Plasma wakefield acceleration for particle physics

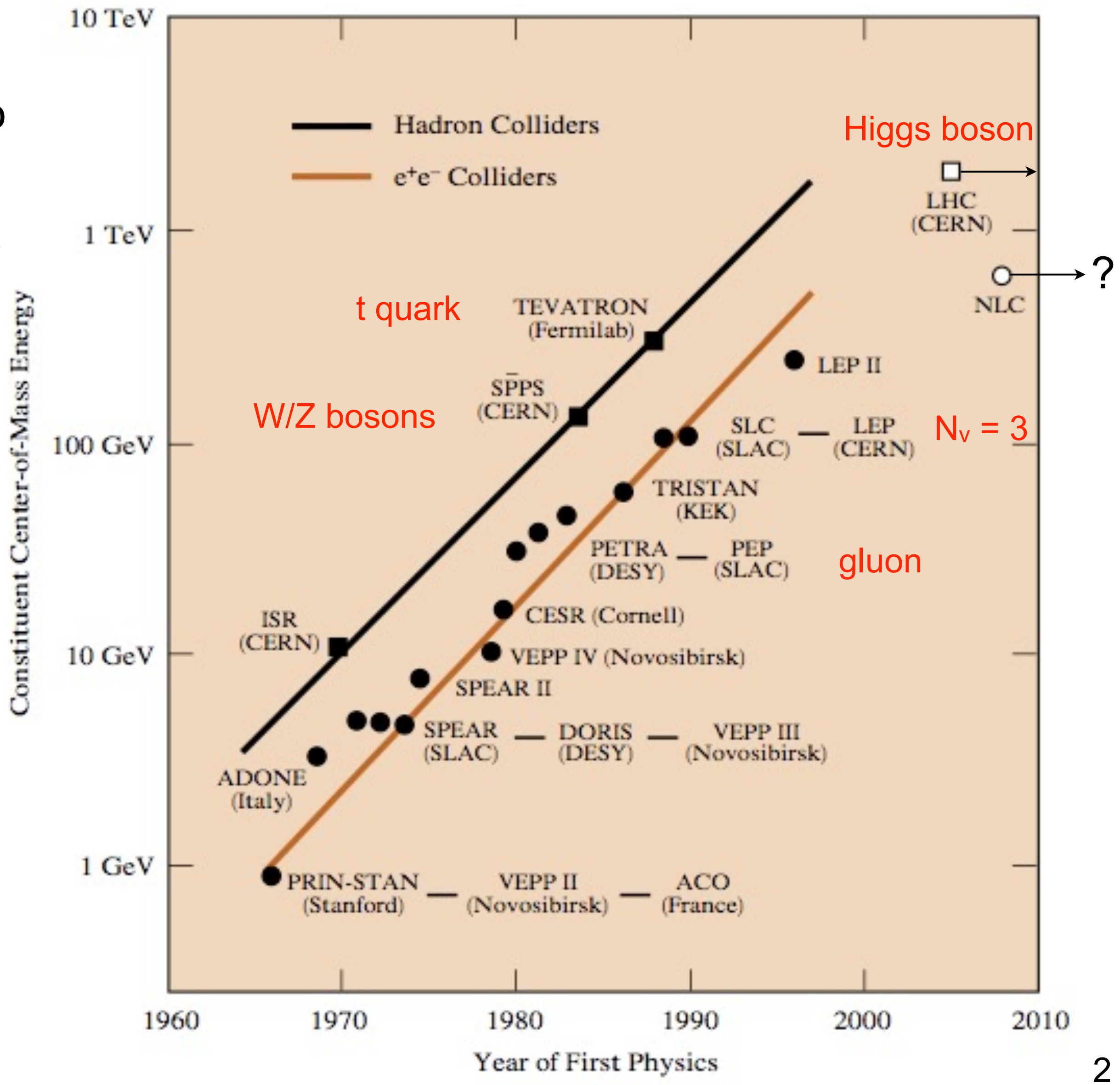
Matthew Wing

- Introduction and motivation
- R&D progress towards collider readiness
- HALHF
- Proton-driven plasma wakefield acceleration
- Outlook and summary

Physics at the Highest Energies with Colliders — GGI, Florence, 30 July 2025

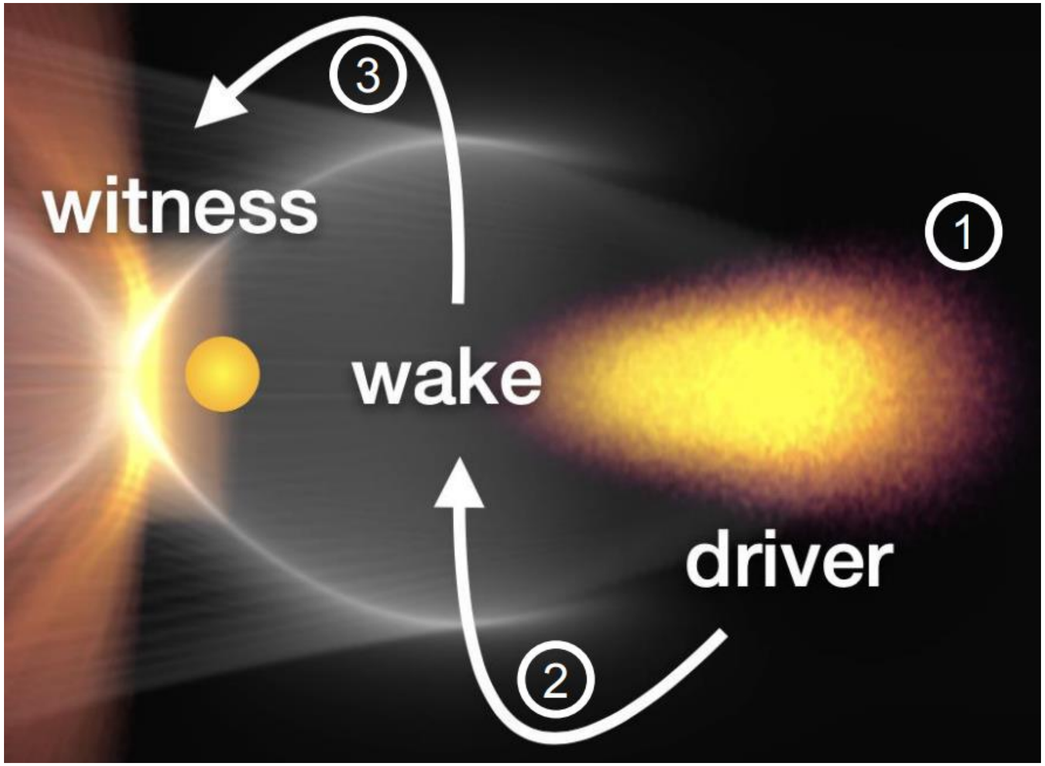
Limits of current accelerator technology

- The use of (large) accelerators has been crucial to advances in particle physics.
- Accelerators using RF cavities limited to *~100 MV/m*; high energies → long accelerators.



Plasma wakefield acceleration — how and why ?

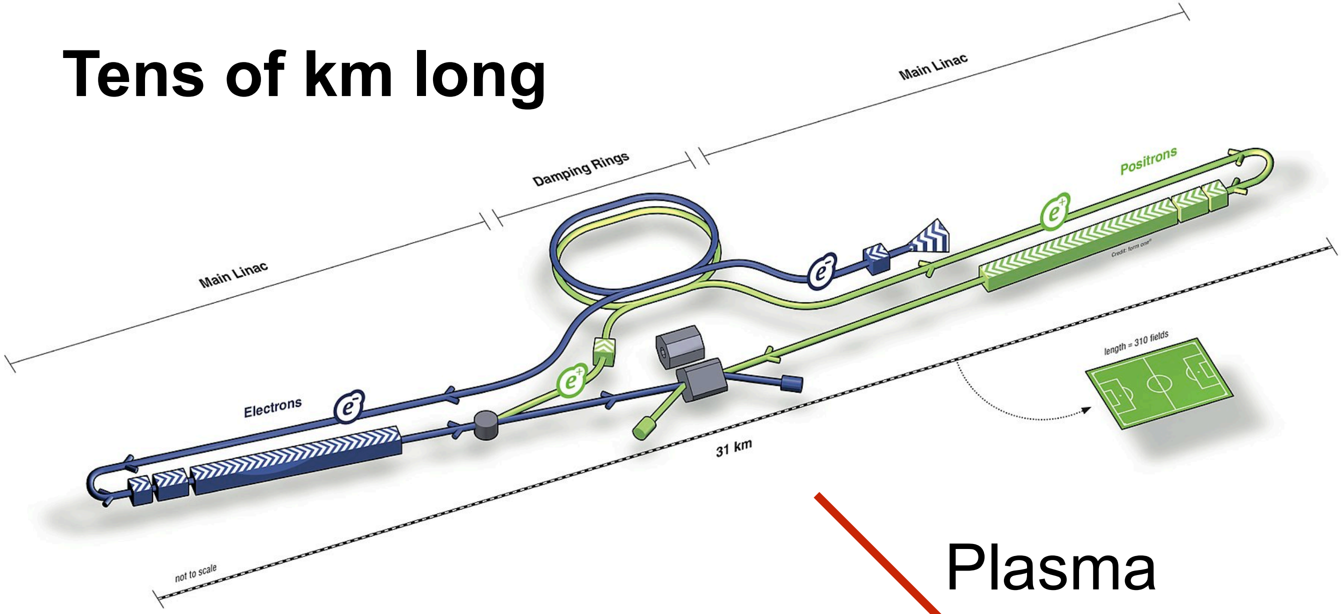
- Plasma electrons disturbed by incoming particle/laser beam.
- Plasma ions remain ~static.
- Bubble-like structure of +ive and –ive charge density.
- Oscillation of plasma electrons creates strong electric fields.
- Longitudinal fields can accelerate witness bunch of electrons.



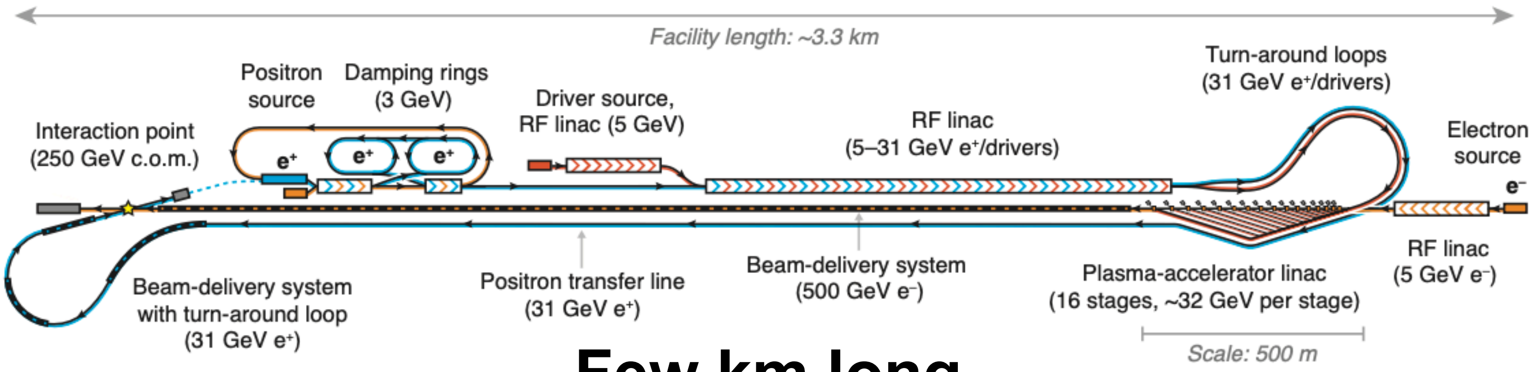
Plasma wakefield acceleration is a promising technique to realise shorter or higher energy particle accelerators.

Use novel accelerator technology

Tens of km long



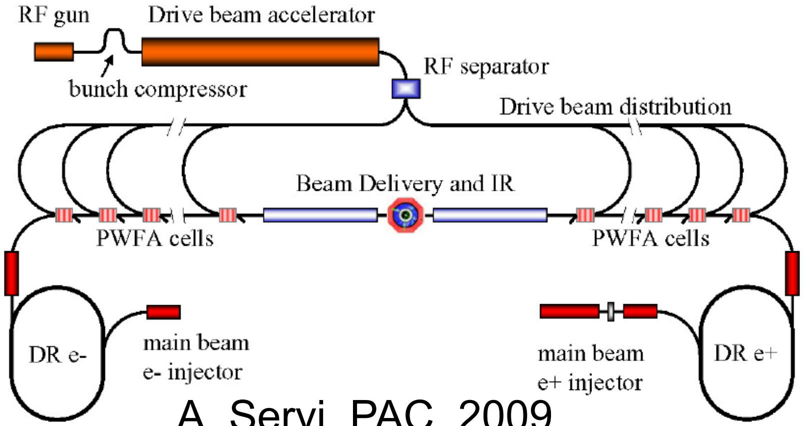
Plasma



Few km long

- Reduce the size of future colliders.
- Reduce the cost of future colliders.
- Reduce the environmental impact of future colliders.
- Go to higher energy.

Designs for future colliders



A. Seryi, PAC, 2009

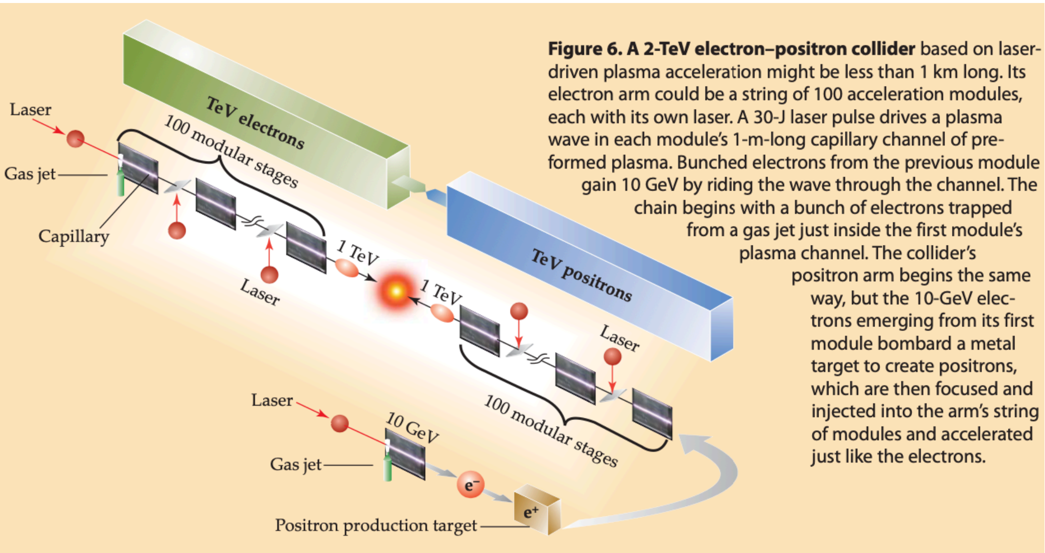
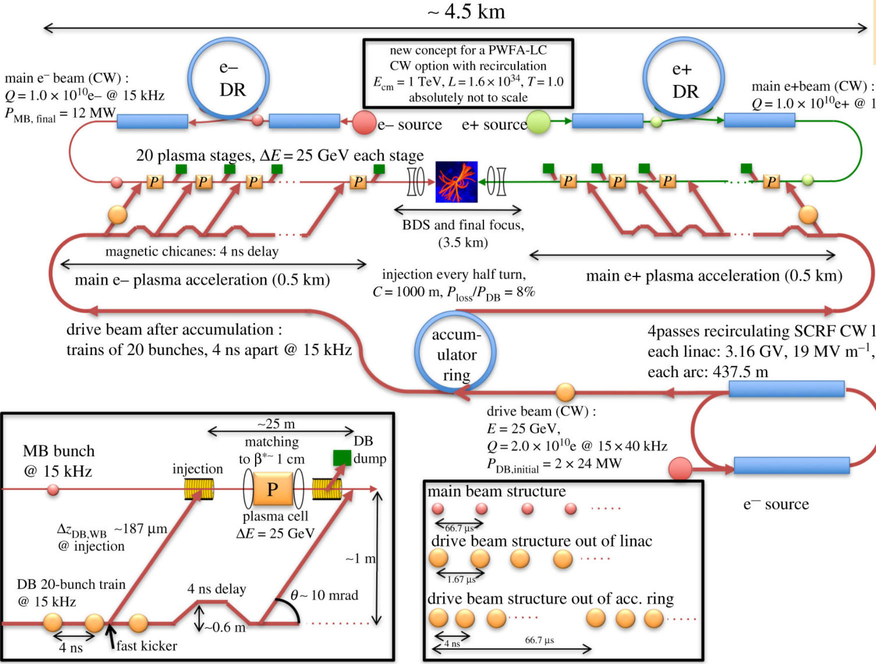


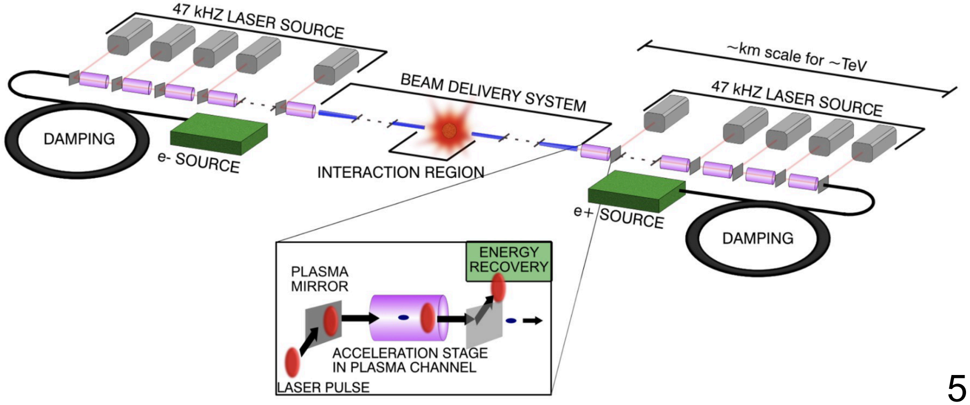
Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans & E. Esarey, Physics Today, 2009



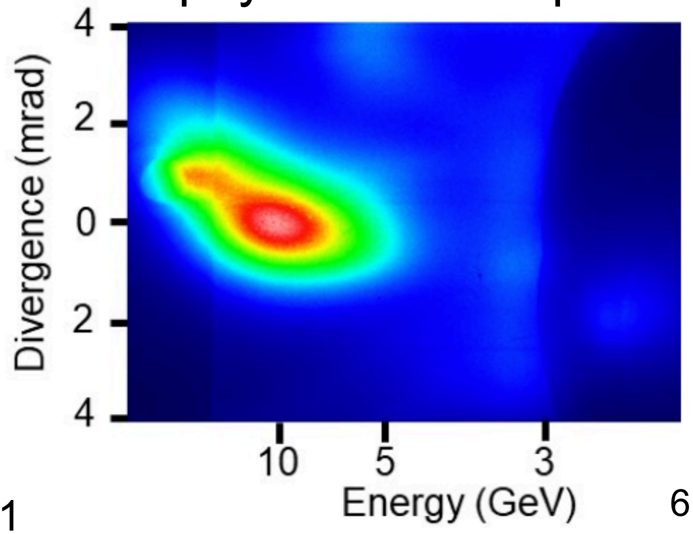
E. Adli et al., Snowmass, 2013

C. Schroeder, JINST, 2023



Plasma wakefield acceleration landscape

- Can use lasers, electron or proton bunches to drive wakefields.
- Accelerating gradients of 1 – 100 GeV/m have been achieved but need:
  - Small energy spread;
  - High repetition rate and high bunch charge;
  - Efficient and highly reproducible beam;
  - Small beam sizes.
- Lots going on worldwide, e.g. FLASHForward, FACET, CLARA, AWAKE, EUPRAXIA, APOLLON, BELLA, KALDERA, ELI, Shanghai, etc.
- One of the accelerator R&D areas in European particle physics roadmap.
- Main focus here will be on beam-driven plasma wakefield acceleration which is currently more relevant for HEP than laser-driven plasma wakefield acceleration.
  - **10 GeV energy gain in laser wakefield acceleration in 10 cm*.**



*C. Aniculaesei et al., *Matter Radiat. Extremes* **9** (2024) 014001

Plasma considerations

Based on linear fluid dynamics :

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

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

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

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 :

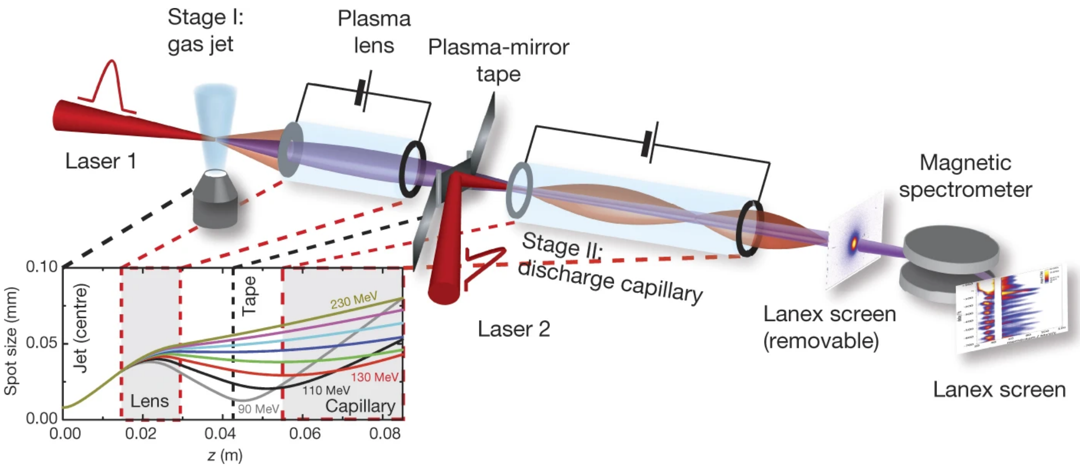
- **Short drive beams**
- **Pulses with large number of particles**

Plasma wakefield acceleration first proposed by T. Tajima and J.W. Dawson, Phys. Rev. Lett. **43** (1979) 267; use of particle beams proposed by P. Chen et al., Phys. Rev. Lett. **54** (1985) 693.

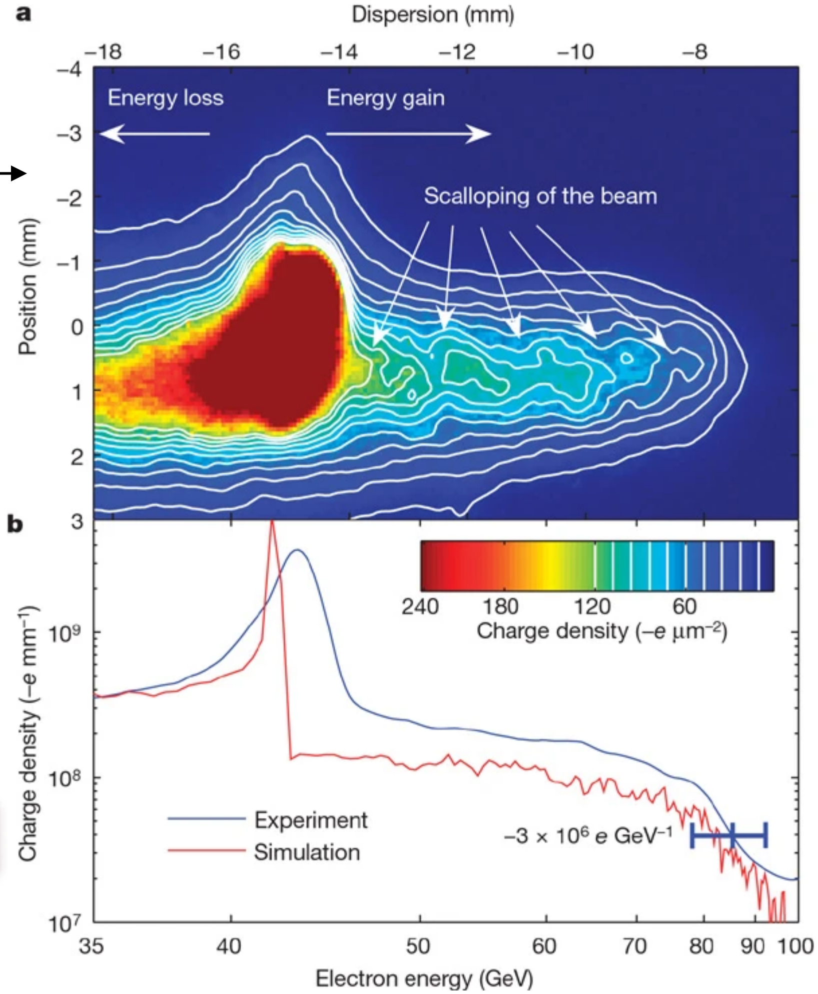
Progress towards collider readiness

Progress towards collider readiness

- Large energy gain
  - Energy doubling (50 GeV/m) in a single plasma module.
  - Staging of two plasma modules.
    - More demonstrations needed.



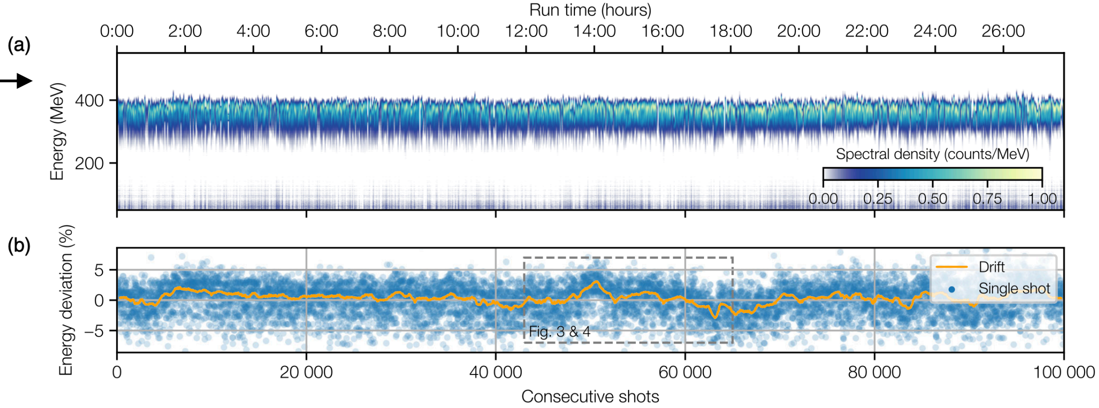
S. Steinke et al.,
Nature **530** (2016) 190.



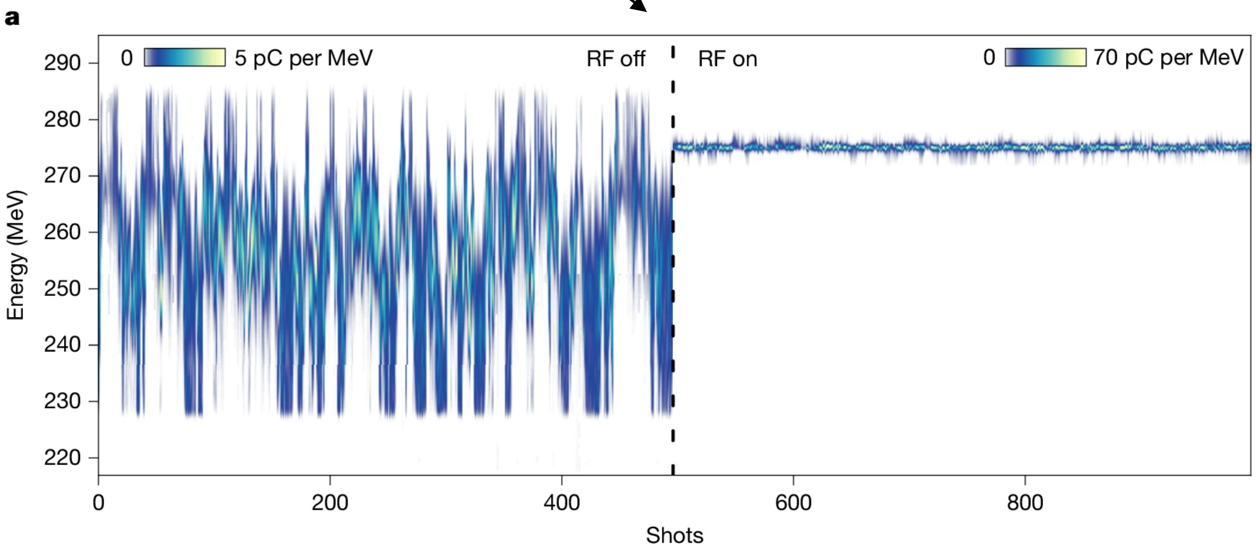
I. Blumenfeld et al.,
Nature **445** (2007) 741.

Beam quality and stability

- Transverse and longitudinal stability.
- Energy spread and jitter at permille level



A. Maier et al., *Phys. Rev. X* **10** (2020) 031039.

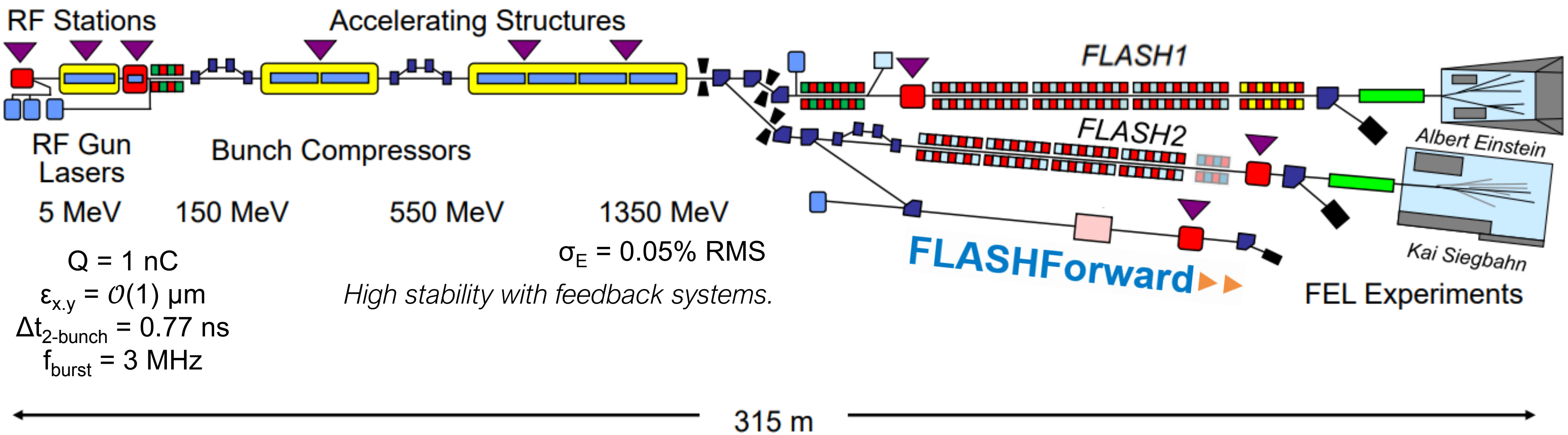


- Laser-plasma electron beams
- Also prerequisites for PETRA IV injector

P. Winkler et al., *Nature* **640** (2025) 907.

FLASHFORWARD▸▸ THE FACILITY

Electron beam-driven plasma wakefield acceleration at DESY



RF Stations

Accelerating Structures

FLASH1

FLASH2

RF Gun Lasers

Bunch Compressors

Albert Einstein

Kai Siegbahn

5 MeV

150 MeV

550 MeV

1350 MeV

$Q = 1$ nC

$\varepsilon_{x,y} = \mathcal{O}(1)$ μm

$\Delta t_{2\text{-bunch}} = 0.77$ ns

$f_{\text{burst}} = 3$ MHz

$\sigma_E = 0.05\%$ RMS

High stability with feedback systems.

FLASHForward▸▸

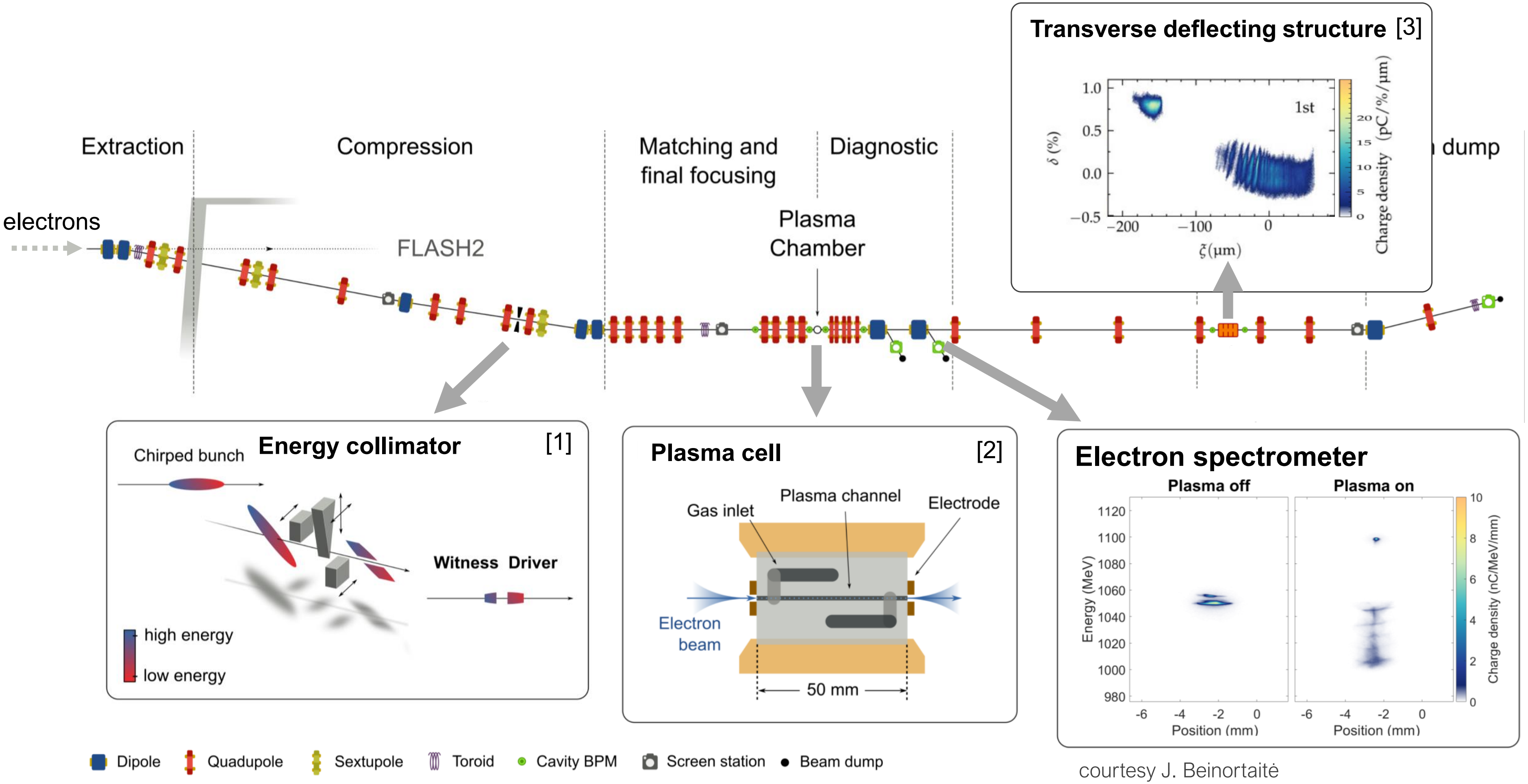
FEL Experiments

315 m

S. Schreiber and B. Faatz, The free-electron laser FLASH, High Power Laser Science and Engineering, 3 (2015)

FLASH Free Electron User Facility — unique conditions for plasma wakefield acceleration testbed.

FLASHFORWARD▸▸ BEAMLINE



courtesy J. Beinortaitė

Diagram courtesy: P. González Caminal

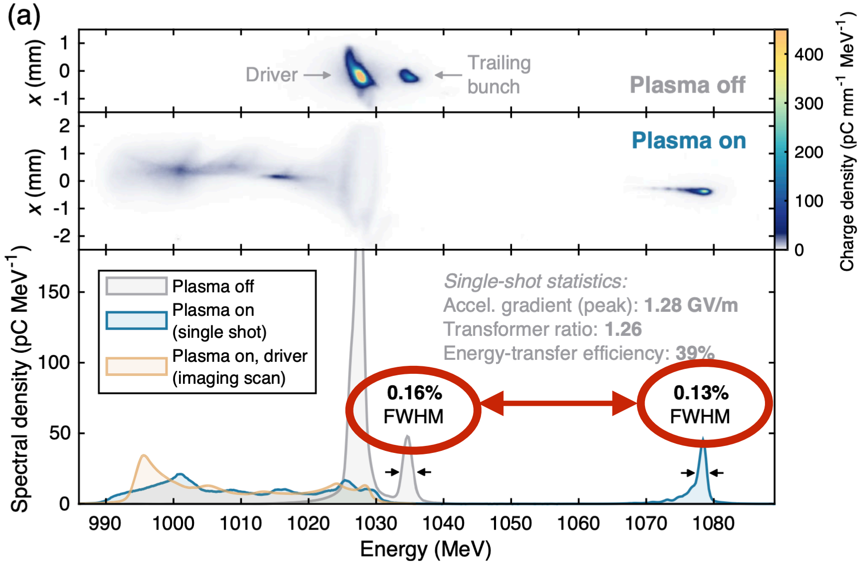
[1] P. Muggli, *et al*. Phys. Rev. Lett. **101**, 054801 (2008); S. Schröder *et al.*, J. Phys. Conf. Ser. **1596**, 012002 (2020)

[2] J. M. Garland *et al.*, Rev. Sci. Instrum. **92**, 013505 (2021)

[3] P. González Caminal, PhD Thesis; B. Marchetti *et al.*, Scientific Reports **11**, 3560 (2021)

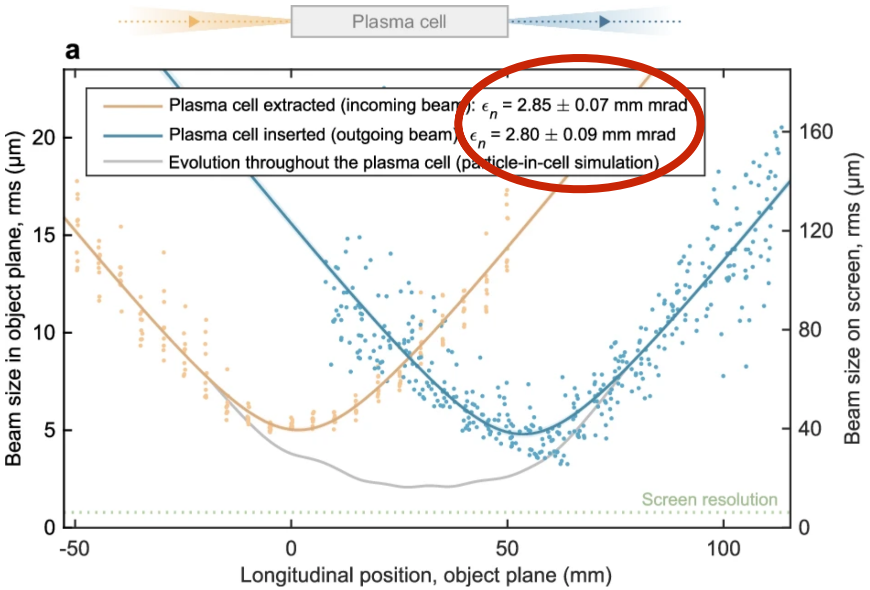
Progress towards collider readiness

- High beam quality (luminosity)
  - Energy-spread preservation
  - Emittance preservation.



C. Lindstrøm et al., *Phys. Rev. Lett.* **126** (2021) 014801.

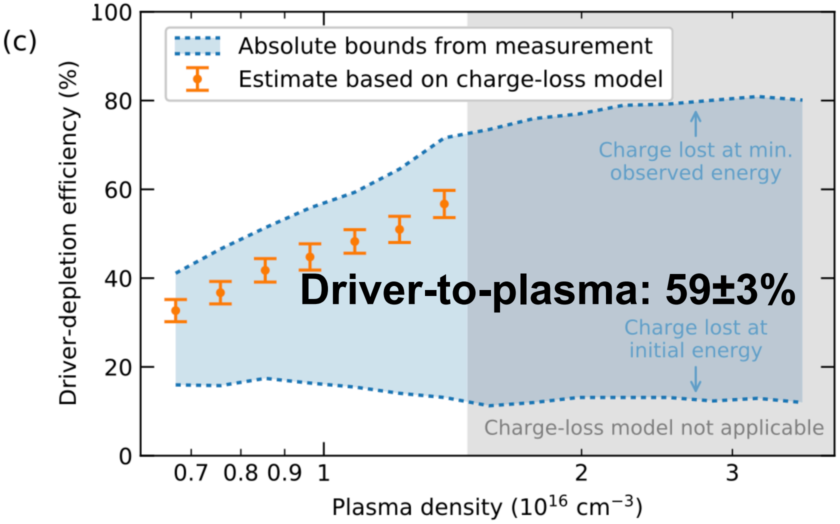
FLASHForward



C. Lindstrøm et al., *Nature* Commun. **15** (2024) 6097.

Progress towards collider readiness

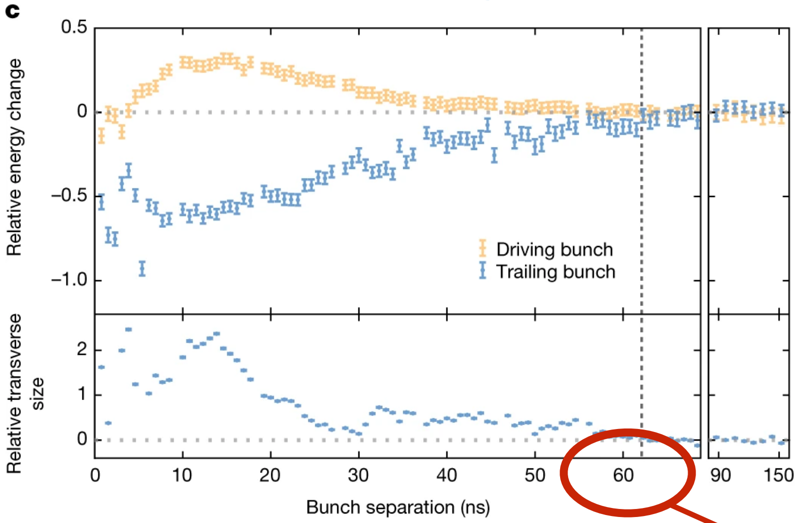
- High beam power (luminosity)
  - High overall efficiency (wall-plug to beam): ***O(10%)***.
  - Repetition rate.



Driver-to-plasma: 59±3%

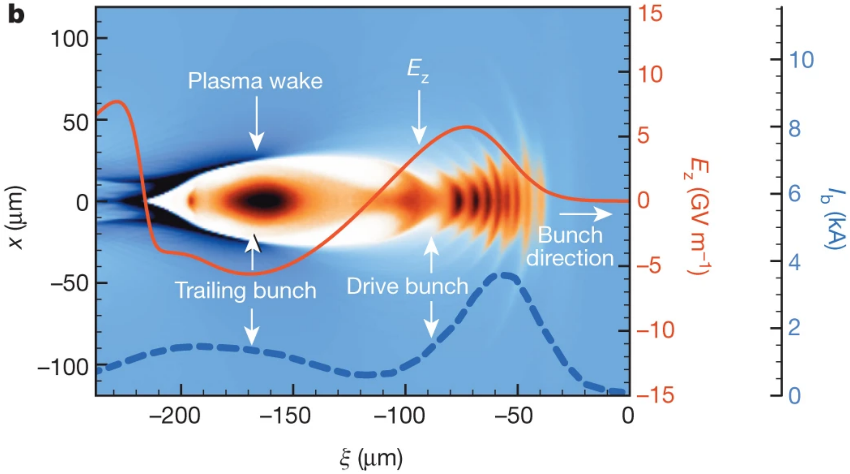
F. Peña et al., *Phys. Rev. Res.* **6** (2024) 043090.

FLASHForward



R. D'Arcy et al., *Nature* **603** (2022) 58.

~63 ns / ~15 MHz

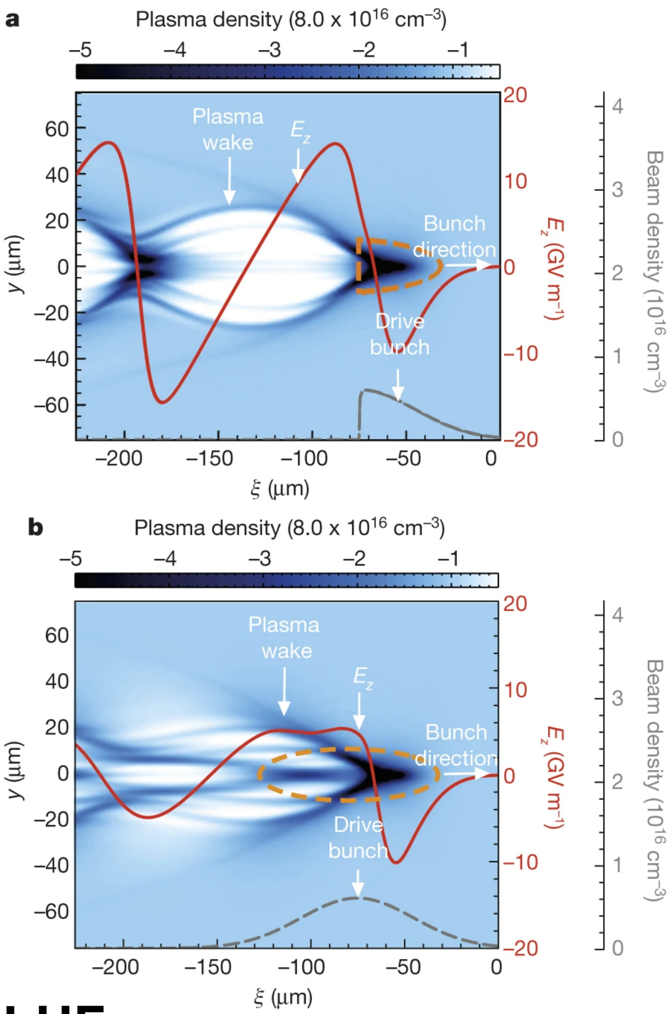


M. Litos et al., *Nature* **515** (2014) 92.

HALHF concept

Positron acceleration

- Positron acceleration has been demonstrated.
  - 5 GeV energy gain with one bunch.
- Acceleration of witness bunch also shown.
  - Driven by positron bunch.
  - Much lower gradient than for electrons.
- Schemes proposed to improve positron acceleration and quality.
  - New/more e^+ test facilities would be highly beneficial.

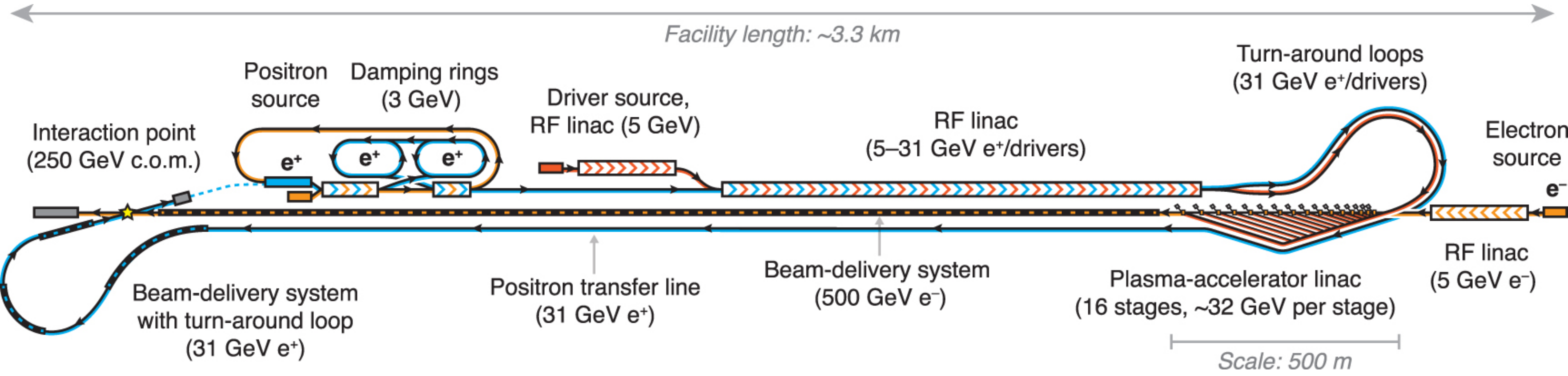


- **Given the challenge of e^+ acceleration → HALHF**
  - **Plasma for e^- and conventional RF for e^+.**

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

S. Gessner et al., arXiv:2304.01700

HALHF: a hybrid, asymmetric, linear Higgs factory

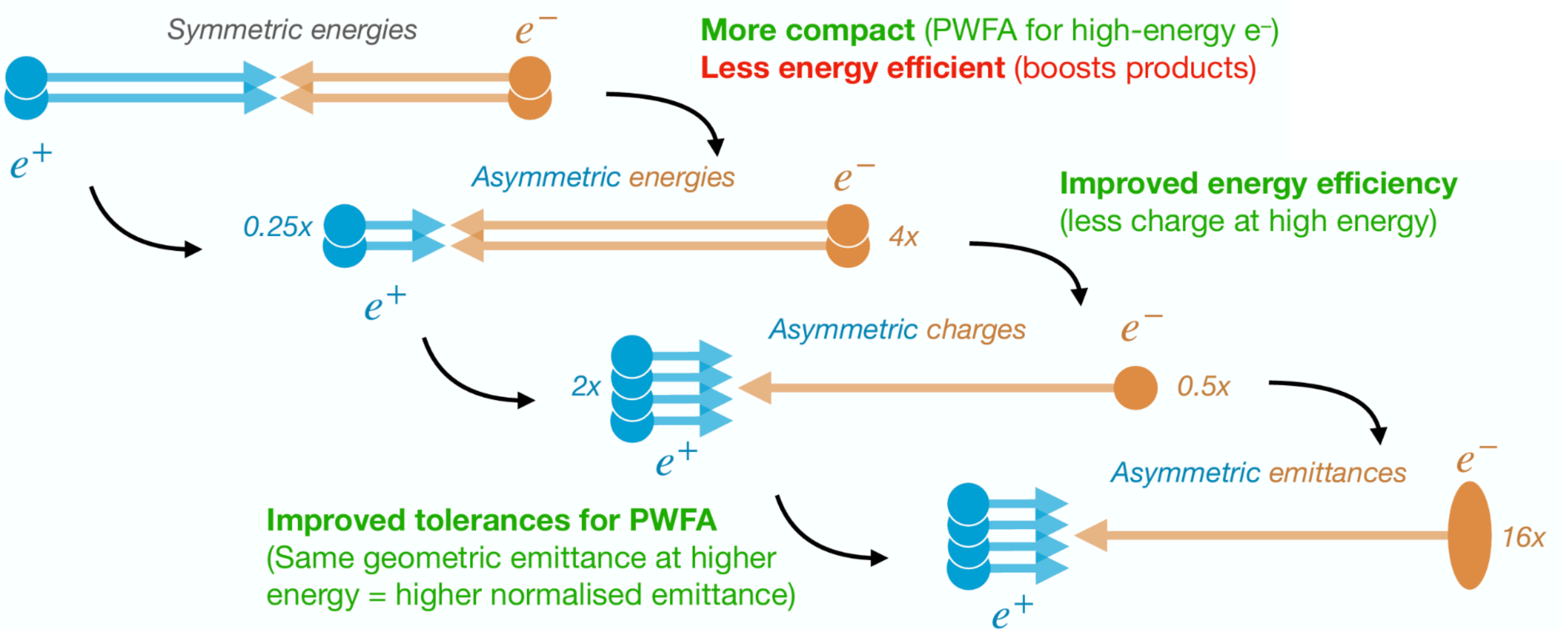


- Plasma gives 500 GeV e^- and RF gives 31 GeV e^+.
- Boost of 2.13 (HERA was 3).
- Luminosity $L \sim 10^{34}$ cm^{-2} s^{-1}, similar to ILC.
- Overall length ~3.3 km, dominated by beam-delivery system.
- Workshops:
  - Oslo, Apr/24, https://indico.cern.ch/event/1370201/
  - Erice, Oct/24, https://indico.cern.ch/event/1448913/
  - DESY, Feb/25, https://indico.desy.de/event/47927/

B. Foster, R. D’Arcy, C.A. Lindstrøm, *New J. Phys.* **25** (2023) 093037

Asymmetric collider

ILC



More compact (PWFA for high-energy e-)
Less energy efficient (boosts products)

Improved energy efficiency
(less charge at high energy)

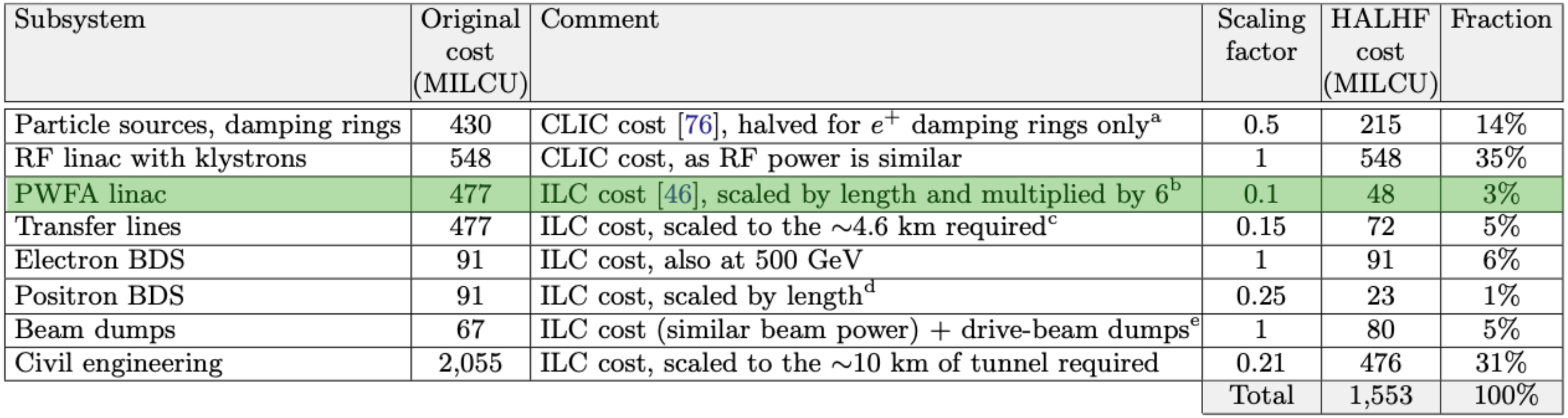
Improved tolerances for PWFA
(Same geometric emittance at higher energy = higher normalised emittance)

HALHF

	E (GeV)	σ_z (µm)	N (10^{10})	ϵ_{nx} (µm)	ϵ_{ny} (nm)	β_x (mm)	β_y (mm)	$\mathcal{L}$ (µb^{-1})	$\mathcal{L}_{0.01}$ (µb^{-1})	P/P_0
ILC:	125 / 125	300 / 300	2 / 2	10 / 10	35 / 35	13 / 13	0.41 / 0.41	1.12	0.92	1
HALHF:	31.3 / 500	75 / 75	4 / 1	10 / 40	35 / 140	3.3 / 13	0.10 / 0.41	1.01	0.58	1.25

HALHF cost estimate

- Scaled from existing collider projects (ILC/CLIC) where possible.
  - European accounting (2022 $): **~$1.9B** (~1/4 of ILC TDR cost @250 GeV)
  - US accounting*: **$2.3−3.9B** ($4.6B from ITF model for RF accelerators)
- Dominated by conventional collider costs (97%) — PWFA linac is ~3% of cost



Subsystem	Original cost (MILCU)	Comment	Scaling factor	HALHF cost (MILCU)	Fraction
Particle sources, damping rings	430	CLIC cost [76], halved for e^+ damping rings only[a]	0.5	215	14%
RF linac with klystrons	548	CLIC cost, as RF power is similar	1	548	35%
PWFA linac	477	ILC cost [46], scaled by length and multiplied by 6[b]	0.1	48	3%
Transfer lines	477	ILC cost, scaled to the ~4.6 km required[c]	0.15	72	5%
Electron BDS	91	ILC cost, also at 500 GeV	1	91	6%
Positron BDS	91	ILC cost, scaled by length[d]	0.25	23	1%
Beam dumps	67	ILC cost (similar beam power) + drive-beam dumps[e]	1	80	5%
Civil engineering	2,055	ILC cost, scaled to the ~10 km of tunnel required	0.21	476	31%
			Total	1,553	100%

- Estimated power usage is ~100 MW (similar to ILC and CLIC):
  - 21 MW beam power, 27 MW losses, 2 × 10 MW damping rings, +50% for cooling, etc.

* T. Roser et al., arXiv:2208.06030

A new HALHF baseline

- Combined RF linac for positrons and PWFA electron drivers not ideal due to simultaneous high gradient and high power.

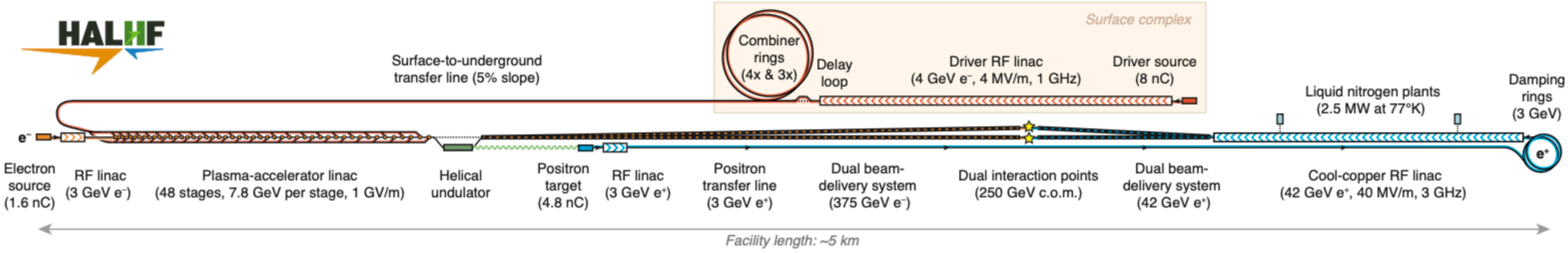


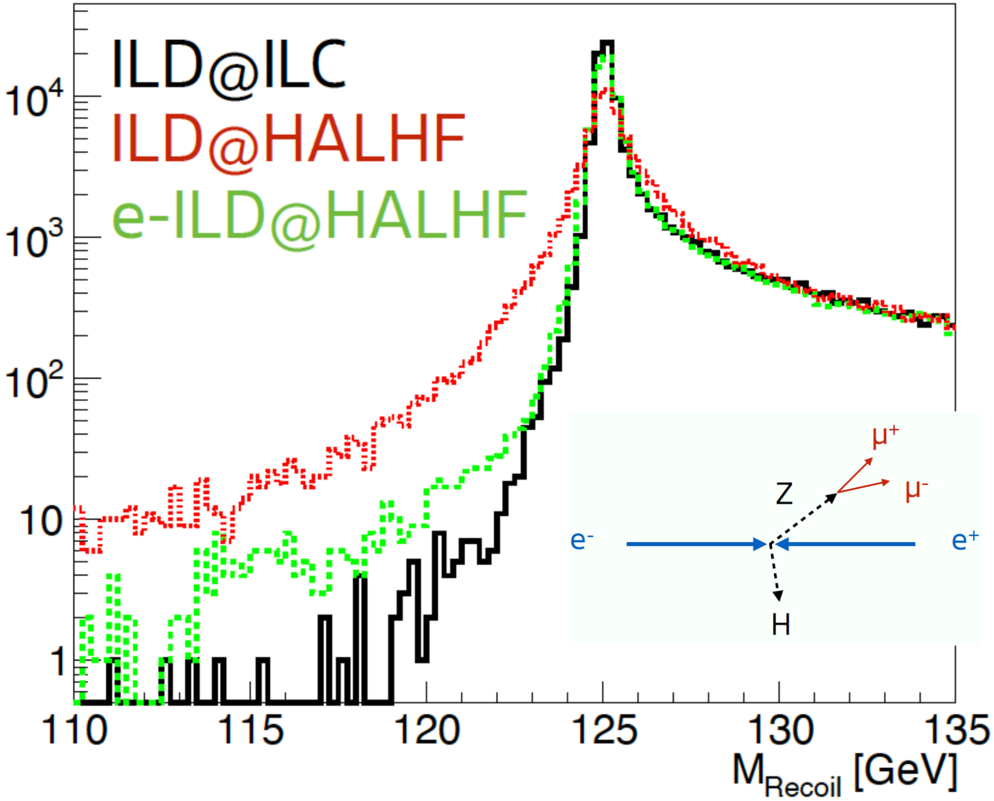
Figure 1: Schematic view of the new HALHF baseline at 250 GeV CoM. The red sections relate to electrons, blue to positrons and green to photons. Other components are as labelled on the figure.

- New baseline: pulsed, separate linacs, CLIC-like drive beam with combiner ring. Cool copper positron linac.
- Design is outcome of Bayesian optimisation for cost.
- Other energies also considered.
- Cost for 250 GeV machine (in 2024 Swiss Francs): **3.8 BCHF**.

EPPSU input: arXiv:2503.19880

HALHF particle physics analysis

- Normal ILC detector needs to be adapted to cater for boost.
- Asymmetric detector in fast simulation.
- *e*⁺*e*⁻ pairs from beamstrahlung crucial for defining geometry.
  - Where can there be instrumentation ?
- Detector geometry in forward region in GEANT4.
  - Full detector simulation needed though.



Proton-driven plasma wakefield acceleration

Why protons ?

Lasers do not have enough energy :

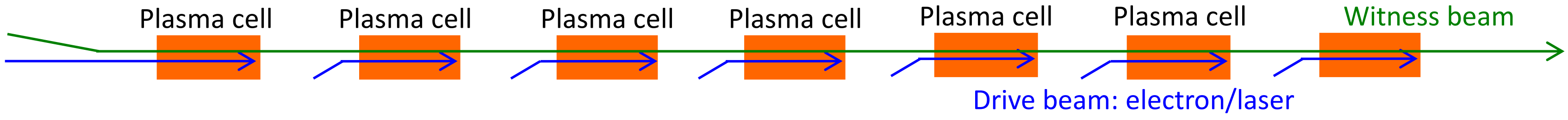
- Can not propagate long distances in plasma
- Can not accelerate electrons to high energy
- For high energy, need multiple stages.

Electrons also limited by initial energy :

- Many stages needed to accelerate to the TeV scale using known electron beams

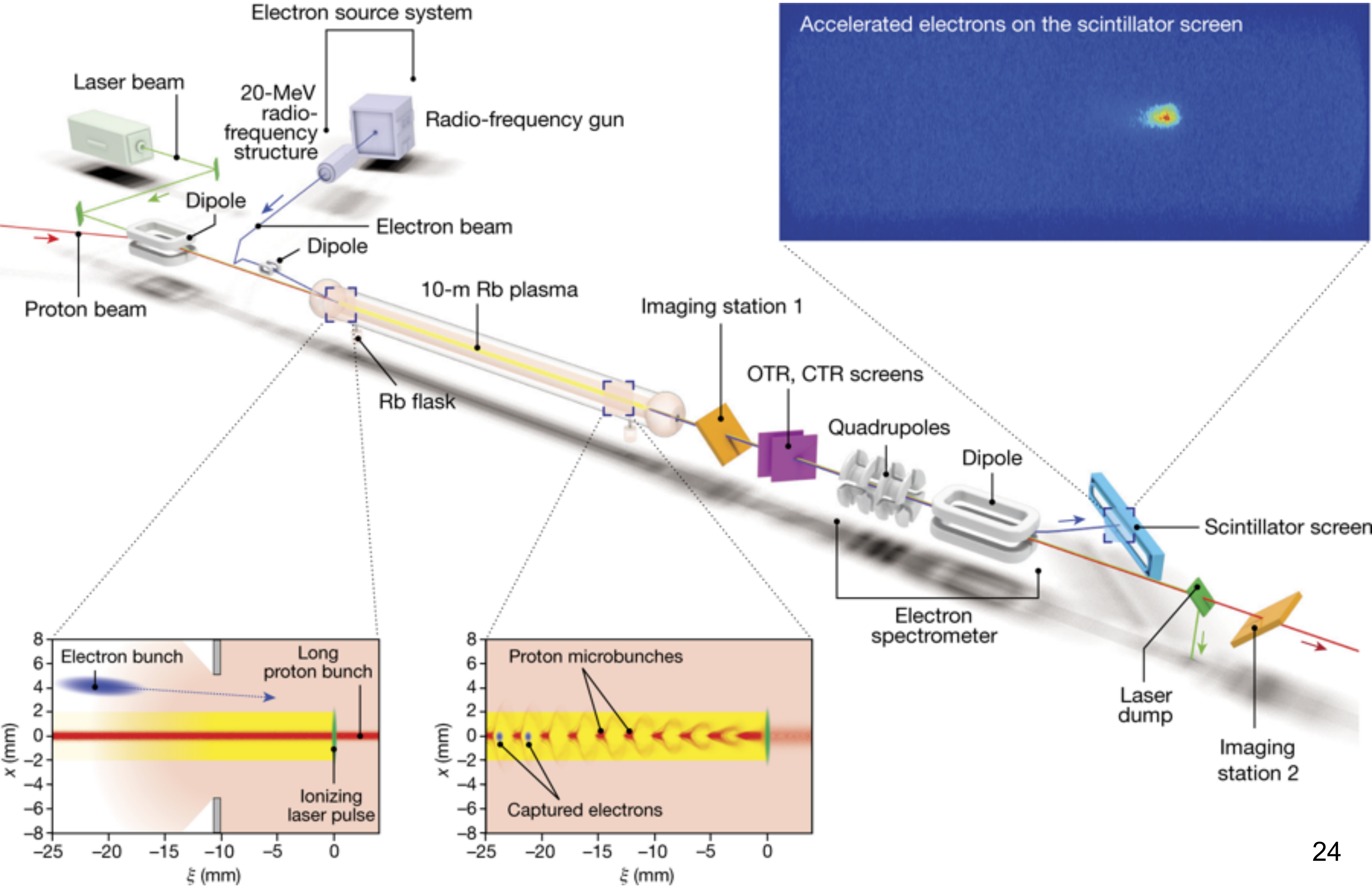
Proton beams at TeV scale and with high stored energy are around today : what about using protons ?

Laser/electron driver



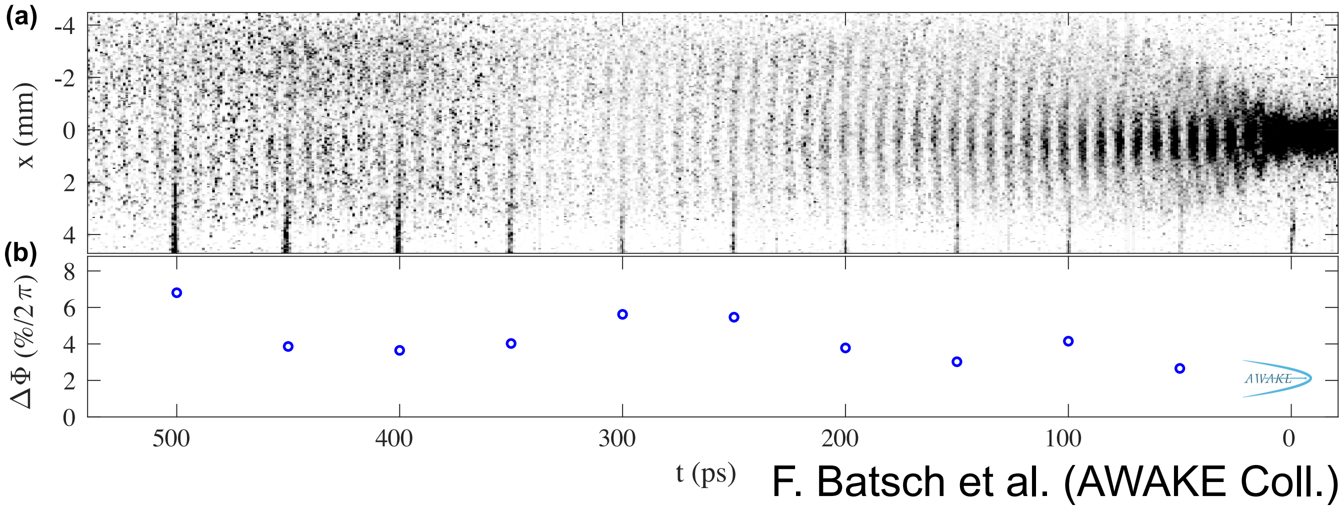
Proton driver

AWAKE schematic

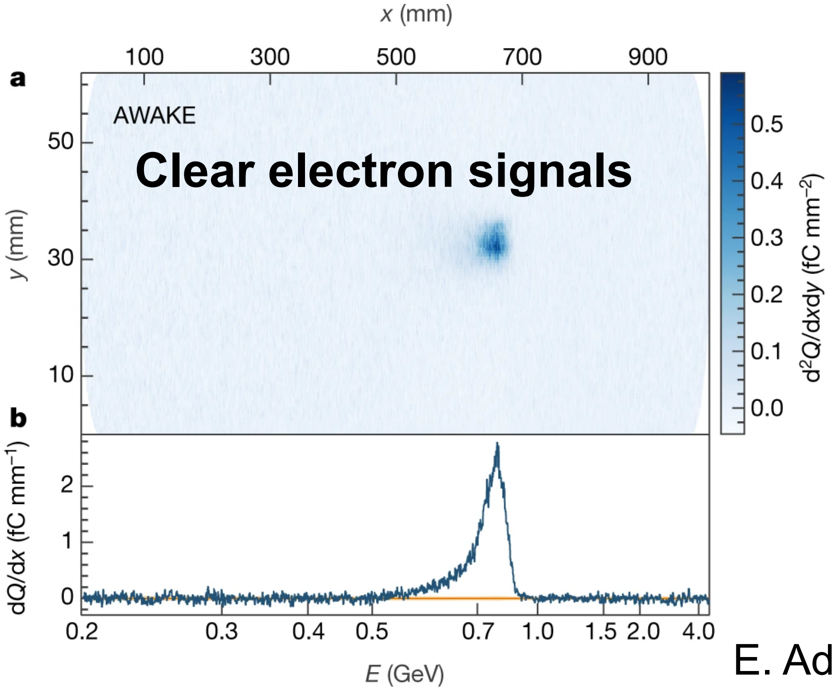


AWAKE: proton-driven plasma wakefield acceleration

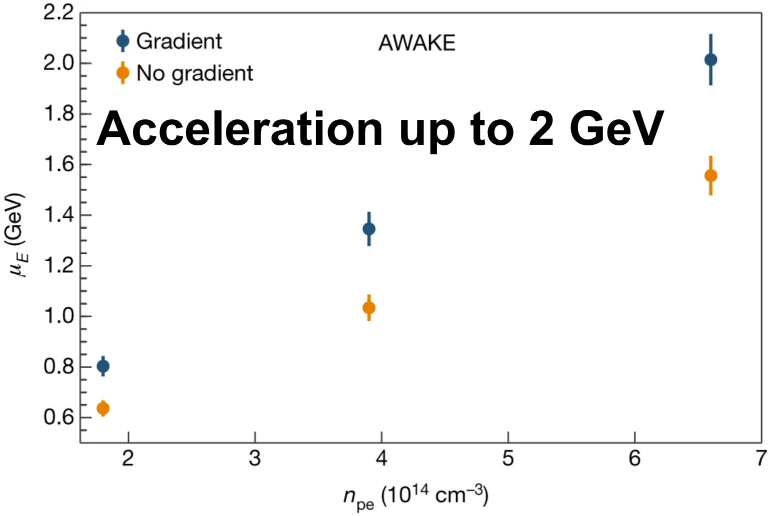
- Use high energy protons → long propagation distance.
- Long bunches microbunched → large wakefields.



F. Batsch et al. (AWAKE Coll.), *Phys. Rev. Lett.* **126** (2021) 164802



Clear electron signals

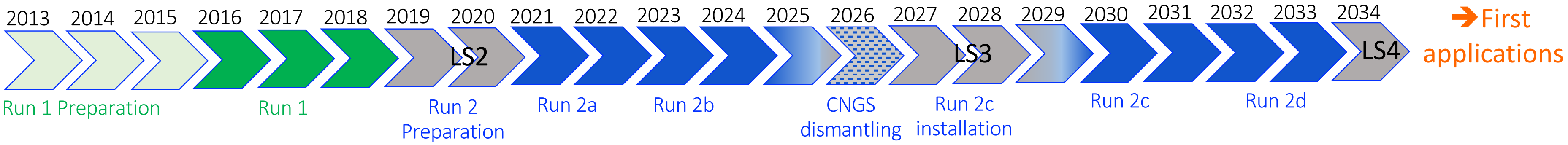


Acceleration up to 2 GeV

E. Adli et al. (AWAKE Coll.), *Nature* **561** (2018) 363

AWAKE Run 2

- Run 2 overarching physics goals:
  - Accelerate electron bunches to high energy with a constant gradient 0.5 − 1 GeV/m.
  - Control electron bunch quality (e.g. emittance < 10 μm).
  - Demonstrate scalable plasma source technology. Overlap with HALHF.
- As with FLASHForward, focus on simultaneous preservation of quality with high gradients. I.e. fully developed accelerator (plasma) module.

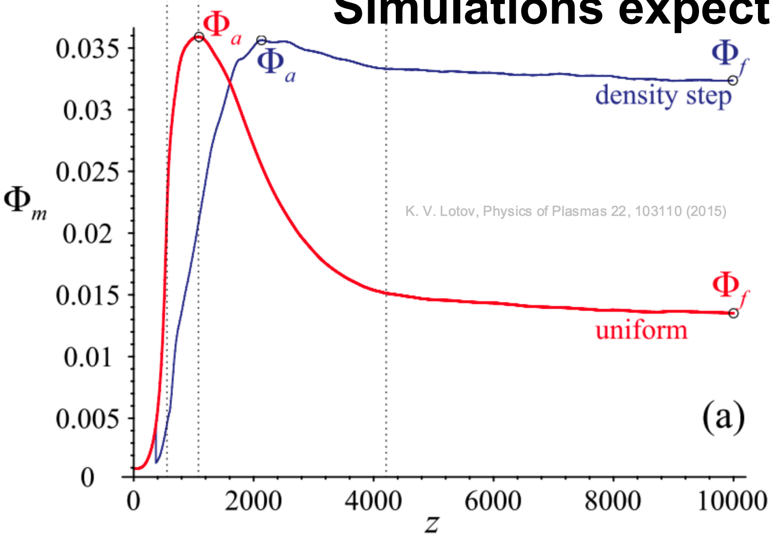


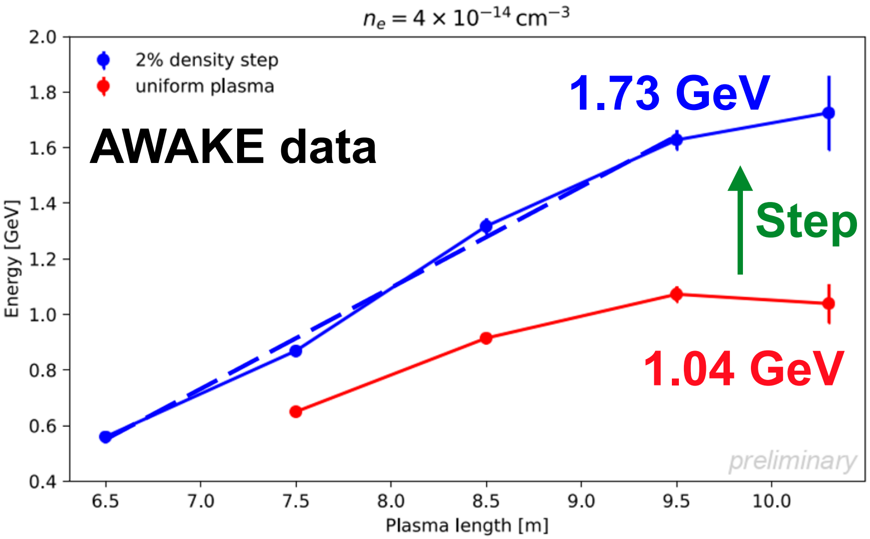
- Run 2 approved at CERN.
- Major challenges:
  - Two plasma sources: modulation and acceleration.
  - Witness electrons injected in gap between sources.
  - Simulation is a major challenge (especially as everything gets longer).

E. Gschwendtner et al. (AWAKE Coll.), *Symmetry* **14** (2022) 1680

AWAKE Run 2 and beyond

Simulations expectations

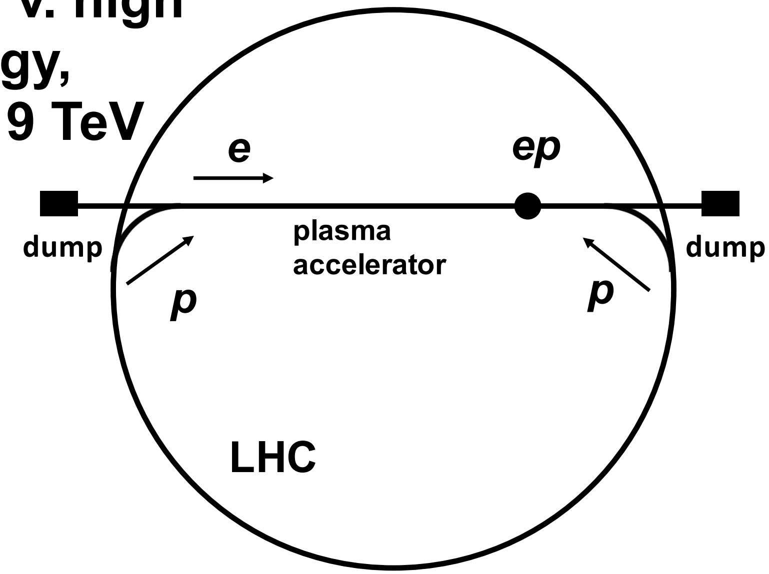




AWAKE Status Report,
https://cds.cern.ch/record/2917426/files/SPSC-SR-356.pdf

- After Run 2, HEP applications.
- High energy electron bunches (~50 GeV)
  - Strong-field QED.
  - Beam dumps for e.g. dark photon search.
  - Low-luminosity *ep* collider.

Also v. high energy, √s ~ 9 TeV



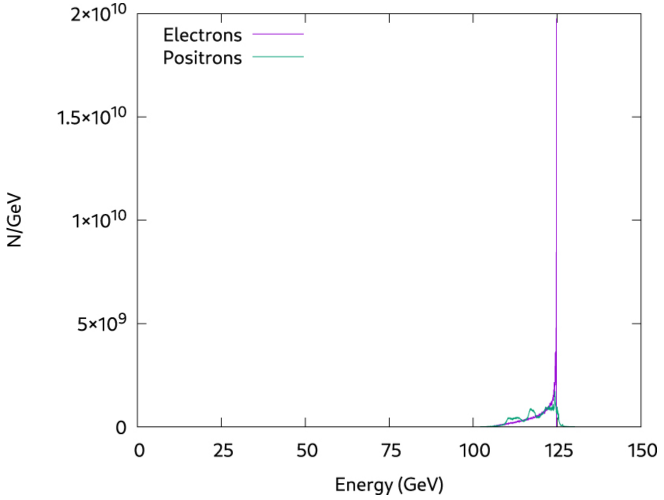
A. Caldwell & M. Wing,
Eur. Phys. J. **C 76** (2016) 463

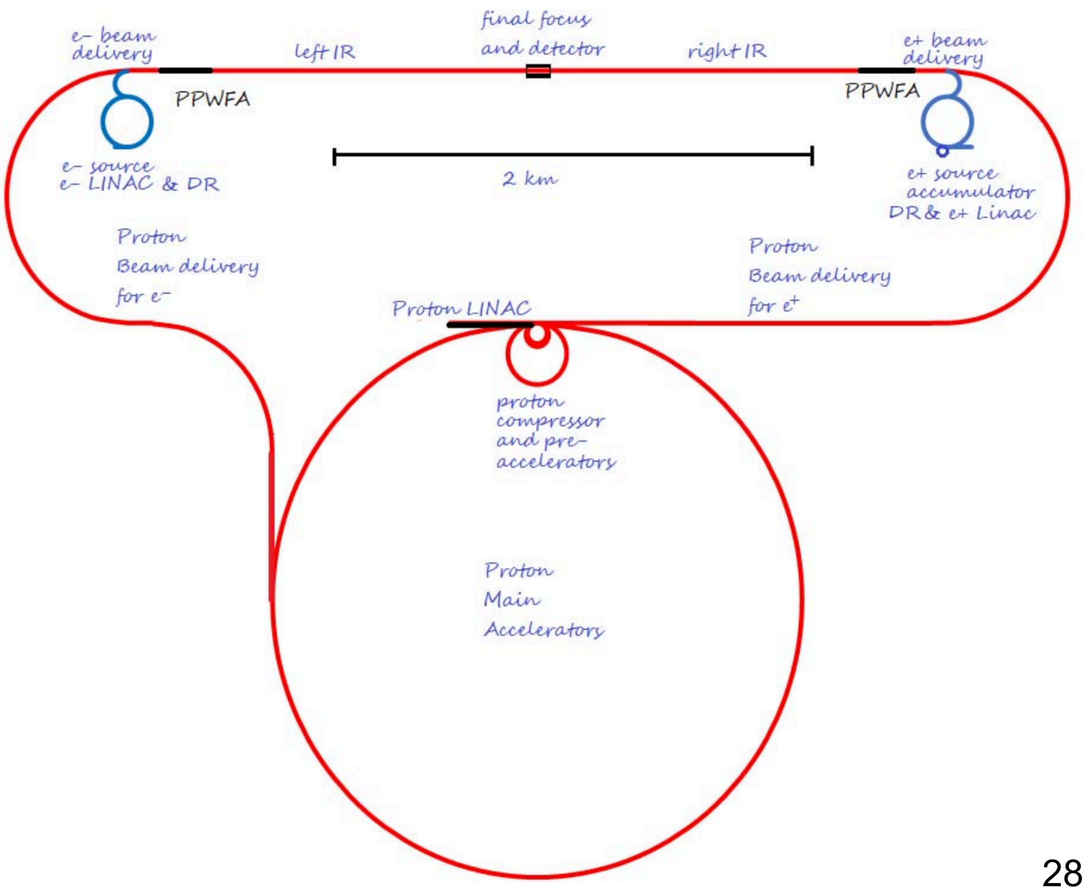
ALIVE

Advanced Linear accelerator for Very high Energies

ALIVE: Advanced LInear accelerator for Very high Energies

- **Short proton bunches**:
  - Higher energy transfer efficiency.
  - Relaxed plasma parameters.
- Good energy scaling:
  - E_p = 400 GeV, E_e = 125 GeV
  - E_p = 7 TeV, E_e ~ multi-TeV





J. Farmer, A. Caldwell & A. Pukhov, *New J. Phys*. **26** (2024) 113011

ALIVE

Advanced Linear accelerator
for Very high Energies

- **Overcoming luminosity limitation with current proton accelerators as drivers:**
  - Two proton accelerator schemes considered.
    - Rapid cycling synchrotrons are not “rapid” enough.
    - **FFAG scheme (F. Willeke)**
      - ✓ Can achieve 500 GeV via several stages with final 6.9 km ring.
      - ✓ Many turns (~ 700) in final ring.
      - ✓ **Rates of 14.4 kHz achievable**.
- Existing tunnels can be used for proton machines to reduce cost and environmental impact.
- Could start with an *ep/eA* collider, e.g. 100s GeV e^- and 7 TeV *p.*
  - High energy (multi-TeV) *ep/eA* physics programme.
  - Initially avoids the positron problem.

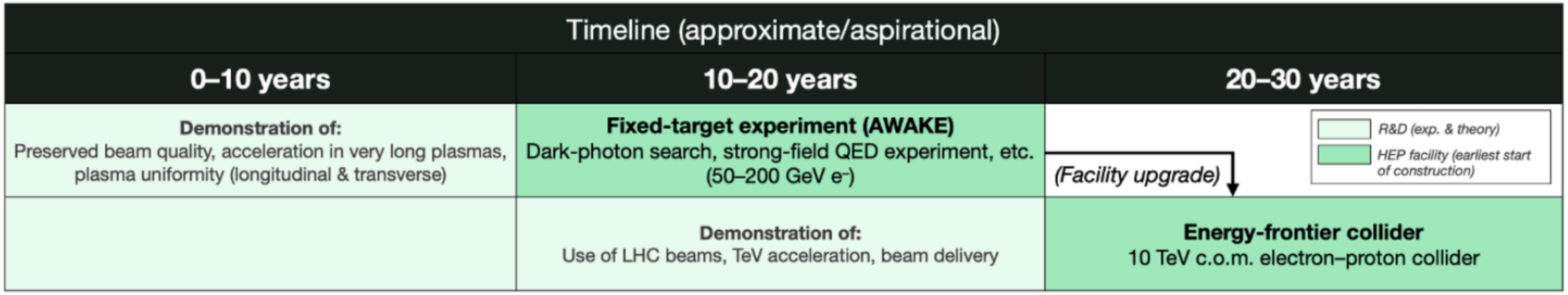
EPPSU input: arXiv:2503.21669

Outlook and summary

Plasma accelerator R&D roadmap for ESPPU

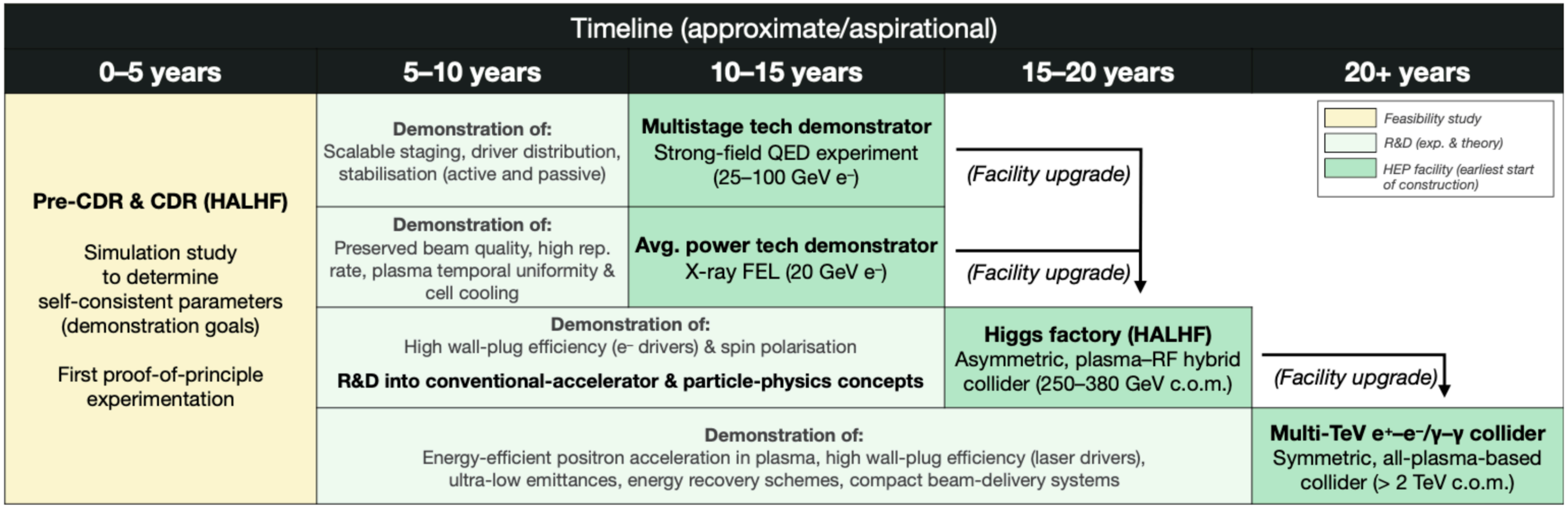
ALIVE adds an extra dimension/possibilities

Single-stage accelerators (proton-driven)



Timeline (approximate/aspirational)		
0–10 years	**10–20 years**	**20–30 years**
Demonstration of: Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon search, strong-field QED experiment, etc. (50–200 GeV e^-)	*(Facility upgrade)* ⬜ *R&D (exp. & theory)* 🟩 *HEP facility (earliest start of construction)*
	Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy-frontier collider** 10 TeV c.o.m. electron–proton collider

Multistage accelerators (Electron-driven or laser-driven)



Timeline (approximate/aspirational)				
0–5 years	**5–10 years**	**10–15 years**	**15–20 years**	**20+ years**
Pre-CDR & CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals) First proof-of-principle experimentation	**Demonstration of:** Scalable staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25–100 GeV e^-)	*(Facility upgrade)*	🟨 *Feasibility study* ⬜ *R&D (exp. & theory)* 🟩 *HEP facility (earliest start of construction)*
	Demonstration of: Preserved beam quality, high rep. rate, plasma temporal uniformity & cell cooling	**Avg. power tech demonstrator** X-ray FEL (20 GeV e^-)	*(Facility upgrade)*	
	Demonstration of: High wall-plug efficiency (e^- drivers) & spin polarisation **R&D into conventional-accelerator & particle-physics concepts**		**Higgs factory (HALHF)** Asymmetric, plasma–RF hybrid collider (250–380 GeV c.o.m.)	*(Facility upgrade)*
	Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser drivers), ultra-low emittances, energy recovery schemes, compact beam-delivery systems			**Multi-TeV e^+–e^-/γ–γ collider** Symmetric, all-plasma-based collider (> 2 TeV c.o.m.)

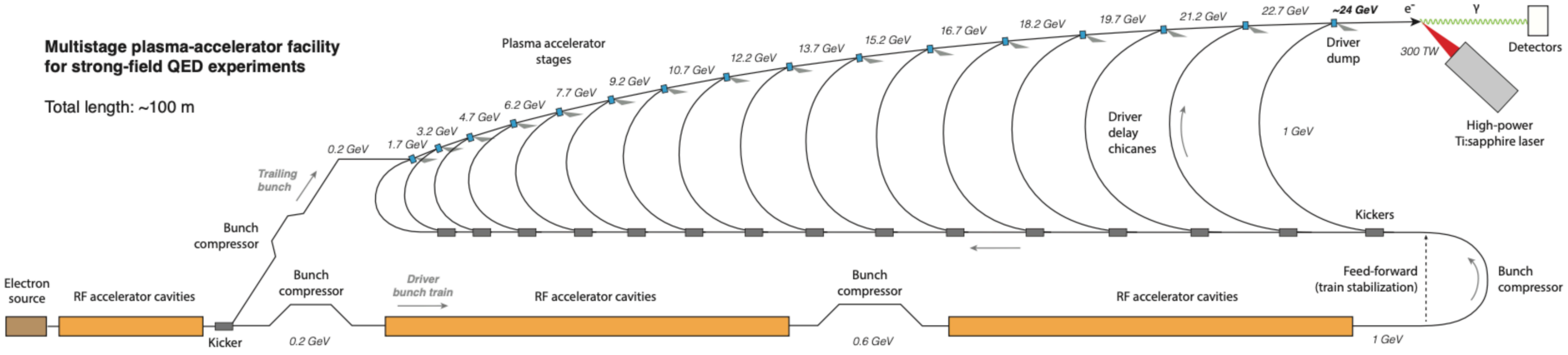
A Hybrid, Asymmetric, Linear Higgs Factory

Major successes

- Achieving, reproducibly, quantities needed for applications:
  - High energy (gradients);
  - Beam quality preservation, especially emittance and energy spread;
  - High energy transfer efficiency;
  - High repetition rates.
- Designs for potential future colliders based on plasma wakefield acceleration becoming more realistic.
  - Meeting the needs of HEP, i.e. energy, luminosity whilst reducing size, cost and environmental impact.
  - Focusing the R&D and challenges.
- Complementary schemes and development of new facilities.
- Also design initiative for a 10 TeV pCM wakefield collider, EPPSU input: arXiv:2503.20214.

Major challenges

- Need to demonstrate single stage accelerator “module” where all criteria are met simultaneously.
- Should demonstrate positron acceleration → needs new facility.
- Demonstration of staging needed especially for electron-driven wakefield acceleration → needs new facility.
- Heating and cooling of plasma cells.
- Spin polarisation expected to be preserved but needs to be demonstrated.
- Multi-stage demonstrator facility with a physics application.



Concept for multi-stage demonstrator facility with strong-field QED experiment.

Image credit: C. A. Lindstrøm

Summary

- Plasma wakefield acceleration has made a lot of progress in recent years.
  - Both in the R&D and design/application to HEP.
- It faces a number of challenges to demonstrate it as technology that can be used for HEP.
  - Significant increase in funding can lead to new facilities and the challenges being met in a timely fashion.
- Great opportunities to make an impact in plasma, accelerator and particle physics and beyond.

Back-up

FLASHFORWARD▸▸ THE FACILITY

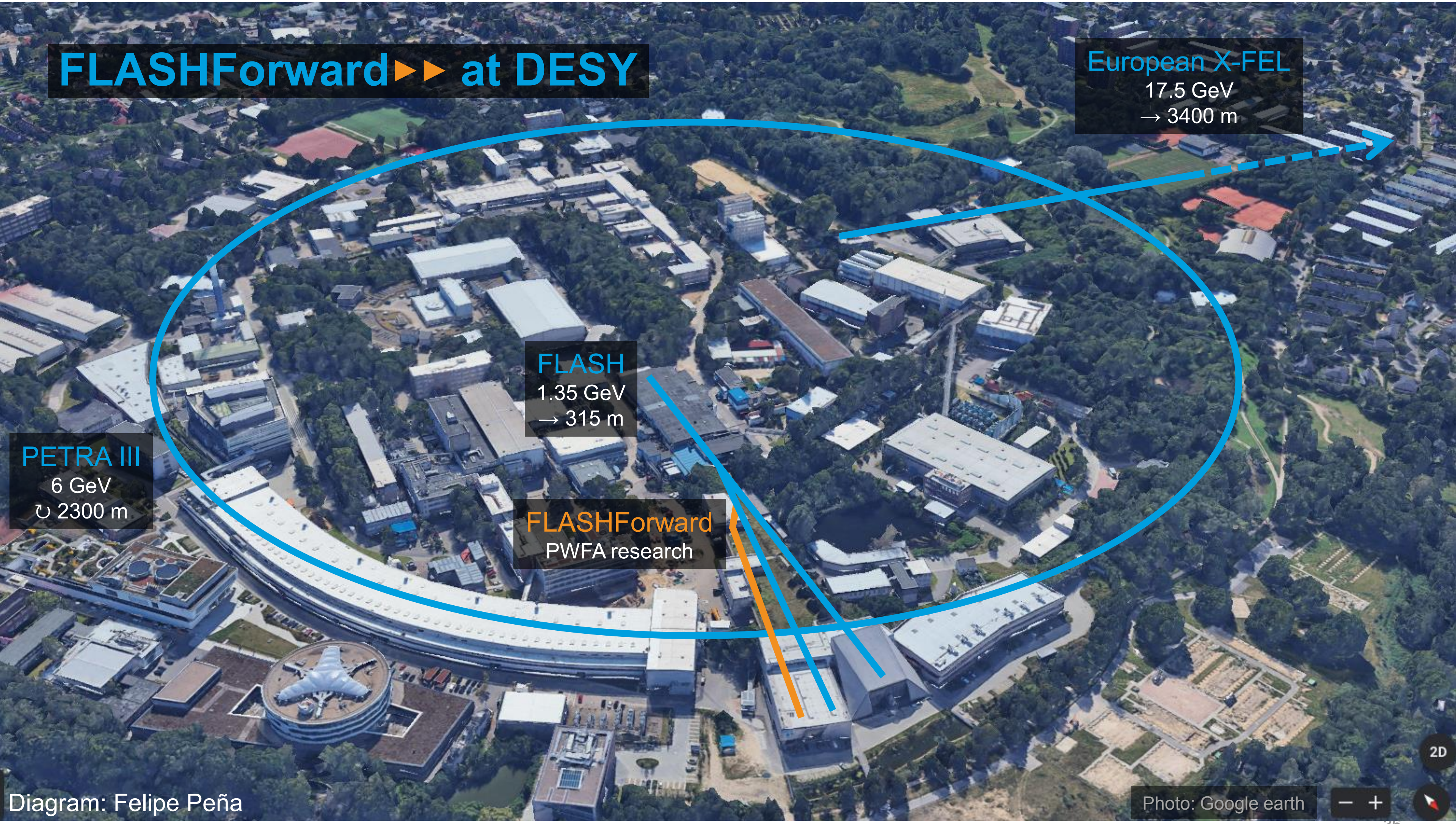


Diagram: Felipe Peña

Photo: Google earth

FLASHForward goals

Develop a self-consistent plasma-accelerator stage

with high quality, high efficiency and high average power at 1 GV/m

High beam quality

Low energy spread

Emittance preservation

High efficiency

Driver depletion

Plasma-to-witness efficiency

High average power

Rapid recovery time

High repetition rate

R. D’Arcy et al., *Phil. Trans. Roy. Soc.* **A 377** (2019) 20180392
https://forward.desy.de/

Recovery time of plasma

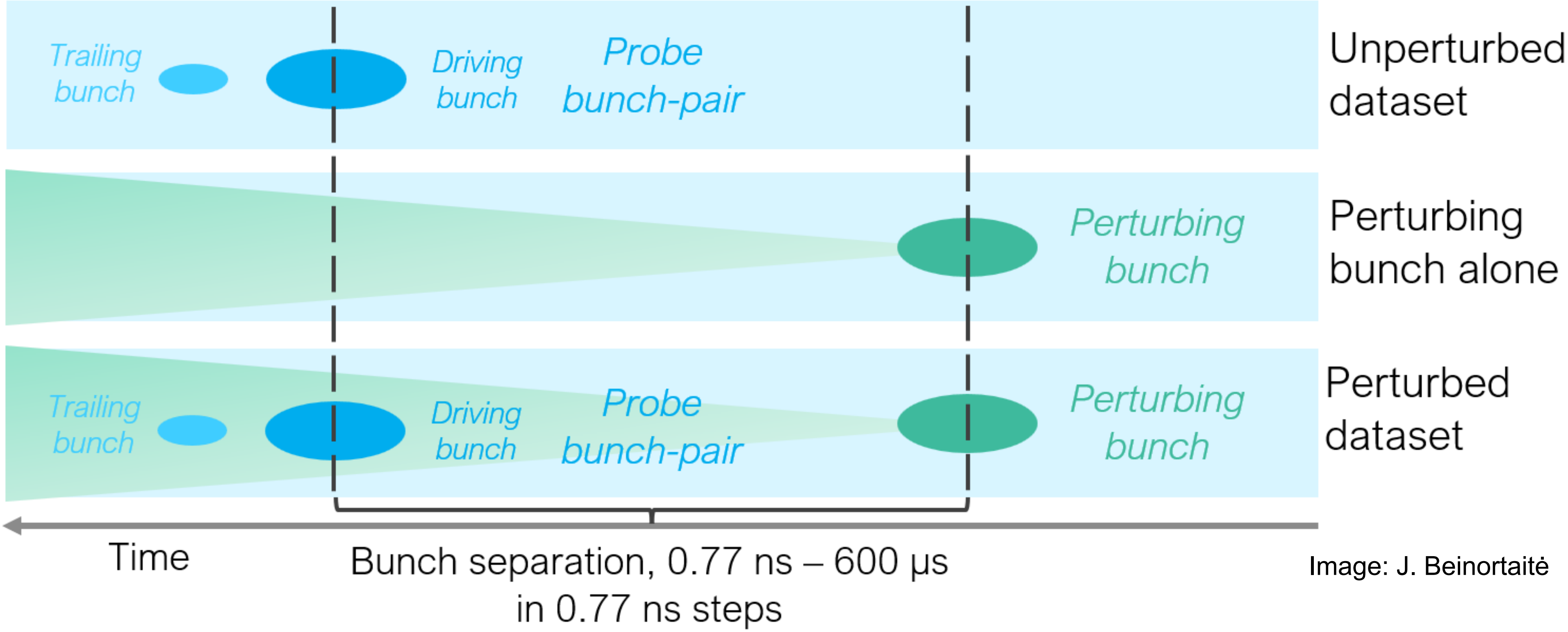
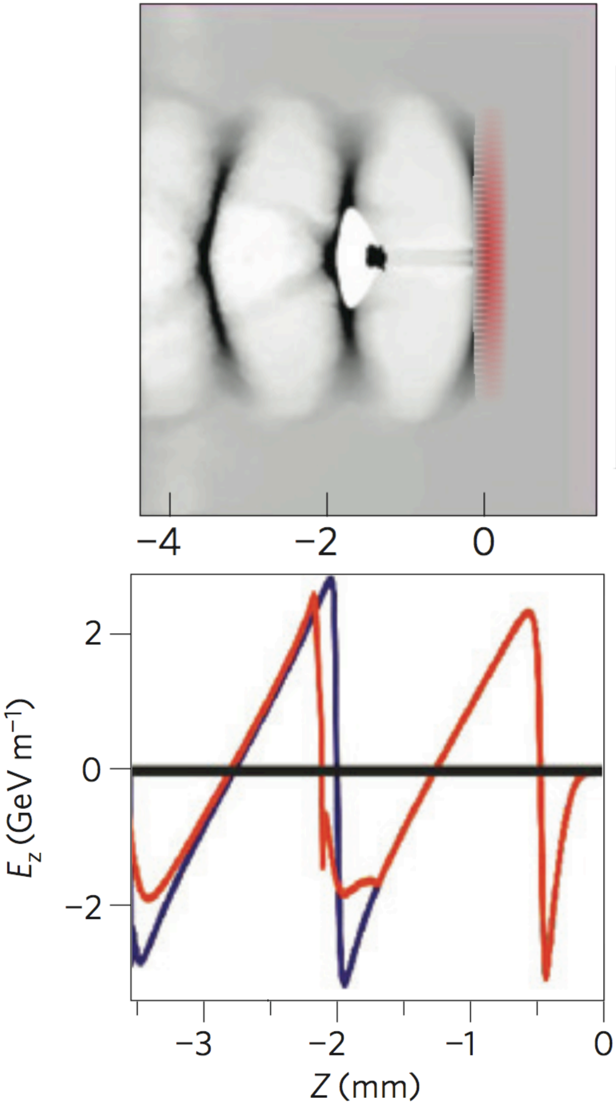
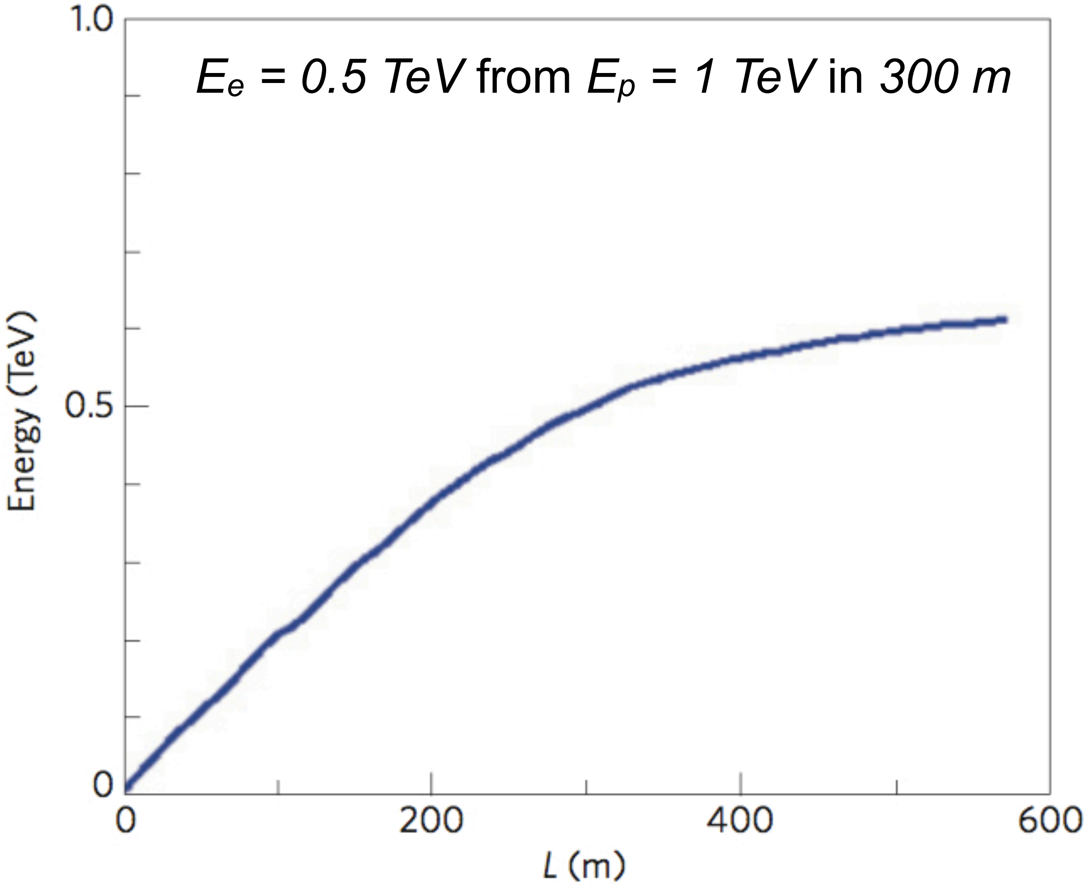


Image: J. Beinortaitė

How soon after acceleration can we accelerate another bunch in the same plasma ?

Proton-driven plasma wakefield acceleration concept*





E_e = *0.5 TeV* from E_p = *1 TeV* in *300 m*

Note proton bunch length, *100 µm*; cf LHC, bunch length, *~10 cm*

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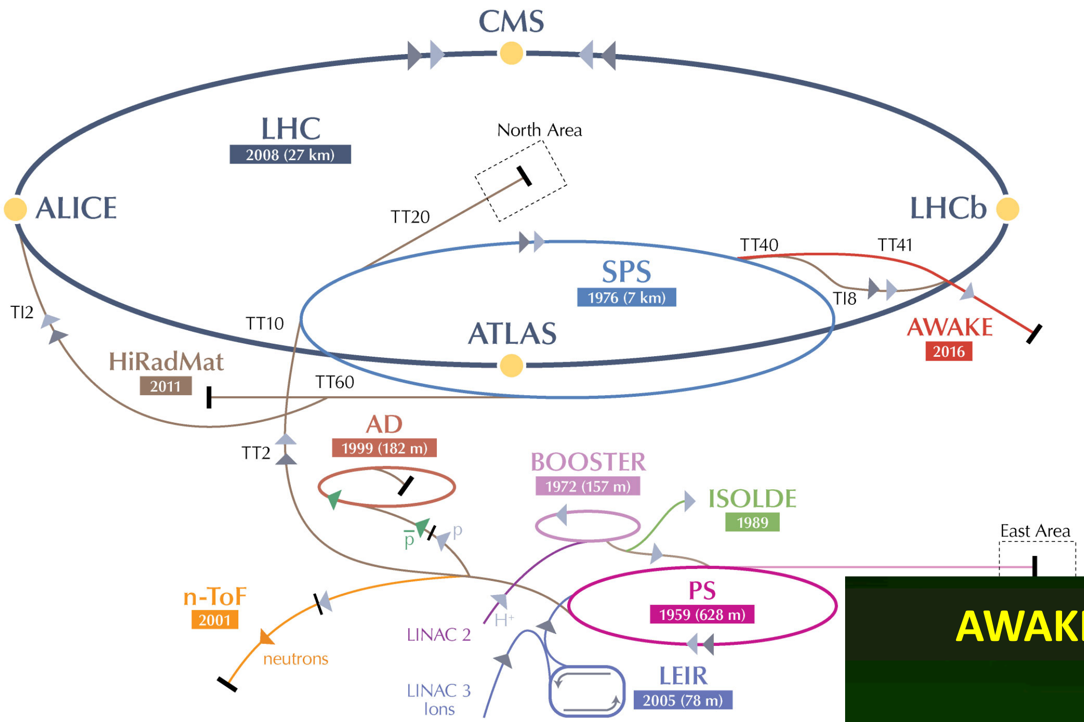
* A. Caldwell *et al.*, Nature Physics **5** (2009) 363.

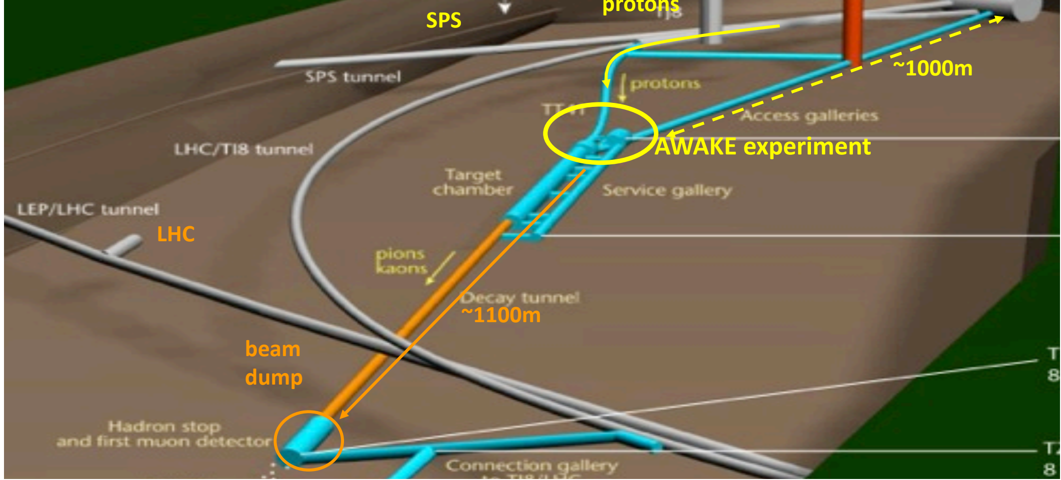
AWAKE experiment at CERN



Demonstrate for the first time proton-driven plasma wakefield acceleration.

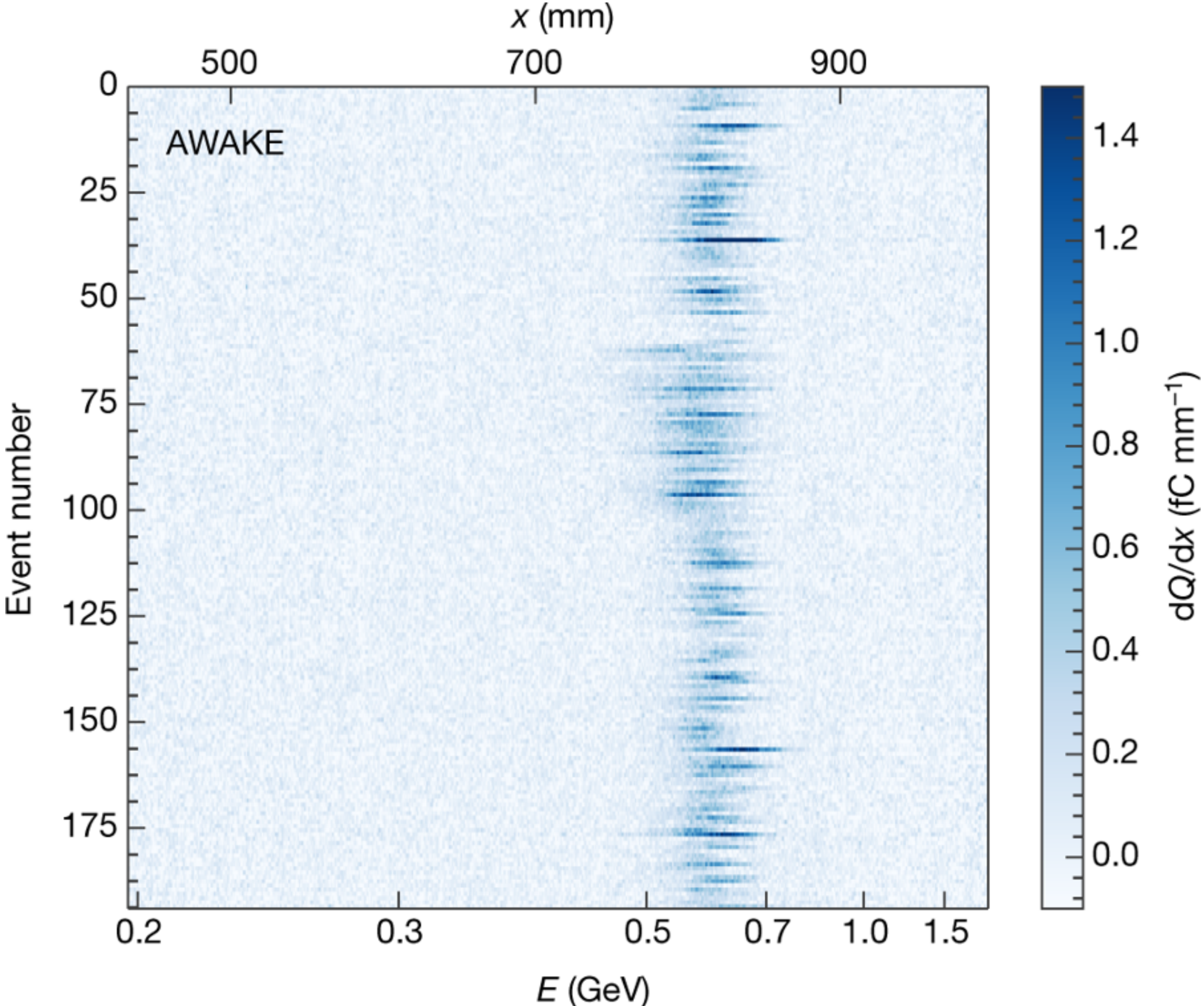
Advanced proton-driven plasma wakefield experiment.

Using *400 GeV* SPS beam in former CNGS target area.



AWAKE Coll., Plasma Phys. Control. Fusion **56** (2014) 084013; Nucl. Instrum. Meth. **A 829** (2016) 3; Nucl. Instrum. Meth. **A 829** (2016) 76.

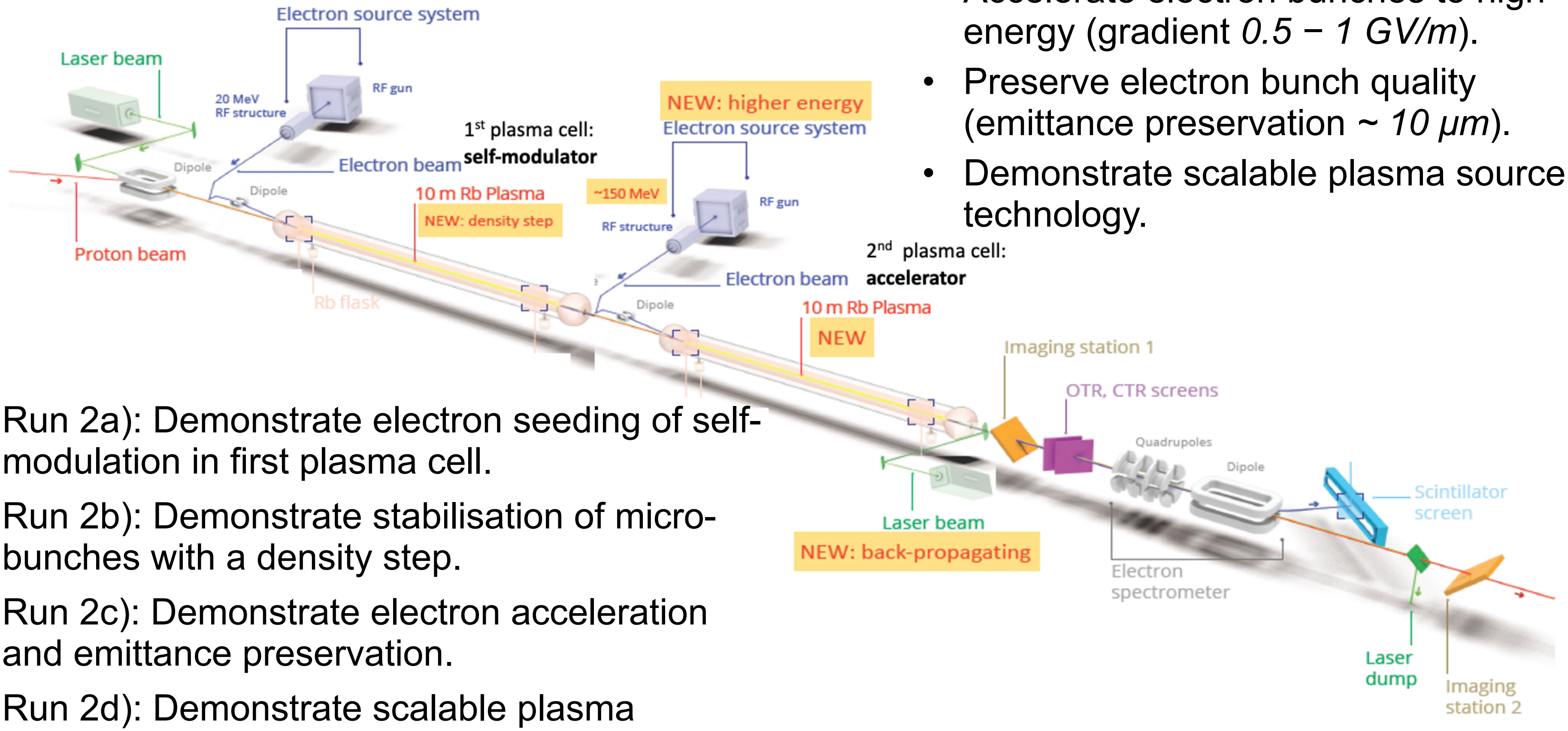
Electron acceleration reproducibility



AWAKE Run 2

Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future.

- Accelerate electron bunches to high energy (gradient *0.5 − 1 GV/m*).
- Preserve electron bunch quality (emittance preservation ~ *10 μm*).
- Demonstrate scalable plasma source technology.

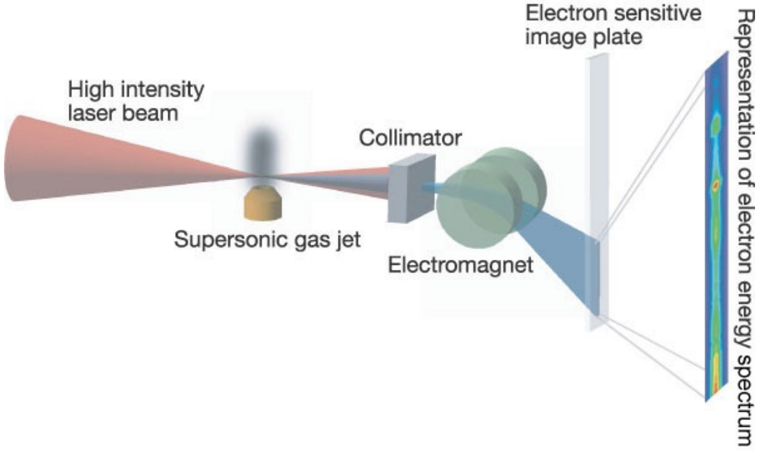


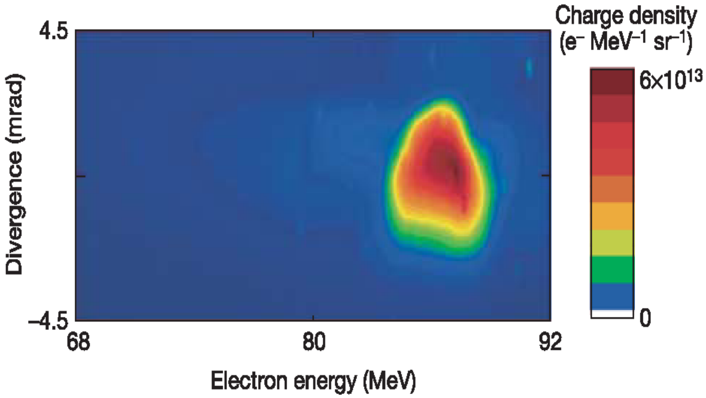
- Run 2a): Demonstrate electron seeding of self-modulation in first plasma cell.
- Run 2b): Demonstrate stabilisation of micro-bunches with a density step.
- Run 2c): Demonstrate electron acceleration and emittance preservation.
- Run 2d): Demonstrate scalable plasma sources.

- **Then applications to particle physics experiments by end of decade**
  - Are there experiments that require an electron beam of *O(50 GeV)* ?
  - Using the LHC beam as a driver, *TeV* electron beams are possible.

First laser-driven plasma wakefield experiments

2004 result: *10 TW* laser, *mm* scale plasma



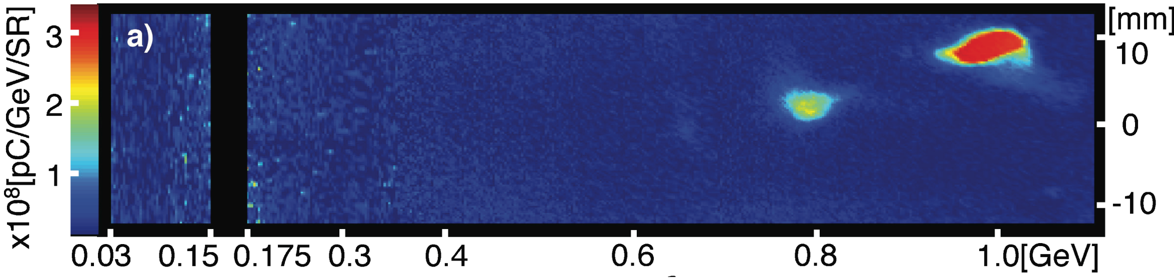


~ *100 MeV* beams.

S. Mangles et al., Nature **431** (2004) 535
C.G.R. Geddes et al., Nature **431** (2004) 538
J. Faure et al., Nature **431** (2004) 541

2006 result: *40 TW* laser, *cm* scale plasma

First *GeV* beams.



W.P. Leemans et al., Nature Phys. **2** (2006) 696
K. Nakamura et al., Phys. Plasmas **14** (2007) 056708