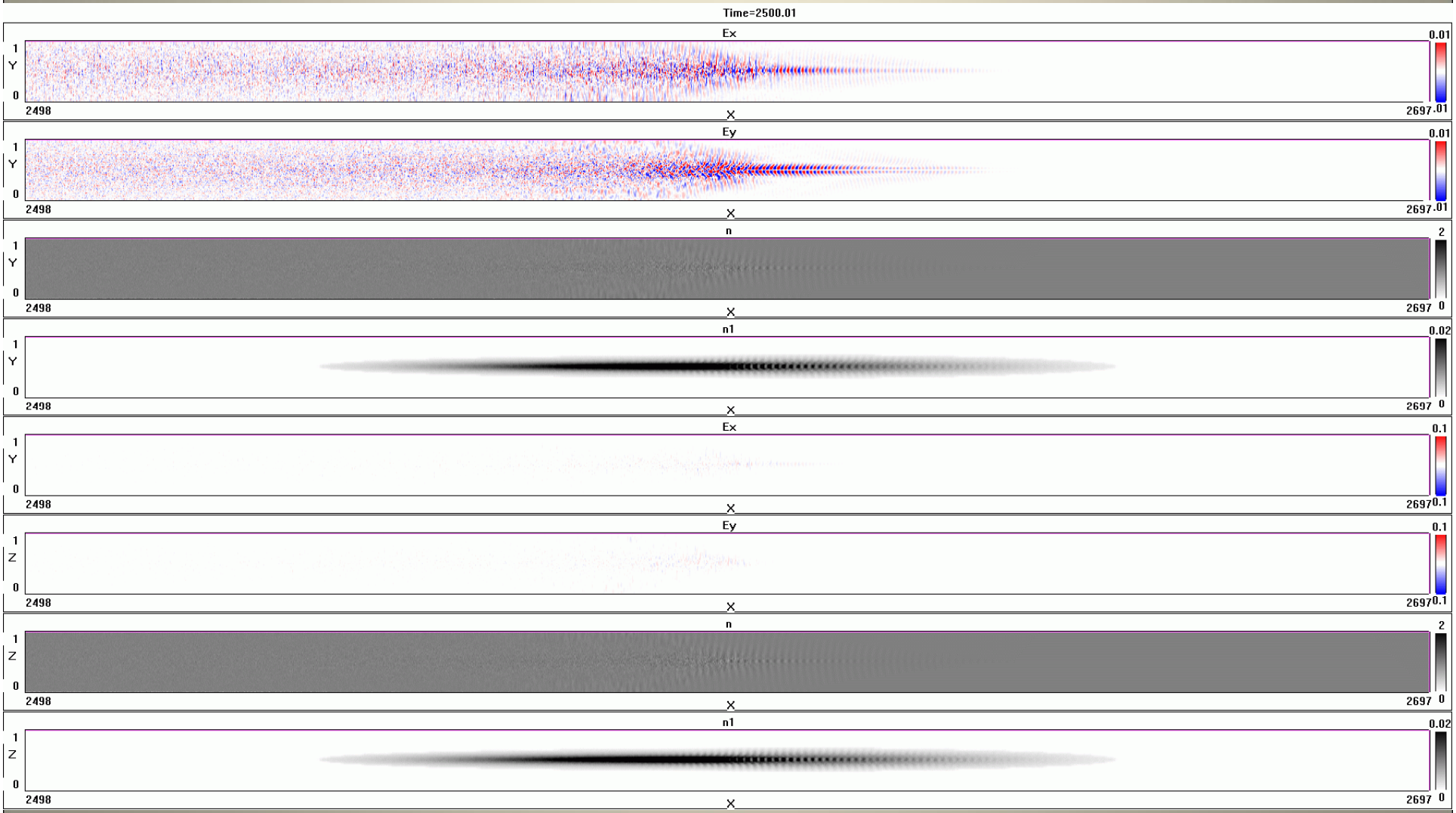
Simulation by K. Lotov for 24 GeV PS beam, no compression


180
160
140
120
100
MV/m
80
60
40
20
0
5
10
15
20
25
meters


800
600
MeV400
200
0
0.5
1
1.5
2
x1e15

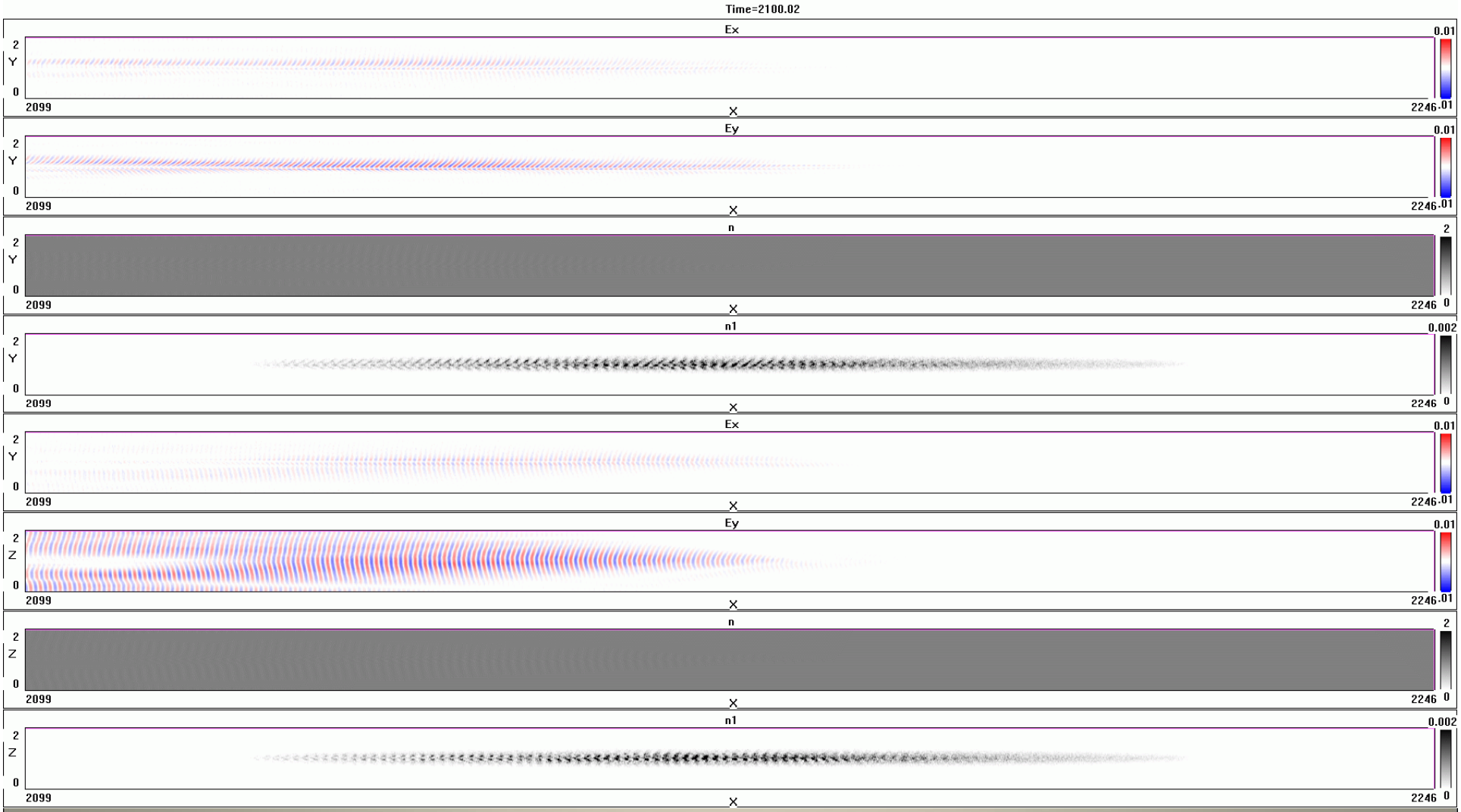
Simulations are ongoing:

- Verification with 3D PIC code (A. Pukhov, Düsseldorf)

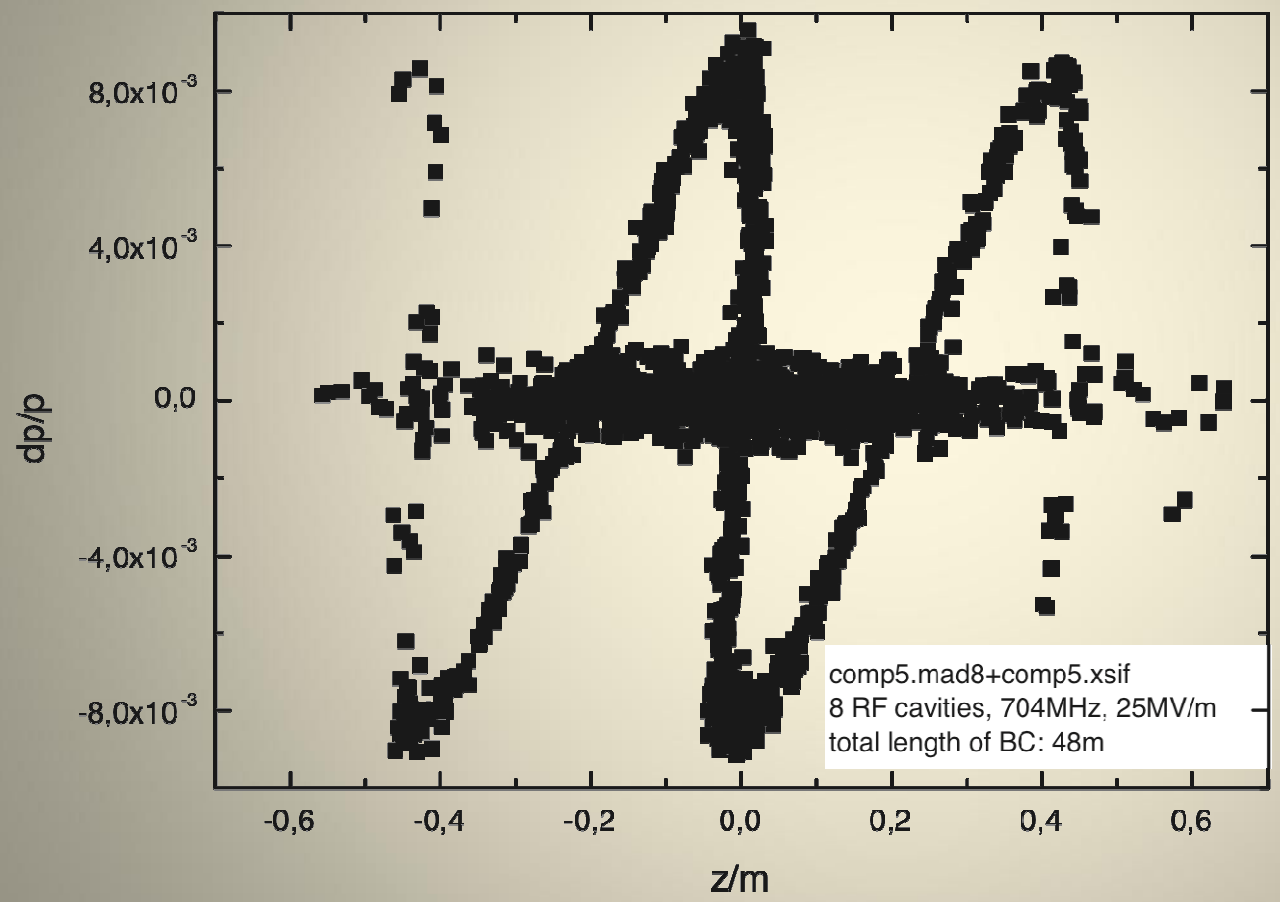


Simulations are ongoing:

- Look at SPS beam & modulation

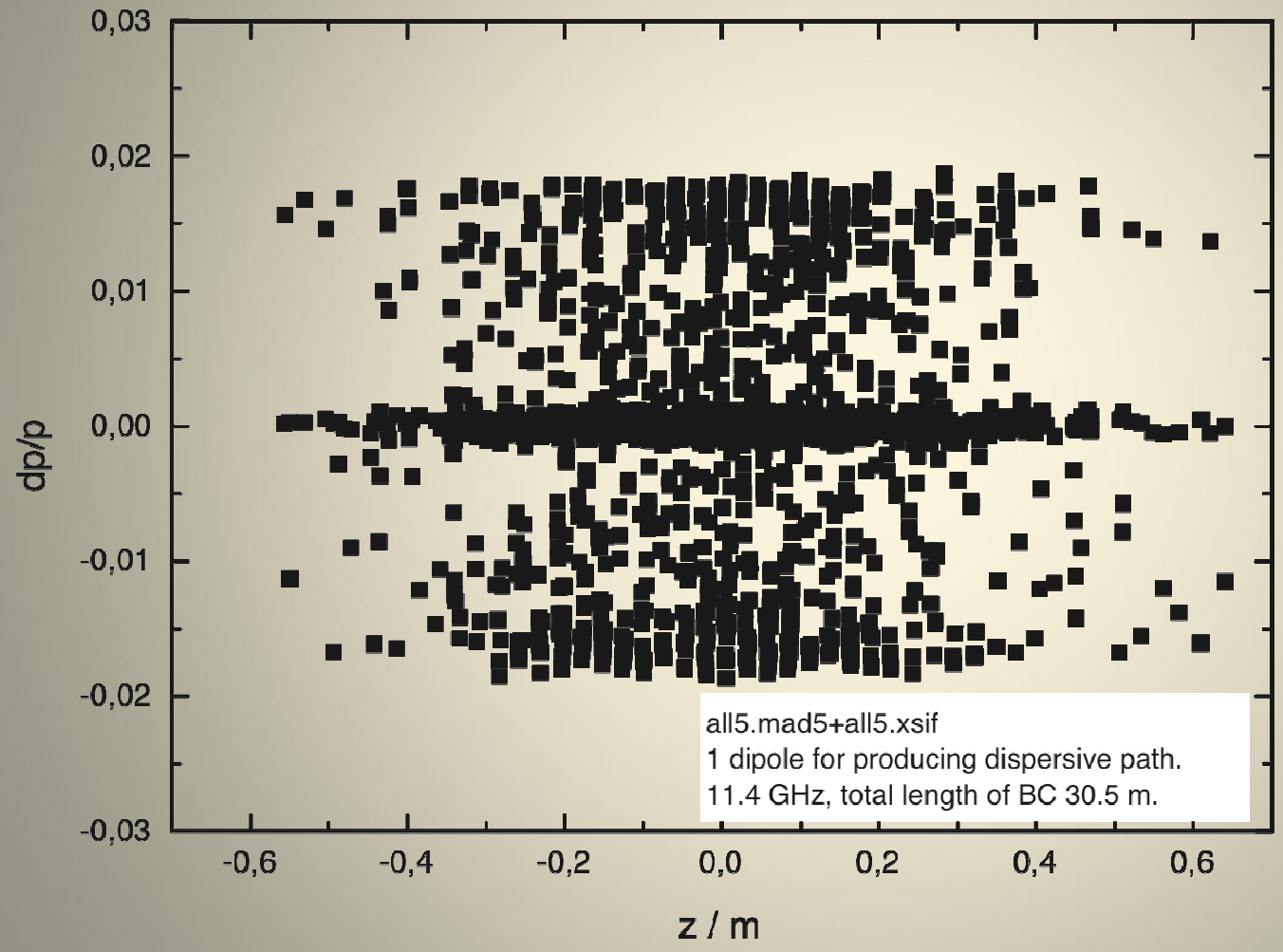


# Compression Schemes for Proton Bunches




e.g., 704 MHz compression scheme for PS bunch (G. Xia, MPP). Rms bunch length about 2cm after 48m.

# Compression Schemes for Proton Bunches




e.g., 11.4 GHz compression scheme for PS bunch (G. Xia, MPP). String of bunches produced separated by 3cm. Bunch charge ~$10^9$ and rms ca 150 µm

Bunch compression for SPS bunch in progress