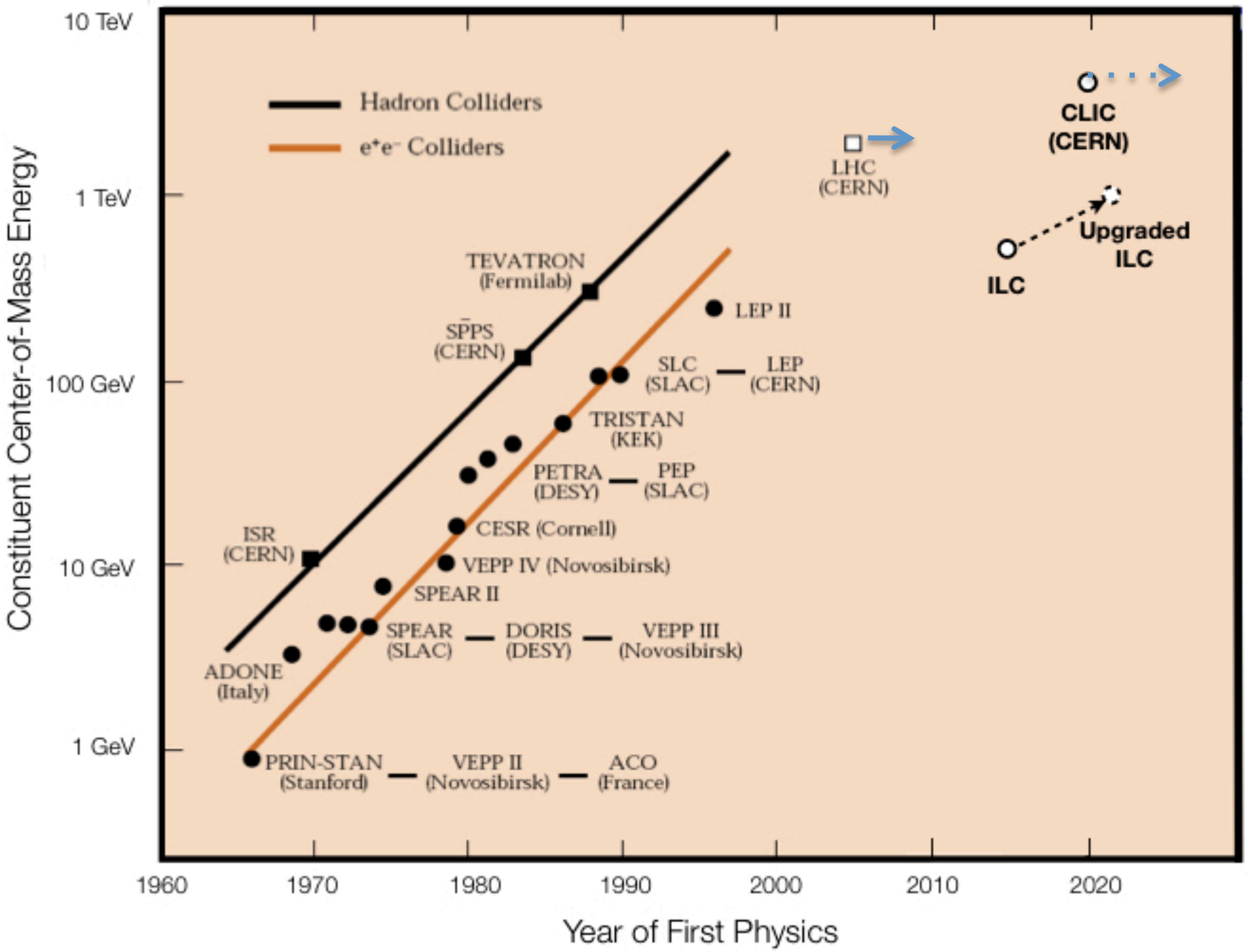
Demonstration Experiment: Proton-Driven Plasma Wakefield Acceleration

1. Introduction
2. Expectations: wakefield acceleration with a modulated proton beam
3. Proposed experiment at CERN
4. Participating groups, tasks, time scale

Allen Caldwell
Max-Planck-Institut für Physik
On behalf of all signees of the Letter of Intent

SPSC Meeting, CERN
June 28, 2011

R&D in new acceleration techniques needed to give particle physics an healthy outlook for the future.



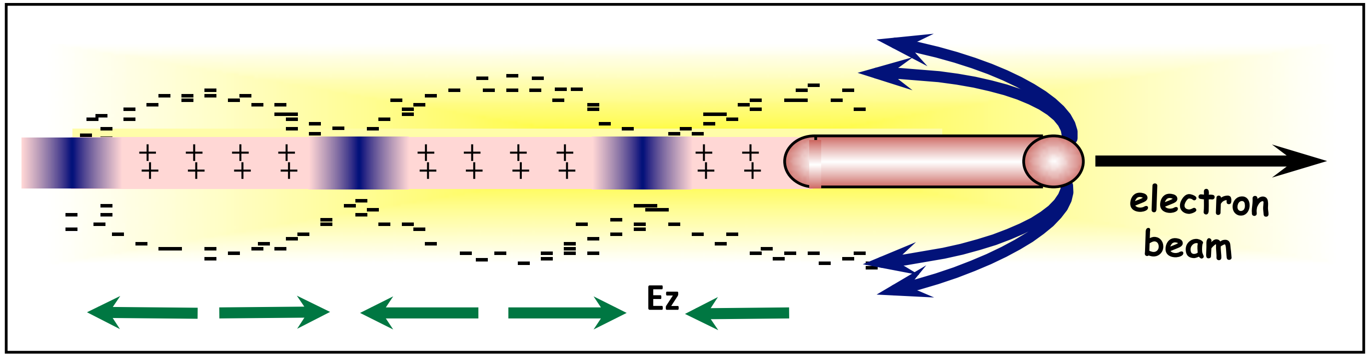
The energy in the constituent frame of electron-positron and hadron colliders. The energy of hadron colliders has here been derated by factors of 6–10 in accordance with the fact that the incident proton energy is shared among its quark and gluon constituents.

From ‘The Evolution of Particle Accelerators & Colliders by WOLFGANG K. H. PANOFSKY (1997)
Update: O. Mete

Plasma Wakefield Acceleration

Original proposal (T. Tajima, J. W. Dawson Phys. Rev. Lett. **43** (1979) 267) considered laser acceleration (LWFA). impressive steps taken in recent years as lasers have become more and more powerful. Gradients of about 100 GV/m demonstrated.

Series of experiments at SLAC using electron beams (PWFA) demonstrated that beam driven wakefield acceleration is also a very attractive option. Gradients 50 GV/m demonstrated.



$$\lambda_p \approx 1 \text{ mm} \sqrt{\frac{1 \cdot 10^{15} \text{cm}^{-3}}{n_p}}$$

Why Proton-Driven Wakefield Acceleration

Both laser-driven and electron-bunch driven acceleration will require many stages to reach the TeV scale.

We know how to produce high energy protons (many TeV) in bunches with population > 10^{11}/bunch today, so if we can use protons to drive an electron bunch we could potentially have a simpler arrangement - single stage acceleration.

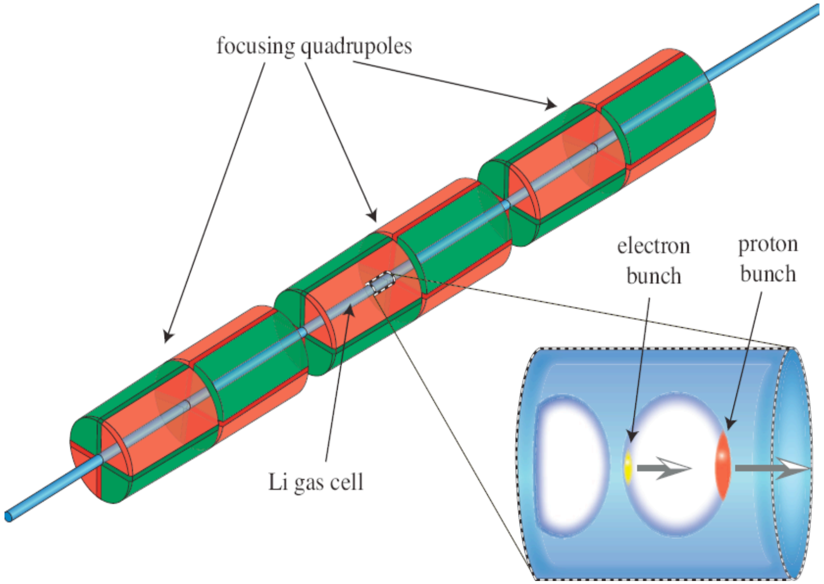
Linear regime ($n_b<n_0$):

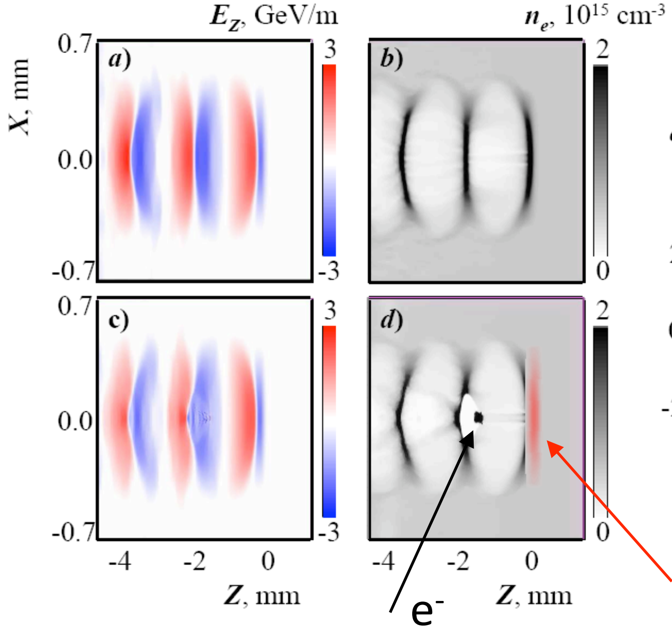
$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

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

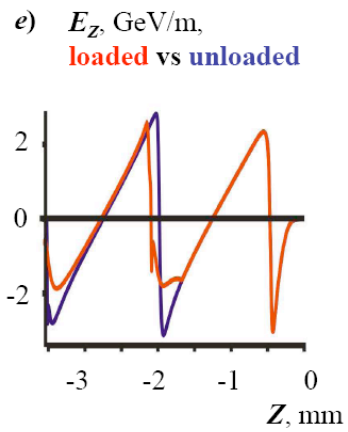
$$\sigma_z \approx 10 - 30\ \mathrm{cm}$$

Proton-driven plasma wakefield acceleration (PDPWA)





A. Pukhov, U. Düsseldorf, VLPL



Drive beam: p^+

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

σ_z=100 µm, σ_r=0.43 mm

σ_θ=0.03 mrad, $\Delta E/E$=10%

Witness beam: e^-

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

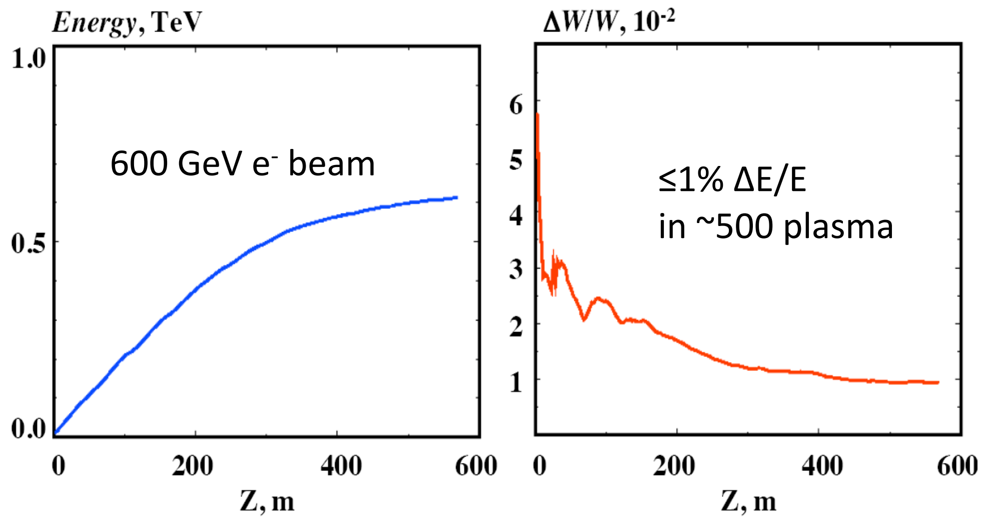
Plasma: Li^+

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

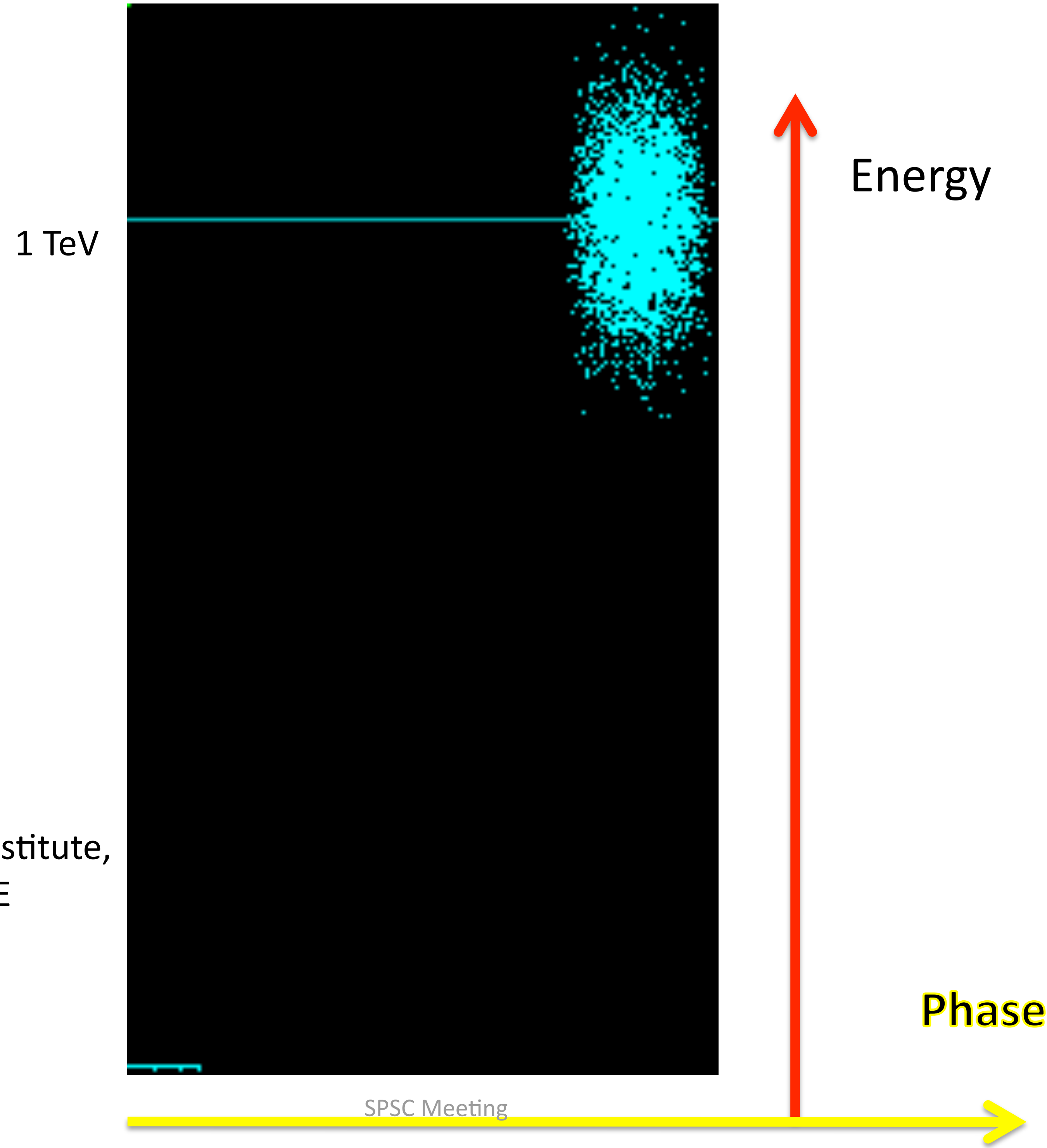
External magnetic field:

Field gradient: 1000 T/m

Magnet length: 0.7 m



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



K. Lotov (Budker Institute, Novosibirsk) LCODE

PWA via Modulated Proton Beam

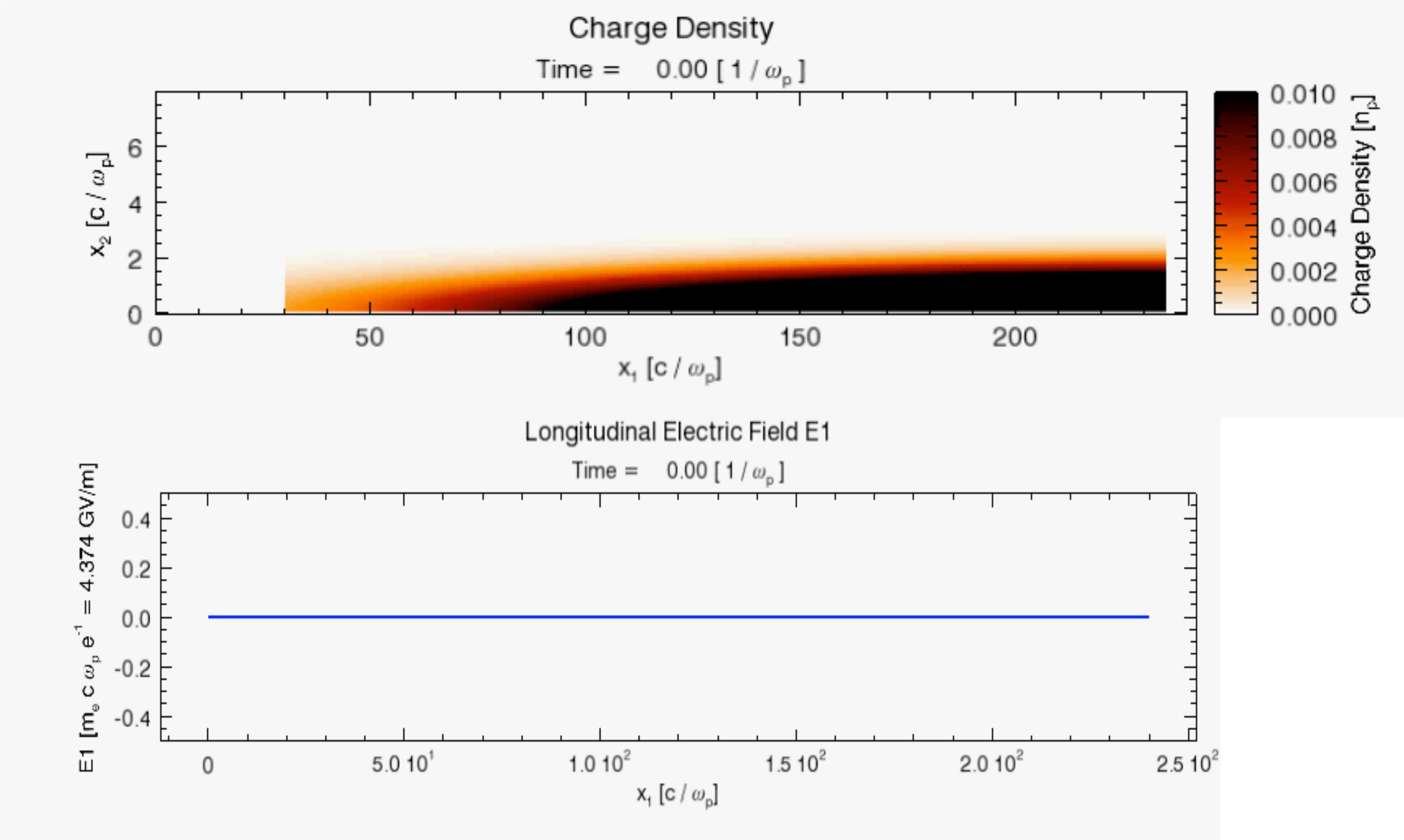
Producing short proton bunches not possible today w/o major investment. Not an option for the short term …

Instead, we investigated modulating a long bunch to produce a series of 'micro'-bunches in a plasma.

The microbunches are generated by a transverse modulation of the bunch density (transverse two-stream instability). The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and theoretically.

See, e.g.,
N. Kumar, A. Pukhov, K. Lotov, 'Self-modulation instability of a long proton bunch in plasmas', Phys. Rev. Lett. **104**, 255003 (2010).

Modulation of long bunch



Simulation: W. Lu, OSIRIS code (UCLA/Tsinghua U.)

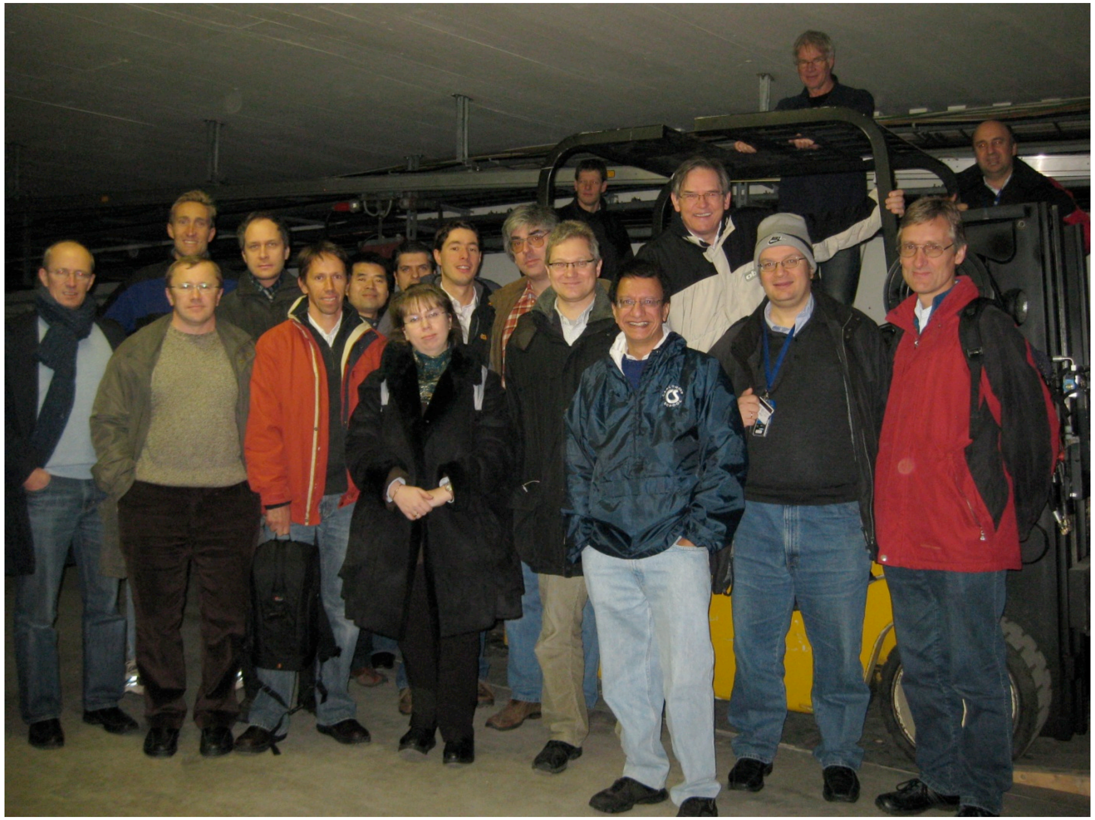
Seeding

Note:
all simulations reported in the LoI performed with seeded modulations (1/2 cut proton bunch). We anticipate seeding will be needed so that the transverse two-stream instability dominates over the hose instability.

Seeding also shortens the length of the plasma cell needed to reach full wake amplitude, and allows the timing for injection of the witness electron bunch.

Different options for seeding under consideration (see later).

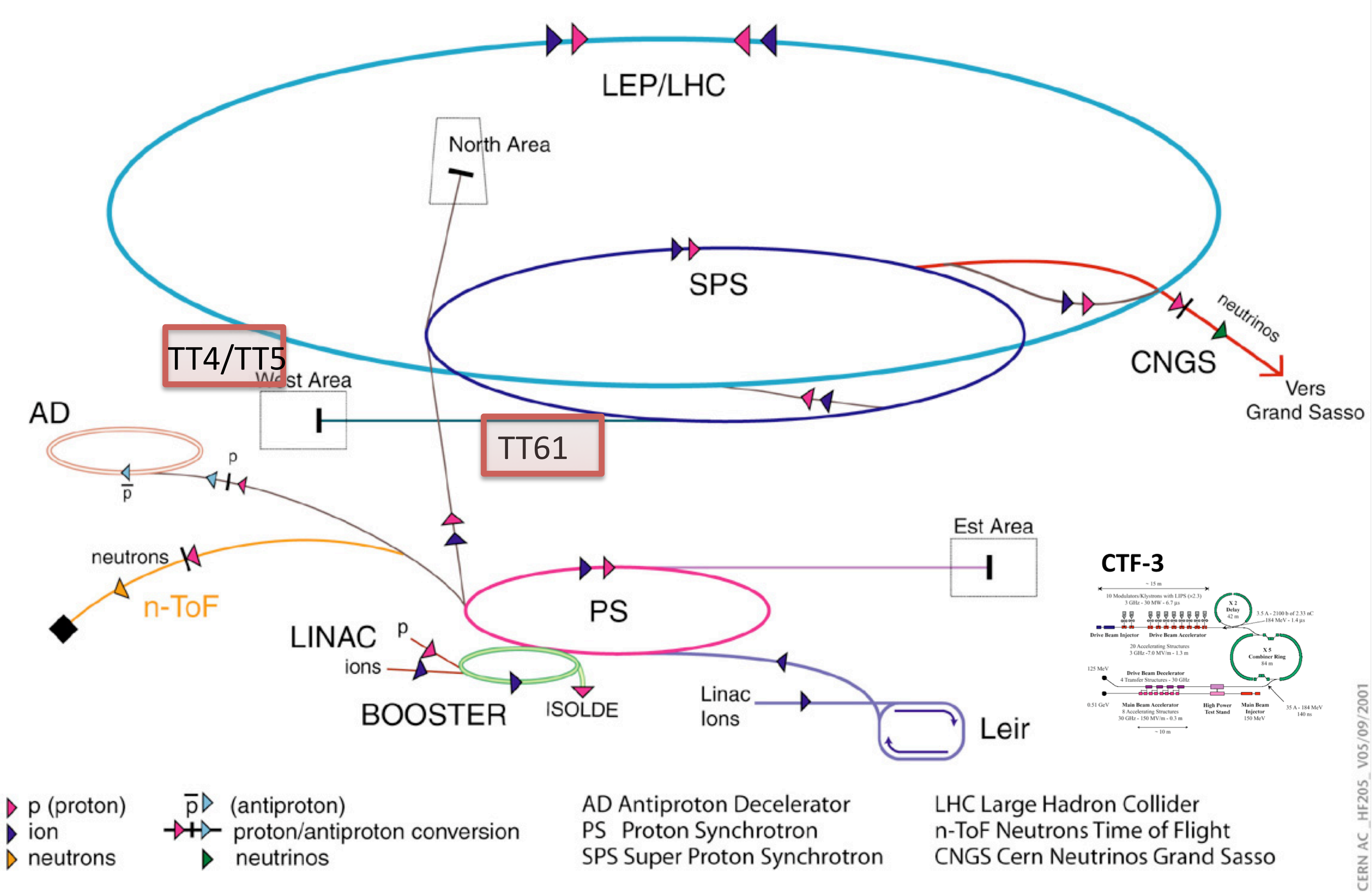
- Kick-off meeting-PPA09 held at CERN December 2009. Several workshops/ meetings since (Munich, London, CERN)
- PS and SPS options considered. From simulation studies, concluded SPS is much better. An unused SPS tunnel for demonstration experiment located.
- Experimental plan has crystallized: demonstrate 1 GeV acceleration of injected electrons within 10 m of plasma.

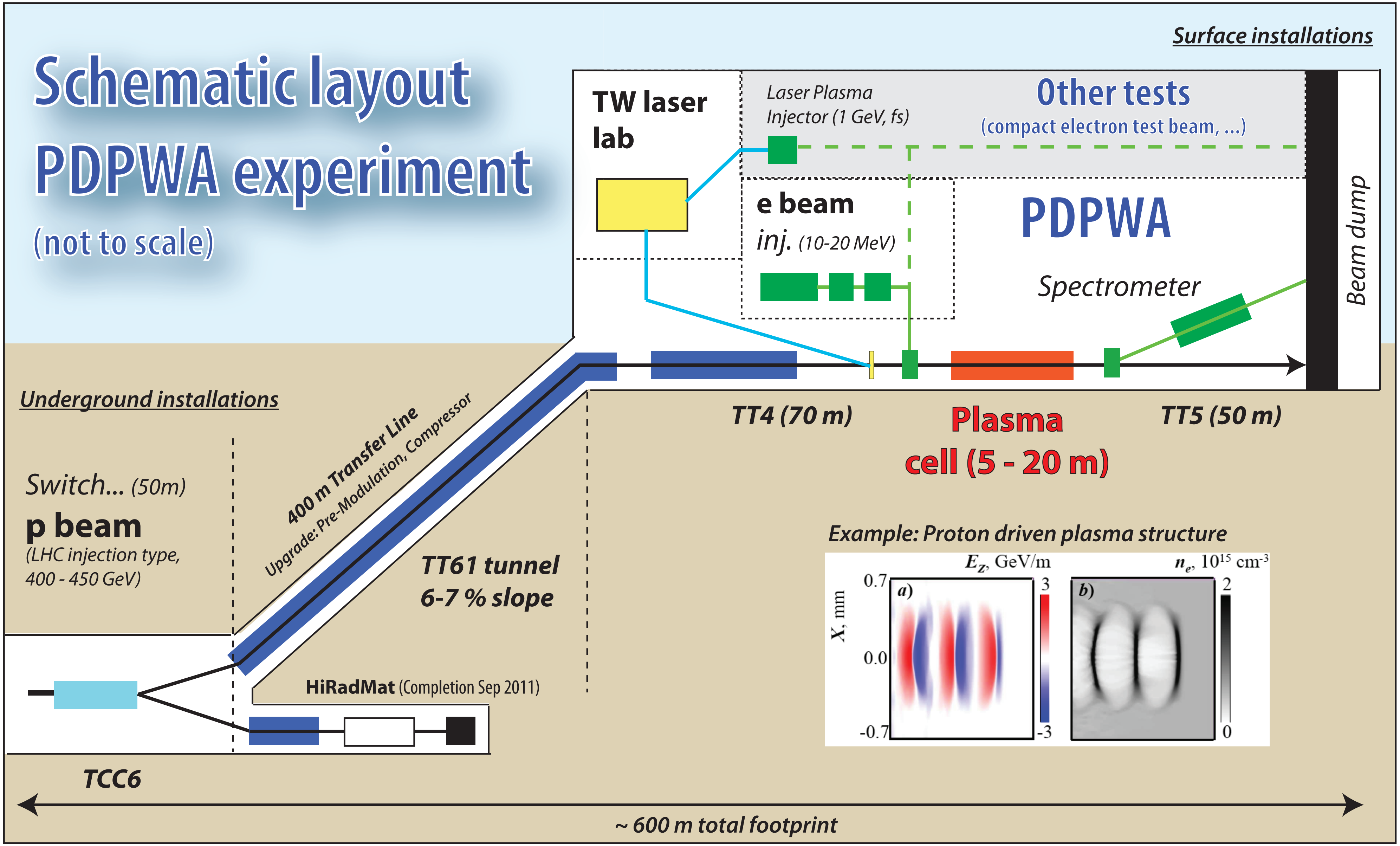


PPA09 workshop photo

Longer term – design/propose 100 GeV acceleration in 100m.

Accelerator chain of CERN (operating or approved projects)




Surface installations
Schematic layout
PDPWA experiment
(not to scale)
TW laser lab
Laser Plasma Injector (1 GeV, fs)
Other tests
(compact electron test beam, ...)
e beam inj. (10-20 MeV)
PDPWA
Spectrometer
Beam dump
Underground installations
400 m Transfer Line
Upgrade: Pre-Modulation, Compressor
TT4 (70 m)
Plasma cell (5 - 20 m)
TT5 (50 m)
Switch... (50m)
p beam
(LHC injection type, 400 - 450 GeV)
TT61 tunnel
6-7 % slope
Example: Proton driven plasma structure
E_z, GeV/m
n_e, 10^{15} cm^{-3}
X, mm
0.7
0.0
-0.7
a)
b)
3
-3
2
0
HiRadMat (Completion Sep 2011)
TCC6
~ 600 m total footprint

TT61 Tunnel

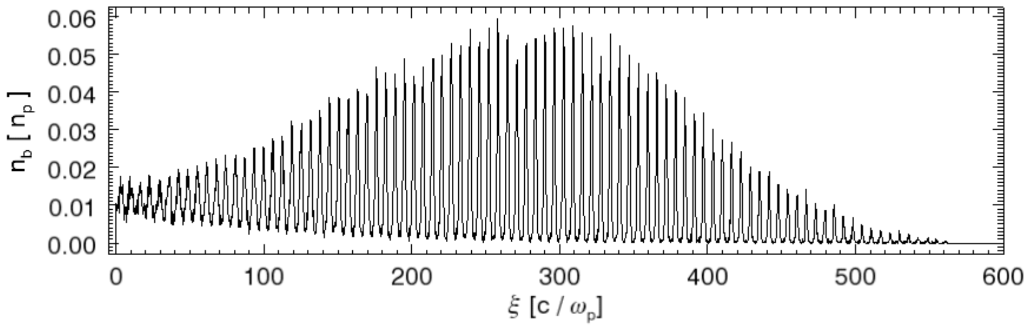
"Up" bends (bring beam horizontal to the old exp. area) - can be used as the spectrometer

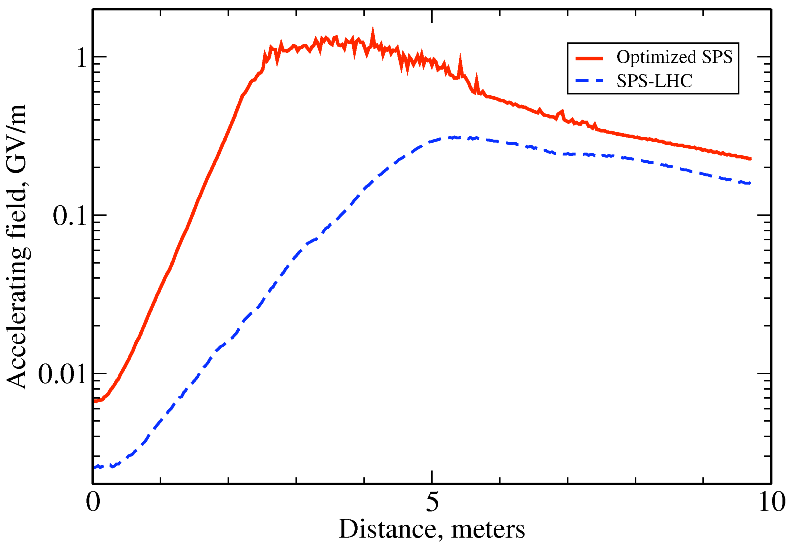
TT4/5 Area

Both halls used for storing beam elements (mostly for TT61 beamline).

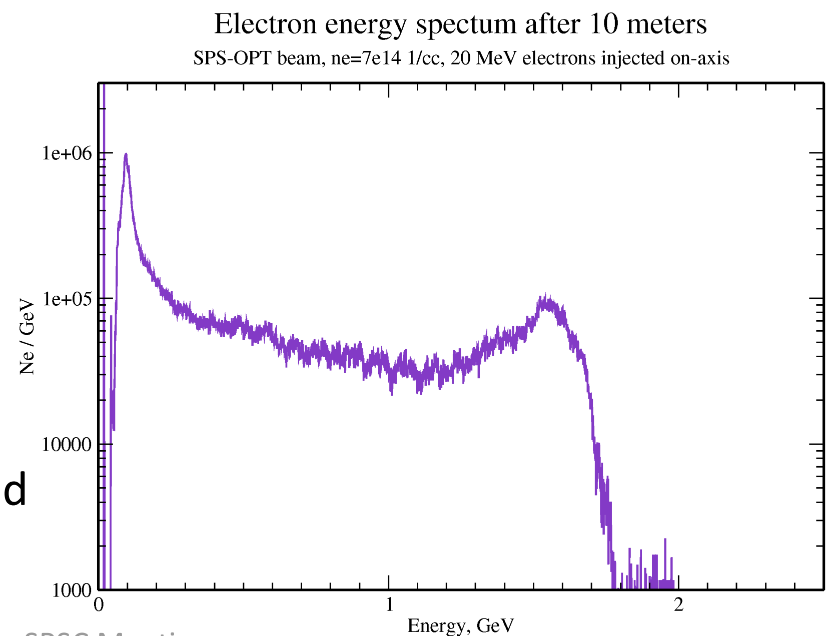
Expected Results

A long SPS drive beam will be sent into a 5-10m long plasma cell. A self-modulation of the beam due to the transverse wakefield occurs which produces many ultrashort beam slices.





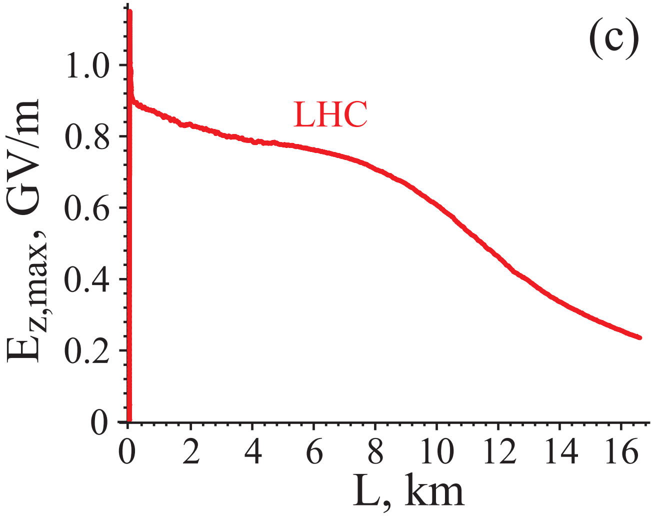
The modulation resonantly drives wakefields in the 100-1000 MV/m regime.



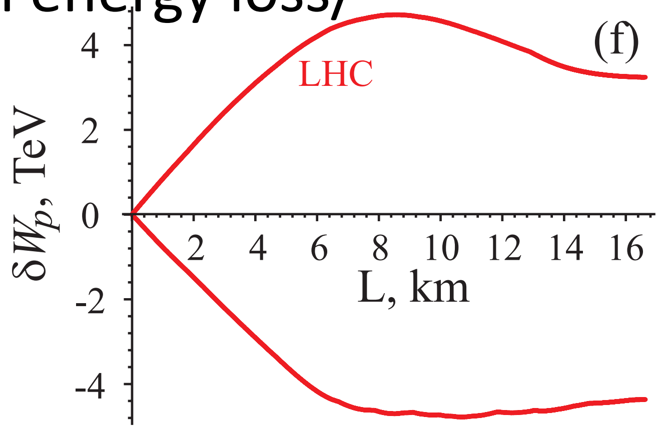
Particle-in-cell simulations predict acceleration of injected electrons to beyond 1 GeV.

Outlook

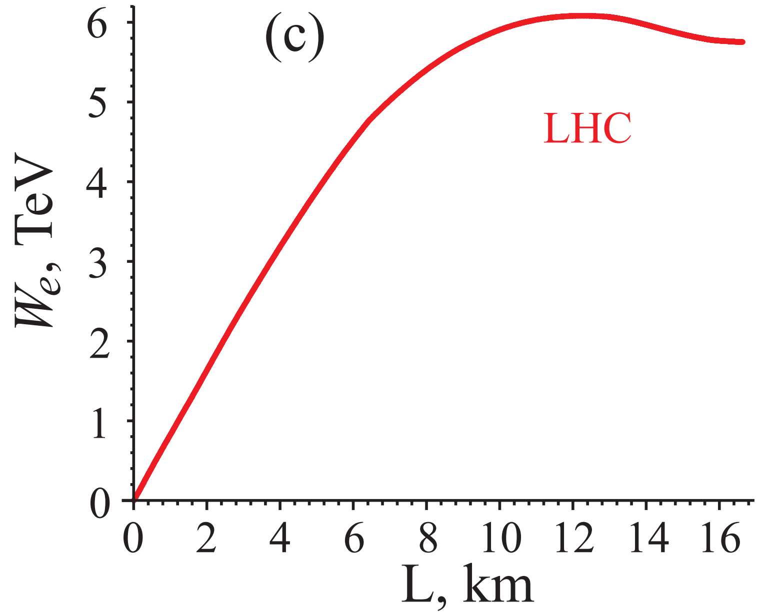
K. Lotov – simulation of existing LHC bunch in plasma with trailing electron bunch …



Proton energy loss/ gain



Electron energy gain



Miracle: no guiding magnetic fields necessary !

Date: May 31, 2011

Proto-collaboration with 25 institutes, including world-experts in all needed categories

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]

1 Brookhaven National Laboratory, Brookhaven, USA
2 Budker Institute of Nuclear Physics, Novosibirk, Russia
3 CERN, Geneva, Switzerland
4 Cockroft Institute, Daresbury, UK
5 DESY, Hamburg, Germany
6 Universität Heidelberg, Heidelberg, Germany
7 Heinrich Heine University, Düsseldorf, Germany
8 Instituto de Plasmas e Fusao Nuclear, IST, Lisboa, Portugal
9 Imperial College, London, UK
10 John Adams Institute for Accelerator Science, Oxford, UK
11 Karlsruher Institute of Technology KIT, Karlsruhe, Germany
12 LAL, Univ Paris-Sud, CNRS/IN2P3, Orsay, France
13 LOA, Laboratoire dOptique Applique, CNRS/ENSTA/X, France
14 Los Alamos National Laboratory, NM, USA
15 Ludwig Maximilian University, Munich, Germany
16 Max Planck Institute for Physics, Munich, Germany
17 Max Planck Institute for Plasma Physics, Greifswald, Germany
18 Panjab University, Chandigarh, India
19 Rutherford Appleton Laboratory, Chilton, UK
20 State Key Laboratory of Nuclear Physics and Technology, Peking University, China
21 Tsinghua University, Beijing, China
22 University of California, Los Angeles, CA, USA
23 University College London, London, UK
24 University of Oslo, Oslo, Norway
25 University of Strathclyde, Glasgow, Scotland, UK

Phases of the Project

• Phase I is the development of a technical design for the demonstration experiment with proton driven wakefields, and would last one year;

• Phase II is the preparation of the experiment, and would last approximately two years;

• Phase III is the actual running of the experiment, and would initially last two years. Expect to run for ca two week periods 4 times/year.

- base-line plan: put together a beamline, a plasma source and a beam modulation diagnostic for the first experiments;
- add seeding, e-injection, other diagnostics as appropriate.

Request from CERN

Parameter	Nominal	Optimized
Momentum [GeV/c]	450	450
Protons/bunch [10^{11}]	1.15	3.0
rms longitudinal emittance [eVs]	0.05	0.05
rms energy spread [MeV]	135	135
rms bunch length [cm]	12	12
rms transverse normalized emittance [μm]	3.5	3.5
beam size [μm]	200	200
beta function at plasma cell [m]	5	5

Rep rate: 1 bunch/ fill

- demonstration of optimized beam parameters
- switch and transport the TT66 beam towards the entrance of the TT61 tunnel during LHC shutdown.
- equip the TT61 beamline if possible during the LHC shutdown, but if not possible after shutdown.
- failsafe interlocking of the switching process between the different beam lines for LHC, HiRadMat and a PDPWA beam line
- beam dump design
- safety/radiation safety investigation

R & D Tasks

Plasma cell

Plasma cells based on laser ionization of a metal vapor have been successfully operated at lengths up to 1.4m, while we require a plasma cell of 5-10m. Alternative designs (discharge, helicon) are in principle scalable to long lengths, but the required uniformity and plasma density need to be demonstrated.

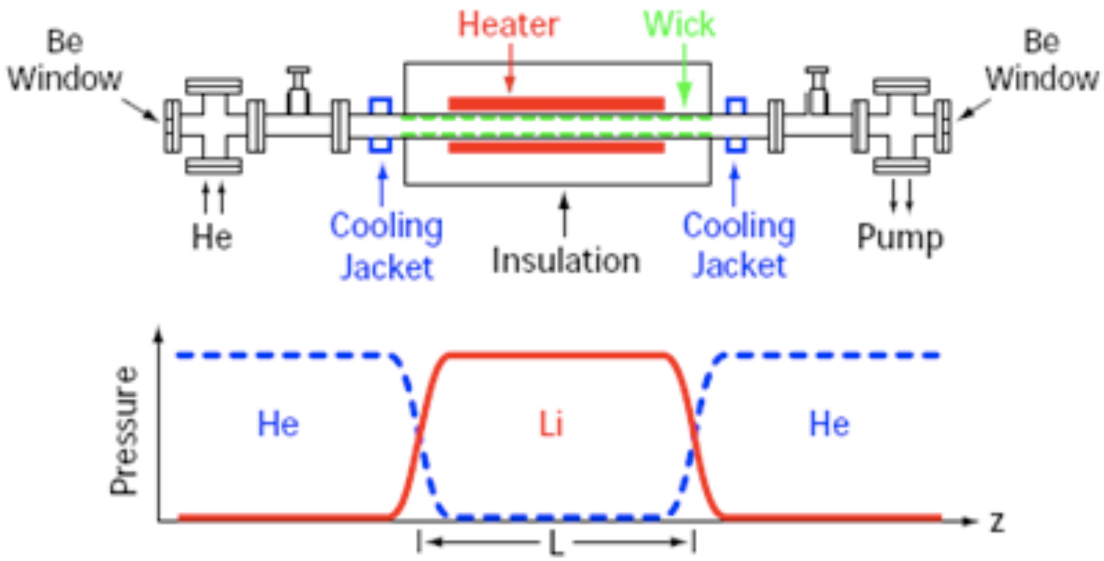
Seeding the instability

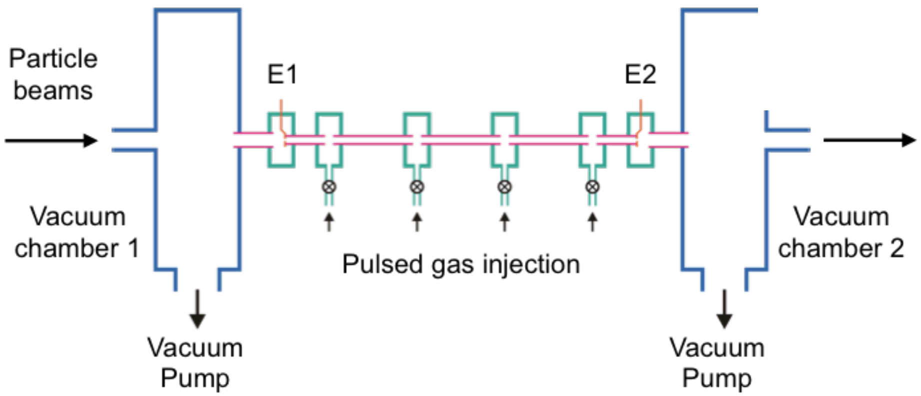
We are currently investigating three scenarios:

- generating the seeding by forming the plasma with a **short laser pulse co-propagating with the proton bunch** (all simulation results reported here assume this type of seeding);
- sending a **short laser pulse into a pre-existing plasma** just before the arrival of the proton bunch;
- sending a **short electron bunch into a pre-existing plasma** just before the arrival of the proton bunch.

Plasma Cell ideas

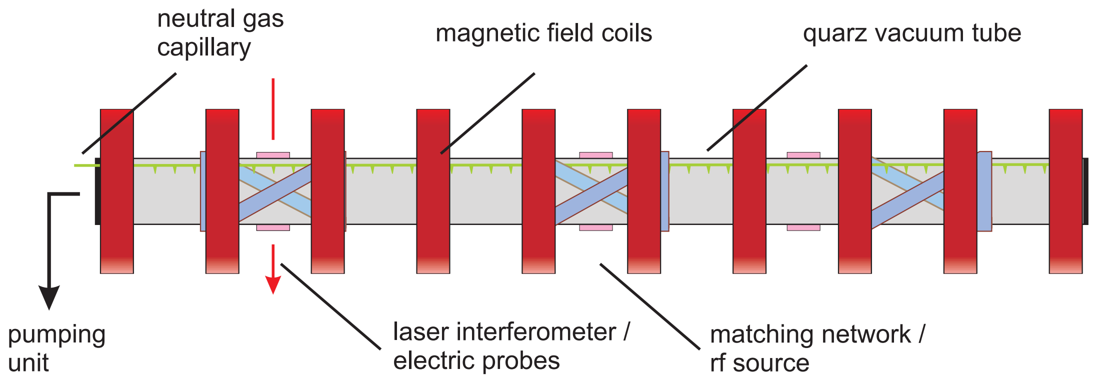
Metal vapor, a la SLAC experiment:
UCLA, Max Planck Institute for Physics





Discharge: IST, Imperial College, Strathclyde

Helicon – Max Planck Institute for Plasma Physics



R & D Tasks - continued

THz optical diagnostic

R&D required to demonstrate effectiveness. These techniques are not required for the demonstration of the acceleration mechanism, but will be essential in the analysis of the dynamics of the beam-plasma interaction.

radiation safety aspects

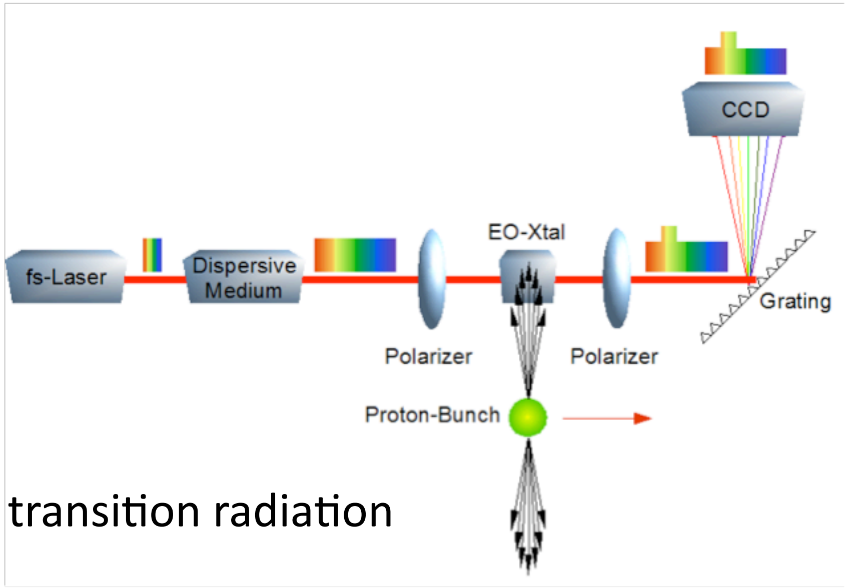
We are confident that we will find solutions for the radiation protection aspects. However, they will need to be studied in detail.

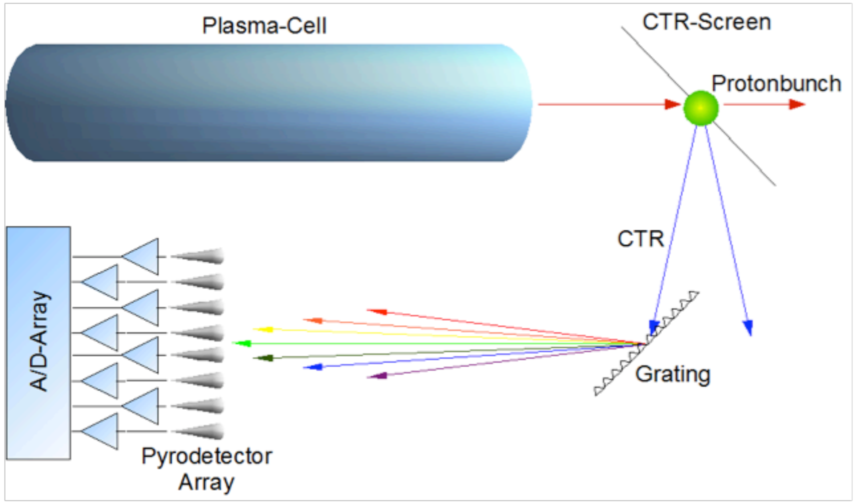
The delivery of the proton bunch, the electron injection and spectrometer systems and the beam dump are judged to be technically realizable, but will require significant efforts.

Diagnostics

Electro-optical sampling for modulations, field strength:

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



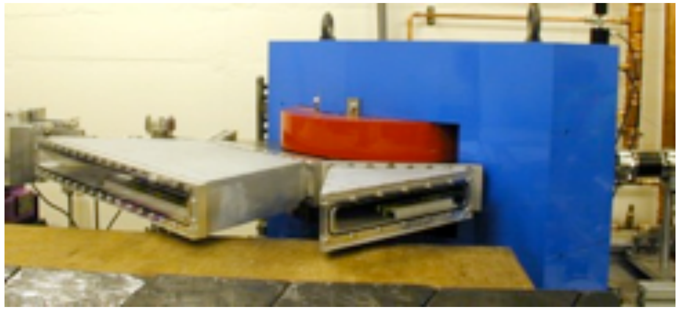


Coherent transition radiation

Electron spectrometer:

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

Injector/spectrometer for electron bunch



Task Breakdown/Assignment/First Cost Estimate

Category	Task	Institute(s)	Cost (kEuro)
Plasma Cell			
	metal vapor Cell	UCLA, TH, MPP	1000
	Helicon Cell	IPP	400
	Pulsed discharge Cell	IST, IC, SC	600
Beams			
	Proton delivery/dump	CERN +	} 16000
	Design of experimental area	CERN, KIT, +	
	Beam monitoring/diagnostics	CERN, LAL, +	
	Radiation safety	CERN	
	Electron Injection	JAI, CI, TH, BNL, SC	2000
Diagnostics			
	Electron spectrometer	CERN, IC, SC, KIT, UCL, D	500
	optical sampling methods	MPP, UCL, RAL, DESY, IC, CI, SC, D	2000
Laser system	plasma, e injector, diagnostics	MPP, UCLA, TH, UCL, SC	1200
Simulations		BINP, D, UCLA, IST, LANL, RAL, UCL, CERN	

Table 2: Breakdown of tasks and groups expressing interest. The codes are as follows: BINP-Budker Institute for Nuclear Physics, BNL-Brookhaven National Laboratory, CI-Cockroft Institute, D-Uni. Düsseldorf, CERN-CERN, IC-Imperial College, IPP-Max Planck Institute for Plasma Physics, JAI-John Adams Institute, KIT-Karlsruhe Institute of Technology, MPP-Max Planck Institute for Physics, RAL-Rutherford Appleton Laboratory, SC-University of Strathclyde, TH-Tsinghua University, UCL-University College London, UCLA-University of California at Los Angeles

Summary

We propose a demonstration experiment in proton-driven plasma wakefield acceleration using the existing CERN SPS beam. This project would be the first beam-driven wakefield acceleration experiment in Europe, and the first proton-driven plasma-wakefield acceleration experiment worldwide.

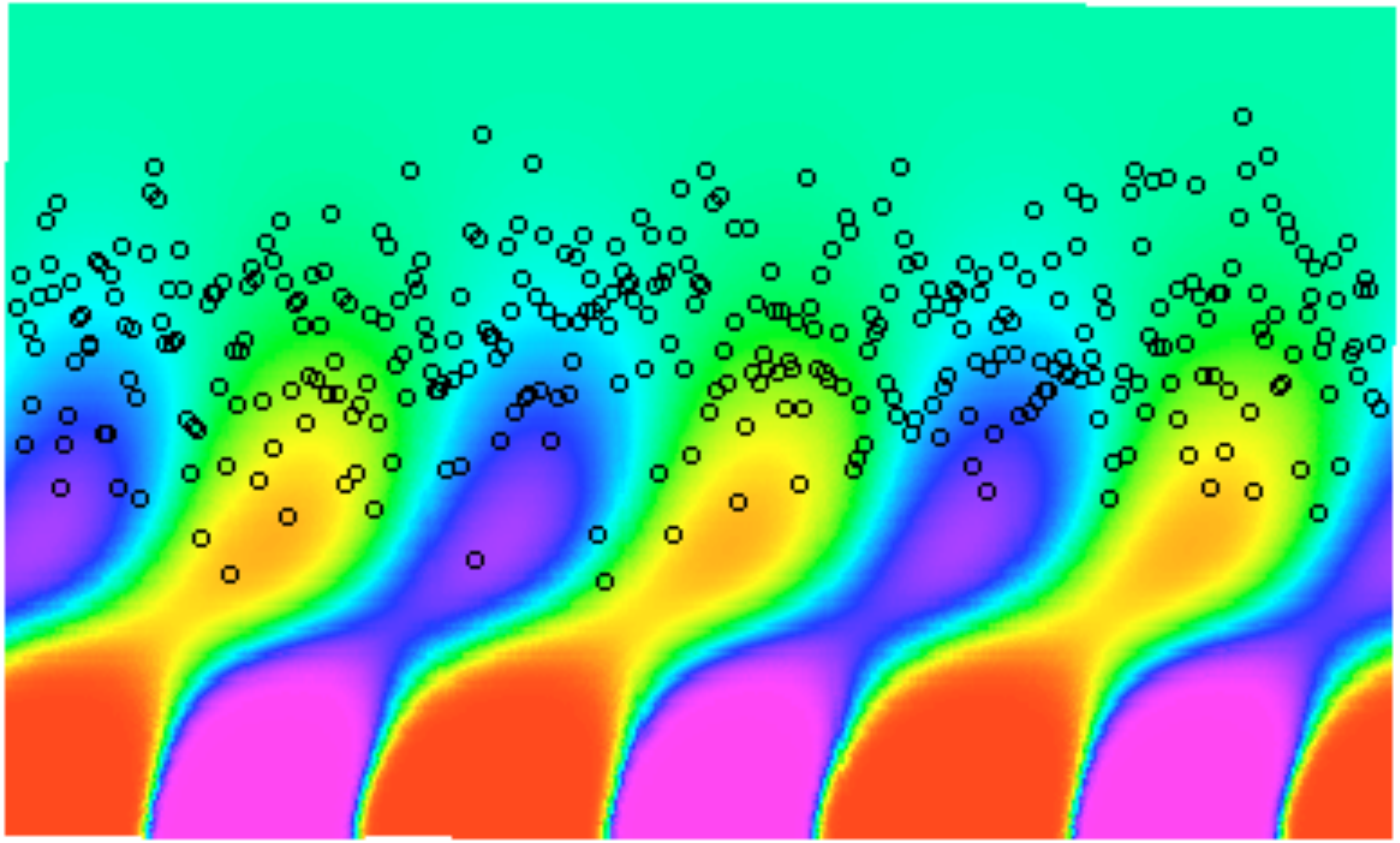
Initial goal: demonstration of 1 GeV energy gain for electrons in 10 m of plasma. A proposal for reaching 100 GeV within 100 m of plasma will be developed using results from the initial round of experimentation.

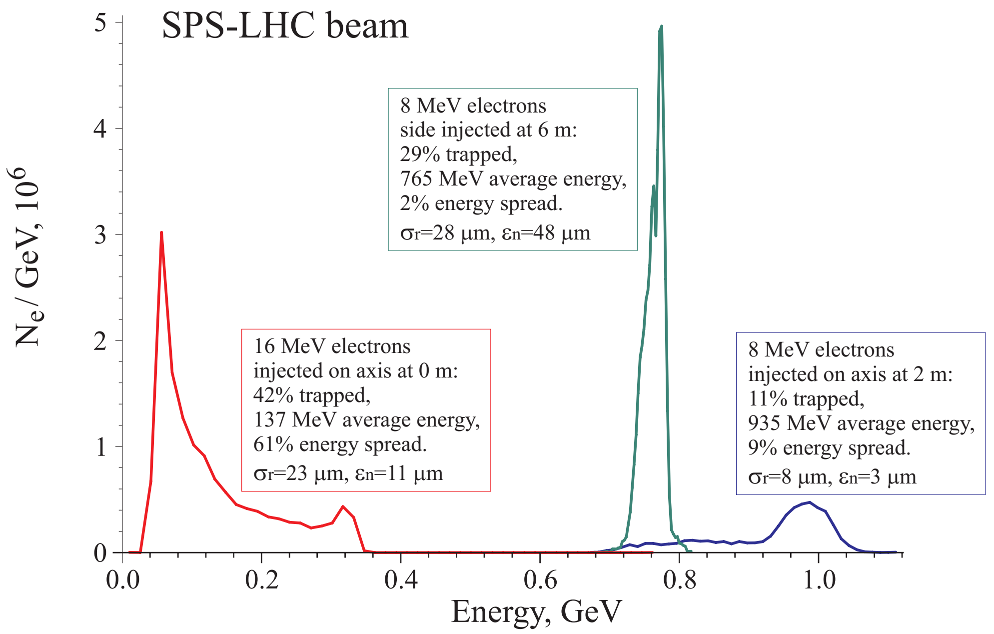
The proposed experimental setup can be extended in the future to perform additional advanced accelerator research at CERN (see LoI).

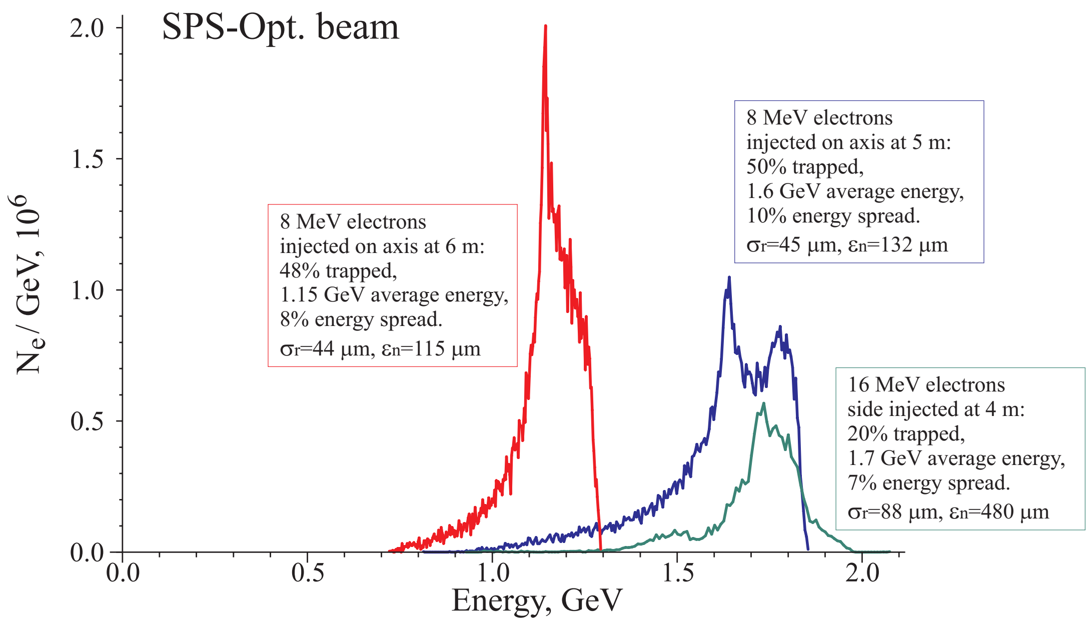
The proto-collaboration is already significant in size, and includes the needed expertise from previous PWA experiments as well as very strong simulation teams.

BACKUP

Continuously coming up with new ideas … side injection of electron beams (K. Lotov)



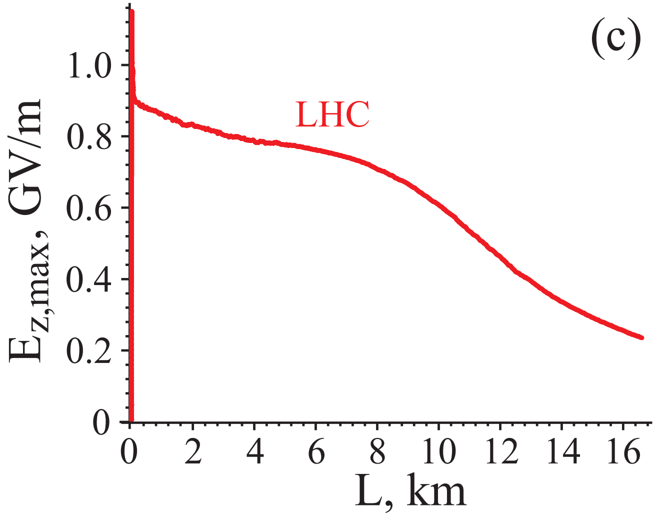

SPS-LHC beam
8 MeV electrons
side injected at 6 m:
29% trapped,
765 MeV average energy,
2% energy spread.
σr=28 μm, εn=48 μm
16 MeV electrons
injected on axis at 0 m:
42% trapped,
137 MeV average energy,
61% energy spread.
σr=23 μm, εn=11 μm
8 MeV electrons
injected on axis at 2 m:
11% trapped,
935 MeV average energy,
9% energy spread.
σr=8 μm, εn=3 μm
Ne / GeV, 10^6
Energy, GeV


SPS-Opt. beam
8 MeV electrons
injected on axis at 5 m:
50% trapped,
1.6 GeV average energy,
10% energy spread.
σr=45 μm, εn=132 μm
8 MeV electrons
injected on axis at 6 m:
48% trapped,
1.15 GeV average energy,
8% energy spread.
σr=44 μm, εn=115 μm
16 MeV electrons
side injected at 4 m:
20% trapped,
1.7 GeV average energy,
7% energy spread.
σr=88 μm, εn=480 μm
Ne / GeV, 10^6
Energy, GeV

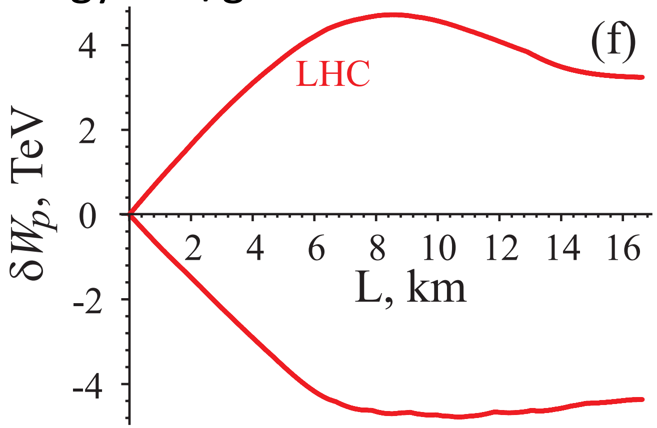
Outlook

Long term prospects for modulated proton bunch intriguing:

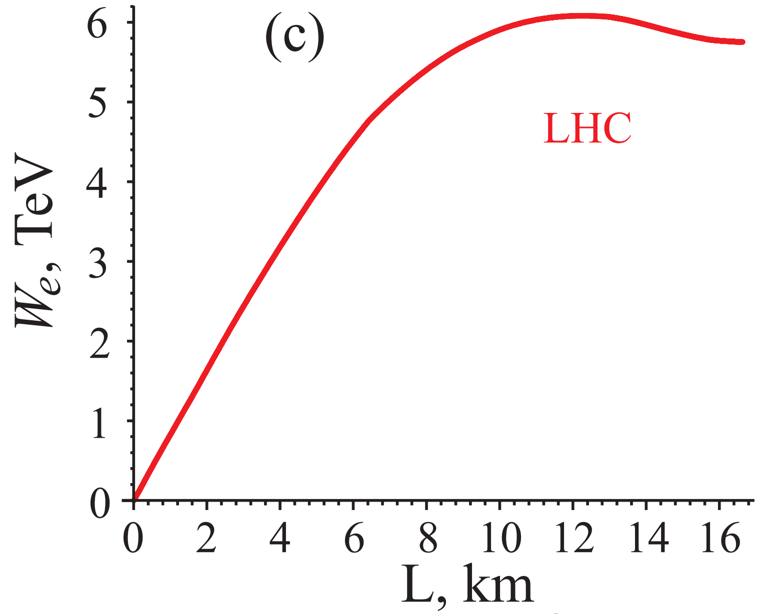
K. Lotov – simulation of existing LHC bunch in plasma with trailing electron bunch …



Proton energy loss/gain



Electron energy gain



Miracle: no guiding magnetic fields necessary !

Luminosity

$$L = f\frac{N_1 N_2}{4\pi\sigma_x\sigma_y} \quad \text{Gaussian shaped beams}$$

$$\text{suppose} \quad N_1 = N_2 = 10^{11}$$

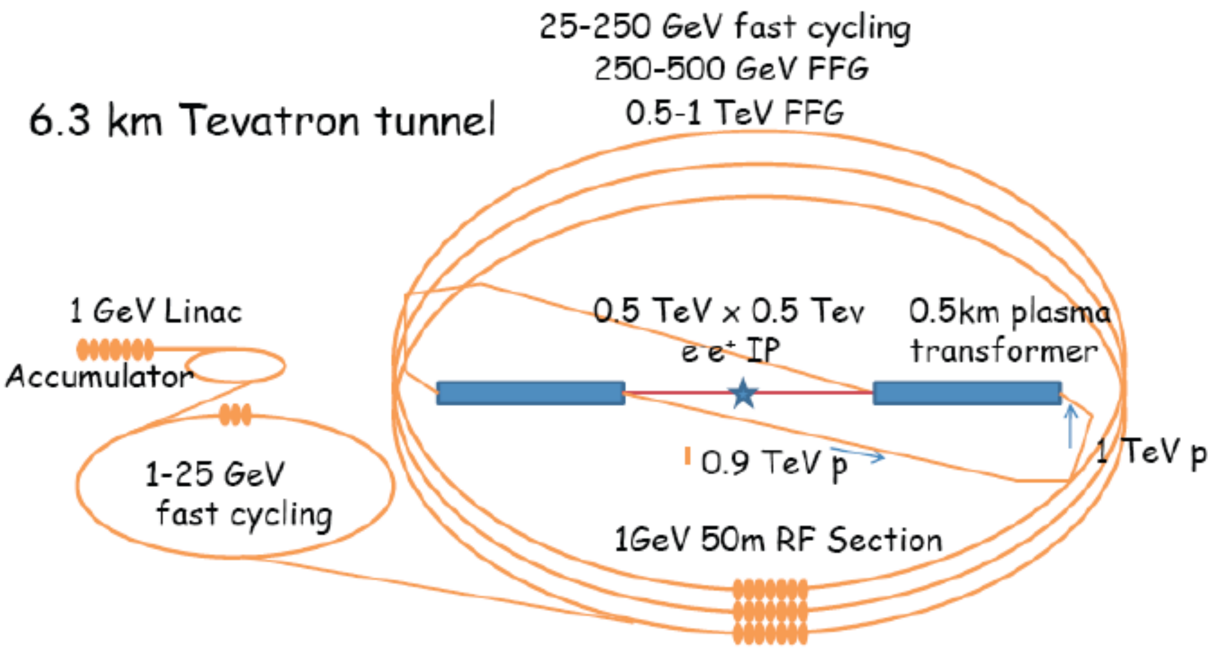
$$\text{SPS} \quad \text{cycle time } \ 22s \quad 288 \ \text{ bunches } \ \text{ so assume } \ f = 15 \text{ Hz}$$

$$L \approx \left(\frac{1\ \mu\text{m}^2}{\sigma_x\sigma_y}\right) 10^{30}\ \text{cm}^{-2}\ \text{s}^{-1}$$

Will need very small cross section beams for significant luminosity

PDPWA-based LC

V. Yakimenko, BNL, T. Katsouleas, Duke



Concept for high repetition rate of proton driven plasma wakefield acceleration

3 ring + injectors + recovery