An Advanced Wakefield Accelerator Experiment

What I will talk about

1. The problem with particle accelerators
2. A solution – Plasma Wakefield Accelerators
3. My work – Developing improved models

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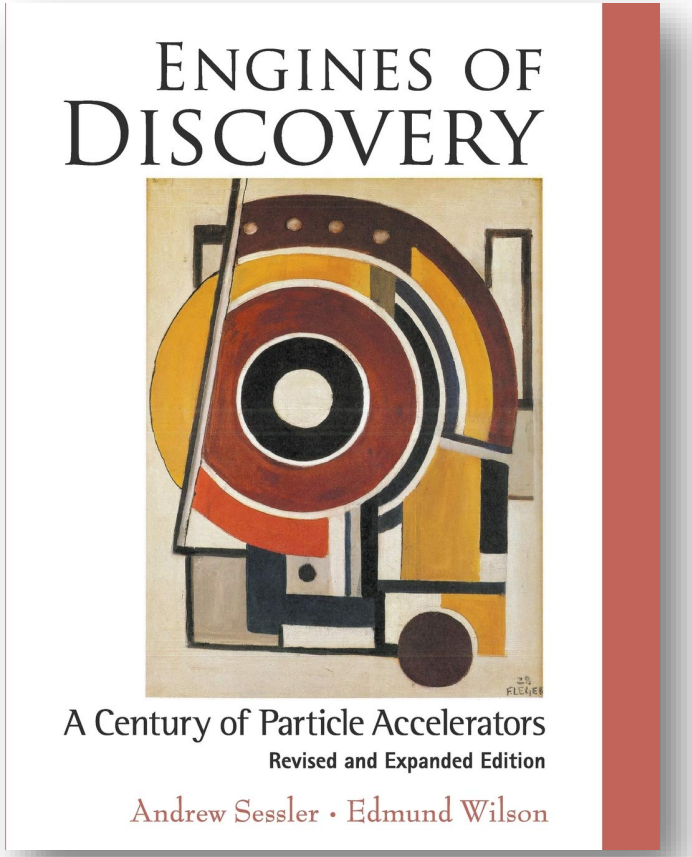
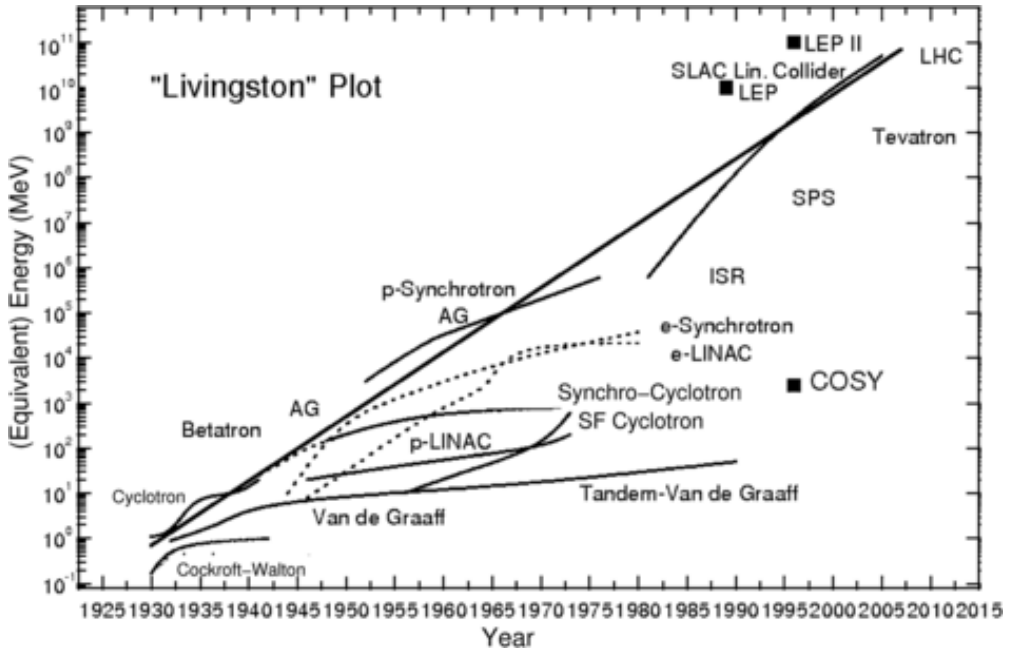
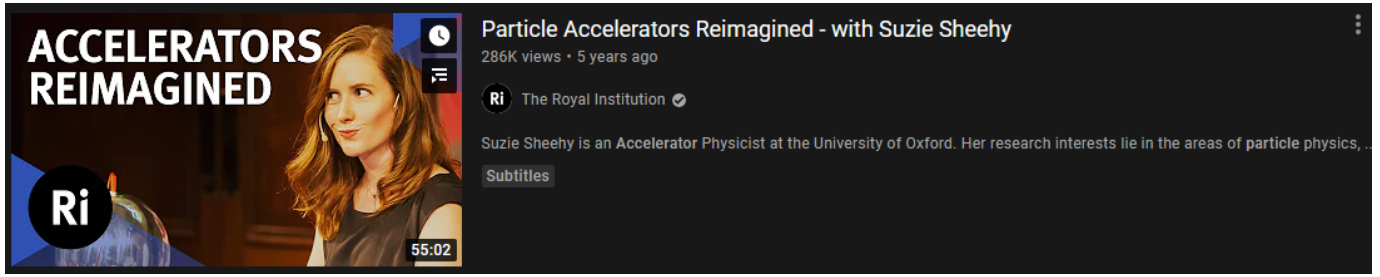
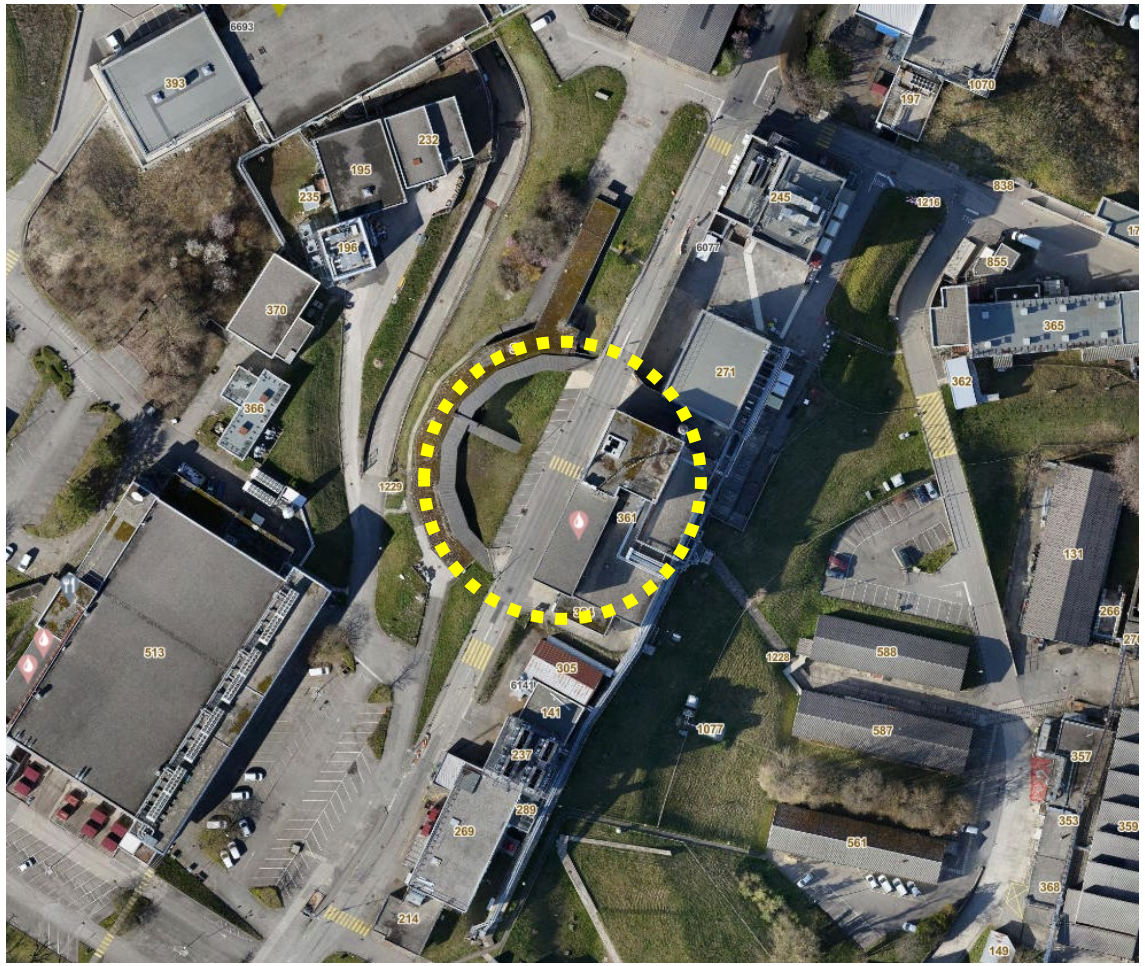
Particle Accelerators

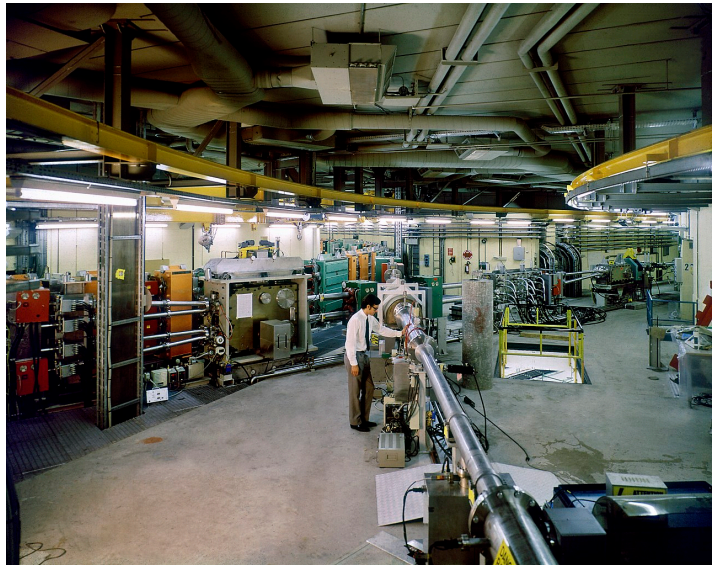






Why are particle accelerators so big?

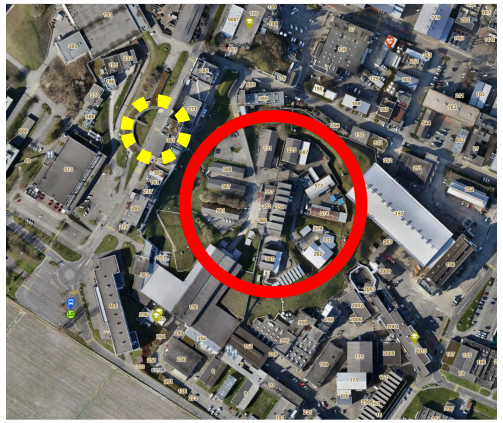




- Protons going to HEP experiments start at the Proton Synchrotron Booster (PSB)
- Protons accelerated to 73% of speed of light, *c or* 786,000,000 kilometers per hour

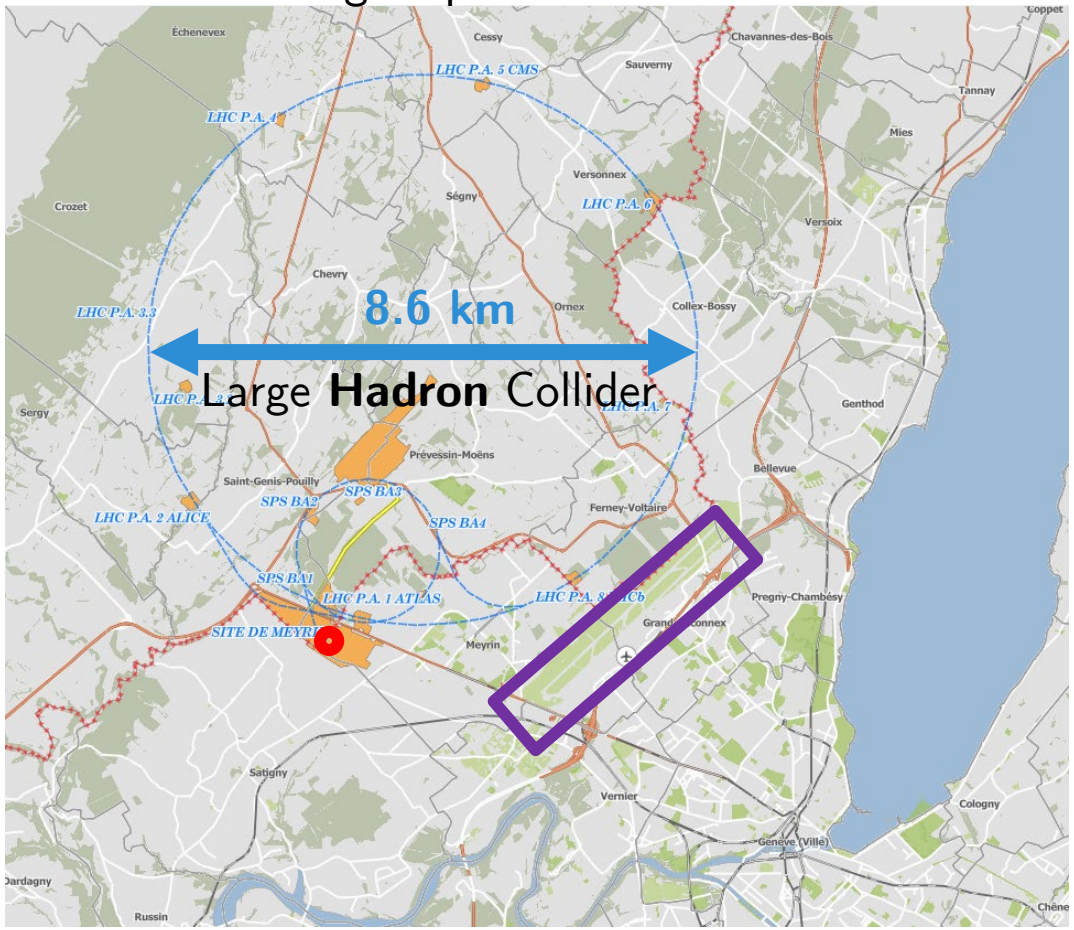
Why are particle accelerators so big?

73% of light speed



98% of light speed

99.999992% of light speed

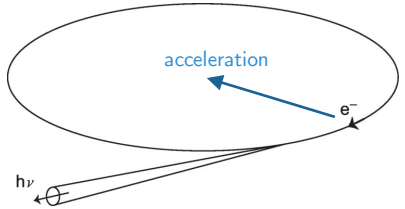


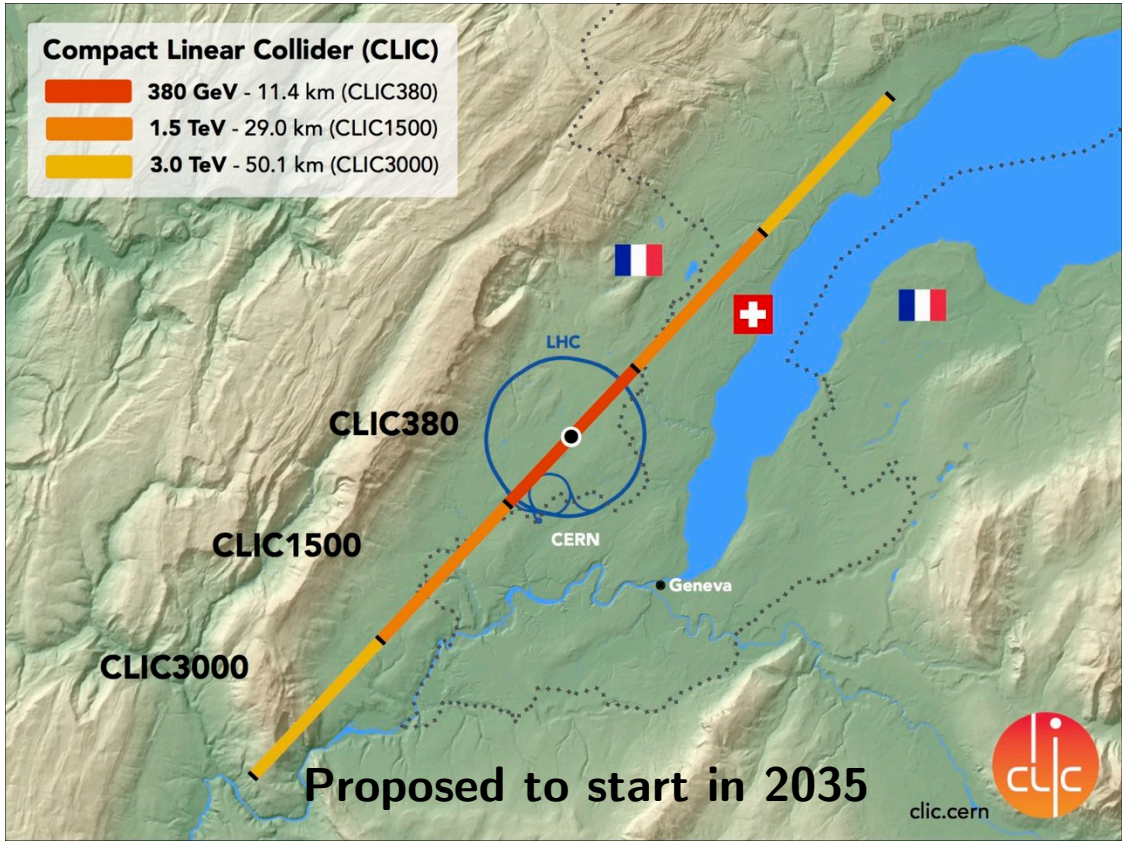
Why are particle accelerators so big?

- Hadron collisions are very messy
  - Can only measure certain properties of Higgs
- Precision measurements require exploring other interactions
  - $e^+e^- \rightarrow ZH$
  - $e^+e^- \rightarrow H\nu_e\bar{\nu}_e$
- Electron-positron (e^+e^-) collisions need a linear collider.

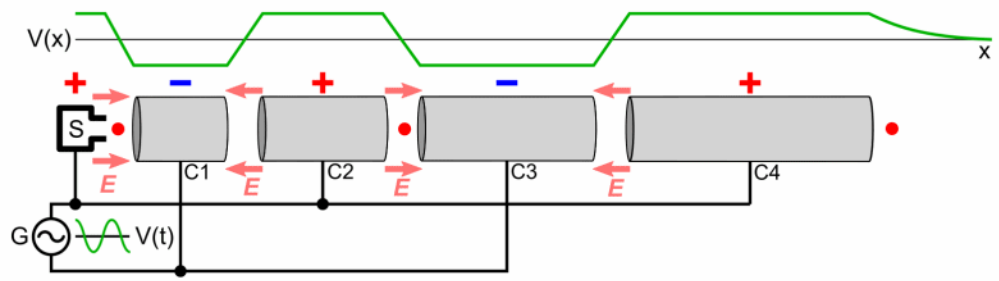
Why? "Synchrotron Radiation"

Electrons and positrons radiate away energy too fast due to centripetal acceleration in a circular accelerator

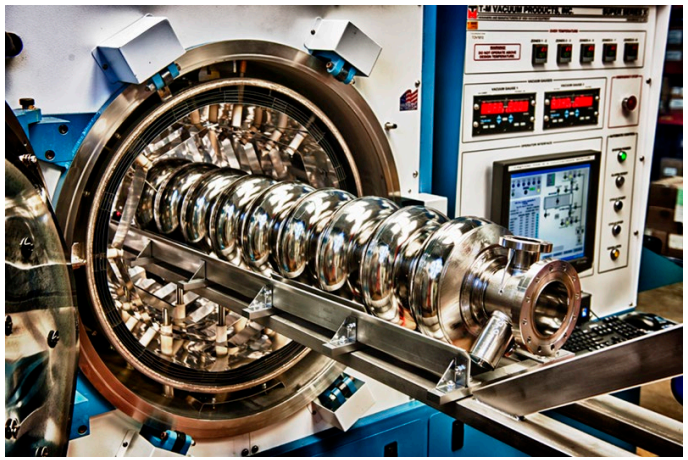


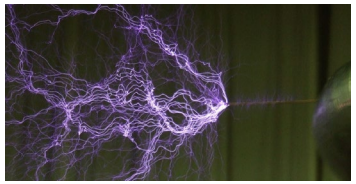


Why are particle accelerators so big?



Problem:
Metal "Klystrons" and cavities can only support about **100 MV/m** of Electric field strength.





"Electric Breakdown"

Solution (?):

We need ~5 TeV of energy gain per electron to produce interactions with interesting physics.

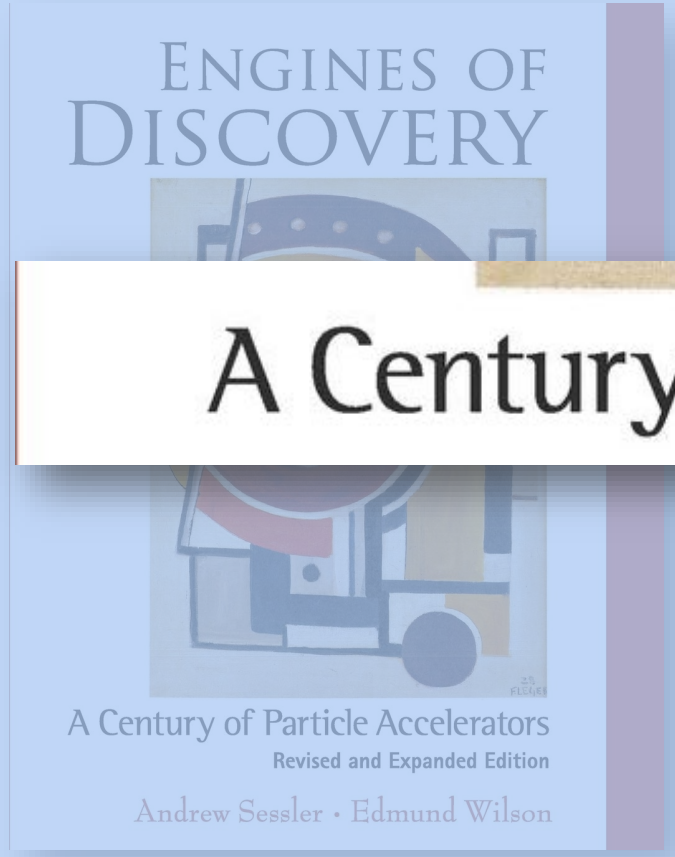
So:

5,000,000 MeV / 100 MV m^{-1} = 50,000 m

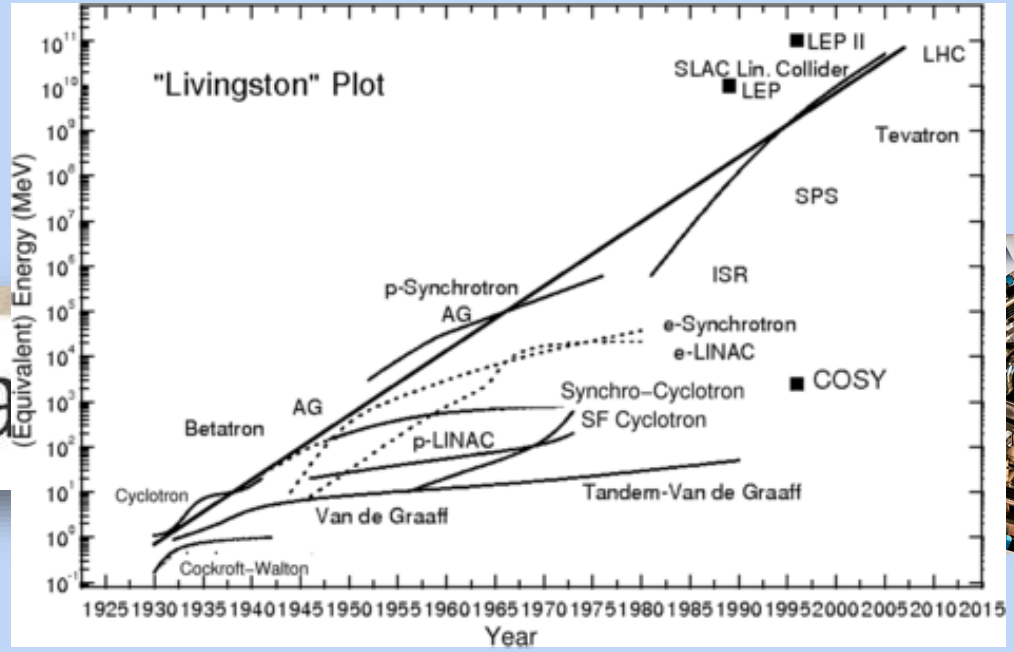
= about **50 km** worth of accelerator

= £10s of billions in construction and maintenance costs

Particle Accelerators (again)



A Century of Pa



Is there a better solution?

(than just making them really long)

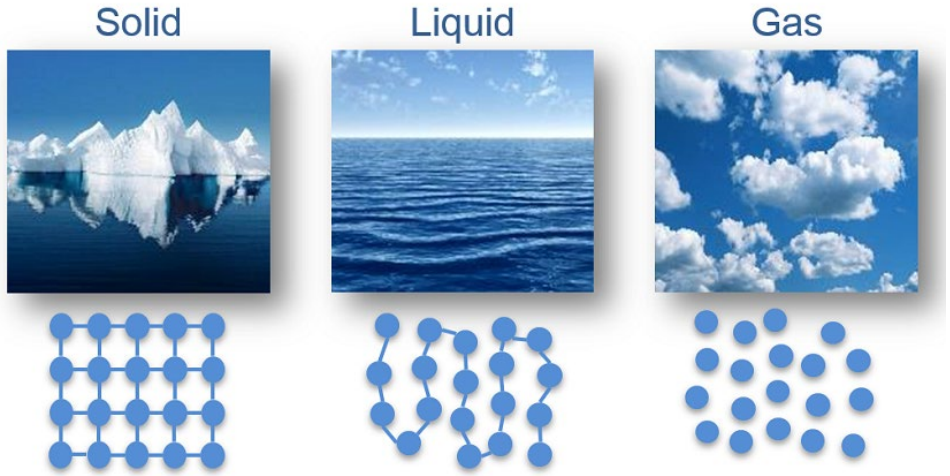
1985-ish

John Dawson

Toshiki Tajima

Plasma Wakefield Acceleration

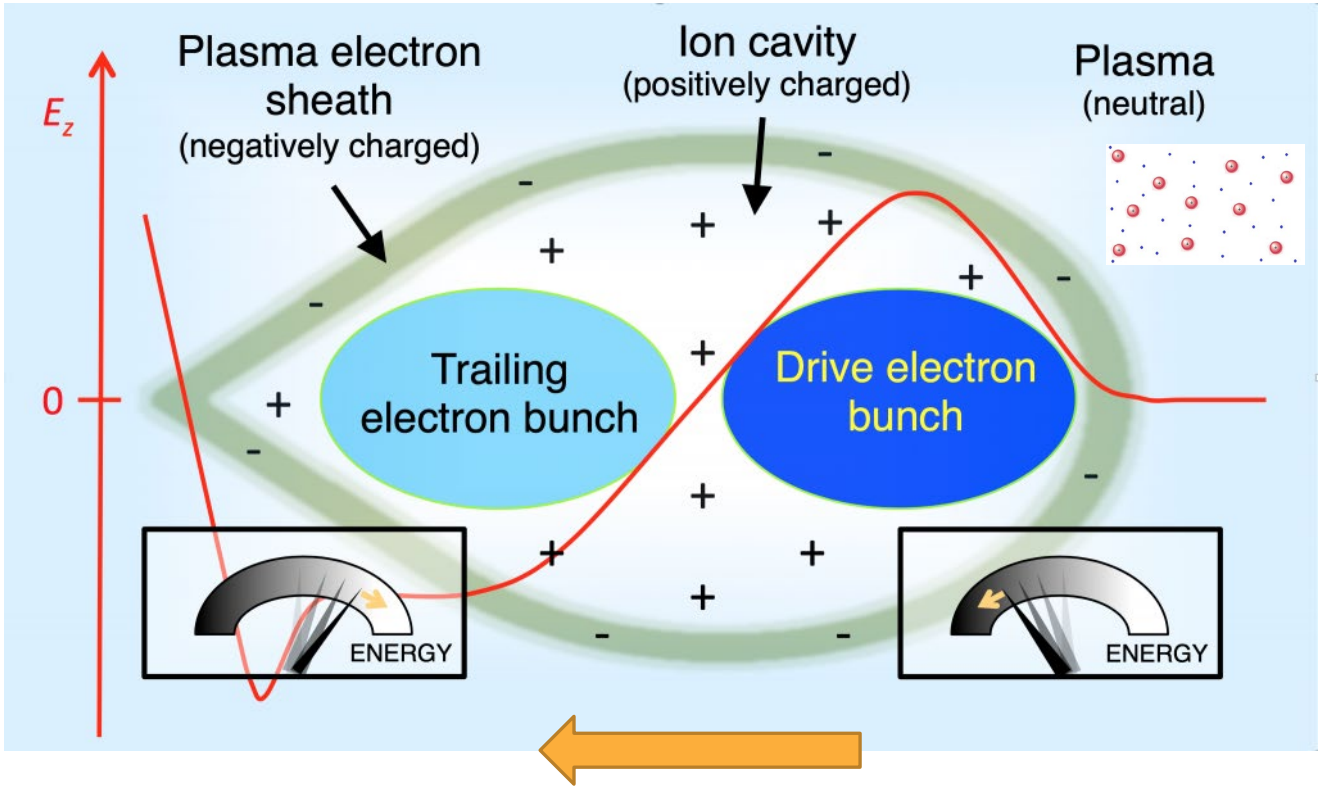
What is a plasma?
Sometimes thought of as "fourth state"



Super-heated gas that has been partially ionized into **free electrons and ions**

"What if we could make an accelerator out of stuff that was already 'broken-down'?"

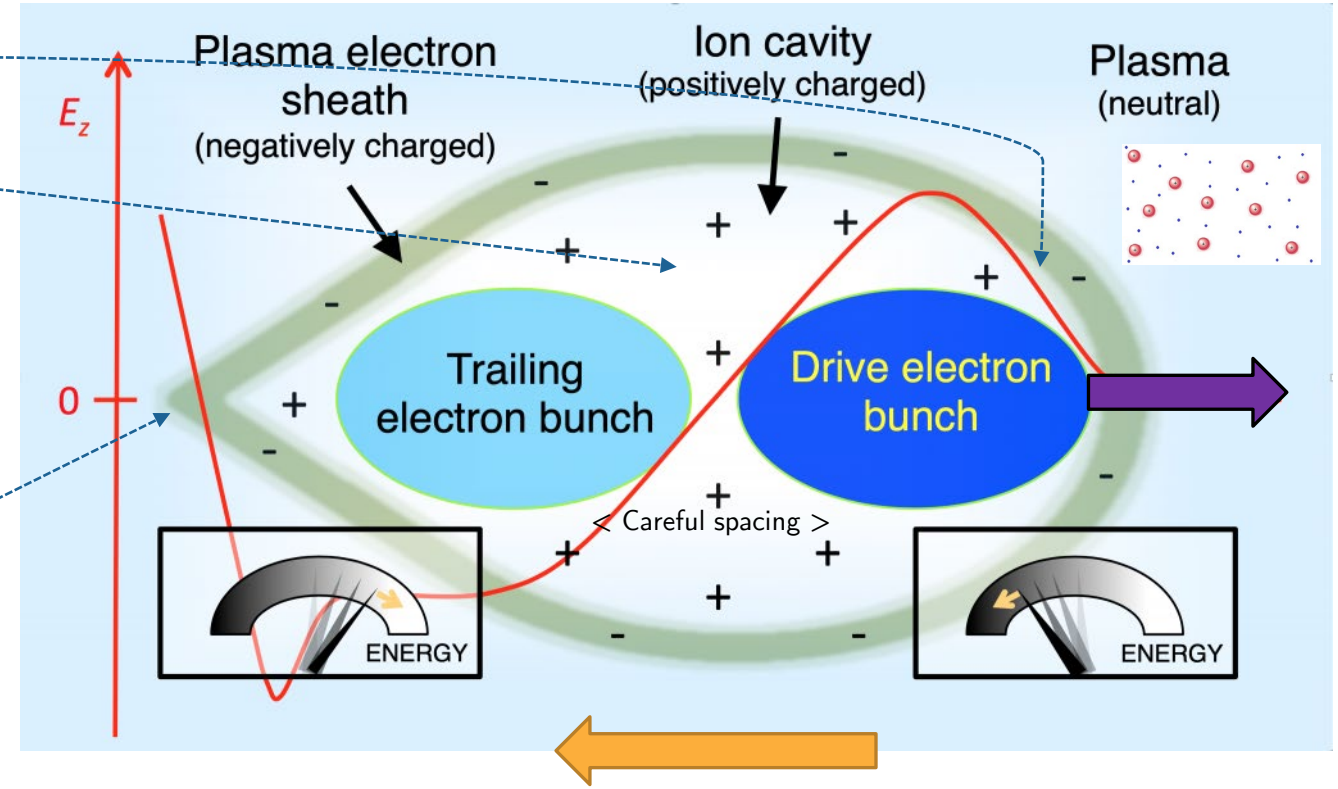
Plasma Wakefield Acceleration



Energy transferred from drive bunch to trailing bunch via plasma

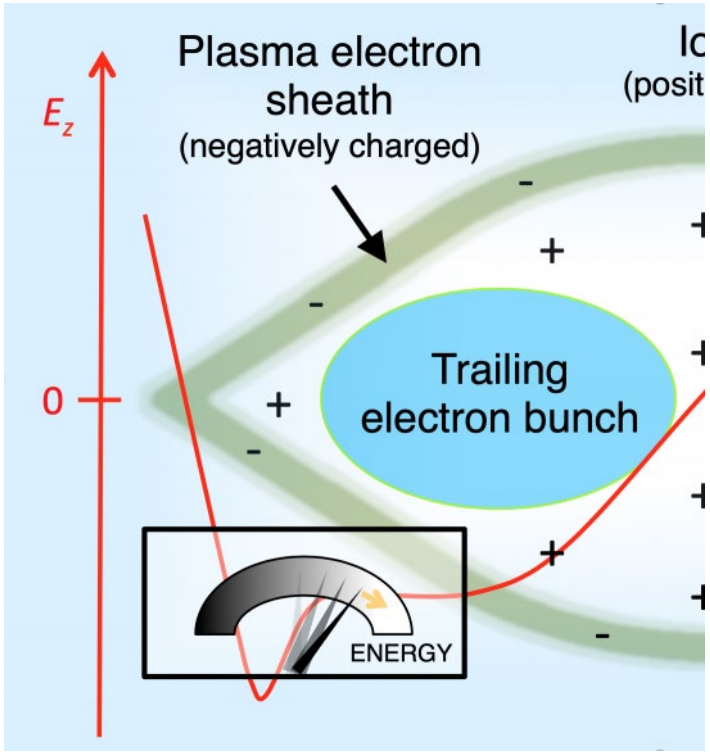
Plasma Wakefield Acceleration (step-by-step)

1. Drive bunch repels and expels plasma electrons in its path
2. Creates a 'cavity' of positively charge ions just behind it
3. After drive bunch passes through, plasma electrons are attracted back towards positive ions.
4. Where they crunch back in, high negative charge.
5. Electric field set up between negative and positive regions.
6. A well-timed trailing bunch can sit in the region of negative E field, being accelerated.



Energy transferred from drive bunch to trailing bunch via plasma

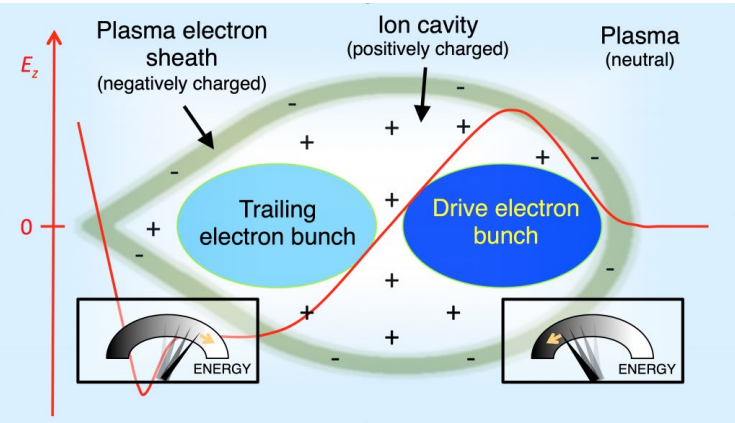
Plasma Wakefield Acceleration



Trailing electrons **surf a plasma wave**, created by the drive bunch

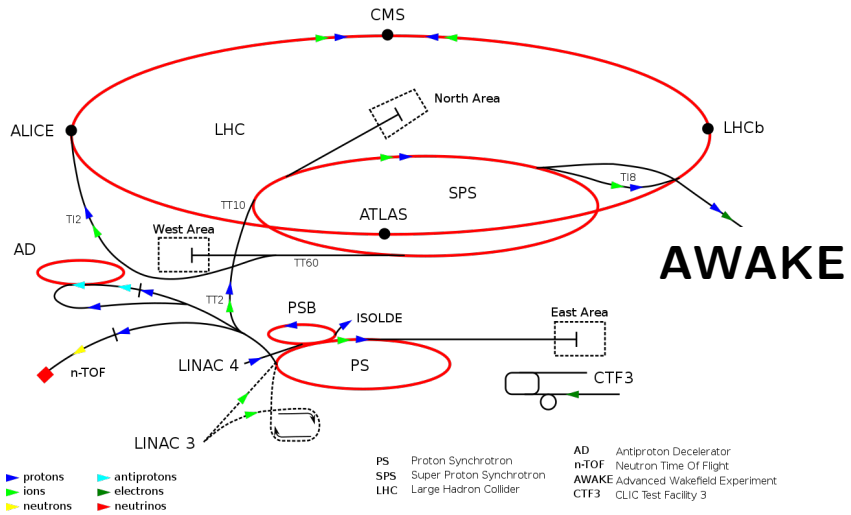
- These Electric fields are about 100 GV/m
- A **thousand times** stronger than the limit that metal accelerators allow
- Theoretically: equally powerful accelerators that are **50m** instead of **50km**

What is special about AWAKE?



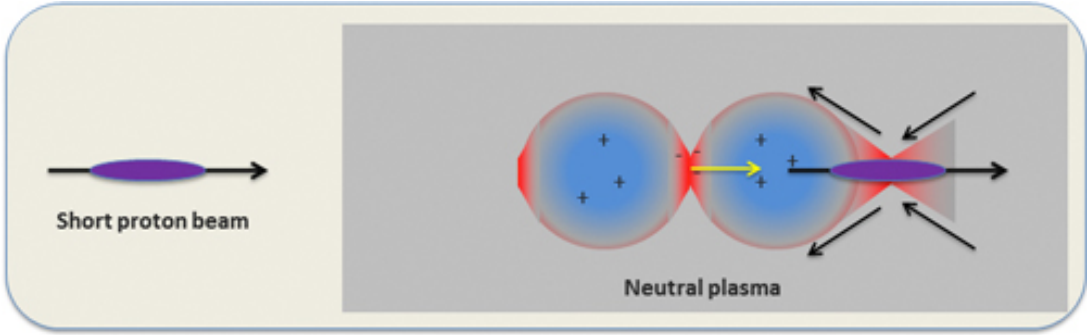
Quickly run into a problem

- Drive **electron** bunches have low energy content
- When energy is depleted, accelerator stops working
- Typically, less than a meter...



AWAKE

What if we use the high-energy beam going to the LHC?



- Proton beam 'sucks' in electrons, but there's still a wave!
- Lasts for **100s of meters**

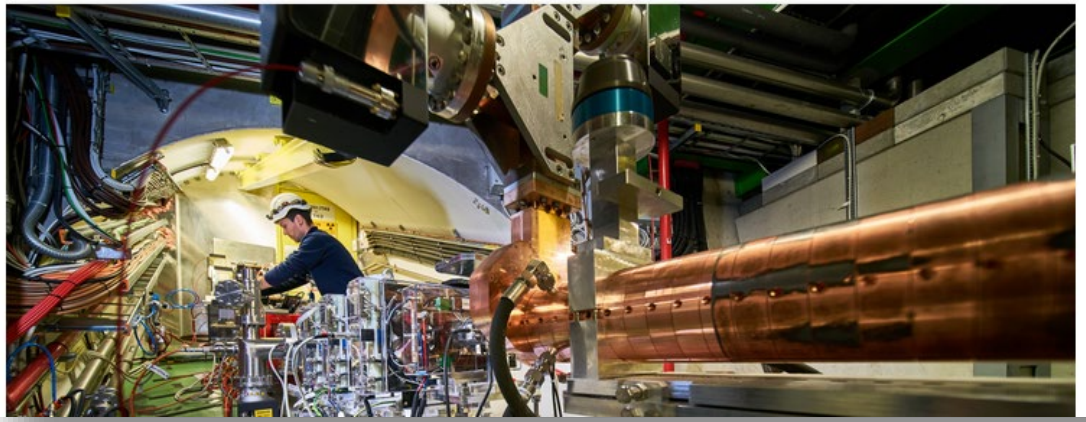
AWAKE is a Proof-of-Principle experiment

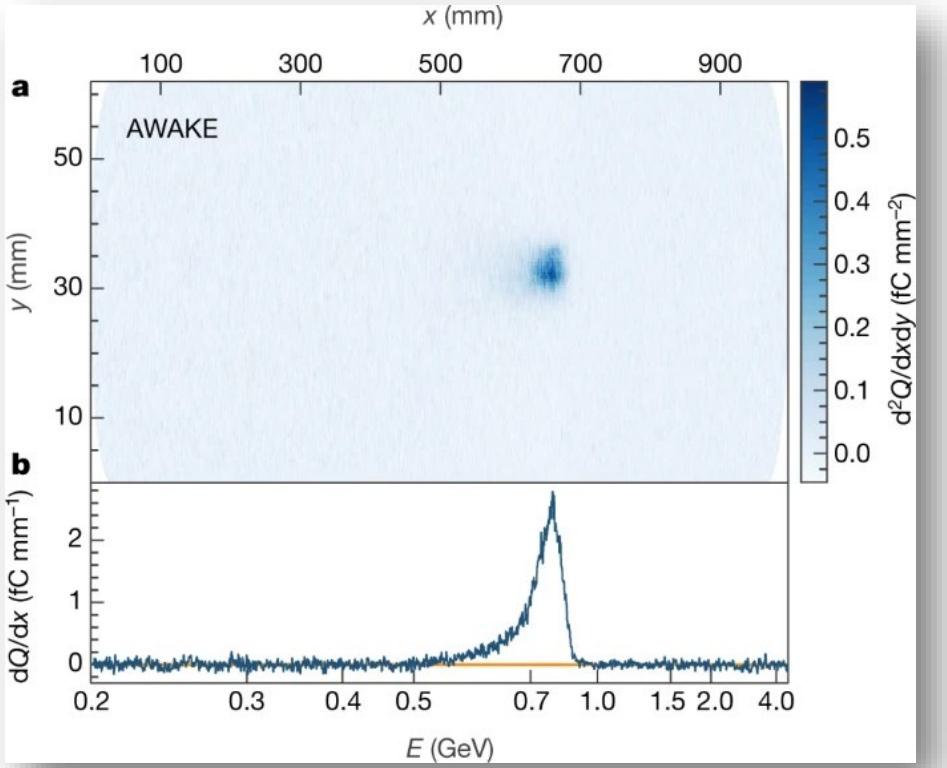
- Exactly 3 years ago, showed successful acceleration of an electron bunch.
- Soon, will demonstrate limits of how much energy can be transferred in a collider-friendly situation.

AWAKE successfully accelerates electrons

Proton beams from the SPS at CERN were used to generate plasma waves upon which the electrons "surfed"

29 AUGUST, 2018 | By Achintya Rao



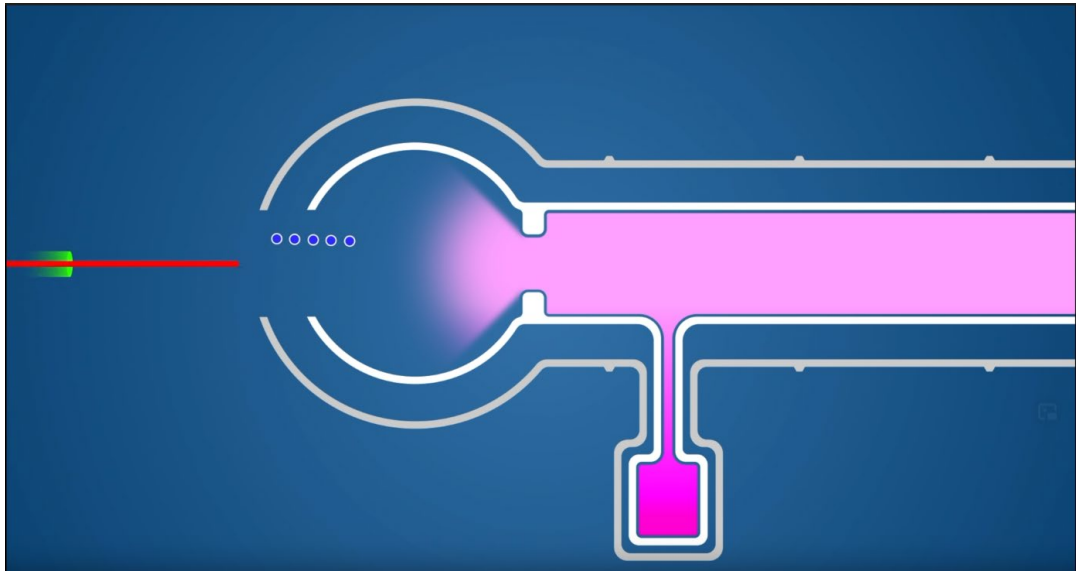


Still some problems to solve...

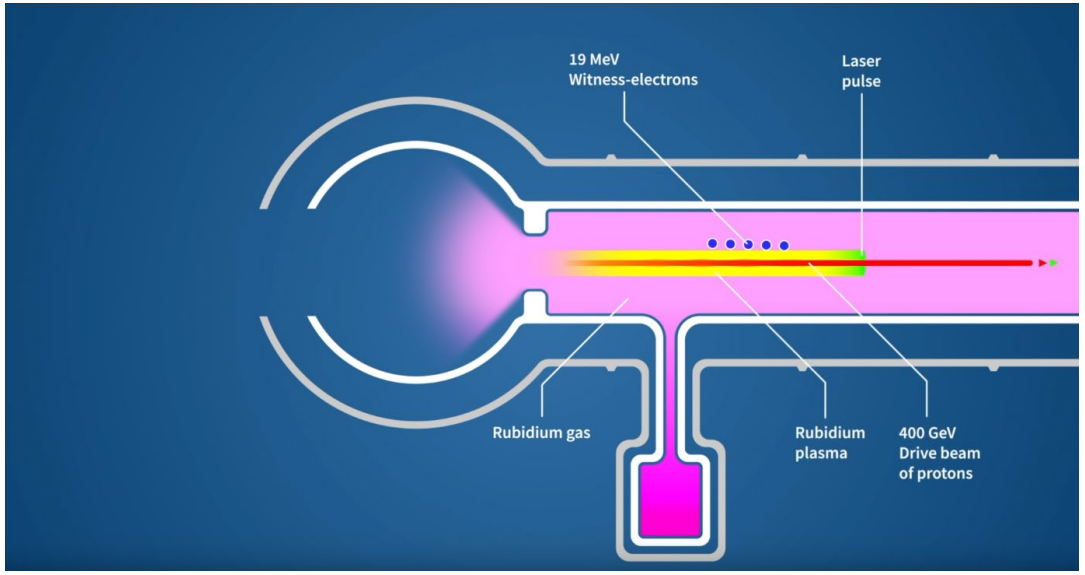
LHC's proton beam is too long!

- Need to self-modulate the beam in plasma into many shorter bunches

Proton bunch is too long!

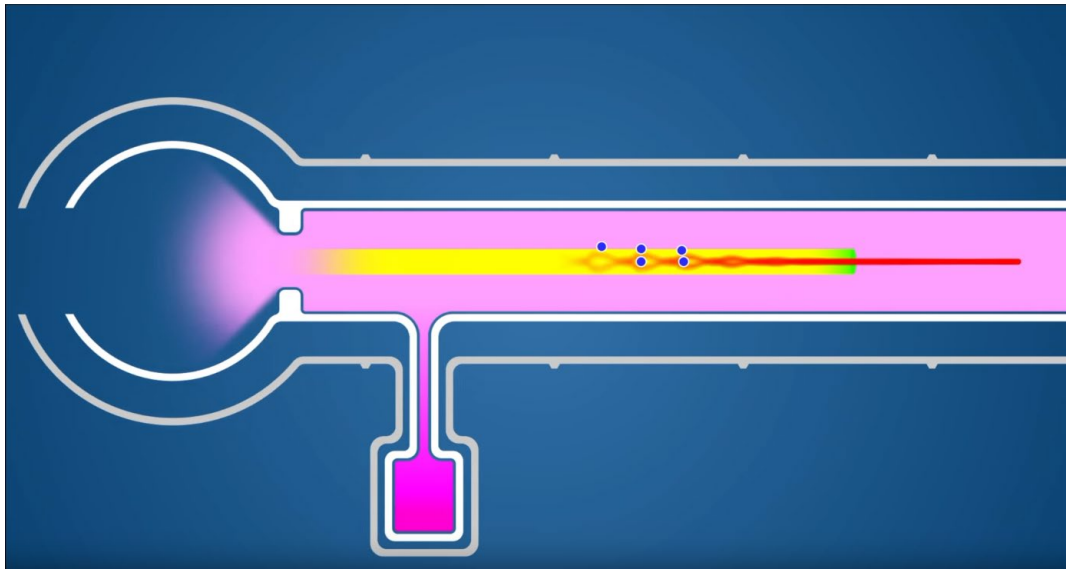


1. **Proton beam, witness electrons injected into plasma channel**



2. **Laser pulse ionizes a channel of gas into plasma, seen by proton bunch tail**

Proton bunch is too long!



5. Electrons enter wakefield of modulated beam

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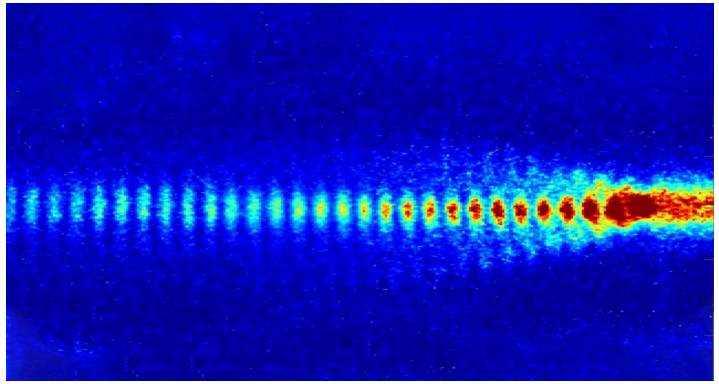
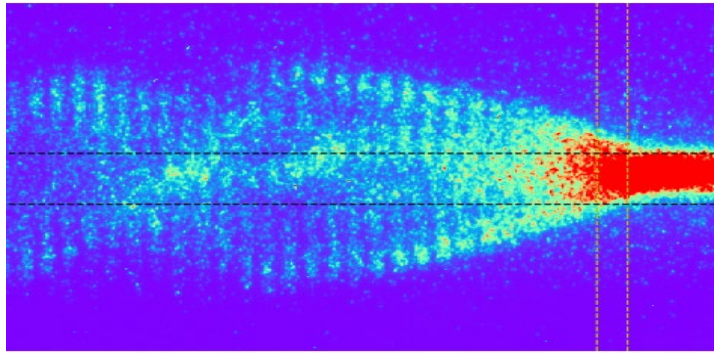


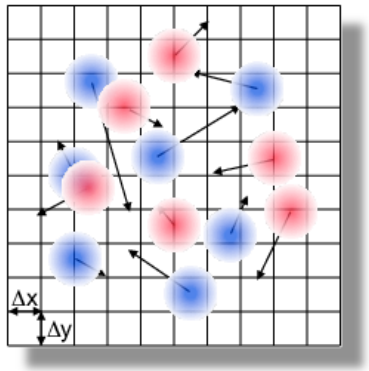
Modulation process doesn't always work
Asymmetries in the beam cause instability

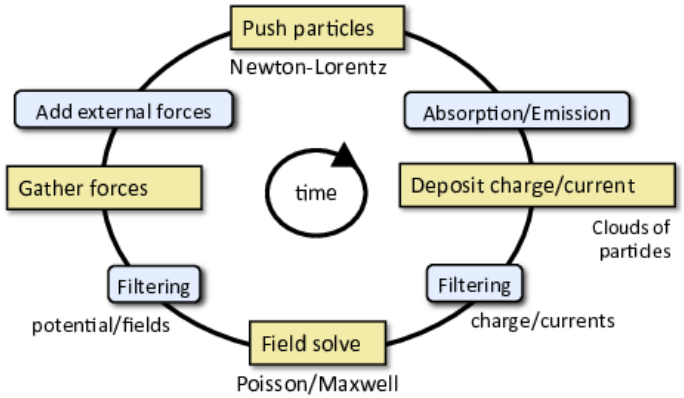
- Why not?
- How badly can it affect the performance of the wakefield accelerator?
- Can we incorporate effects of asymmetry into symmetric models of self-modulation?

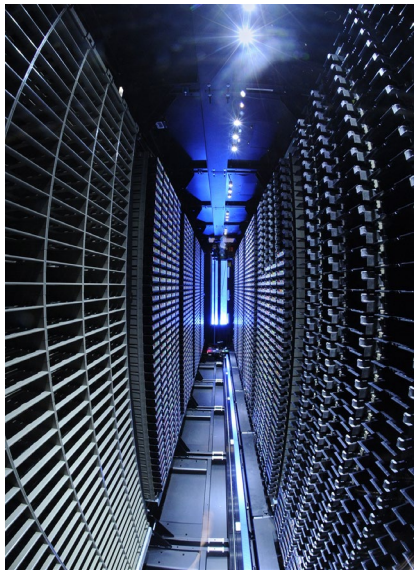


What I do — computer simulations (and some maths)

'Particle-in-cell' Simulations to improve **mathematical models** and understand the **stability** of the modulation process







1. Run on supercomputers with 1000s of CPU cores, taking a few days to a few weeks
2. Represent **trillions** of real particles using **billions** of 'pseudo-particles' being pushed by Electric and Magnetic fields
3. Provide insight into physics of plasma accelerator processes that can't be diagnosed in experimental conditions

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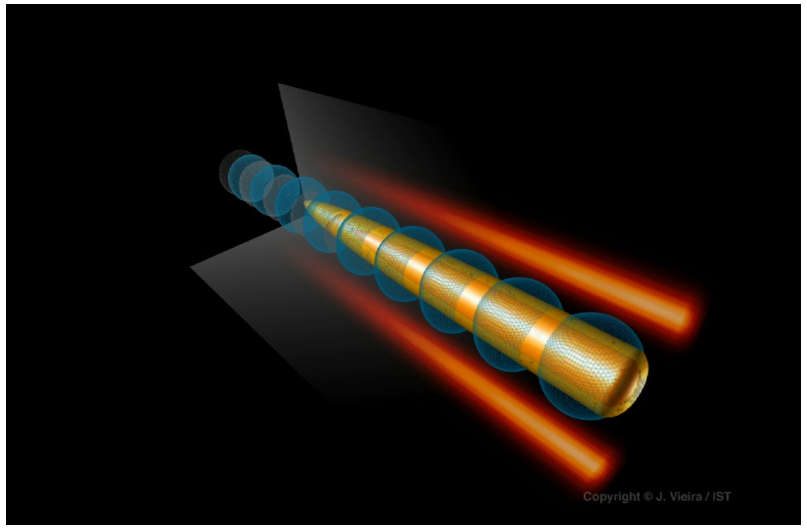

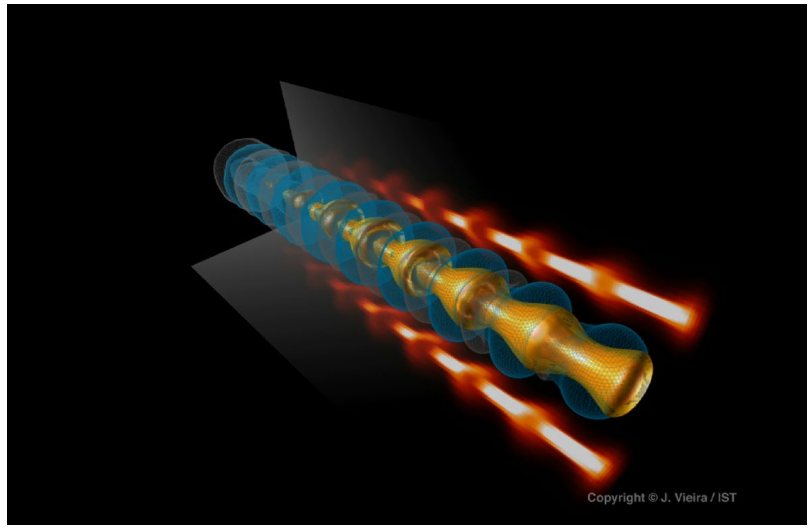

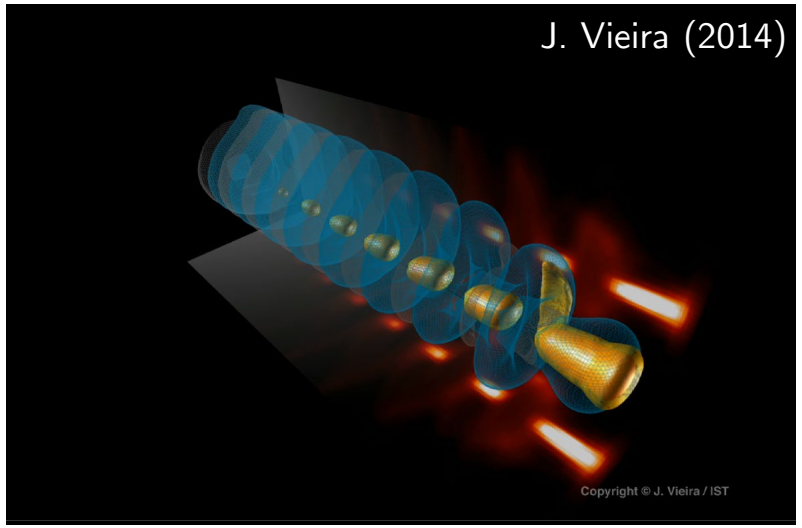

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Summary

- Existing accelerator technology is a century old.
  - It is **limited by electric breakdown** of metals to about 50 MV/m.
- This makes reaching higher and **higher energies** to explore the frontier of physics **very expensive** because accelerators need to be 10s of kilometers in size.
- Plasma accelerators, such as the one being tested at AWAKE promise **1000x fold** *increase* in acceleration power, or a 1000x fold *decrease* in accelerator length.
- Some problems yet to be solved (including many unmentioned here that others are working on)
- There are already plans being made to incorporate AWAKE-like accelerators into future colliders.

Exciting times lie ahead in accelerator science!

Finally:

CERN can neither generate a Black Hole...

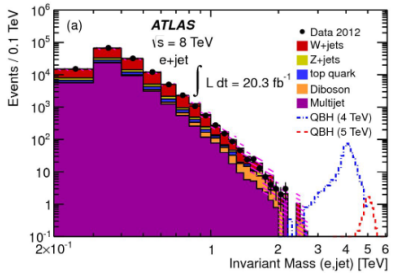
BSM physics: Microscopic black holes

Could The Large Hadron Collider Make An Earth-Killing Black Hole? (NO!)

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.

This article is more than 5 years old.

- Numerous BSM theories predict we could produce microscopic black holes at the LHC.
- QBHs distinct from cosmological black holes → CERN is not going to end the world!



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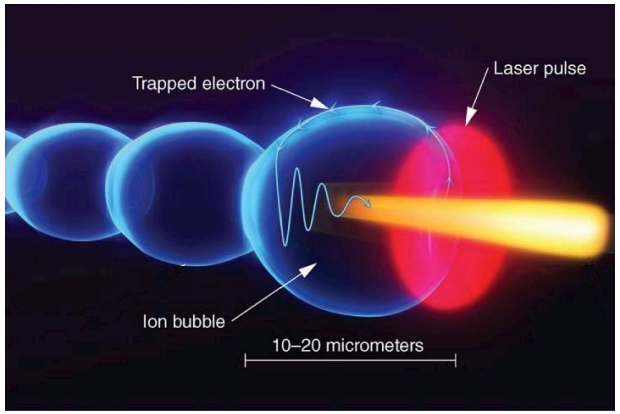
(From Matt Sullivan, yesterday)

...nor open a portal.

AWAKE

An Advanced Wakefield Accelerator Experiment

Laser-driven plasma wakefield accelerator



Any questions?

More on AWAKE and Plasma Accelerators – also try Googling 'Plasma wakefield acceleration'.

- A video explanation of AWAKE - https://www.youtube.com/watch?v=vfy7glPtV_8
- A bit more mathematically involved explanation of primary challenges in AWAKE - https://arxiv.org/pdf/2007.05226.pdf

- Particle Physics with the AWAKE scheme - https://arxiv.org/pdf/1812.11164.pdf
- Particle Physics applications of novel high-acceleration-gradient schemes in general - https://arxiv.org/pdf/1901.08436.pdf

- Easy read: Plasma accelerators in the UK and Europe - https://physicsworld.com/a/europe-draws-up-plans-for-plasma-based-particle-accelerators/
- A more detailed plan of plasma accelerator research up to 2040 in the UK - https://arxiv.org/pdf/1904.09205.pdf

A couple of "better" answers

1. "Why is synchrotron radiation not as much of a problem for protons [as for electrons]?"

The average radiated power is given by:

$$\langle P_{SR} \rangle = \frac{U_0}{T_0} = \frac{4\pi c\, r_e}{3(m_0 c^2)^3} \frac{E_0^4}{\rho L} \qquad where\ L \equiv\ ring\ circumference$$

US Particle Accelerator School

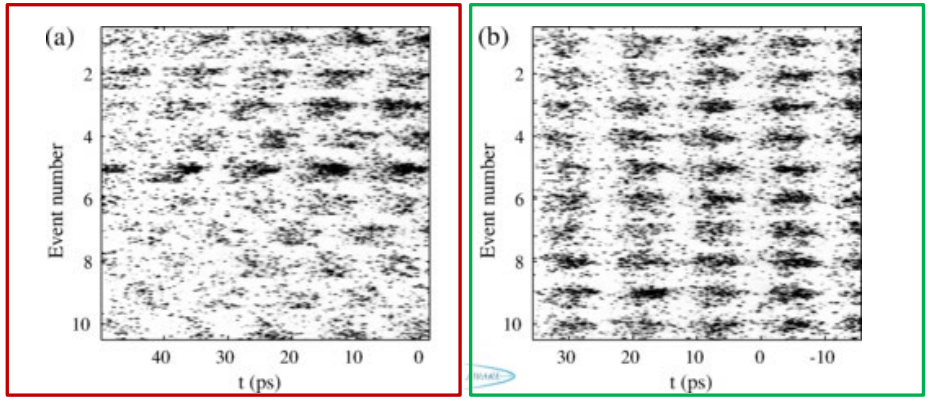
At the same particle energy, E_0, same accelerator 'bending' radius ρ, and same circumference L, power emitted by synchrotron radiation varies as 1/rest-mass^3

More: https://uspas.fnal.gov/materials/09UNM/Unit_11_Lecture_18_Synchrotron_radiation.pdf

2. "Why [should] there [be] more [beam] density [at the point the plasma is generated]?"

Plasma-producing laser placed too **near the low-density 'head'** of the bunch.

Self Modulation is an "instability" which grows from random noise → not reproducible



Laser placed close to the **central density peak** of the bunch.

"*Seeded* Self-Modulation" pattern is **reproducible** from Event to Event --> acceleration efficiency is reproducible