Beam Driven Plasma wakefield acceleration
and
A selection from the activities
in Lancaster University and The University of Manchester

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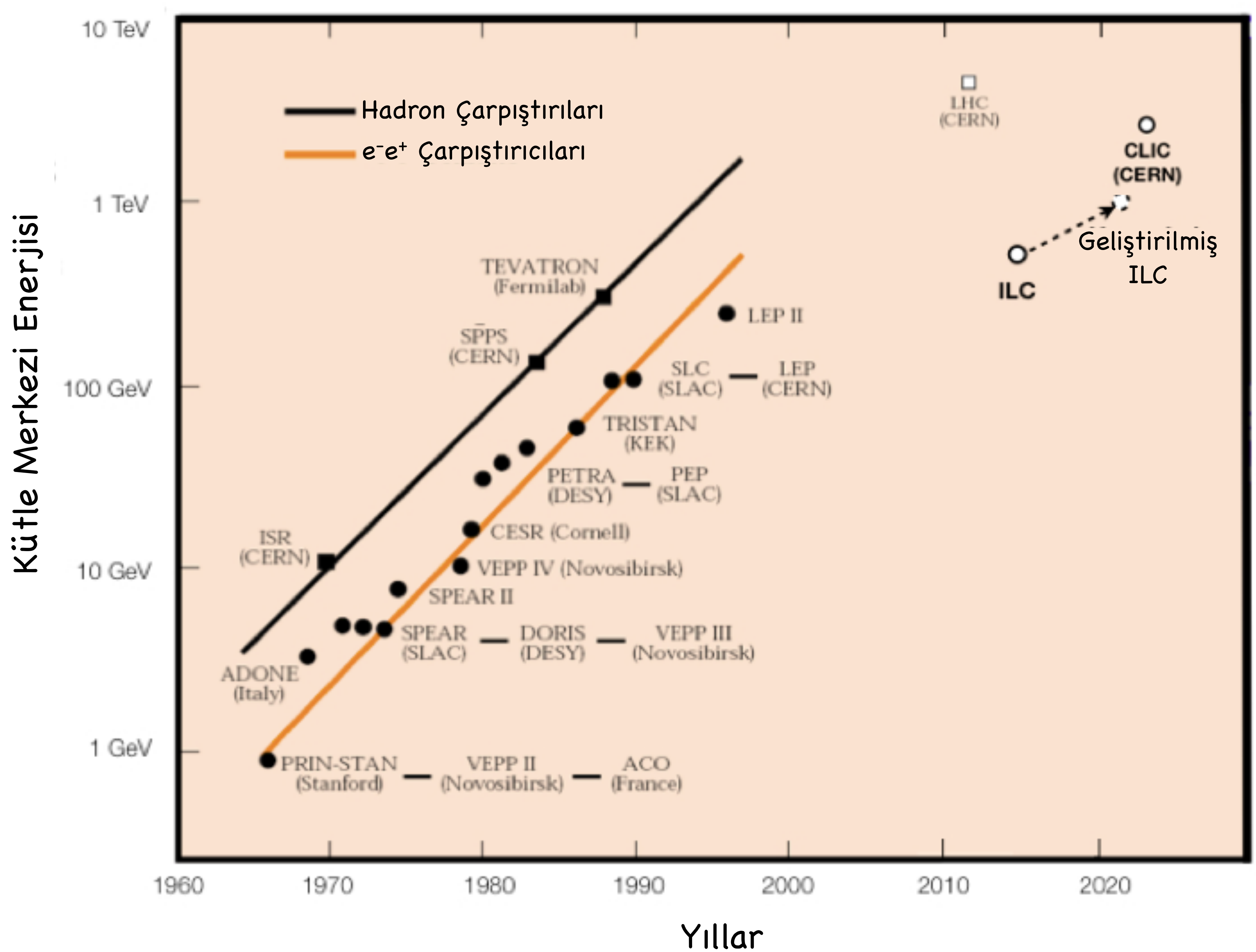
The Cockcroft Institute of Accelerator Science and Technology

The Cockcroft Institute
of Accelerator Science and Technology

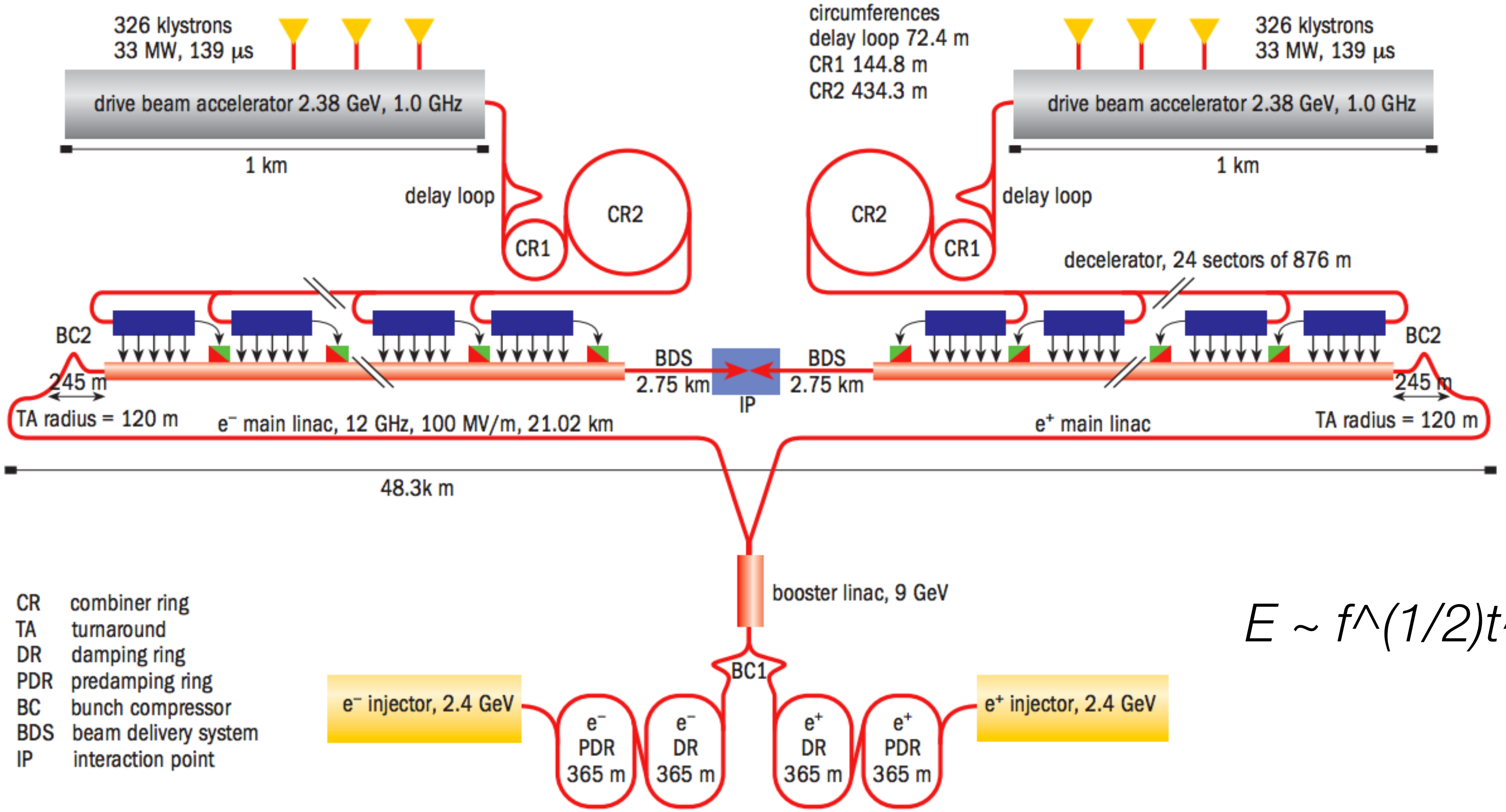
Outline

- Examples of advance acceleration technologies
  - Terahertz driven acceleration
  - Dielectric accelerators
  - Laser and beam driven plasma accelerators
- AWAKE Project
  - Witness production
  - 3D simulations for unresolved phenomena in 2D
- Future collider studies based on PDPWA
  - Possible layouts using existing infrastructure
  - Design issues
- Plasma Acceleration Research Station (PARS) Project
  - Optimisation for various regimes of CLARA
  - Plasma sources
- iMPACT Proposal
  - Multi-bunch PWA
  - PIC simulations for CLARA and CLARA Front End

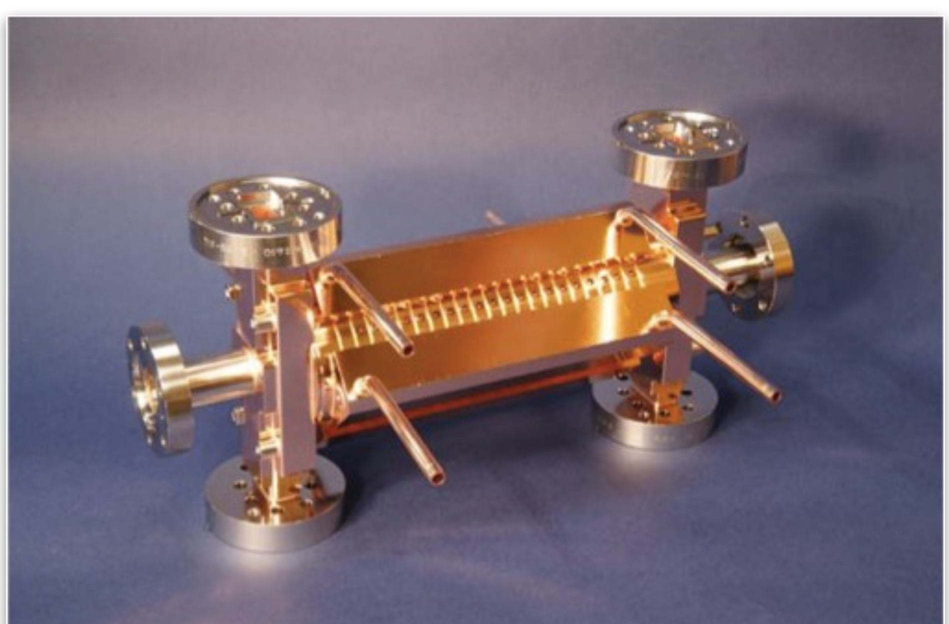
S. Livingstone'ın hazırladığı çizelgeden güncelleştirilmiştir.



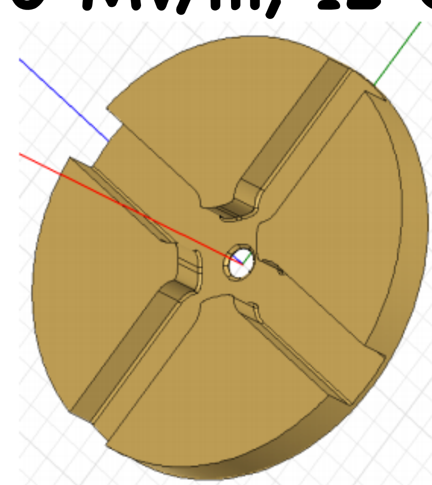
Normal iletken metalik teknolojinin limiti

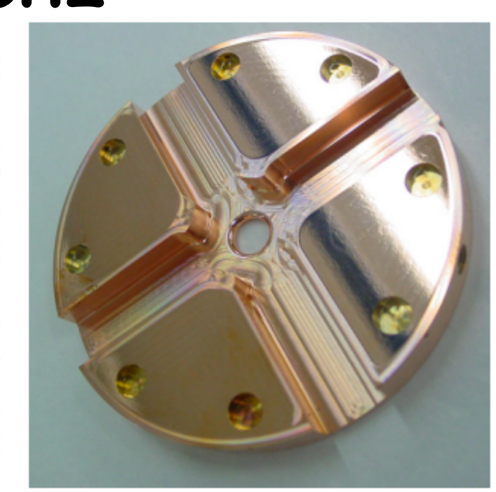


$E \sim f^{(1/2)} t^{(-1/4)}$



100 MV/m, 12 GHz





FCC Future Circular Colliders

- CERN'de 80-100km'lik tünel içerisine kurulacak bir pp çarpıştırıcısı.
- Daha sonra e^-e^+ (TLEP) ve e^-p (VLHeC) çarpıştırıcısına dönüştürülmesi olasılığı da var.
- Kavramsal tasarımı ile ilgili bir konuşma: http://indico.cern.ch/getFile.py/access?contribId=1&sessionId=5&resId=1&materialId=slides&confId=257713
- FCC kick-off toplantısı (12-15 Şubat 2014): http://indico.cern.ch/conferenceDisplay.py?confId=282344

YEARS/ANS CERN

"ILC in Japan"

- International Workshop on Future Linear Colliders http://www.icepp.s.u-tokyo.ac.jp/lcws13/
- Japonya ILC'yi Japonya'da yapmak istiyor.

INTERNATIONAL WORKSHOP ON FUTURE LINEAR COLLIDERS (LCWS13)
11-15 NOVEMBER 2013, THE UNIVERSITY OF TOKYO, JAPAN

"LHeC"

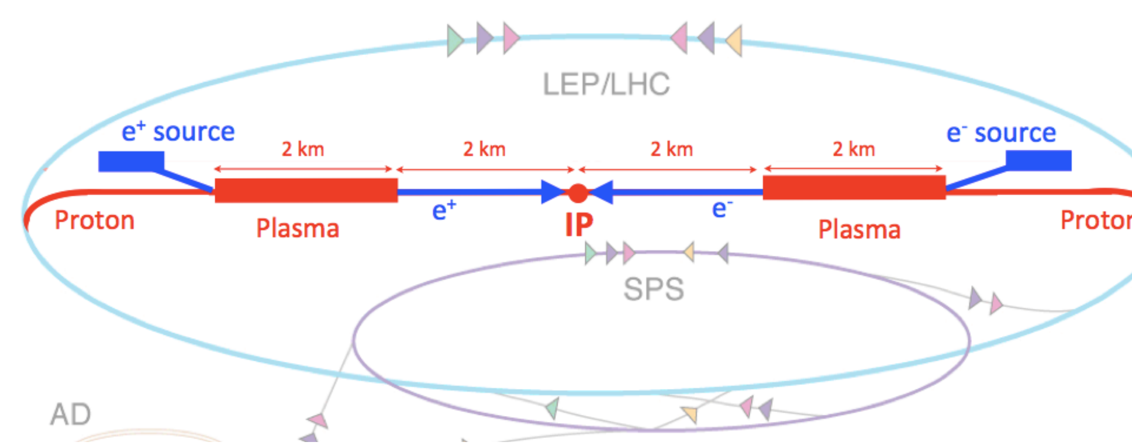
- CERN'den olur almışken ilginç bir şekilde inişe geçti.
- European Strategy for Particle Physics raporunda öncelikli projeler arasında yer almadı.

"CLIC"

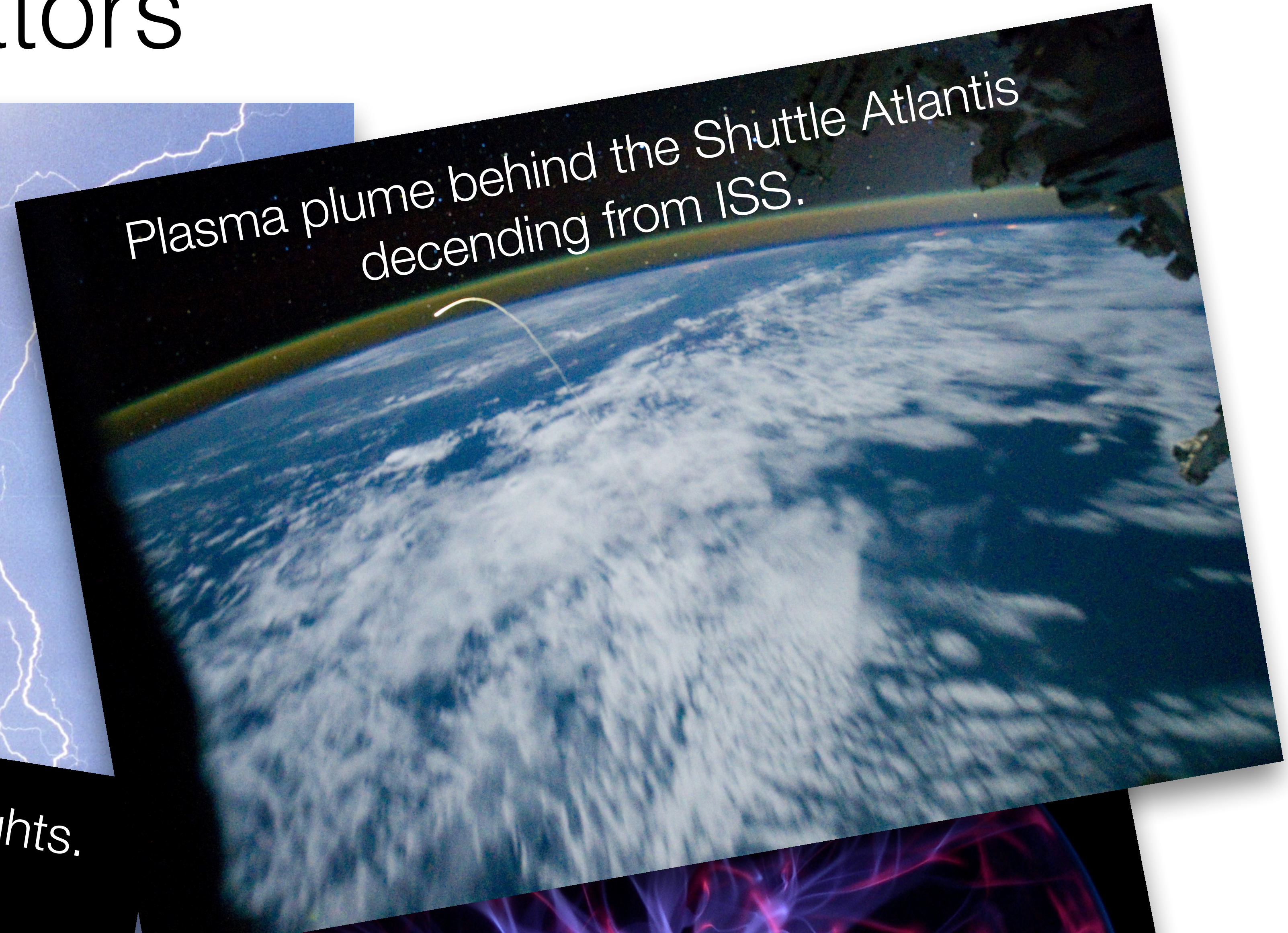
- "Compact Linear Collider" test evresi 2016'da sona eriyor…
- Yüksek gradyenli, normal iletken hızlandırma kaviteleri ve ikili demet hızlandırma gibi CLIC teknolojileri başarı ile test edildi ve onaylandı.

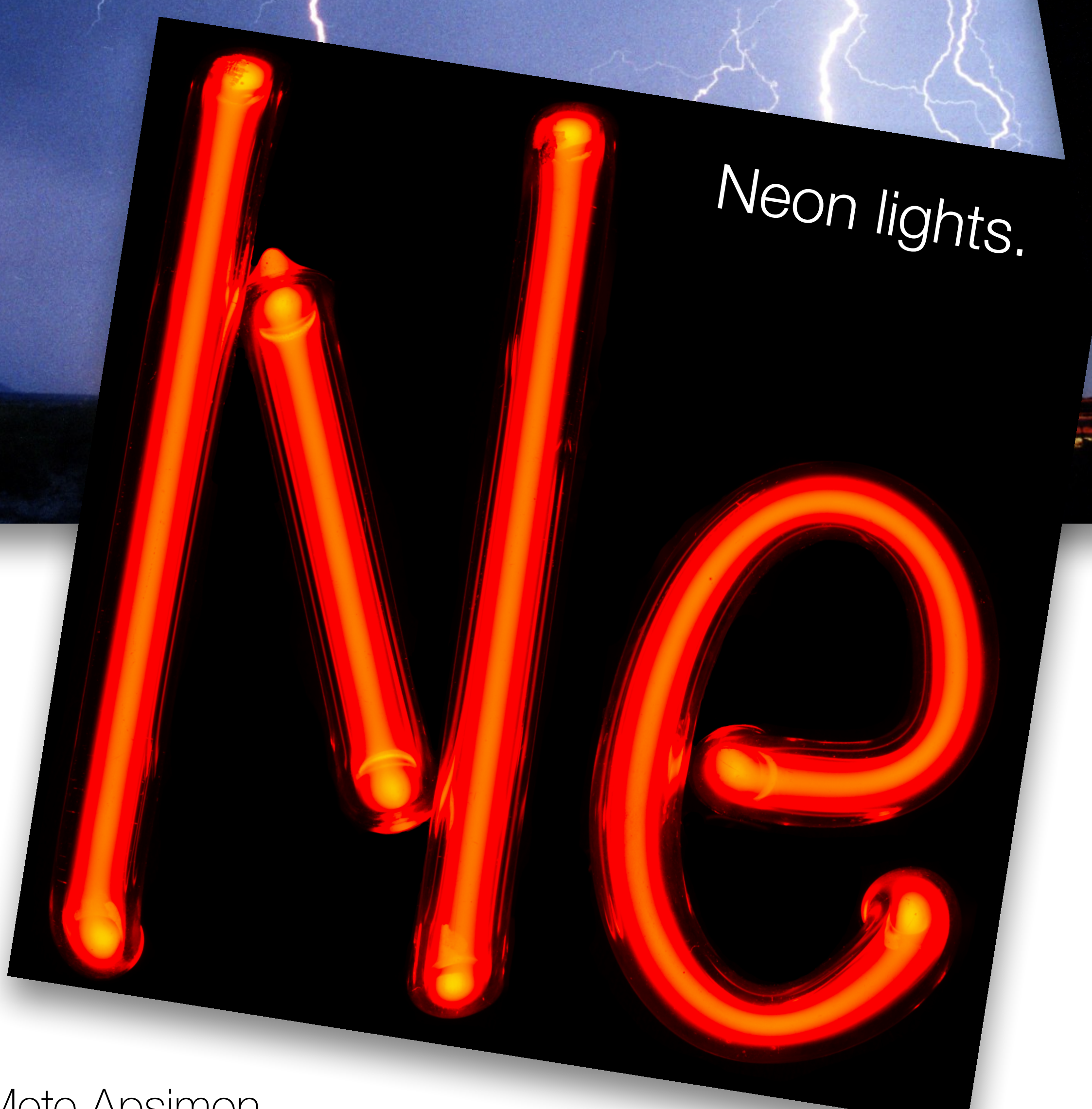
"Blue Sky"

- Alternatif hızlandırma teknikleri kullanılan çarpıştırıcılar,
- Proton sürümlü plazma girdabı ile hızlandırma,
- Sürücü demet LHC protonları ile sürülen çarpıştırıcılar tasarlanabilir,
- e^-e^+ ve e^-p seçenekleri sunuyor.



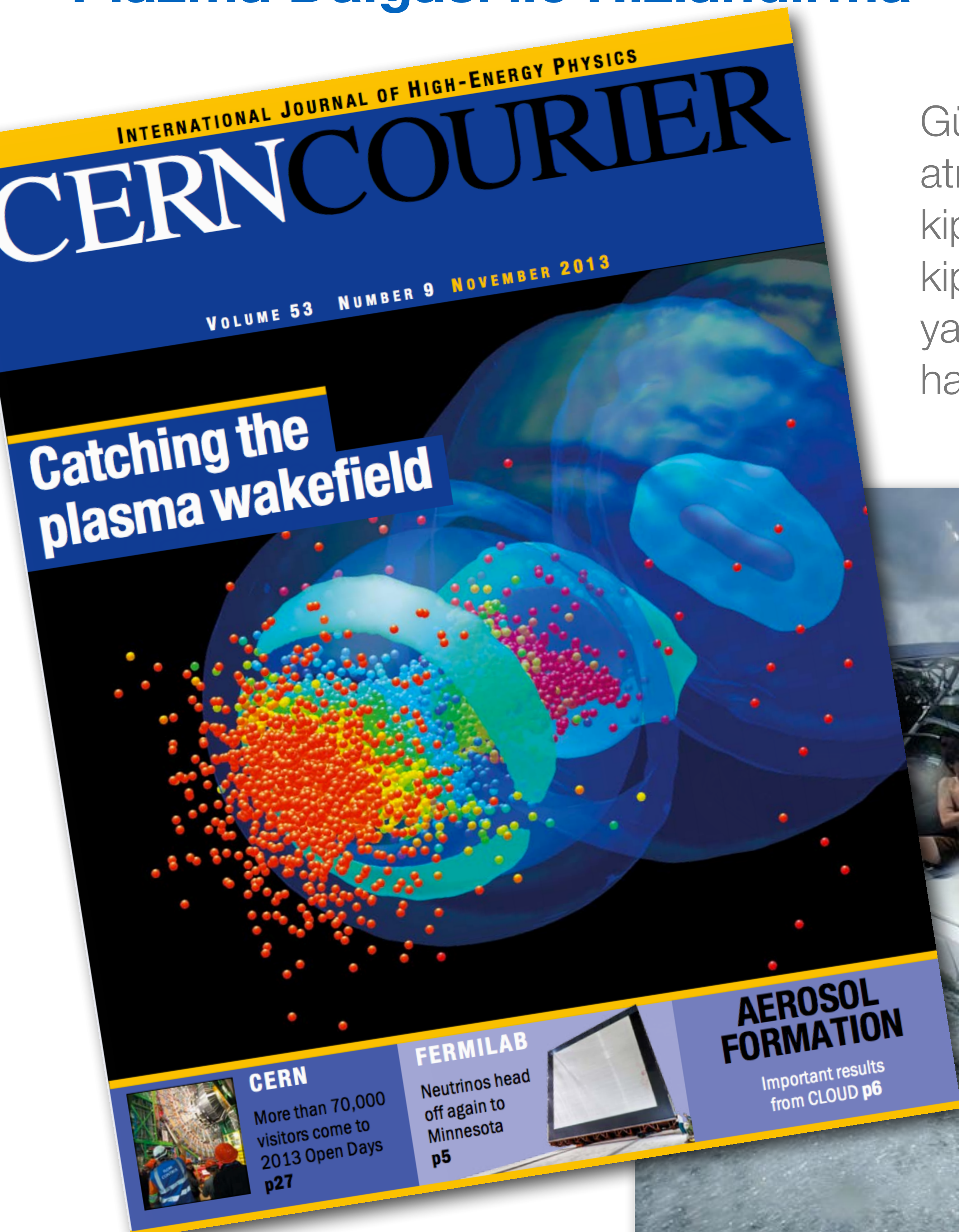
Plasma Accelerators

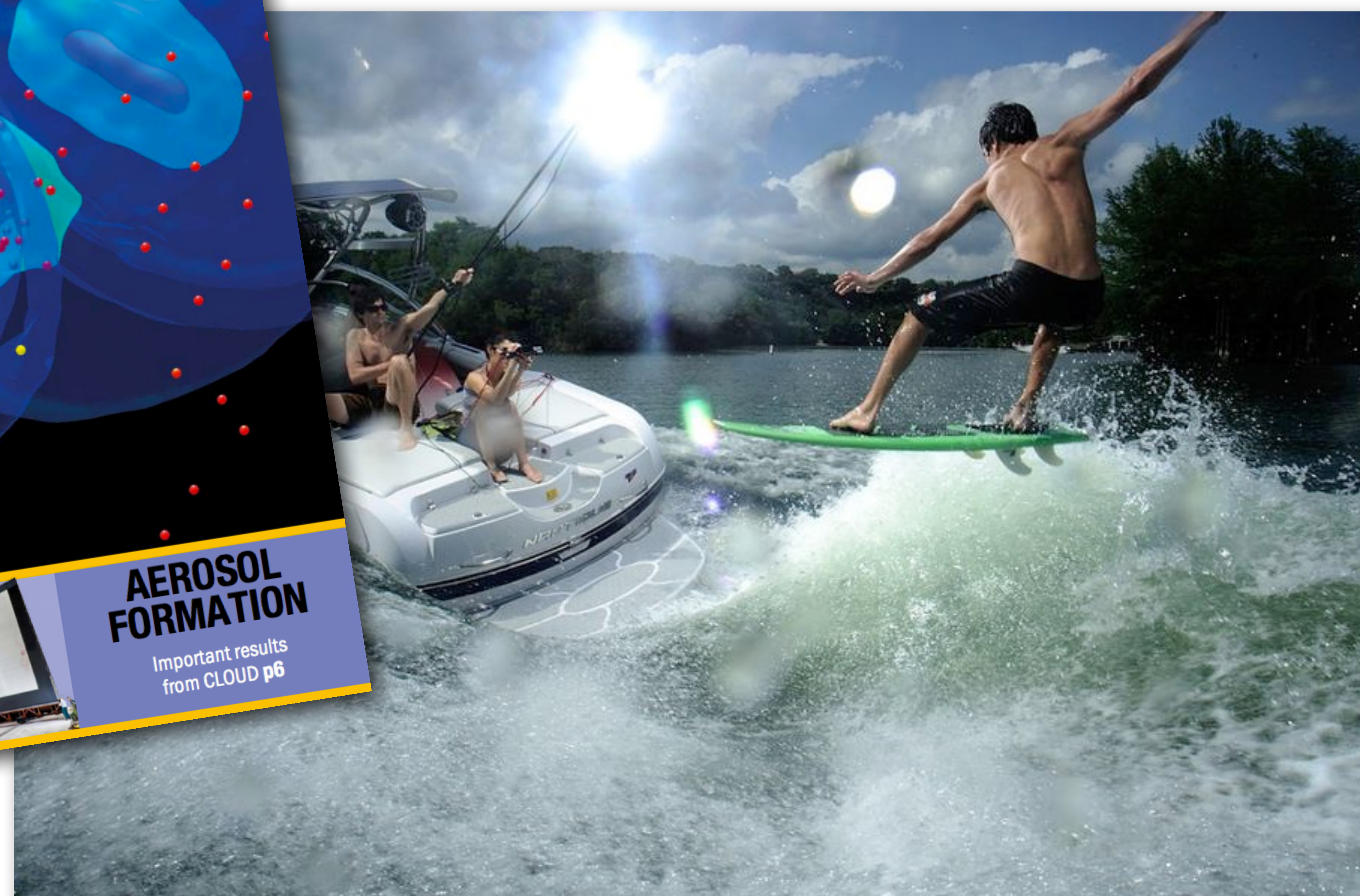




Plazma Dalgası ile Hızlandırma

Güçlü lazer ya da yüklü göreli parçacık demeti atmaları bir plazma ortamında aşırı yoğunluk kipleniminleri uyarmak için kullanılabilir. Bu kiplenimler 100 GV/m’den yüksek ve ışık hızına yakın hızlarda, dalga şeklinde, kiplenim boyunca hareket eden alan gradyenleri oluşturabilir.





Laser Driven PWA

Physics of laser-driven plasma-based electron accelerators

E. Esarey, C. B. Schroeder, and W. P. Leemans
Rev. Mod. Phys. **81**, 1229 – Published 27 August 2009

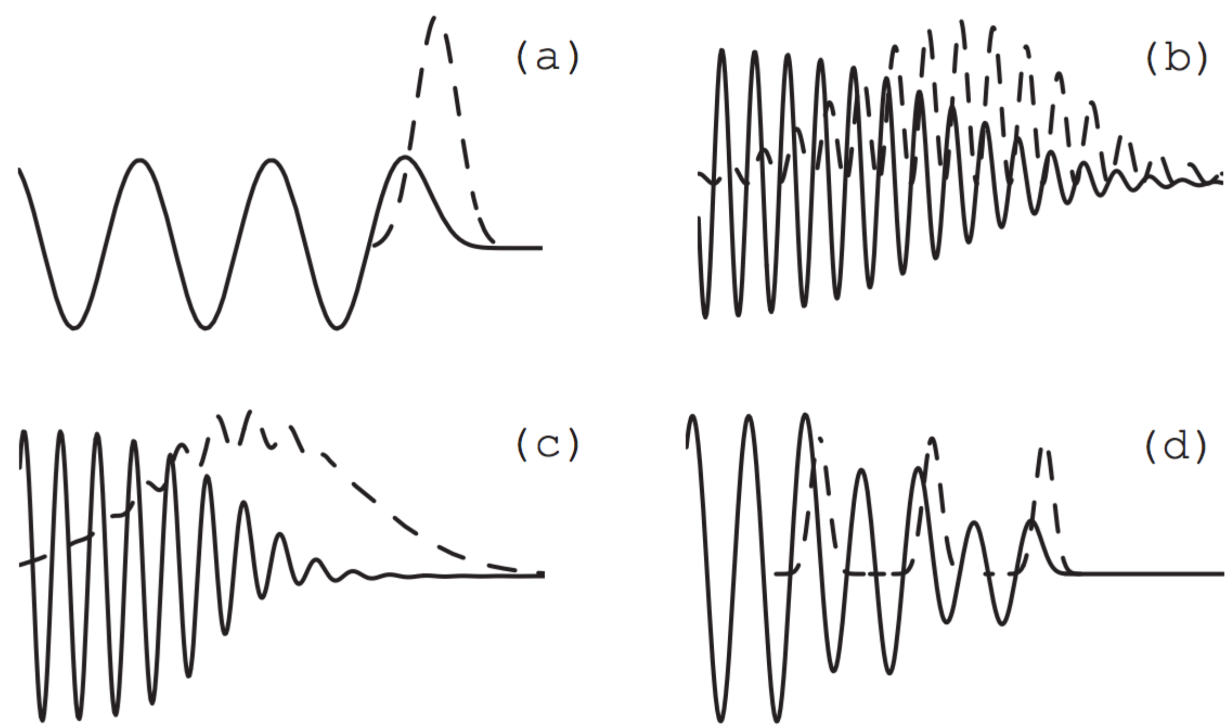


FIG. 1. Schematic of LPAs: (a) LWFA, (b) PBWA, (c) self-modulated (SM) LWFA, and (d) resonant laser pulse train. Shown are the excited plasma wave potentials (solid lines) and right-moving laser intensity envelopes (dashed lines).

Laser Driven PWA

Plasma-based accelerators are of great interest because of their ability to sustain extremely large acceleration gradients. The accelerating gradients in conventional radio-frequency (rf) linear accelerators (linacs) are currently limited to ~100 MV/m, partly due to breakdown that occurs on the walls of the structure. Ionized plasmas, however, can sustain electron plasma waves with electric fields in excess of $E_0 = cm_e\omega_p/e$ or

$$E_0(\mathrm{V/m}) \simeq 96\sqrt{n_0(\mathrm{cm}^{-3})}, \qquad (1)$$

where $\omega_p = (4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency, n_0 is the ambient electron number density, m_e and e are the electron rest mass and charge, respectively, and c is the speed of light in vacuum. Equation (1) is referred to as the cold nonrelativistic wave breaking field (Dawson, 1959). For example, a plasma density of $n_0 = 10^{18}\ \mathrm{cm}^{-3}$ yields $E_0 \simeq 96\ \mathrm{GV/m}$, which is approximately three orders of magnitude greater than that obtained in conventional linacs. Accelerating gradients on the order of 100 GV/m have been inferred in plasma-based accelerator experiments (Gordon *et al.*, 1998; Malka *et al.*, 2002).

Beam Driven PWA

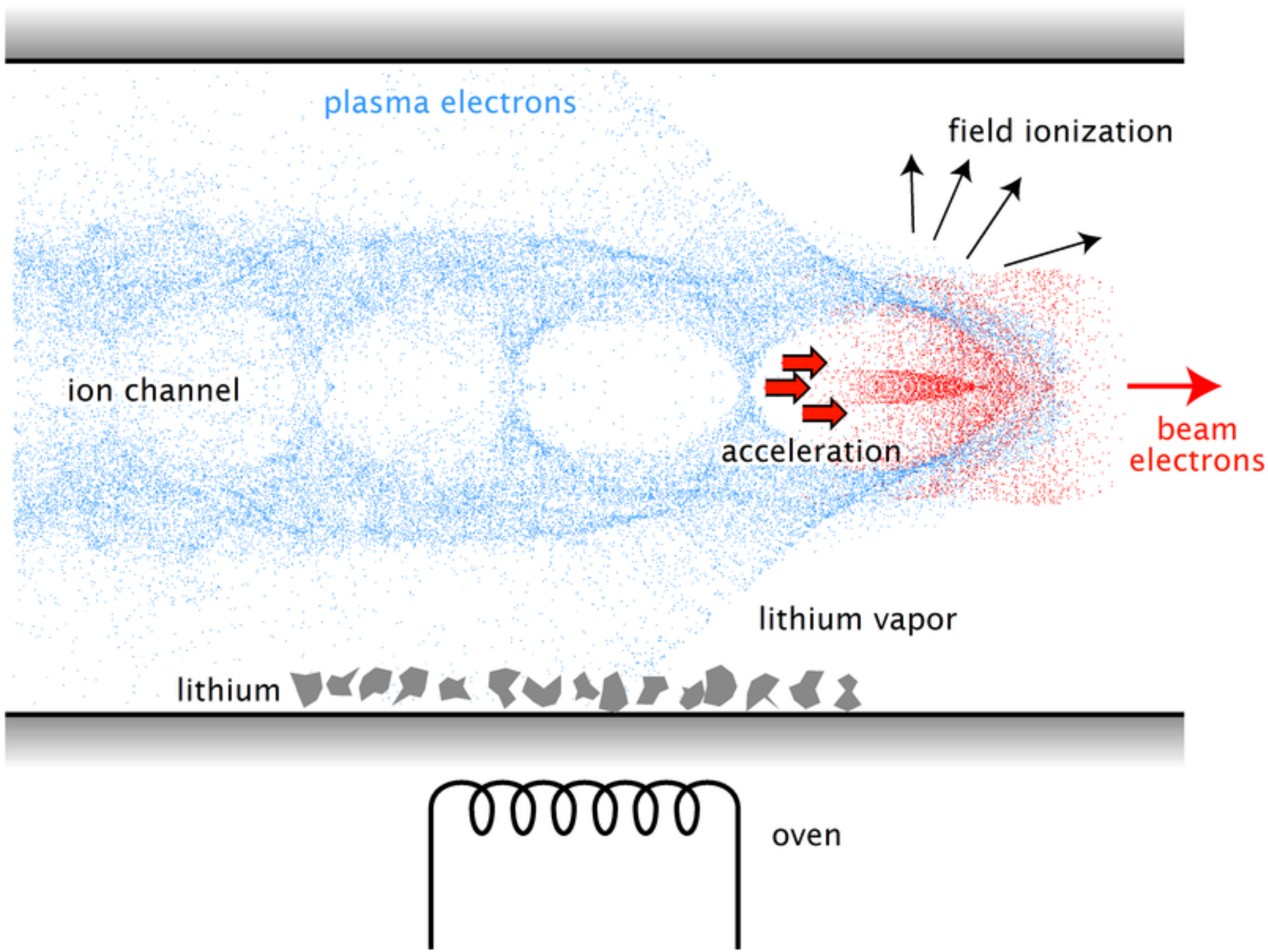


Illustration of the wake created by an electron beam in a plasma. This wake can be used to accelerate charged particles. Author: Rasmus Ischebeck.

Plazma-Demet Etkileşmesinin farklı bölgeleri

- Plazma dalgası altında devinim
  - Demet ölçülerinin plasma deri kalınlığına (c/ω_p) göre değerlerine (hızlandırma; öz-kipleme ve akım liflenmesi kararsızlıkları), AIP Conf. Proc. 1507, 594-599 (2012)
  - Plazma ve sürücü demet elektron yoğunluklarına (doğrusal, doğrusal olmayan), Physics of Plasmas 12, 063101 (2005)

göre değişik bölgelerde kendini gösterir.

> For theory of wakefield generation and other advanced acceleration schemes (terahertz laser and dielectric acceleration):
> This workshop's training session: https://indico.cern.ch/event/489217/

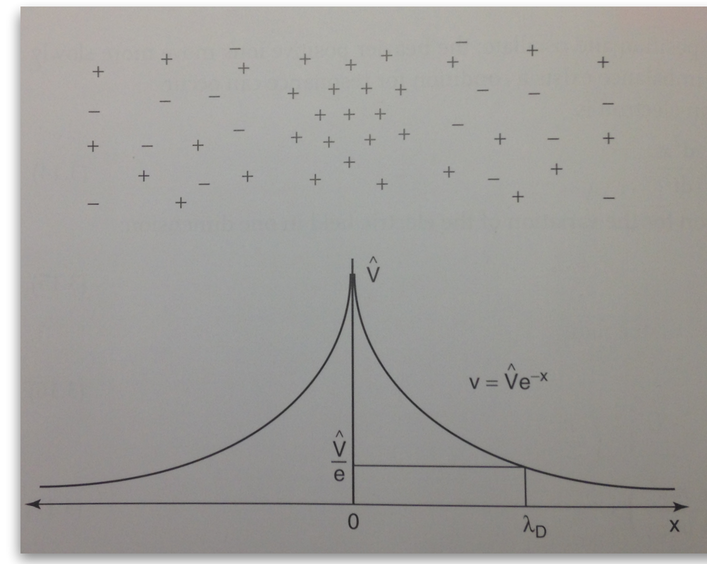
Kolay birimler türünden bazı devinim değişkenleri

- Plazma elektronları denge noktası çevresinde ω_p frekansında salınım yaparlar.

$$\omega_p = \sqrt{\frac{n_p e^2}{\epsilon_0 m}}$$

- Debye uzunluğu

$$\lambda_d = \sqrt{\frac{\epsilon_0 k_b T_e}{n_e e^2}}$$



- Doğrusal kuram için ($n_b > n_p$) elde edilebilecek en yüksek elektrik alan:

$$E = 240(MV/m)(\frac{N}{4\times 10^{10}})(\frac{0.6}{\sigma_z(mm)})^2$$

- Dönüşüm oranı, sürücü demetten tanık demete aktarılabilecek en büyük enerji:

$$R = E_+/E_-$$

Enerji ikiye katlama deneyi

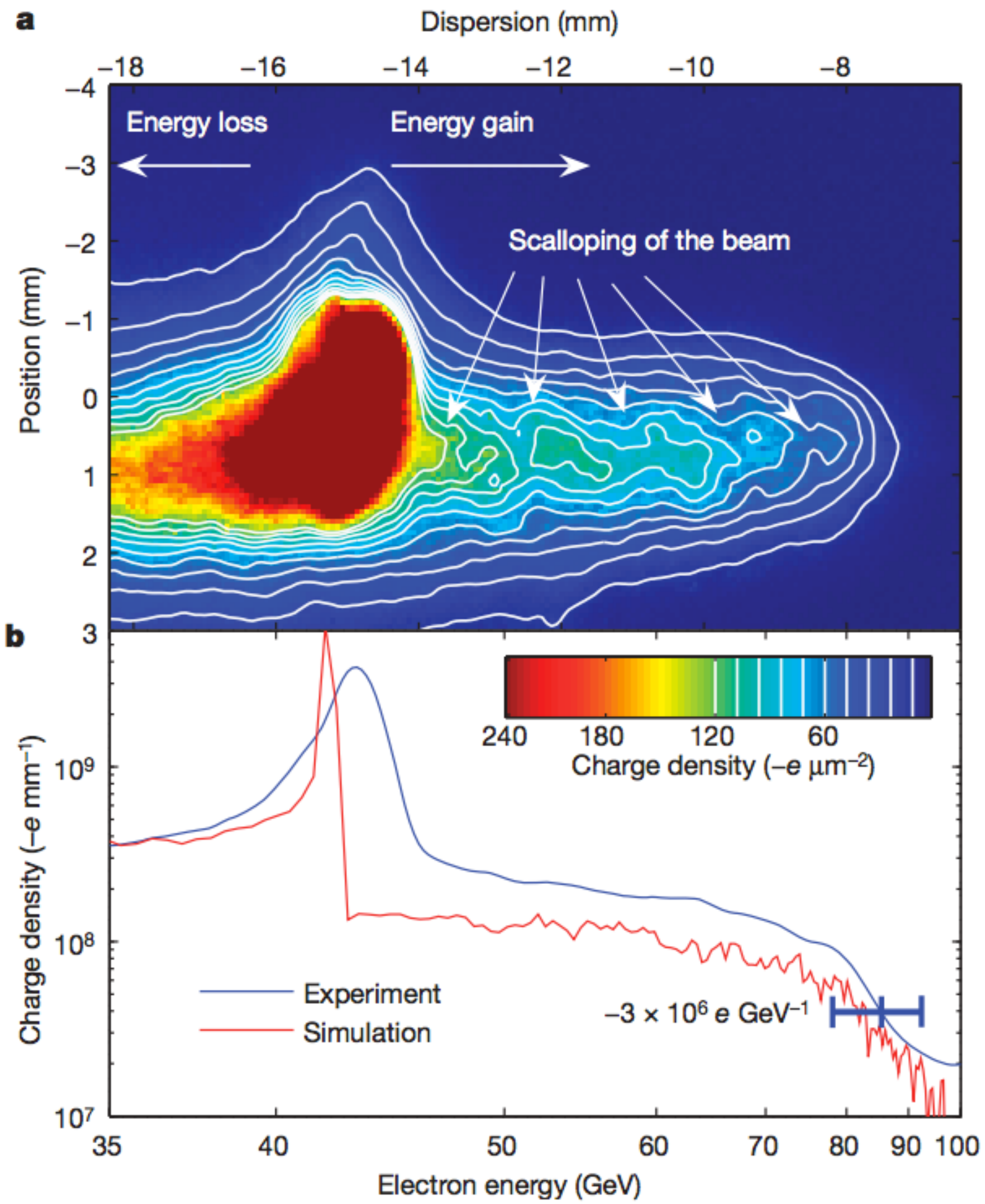


Figure 2 | Energy spectrum of the electrons. a, Energy spectrum of the electrons in the 35–100 GeV range as observed in plane 2. The dispersion (shown on the top axis) is inversely proportional to the particle energy (shown on the bottom axis). The head of the pulse, which is unaffected by the plasma, is at 43 GeV. The core of the pulse, which has lost energy driving the plasma wake, is dispersed partly out of the field of view of the camera. Particles in the back of the bunch, which have reached energies up to 85 GeV, are visible to the right. The pulse envelope exits the plasma with an energy-dependent betatron phase advance, which is consistent with the observed scalloping of the dispersed beam. **b,** Projection of the image in **a**, shown in blue. The simulated energy spectrum is shown in red. The differences between the measured and the simulated spectrum near 42 GeV are due to an initial correlated energy spread of 1.5 GeV not included in the simulations. The horizontal error bar is due to the uncertainty in estimating the deflection angle and the spot size of the beam.

Vol 445 | 15 February 2007 | doi:10.1038/nature05538 nature

LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]

- 2007 yılında Stanford Linear Accelerator Center (SLAC)'da yürütülen elektron sürümlü çalışmalar sonucunda,
- 85 cm uzunluğunda plazma içinde elektron bohçasının kuyruğundaki parçacıkların enerjisi 42 GeV'den 85 GeV'ye çıkarıldı.
- Bu enerji kazanımı açısından SLAC hızlandırıcısının 3 km'de oluşturabileği enerjinin 1 m'nin altında oluşturulması demek!
- Yaklaşık 52 GV/m'lik hızlandırma alanı oluşturuldu!

Benzetim Yazılımları ve Örnek Çalışma

- LCODE (2D, fluid and kinematic models),
- VORPAL (2D, 3D particle-in-cell code),
- EPOCH,
- OSIRIS,
- VPLC,
- WARP,
- QuickPIC
- ...

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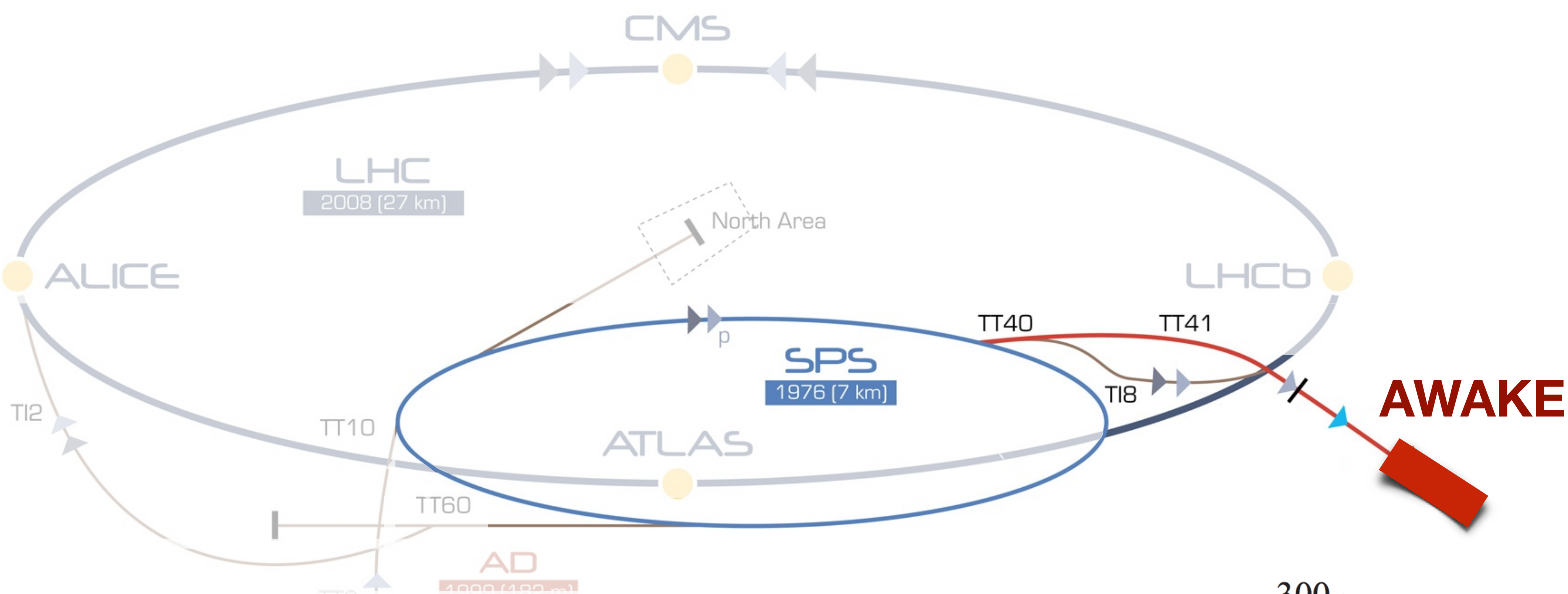
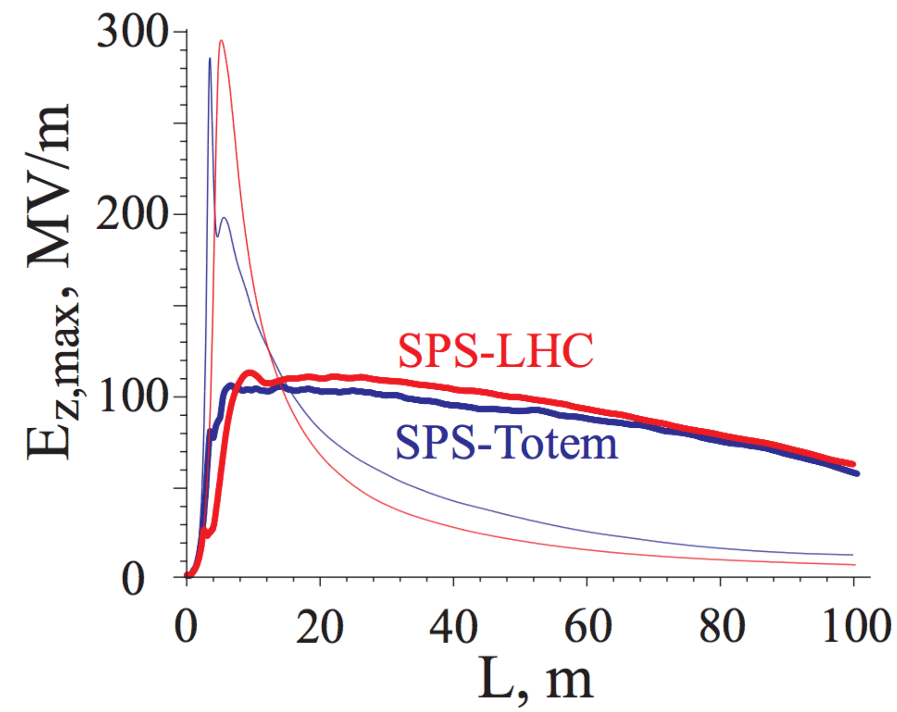
AWAKE Project



AWAKE project, a proton driven plasma wakefield acceleration (PDPWA) experiment is approved by CERN. The PDPWA scheme consists of a seeding laser, a drive beam and a witness beam to be accelerated. The primary goal of this experiment is to demonstrate acceleration of a 16 MeV single bunch electron beam up to 1 GeV in a 10m of plasma.



A. Caldwell, K. V. Lotov, PHYSICS OF PLASMAS 18, 103101 (2011).

Proton sürümlü plasma dalgası ile hızlandırma çalışmaları

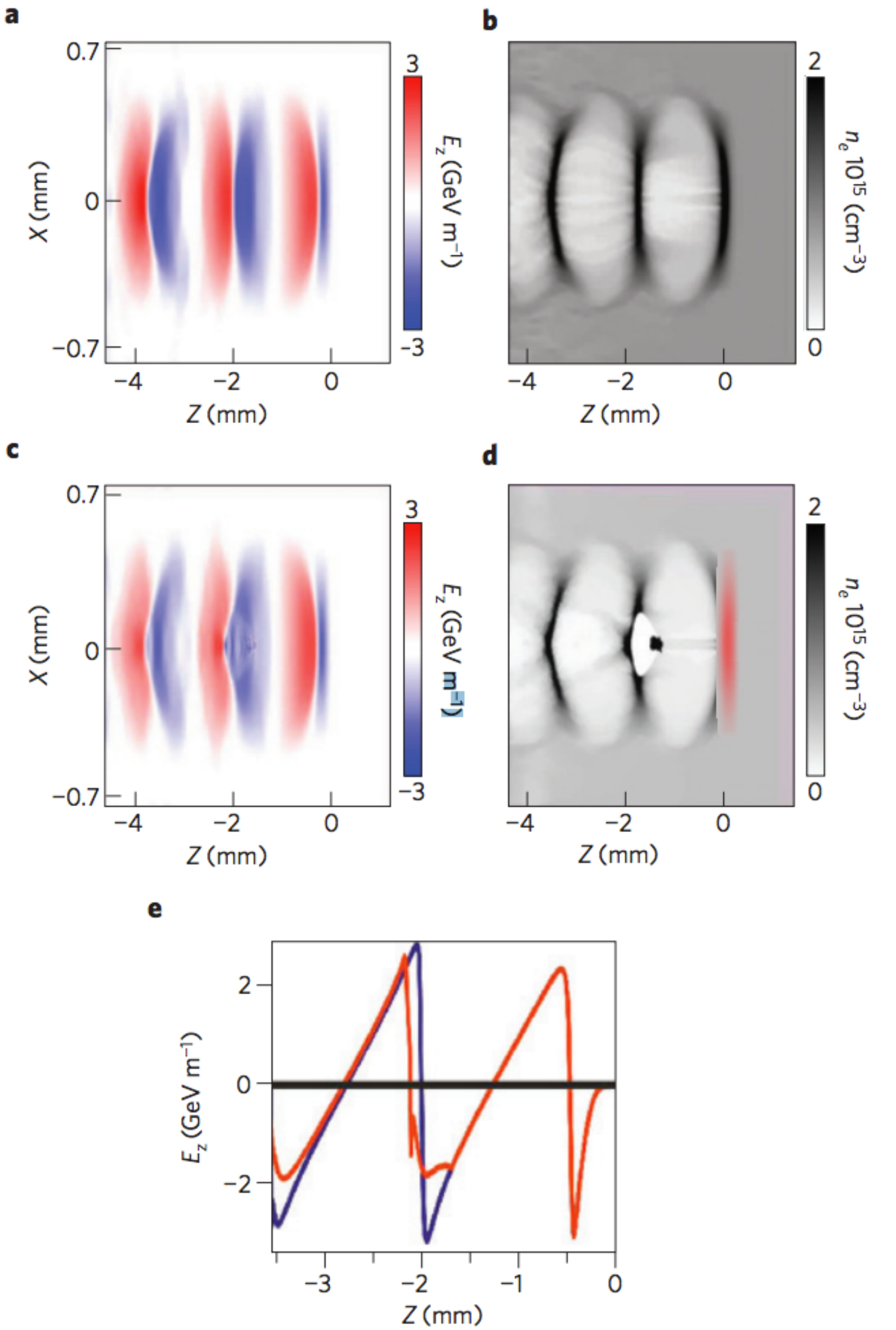


Figure 2 | The electric field strength and the electron density in the plasma. a–d, Simulation results for the unloaded (no witness bunch) case (**a**,**b**) and in the presence of a witness bunch (**c**,**d**). The witness bunch is seen as the black spot in the first wave bucket in **d**. **d** also 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.

nature physics

ARTICLES

PUBLISHED ONLINE: 12 APRIL 2009; CORRECTED ONLINE: 24 APRIL 2009 | DOI: 10.1038/NPHYS1248

Proton-driven plasma-wakefield acceleration

Allen Caldwell[1]*, Konstantin Lotov[2,3], Alexander Pukhov[4] and Frank Simon[1,5]

Plasmas excited by laser beams or bunches of relativistic electrons have been used to produce electric fields of 10–100 GV m^{-1}. This has opened up the possibility of building compact particle accelerators at the gigaelectronvolt scale. However, it is not obvious how to scale these approaches to the energy frontier of particle physics—the teraelectronvolt regime. Here, we introduce the possibility of proton-bunch-driven plasma-wakefield acceleration, and demonstrate through numerical simulations that this energy regime could be reached in a single accelerating stage.

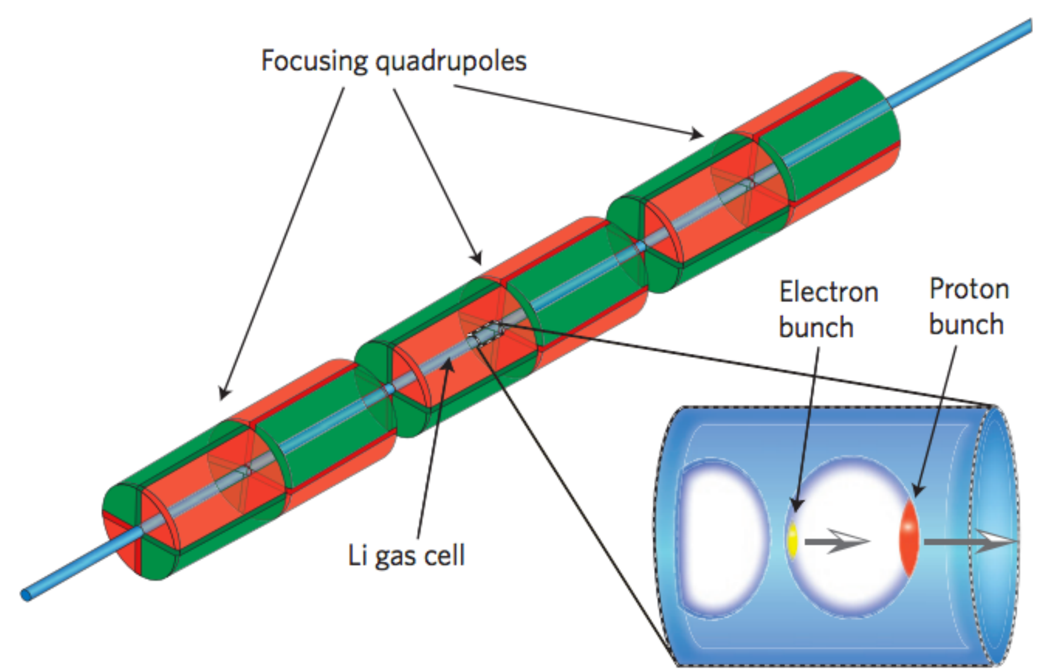
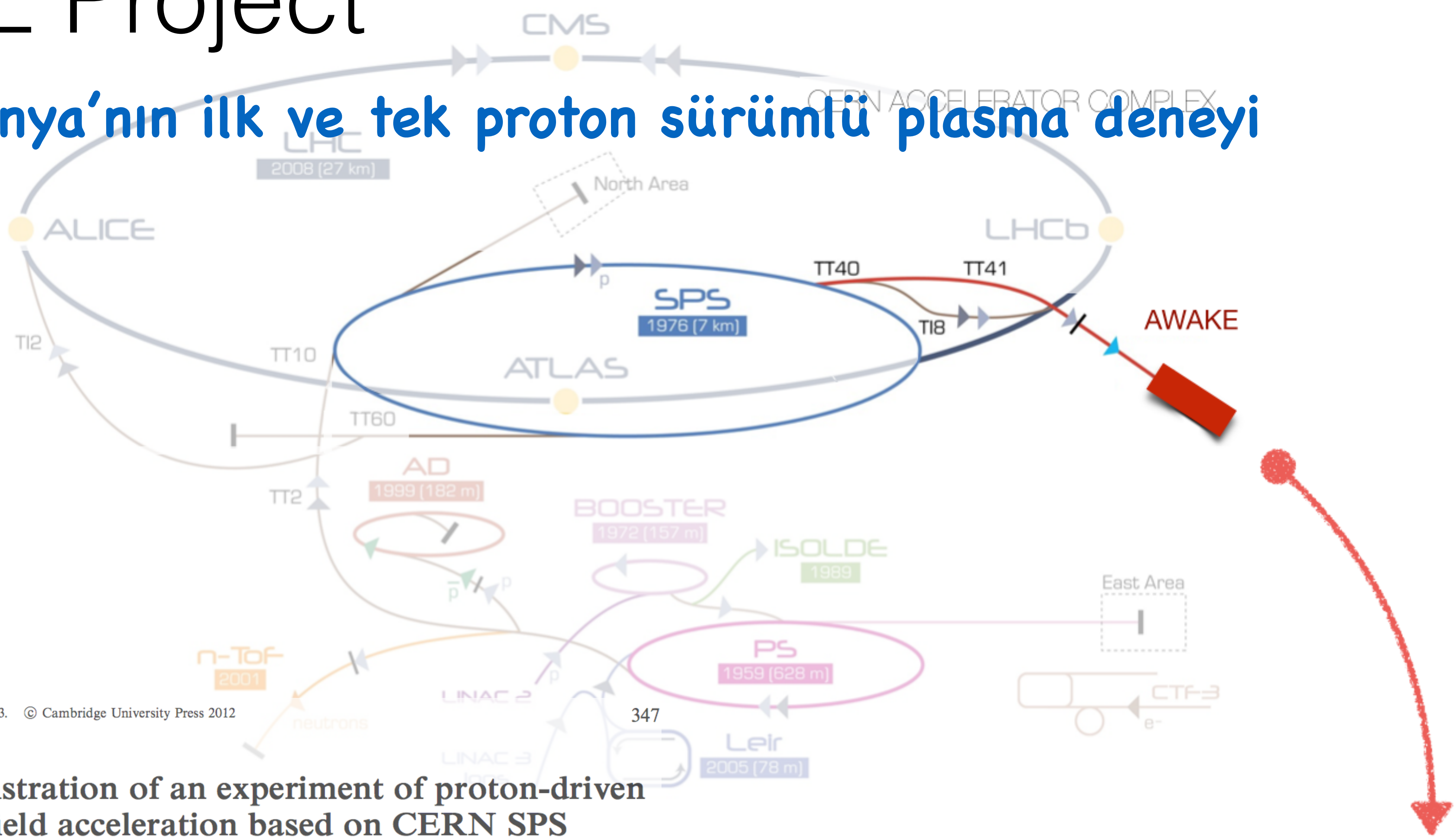


Figure 1 | A schematic description of a section of the plasma-wakefield-accelerating structure. A thin tube containing Li gas is surrounded by quadrupole magnets with alternating polarity. The magnification shows the plasma bubble created by the proton bunch (red). The electron bunch (yellow) undergoing acceleration is located at the back of the bubble. Note that the dimensions are not to scale.

AWAKE Project

AWAKE, Dünya'nın ilk ve tek proton sürümlü plasma deneyi



J. Plasma Physics (2012), *vol.* 78, *part* 4, *pp.* 347–353. © Cambridge University Press 2012
doi:10.1017/S0022377812000086 347

A proposed demonstration of an experiment of proton-driven plasma wakefield acceleration based on CERN SPS

G. XIA[1], R. ASSMANN[2], R. A. FONSECA[3], C. HUANG[4], W. MORI[5], L. O. SILVA[3], J. VIEIRA[3], F. ZIMMERMANN[2] and P. MUGGLI[1]
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[1]Max Planck Institute for Physics, Munich, Germany
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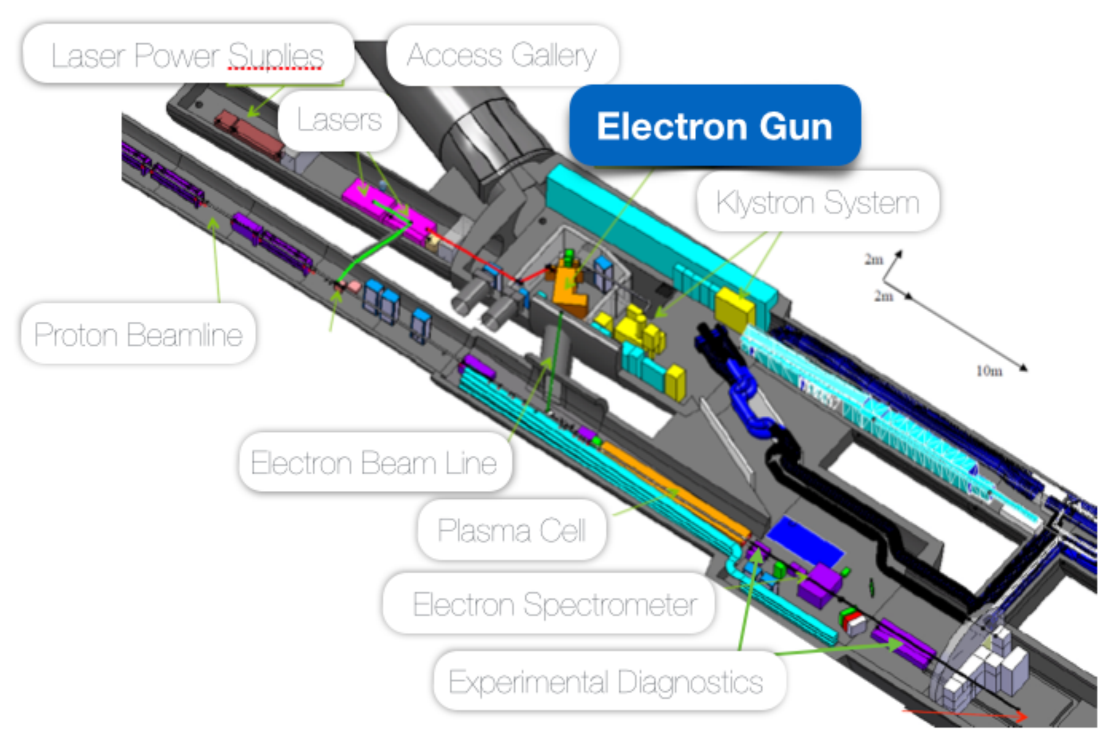
[2]CERN, Geneva, Switzerland
[3]GoLP/Instituto de Plasmas e Fusao Nuclear-Laboratório Associado, IST, Lisboa, Portugal
[4]Los Alamos National Laboratory, Los Alamos, NM, USA
[5]University of California, Los Angeles, CA, USA

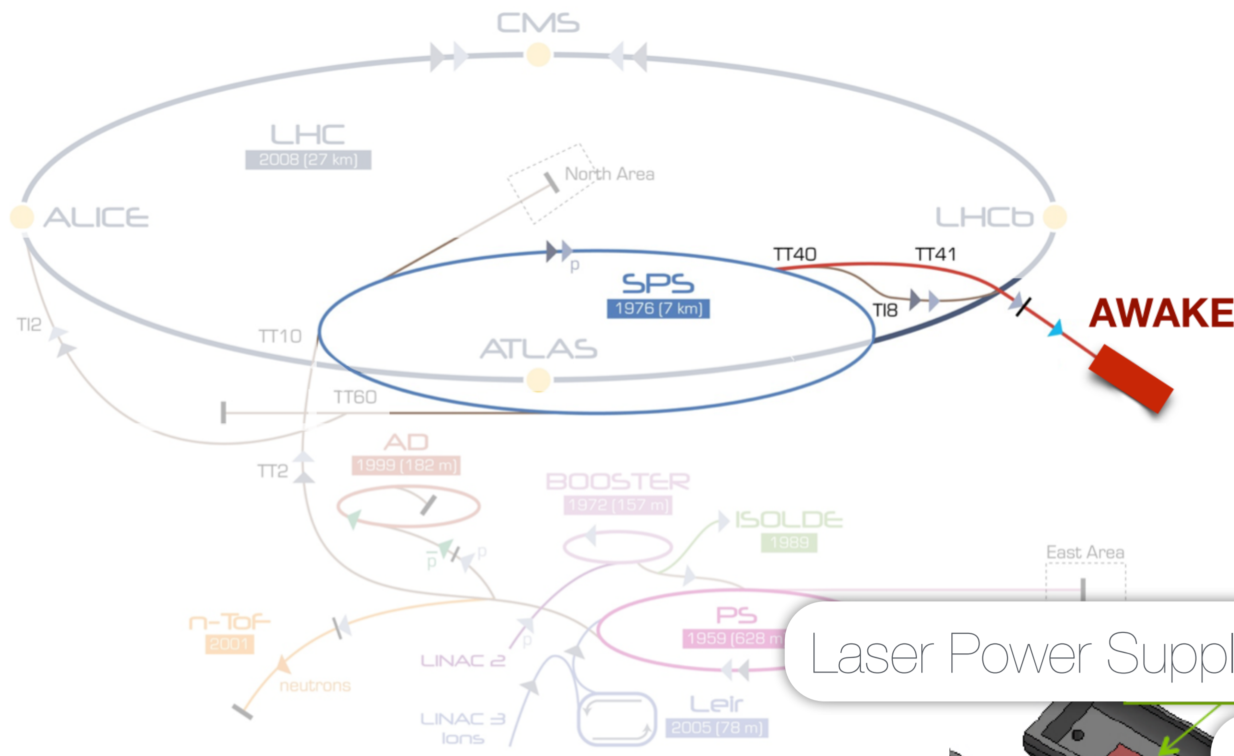
(Received 20 September 2011; accepted 2 January 2012; first published online 7 February 2012)



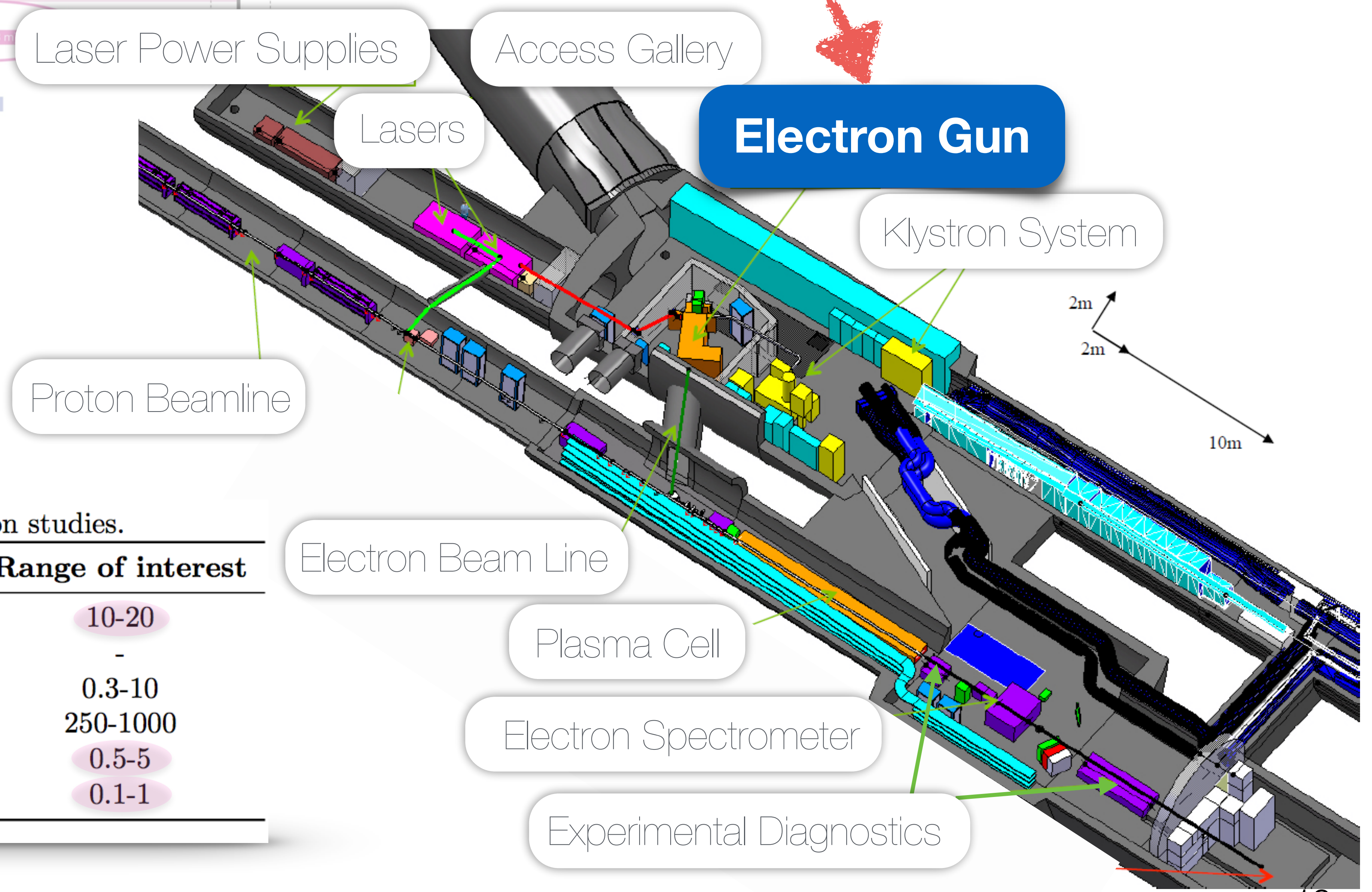
AWAKE Design Report
A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN
CERN-SPSC-2013-013 ; SPSC-TDR-003

Dr O. Mete Apsimon

AWAKE Project



Production of a Witness Beam



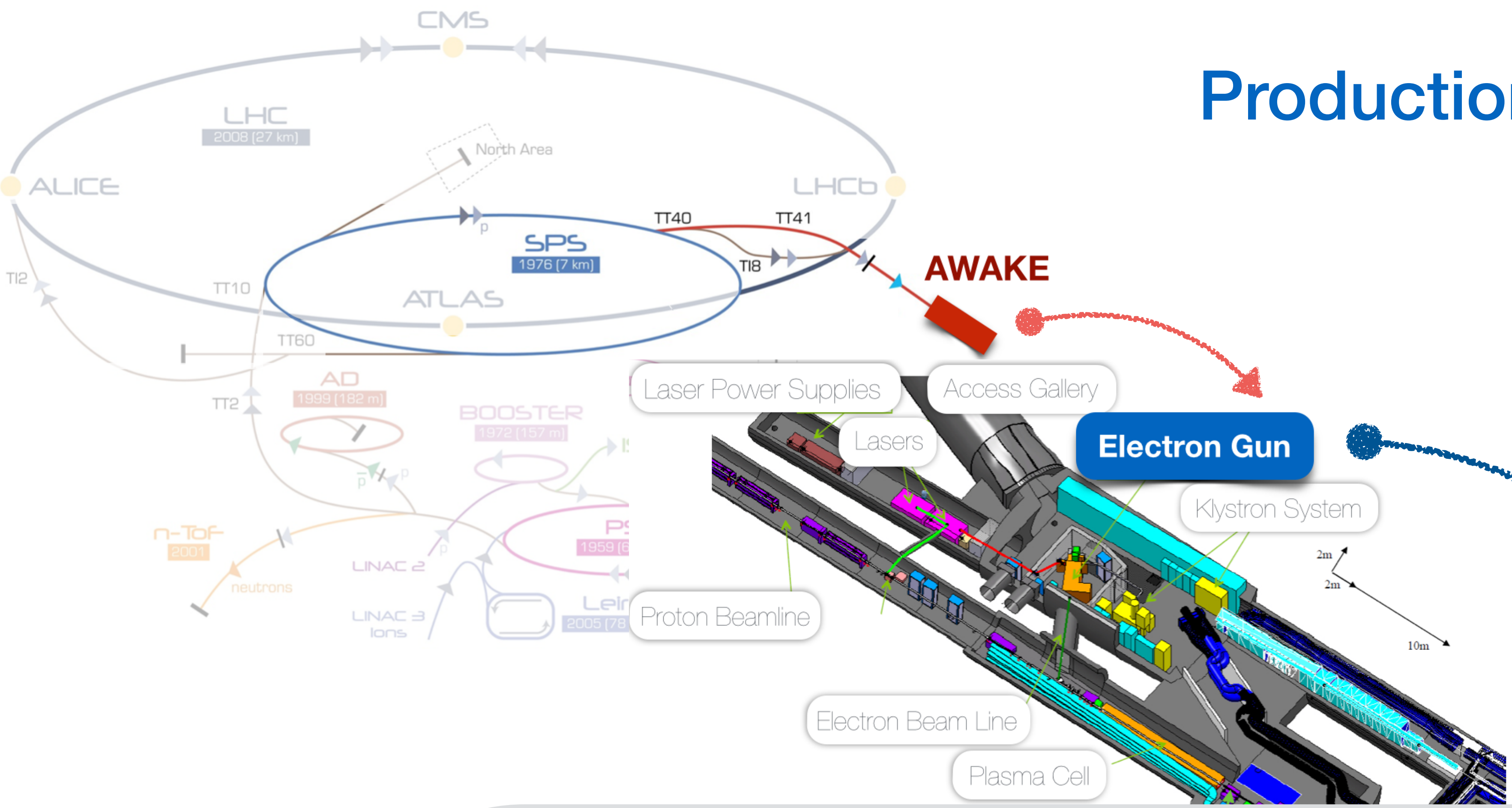
Baseline specifications for AWAKE e⁻ beam.

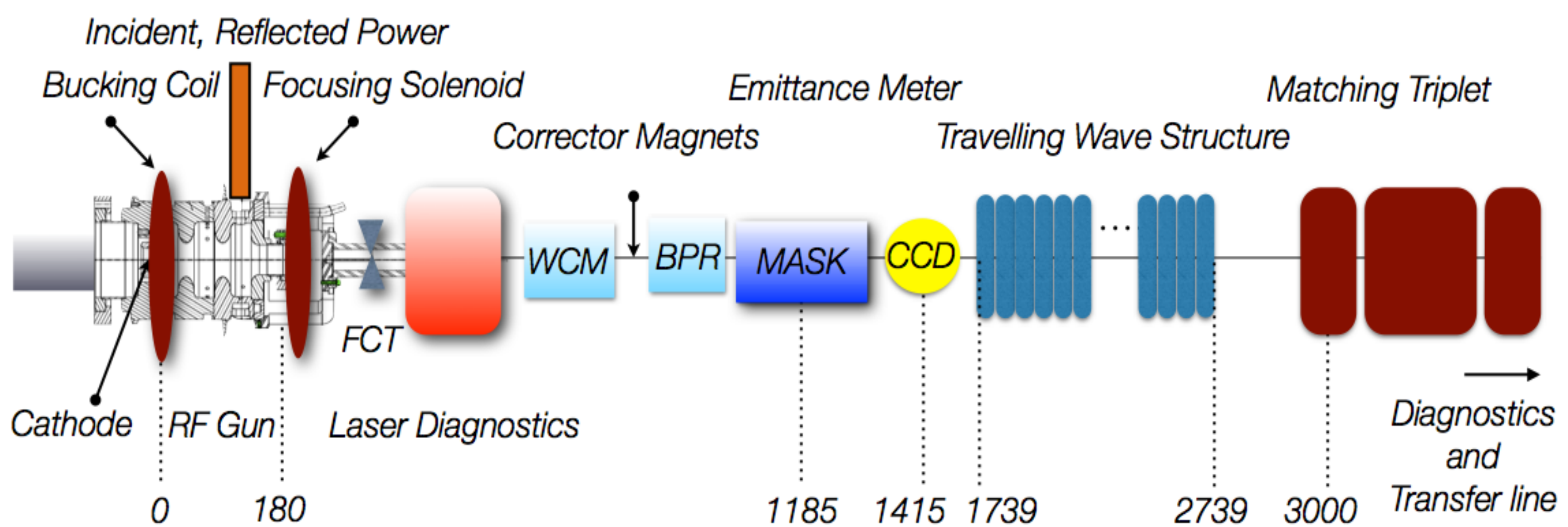
Table 1: Specifications for the simulation studies.

Parameter	Baseline	Range of interest
Beam energy (MeV)	16	10-20
Energy spread (σ, %)	0.5	-
Bunch length, (σ, ps)	4	0.3-10
Beam focus size, (σ, μm)	250	250-1000
Norm. emittance (rms, mm-mrad)	2	0.5-5
Bunch charge, (nC)	0.2	0.1-1

AWAKE Project

Production of a Witness Beam





The Cockcroft Institute of Accelerator Science

Alternative to External Injection

Preserved on the seafront at Çanakkale, Turkey after the film Troy (2004).

Beyond Injection: Trojan Horse Underdense Photocathode Plasma Wakefield Acceleration

B. Hidding[*,†], J.B. Rosenzweig[†], Y. Xi[†], B. O'Shea[†], G. Andonian[†], D. Schiller[†], S. Barber[†], O. Williams[†], G. Pretzler[*], T. Königstein[*], F. Kleeschulte[*], M. J. Hogan[**], M. Litos[**], S. Corde[**], W. W. White[**], P. Muggli[‡], D.L. Bruhwiler[§,¶] and K. Lotov[||,††]

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[†] *Particle Beam Physics Laboratory, Department for Physics and Astronomy, UCLA, USA*
[**] *Stanford Linear Accelerator Center, USA*
[‡] *Max-Planck-Institut für Physik, München, Germany*
[§] *Tech-X Corporation, Boulder, Colorado, USA*
[¶] *Present address: 1348 Redwood Ave., Boulder, Colorado 80304, USA; email: bruhwile@gmail.com*
[||] *Budker Institute of Nuclear Physics SB RAS, 630090, Novosibirsk, Russia*
[††] *Novosibirsk State University, 630090, Novosibirsk, Russia*

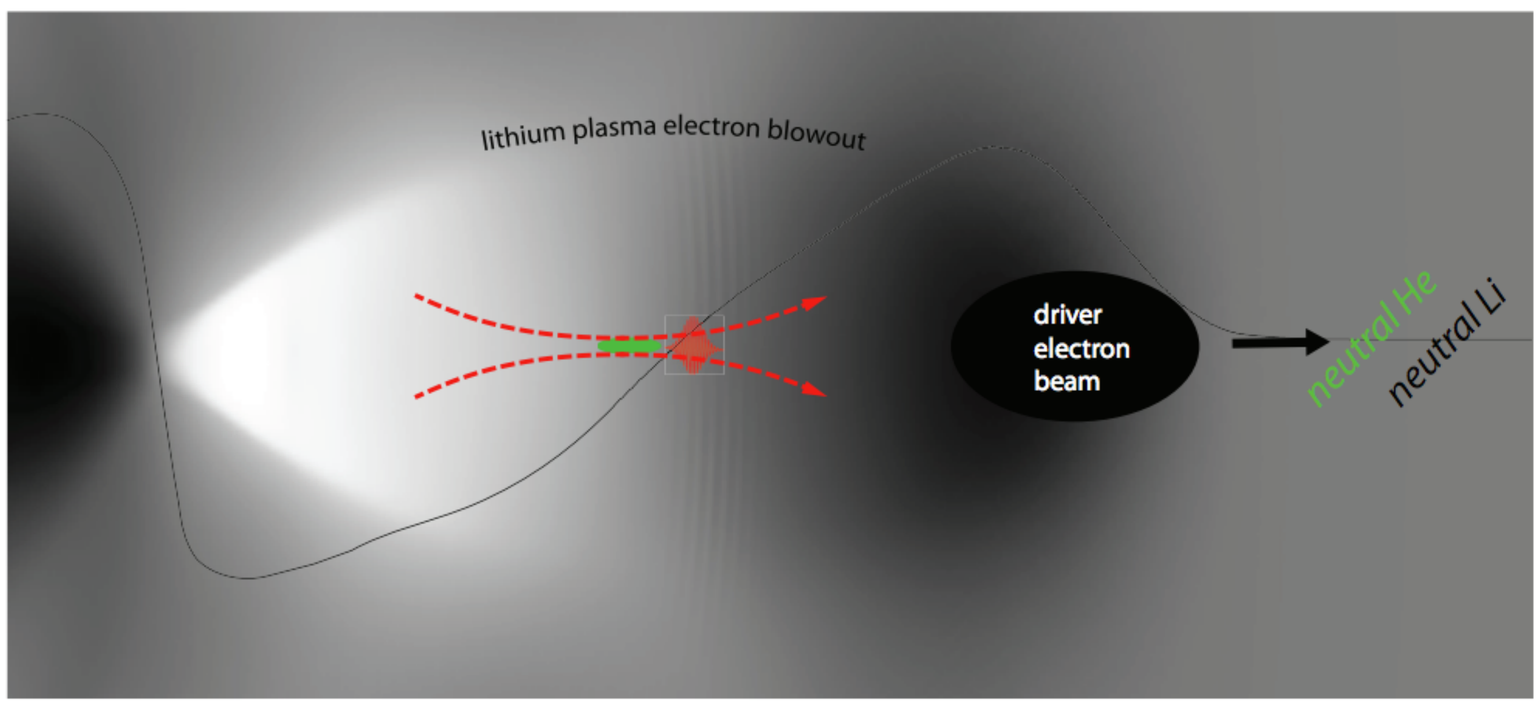

FIGURE 1. The electron bunch driver ionizes the low-ionization threshold (LIT) component lithium and drives a Li-based blowout, but does not ionize the higher-ionization-threshold (HIT) component helium, which remains neutral during passage of the electron bunch driver. The synchronized, subsequent laser pulse, however, ionizes electrons (green) in its focus and thus produces electrons directly within the plasma blowout.

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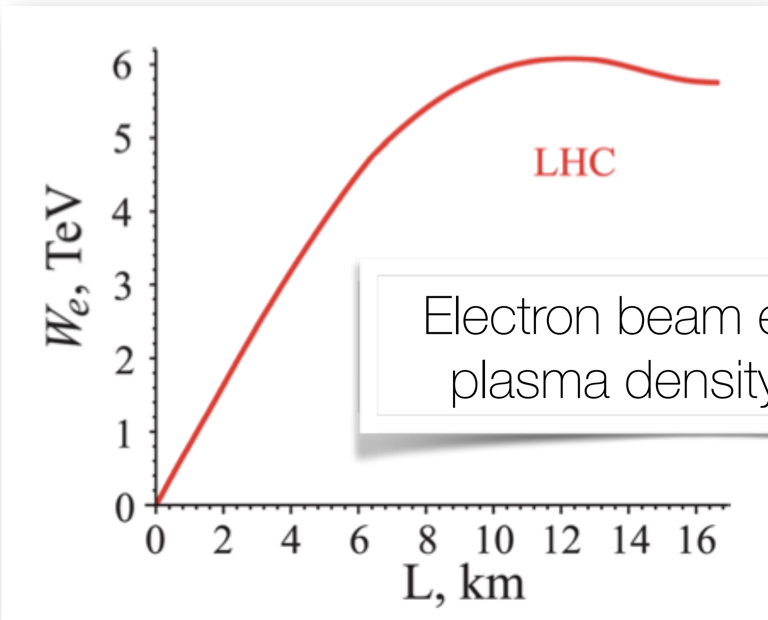
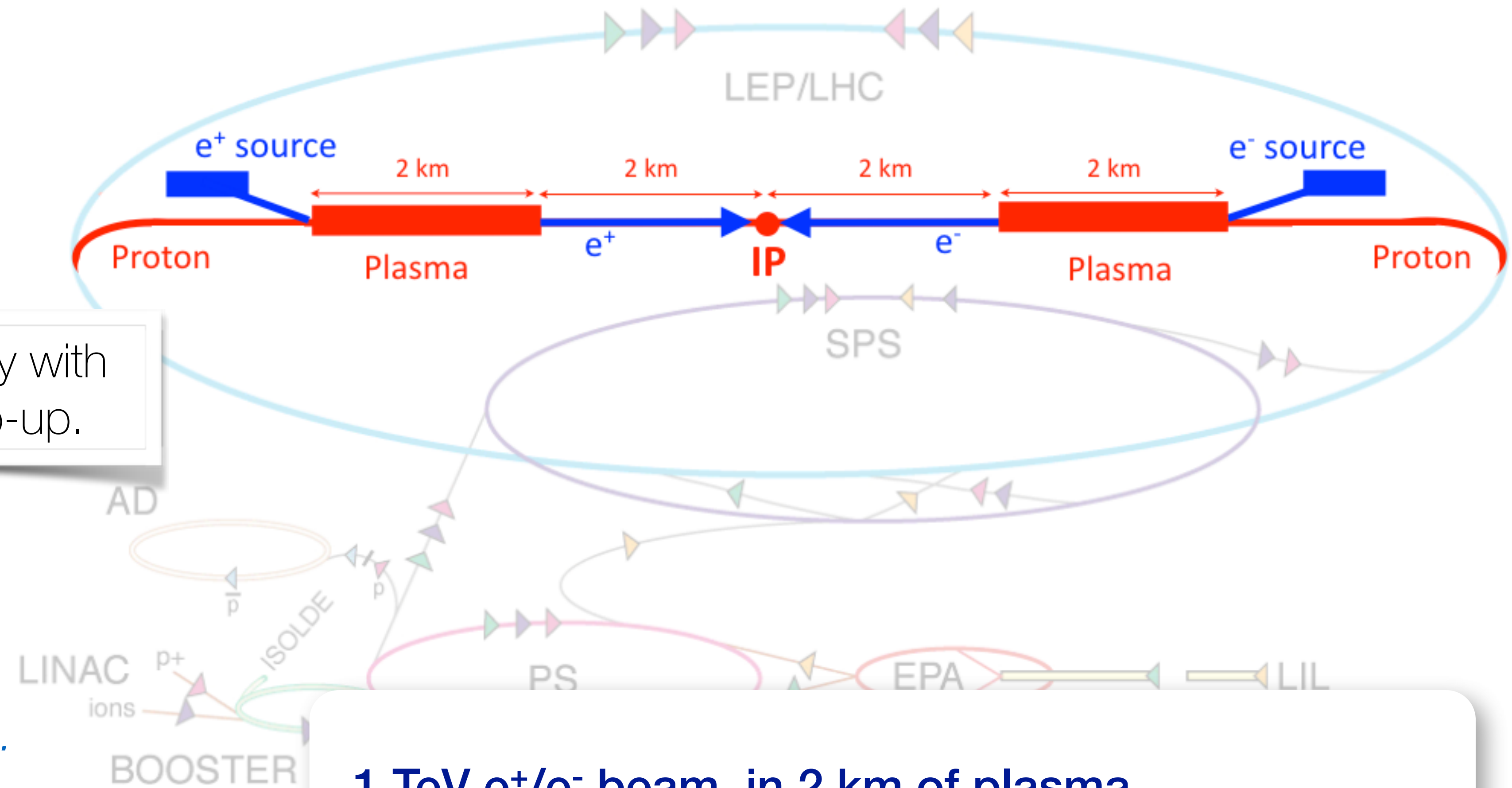
Towards the Future

An electron-positron collider



Electron beam energy with plasma density step-up.

A. Caldwell, K. V. Lotov, PHYSICS OF PLASMAS 18, 103101 (2011).



For this PDPWA-based e^+e^- collider design, half of the LHC bunches (1404 bunches) are used for driving electron acceleration and the other half for positron acceleration. Taking into account that the ramping time of the LHC is about 20 min and assuming that the loaded electron (and positron) beams have a bunch charge of 10% of the drive proton bunch, i.e. electron (and positron) bunch charge of $N_e = 1.15 \times 10^{10}$, and the beam spot sizes at IP are the same as that of the CLIC beam, as shown in Table 1, the resulting luminosity for such an e^+e^- linear collider is about $3.0 \times 10^{31}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is about three orders of magnitude lower than that of the ILC or the CLIC.

G. Xia, O. Mete et al., NIMA Volume 740, 11 March 2014, 173–179

1 TeV e^+/e^- beam in 2 km of plasma

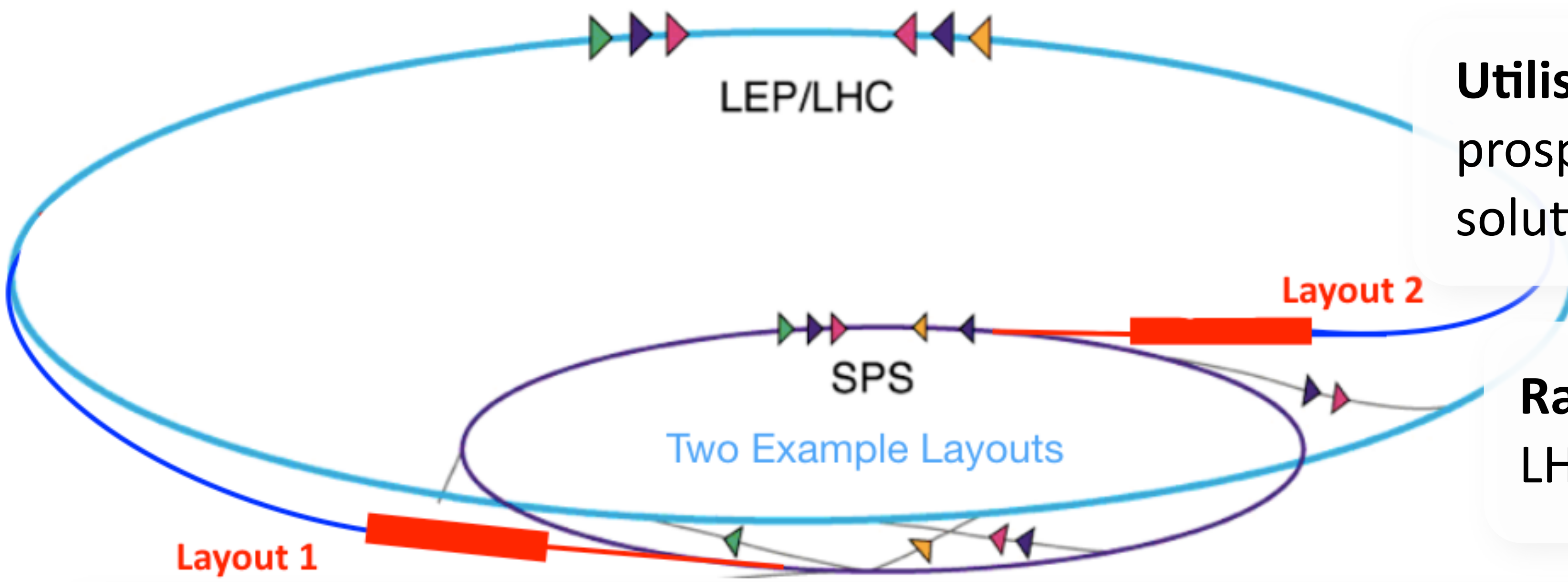
- Via plasma step up and self modulation instability.

LHC radius, 4.3 km

- Transfer and matching of protons&plasma.
- Dedicated e^- source
- 2 km plasma section (0.5 GeV m^{-1}).
- 2 km beam delivery and final focusing section.
- “Used” protons to be extracted, dumped or may be recycled.

Towards the Future

An electron-proton collider



Utilisation of existing CERN infrastructure
prospects of a cheaper and more compact solution than LHeC.

Ramping times
LHC ➟ 20 mins, LHC pre-injectors ➟ 2 s.

SPS protons can excite the plasma
PIC simulations: 1 GV m^{-1} ➟ accelerates e^- beam up to 100 GeV in 170 m of plasma.

Parasitic e^-p collisions*
establish collisions between 100 GeV e^- beam and 7 TeV LHC protons.
*LHC collisions can continue in parallel

of the linac. Using the LHC beam parameters, for example, $N_p = 1.15 \times 10^{11}$, $\gamma_p = 7460$, $\beta_p^* = 0.1$ m, $\epsilon_p^N = 3.5$ μm and assuming the electron beam parameters as follows: $Ne = 1.15 \times 10^{10}$ (10% of the loaded drive bunch charge), $E_e = 100$ GeV, $n_b = 288$ and $f_{rep} \approx 15$, the calculated luminosity of the electron proton collider is about 1×10^{30} cm^{-2} s^{-1} for this design, which is about three to

G. Xia, O. Mete et al.,
NIMA Volume 740, 11 March 2014, 173–179

Issues of **Proton Driven** Plasma Wakefield Acceleration

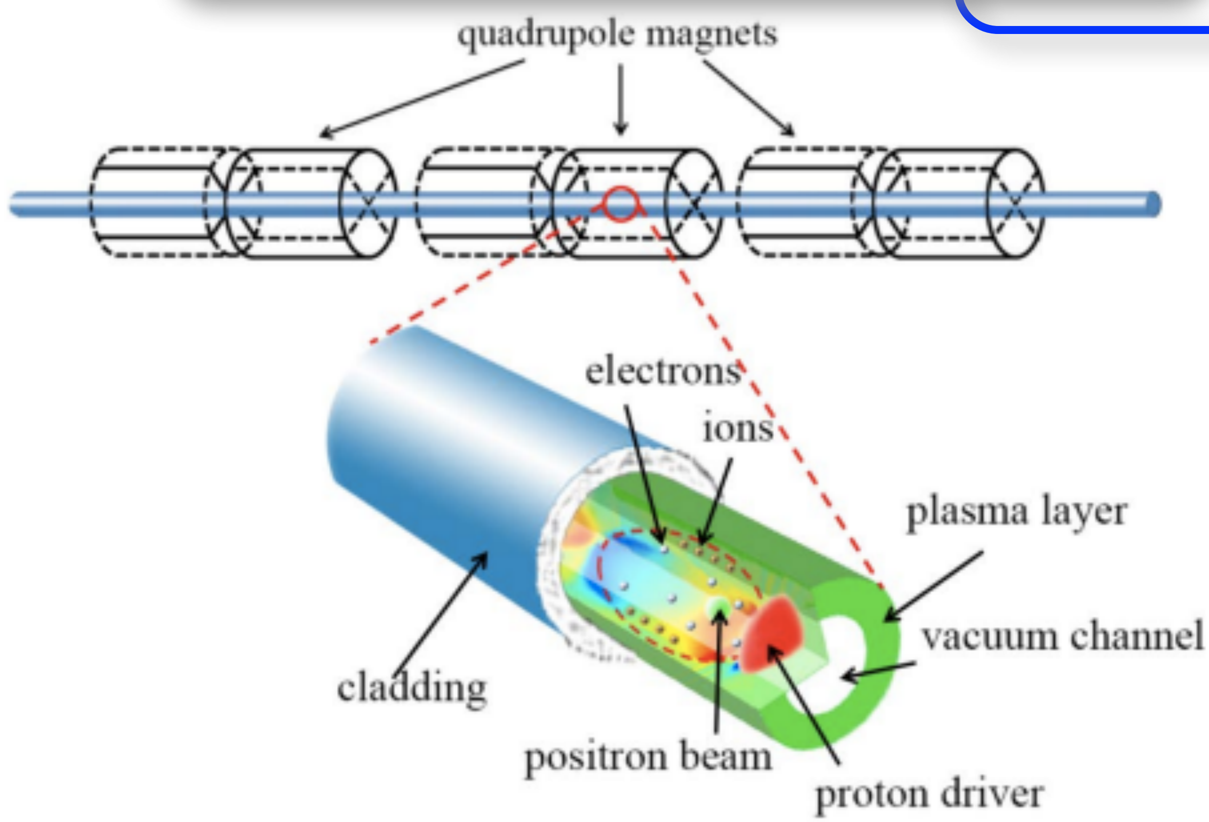
- Phase slippage
- Interaction of “driver” beam with plasma
- Interaction of “witness” beam with plasma
- Positron acceleration (in case of e^-p collider)

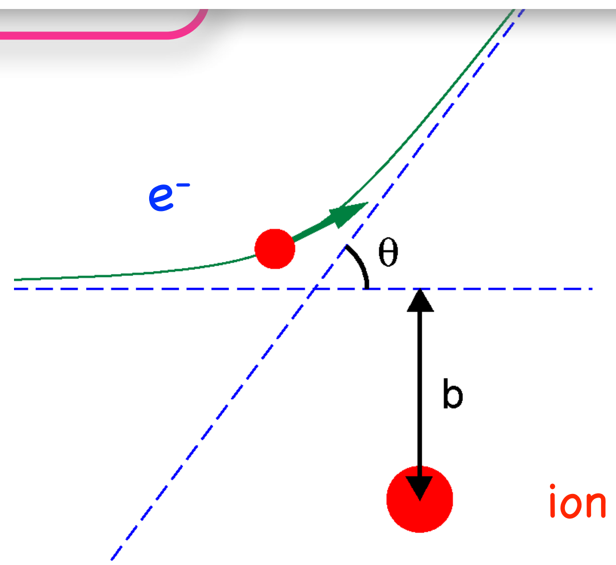
Group velocity of wakefields is the same as the velocity of the driver, protons. **Electrons may overrun the wakefields - no acceleration.**

Bunch lengthening due to energy spread and **focusing** issues of protons.

Production of accelerating field by using a **hollow plasma** for positron acceleration.

Electron beam scattering by plasma electrons and ions - **luminosity degradation through emittance growth**





PHASE SLIPPAGE (DEPHASING)

Key Issues in Collider Design

$$\delta \leq \pi$$

LHC

$$\delta = k_p \Delta s \approx \frac{1}{eE_{acc}/m_e c\omega_p}(\gamma_{ef} - \gamma_{e0})\left[1 - \frac{(\gamma_{if} - \gamma_{i0})}{\left(\sqrt{\gamma_{if}^2 - 1} - \sqrt{\gamma_{i0}^2 - 1}\right)}\right]$$

otherwise the electrons will overrun the protons.

For a single stage PDPWA based e^+e^- collider design, a 7 TeV LHC proton beam will excite plasma wakefields and accelerate electron bunches to 1 TeV (assuming electron injection energy of 10 GeV which is far less than 1 TeV), $\gamma_{i0} \approx 7000$, $\gamma_{ef} - \gamma_{e0} \approx 2 \times 10^6$. If we assume that the amplitude of wakefields is $eE_{acc}/m_e c\omega_p \sim 1$, then the phase slippage is

$$k_p \Delta s = 2 \times 10^6 \left[1 - (\gamma_{if} - 7000)/(\sqrt{\gamma_{if}^2 - 1} - \sqrt{7000^2 - 1})\right]$$

The calculation shows that the phase slippage length (or maximum acceleration length) is about ~ 4 km assuming the plasma density of 10^{15} cm^{-3} for a final proton beam energy of around 1 TeV. Therefore a 2 km acceleration channel meets the phase slippage requirement for an e^+e^- collider design.

SPS

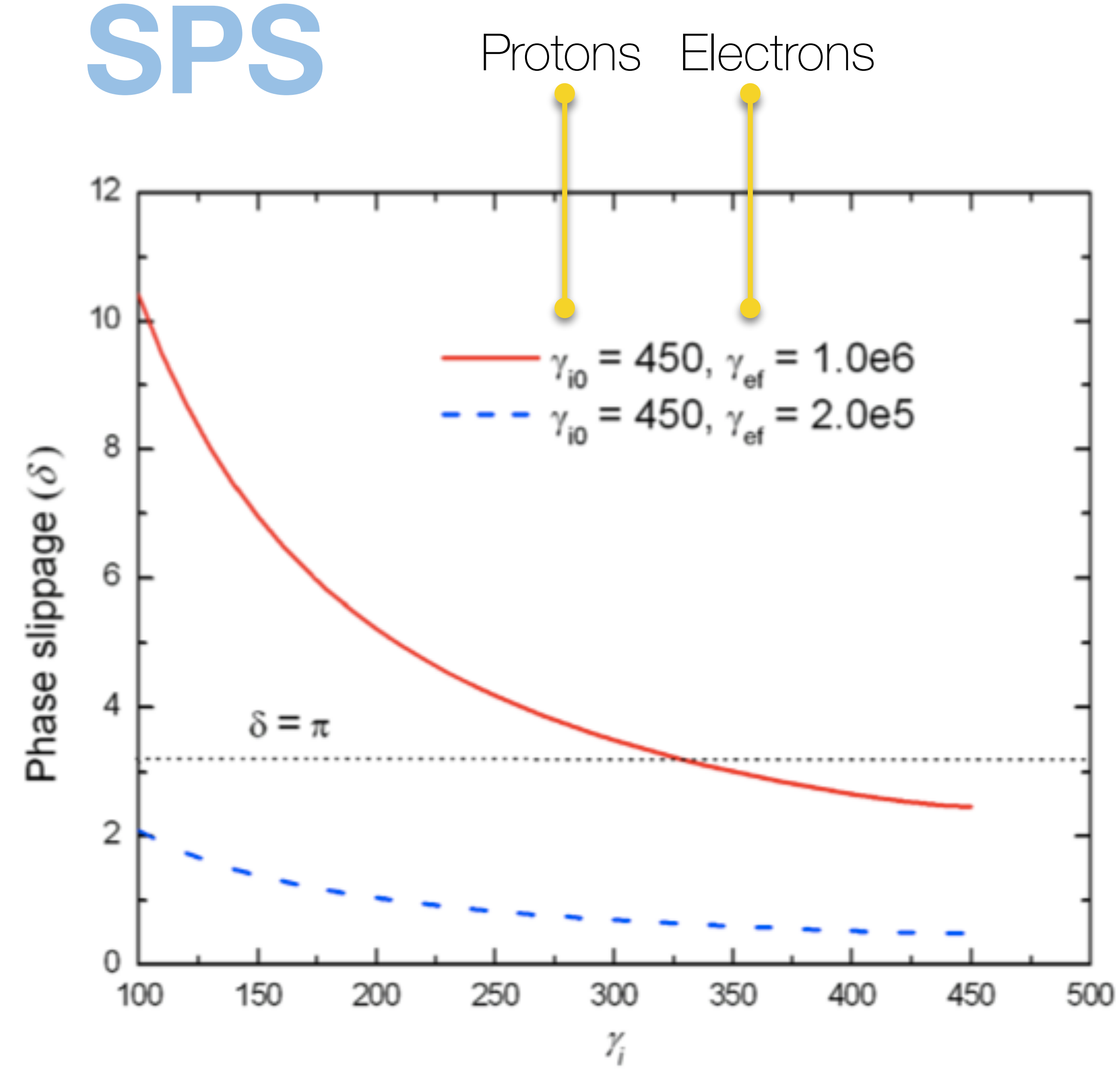


Fig. 2. Phase slippage between the SPS proton beam and the electron beam as a function of γ_i of the proton driven beam for a single 500 GeV stage and 100 GeV stage electron beam production.

G. Xia, O. Mete et al., NIMA Volume 740, 11 March 2014, 173–179

PROTON PROPAGATION IN THE PLASMA

Key Issues in Collider Design

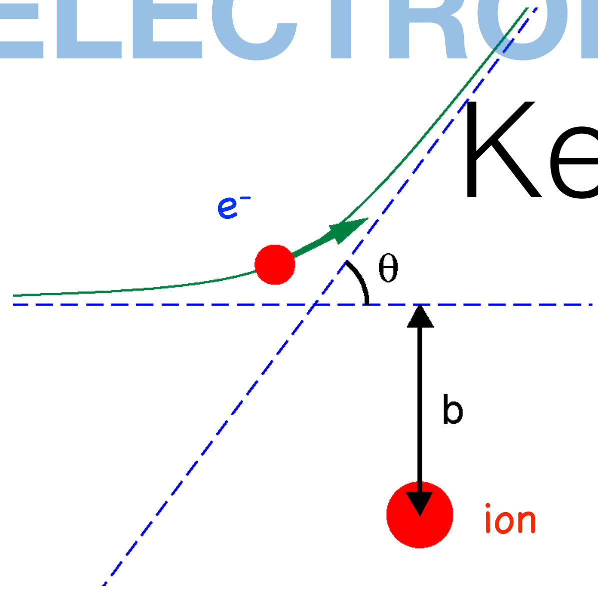
Assume a gradient of 1 GeV/m: e^+/e^- acceleration ➟ several hundred - few thousand meters,

- **Issue I:** guiding of the drive beam over such long distances,
  - Focusing: external by quads, transverse plasma wakefields.
- **Issue II:** Moreover, drive bunch lengthening due to finite momentum spread,
  - 7 TeV LHC beam, $\Delta p/p = 10^{-4}$ spread leads to 0.01 μm/m,
  - Initial LHC bunch length 7.55 cm >> 20 μm after 2 km of travel in plasma - negligible!
  - Lengthening should be carefully considered for the self modulation regime.

$$\Delta d \approx \frac{L}{2\Delta\gamma^2} \approx \frac{\Delta p}{p}\frac{m_p^2 c^4}{p^2 c^2} L$$

ELECTRON-PLASMA INTERACTIONS

Key Issues in Collider Design



$$\frac{d\sigma}{d\Omega} \approx (\frac{2Zr_0}{\gamma})^2 \frac{1}{(\theta^2 + \theta^2_{min})^2}$$

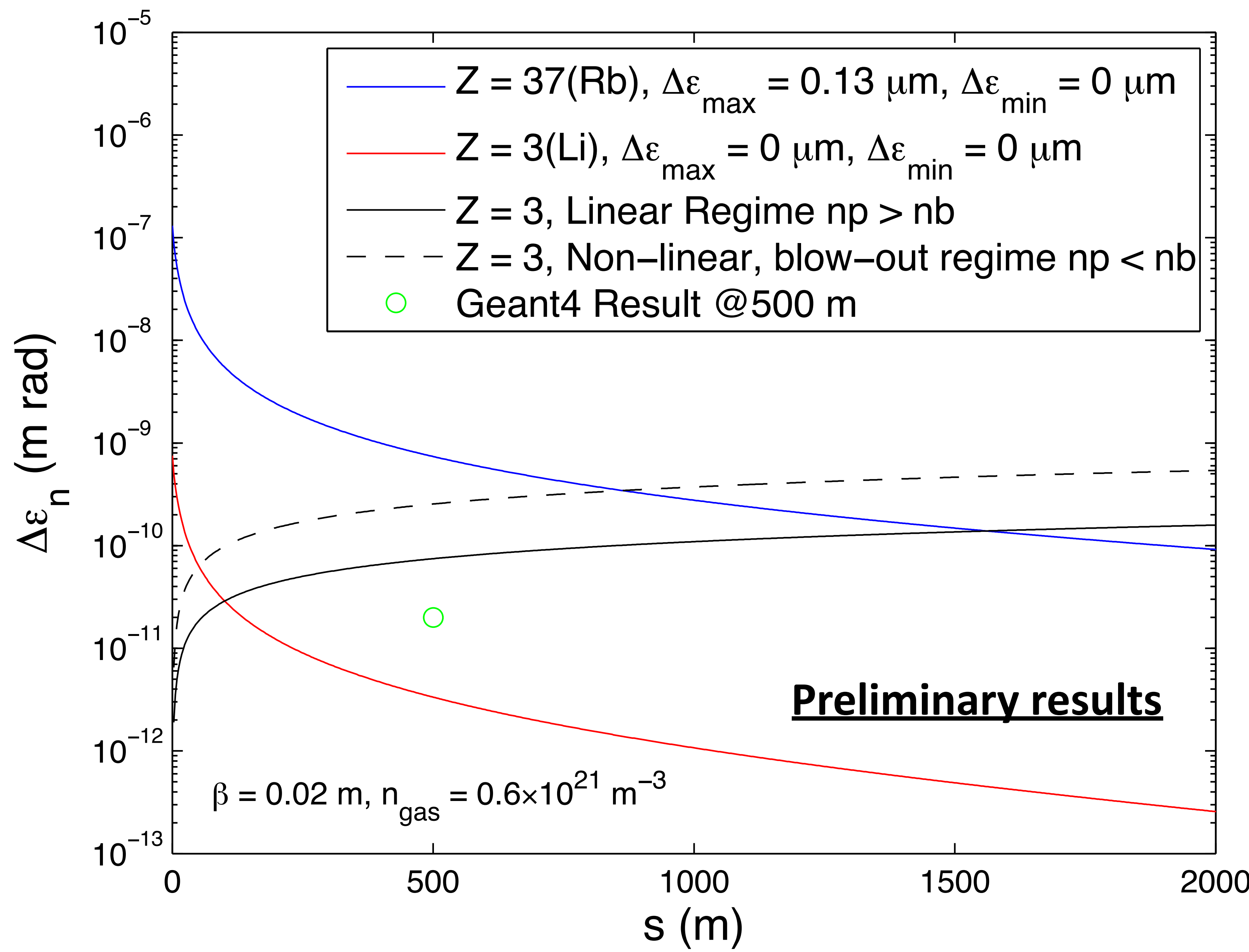
Coulomb scattering cross section.

$$\Delta\epsilon_{n,x,y} = \frac{\gamma\beta_{x,y}}{2}\overline{\mathcal{N}\langle\theta^2_{x,y}\rangle}$$

Diffusion equation representing the emittance growth.

- Elastic/inelastic scattering of the witness particles,
  - by plasma ions -- assumed stationary,
  - by plasma electrons (insignificant in the blow-out regime?) -- mobile.

- Black ➟ estimations modified from the model[1] for beam-gas scattering in a damping ring,
- Blue, red ➟ preliminary model,
- Green ➟ Geant4 result[2],
- ***Realistic model development and GEANT4 simulations in progress.***



[1] *T.O. Raubenheimer, (Ph.D. thesis), SLAC-387, 1991.* [2] *A. Caldwell et al, Nature Physics 5, 363 (2009).*

Key Issues in Collider Design

Tracking Scenario

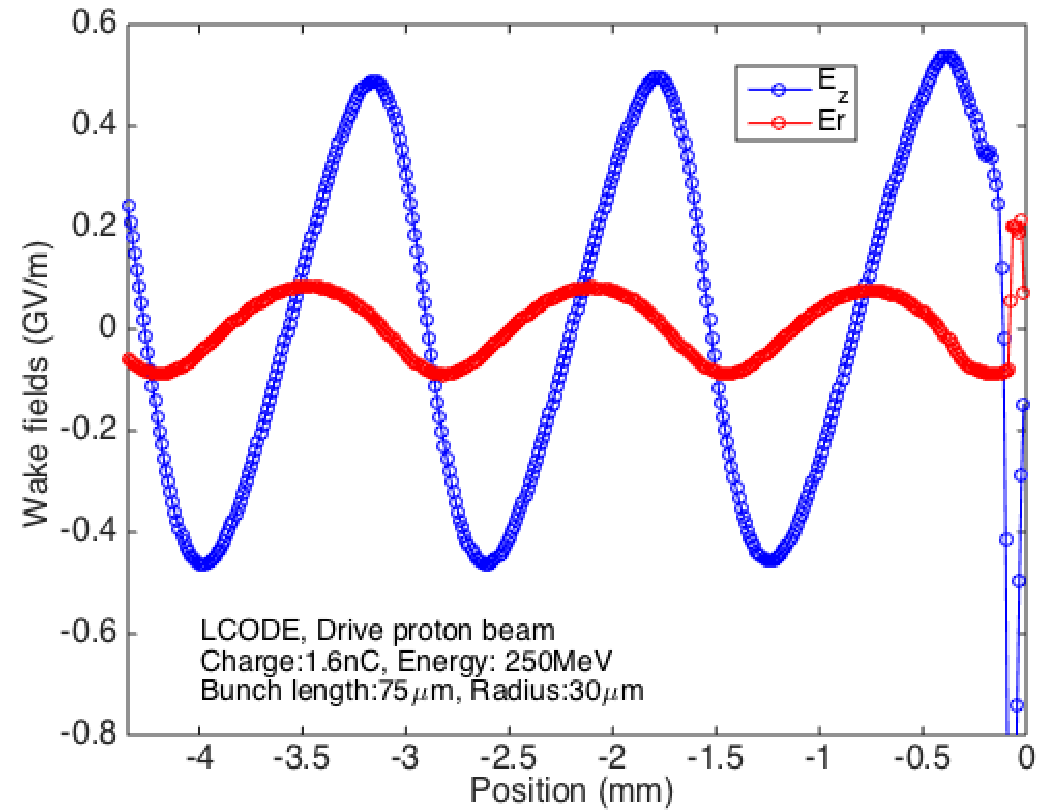
Pre-formed wakefields by LCODE

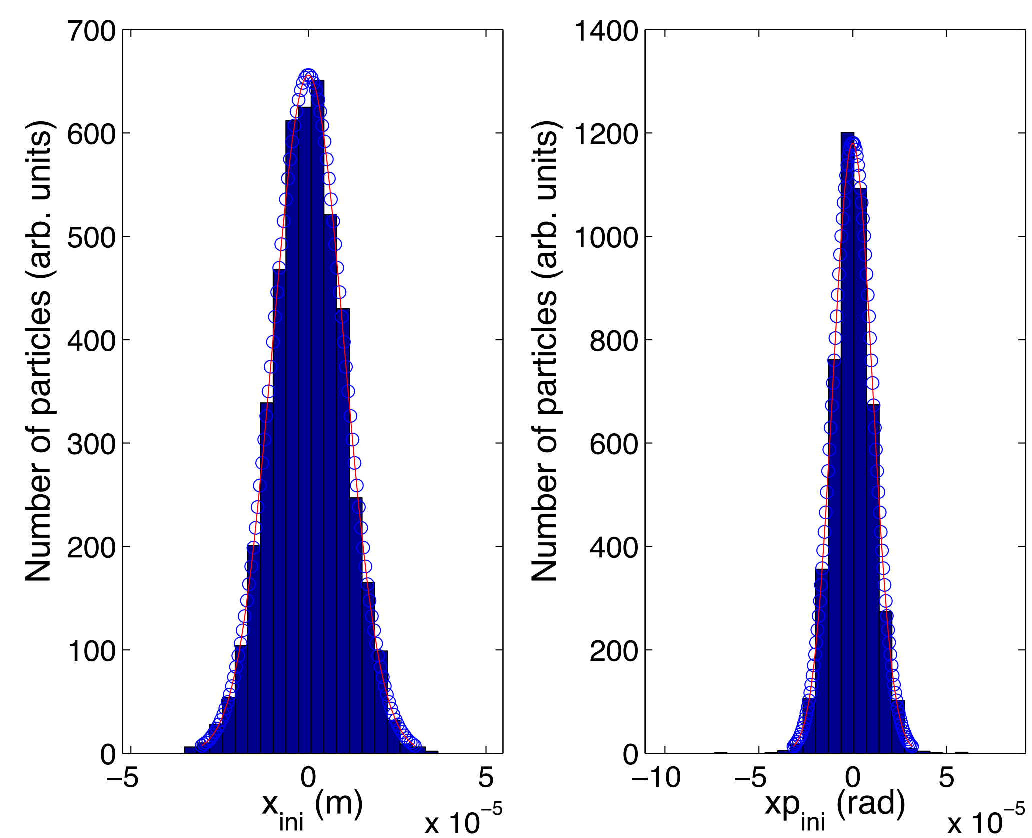
- Longitudinal (0.5 GV/m) and transverse (0.1 GV/m) fields defined in Geant4,
- Li (Z = 3, a = 6.941 g/mol)
- and Rb ((Z = 37, a = 85.468 g/mol)) gasses were considered,
- Uniform medium: 500m long, 100mm radial extent.

Initial beam

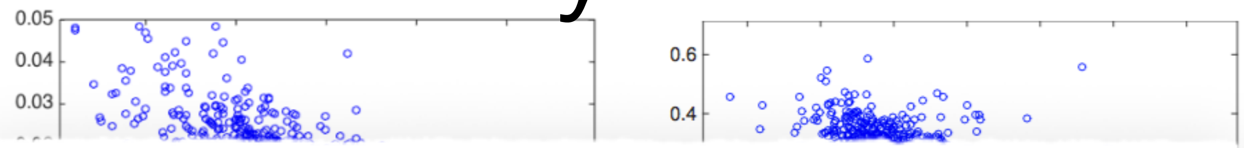
- 10k particles at 10 GeV
- Gaussian distribution for beam size and divergence, with standard deviation of 10μm and 10μrad.

O. Mete et al.,
Physics of Plasmas 22, 083101 (2015).



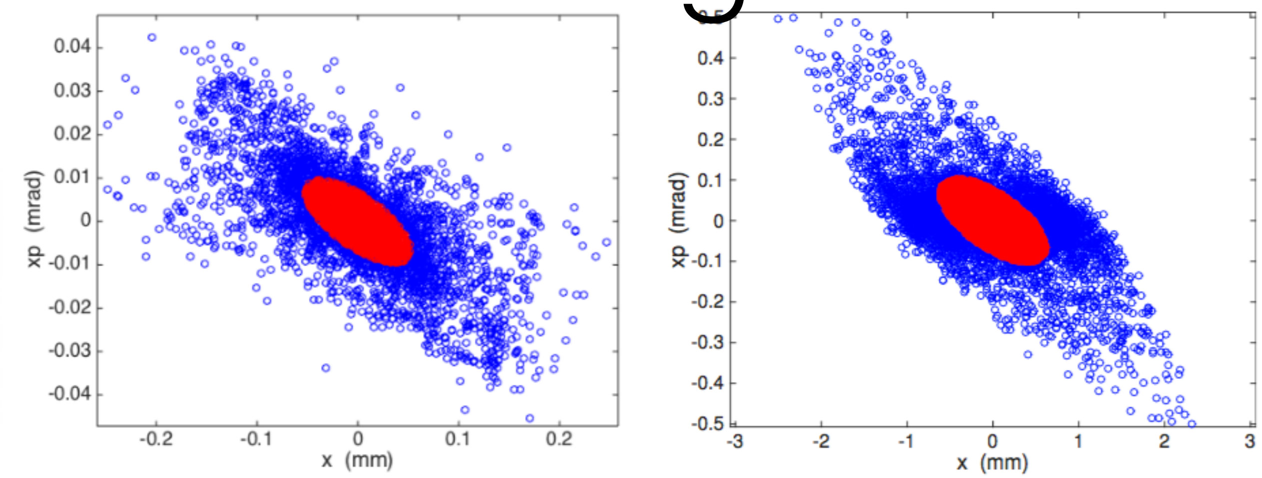


Key Issues in Collider Design



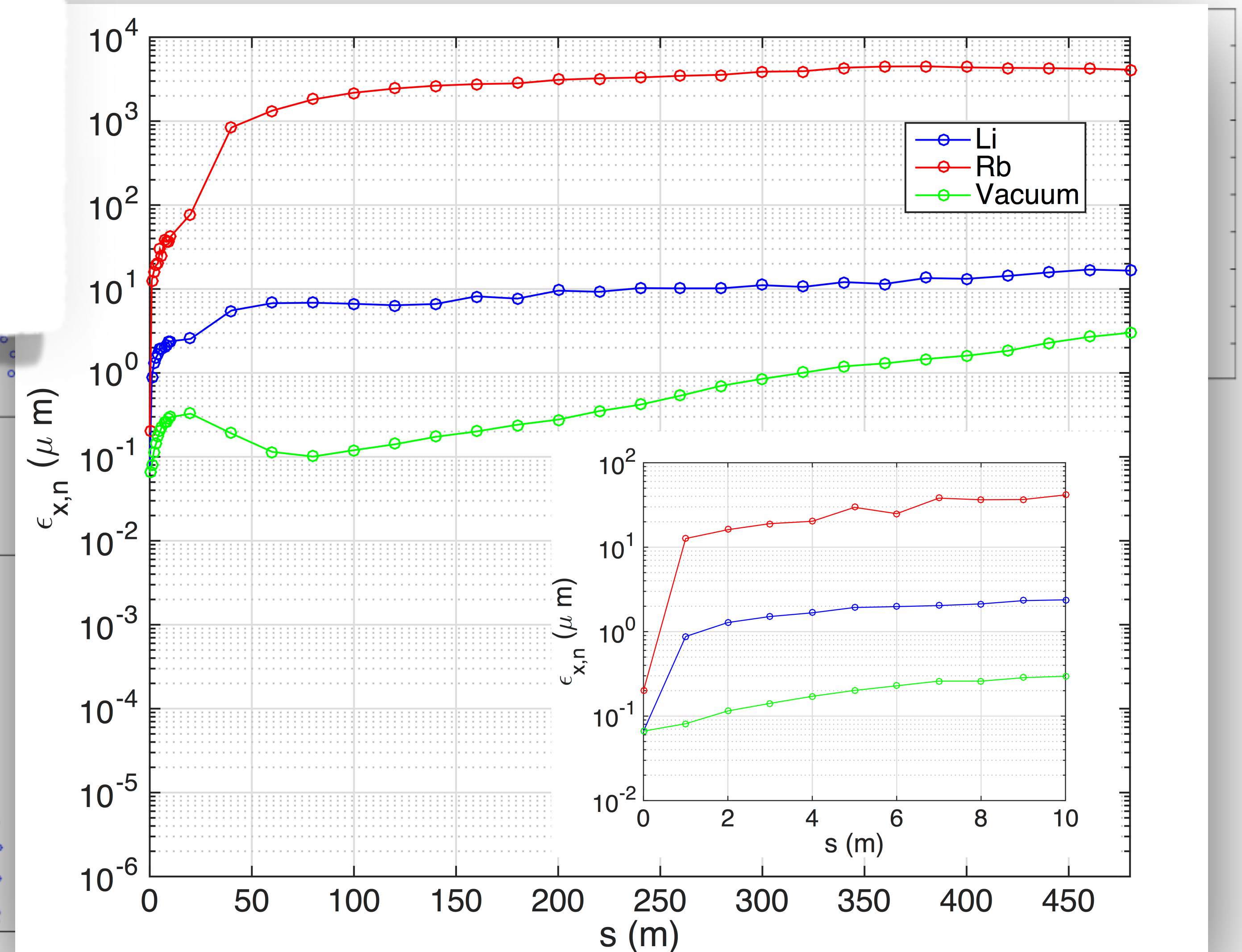
According to the simulations, the largest growth is induced by the multiple scattering of the beam particles by plasma particles. Rb gas yields two orders of magnitude larger emittance growth (41 mm mrad/m) than Li gas (0.5 mm mrad/m) in average over 500 m, as expected, since the scattering cross section is proportional to the square of the atomic number. Both cases are compared to the vacuum case where beam travels through vacuum under the effect of the transverse and longitudinal wakefields, and an average emittance growth of 6 nm/m was calculated due to effects other than scattering such as plasma-beam mismatch.

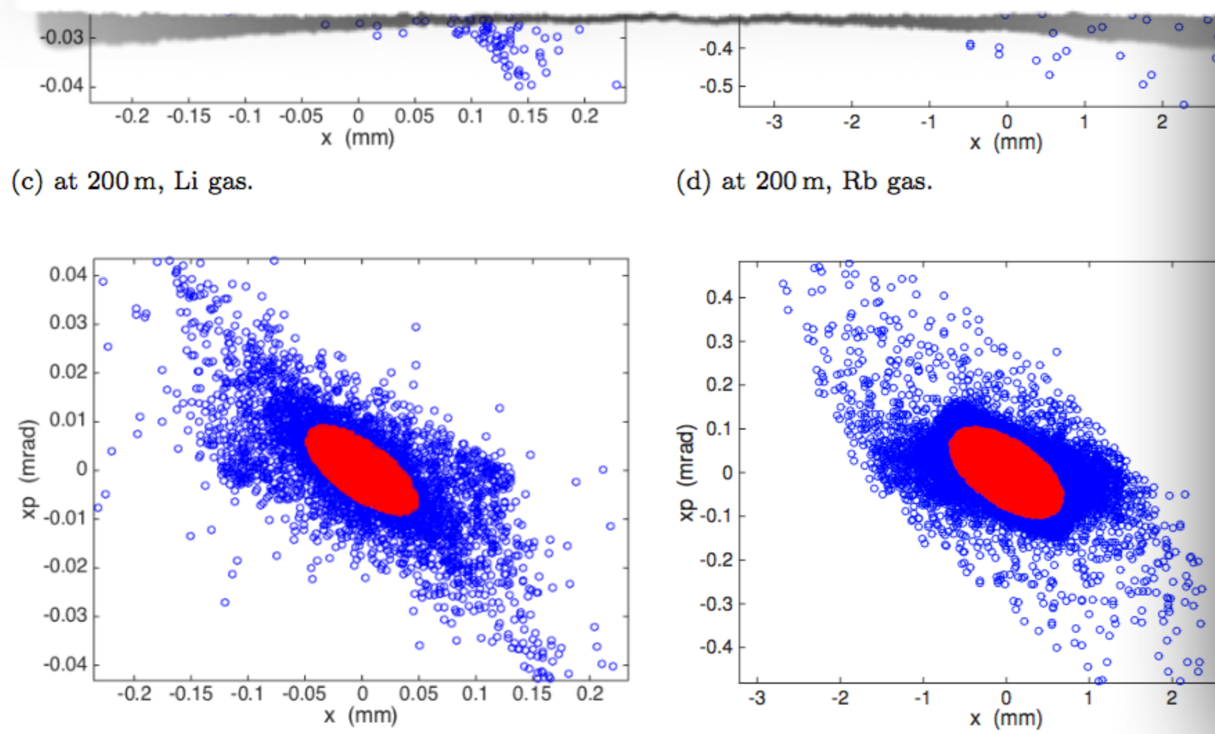
O. Mete et al.,
Physics of Plasmas 22, 083101 (2015).



(g) at 400 m, Li gas.

(h) at 400 m, Rb gas.





(c) at 200 m, Li gas.

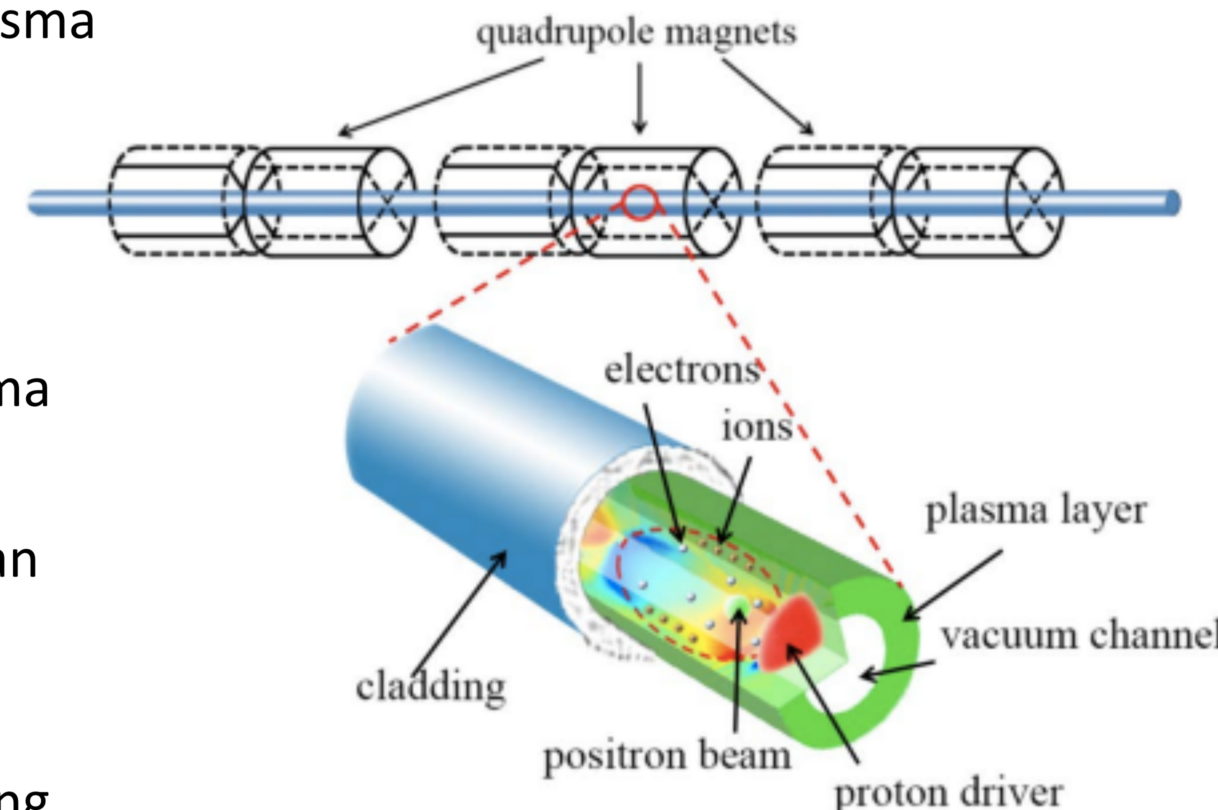
(d) at 200 m, Rb gas.

(e) at 300 m, Li gas.

(f) at 300 m, Rb gas.

Key Issues in Collider Design

- Electron acceleration can be done by proton-driven plasma wakefield acceleration,
- What about the positrons of a e^+e^- collider?[1,2,3]
- Hollow plasma beam:
  - **Focusing of witness:** Charge separation on the plasma layer wall due to driver space charge force,
  - **Acceleration:** Buckets (hollow plasma) are larger than uniform plasma case ➟ Stable acc. over long plasma distance,
  - **Witness - Wave Phasing:** Possible to tune by changing plasma channel radius,



Driver: LHC type beam
Energy, 2 TeV
Bunch length, 100 μm
Intensity, 10^{11}
Energy spread, 10%

Plasma
Hollow
Density, 6 x 10^{14} cm^{-3}
Length, 1 km

- 2D simulation result:
  - Energy gain **1.3 TeV.**
- Feasible **for positrons**[4]**.**

[1] L. Yi et al., arXiv:1309.5691 [physics.plasm-ph] [2] L. Yi et al., arXiv:1306.1613 [physics.plasm-ph]
[3] W. D. Kimura et al., Phys. Rev. ST Accel. Beams 14, 041301
[4] New results from FACET for positrons —> Nature 524, 442–445 (27 August 2015)

Outline

- Examples of advance acceleration technologies
  - Terahertz driven acceleration
  - Dielectric accelerators
  - Laser and beam driven plasma accelerators
- AWAKE Project
  - Witness production
  - 3D simulations for unresolved phenomena in 2D
- Future collider studies based on PDPWA
  - Possible layouts using existing infrastructure
  - Design issues
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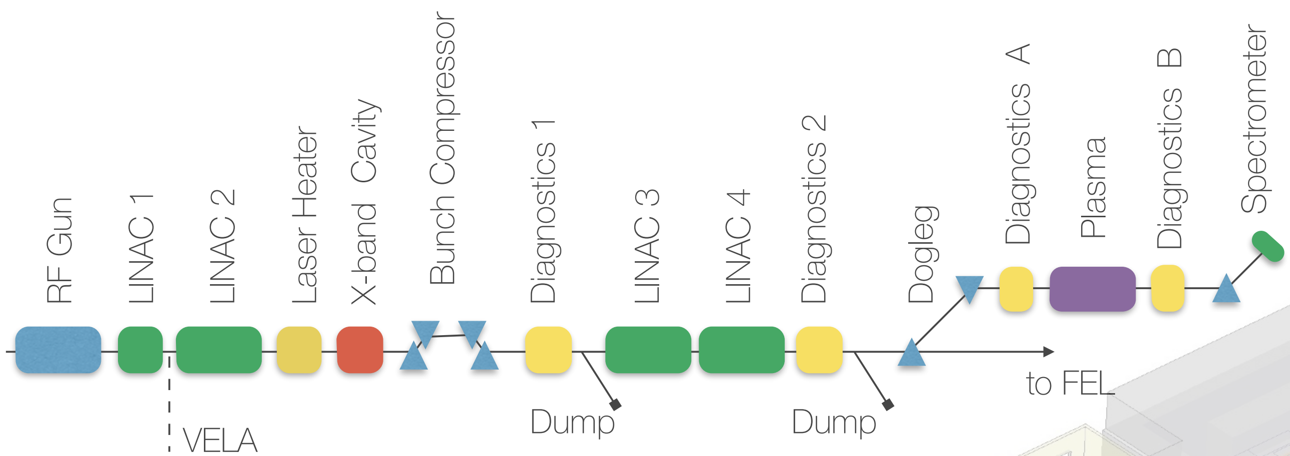
  - Optimisation for various regimes of CLARA
  - Plasma sources
- iMPACT Proposal
  - Multi-bunch PWA
  - PIC simulations for CLARA and CLARA Front End

PARS Project



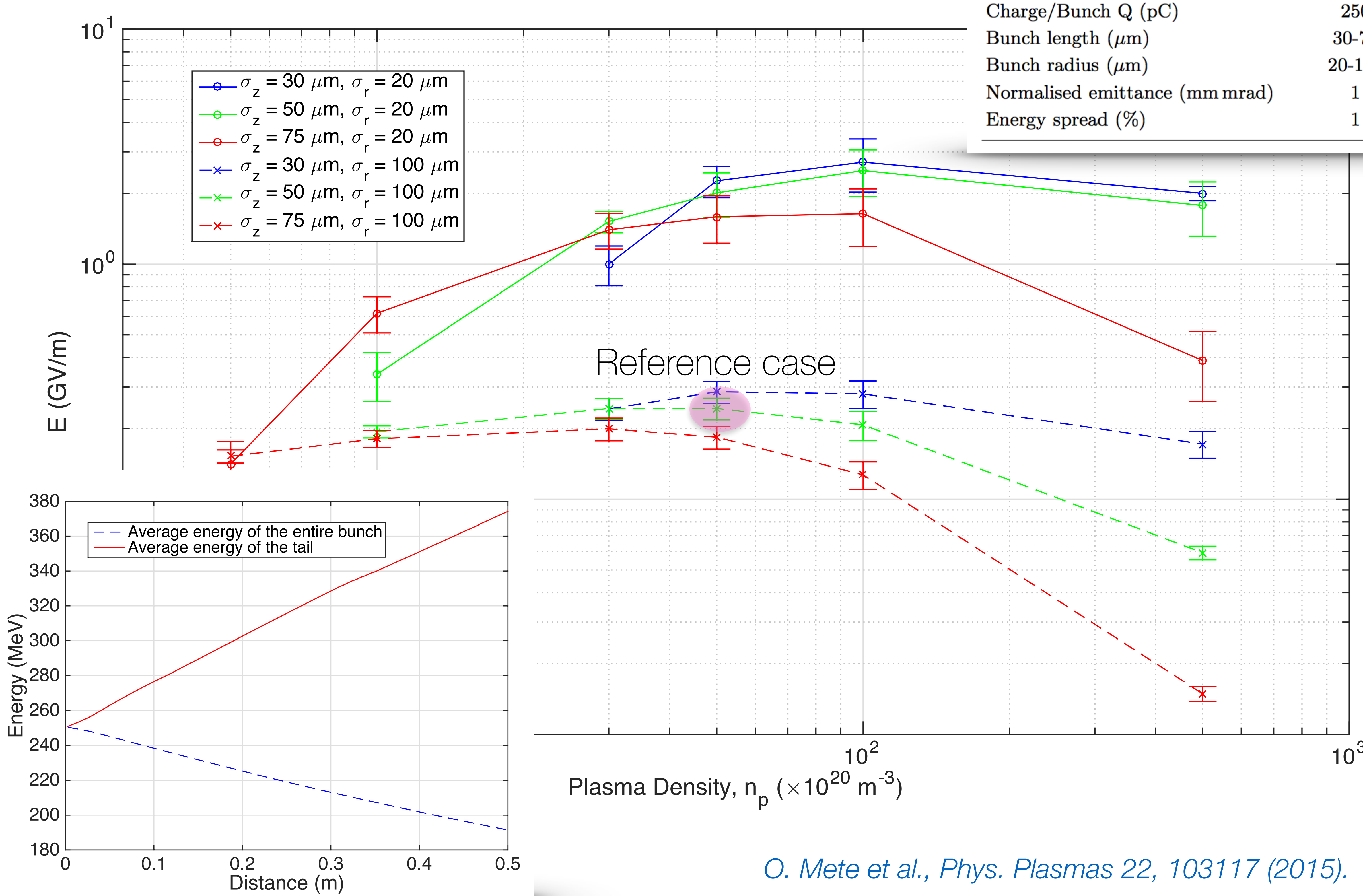
Operating modes	Long Pulse	Short Pulse	Ultra-Short Pulse
Beam energy (MeV)	250	250	250
Charge/Bunch Q (pC)	250	250	20-100
Electron/Bunch N_b ($\times 10^9$)	1.56	1.56	0.125-0625
Bunch length rms (fs)	250-800 (flat top)	100-250	$\leq$ 30
Bunch length (μm)	75-240	30-75	9
Bunch radius (μm)	20-100	20-100	20-100
Normalised emittance (mm mrad)	$\leq$ 1	$\leq$ 1	$\leq$ 1
Energy spread (%)	1	1	1

…in collaboration with Deepa Angal-Kalinin and other ASTeC and CI colleagues.

Single Bunch

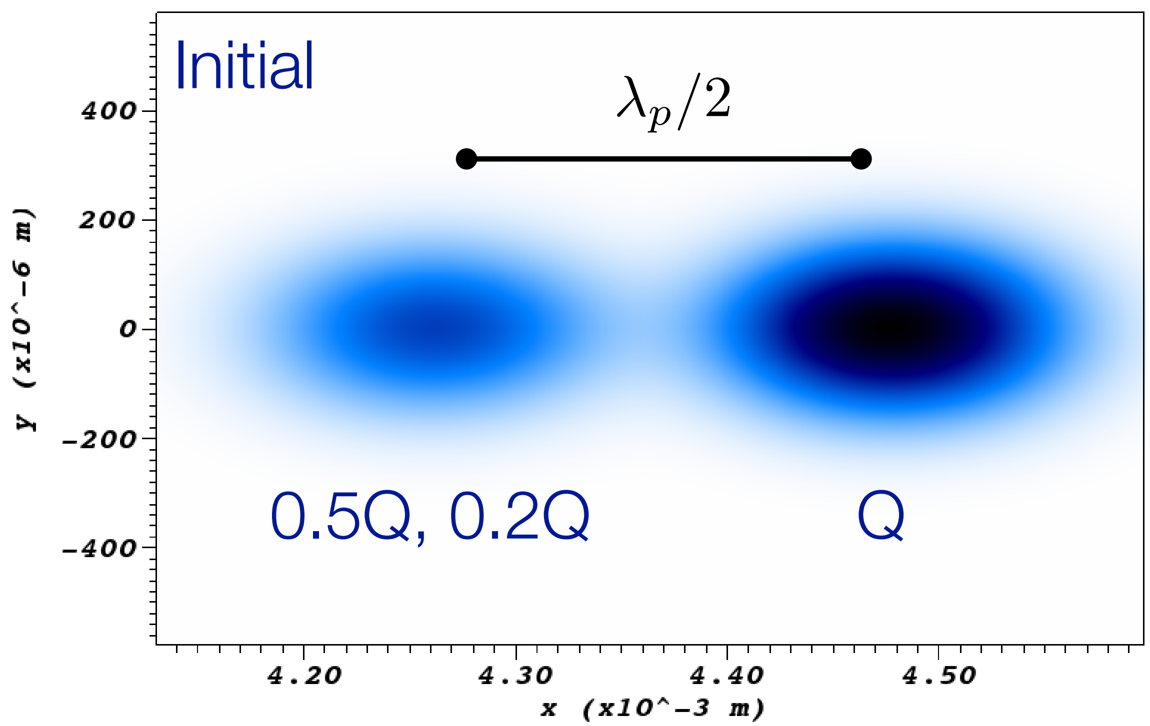
PARS Project

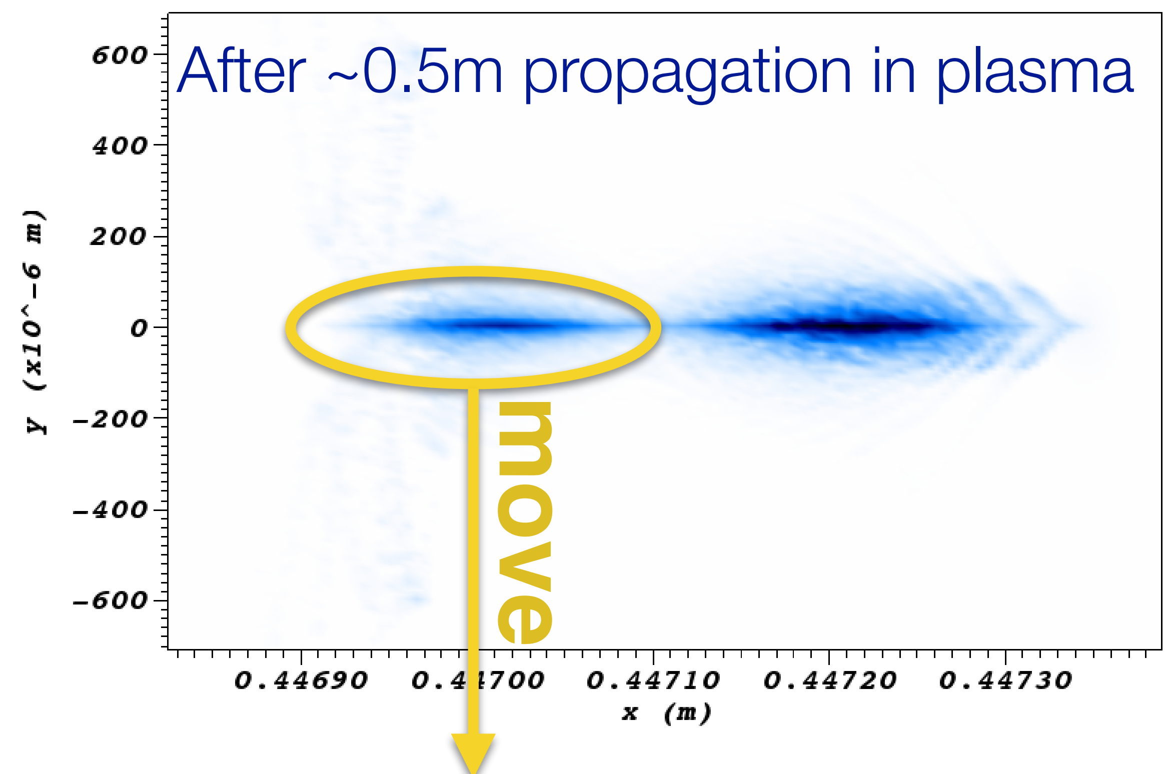
Plasma	
Density (m^3)	1×10^{20}-5×10^{22}
Length (cm)	10-50
Gas type	Ar, H_2
Electron Beam	
Beam energy (MeV)	250
Charge/Bunch Q (pC)	250
Bunch length (μm)	30-75
Bunch radius (μm)	20-100
Normalised emittance (mm mrad)	1
Energy spread (%)	1

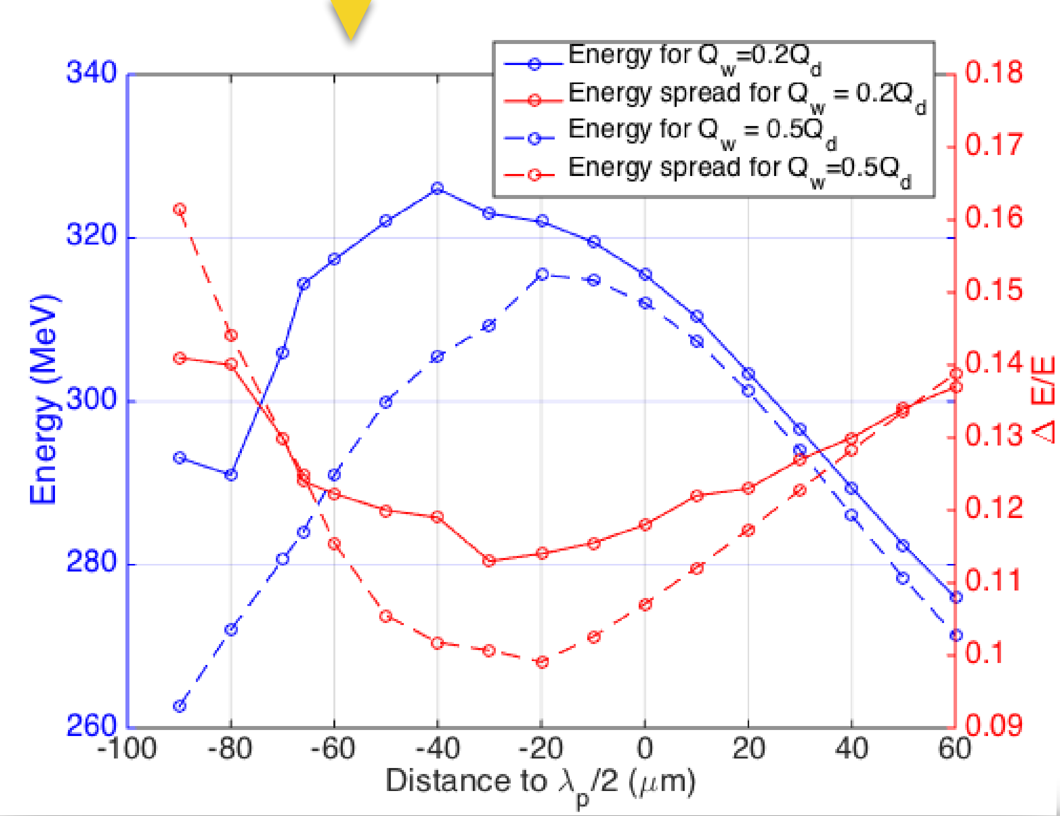


O. Mete et al., Phys. Plasmas 22, 103117 (2015).

PARS Project







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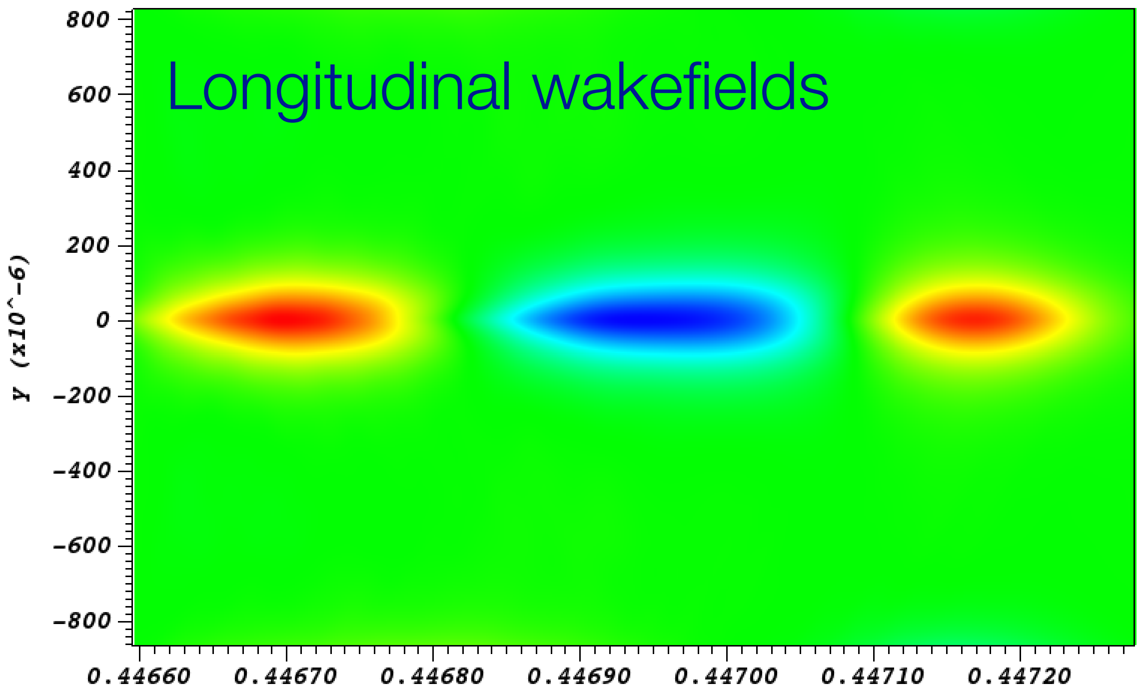
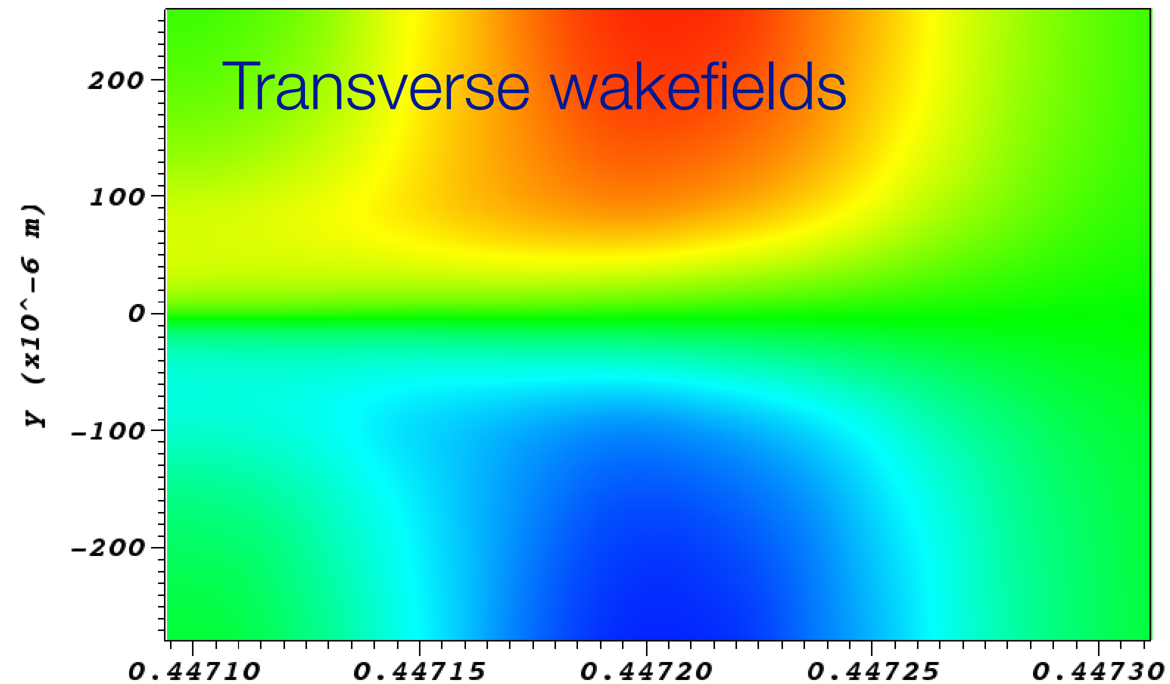
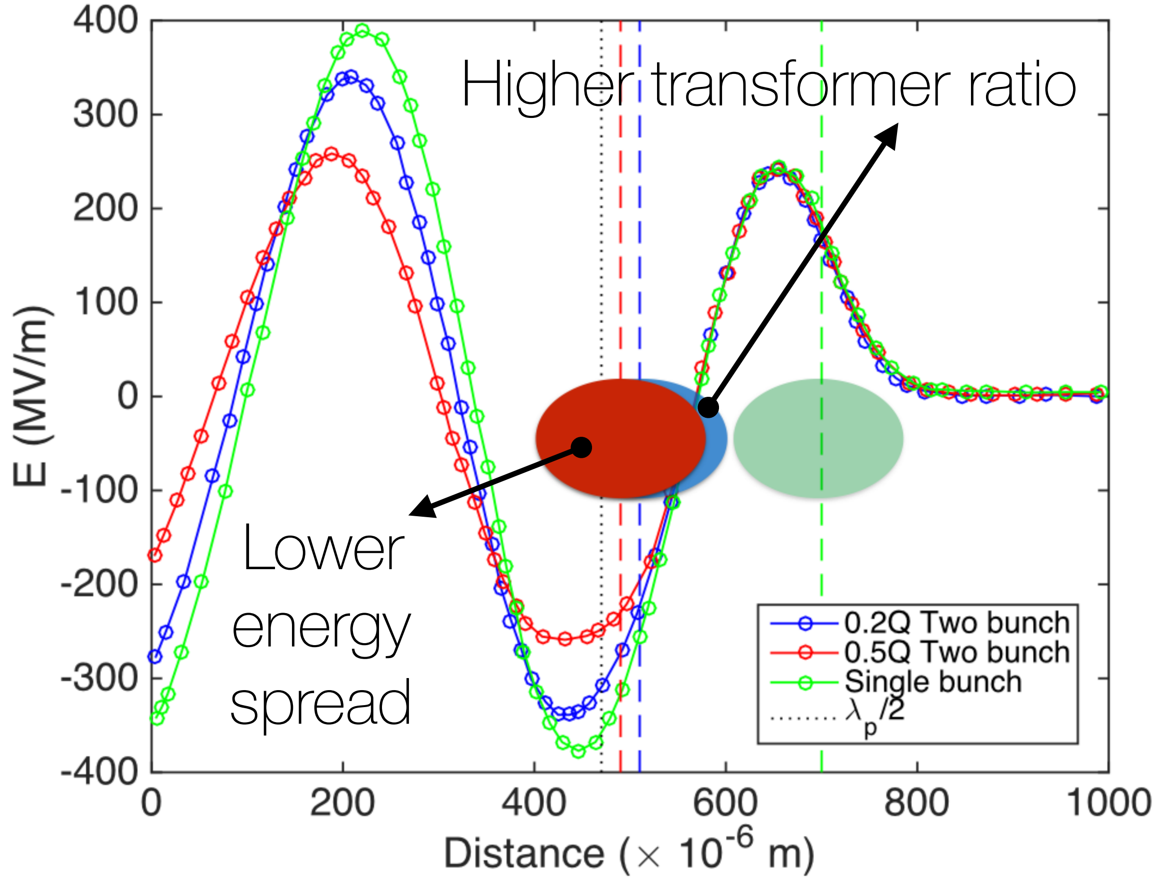
Bunch radius (μm)	20-100
Normalised emittance (mm mrad)	1
Energy spread (%)	1

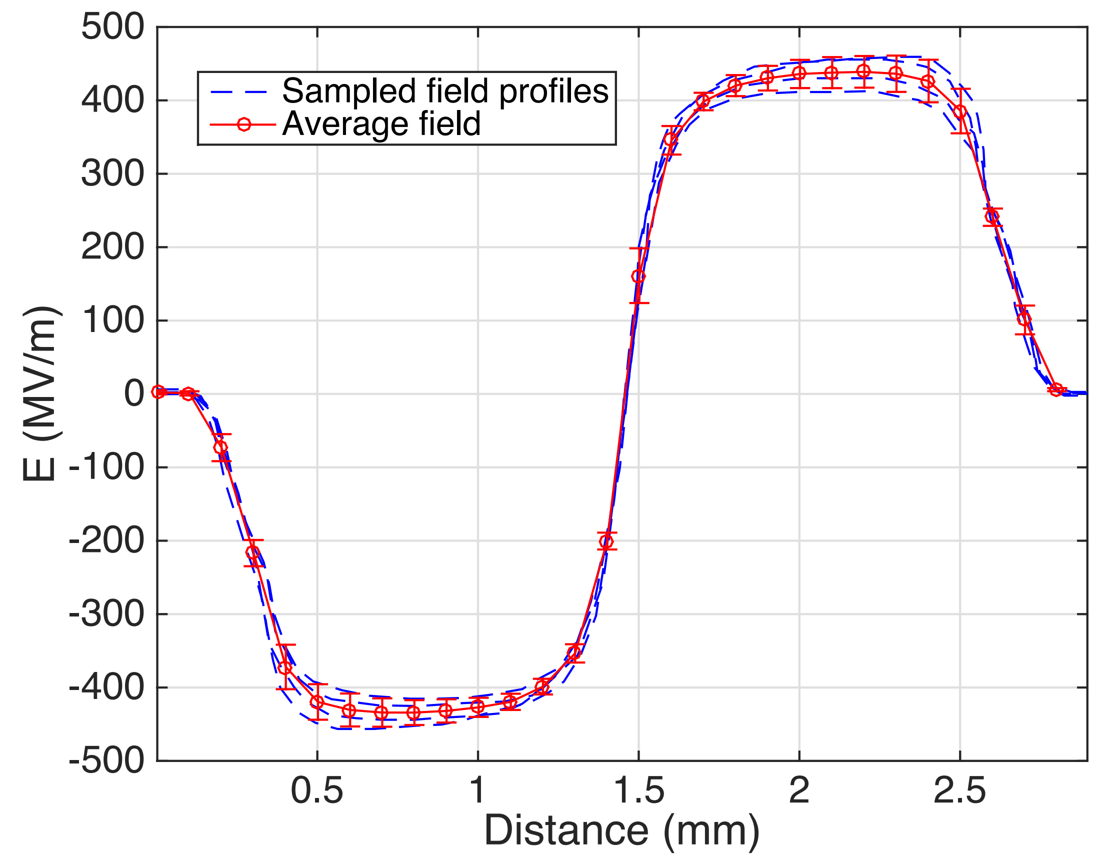
O. Mete et al., Phys. Plasmas 22, 103117 (2015).

PARS Project









O. Mete et al., Phys. Plasmas 22, 103117 (2015).

Beam quality studies

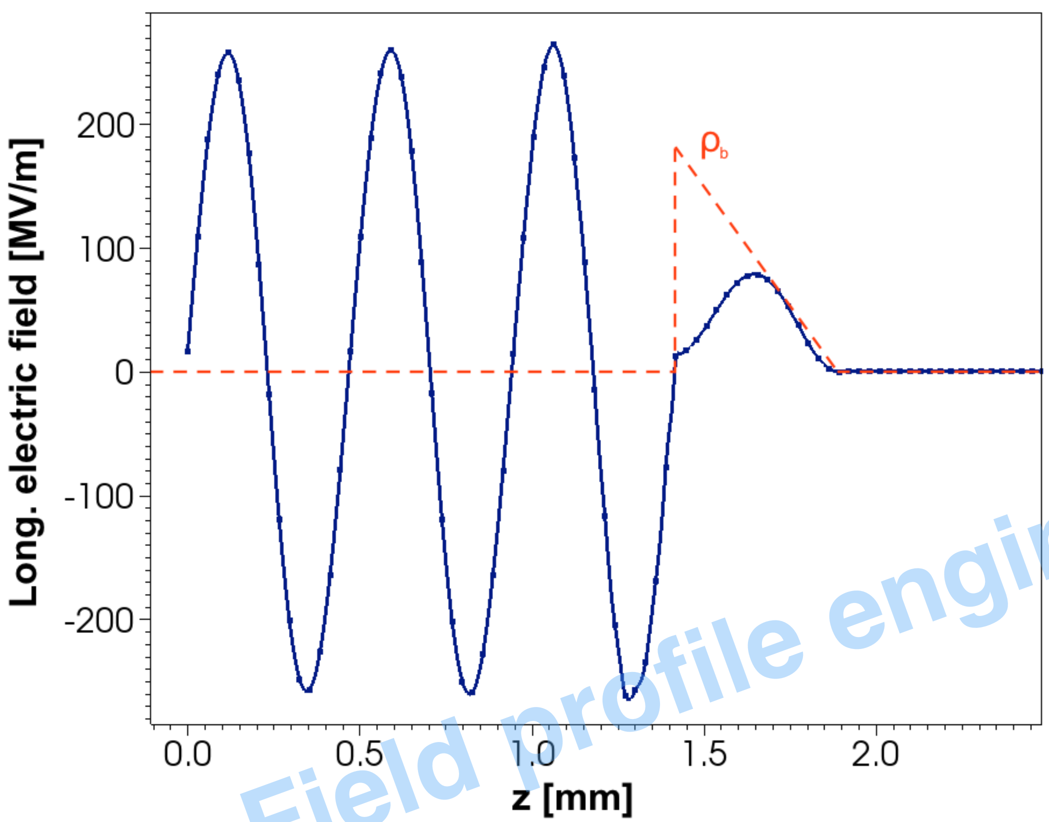
PARS Project

Energy Spread Energy Transfer Efficiency

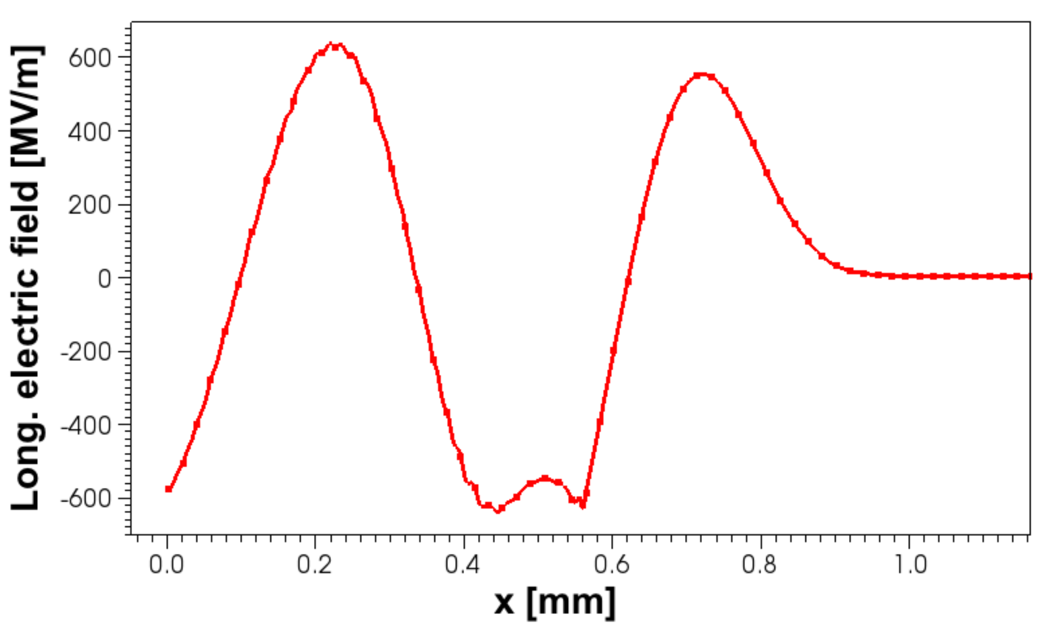
Results from Kieran Hanahoe CI PhD Student - to be submitted for publication soon.

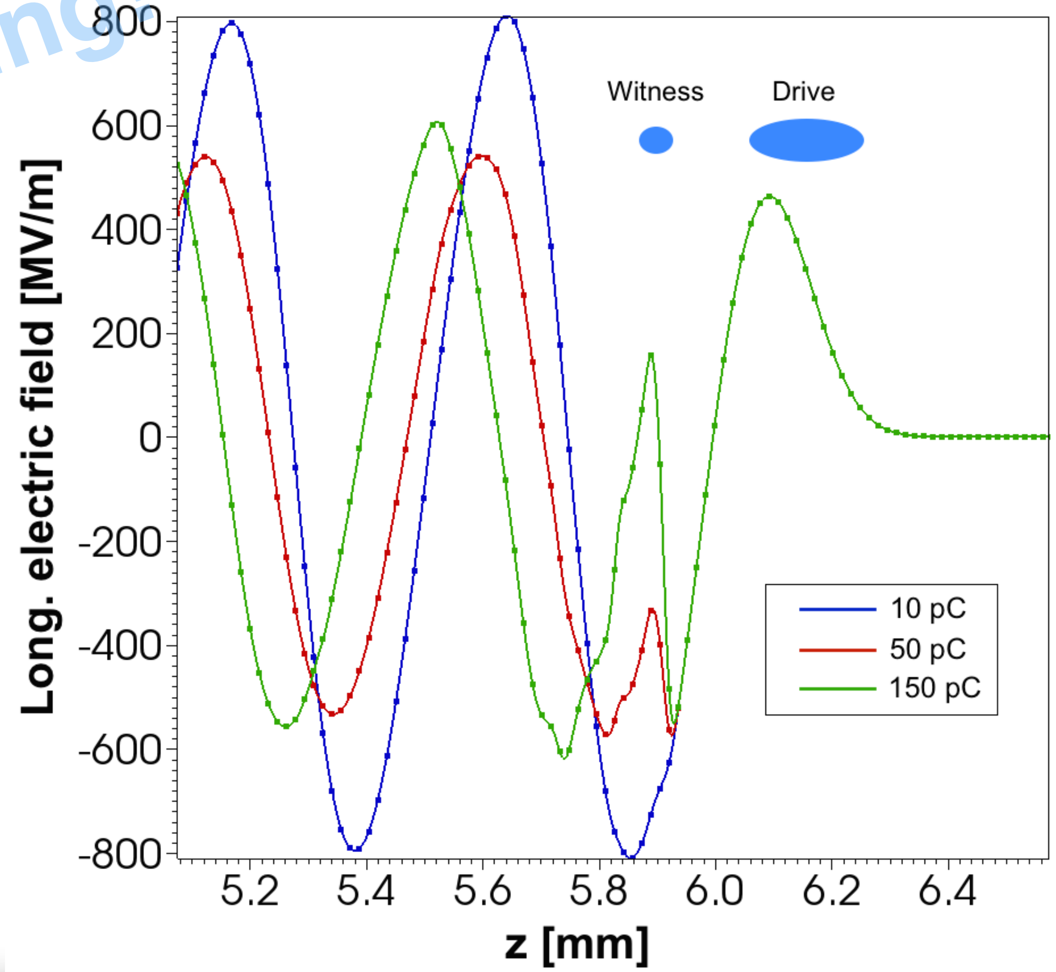
$$R = \frac{E_+}{E_-}$$

$$E = RE_0$$



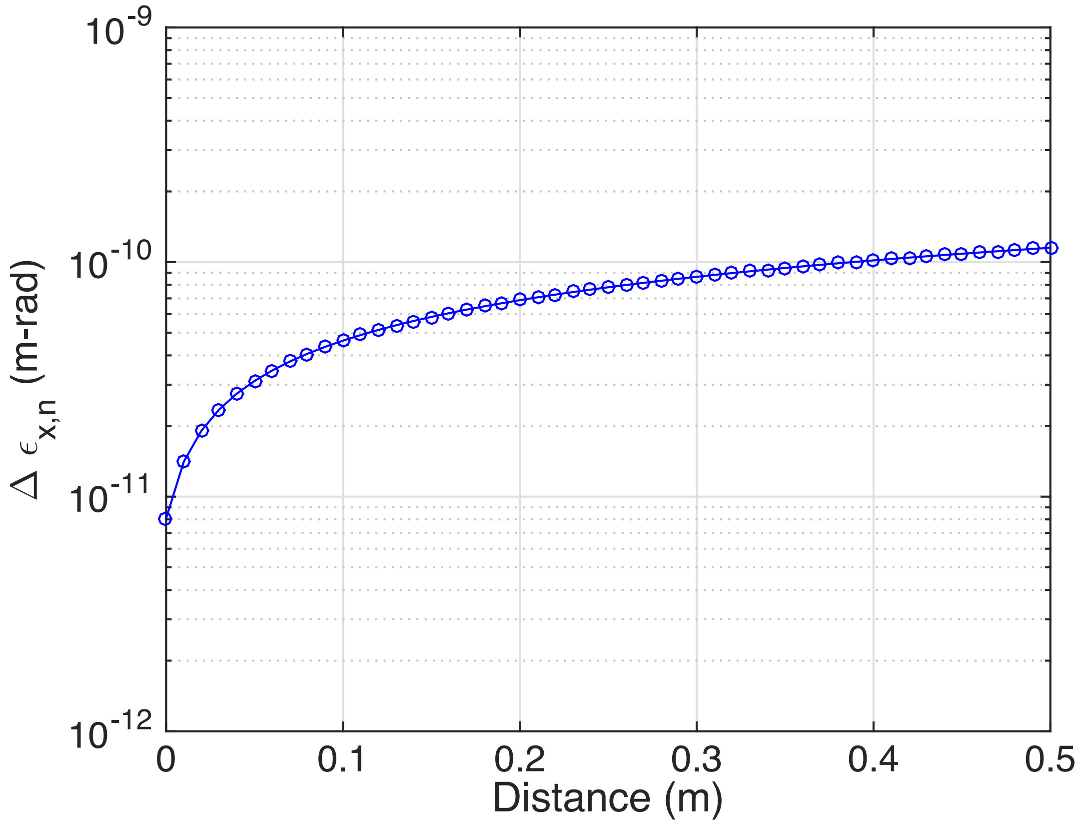
Field profile engineering!

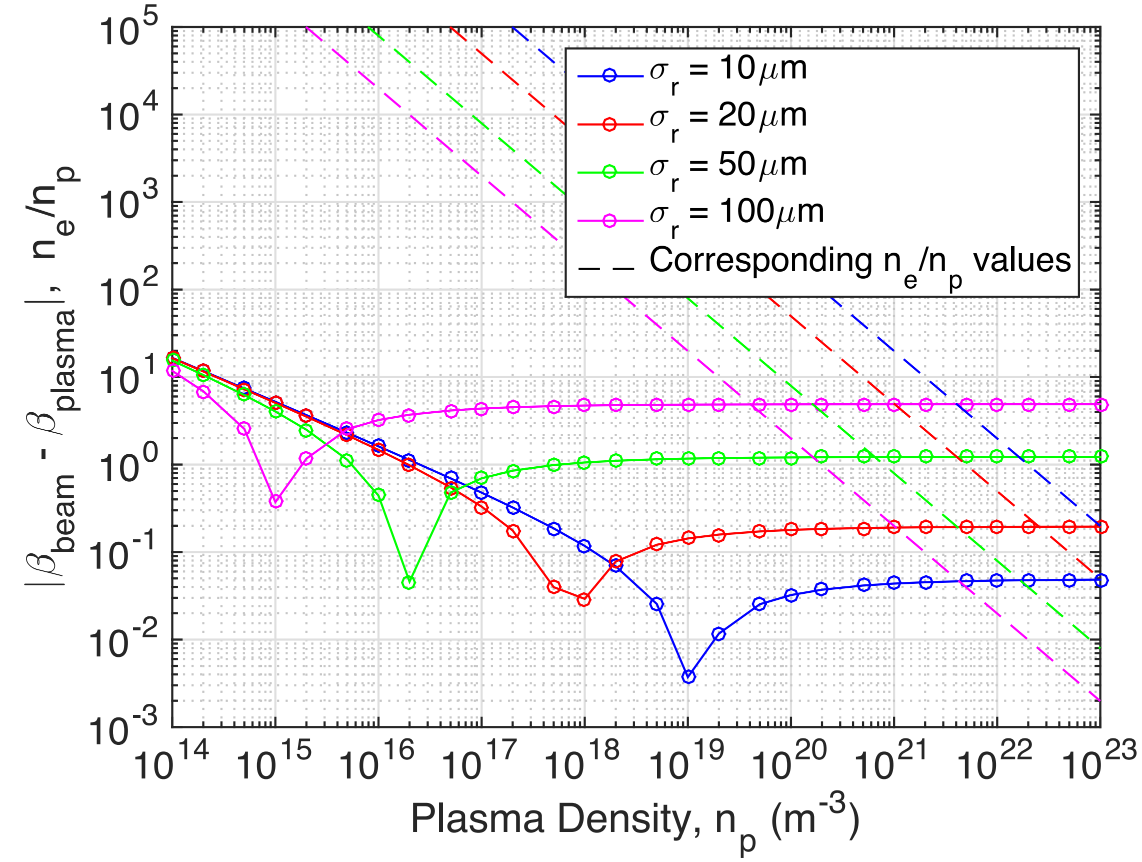




Beam quality studies Emittance Growth

PARS Project





Emittance growth due to scattering for the reference case.

- Theory (based on gas-scattering in damping rings) suggested negligible growth.
- Model is being updated considering ion case where the effective potential is modified including the electronic structure of ions.

Beam-plasma matching.

- Beta functions of the beam and plasma should match.

non-linear bubble focusing

$$K = (eE_r/rm_e\gamma c^2)^{1/2} \qquad K = \omega_p^2/(2\gamma c^2)$$

$$\sigma_r''(z) + \left[K^2 - \frac{\varepsilon_N^2}{\gamma^2\sigma_r^4(z)}\right]\sigma_r(z) = 0$$ envelope eq.

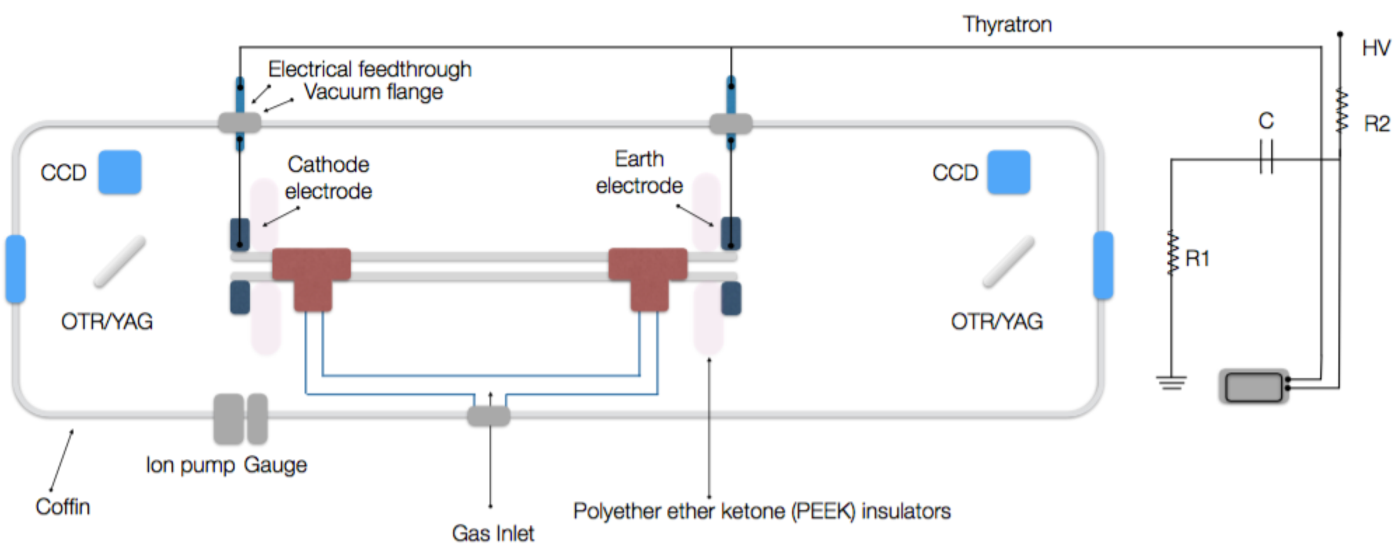
$$\beta_{beam} = \gamma\sigma_r^2/\varepsilon_N \approx \beta_{plasma} = 1/K$$ matching condition

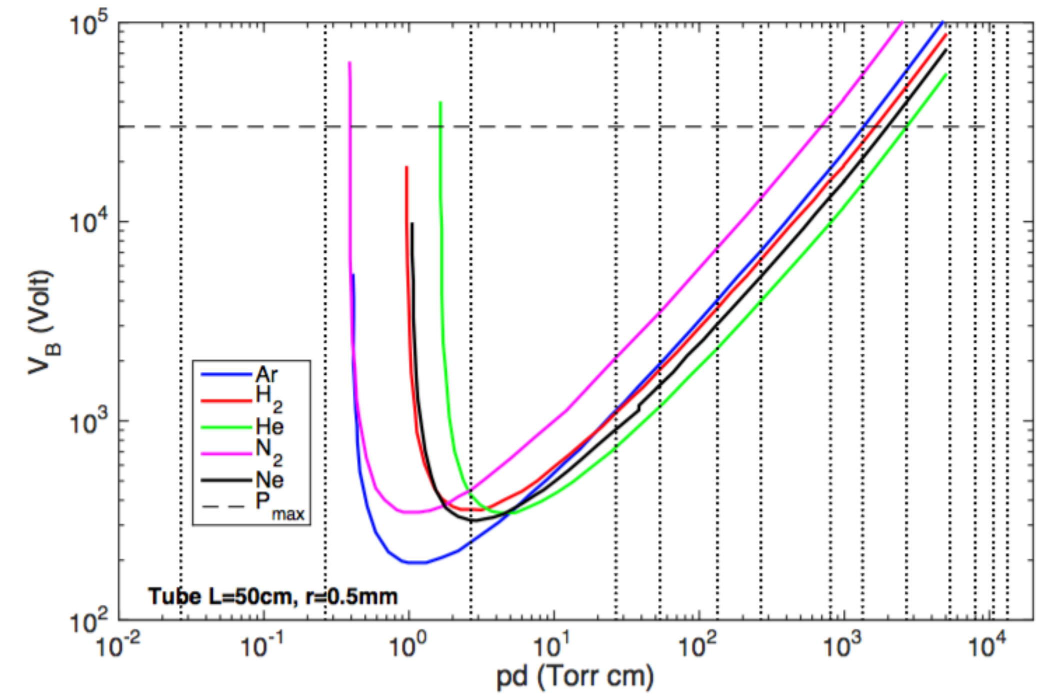
$$\omega_p = \sqrt{n_p e^2/\epsilon_0 m_e}$$

O. Mete et al., Phys. Plasmas 22, 103117 (2015).

Gas filled capillary based discharge Plasma Source

LAYOUT AND WORKING CONDITIONS





A plasma medium can be formed when a gas is discharged via an applied high voltage within a capillary tube [1, 2]. A high voltage discharge based plasma source was designed to provide the plasma medium required by the plasma wakefield acceleration experiments. A set of glass capillary tubes are available for the tests with a inner radius ranging from 600 µm to 1200 µm in a selection of lengths between 10-30 cm.

In a confined volume gas discharge occurs as a function of the gas pressure, *p*, distance between the high voltage and earth electrodes, *d*, and the value of the high voltage, *V*. This relation, Paschen's law [3], is represented with empirical curves. These empirical curves were extrapolated towards larger *pd* values in order to investigate the higher range of gas pressures required for plasma wakefield acceleration experiments.

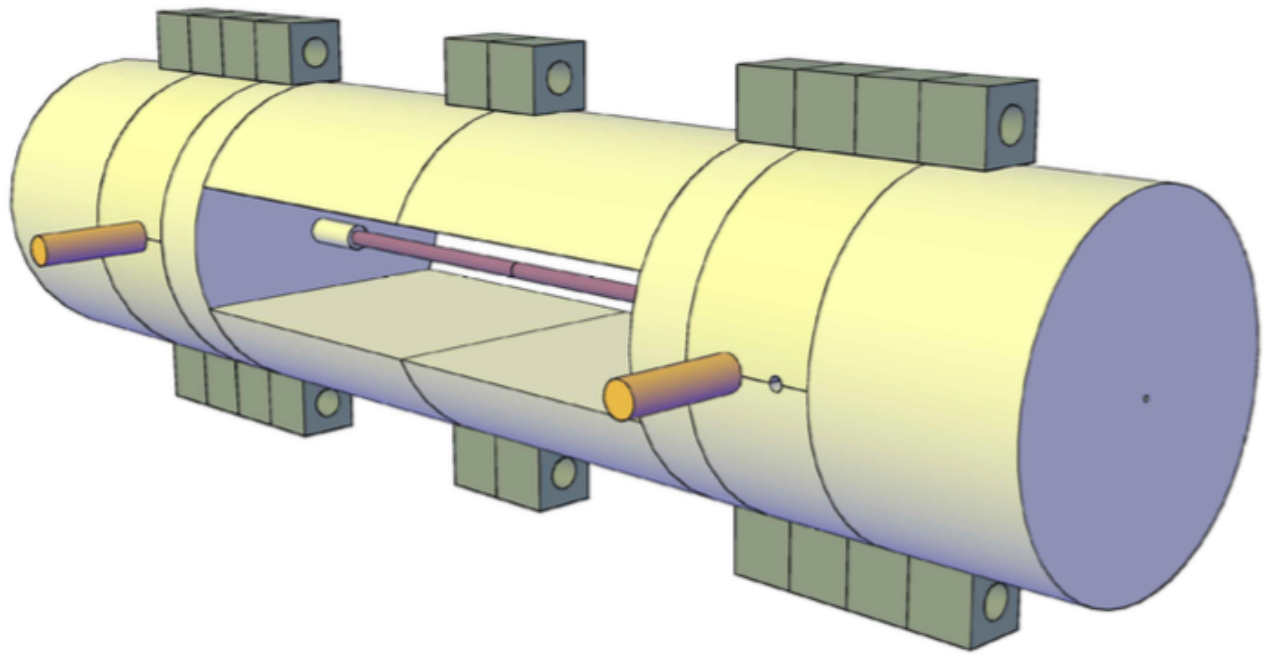
n (m^{-3})	Pressure (mbar)	Pd (5 cm) (mm mbar)	Pd (10 cm) (mm mbar)	Pd (50 cm) (mm mbar)
1×10^{17}	0.000533	0.002665^a	0.00533^a	0.02665^a
1×10^{18}	0.00533	0.02665^a	0.0533^a	0.2665^a
1×10^{19}	0.0533	0.2665^a	0.533	2.665
1×10^{20}	0.533	2.665	5.33	26.65
2×10^{20}	1.067	5.335	10.67	53.35
5×10^{20}	2.7	13.5	27	135
1×10^{21}	5.33	26.65	53.3	266.5
3×10^{21}	16	80	160	800
5×10^{21}	26.7	133.5	267	1335
1×10^{22}	53.33	266.65	533.3	2666.5
2×10^{22}	106.67	533.35	1066.7	5333.5^b
3×10^{22}	160	800	1600	8000^b
4×10^{22}	213	1065	2130	10650^b
5×10^{22}	266.7	1333.5	2667	13335^b

[a] No discharge can occur due to low pressure. [b] No discharge can occur due to power limit.

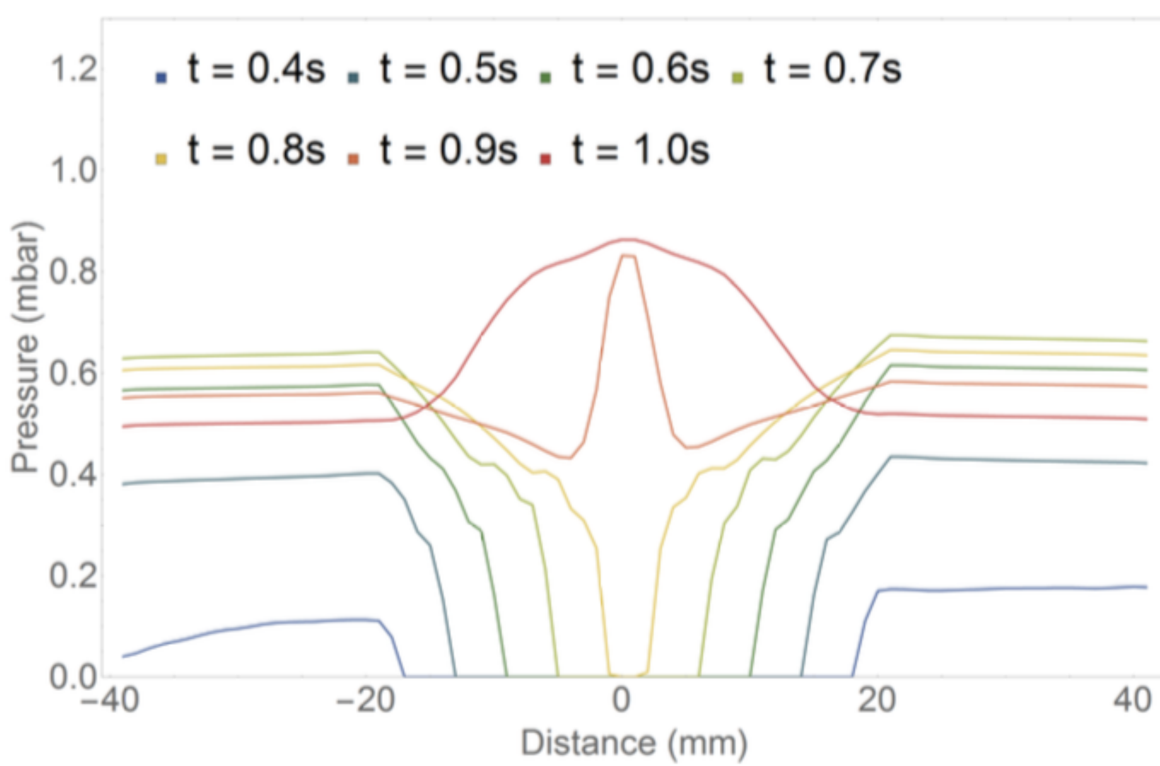
…in collaboration with Anthony Dyson, Simon Hooker (JAI); Bernhard Hidding (The Univ. of Strathclyde), Ali Alacakir, TAEK.

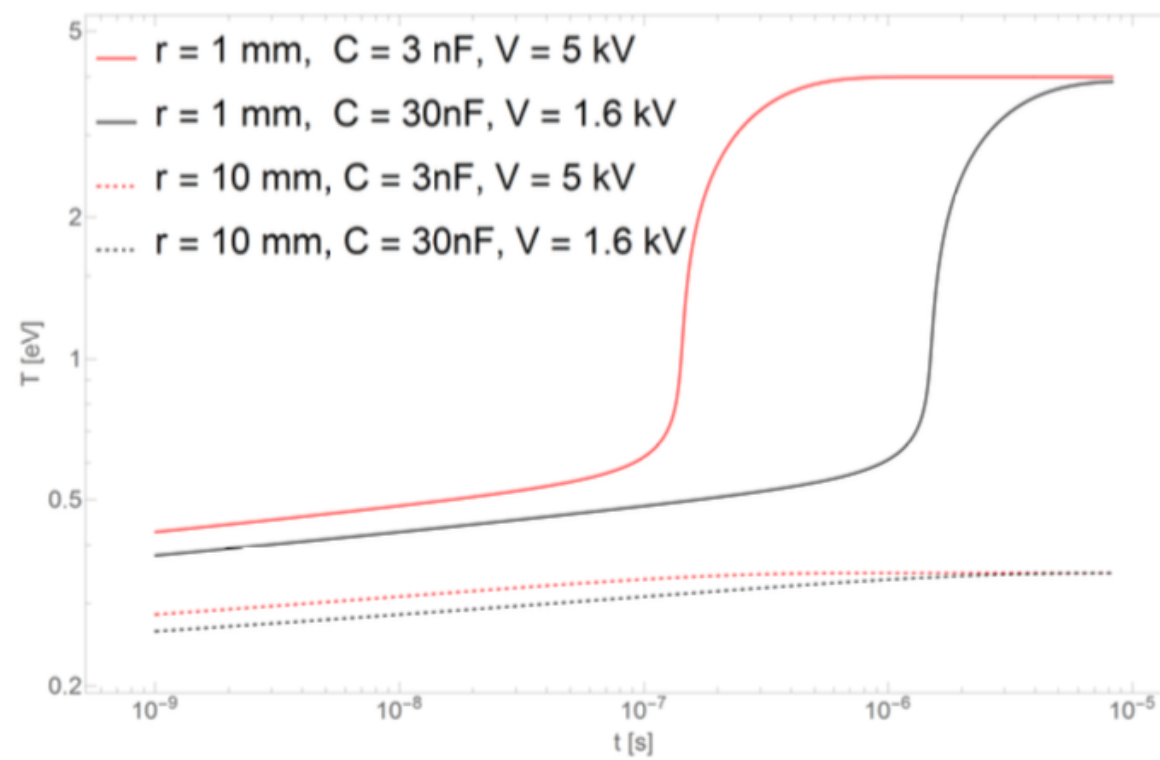
Gas filled capillary based discharge

Plasma Source



Results from Thomas Pacey
CI PhD Student





Computational Fluid Dynamics Studies with AutoDesk CFD Flex.

Outline

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  - Terahertz driven acceleration
  - Dielectric accelerators
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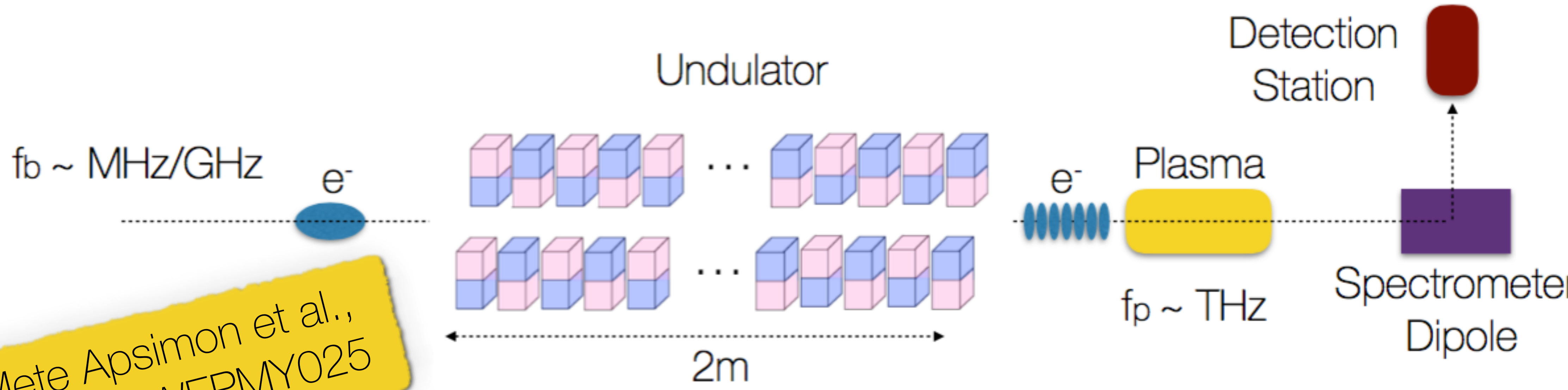
Multi-Bunch Plasma Acceleration

iMPACT Proposal



O Mete Apsimon et al.,
IPAC2016, WEPMY025

Parameter	Undulator I	Undulator II
λ (μm)	313	156
λ_u (mm)	80	40
B (T)	0.3	0.3
K	2	2
L_{1D} (m)	0.1	0.08
L_{sat} (m)	2	1.6

Beam	
Total charge, Q (nC)	8
Charge/Microbunch, q (nC)	1
Initial bunch length, σ_{z_0} (ps)	4
Microbunch length, σ_z (ps)	0.5
Beam size (μm), σ_x	715
Beam Beta (m), β	5
Initial beam energy, E (MeV)	200
Beam number density, n_e (m^{-3})	5.2×10^{18}
Plasma	
Plasma wavelength, λ_p (μm)	300
Plasma number density, n_p (m^{-3})	1.24×10^{22}

Preliminarily, the saturation length, L_{sat}, where microbunching occurs is assumed to be a factor of 20 larger than the gain length calculated using Eq.1 and the Pierce parameter given in Eq.2,

$$L_g = \lambda_u / 4\pi\sqrt{3}\rho \qquad (1)$$

$$\rho = \left[\left(\frac{I}{I_A}\right)\left(\frac{\lambda_u A_u}{2\pi\sigma_x}\right)^2\left(\frac{1}{2\gamma_0}\right)^3\right]^{1/3} \qquad (2)$$

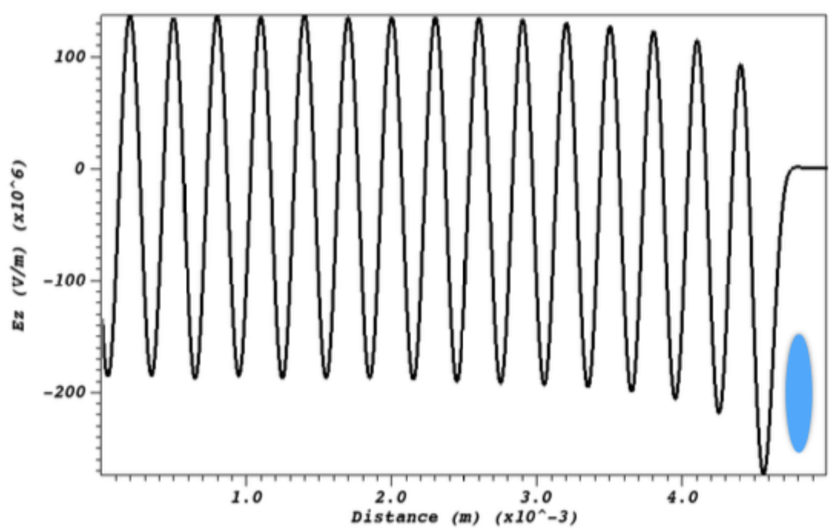
where, for the planner undulators, $A_u = a_u(J_0(\zeta) - J_1(\zeta))$ and $a_u = K/\sqrt{2}$. In the equation, J_0 and J_1 are the Bessel functions of the zeroth and the first kind, respectively, where ζ is $\zeta = a_u^2/2(1 + a_u^2)$. A general parametrisation for undulators with two different period are presented in Table 1.

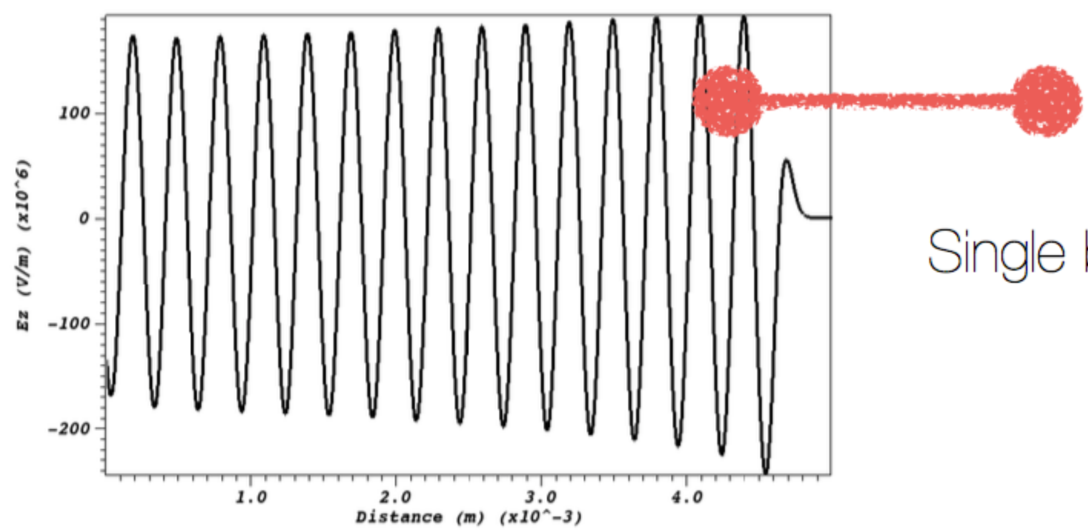
Multi-Bunch Plasma Acceleration

iMPACT Proposal

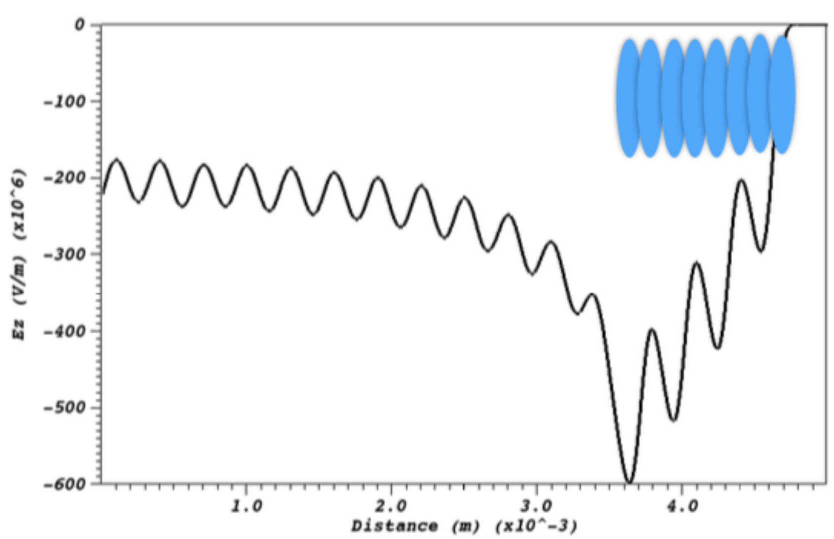
Plasma wakefields at the first time step (10mm).

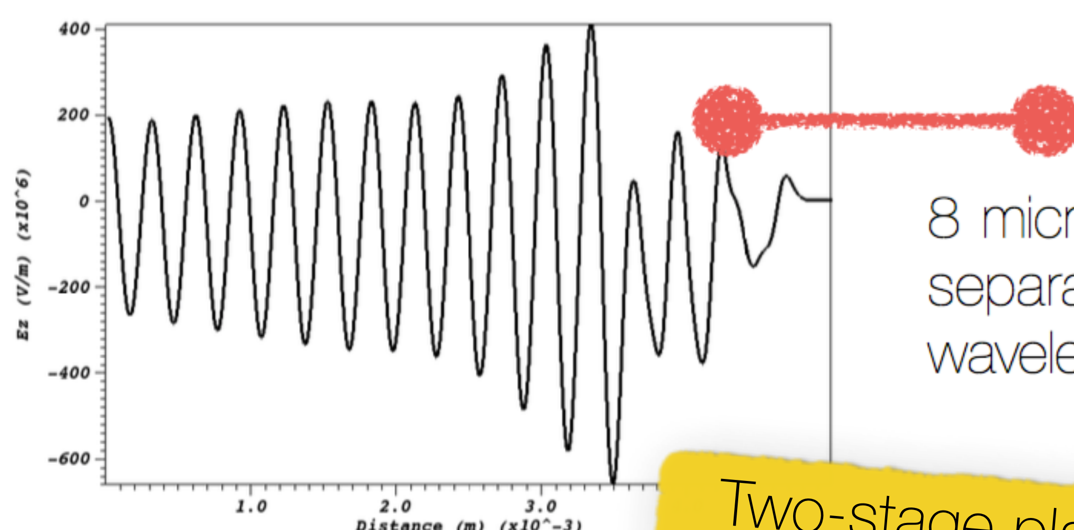
Plasma wakefields after 10cm propagation into the plasma.





Single bunch at 200 MeV.



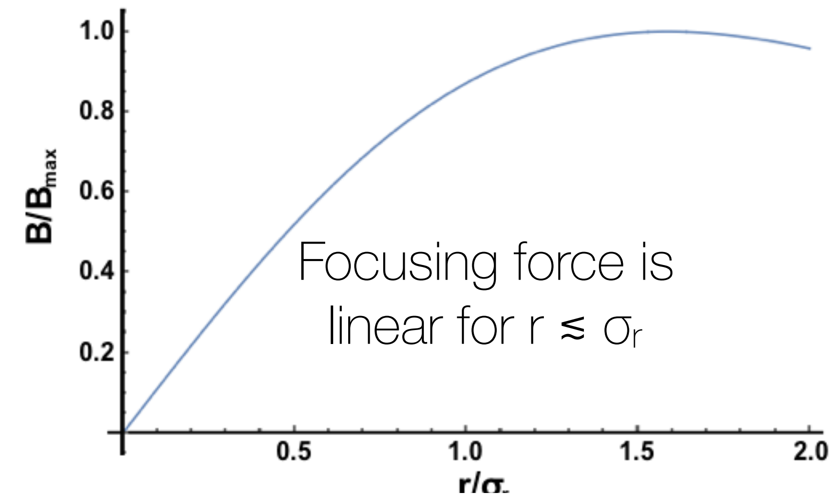


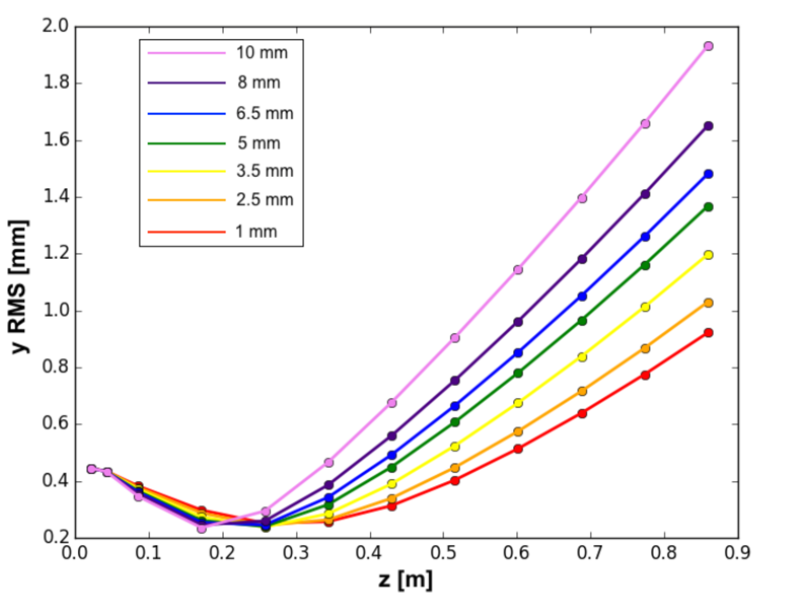
8 microbunches at 200 MeV separated by one plasma wavelength, $\lambda_p/2$.

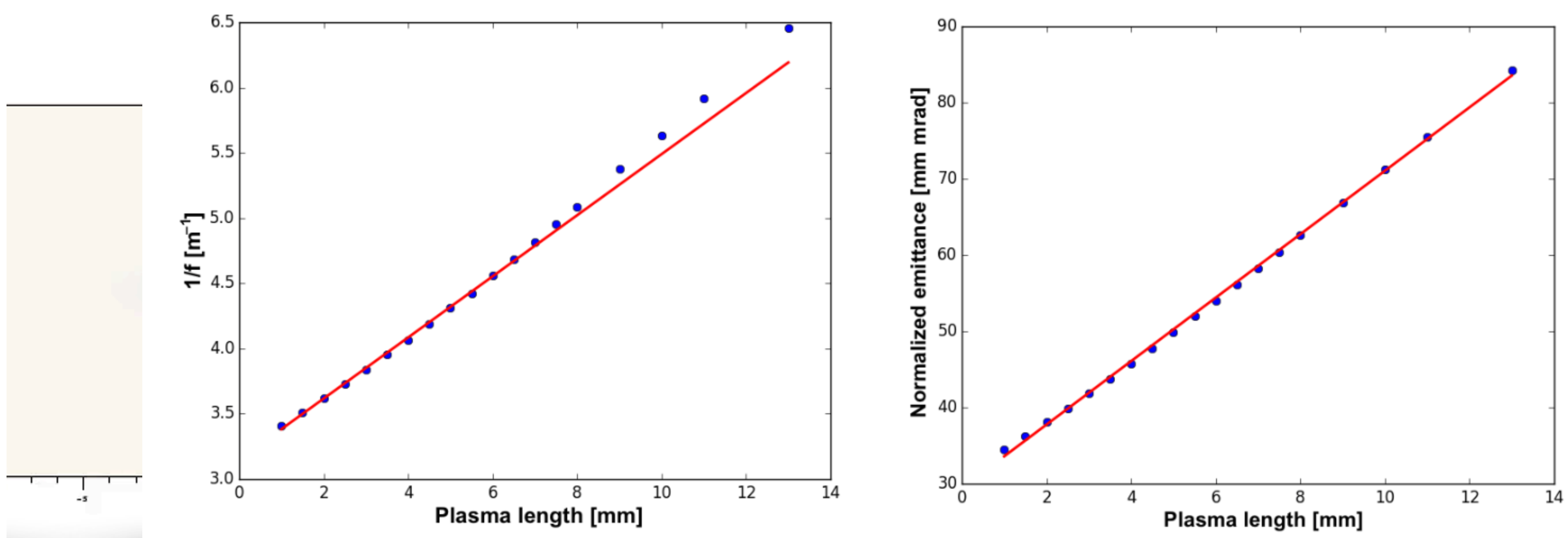
Two-stage plasma-undulator plasma accelerator is to be published soon.

Plasma Lens

- Plasma responds to cancel the space charge of a relativistic bunch.
- Plasma ions cancel the electric field of the bunch.
- Magnetic field of the bunch focuses the beam.





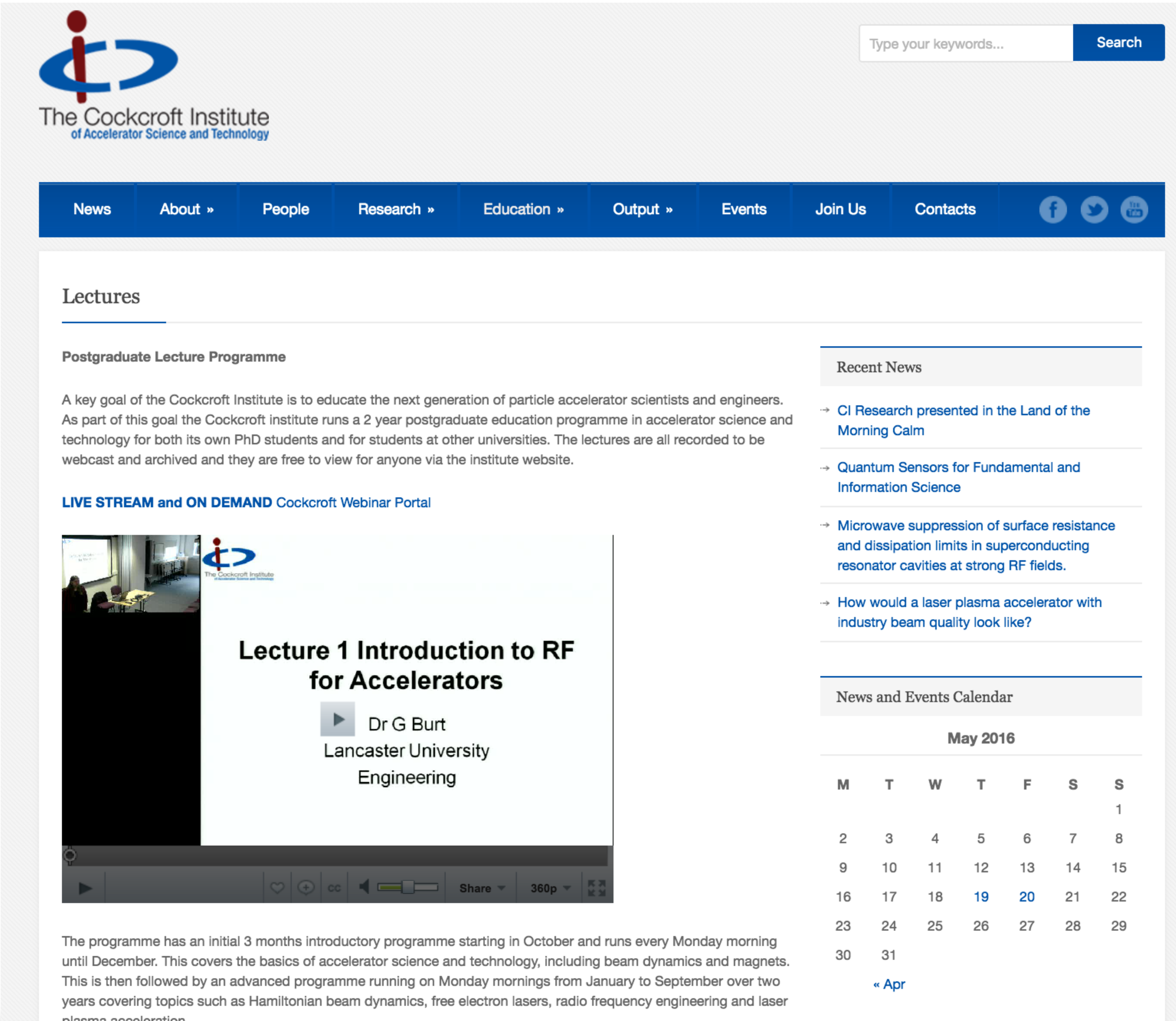


Focusing force differs from that of an ideal lens, leading to emittance growth.

- **Spherical aberration,** Focusing force not linear with radius.
- **Longitudinal aberration,** Focusing force varies with longitudinal position in bunch.

K. Hanahoe, et al., Simulation Studies of Plasma Lens Experiments at Daresbury Laboratory, Plasma Phys. Control. Fusion 58, 034002 (2016).

https://www.cockcroft.ac.uk/lectures



Lecture Slides available here

- Academic Training Programme 2015 - 2016
- Academic Training Programme 2014 - 2015
- Academic Training Programme 2013 - 2014
- Academic Training Programme 2012 - 2013
- Academic Training Programme 2011 - 2012
- Academic Training Programme 2010 - 2011
- Academic Training Programme 2009 - 2010
- Academic Training Programme 2008- 2009
- Academic Training Programme 2007- 2008
- Academic Training Programme 2006 - 2007
- Academic Training Programme 2005 - 2006
- Academic Training Programme 2004 - 2005

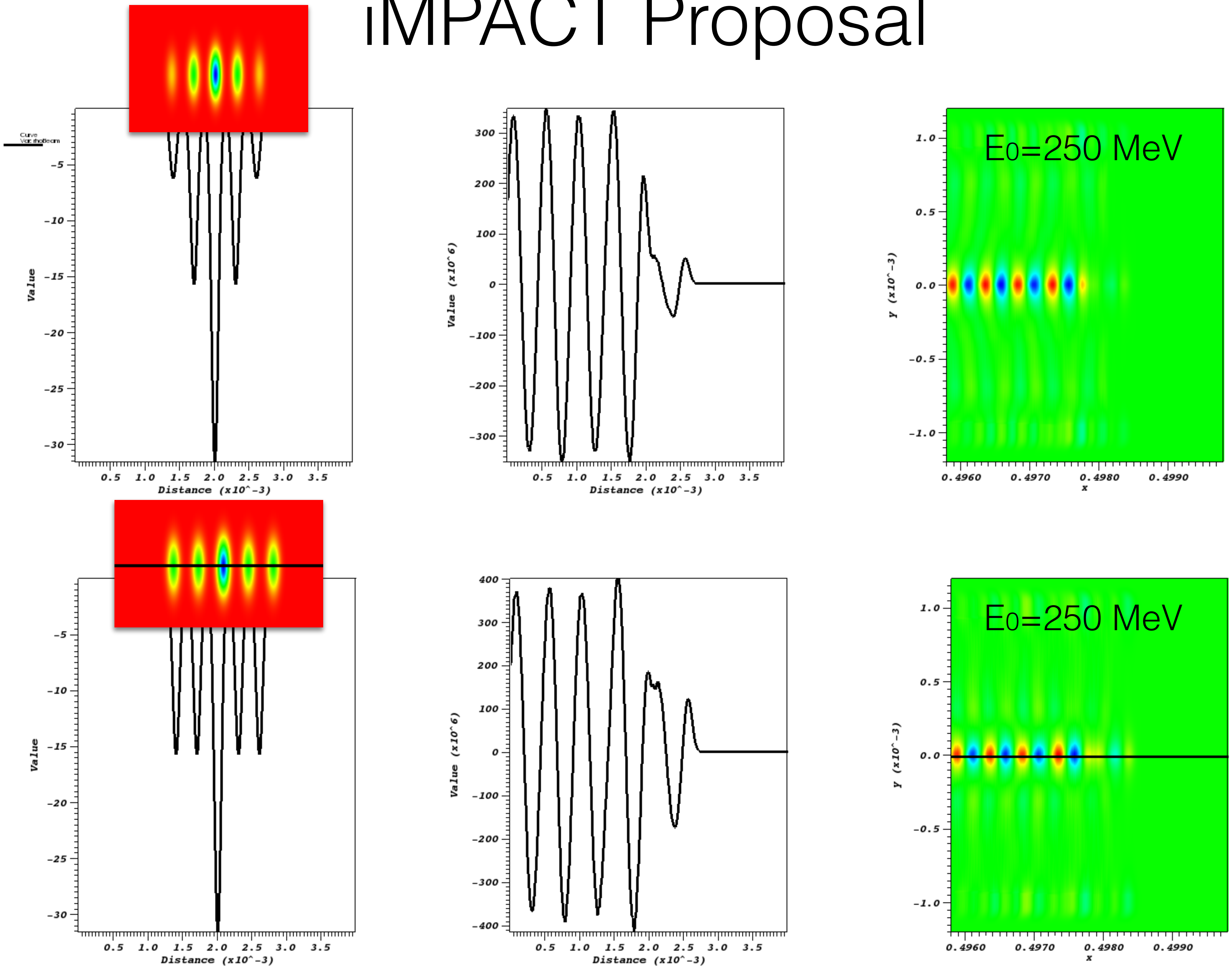
Conclusions

- We contribute to the search for advanced accelerating techniques through following activities:
  - designing and characterising of electron sources and injectors with flexible-wide range specifications,
  - numerical and analytical plasma-beam interaction; wakefield generation, high quality beam production,
  - future uses of the technology; e^-p, e^-e^+ colliders,
  - implementation in the local facilities; PARS at CLARA, iMPACT at CLARA Front End,
  - plasma sources, diagnostics and beam diagnostics.


ZZZzzzzzzzz...
Thank you for your attention...

Multi-Bunch Plasma Acceleration

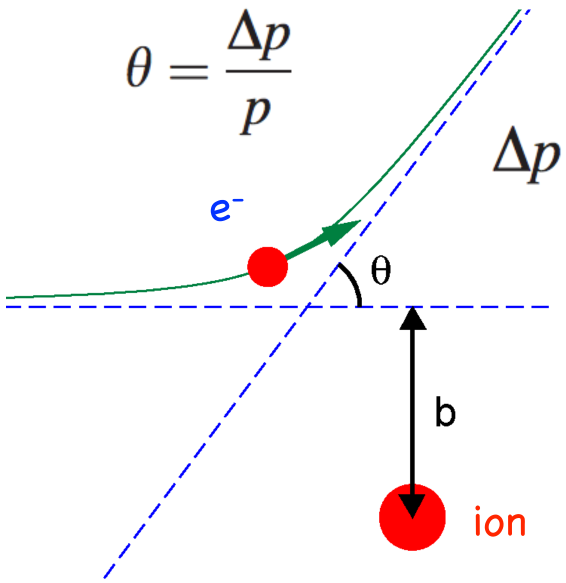
iMPACT Proposal



ELECTRON-PLASMA INTERACTIONS

Key Issues in Collider Design

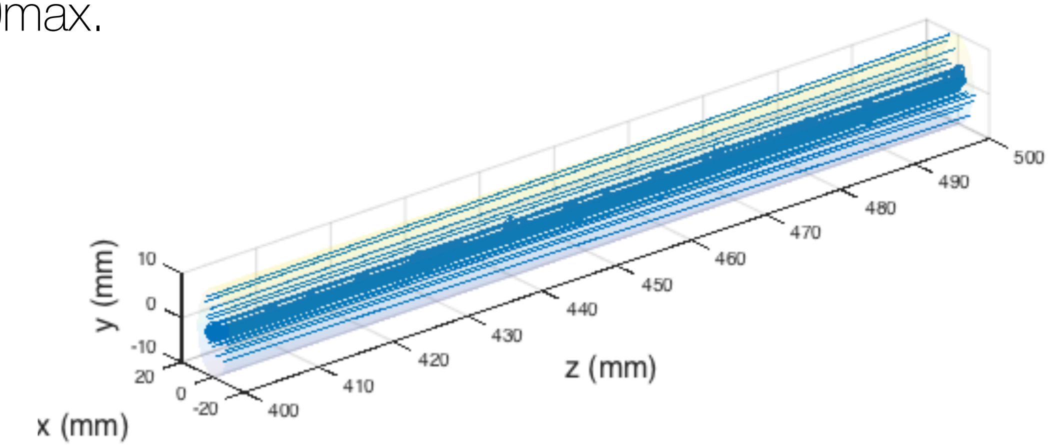
$$\theta = \frac{\Delta p}{p}$$

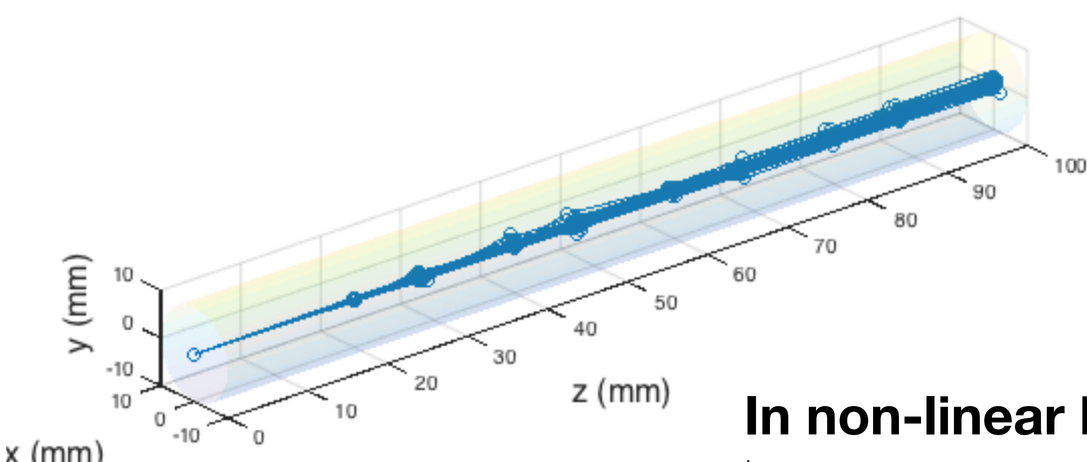


$$\Delta p\, b \geq \hbar$$

$$\theta_{min,\,max} = \frac{\hbar}{p\, b_{max,min}}$$

Minimum impact factor, can be related to the effective Coulomb radius of the nucleus, R (ion impact is larger than neutral atom case - due to the potential including the electronic structure of the ion). Simulations might overestimate θmax.





$$\epsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\langle x^2\rangle = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)^2$$

$$\langle x'^2\rangle = \frac{1}{N}\sum_{i=1}^{N}(x'_i - \langle x'\rangle)^2$$

$$\langle xx'\rangle = \frac{1}{N}\sum_{i=1}^{N}(x_i - \langle x\rangle)(x'_i - \langle x'\rangle)$$

In non-linear bubble regime, maximum impact parameter will be defined by the bubble radius yielding much smaller scattering angles.

In a fully ionised plasma, maximum impact parameter corresponds to the plasma Debye length.

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}$$