Proton-Driven Plasma Wakefield Acceleration at CERN

Steffen Hillenbrand,
For the PDPWFA collaboration

The PDPWFA Collaboration

Letter of Intent
for a Demonstration Experiment in
Proton-Driven Plasma Wakefield Acceleration

E. Adli[24], W. An[22], R. Assmann[3], R. Bingham[19], A. Caldwell[16], S. Chattopadhyay[4], N. Delerue[12], F. M. Dias[8], I. Efthymiopoulos[3], E. Elsen[5], S. Fartoukh[3], C. M. Ferreira[8], R. A. Fonseca[8], G. Geschonke[3], B. Goddard[3], O. Grülke[17], C. Hessler[3], S. Hillenbrand[11], J. Holloway[19,23], C. Huang[14], D. Jarozinsky[25], S. Jolly[23], C. Joshi[22], N. Kumar[7], W. Lu[21,22], N. Lopes[8], M. Kaur[18], K. Lotov[2], V. Malka[13], M. Meddahi[3], O. Mete[3], W.B. Mori[22], A. Mueller[11], P. Muggli[16], Z. Najmudin[9], P. Norreys[19], J. Osterhoff[5], J. Pozimski[9], A. Pukhov[7], O. Reimann[16], S. Roesler[3], H. Ruhl[15], H. Schlarb[5], B. Schmidt[5], H.V.D. Schmitt[16], A. Schöning[6], A. Seryi[10], F. Simon[16], L.O. Silva[8], T. Tajima[15], R. Trines[19], T. Tückmantel[7], A. Upadhyay[7], J. Vieira[8], O. Willi[7], M. Wing[23], G. Xia[16], V. Yakimenko[1], X. Yan[20], F. Zimmermann[3]

CERN-SPSC-2011-020 / SPSC-I-240

Outline

- Motivation: Protons as Driver for HEP
  (High Energy Physics)
- The Planned Experiment
- High Energy Outlook

LWFA and HEP – Staging Unavoidable

Example Linear Collider

(15 MW beam power, 3 TeV):

- Energy Laser pulse:

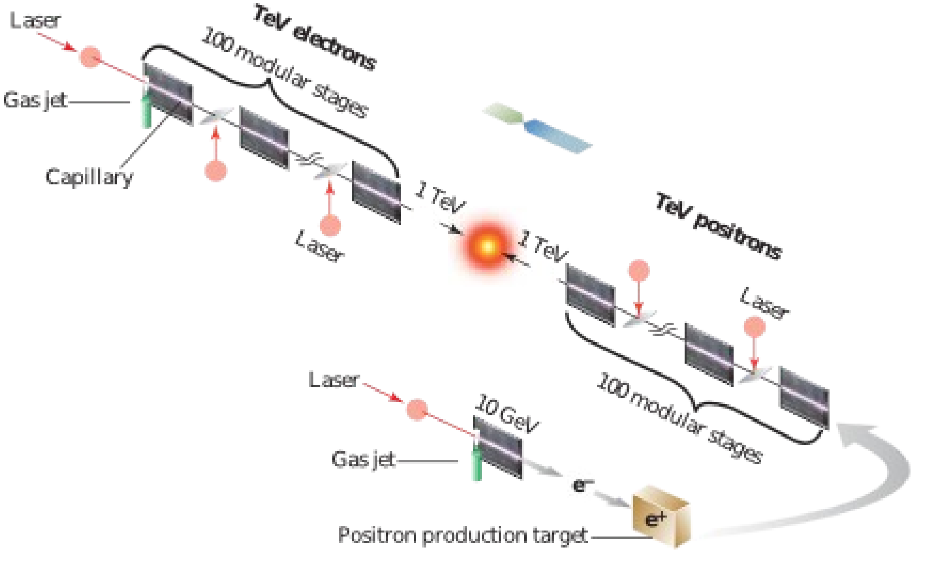
  0.5 J – 40 J

- Energy need witness bunch:

  300 J – 1000 J

- This means many stages at kHz rep rates!

- Alignment / Synchronization very challenging ($\ll \lambda_p$) !



Picture:
Leemans 2009, doi: 10.1063/1.3099645

PWFA - Transformer Ratio and e⁻-Driver

- For unshaped bunches, the energy gain of the witness bunch is limited by the Transformer Ratio*:

$$\Delta E_{witness} = R \cdot E_{drive} \qquad R = 2 - \frac{N_{witness}}{N_{drive}}$$

- This means means that to reach the TeV scale, we need a high energy drive beam or again several stages.

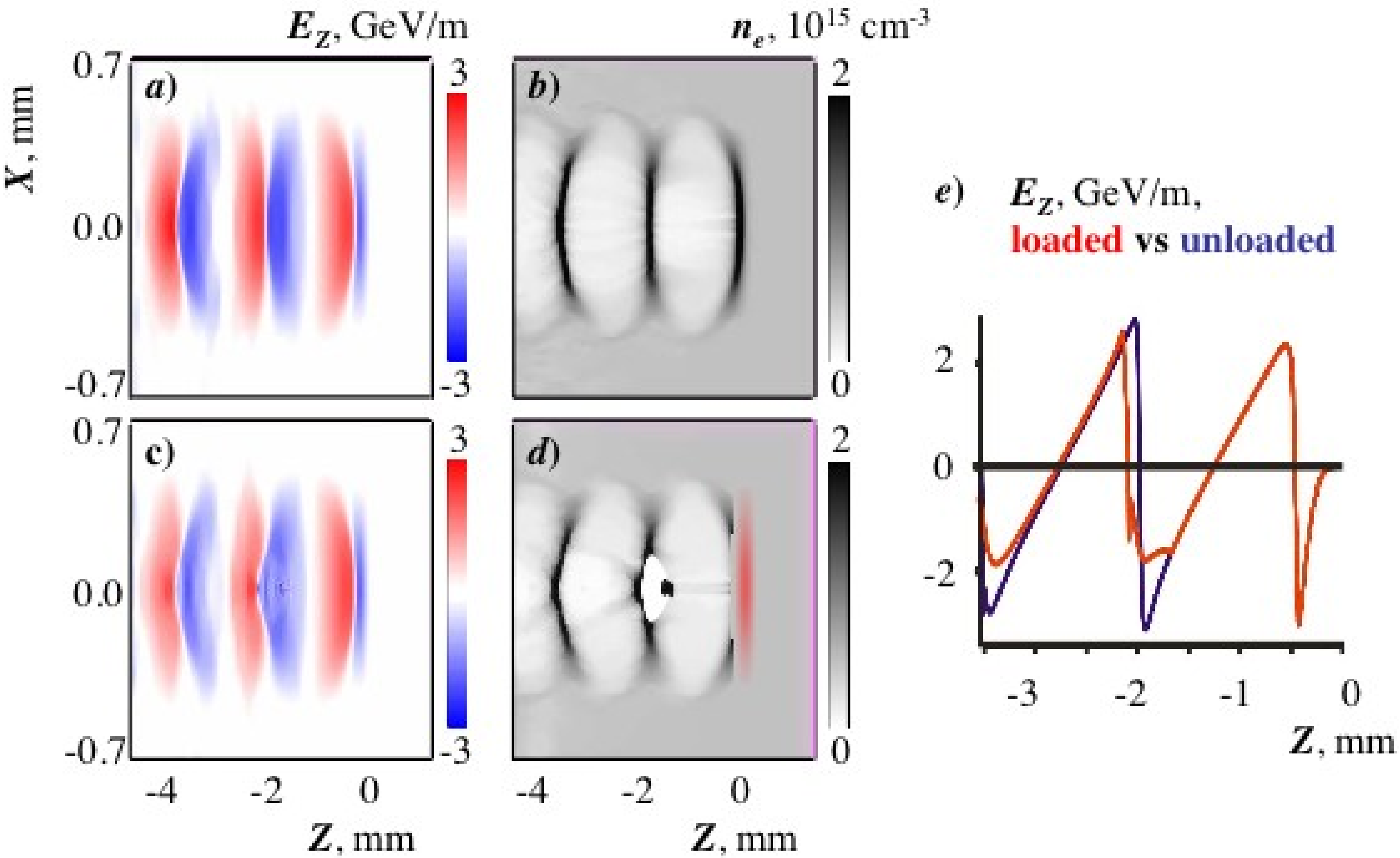
- For a high energy electron drive beam, Synchrotrons get prohibitevely expensive due to Synchrotron radiation losses ($\alpha \frac{E^2}{m^4}$).

* See e.g. R. Ruth et al., SLAC-PUB-3374, 1984

Protons as Driver

- Unlike electrons, protons can be accelerated to very high energies using synchrotrons.
- With a 1 TeV p-driver an electron beam could be accelerated to up to 1 TeV in *<u>one single stage</u>*!
- Protons are positively charged.
  - They don't blow out the plasma electrons, they suck them in.
  - The general acceleration mechanism is similar.

Density & Fields



A. Caldwell et al., Nature Physics 5, 363 - 367 (2009)

Ideal Proton Beam

- Linear regime ($N_b < n_0$):

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

- Available SPS Beam:

$$N_b \approx 3 \cdot 10^{11} \qquad \sigma_z \approx 12\, cm$$

- Proton beam should to be compressed by four orders of magnitude!

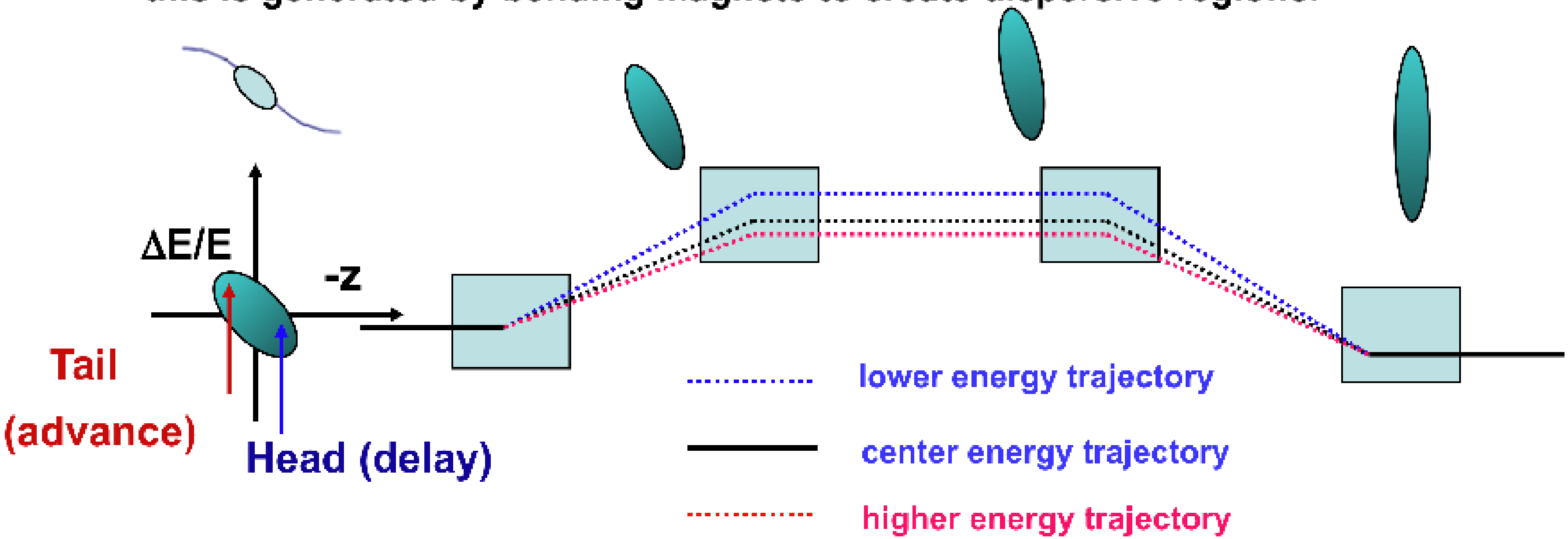
Magnetic Bunch Compression

G. Xia at LPWA09 in Kardamili, Greece, 2009

- ❑ **Beam compression**

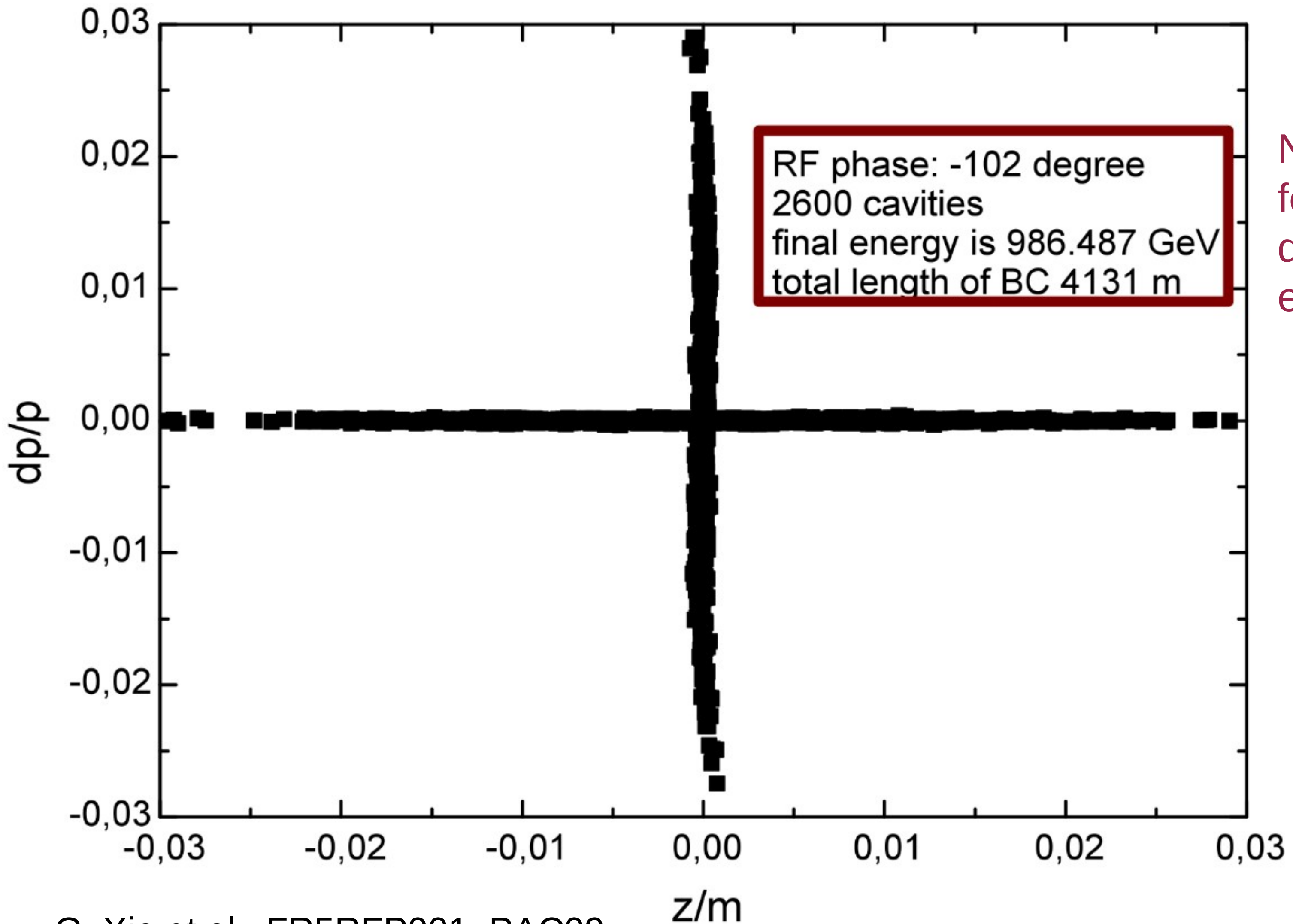
  (1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage

  (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.**

Magnetic Bunch Compression

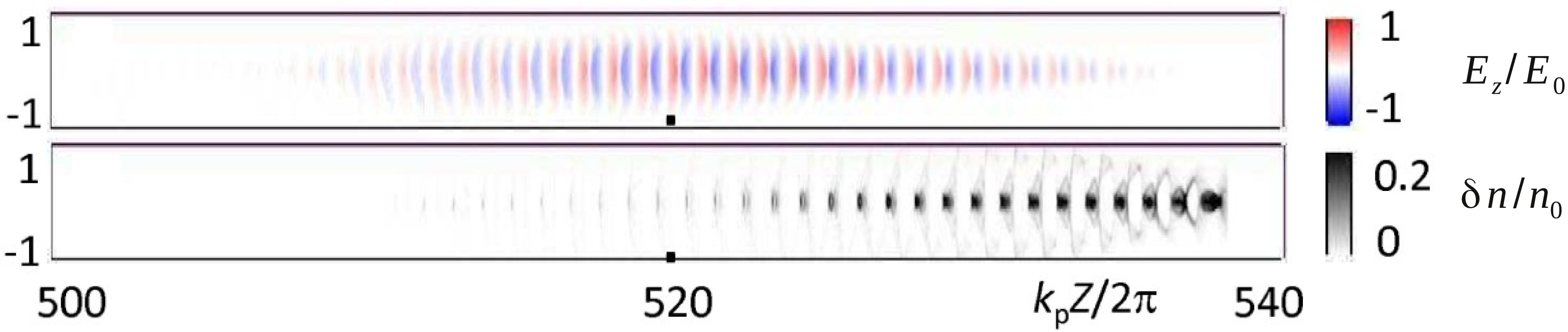


Not possible for a first demonstration experiment!

G. Xia et al., FR5RFP001, PAC09

Self-modulated Proton Driver

- Production of short proton bunches not possible without major investment.
- Transverse two-stream instability can modulate a long bunch into micro bunches, naturally spaced in the right way to drive a strong wakefield.
- Studied both theoretically and numerically*.



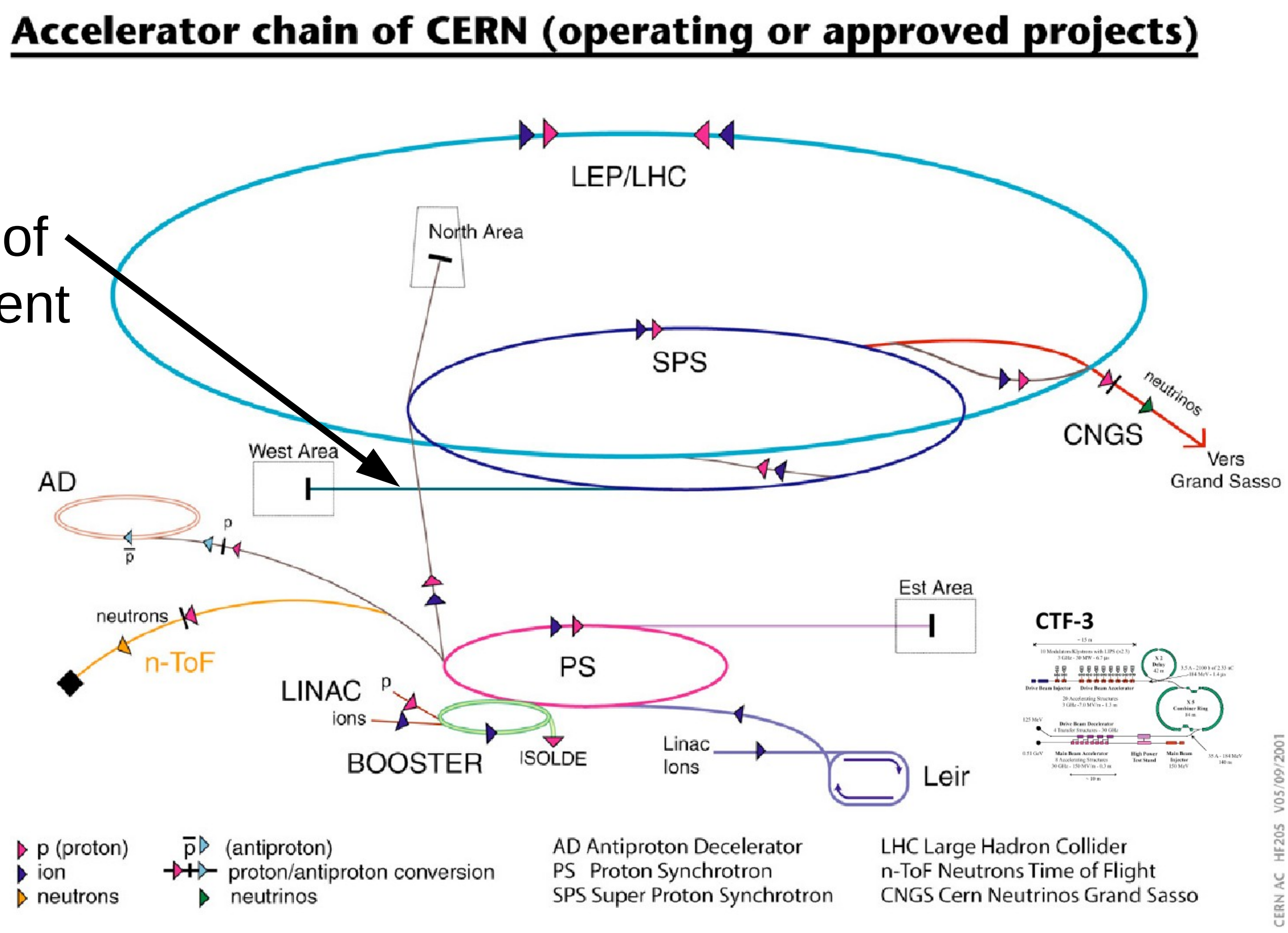
* N. Kumar et al., PRL 104, 255003 (2010)

What can CERN do?

- LWFA and PWFA (e^-) well covered in research.
- No experiments on Proton-driven acceleration yet, but very promising for High Energy Physics!
- CERN has the needed p-beam infrastructure and resourced for an experiment.

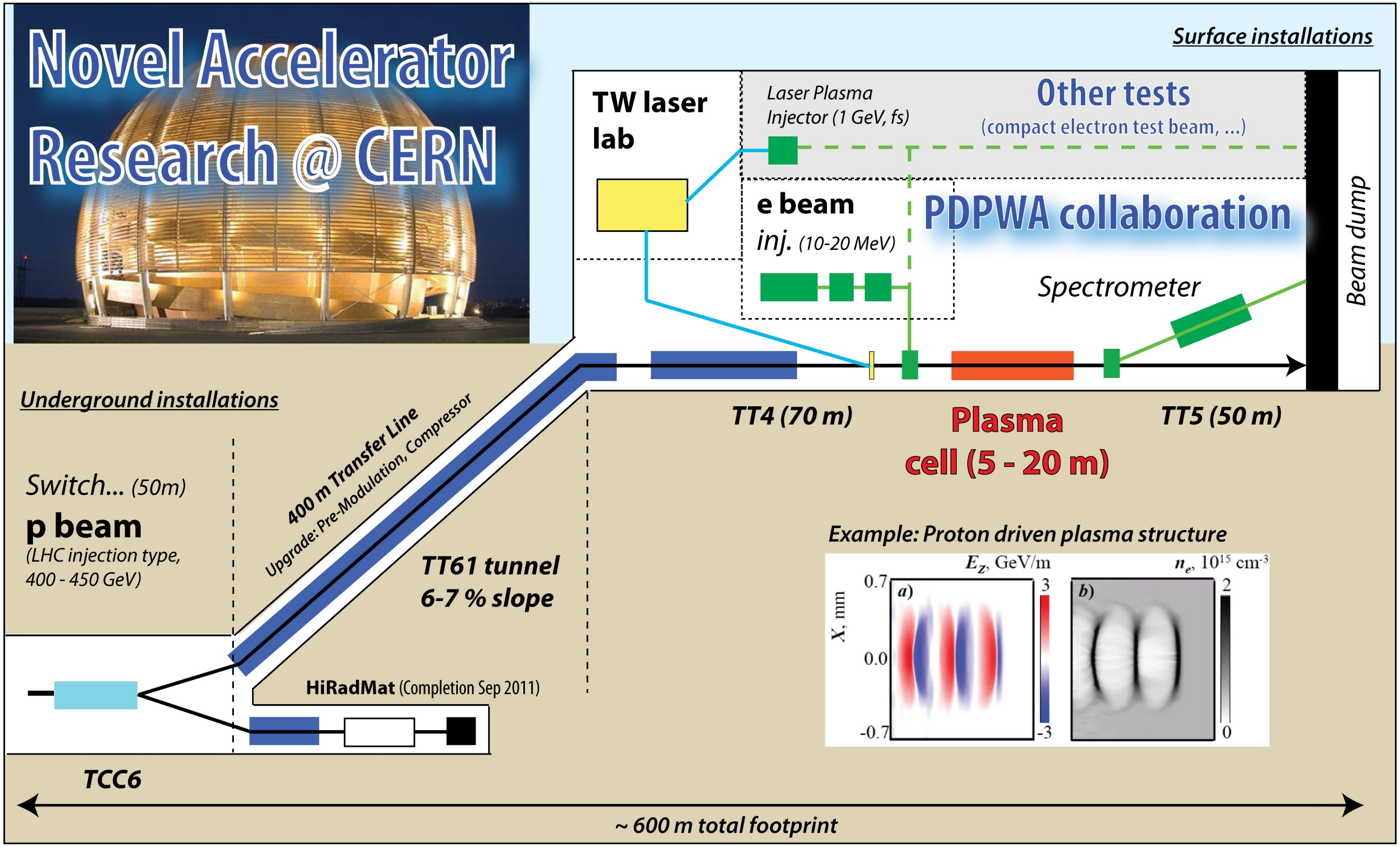
CERN Accelerators

Planned location of experiment



Experiment Description

Picture: CERN-SPSC-2011-020 / SPSC-I-240



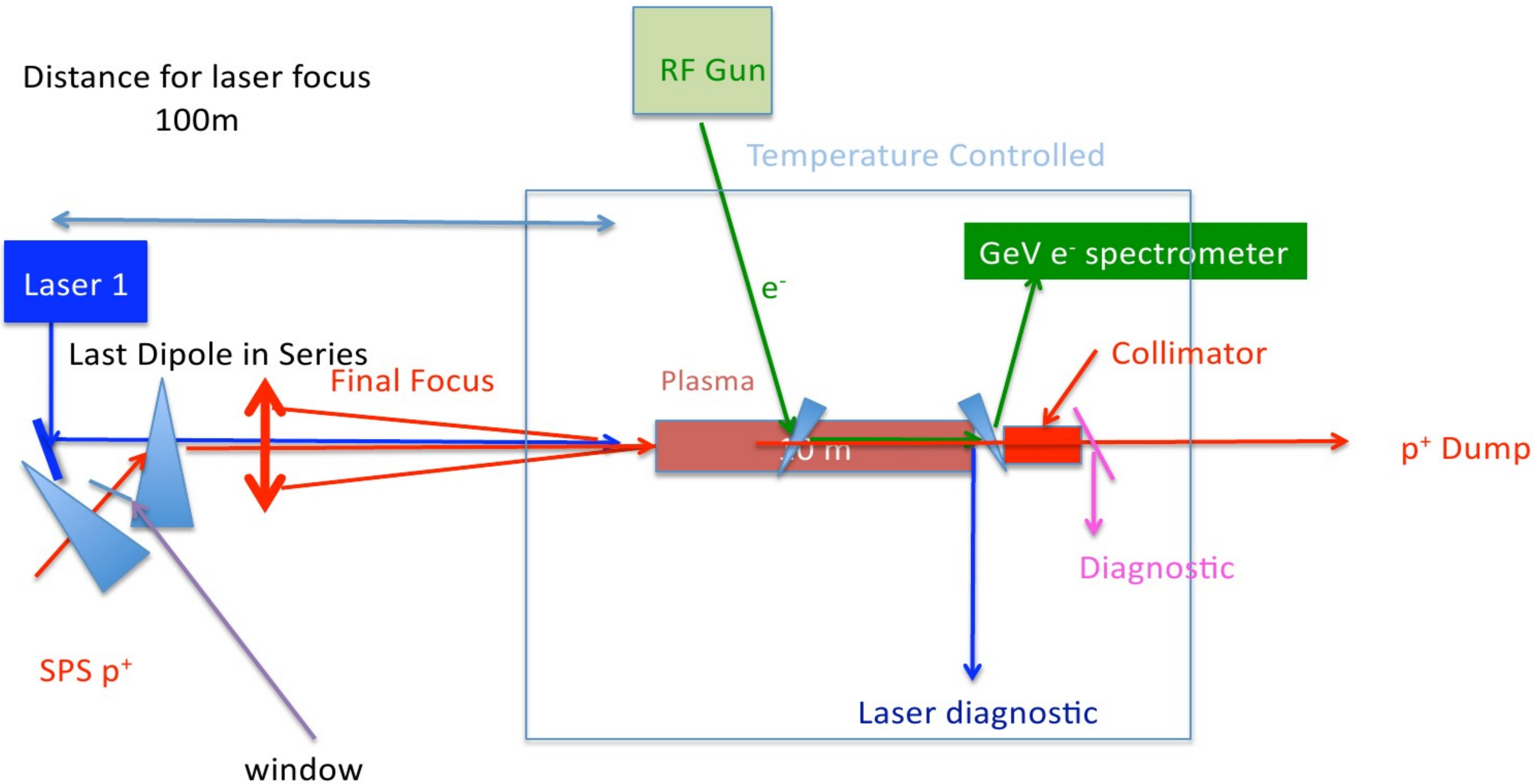
Proton Beam Parameters
(Approximate)

- Beam type: p^+ (Pb ions possible)
- Beam energy: 450 GeV ←
- Bunch intensity N_b: 3×10^{11} ←
- Energy in Bunch: 8.5 kJ ←
- Number of bunches: 1
- Repetition rate: 0.03 Hz
- Energy spread: 0.03% (rms)
- Transv. Emittance: 3.3 – 3.5 µm (normalized)
  6.9 – 7.3 nm (geometric)
- Radial. beam size: 0.2 mm (rms)
- Matched beta value: 1 m
- Bunch length: 12 cm (rms) ←

Baseline Plasma Parameters

- Type of gas: Li
- Type of plasma cell: Laser ionized
- Plasma electron density n_0: $\sim 10^{15}$ cm^{-3}
- Plasma diameter: few mm
- Plasma length: 5 – 10 m

Experiment description



- Initial goal: Observe 1 GeV electron energy gain
- Develop plan for 100 GeV in 100m of plasma based on results

Challenge: Phase Velocity of the Instability

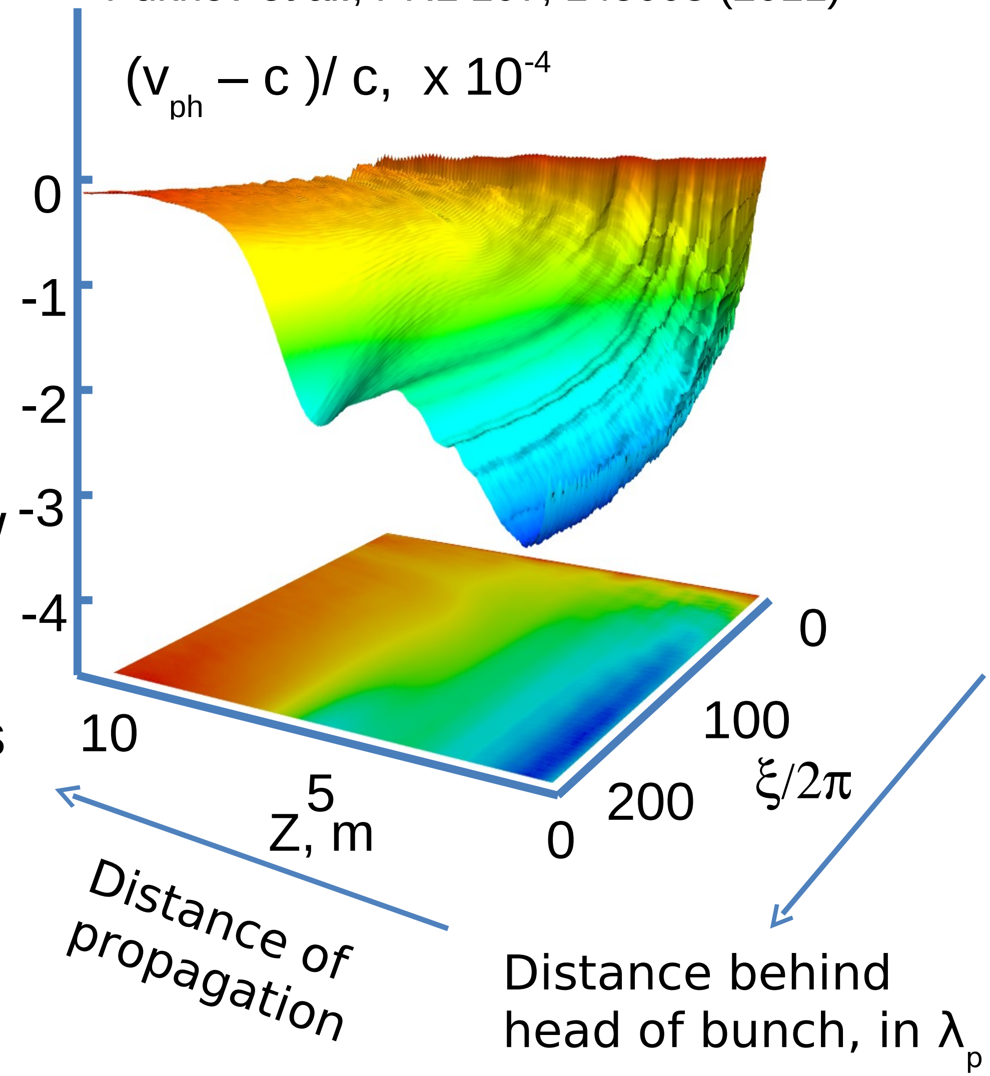
To trap & accelerate electrons in the wake of the protons, it is important that the wake phase velocity matches the electron velocity. Initially, the gamma-factor is

$$\gamma_{min} \sim 40$$

This is order of magnitude below that of the beam.

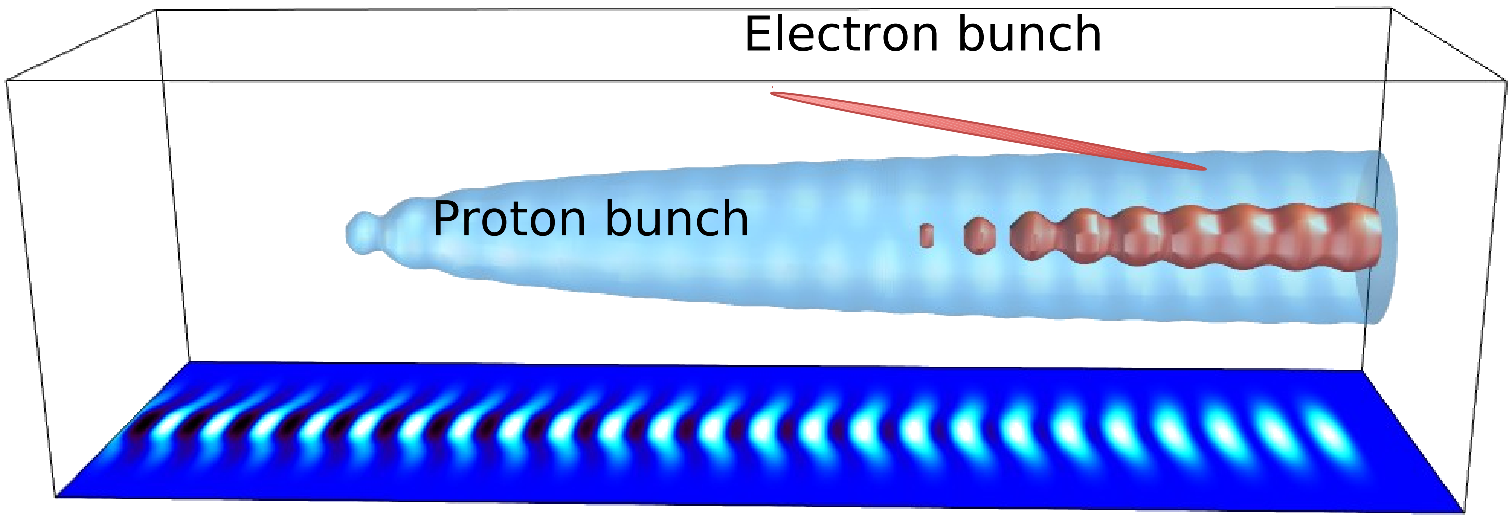
Requires that we inject electrons after the phase velocity has stabilized.

Pukhov et al., PRL 107, 145003 (2011)



Solution: Delayed Electron Injection

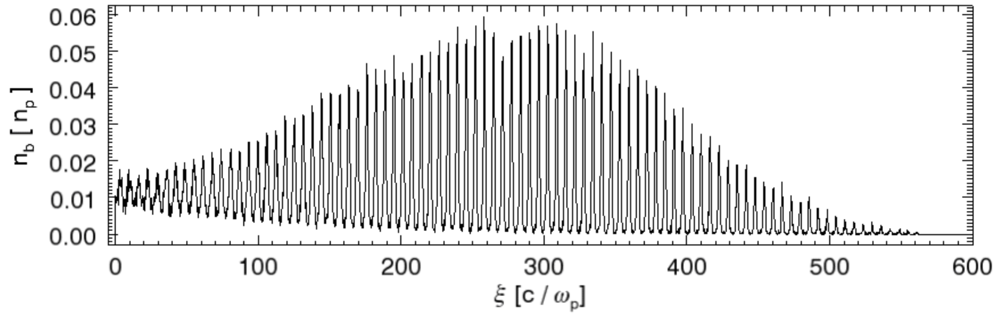
Pukhov et al., PRL 107, 145003 (2011)

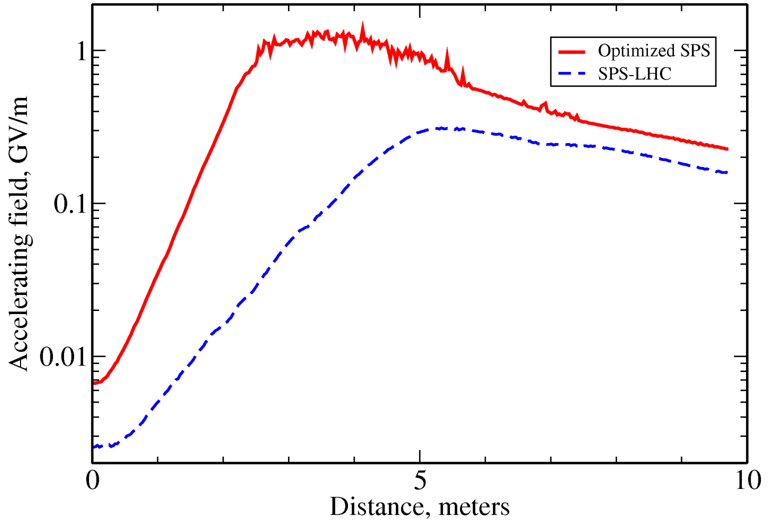


Electron bunch injected off-axis at an angle, so that it merges with the proton bunch once the modulation is developed and the phase velocity is high.

Expected Results

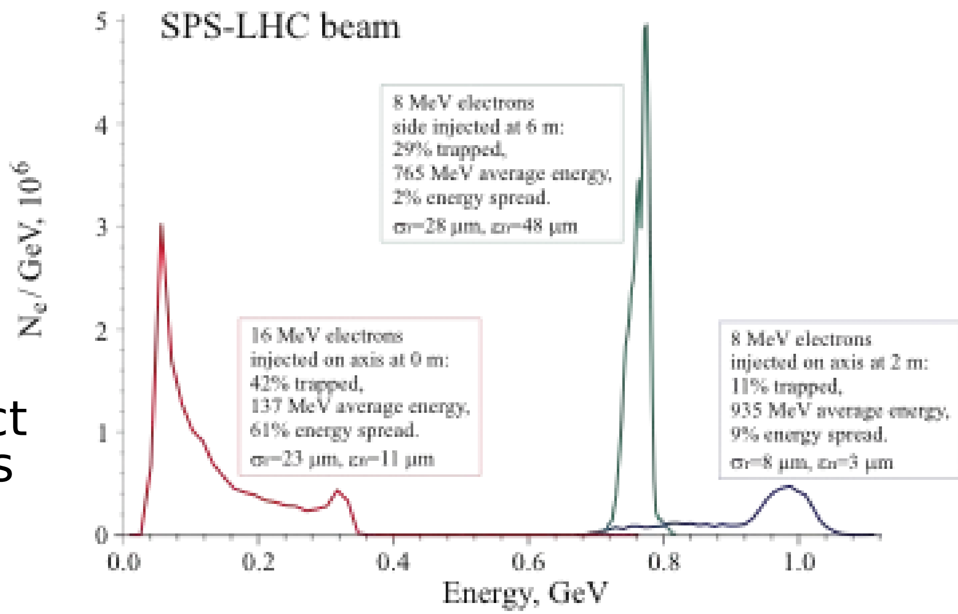
Long SPS drive beam will be sent into a 5-10m long plasma cell. Self-modulation of the beam occurs due to transverse wakefields. Produces many ultrashort beam slices.





The modulation resonantly drives wakefields in the 100-1000 MV/m regime.

Particle-in-cell simulations predict acceleration of injected electrons to beyond 1 GeV.



Milestones

End 2012 (Conceptual Design report):

- Demonstrate at least one technology for a 1 m plasma cell with $n_0 = 10^{14}$-10^{15} cm^{-3}, uniformity better than 5%
- Define seeding scenario in 3D simulations, define experimental test
- Technical design of e-beam injection into plasma, spectrometer, p-beamline
- Radiation and safety study
- Layout experimental area (beam delivery & dump, plasma cell, diagnostics, lasers)

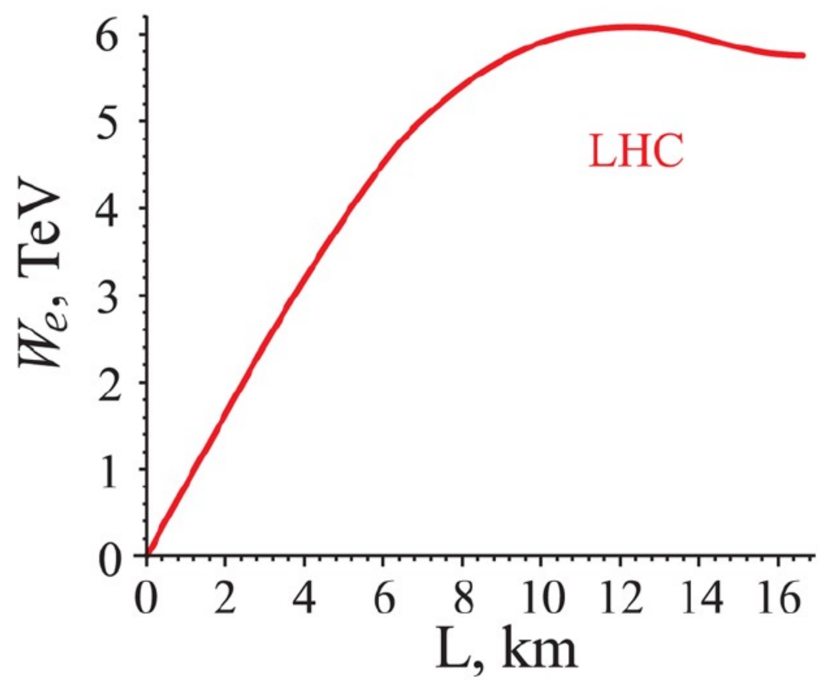
Milestones - Continued

- End 2013:
  - Demonstrate 5 m plasma cell(s) with $n_0 = 10^{15}$ cm^{-3}, uniformity better than 2%
  - Demonstrate seeding in experiments
  - Define baseline choices
- End 2014:
  - Demonstrate completely operational plasma cell(s)
  - Installation of beam switch at end of LHC shutdown
- End 2015:
  - Installation of beam lines, experimental area
  - Beam commissioning, first beam to plasma

High Energy Outlook

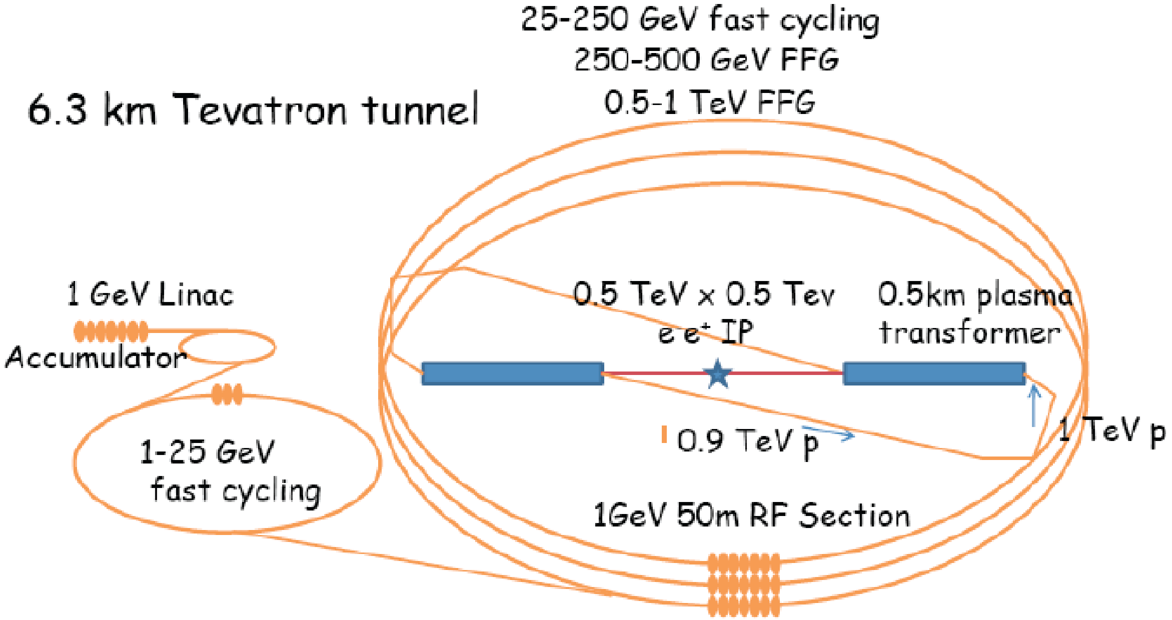
- Long term prospect: Modulated LHC beam
- Simulation results show electron energies of several TeV!
- No guiding magnetic fields necessary!

A. Caldwell, K. Lotov
Phys. Plasmas **18**, 103101 (2011)



PDPWFA-based Linear Collider

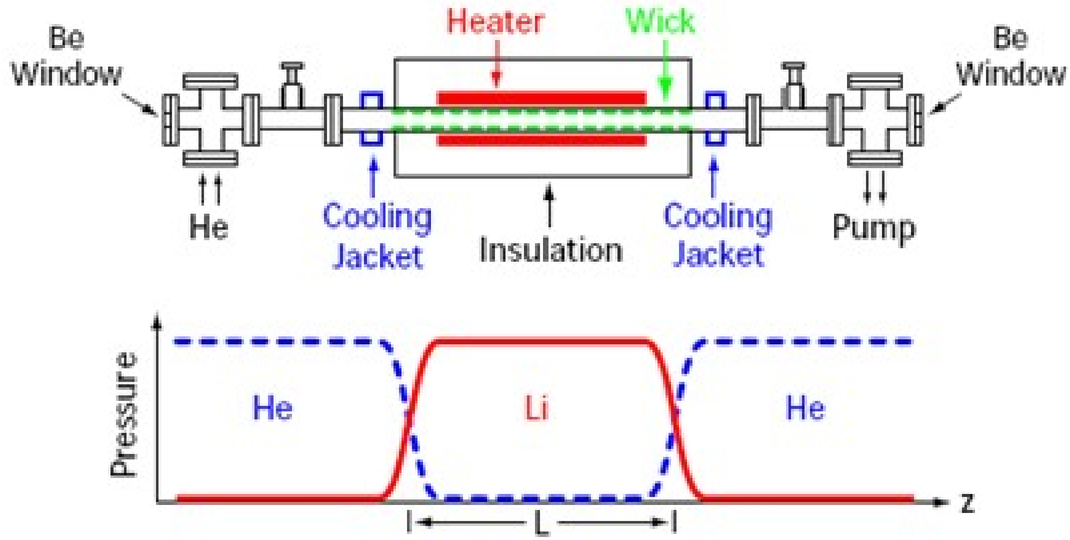
V. Yakimenko, BNL, T. Katsouleas,
Plasma Phys. Control. Fusion 53 (2011) 085010

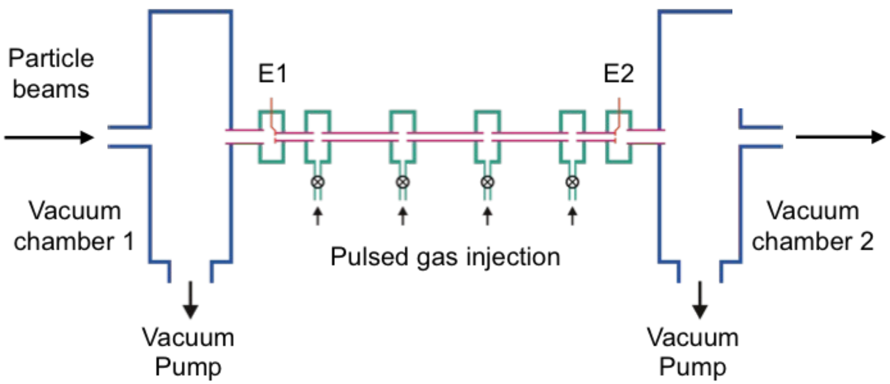


Concept for high repetition rate of proton driven plasma wakefield acceleration 3 ring + injectors + recovery

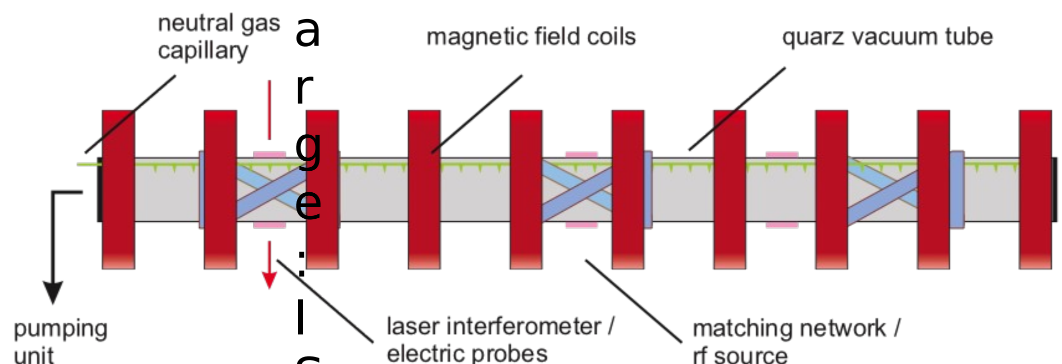
Thank you for your attention!

Backup Slides





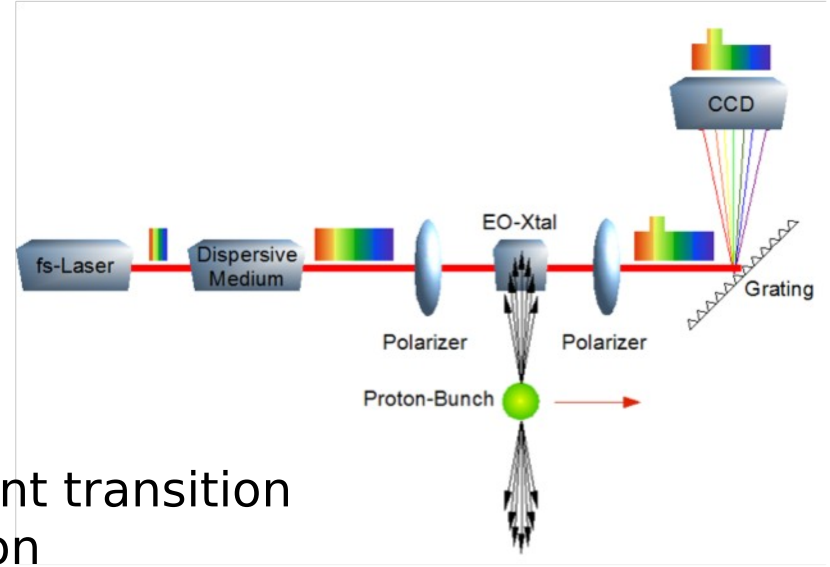
Discharge: IST,

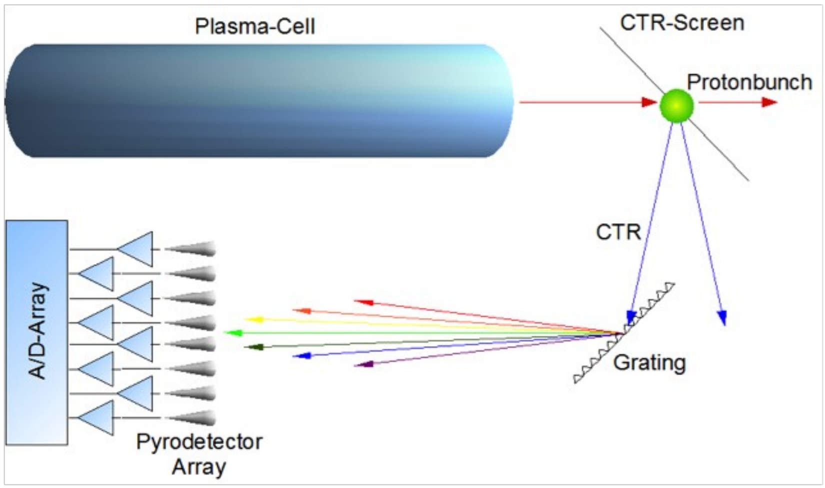


Diagnostics

Electro-optical sampling for modulations, field strength:

University College, RAL, DESY, Imperial College, Cockroft Institute, Strathclyde, MPP





Coherent transition radiation

Electron spectrometer:

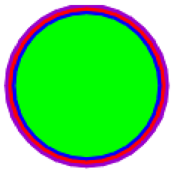
CERN, Imperial College, Cockroft Institute, Strathclyde, KIT, UCL, D

Injector/spectrometer for electron bunch

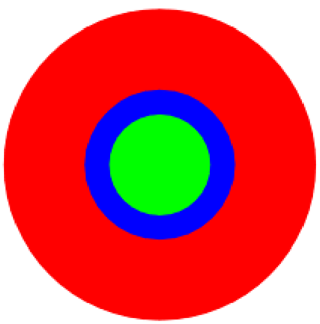
Seeding of instability

Slide: A. Caldwell - CERN Colloquium 2012

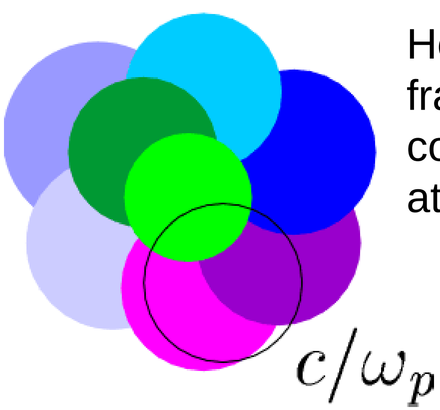
Spontaneous instability vs Seeded instability



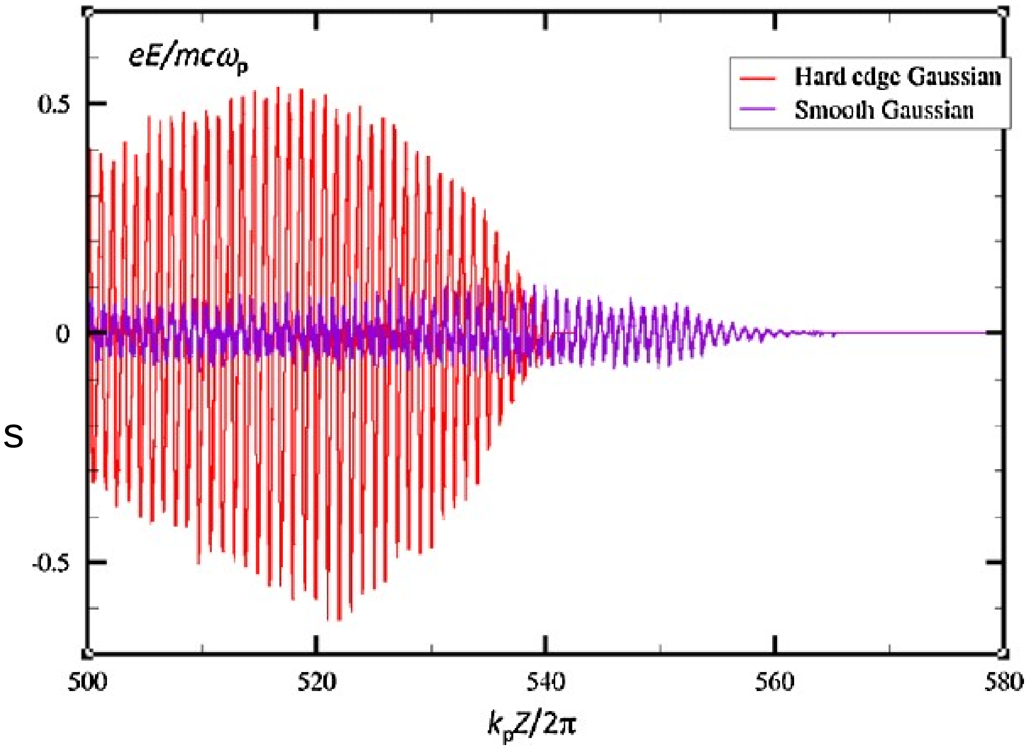
Original beam
(front view)



Axisymmetric mode
(half of the beam
contributes to on-axis
field excitation)



Hosing mode (small
fraction of the beam
contributes to the field
at a given point)



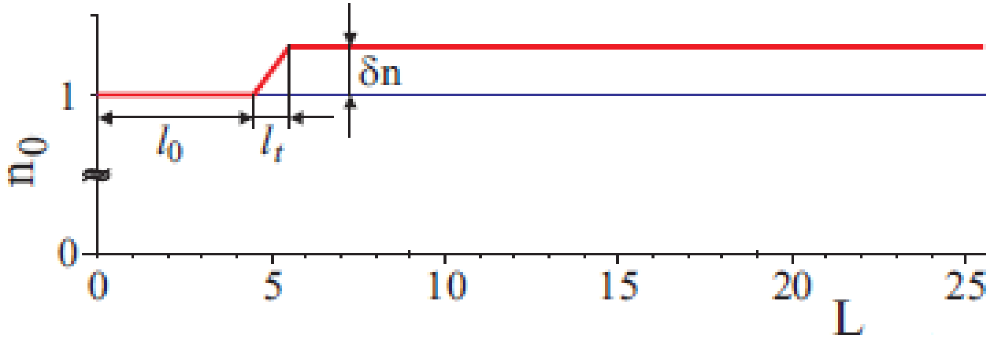
No regular strong fields are possible with hosing

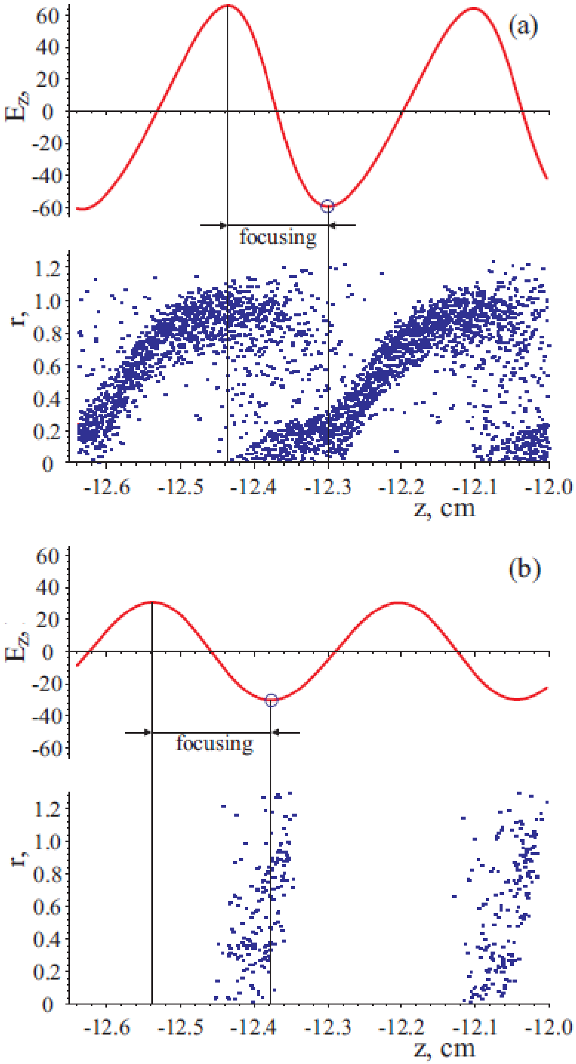
Instability seeding is necessary to produce the axially symmetric mode

High Energy Outlook

Slide: A. Caldwell - CERN Colloquium 2012

- Wakefield amplitude drops quickly once beam is modulated.
- Reason: Defocusing regions move along bunch and destroy it.
- Remedy: Control of wake phase by plasma density profile.





Steffen Hillenbrand
EuroNNAc, CERN, 2012

Issues with a Proton Driven PWA:

- Small beam dimensions required

$$eE_{linear} = 240(\text{MeV/m})\left(\frac{\text{N}}{4\cdot 10^{10}}\right)\left(\frac{0.6}{\sigma_z(\text{mm})}\right)^2$$

$\sigma_z = 100\mu m$,N = 1 10^{11} yields 21 GeV/m

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

Issues with a Proton Driven PWA:

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

$$\delta = \frac{\pi L}{\lambda_p}\left[\frac{1}{\gamma_{1i}\gamma_{1f}} - \frac{1}{\gamma_{2i}\gamma_{2f}}\right] \approx \frac{\pi L}{\lambda_p}\left[\frac{M_P^2 c^4}{E_{driver,i}E_{driver,f}}\right]$$

$$L \leq \frac{1}{2}\left[\frac{E_{driver,i}E_{driver,f}}{M_P^2 c^4}\right]\lambda_p \approx 300 \text{ m for } E_{driver,i} = 1TeV, E_{driver,f} = 0.5TeV, \lambda = 1mm$$

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

$$d = \Delta v \cdot t \approx \Delta\beta \cdot L = (\gamma_1^{-2} - \gamma_2^{-2})L \approx 2\left(\frac{\Delta E}{E}\right)\frac{M_P^2 c^4}{E^2} L$$

$$\text{For } d = 100\mu m, \quad L = 100m, \quad E = 1.TeV, \quad \frac{\Delta E}{E} = 0.5$$

Large momentum spread is allowed !

Issues - continued

Proton interactions

$$\lambda = \frac{1}{n\sigma} < \frac{1}{n(10^{-23}\ \mathrm{cm}^2)} \qquad n = 1 \cdot 10^{15} cm^{-3} \quad \Rightarrow \quad \lambda = 1000\ \mathrm{km}$$

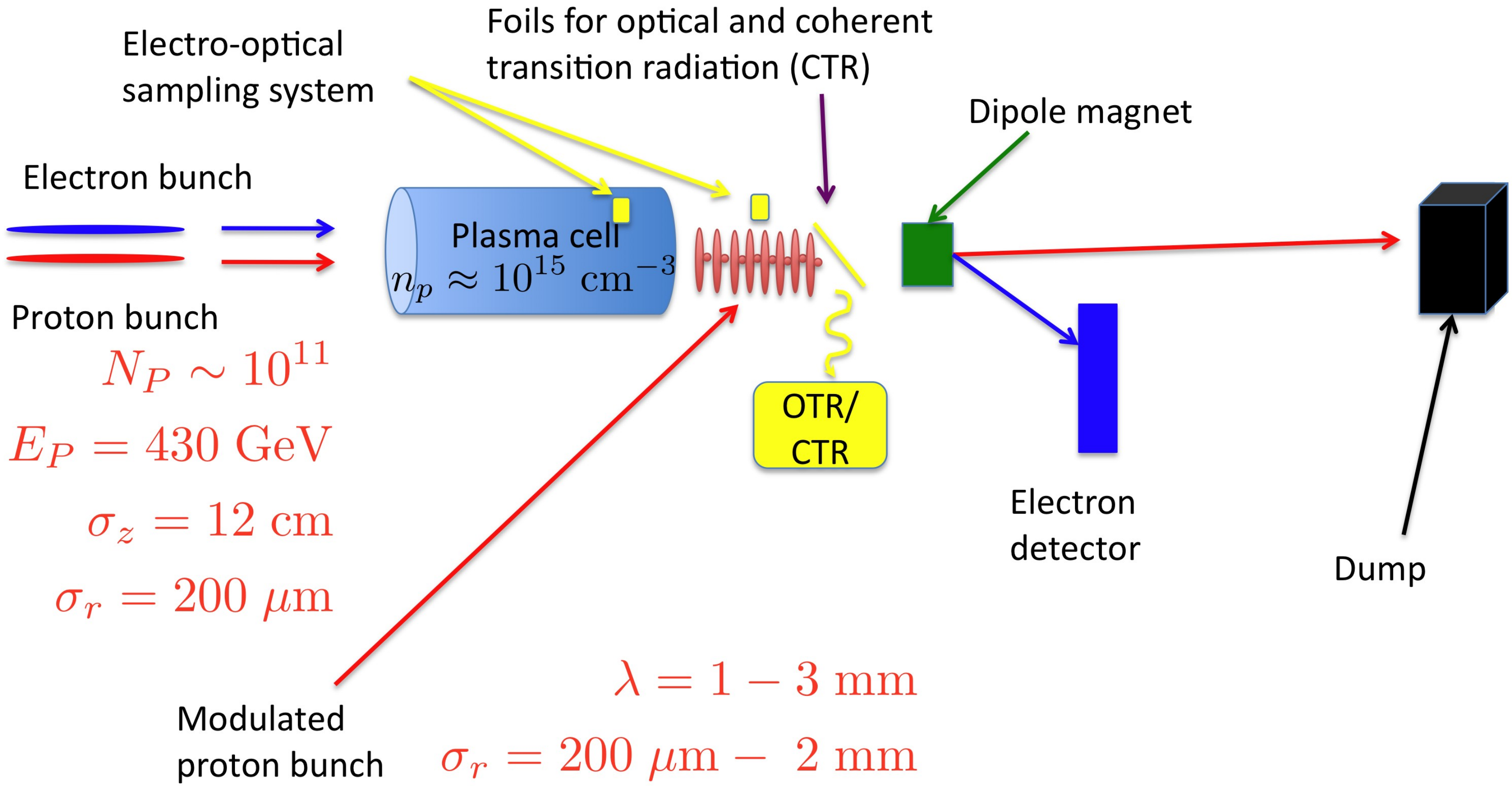
Only small fraction of protons will interact in plasma cell

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.

Experiment description



- Initial goal: Observe 1 GeV electron energy gain
- Develop plan for 100 GeV in 100m of plasma based on results

Issues with a Proton Driven PWA:

- Small beam dimensions required

$$eE_{linear} = 240(\text{MeV/m})\left(\frac{\text{N}}{4\cdot 10^{10}}\right)\left(\frac{0.6}{\sigma_z(\text{mm})}\right)^2$$

$$\sigma_z = 100\mu m \text{ ,N} = 1\ 10^{11} \text{ yields 21 GeV/m}$$

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)

$$\delta = \frac{\pi L}{\lambda_p}\left[\frac{1}{\gamma_{1i}\gamma_{1f}} - \frac{1}{\gamma_{2i}\gamma_{2f}}\right] \approx \frac{\pi L}{\lambda_p}\left[\frac{M_P^2 c^4}{E_{driver,i}E_{driver,f}}\right]$$

$$L \leq \frac{1}{2}\left[\frac{E_{driver,i}E_{driver,f}}{M_P^2 c^4}\right]\lambda_p \approx 300 \text{ m for } E_{driver,i} = 1TeV, E_{driver,f} = 0.5TeV, \lambda = 1mm$$

Few hundred meters possible but depends on plasma wavelength

Summary

- Proton-driven plasma wakefield acceleration could yield high energy electrons
  without a need for staging.

- A demonstration experiment
  is planned at Cern.

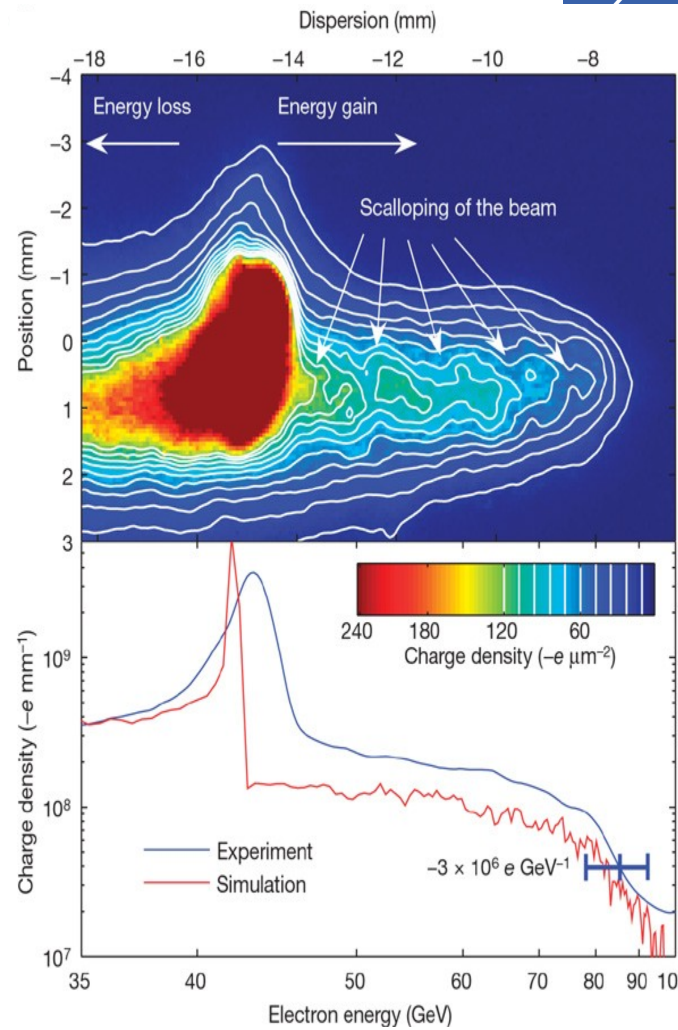
PWFA – Problems for HEP

- Plasma does not accelerate by itself, only acts as a transformer.
- Energy gain of accelerated „witness“ bunch is limited by the energy of the driver (Laser or particle beam).
- I.e. to reach high energies one needs:
  - A driver with very high energy and / or
  - Staging of several acceleration modules.

PWFA – Why?

- Plasmas can support very high fields without risk of material breakdown.
- Acceleration gradients of up to 100 GV/m have been demonstrated recently.*
- This could reduce the length (and cost) of future accelerators by up to 3 orders of magnitude!

*Blumenfeld 2007, doi: 10.1038/nature05538
Leemans 2006, doi: 10.1038/nphys418

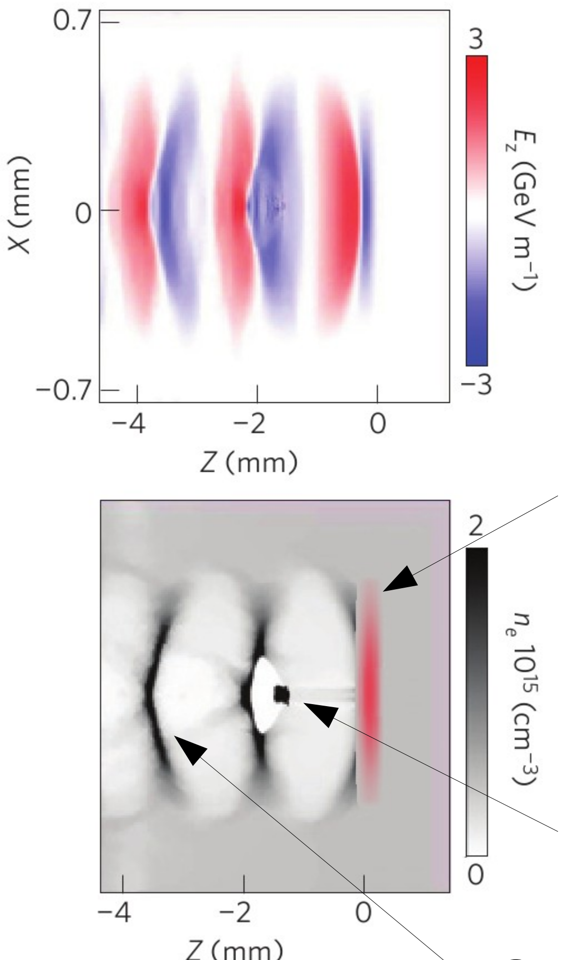


Energy doubling of 42 GeV Electrons at SLAC

Possible Experiment

- A proton beam will be extracted from the SPS and fired into a Lithium vapor oven.
- A co propagating Laser will generate a plasma in the middle of the (long) proton bunch.
- This way the plasma sees a proton bunch with a very sharp current flank.
- The instability seeded by this flank modulates the density of the proton bunch
- The modulated proton bunch creates plasma wakes.
- The resulting fields will be used to accelerate injected electrons.

Plans for CERN Experiment



Map of electric fields in the plasma

Driving Proton Bunch

Accelerated Electron Bunch

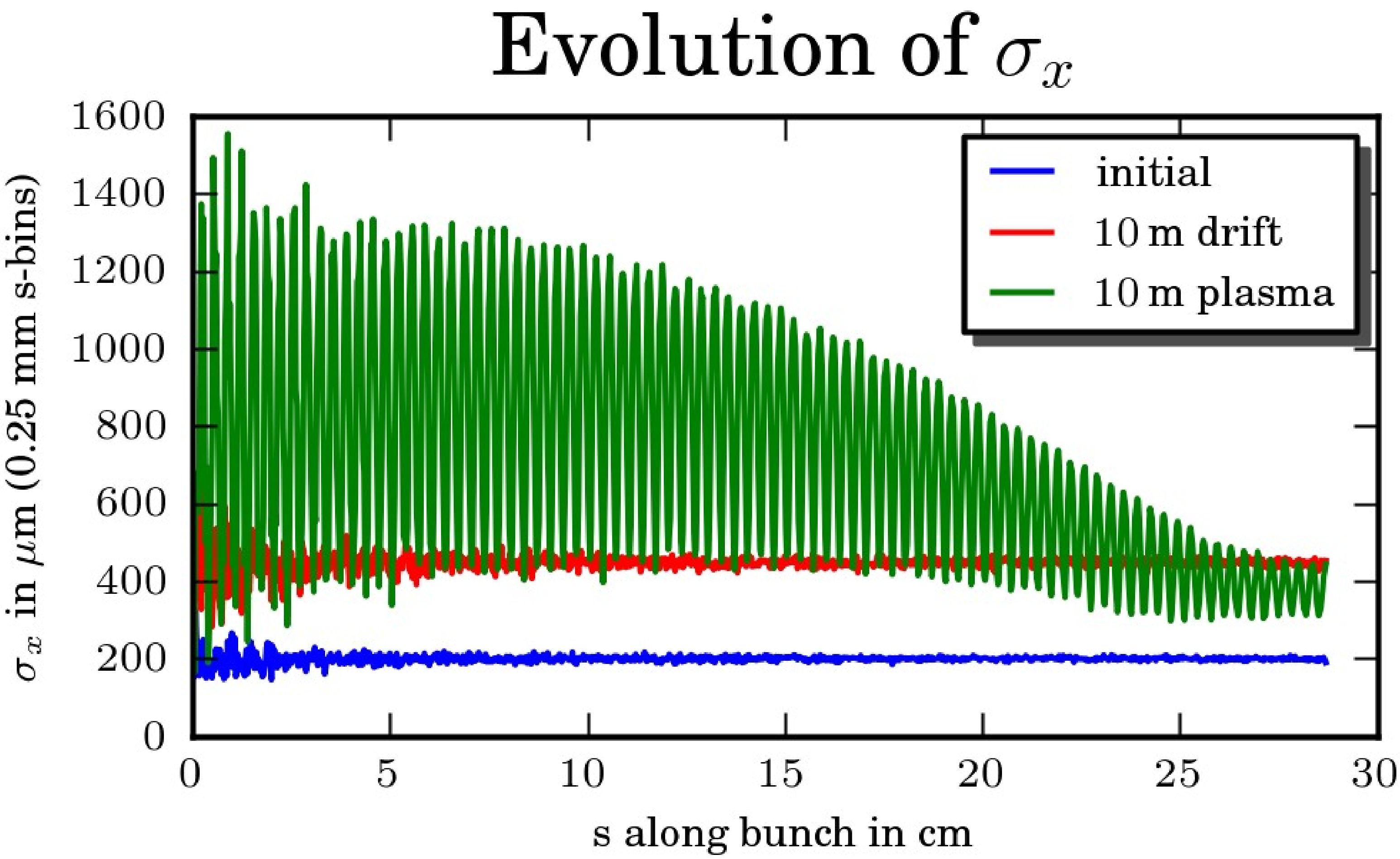
Created plasma electron density modulation

Caldwell 2009, doi:10.1038/nphys1248

- Within an international collaboration, protons as drives are studied.
- A Letter of Intent for a demonstration experiment has been submitted to SPSC*.

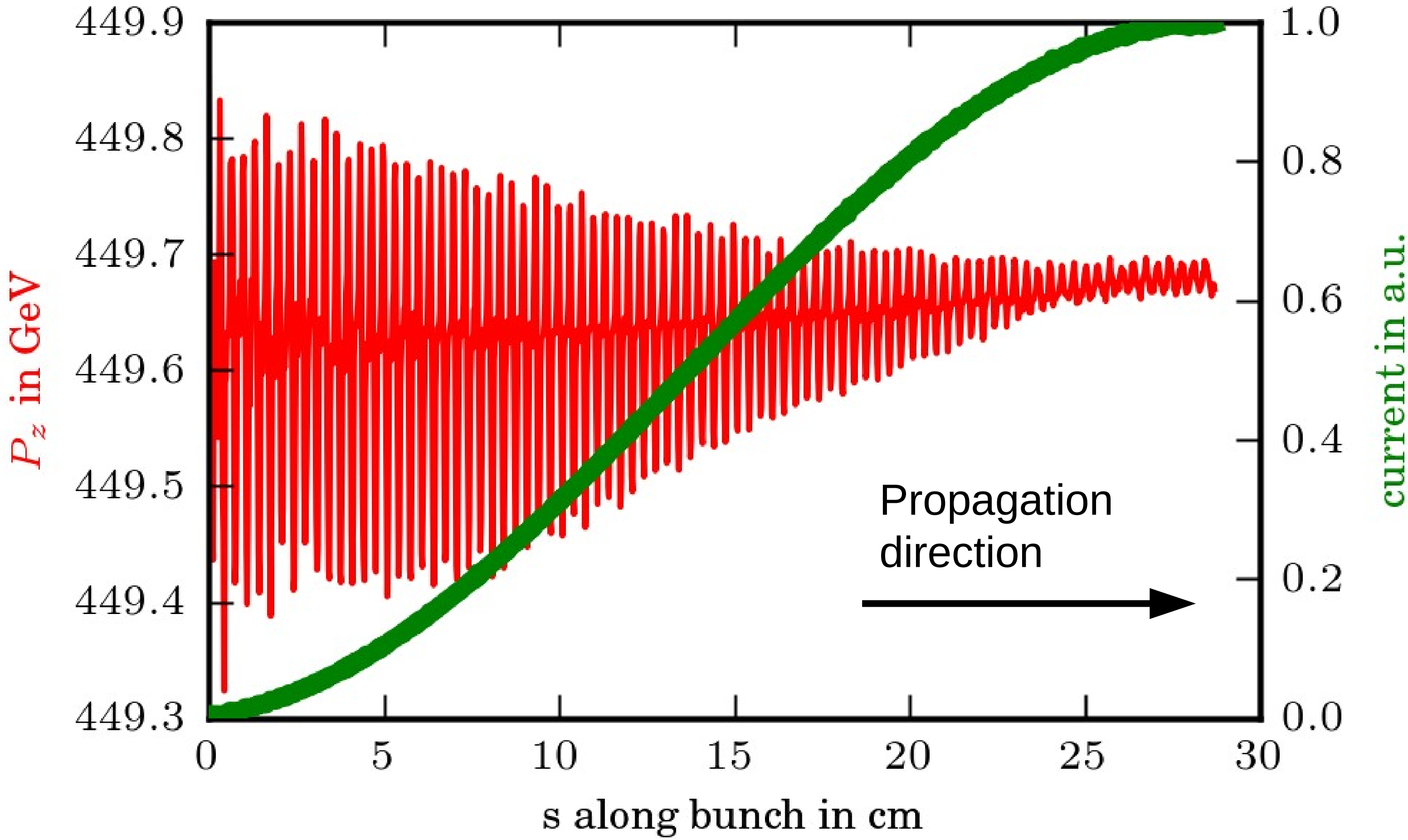
*Adli et al., CERN-SPSC-2011-020 / SPSC-I-240, “Letter of Intent for a Demonstration Experiment in Proton-Driven Plasma Wakefield Acceleration”

Transverse P-Beam Modulation



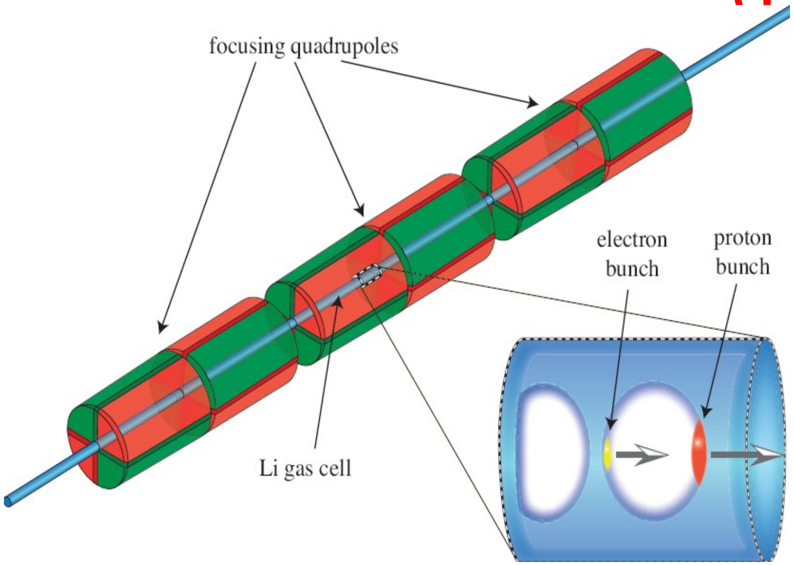
Evaluation based on Beam-Plasma Simulations by K. Lotov, Budker Institute of Nuclear Physics

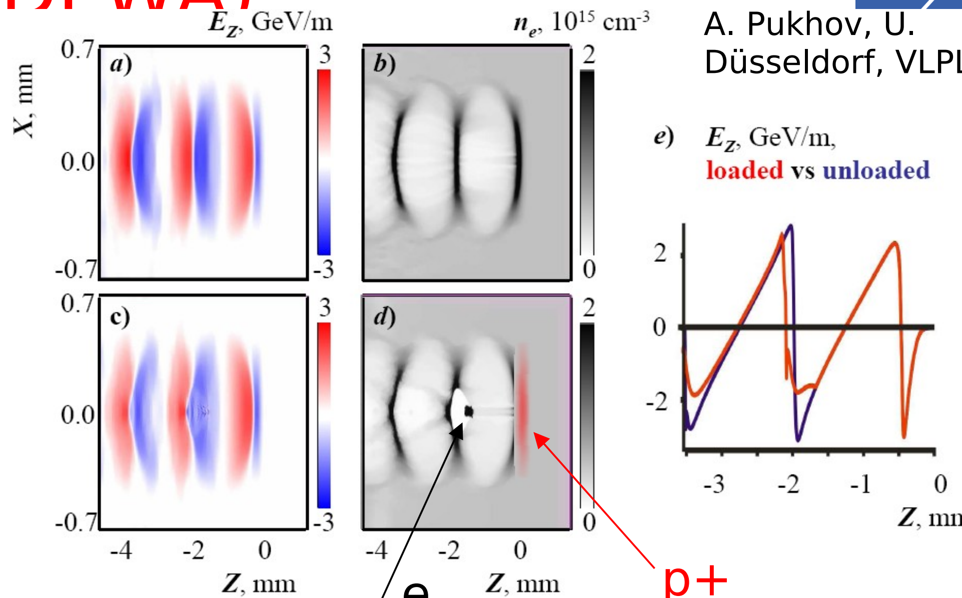
P-Beam Energy Modulation



Evaluation based on Beam-Plasma Simulations by K. Lotov, Budker Institute of Nuclear Physics

Proton-driven plasma wakefield acceleration (PDPWA)





A. Pukhov, U. Düsseldorf, VLPL

Drive beam: p+

E=1 TeV, Np=1011
σz=100 μm,σr=0.43 mm
σθ=0.03 mrad,
ΔE/E=10%

Witness beam: e-

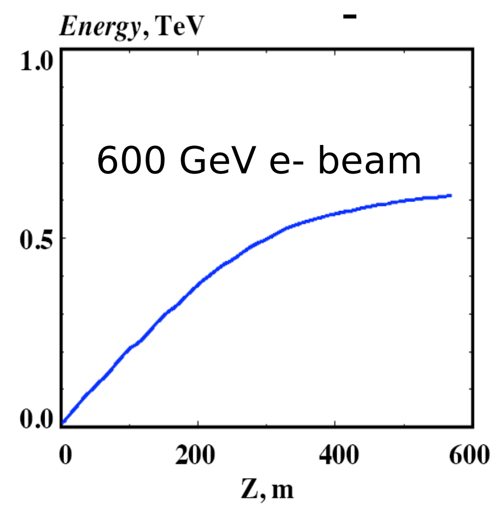
E0=10 GeV,
Ne=1.5x1010

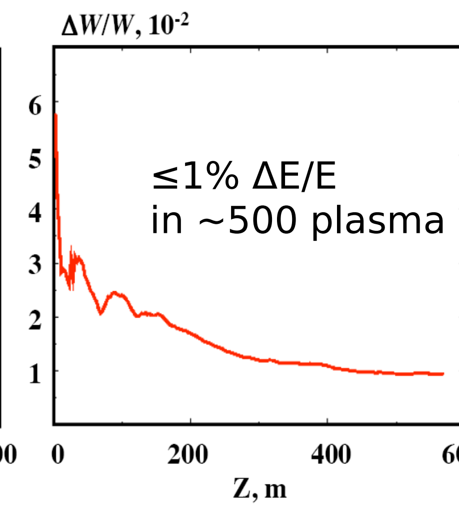
Plasma: Li+

np=6x1014cm-3

External magnetic field:

Field gradient: 1000 T/m
Magnet length: 0.7 m





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