Proton Driven Plasma Wakefield Acceleration

1st Annual EuCARD Meeting **Rutherford Appleton Laboratory**

Allen Caldwell





Particle Physics Accelerators



ILC discussed as next collider → 30 km linear accelerator

The Livingston plot shows a saturation effect !

Practical limit for accelerators at the energy frontier: Project cost increases as the energy must increase!

New technology needed...

Plasma Wakefield Acceleration (Beam Driven)

driving force:

Space charge of drive beam displaces plasma electrons.



Space charge oscillations (Harmonic oscillator)

restoring force:

Plasma ions exert restoring force



Longitudinal fields can accelerate and decelerate!

Plasma also provides super-strong focusing force ! (many thousand T/m in frame of accelerated particles)



Highlight: latest SLAC/UCLA/USC results (Nature 2007)



- SLAC beam
- 42 GeV
- 3 nC @ 10 Hz
- focused to 10 µm spot size
- compressed to 50 fs

- Some electrons double their energy: from 42 to > 80 GeV
- E=50 GV/m over 0.8 meters



Jérôme Faure

Why not continue with electrons ???

There is a limit to the energy gain of a trailing bunch in the plasma:

$$R = \frac{\Delta T^{\text{witness}}}{\Delta T^{\text{drive}}} \le 2 \quad \text{T is the kinetic energy}$$

(for longitudinally symmetric bunches).

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

This means many stages required to produce a 1TeV electron beam from known electron beams (SLAC has 45 GeV)

Proton beams of 1TeV exist today - so, why not drive plasma with a proton beam ?

Maximum accelerating gradient

Assuming Gaussian beams:

$$E_{z,\max} = eNk_p^2 \exp\left(-\frac{k_p^2\sigma_z^2}{2} + \frac{k_p^2\sigma_r^2}{2}\right) \Gamma\left(0, k_p^2\sigma_r^2/2\right),$$

Linear regime $(n_b < n_0)$:

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

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

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

Compression of proton bunch needs to be solved for PDPWA (?)

Simulation study



A. Caldwell, K. Lotov, A. Pukhov, F. Simon Nature Physics 5, 363 - 367 (2009)

Simulation

Table 1: Table of parameters for the simulation.

Parameter	Symbol	Value	Units
Protons in Drive Bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial Proton momentum spread	σ_p/p	0.1	
Initial Proton longitudinal spread	σ_Z	100	μ m
Initial Proton bunch angular spread	$\sigma_{ heta}$	0.03	mrad
Initial Proton bunch transverse size	$\sigma_{X,Y}$	0.4	mm
Electrons injected in witness bunch	N_e	$1.5 \cdot 10^{10}$	
Energy of electrons in witness bunch	E_e	10	GeV
free electron density	n_p	$6 \cdot 10^{14}$	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1000	T/m
Magnet length		0.7	m

Densities & Fields









A Tevatron or HERA type proton beam, compressed to 100 microns but with 10% momentum spread, would allow to create a 600 GeV electron beam.

Alternative to short bunch – modulation of long bunch



- (green) field Ez at the distance σ_r from axis, scale +-200 MV/m

- (blue) beam density at the distance σ_r from axis, axis: 0 - 8e-4 of plasma density

- (red) beam radius, 0 1.4 mm
- (grey) energy stored in the plasma, arb. units

PS beam simulation, K. Lotov, LCODE

Can this be used to generate strong wakefields for acceleration?





Simulation: W. Lu, OSIRIS code (UCLA)

We are considering an experimental program at CERN to demonstrate plasma acceleration using a modulated proton driver.



Workshop at CERN December 17-18, 2009 **Supported by EuCARD** ! Follow-up on March 11-12, 2010

Current activities:

Plasma Cell designs under investigation: UCLA, IPP

Helicon Plasma Cell (IPP)





Four different groups undergoing benchmarking of codes for specified parameter sets: K. Lotov (2D, Novosibirsk), A. Pukhov (3D, Düsseldorf), W. Lu (2D, 3D, UCLA), C. Huang (2D, 3D Argonne)

Parametric studies, investigations of hosing, two-stream instability, ...

Investigations into bunch compression

Currently most promising: uncompressed SPS bunch in long plasma cell; expect few 100 MV/m gradients.

Self-modulation instability of a long proton bunch in plasmas

Naveen Kumar^{*} and Alexander Pukhov Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, D-40225 Germany

Konstantin Lotov Budker Institute of Nuclear Physics and Novosibirsk State University, 630090 Novosibirsk, Russia

Theoretical analysis of modulation process

http://arxiv.org/abs/1003.5816

Assuming full modulation can be achieved, and central $+-\sigma/2$ contribute to E field, I find

Parameter	\mathbf{PS}	SPS-LHC	SPS-Totem	LHC
$E_P (GeV)$	24	450	450	7000
$N_P (10^{10})$	13	11.5	3.0	11.5
$\sigma_P ~({ m MeV})$	12	135	80	700
$\sigma_z ~({ m cm})$	20	12	8	7.6
$\sigma_r~(\mu{ m m})$	400	200	100	100
$\sigma_{ heta} \; ({ m mrad})$	0.25	0.04	0.02	0.005
eta^* (m)	1.6	5	5	20
$\epsilon \text{ (mm-mrad)}$	0.1	0.008	0.002	$5 \cdot 10^{-4}$
$n_0 \ (10^{15} \ {\rm cm}^{-3})$	0.16	0.63	2.5	2.5
$eE_0 ~({\rm GeV/m})$	1.28	2.55	5.1	5.1
c/ω_b (m)	2.4	4.0	3.3	13
$eE_{\rm z,max}~({\rm GeV/m})$	0.11	0.4	0.4	1.6
α	0.09	0.16	0.08	0.31
L_{dephase} (m)	9	230	170	2850
W_{β^*} (GeV)	0.18	2.0	2.1	32
$W_{dephase}$ (GeV)	1.0	90	70	4500

Accelerator chain of CERN (operating or approved projects)



TT61 tunnel



- Services and infrastructure still in place from the old beam line
- However the power supplies have been dismounted and used as spares for the SPS North Area
- Steep slope 6-7%

Experimental Layout



Electrooptical sampling \rightarrow time domain information

Summary

 Plasma wakefields have been demonstrated to produce very large electric fields (>10 GV/m)

• Hope for a more compact/less expensive accelerator

Proton driven PWA would allow a simpler design – one stage

demonstration of PDPWA to be proposed at CERN