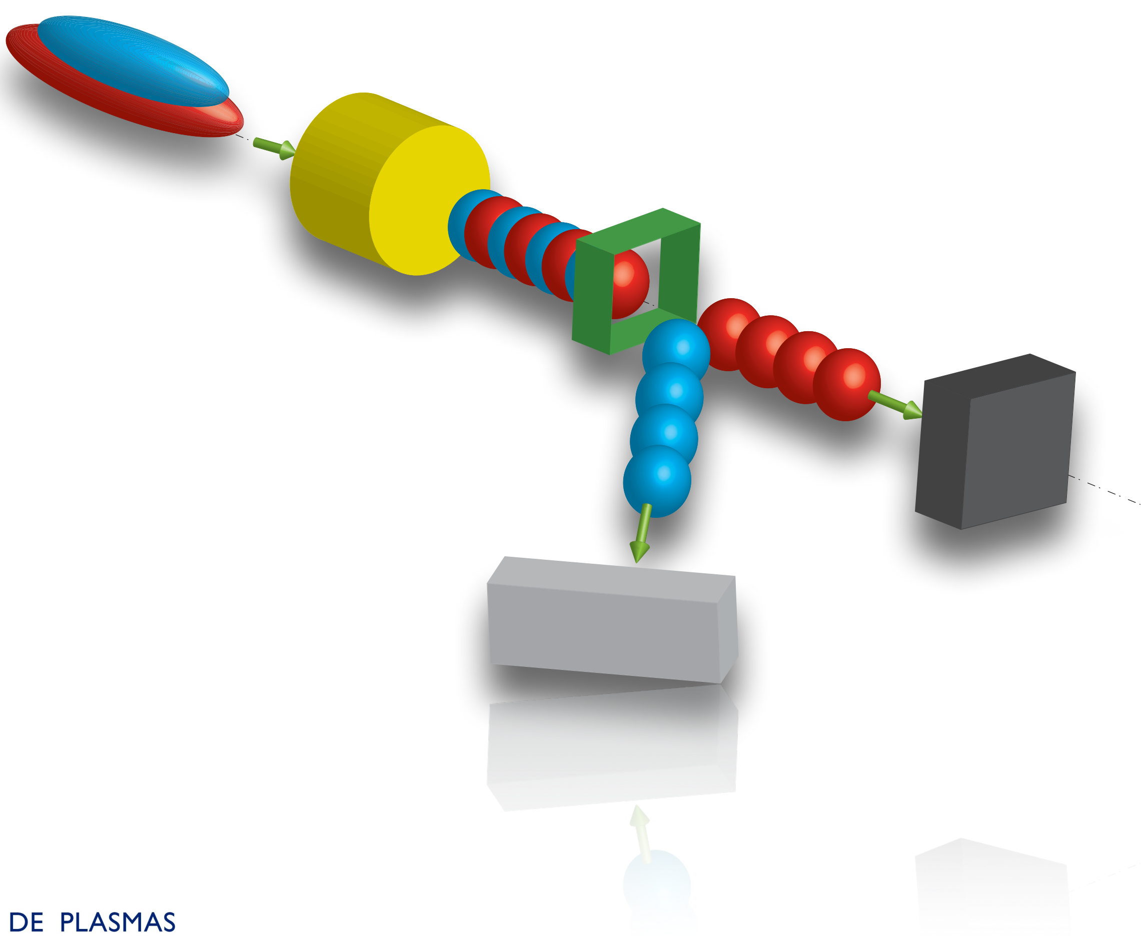
AWAKE Advanced Wakefield Acceleration Experiment

J. Vieira

for the AWAKE collaboration

Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico
Lisbon, Portugal

http://epp.ist.utl.pt[/jorgevieira]



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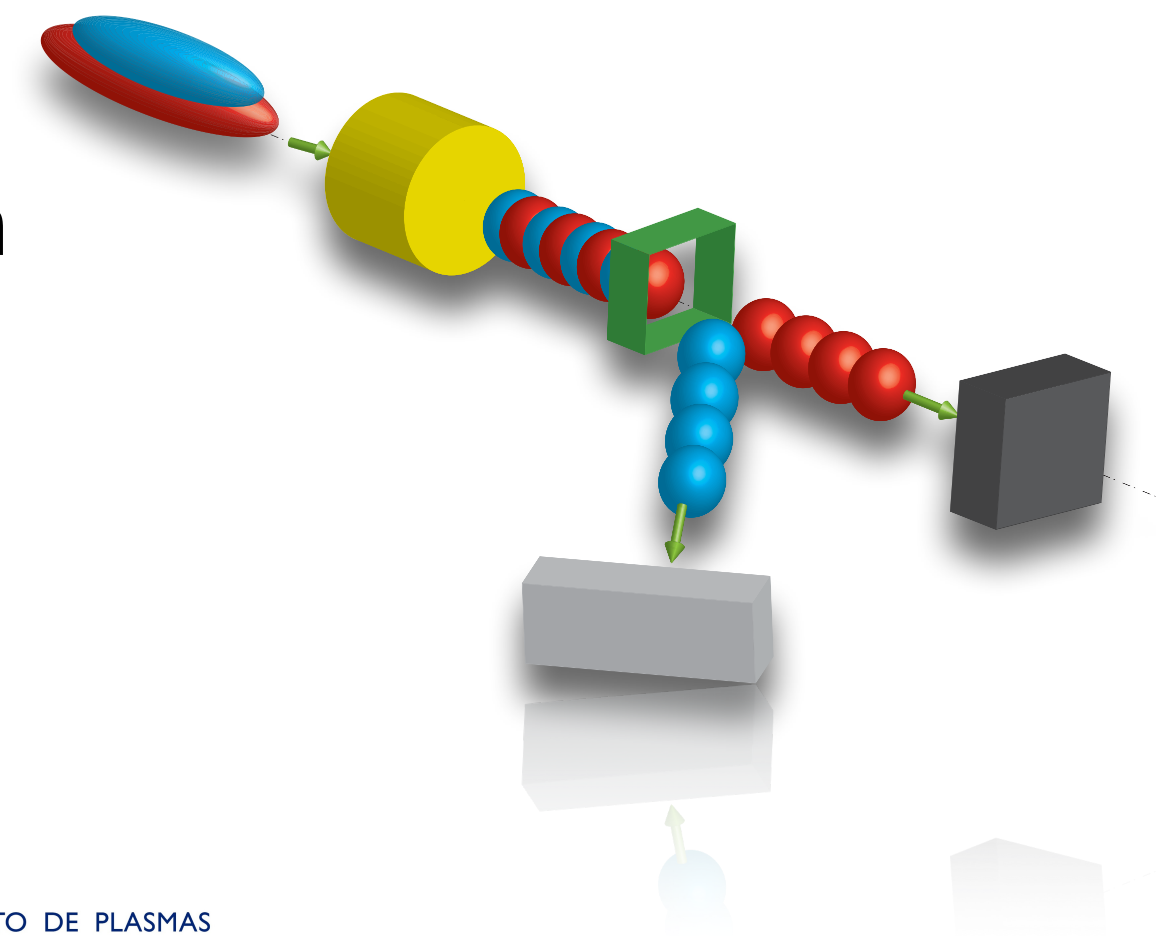
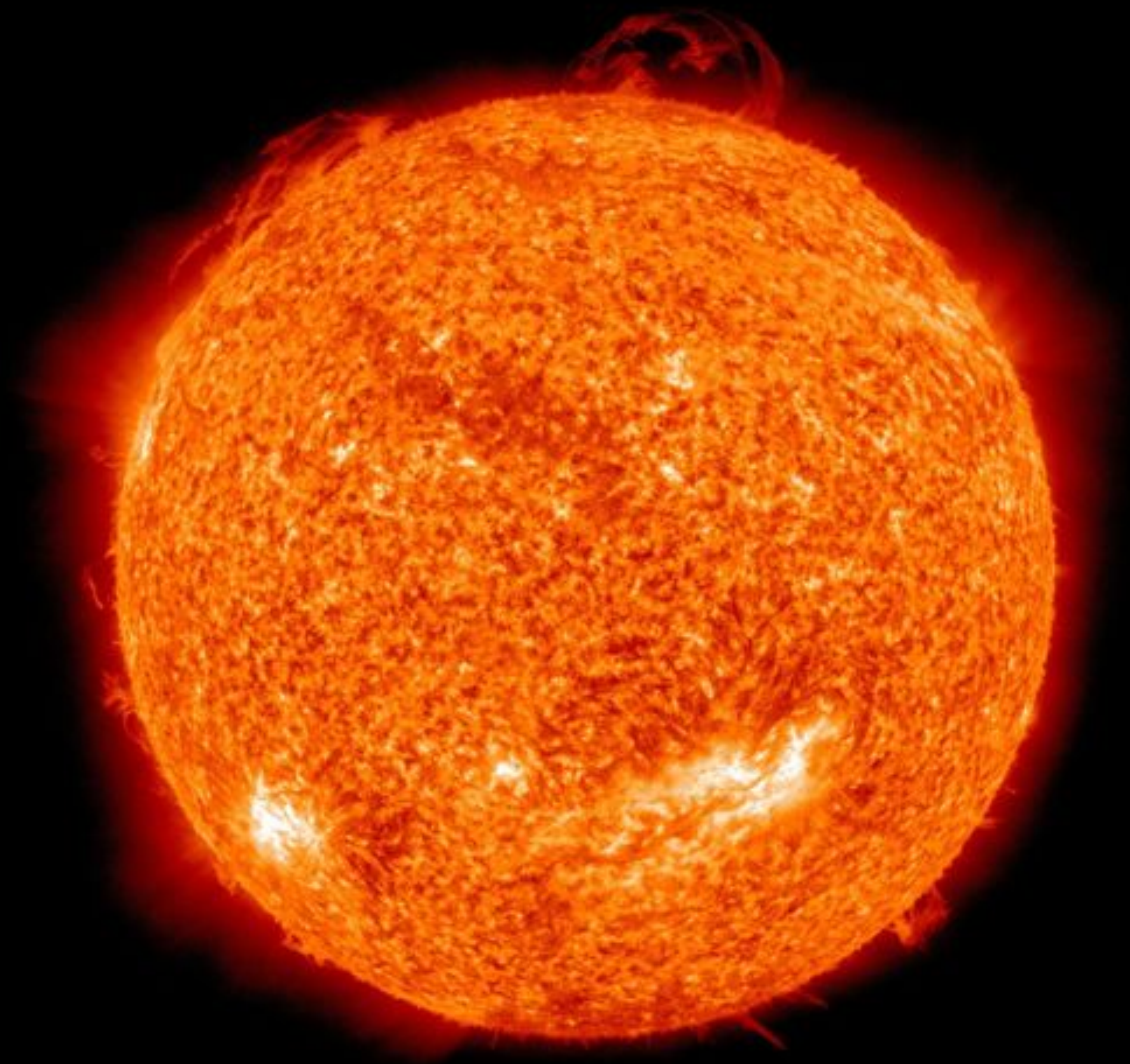


golp grupo de lasers e plasmas

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

Plasma is a fourth state of matter made of unbounded ions and electrons.



Plasmas can be created using different approaches

- Intense electric discharge between two electrodes
- Ionisation by intense laser or particle beams

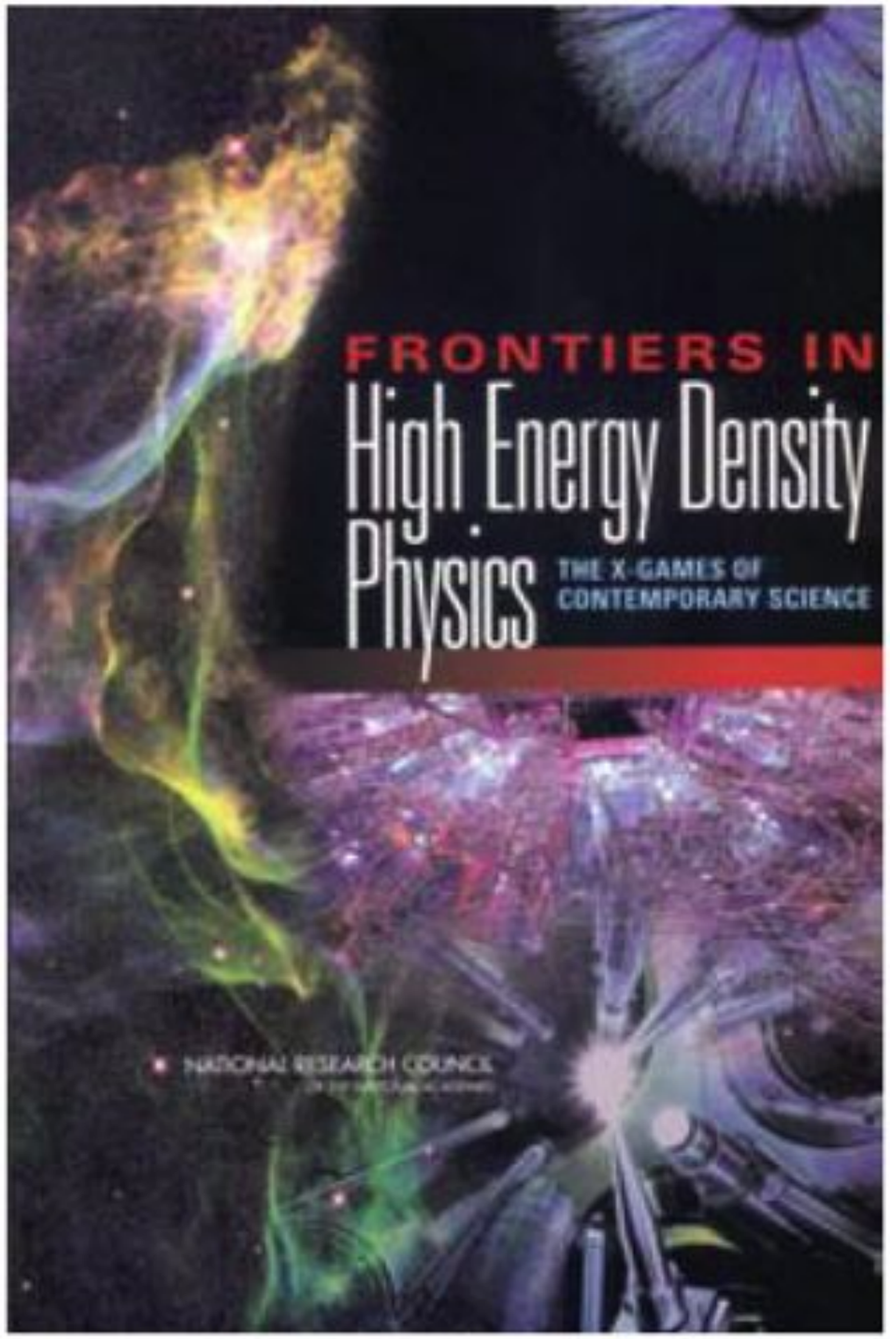
Plasma examples

- Lamps
- Sun and Tokamaks (fusion devices)

Support extremely large fields

- Typical electric field E ~ $(n_0\ [cm^{-3}])^{1/2}$ V/cm
- Example: n_0 ~10^{18} cm^{-3} (typical) E ~ 100 GV/m

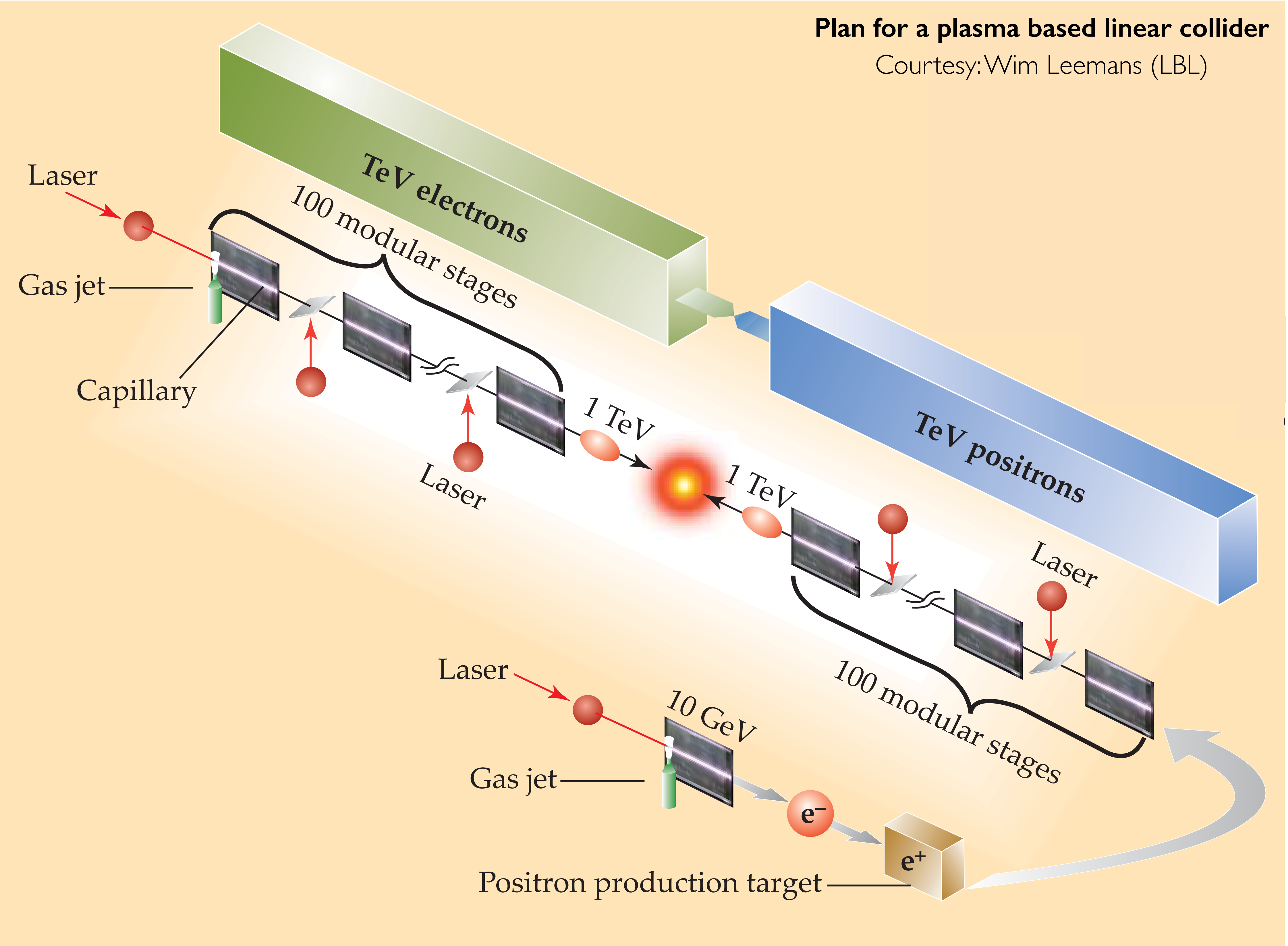
National Academy of Sciences (US) report states importance of plasma acceleration to the future of high energy physics.



physics of matter under high energy density conditions. The following list of questions is not intended to be complete but rather to be illustrative of important questions of high intellectual value in high energy density physics:

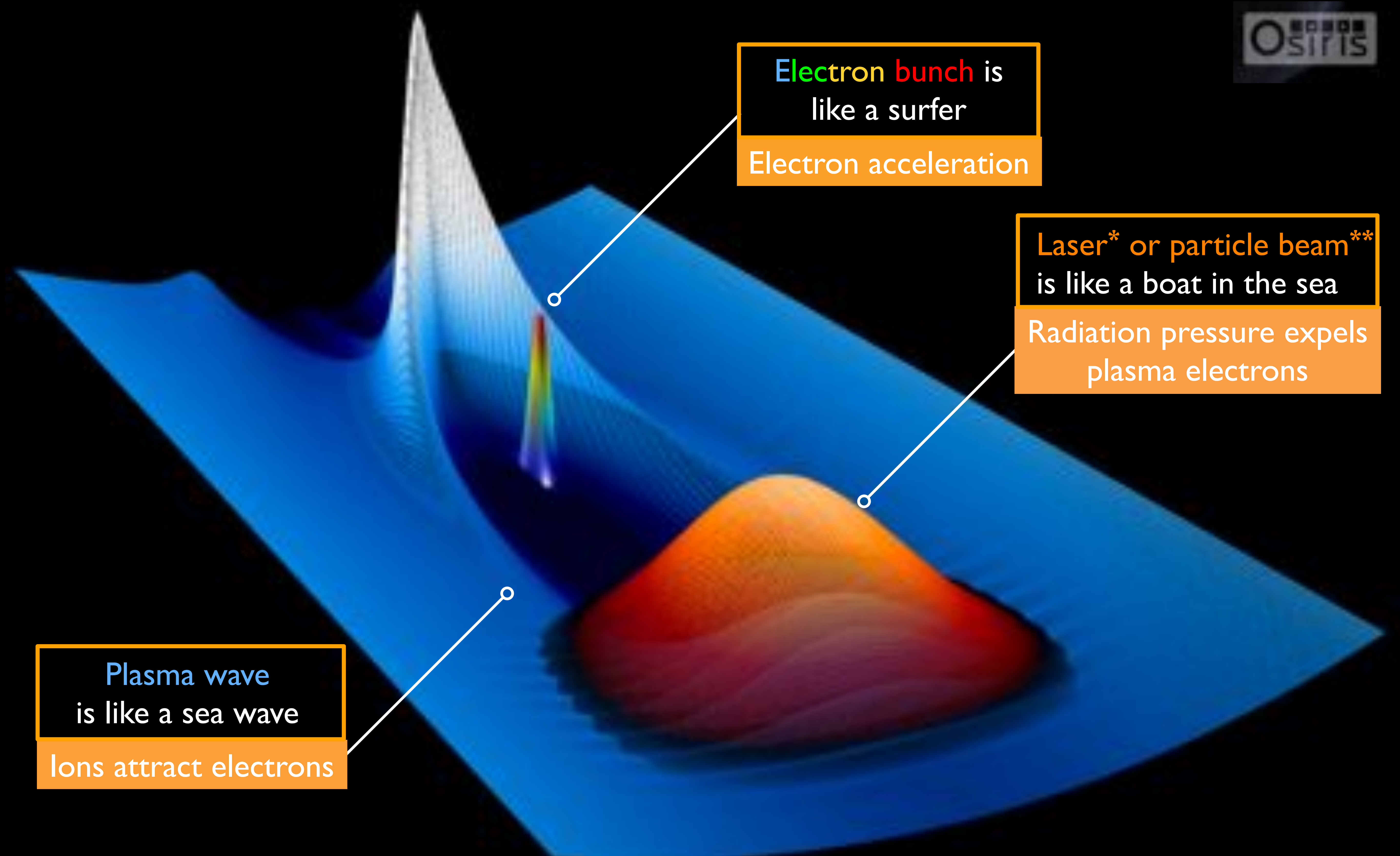
- How does matter behave under conditions of extreme temperature, pressure, density, and electromagnetic fields?
- What are the opacities of stellar matter?
- What is the nature of matter at the beginning of the universe?
- How does matter interact with photons and neutrinos under extreme conditions?
- What is the origin of intermediate-mass and high-mass nuclei in the universe?
- Can nuclear flames (ignition and propagating burn) be created in the laboratory?
- Can high-yield ignition in the laboratory be used to study aspects of supernovae physics, including the generation of high-Z elements?
- Can the mechanisms for formation of astrophysical jets be simulated in laboratory experiments?
- Can the transition to turbulence, and the turbulent state, in high energy density systems be understood experimentally and theoretically?
- What are the dynamics of the interaction of strong shocks with turbulent and inhomogeneous media?
- Will measurements of the equation of state and opacity of materials at high temperatures and pressures change models of stellar and planetary structure?
- Can electron-positron plasmas relevant to gamma-ray bursts be created in the laboratory?
- Can focused lasers "boil the vacuum" to produce electron-positron pairs?
- Can macroscopic amounts of relativistic matter be created in the laboratory and will it exhibit fundamentally new collective behavior?
- Can we predict the nonlinear optics of unstable multiple and interacting beamlets of intense light or matter as they filament, braid, and scatter?
- Can the ultraintense field of a plasma wake be used to make an ultrahigh-gradient accelerator with the luminosity and beam quality needed for applications in high energy and nuclear physics?
- Can high energy density beam-plasma interactions lead to novel radiation sources?

One of the goals for this technology is to design and construct a plasma based linear collider.



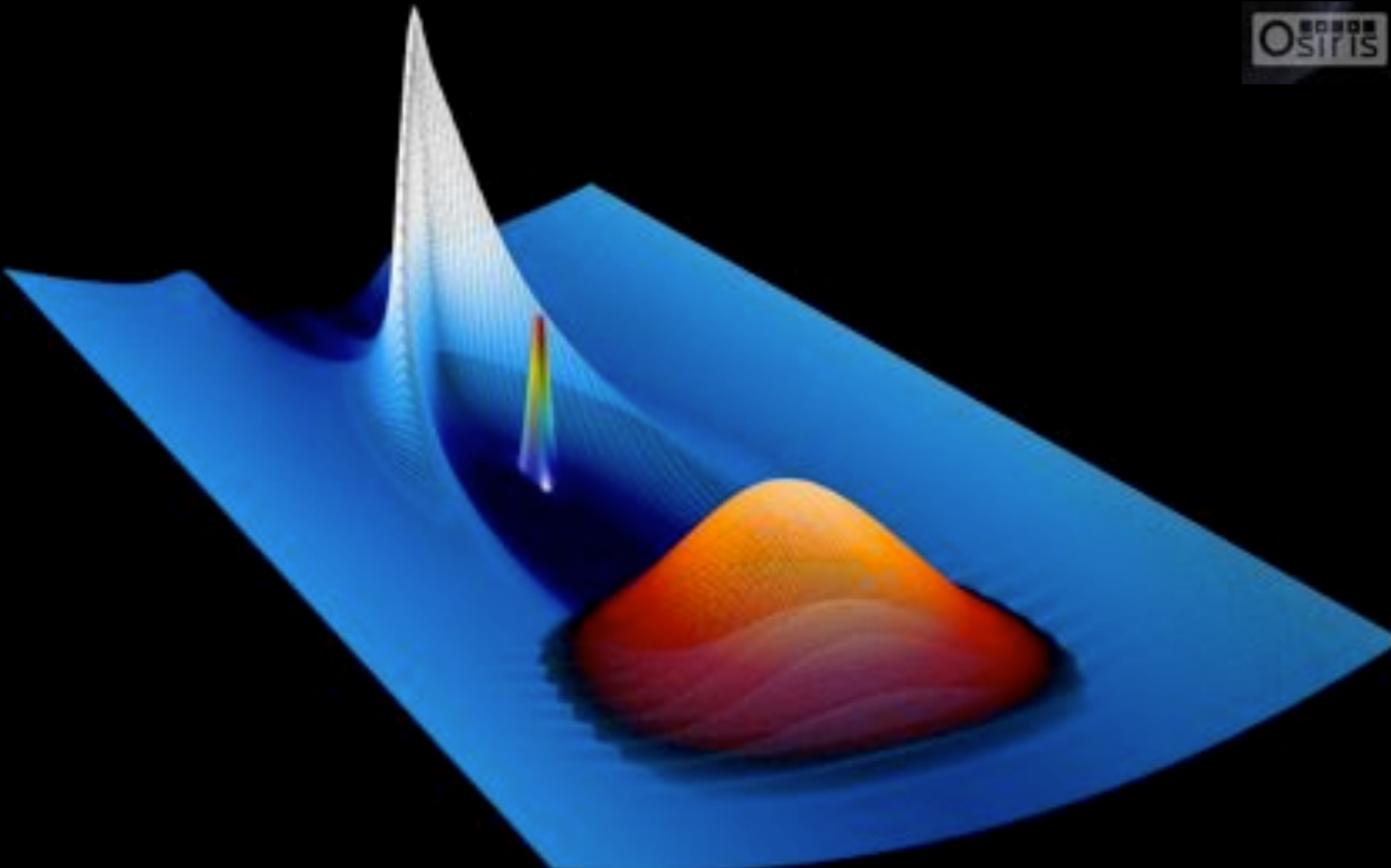
Surfing a sea wave and plasma acceleration

Plasma based acceleration uses intense beams to drive plasma waves



*T. Tajima and J.M. Dawson Phys. Rev. Lett. **43** 267 (1979)
P. Chen, J. Dawson et al Phys. Rev. Lett. **54 693 (1985)

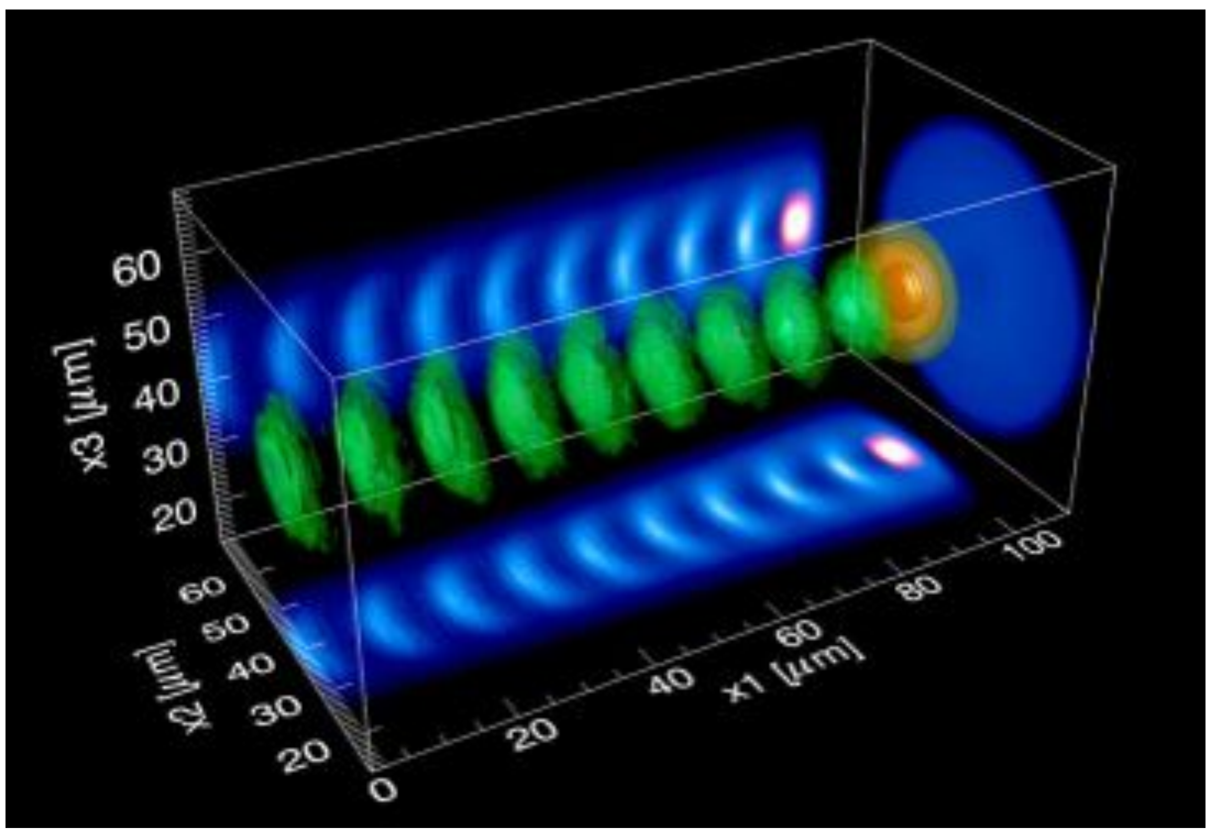
Electrons gain energy while crossing the wakefield



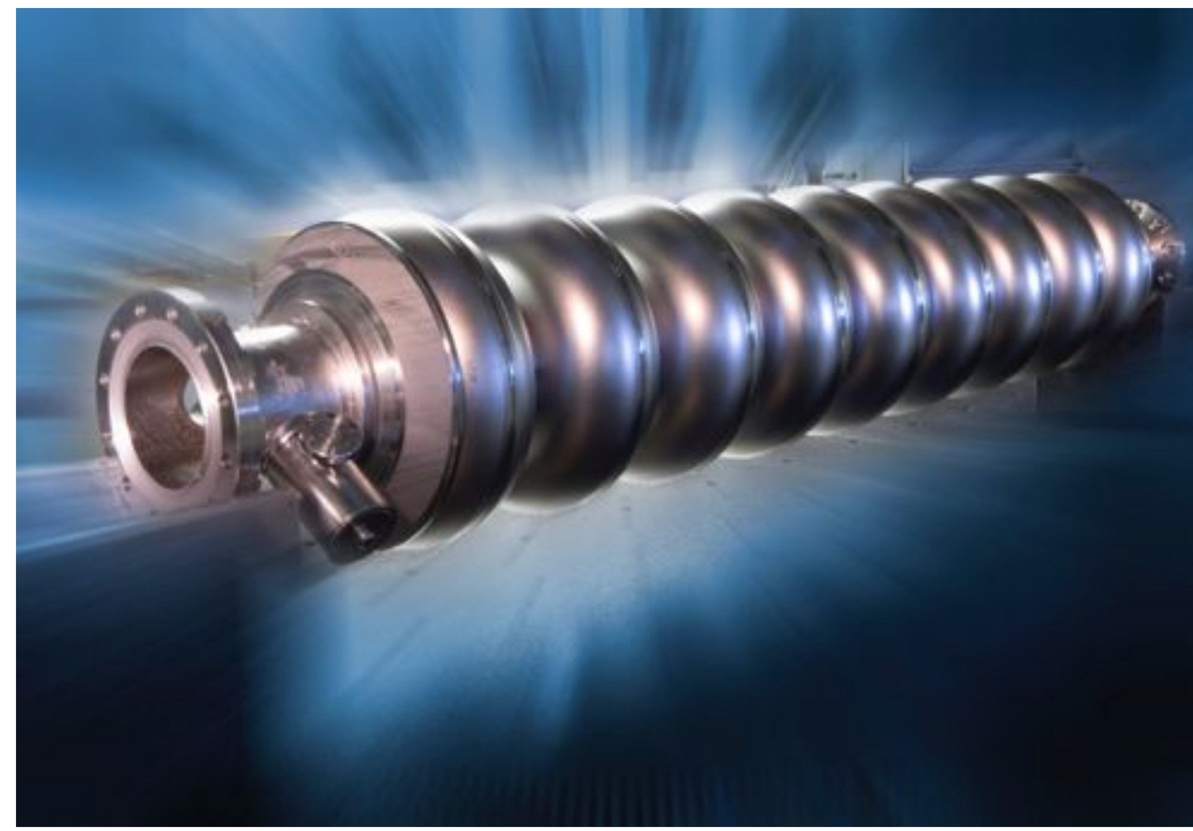
Movie in a frame that travels at c

Plasma accelerators are compact because plasma waves are much smaller than standard devices

Plasma waves	RF device
$E_{accel} \sim n_0^{1/2}$ [cm^{-3}] V/cm ~ 1 GV/cm	E_{accel} ~ 40 MV/m

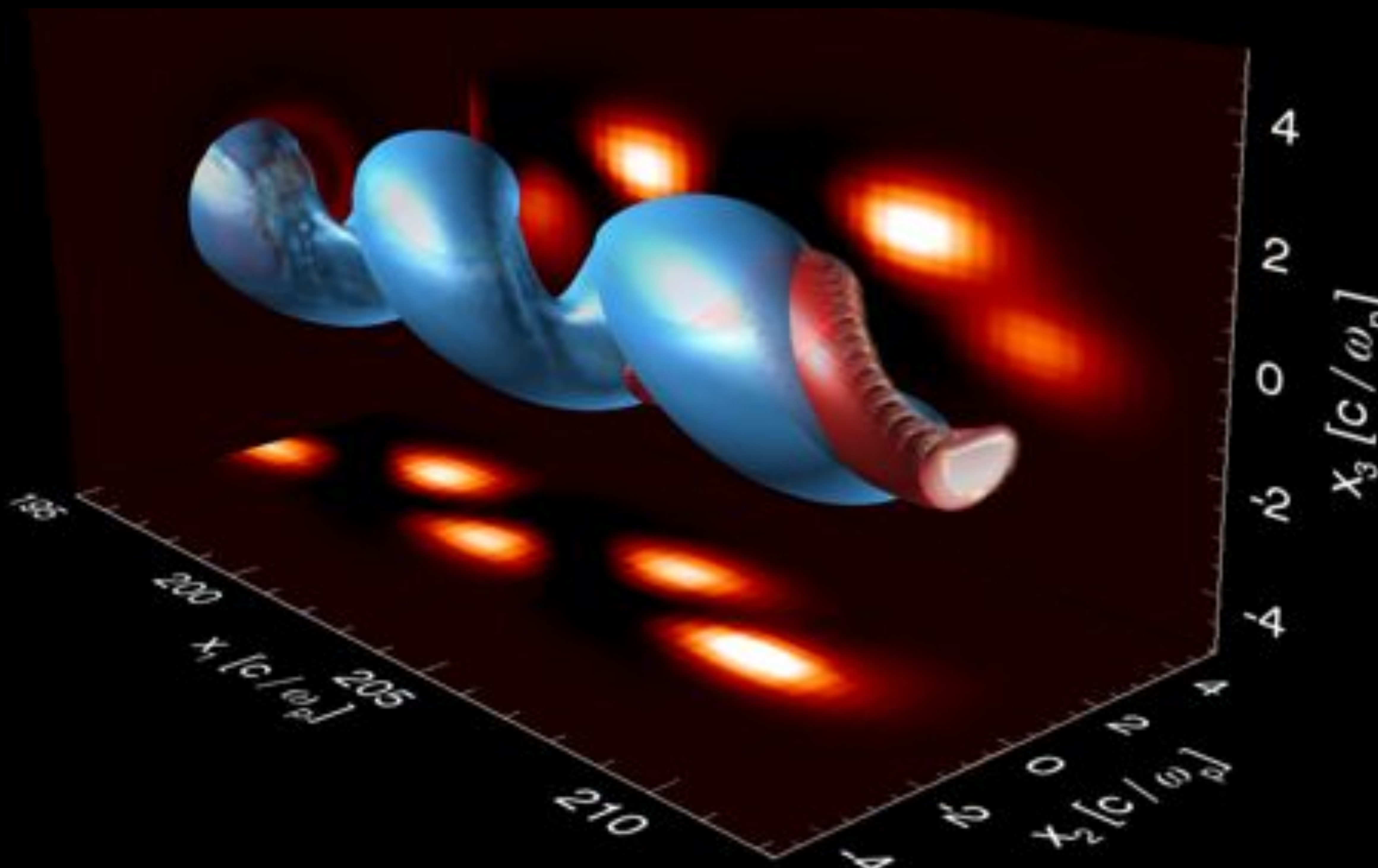


← 100 microns →



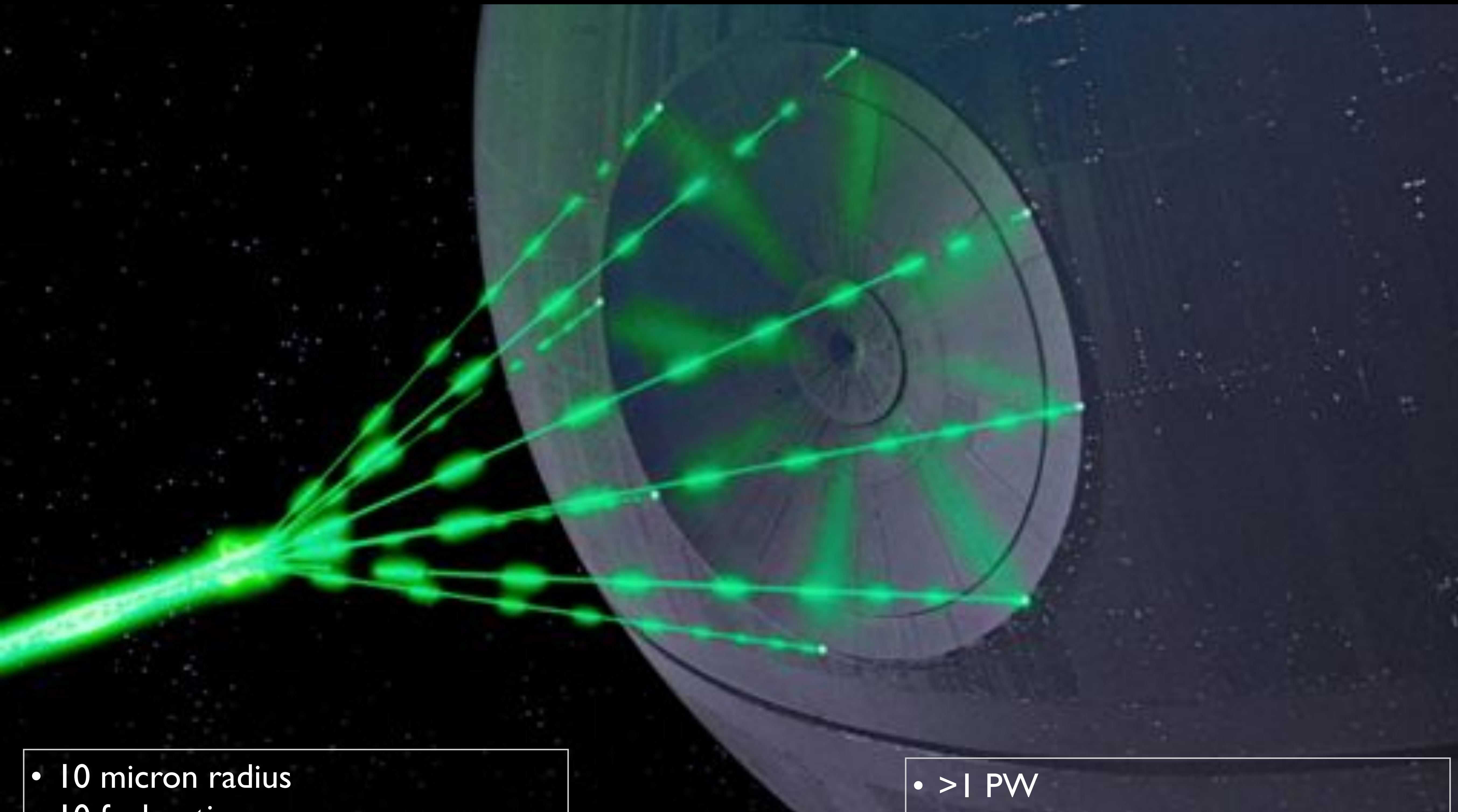
← 100 centimeters →

Plasma waves can be bent in nearly any possible way thus opening exciting possibilities for beam shaping



J. Vieira, F. Quéré (CEA), J.T. Mendonça (IST) *et al.*

The generation of plasma waves requires ultra-intense particle or laser beam drivers

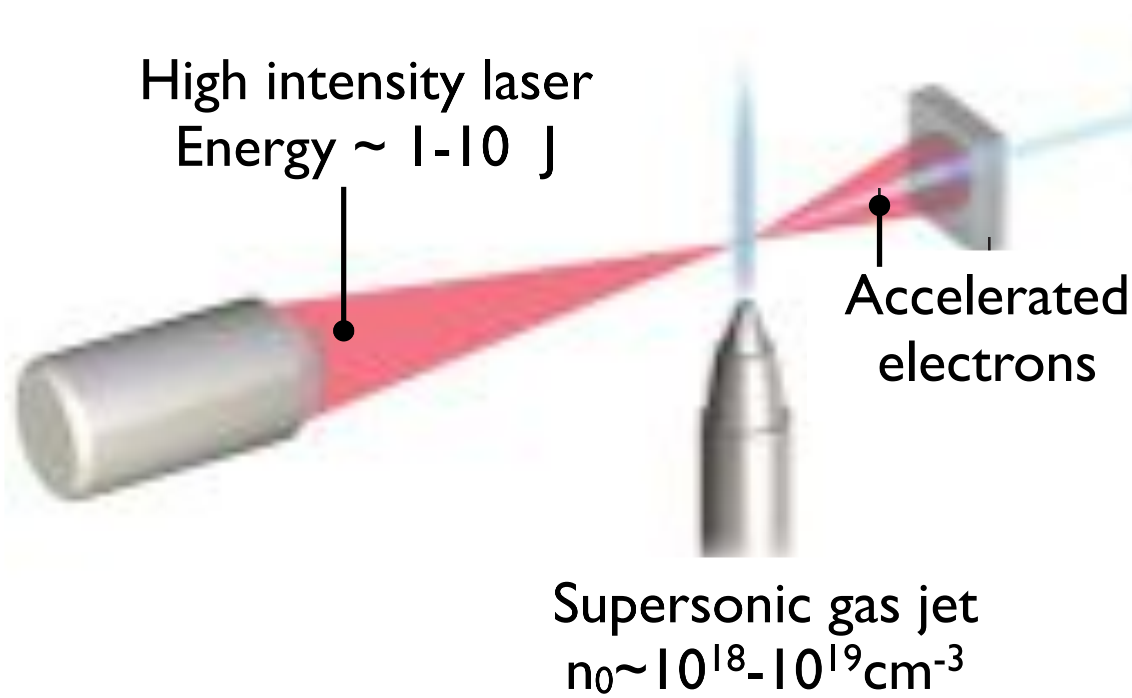


- 10 micron radius
- 10 fs duration
- 1-100 J

- >1 PW
- $>10^{19}$ - 10^{20} W/cm^2

Proof-of-principle experiments demonstrated 100 MeV electron acceleration in less than one cm.

Proof-of-principle experiments

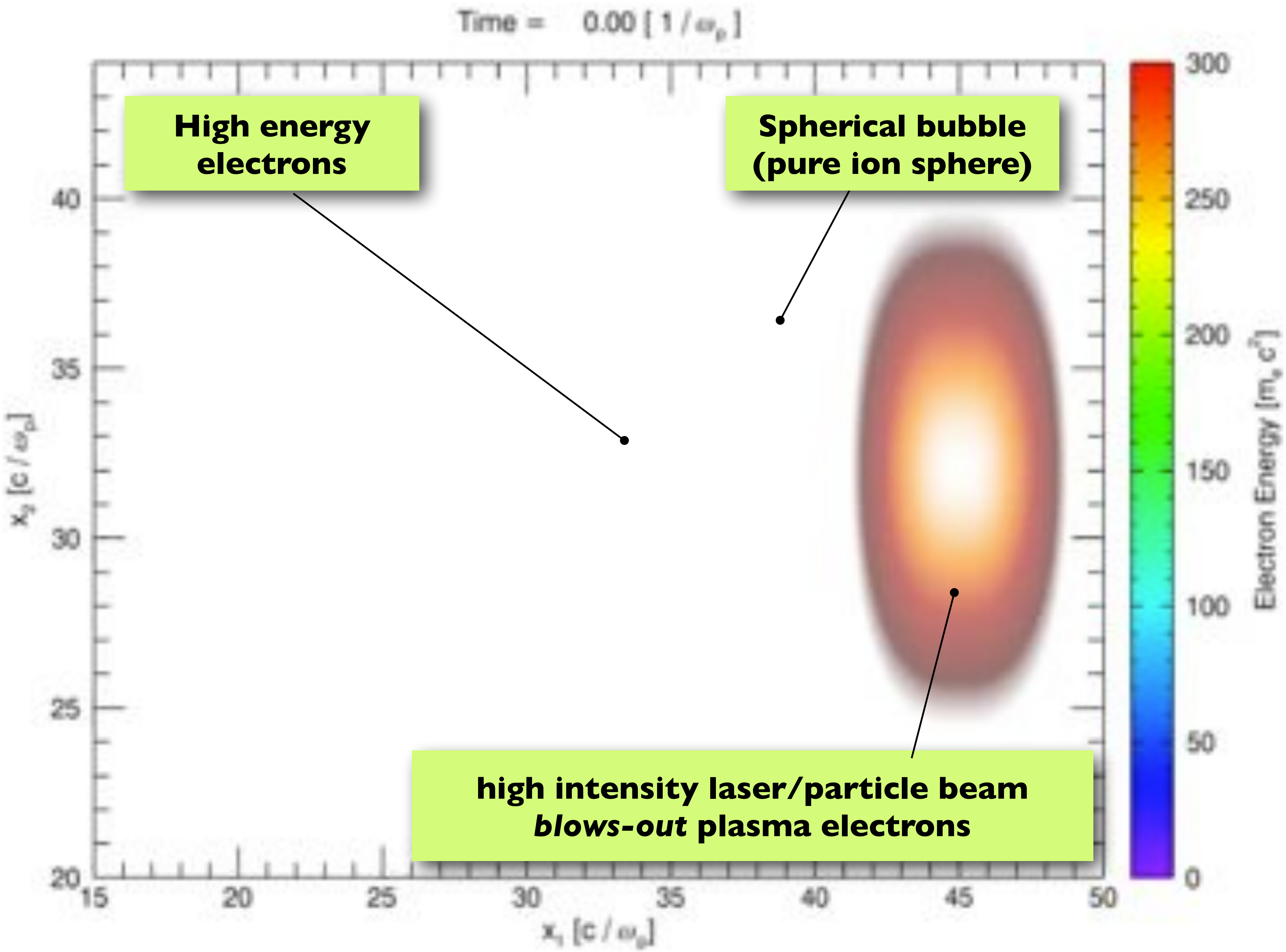


Very large sea waves trap water foam

The foam from the water gains enough momentum and catches the wave

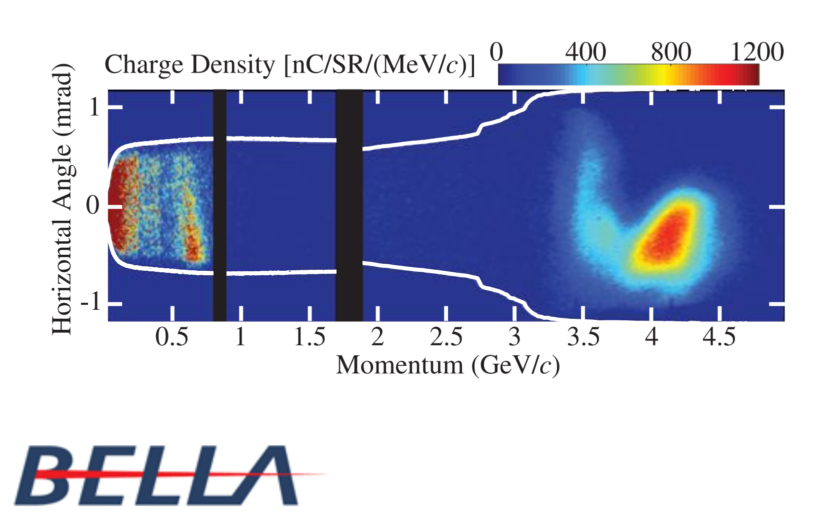
Early experiments: background plasma electrons trapped by large amplitude plasma wave

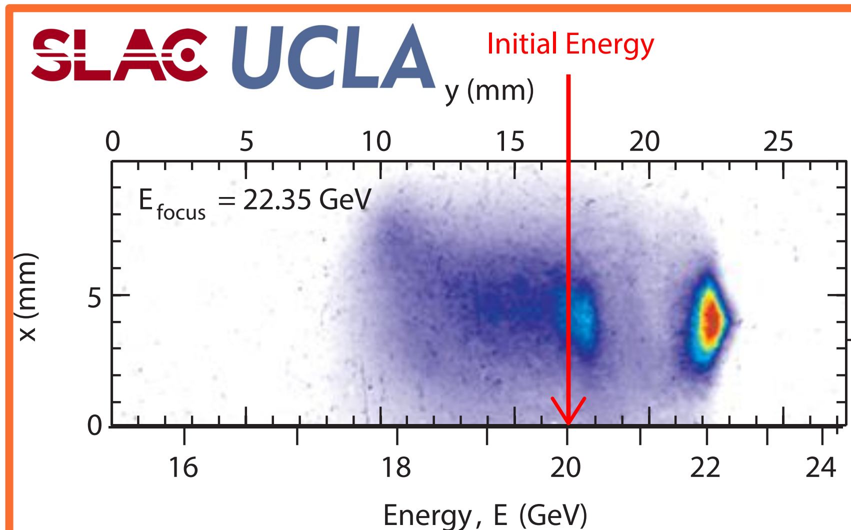
Simulation window travels at c. Laser is almost stationary.
Plasma flows from left to right

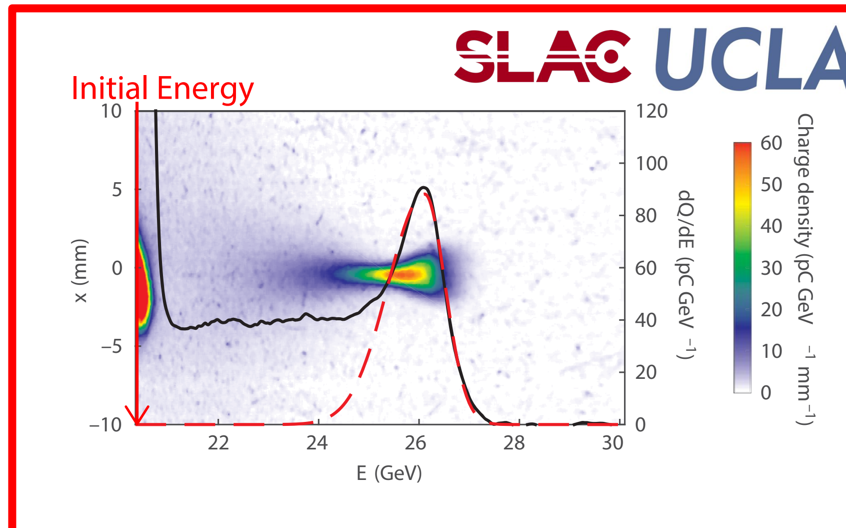


Recent experiments pave the way for exciting future developments

Leemans *et al.* PRL 2014	Litos *et al.* Nature 2015	Corde *et al.* Nature 2015







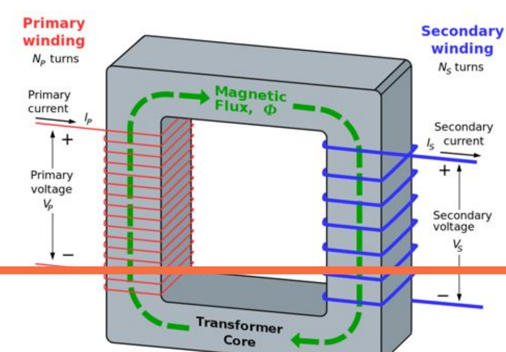
- 0.3 PW laser pulse
- 4 GeV in 10 cm
- 6% energy spread

- 20 GeV electron bunch
- 30% efficiency (max)
- 0.7% energy spread (min)

- 20 GeV positron bunch
- 5 GeV in 1.3 meters
- 1.8 % energy spread (min)

Laser driven	e- beam driven	e+ beam driven

A driver with more than 100 kJ would be required to achieve 10 TeV electron acceleration in a single stage.

	Laser / Particle beam	Plasma	Accelerated e-/e+
Today	**1-10 J lasers** **100 J e-/e+ (SLAC)**	**20 % Efficiency** 	**0.2-20 J** **1 nC ~ $6x10^9$ particles**
1000 stages	**100 drivers , < 10 fs synchronisation precision**	**1000 + (10 cm + 10 m spacing/stage) = 10 km**	**0.1 GeV - 10 GeV** **10 TeV / particle**
Single stage	**100 kJ driver**	**1-10 Km (depends on acceleration gradient)**	**10 TeV/particle**

Proton driven plasma wakefield accelerator

LHC proton bunches at CERN can accelerate > 1 TeV electrons in a single stage

LHC bunch at CERN

- Proton number: 10^{11}
- Energy: > 1 TeV
- Transverse size: 0.2 - 0.4 mm
- Longitudinal size: 10 cm
- Energy spread: 10^{-2} %

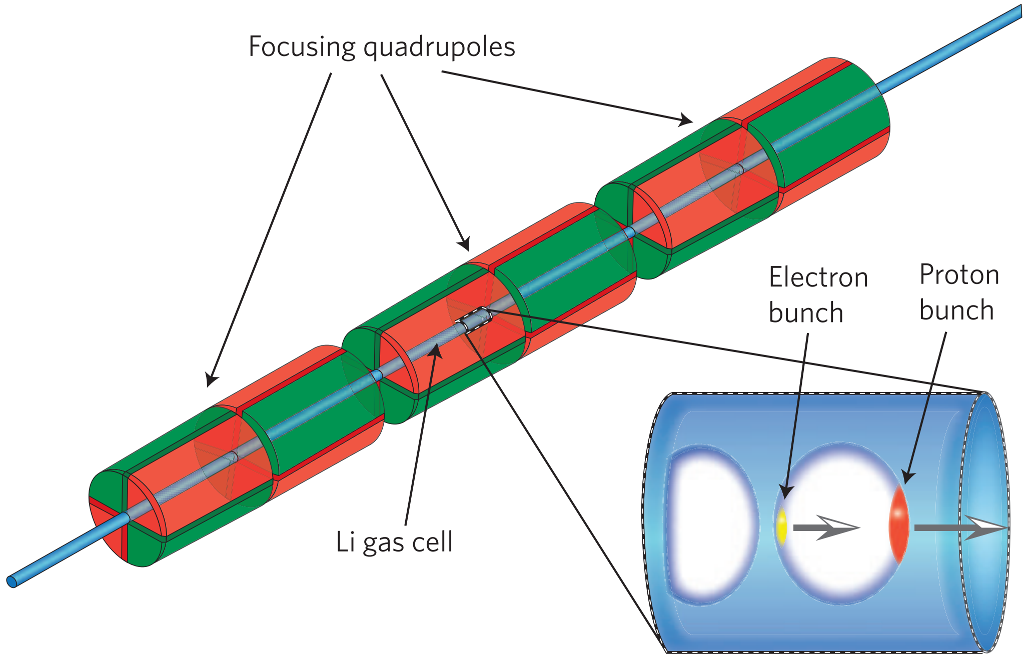
Linear theory

$$E_{\text{accel}} = 240\text{MV m}^{-1}\left(\frac{N}{4\times10^{10}}\right)\left(\frac{0.6}{\sigma_z(\text{mm})}\right)^2$$

E_{accel} = 0.0216 MV/m

Ideal bunch for plasma acceleration

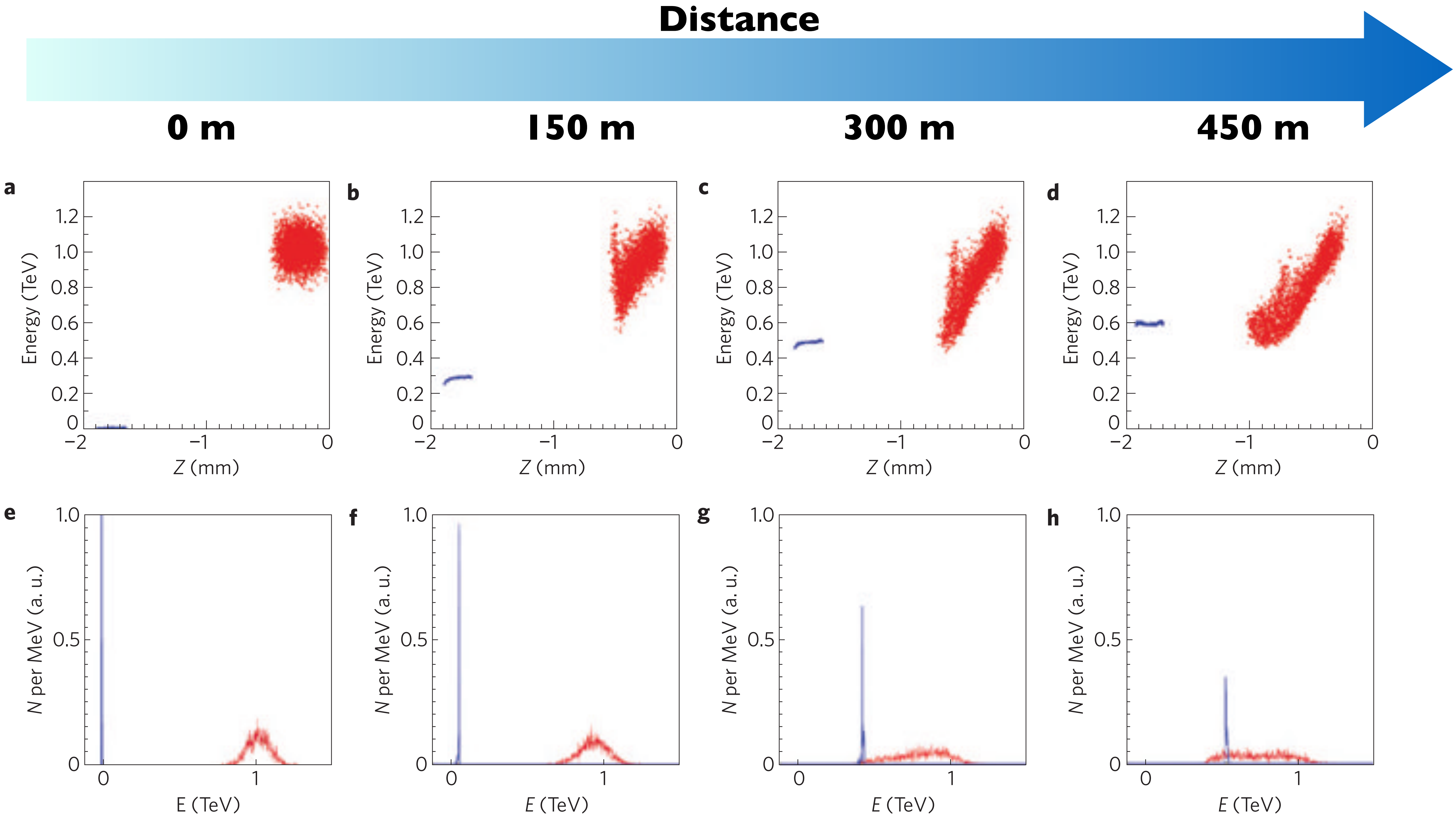
- Plasma density: 6×10^{14} cm^{-3}
- Quadrupolar focusing magnetic field
- Plasma wavelength: 1.35 mm
- Longitudinal size: 100 µm



A. Caldwell *et al.* Nature Physics 5 363 (2009)

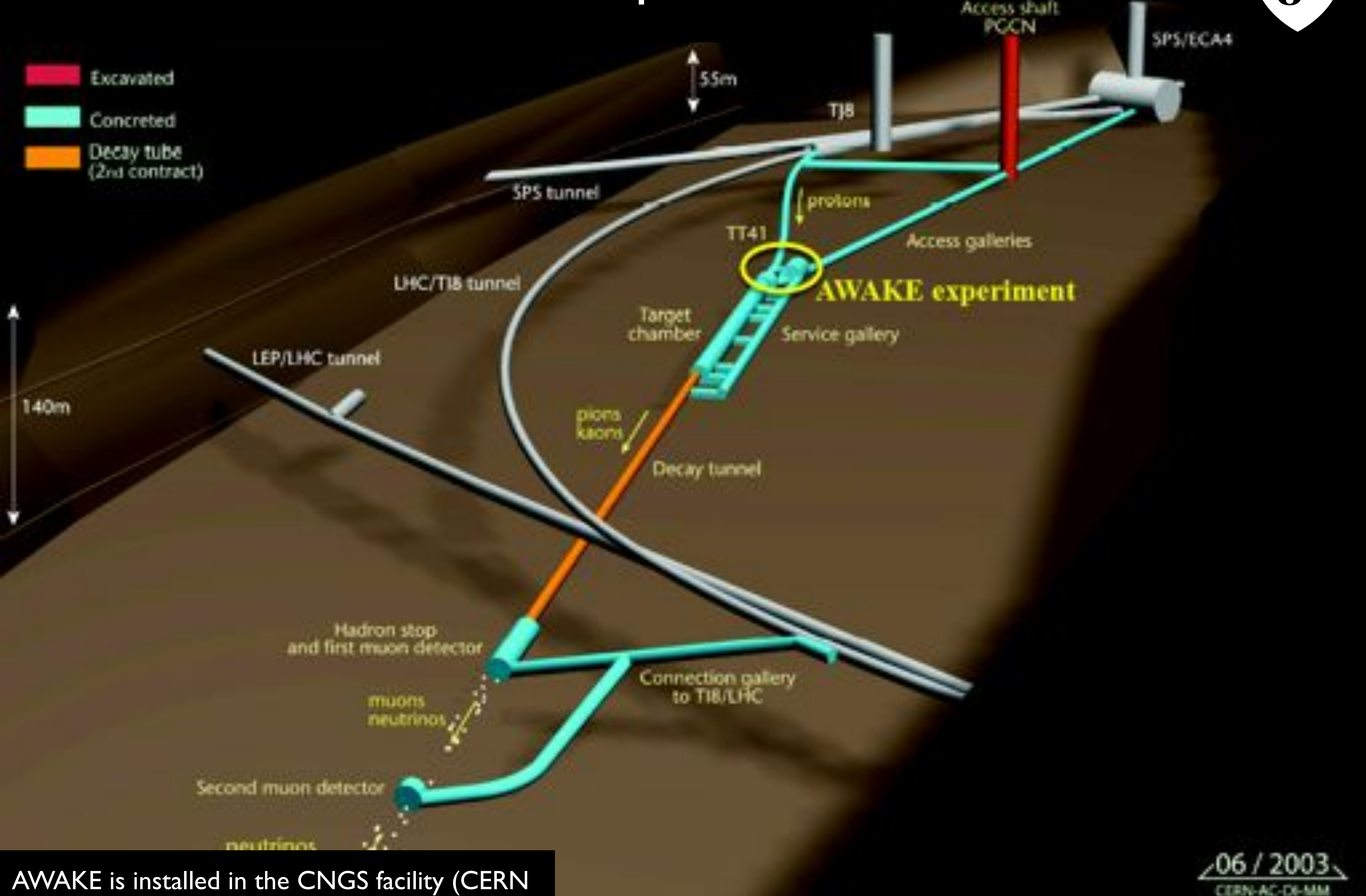
Proton driven plasma wakefield accelerator

External electron injection



A. Caldwell *et al.* Nature Physics 5 363 (2009)

AWAKE Advanced Wakefield experiment

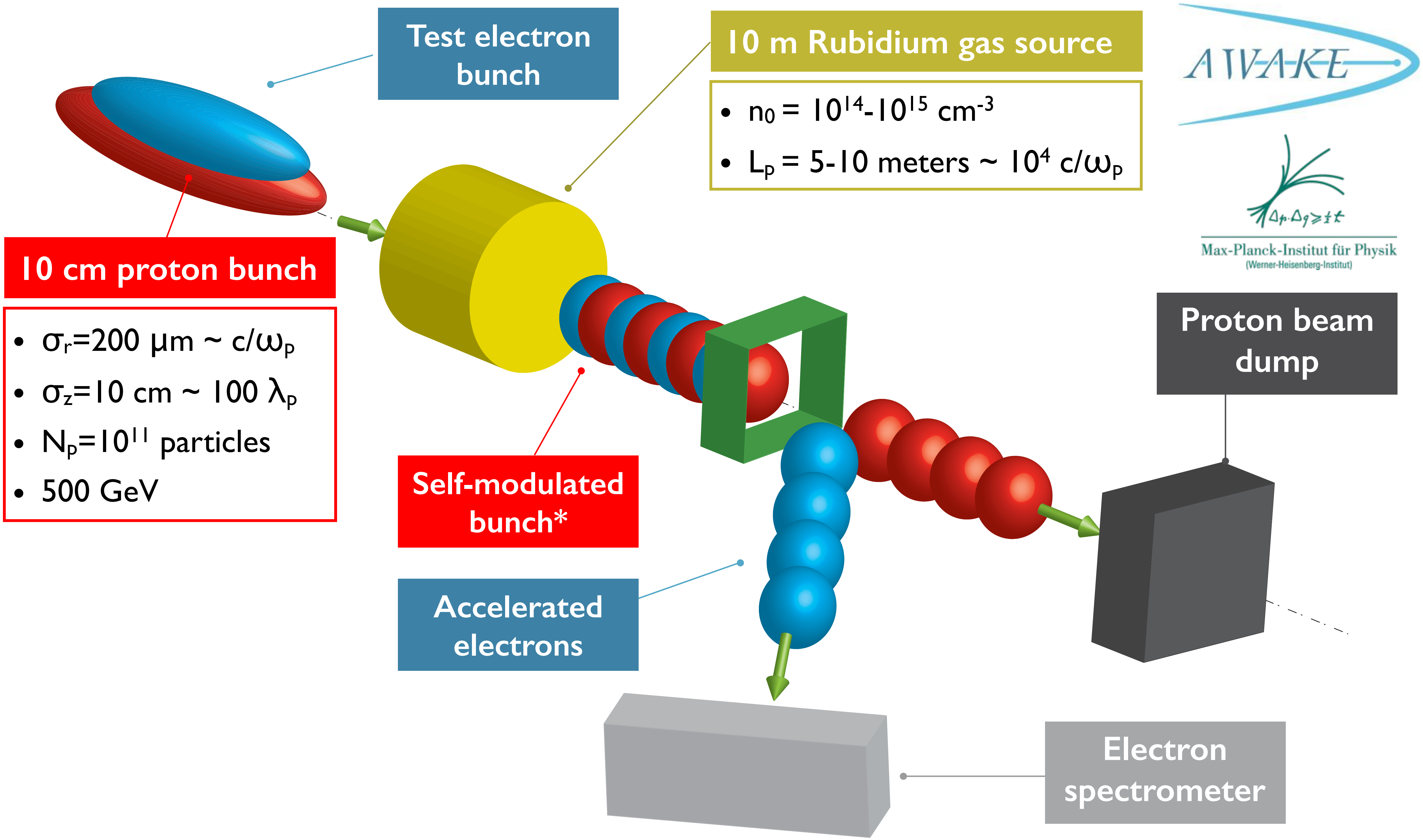


AWAKE is installed in the CNGS facility (CERN Neutrinos to Gran Sasso - program end in 2012)

AWAKE collaboration

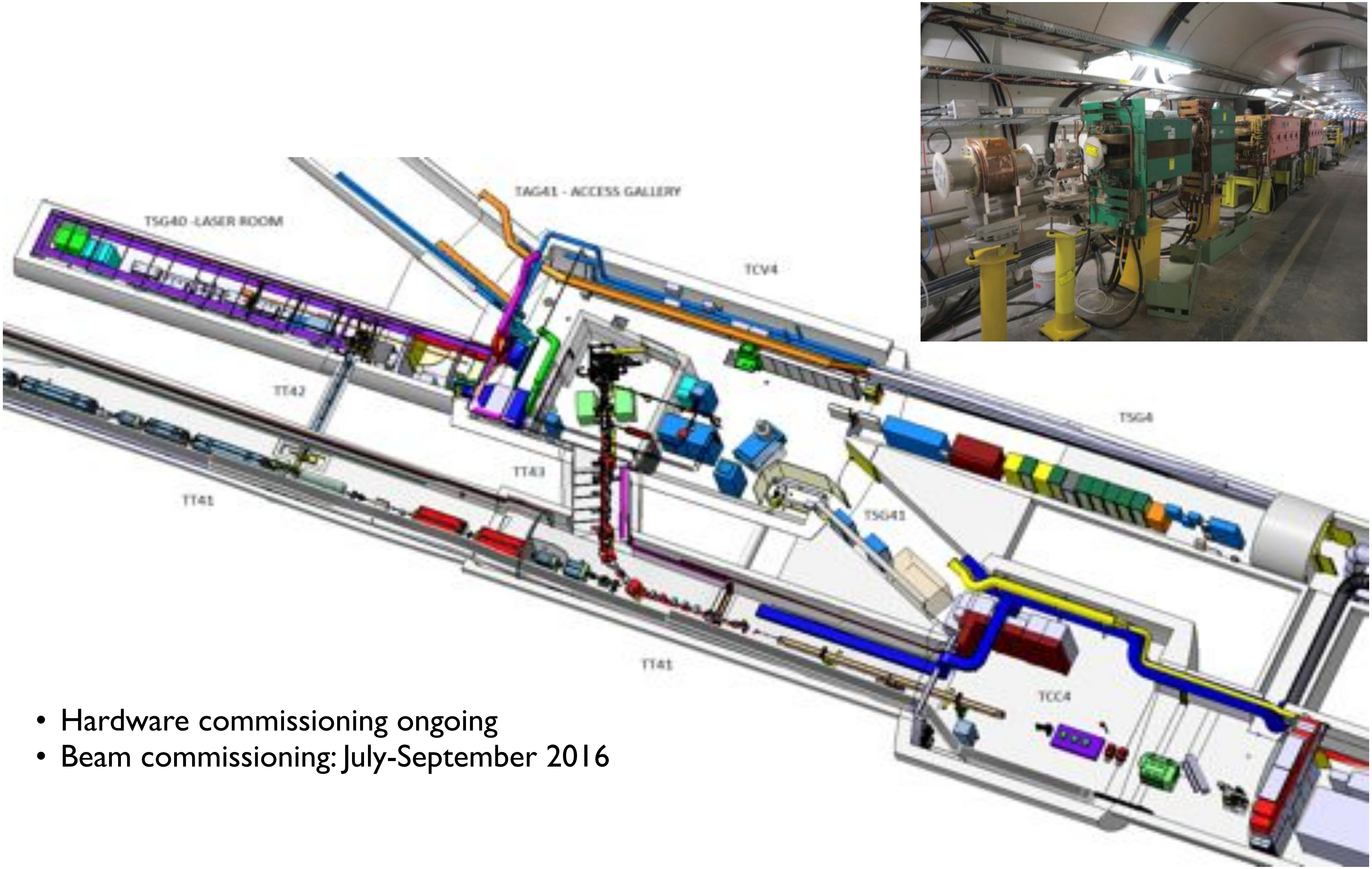
AWAKE collaboration, PPCF (2014); also at arXiv:1401.4823

Self-modulated proton driven plasma wakefield accelerator



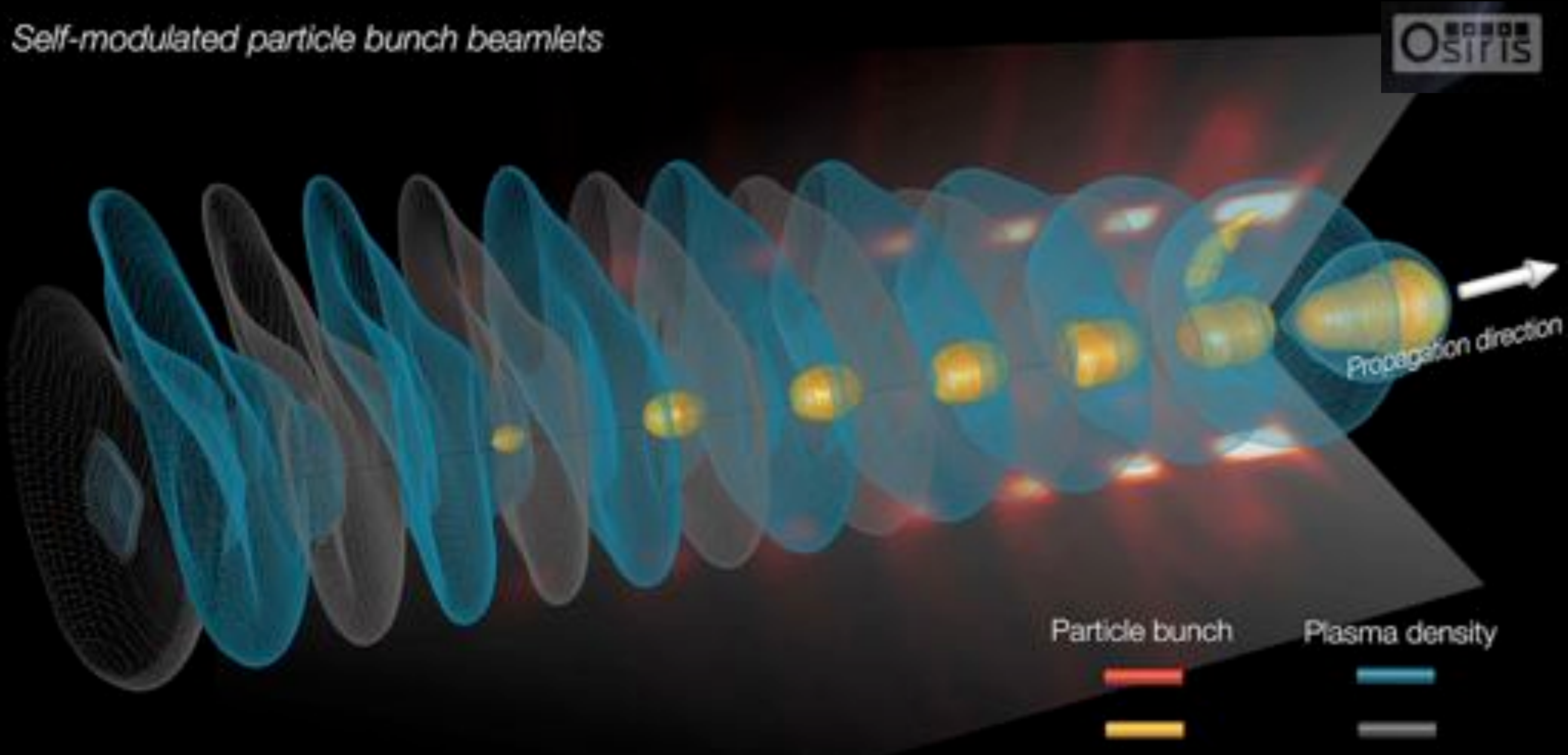
- N. Kumar *et al.* PRL 104 255003 (2010)
- C. Schroeder *et al.* PRL 107 145002 (2011)

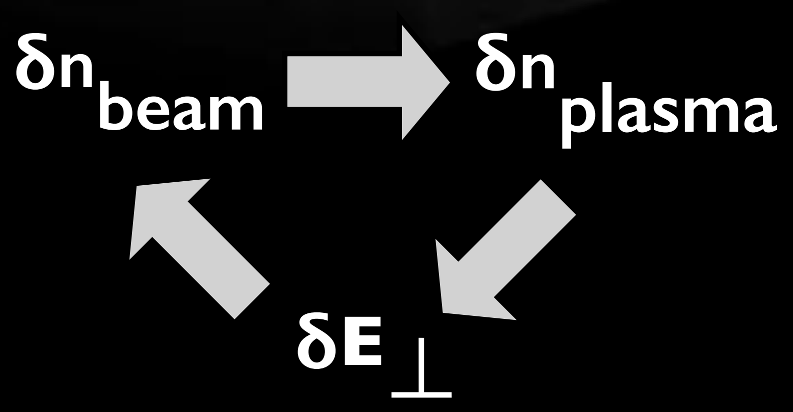
AWAKE proton beam line



- Hardware commissioning ongoing
- Beam commissioning: July-September 2016

Self-modulation instability in AWAKE



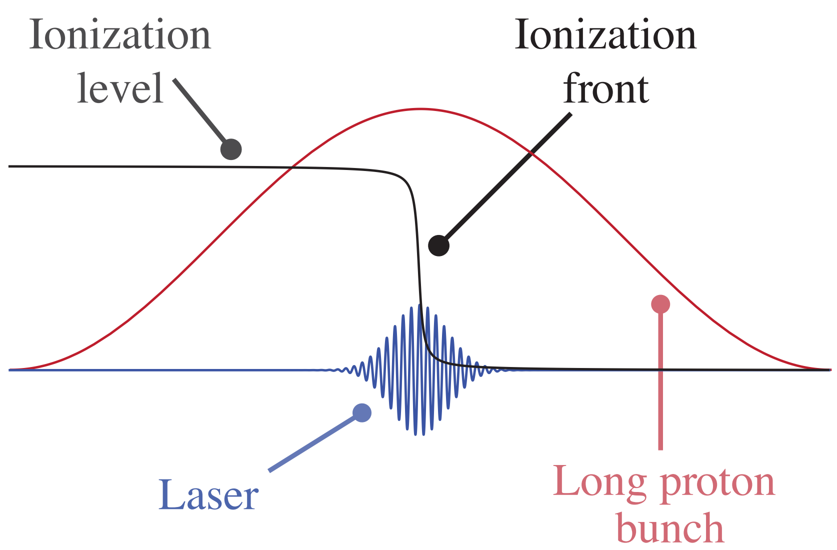


Ionisation seeding for the self-modulation instability

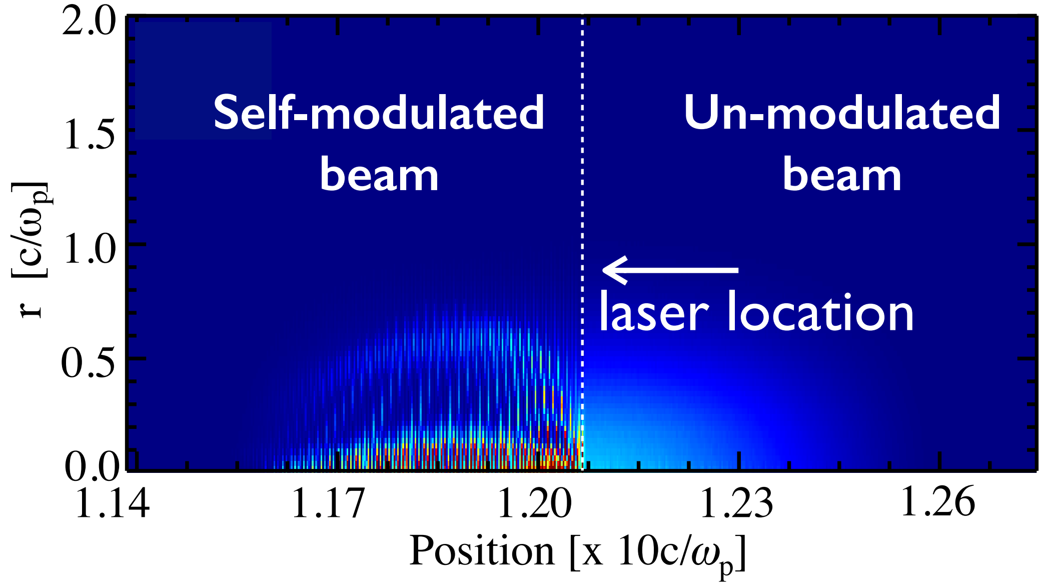
Ionisation seeding

Seeding the self-modulation instability:

- **Beam with a short rise time (compared with plasma wavelength)**
- **Create sharp ionisation front**



Ionisation effectively seeds the self-modulation instability



Simulations confirm ionisation seeding for the self-modulation:

- **No modulation before the laser**
- **Proton beam is fully self-modulated after the laser pulse**

Ionisation seeding for the self-modulation instability

Ionisation seeding

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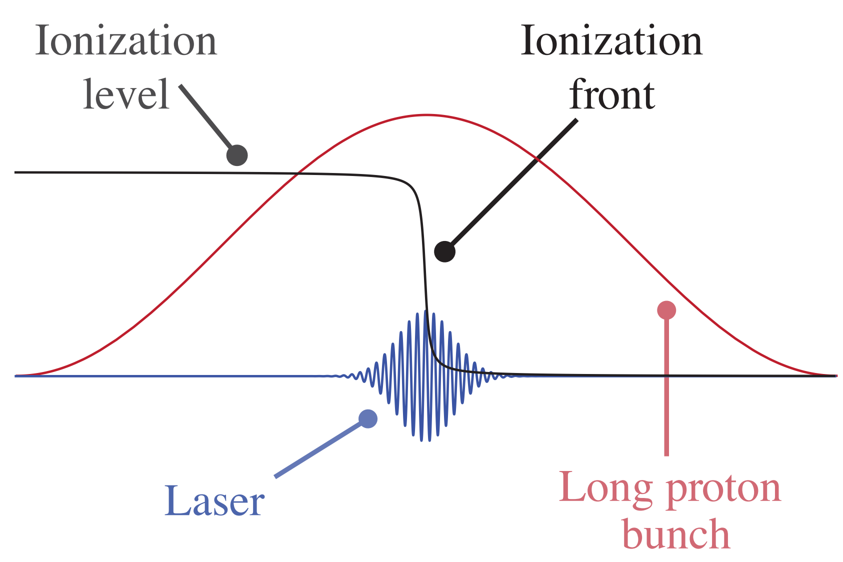
- **Beam with a short rise time (compared with plasma wavelength)**
- **Create sharp ionisation front**

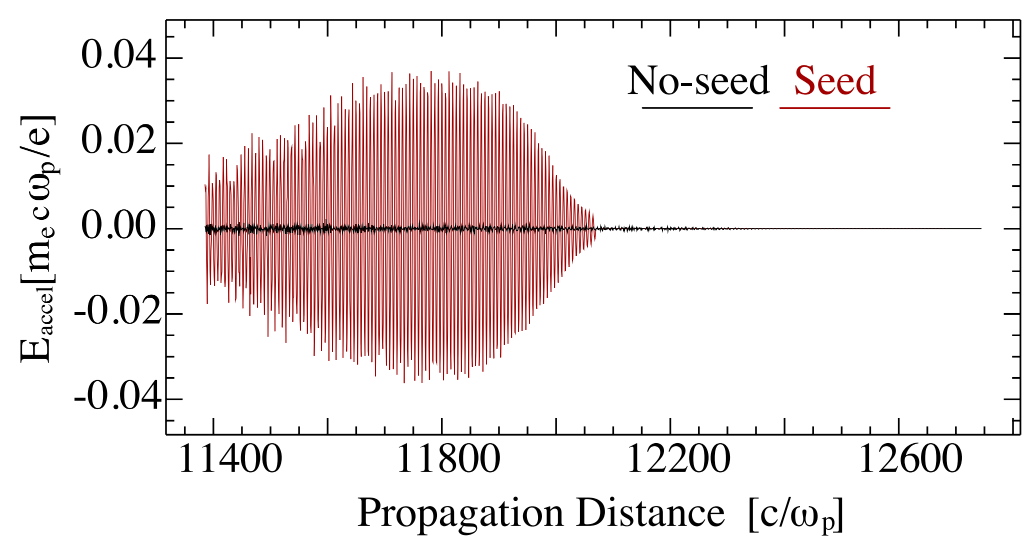


Test to measure SMI

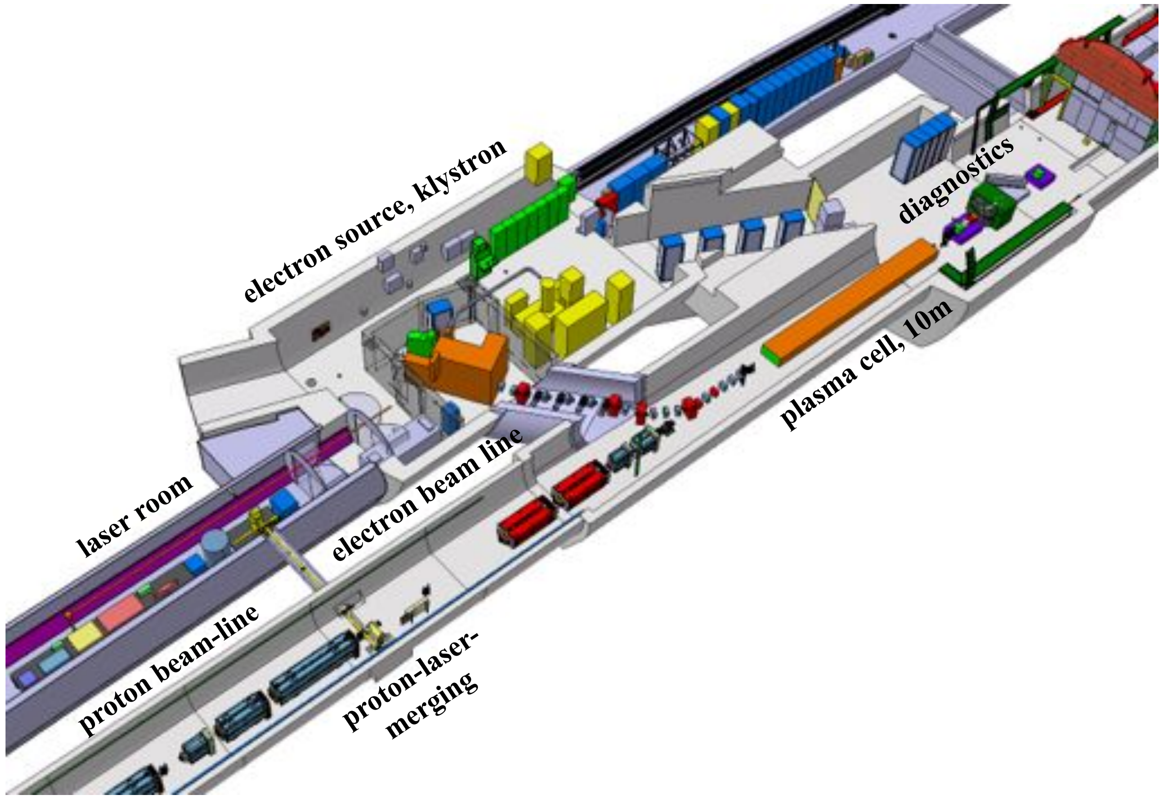
Ionisation seeding laser: intensity must exceed ionisation threshold at plasma end over a plasma radius of $3\sigma_r = 0.6$ mm

- **100 fs long**
- **1 mm transverse width**
- **4.5 TW**
- **450 mJ**

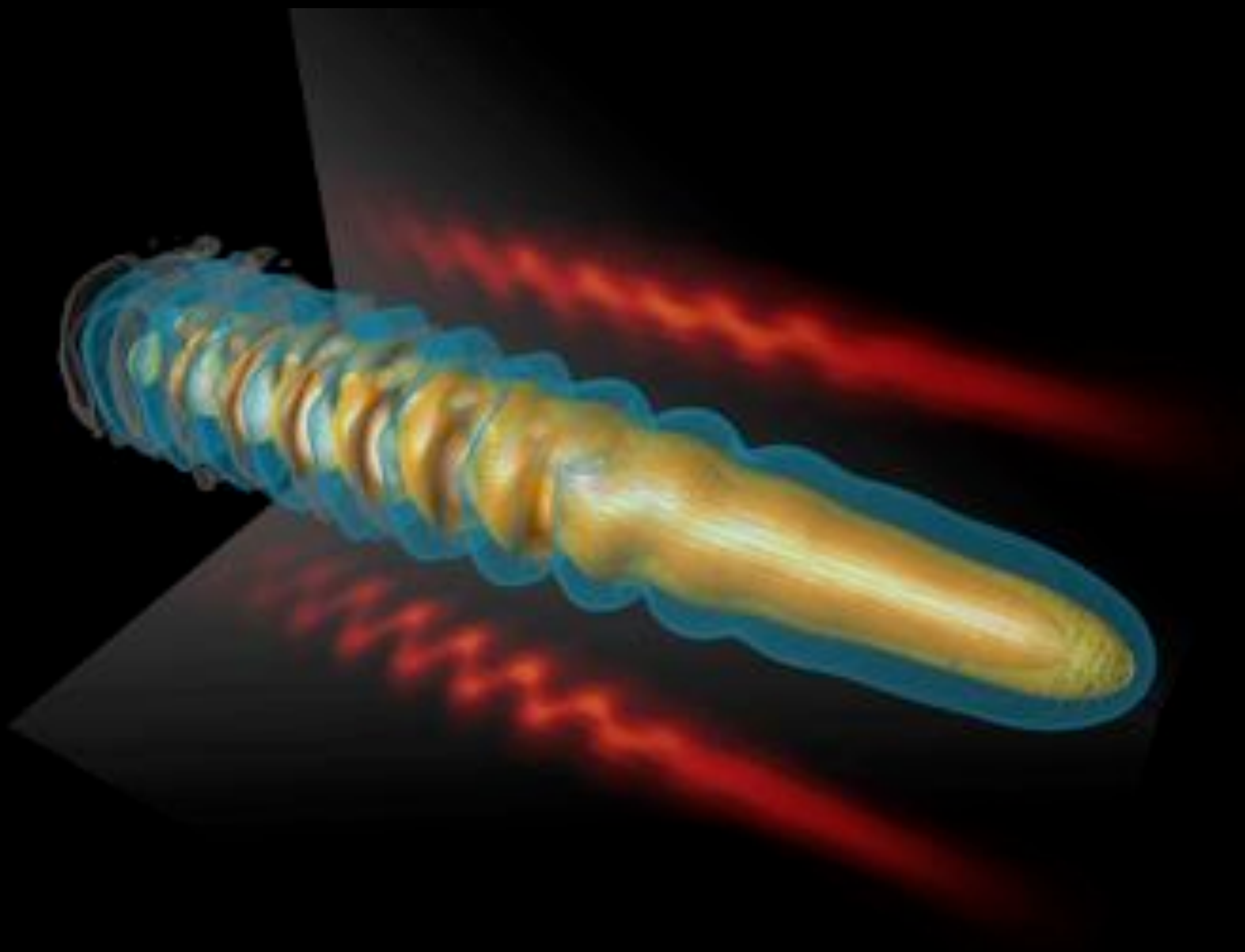
Laser On/Off ↔ SMI/NoSMI measurements



Laser beam line

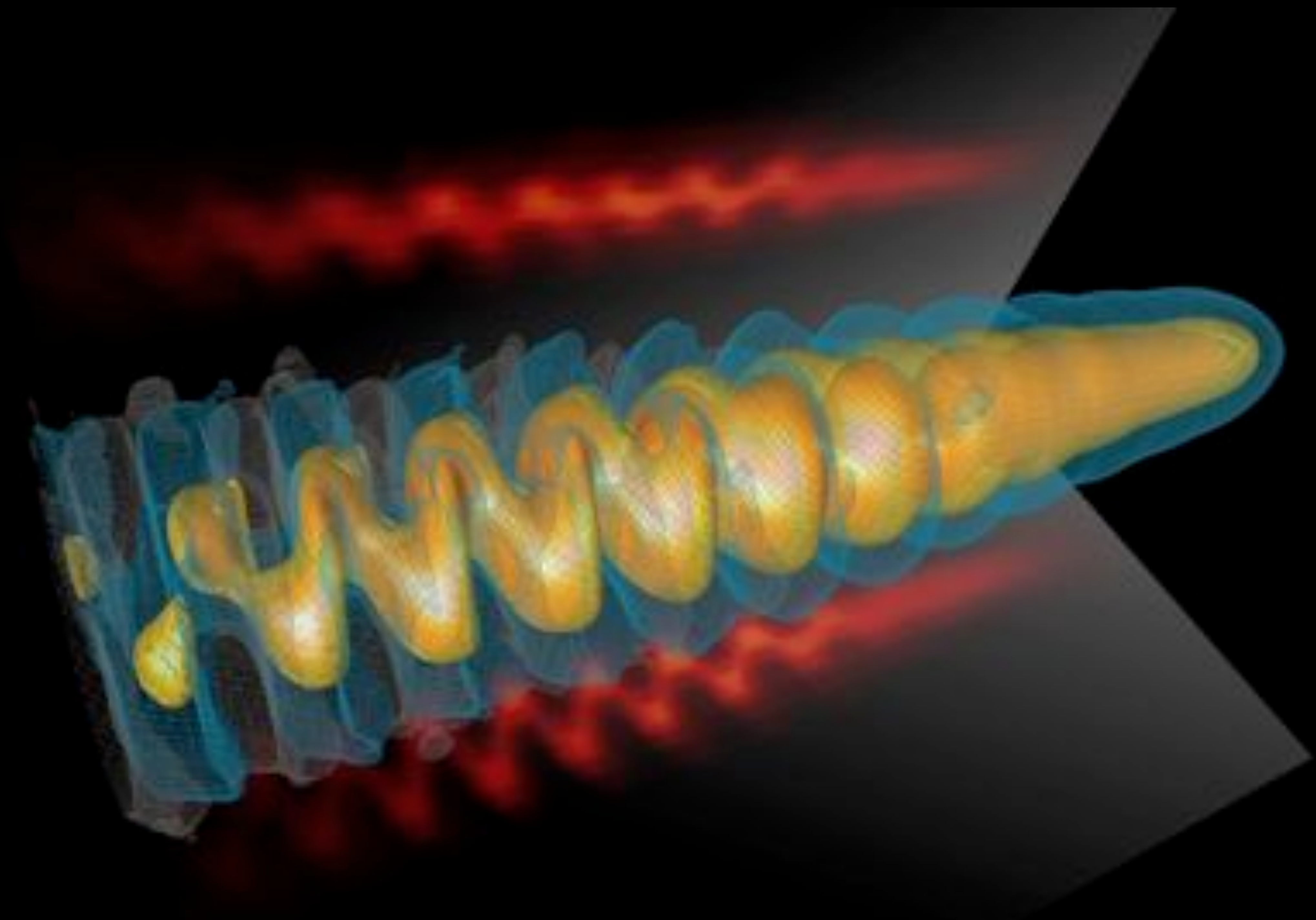


Competition between hosing and self-modulation



C.B. Schroeder *et al.* PRE 86 026402 (2012)

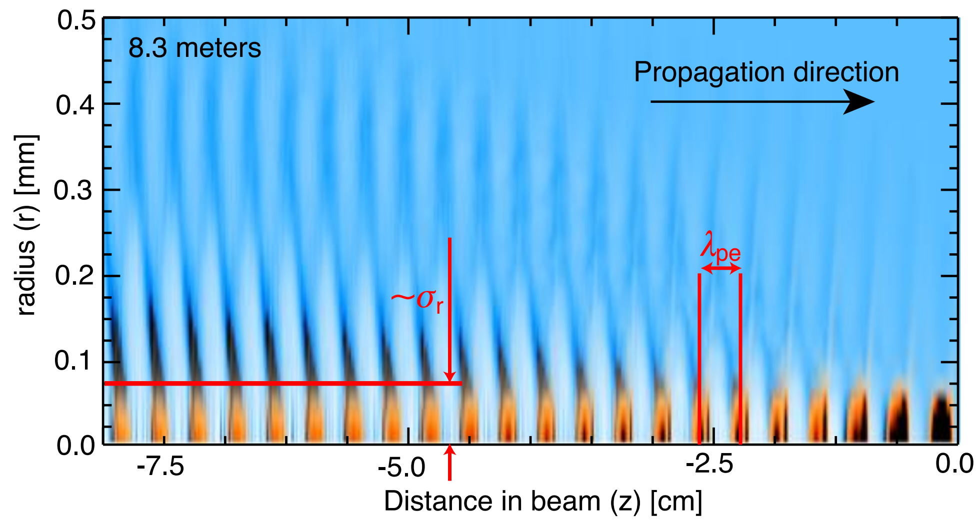
Beam breakup due to hosing



J. Vieira *et al*. PRL 112 205001 (2014)

Direct measurements of the self-modulation instability are possible

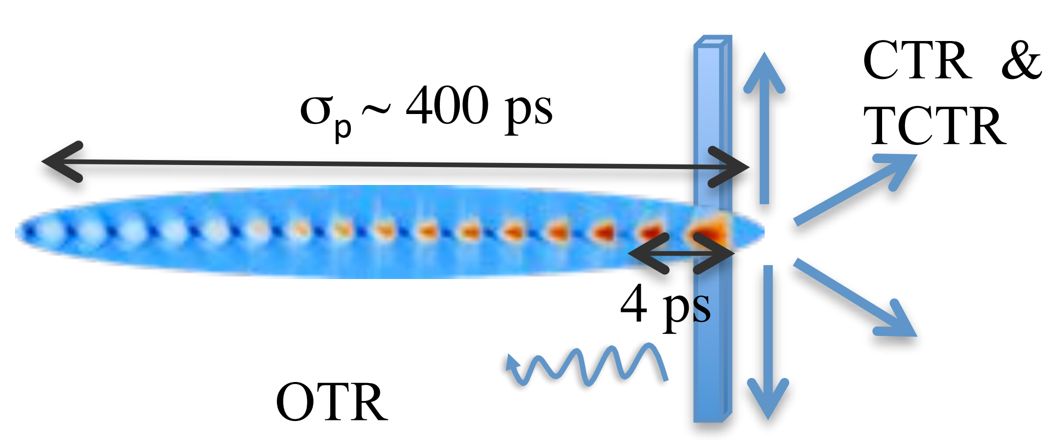
Direct measurements: space charge fields and transition radiation



J. Vieira *et al.* POP 19, 063105 (2012)

- Direct sampling bunch space charge with Streak-camera
- Measurement of radiation emitted when bunch crosses dielectric interface
- Transition radiation encodes charge distribution

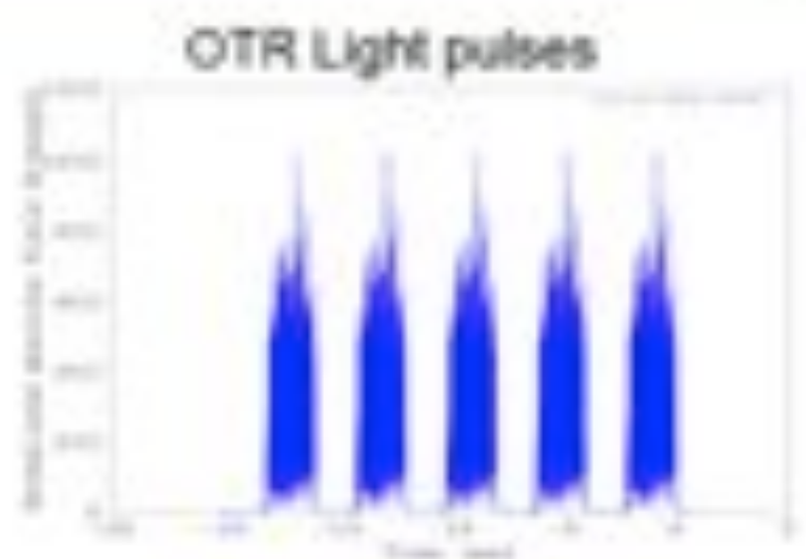
Example: Transition Radiation



K. Rieger, P. Muggli, M. Martyanov MPP

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

CERN



The design of the plasma source obeys stringent criteria to ensure maximum accelerating gradients and stable acceleration

Plasma source prototype

Key features

- Rubidium vapour plasma source
- Oil heated system: 150°-200° C
- Variable plasma (vapour) density: 10^{14}-10^{15} cm^{-3}
- 10 m long
- 4 cm diameter

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

E. Oz, P. Muggli, Nucl. Instr. Meth. A 740, 197 (2014)

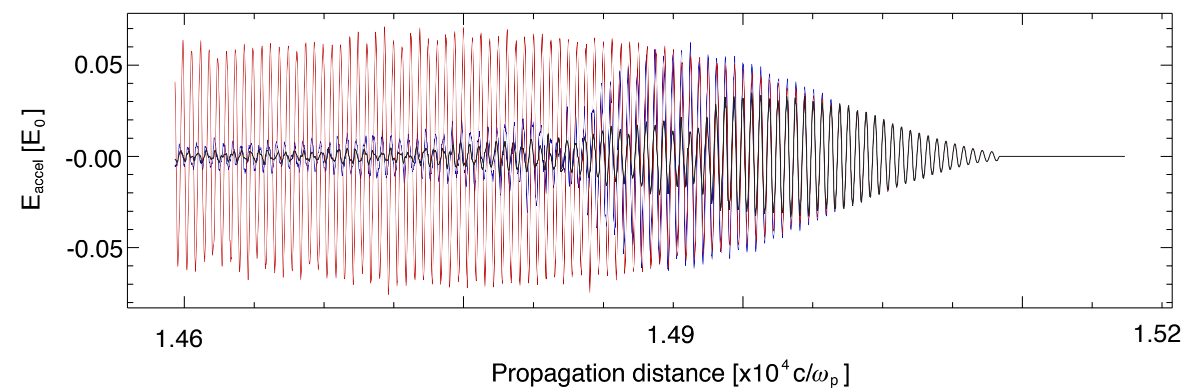
Requirements

Rubidium ensures no background plasma ion motion

Lithium (Li^{3+}) ions

Hydrogen (H^+) ions

Immobile ions = Rb



J. Vieira *et al.* PRL 109 145005 (2012)

Temperature uniformity $\Delta T/T<0.002$ ensures plasma density uniformity $\Delta n/n = \Delta T/T$

required to ensure stable electron acceleration

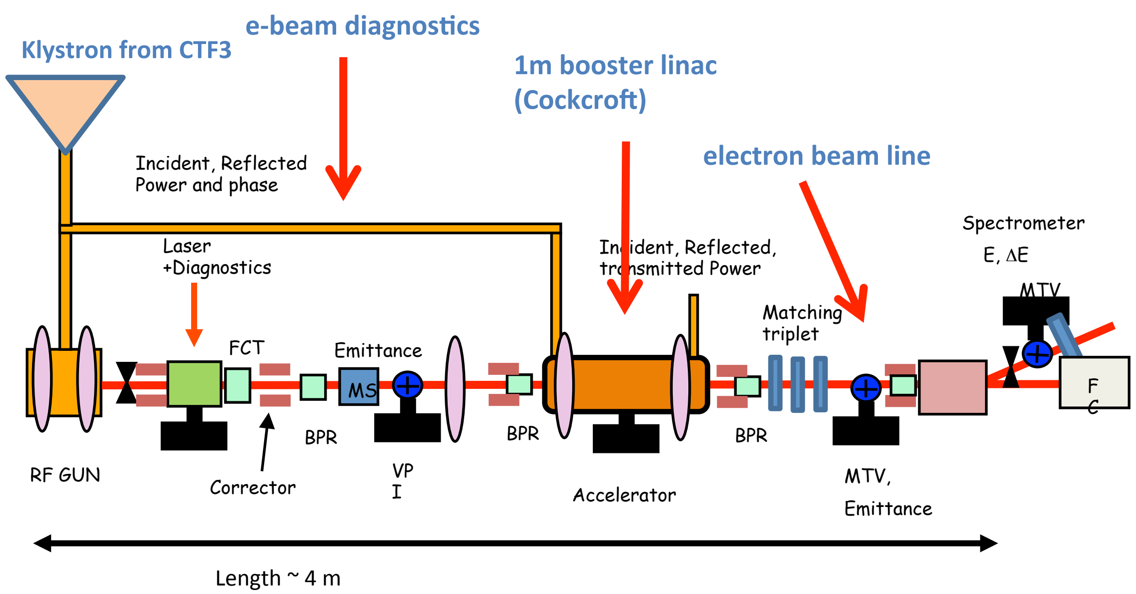
10 meter long plasma cell

required to reach saturation of self-modulation and electron acceleration

AWAKE will accelerate > 1 GeV electron bunches

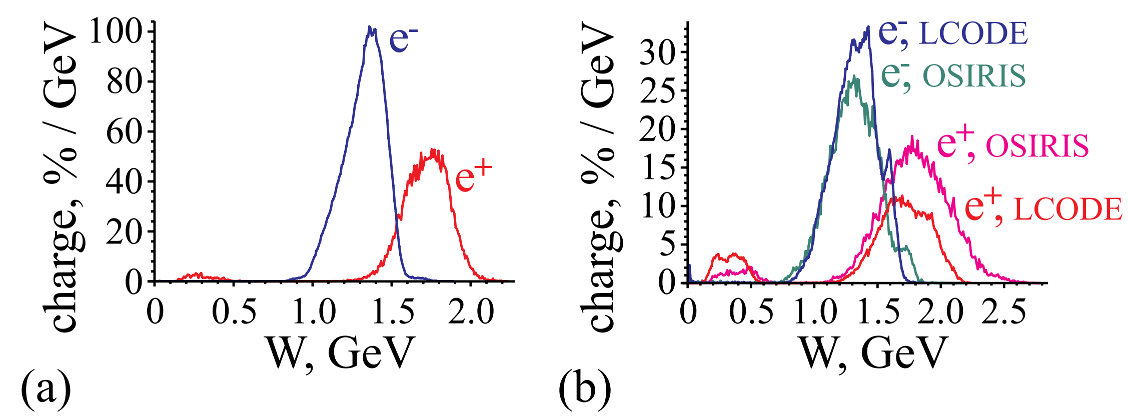
External electron injector

PHIN Photo-injector for CTF3/CLIC



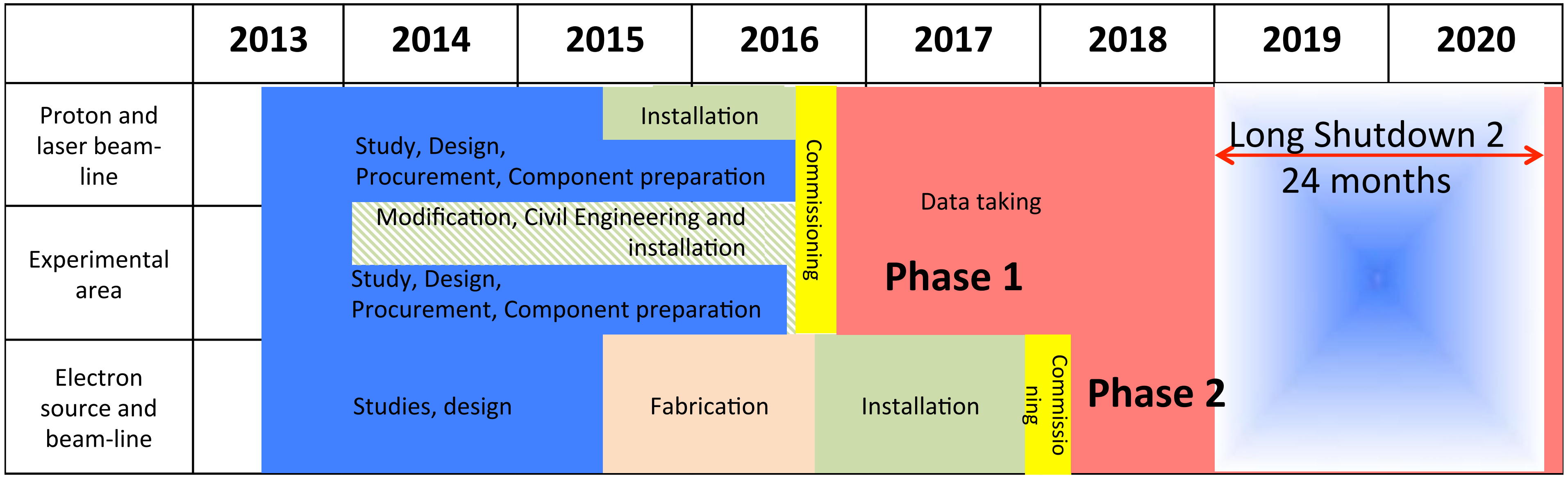
Electron beam for AWAKE	Baseline	Range for upgrade phase
Momentum	16 MeV/c	10-20 MeV
Electrons/bunch (bunch charge)	1.25 E9	0.6 – 6.25 E9
Bunch charge	0.2 nC	0.1 – 1 nC
Bunch length	σ_z =4ps (1.2mm)	0.3 – 10 ps
Bunch size at focus	$\sigma^*_{x,y}$ = 250 μm	0.25 – 1mm
Normalized emittance (r.m.s.)	2 mm mrad	0.5 – 5 mm mrad
Relative energy spread	Δp/p = 0.5%	<0.5%

>1 GeV in 10 meters



K. Lotov *et al.* PoP 21, 123116 (2014)
A. Pukhov *et al.* PRL 107, 145003 (2011)

Key goals and schedule for AWAKE



Phase 1	Phase 2	Future
• Demonstration of self-modulation laser ionisation seeding • Demonstrating the growth and saturation of the self-modulation instability	• Add external electron beam • Demonstrate trapping of external electron beam • Demonstrate electron > 1 GeV acceleration over 10 meters	• Positron acceleration • Separate acceleration stage from SMI stage • Implementation of strategies to enhance acceleration • Development of additional plasma sources

Conclusions

Plasma based acceleration

- Promising technology to assist high energy physics
- Successful experiments demonstrated acceleration of electron and positron bunches

AWAKE: Advanced Wakefield Acceleration Experiment

- First proton driven plasma wakefield acceleration experiment in the world
- Experiments starting end of 2016
- First step into a single stage plasma wakefield acceleration experiment towards very high energy gains

Main challenges

- Beam quality
- Reproducibility
- Average power in the accelerated beam