# Proton Driven Plasma Wakefield Acceleration

1st Annual EuCARD Meeting

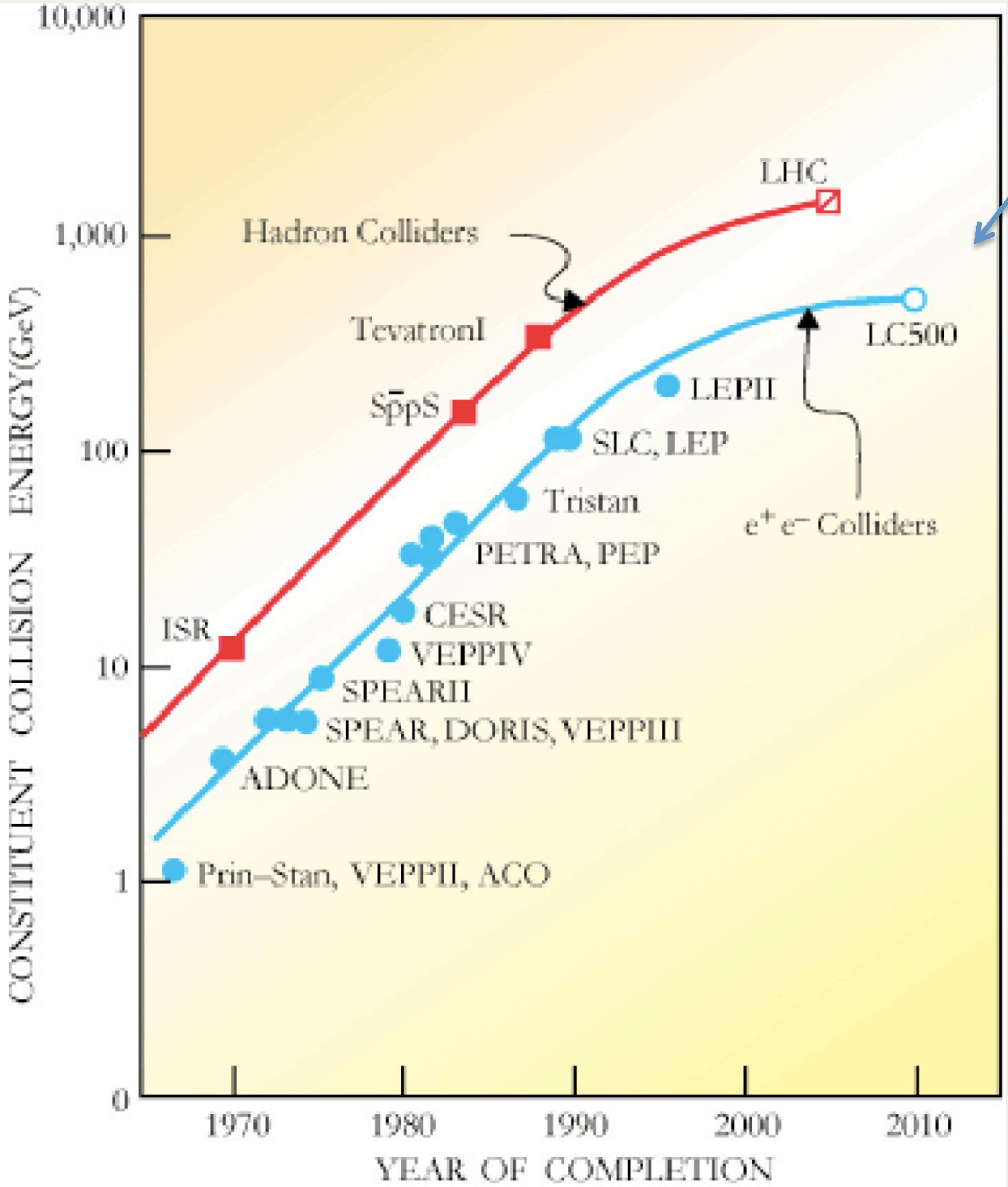
Rutherford Appleton Laboratory

Allen Caldwell

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

# Particle Physics Accelerators




ILC discussed as next collider → 30 km linear accelerator

The Livingston plot shows a saturation effect !

Practical limit for accelerators at the energy frontier: Project cost increases as the energy must increase!

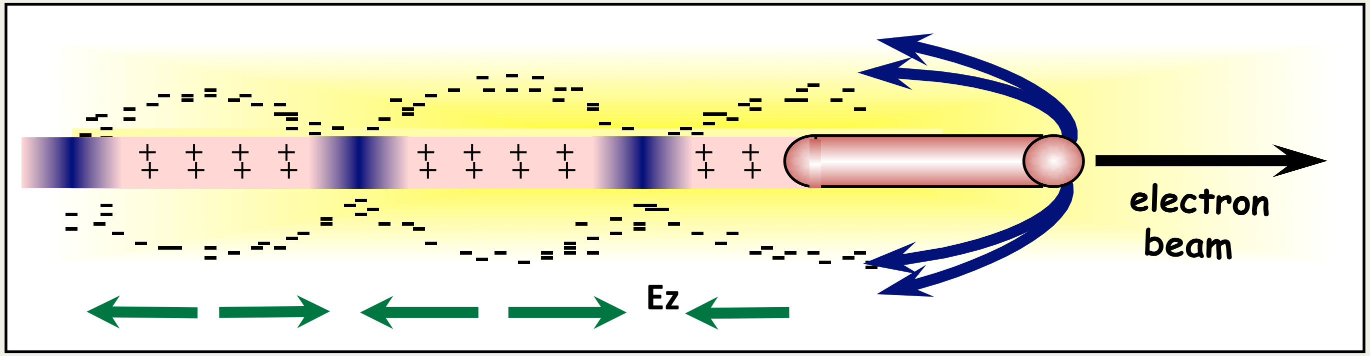
New technology needed…

# Plasma Wakefield Acceleration (Beam Driven)

**driving force:** Space charge of drive beam displaces plasma electrons.

**restoring force:** Plasma ions exert restoring force

→ **Space charge oscillations (Harmonic oscillator)**



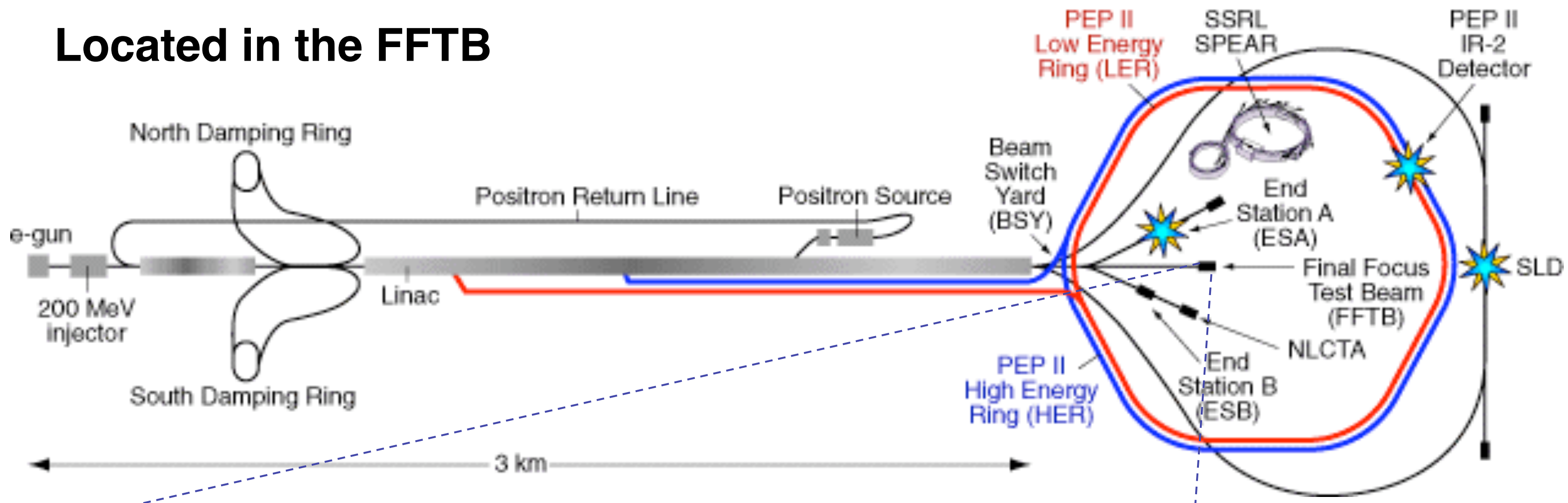

Longitudinal fields can **accelerate** and **decelerate**!

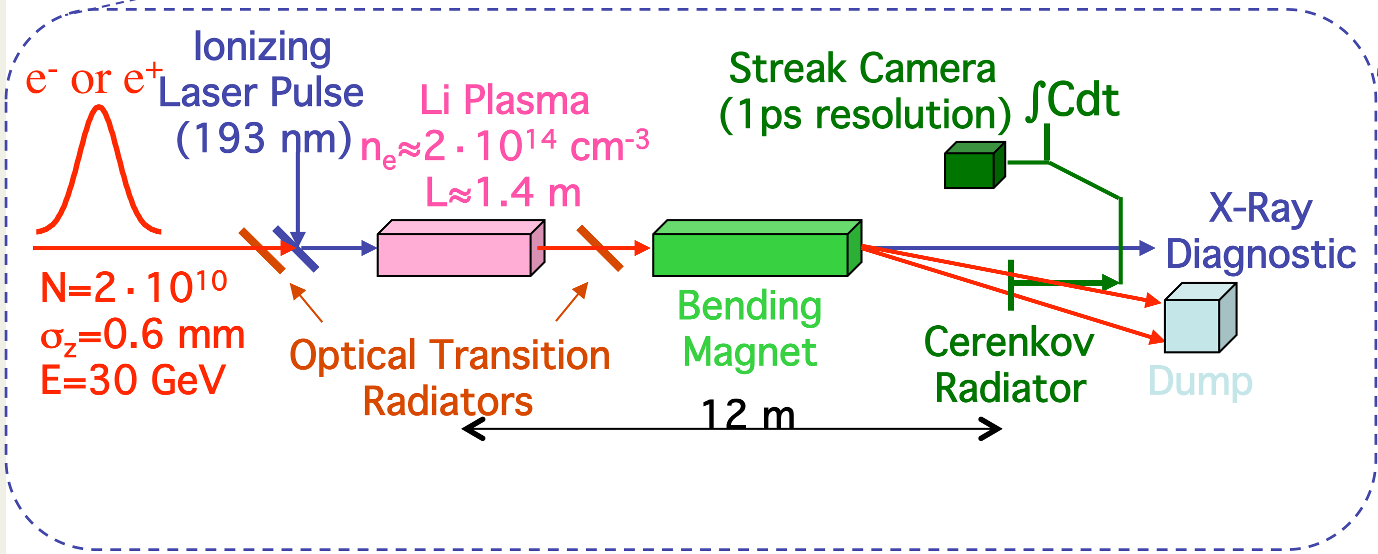
**Plasma also provides super-strong focusing force !**
**(many thousand T/m in frame of accelerated particles)**

# Experimental Layout (E-157)

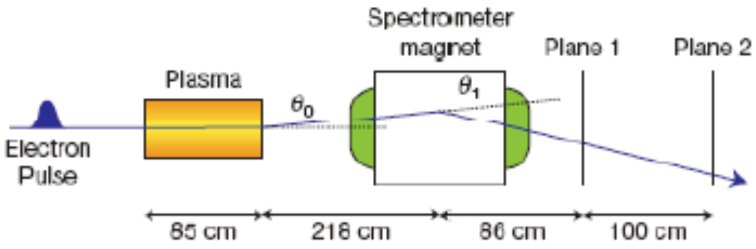


## Located in the FFTB

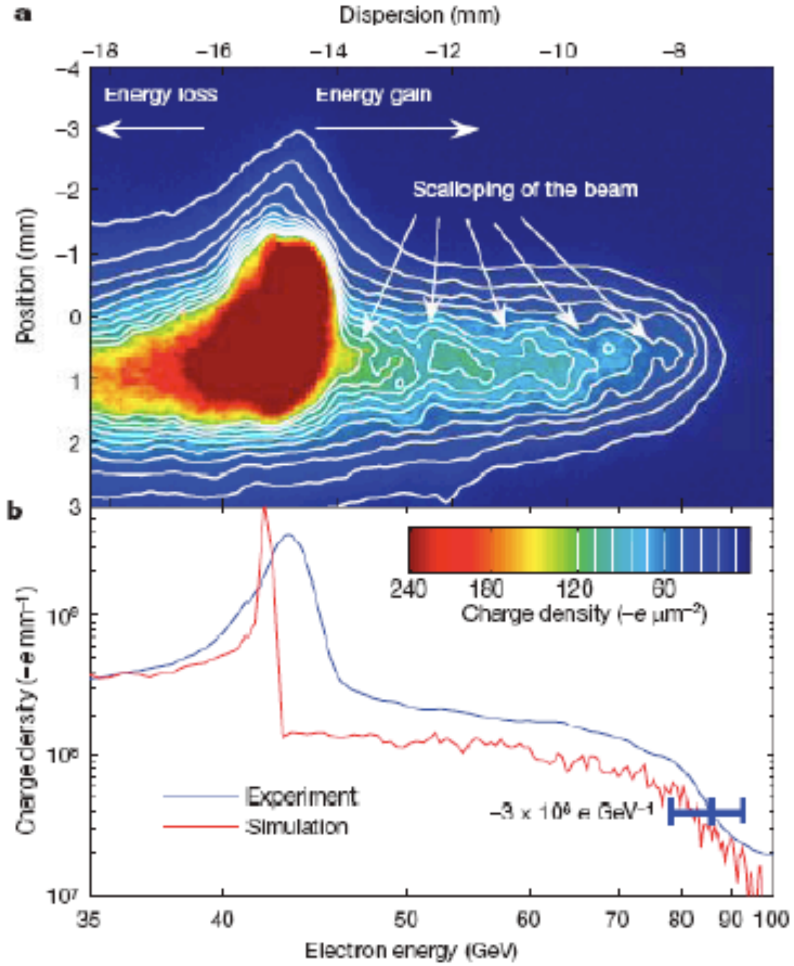



# Highlight: latest SLAC/UCLA/USC results
(Nature 2007)




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

Why not continue with electrons ???

There is a limit to the energy gain of a trailing bunch in the plasma:

$$R = \frac{\Delta T^{\mathrm{witness}}}{\Delta T^{\mathrm{drive}}} \leq 2 \quad \text{T is the kinetic energy}$$

(for longitudinally symmetric bunches).

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

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 ?**

# Maximum accelerating gradient

Assuming Gaussian beams:

$$E_{z,\max} = eNk_p^2 \exp\left(-\frac{k_p^2\sigma_z^2}{2} + \frac{k_p^2\sigma_r^2}{2}\right)\Gamma\left(0, k_p^2\sigma_r^2/2\right),$$

Linear regime ($n_b < n_0$):

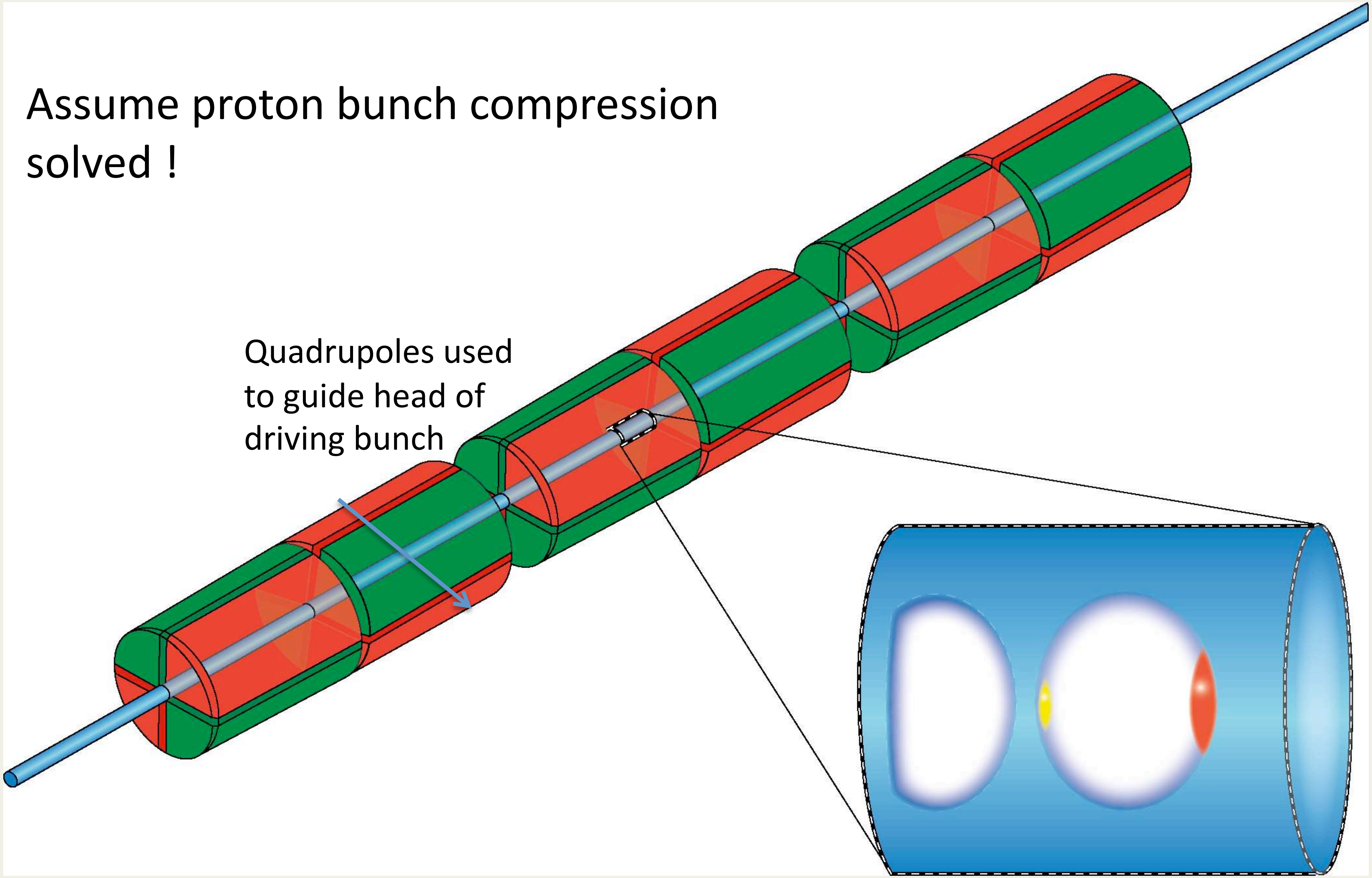
$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

Need very short proton bunches for strong gradients. Today's proton beams have

$$\sigma_z \approx 10 - 30\ \mathrm{cm}$$

Compression of proton bunch needs to be solved for PDPWA (?)

# Simulation study





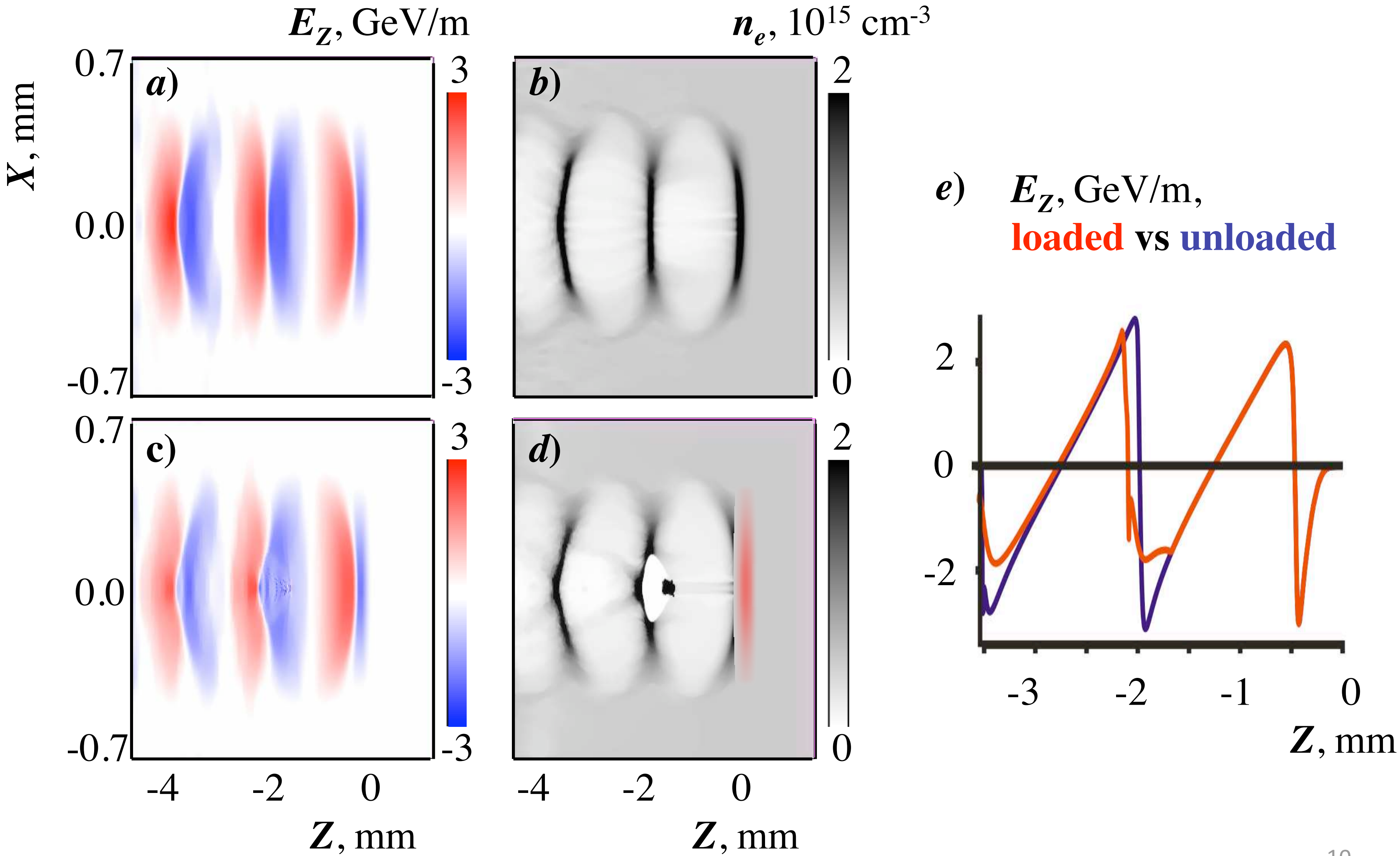

A. Caldwell, K. Lotov, A. Pukhov, F. Simon *Nature Physics* ***5, 363 - 367 (2009)***

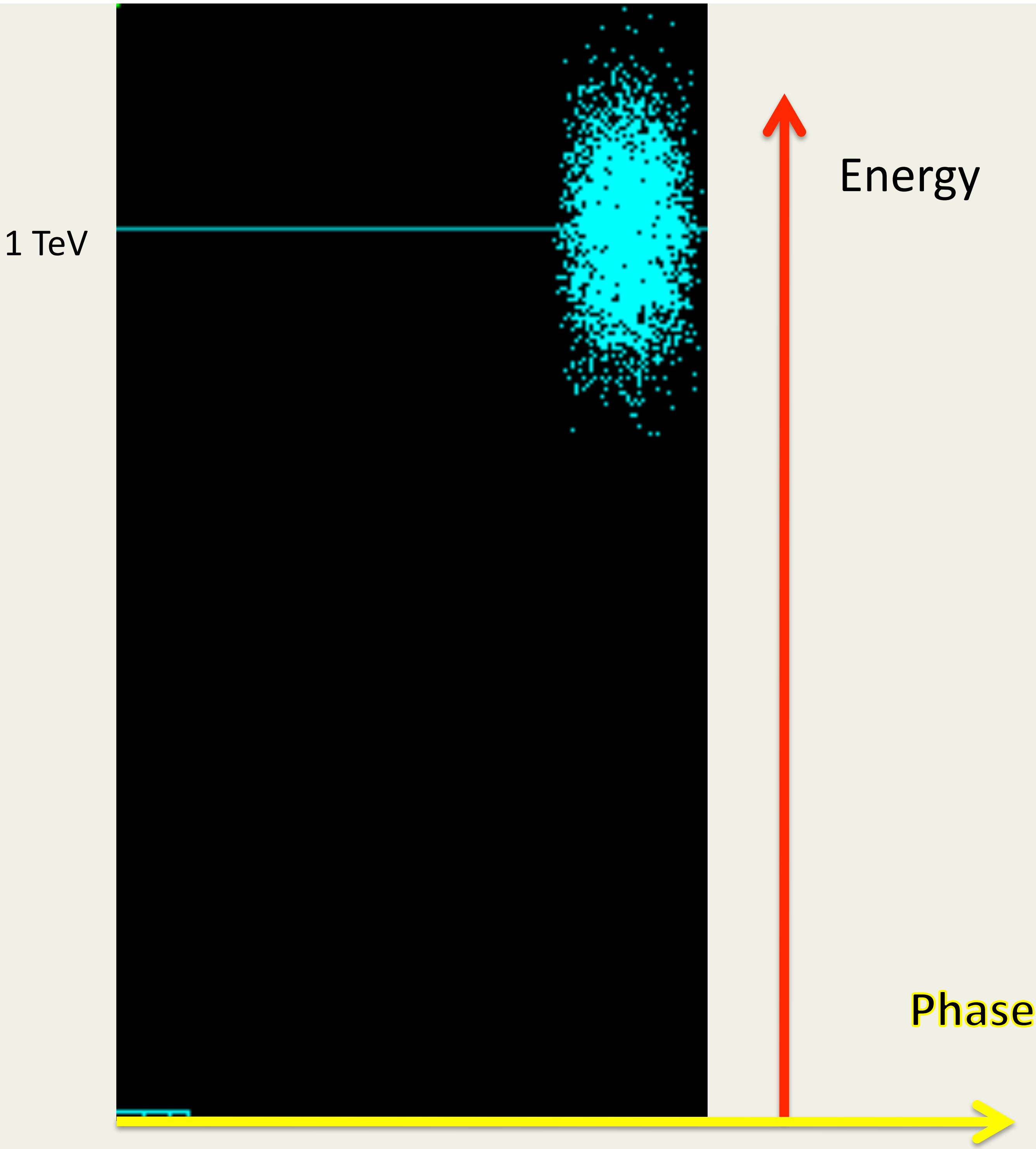
# Simulation

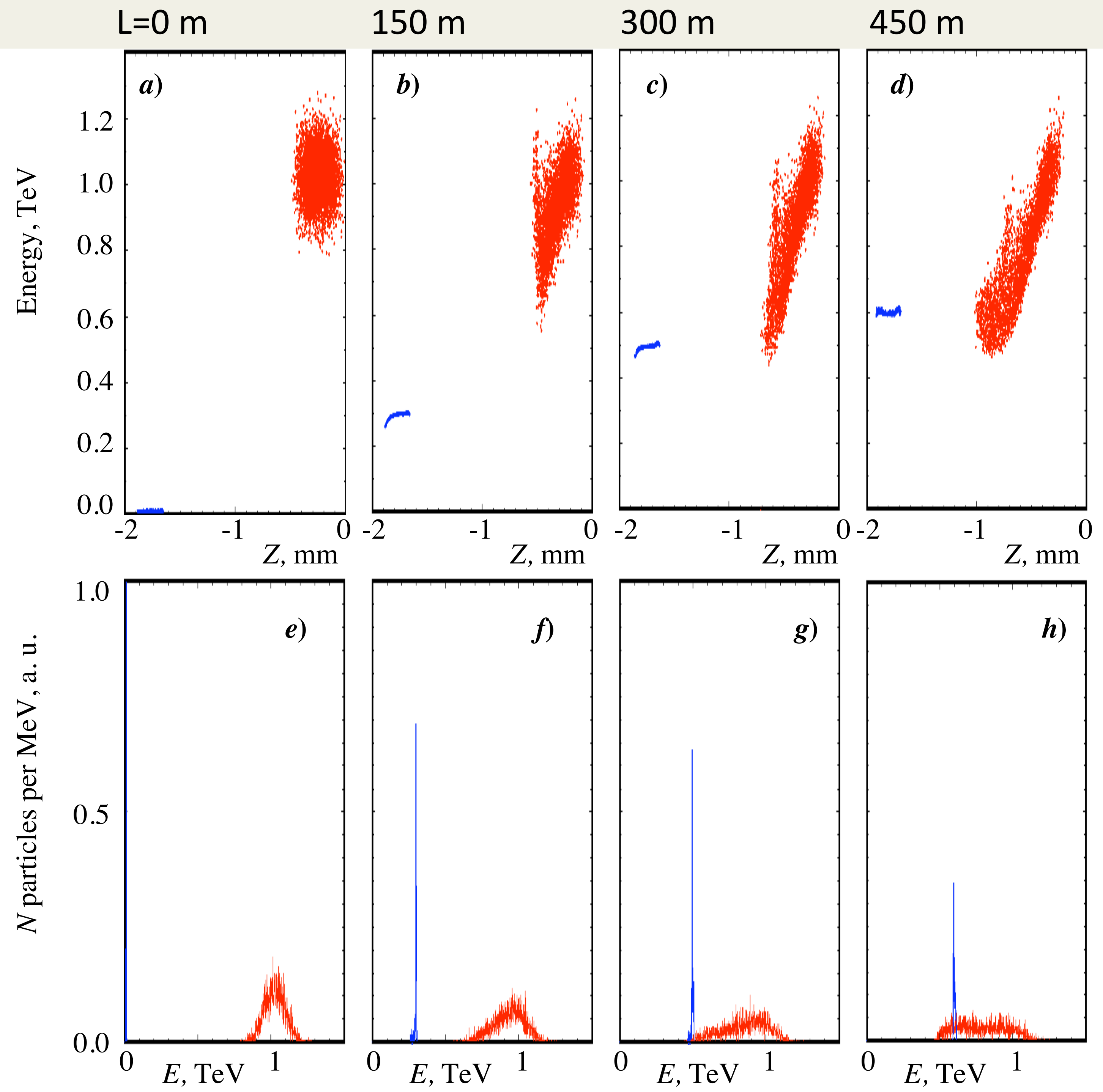
Table 1: Table of parameters for the simulation.

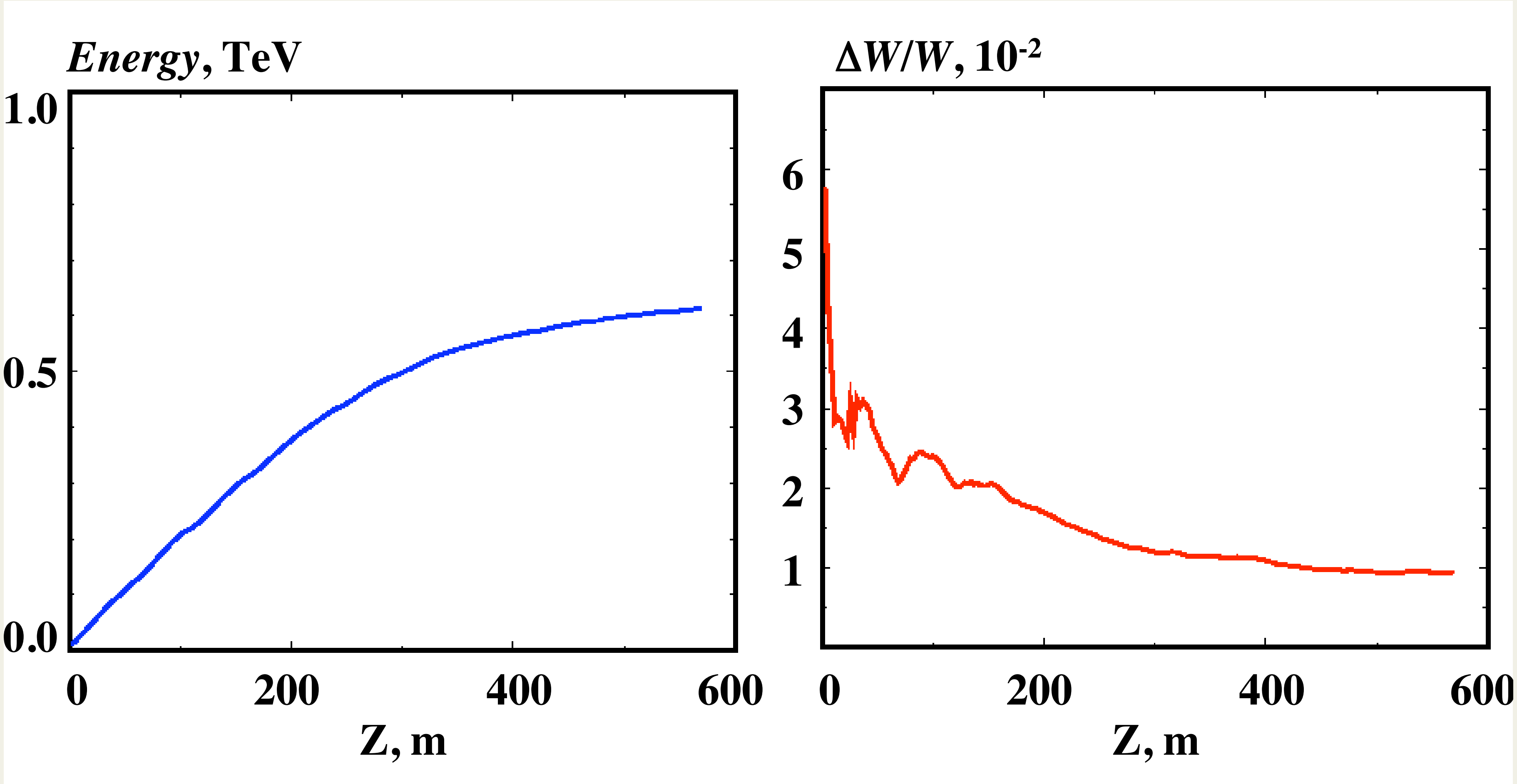
| Parameter | Symbol | Value | Units |
|---|---|---|---|
| Protons in Drive Bunch | $N_P$ | $10^{11}$ | |
| Proton energy | $E_P$ | 1 | TeV |
| Initial Proton momentum spread | $\sigma_p/p$ | 0.1 | |
| Initial Proton longitudinal spread | $\sigma_Z$ | 100 | $\mu$m |
| Initial Proton bunch angular spread | $\sigma_\theta$ | 0.03 | mrad |
| Initial Proton bunch transverse size | $\sigma_{X,Y}$ | 0.4 | mm |
| Electrons injected in witness bunch | $N_e$ | $1.5 \cdot 10^{10}$ | |
| Energy of electrons in witness bunch | $E_e$ | 10 | GeV |
| free electron density | $n_p$ | $6 \cdot 10^{14}$ | $\text{cm}^{-3}$ |
| Plasma wavelength | $\lambda_p$ | 1.35 | mm |
| Magnetic field gradient | | 1000 | T/m |
| Magnet length | | 0.7 | m |

# Densities & Fields



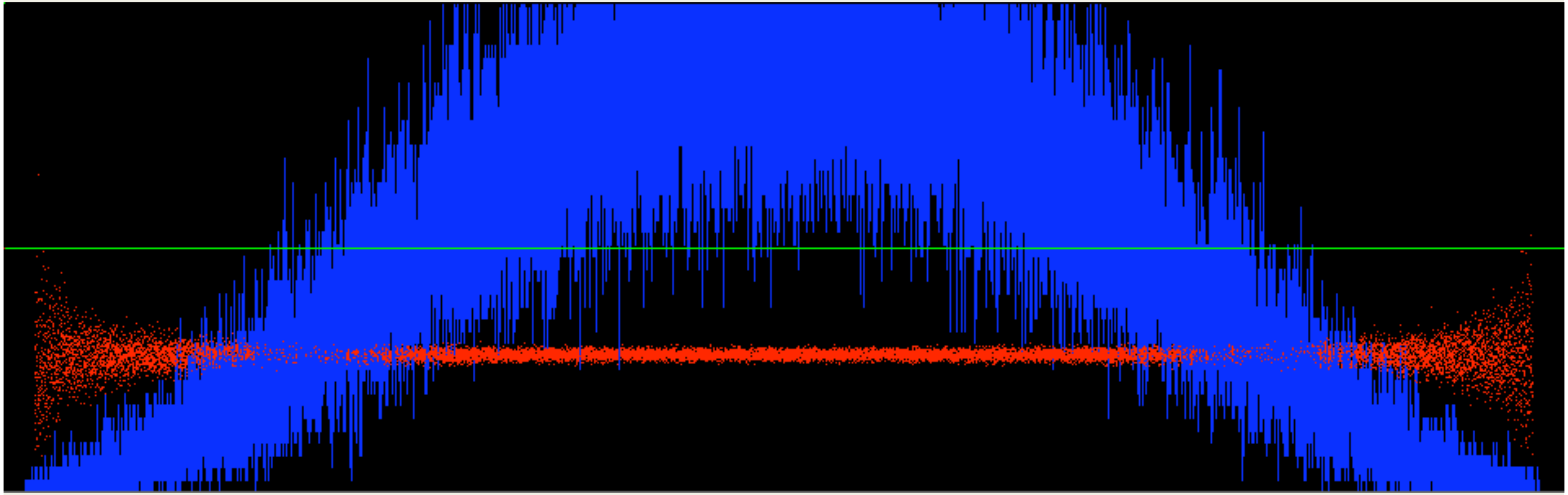

1 TeV
Energy
Phase


L=0 m
150 m
300 m
450 m
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
1
E, TeV




A Tevatron or HERA type proton beam, compressed to 100 microns but with 10% momentum spread, would allow to create a 600 GeV electron beam.

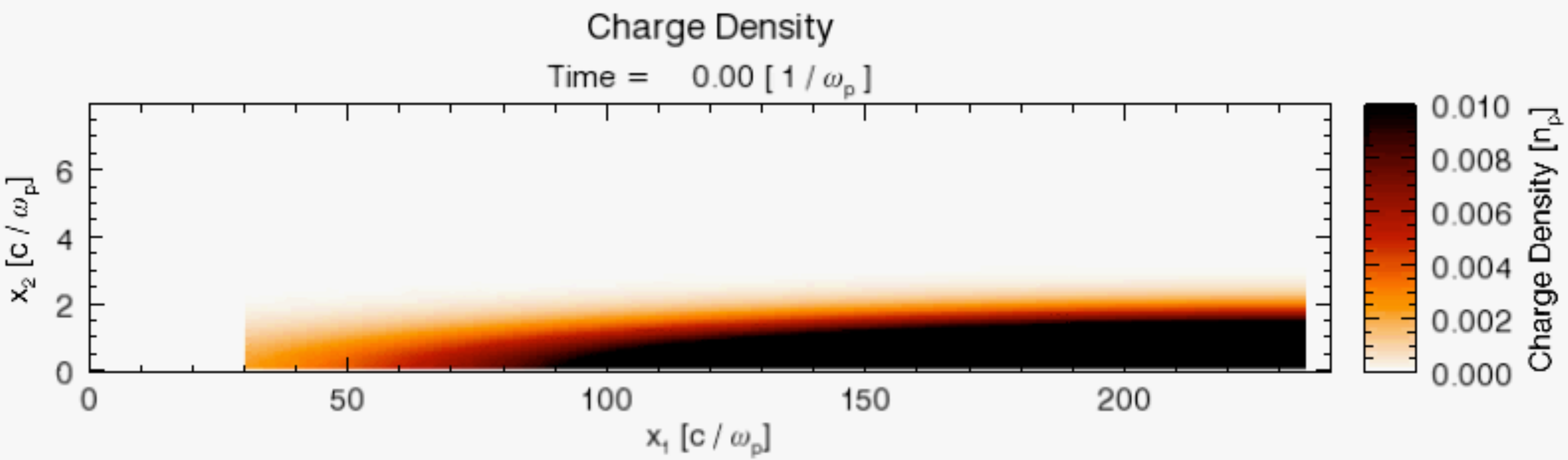
# Alternative to short bunch – modulation of long bunch



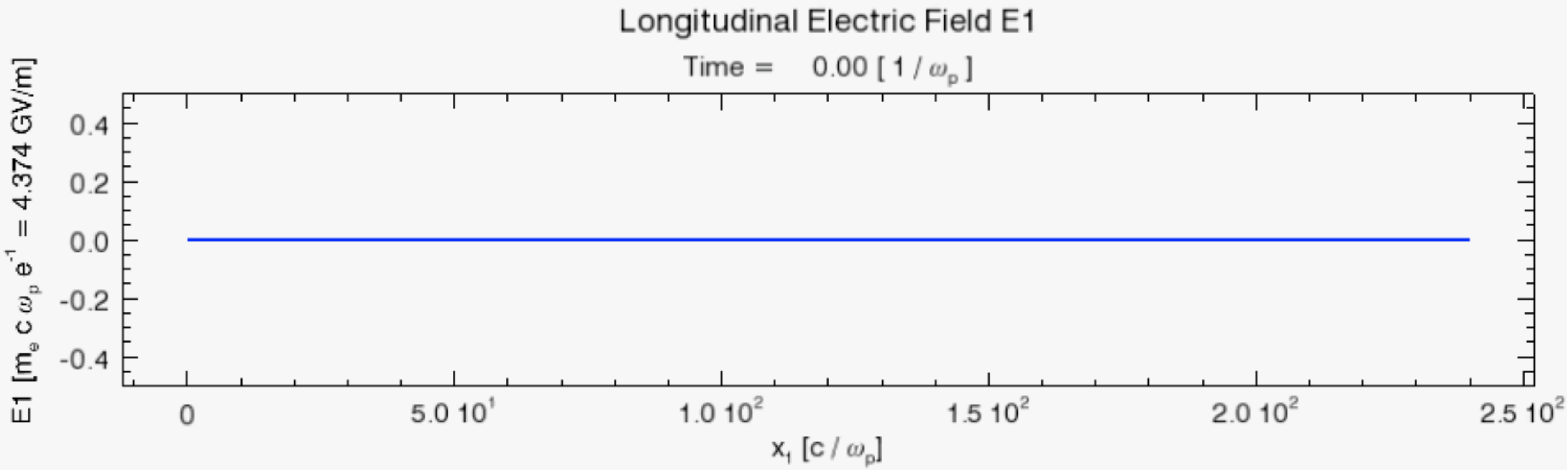
- (green) field Ez at the distance $\sigma_r$ from axis, scale +-200 MV/m
- (blue) beam density at the distance $\sigma_r$ from axis, axis: 0 - 8e-4 of plasma density
- (red) beam radius, 0 - 1.4 mm
- (grey) energy stored in the plasma, arb. units

PS beam simulation,
K. Lotov, LCODE

Can this be used to generate strong wakefields for acceleration ?




Simulation: W. Lu, OSIRIS code (UCLA)

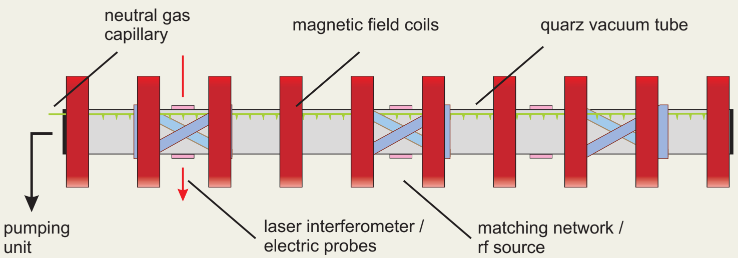



Simulation: W. Lu, OSIRIS code (UCLA)

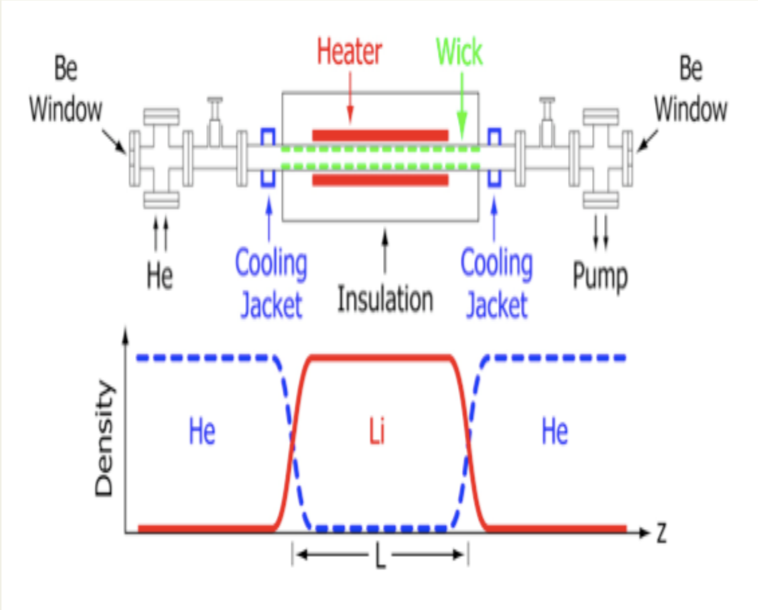
Current activities:

Plasma Cell designs under investigation: UCLA, IPP

Helicon Plasma Cell (IPP)




Heat pipe oven - UCLA




Four different groups undergoing benchmarking of codes for specified parameter sets: K. Lotov (2D, Novosibirsk), A. Pukhov (3D, Düsseldorf), W. Lu (2D, 3D, UCLA), C. Huang (2D,3D Argonne)

Parametric studies, investigations of hosing, two-stream instability, …

Investigations into bunch compression

Currently most promising: uncompressed SPS bunch in long plasma cell; expect few 100 MV/m gradients.

Self-modulation instability of a long proton bunch in plasmas

Naveen Kumar* and Alexander Pukhov
*Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, D-40225 Germany*

Konstantin Lotov
*Budker Institute of Nuclear Physics and Novosibirsk State University, 630090 Novosibirsk, Russia*

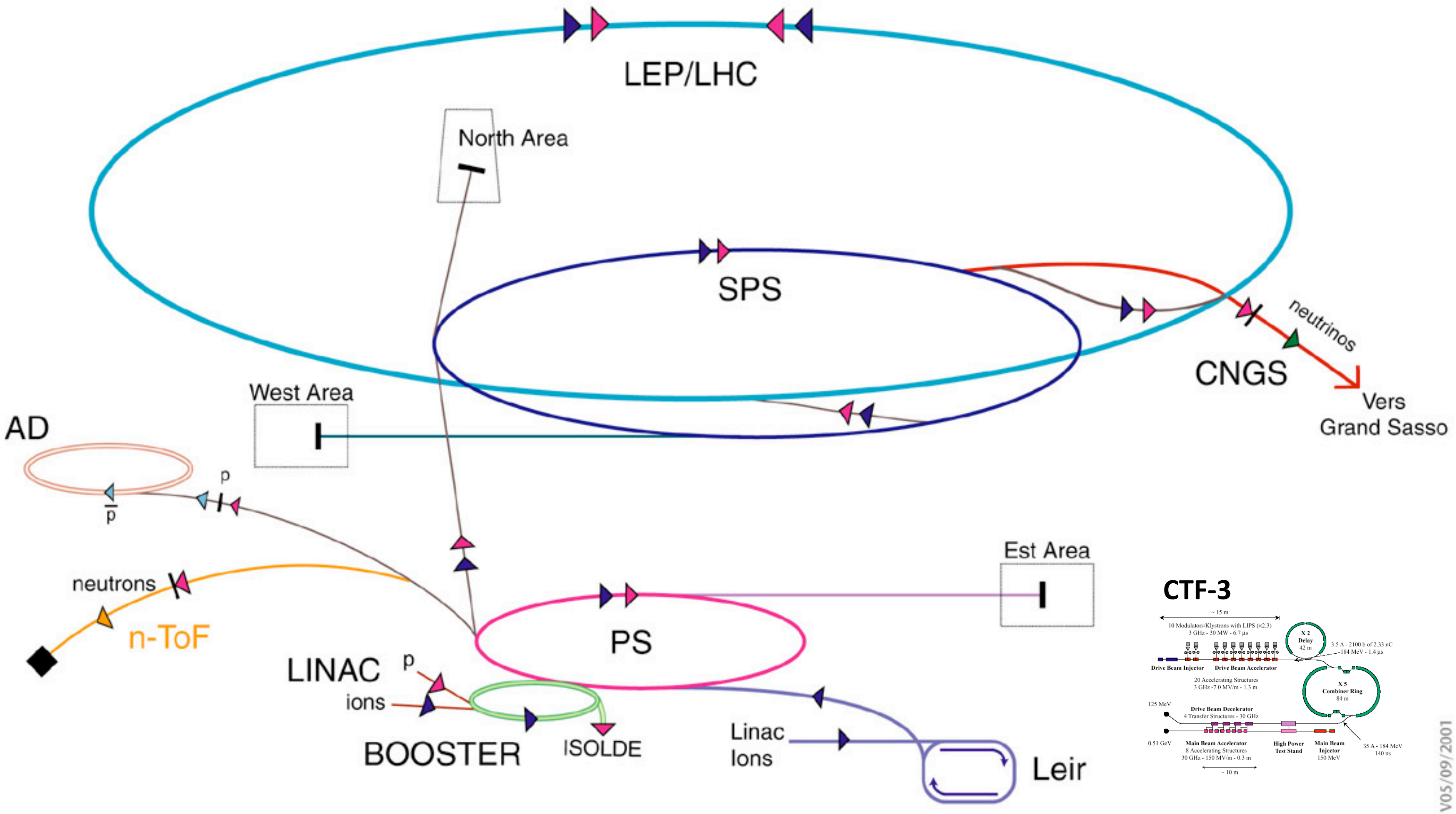
## Theoretical analysis of modulation process

http://arxiv.org/abs/1003.5816

**Assuming full modulation can be achieved, and central +-σ/2 contribute to E field, I find**

| Parameter | PS | SPS-LHC | SPS-Totem | LHC |
|---|---|---|---|---|
| $E_P$ (GeV) | 24 | 450 | 450 | 7000 |
| $N_P$ ($10^{10}$) | 13 | 11.5 | 3.0 | 11.5 |
| $\sigma_P$ (MeV) | 12 | 135 | 80 | 700 |
| $\sigma_z$ (cm) | 20 | 12 | 8 | 7.6 |
| $\sigma_r$ ($\mu$m) | 400 | 200 | 100 | 100 |
| $\sigma_\theta$ (mrad) | 0.25 | 0.04 | 0.02 | 0.005 |
| $\beta^*$ (m) | 1.6 | 5 | 5 | 20 |
| $\epsilon$ (mm-mrad) | 0.1 | 0.008 | 0.002 | $5 \cdot 10^{-4}$ |
| $n_0$ ($10^{15}$ cm$^{-3}$) | 0.16 | 0.63 | 2.5 | 2.5 |
| $eE_0$ (GeV/m) | 1.28 | 2.55 | 5.1 | 5.1 |
| $c/\omega_b$ (m) | 2.4 | 4.0 | 3.3 | 13 |
| $eE_{z,\max}$ (GeV/m) | 0.11 | 0.4 | 0.4 | 1.6 |
| $\alpha$ | 0.09 | 0.16 | 0.08 | 0.31 |
| $L_{\text{dephase}}$ (m) | 9 | 230 | 170 | 2850 |
| $W_{\beta^*}$ (GeV) | 0.18 | 2.0 | 2.1 | 32 |
| $W_{dephase}$ (GeV) | 1.0 | 90 | 70 | 4500 |

# Accelerator chain of CERN (operating or approved projects)




p (proton)
ion
neutrons

p̄ (antiproton)
proton/antiproton conversion
neutrinos

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutrons Time of Flight
CNGS Cern Neutrinos Grand Sasso

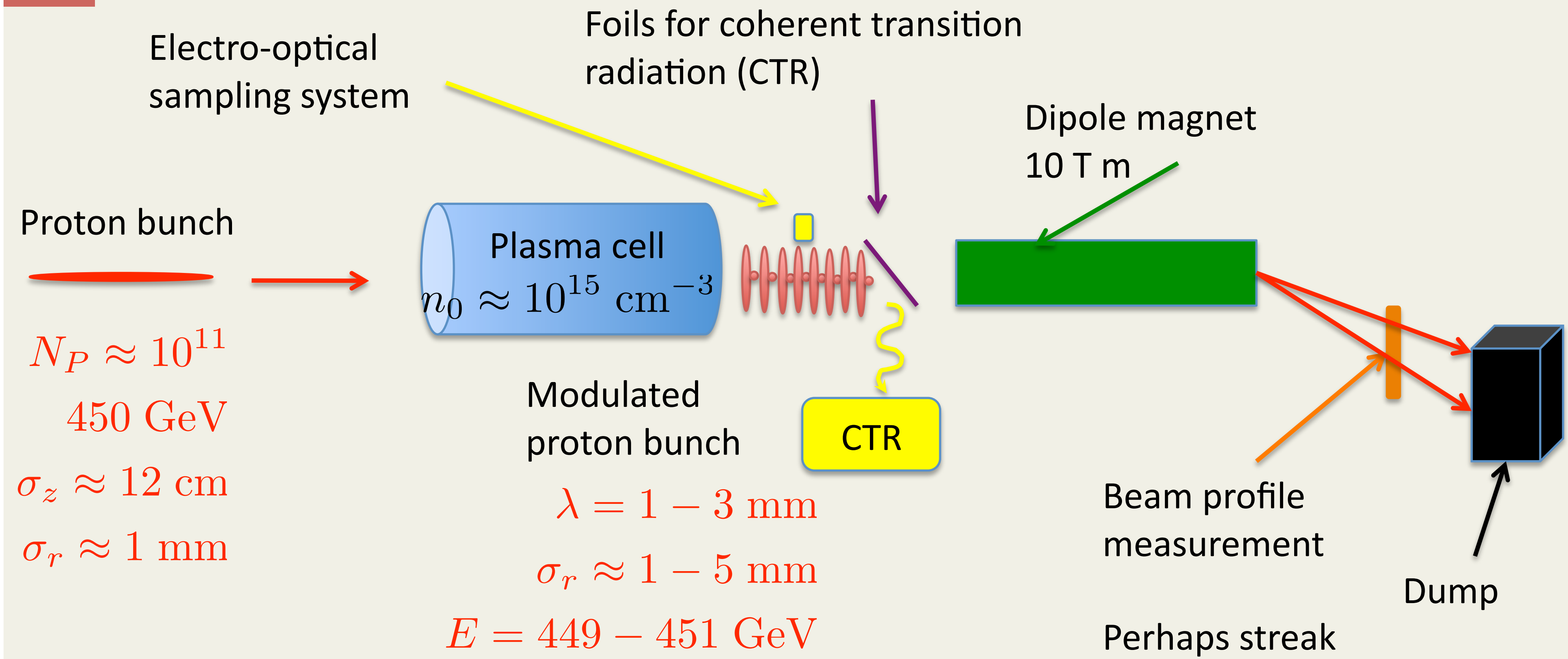
# TT61 tunnel



- Services and infrastructure still in place from the old beam line
- However the power supplies have been dismounted and used as spares for the SPS North Area
- Steep slope 6-7%

# Experimental Layout






Perhaps streak camera to also get time dependence

Coherent transition radiation (CTR) ➔ frequency domain
Electrooptical sampling ➔ time domain information

# Summary

- Plasma wakefields have been demonstrated to produce very large electric fields (>10 GV/m)

- Hope for a more compact/less expensive accelerator

- Proton driven PWA would allow a simpler design – one stage

- demonstration of PDPWA to be proposed at CERN