Status of PDPWA, Muon Cooling, and ILC

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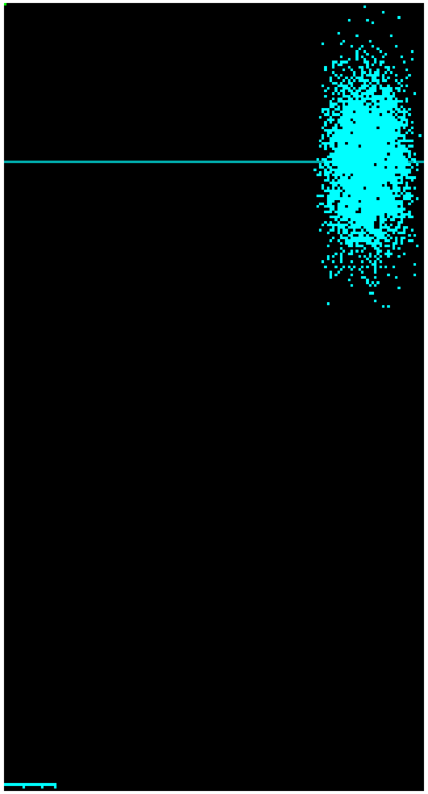
Project Review 2010

MAX-PLANCK-GESELLSCHAFT

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

Proton-driven plasma Wakefield Acceleration (PDPWA)

- Motivation
- Demonstration experiment at CERN
- Simulation of SPS beam-driven PWA
- Status and outlook



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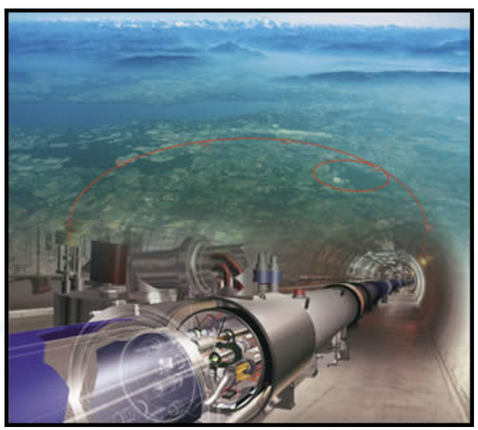
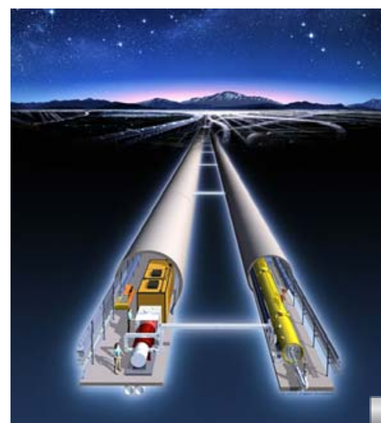
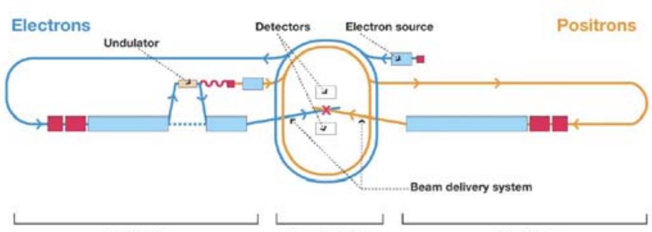
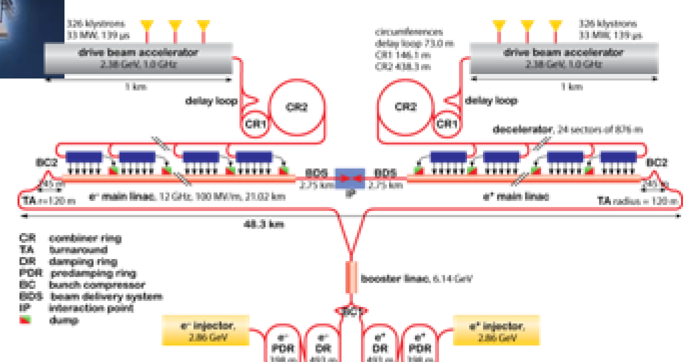
Motivation

- With an increase of beam energy, the size and cost of modern high energy particle accelerators reach the limit (break down+power)
- 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 20 years, 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?
- It will be the PWFA experiment in Europe and first PDPWA experiment around the world.

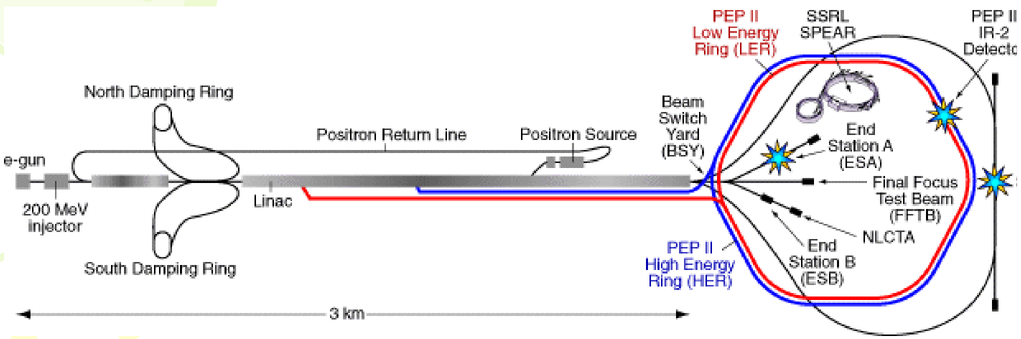


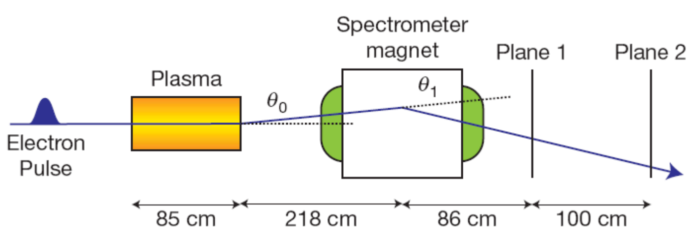


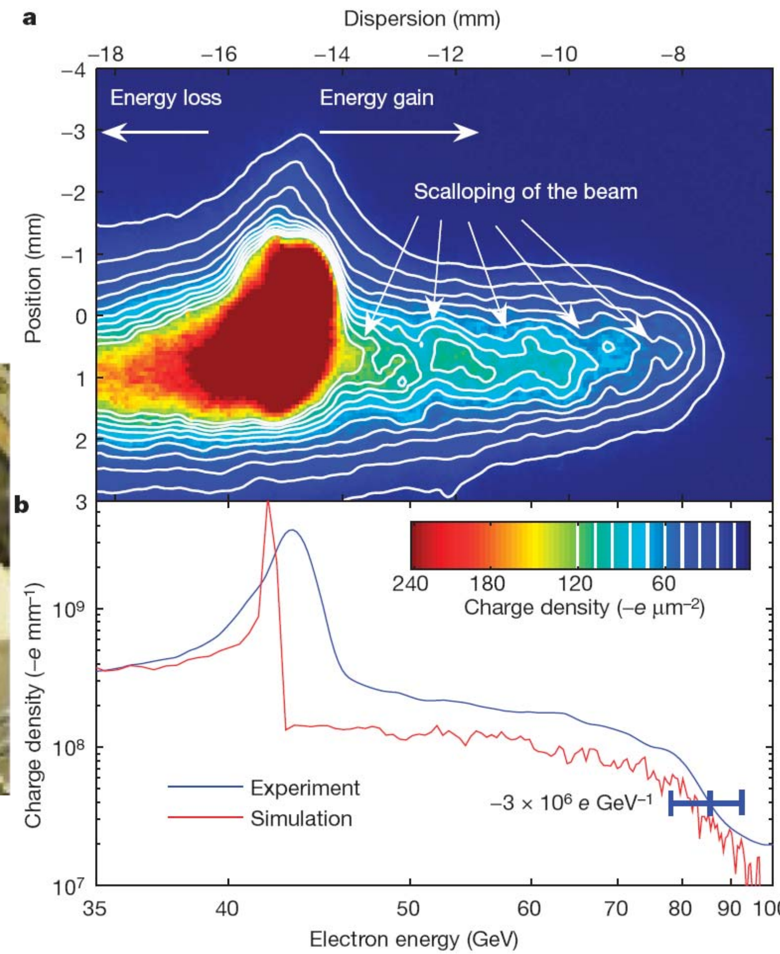




PWFA







Electron beam (beam energy 42GeV, bunch length 50 fs, bunch charge 2.9 nC)

Plasma (length 85 cm, density 2.7e17 cm-3)

Max. energy gain
43 GeV (85 cm column) = 52 GeV/m !
29 GeV (113 cm column)

Energy spectrum of the electrons in the 35-100 GeV range as observed in plane 2

Blumenfeld et al., Nature 445 (2007) 741

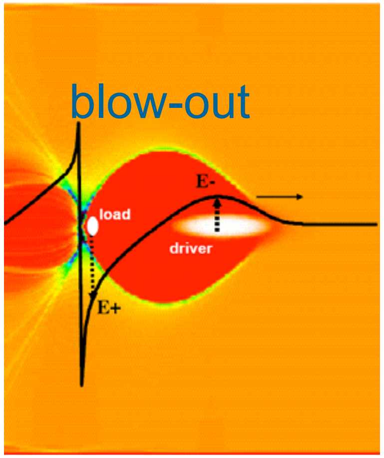
PWFA and PDPWA

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

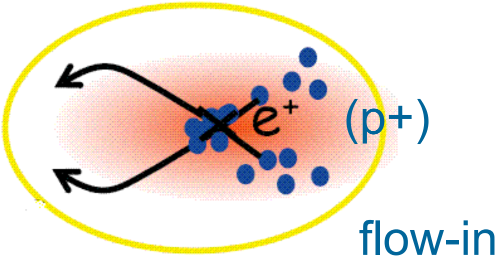
One stage energy gain is limited by transformer ratio, therefore maximum electron energy is about 100 GeV using SLC beam.

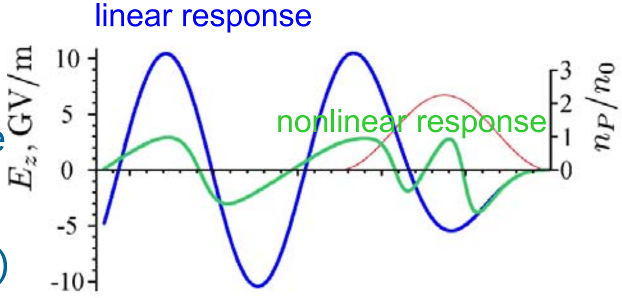
Easy to be subject to the head erosion due to small mass of electrons

Pros. of PDPWA

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

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





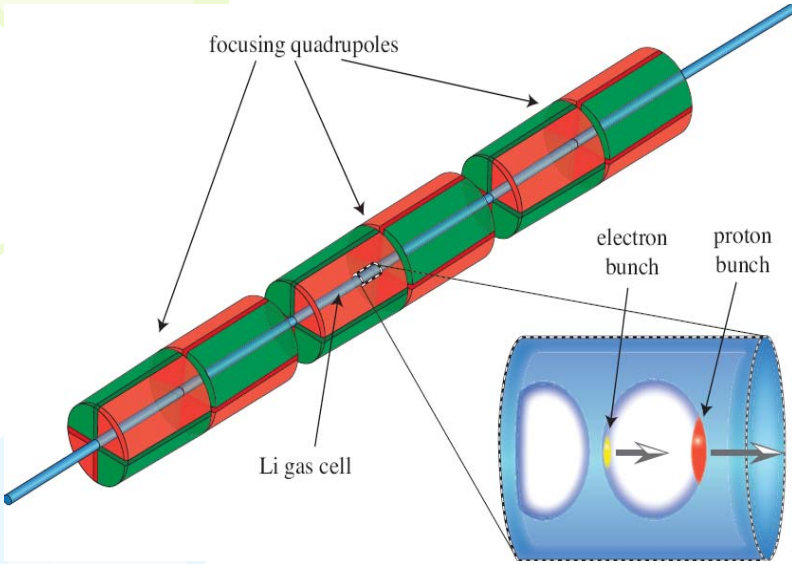
Cons. of PDPWA

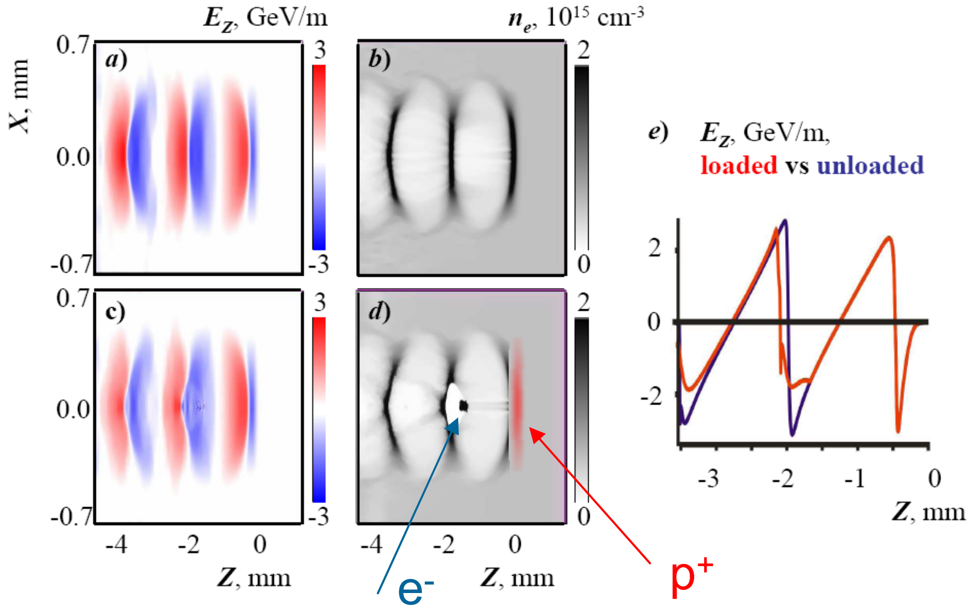
Flow-in regime responds a relatively low field *vs*. blow-out regime

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

PDPWA





Drive beam: p^+

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

σ_z=100 μm,σ_r=0.43 mm

σ_θ=0.03 mrad, ΔE/E=10%

Witness beam: e^-

E_0=10 GeV, N_e=1.5x10^{10}

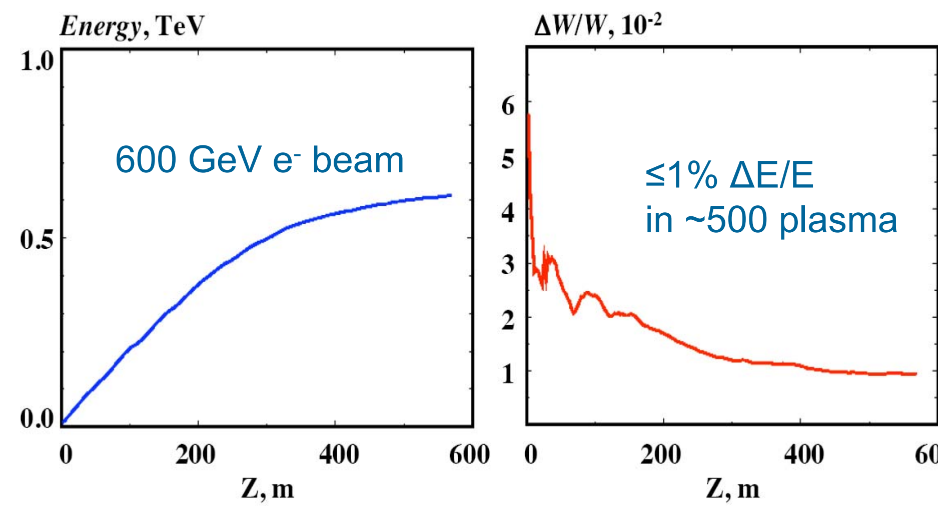
Plasma: Li^+

n_p=6x10^{14}cm^{-3}

External magnetic field:

Field gradient: 1000 T/m

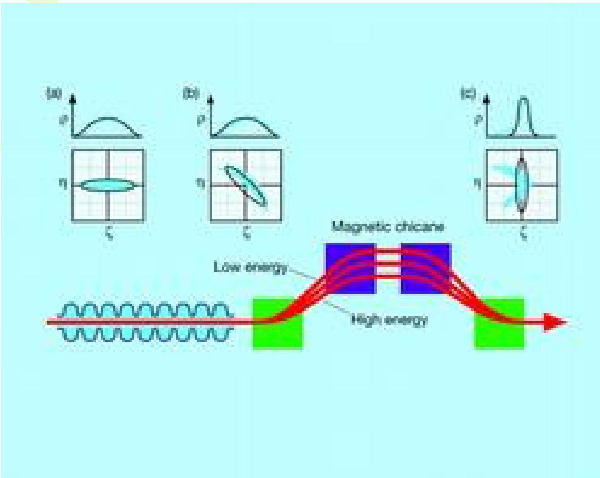
Magnet length: 0.7 m

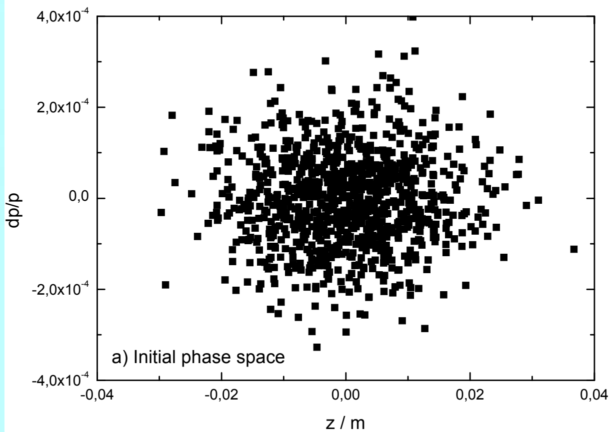


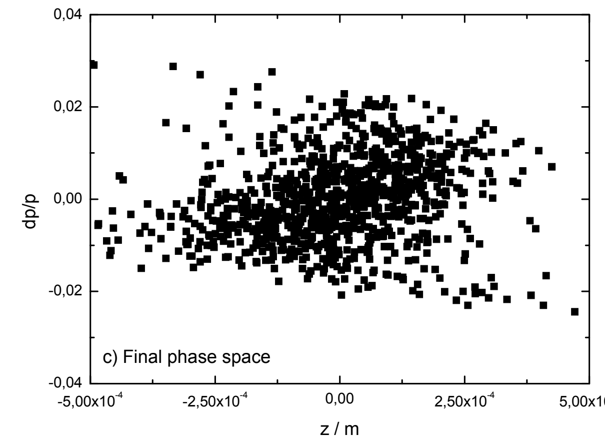
A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics 5, 363 (2009).

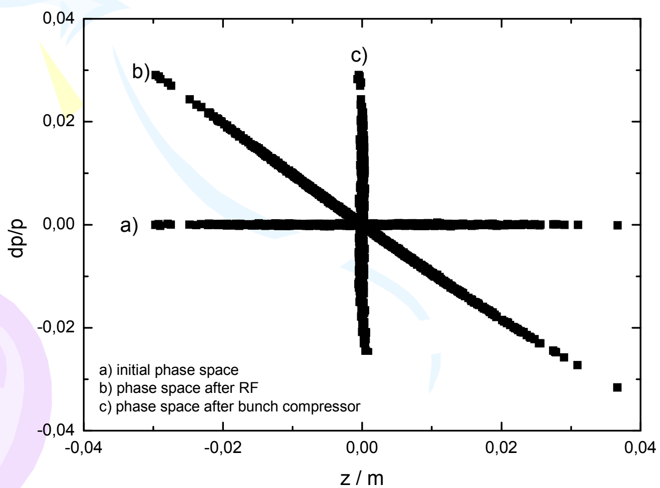
Short proton driver

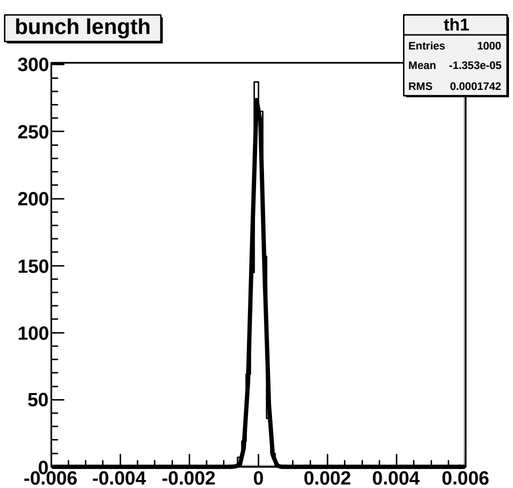
- A magnetic chicane for bunch compression

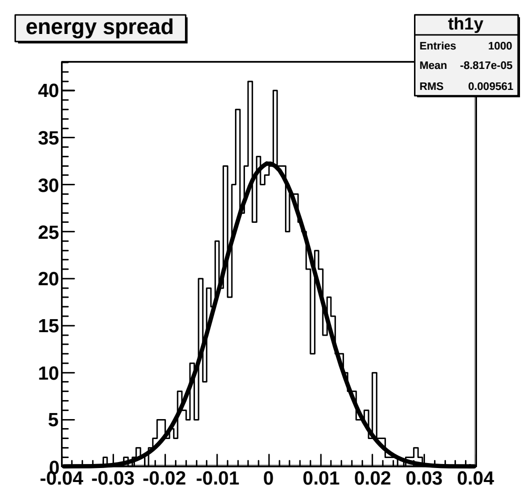












4 km bunch compressor is required for 1 TeV p+ beam!

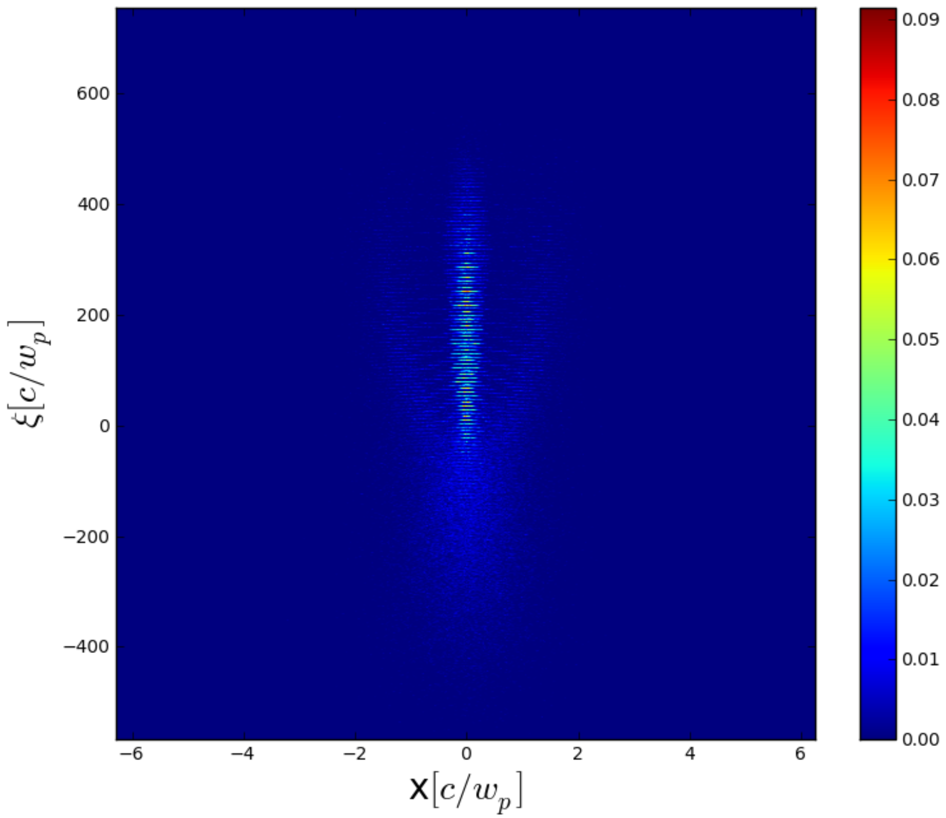
G. Xia, A. Caldwell et al., Proceedings of PAC09

Short bunch driver

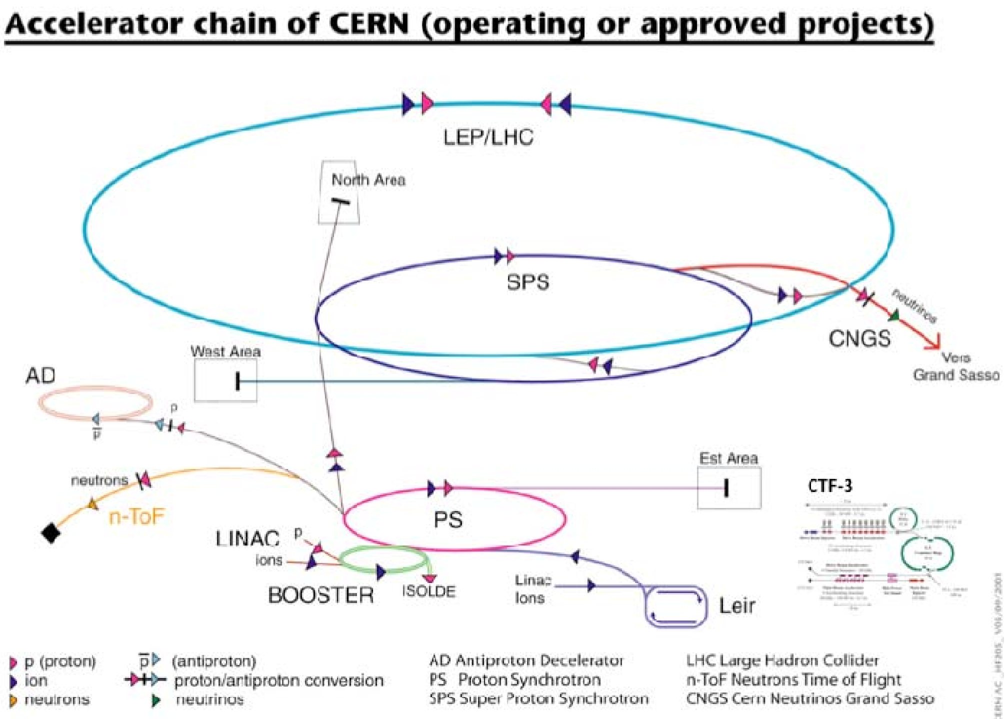
- Self-modulation via plasma wakefield (the transverse two-stream instability modulates the long bunch into many ultra short beamlets at plasma wakelength*.

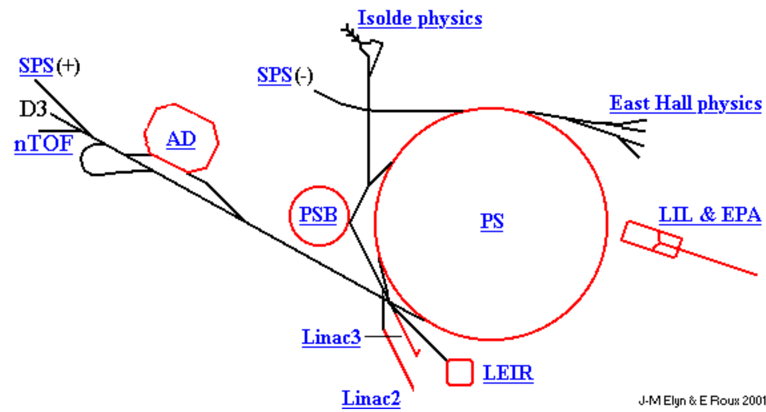
SPS beam at 5m

Plasma @ 1e14 cm^{-3}



Demonstration experiment at CERN





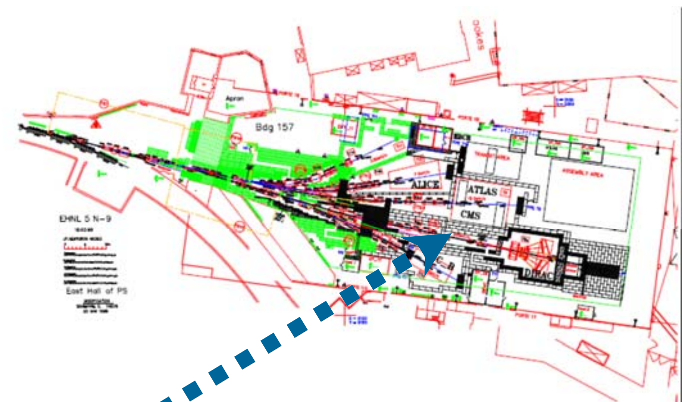
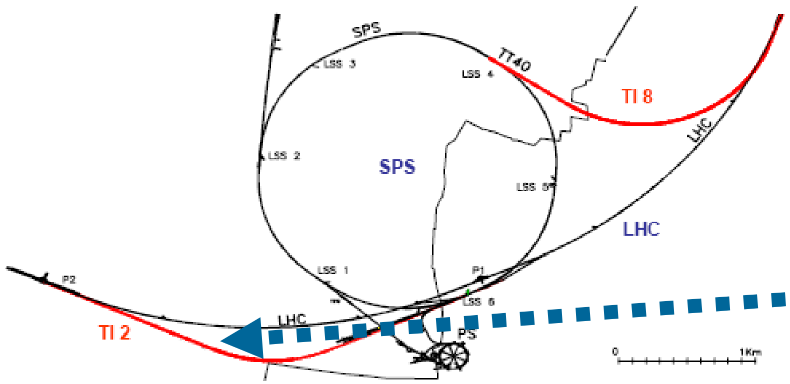


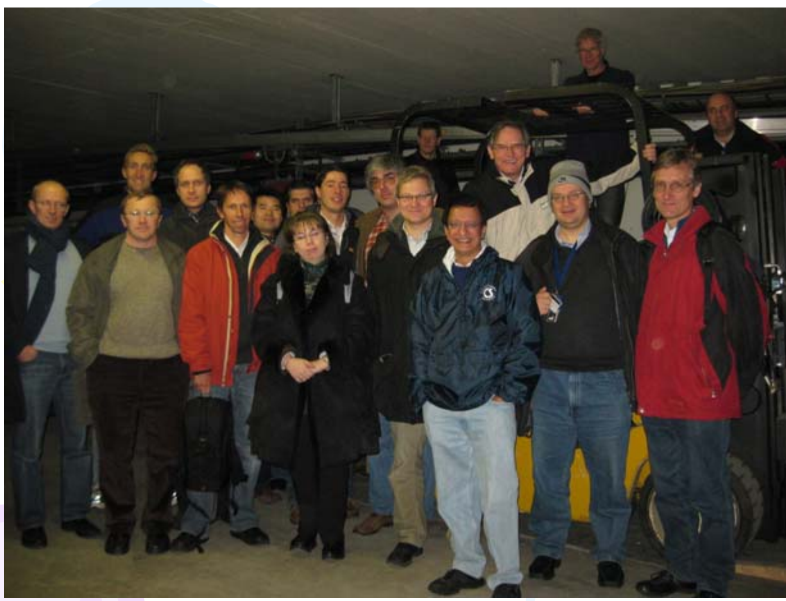
Figure: Beam lines in the PS East Hall. T7 and T8 are near the bottom. The maximum length is below 100 m.



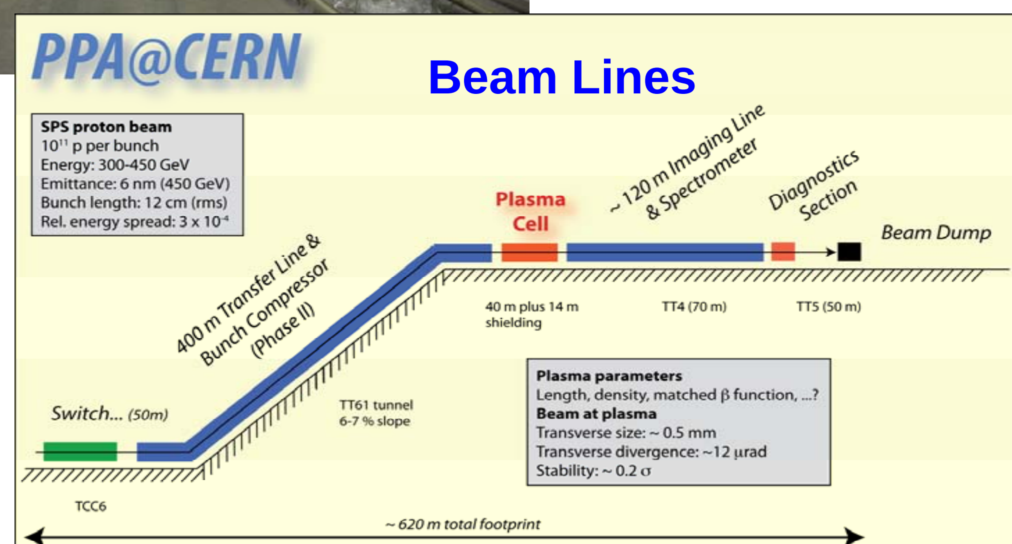
PS (East Hall Area) and **SPS** (West Area) could be used for our demonstration experiment

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 last December
- A spare SPS tunnel is available for demonstration experiment
- With no bunch compression in the beginning



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



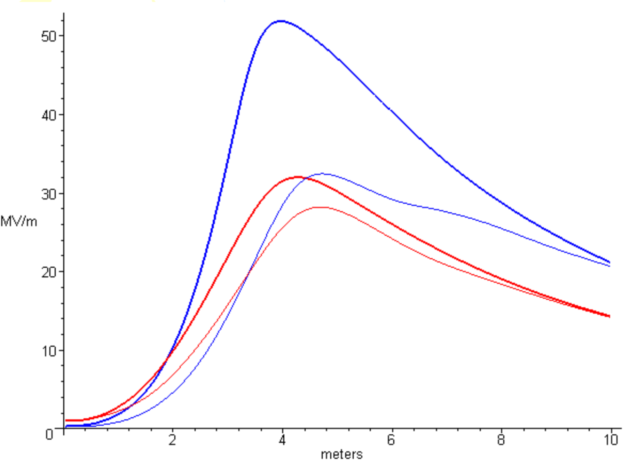
PS vs. SPS

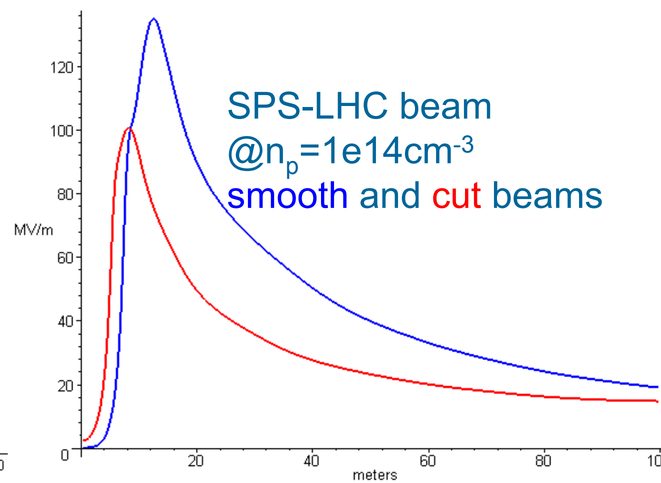
	PS	SPS
Energy [GeV]	24	450
Protons/bunch [10^{11}]	1.3	1.15
rms bunch length [cm]	20	12
Norm.transverse emittance [μ m]	3.5	3.5
rms energy spread [10^{-4}]	5	3
Bunch spacing [ns]	25	25

	PS,	**SPS**
energy:	low,	high
bunch length:	long,	short
beam intensity:	low,	high
emittance:	big,	small
plasma focusing:	weak,	strong
tunnel length:	**60 m,**	**600m**

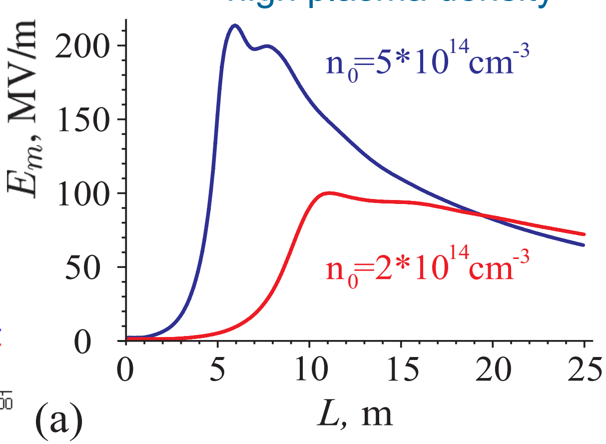
Simulation shows that SPS beam can drive a higher plasma wakefield compared to the PS beam. This is largely due to the smaller emittance of the SPS beam. The lower emittance of SPS beam allows the instability to develop before the beam diverges due to the angular spread.

PS beam@n_p=1e14cm^{-3}
smooth and cut beams





SPS-LHC beam
high plasma density



(a)

K. Lotov

Codes benchmarking

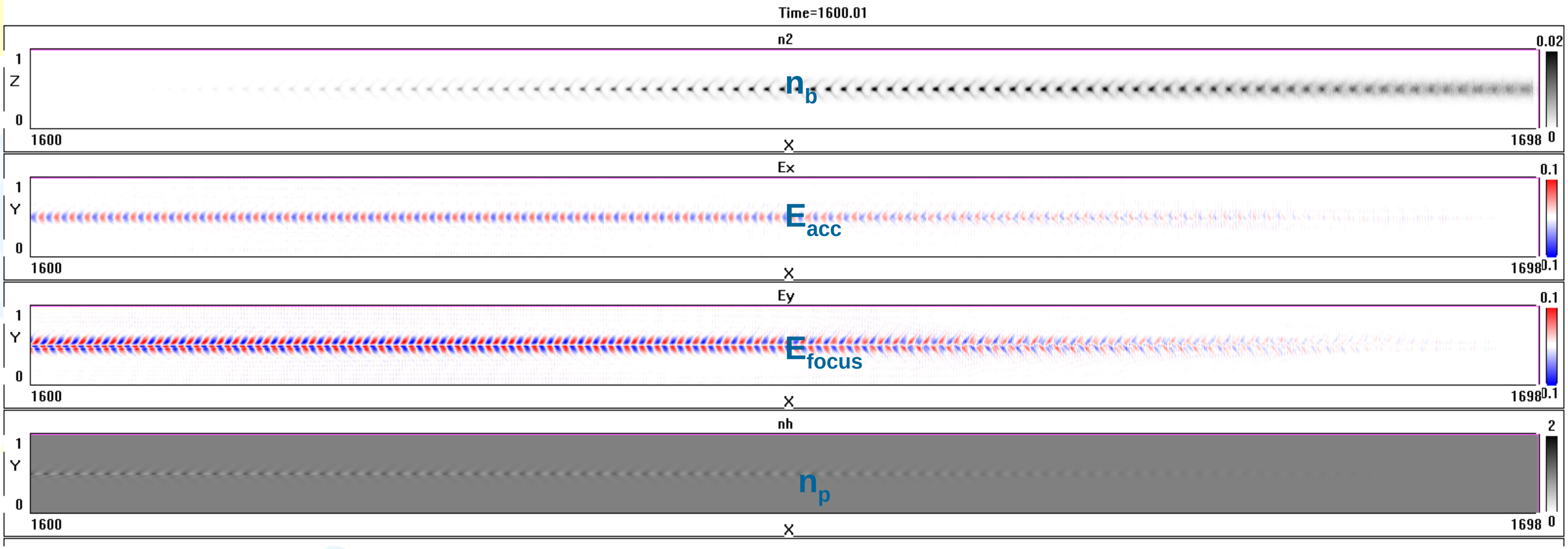
TABLE 1. PS, SPS and LHC parameter sets. The different symbols are defined in the text. SPS-LHC means the standard parameters of bunches in the SPS for injection into the LHC. SPS-Totem means the special parameters for bunches for use by the Totem experiment.

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
σ_{E_P} (MeV)	12	135	80	700
$\sigma_{z,0}$ (cm)	20	12	8	7.6
σ_r (μm)	400	200	100	100
c/ω_b (m)	2.3	4.0	3.2	6.3
σ_θ (mrad)	0.25	0.04	0.02	0.005
L_θ (m)	1.6	5	5	20
ϵ (mm-mrad)	0.1	0.008	0.002	$5 \cdot 10^{-4}$

Various particle-in-cell (PIC) codes are 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)

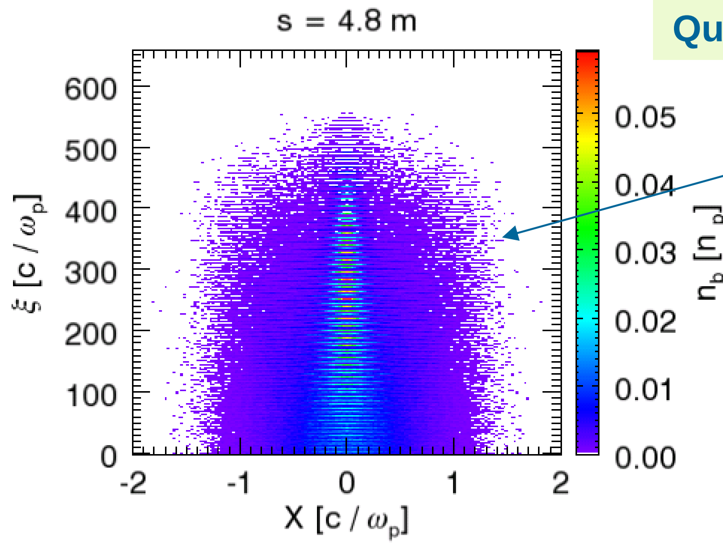


For SPS half-cut beam, at plasma density $n_p=10^{14}$ cm^{-3} ($\lambda_p \approx 3.33$ mm)
A strong beam density modulation is observed,
A nice wakefield structure is excited and
the wakefield amplitude is around 100 MV/m at 5 m plasma.

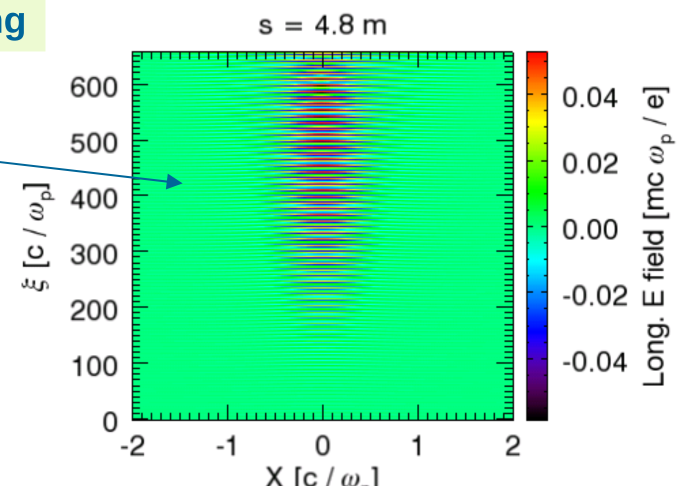
VLPL results from A. Pukhov

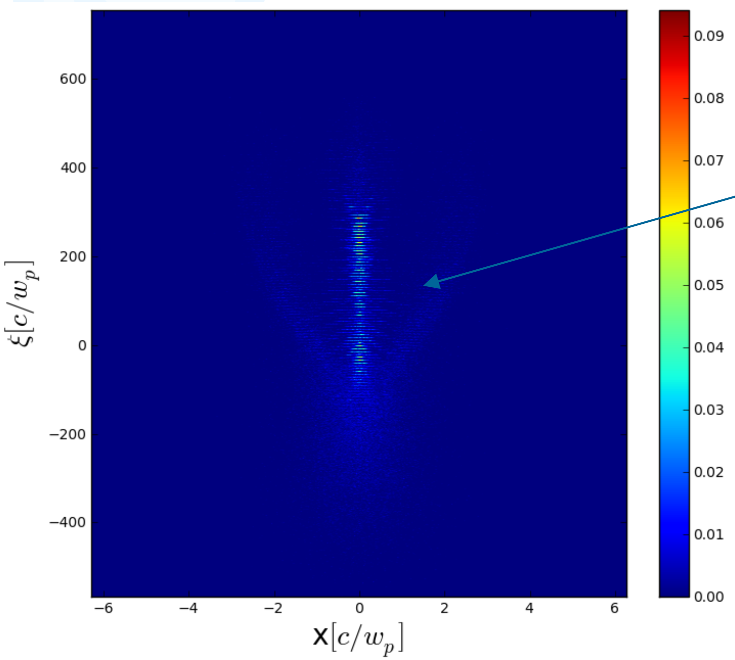
Simulations of SPS beam-driven PWFA

QuickPIC results from C. Huang

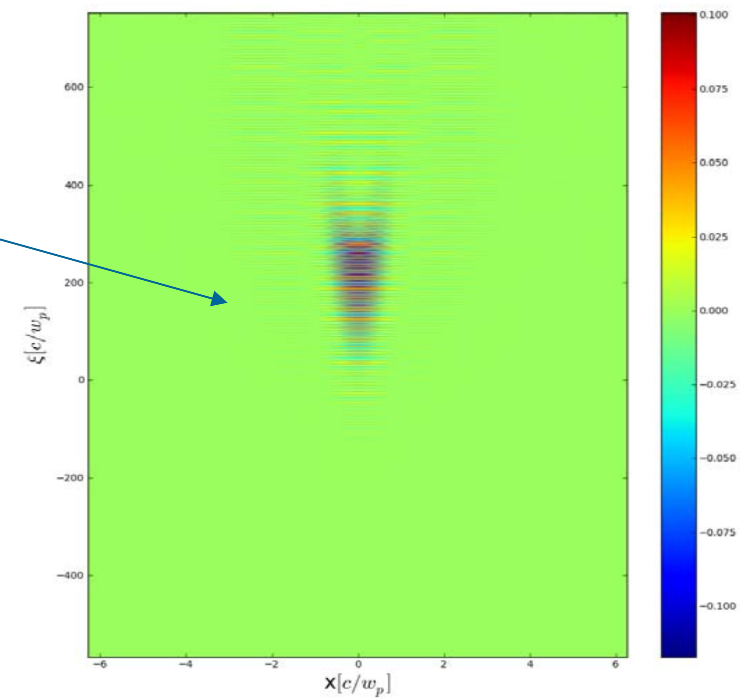


Half-cut
SPS beam
@4.8m plasma
($n_p=10^{14}$ cm^{-3})





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

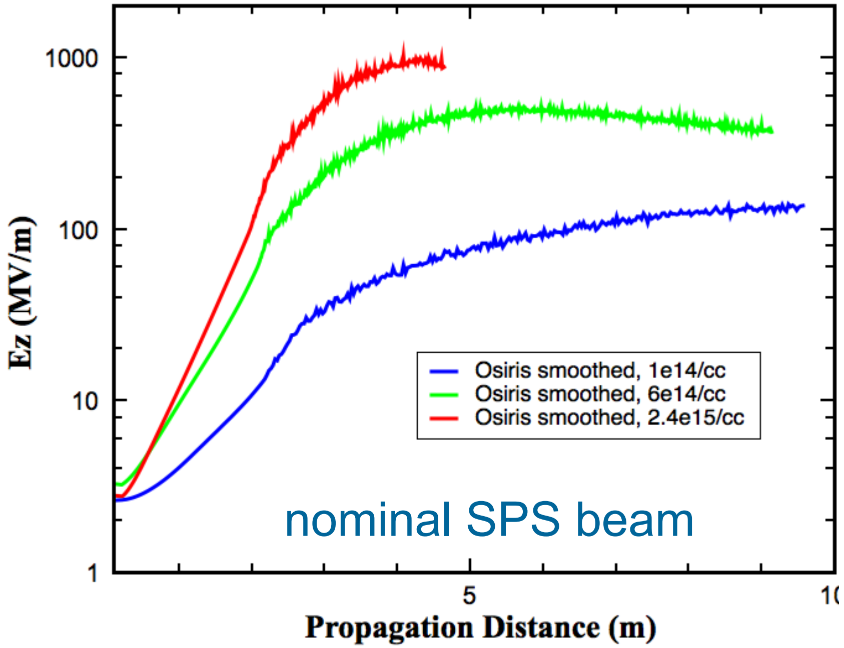


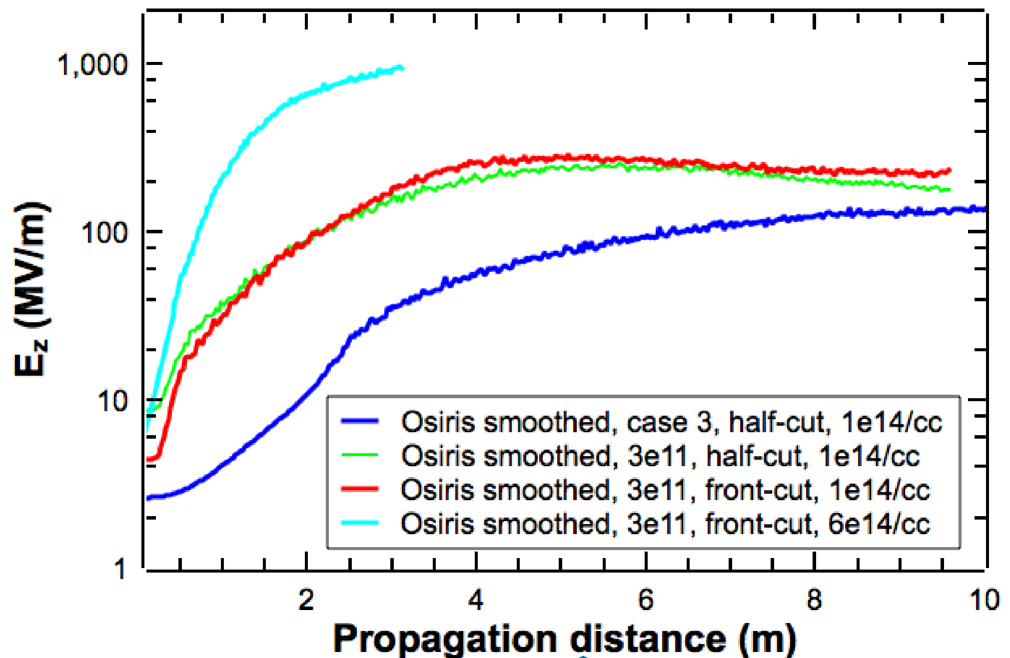
Beam density modulation

Maximum longitudinal e field is ~120 MV/m

Simulations of SPS beam-driven PWFA

Simulation from 2D OSIRIS





Bunch population, N_p	1.15×10^{11}
Bunch length, σ_z	12 cm
Beam radius, $\sigma_{x,y}$	200 μm
Beam energy, E	450 GeV
Energy spread, dE/E	0.03%
Normalized emittance, $\varepsilon_{x,y}$	3 μm
Angular spread, σ_θ	0.02 mrad

Bunch population, N_p	3×10^{11}
Bunch length, σ_z	8.5 cm
Beam radius, $\sigma_{x,y}$	200 μm
Beam energy, E	450 GeV
Energy spread, dE/E	0.04%
Normalized emittance, $\varepsilon_{x,y}$	2 μm
Angular spread, σ_θ	0.02 mrad

Plasma density variation

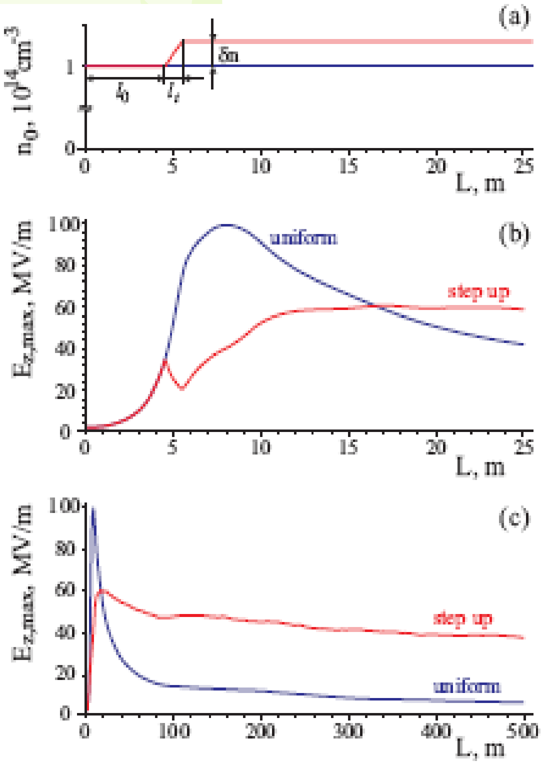
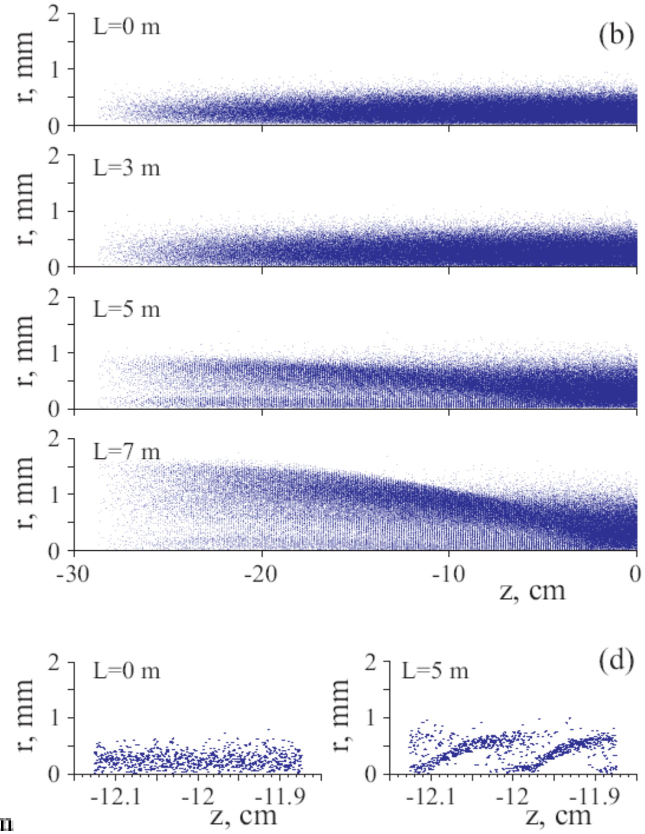
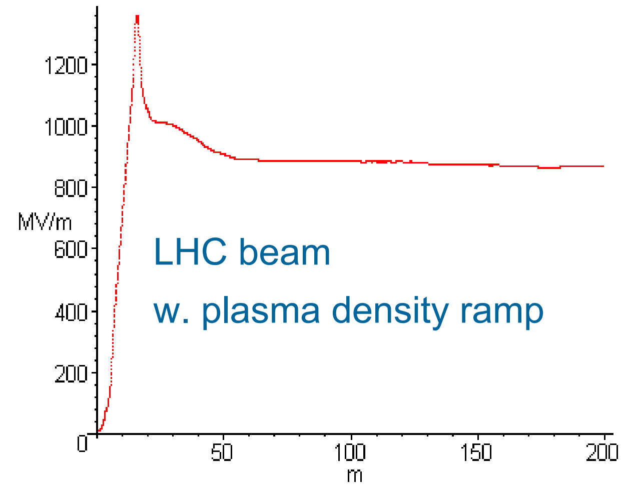


FIG. 4. Parametrization of the density profile (a); maximum wakefield amplitude behind the beam versus propagation distance on small (b) and large (c) scales for uniform and step-up plasma density profiles.

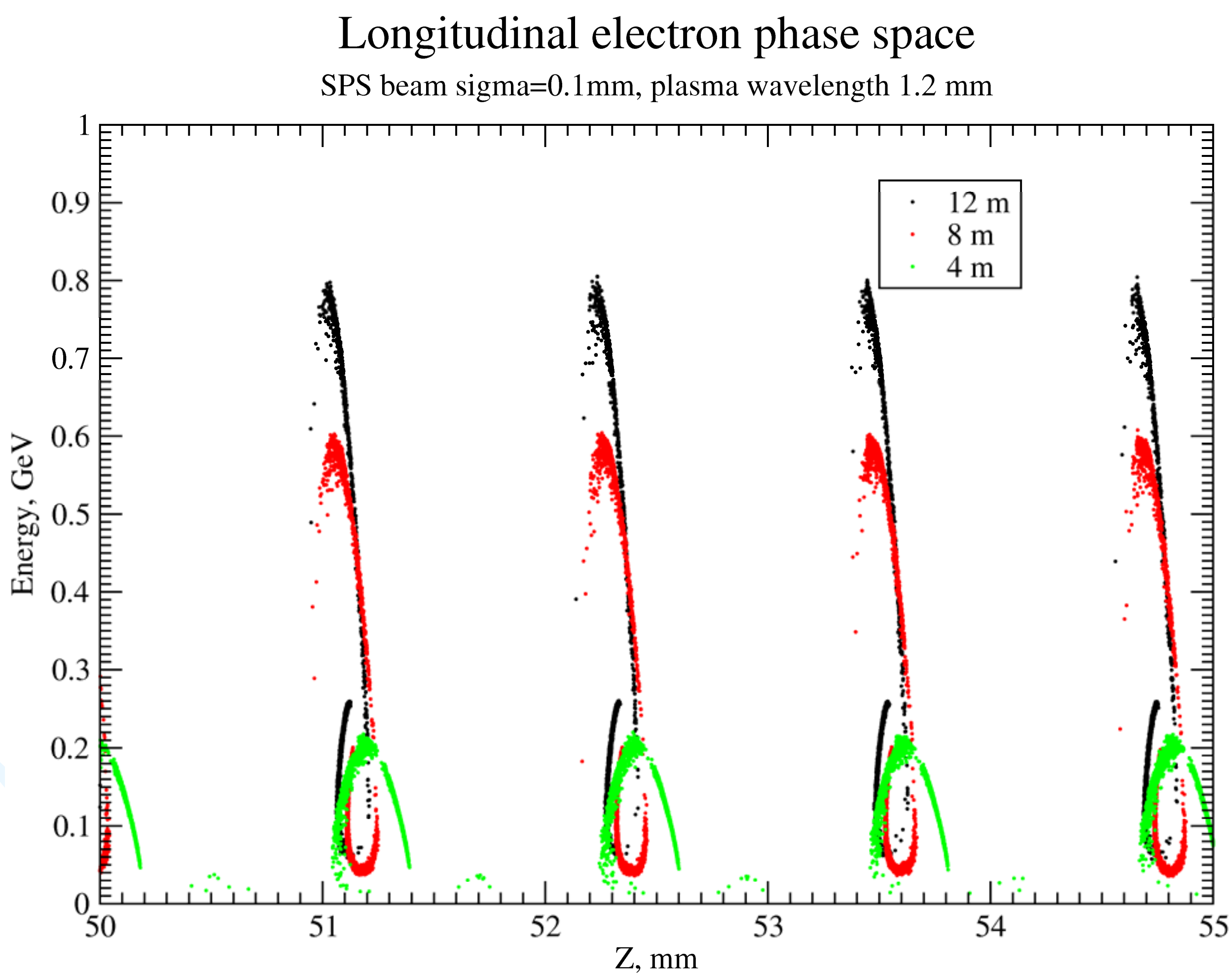




~ 900 MV/m field propagates stably for 200 m!

Increasing the plasma density properly at the moment of developed instability, the wave shift with respect to the main body of the beam will be stopped and one can obtain a stable bunch train that propagates in plasma for a long distance

Electron acceleration



VLPL3D hydro-dynamic code

10 MeV continuous e- beam injection

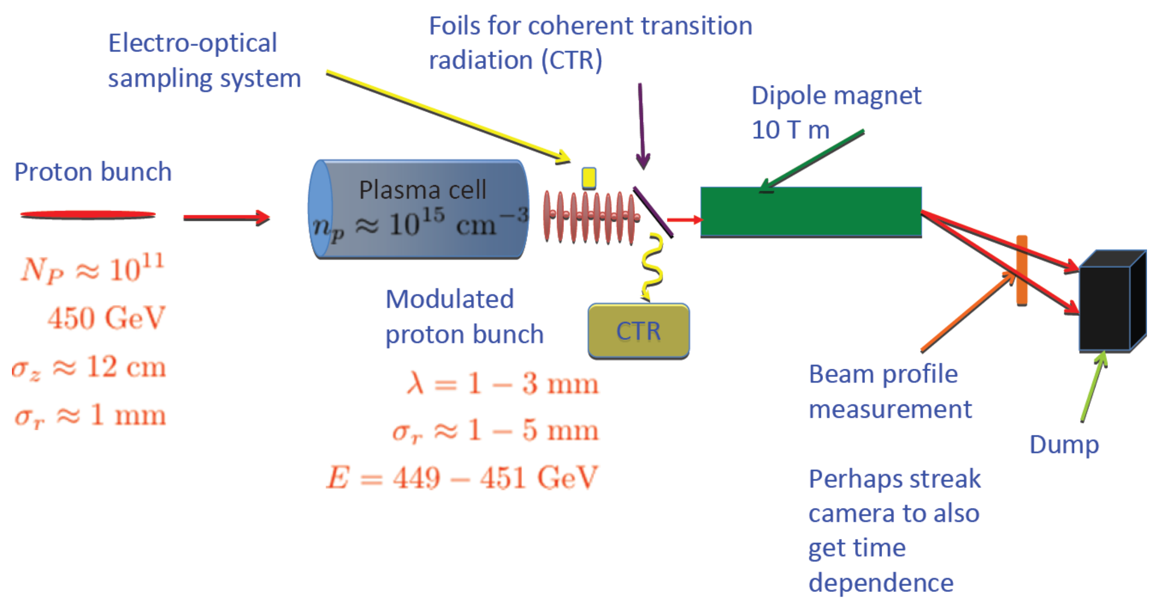
A. Pukhov

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 drive beam (without compression) will be used in the first experiment. a self-modulation of the beam due to two-stream instability which produces many ultrashort beam slices at plasam.
- The modulation resonantly drives wakefield in the 200-500 MV/m with CERN SPS beam.
- Simulation shows with the optimum beam and plasma parameters, ≥ 1 GV/m field can be achieved in the experiment.

Status and outlook

- We have very strong simulation teams around the world (UCLA, LANL, BINP, Düsseldorf Univ. IST)
- Phone conferences biweekly to exchange the results
- A face-to-face meeting next year in London to discuss what to put in the Letter of Intent

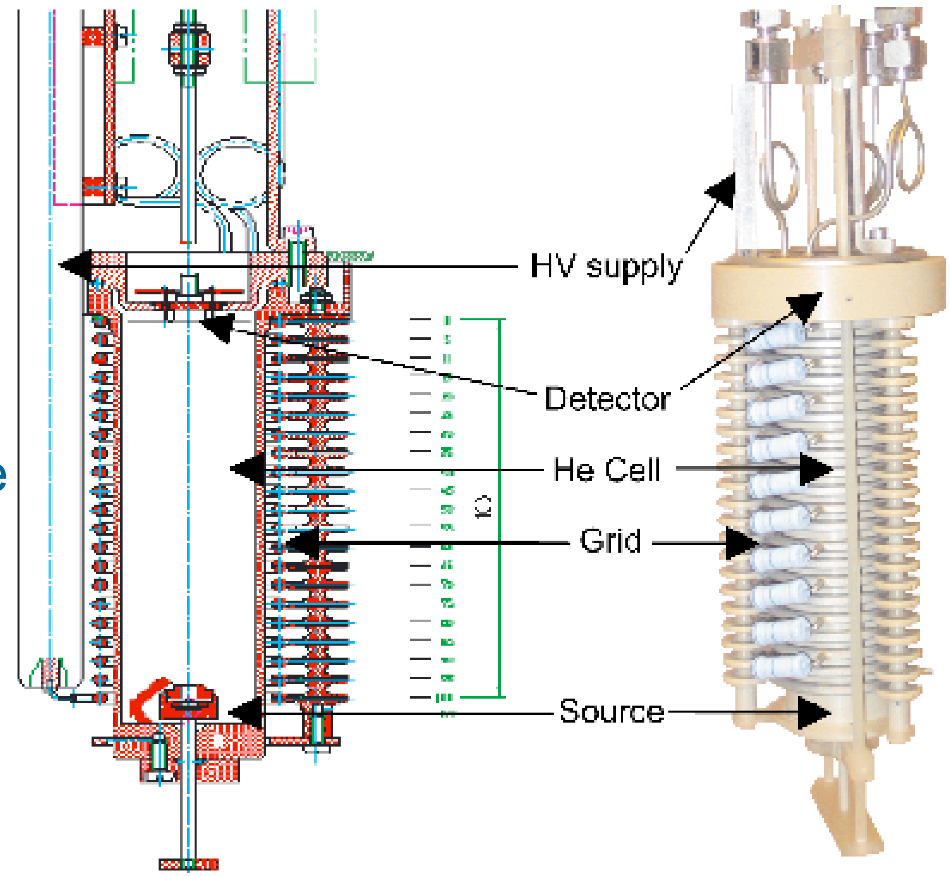
- The PDPWA demonstration experiment will be proposed as a future project
- Simulation shows that working in self-modulation regime, SPS beam can excite the field around 1 GV/m with a high density plasma.
- Future experiment will be carried out based upon the first round experiments.

Status of the FCD Experiment

The proton spectra have been measured without the gas cell.

The gas feedthroughs are proved to be too thin to efficiently pump down the gas cell. The water in the air remaining in the gas cell might freeze on the cold detector to form a dead layer.

Next Step: New gas feedthroughs with 3 times larger diameters are being manufactured, after which the Frictional cooling data will be taken.

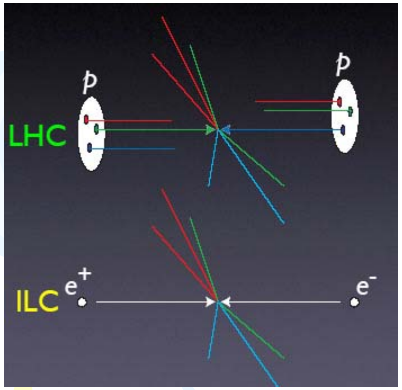


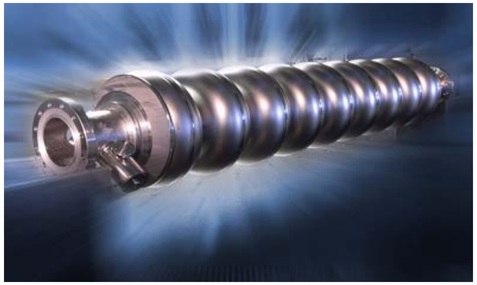
The Frictional Cooling Demonstration Experiment is searching for a new method of efficiently reducing the beam emittance

International Linear Collider-ILC

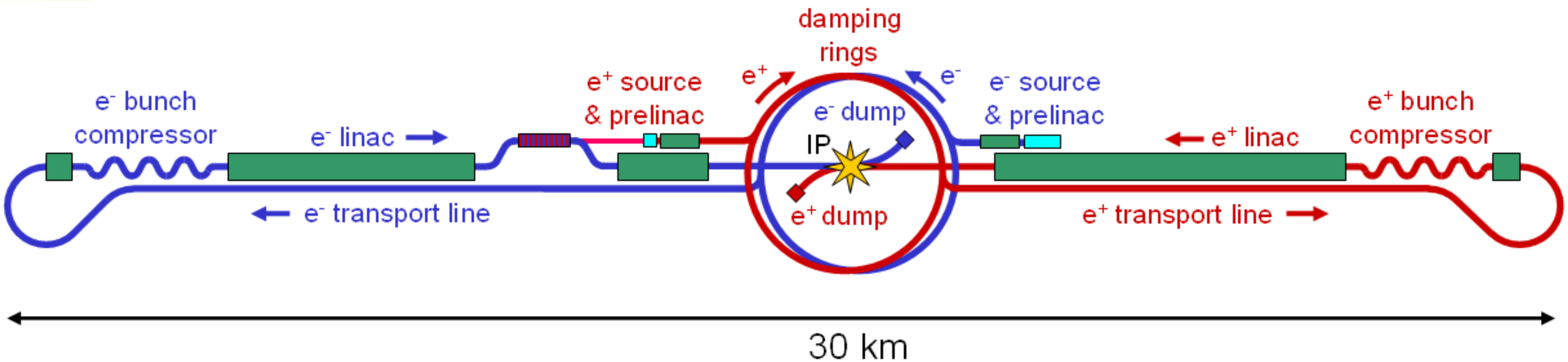
The next *big* thing. After LHC, a lepton Collider of over 30 km length, will probably be needed, to complement the LHC.

Max. COM. energy	500	GeV
Peak Luminosity	~$2x10^{34}$	$1/cm^2s$
Beam Current	9.0	mA
Repetition rate	5	Hz
Aver. accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW





Machine layout



Subsystems:

e+, e- sources, damping rings, main linacs, beam delivery systems, IPs, beam dumps

Features:

- Two linear accelerators, with tiny intense beams of electrons and positrons colliding head-on-head
- Total length ~ 30 km long (comparable scale to LHC)
- COM energy = 500 GeV, upgradeable to 1 TeV

R&D Goals for Technical Design

Accelerator Design and Integration (AD&I)

- Studies of possible cost reduction designs and strategies for consideration in a re-baseline in 2010

SCRF

- High Gradient R&D - globally coordinated program to demonstrate gradient by 2010 with 50% yield;

ATF-2 at KEK

- Demonstrate Fast Kicker performance and Final Focus Design

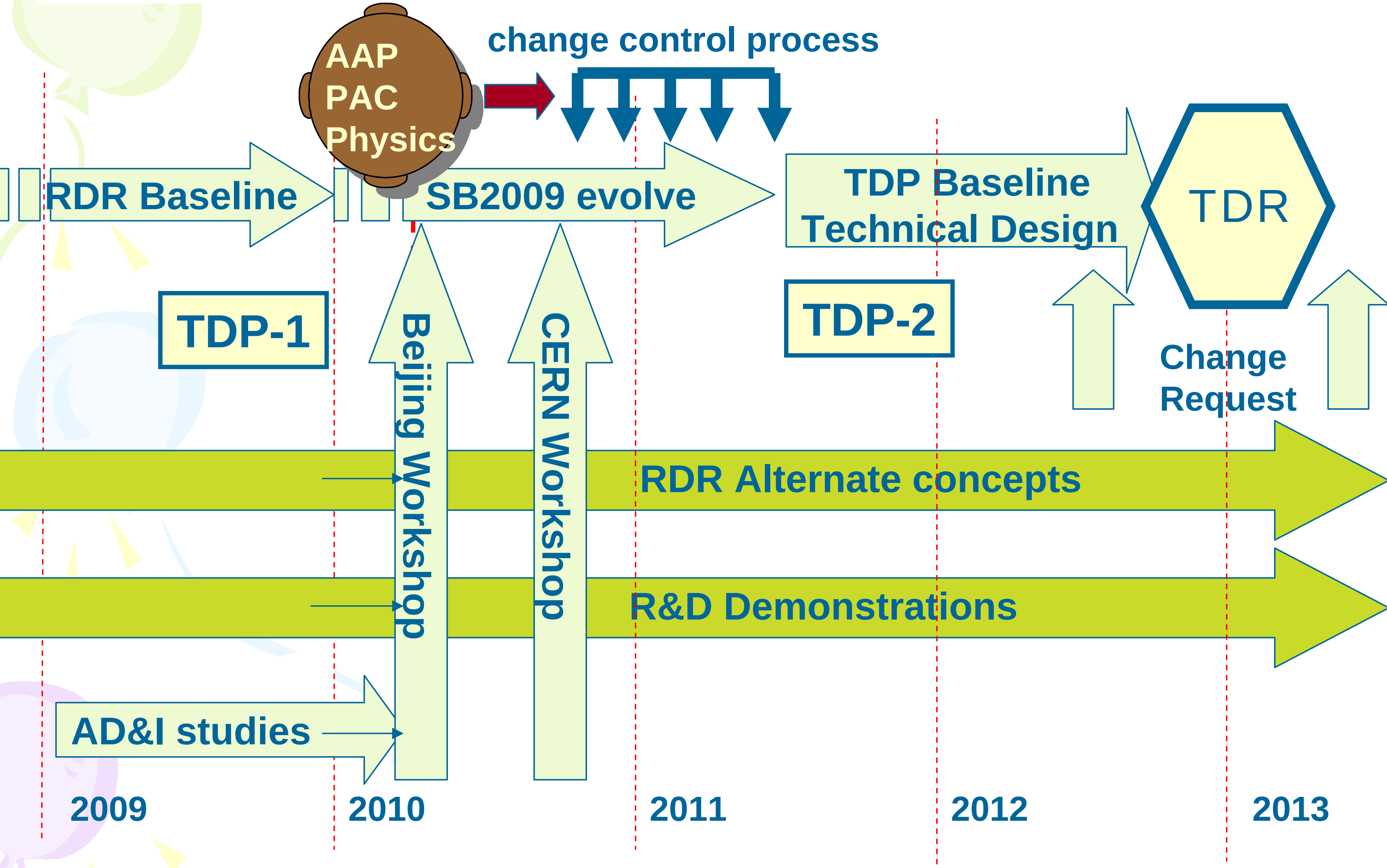
Electron Cloud Mitigation – (CesrTA)

- Electron Cloud tests at Cornell to establish mitigation and verify one damping ring is sufficient.

Why change from RDR design?

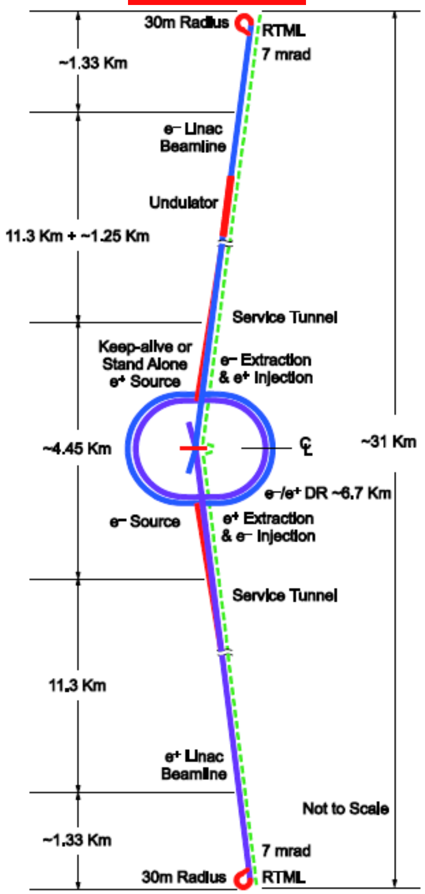
- Timescale of ILC demands we continually update the technologies and evolve the design to be prepared to build the most forward looking machine at the time of construction.
- Our next big milestone – the technical design (TDR) at end of 2012 should be as much as possible a "construction project ready" design with crucial R&D demonstrations complete and design optimised for performance to cost to risk.
- Cost containment vs RDR costs is a crucial element. (Must identify costs savings that will compensate cost growth)

Technical Design Phase and Beyond

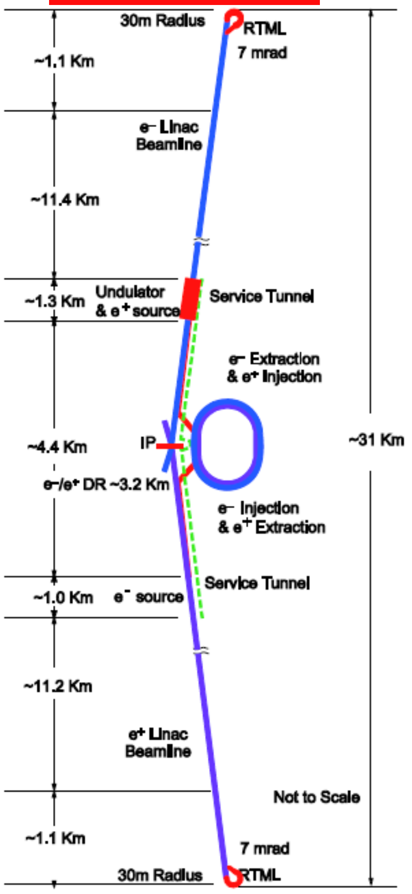


Proposed Design changes for TDR

RDR

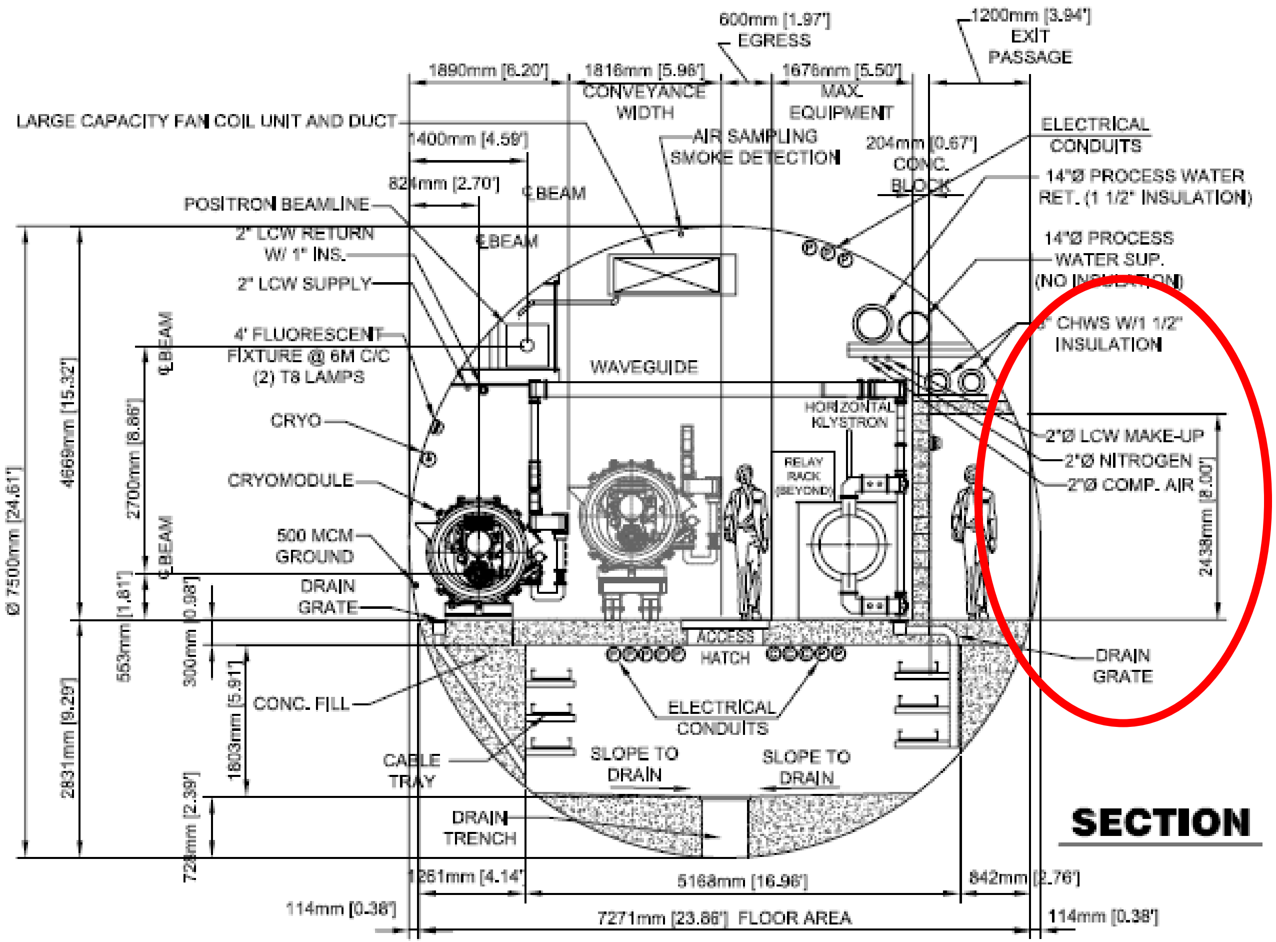


SB2009



- Single Tunnel for main linac- approved!
- Move positron source to end of linac
- Reduce number of bunches factor of two (lower power)
- Reduce size of damping rings (3.2km)
- Integrate central region
- Single stage bunch compressor

Single tunnel configuration



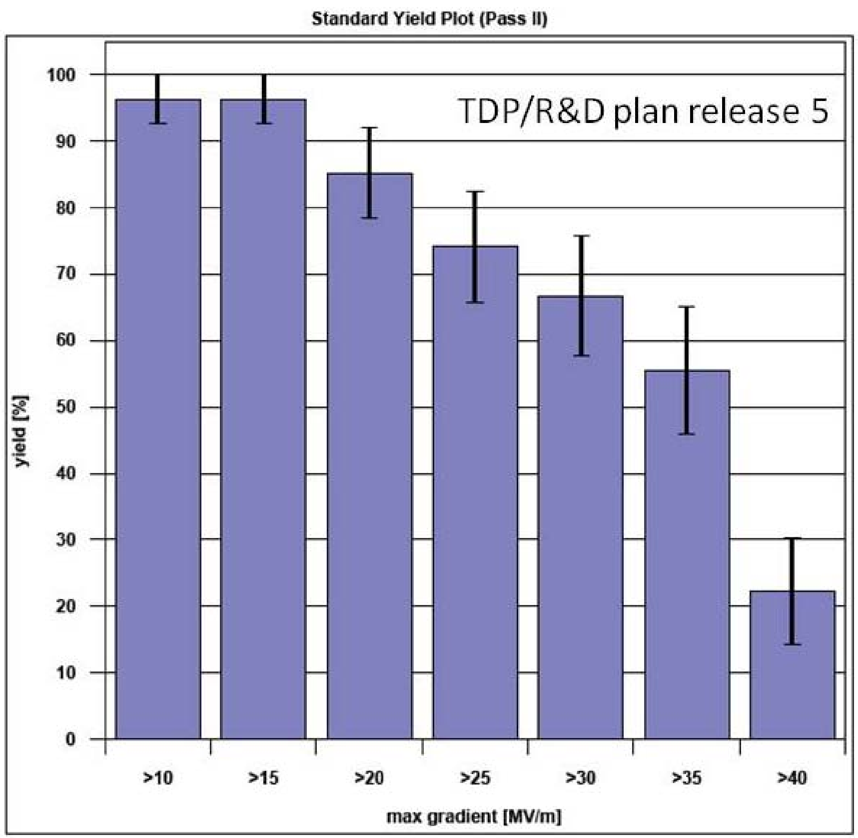
- Egress passageway not needed;
- 7 m Ø ok

The ILC SCRF Cavity

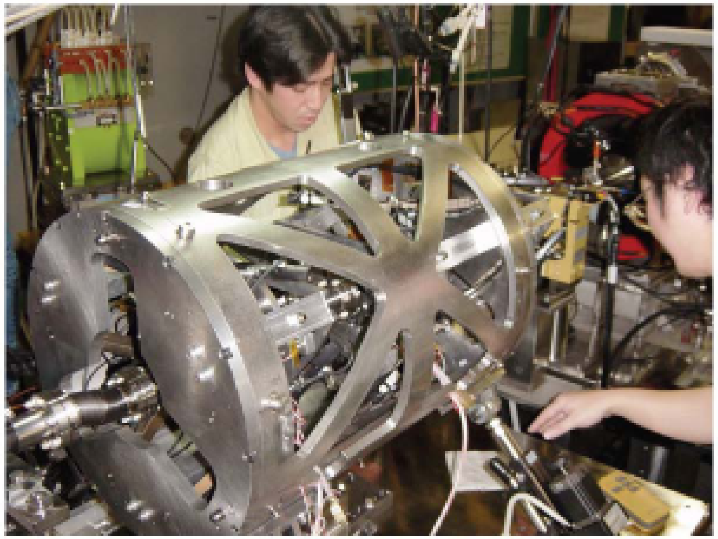
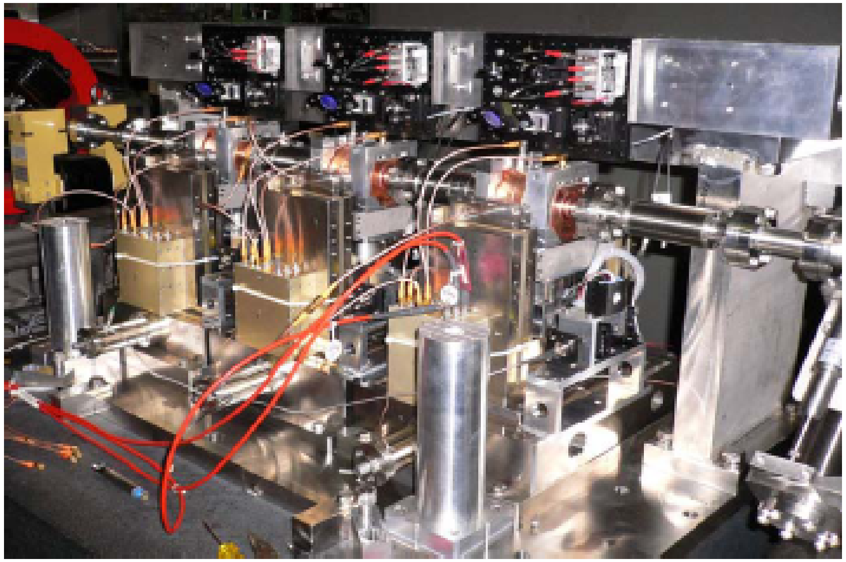
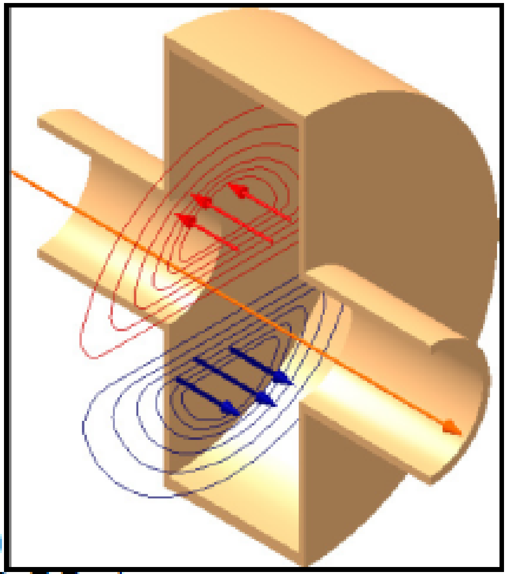
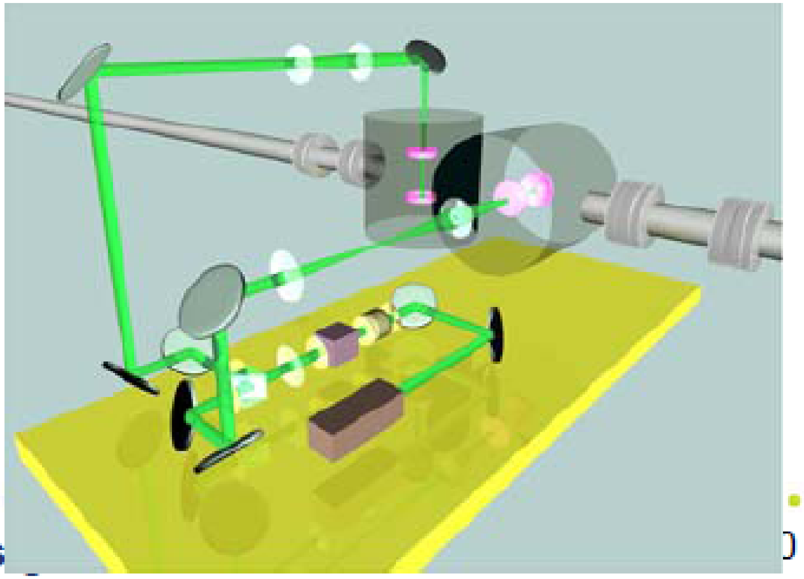
Figure 1.2-1: A TESLA nine-cell 1.3 GHz superconducting niobium cavity.

- Achieve high gradient (35MV/m); develop multiple vendors; make cost effective, etc
- Focus is on high gradient; production yields; cryogenic losses; radiation; system performance

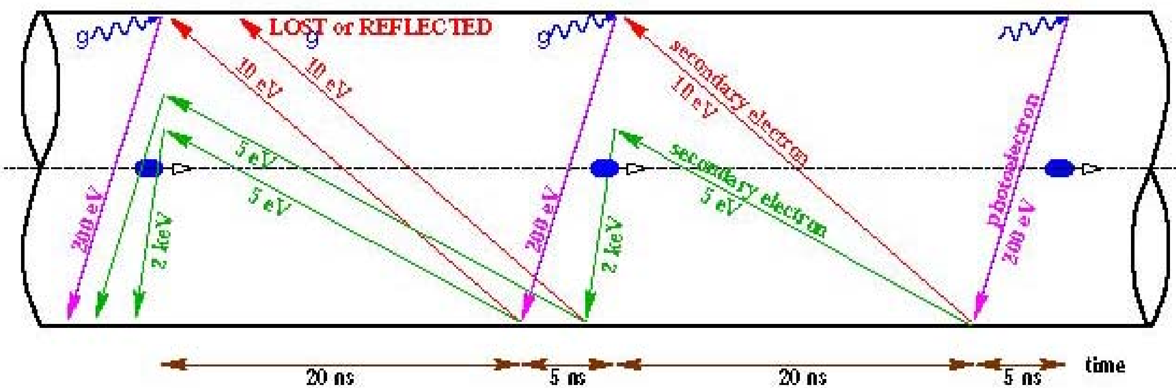
SCRF cavity production yield



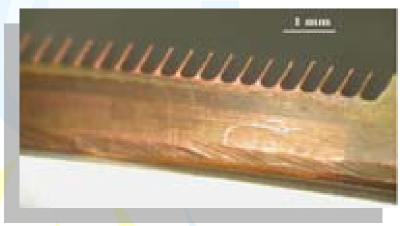
KEK ATF-2 Studies
(Beam Sizes at Collision)

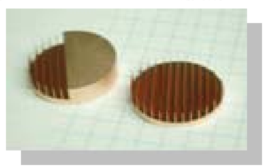





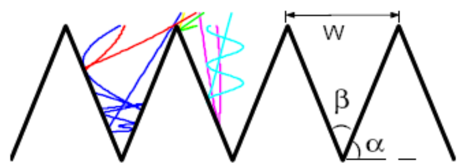
Electron cloud studies at CESR-TA



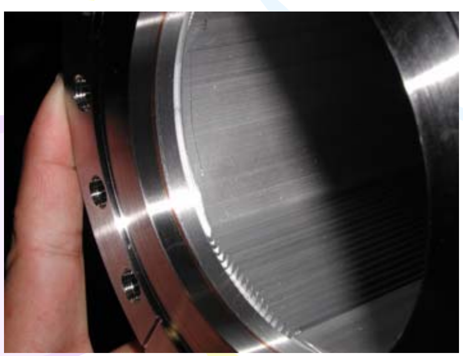
schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission**

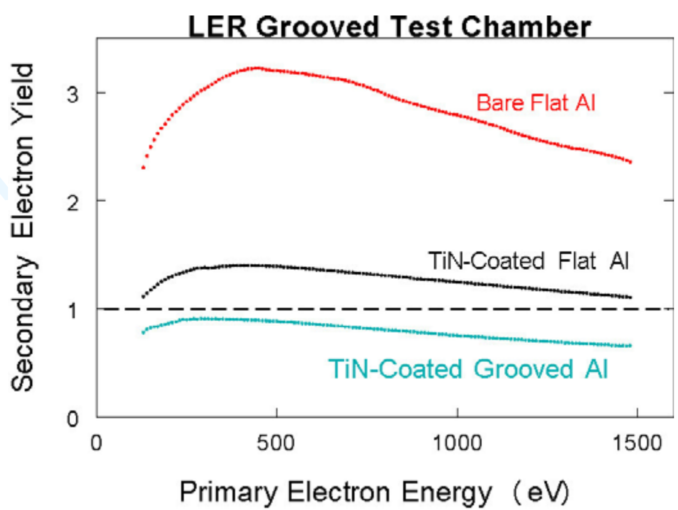






Strategies to reduce EC:
Coatings: TiN, TiZrV (NEG), Carbon, enamel…
Grooved surface in vacuum
Combined techniques
Solenoid in the drift
Clearing electrodes…





Test now in CESR-TA !

Summary

- Proton driven plasma wakefield accelerator has potential to take electron beam to the energy frontier in a single stage of acceleration
- We will propose an experimental study of PDPWA and will use the existing proton beam from the CERN SPS
- Simulation shows that working in the self-modulation regime, we could achieve 1 GeV energy gain within 5 m plasma
- Muon cooling experiment is still ongoing in lab and we expect more result will come in this year. We will measure the equilibrium energy of protons will be measured in various conditions, e.g. gas pressure, electric fields
- ILC, enters the TDR phase, and currently more effort has been put on the design optimization and cost reduction.