The *AWAKE* Experiment:
Beam-Plasma Interaction Simulations

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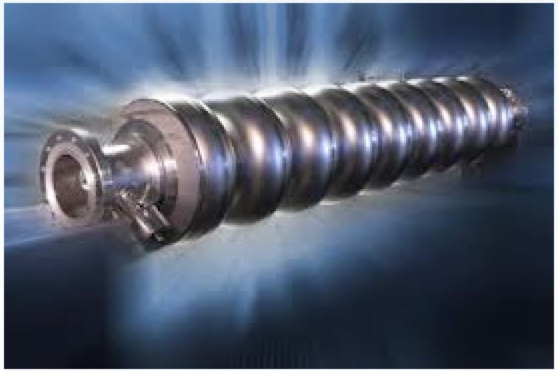
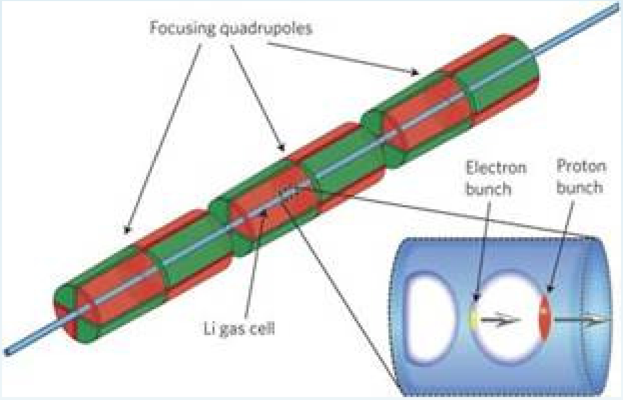
Outline

1. What is proton-driven plasma wakefield acceleration?
2. The AWAKE experiment
3. Simulations
    - 3.1 Experiment-level simulations
    - 3.2 Theoretical-benchmarking simulations
4. Conclusions

1. Proton-driven plasma wakefield acceleration

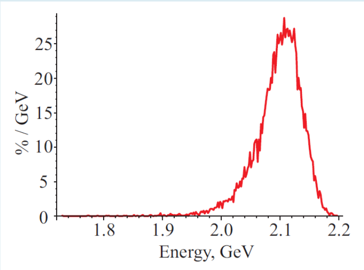
- Conventional RF accelerators are limited to 150 MV/m.
- Current proposals for lepton colliders range from *30-100 km*.



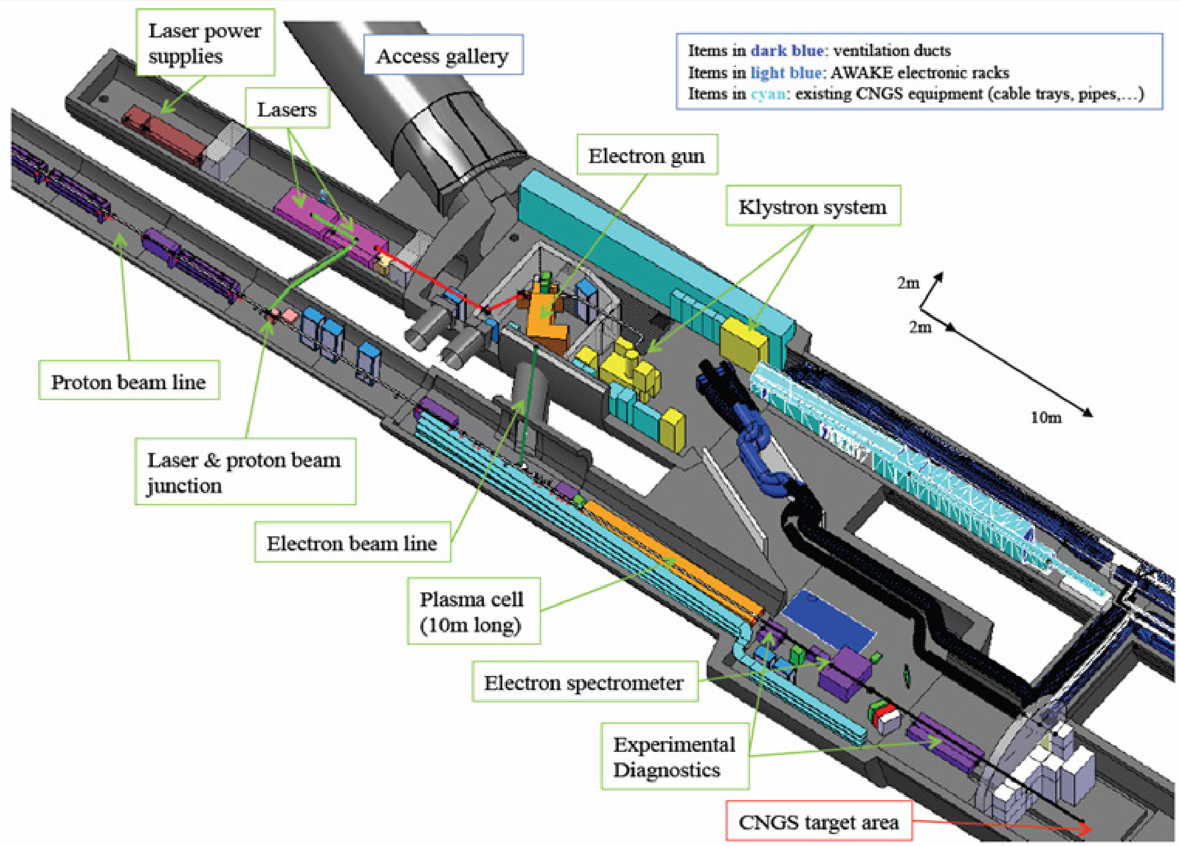


- Laser driven plasma wakefield accelerators has demonstrated 100 GV/m over a few cm.
- Using ~TeV protons, it may be possible to accelerate e^-/e^+ at ~1 GV/m over the *km* scale.
- For now we want to do this over the 10 m scale.

2. The AWAKE experiment



- Proof of principle experiment to accelerate electrons by *2 GeV* in ~*7m* of plasma.
- Will use the CERN SPS *400 GeV* proton beam to drive a plasma wakefield.
- Due to start late 2016.



3. Simulations

3.1 Experiment-level simulations

3.1 Experiment-level simulations

The Simulation Code Used

- The open source **Particle-in-cell (PIC) code EPOCH**.[1]
- Simulations are a **2D slab** (Cartesian) geometry, but the underlying physics is 3D.
- **Very computationally intensive**
  - Takes typically 5 core years to run on the MPI supercomputer Hydra.
  - Therefore *not suitable* for parameter scans.

[1] C.S. Brady, T.D. Arber (2011) Plasma Phys. Control. Fusion, 53, 015001.

3.1 Experiment-level simulations

Experimental parameters (e^- side-injection)

Drive-beam (protons)	
p^+/bunch	3.5×10^{11}
p	450 GeV
σ_r	0.19 mm
σ_z	12 cm

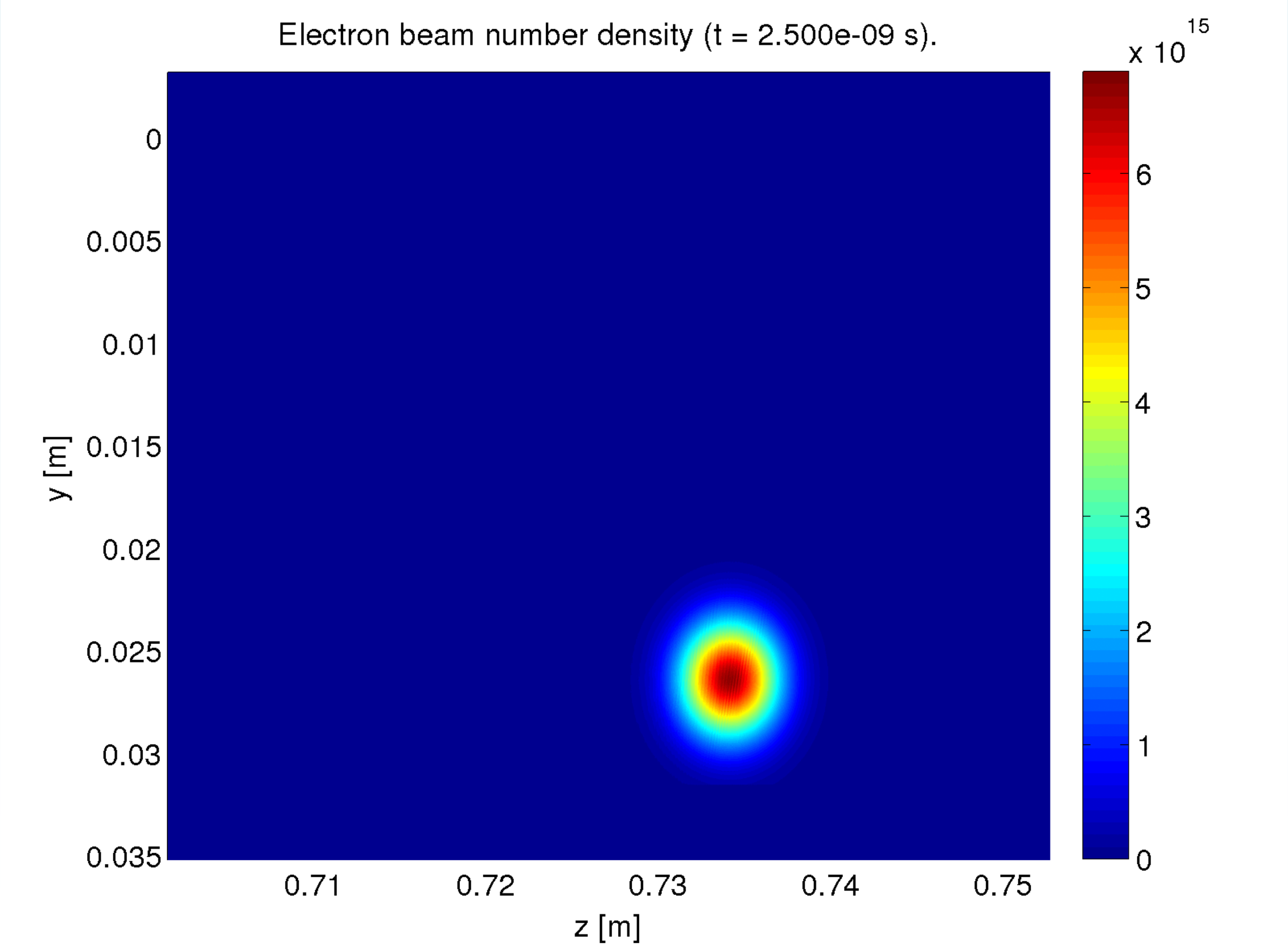
Plasma	
Element	caesium
Number density	7.7×10^{14} cm^{-3}
Plasma wavelength	1.2 mm

Captured-beam (electrons)	
e^-/bunch	10^9
p	20 MeV
σ_r	2 mm
σ_z	2 mm

Beam-injection	
Laser ionisation	p^+ centroid
e^- injection angle	5 mrad
e^--p^+ intersection	3 m
e^--p^+ delay	20 cm

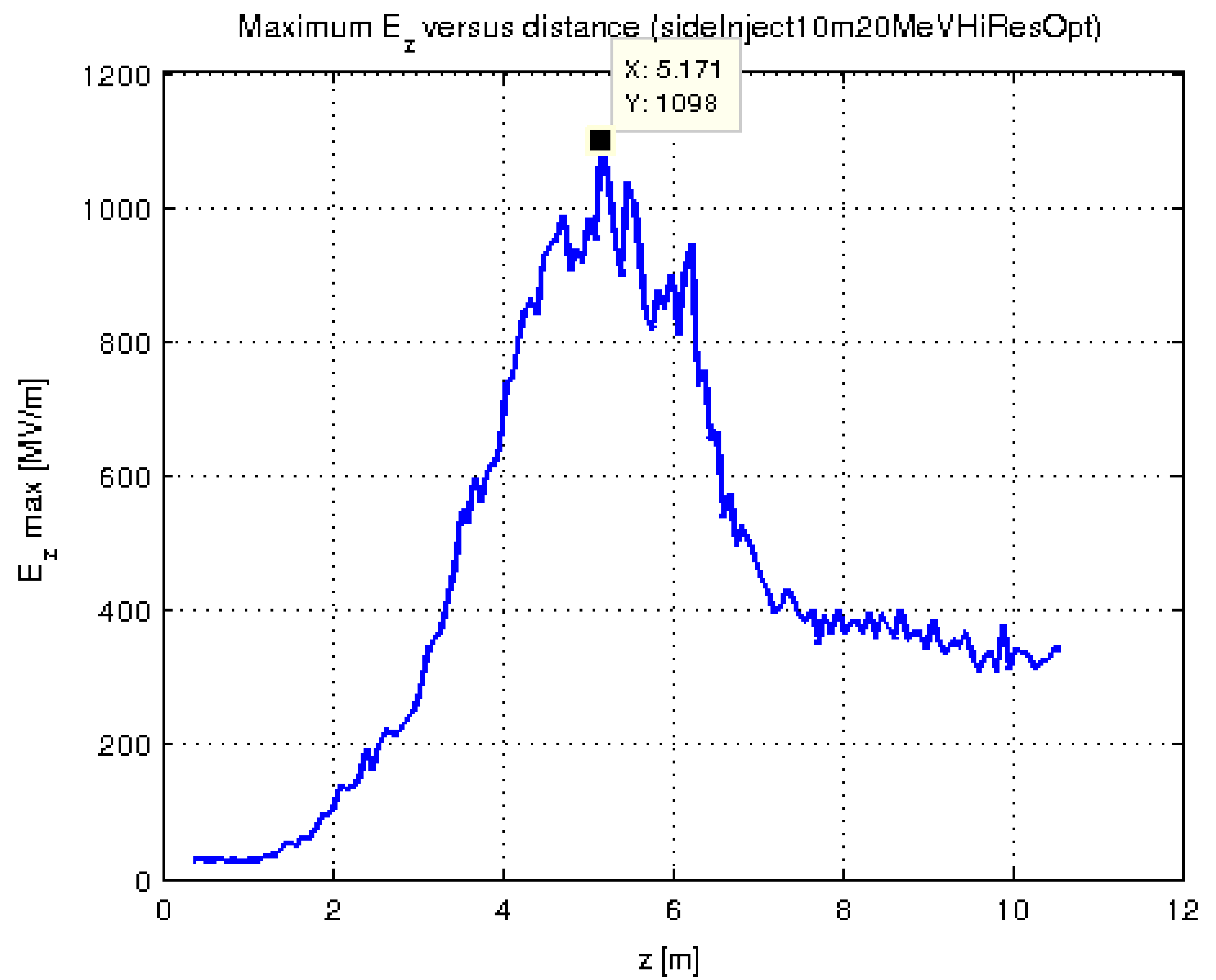
3.1 Experiment-level simulations

Electron capture



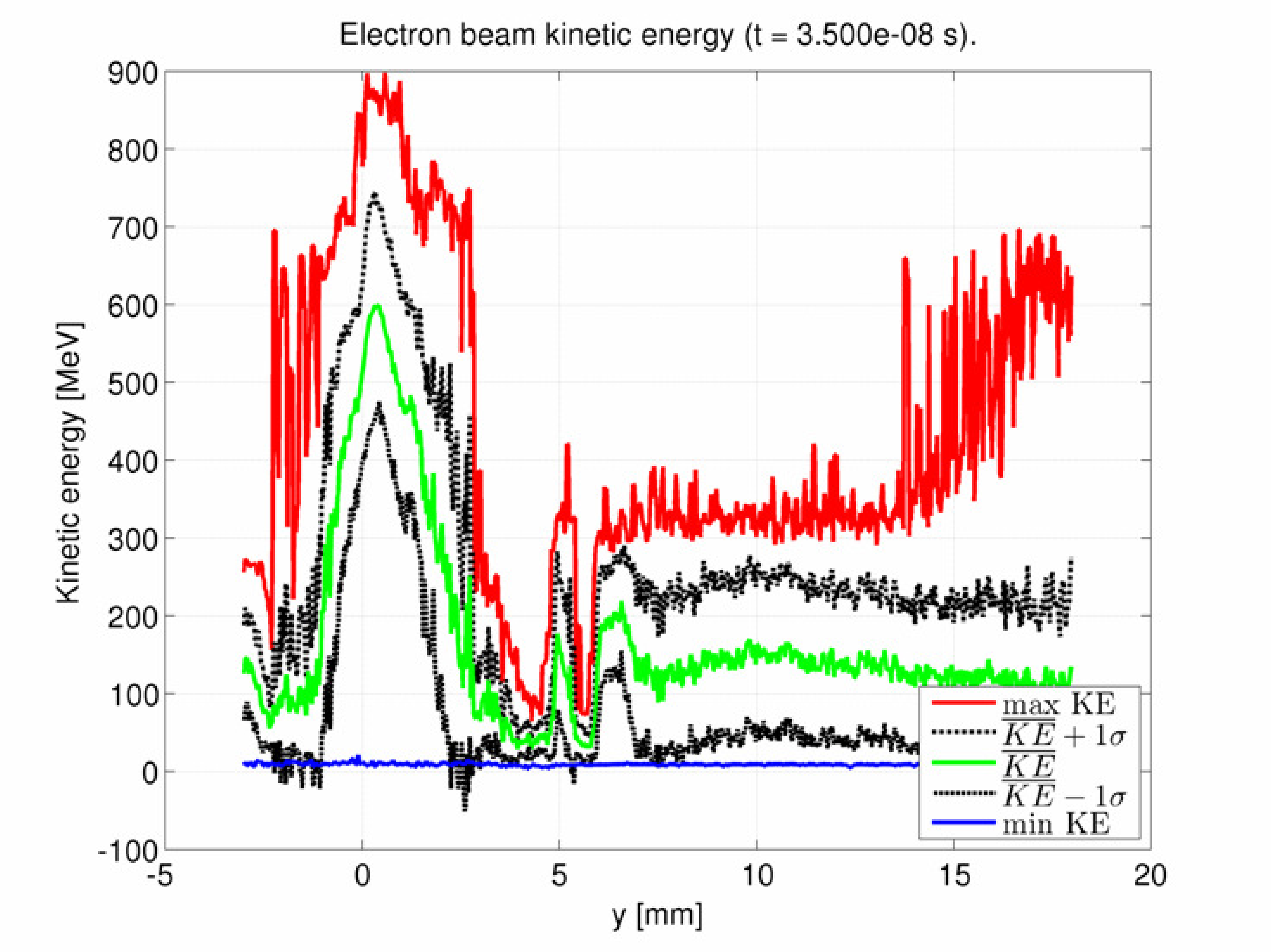
3.1 Experiment-level simulations

E_z Max (z)



3.1 Experiment-level simulations

Electron Kinetic Energy Distribution (10.5m)



3. Simulations

3.2 Theoretical-benchmarking simulations

3.2 Theoretical-benchmarking simulations

The Simulation Code Used

- Uses the freely distributed **hybrid code LCODE**.[2]
- *Not* open-source.
- Simulations are **2D cylindrical** geometry.
- **Computationally modest**
  - Takes ~1 week for a single core machine to process.
  - Not parallelisable, but more accessible.

[2] K.V.Lotov, (2003) Phys. Rev. ST. Accel. Beams, 6, 061301.

3.2 Theoretical-benchmarking simulations

Theory 1/2

- Linear wakefield theory predicts *testable* results when driven by a rectangular bunch.
- This acts as a constant n_b in the integral:

$$E_z(\xi, r) = \frac{q_e}{\varepsilon_0} \int_{-\infty}^{\xi} \int_0^{\infty} n_b(\xi, r) \cos(\xi - \xi') f(r)\, dr\, d\xi'$$

- … so, we get a predicted longitudinal field of:

$$\Rightarrow E_z(\xi) = \frac{q_e n_b}{k_p \varepsilon_0} \int_0^{\infty} f(r)\, dr \begin{cases} \sin(k_p \xi), & 0 \le \xi \le L_b \\ \sin(k_p \xi) - \sin(k_p(\xi - L_b)). & L_b < \xi \end{cases}$$

3.2 Theoretical-benchmarking simulations:
Theory 2/2

- Building on work by Yun Fang[3]; for a *longitudinally* rectangular, *transversely* Gaussian beam, the E-field can be derived:
  - The E-field **inside the bunch** is:

$$E'_{z,\max} = \frac{Q}{\varepsilon_0 L^2 \sigma_r^2} \int_0^\infty \exp\left(\frac{-r^2}{2\sigma_r^2}\right) K_0\left(\frac{2\pi r}{L_b}\right) r\,dr$$

  - …and the E-field **behind the bunch** is:

$$E''_{z,\max} = E'_{z,\max} T$$

    …where T is the interference of the front & back edges (the transformer ratio):

$$T = \sqrt{2(1-\cos k_p L_b)}$$

  - Its maximum is 2:
    - when $L_b = \lambda(n + ½)$
  - Its minimum is 0:
    - when $L_b = n\lambda$.

[3] PhD Thesis: *Resonant Excitation of Plasma Wakefield*

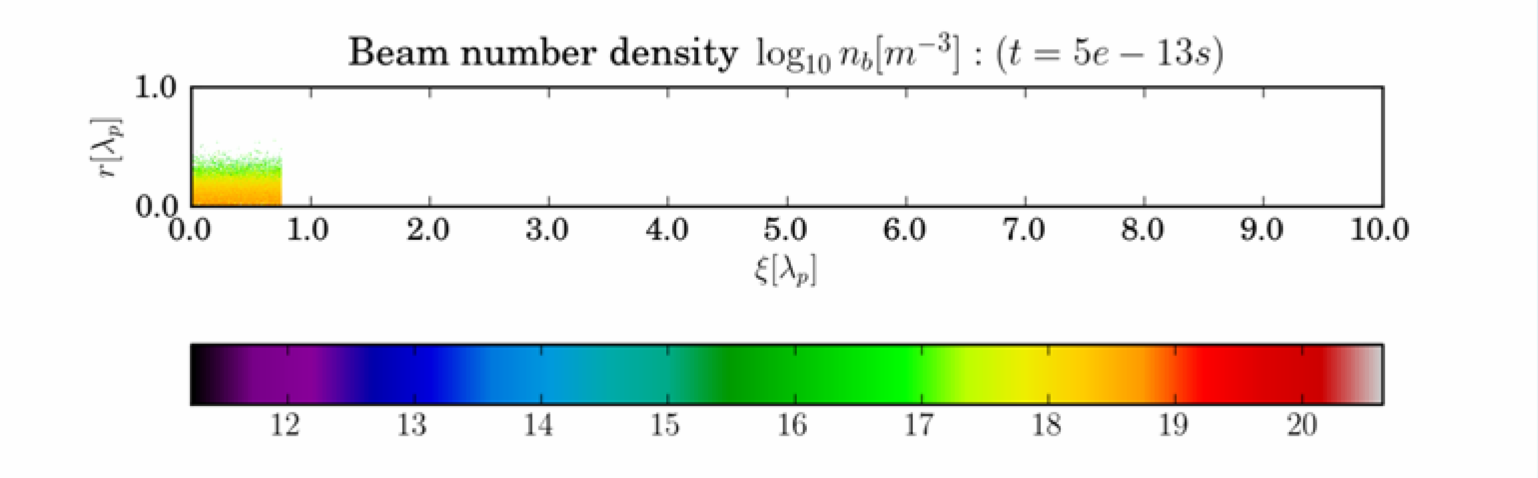
3.2 Theoretical-benchmarking simulations

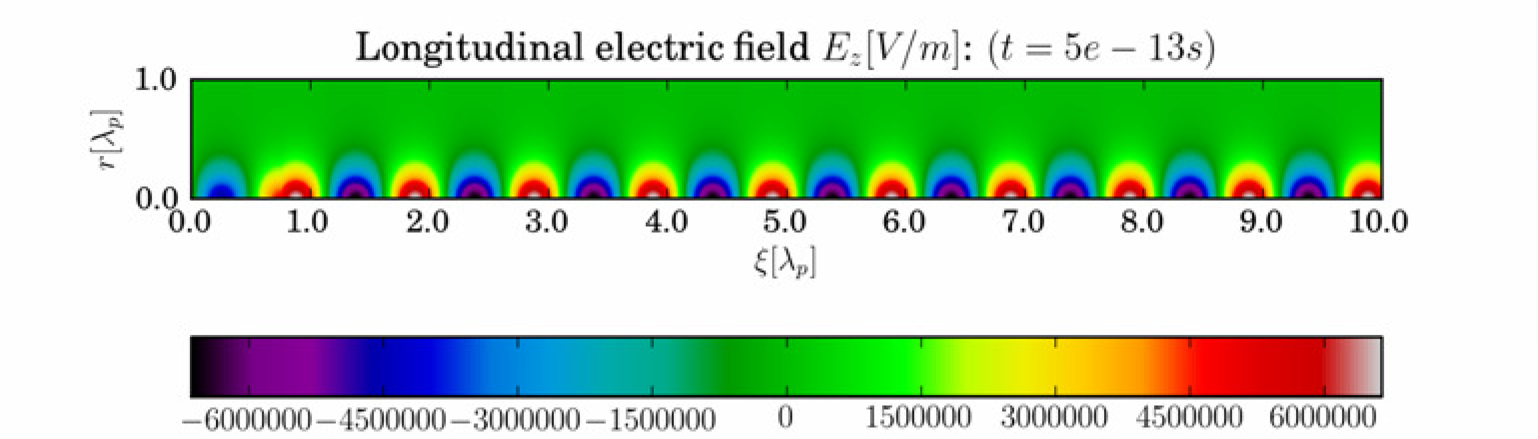
Drive-beam (electrons)	
bunch charge	50 pC
e^-/bunch	3.12×10^8
p	58.3 ± 0.48 MeV
σ_r	0.12 mm
L_z	[1.0, 0.75, 0.5] mm
ε_r	13 mm mrad

Plasma	
Element	hydrogen
Number density	1.1×10^{15} cm^{-3}
Plasma wavelength	1 mm

3.2 Theoretical-benchmarking simulations:

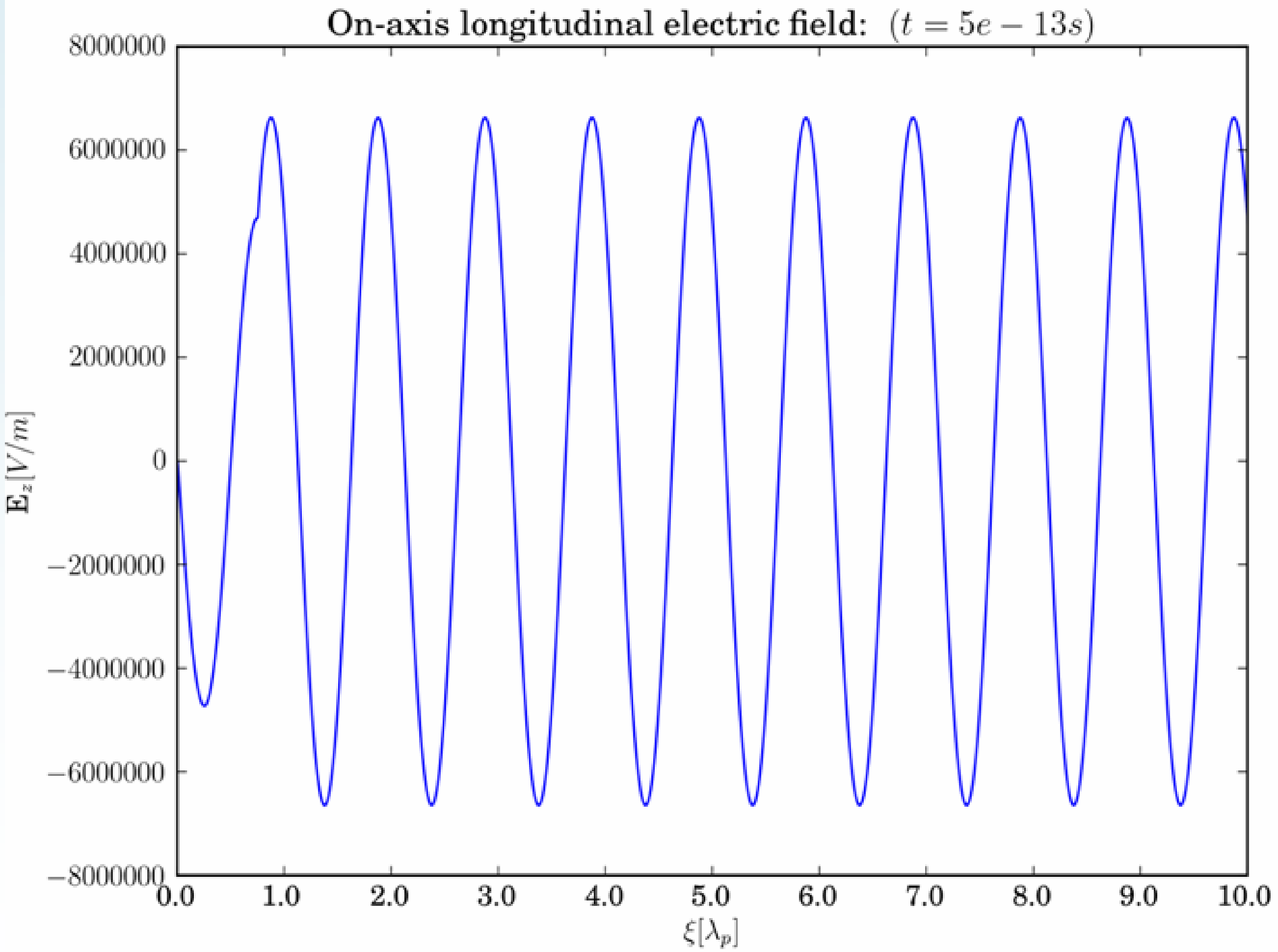
¾ length bunch





3.2 Theoretical-benchmarking simulations

¾ length bunch



3.2 Theoretical-benchmarking simulations

Results versus theory

	Simulation (λ_p = 1mm)	L_b/λ_p	$\frac{Q}{\varepsilon_0 L_b^2 \sigma_r^2}$	$\int_0^\infty \exp\left(\frac{-r^2}{2\sigma_r^2}\right) K_0\left(\frac{2\pi r}{L_b}\right) r\,dr$	T	$E_z(theory)$ $[MV/m]$	$E_z(sim.)$ $[MV/m]$	$\frac{E_z(theory)}{E_z(sim.)}$
Inside bunch	ATFsquareBunch	1	3.92×10^{14}	9.05×10^{-9}	-	3.55	3.5	**1.01**
	ATFsquareBunch3qtr	0.75	6.97×10^{14}	6.60×10^{-9}	-	4.60	4.75	**0.97**
	ATFsquareBunch1half	0.5	1.57×10^{15}	3.93×10^{-9}	-	6.16	7	**0.88**
Outside bunch	ATFsquareBunch	1	3.92×10^{14}	9.05×10^{-9}	0	0	0.05	-
	ATFsquareBunch3qtr	0.75	6.97×10^{14}	6.60×10^{-9}	$\sqrt{2}$	6.51	6.7	**0.97**
	ATFsquareBunch1half	0.5	1.57×10^{15}	3.93×10^{-9}	2	12.3	14	**0.88**

4. Conclusions

- AWAKE: Strong acceleration fields expected.
  - Up to 1GV/m
  - Average fields ~400MV/m, sustained over 10m
- Un-optimised EPOCH simulations see:
  - ~ GeV energy electrons
  - Significant capture efficiencies
- With the new LCODE simulations…
  - We see agreement with theory to the 1%-10% level.
  - Can now start parameter scans to optimise the experiment, ready for 2016!
- Exciting times ahead!!!

The end

Backup slides

Background references

- AWAKE experiment
  - Technical design report: CERN SPSC-TDR-003.
  - M. Wing et al. (2014, Jan.) “Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics,” arXiv:1401.4823.
  - Muggli et al. (2013) “Physics of the AWAKE project,” Proceedings of IPAC2013, TUPEA008.
- Proposals for future RF e+/e- accelerators:
  - The 150 MV/m RF accelerator limit:
    - G. Guignard et al. (2000) “A 3TeV e+e– linear collider based on CLIC technology,” CERN-2000-008.
  - The 30 km e^+/e^- proposal:
    - J. Brau et al. (2008, Jun.) “International Linear Collider Reference Design Report,” SLAC-R-857.
  - The 80-100 km e^+/e^- proposal:
    - A. Blondel et al. (2012, Aug.) “LEP3: A high luminosity e+e– collider to study the Higgs boson,” arXiv:1208.0504v2.
    - M. Koratzinos et al (2013, May) “TLEP: A High-Performance Circular e+e- Collider to study the Higgs Boson,” arXiv:1305.6498.
- Laser-driven wakefield:
  - 100 GV/m result:
    - W.P. Leemans et al. (2006, Oct.) “GeV electron beams from a centimetrescale accelerator,” Nature Physics, vol. 2, No. 10, pp. 696–699.
- Particle-driven wakefield:
  - Landmark proton beam simulations:
    - A. Caldwell et al. (May 2009) “Proton-driven plasma-wakefield acceleration,” Nature physics vol. 5, pp.363-367
  - SLAC energy doubling result:
    - I. Blumenfeld et al. (Feb 2007) “Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator,” Nature vol. 4, no. 45, pp. 741-744.

The AWAKE experiment

Baseline design parameters

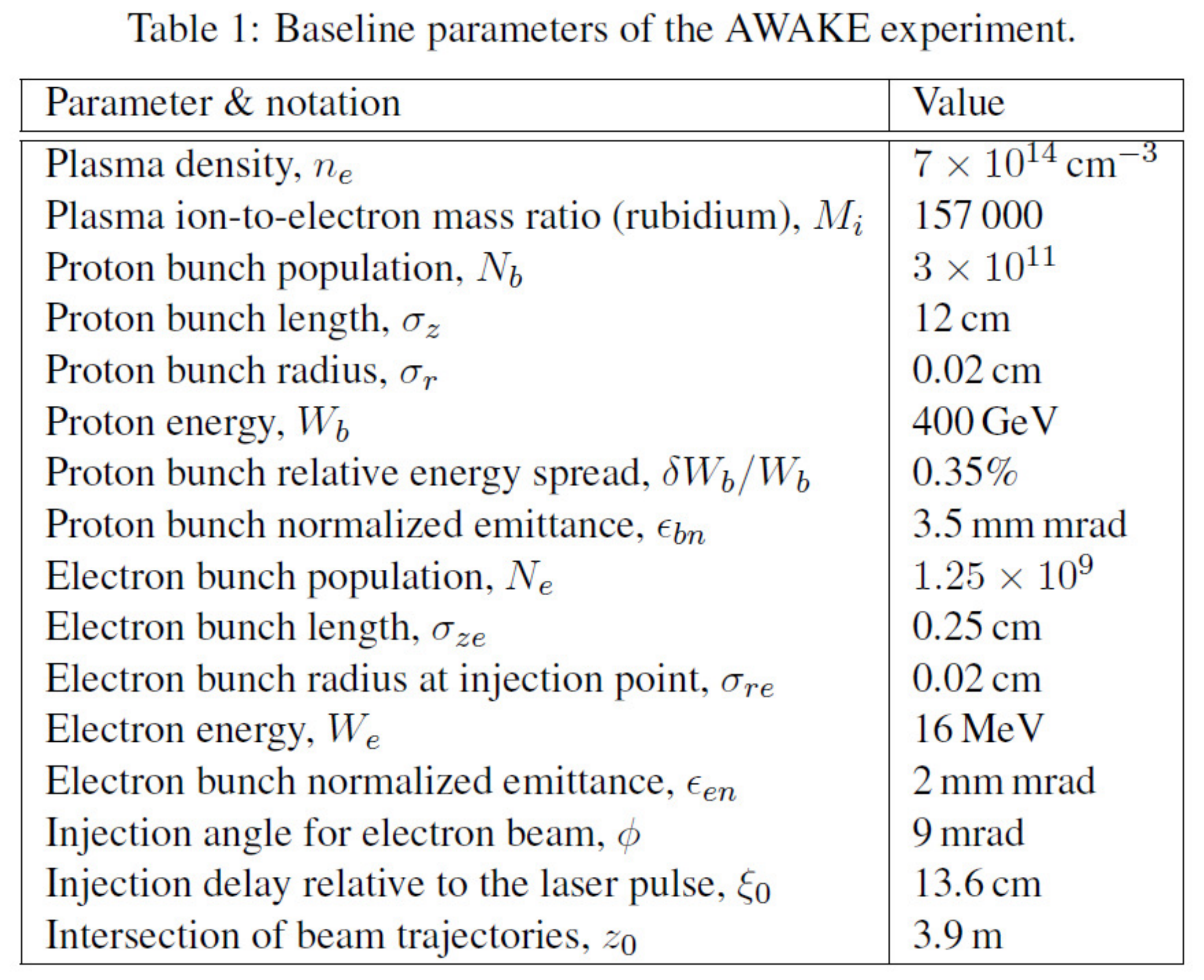


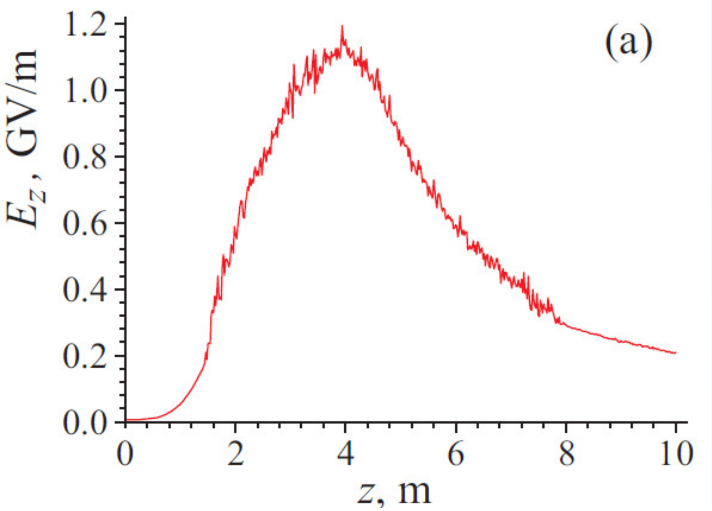
Table 1: Baseline parameters of the AWAKE experiment.

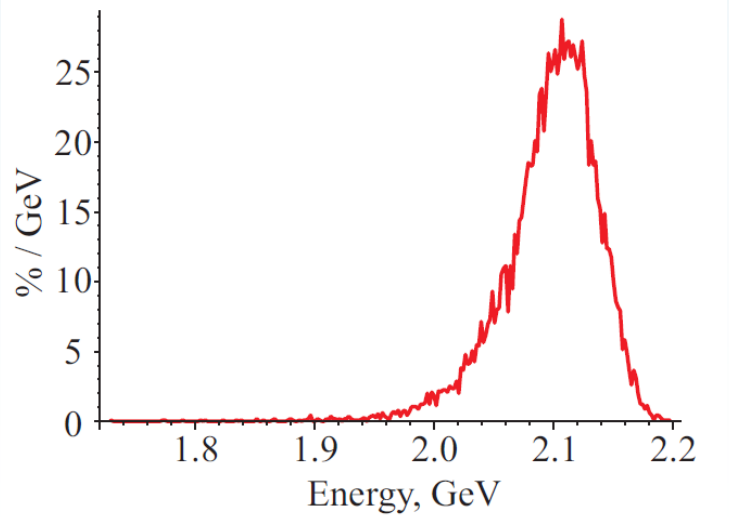
Parameter & notation	Value
Plasma density, n_e	7×10^{14} cm^{-3}
Plasma ion-to-electron mass ratio (rubidium), M_i	157 000
Proton bunch population, N_b	3×10^{11}
Proton bunch length, σ_z	12 cm
Proton bunch radius, σ_r	0.02 cm
Proton energy, W_b	400 GeV
Proton bunch relative energy spread, $\delta W_b / W_b$	0.35%
Proton bunch normalized emittance, ϵ_{bn}	3.5 mm mrad
Electron bunch population, N_e	1.25×10^9
Electron bunch length, σ_{ze}	0.25 cm
Electron bunch radius at injection point, σ_{re}	0.02 cm
Electron energy, W_e	16 MeV
Electron bunch normalized emittance, ϵ_{en}	2 mm mrad
Injection angle for electron beam, ϕ	9 mrad
Injection delay relative to the laser pulse, ξ_0	13.6 cm
Intersection of beam trajectories, z_0	3.9 m

The AWAKE experiment

Expected performance (Baseline parameters)

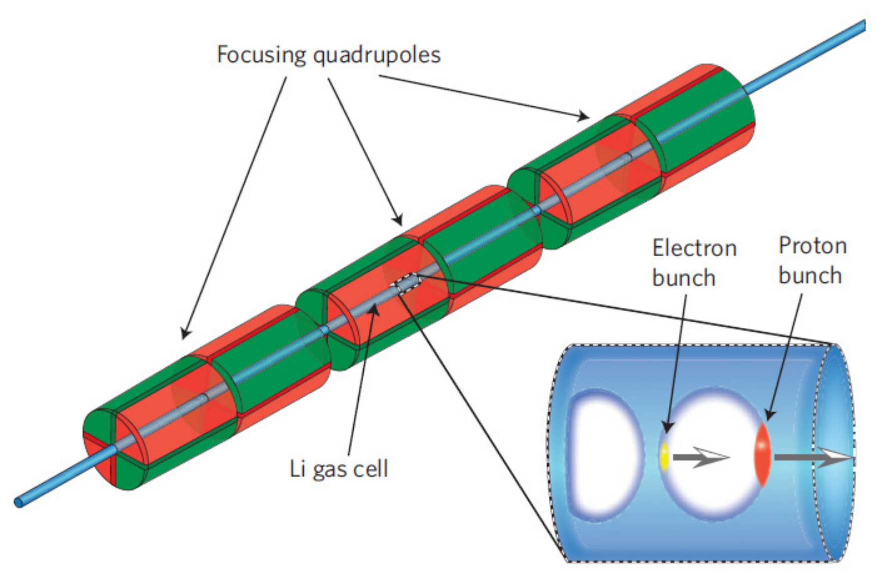
- Peak Ez fields of 1.1 GV/m expected
- Average fields ~400 MV/m
- Hope to see electrons with:
  - 2 GeV ± 3%
  - 5% capture efficiency
  - 54 π mm mrad norm. emittance.
- Higher capture efficiencies possible too, but with different run-parameters.



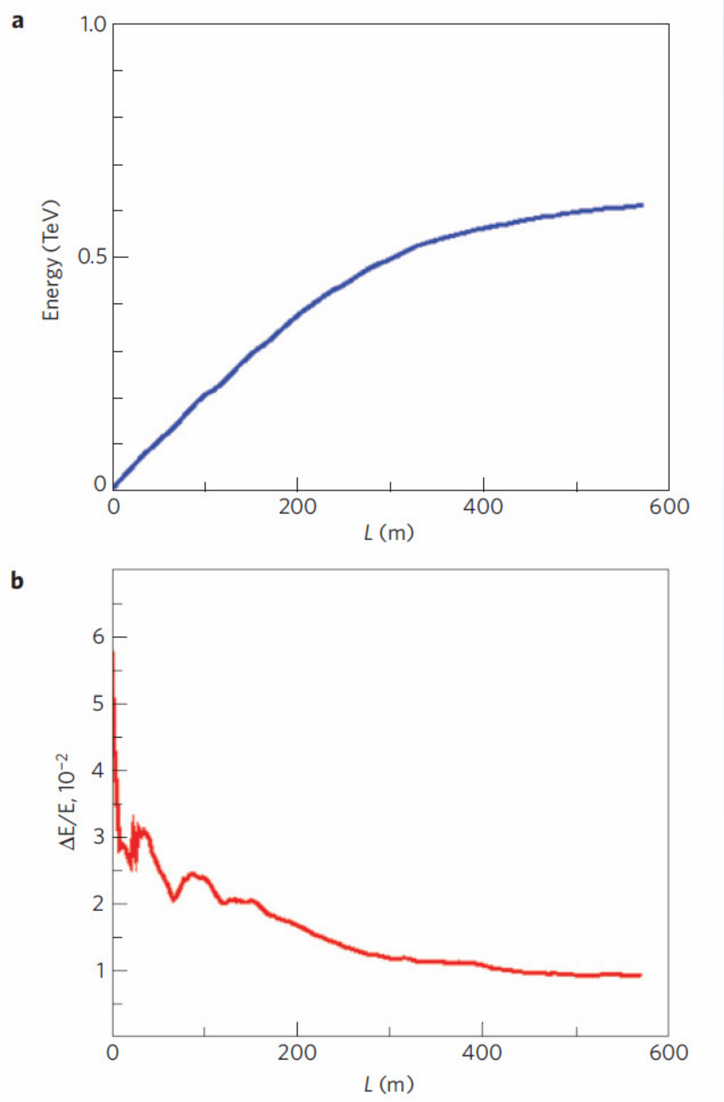


Simulation result: (Nature physics)

LHC beam driving electrons to 0.5 TeV after 500m

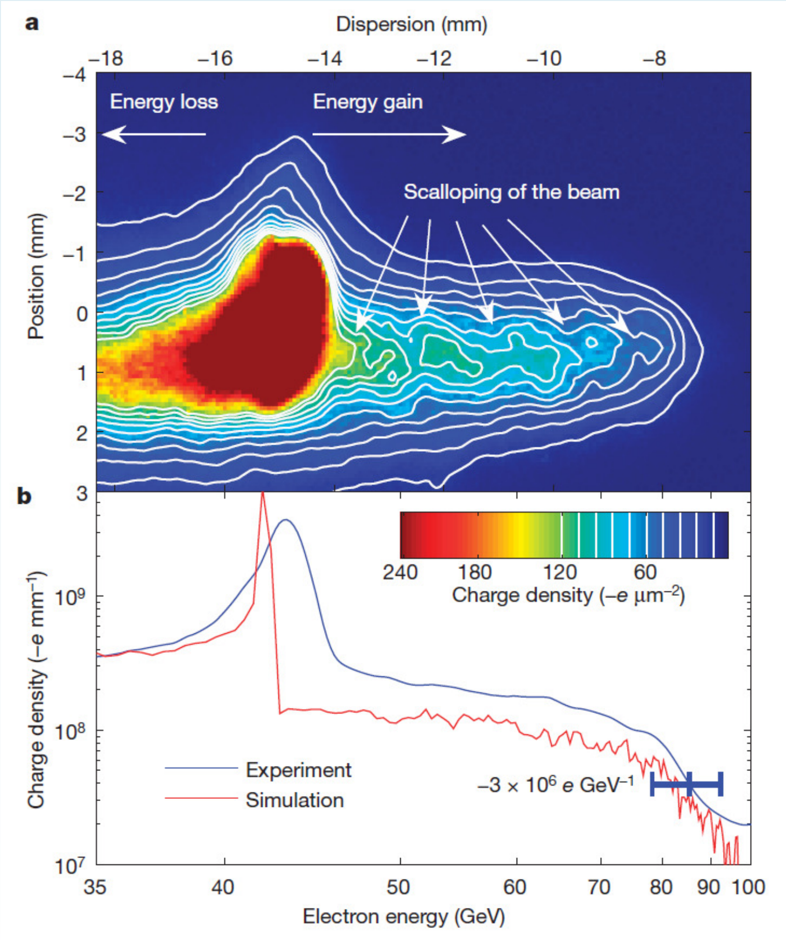


- Compressing the LHC beam longitudinally creates a strong sustainable acceleration.
- Currently, CERN beams are long…
  - But if we prove it works over 10m, then it may be worth investing in a beam compressor…



SLAC Result: (Nature physics)

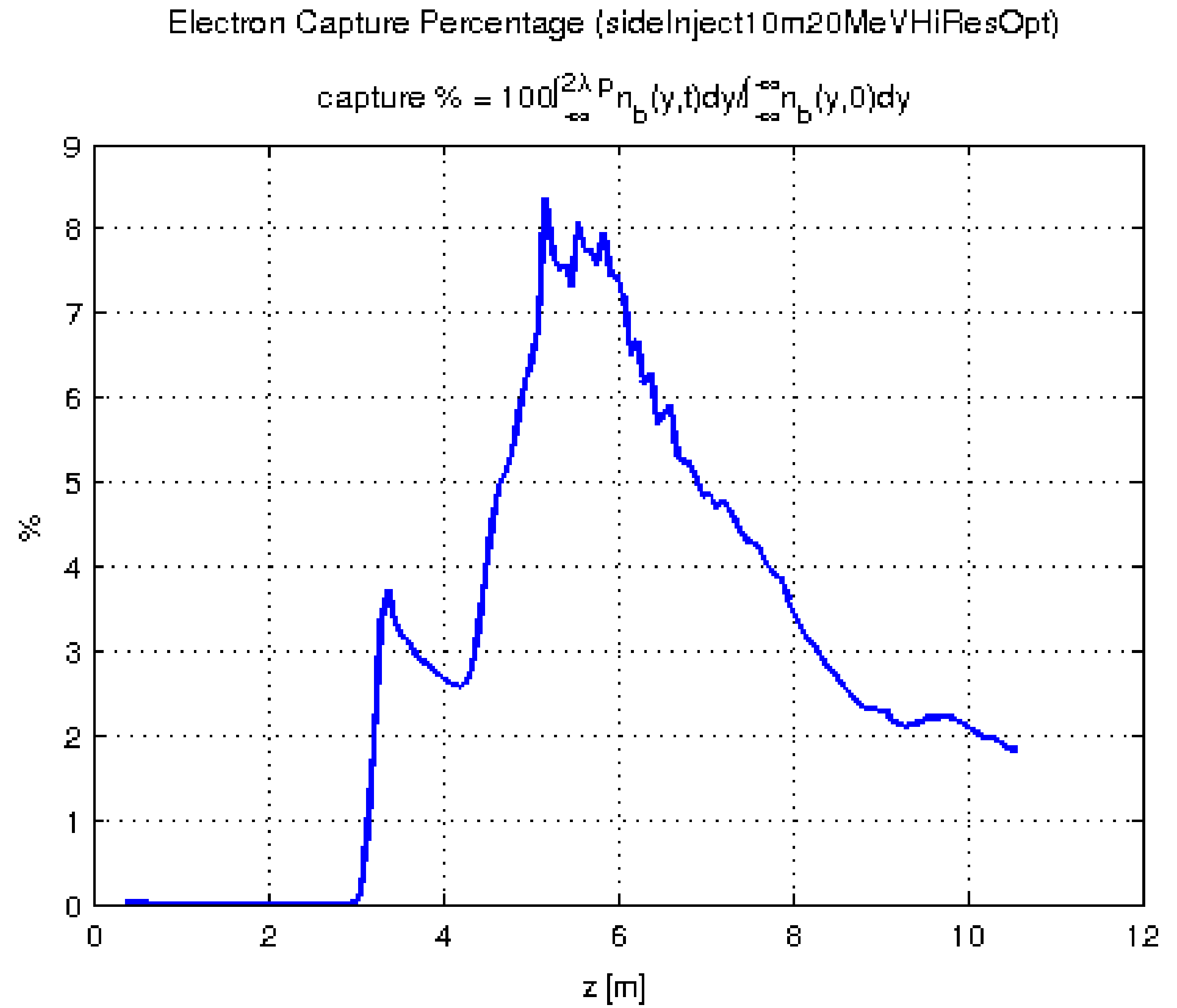
Energy doubling of 42 GeV e^- beam in < 1m



- Using a 42 GeV electron drive & witness beam, a small number of the trailing electrons reached over 80 GeV in 85 cm.

Simulation (e$^-$ beam side-injection)

Electron Capture Percentage



Important Formulae

- Plasma wavelength λ_p
  - Wavelength of plasma electron oscillations

$$\lambda_p = \frac{2\pi c\sqrt{m_e \varepsilon_0}}{q_e}\sqrt{\frac{1}{n}}$$

- Skin depth c/ω_p
  - Maximum range of relativistic particles.
  - Also ideal value for the RMS beam width σ_r

$$c/\omega_p = \frac{\lambda_p}{2\pi}$$

- Beam co-ordinate ξ

$$\xi = z - ct$$

- Maximum attainable electric field (via microbunching)
  - A beam of RMS length σ_z breaks up into microbunches of skin-depth length $\sigma_\mu = \lambda_p/2\pi$

$$E_{z,\mu,\max}[V/m] = \frac{5q_e}{\pi e c\sqrt{m_e \varepsilon_0}}\frac{N}{\lambda_p \sigma_z^2}$$

- Alfvén current
  - Limit of a stable beam before internal forces break up beam

$$I_A = \frac{4\pi\varepsilon_0 m_e c^3}{q_e} \approx 17kA$$