Proton Driven Plasma Wakefield Acceleration

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Outline

- Motivation
- Plasma wakefield acceleration
- Proton driven plasma wakefield acceleration (PDPWA)
- Short proton bunch production
- Demonstration experiment at CERN
- Summary

Motivation

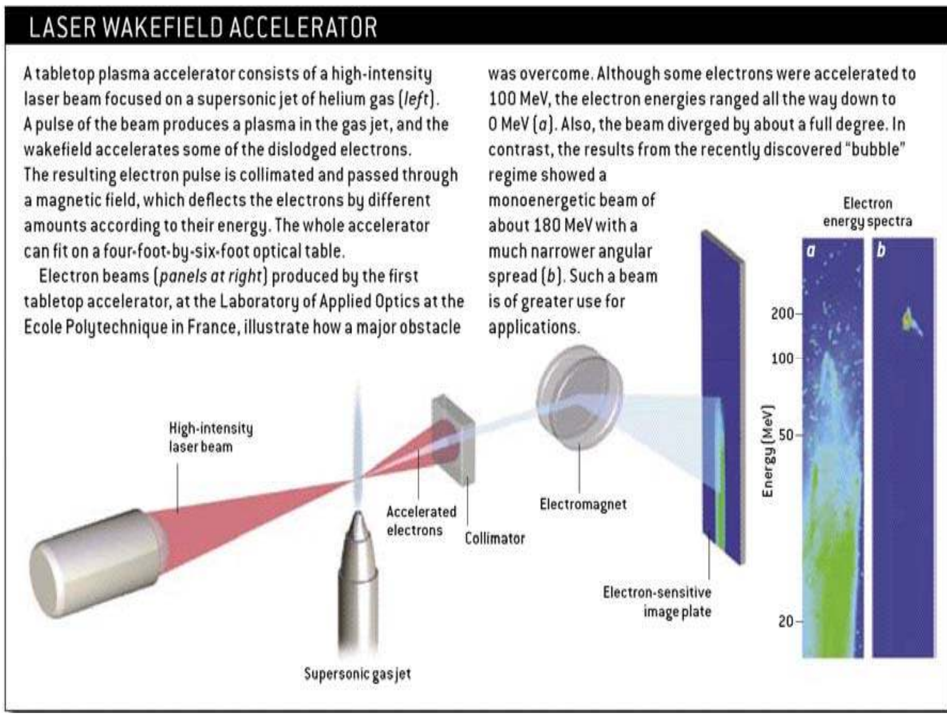
- Particle physics enters terascale era
- LHC will start commissioning late this year
- International Linear Collider (ILC) is proposed as the next generation machine
- However, the cost and size of these machines reach the limit
- New ideas to make the machine more compact and cost effective are highly demanding
- Plasma wakefield accelerator hold promise in this aspect to economize the machines scale

- Plasma, already in ionized state, can sustain very large electric field, e.g. orders of magnitude larger than conventional accelerating structures
- Therefore, for a fixed energy machine, it can reduce the machine sizes significantly !
- In last few decades, the plasma wakefield driven by laser pulse and electron beam has already achieved very good results; > 10~100 GeV/m acceleration gradients have been demonstrated.
- In Europe, there is no activity on the study of beam-driven plasma wakefield acceleration, therefore we want to investigate the possibility of using the beam at CERN

Highlights of plasma accelerators

Acceleration, Radiation Sources, Refraction, Medical Applications

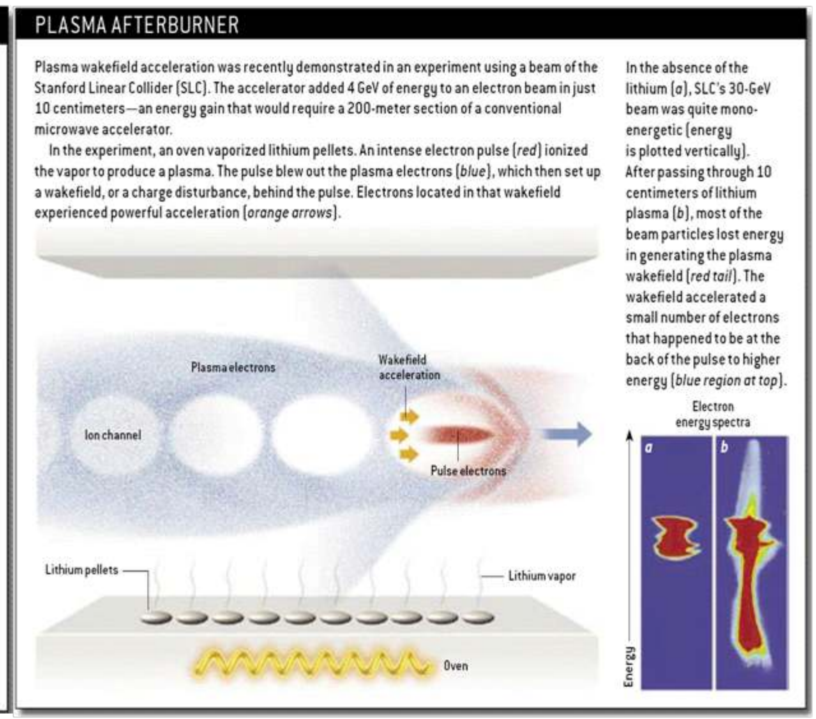
Laser & electron beam driven plasma accelerators



LASER WAKEFIELD ACCELERATOR

A tabletop plasma accelerator consists of a high-intensity laser beam focused on a supersonic jet of helium gas (*left*). A pulse of the beam produces a plasma in the gas jet, and the wakefield accelerates some of the dislodged electrons. The resulting electron pulse is collimated and passed through a magnetic field, which deflects the electrons by different amounts according to their energy. The whole accelerator can fit on a four-foot-by-six-foot optical table.

Electron beams (*panels at right*) produced by the first tabletop accelerator, at the Laboratory of Applied Optics at the Ecole Polytechnique in France, illustrate how a major obstacle was overcome. Although some electrons were accelerated to 100 MeV, the electron energies ranged all the way down to 0 MeV (*a*). Also, the beam diverged by about a full degree. In contrast, the results from the recently discovered "bubble" regime showed a monoenergetic beam of about 180 MeV with a much narrower angular spread (*b*). Such a beam is of greater use for applications.



PLASMA AFTERBURNER

Plasma wakefield acceleration was recently demonstrated in an experiment using a beam of the Stanford Linear Collider (SLC). The accelerator added 4 GeV of energy to an electron beam in just 10 centimeters—an energy gain that would require a 200-meter section of a conventional microwave accelerator.

In the experiment, an oven vaporized lithium pellets. An intense electron pulse (*red*) ionized the vapor to produce a plasma. The pulse blew out the plasma electrons (*blue*), which then set up a wakefield, or a charge disturbance, behind the pulse. Electrons located in that wakefield experienced powerful acceleration (*orange arrows*).

In the absence of the lithium (*a*), SLC's 30-GeV beam was quite monoenergetic (energy is plotted vertically). After passing through 10 centimeters of lithium plasma (*b*), most of the beam particles lost energy in generating the plasma wakefield (*red tail*). The wakefield accelerated a small number of electrons that happened to be at the back of the pulse to higher energy (*blue region at top*).

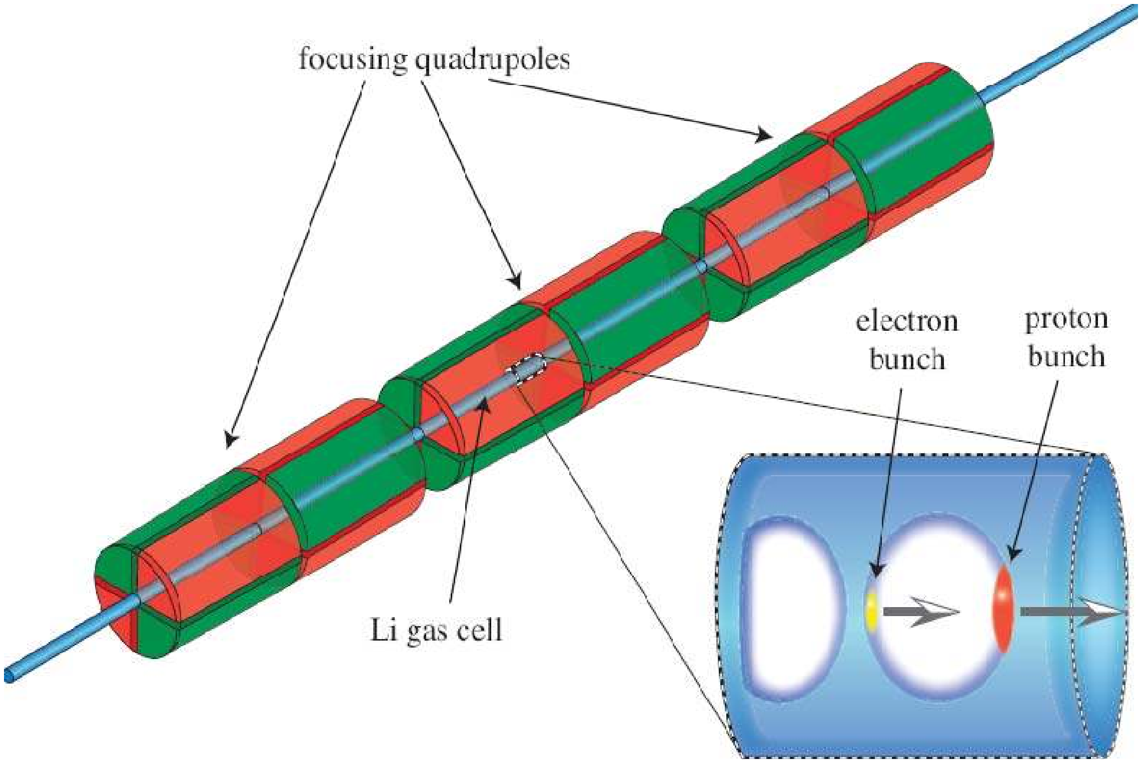
C. Joshi, Scientific American, Feb, 2006.

Proton driven plasma wakefield acceleration

- In the linear regime of PWFA, the maximum achievable gradient scales as N_p/σ_z^2, therefore we need high current and short bunch
- Transformer ratio (the gained energy of witness beam / the energy of driver beam) is limited to 2 for longitudinal symmetric driven bunches.
- Our idea is to use the existing high energy proton beam to drive plasma wakefield and then accelerate the electron beam to high energies*.
- 2D and 3D Particle-in-cell simulations have given very promising results.
- Therefore further study on this issue is needed to make this idea feasible.
- So far, one of the main constraints is to produce the short proton beam, in the scale of 100 micron.

* See A. Caldwell et al., Nature Physics, NPHYS1248(2009)

Schematics of PDPWA



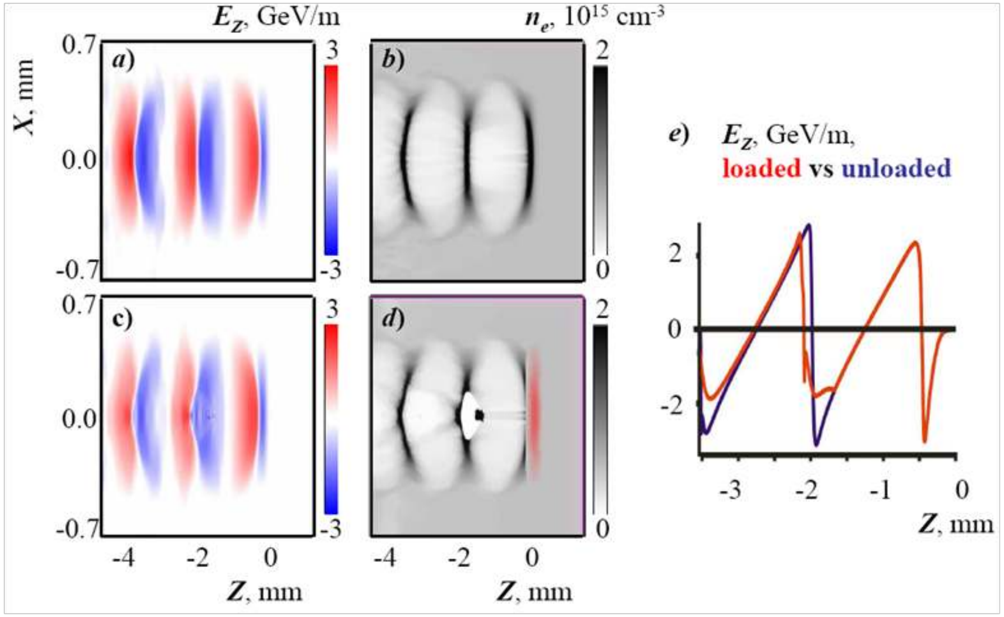
A thin tube containing Li gas is surrounded by quadrupole magnets with alternating polarity. The magnification shows the plasma bubble created by the proton bunch (red). The electron bunch (yellow) undergoing acceleration is located at the back of the bubble. Note that the dimensions are not to scale.

Parameter settings

	Symbol	Value
Drive Beam		
Protons in drive bunch[10^{11}]	N_p	1
Proton energy [TeV]	E_p	1
Initial proton momentum spread	σ_p/p	0.1
Initial longitudinal spread [μm]	σ_z	100
Initial angular spread [mrad]	σ_θ	0.03
Initial bunch transverse size [mm]	$\sigma_{X,Y}$	0.4
Witness Beam		
Electrons in witness bunch[10^{10}]	N_e	1.5
Energy of electrons [GeV]	E_e	10
Plasma Parameters		
Free electron density [cm^{-3}]	n_p	6×10^{14}
Plasma wavelength [mm]	λ_p	1.35
External Field		
Magnetic field gradient [T/m]		1000
Magnetic length [m]		0.7

Simulations

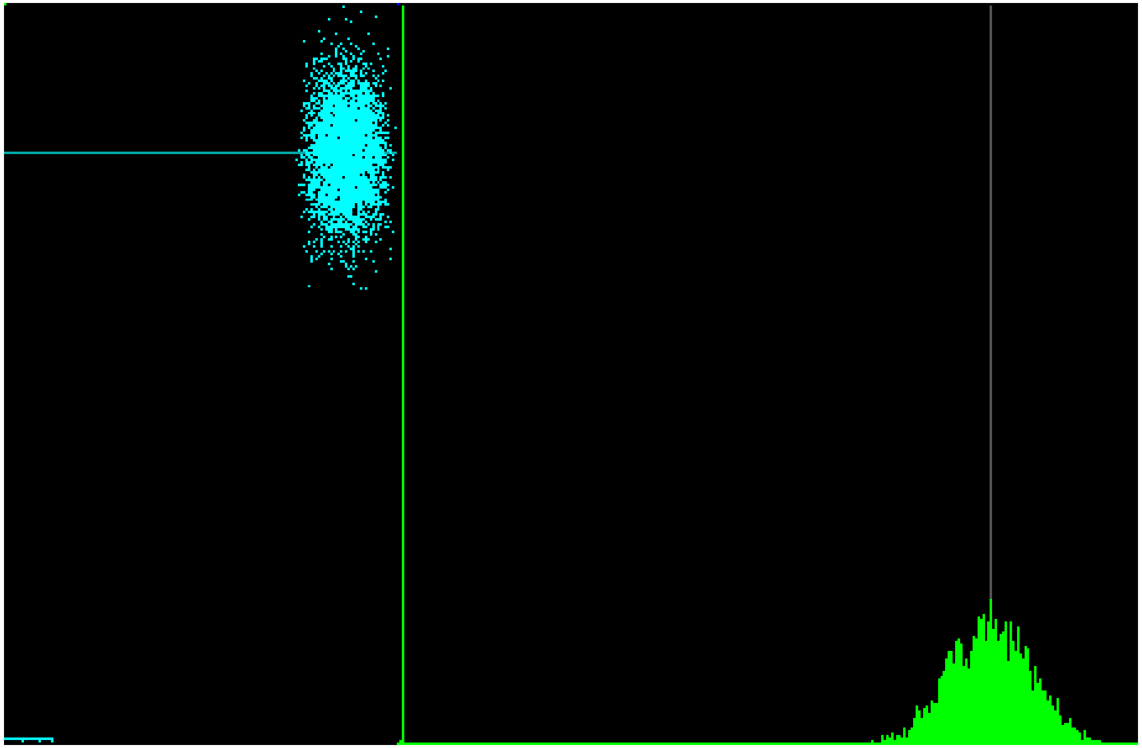
- 2 D and 3 D Particle-In-Cell (PIC) codes are employed to simulate the interactions between plasma and beams.



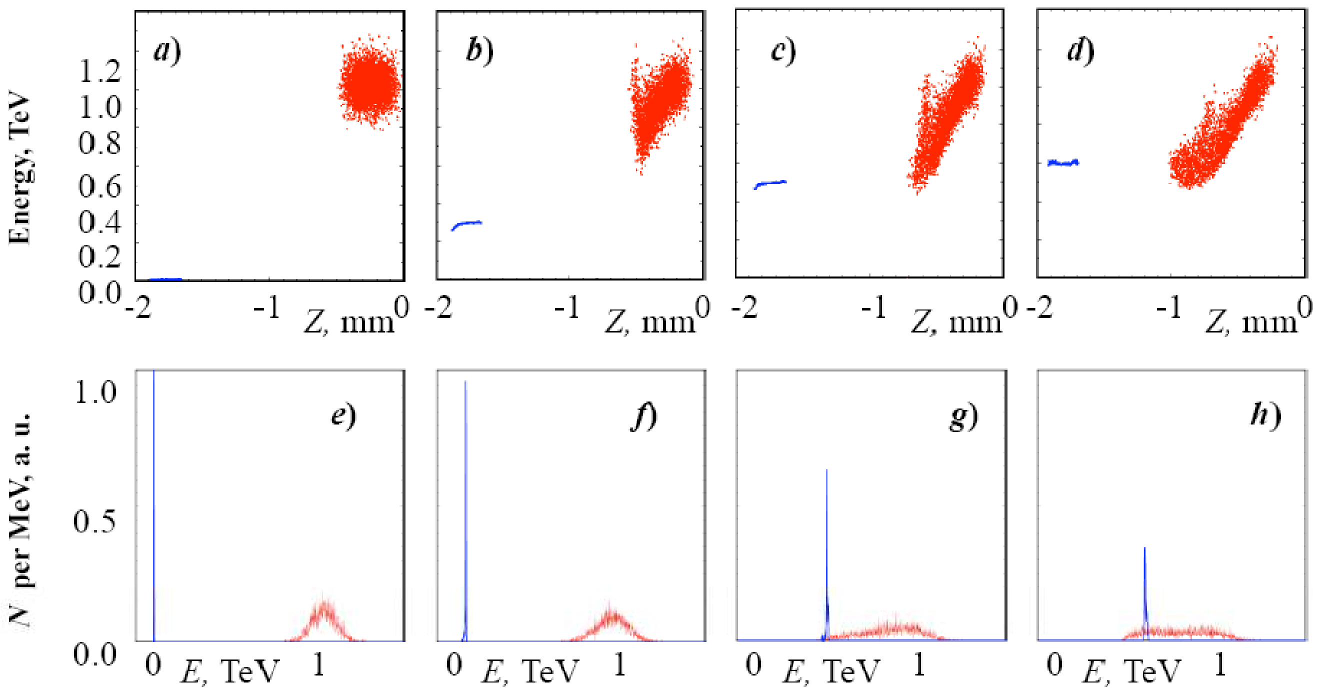
a-d, Simulation results for the unloaded (no witness bunch) case (a,b) and in the presence of a witness bunch (c,d). The witness bunch is seen as the black spot in the first wave bucket in d. d also shows the driving proton bunch at the wavefront (red). e, The on-axis accelerating field of the plasma wave for the unloaded (blue curve) and loaded (red curve) cases.

Simulation results

- Energy gain

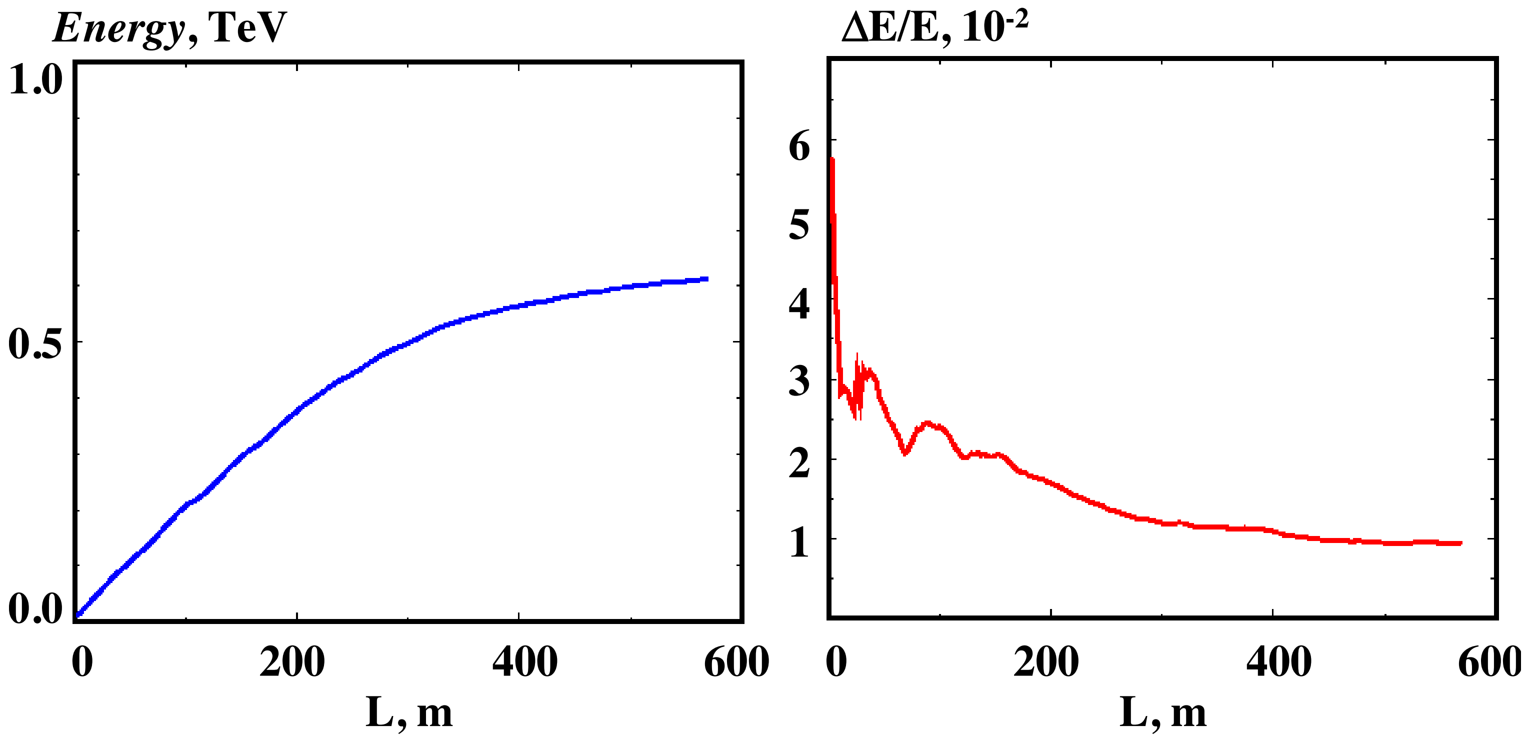


Phase space of driver & witness



a-h, Snapshots of the combined longitudinal phase space of the driver and the witness bunches (energy versus coordinate) (a–d) and corresponding energy spectra (e–h). The snapshots are taken at acceleration distances *L*=0, 150, 300, 450 m. The electrons are shown as blue points and the protons are depicted as red points.

Energy gain & energy spread



a,b, The mean electron energy in TeV (a) and the r.m.s. variation of the energy in the bunch as a percentage (b) as a function of the distance travelled in the plasma.

Conclusions from simulation results

- Proton beam can indeed to be used as the drive beam
- PDPWA can bring a bunch of electrons to the energy frontier in only one stage.
- An unsolved questions, short beam!

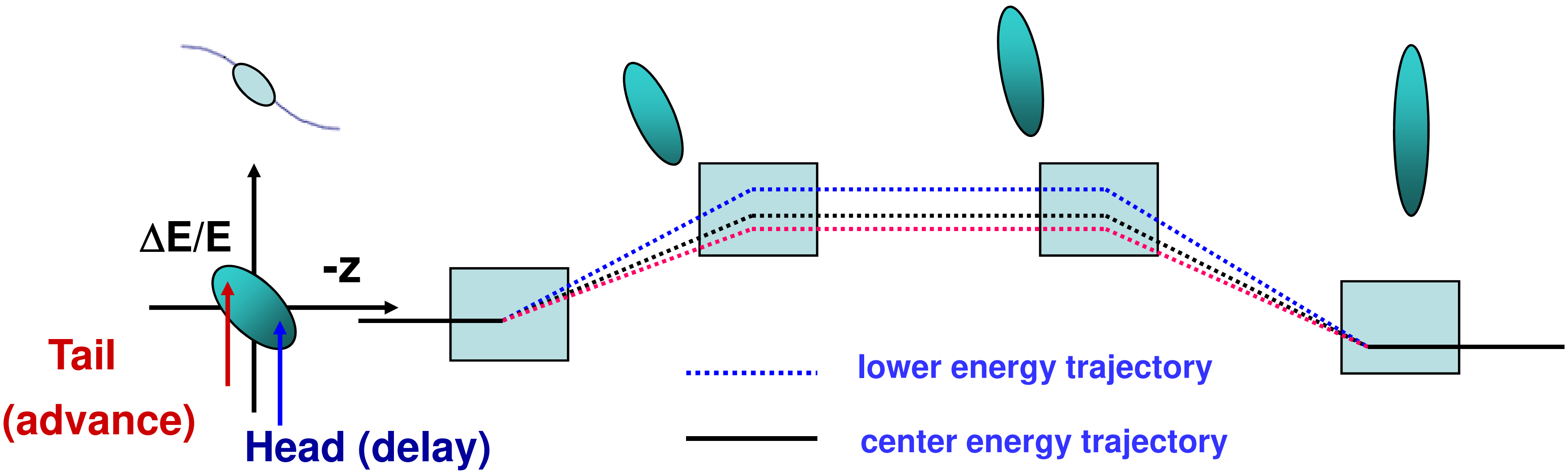
Short proton bunch production

- There are several ways to obtain short bunch
- Laser striking thin foil can produce short and low energy proton beam
- Emittance exchange technique, exchanges the longitudinal emittance to horizontal emittance
- Fast quads tunning for low momentum compaction factor before extraction in the ring*
- Plasma wakefield beam slicing
- Fast nanochoppers to get microbeam?
- Conventional bunch magnetic compression

* See F.Zimmermann et al., Generation of short proton bunches in the CERN accelerator complex, Proceedings of PAC09, May 3-8, 2009, Vancouver, Canada

Magnetic bunch compression (BC)

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

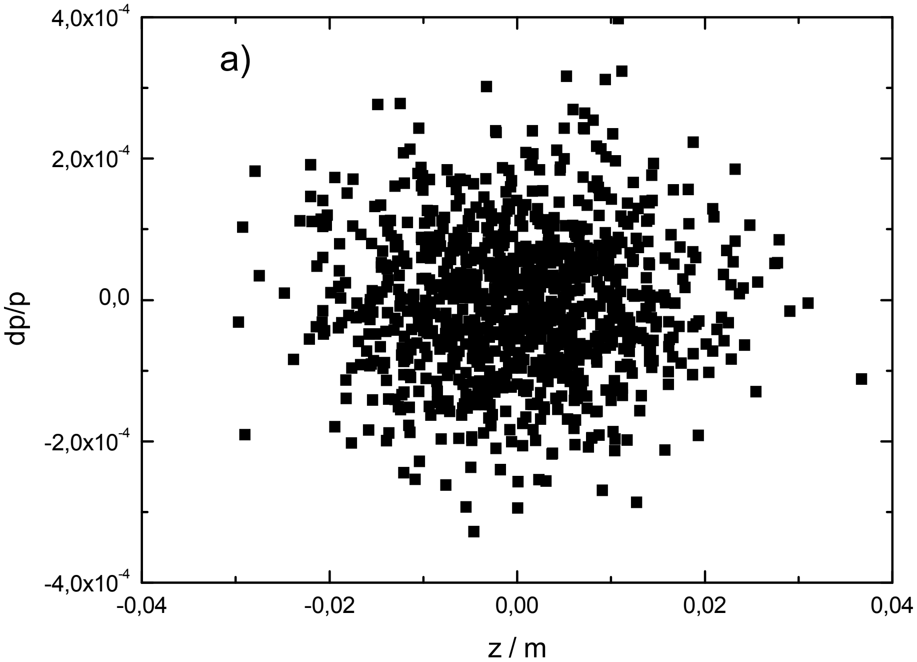


- **To compress a bunch longitudinally, trajectory in dispersive region must be <u>shorter for tail of the bunch than it is for the head</u>.**

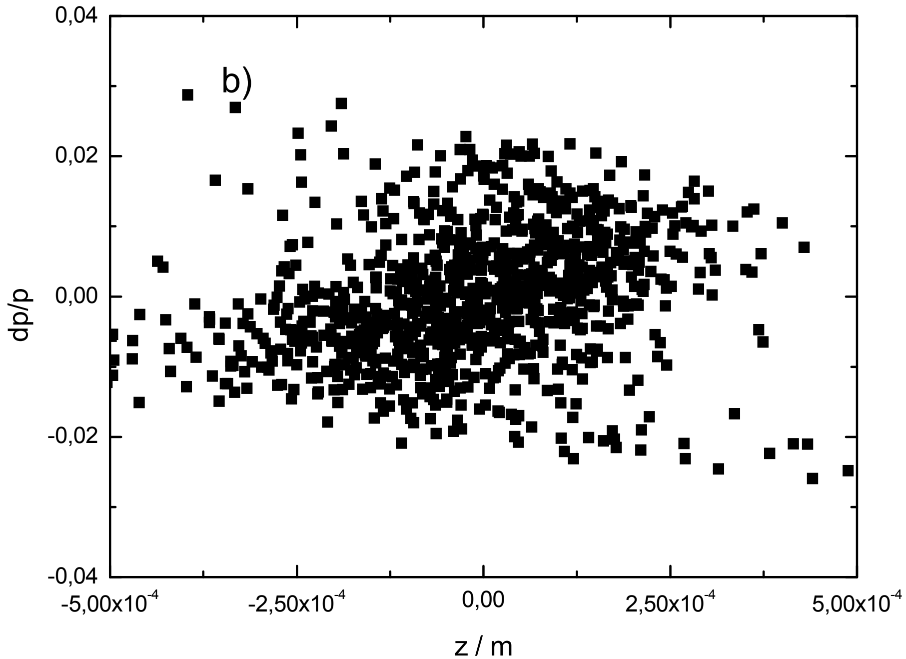
BC parameters

	Value
Bunch charge	10^{11}
Proton energy [TeV]	1
Initial energy spread [%]	0.01
Initial bunch length [cm]	1.0
Final bunch length [μm]	165
RF frequency [MHz]	704.4
Average gradient of RF [MV/m]	25
Required RF voltage [MV]	65,000
RF phase [degree]	-102
Compression ratio	~60
Momentum compaction (MC) [m]	-1.0
Second order of MC [m]	1.5
Bending angle of dipole [rad.]	0.05
Length of dipole [m]	14.3
Drift space between dipoles [m]	190.6
Total BC length [m]	4131
Final beam energy [GeV]	986.5
Final energy spread [%]	0.93

Phase space of beam

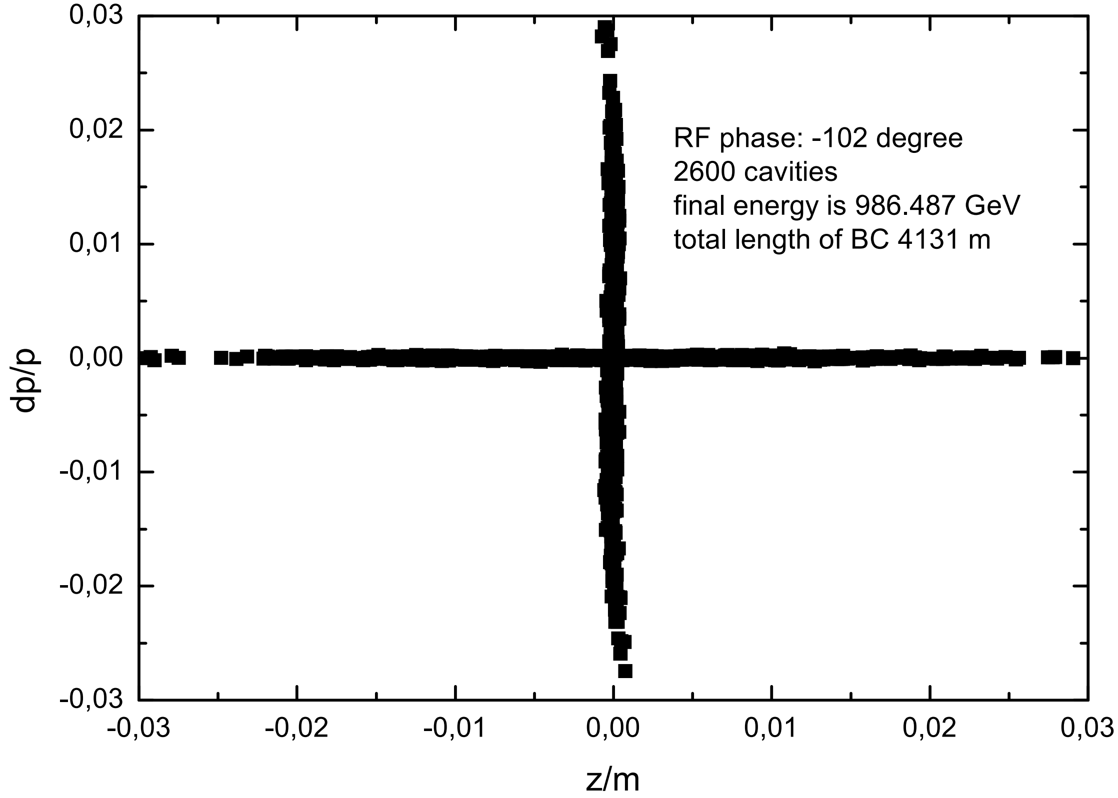


Before BC



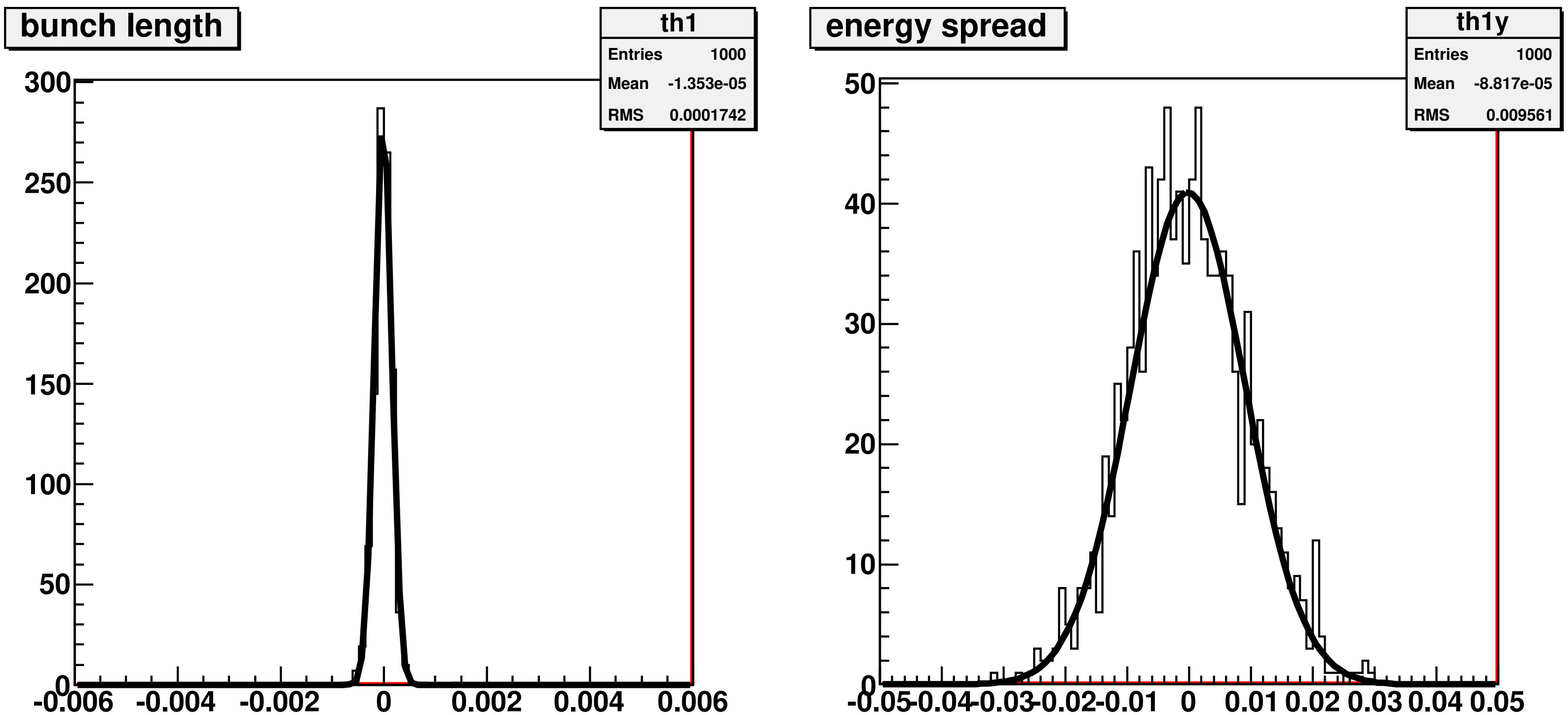
After BC

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 on PDPWA at CERN

- Near-term plan is to use the extracted proton beam from PS (need compression!).
- 2 beamlines available from East hall of PS extraction area. However, the maximum space is limited to 100 m for bunch compression !

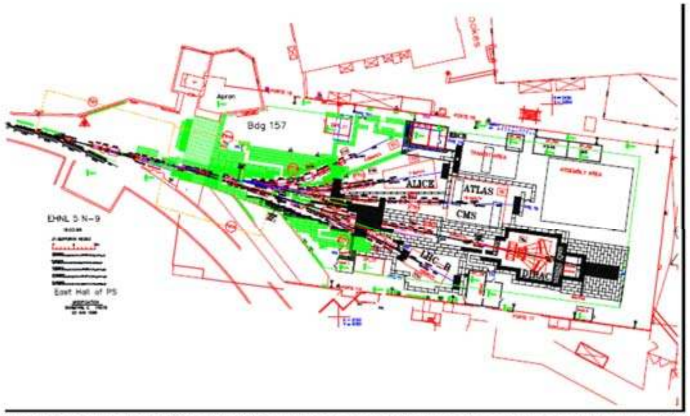


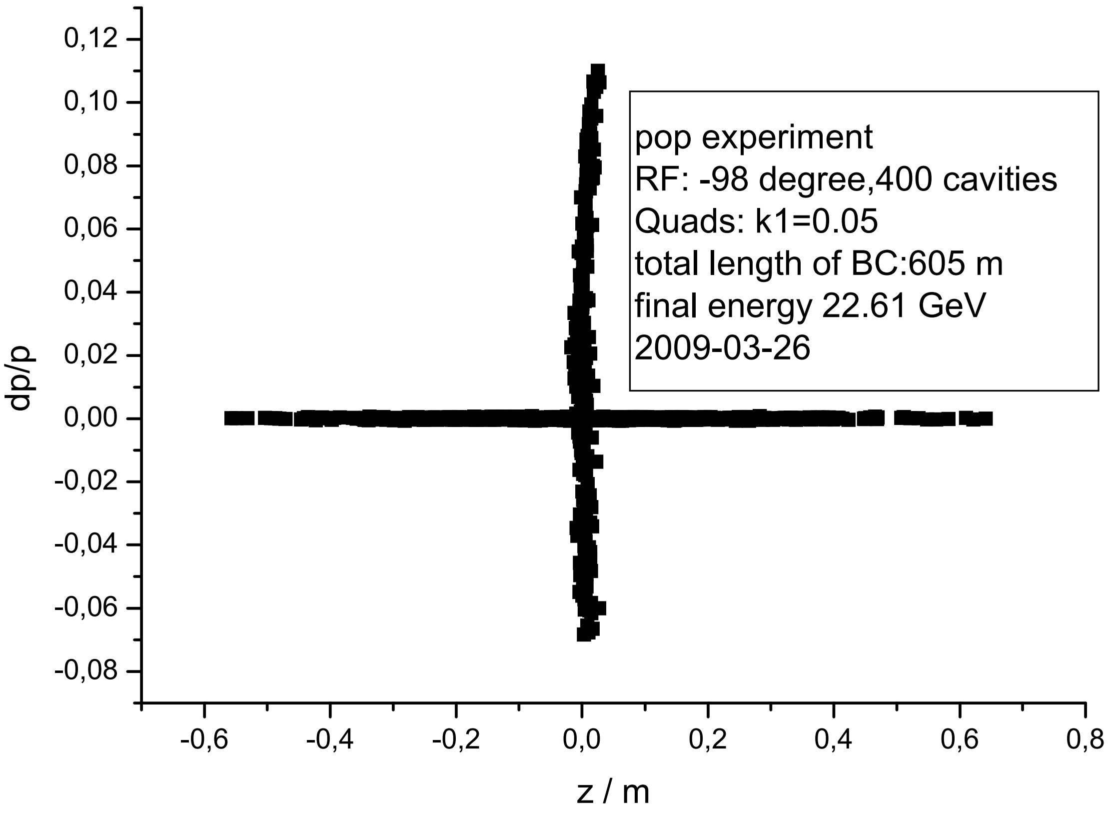
Figure: Beam lines in the PS East Hall. T7 and T8 are near the bottom. The maximum length is below 100 m.

- Intermediate-term plan is to use SPL beam (extremely short beam of 60 micron) to drive plasma wave.
- In the future, LHC beam to drive plasma wave for future collider

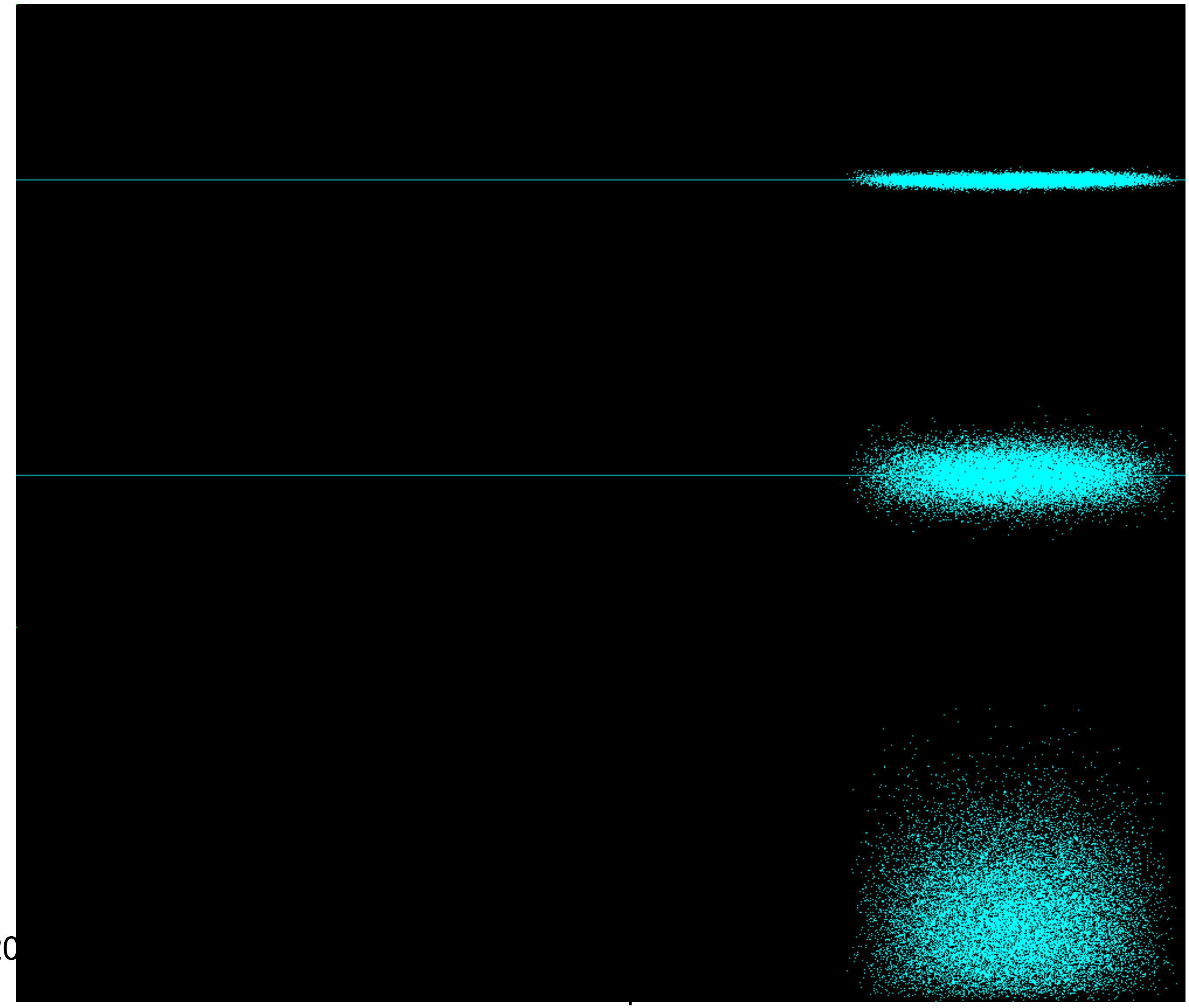
Beam parameters

- Energy: 24 GeV
- Single bunch intensity:1e9~1e11
- Bunch length: 15~30 cm rms
- Relative rms energy spread: 5e-4
- Normalized transverse emittance: 2 micron (transverse size: 1 mm)
- Normalized longitudinal emittance:7e-3 eVs.

A trial


0,12
0,10
0,08
0,06
0,04
0,02
0,00
-0,02
-0,04
-0,06
-0,08
dp/p
-0,6
-0,4
-0,2
0,0
0,2
0,4
0,6
0,8
z / m
pop experiment
RF: -98 degree,400 cavities
Quads: k1=0.05
total length of BC:605 m
final energy 22.61 GeV
2009-03-26

Results from LCODE



VLPL3D simulation PS-beam: 10cm,10e11 p Plasma: 10e13 1/cc

Summary

- Simulation shows that proton driven plasma wakefield acceleration holds promise to accelerate the electron bunch to beyond 500 GeV in only one stage
- Short high energy proton bunch could be produced via conventional magnetic bunch compression or combined other short proton beam production schemes.
- Demonstration experiment on PDPWA is planning as a future project
- Further investigations are ongoing on the key issues such as accelerating positron beam, high repetition rate for high luminosity, beam instabilities, mobile ions, etc.

Thanks for your attention !