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UiO research towards plasma accelerators and a plasma collider

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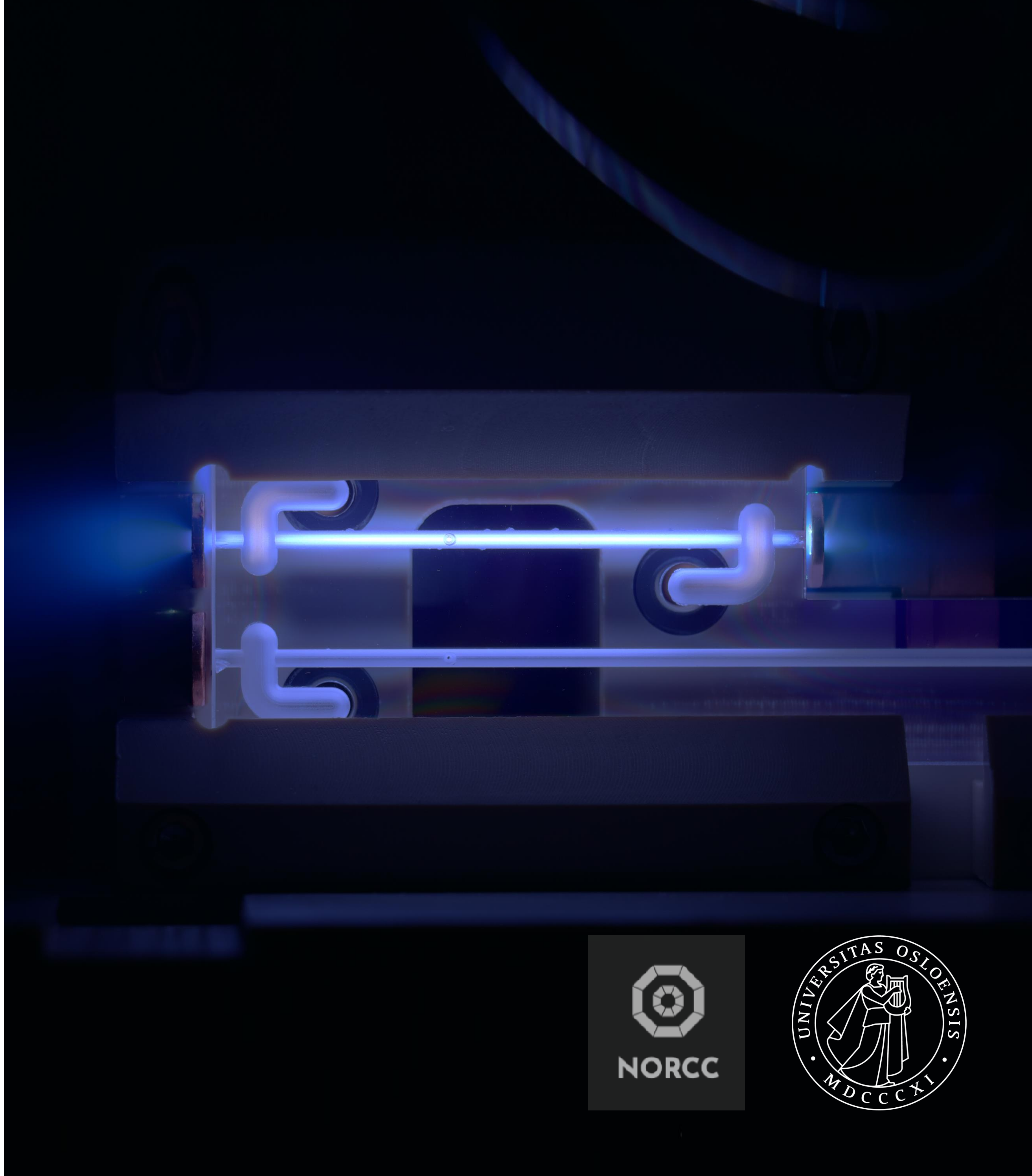
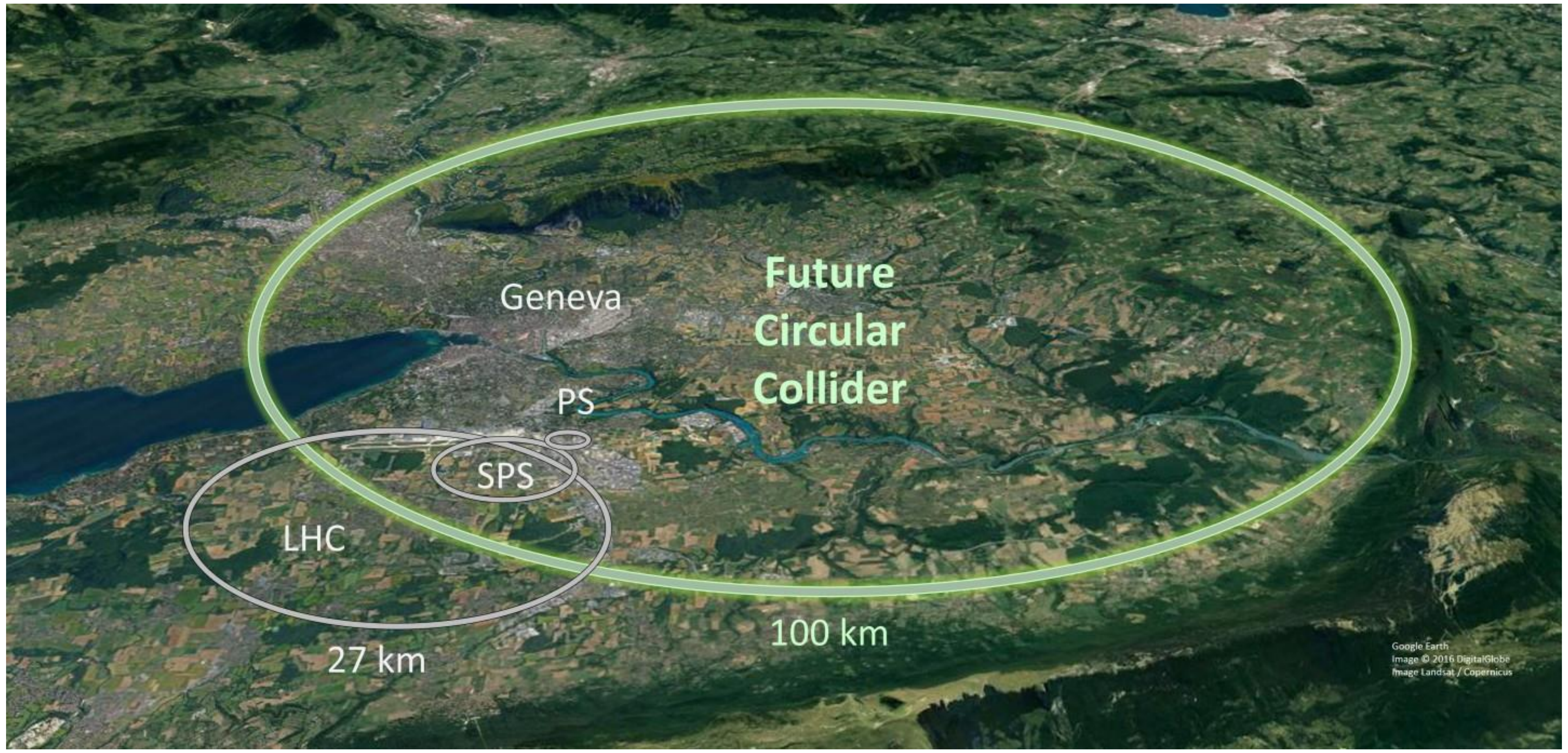


Particle colliders are too expensive

- Proposed next-generation colliders are **priced at \$7–25 billion** ⇒ no one can afford to host it…
- Driven by limits in accelerator technology:
  - *Circular colliders: magnetic field (10–20 T) for p^+, and synchrotron radiation for e^+/e^-*
  - ***Linear colliders: accelerating gradient (~100 MV/m)***



Future Circular Collider
\$20–25 billion

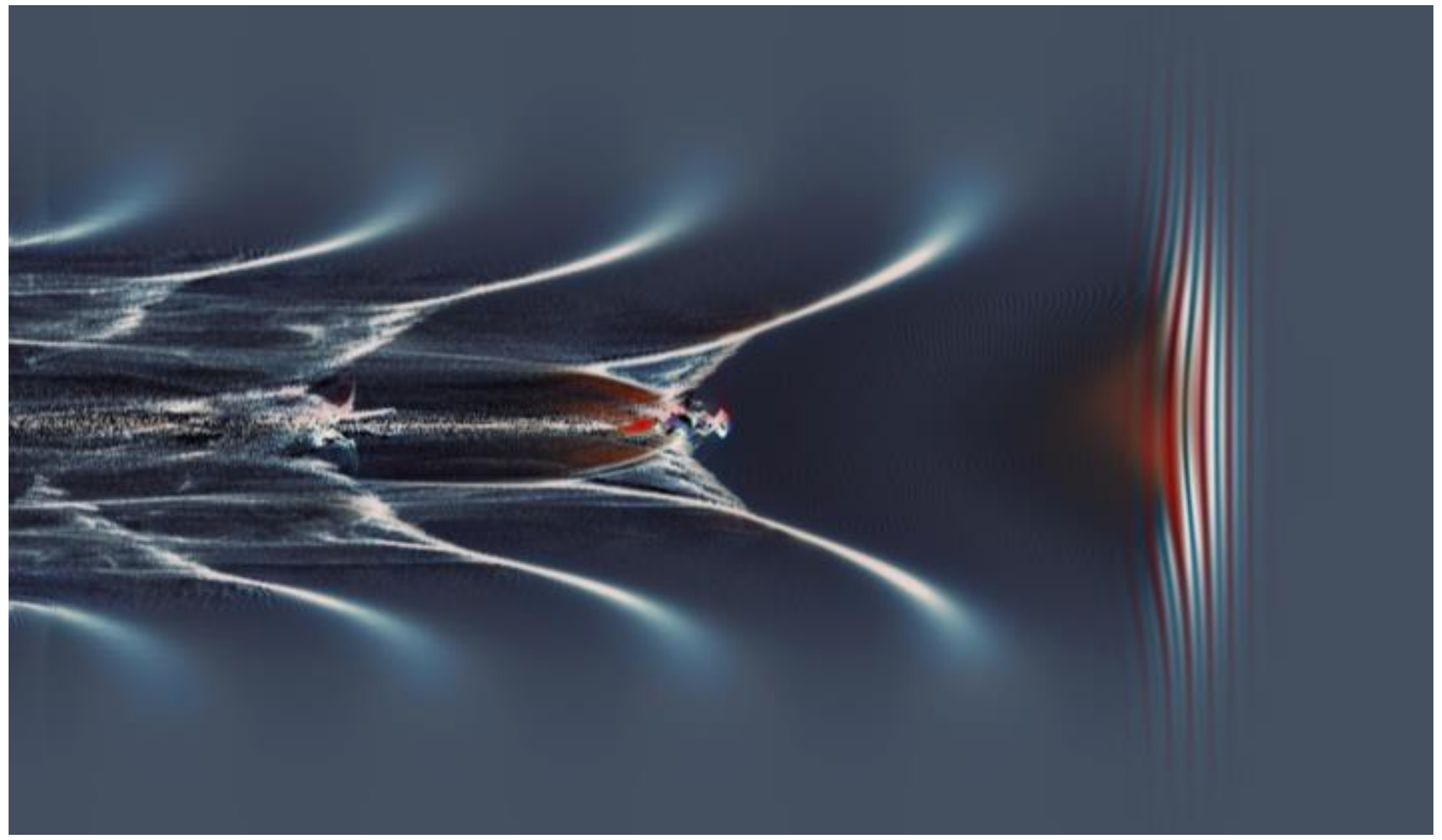
Plasma-based collider
< \$1 billion ?

Plasma wakefields: What are they?

- **Plasma wake: charge-density wave in a plasma,** driven by intense laser- or particle beam
- Plasma wakefield: strong electromagnetic fields caused by the **separation of electric charges** (electrons from ions)
  - Can be used to accelerate charged particles
  - Analogy: a surfer in the wake behind a boat
- **Discovered in 1979** by Tajima and Dawson (UCLA)…
  - …similar ideas by Veksler *et al.* in 1956 (in Soviet Ukraine).

Vladimir I. Veksler
“Coherent principle of acceleration” (1956)

Toshiki Tajima and **John M. Dawson**
“Laser electron accelerator” PRL 43, 267 (1979)



From: Sören Jalas/Universität Hamburg

Plasma wakefields: Unlimited accelerating fields

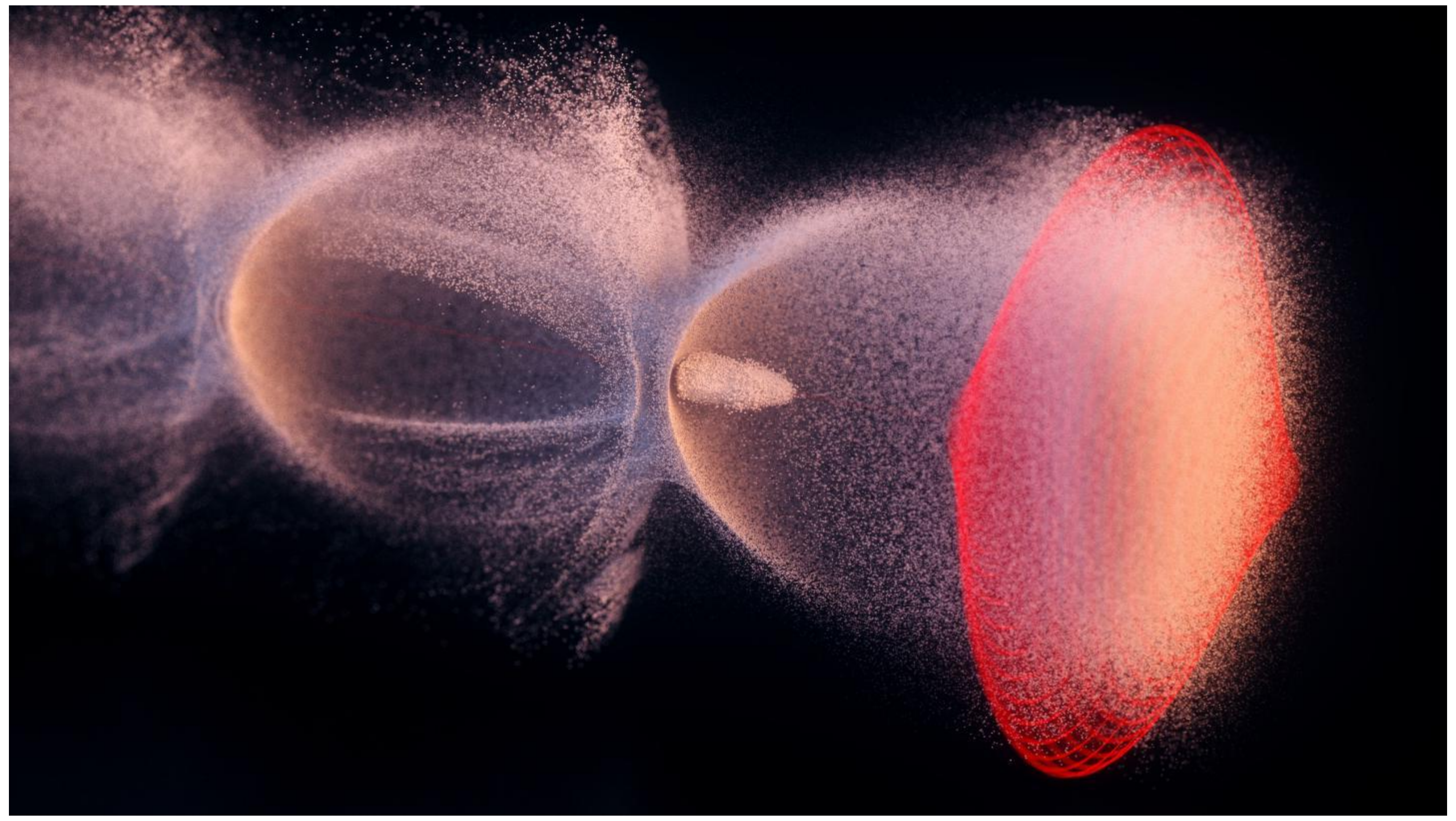
- Single-use accelerator cavity, travelling at speed ***c***
  ⇒ **not affected by breakdowns** (it *is* the breakdown)
  - *Laser driver: radiation pressure (ponderomotive force)*
  - *Beam driver: electric repulsion*
- **Higher plasma density ⇒ higher gradient**
  ⇒ smaller dimensions

Accelerating gradient:
(wave-breaking field)

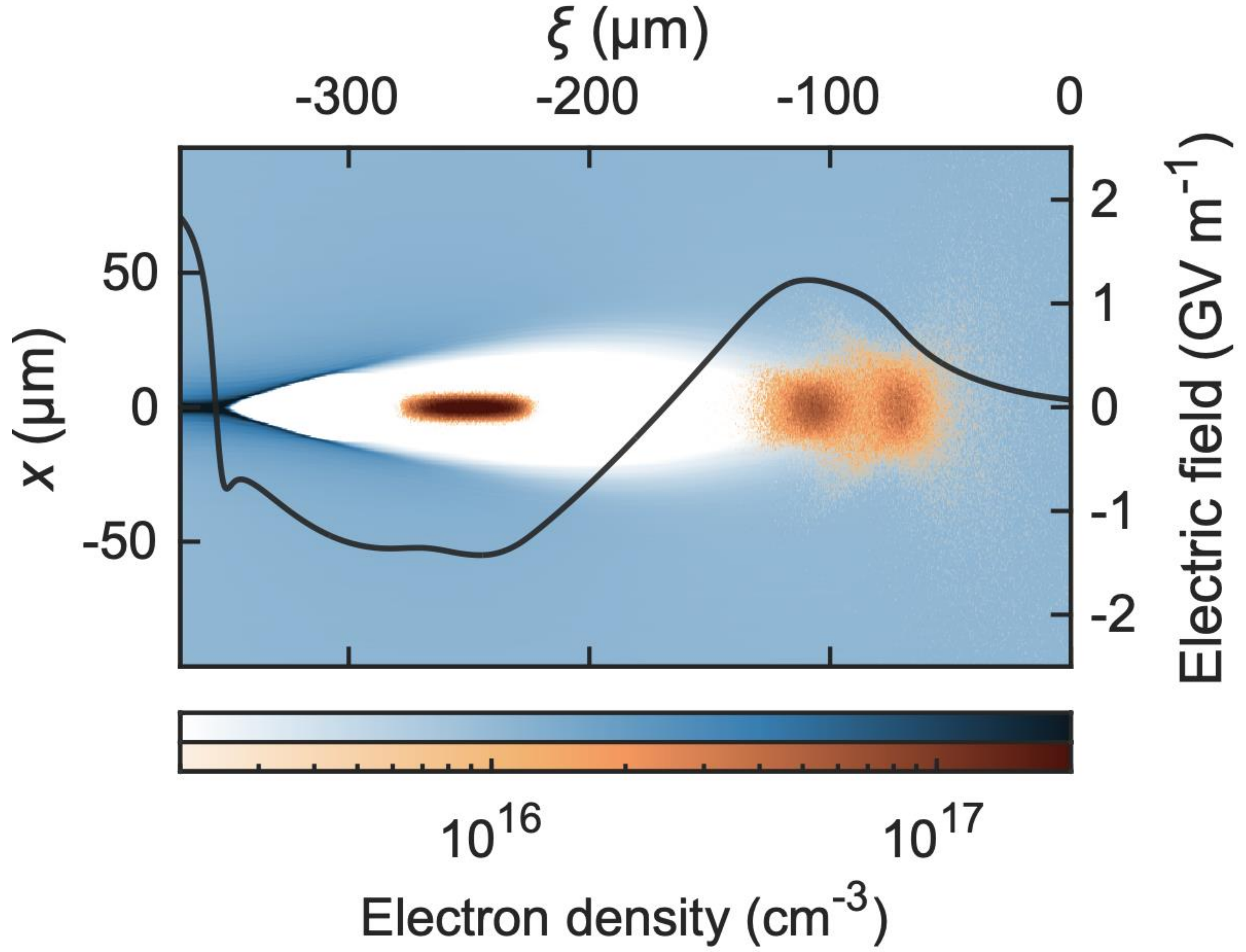
$$E_z[\mathrm{GV/m}] \approx 9.6\sqrt{n_e[10^{16}\mathrm{cm}^{-3}]}$$

Characteristic dimensions:
(plasma skin depth)

$$\frac{1}{k_p}[\mu\mathrm{m}] \approx 53\sqrt{\frac{1}{n_e[10^{16}\mathrm{cm}^{-3}]}}$$



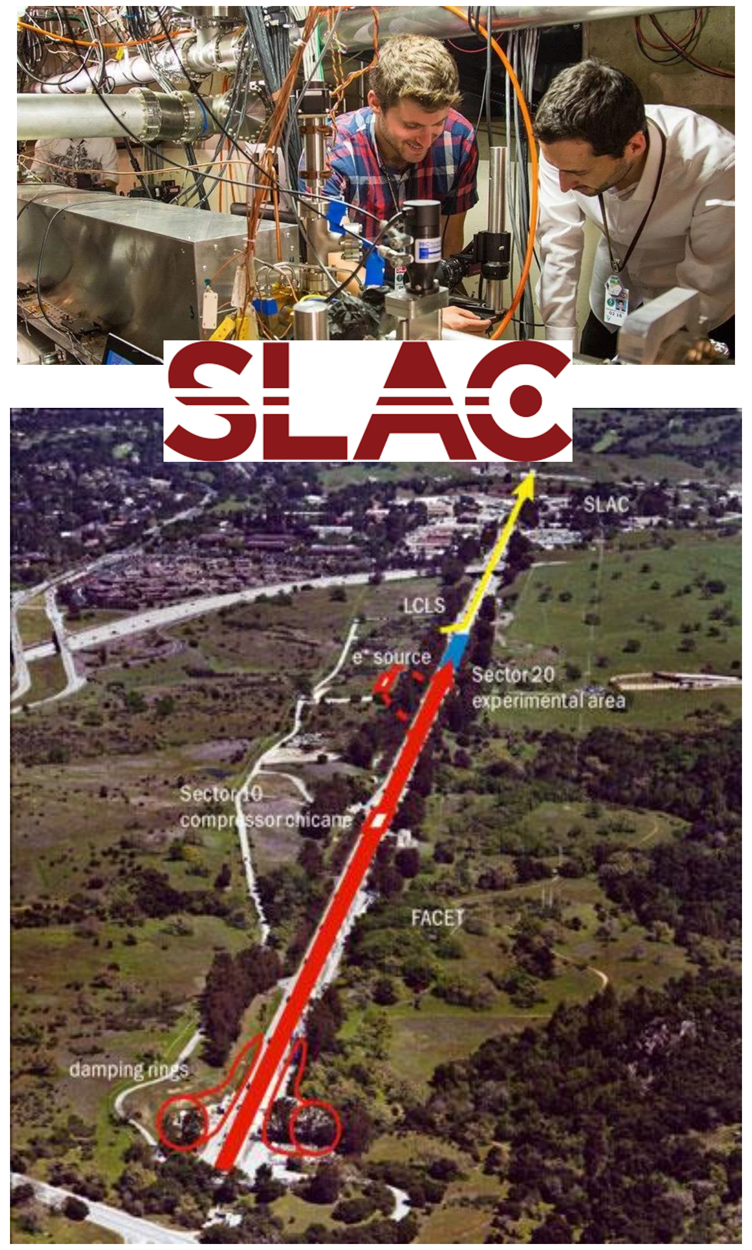
From: DESY/SciComLab

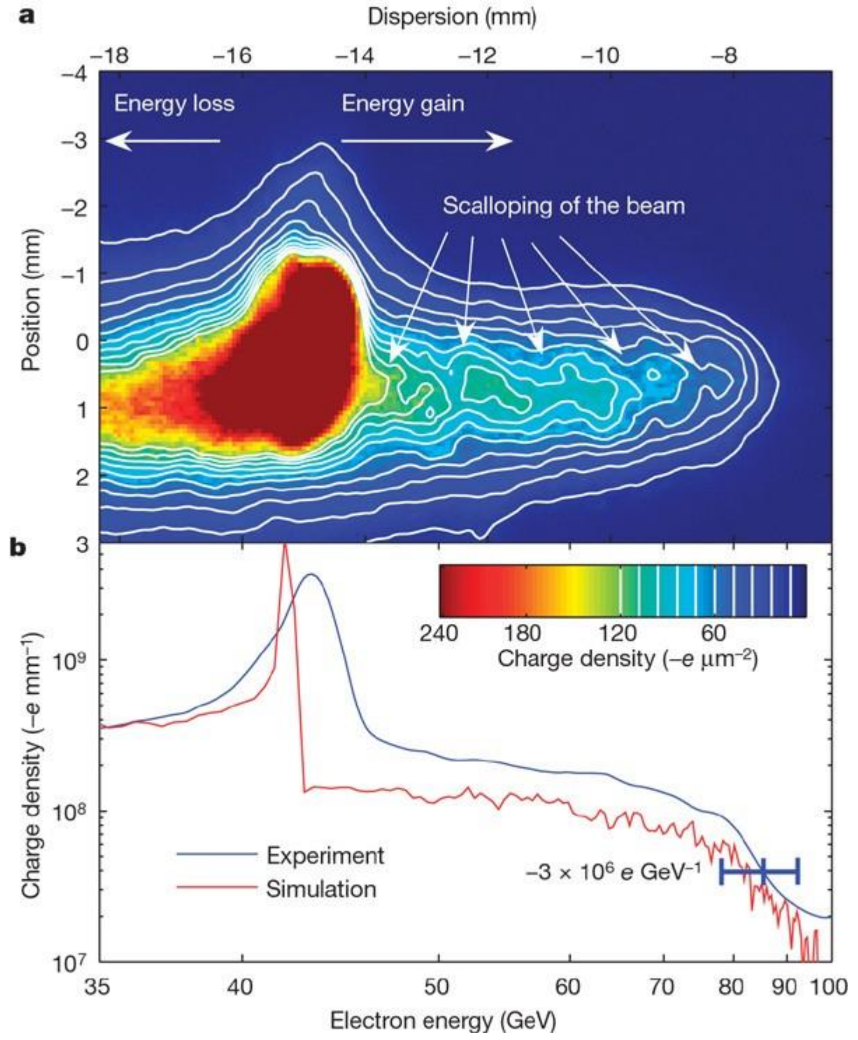


From: Lindstrøm et al. (submitted)

Plasma-accelerator experiments around the world

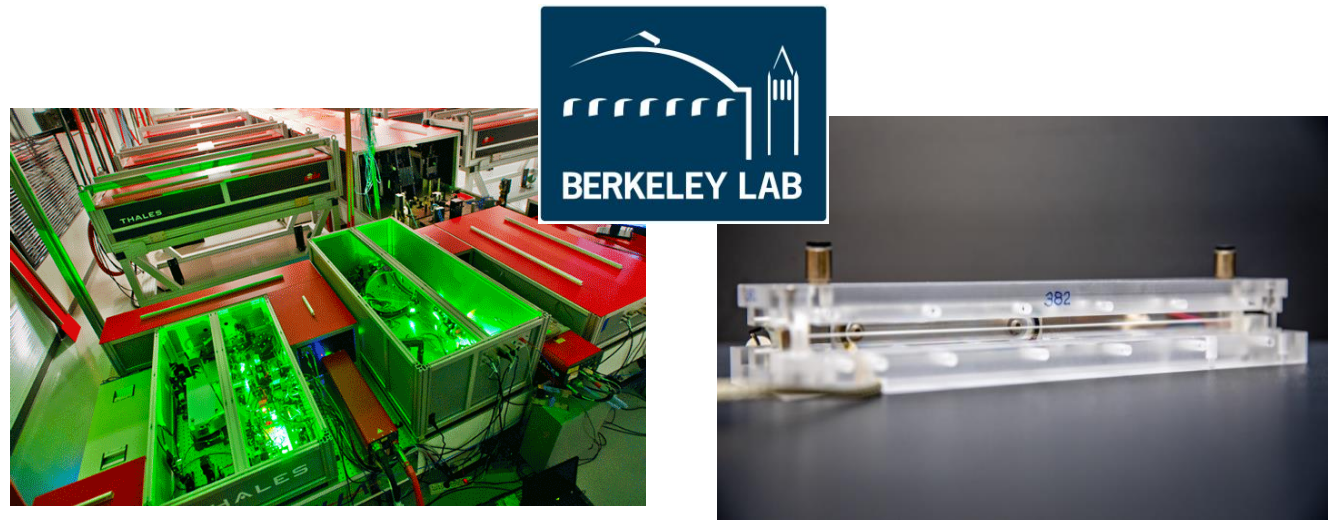
- First experiments in 1980–1990s.
- **Large energy gain achieved in 2007 at SLAC: 42 GeV acceleration in 85 cm**
- Currently several large-scale experiments worldwide: SLAC, LBNL, DESY, CERN, ++

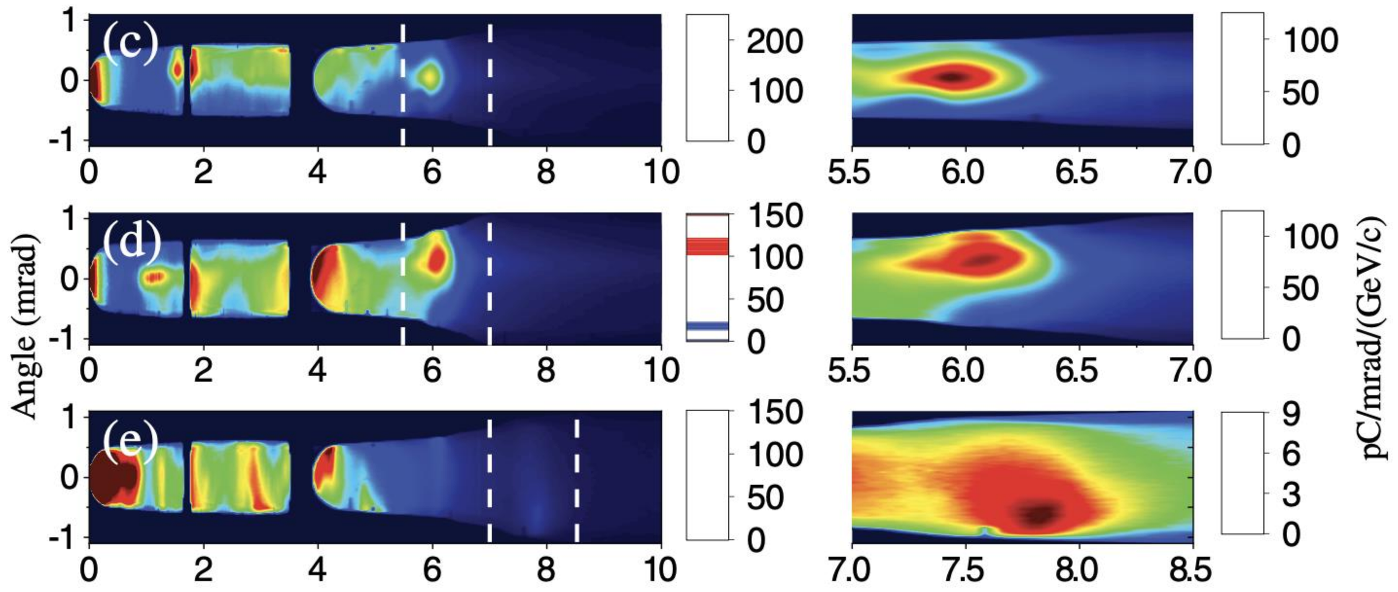




Energy doubling of 42 GeV electrons in 85 cm (electron-driven)

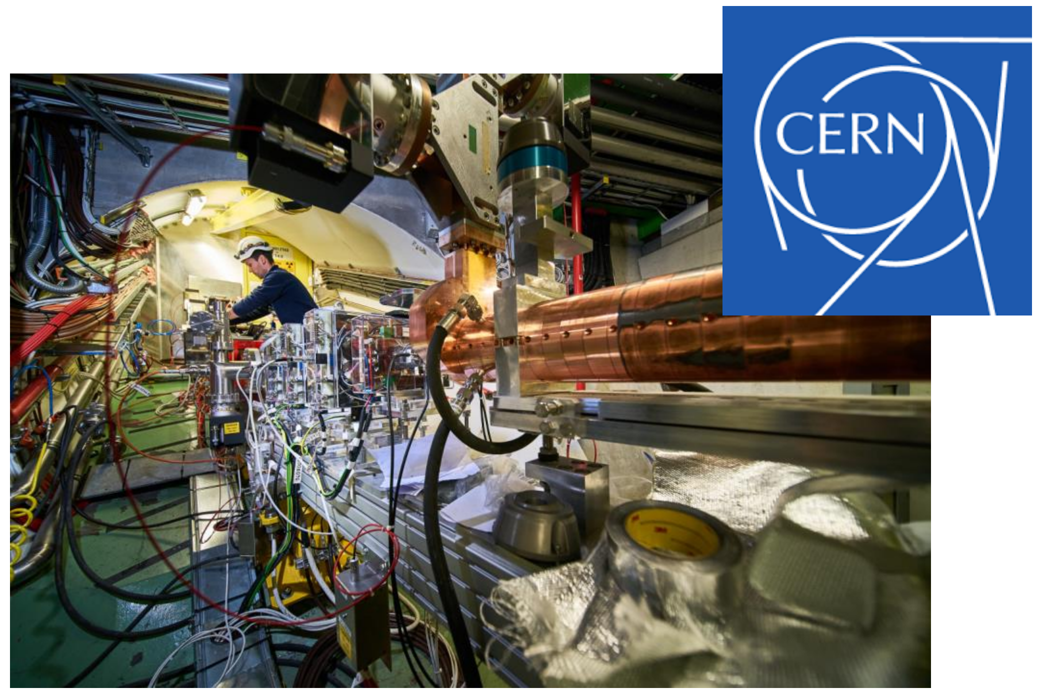
From: Blumenfeld et al., Nature 445, 741 (2007)

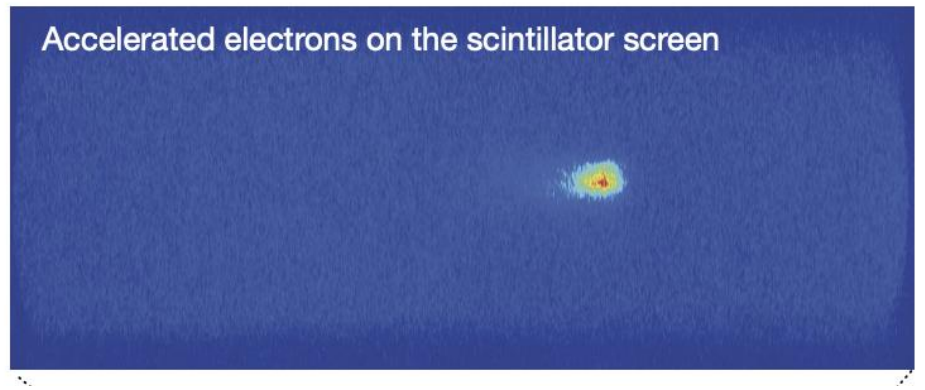




8 GeV energy gain in 20 cm (laser-driven).

From: Gonsalves et al., PRL 122, 084801 (2019).





2 GeV energy gain in 10 m (proton-driven).

From: Adli et al. (AWAKE), Nature 561, 363 (2018).

Plasma-wakefield accelerators: how do they perform?

> Main metric for colliders: **Luminosity per power**

$$\mathcal{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\mathrm{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx} \epsilon_{ny}}}$$

High average power

High energy efficiency

High charge

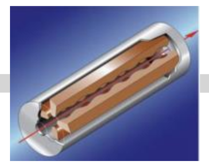
Low energy spread
(luminosity spectrum, final focusing)

Low emittance

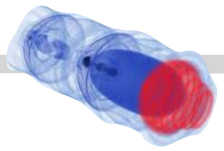
High energy efficiency is possible

> **Three-part efficiency:**

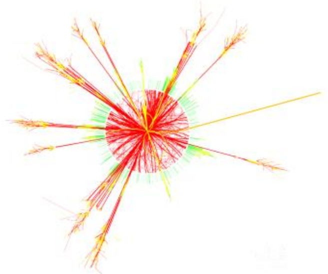
Production of the driver
(wall-plug to driver)

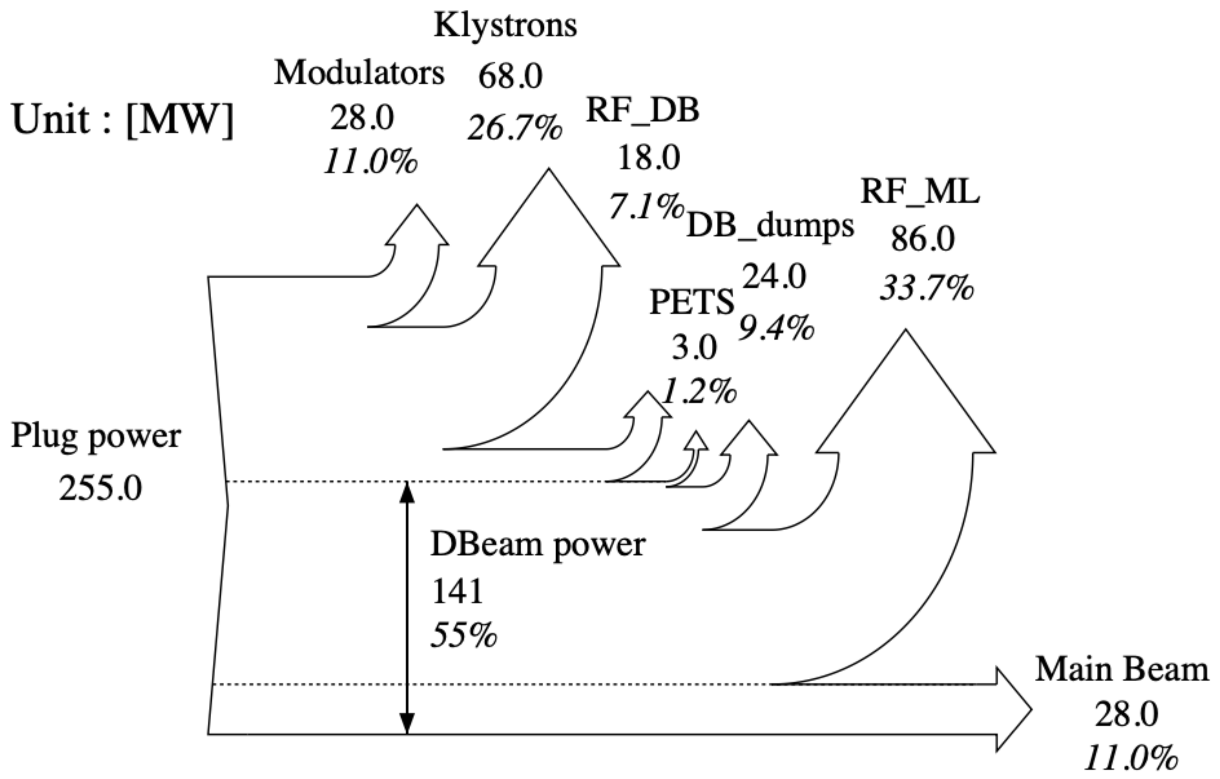


Driver energy depletion
(driver to plasma wake)

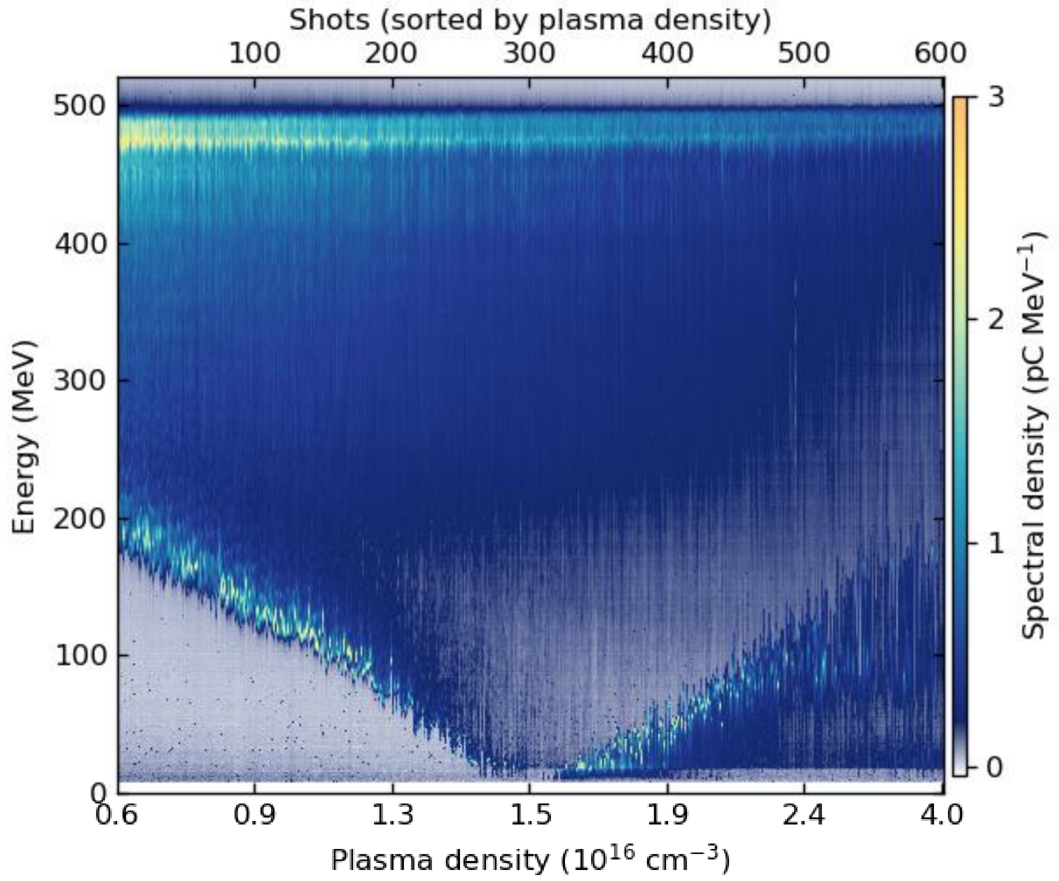


Acceleration efficiency
(plasma wake to beam)

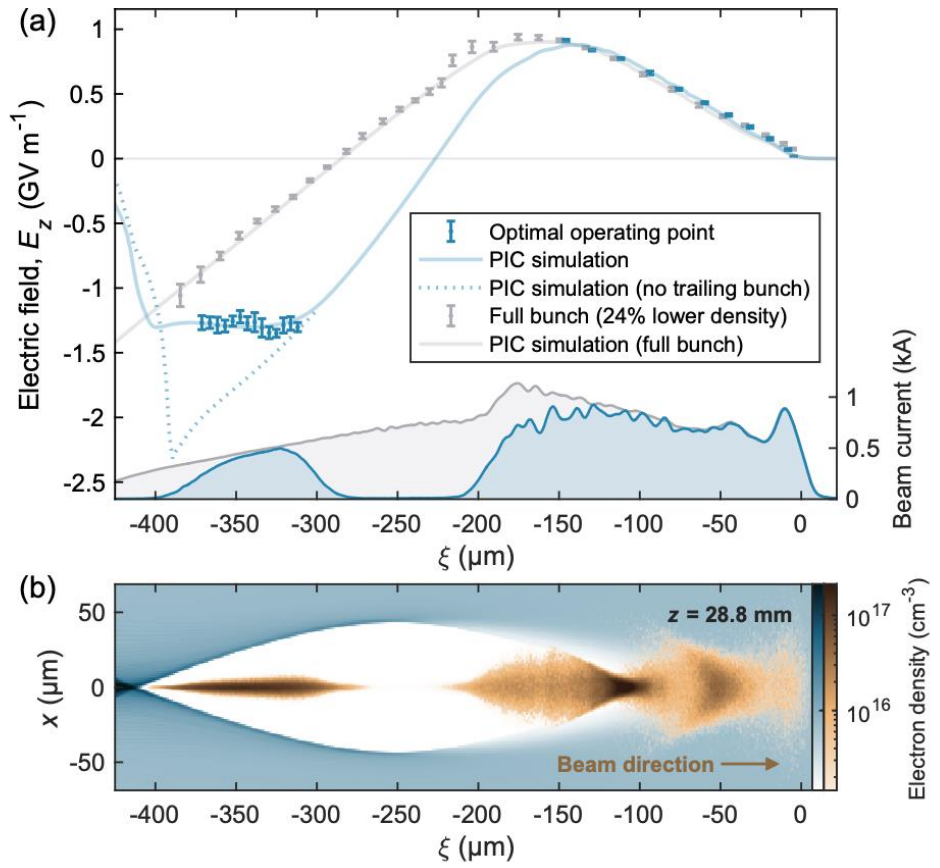




From: CLIC Conceptual Design Report (2012)



From: Peña et al. (manuscript in preparation).



From: Lindstrøm et al., PRL 126, 014801 (2021)

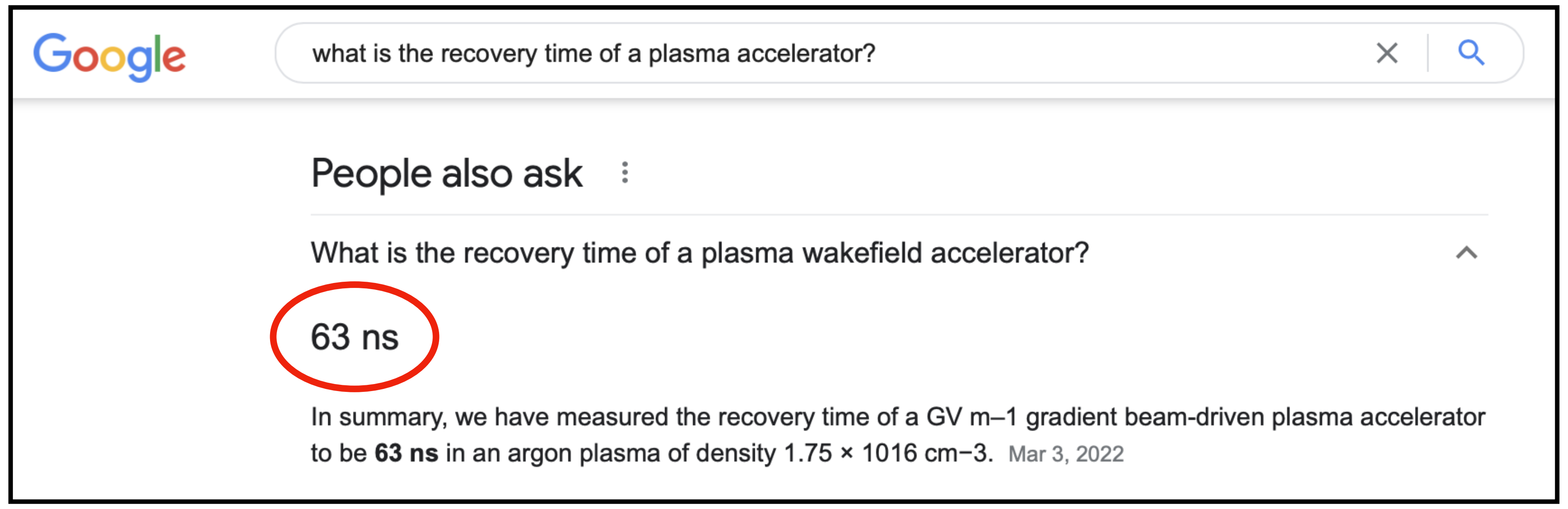
55% predicted for CLIC × ~50% achieved in experiment (up to ~90% in theory) × 42% achieved in experiment (up to ~90% in theory) = *12% if combined (~40% in theory)*

> **Beam drivers are superior in efficiency** (compared to laser drivers) => UiO is focusing on beam-driven

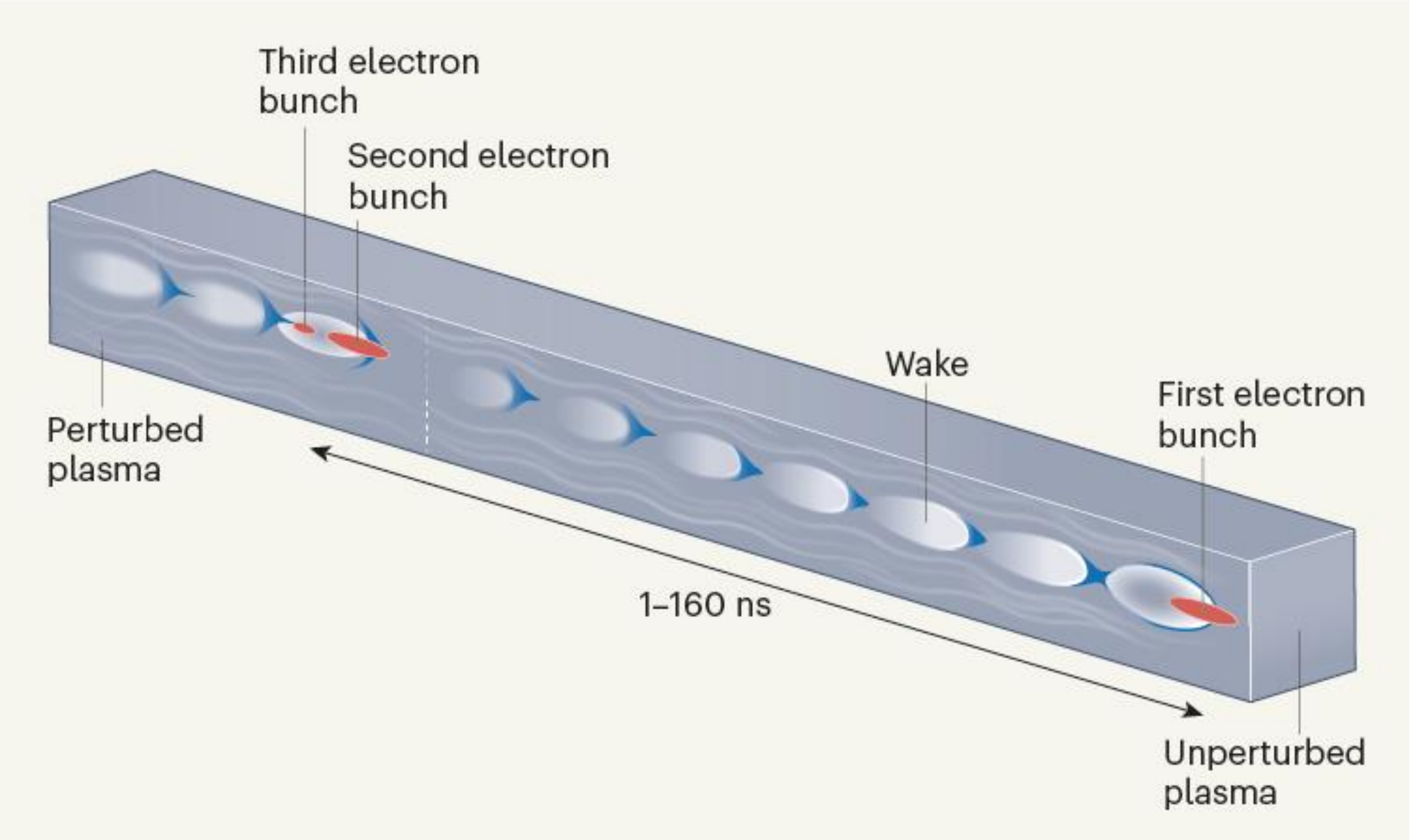
> Beam-driven plasma accelerators comparable to (or better than) CLIC technology

High repetition rate *may* be possible

- High *integrated luminosity* requires high repetition rate.
- Recent experimental result indicates that the **plasma recovers in less than 10–100 ns ⇒ 10–100 MHz**



- Many questions remain:
  - How quickly can the plasma be renewed?
  - What is the effect of heating of the plasma (by the energy left in the plasma wake)

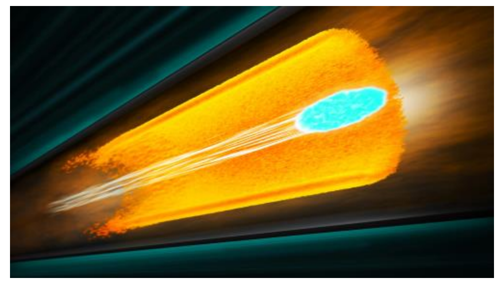


How long before the plasma disturbance is gone?
From: R. D'Arcy et al., Nature 603, 58 (2022)

Positron acceleration is difficult

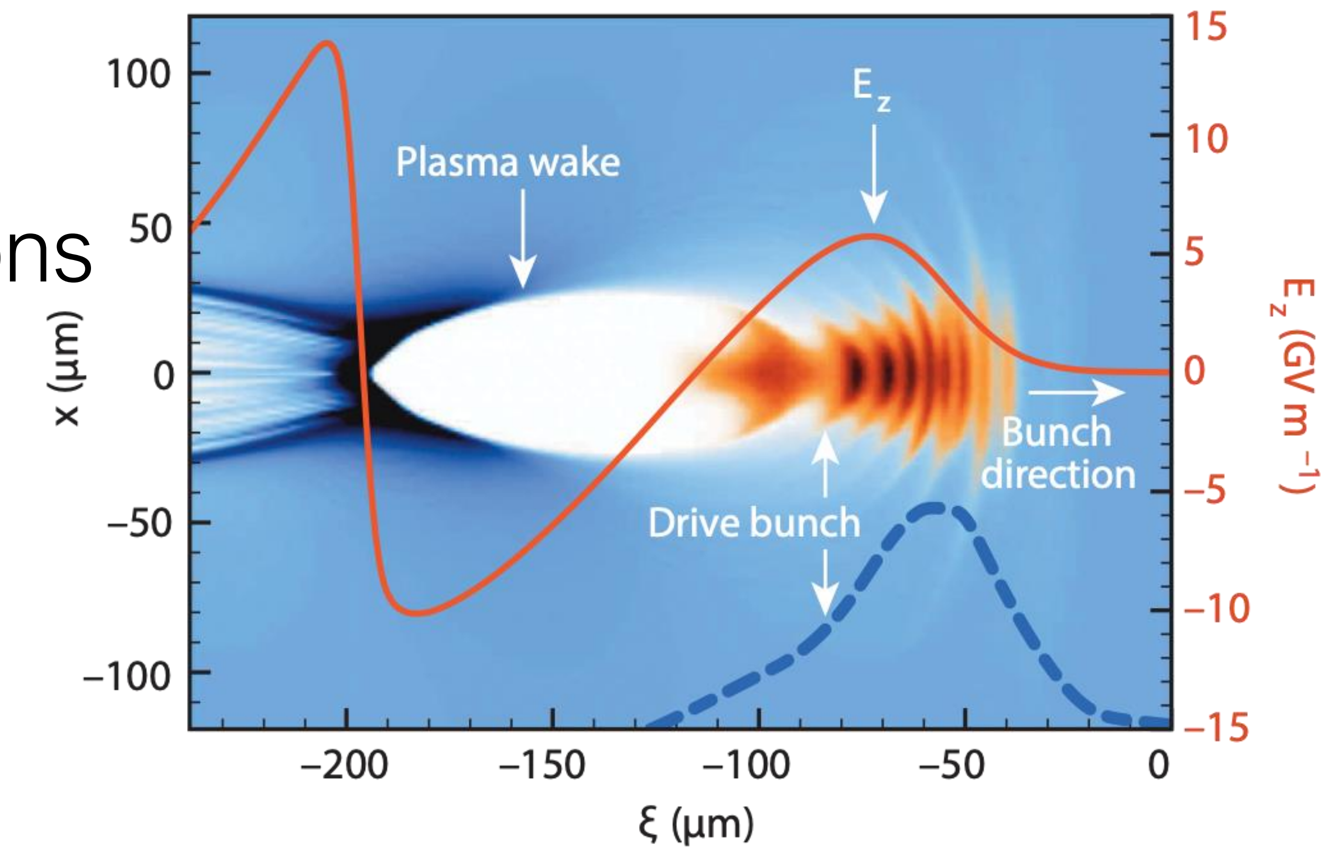
- RF accelerator: charge symmetry (just change phase by 180 degrees)
- Plasma accelerator: **charge asymmetry** (electrons are light, ions are heavy)

- **Experiments have demonstrated positron acceleration (SLAC, 2015)**
  - However, beam quality is destroyed.
- Proposed solution: **Hollow plasma channel?**
  - Demonstrated in experiment (SLAC)
  - Beam quality okay, but fundamentally unstable.



- Some ideas, but **currently no known solution**.

Electrons



From: M. Litos *et al.*, Nature 515, 92 (2014)

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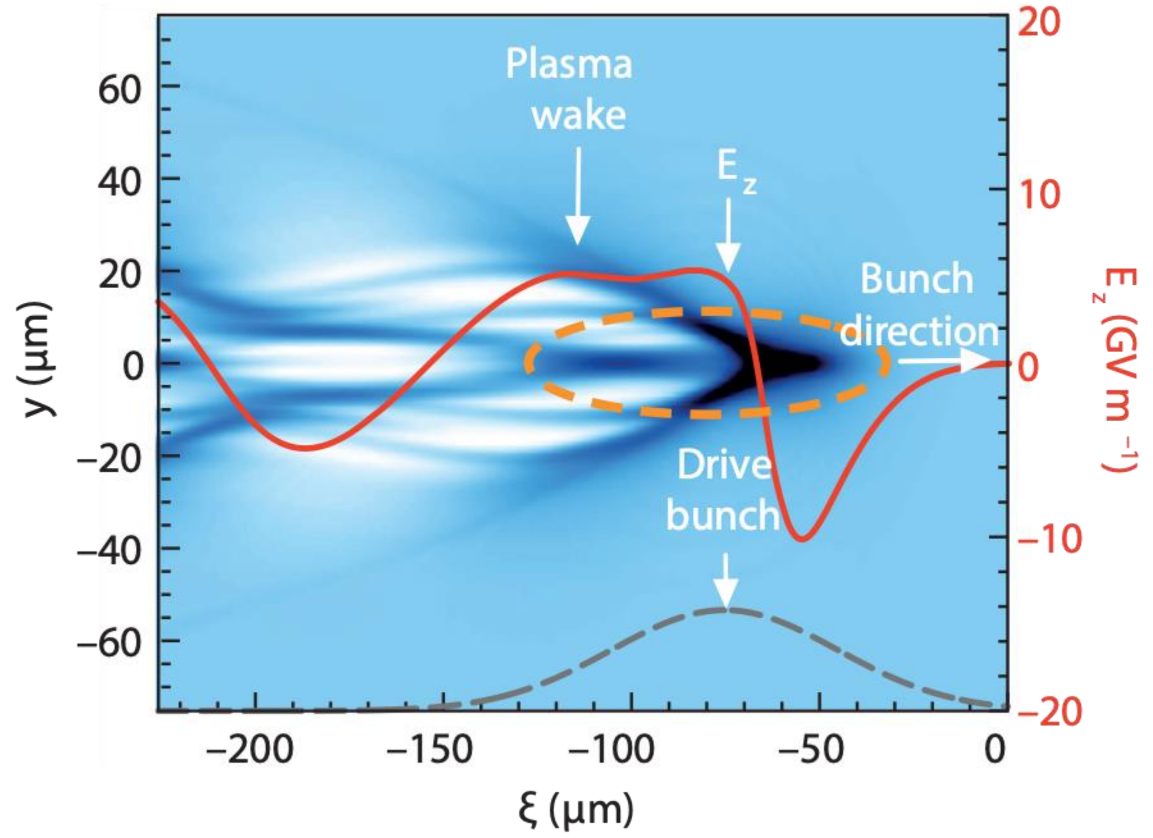
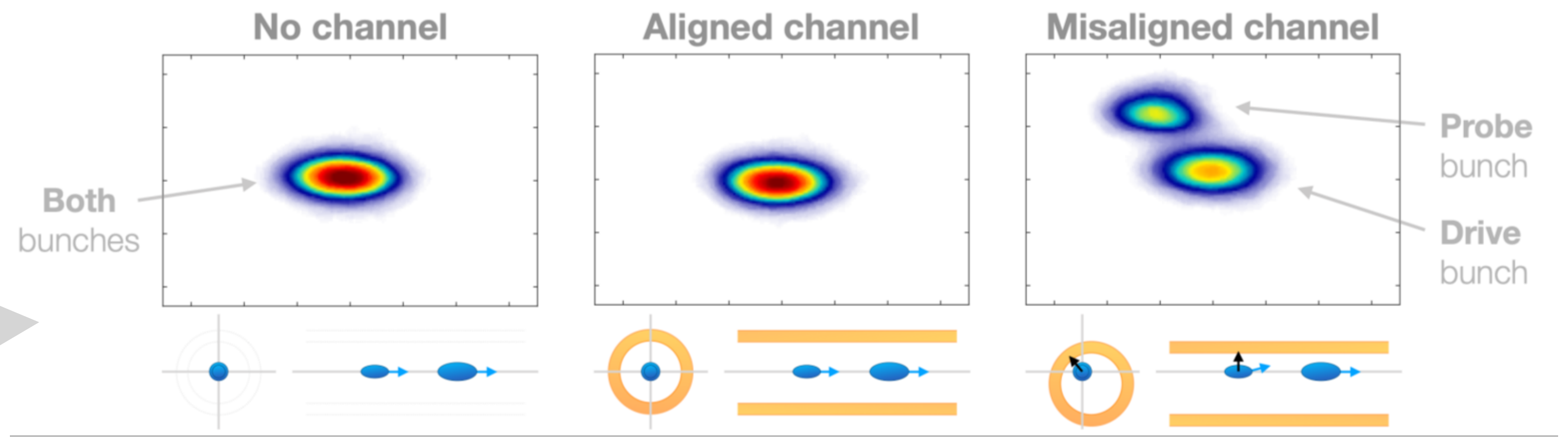
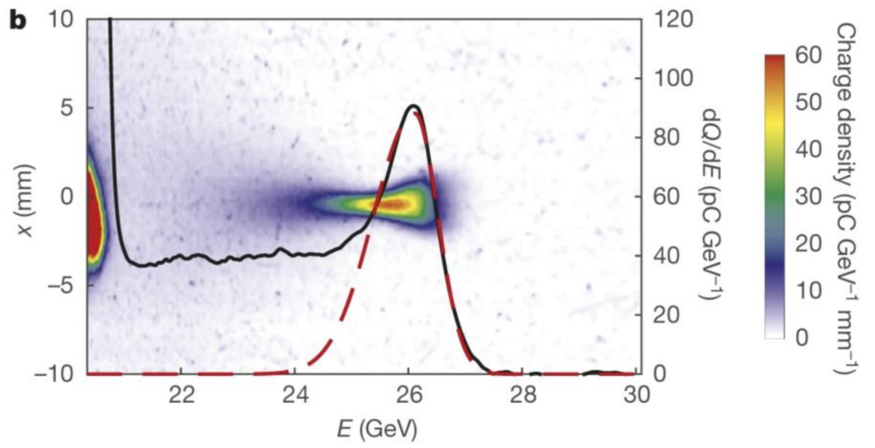
Positrons



From: S. Corde *et al.*, Nature 524, 442 (2015)



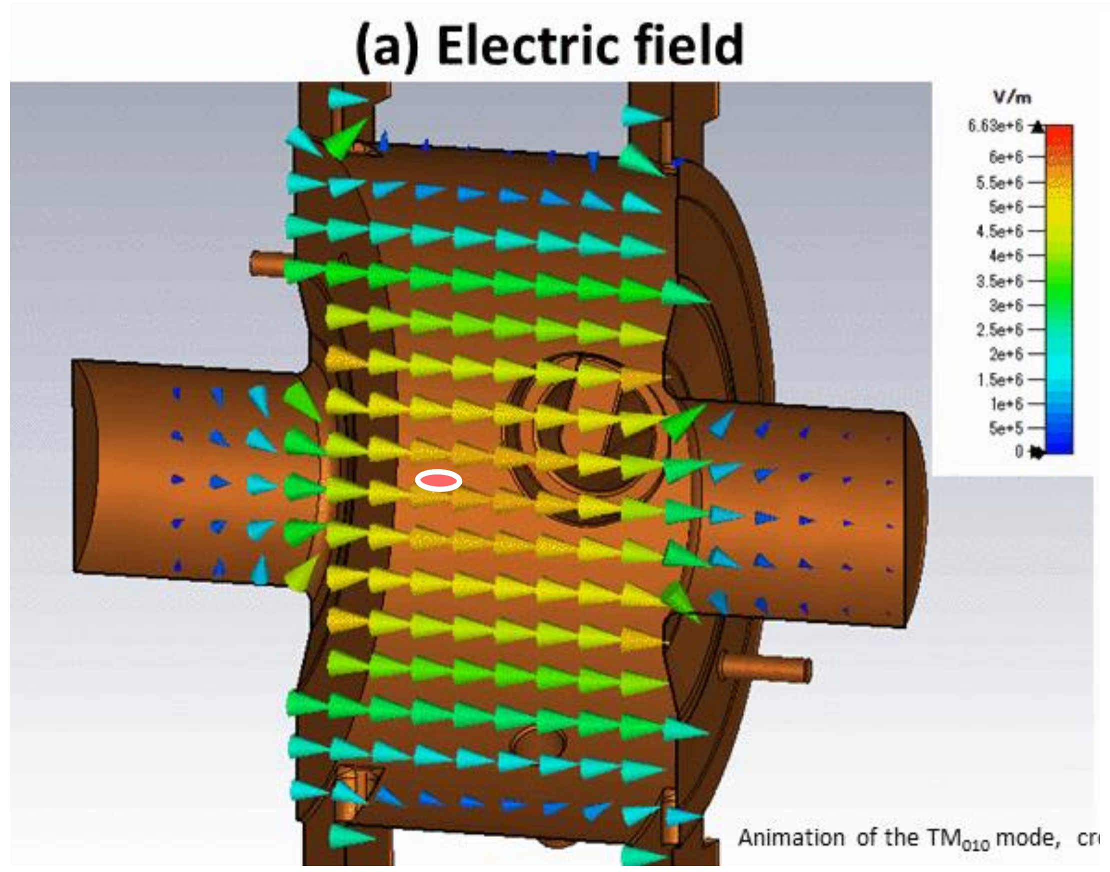
Hollow plasma channels suffer from a transverse instability.
From: Lindstrøm et al., PRL 120.124802 (2018)



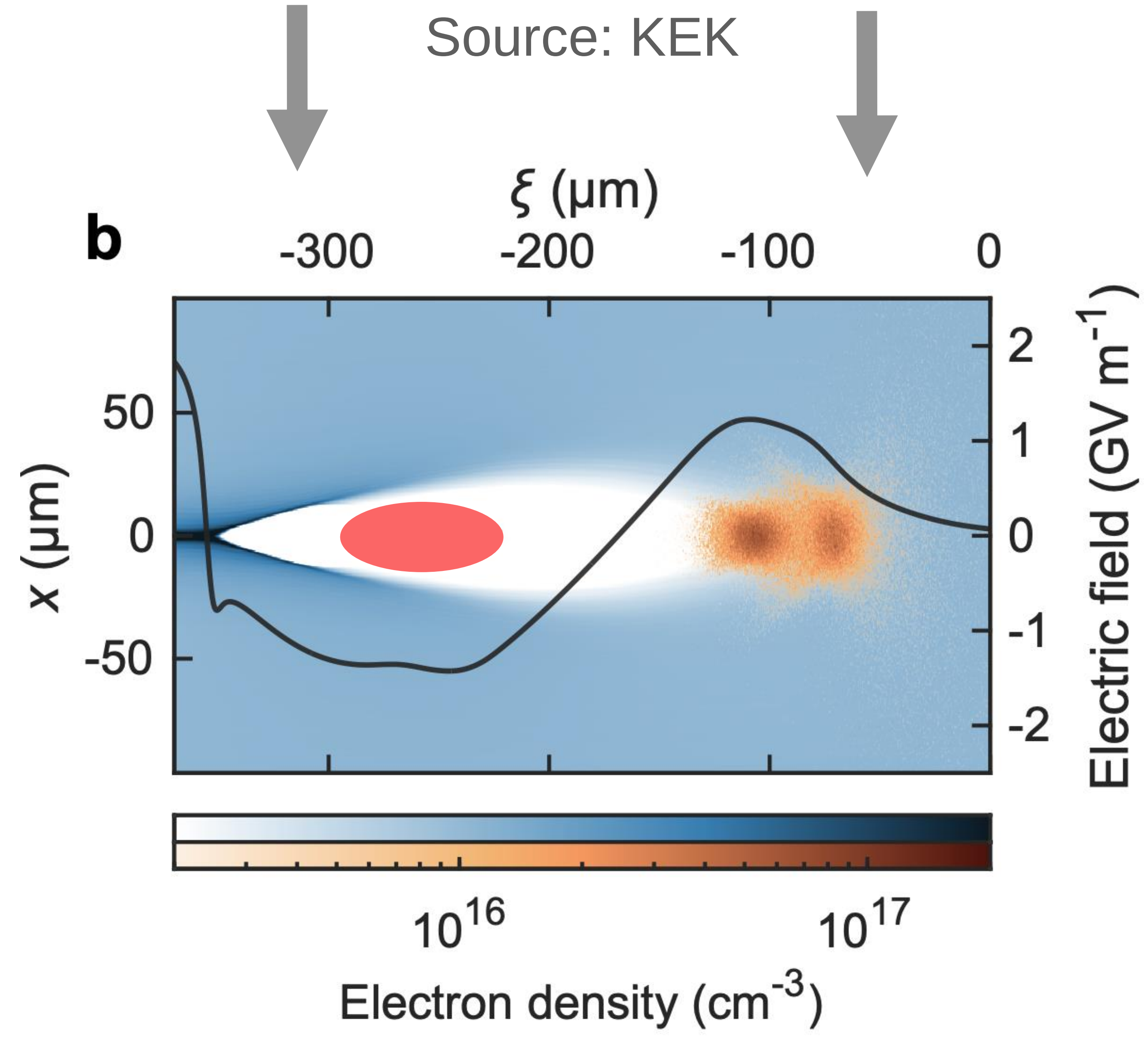
Positrons accelerated in a plasma
From: S. Corde et al., Nature 524, 442 (2015)

Fundamental challenge: Gradient vs. beam quality

- General rule: **higher gradient means smaller dimensions:**
  - Bunch dimensions takes up a larger proportion of the cavity dimensions
  - Timing and alignment jitter is proportionally larger
- Beam quality requires:
  - Field uniformity (longitudinally)
  - Field linearity (transversely)
- Consequently, **fields must be:**
  - *…controlled to higher order (further out, proportionally)*
  - *…controlled smaller dimensions (microscopic)*
  - *…more stable (synchronisation and alignment)*
- **Everything becomes more difficult.**

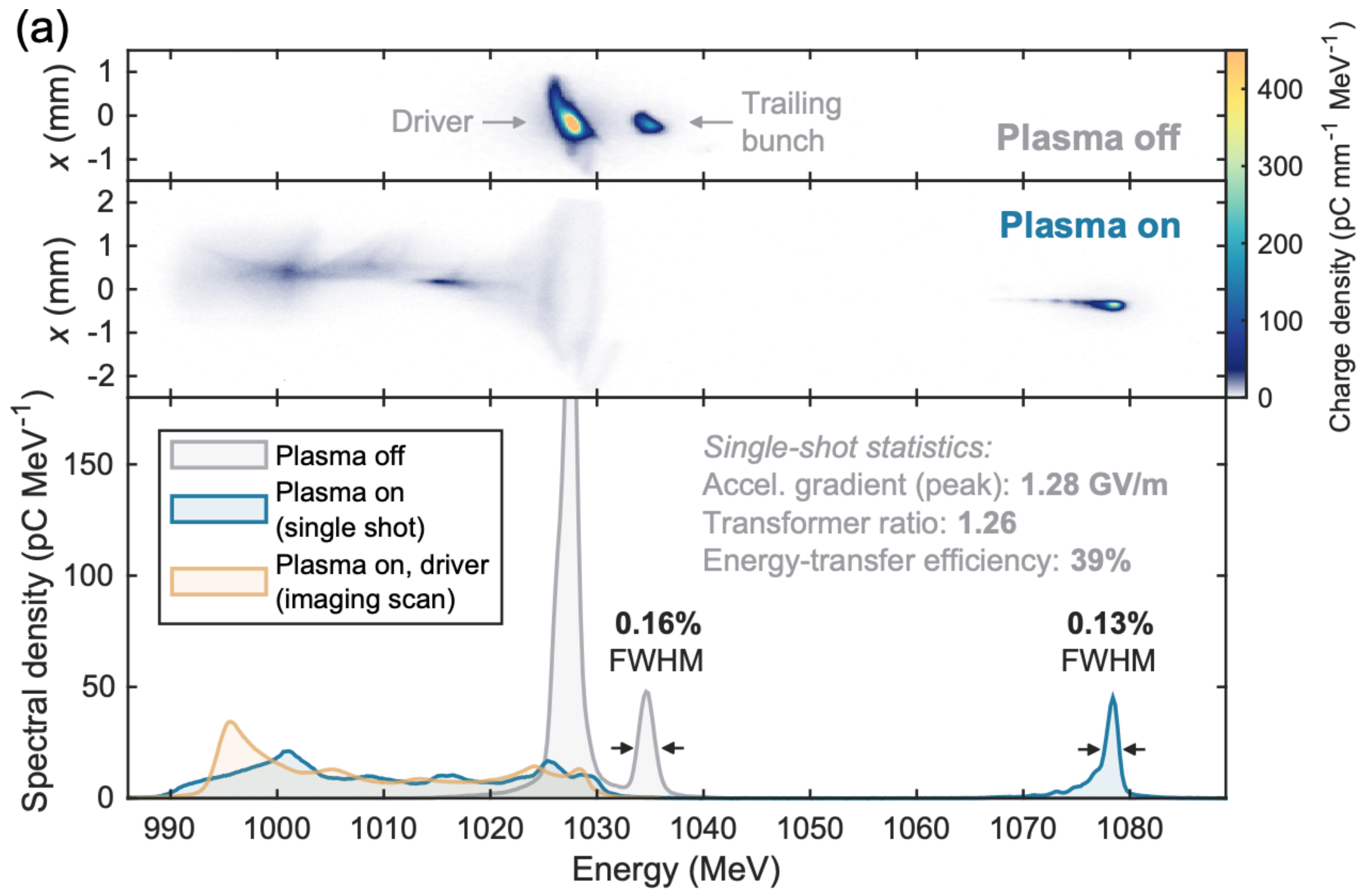


Source: KEK

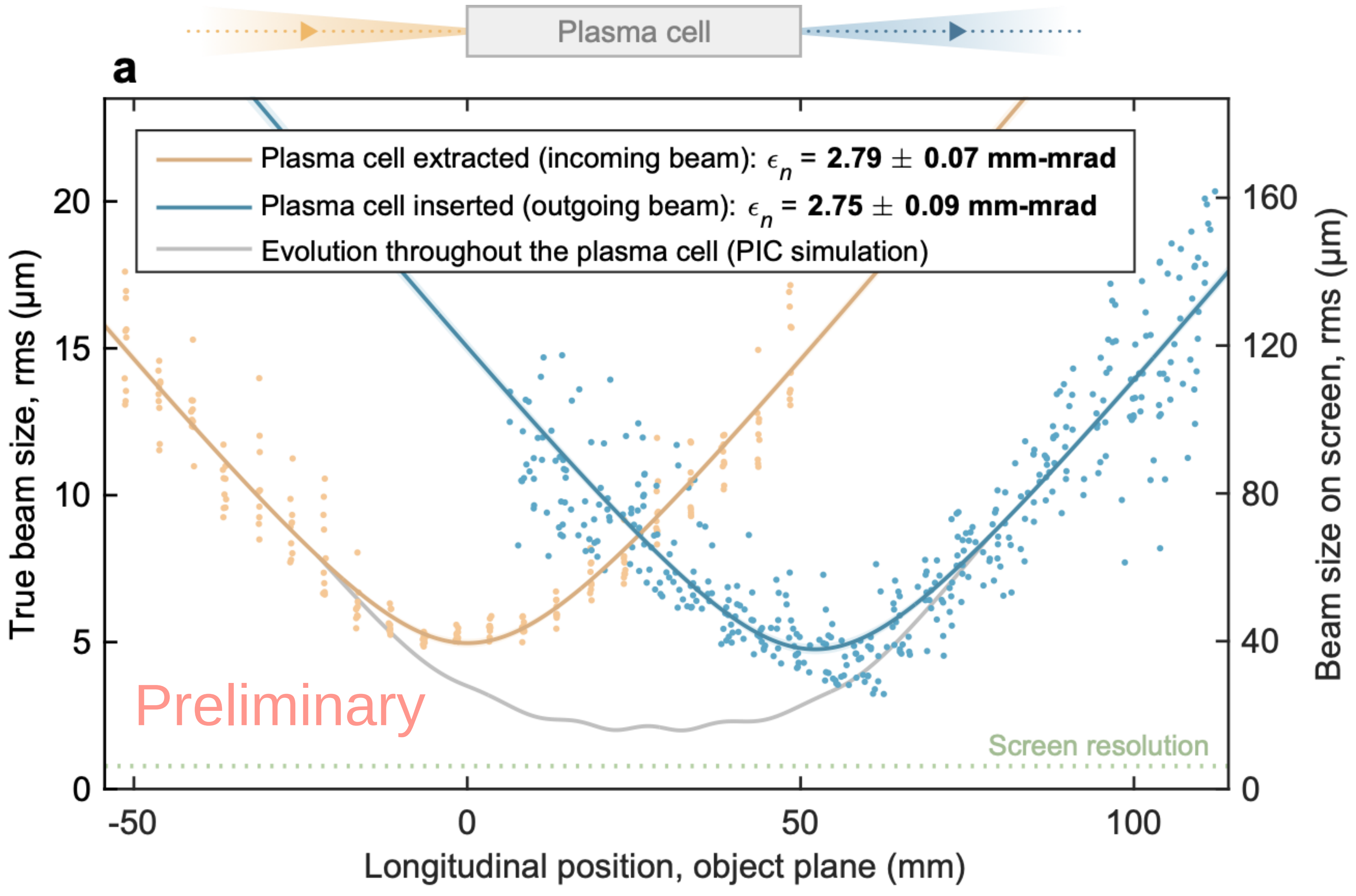


Preserving beam quality: charge, energy spread, and emittance

- Several beam qualities are key to a collider: all **must be preserved throughout the plasma accelerator**.
  - *Energy-spread can be preserved by precise shaping of current profile (beam loading).*
  - *Possible, but very challenging, to preserve emittance in the blowout regime (nonlinear wakes).*
- **Recently achieved experimentally** in the FLASHForward facility at DESY (1 GeV electron beam).
  - Short accelerator stage (5 cm) — **next step is more energy gain** (longer stage, more stages)



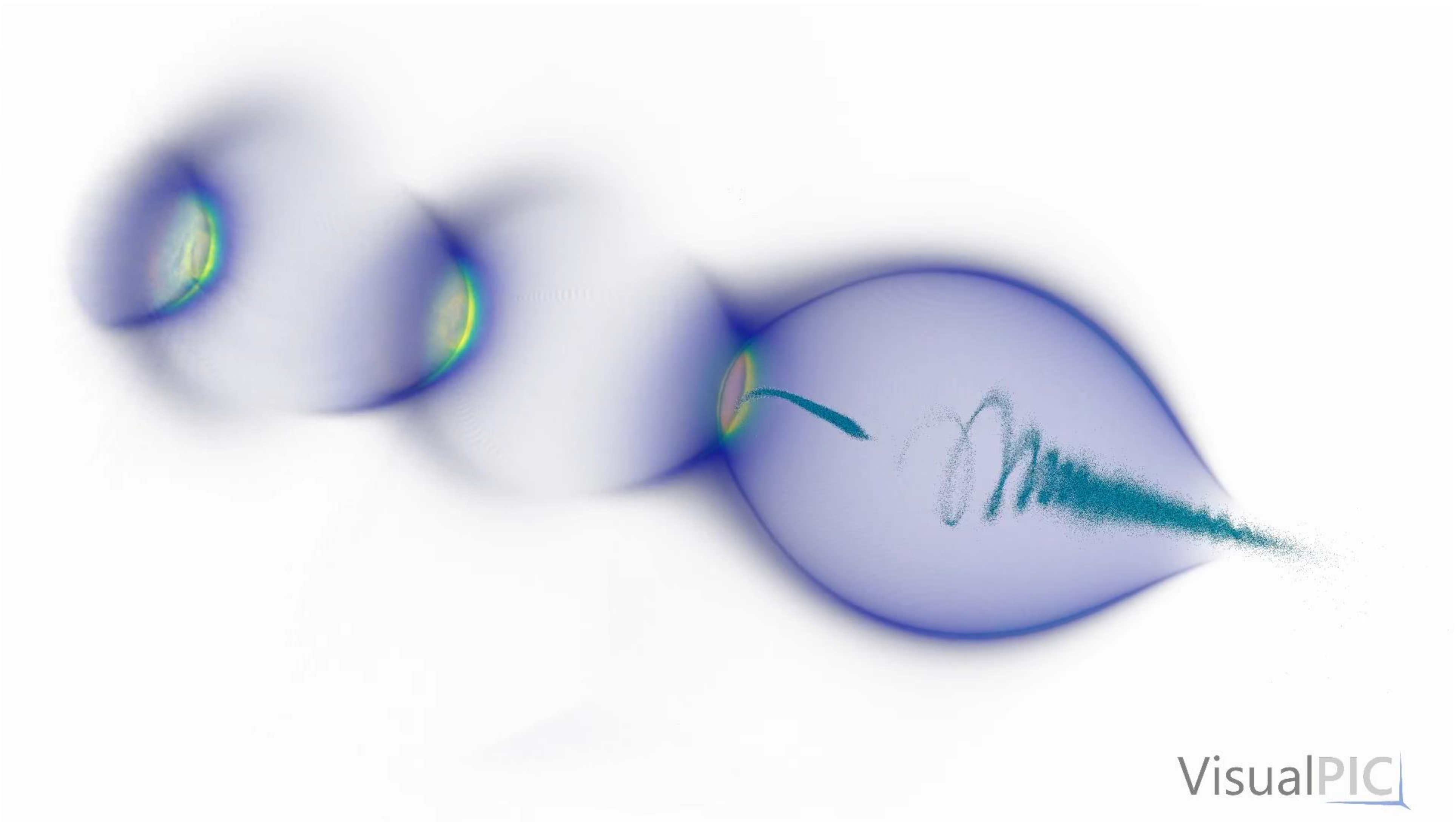
Energy spread and charge preservation.
From: Lindstrøm et al., PRL 126, 014801 (2021).



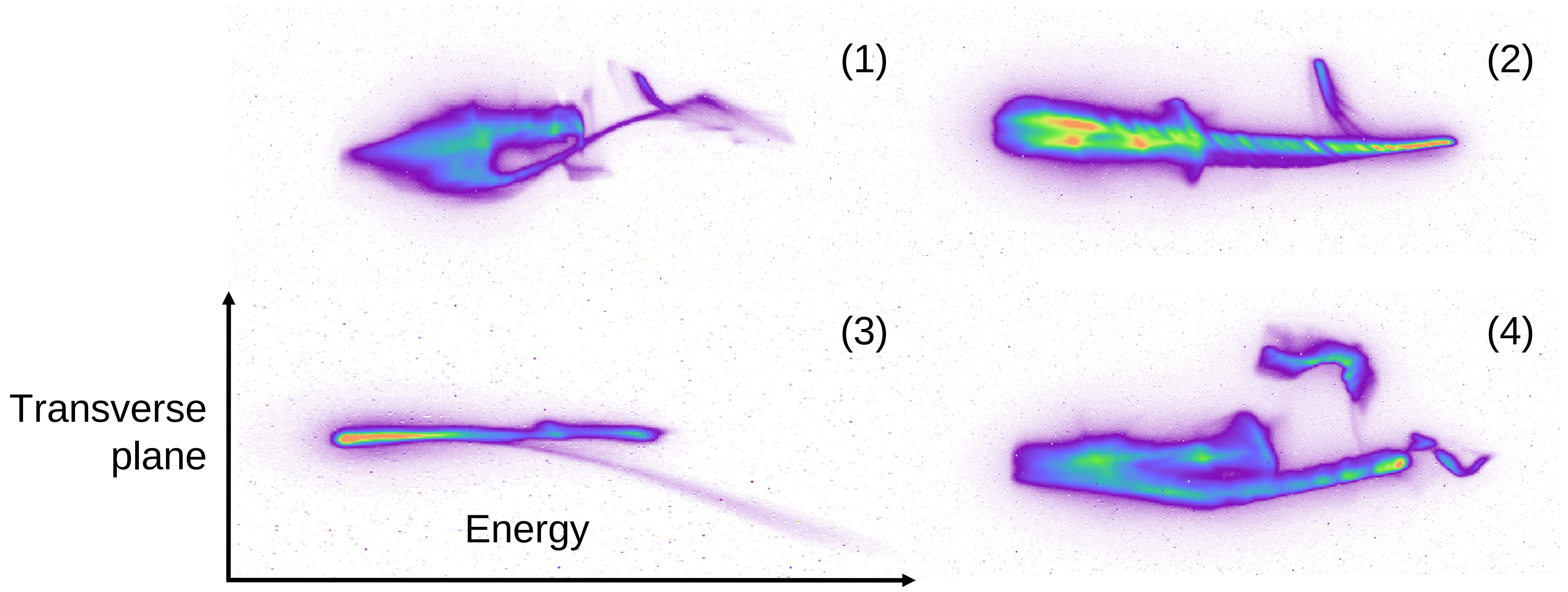
Emittance preservation (+ energy spread + charge).
From: Lindstrøm et al. (submitted).

UiO research topic: Transverse instabilities

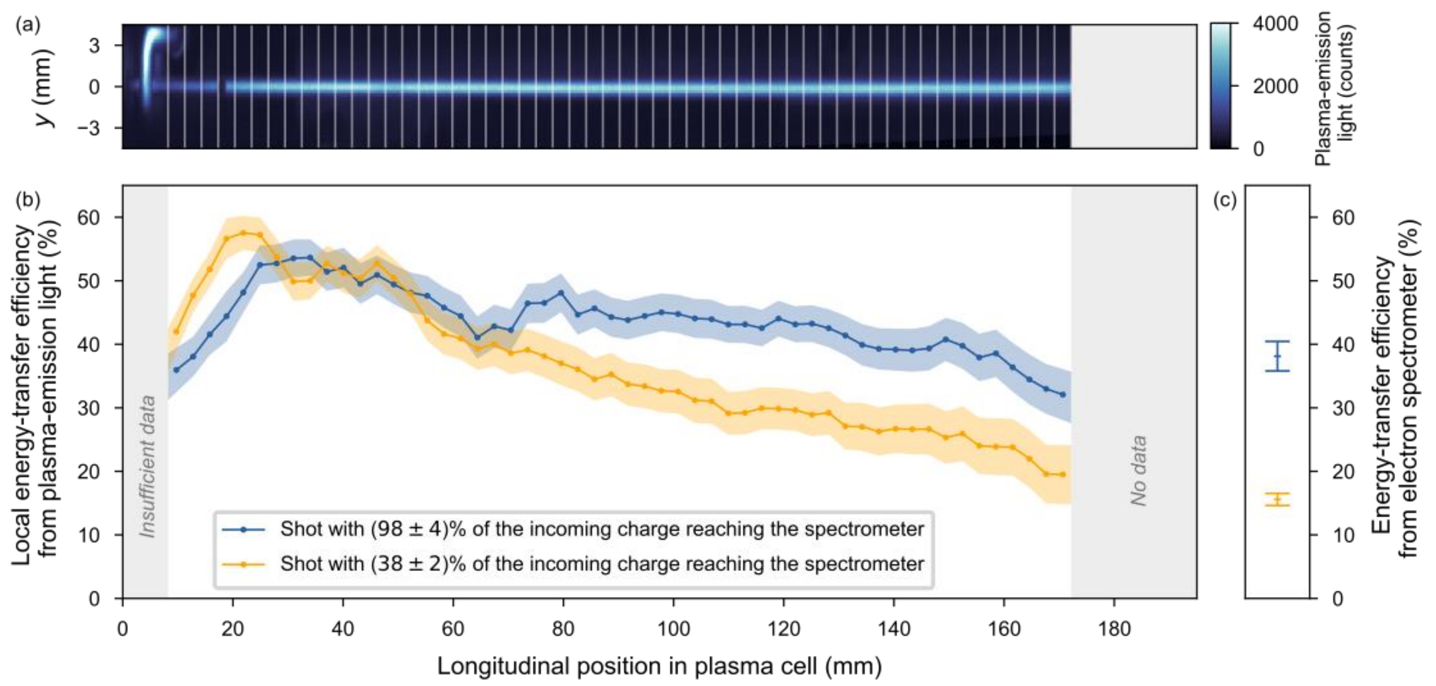
- Problem in long plasma accelerators: instabilities
  - ***Caused by a resonance between beam and wake.***
  - *Must be suppressed.*
- Several questions remain unanswered:
  - *How do we measure this instability?*
  - *How do we suppress the instability? (ideas exist)*
- **UiO is leading experiments at FACET-II at SLAC**



Transverse instability due to a beam–plasma resonance.
From: S. Diederichs (simulated in HiPACE++)



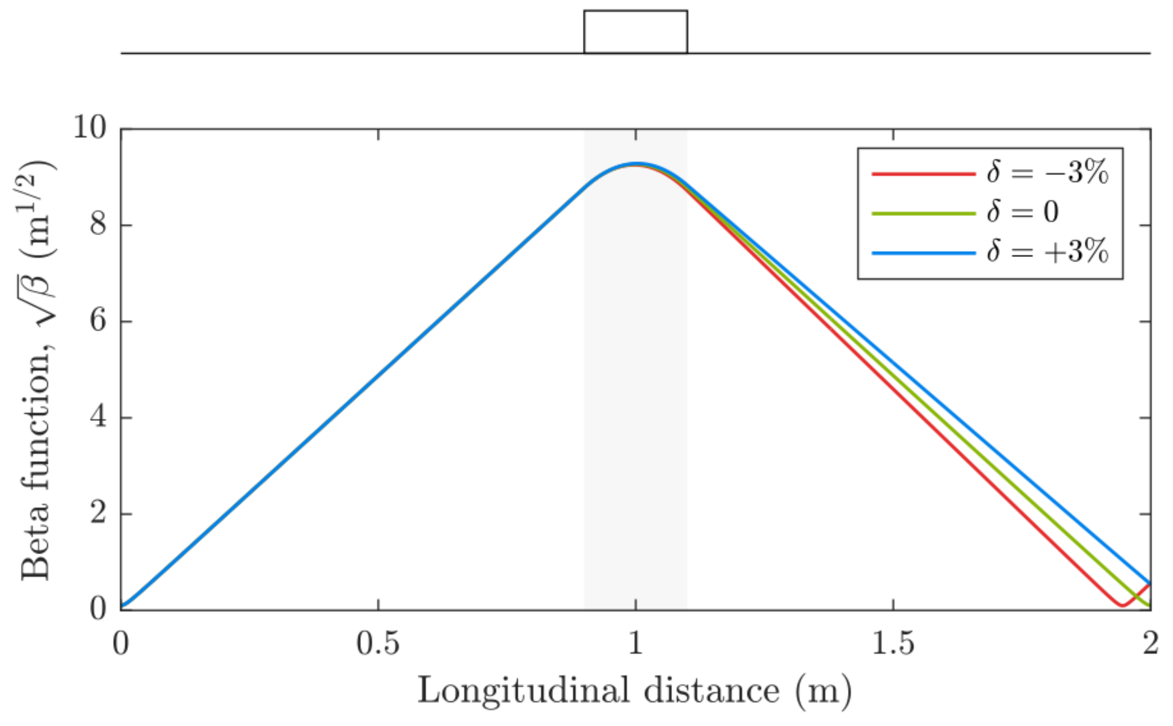
<u>Conventional diagnostics</u>: dipole spectrometer (measure output)



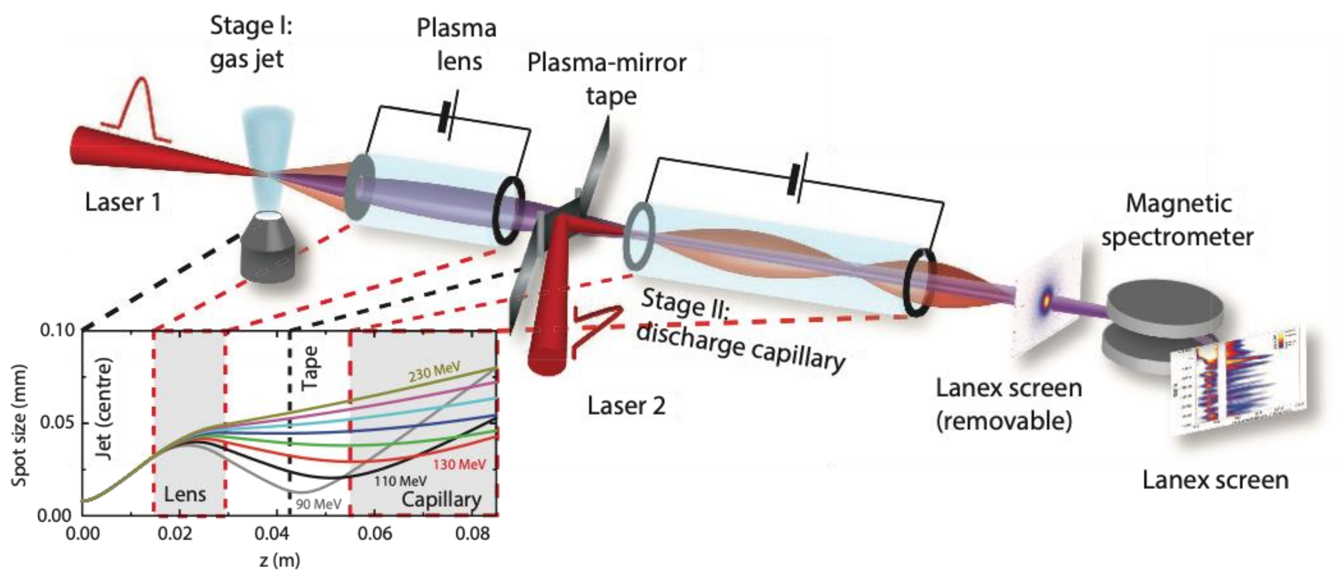
<u>Novel diagnostics</u>: plasma-emission light (measure along accelerator)
From: Boulton et al. (submitted)

UiO research topic: Connecting multiple accelerator stages

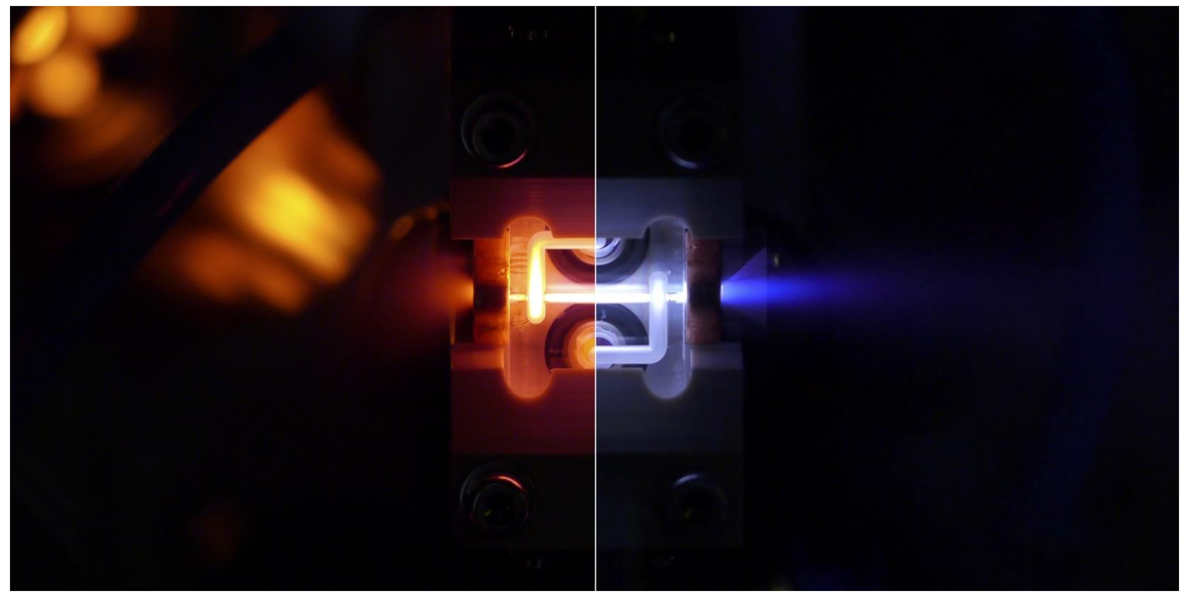
- Problem with “staging”: **chromatic focusing**
  - **Strong focusing ⇒ rapid divergence**
  - Particles of different energy are focused differently ⇒ beam is not coupled well
- Solution: achromatic optics
- **UiO is leading the development of advanced beam optics based on plasma lenses.**



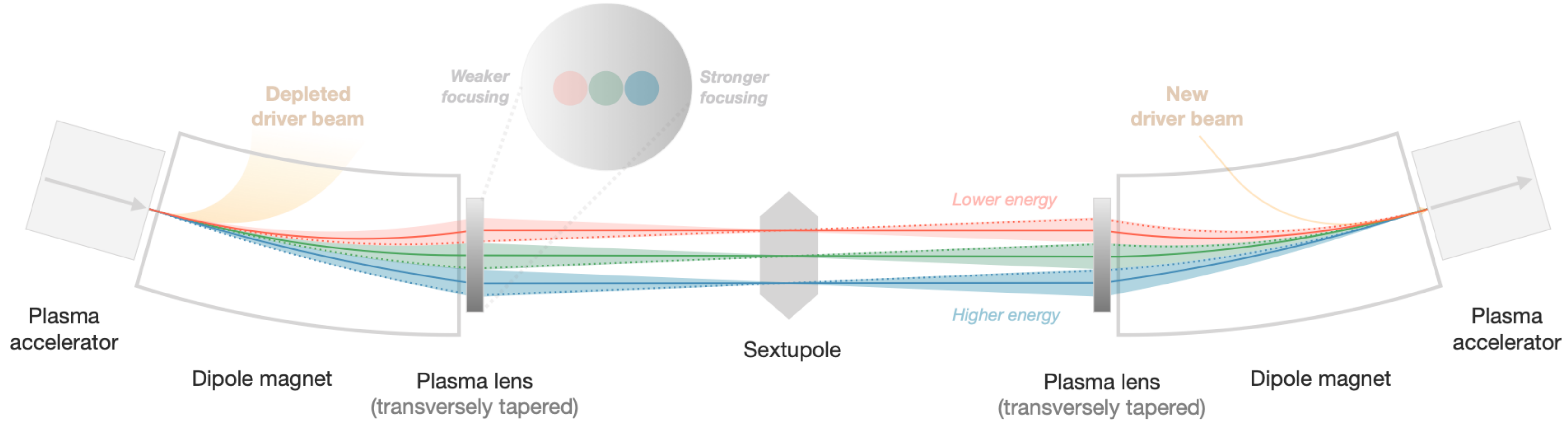
Chromaticity between stages.
From: Lindstrøm, PRAB 24, 014801 (2021).



Experimental demonstration of staging (LBNL), which suffered from strong chromaticity.
From: Steinke et al., Nature 530, 190 (2016).



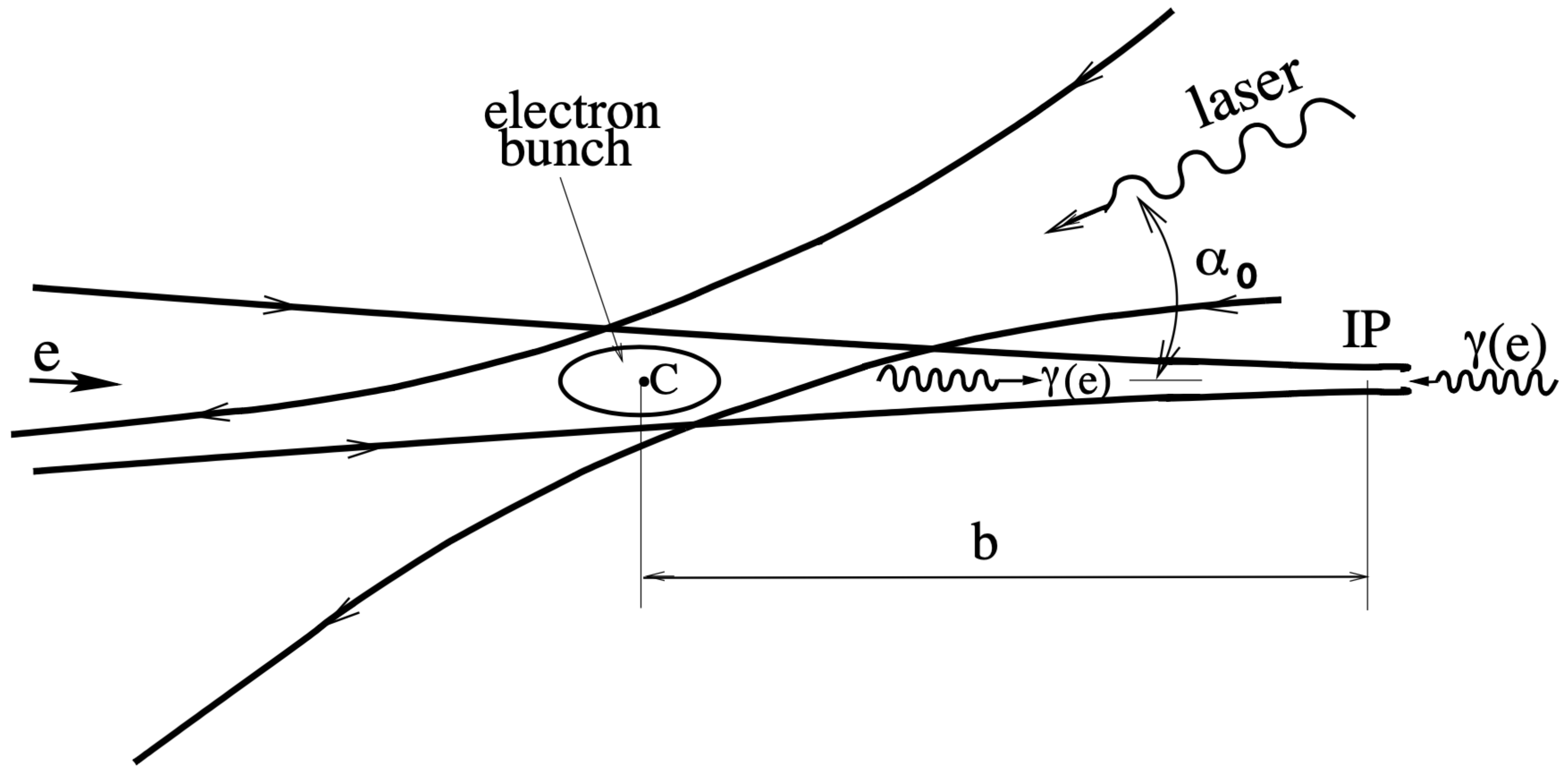
Plasma lens (left: helium, right: argon).
Photo by Kyrre N. Sjøbæk.



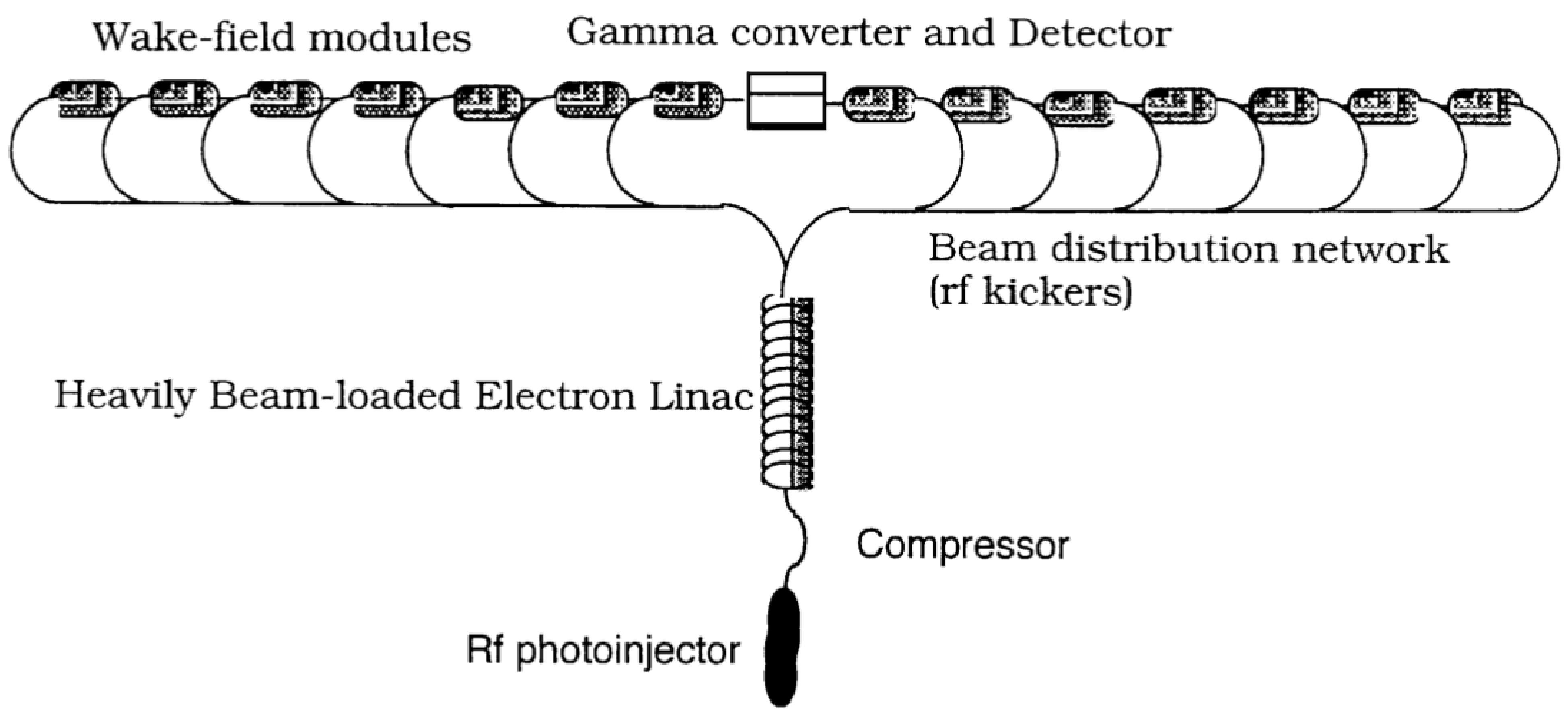
Proposed plasma-lens optics with nonlinear plasma lenses.

UiO research topic: A plasma-based photon (γ–γ) collider

- Question: How can we use plasma accelerators for particle physics, near-term?
- Answer: Build a photon collider!
  - Just before IP: Convert laser pulse to gammas by colliding with electrons (inverse Compton scattering)
  - **Advantage: Only need two electron accelerators (no positrons)**
  - Advantage: Can operate directly at the Higgs resonance (125 GeV) instead of HZ (250 GeV).
  - Disadvantage: R&D required for ultra-powerful laser.
- **UiO is investigating the feasibility of a plasma-based photon collider.**
  - Idea first proposed in 1998.
  - Now, we finally have the necessary solutions to make a plasma-based design concept (i.e., staging + stability)



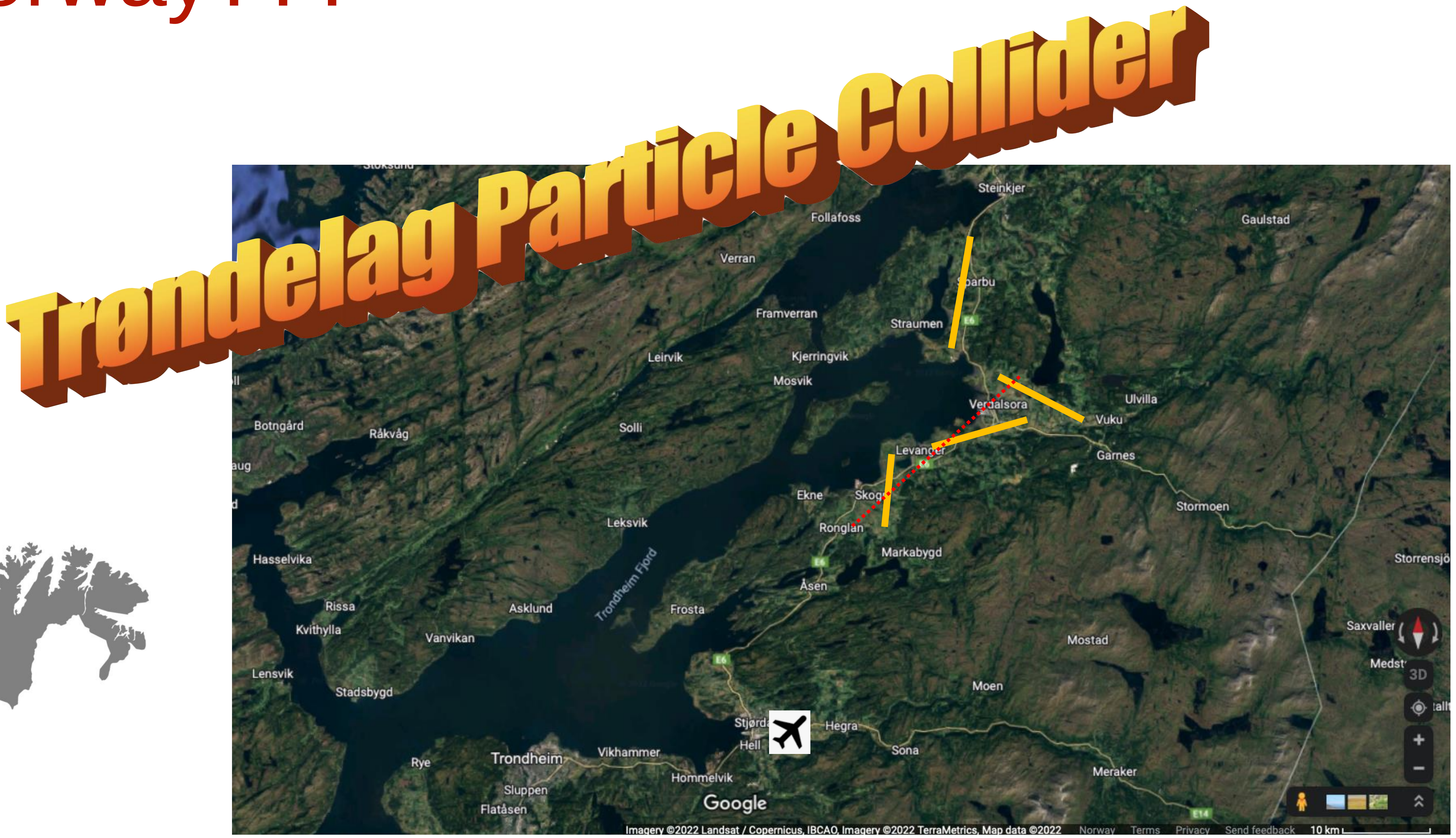
From: Badelek et al., TESLA Technical Design Report, Part VI (2001)



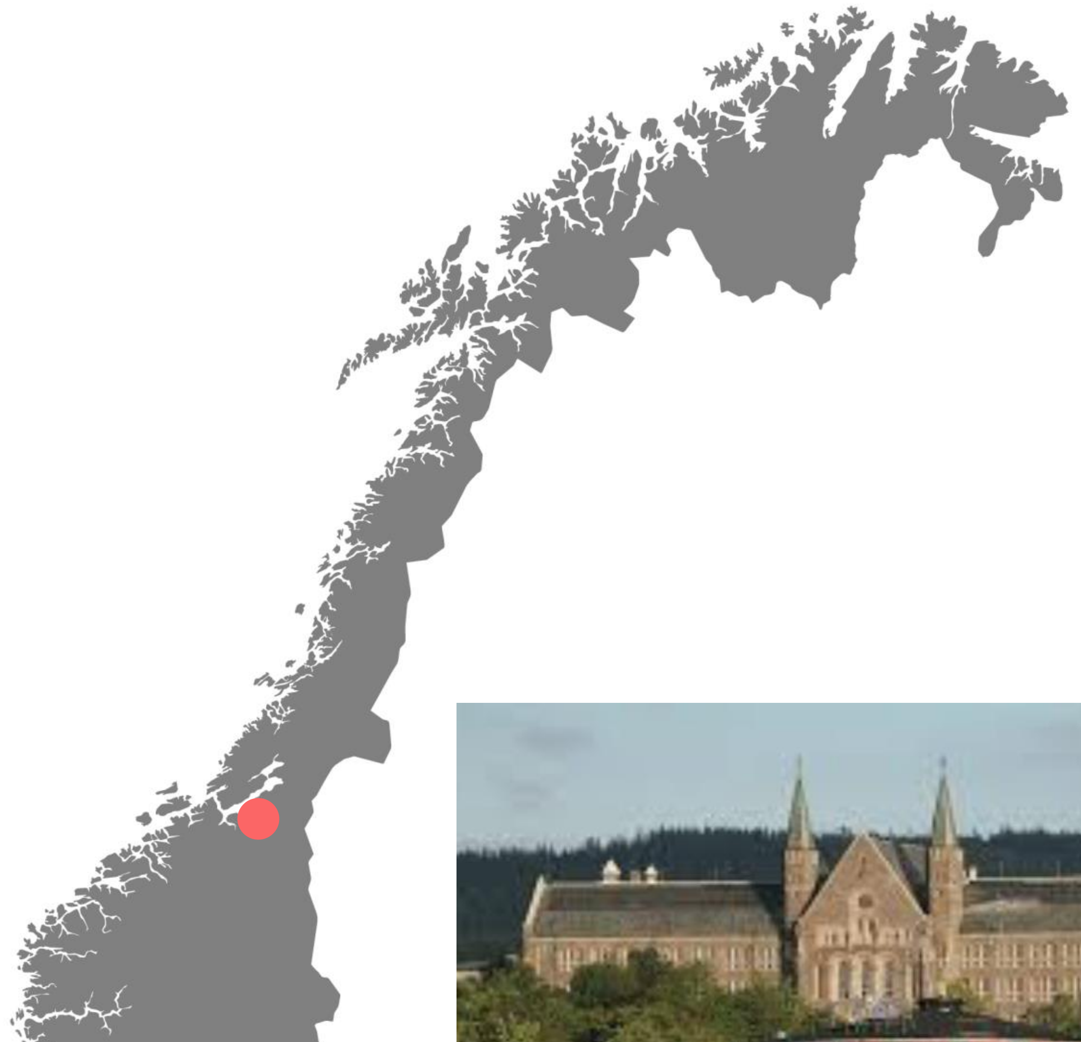
From: Rosenzweig et al., NIM A 410, 532 (1998)

A plasma-based collider in Norway???

- *Rough, preliminary cost estimate of a Higgs factory (125 GeV centre-of-mass energy):*
  - **Construction cost: ~$300 million**
  - Running cost (CERN): ~$70 million/year
  - **Running cost (Trøndelag): ~$4 million/year**



Cost similar to *two* F-35 jets
(Norway has ordered 52 of these)



Cheap electricity!

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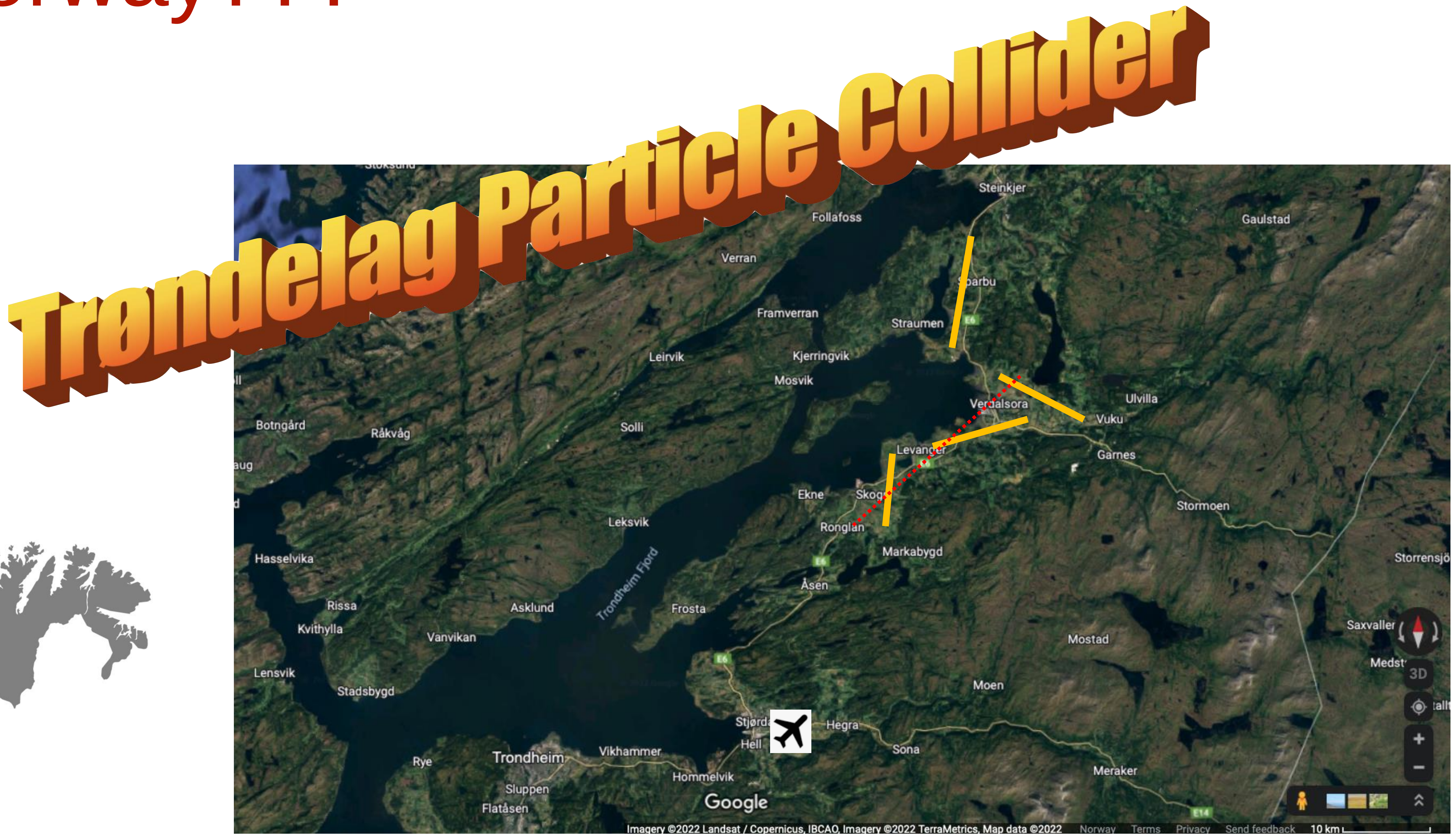

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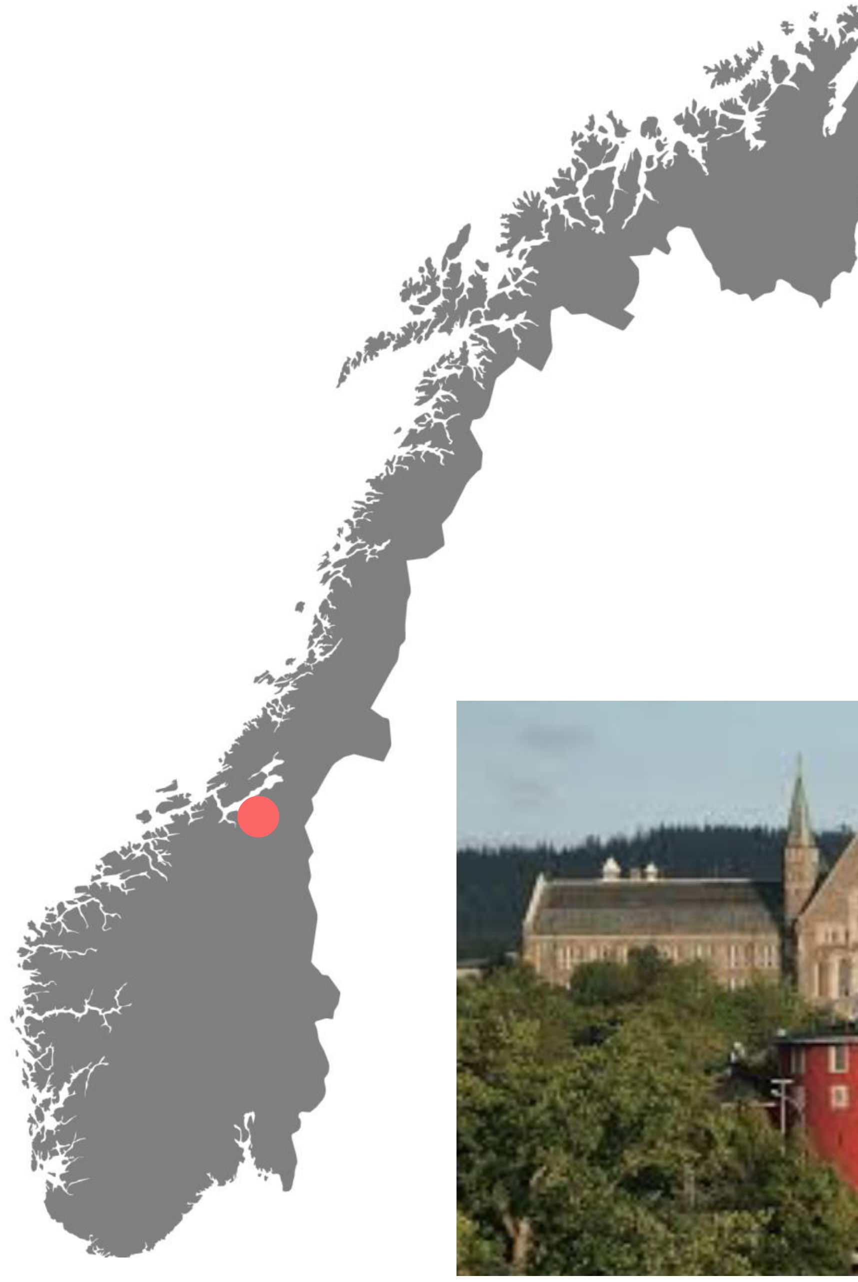
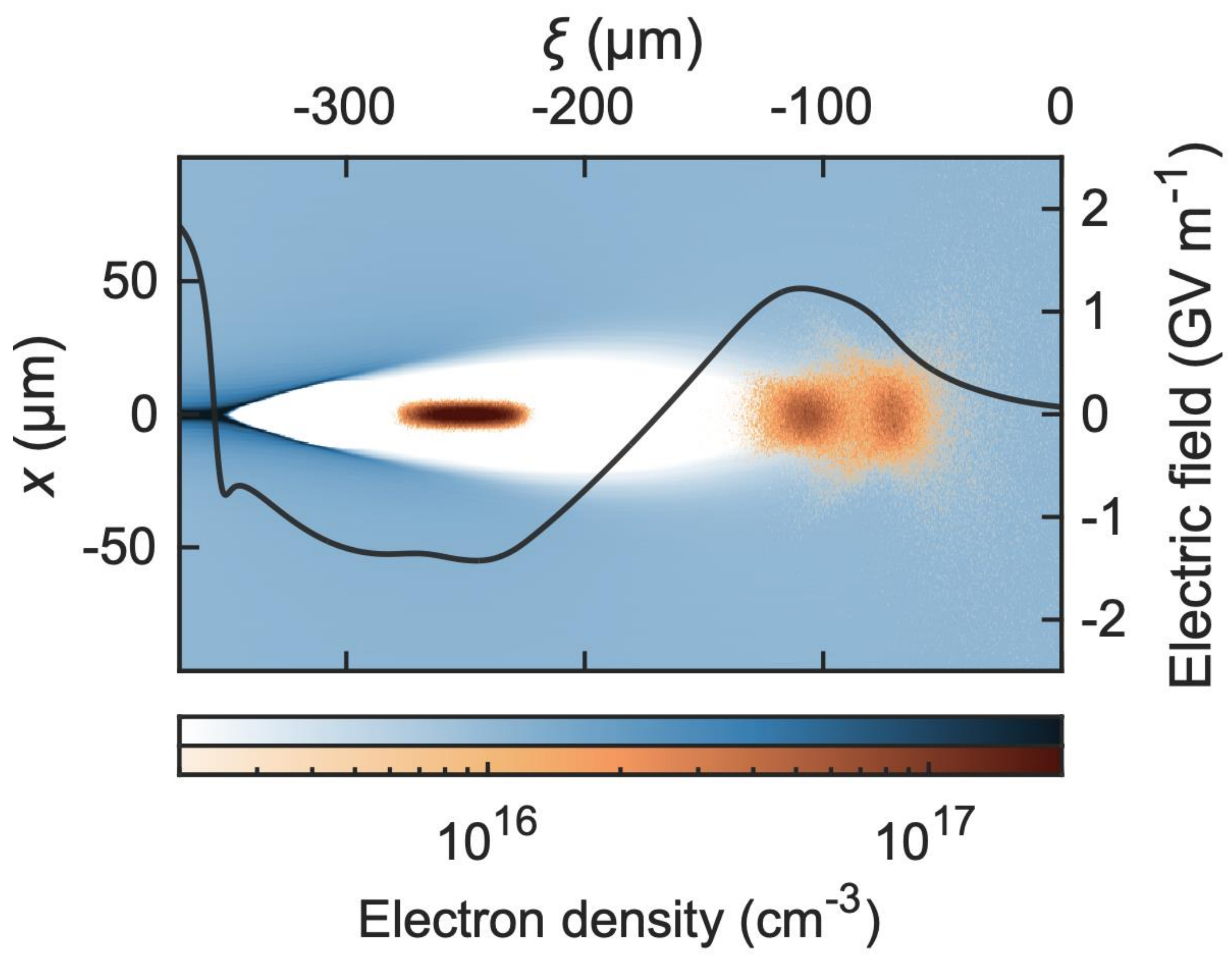
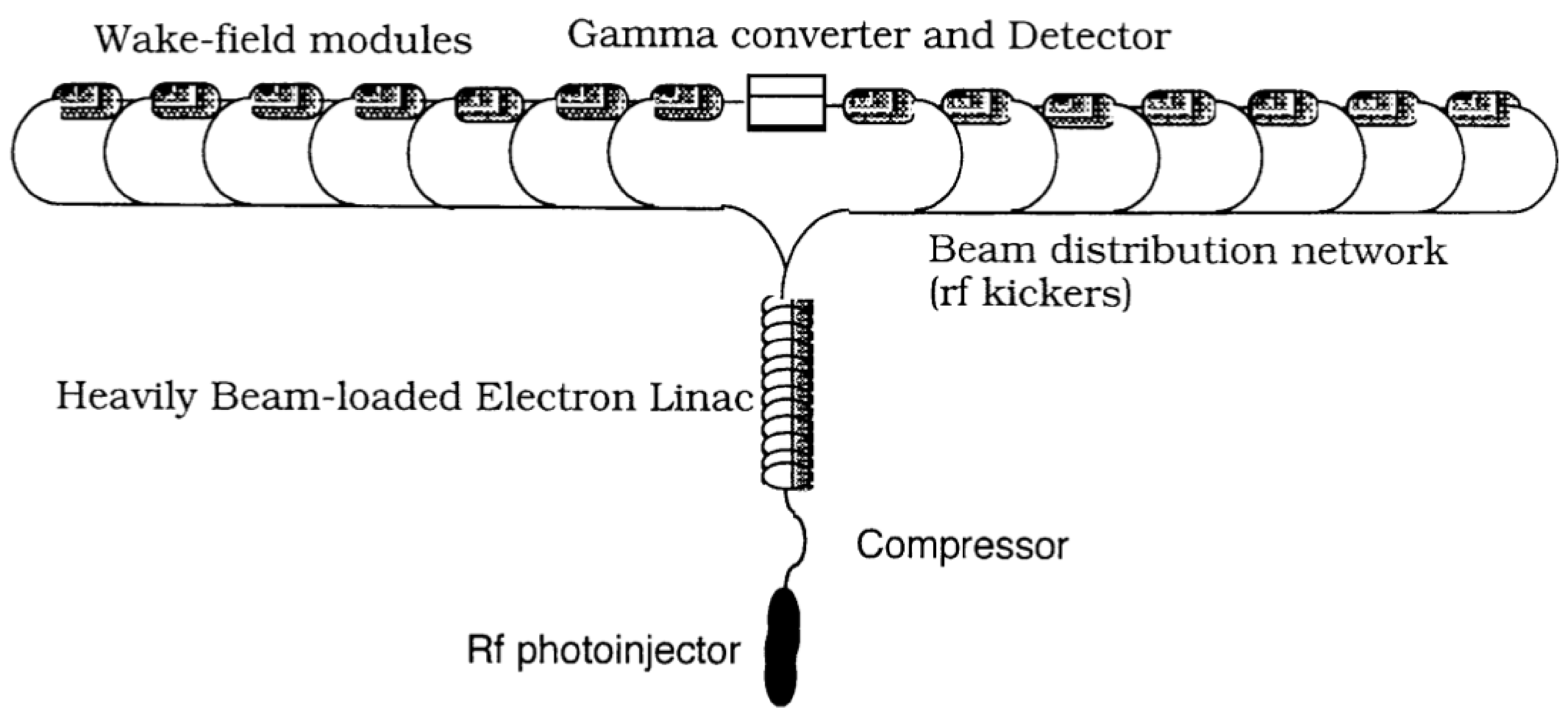


Cheap electricity!

In conclusion

- Particle **colliders are too expensive**, due to low acceleration gradient in RF accelerators
- Plasma wakefield accelerators promise:
  - ***High acceleration gradient, energy efficiency, repetition rate, and beam quality.***
  - *But… positrons are challenging.*
- Several UiO research topics in plasma acceleration:
  - *Suppressing transverse instabilities.*
  - *Coupling of accelerator stages*
  - *Concept for a photon collider*
- Conclusion: **Particle physics with plasma-wakefield accelerators now seems within reach**





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