# A Proposed test of proton-driven plasma wakefield acceleration based on CERN SPS

- Motivation
- Demonstration experiment at CERN
- Simulation of SPS beam-driven PWA
- Summary

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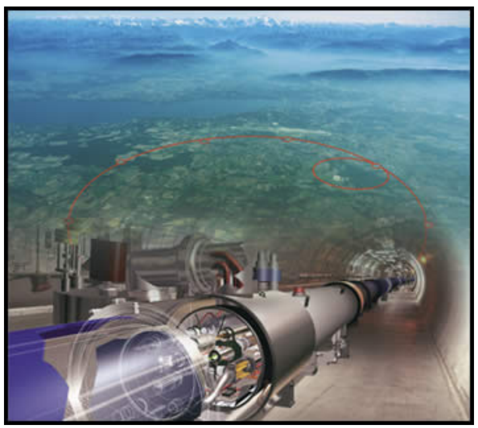
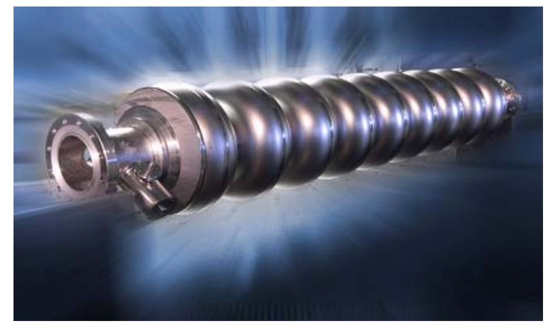
MAX-PLANCK-GESELLSCHAFT

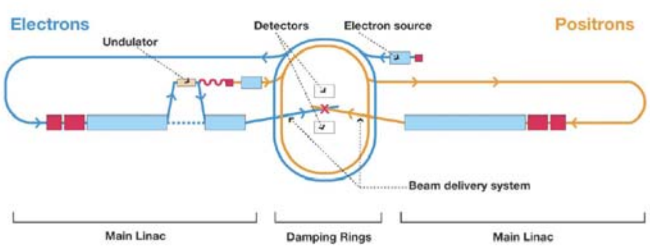
$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

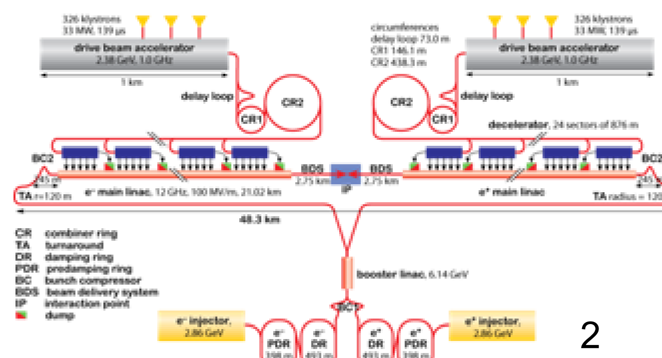
# Motivation

- With an increase of beam energy, the size and cost of modern high energy particle accelerators reach the limit
- Plasma can sustain very large electric fields, a few orders of magnitude higher than the fields in metallic structures
- The plasma accelerators (laser driven-LWFA or beam driven-PWFA) developed rapidly in last decade, 50-100GV/m accelerating gradients have been demonstrated in labs
- The novel plasma accelerators can potentially minimize the size and cost of future machines
- Very high energy proton beams are available nowadays, why not use these proton beam to excite wakefield for electron acceleration?
- Proton driven plasma wakefield hold promise to accelerate electron beam to energy frontier in a single passage of acceleration.

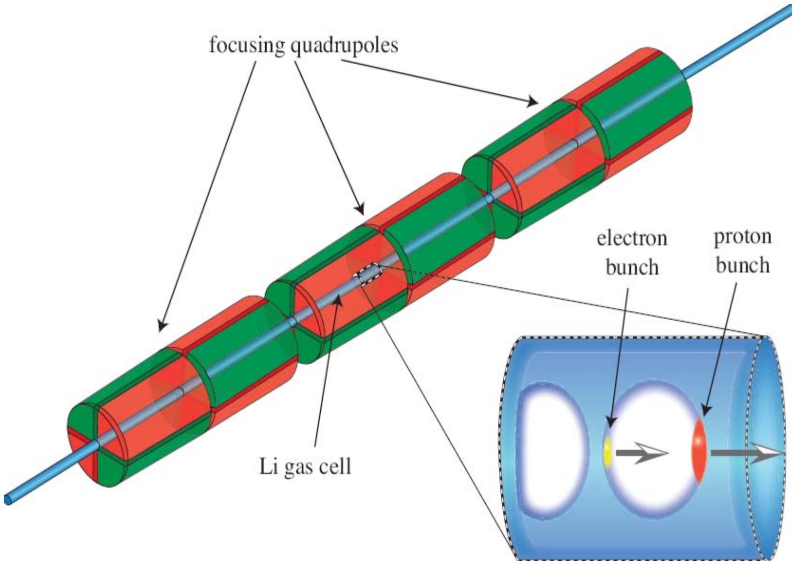


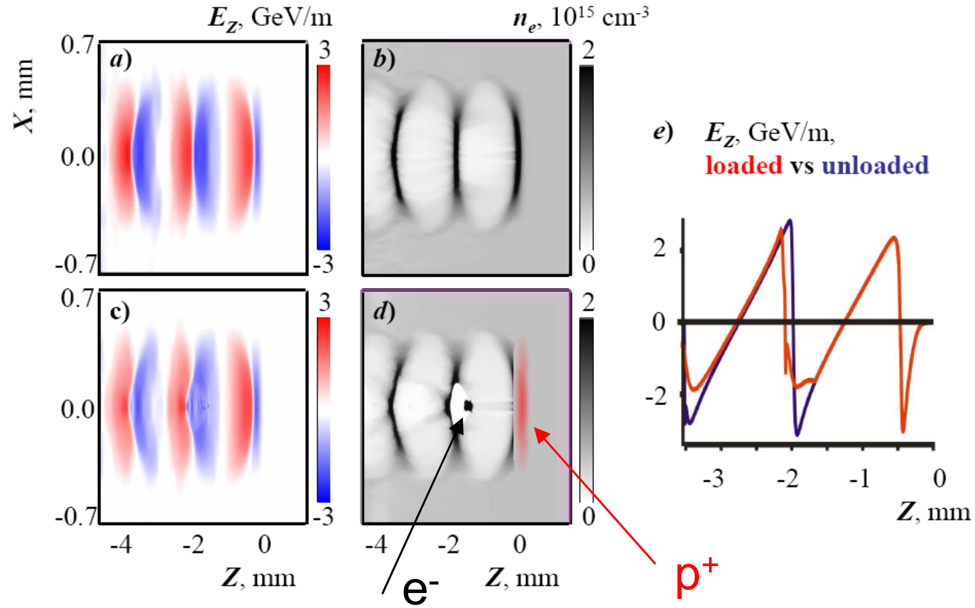




# PDPWA




Drive beam: $p^+$

E=1 TeV, $N_p=10^{11}$

$\sigma_z=100\ \mu m, \sigma_r=0.43$ mm

$\sigma_\theta=0.03$ mrad, $\Delta E/E=10\%$

Witness beam: $e^-$

$E_0=10$ GeV, $N_e=1.5\times10^{10}$

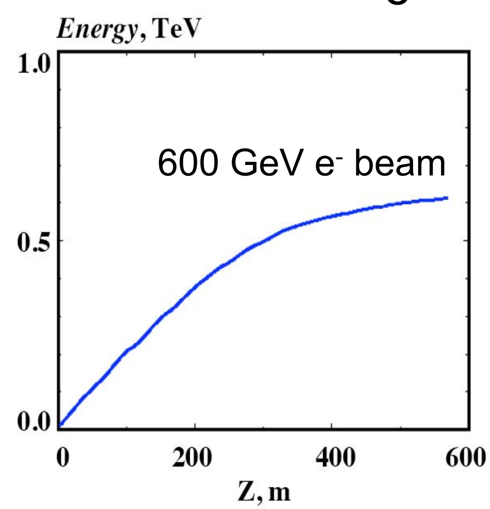
Plasma: $Li^+$

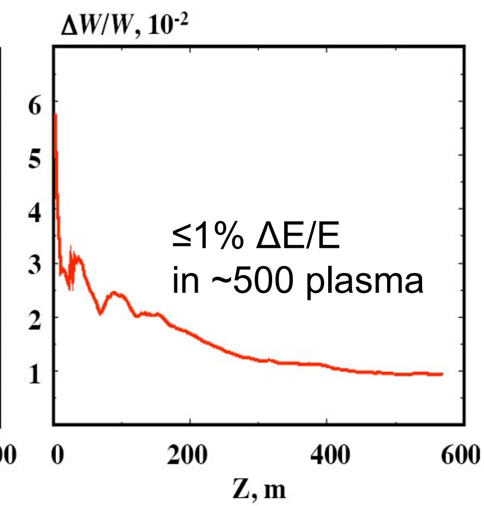
$n_p=6\times10^{14}cm^{-3}$

External magnetic field:

Field gradient: 1000 T/m

Magnet length: 0.7 m






A. Caldwell et al, Nature Physics 5, 363 (2009).

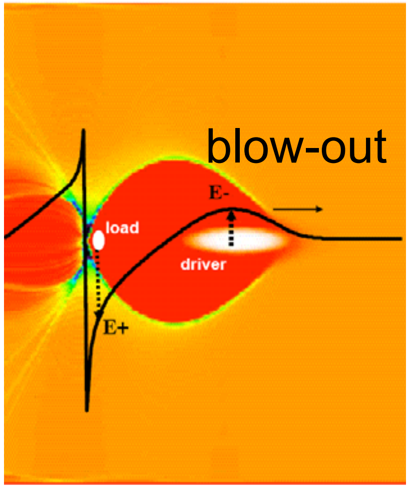
# PWFA *vs.* PDPWA

**Pros. of PWFA**

Plasma electrons are expelled by space charge of beam, a nice bubble will be formed for beam acceleration and focusing.

The short electron beam is relatively easy to have (bunch compression).

Wakefield phase slippage is not a problem.




**Cons. of PWFA**

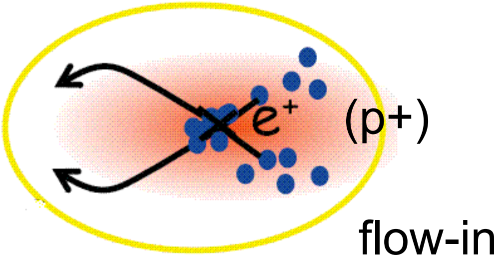
One stage energy gain is limited by transformer ratio, therefore maximum electron energy is about 100 GeV using SLC beam.

Easy to be subject to the head erosion due to small mass of electrons

**Pros. of PDPWA**

Very high energy proton beam are available today, the energy stored at SPS, LHC, Tevatron

SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ
LHC (1 TeV, 1.15e11 p/bunch) ~ 20 kJ
LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ
SLAC (50 GeV, 2e10 e-/bunch) ~ 0.1 kJ

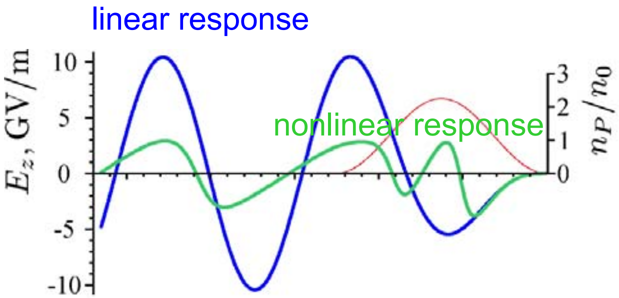



**Cons. of PDPWA**

Flow-in regime responds a relatively low field *vs*. blow-out regime.

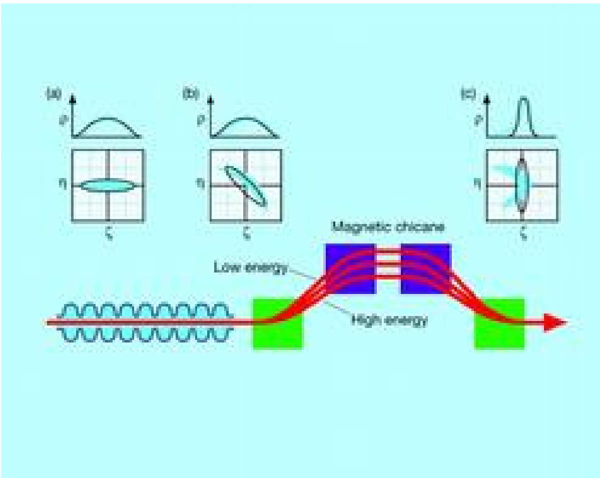
Long proton bunches (tens centimeters), bunch compression is difficult.

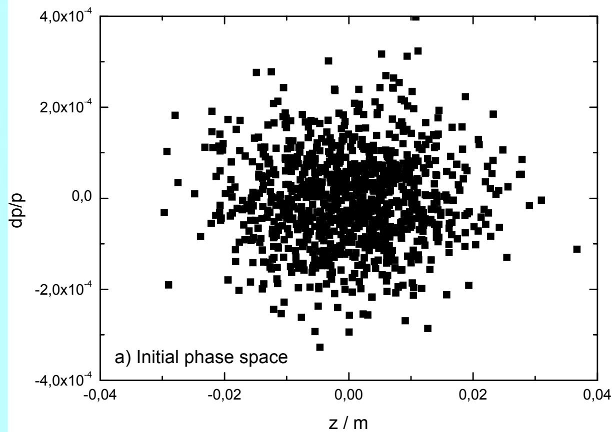
Wave phase slippage for heavy mass proton beam (small γ factor), especially for a very long plasma channel

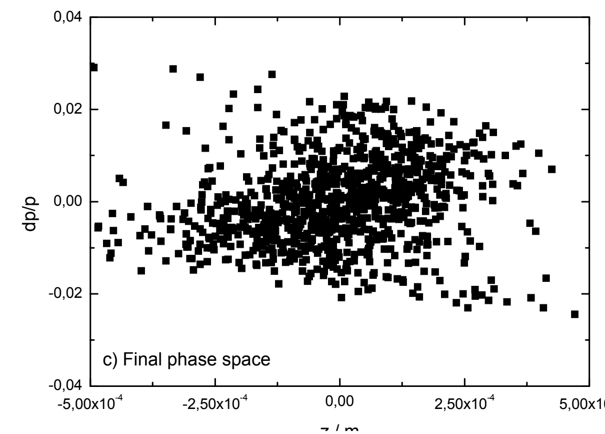


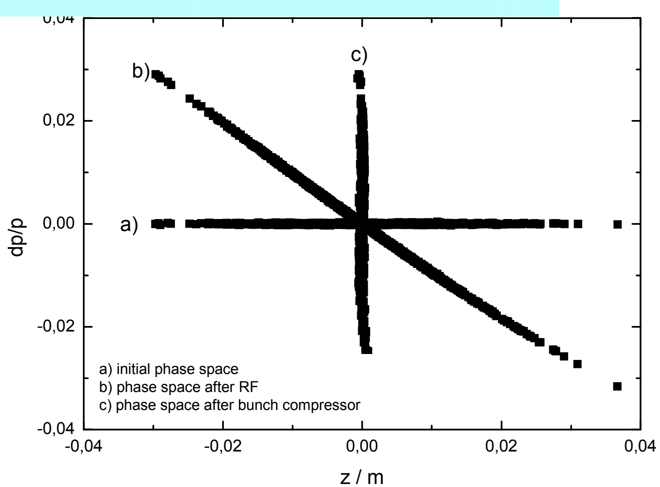
# Short proton driver

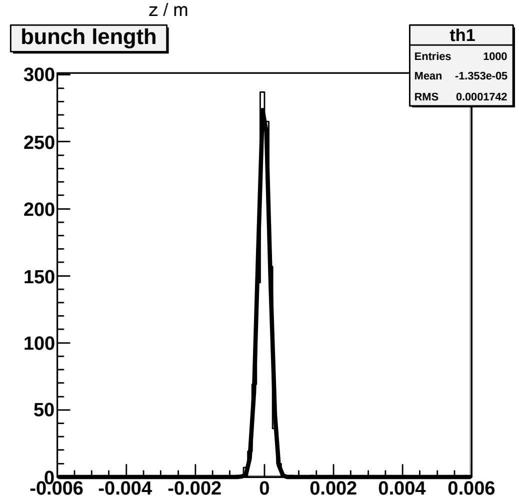
- A magnetic chicane for bunch compression

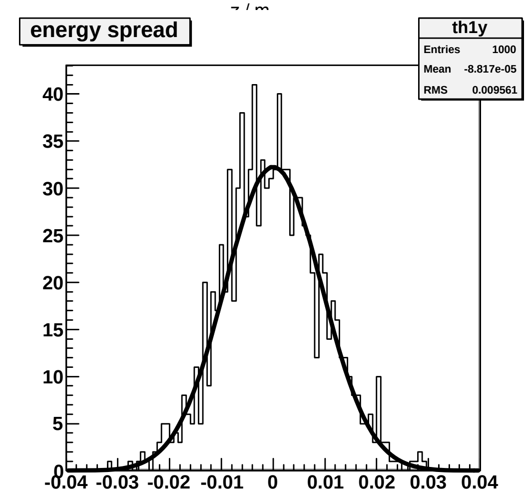



**4 km bunch compressor is required for 1 TeV p+ beam!**

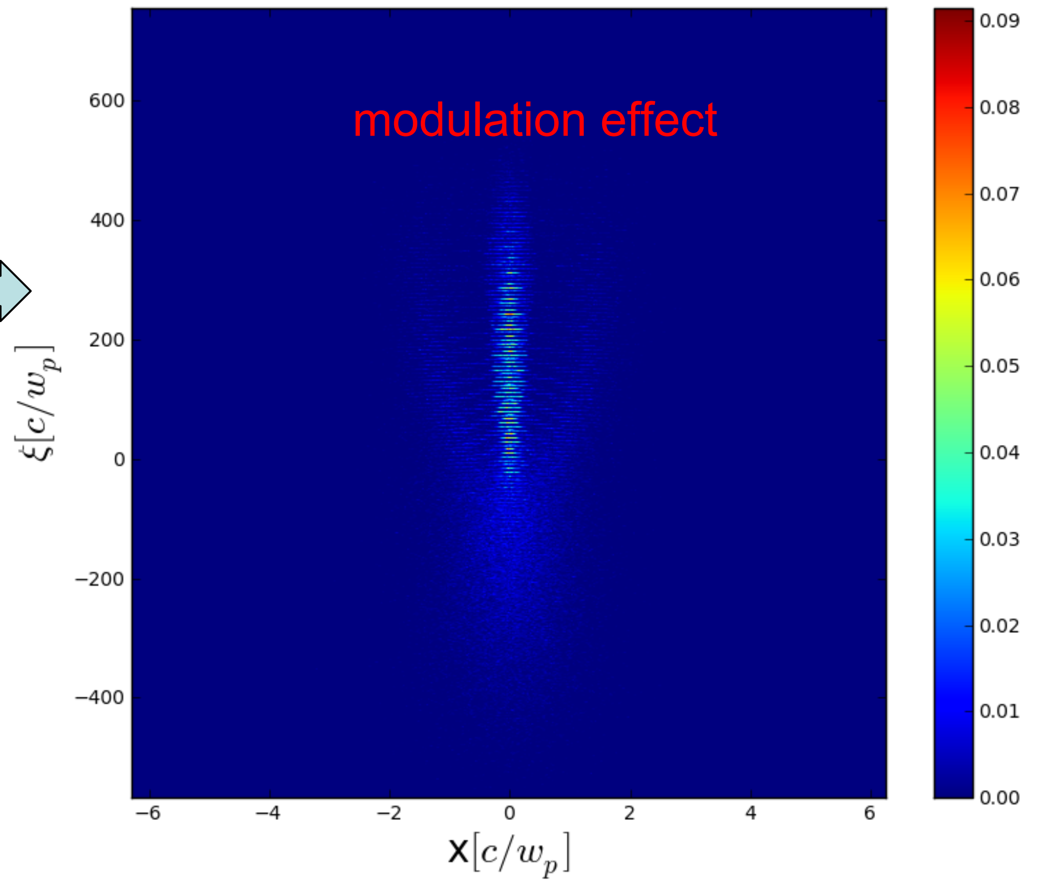


G. Xia et al., Proceedings of PAC09

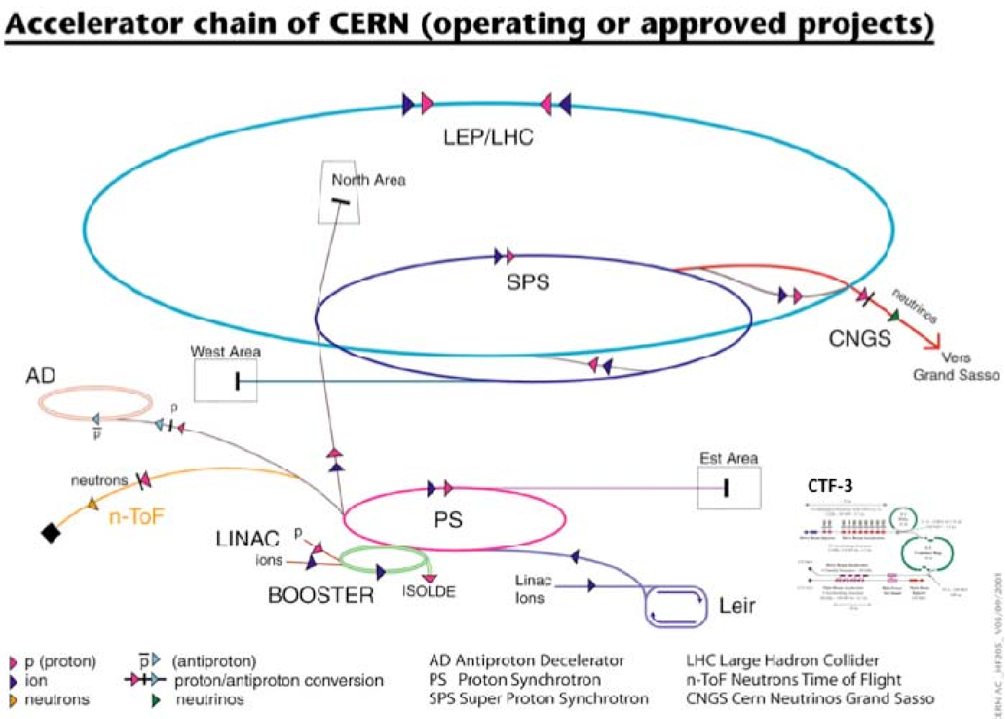
# Short bunch driver

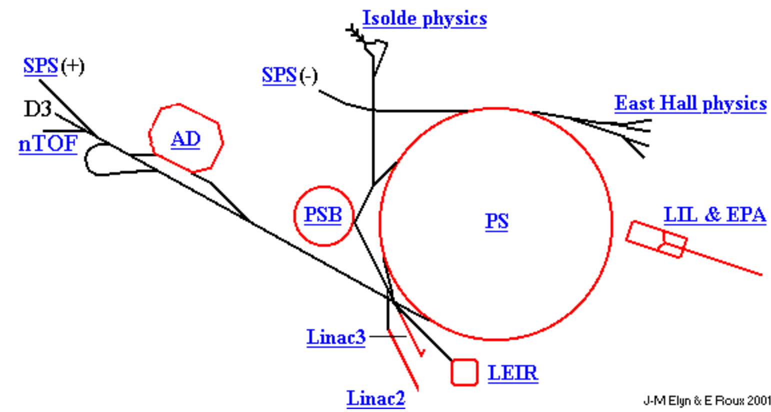
- Self-modulation via plasma wakefield (the transverse instability modulates the long bunch into many ultra short beamlets at plasma wakelength.

SPS beam at 5m
Plasma @ 1e14 $cm^{-3}$



# Demonstration experiment at CERN



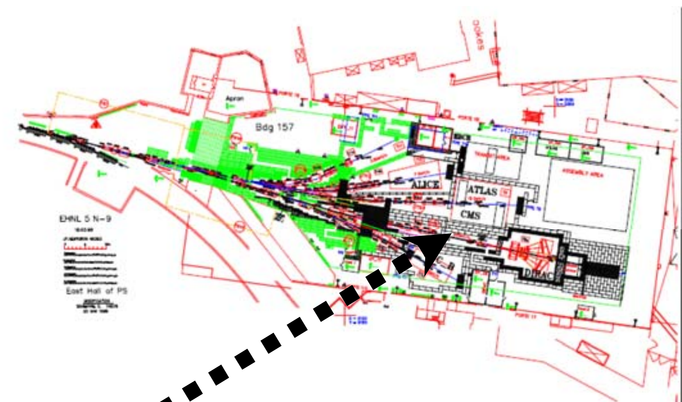
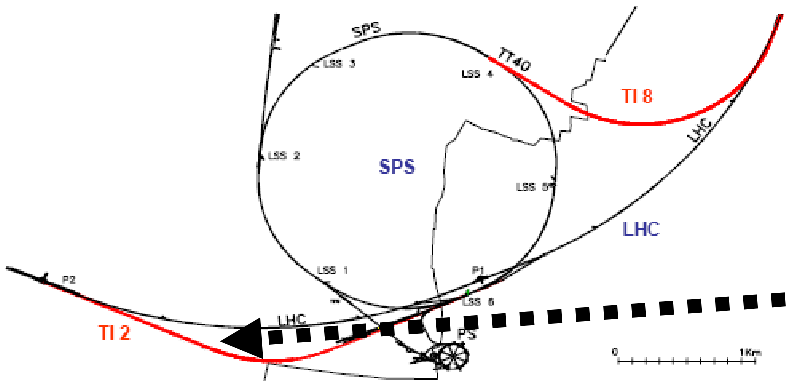



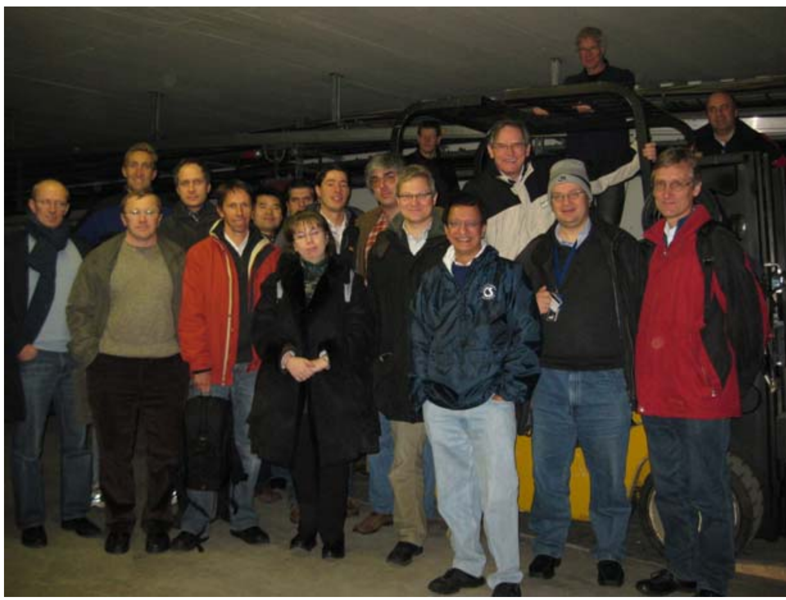
Figure: Beam lines in the PS East Hall. T7 and T8 are near the bottom. The maximum length is below 100 m.



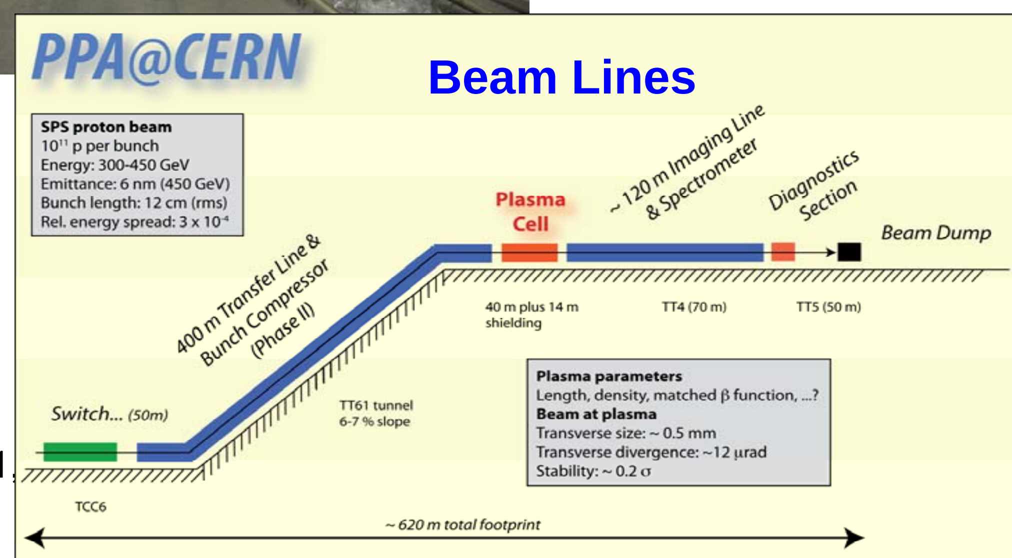

**PS** (East Hall Area) and **SPS** (West Area) could be used for our demonstration experiment

# Demonstration experiment at CERN

- PDPWA has the potential to accelerate electron beam to the TeV scale in a single stage. As a first step, we would like to demonstrate the scaling laws of PDPWA in an experiment with an existing beam
- kick-off meeting-PPA09 held at CERN in December 2009
- A spare SPS tunnel is available for demonstration experiment
- With no bunch compression in the beginning



http://indico.cern.ch/conferenceDisplay.py?confId=74552



# Codes benchmarking

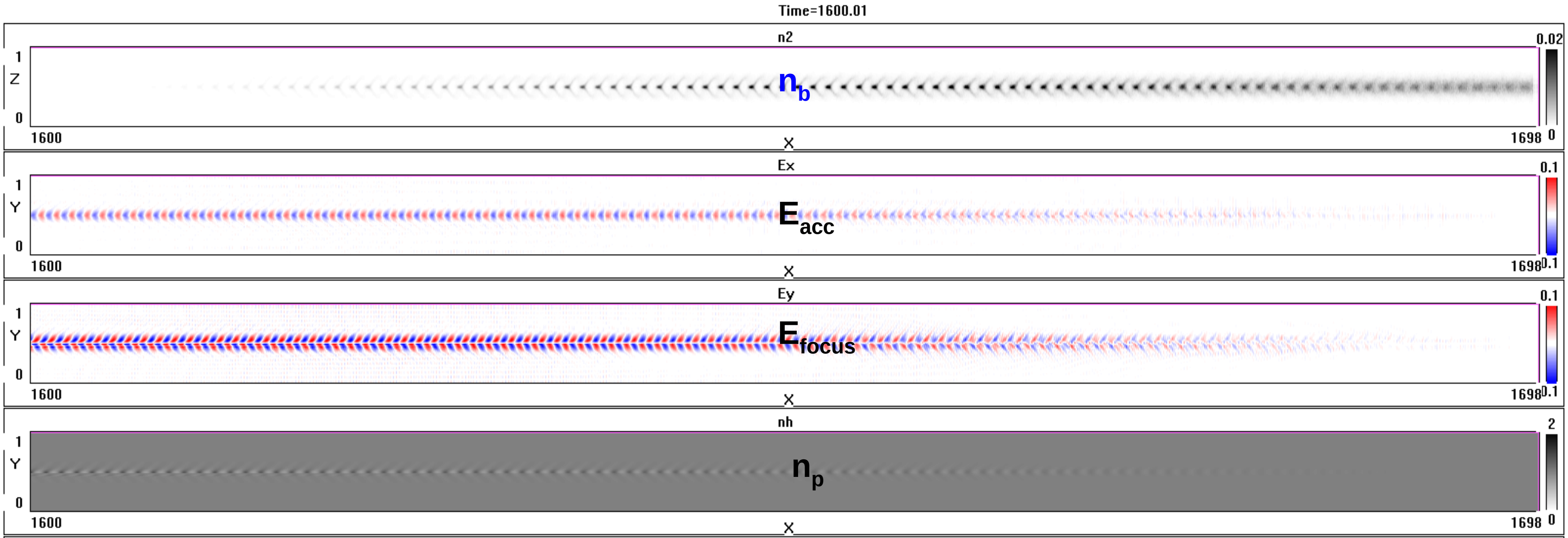
TABLE 1. PS, SPS and LHC parameter sets. The different symbols are defined in the text. SPS-LHC means the standard parameters of bunches in the SPS for injection into the LHC. SPS-Totem means the special parameters for bunches for use by the Totem experiment.

| 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 |
| $\sigma_{E_P}$ (MeV) | 12 | 135 | 80 | 700 |
| $\sigma_{z,0}$ (cm) | 20 | 12 | 8 | 7.6 |
| $\sigma_r$ ($\mu$m) | 400 | 200 | 100 | 100 |
| $c/\omega_b$ (m) | 2.3 | 4.0 | 3.2 | 6.3 |
| $\sigma_\theta$ (mrad) | 0.25 | 0.04 | 0.02 | 0.005 |
| $L_\theta$ (m) | 1.6 | 5 | 5 | 20 |
| $\epsilon$ (mm-mrad) | 0.1 | 0.008 | 0.002 | $5 \cdot 10^{-4}$ |

Various particle-in-cell (PIC) and hybrid codes have been used to benchmark the results based on same parameter set. Presently they show very good agreement !

# Seeding the instability

- Seed the instability via laser or electron beam prior to the proton beam (the instability will not start from random noise, rather from a well-defined seeded field
- The instability is seeded via half-cut beam (beam density abruptly increases)



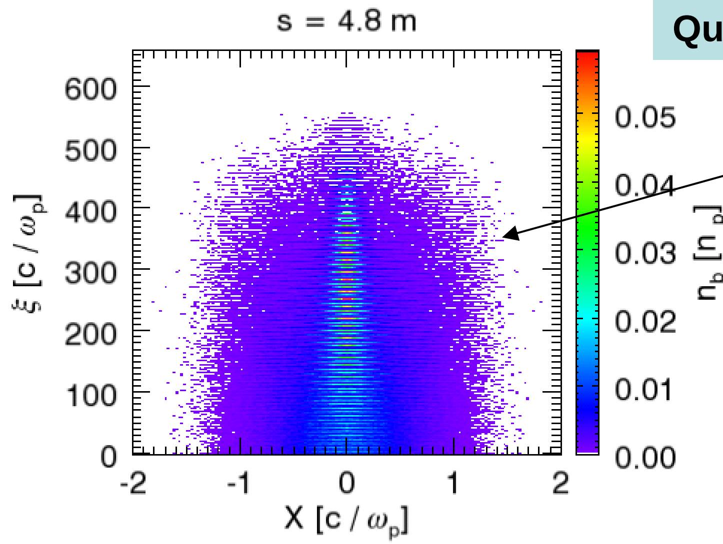

For SPS half-cut beam, at plasma density $n_p=10^{14}$ $cm^{-3}$ ($\lambda_p \approx 3.33$ mm)
A strong beam density modulation is observed,
A nice wakefield structure is excited and
the wakefield amplitude is around 100 MV/m at 5 m plasma.



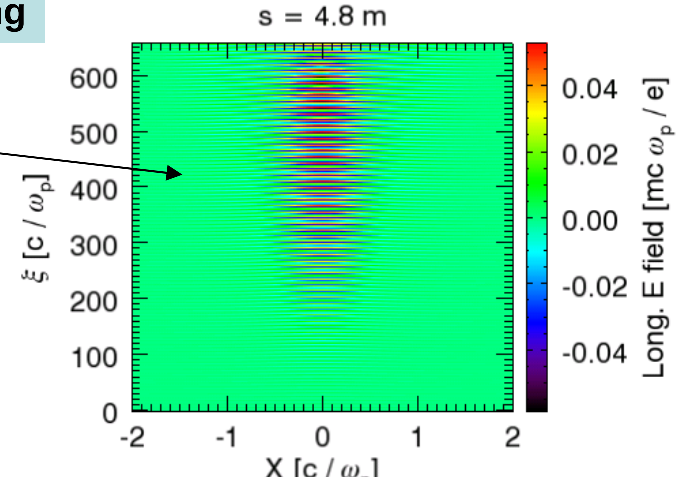

A. Pukhov (Duesseldorf Uni.)

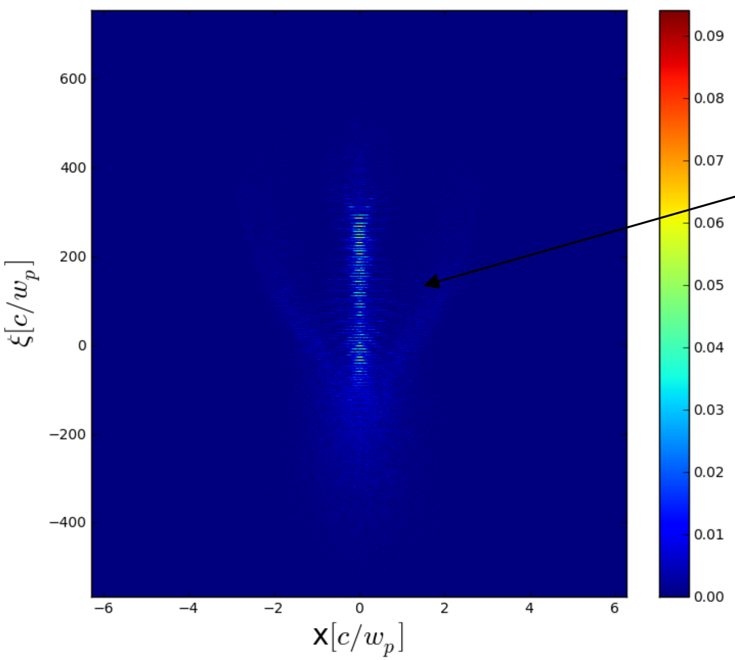
# Simulations of SPS beam-driven PWFA

**QuickPIC results from C. Huang**

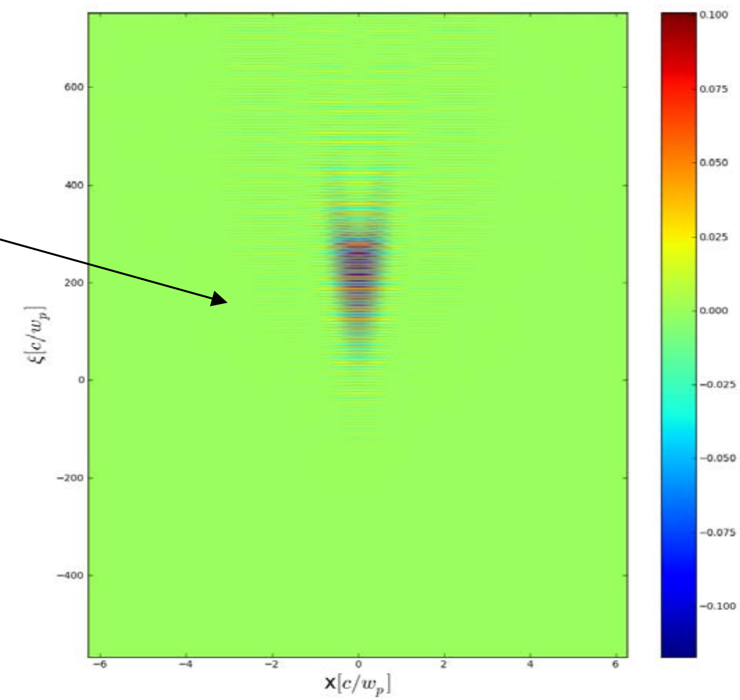



Half-cut SPS beam @4.8m plasma ($n_p=10^{14}$ cm$^{-3}$)




Full SPS beam @ 10m plasma ($n_p=10^{14}$ cm$^{-3}$)



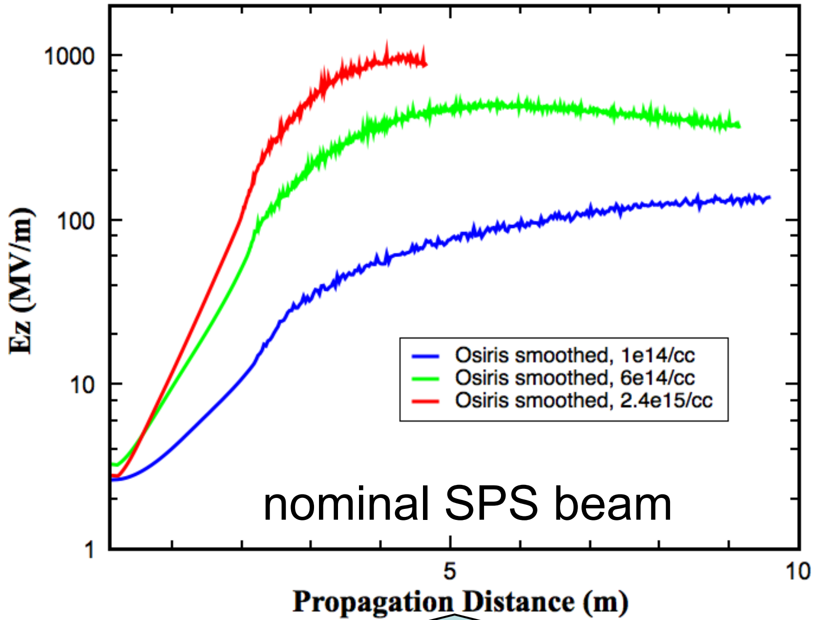

PAC11, New York, USA

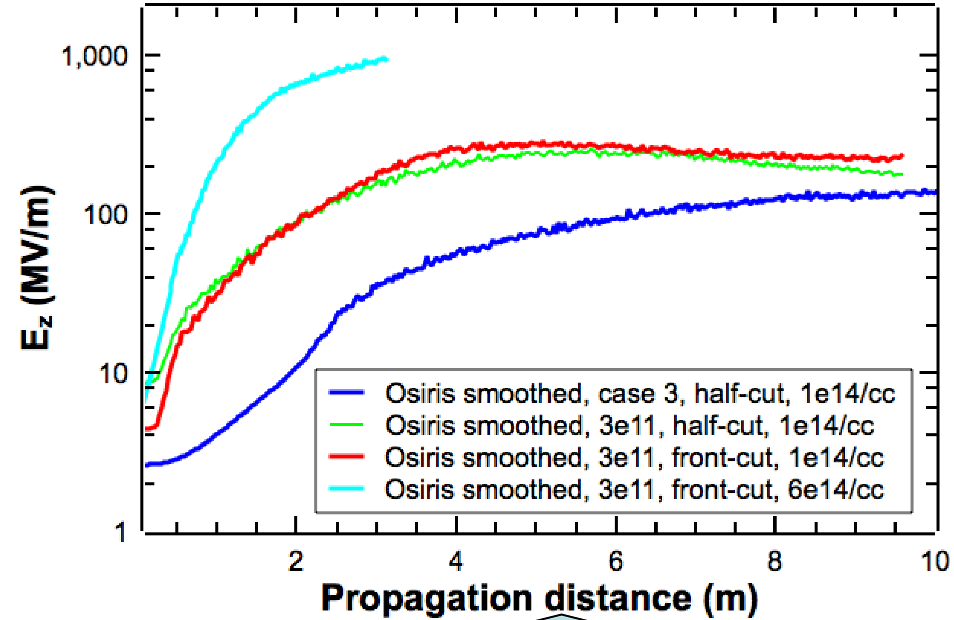
**Beam density modulation**

**Maximum longitudinal e field is ~120 MV/m**

# Simulations of SPS beam-driven PWFA

Simulation from 2D OSIRIS

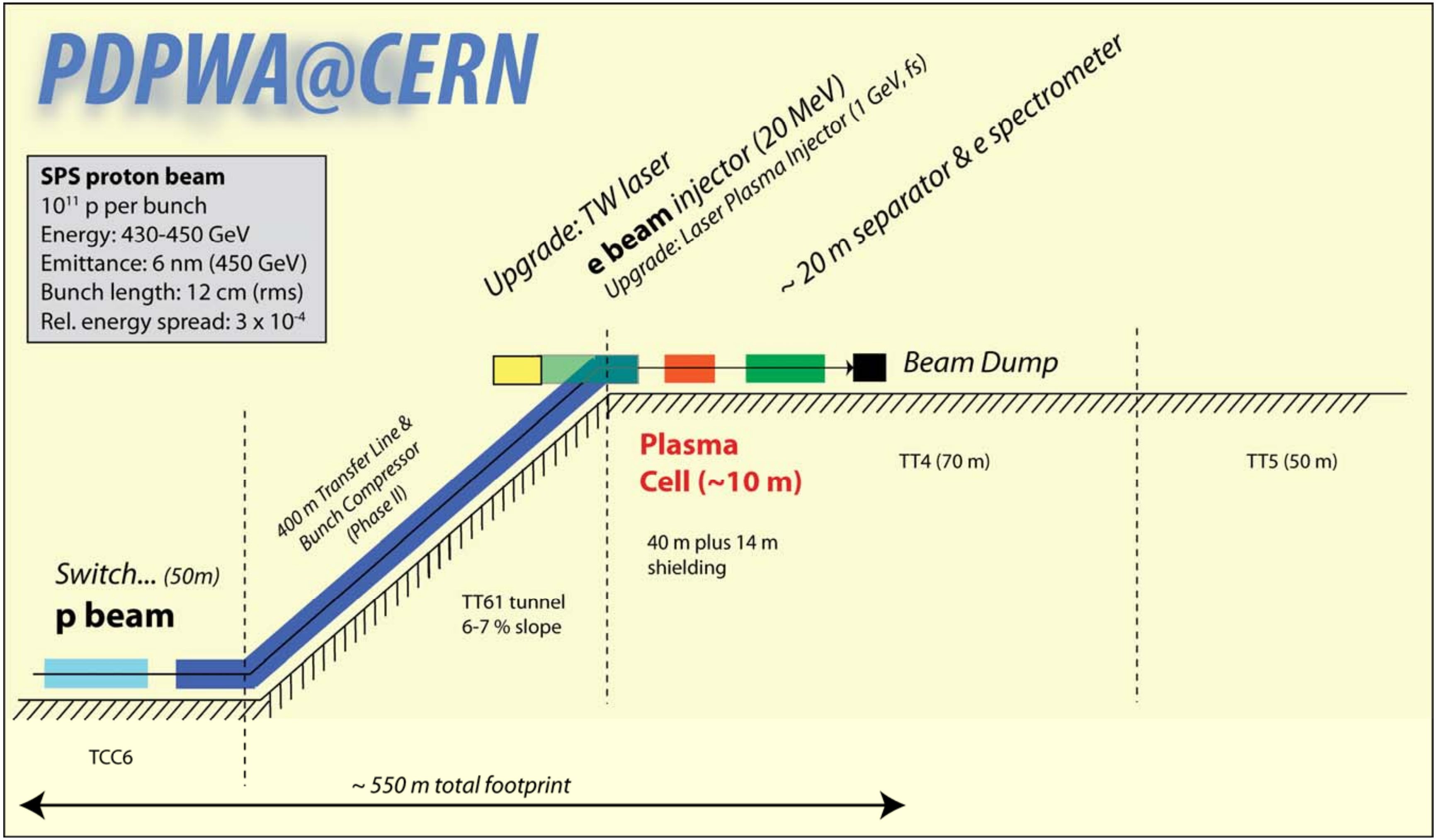


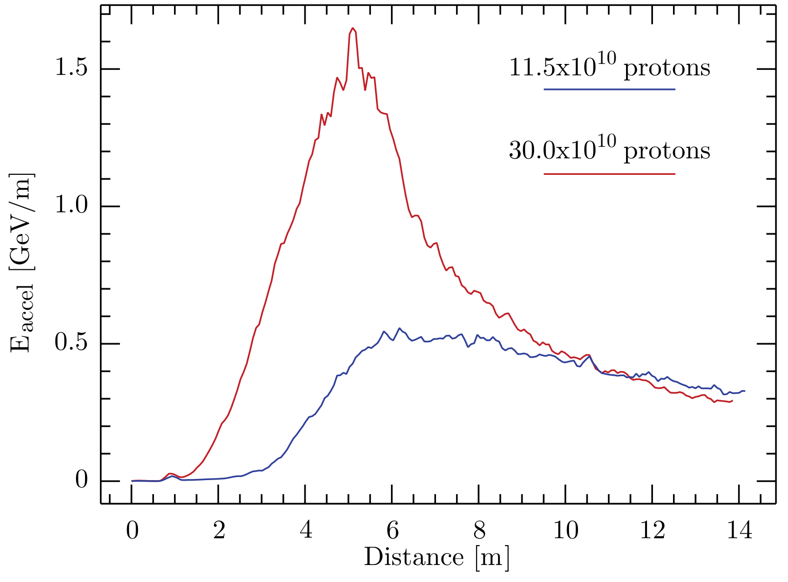

| | |
|---|---|
| Bunch population, $N_p$ | 1.15x$10^{11}$ |
| Bunch length, $\sigma_z$ | 12 cm |
| Beam radius, $\sigma_{x,y}$ | 200 μ m |
| Beam energy, E | 450 GeV |
| Energy spread, dE/E | 0.03% |
| Normalized emittance, $\varepsilon_{x,y}$ | 3 μ m |
| Angular spread, $\sigma_\theta$ | 0.02 mrad |

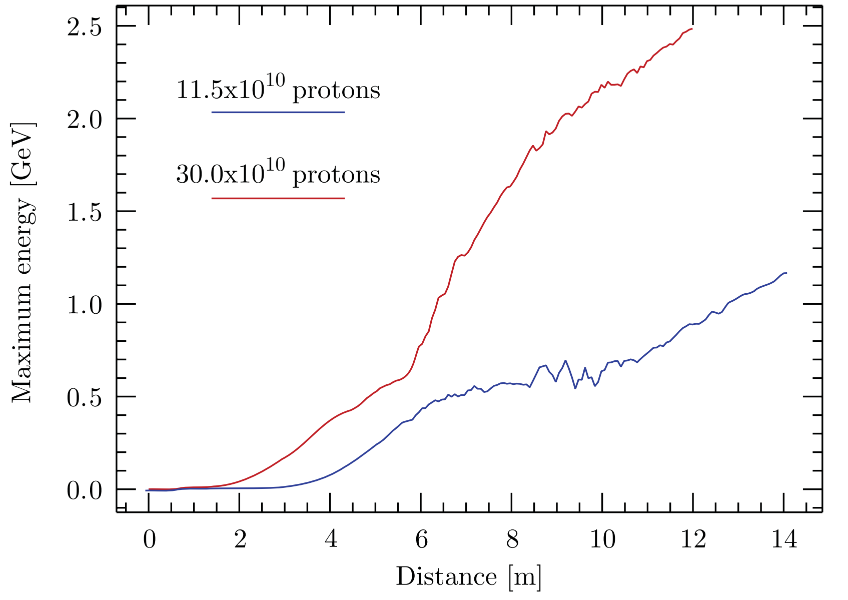
| | |
|---|---|
| Bunch population, $N_p$ | 3x$10^{11}$ |
| Bunch length, $\sigma_z$ | 8.5 cm |
| Beam radius, $\sigma_{x,y}$ | 200 μ m |
| Beam energy, E | 450 GeV |
| Energy spread, dE/E | 0.04% |
| Normalized emittance, $\varepsilon_{x,y}$ | 2 μ m |
| Angular spread, $\sigma_\theta$ | 0.02 mrad |

# Layout of beam line



# Electron acceleration



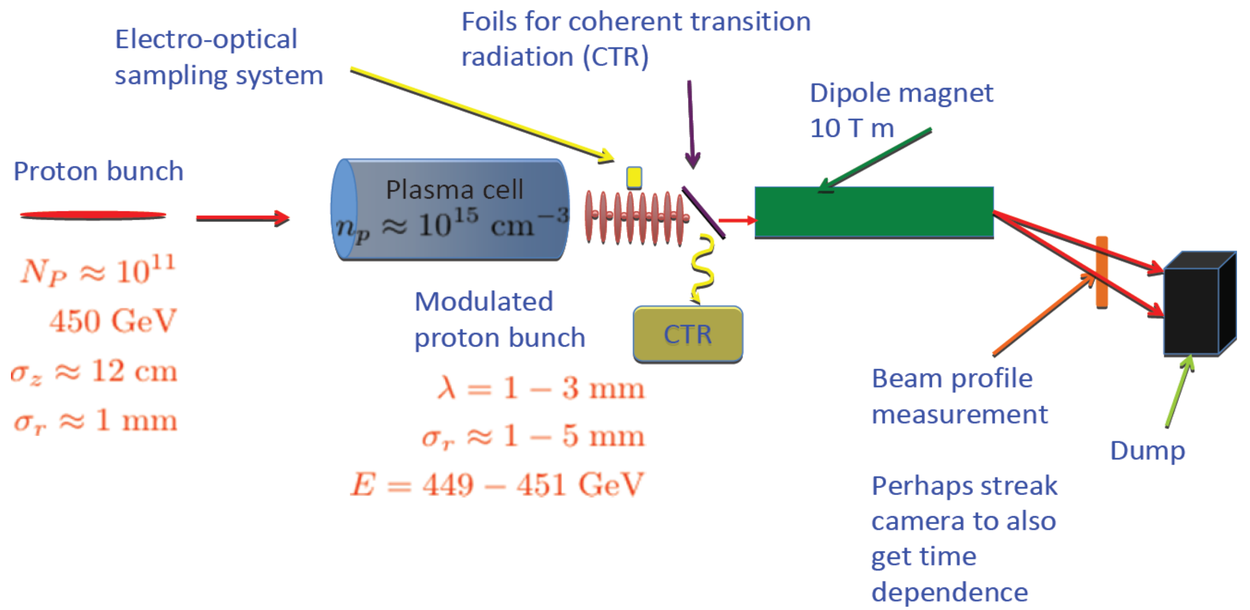

| | SPS-LHC | SPS-Opt. |
|---|---|---|
| Beam energy [GeV] | 450 | 450 |
| Bunch population [$10^{11}$] | 1.15 | 3.0 |
| Beam radius [ μ m] | 200 | 200 |
| Angular spread [mrad] | 0.04 | 0.04 |
| Normalized emittance [ μ m] | 3.5 | 3.5 |
| Bunch length [cm] | 12 | 12.4 |
| Energy spread [%] | 0.03 | 0.03 |

# Demonstration experiment at CERN

**Scientific Goal of Experiments:**

- Initial goal is to observe the energy gain of 1 GeV in 5 m plasma.
- A plan for reaching 100 GeV within 100 m plasma will be developed based on the initial round of experiments

**Experimental Setup:**




**Expected Results:**

- A long SPS beam (uncompression) will be used in the first experiment. a self-modulation of the beam due to the transverse instability will produce many ultrashort beam slices at plasma wavelength.
- The modulation could resonantly drives wakefield in hundreds MeV/m with CERN SPS beam.
- Simulation shows that at optimum beam and plasma parameters, ≥ 1 GV/m field can be achieved.

# List of people discussing project

**Max Planck Institute for Physics, Germany**
A. Caldwell, O. Reimann, H.V.D. Schmitt,
F. Simon, G. Xia

**DESY**
E. Elsen, B. Schmidt, H. Schlarb, J. Osterhoff

**Duesseldorf University, Duesseldorf, Germany**
A. Pukhov, N. Kumar, A. Upadhyay

**Heidelberg University, Heidelberg, Germany**
A. Schoening

**Karlsruher Institute for Technology, Germany**
A. Mueller, S. Hillenbrand

**Ludwig-Maximilians Universität LMU, Germany**
T. Tajima

**Max Planck Institute for Plasma Physics, Germany**
O. Gruelke, T. Klinger

**Budker Institute for Nuclear Physics, Russia**
K. Lotov

**CERN, Geneva, Switzerland**
R. Assmann, F. Zimmermann, I. Efthymiopoulos,
J.P. Koutchouk, G. Geschonke

**GoLP/Instituto de Plasmas e Fusao Nuclear, IST, Lisboa, Portugal**
J. Vieira, R. A. Fonseca, N. Lopes, L.O. Silva

**University of College London, London, UK**
A. Lyapin, M. Wing, J. Holloway

**Rutherford Appleton Laboratory, Chilton, UK**
R. Bingham, R. Trines

**John Adams Institute for Accelerator Science, UK**
A. Seryi

**Imperial College, London**
Z. Najmudin

**University of California, Los Angeles, CA, USA**
W. An, C. Joshi, W. Lu, W.B. Mori

**Los Alamos National Laboratory, NM, USA**
C. Huang

**University of Southern California, CA, USA**
P. Muggli

**SLAC National Accelerator Laboratory**
M. Hogan

# CERN's interest

PDPWA collaboration:
Several workshops, biweekly phone meeting, and site visit at CERN

Steve Myers
CERN Director of Accelerators & Technology

**CERN COURIER**

Feb 24, 2010

**Workshop pushes proton-driven plasma wakefield acceleration**

PPA09

PPA09, a workshop held at CERN on proton-driven plasma wakefield acceleration, has launched discussions about a first demonstration experiment using a proton beam. Steve Myers, CERN's director for Accelerators and Technology, opened the event and described its underlying motivation. Reaching higher-energy collisions for future particle-physics experiments beyond the LHC requires a novel accelerator technology, and "shooting a high-energy proton beam into a plasma" could be a promising first step. The workshop, which brought together participants from Germany, Russia, Switzerland, the UK and the US, was supported by the EuCARD AccNet accelerator-science network (**CERN Courier** November 2009 p16).

Plasmas, which are gases of free ions and electrons, can support large

*"CERN is very interested in following and participating in novel acceleration techniques, and has as a first step agreed to make protons available for the study of proton-driven plasma wakefield acceleration."*

# Summary

- **High energy proton bunch can indeed drive a high wakefield for electron beam acceleration**
- **Simulation shows that working in self-modulation regime, SPS beam can excite the field around 1 GV/m with a high density plasma.**
- **Externally injected electron can be accelerated to 1-2 GeV in 10 m plasma.**
- **The PDPWA demonstration experiment will be proposed as a future project**
- **Future experiment will be carried out based upon the first round experiments.**

*Thanks for your attention*!