Plasma Wakefield Acceleration Technology

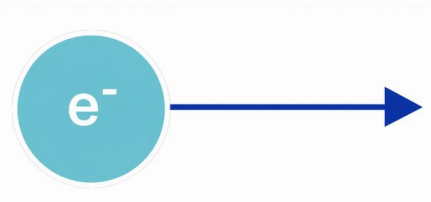
Marlene Turner

Outline

Seven Questions About Particle Acceleration

- Q1: How to accelerate charged particles?
- Q2: How to generate strong electric fields?
- Q3: How have conventional accelerators taken us to the energy frontier?
- Q4: What's next?
- Q5: Can R&D help us build smaller colliders in the future?
- Q6: Does plasma wakefield acceleration work in practice?
- Q7: Where else could compact accelerator technology make a difference?

Q1: How to Accelerate Charged Particles ?

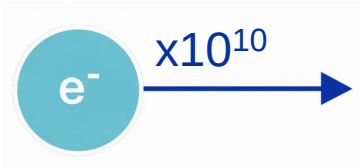


Acceleration of Charged Particles

- Accelerating a particle means increasing its velocity → increasing (kinetic) energy
- To increase the kinetic energy, work must be done

50 km/h → 70 km/h

3.5 t



Δz ~100 m
F_z ~ 4 kN → a = 1.14 m/s^2

Accelerating gradient ~ 100 MeV/m → Δz = 10 m

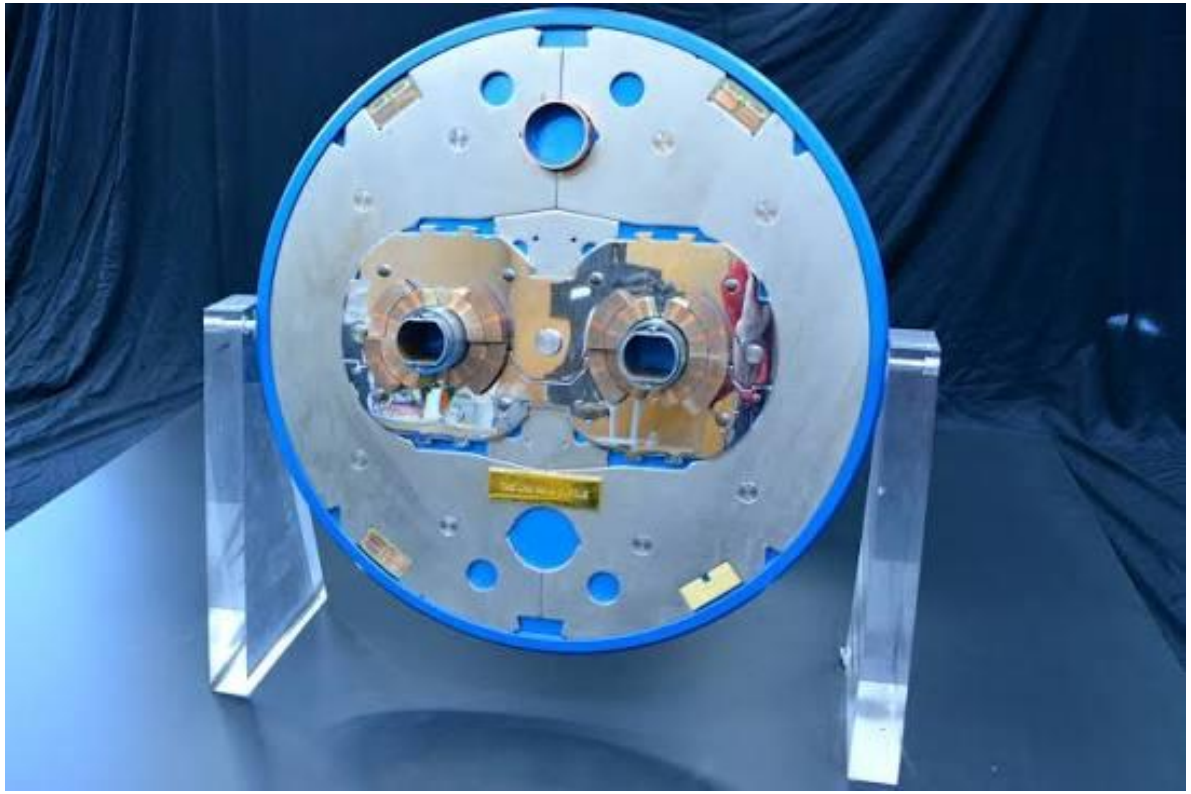
338 kJ → 662 kJ
ΔW = + 324 kJ

1 eV = 1.6 x 10^{-19} J

1 GeV → 2 GeV
1.6 J → 3.2 J
+ 1.6 J

Electric Fields

Magnetic Fields



The Lorentz Force

- The motion of a charged particle in an electromagnetic field is governed by the Lorentz force:

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$$\vec{F} = q\vec{E}$$

$\vec{E}$

$\vec{F}$

$$\vec{F} \neq 0 \text{ if } q, |\vec{E}| > 0$$

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right)$$

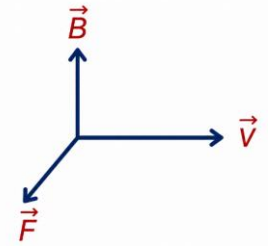
$\vec{v}$

$\vec{B}$

1) $\vec{v} = 0 \rightarrow \vec{F} = 0$

2) $\vec{v} \parallel \vec{B} \rightarrow \vec{F} = 0$

3) $\vec{v} \perp \vec{B} \rightarrow \vec{F} \neq 0$



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$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$$\vec{F} = q\vec{E} \qquad \vec{F} = q\left(\vec{v} \times \vec{B}\right)$$

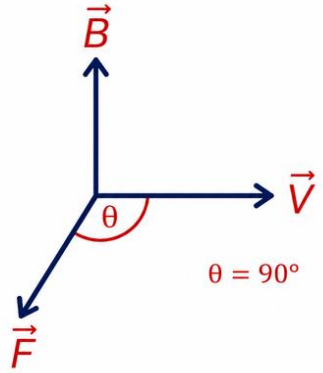
$$\vec{F}_z = q\vec{E}_z$$

- Use to electric fields to increase the particle energy

Why Can’t We use a B-Field to Increase Energy ?

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right)$$

$$W = \int \vec{F} \cdot d\vec{s}$$



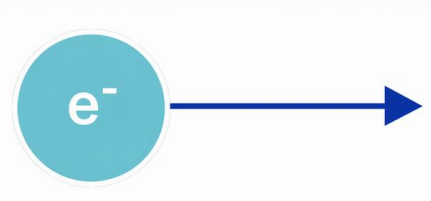
Reminder of the dot product:

$$\vec{A} \cdot \vec{B} = |A| \cdot |B| \cdot \cos(\theta)$$

$$\cos(90^\circ) = 0$$

- Magnetic fields change only the direction of a charged particle’s velocity, not its speed or kinetic energy
  - because the magnetic force acts perpendicular to the particle’s motion and therefore performs no work.

Q1: How to Accelerate Charged Particles?

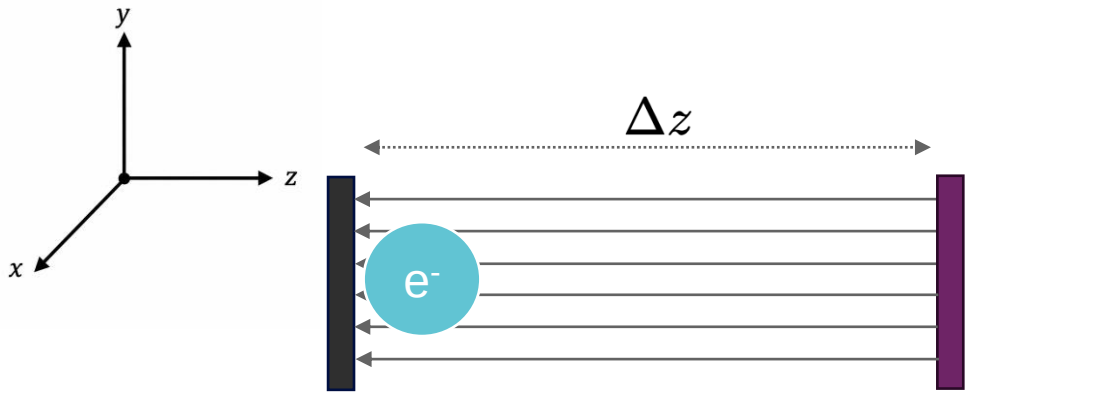


A1: With an Electric Field.

Q2: How To Generate (Strong) Electric Fields?

Electrostatic Fields

- An electrostatic field is generated by separating electric charges or, equivalently, by applying a voltage difference between conductors



$$E_z = -\frac{\partial U}{\partial z} \approx -\frac{\Delta U}{\Delta z}$$

Let's put an electron in this field:

$$W = \int F \cdot dz = q \int E_z \cdot dz = qE_z\Delta z$$

$$W = 1e \cdot 2000\,\frac{\mathrm{V}}{\mathrm{m}} \cdot 0.5\,\mathrm{m} = 1000\,\mathrm{eV}$$

→ Electron gains 1 keV of energy

Particle Physicist Wishlist

More!

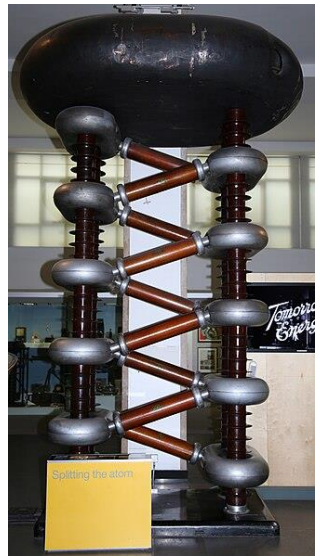
To further increase the energy gain we need to increase:

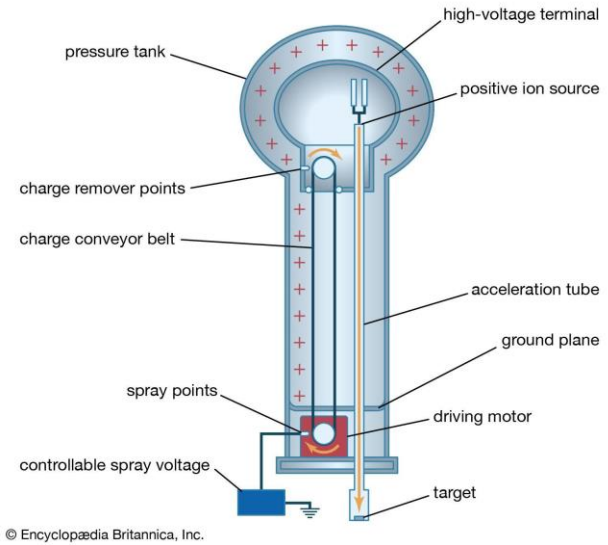
$$W = \int F \cdot dz = q \int E_z \cdot dz = qE_z\Delta z$$

Electrostatic Accelerators

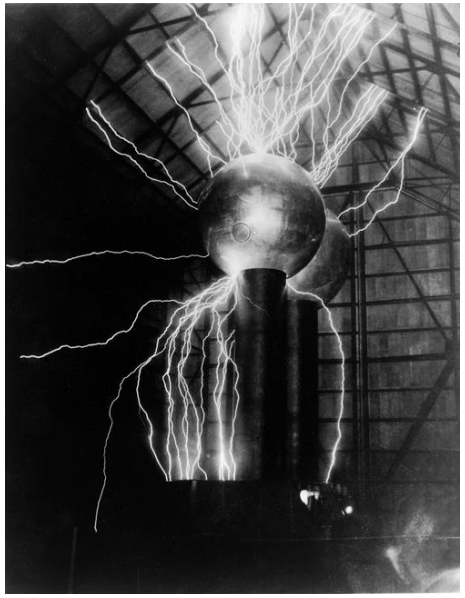
- Cockcroft–Walton accelerator
- Van de Graaff accelerator

Final particle energy < 25 MeV



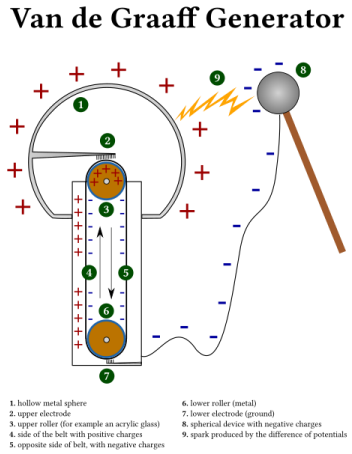


Limit: Air breaks down around 3 MV/m



Electrostatic accelerators remain useful for many applications where moderate particle energies are sufficient

- X-ray production
  - Cancer treatment
- Material treatment
- …



Particle Physicist Wishlist

We want many GeV and TeV!

1 GeV = 10^9 eV

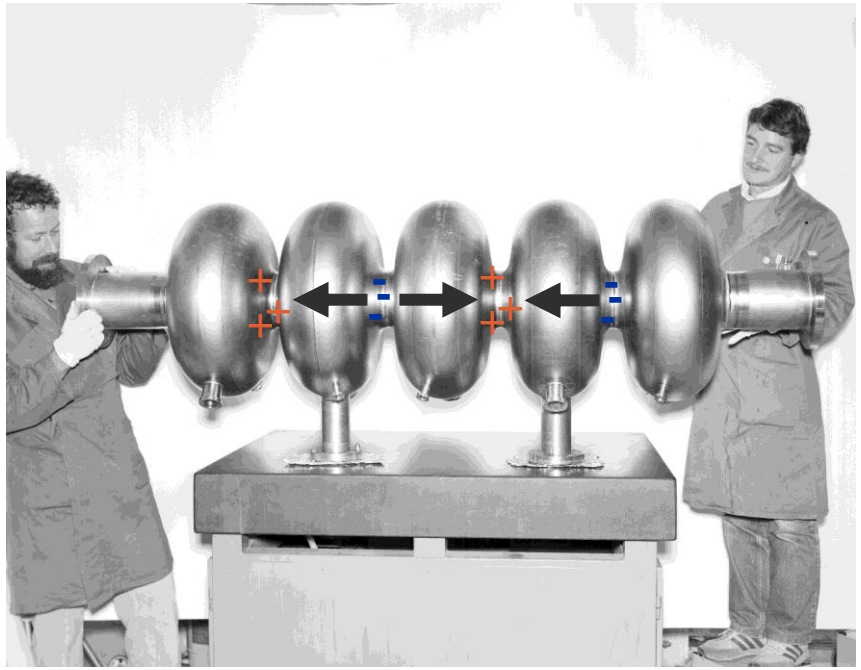
1 TeV = 10^{12} eV

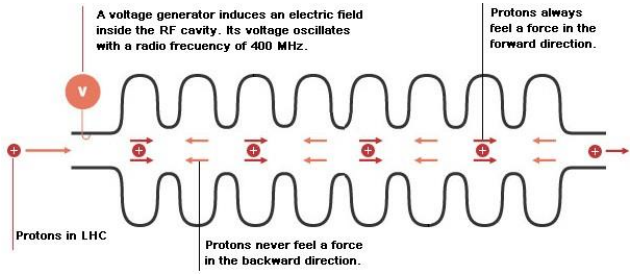
To further increase the energy gain we need to increase:

$$W = \int F \cdot dz = q \int E_z \cdot dz = qE_z\Delta z$$

Radiofrequency (RF) Acceleration

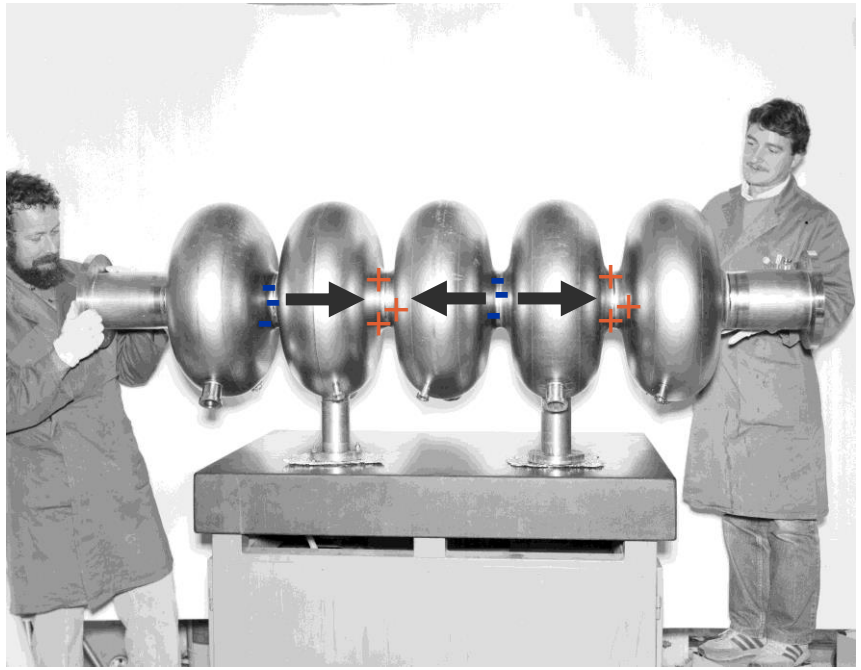
RF specifies the wavelength (radio waves 1 mm -100 km)





- 1) Metallic structure (e.g. copper, niobium)
- 2) Vacuum inside
- 3) Use of oscillating electric fields

Radiofrequency (RF) Acceleration



Accelerating gradient up to ~100 MeV/m

New limit:

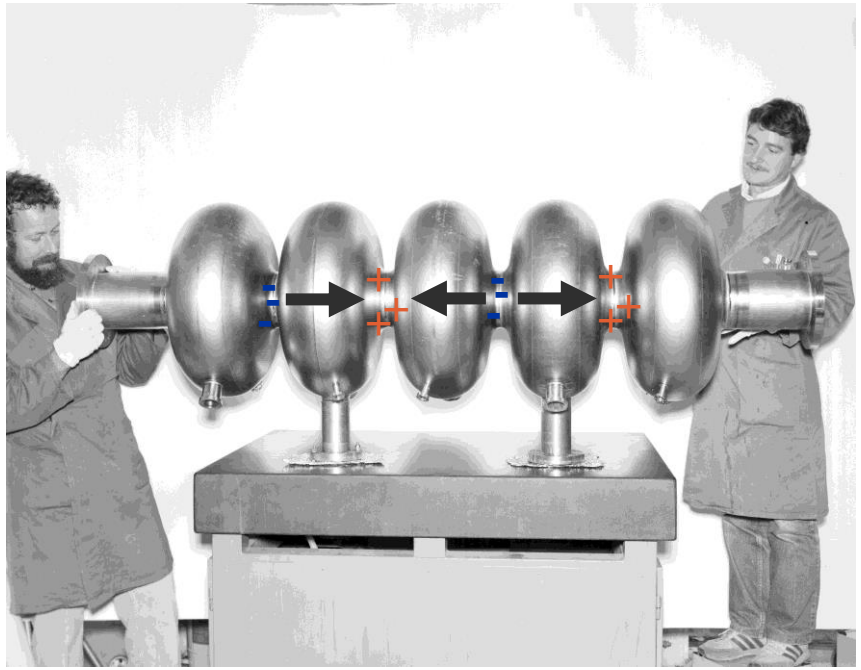
- Electrical breakdown at or near the metallic surface

Q2: How To Generate Strong Electric Fields?

A2: By Applying High Voltages Across Carefully Designed Gaps or RF Fields in RF Cavities.

Q3: How Have RF Cavities Taken Us To The Energy Frontier?

Radiofrequency (RF) Acceleration



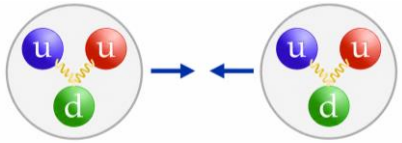
New limit:

- Electrical breakdown at or near the metallic surface

Typical operation: 5 - 80 MeV/m

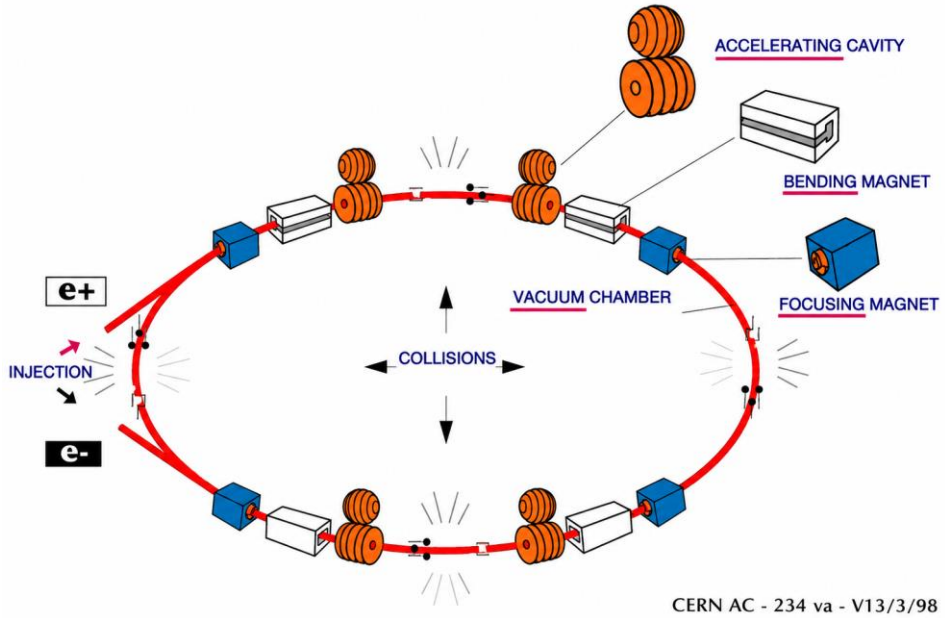
- **State-of-the-art accelerator technology**
- The key technology in modern particle accelerators and are used in many large-scale facilities, including the LHC.

When Accelerating Heavy Particles



(pp)

Circular Accelerator



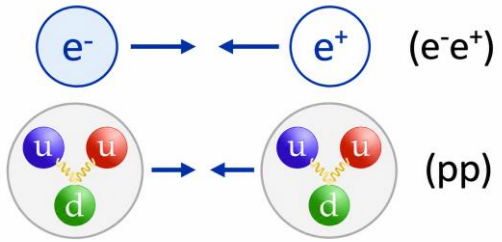
- **+**: Beam passes accelerating section many times

e.g. protons up to 7+7 TeV (LHC)

→ Limit is the Dipole magnetic field strength

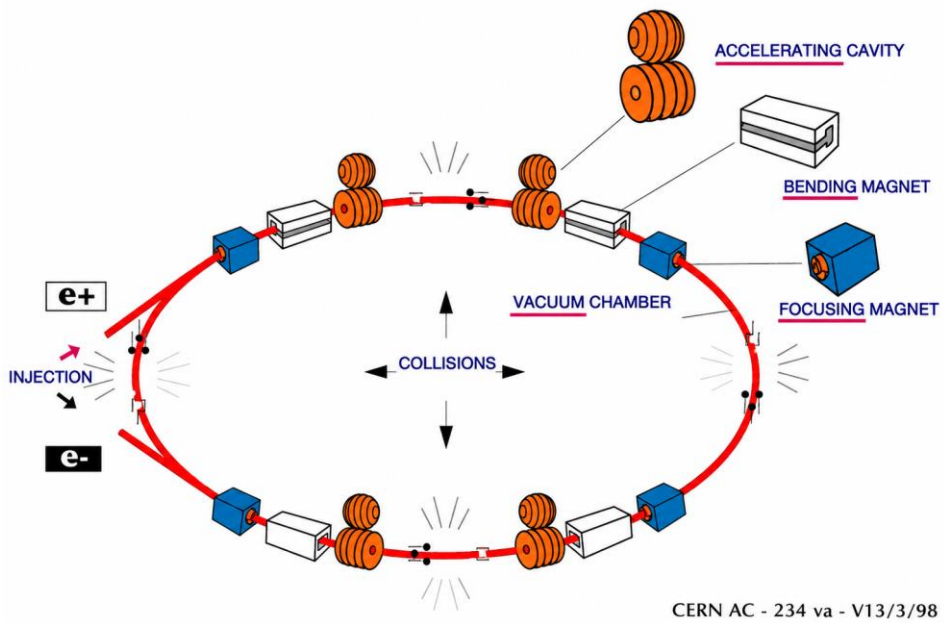
Particle Physicist Wishlist

We also want leptons



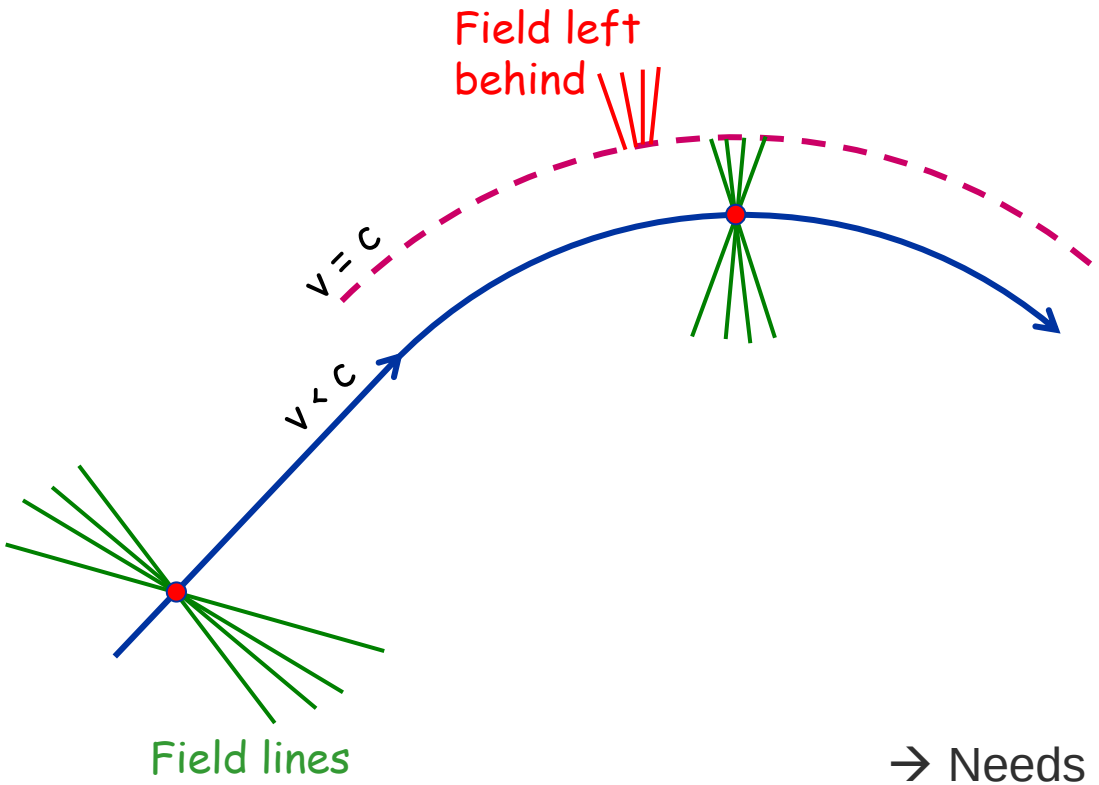
Two Types of Particle Accelerators

Circular Accelerator



- Beam passes accelerating section many times
- Synchrotron radiation losses on each turn

Synchrotron Radiation



Drawing from A. Seryi, Unifying Physics of Accelerators, Lasers and Plasmas

- Synchrotron radiation is caused by leaving part of fields behind when the beam moves along the curve

$$\propto E^4/(r^2 m^4)$$

Particle energy

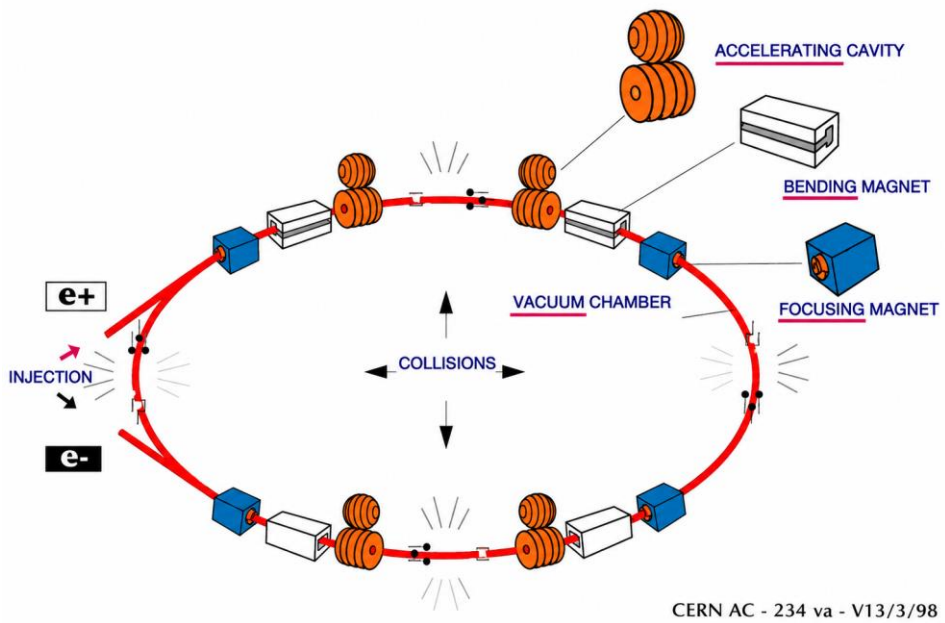
Bending radius

Mass of the particle

→ Needs to be considered when accelerated charged particles are deflected in the radial direction

Two Types of Particle Accelerators

Circular Accelerator



- Beam passes accelerating section many times
- Synchrotron radiation losses on each turn

Examples:

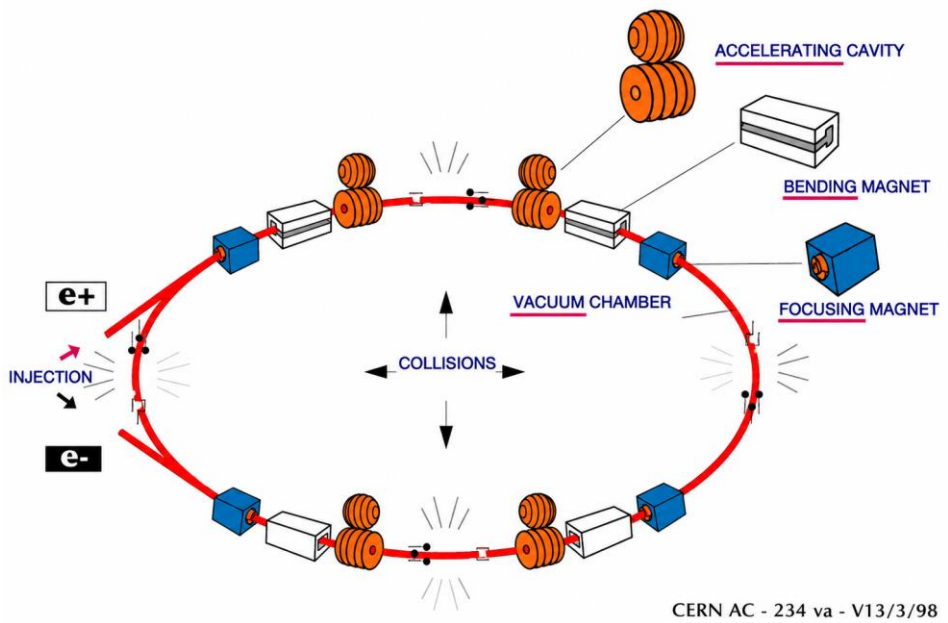
Circular Accelerator with ~27 km circumference

→ Highest collision energies to date

LEP: 209 GeV (e^-e^+)
LHC: 14 TeV (pp) → limited by dipole field strength

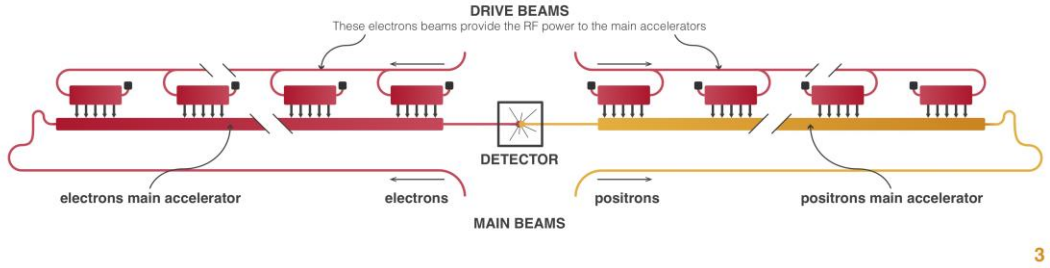
Two Types of Particle Accelerators

Circular Accelerator



- Beam passes accelerating section many times
- Synchrotron radiation losses on each turn

Linear Accelerator



- Beam passes acceleration section only once
- Negligible synchrotron radiation losses
- Desired beam energy and available acceleration gradient define the length of the machine

1 TeV = 10 000 m x **100 MeV/m**

SLC: 91 GeV

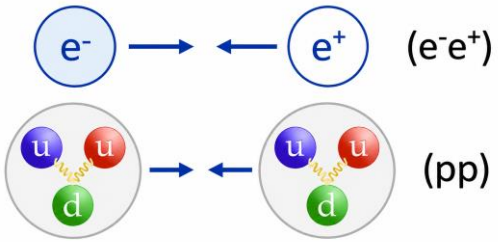
Q3: How Have RF Cavities Taken Us To The Energy Frontier?

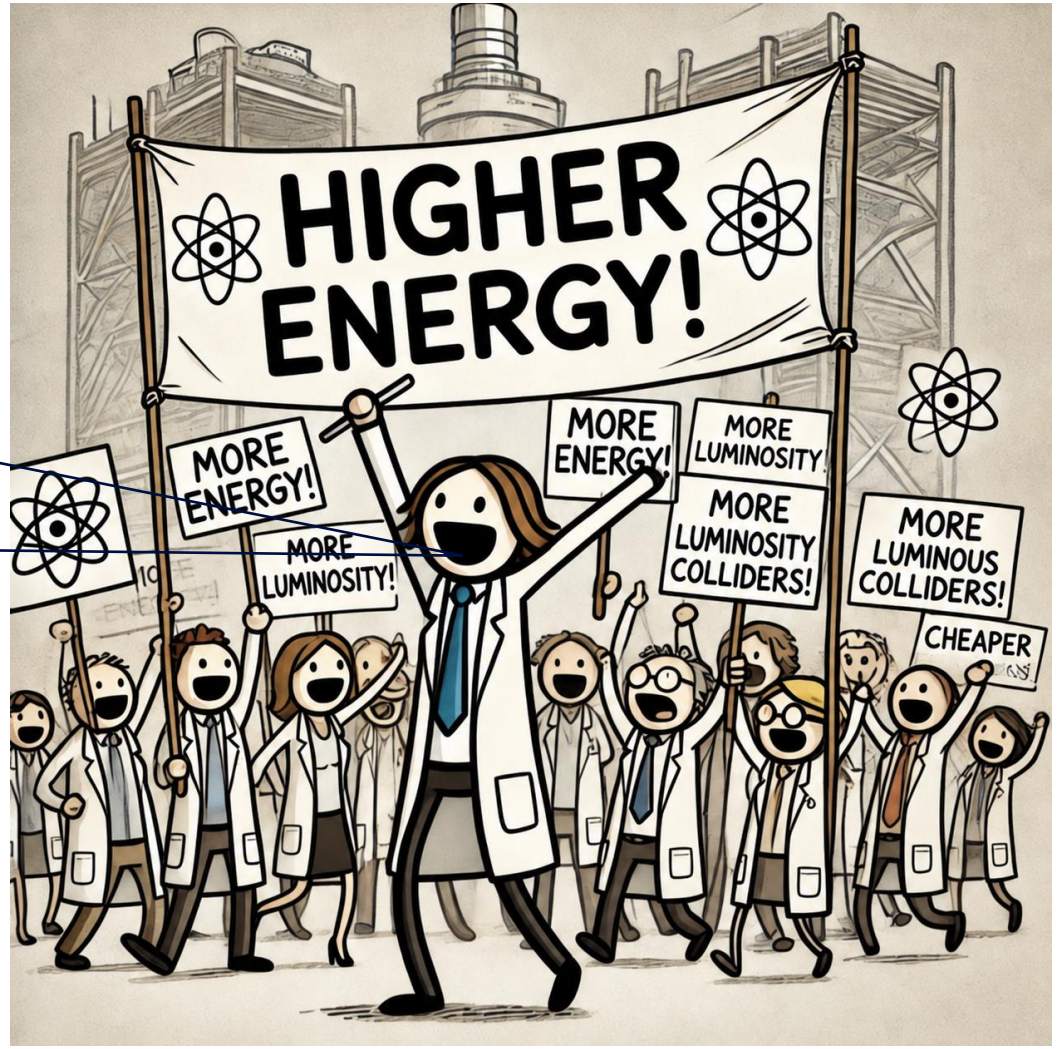
A3: By Combining Them with Magnetic Steering (Circular Machine) or Having a Long Sequence (Linear Machine).

Q4: What's Next?

Particle Physicist Wishlist

- Higher collision energy
- Higher luminosity
- Precision machines

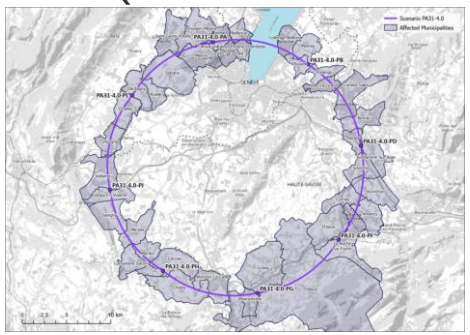




Future Collider Possible Strategies

Circular Accelerator

- **Larger ring**
  - FCC (circumference 90 km)



FCCee: 0.09-0.37 TeV
FCChh: 100 TeV

Similar project proposed in China CEPC

Linear Accelerator

- **Make it longer**
  - ILC baseline ~20 km 0.25 TeV
  - CLIC 13.4 km 0.38 TeV, ~42 km 3 TeV

Q4: What's Next?

A4: CERN Makes a Strong Push for FCC.

10:15 **The Future Circular Collider (FCC)**

Speaker: Michael Benedikt (CERN)

Funding Agency Wishlist

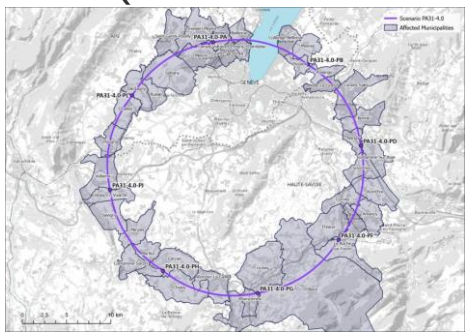
Cheaper
→
Smaller

Q5: Can R&D Help us Build Smaller Colliders in the Very Long Term Future?

Future Collider Possible Strategies

Circular Accelerator

- **Larger ring**
  - FCC (circumference 90 km)

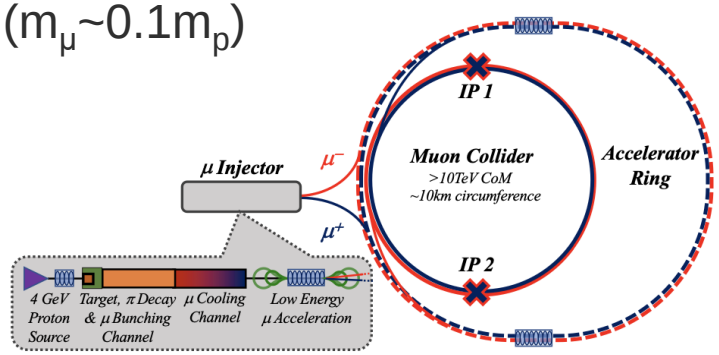


FCCee: 0.09-0.37 TeV
FCChh: 100 TeV

Similar project proposed in China CEPC

- **Accelerate heavier particles**
  - Muon Collider ($m_\mu \sim 0.1 m_p$)

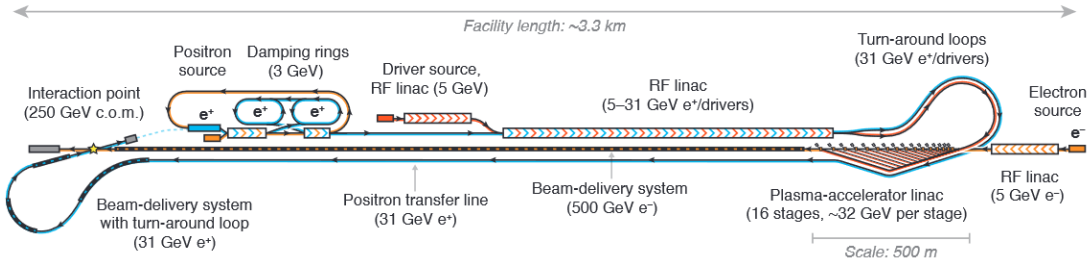
27 km ~10 TeV



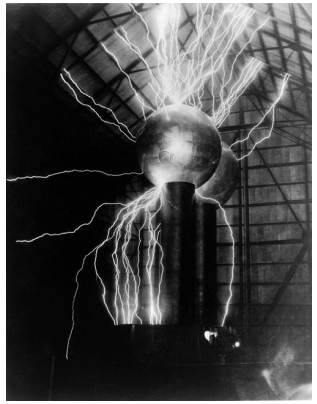
Linear Accelerator

- **Make it longer**
  - ILC baseline ~20 km 0.25 TeV
  - CLIC 13.4 km 0.38 TeV, ~42 km 3 TeV

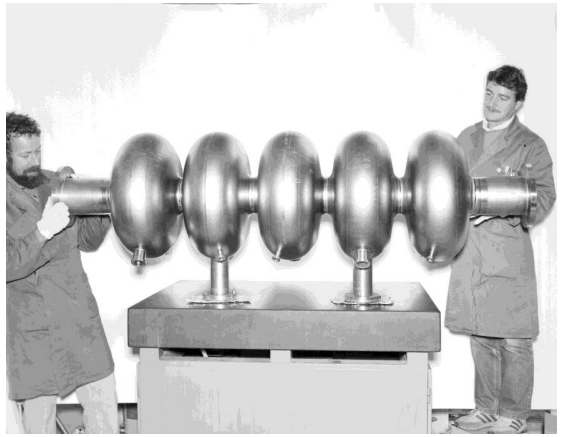
- **Increase acceleration gradient**
  - E.g. C^3(~150 MeV/m): 3.7km 0.25 TeV or plasma-based (~GeV/m)



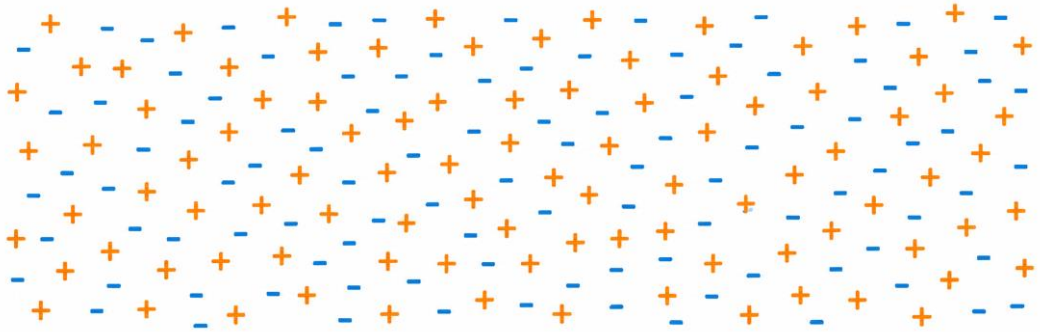
Revisiting the Limits of Electrostatic and RF Accelerators



Electrical breakdown of air 3 MV/m



Electrical breakdown at or near the metallic surface E_z~100 MV/m

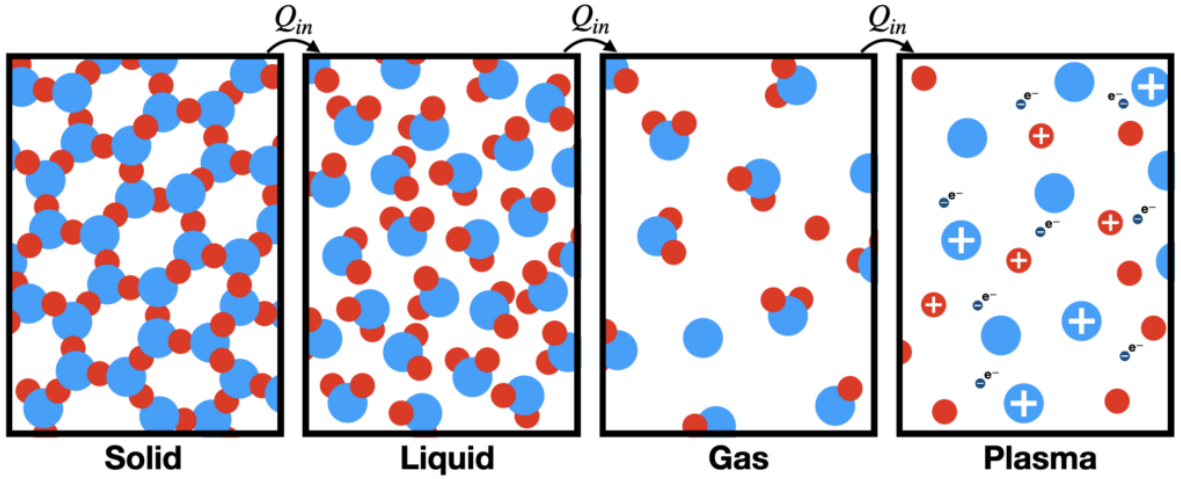


Plasmas are not limited by electrical breakdown

→ **Need to overcome the electrical breakdown limit**

Definition of a Plasma

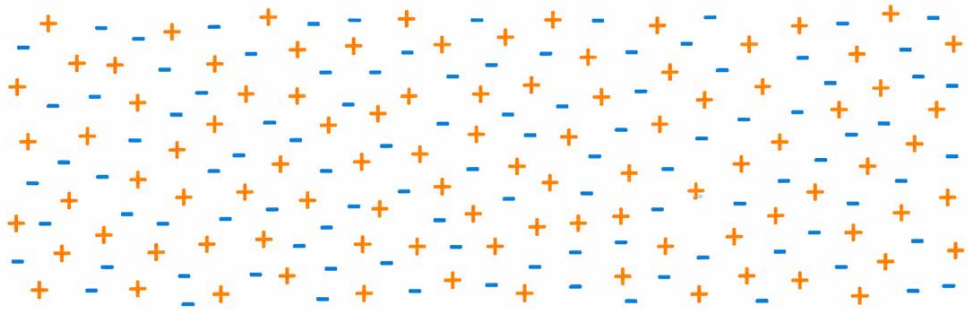
Plasma: ionizes gas (4th state of matter)



From: https://www.jessearodriguez.com/what-is-plasma/

99% of the universe is plasma

- A plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior



$m_i >> m_e$ (Hydrogen: $m_i \cong 1836\ m_e$)

Definition of a Plasma

Candle flame

Partially/weakly ionized gas

Not a plasma → too many neutrals → collisions (with neutrals) dominate
A candle flame doesn't get hot enough to ionize a significant number of atoms (~10^{-15})

Fluorescent lamp

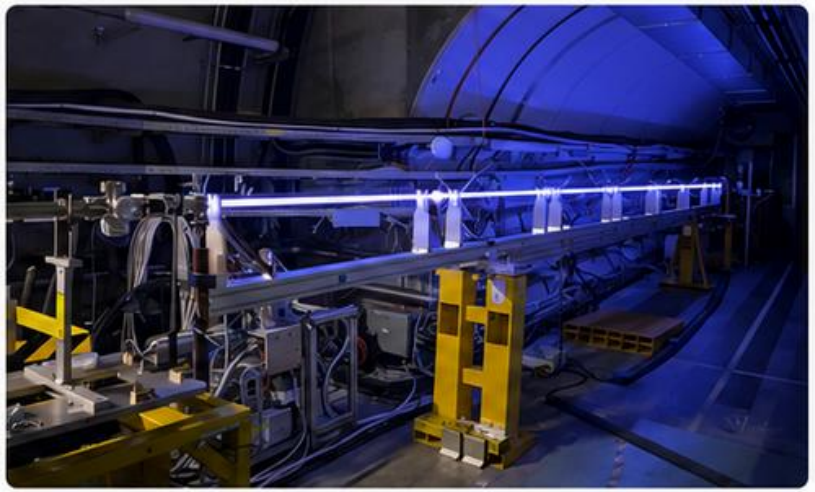
Plasma
→ sufficient fraction of atoms are ionized (~10^{-7})

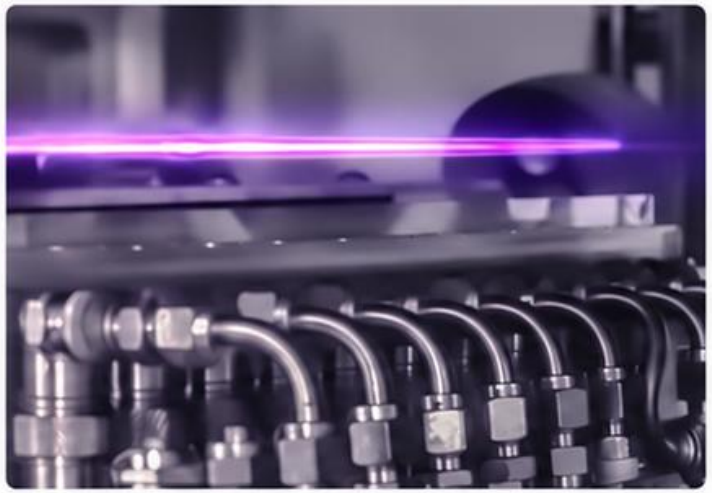
→ Plasmas often glow

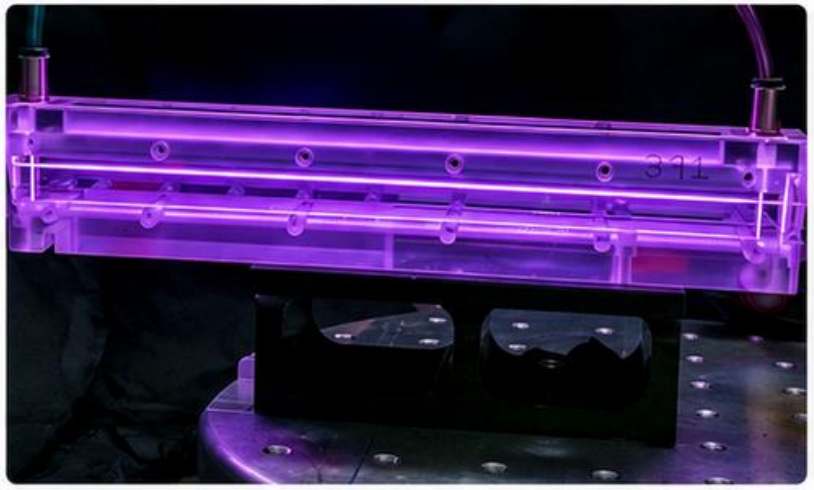
Plasmas for Plasma Wakefield Acceleration

Lengths:
0.0001–10+ m

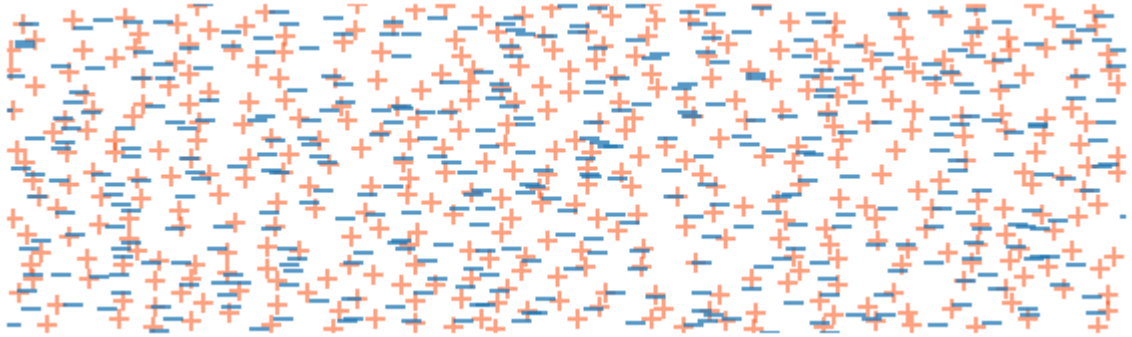
Densities:
1×10^{14}–10^{20} cm^{-3}

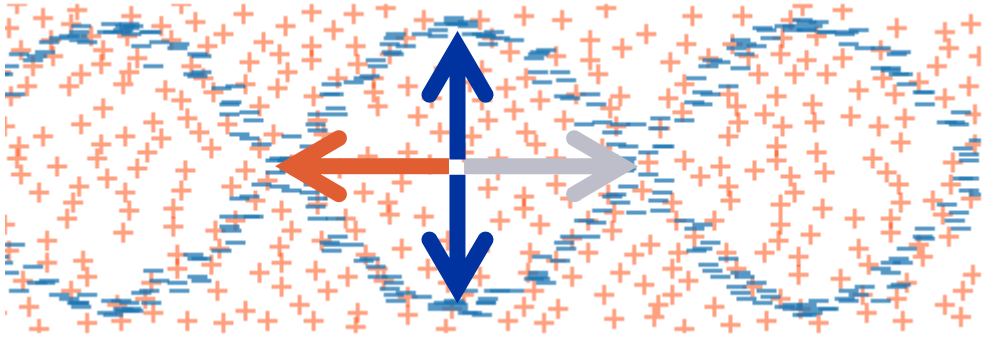






Plasma Wakefield Acceleration





→ Accelerating gradients up to **10-100 GeV/m**

Plasma Wakefield Acceleration

Plasma

Quasi-neutral plasma in which **electrostatic interactions dominate** and charged particles are dense enough to support **collective behaviour**

Drive bunch or pulse

Relativistic **charged particle** bunch/es
or
laser pulse/s

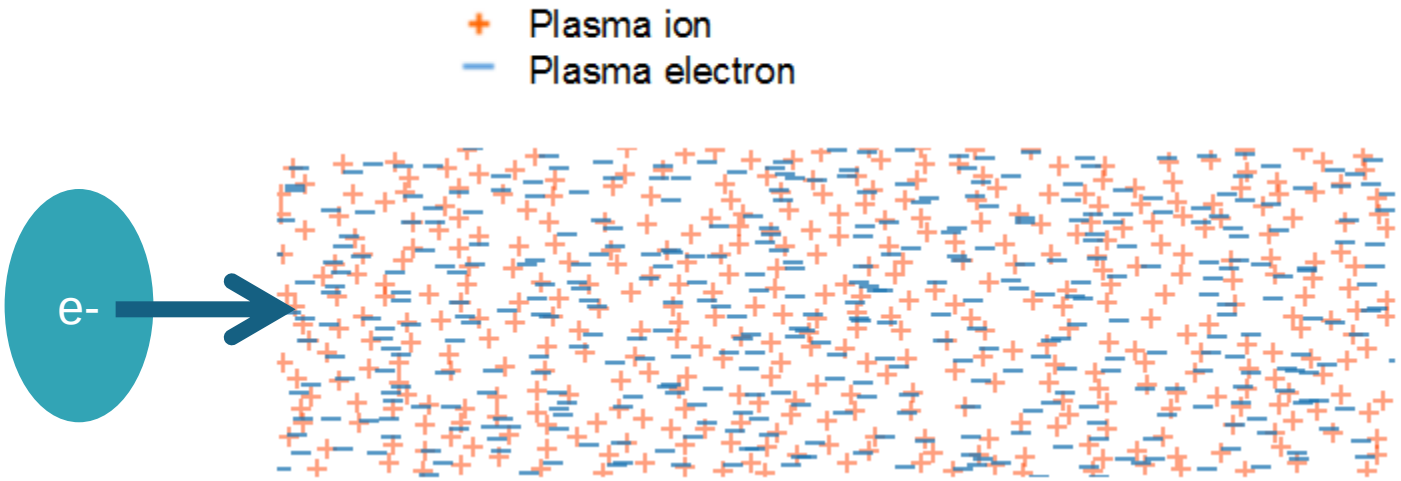
Plasma Wakefield Acceleration

Plasma

Quasi-neutral plasma in which **electrostatic interactions dominate** and charged particles are dense enough to support **collective behaviour**

Drive bunch or pulse

Relativistic **charged particle** bunch/es
or
laser pulse/s



Plasma Wakefield Acceleration

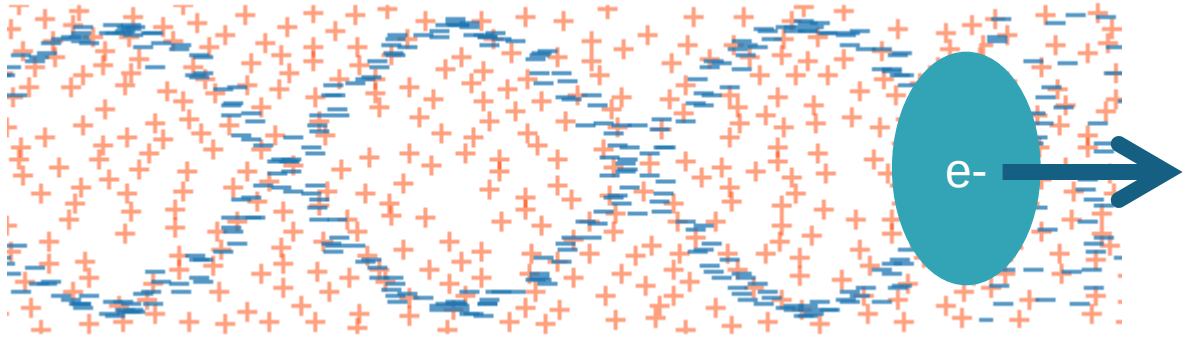
Plasma

Quasi-neutral plasma in which **electrostatic interactions dominate** and charged particles are dense enough to support **collective behaviour**

Drive bunch or pulse

Relativistic **charged particle** bunch/es
or
laser pulse/s

+ Plasma ion
− Plasma electron



Plasma Wakefield Acceleration

Plasma
Quasi-neutral plasma in which **electrostatic interactions dominate** and charged particles are dense enough to support **collective behaviour**

Drive bunch or pulse
Relativistic **charged particle** bunch/es
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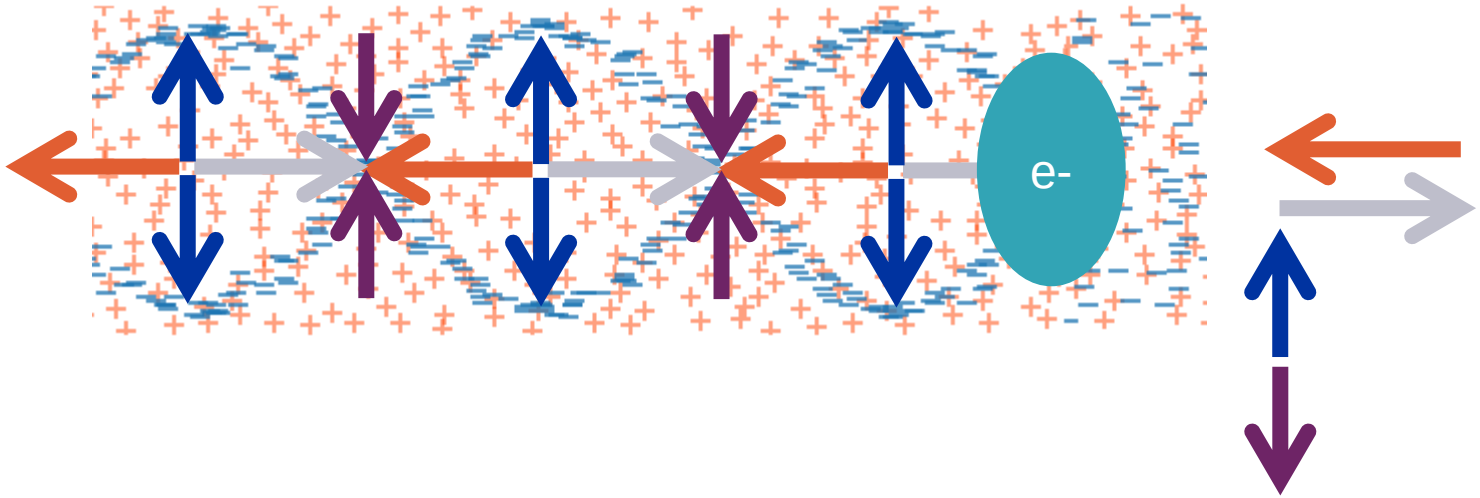


Q5: Can R&D Help us Build Smaller Colliders in the Very Long Term Future?

A5: Yes — e.g. Plasma Wakefield Acceleration by Producing Accelerating Fields Far Stronger than those in RF Cavities.

Q6: Does Plasma Wakefield Acceleration Work In Practice?

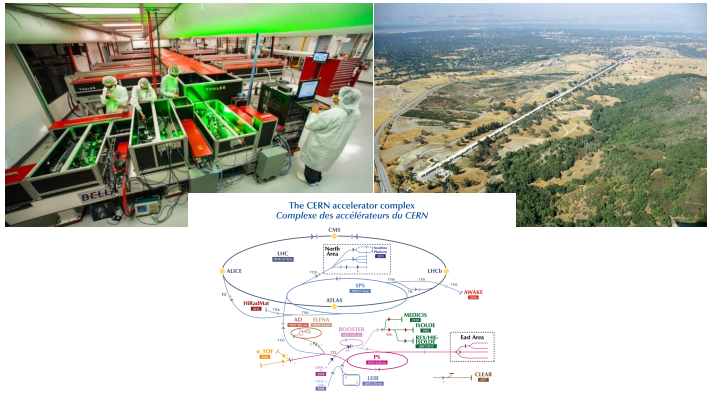
Let’s Do An Experiment…

Step 1

Choose a plasma

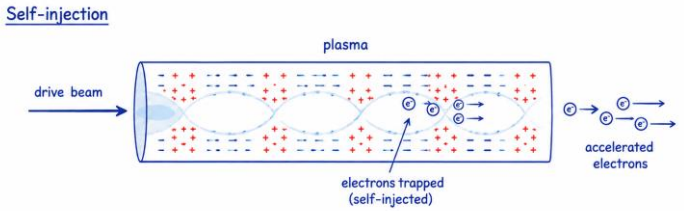
Step 2

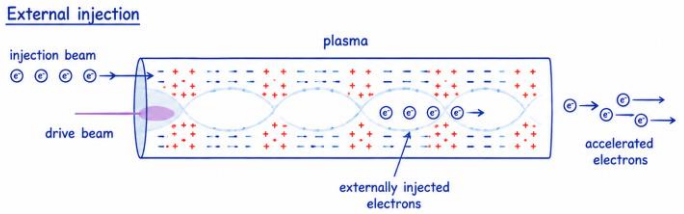
Choose a driver



Step 3

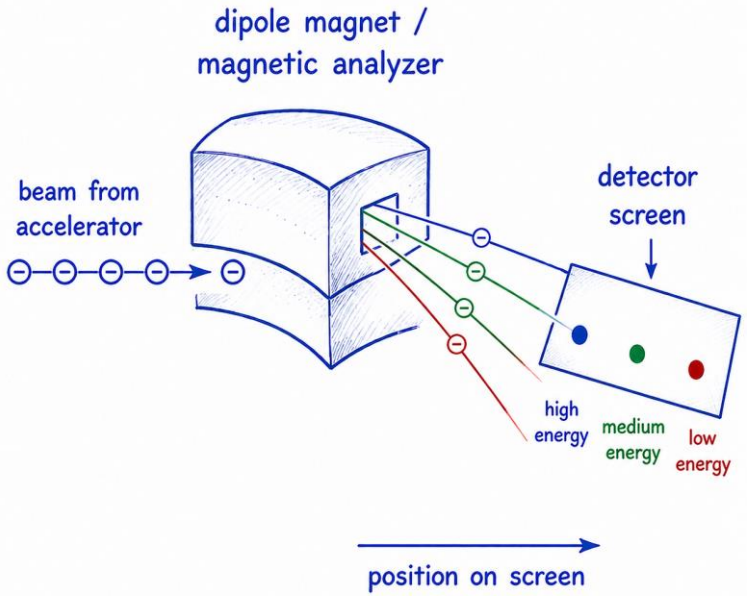
Inject the particles to accelerate





Step 4

Measure the energy of the accelerated particles

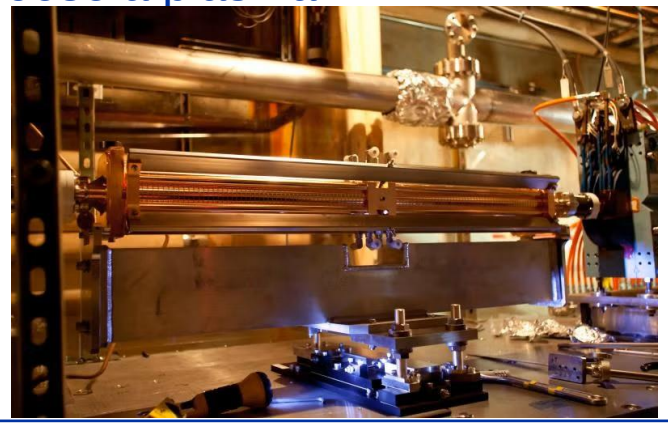


Let’s Do An Experiment…

SLAC (Stanford, California)

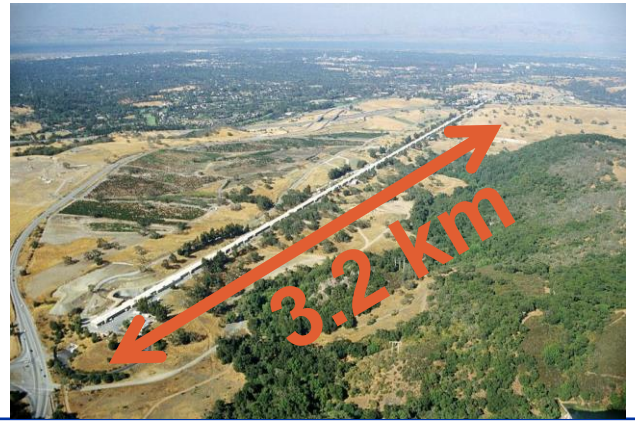
Step 1

Choose a plasma



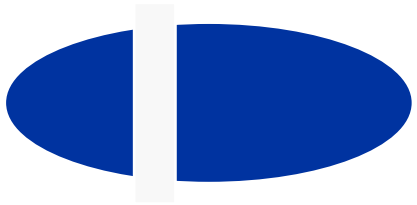
Step 2

Choose a driver 42 GeV electron bunch



Step 3

Inject the particles to accelerate

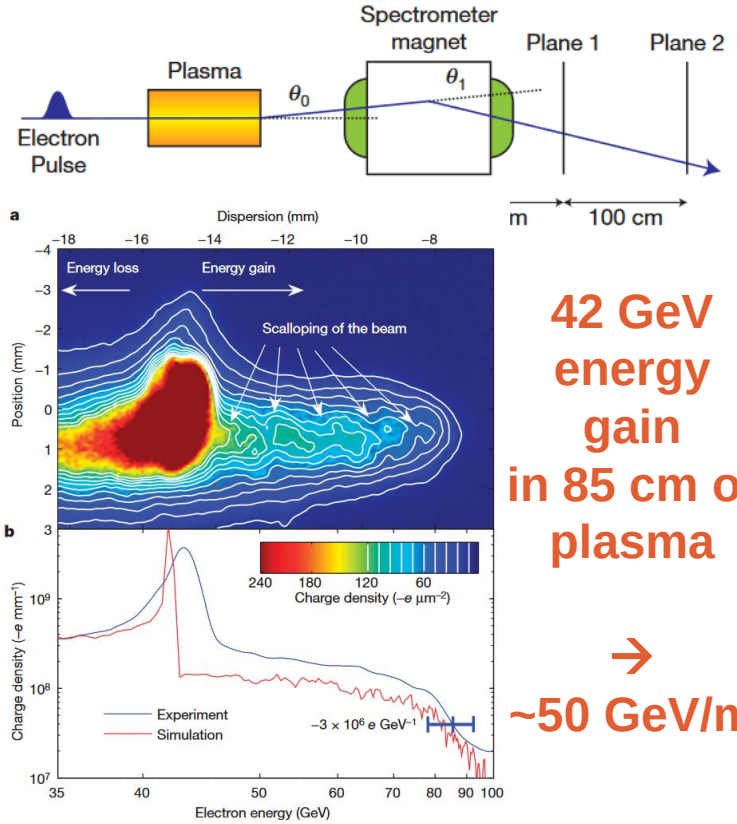


Witness Driver

Blumenfeld, I., Clayton, C., Decker, FJ. *et al.* Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator. *Nature* **445**, 741–744 (2007).

Step 4

Measure the energy of the accelerated particles



42 GeV energy gain in 85 cm of plasma

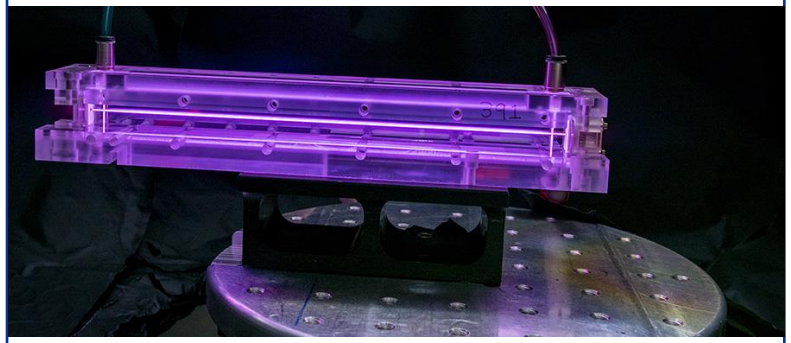
→

~50 GeV/m

Let's Do An Experiment… BELLA (Berkeley, California)

Step 1

Choose a plasma

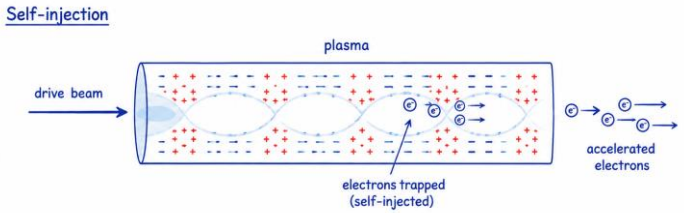


Step 2

Choose a driver

Step 3

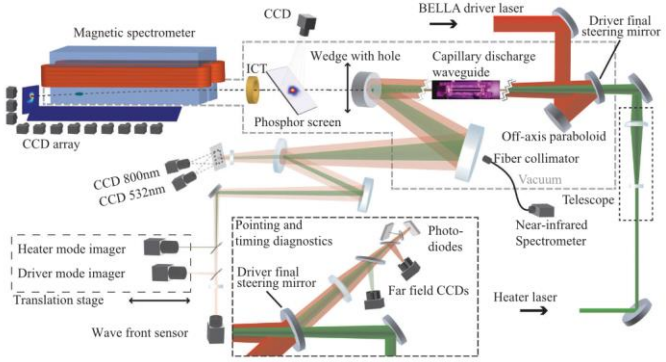
Inject the particles to accelerate

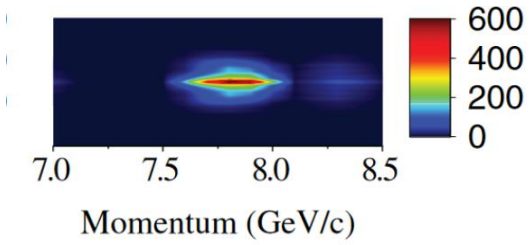


Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide
A. J. Gonsalves et al., Phys. Rev. Lett. 122, 084801

Step 4

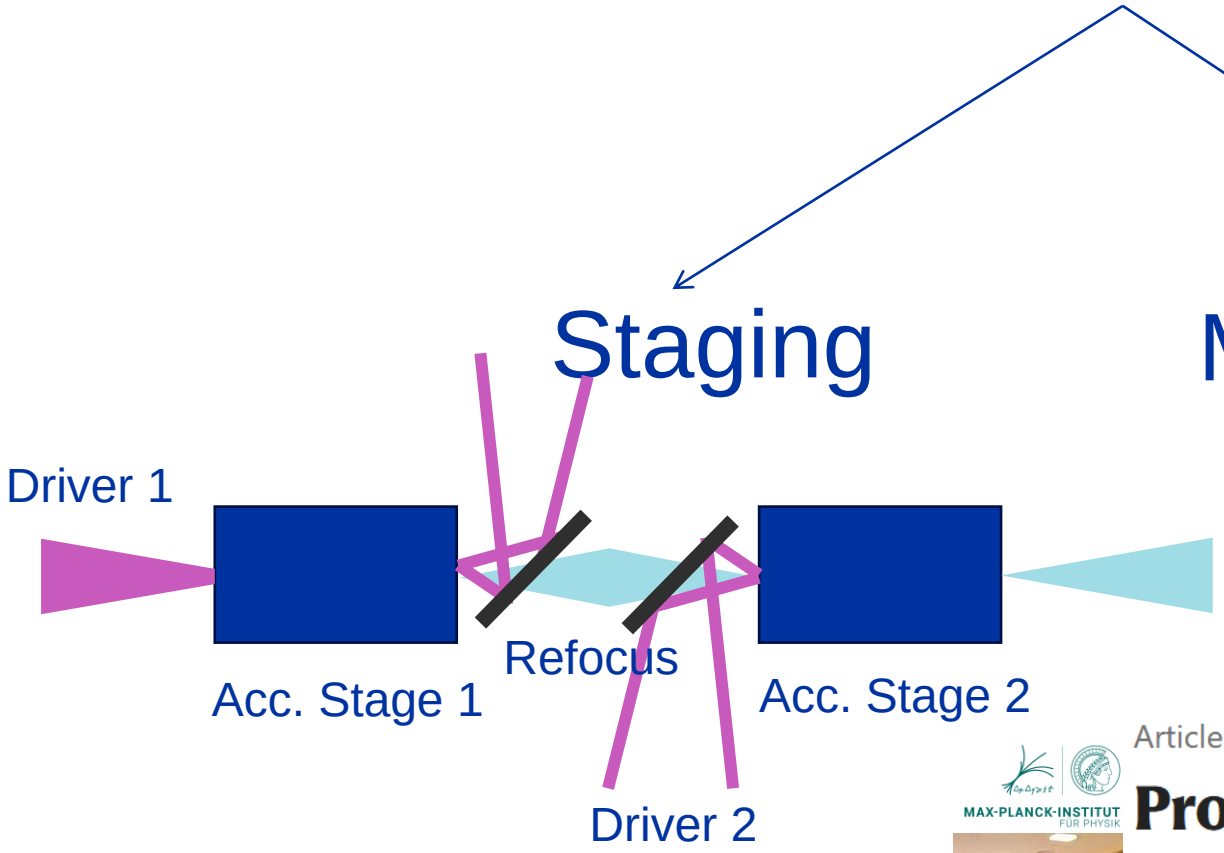
Measure the energy of the accelerated particles





~8 GeV energy gain in 20 cm of plasma→ ~40 GeV/m

How to Reach Even Higher Energies?



Goal: Keep interstage distance short

Article | Published: 12 April 2009

Proton-driven plasma-wakefield acceleration

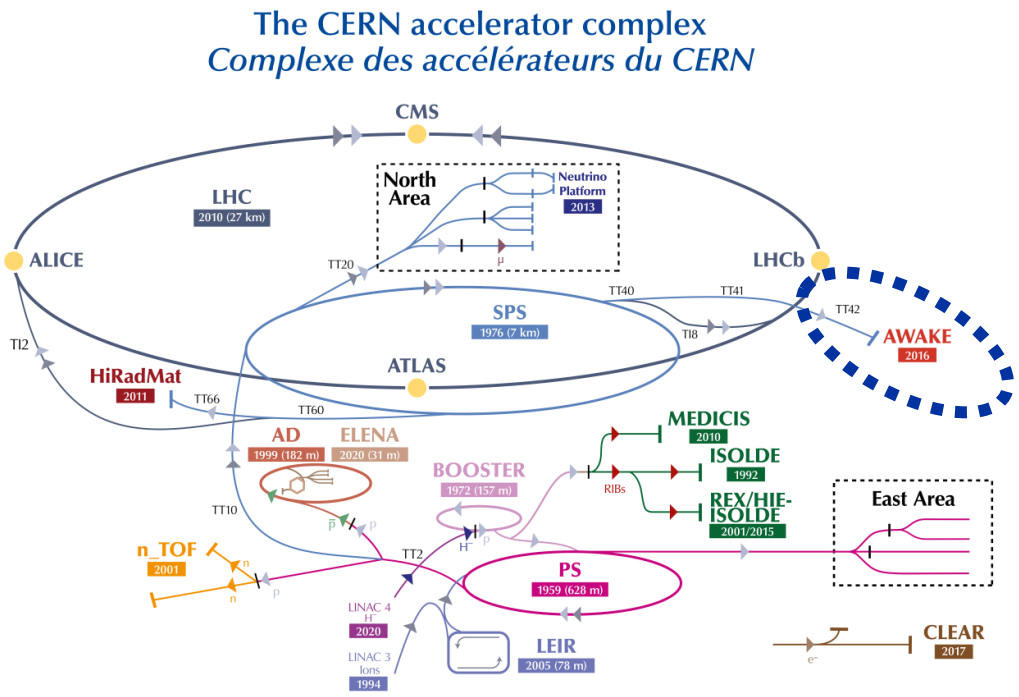
Allen Caldwell, Konstantin Lotov, Alexander Pukhov & Frank Simon

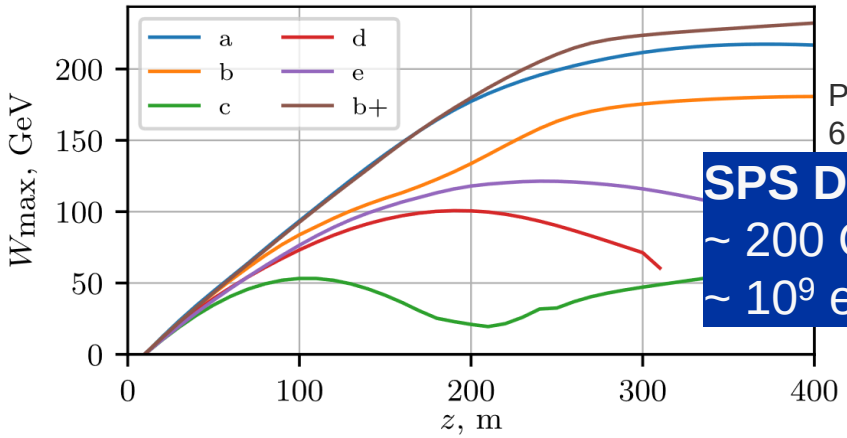
Nature Physics **5**, 363–367 (2009) | Cite this article

AWAKE is Unique in Using Proton Drivers

- Highly-relativistic, highly-energetic (hundreds of kJ) bunches are available at CERN
- Accelerating externally-injected electrons (e^-)

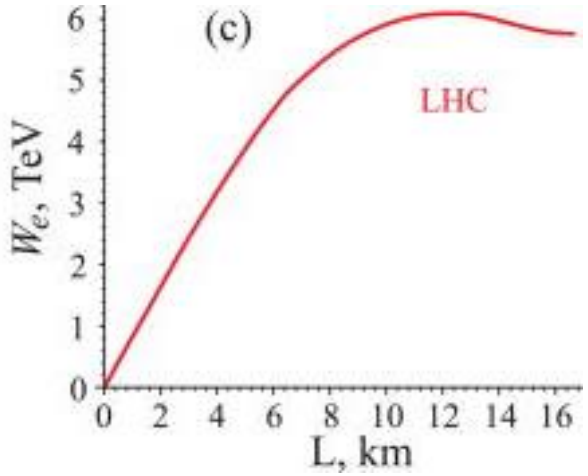
  to GeV (SPS) or TeV (LHC) energy scale





P. Tuev, K. V. Lotov, PPFC 63, 125027 (2021)

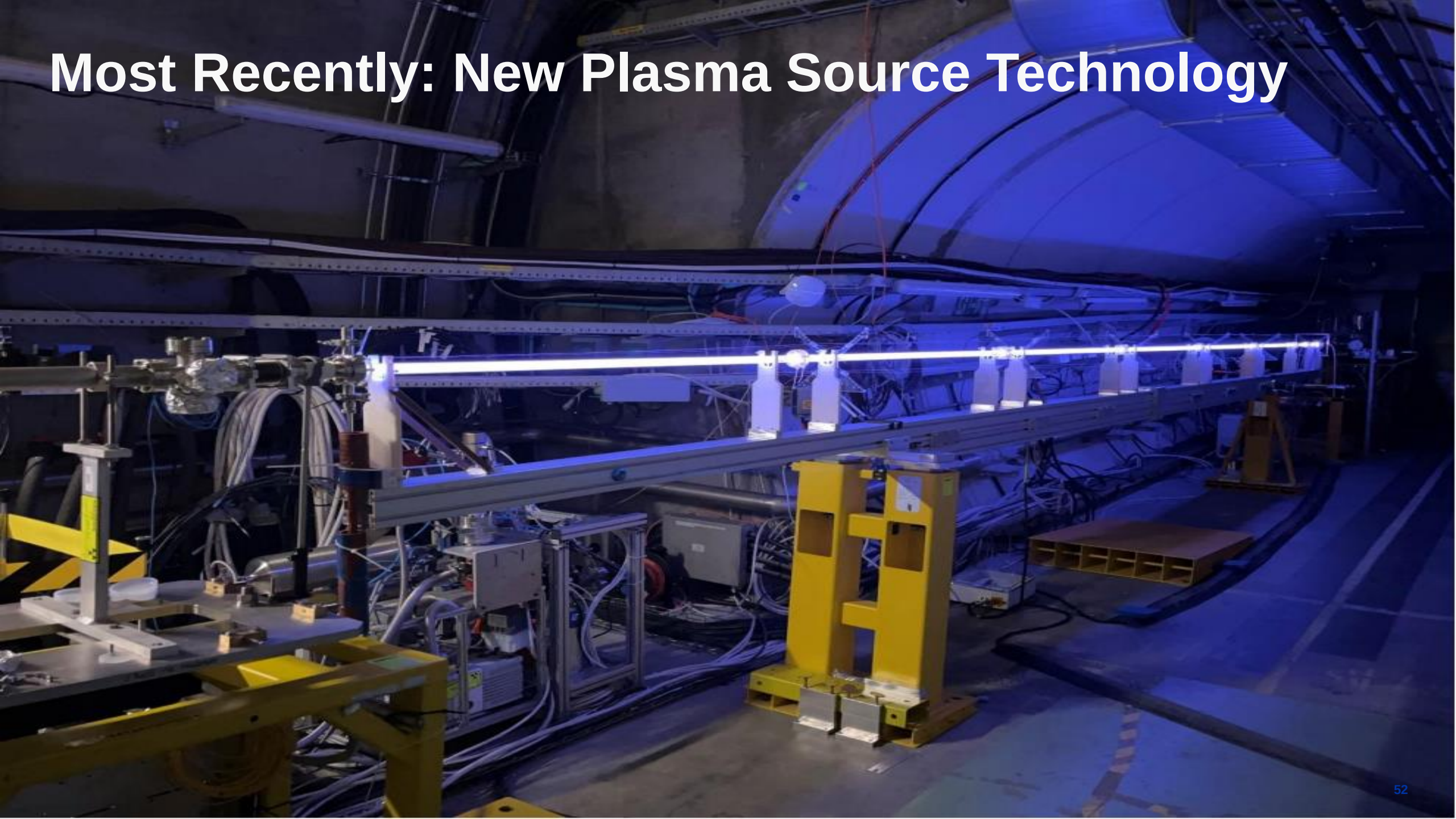
SPS Driver (19 kJ):
~ 200 GeV in ~200 m
~ 10^9 e^-



A. Caldwell, K. V. Lotov, Phys. Plasmas 18, 13101 (2011)

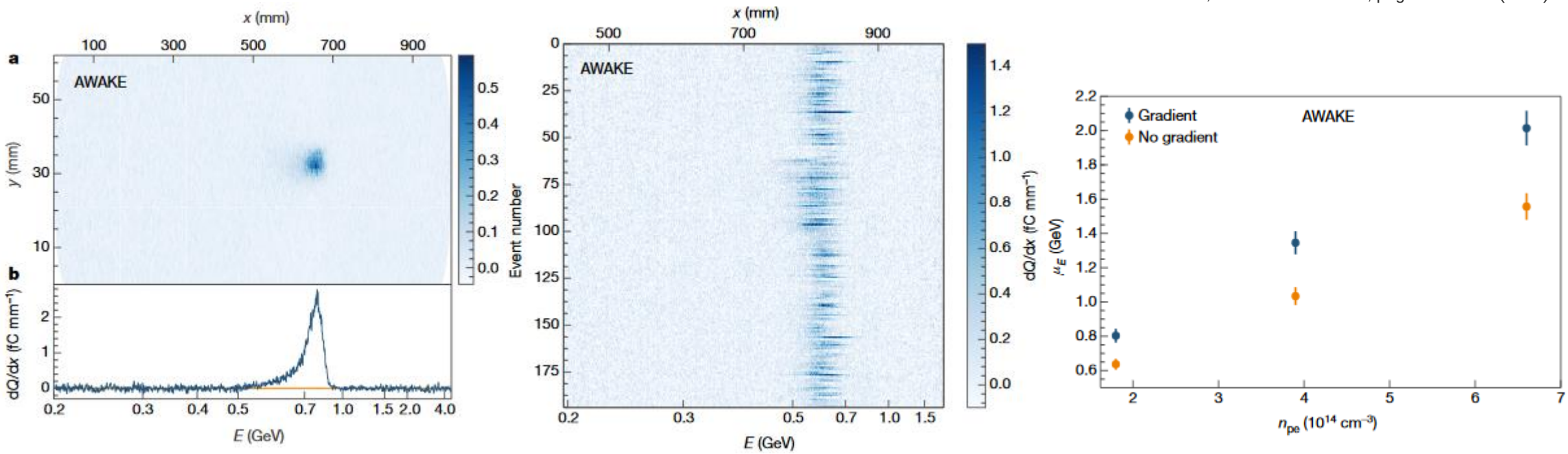
LHC Driver (112 kJ):
~ 5 TeV in ~7 km
~ 10^9 e^-

Most Recently: New Plasma Source Technology



AWAKE Electron Acceleration Results

AWAKE Collaboration, *Nature* **volume 561**, pages 363–367 (2018)



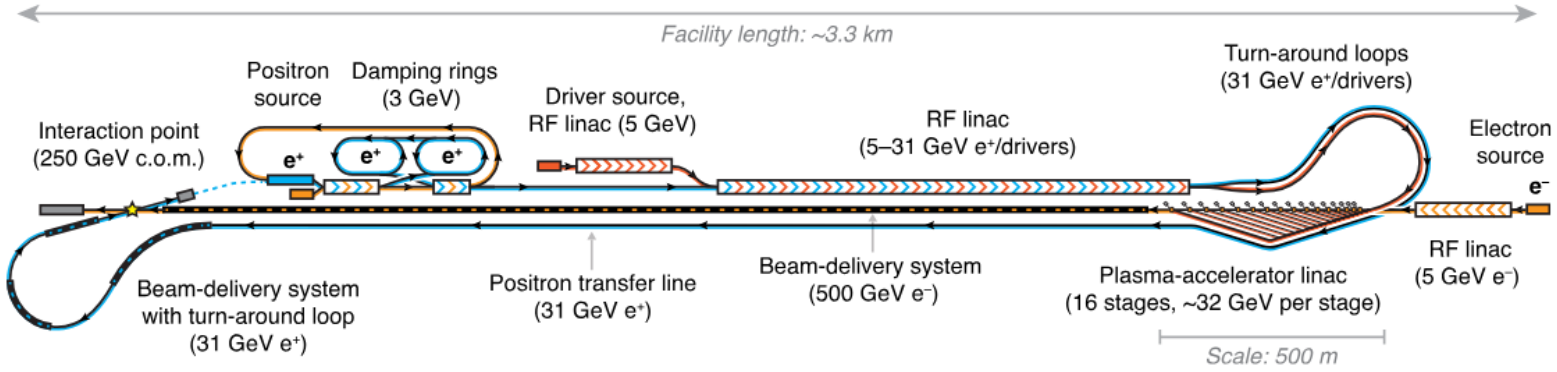
- **Proof-of-principle demonstration:** showed that proton beams can also be used as drivers, and that electrons can be injected and accelerated in a plasma wakefield
- An energy gain of **2 GeV** was achieved, corresponding to an accelerating gradient of a few hundred **MeV/m**
- **But:** the acceleration length could be extended significantly further

Future Plasma Based Colliders

B. Foster et al.

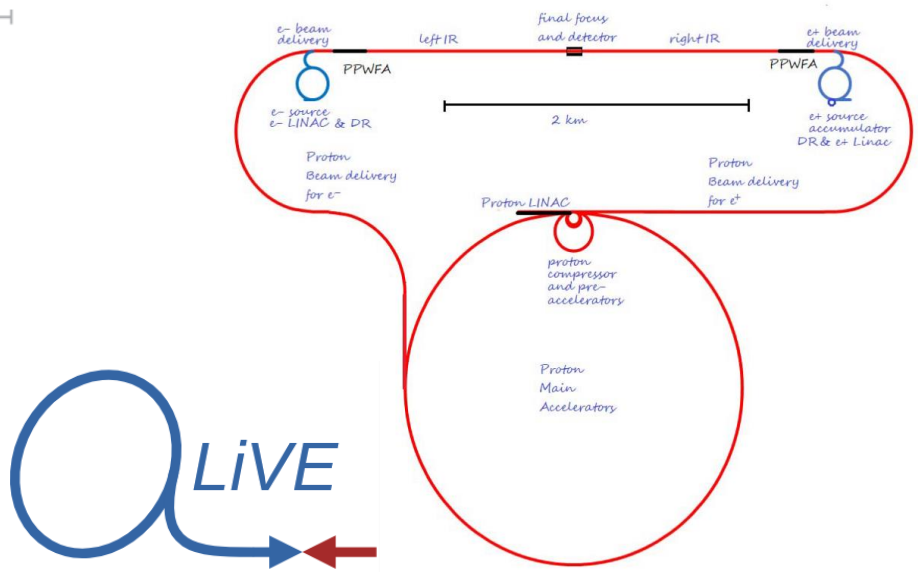
HALHF

Physics Open 23 (2025) 100261



R&D challenges include:

- **Beam quality:** preserve low emittance and low energy spread
- **Staging:** connect many plasma modules without losing beam quality
- **Positrons:** develop efficient, high-quality positron acceleration
- **Luminosity:** achieve collider-level beam stability and collision rates
- **Efficiency:** improve driver-to-beam and wall-plug efficiency



Q6: Does Plasma Wakefield Acceleration Work In Practice?

A6: Yes, Proof-Of-Principle Experiments Successful. More Work Needed on Beam Quality.

Q7: Where Else Could Compact Accelerator Technology Make a Difference?

Medical Applications

For example:

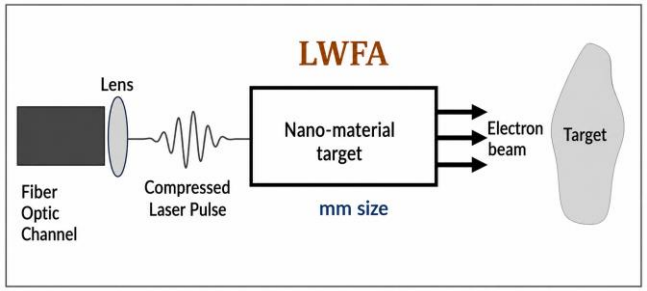
- Radiotherapy for cancer treatment

compacter, cheaper
+ FLASH effect

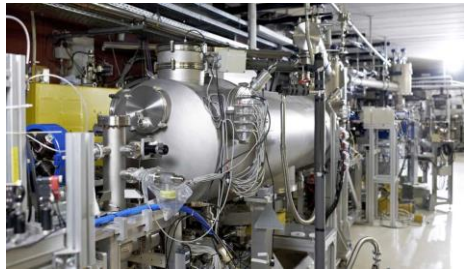
Potential using plasma wakefield acceleration

Towards micron-scale electron therapy at the tip of endoscopy – Source and delivery of fiber-optic based laser wakefield accelerator

T. Tajima[1a], W. Sha[2], J. Kuo[1b] D. Roa[1b], J.-C. Chanteloup[3], G. Mourou[3], D. Strickland[4], T. Kawachi[5], M. Mori[6], S. Aramaki[7], K. Nakamura[7], H. Lee[1a], and F. Tamanoi[8,9], A. Sytov[10], S. Iijima[13], Q. Dang[1a], V. Klumper[1a], S. Mukamel[1a,1c] P. Boulanger[11], C. Welsch[14], G. Koumarianou[12]



- Production of medical isotopes



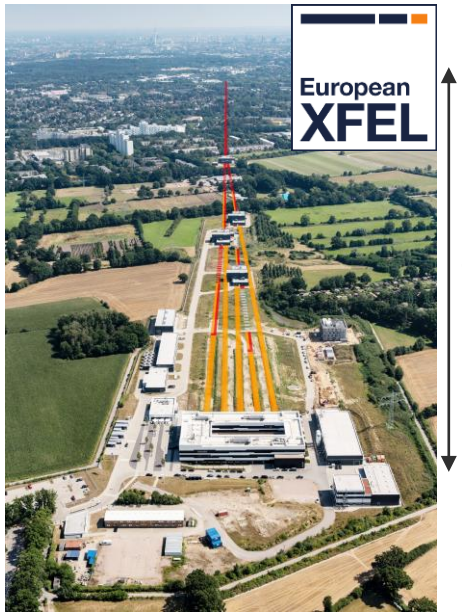
https://physicsworld.com/wp-content/uploads/2022/03/ELBE-radiation-source.jpg

compacter, cheaper

~ cm

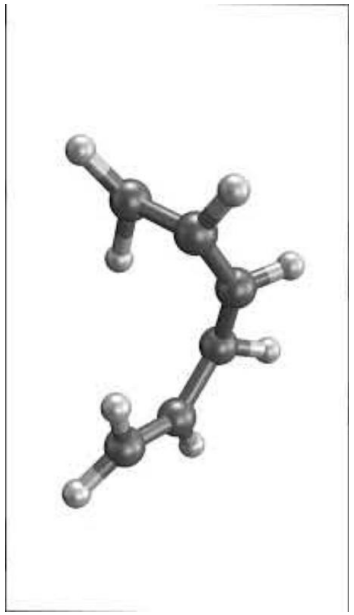
Ultrafast Science

Observe matter on its natural timescales



~3.4 km

SLAC

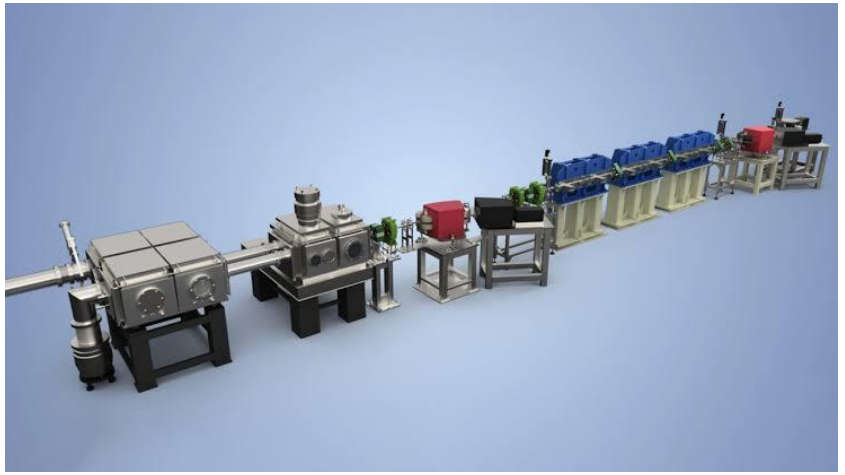


XFELs can make “molecular movies”

- They captured, in atomic detail, how a ring-shaped molecule opens within **800 femtoseconds** after a laser flash.
- Such ring-opening reactions are important in chemistry and biology, including the light-driven production of **vitamin D** in our bodies.

Potential using plasma wakefield acceleration

- Compact light sources for universities and smaller lab
- Produce extremely short particle and light pulses



~10 meters

Q7: Where Else Could Compact Accelerator Technology Make a Difference?

A7: Many Applications, e.g. Medical Applications, Material Science…

Summary & Conclusion

Summary and Conclusions

- **Electric fields accelerate charged particles, while magnetic fields guide and focus them.**
- **Conventional RF accelerators have taken us to the energy frontier, but higher energies require increasingly large and costly machines.**
- **Plasma wakefields can produce much stronger accelerating fields, potentially making future accelerators far more compact.**
- **Experiments have proven that plasma wakefield acceleration works, but challenges remain.**
- **Compact accelerators could benefit many fields, including particle physics, medicine, materials science and ultrafast imaging.**

Early Teachers and Mentors

A big thank you to my High School Teachers and mentors for:

1) Their enthusiasm and willingness to teach
2) Motivating by example and being passionate
3) Believing in my abilities and support

Their hard work and their example during my teenager years made me believe that physics is also the right career for me.
They all went the extra mile.

Math / Physics

MMag. Robert Schantl

Math

Mag. Peter Kaltenboeck

Physics

Mag. Peter Rabl

My fascination with particle accelerators started when our high school physics teacher organized a trip to DESY during our final year….

→ First exposure with the field that stuck…

→ Many, many opportunities that followed

Q&A

marlene.turner@cern.ch