Future Accelerators

Presented by

Patric Muggli

Project Review 2011

December 20

- Future detectors (presented by Frank Simon)
- Muon Cooling (slides by D. Greenwald)
- Plasma Wakefield Acceleration

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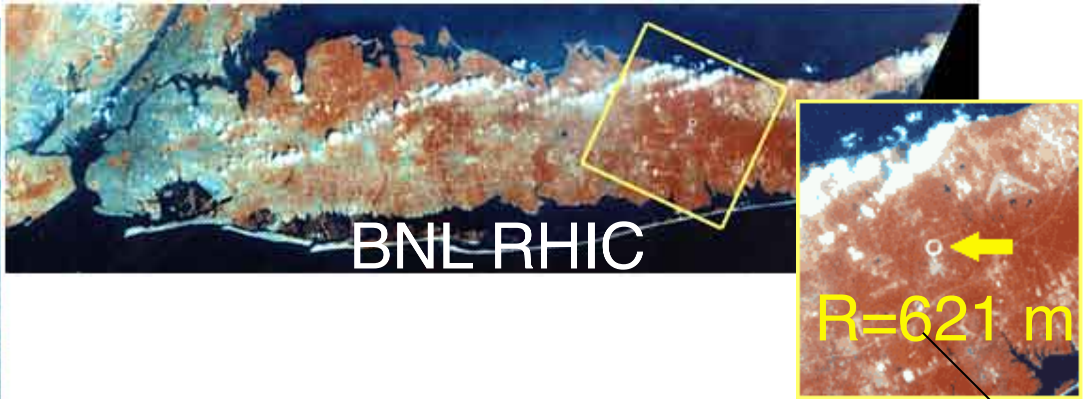
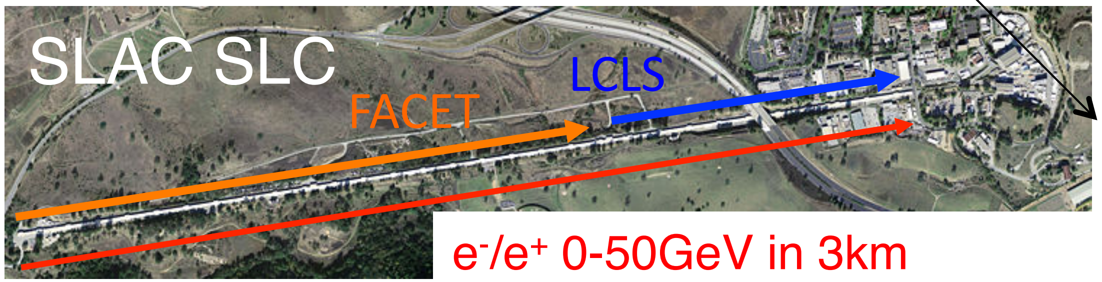
PARTICLE ACCELERATORS

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





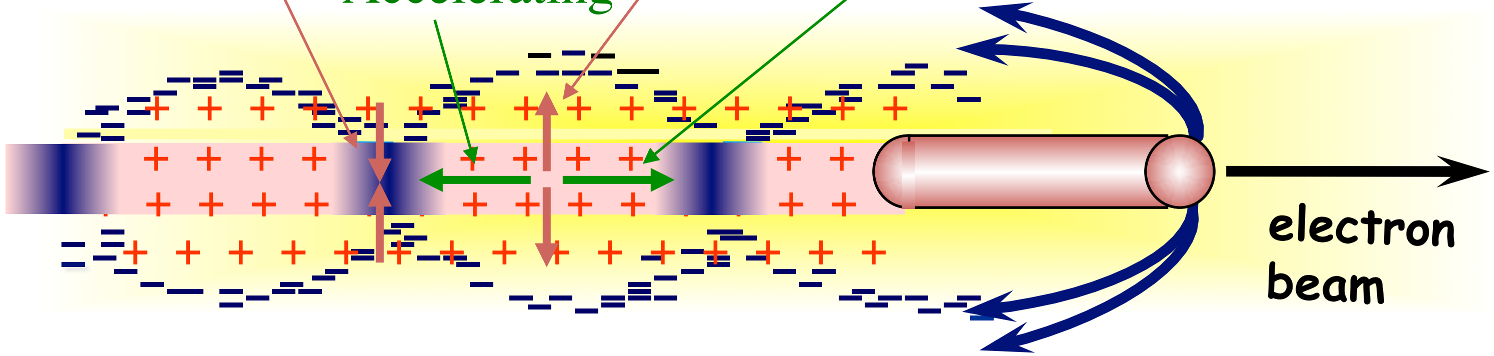
e^-/e^+ 0-50GeV in 3km

e^-/e^+ 0-23GeV in 2km FACET

e^- 0-14GeV in 1km LCLS

- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use rf technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?
- Can plasmas be the next generation of high-gradient accelerating "structure" … without structure? (linear colliders)

PLASMA WAKEFIELD ACCELERATOR (PWFA)



- Linear theory (n_b<<n_e) scaling: $$E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2} \approx N/\sigma_z^2$$

  when $\sigma_z \approx \lambda_{pe}$ and $\sigma_z \approx \lambda_p$ $\quad \lambda_{pe} = \frac{2\pi c}{\omega_{pe}} \quad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$ Plasma Wavelength, Frequency

- Focusing strength: $$\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c} = 3kT/m \times n_e(10^{14}\,cm^{-3})$$ (n_b>n_e)

- N=2x10^{10}: σ_z=600 μm, n_e=2x10^{14} cm^{-3}, E_{acc}~100 MV/m, B_θ/r=6 kT/m
  σ_z= 20 μm, n_e=2x10^{17} cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

- Frequency: 100GHz to >1THz, "structure" size 1mm to <100μm

- Conventional accelerators: MHz-GHz, E_{acc}<150 MV/m, B_θ/r<2 kT/m

PLASMA WAKEFIELD ACCELERATOR (PWFA)

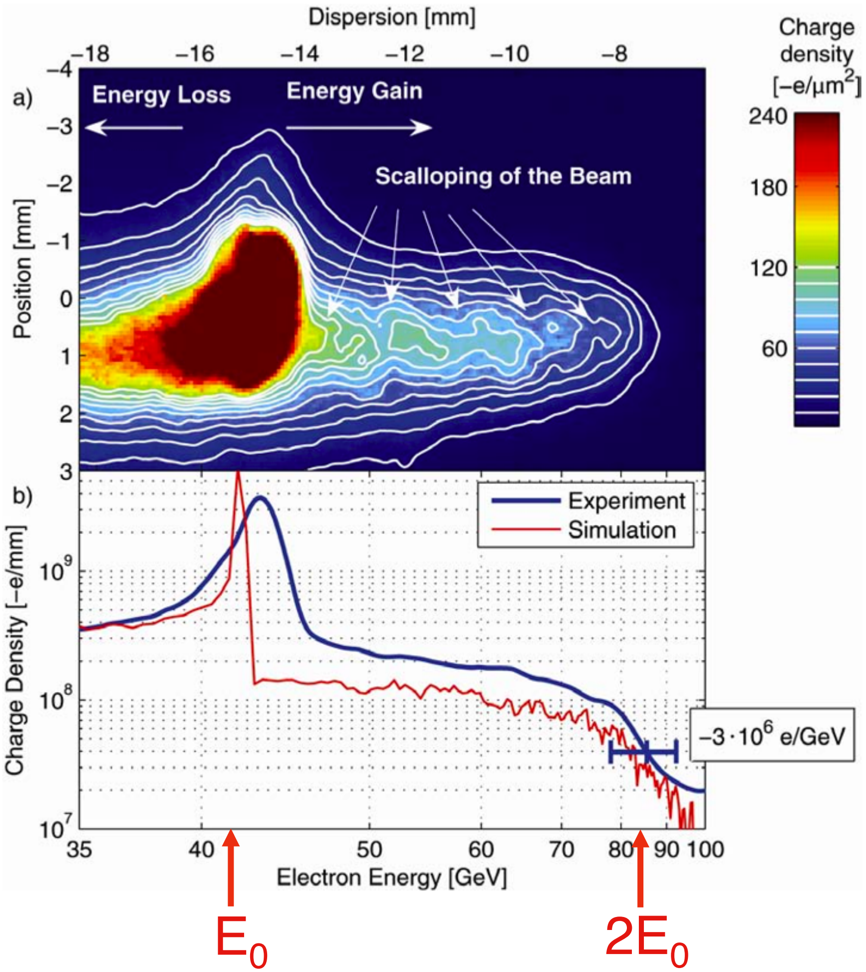
The plasma:

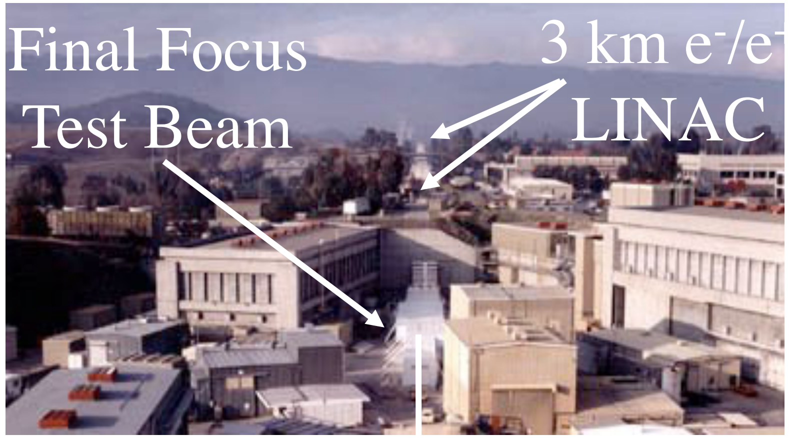
- Converts transverse into longitudinal fields (ES wave)
- Supports the relativistic (v_z~c) plasma wave with E_z=1-100GV/m
- Supports the accelerating structure
- Suppresses need for cavity fabrication
- Needs only one wave period
- Overcomes the breakdown limit

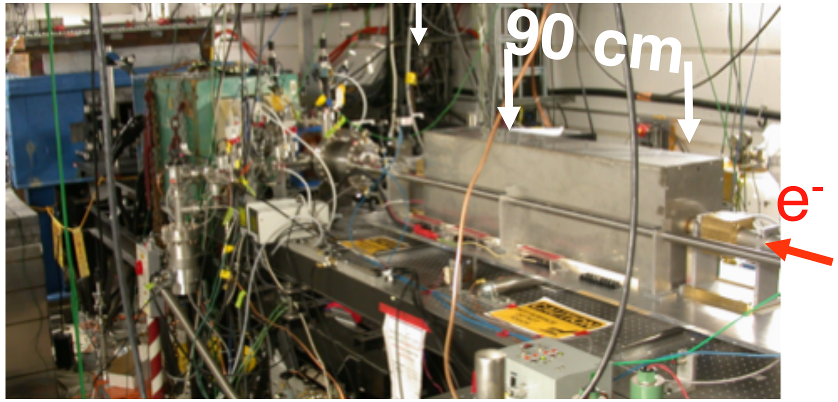
Conventional accelerators: MHz-GHz, E_{acc}<150 MV/m, B_θ/r<2 kT/m

e^- ENERGY DOUBLING @ SLAC

Blumenfeld, Nature 445, 2007







- E_0=42 GeV, $\sigma_z\approx$25 μm, σ_z<10 μm, N=1.8×10^{10} e^-
- Energy doubling of trailing e^- over $L_p\approx$85 cm, $n_e=2.7\times10^{17}$ cm^{-3} plasma
- Unloaded gradient ≈52 GV/m (≈150 pC accel.)

PWFA DRIVERS, WHY p^+?

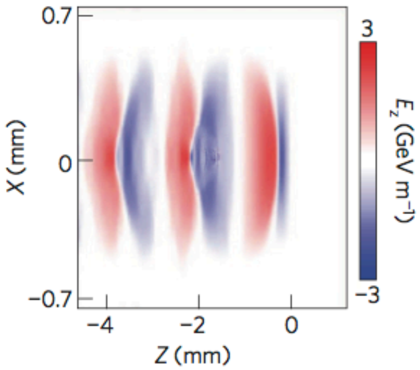
Energy considerations, PWFA = energy transformer:

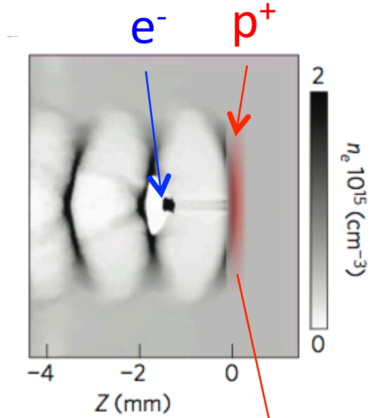
- A SLAC, 28.5GeV bunch with $2\times10^{10}e^-$ caries ~90J
  An ILC, 0.5TeV bunch with $2\times10^{10}e^-$ caries ~1.6kJ
- A SLAC-like driver for staging (FACET, +25GeV)
- A SPS, 450GeV bunch with $10^{11}p^+$ caries ~7.2kJ
  A LHC, 7TeV bunch with $10^{11}p^+$ caries ~112kJ
- A single SPS or LHC p^+ bunch could produce an ILC e^- bunch in a single PWFA stage!
- Requires long plasmas (~100's m)
- Requires short p+ bunch (~100µm)

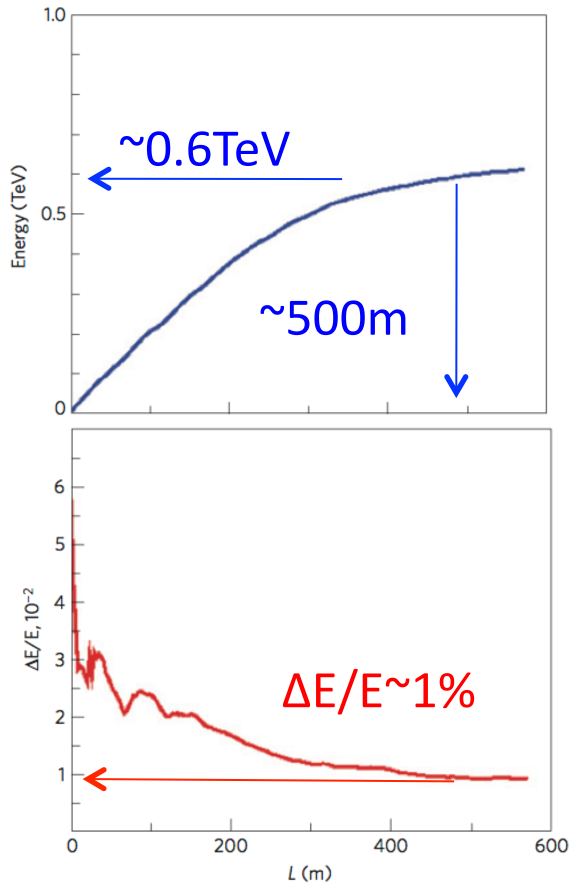
PROTON-DRIVEN PWFA @ CERN

Caldwell, Nat. Phys. 5, 363, (2009)

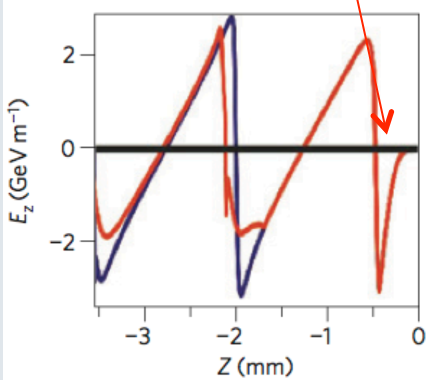
p+:
E_0=1TeV
σ_z=100µm
N=10^{11}
e^-:
E_0=1GeV
N=1.5x10^{10}





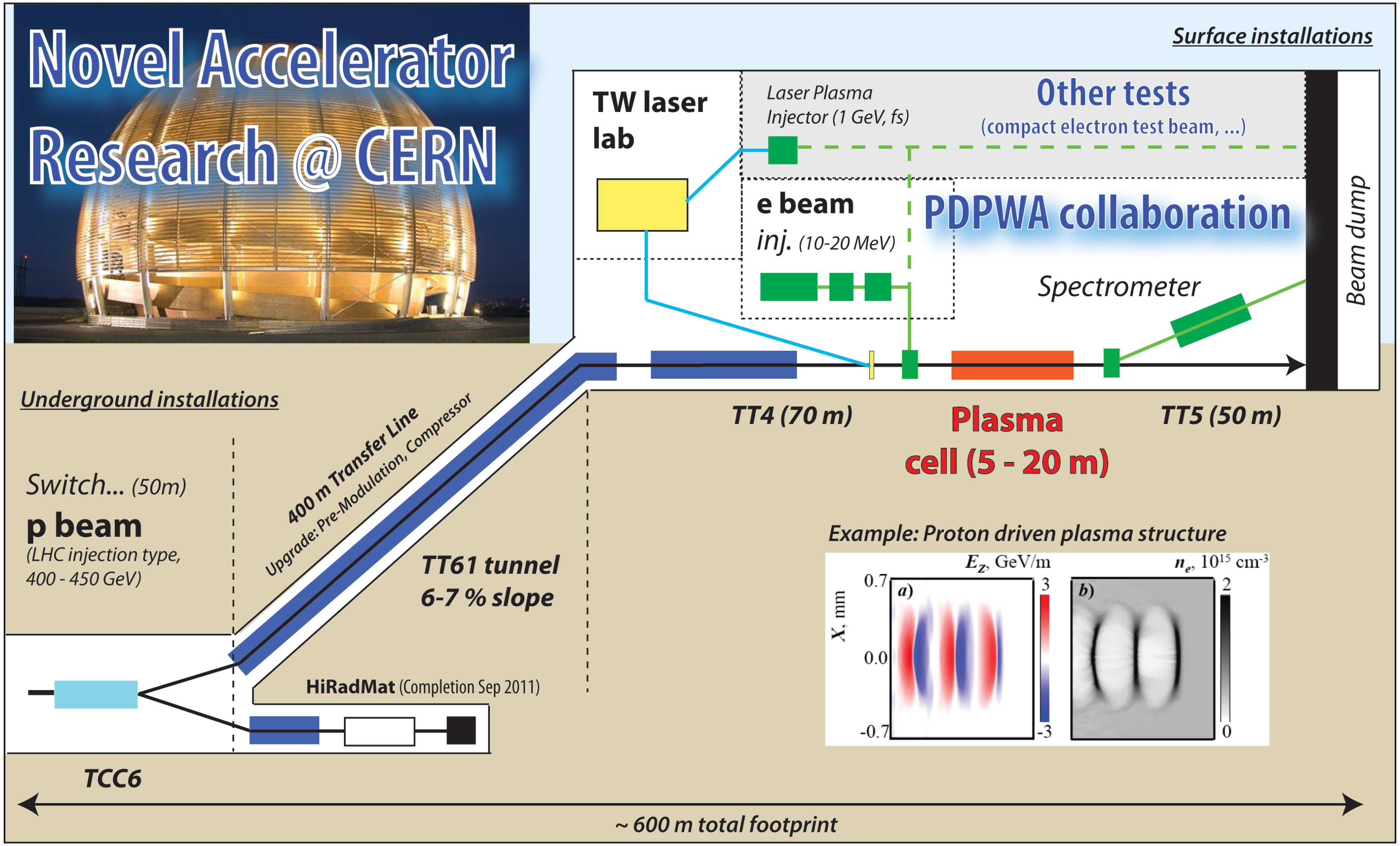


Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	T m^{-1}
Magnet length		0.7	m



- Use "pancake" p^+ bunch to drive non-linear wake (cylinder for e^- driver)
- Gradient ~1.5GV/m (av.), efficiency ~ 10%
- ILC-like e^- bunch from a single p^+-driven PWFA

PROTON-DRIVEN PWFA @ CERN



- Program for TeV class e- from p$^+$-driven PWFA@CERN, driven by MPP
- New advanced accelerator facility

PWFA GROUP

Patric Muggli, group leader
Allen Caldwell, director
Olaf Reimann, scientist
Guoxing Xia, postdoc (departing)
Erdem Oz, postdoc (starting now, welcome!)
Roxanna Tarkeshian, postdoc (starting March 1)
Frank Simon, scientist
Hans von der Schmitt, scientist

… expanding, looking for excellent students

Work with Mr. Thomas Haubold and Gennadiy Finenko on metal vapor (plasma) source design/construction

Jorge Vieira, IST Portugal, simulations, applying for Humboldt fellowship

Strong collaboration with CERN: Ralph Assmann, Frank Zimmerman, Steffen Hillenbrand, …

2011 SIGNIFICANT EVENTS

Obtained significant funding (successful MPG Großgeräteantrag) to support MPP and IPP-Greiswald (Olaf Grulke)

MPP:
Develop and lead experimental program (all)
Develop a ~5-10m plasma source (E. Oz, P. Muggli)
Develop wakefields/plasma/beam diagnostics (R. Tarkeshian, P. Muggli, O. Reimann)

IPP:
Explore the possibility of using a helicon source for producing very long plasma, 10-100m (Olaf Grulke)

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2011 Significant Events

- Letter of Intent submitted to CERN SPSC in May

- Significant interest expressed by the advanced accelerators community

- Proto-collaboration meetings held:
  CERN (2010)
  MPP (2010)
  UC-London (2011)
  MPP, Nov. 30-Dec. 1
  Next:
  CERN March 5-6, 2012

- April 1, 2011, P. Muggli joins MPP

Date: May 24, 2011

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

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

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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, Karlsruher, Germany
12 LAL, Univ Paris-Sud, CNRS/IN2P3, Orsay, France
13 Los Alamos National Laboratory, NM, USA
14 Ludwig Maximilian University, Munich, Germany
15 Max Planck Institute for Physics, Munich, Germany
16 Max Planck Institute for Plasma Physics, Greifswald, Germany
17 Rutherford Appleton Laboratory, Chilton, UK
18 State Key Laboratory of Nuclear Physics and Technology, Peking University, China
19 Tsinghua University, Beijing, China
20 University of California, Los Angeles, CA, USA
21 University College London, London, UK
22 University of Oslo, Oslo, Norway
23 University of Strathclyde, Glasgow, Scotland, UK

2011 SIGNIFICANT EVENTS

- Positive review by the CERN SPSC (Oct. 27, 2011):

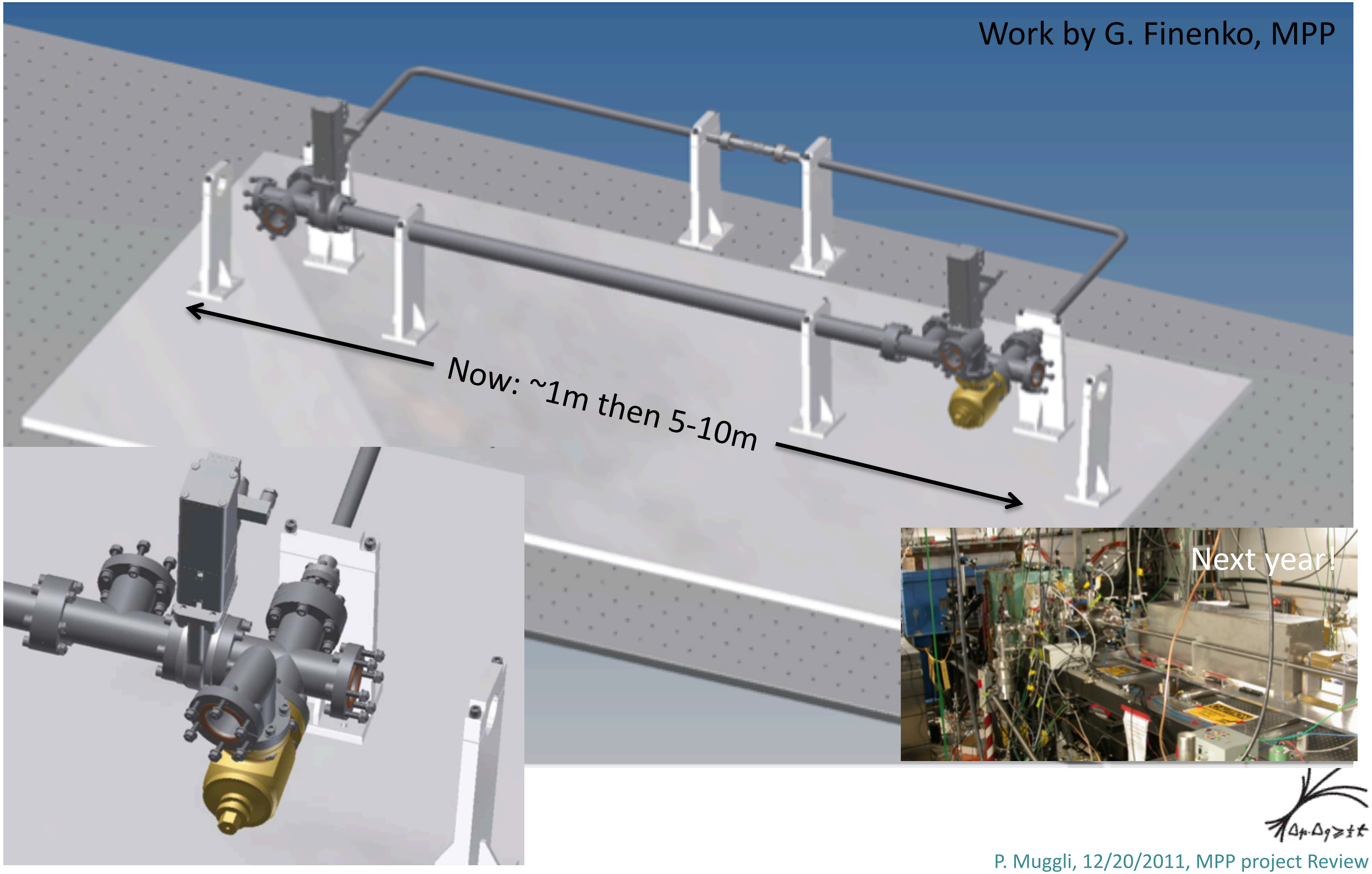
7.1 DISCUSSION ON THE LOI ON PROTON-DRIVEN PLASMA WAKEFIELD ACCELERATION

The SPSC recognises the interest in testing plasma acceleration with proton drivers and its possible technological implications for future accelerators at CERN and elsewhere. The Committee recognises the opportunity to use the SPS beams for these studies. The Committee encourages the collaboration to work towards a Technical Design Report in order to allow CERN to fully assess the technical feasibility, the timescale and the resources within the overall CERN programme.

- Plan for the technical design report: submit by September 2012

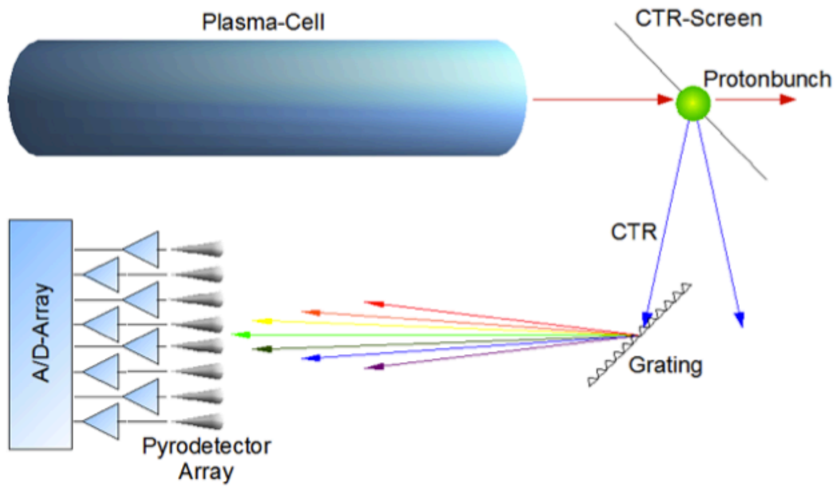
2011 SIGNIFICANT EVENTS

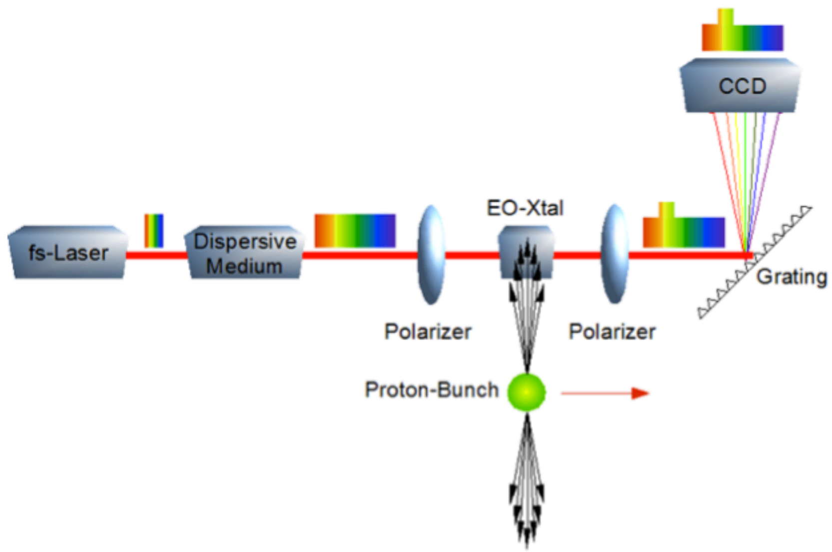
- Progress with metal vapor source @MPP, source in the design/purchasing phase



2011 SIGNIFICANT EVENTS

•Progress on diagnostics development (O. Reimann)





•Measurement of p^+-bunch self modulation through spectrum of coherent transition radiation

•Measurement of wakefield fringing field with electro-optical sampling techniques

•Explore diagnostics in the sub-THz range (n_e=6x10^{14} cm^{-3} -> f_{pe}~300GHz)

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A Muon Collider compared to current and planned ee, pp colliders:

Advantage over the electron:

$m_\mu = 207\ m_e$

$$\Delta E_{\rm turn} = \frac{4\pi\alpha\hbar c}{3R}\left(\frac{E}{mc^2}\right)^4$$

(Synchrotron Radiation)

higher energies with smaller machines (d=2km)

Advantage over the proton:

Muon is a point-like particle

well defined interaction energy (no PDFs)

higher precision

Physics Potential:

100 – 500 GeV CoM (L ≈ 10^{31}–10^{33} $cm^{-2}s^{-1}$)

Higgs Factory: resonant mass scan

$\Delta m_{\rm h}/m_{\rm h} \sim 10^{-6}$

$\sigma_{\mu\mu\to h} \sim (m_\mu/m_{e-})^2 \sigma_{e\text{-}e\to h}$

threshold scans for W^+W^-, $t\bar{t}$, Z h

$\Delta M_{\rm W} \sim 6{\rm MeV},\ \Delta M_{\rm t} \sim 70{\rm MeV}$

3 – 4 TeV CoM (L ≈ 10^{34} $cm^{-2}s^{-1}$)

s-channel resonant production of new particles:

Z′, Extra Dimensions,

heavy SUSY particles

pair production of new particles

strong scattering of weak bosons

t-channel resonant production

plus

front end muon physics:

$\mu \to e\Upsilon$, $\mu \to e$, a_μ

neutrino factory:

pure $\nu_\mu \bar{\nu}_e$ ($\bar{\nu}_\mu \nu_e$) beam

$\theta_\nu \approx \tan\theta_\nu \approx \gamma_\mu^{-1}$

μp collider:

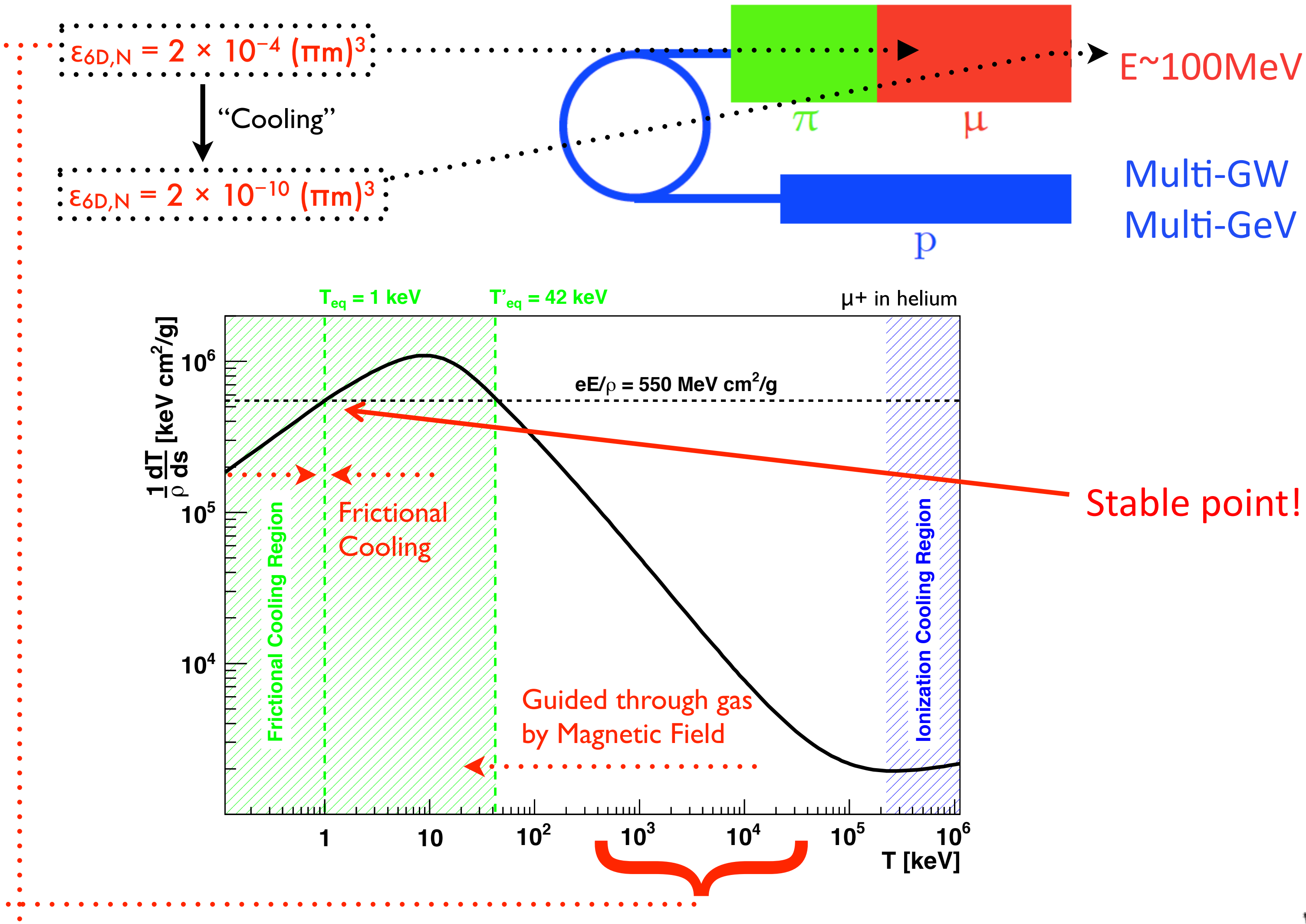
Q^2 reach of 10^5 GeV^2

with high luminosity

$\Delta p \cdot \Delta q \geq \hbar$

Frictional Cooling

muon decay time (2.2 microsecond) → fast schemes for beam preparation required



- Slow down ~100MeV to >42 KeV in gas and guiding magnetic field (energy loss only)
- Then momentum/energy piles-up at 1KeV stable point (friction-acceleration)

Recent Development: Understanding Charge Exchange Processes

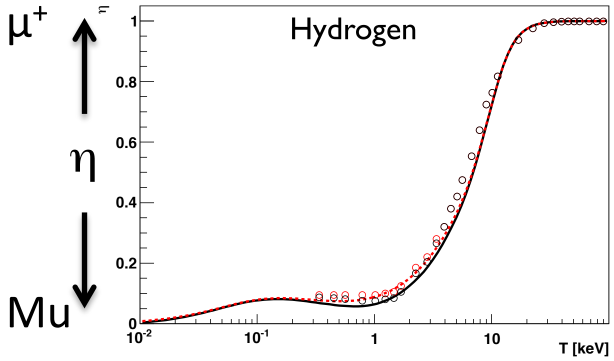
At low energies, positively charged particles trade electrons back and forth with the medium atoms

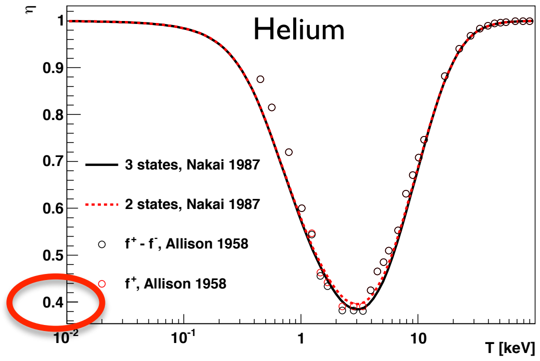
Since the μ+ switch in and out of atomic Mu states, we approximate its charge with an effective charge

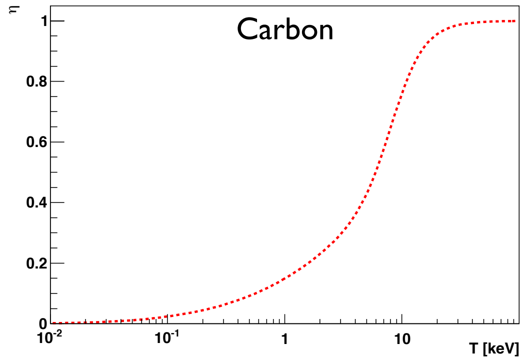
$$\eta = \frac{\sigma_{0+}}{\sigma_{+0} + \sigma_{0+}}$$

σ_{0+}: cross section for $\mu + e^- \rightarrow Mu$

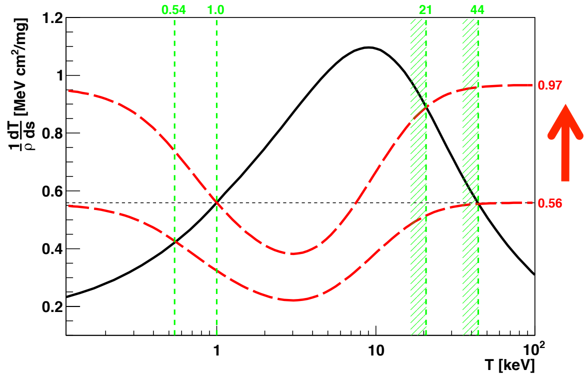
σ_{+0}: cross section for $Mu \rightarrow \mu + e^-$







Hydrogen gas cooling schemes require very high electric field strengths and are inefficient



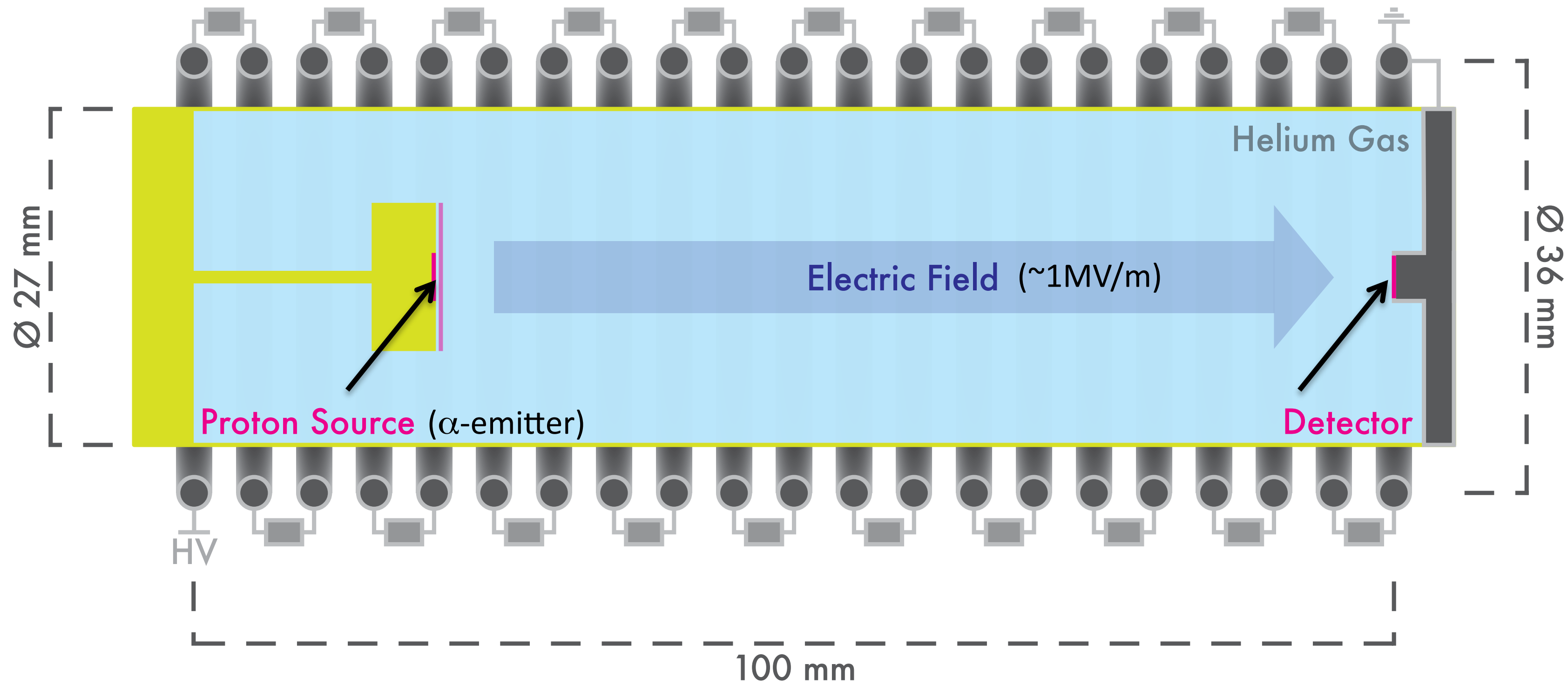
Carbon foil cooling schemes are not possible for μ+

The range for T_{eq} in helium is reduced to T_{eq} <~ 4 keV, and field larger field strengths are required than previously thought (arXiv: 1111.2813)

- Must cool μ^- and μ^+, but μ^+ are different: charge exchange lowers the effective charge (η<1)
- Since η<1, must use larger E-field and only He is appropriate (largest η(E) @ low η)

Frictional Cooling Demonstration Experiment (with p^+)

(arxiv: 1012.3946)



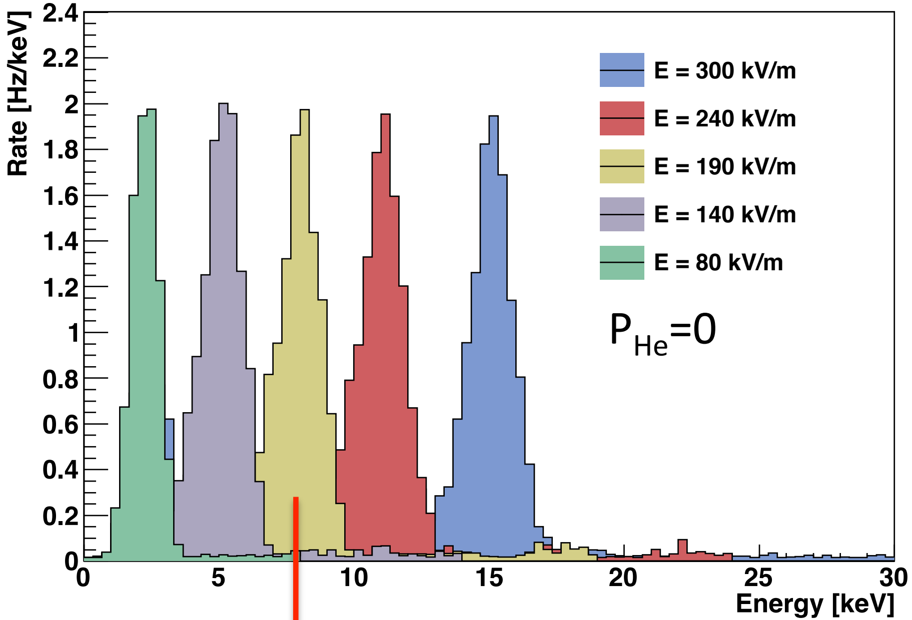
This year, we fixed problems with the flow of helium gas into the cooling cell by a change of construction to the flange of the cell

this allowed us to take first proton spectra with helium gas in the cell at pressures between 3 and 500 μbar

these pressures are too low to see the cooling effect, but perfect for observing charge exchange effects

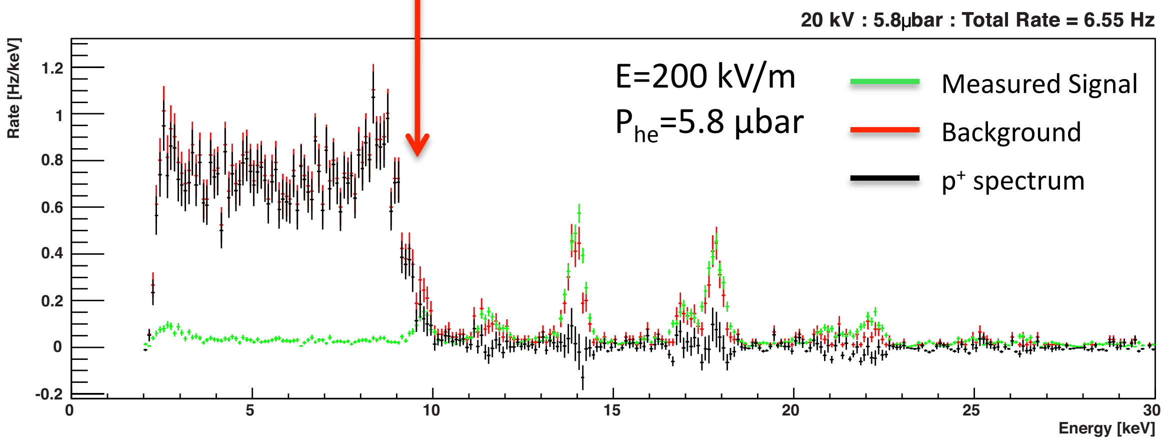
Slides by D. Greenwald

Proton Spectra



- Mean, narrow energy spectrum increases ~linearly with electric field (applied voltage)

A detailed analysis of proton spectra carried out (paper in progress), for protons in vacuum (examples above) and protons in light-density helium (example below)



- Change is energy spectrum with He due to charge exchange effect?

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Frictional Cooling Demonstration Experiment & Muon Collider Studies

Director
A. Caldwell

PhD Student / Post-Doc — Two doctorates granted
Y. Bao
D. Greenwald

Construction
K. Ackermann
G. Winklmueller

Electronics
R. Maier
S. Tran

Two papers (from previous slides) in preparation,
and "Low-energy muons via frictional cooling" in NIMA 622, 2010

The experiment lives on!
In 2012, experiment structures will be transported to Paul Scherrer Institute.
The experiment will continue there under Y. Bao.

A LOOK AT 2012

PWFA:

•Strong activity preparing the technical report
•Development of plasma sources (MPP, MPP-IST-ICL)
•Laser ionization test
•Development of diagnostics
•Steps towards in-house simulation capabilities
•Develop strong collaborations (CERN, IST, ICL, IPP, …)
•Plasma source for PWFA experiments at DESY-Zeuthen
•Proposed self-modulation physics experiments at SLAC FACET (e^- and e^+)

•Expansion of the group at MPP to create a critical mass for an explosion of ideas and accomplishments

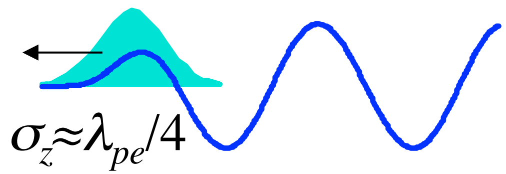
Muon Cooling:

•Publish the results
•Continuation of activities at PSI-Switzerland
•The experiment lives on …

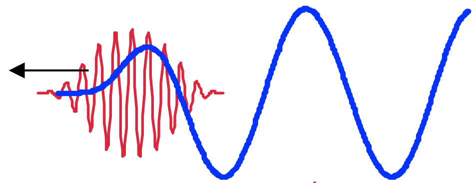

Thank you …
… and Happy Holidays to all!
The Great Salt Lake, Utah

4 PLASMA ACCELERATORS*

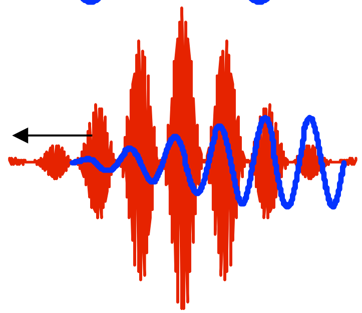
- Plasma Wakefield Accelerator (PWFA)
  A high energy particle bunch (e^-, e^+, ...)



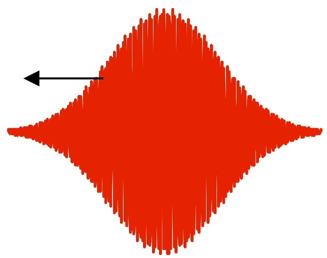
- Laser Wakefield Accelerator (LWFA)
  A short laser pulse (photons)



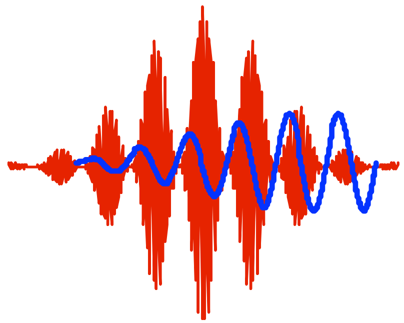
- Plasma Beat Wave Accelerator (PBWA)
  Two frequencies laser pulse, i.e., a train of pulses



- Self-Modulated Laser Wakefield Accelerator (SMLWFA)
  Raman forward scattering instability in a long pulse

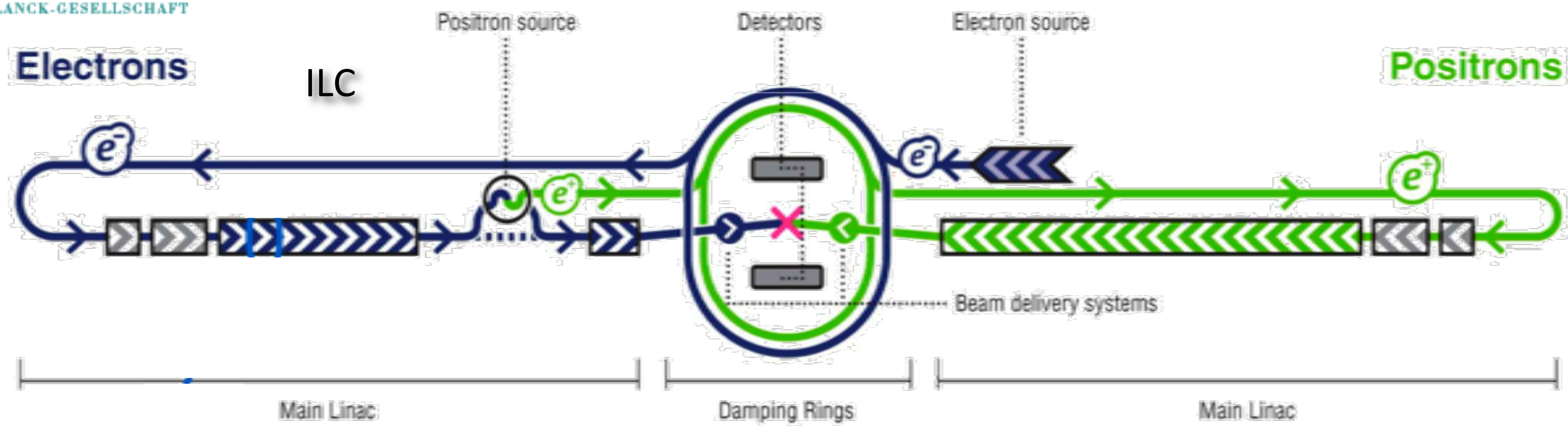


evolves into



*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

FUTURE LEPTON (e^-/e^+) COLLIDER

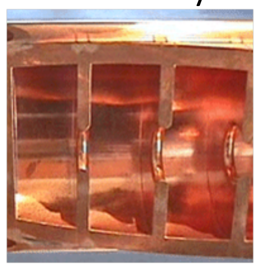


≈25 km site?

- Linear accelerator to avoid synchrotron radiation limitation ($\sim\gamma^4/r^2 \sim E^4/m^4r^2$)
- Energy frontier: 0.5-3 TeV, e^-/e^+
- Accelerator length with (cold) rf technology:

$$\frac{1\ \text{TeV}}{<50\ \text{MeV/m}} > 20\ \text{km}$$

Pillbox Cavity



<150MV/m?

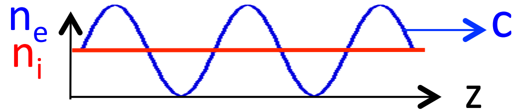
Is there a high-gradient alternative to rf technology?
Could it be plasmas?

WHAT ABOUT PLASMAS?

- Relativistic Electron Electrostatic Plasma Wave (Electrostatic, E_z):

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0} \qquad k_p E_z = \frac{\omega_{pe}}{c}E_z = \frac{n_e e}{\varepsilon_0} \qquad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$$

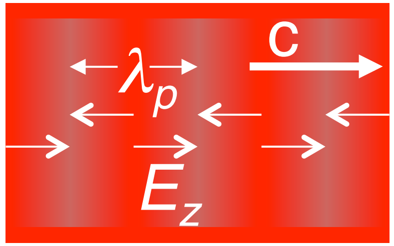
Plasma Frequency



$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e\left(cm^{-3}\right)} = 1\,GV/m$$

Cold Plasma "Wavebreaking" Field

$n_e=10^{14}$ cm^{-3}



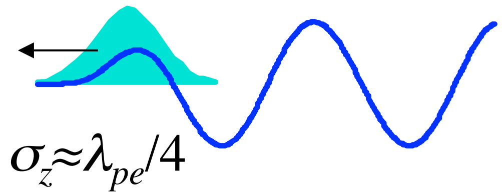
LARGE

Collective response!

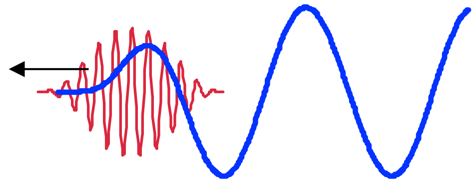
- Plasmas can sustain very large (collective) E_z-field, acceleration
- Wave, wake phase velocity = driver velocity (~c when relativistic)
- Plasma is already (partially) ionized, difficult to "break-down"
- Plasmas wave or wake can be driven by:
  - Intense laser pulses (LWFA)
  - Short particle bunch (PWFA)

5 ~~4~~ PLASMA ACCELERATORS*

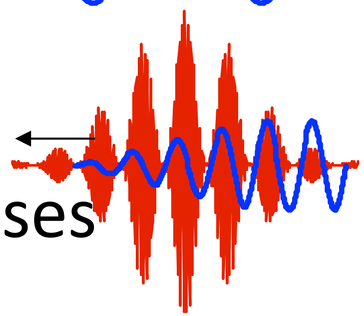
- Plasma Wakefield Accelerator (PWFA)
  A high energy particle bunch (e^-, e^+, ...)



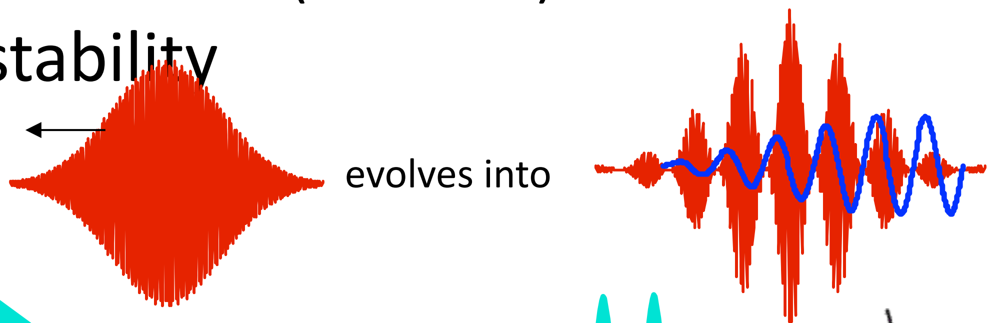
- Laser Wakefield Accelerator (LWFA)
  A short laser pulse (photons)



- Plasma Beat Wave Accelerator (PBWA)
  Two frequencies laser pulse, i.e., a train of pulses



- Self-Modulated Laser Wakefield Accelerator (SMLWFA)
  Raman forward scattering instability
  in a long laser pulse

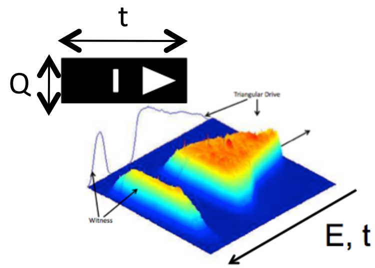


- Self-Modulated PWFA (SMPPWFA)

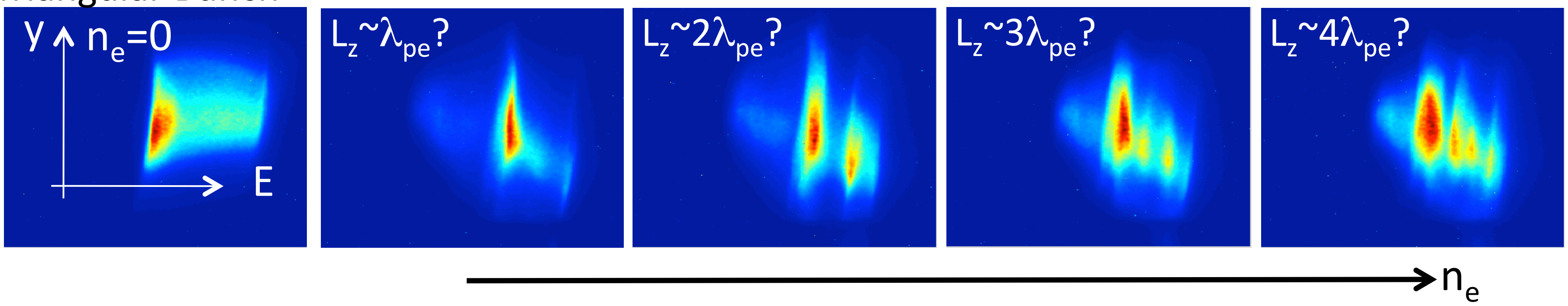
*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

TEST SELF-MODULATION @ ATF-BNL

- E_0=60MeV, σ_r~100µm, N~4x10^9, L_z~1500µm



Triangular Bunch



- First evidence of self-modulation (in energy) in a plasma?
- Coherent transition radiation energy (~1/σ_z) measurements indicate S-M
- Encouraging preliminary results
- Will repeat next week ….