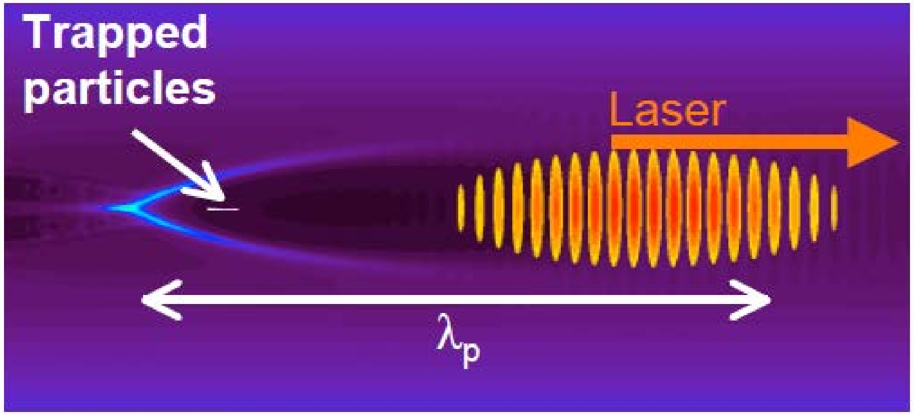
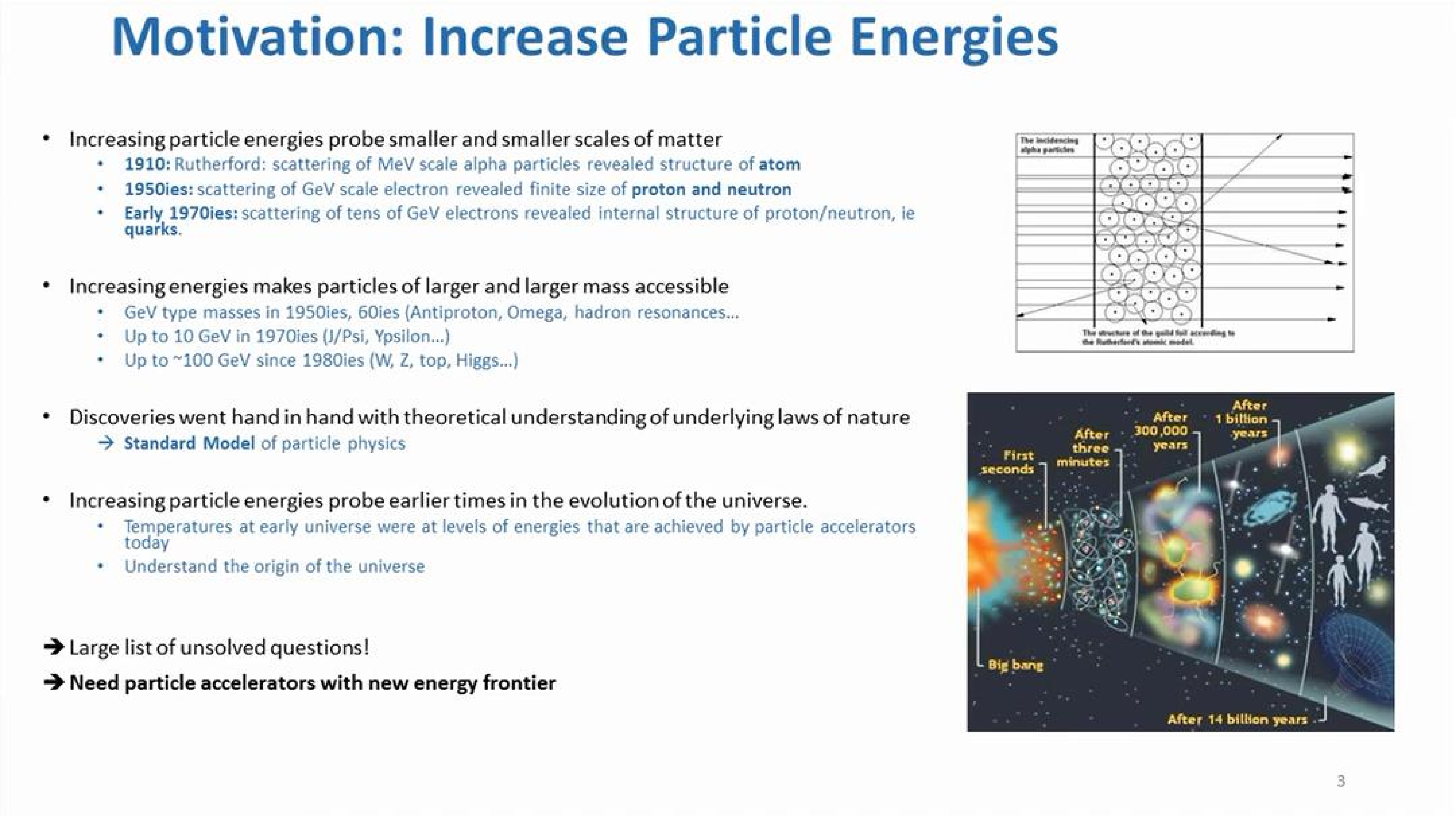
Wakefield Accelerator

Process: Laser radiation pressure displaces electrons
Space charge causes oscillating density ‘wake’ moving with the laser
Wake electric fields of ~GV/cm accelerate particles



Analogy: boat displacing water

Particle injection



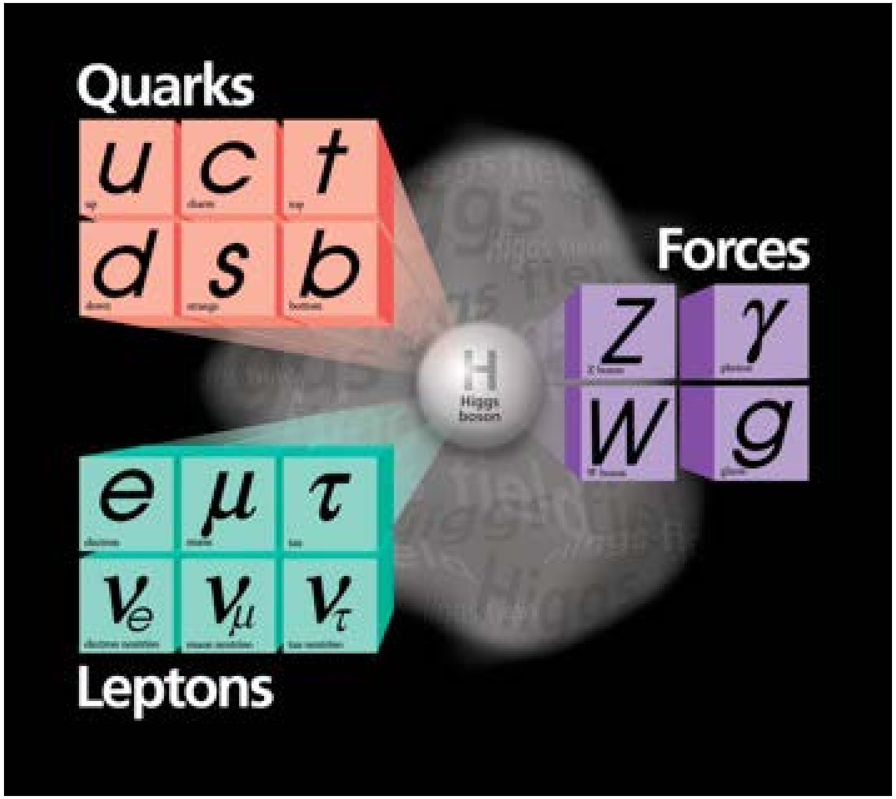
Motivation: Increase Particle Energies

- Increasing particle energies probe smaller and smaller scales of matter
    - **1910:** Rutherford: scattering of MeV scale alpha particles revealed structure of **atom**
    - **1950ies:** scattering of GeV scale electron revealed finite size of **proton and neutron**
    - **Early 1970ies:** scattering of tens of GeV electrons revealed internal structure of proton/neutron, ie **quarks**.
- Increasing energies makes particles of larger and larger mass accessible
    - GeV type masses in 1950ies, 60ies (Antiproton, Omega, hadron resonances...
    - Up to 10 GeV in 1970ies (J/Psi, Ypsilon...)
    - Up to ~100 GeV since 1980ies (W, Z, top, Higgs...)
- Discoveries went hand in hand with theoretical understanding of underlying laws of nature
    → **Standard Model** of particle physics
- Increasing particle energies probe earlier times in the evolution of the universe.
    - Temperatures at early universe were at levels of energies that are achieved by particle accelerators today
    - Understand the origin of the universe

➔ Large list of unsolved questions!

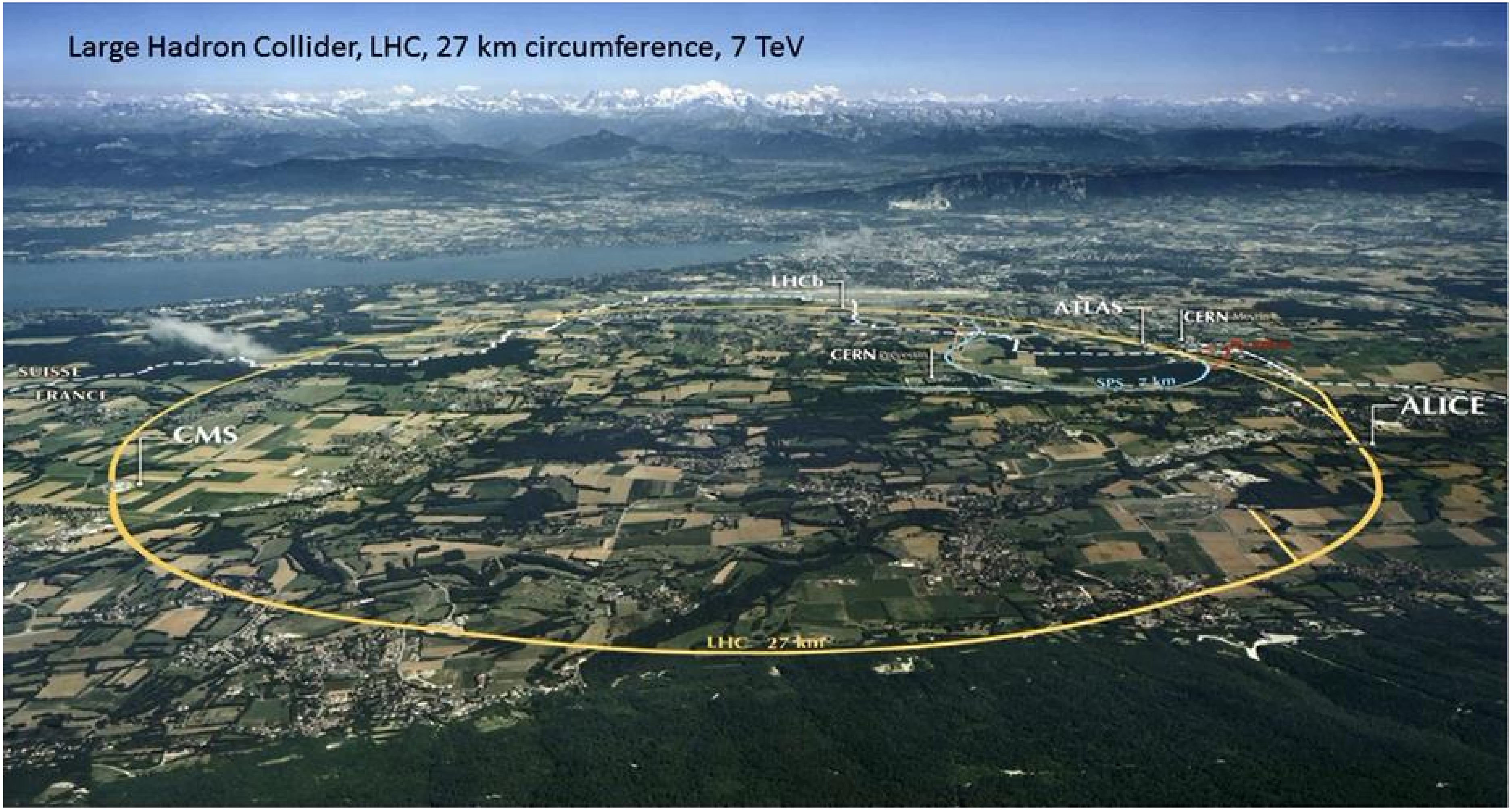
➔ **Need particle accelerators with new energy frontier**

Big questions in particle physics



The Standard Model is amazingly successful, but there are unanswered questions:

- What are the consequences of the "Higgs" particle discovery?
- Why is there so much matter (vs. anti-matter) ?
- Why is there so little matter (5%) in the Universe?
- Can we unify the forces?



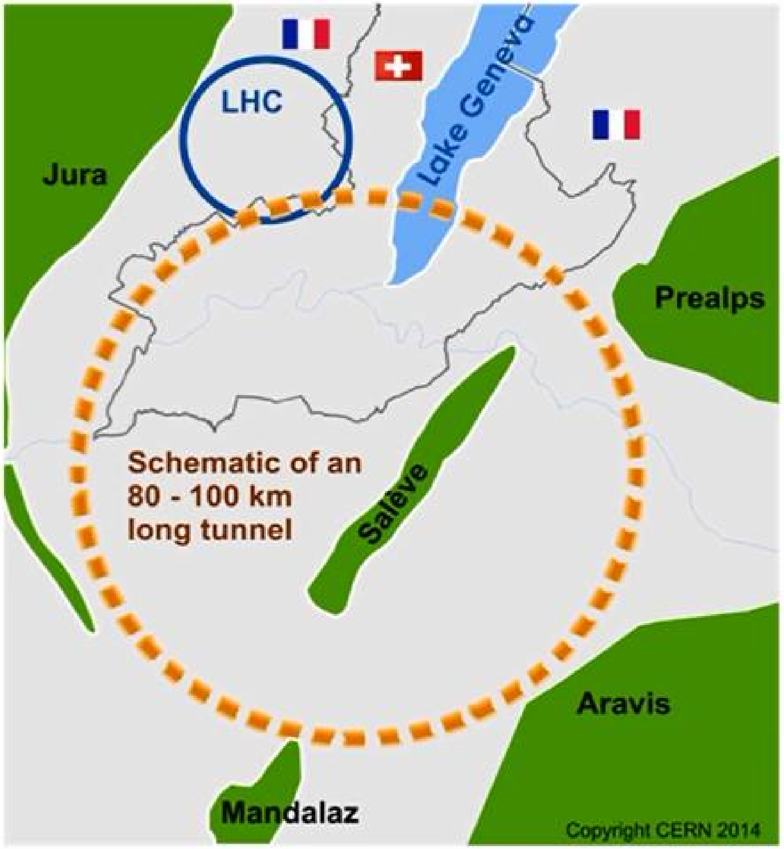
Large Hadron Collider, LHC, 27 km circumference, 7 TeV

Circular Collider

FCC, Future Circular Collider

80 – 100 km diameter
100 TeV (pp)
>350 GeV (e^+e^-)

20 T dipoles



Schematic of an 80 - 100 km long tunnel

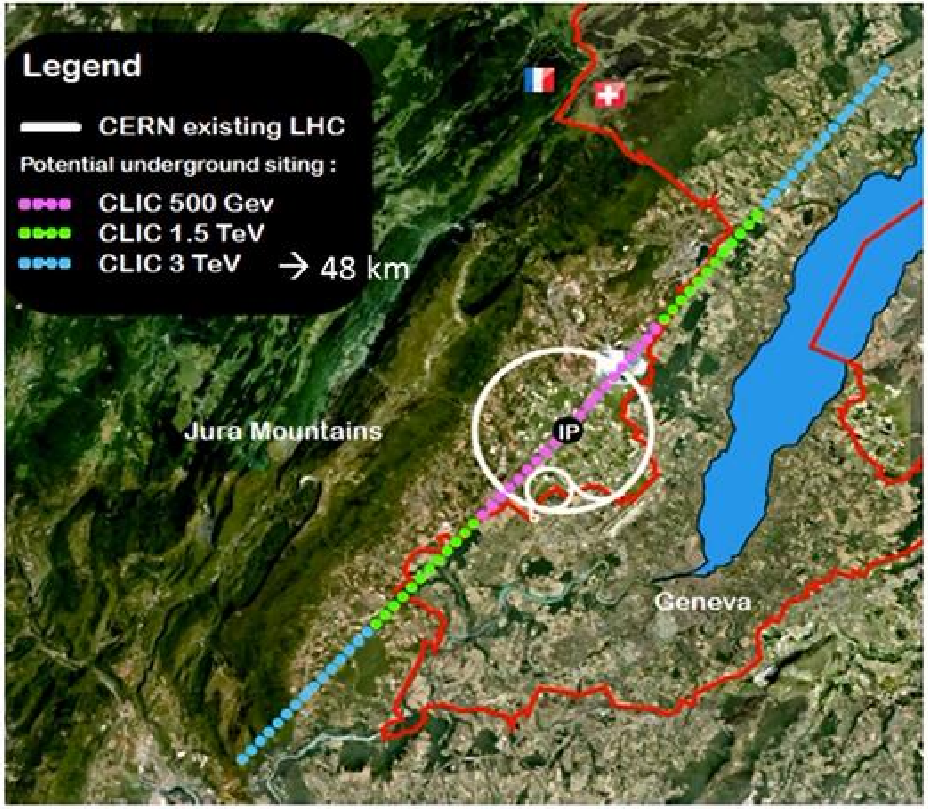
Copyright CERN 2014

Linear Colliders

CLIC

48 km length
3 TeV (e^+e^-)

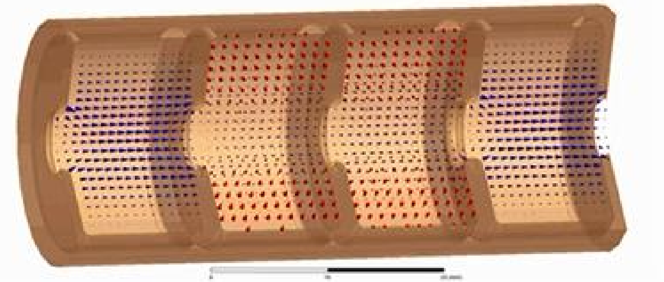
Accelerating elements:
Cavities: 100 MV/m



Conventional Accelerating Technology

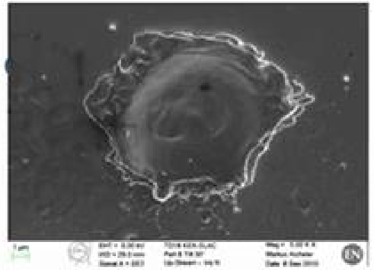
Today's RF cavities or microwave technology:

- Very successfully used in all accelerators (hospitals, scientific labs,...) in the last 100 years.



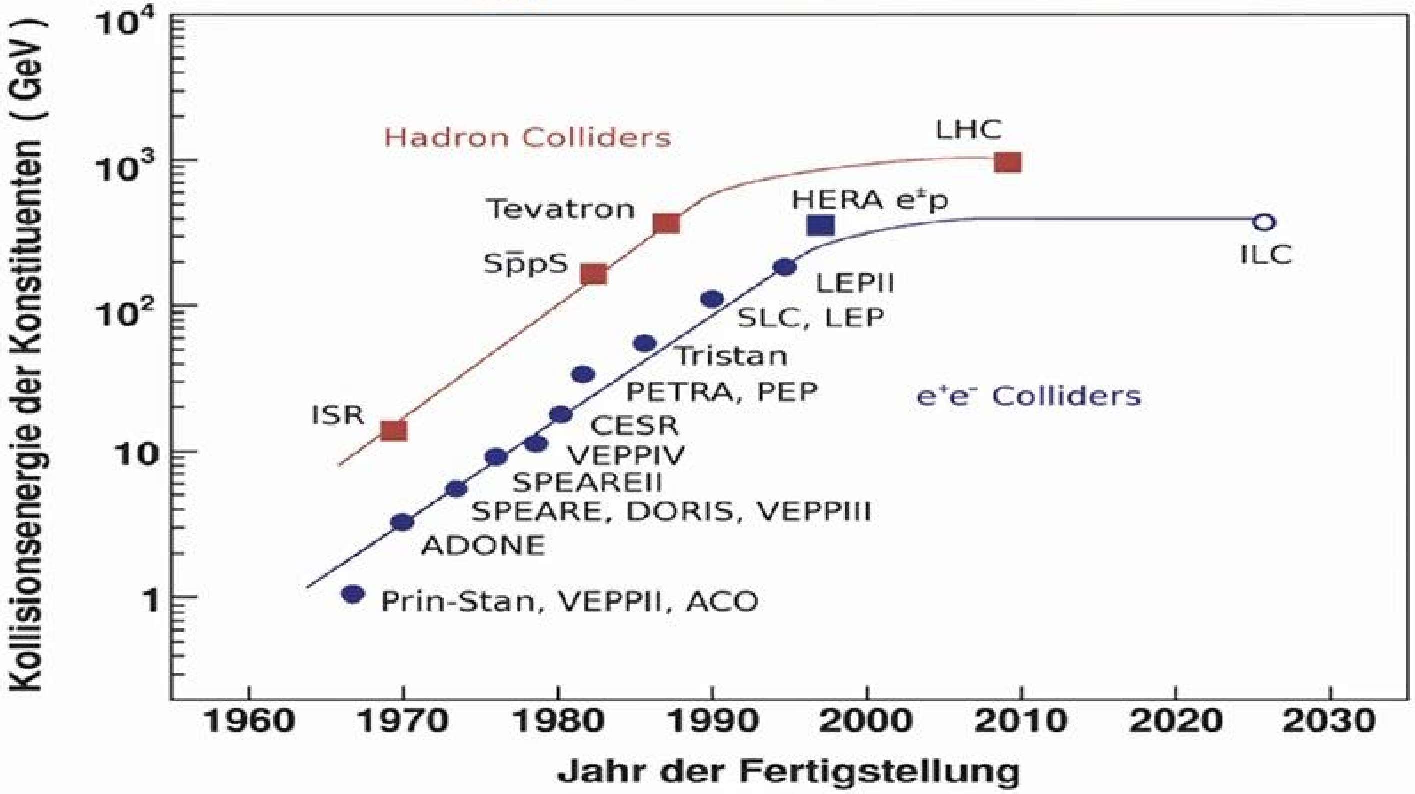
- Typical gradients:
  - LHC: 5 MV/m
  - ILC: 35 MV/m
  - CLIC: 100 MV/m

However:



- accelerating fields are limited to <100 MV/m
  - In metallic structures, a too high field level leads to break down of surfaces, creating discharge.
  - Fields cannot be sustained, structures might be damaged.
- several tens of kilometers for future linear colliders

Saturation at Energy Frontier for Accelerators



➔ **Project size and cost increase with energy**

Motivation

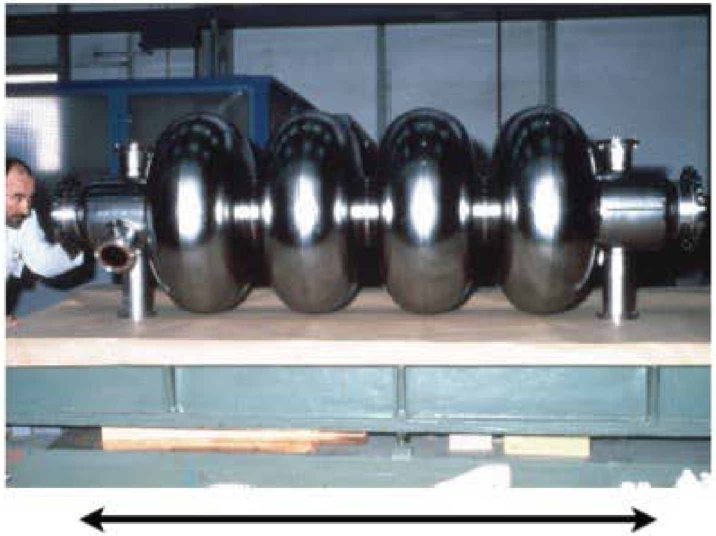
New directions in science are launched by ***new tools*** much more often than by ***new concepts***.

The effect of a ***concept-driven*** revolution is to explain old things in new ways.

The effect of a ***tool-driven*** revolution is to discover new things that have to be explained.

from Freeman Dysen ‘Imagined Worlds’

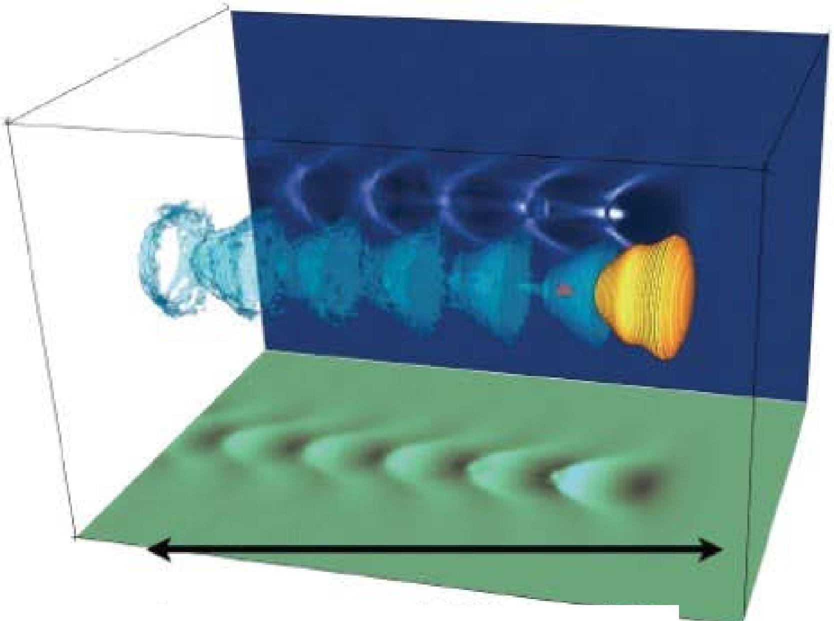
RF Cavity



1 m ⇒ 50 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



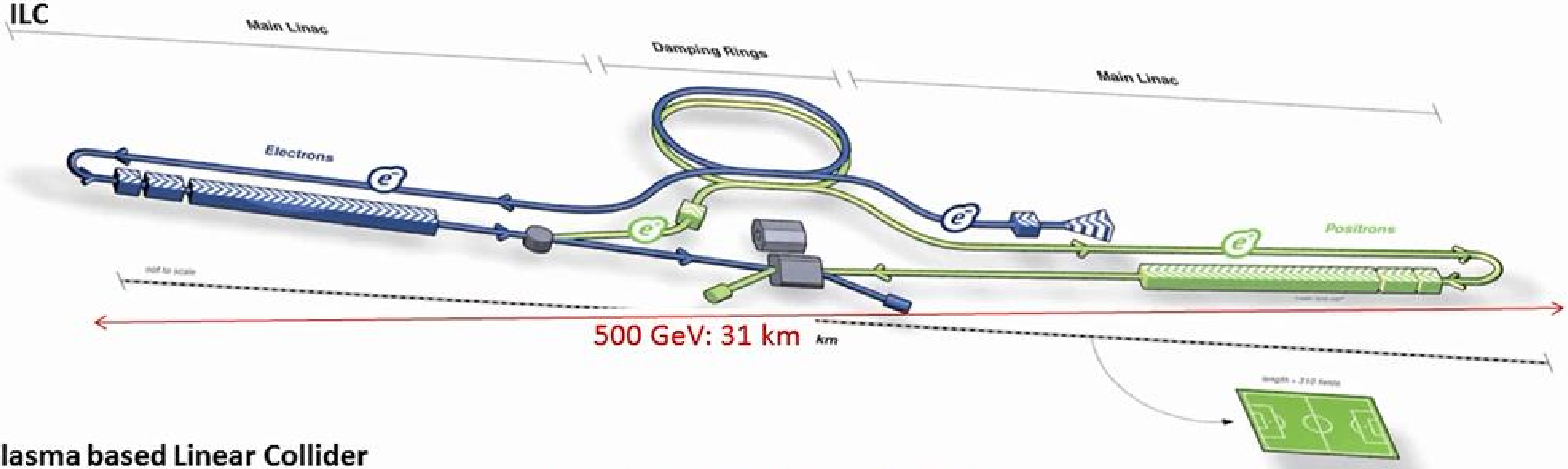
1 mm ⇒ 100 MeV

Electric field > 100 GV/m

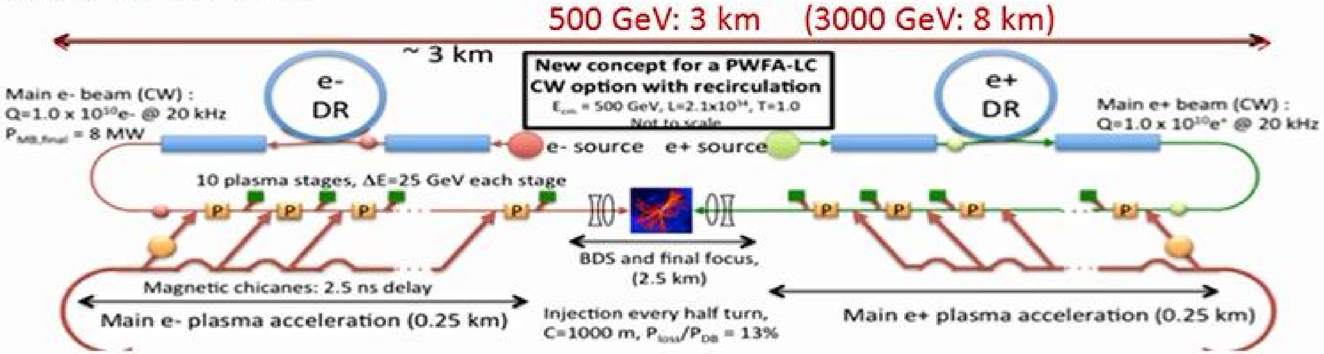
Compactness of plasma ‘cavity’. Left: Radiofrequency cavity. Right: Non-linear laser plasma wakefield. The laser pulse in yellow propagates from left to right, the iso-electronic density is shown in blue and the electron bunch in red.

Linear Colliders

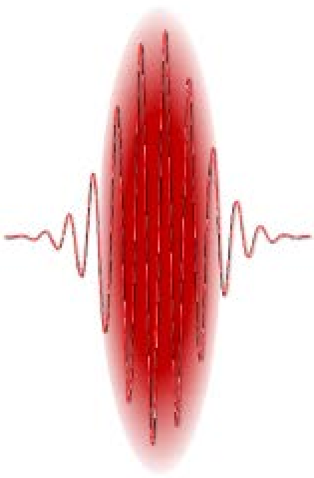
ILC



Plasma based Linear Collider



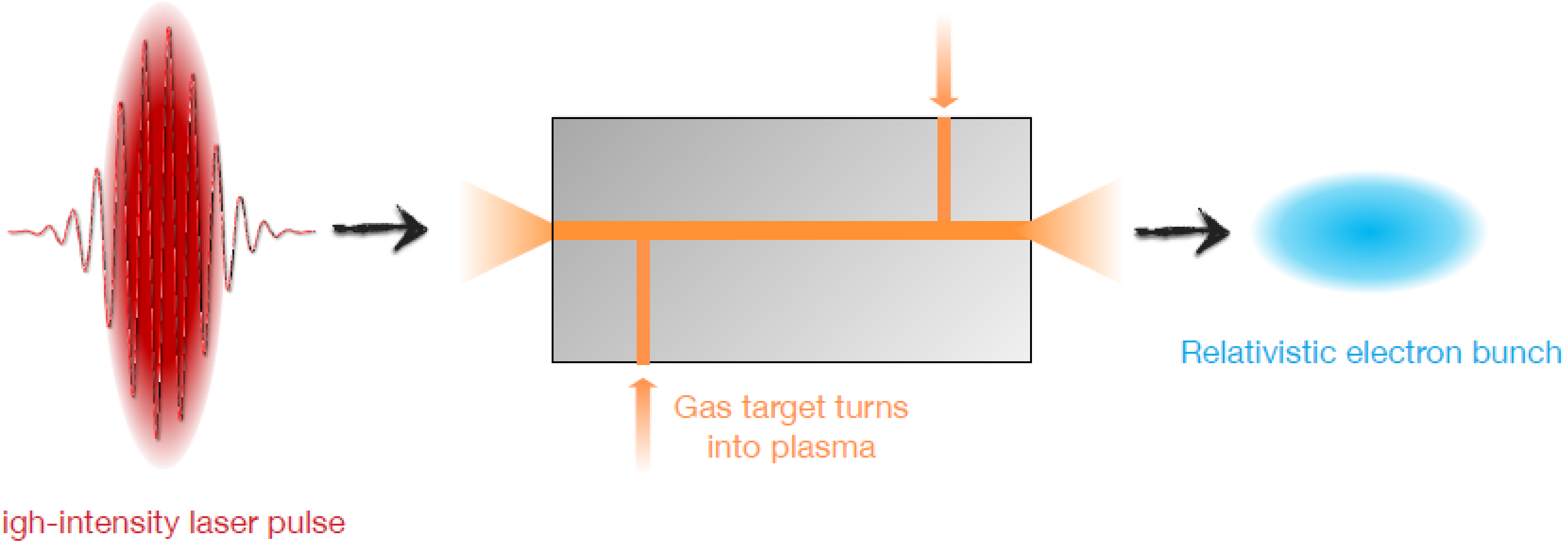
Let’s look at the driver first: a relativistically intense laser pulse



- Peak power 1 PW or 1,359,621,617,300 PS (if you are into cars) compare to total nuclear power output in the world 0.000 374 PW
- Energy ~ 10 J in ~ 10 fs = 0.000 000 000 000 01 s duration focused to ~ 50 µm spots (size of thin hair)
- $\sim 4 \cdot 10^{19}$ photons
- Intensity $\sim 10^{19}\ W/cm^2$ electrons become relativistic
- Electric fields of 8.6 TV/m, magnetic fields of ~28954 Tesla

Burning question: can these fields be used for particle acceleration?

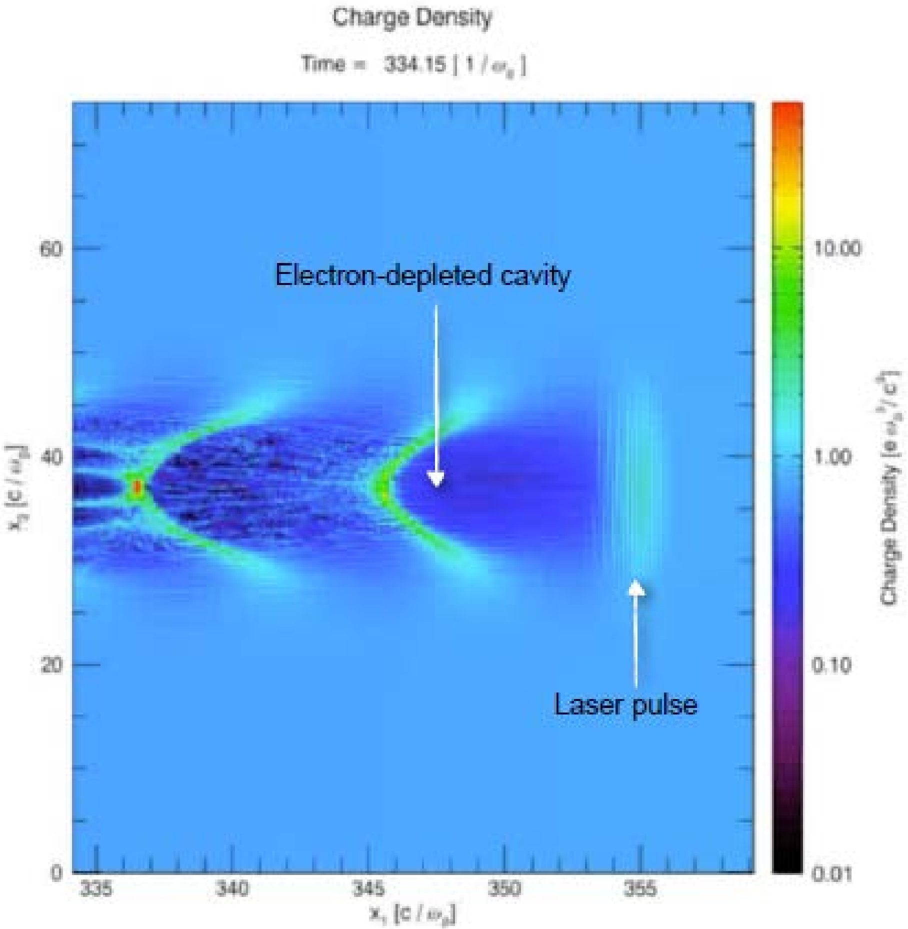
But interacting the laser with matter works!



- Intensity $\sim 10^{19}\ W/cm^2$ → light pressure on matter $\sim 300\ Tbar$, electron temperature $\sim MeV$ or $\sim G^0C$!

Laser excitation of strong plasma waves

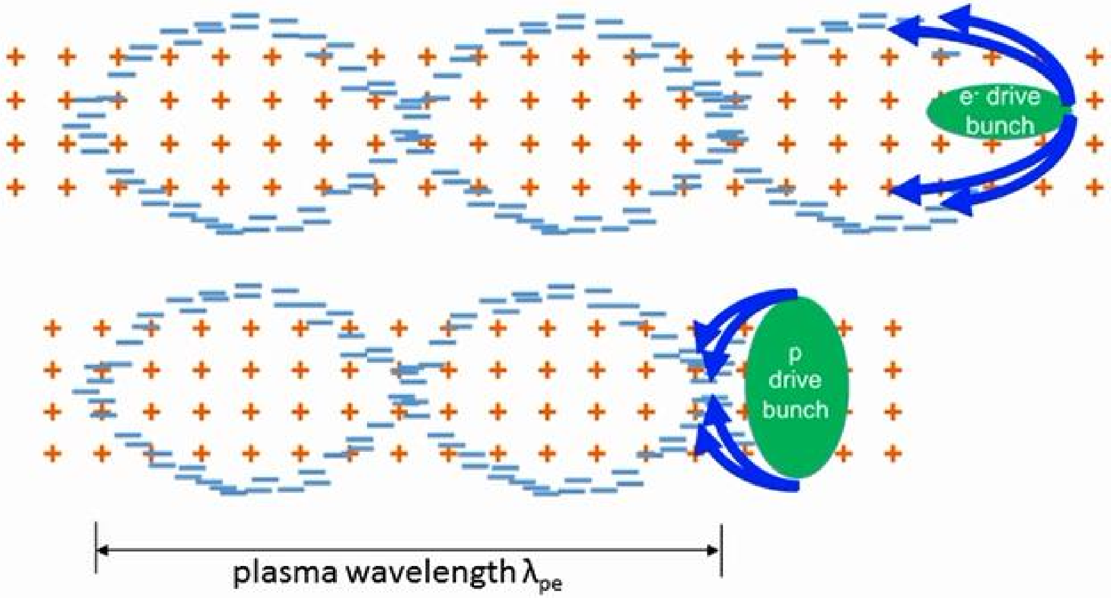
- Intense laser-pulse from left to right
- Pushes away electrons by its light pressure or ponderomotive force (ions are too heavy, hardly move)
- Creates electron-depleted cavity and sets up charge separation
- Strong electrostatic fields pull back electrons on axis
- Electrons oscillate and create copropagating wakefield



Principle of Plasma Wakefield Acceleration

- Laser drive beam
  ➔ Ponderomotive force
- Charged particle drive beam
  ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam

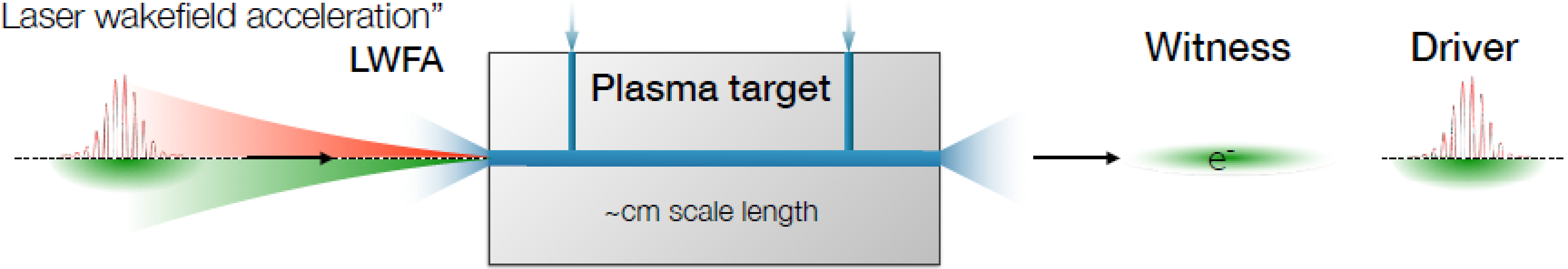
use transverse field to create a longitudinal field for acceleration



- Plasma wave/wake excited by relativistic particle bunch
- Plasma e⁻ are expelled by space charge force
- Plasma e⁻ rush back on axis
- Acceleration physics identical for LWFA, PWFA

Plasma wakefield acceleration in a nutshell

Laser-pulse driven
“Laser wakefield acceleration”
LWFA



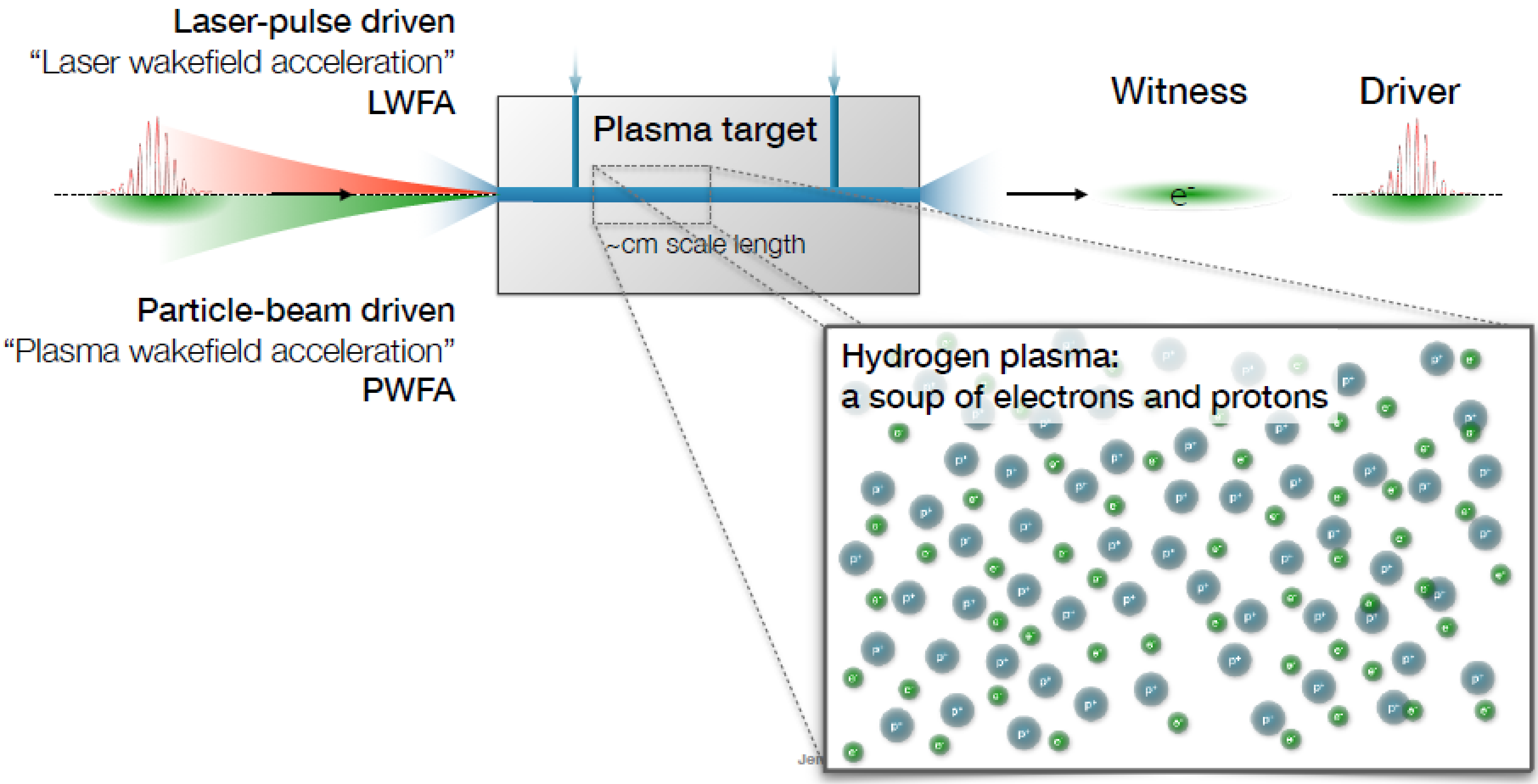
Particle-beam driven
“Plasma wakefield acceleration”

PWFA vs. LWFA

- average power of up to MW (vs. ~100 W)
- wall-plug efficiency of ~10% (vs. < 0.1%)

→ beam-driven wakes (currently) the only viable solution for high-average-power applications

Plasma wakefield acceleration in a nutshell



Laser-pulse driven
“Laser wakefield acceleration”
LWFA

Particle-beam driven
“Plasma wakefield acceleration”
PWFA

Plasma target

~cm scale length

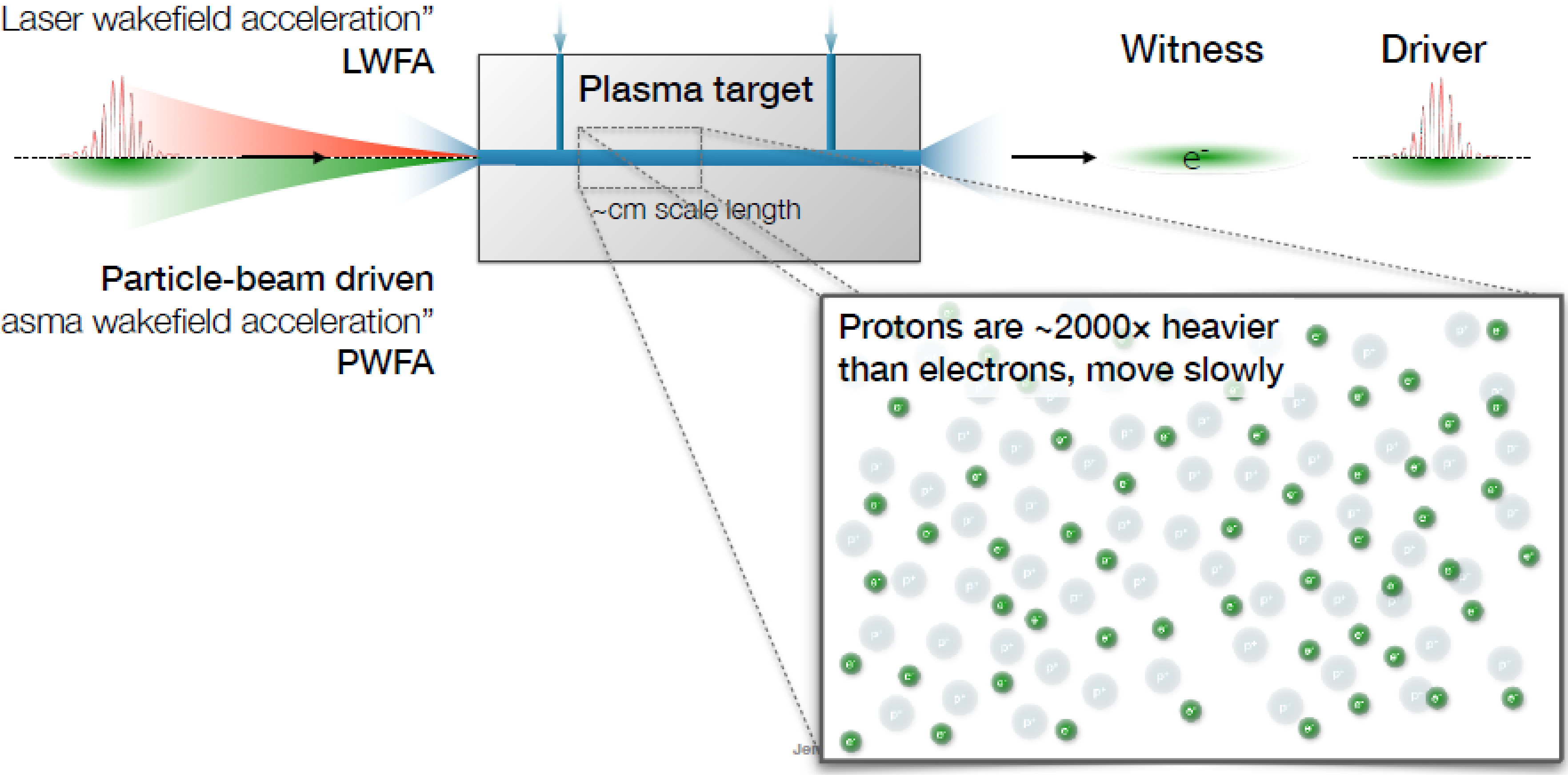
Witness

Driver

e^-

Hydrogen plasma:
a soup of electrons and protons

Plasma wakefield acceleration in a nutshell



Laser-pulse driven
“Laser wakefield acceleration”
LWFA

Particle-beam driven
“Plasma wakefield acceleration”
PWFA

Plasma target

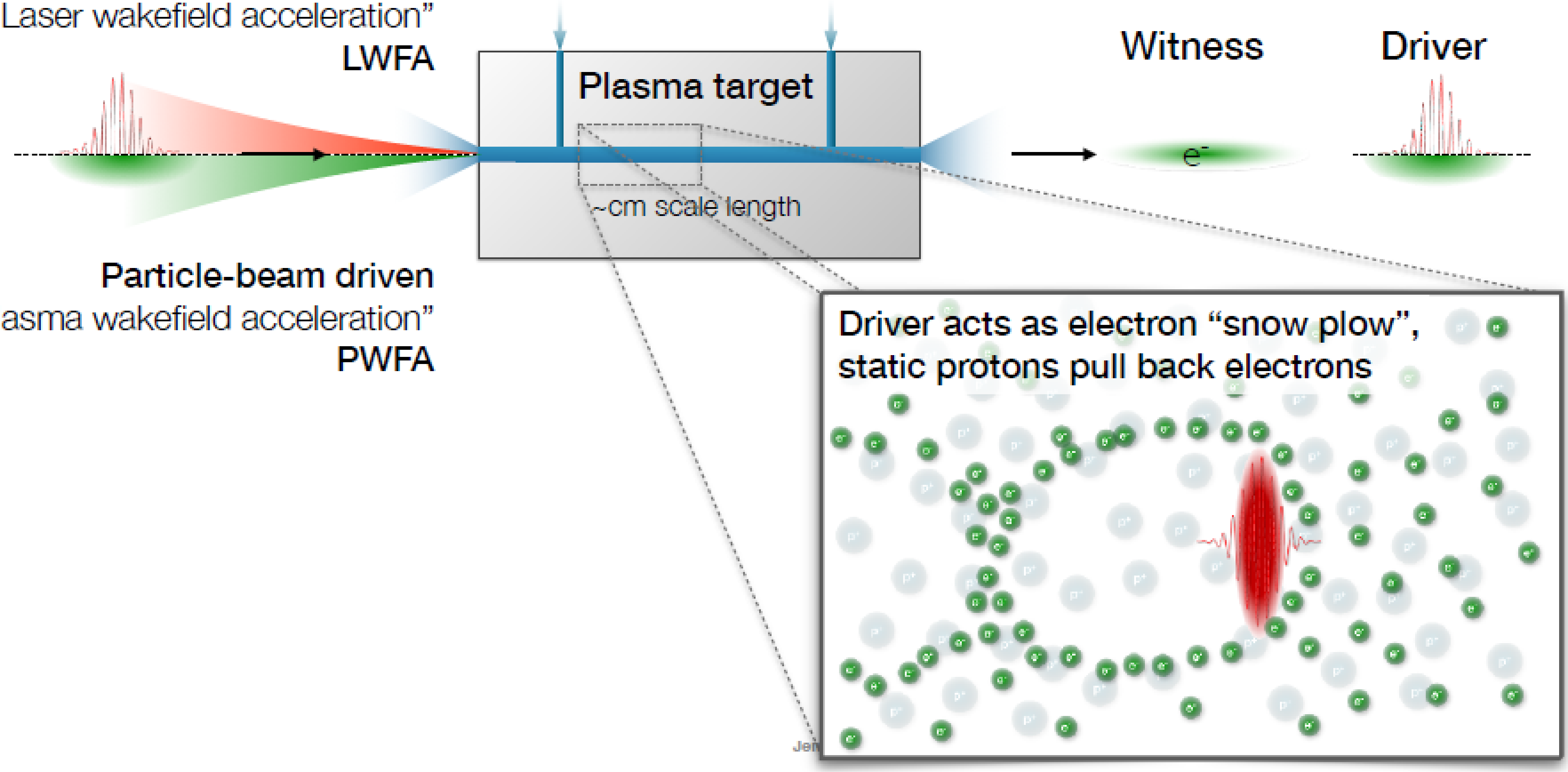
~cm scale length

Witness

Driver

Protons are ~2000x heavier than electrons, move slowly

Plasma wakefield acceleration in a nutshell



Laser-pulse driven
"Laser wakefield acceleration"
LWFA

Particle-beam driven
"Plasma wakefield acceleration"
PWFA

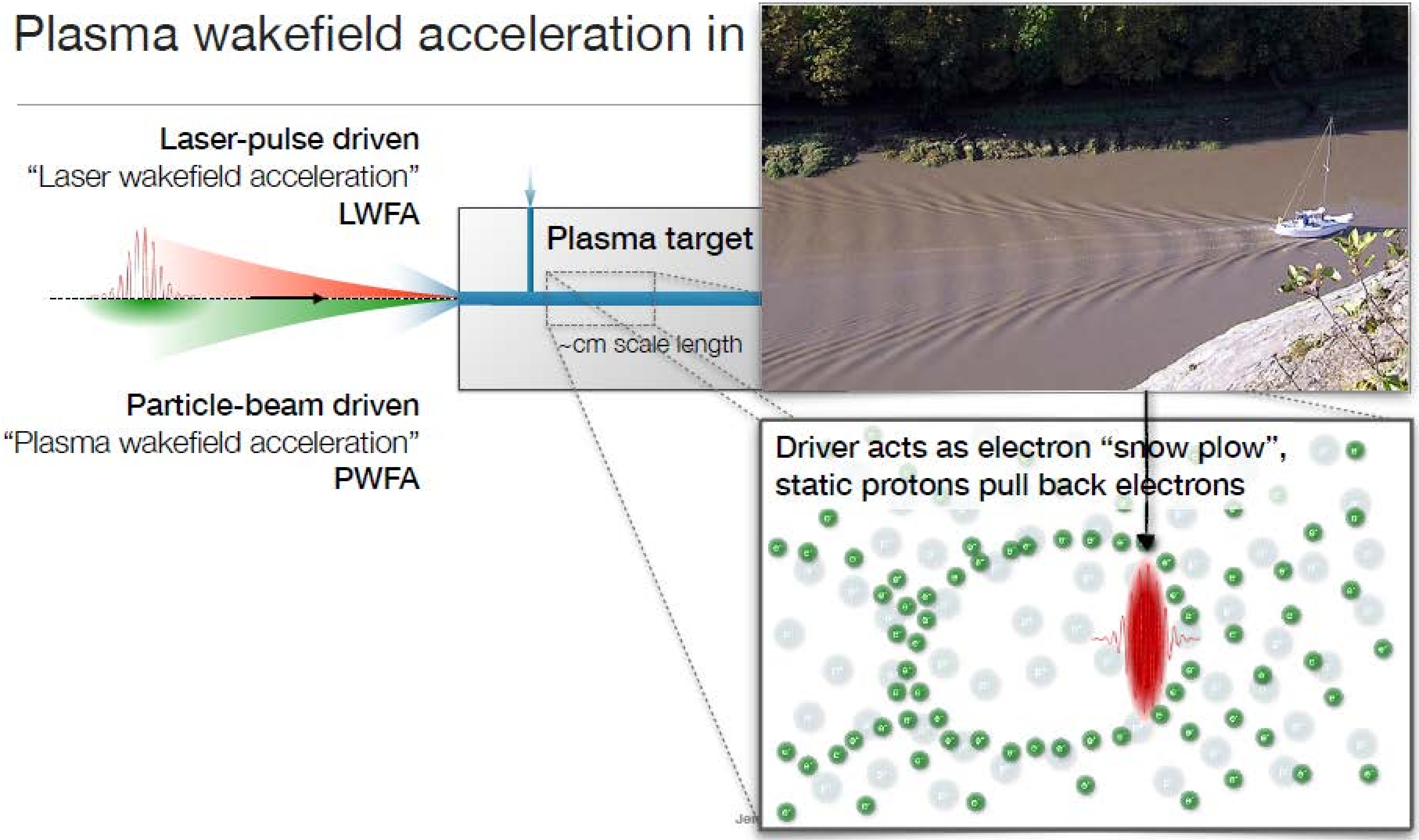
Plasma target

~cm scale length

Witness

Driver

Driver acts as electron "snow plow", static protons pull back electrons



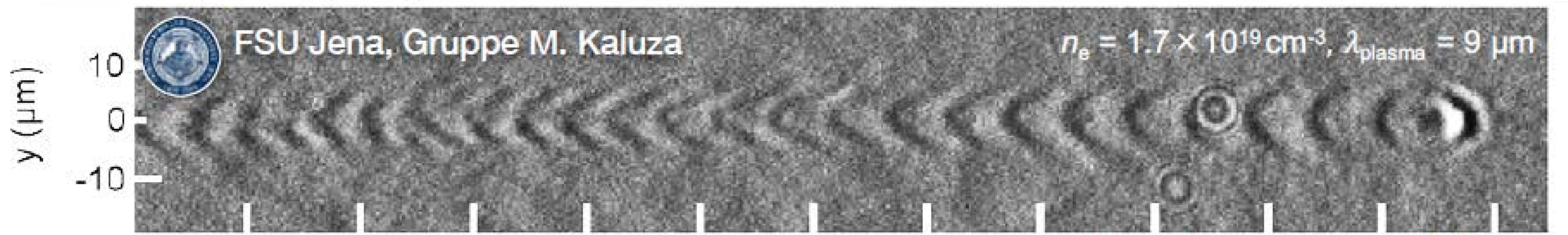
Plasma wakefield acceleration in

Laser-pulse driven
"Laser wakefield acceleration"
LWFA

Particle-beam driven
"Plasma wakefield acceleration"
PWFA

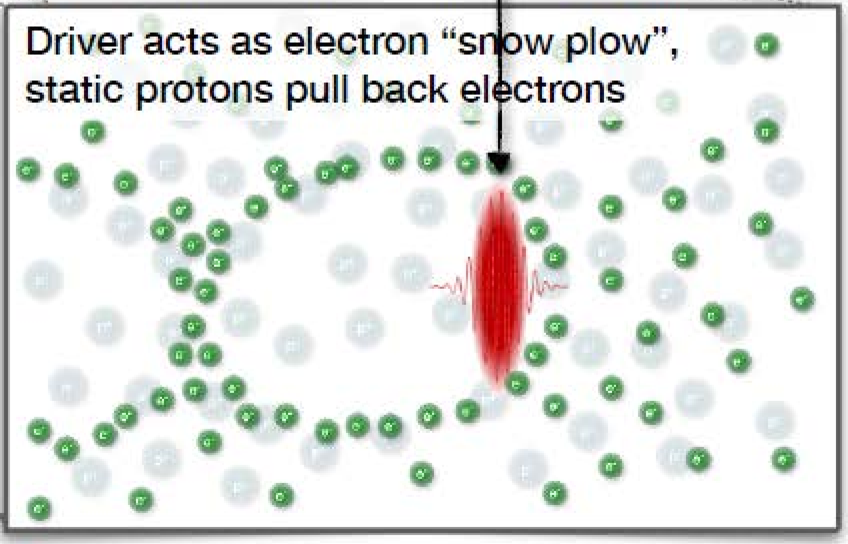
Driver acts as electron "snow plow",
static protons pull back electrons

Plasma wakefield acceleration in a nutshell



M. Schnell *et al.*, Nat. Comm. 4, 2421 (2013)

Particle-beam driven
"Plasma wakefield acceleration"
PWFA



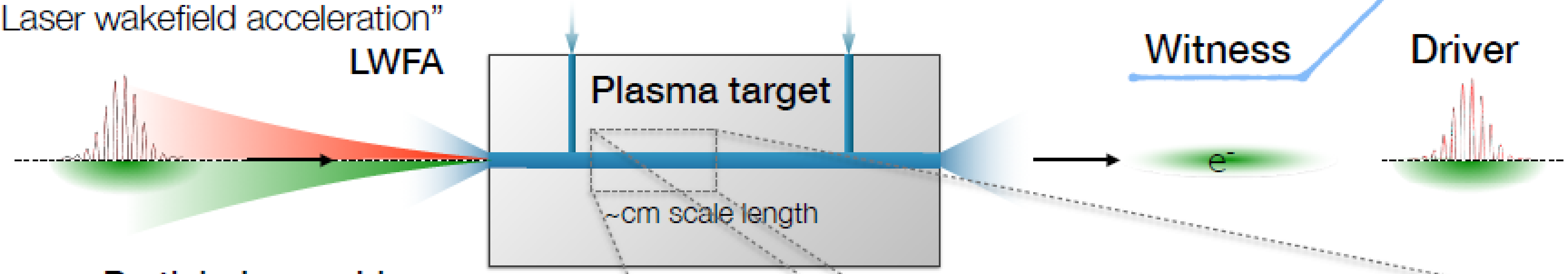
Driver acts as electron "snow plow", static protons pull back electrons

Plasma wakefield acceleration in a nutshell

Interesting for applications

~GeV energy < µm emittance
~fs duration ~kA current

Laser-pulse driven
"Laser wakefield acceleration"
LWFA



Particle-beam driven
"Plasma wakefield acceleration"
PWFA

Bunch duration: fs

- → O. Lundh *et al.*, Nature Physics 7, 219 (2011)
- → A. Buck *et al.*, Nature Physics 7, 543 (2011)

GeV energy gain over cm

- → W.P. Leemans *et al.*, Nature Physics 2, 696 (2006)

Size of structure

$$\lambda_p \approx \frac{2\pi c}{\omega_p} \approx (33\ \mathrm{km})\sqrt{n_e^{-1}[\mathrm{cm}^{-3}]}$$

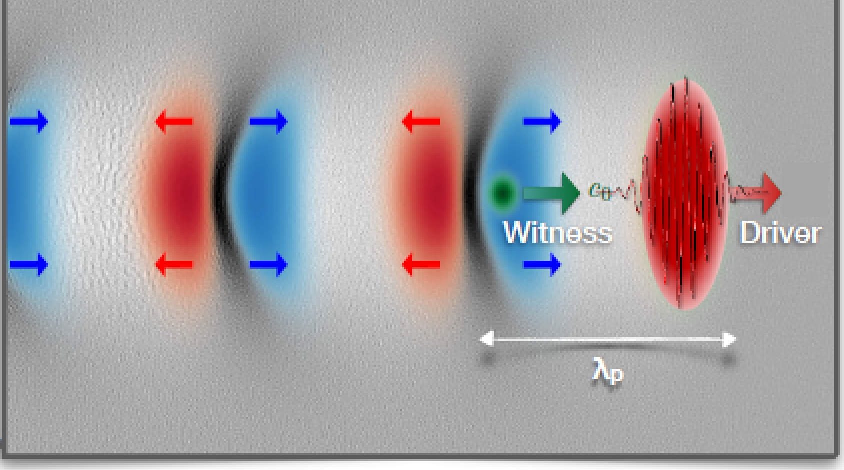
typically $\lambda_p \approx 33$ µm (for $n_e \approx 10^{18}$ cm^{-3})

Electric field strength

$$E \approx \frac{mc\omega_p}{e} \approx (96\ \mathrm{V/m})\sqrt{n_e[\mathrm{cm}^{-3}]}$$

typically E ≈ 100 GV/m (for $n_e \approx 10^{18}$ cm^{-3})

Co-propagating, strong fields for acceleration



Plasma considerations

Based on linear fluid dynamics:

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

$$\lambda_p \approx 1\,[mm] \cdot \sqrt{\frac{10^{15}\,[cm^{-3}]}{n_p}} \quad or \quad \approx \sqrt{2} \cdot \pi \cdot \sigma_z$$

$$E \approx 2\,[GV\,m^{-1}] \cdot \left(\frac{N}{10^{10}}\right) \cdot \left(\frac{100\,[\mu m]}{\sigma_z}\right)^2$$

Relevant physical quantities:

- Oscillation frequency ω_p
- Plasma wavelength λ_p
- Accelerating gradient E

where

- n_p is the plasma density
- e is the electron charge
- ϵ_0 is the permittivity of free space
- m_e is the mass of electron
- N is the number of drive-beam particles
- σ_z is the drive-beam length

High gradients with:

- Short drive beams (and short plasma wavelength)
- Pulses with large number of particles (and high plasma density)

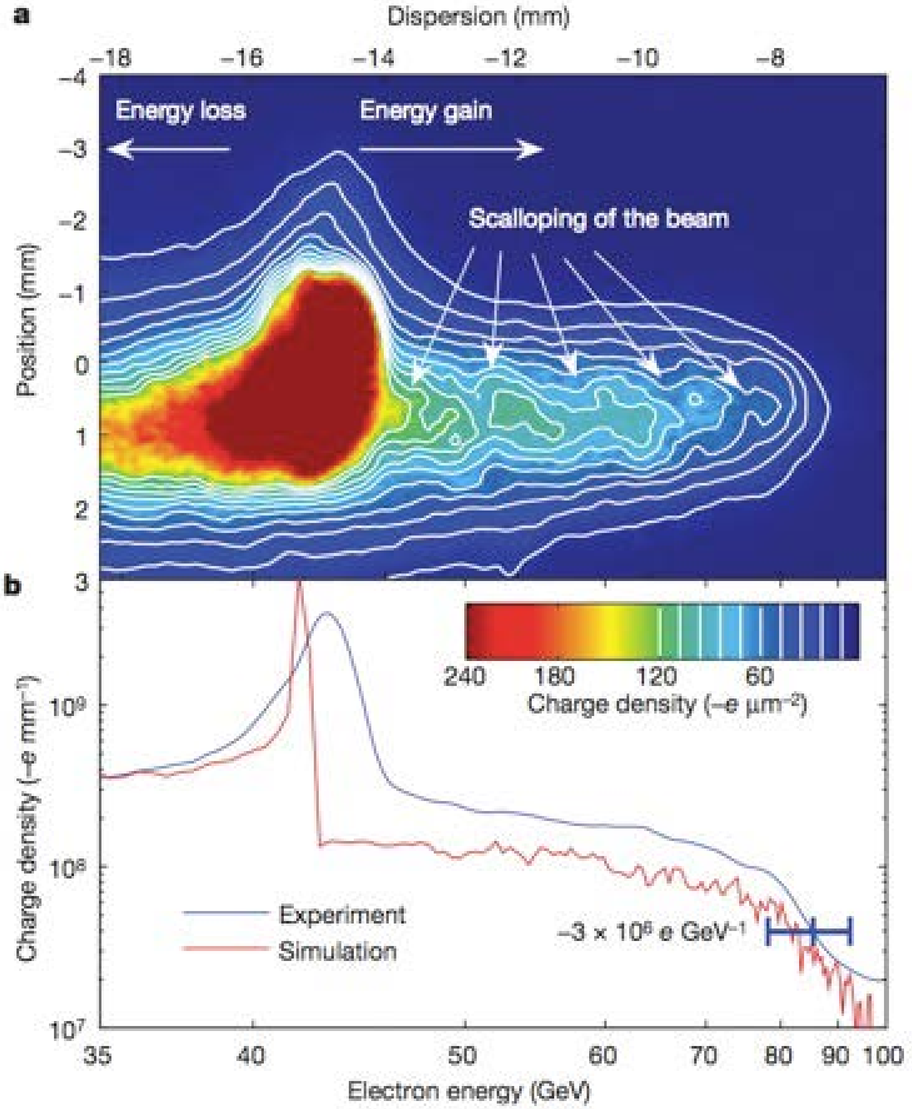
T. Tajima & J.W. Dawson; Phys. Rev. Lett. 43 (1979) 267
P. Chen et al.; Phys. Rev. Lett. 54 (1985) 693

Plasma wakefield experiments

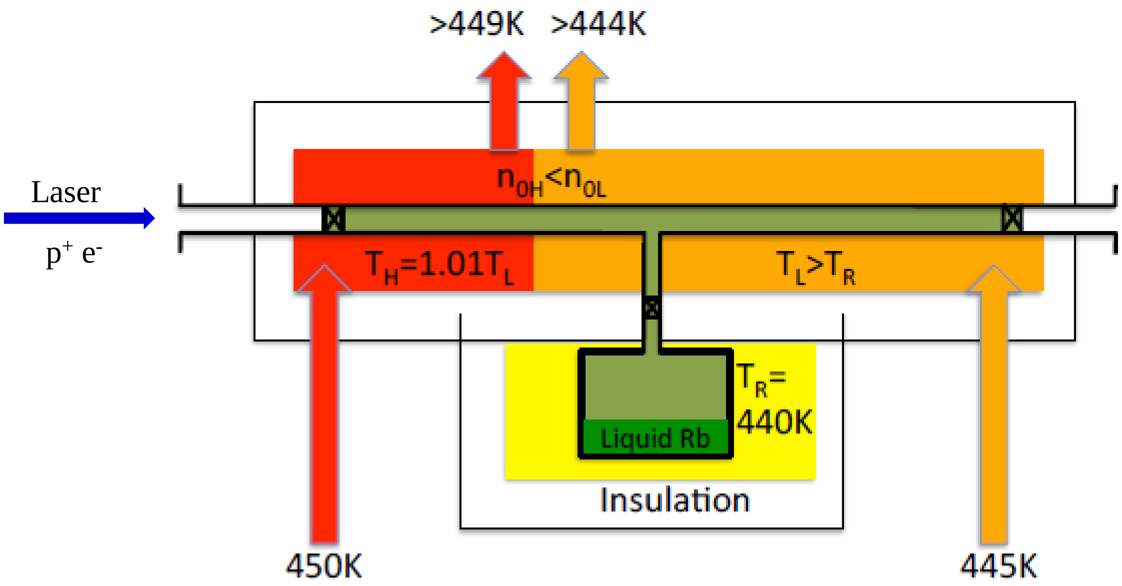
- Pioneering work using a LASER to induce wakefield up to 100 GV/m.

- Experiments at SLAC have used a particle (electron) beam:
  - Initial energy $E_e = 42\ GeV$
  - Gradients up to $\sim 52\ {}^{GV}/_{m}$
  - Energy doubled over $\sim 1\ m$
  - Next stage FACET project http://facet.slac.stanford.edu

- High proton beams of much higher energy:
  - HERA (DESY): $1\ TeV$
  - Tevatron (FNAL): $1\ TeV$
  - CERN: $24/450\ \ GeV\ and\ 3.5\ (7)\ TeV$

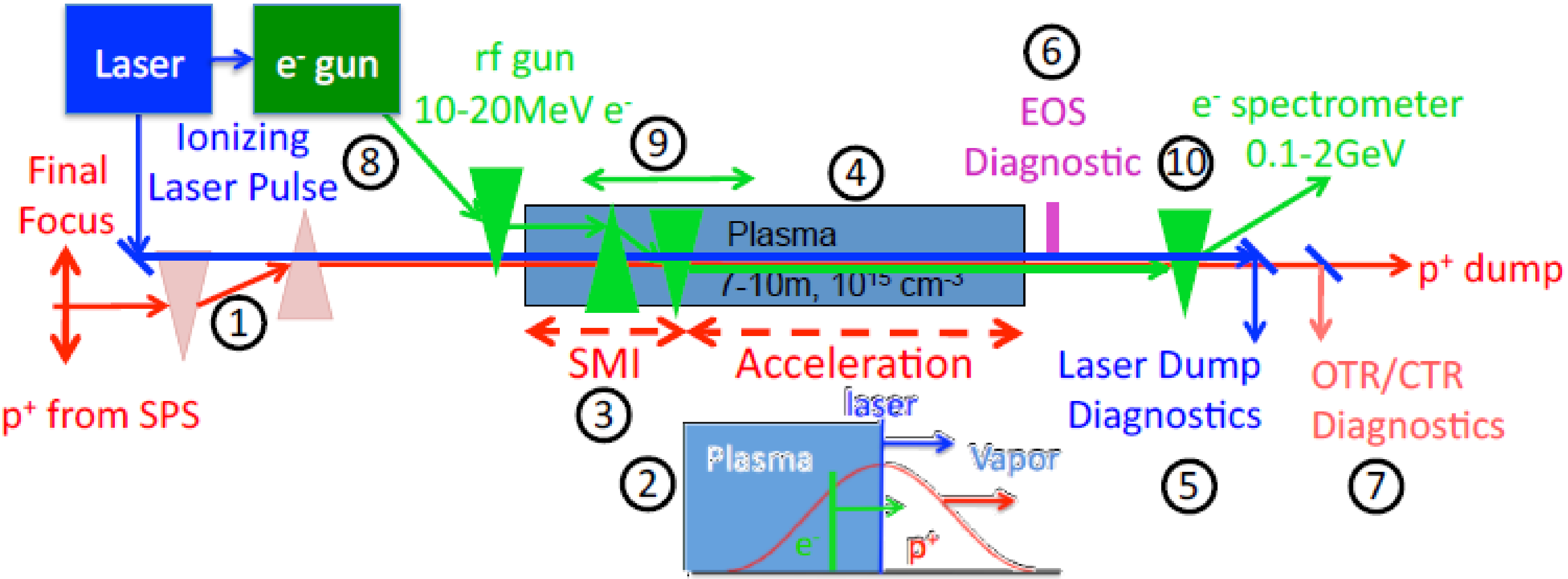


Rubidium plasma source



- Synthetic oil surrounding Rb for temperature stability and hence density uniformity
- Vacuum tube surrounding oil suppressing heat loss
- Rubidium vapor sources available commercially; development of fast valves started in collaboration with industry
- Need *1 – 2 TW* laser with *30 – 100 fs* pulse

Experimental setup



1. Merging of SPS proton beam & ionizing/seeding laser pulse
2. Schematic relative timing
3. SMI developing, electron bunch parallel to proton bunch
4. Acceleration sections
5. Laser pulse dumped & diagnosed
6. Electro-optical sampling diagnostic
7. Transition radiation diagnostics
8. RF electron gun
9. e/p bunch merging section
10. Electron spectrometer system

Many, Many Electron and Laser Driven Plasma Wakefield Experiments…!

Now first Proton Driven Plasma Wakefield Experiment

Doubling energy in a plasma wake

FULL SPEED AHEAD

Dream beam

The dawn of compact particle accelerators

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

A laser–plasma accelerator producing monoenergetic electron beams

Not-So-Large Colliders Cou… Revolutionize Physics

LETTER

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

Plasma-Surfing Mini-Accelerato…

LATEST NEWS

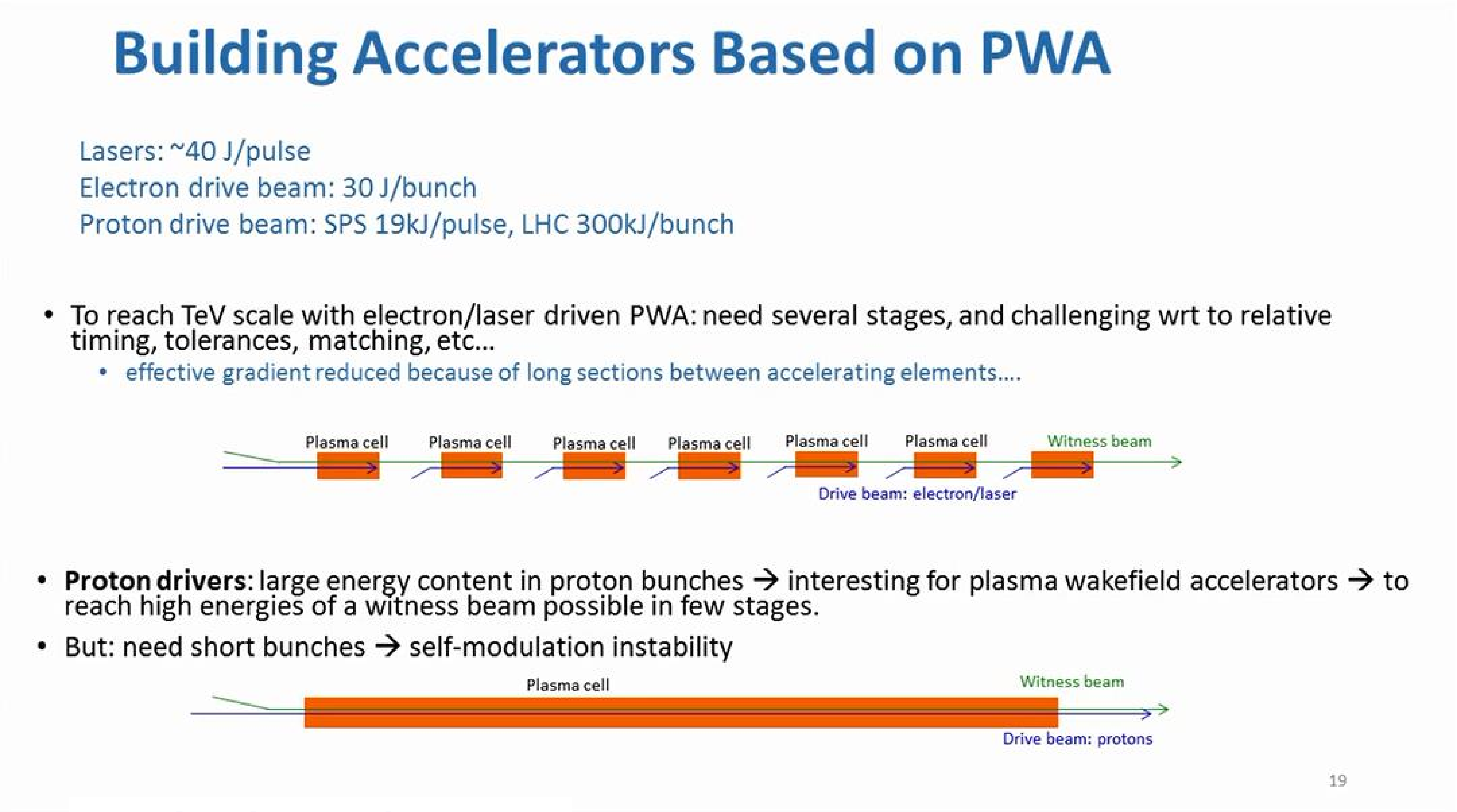
Physicists crank up current in new type of accelerator

US Scientists Build the Sma… Accelerator

Gli acceleratori di particelle saranno più "piccoli" e low cost

Surfing wakefields to create smaller accelerators

Why protons?



Building Accelerators Based on PWA

Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

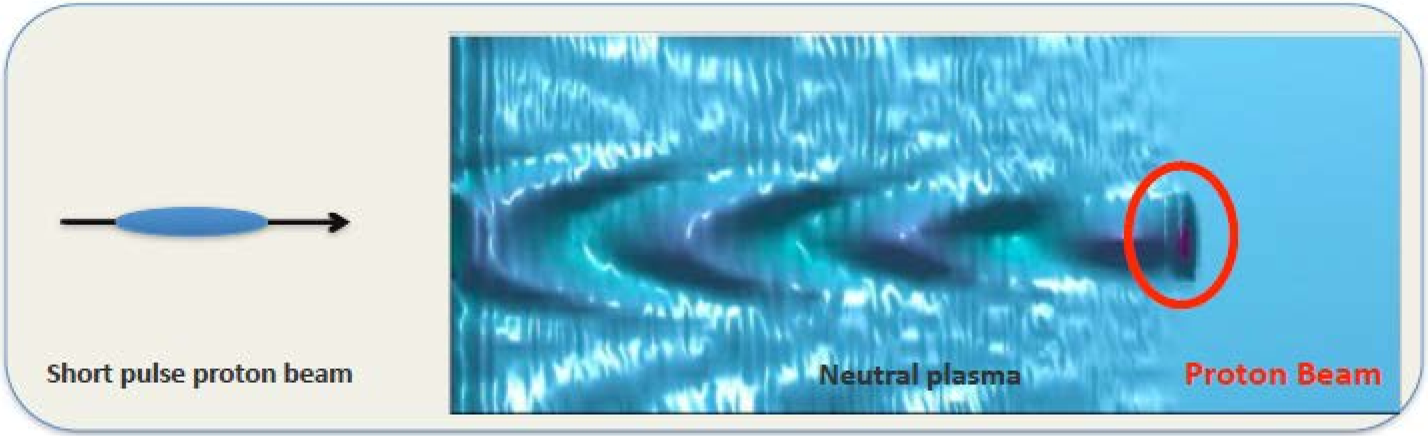
- To reach TeV scale with electron/laser driven PWA: need several stages, and challenging wrt to relative timing, tolerances, matching, etc...
  - effective gradient reduced because of long sections between accelerating elements....

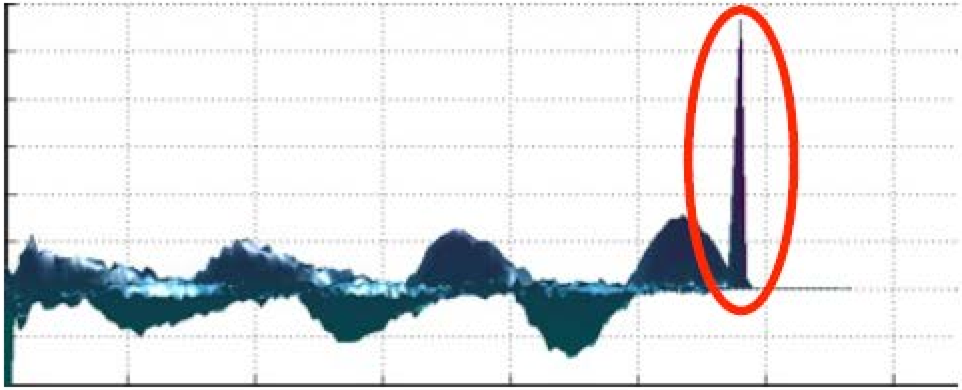
- **Proton drivers**: large energy content in proton bunches → interesting for plasma wakefield accelerators → to reach high energies of a witness beam possible in few stages.
- But: need short bunches → self-modulation instability

Lasers do not have enough energy:

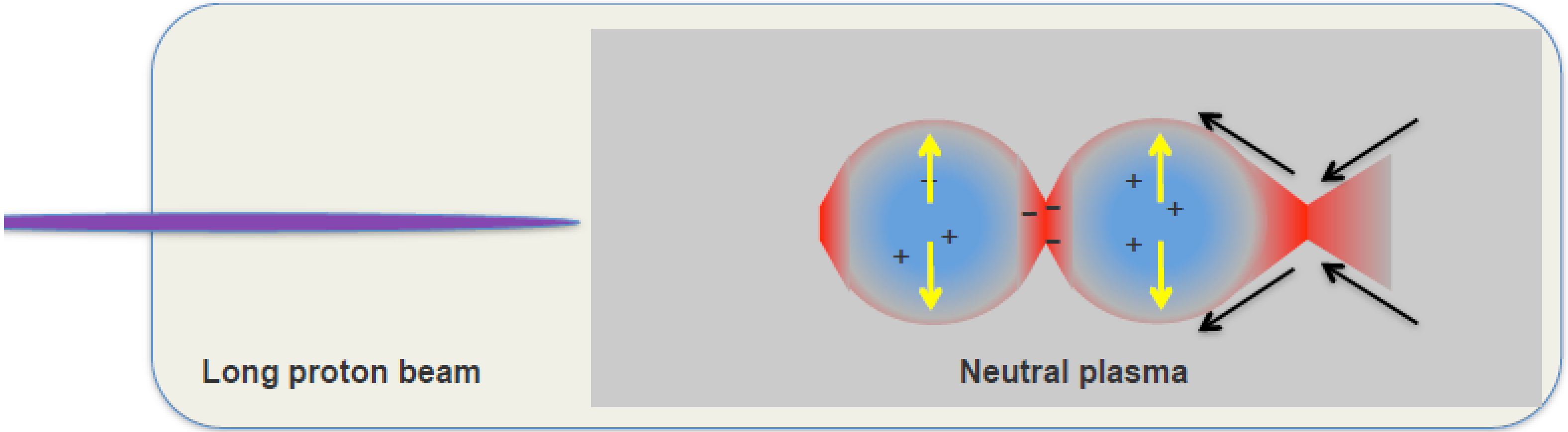
- Can not propagate long distances in plasma
- Can not accelerate electrons to high energy
- For high energy, need multiple stages

Plasma wakefield accelerator



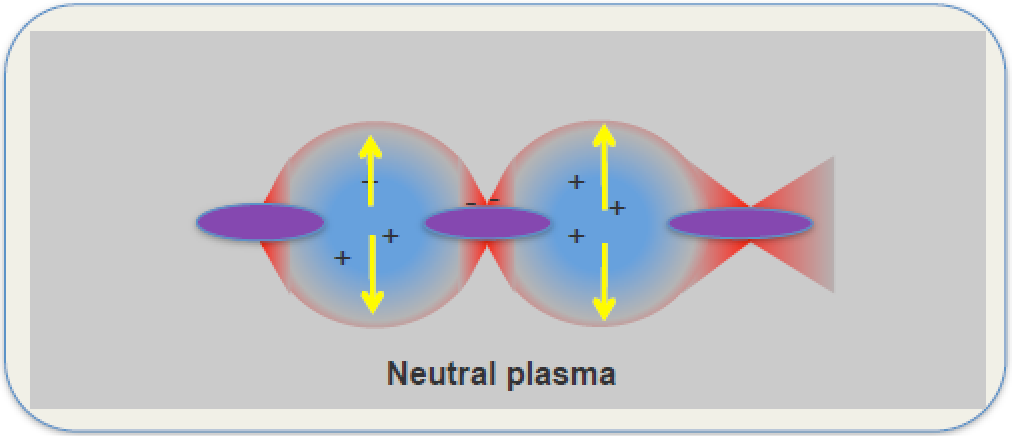


Long beam : self-modulation



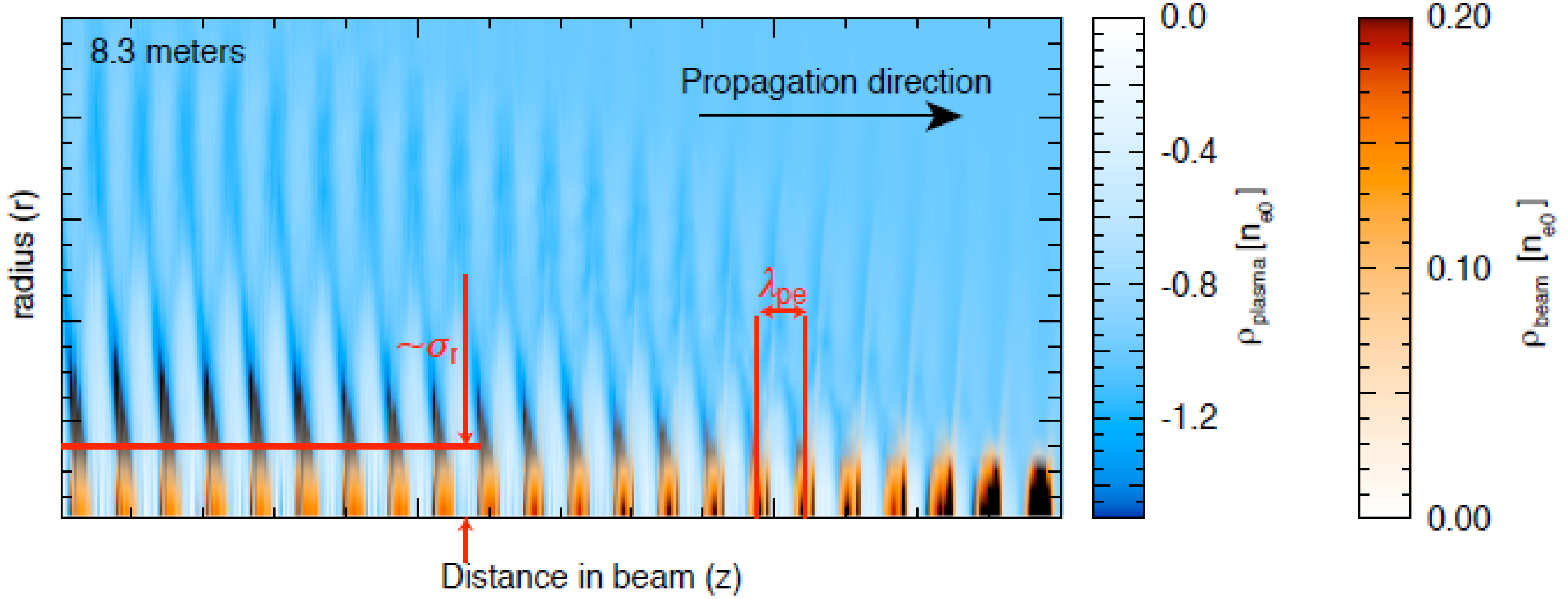
- Microbunches are spaced at the plasma wavelength and act constructively to generate a strong plasma wake.
- Seeding the modulation is critical. Use laser pulse (or short electron beam).

Thanks to J. Holloway (UCL)



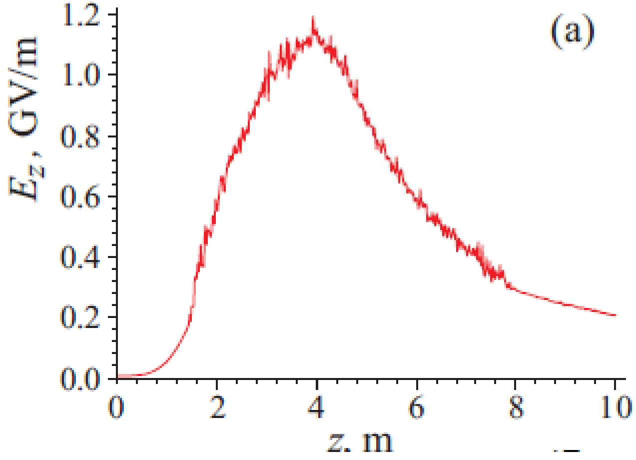
Self-modulated driver beam

Self-modulation of the proton beam

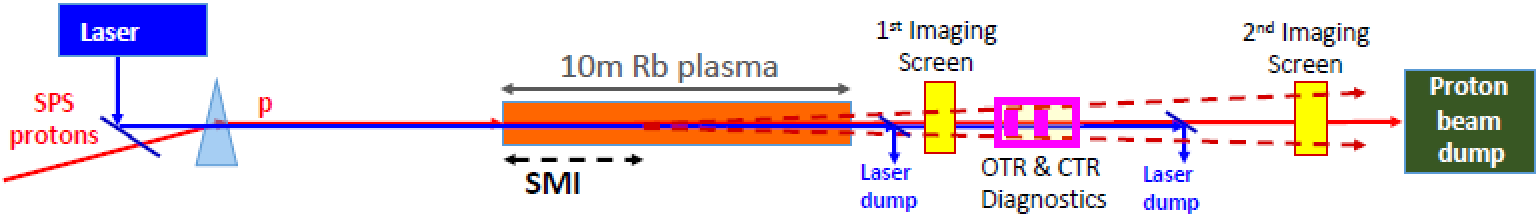


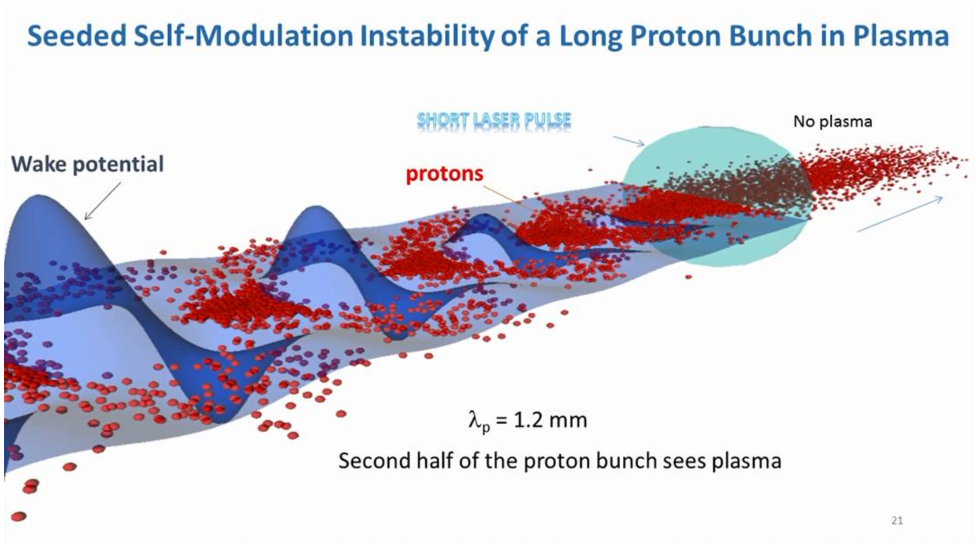
CERN SPS proton beam

Proton bunch population N_b	$3 \cdot 10^{11}$
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}	$3.5\ mm\ mrad$



First experiment: Seeded Self-Modulation



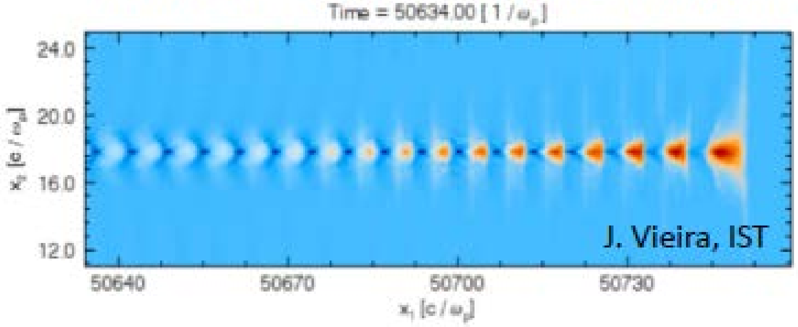

Seeded Self-Modulation Instability of a Long Proton Bunch in Plasma

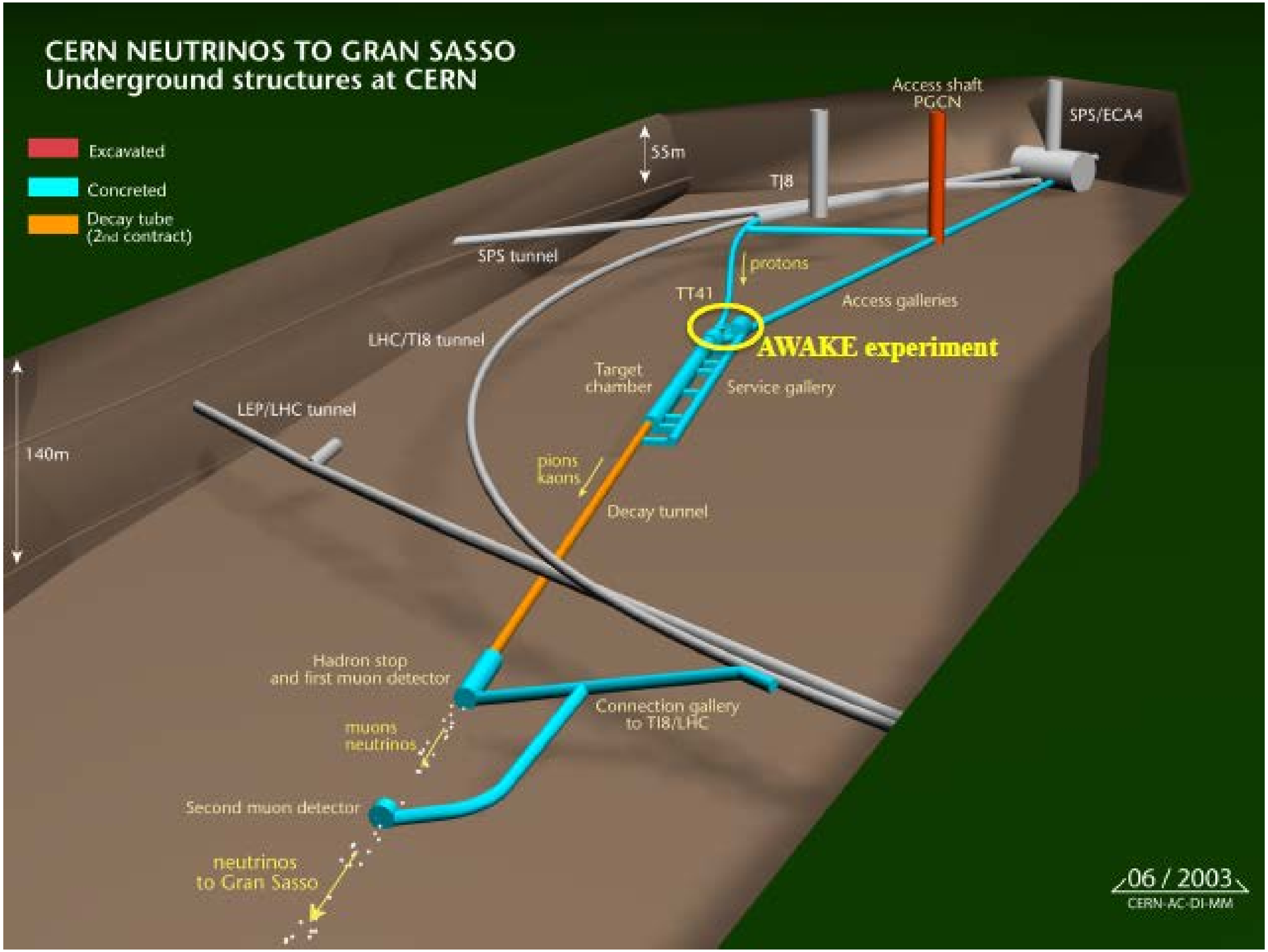
λ_p = 1.2 mm

Second half of the proton bunch sees plasma

21

What we want to see in the diagnostics:




CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
TJ8
Access shaft
PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
AWAKE experiment
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM