Beam Driven Experiments

CERN Accelerator School
High Gradient Wakefield Accelerator
11 – 22 March 2019, Sesimbra, Portugal

Edda Gschwendtner, CERN

Many thanks for valuable input from:

Massimo Ferrario, Spencer Gessner, Bernhard Hidding, Patric Muggli,
Jens Osterhoff, Guoxing Xia

Outline

- Introduction
    - Motivation and basic numbers for PWFA

- **Facilities** and **Experimental Results** of **Key Challenges** for PWFA

- Future Facilities and Experiments

Note that I show a personal selection of experiments!

Motivation for PWFA

- Short term perspective of PWFA (< 10 years):
  - Compact FEL based: 5 – 10 GeV energy range
  - Compact X-ray sources: electron accelerated in strong transverse field of plasma emit betatron radiation

  ➔applications in medicine, radiobiology, material science

- Long term perspective of PWFA (>20 years):
  - High energy physics applications: Plasma-based high energy linear collider

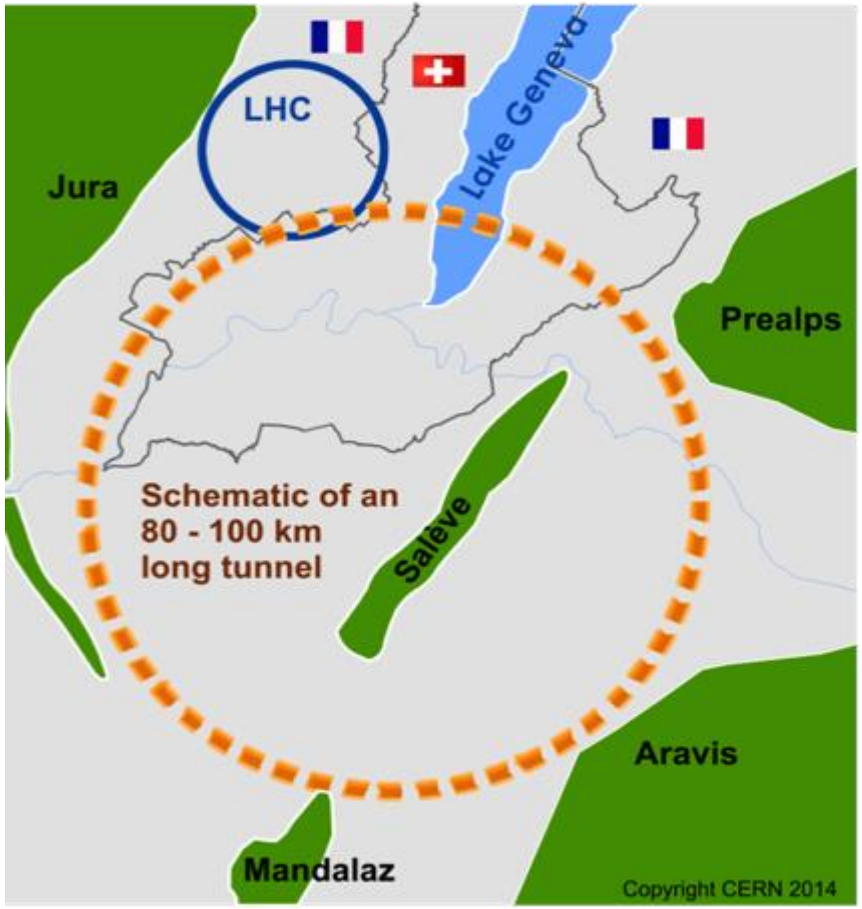
  ➔ depends strongly on progress in many fields.

The most demanding application of plasma wakefield acceleration is to build a **compact, efficient, Plasma-Based Linear Collider**.

Discover New Physics

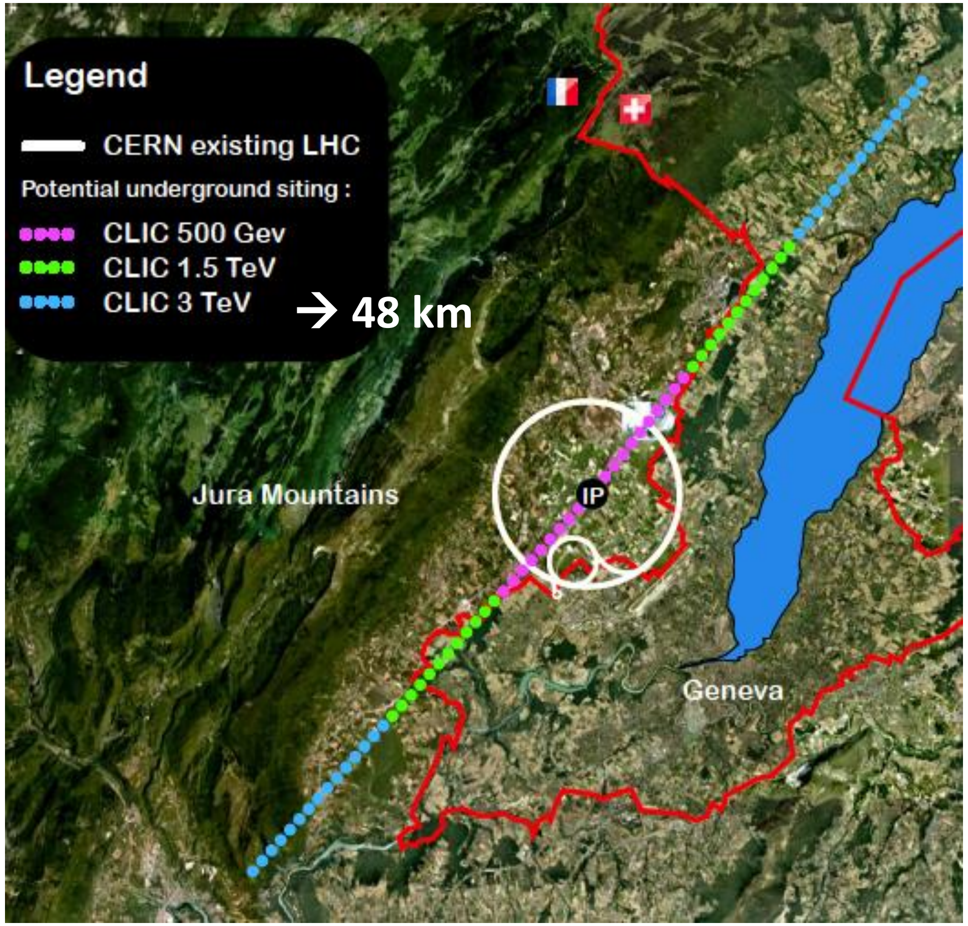
Accelerate particles to even higher energies → **Bigger accelerators**

Future Circular Collider FCC



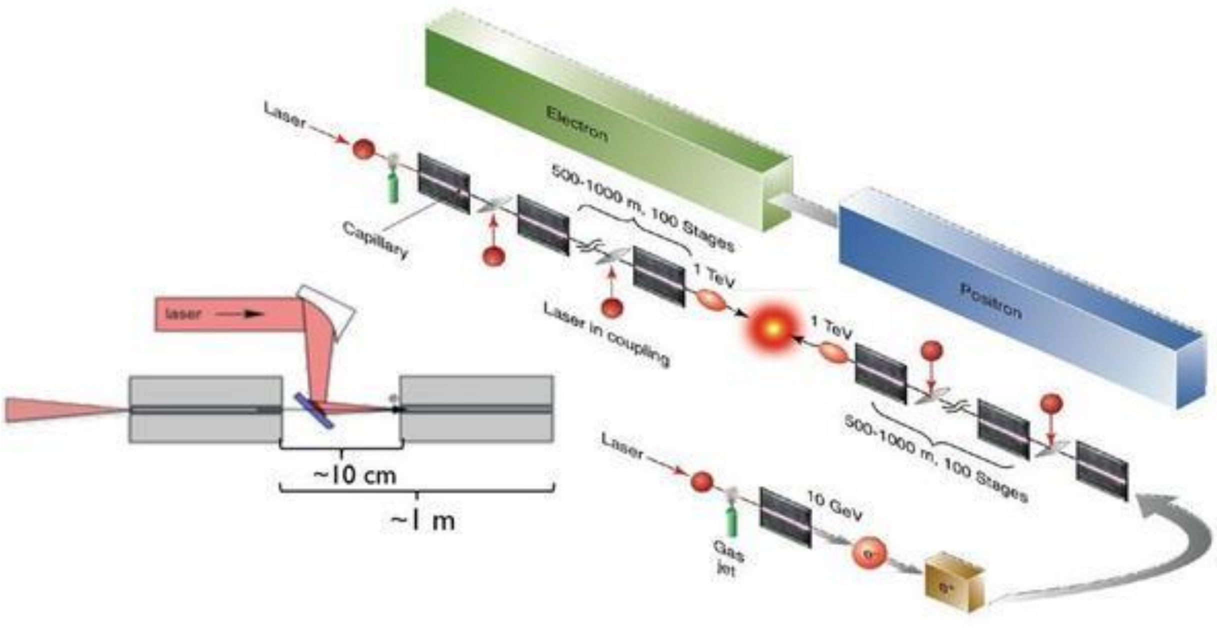
Hadrons: 16T magnets to reach 100TeV
Electrons: synchrotron radiation limits – 350GeV

CLIC, electron-positron collider with 3 TeV energy

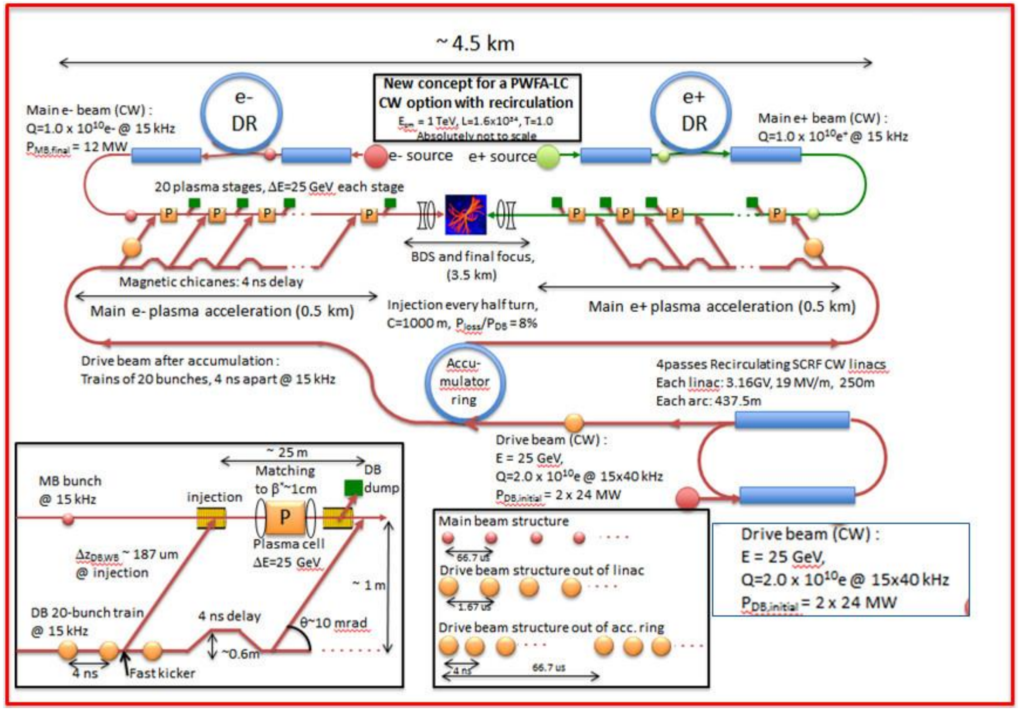


Gradient: < 100MV/m
Linear collider: single pass

Plasma Based Linear Colliders



C. B. Schroeder *et. al*. Phys. Rev. ST Accel. Beams **13**, 101301



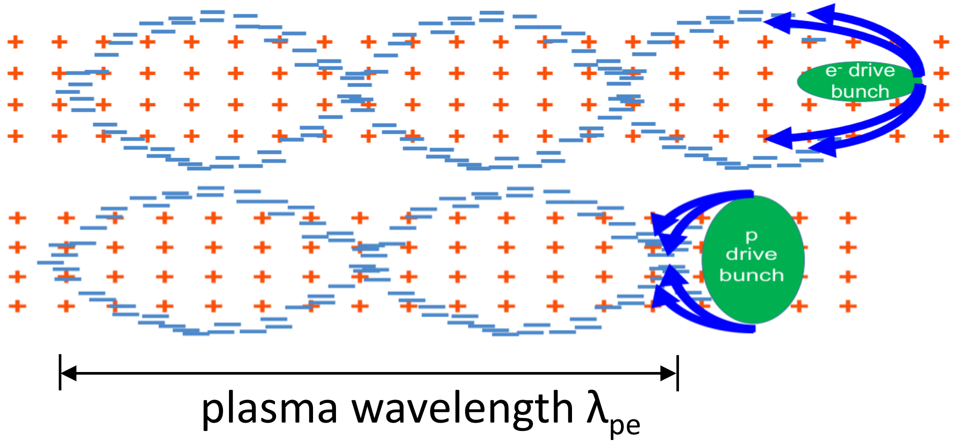
E. Adli *et. al*.,arXiv:1308.1145 [physics.acc-ph]

In 2011 and 2013, the plasma acceleration groups from Berkeley and SLAC put forward white papers for laser and beam-driven plasma-based linear colliders. → **3 TeV in ~5km.**

Plasma Wakefield Acceleration

Different ways to excite the wakes - most commonly used:

- Laser bunches, Electron beams, Protons bunches



A plasma of density n_{pe} is characterized by the plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \rightarrow \frac{c}{\omega_{pe}} \text{ ... unit of plasma [m]} \qquad k_{pe} = \frac{\omega_{pe}}{c}$$

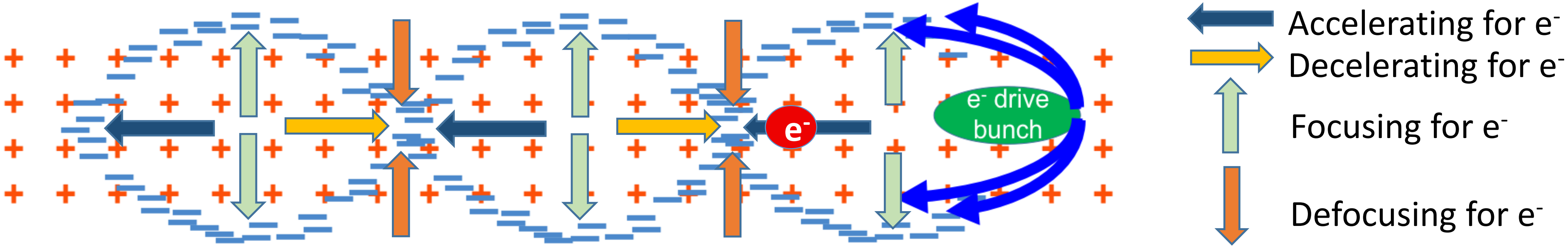
Example: $n_{pe} = 7\text{x}10^{14}\ \text{cm}^{-3}$ (AWAKE) → $\omega_{pe} = 1.25\text{x}10^{12}$ rad/s → $\frac{c}{\omega_{pe}}$ **= 0.2mm** → $k_{pe} = 5\ \text{mm}^{-1}$

This translates into a wavelength of the plasma oscillation

$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \rightarrow \lambda_{pe} \approx 1\ \text{mm} \sqrt{\frac{10^{15}\ \text{cm}^{-3}}{n_{pe}}}$$

$$\boxed{\lambda_{pe} = 1.2\ \text{mm}}$$ → **Cavities with mm size!**

Wakefields



How strong can the fields be?

- The plasma oscillation leads to a longitudinal accelerating field. The maximum accelerating field (wave-breaking field) is:

$$e\,E_{WB} = 96\,\frac{V}{m}\sqrt{\frac{n_{pe}}{cm^{-3}}}$$

- The ion channel left on-axis, where the beam passes, induces an **ultra-strong focusing field:**

$$g = 960\,\pi\,\frac{n_{pe}}{10^{14}\,cm^{-3}}\,\frac{T}{m}$$

Example: n_{pe} = 7×10^{14} cm^{-3} (AWAKE) ➔ eE_{WB} = 2.5 GV/m ➔ g = 21kT/m

Example: n_{pe} = 7×10^{17} cm^{-3} ➔ eE_{WB} = 80 GV/m ➔ g = 21MT/m

Linear Theory

(R. D. Ruth, P. Chen, SLAC-PUB-3906, 1986)

When drive beam density is smaller than plasma density ($n_b << n_p$) → **linear theory.**

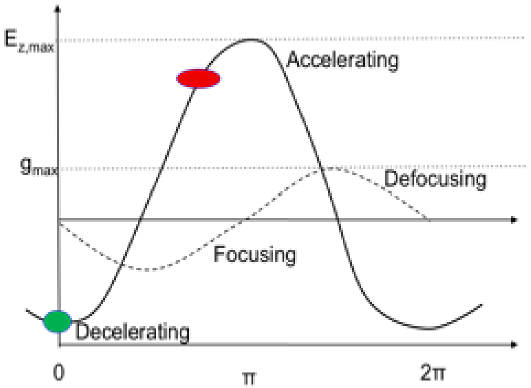
- Peak accelerating field in plasma resulting from drive beam with Gaussian distribution:

$$eE_z = \sqrt{n_p}\,\frac{n_b}{n_p}\,\frac{\sqrt{2\pi}\,k_p\sigma_z e^{-k_p^2\sigma_z^2/2}}{1+\frac{1}{k_p^2\sigma_r^2}}\sin k_p(z-ct) \quad (eV/cm)$$

B.E. Blue 2003

$$\boxed{\Rightarrow eE_z \approx N/\sigma_z^2}$$

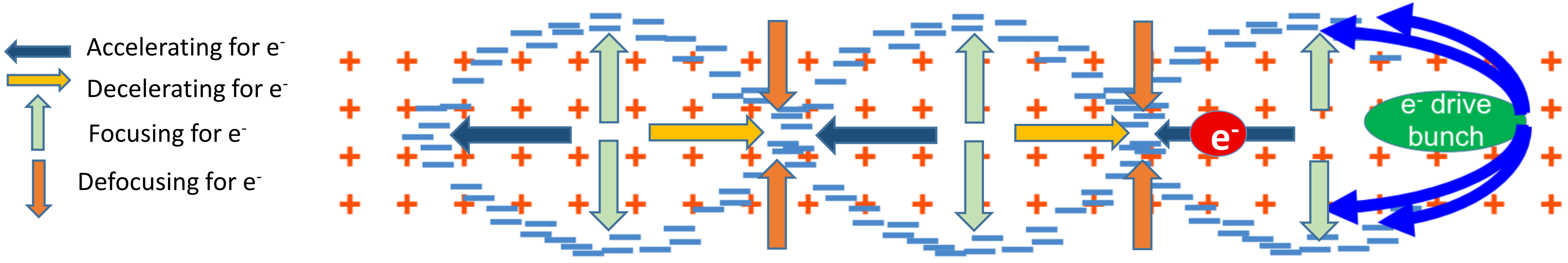
- **Wakefield** excited by bunch oscillates **sinusoidally** with frequency determined by plasma density
- **Accelerating gradient** increases linearly with $\mathbf{N/\sigma_z}$
- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**
- The **accelerating field is maximized** for a value of

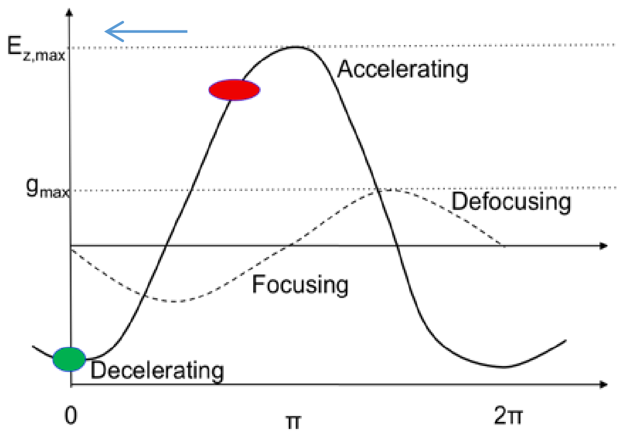


$$\boxed{\begin{array}{l} k_{pe}\,\sigma_z \approx \sqrt{2} \\ k_{pe}\,\sigma_r \leq 1 \end{array}}$$

Example: $n_{pe} = 7\text{x}10^{14}\ \text{cm}^{-3}$ **(AWAKE),** $k_{pe} = 5\ \text{mm}^{-1}$ → **drive beam:** $\sigma_z = 300\mu\text{m}$, $\sigma_r = 200\mu\text{m}$

Linear Theory





Linear Theory: Maximum accelerating electric field reached with drive beam of N and σ_z:

$$E_{acc} = 110 \frac{\mathrm{MV}}{\mathrm{m}} \frac{N/(2 \times 10^{10})}{(\sigma_z / 0.6\mathrm{mm})^2}$$

← Driver must be short compared to plasma wavelength, easy for laser and electron bunches.

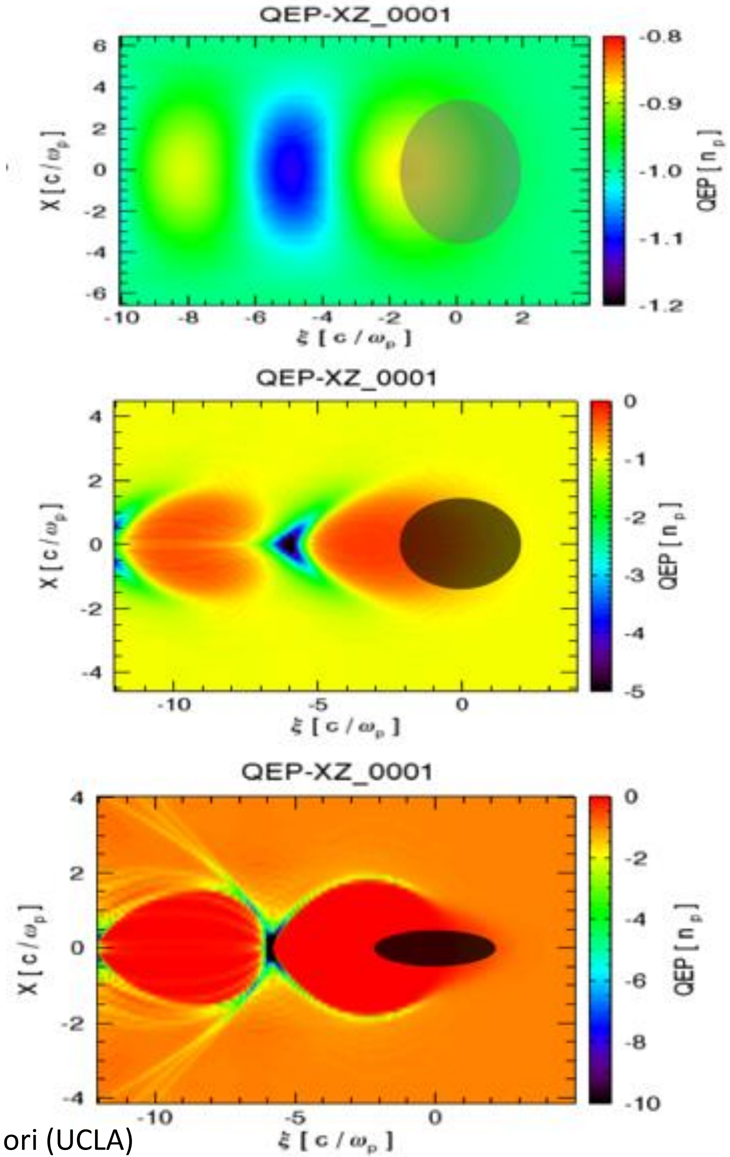
Examples of accelerating fields for different beam parameters and plasma parameters fields:

N = $3x10^{10}$, σ_z = 300µm, n_{pe}= $7x10^{14}$ cm^{-3} ➔ **E_{acc} = 600 MV/m**

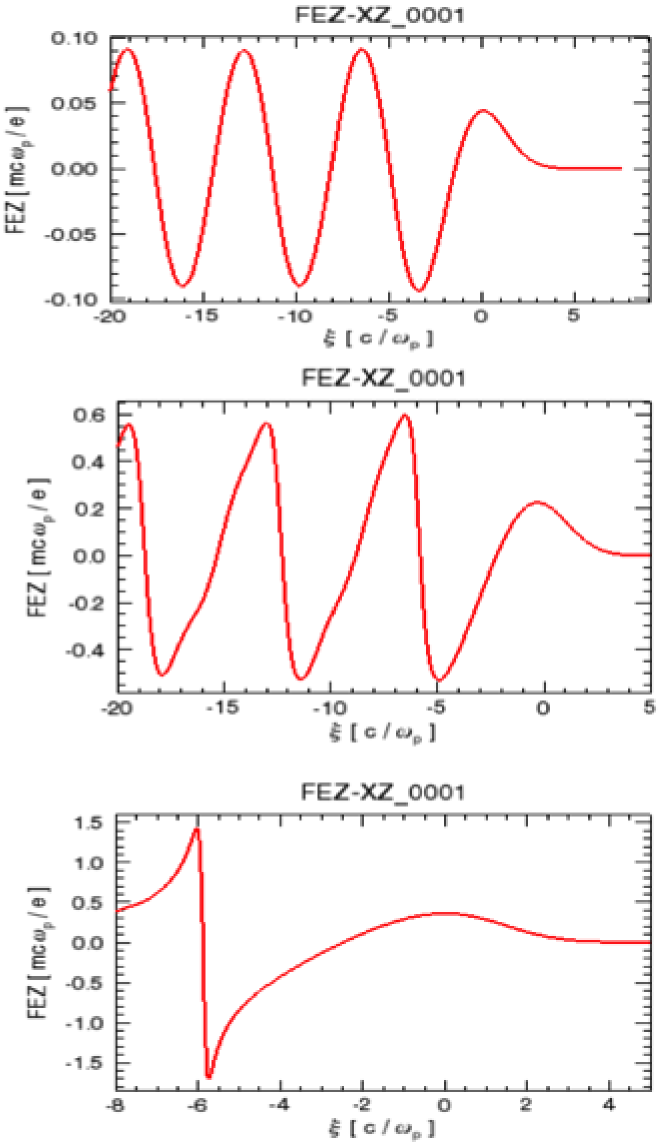
N = $3x10^{10}$, σ_z = 20µm, n_{pe}= $2x10^{17}$ cm^{-3} ➔ **E_{acc} = 15 GV/m**

From Linear to Non-Linear

Electron density :



Longitudinal fields :



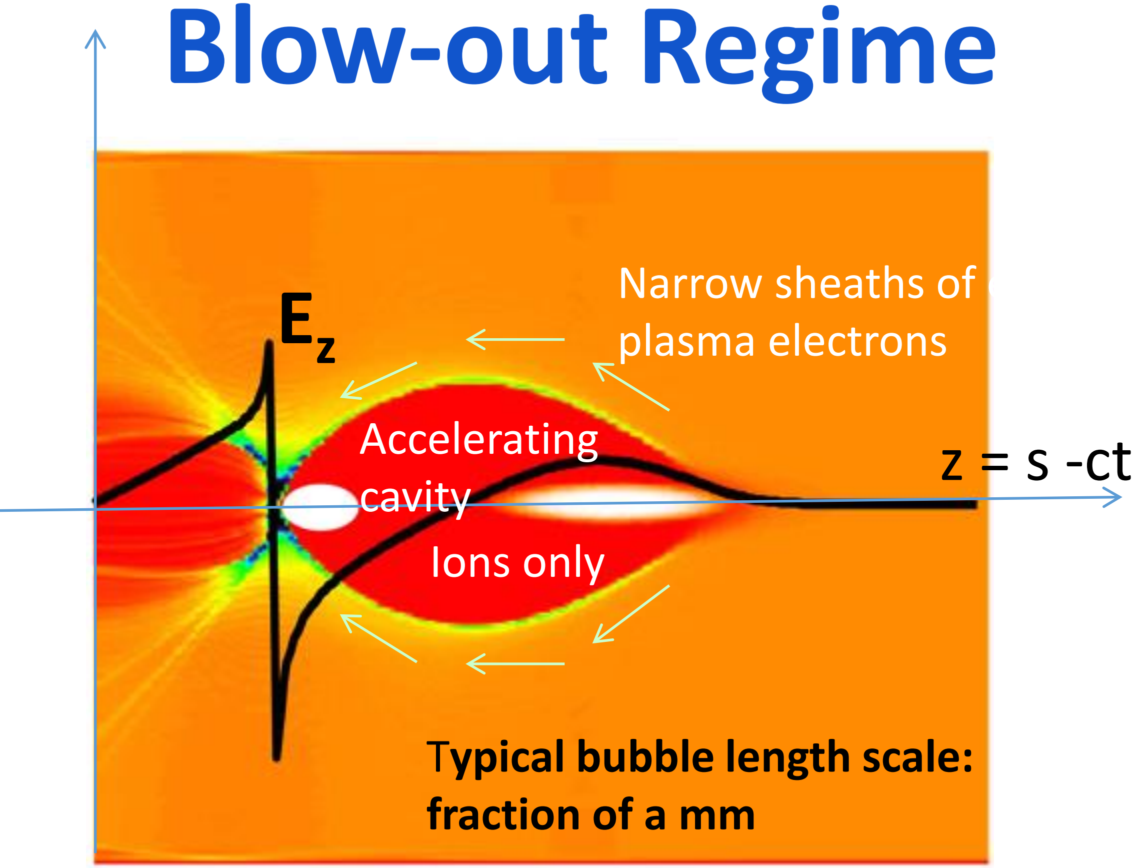
$n_b << n_{pe}$ – linear regime

$n_b \sim n_{pe}$ – non-linear wakes

$n_b >> n_{pe}$ – **blow-out regime**

W. Mori (UCLA)

Blow-out Regime



Typical bubble length scale: fraction of a mm

- **Space-charge force** of the driver blows away **all the plasma electrons** in its path, leaving a uniform layer of ions behind (ions move on a slower time scale).
- Plasma electrons form a **narrow sheath** around the evacuated area, and are **pulled back by the ion-channel** after the drive beam has passed
- An **accelerating cavity** is formed in the plasma
- The back of the blown-out region: **ideal for electron acceleration**

→ **High charge witness** acceleration possible → charge ratio to witness of same order
→ **Linear focusing in r**, for electrons; very strong quadrupole (MT/m)
→ **High transformer ratios (>2)** can be achieved by shaping the drive bunch
→ **E_r independent of x**, can **preserve incoming emittance** of witness beam

Challenges to Build Plasma Wakefield Accelerators

Typically in plasma wakefield accelerators we have

- gradient of several GV/m
- strong focusing fields of several 100 kT/m
- the matched beam size of the witness beam is small , $\sigma_w \approx \mu m$
- optical beta function of witness beam is small, e.g. $\beta \approx \mu m$
- tolerances for emittance growth is small! (100% growth for 1σ offset)

- Energy spread ←→ uniformity of the accelerating fields (in r, z)
  - Control charge and beam loading to compensate energy spread
  - Use short bunches to minimize energy spread

- Emittance preservation ←→ focusing field (in r,z)

- Alignment control between wakefield driver and witness electron bunch at 1 μm level.

- Many more!….

Beam-Driven Wakefield Acceleration: Landscape Today

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II preparation, starting 2018
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments

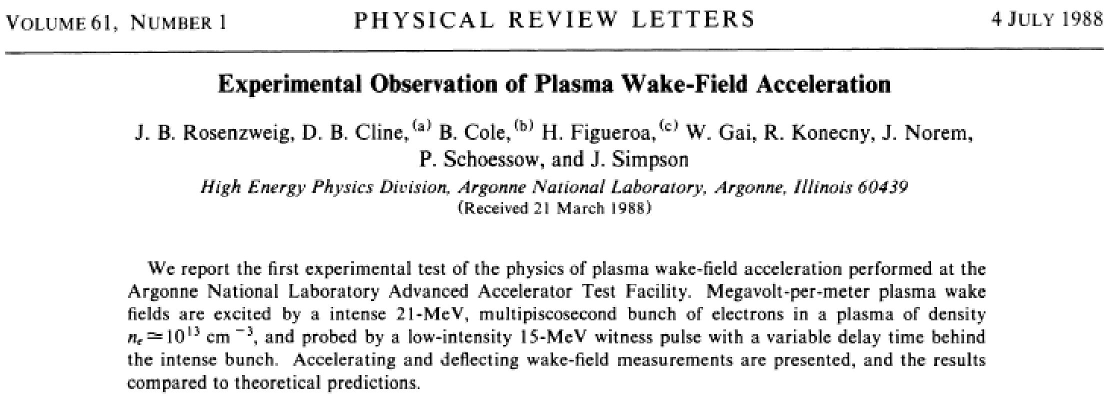
Key Challenges for PWFA

- Accelerating gradient
- Beam quality
- Transformer Ratio
- Positron acceleration
- Protons as drive beam

Facilities and Experimental Results of Key Challenges for PWFA

- Accelerating gradient
- Beam quality
- Transformer Ratio
- Positron acceleration
- Protons as drive beam

First Beam Driven Acceleration 1988



VOLUME 61, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1988

Experimental Observation of Plasma Wake-Field Acceleration

J. B. Rosenzweig, D. B. Cline,[a] B. Cole,[b] H. Figueroa,[c] W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson

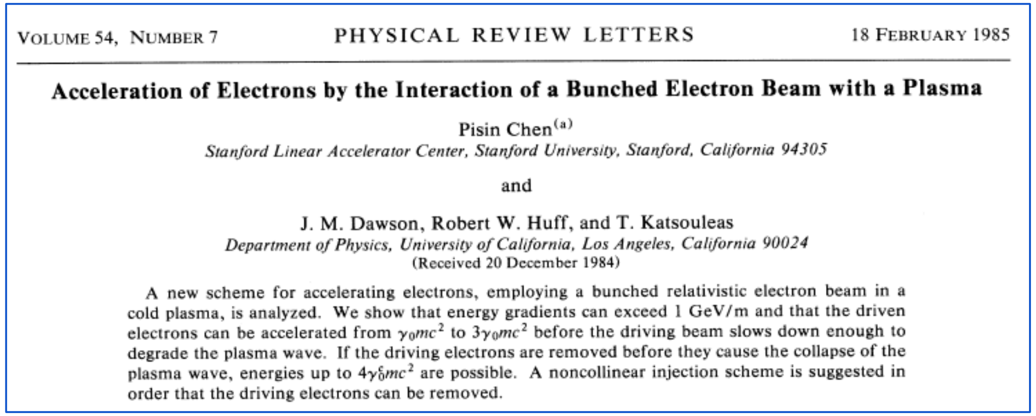
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 21 March 1988)

We report the first experimental test of the physics of plasma wake-field acceleration performed at the Argonne National Laboratory Advanced Accelerator Test Facility. Megavolt-per-meter plasma wake fields are excited by a intense 21-MeV, multipiscosecond bunch of electrons in a plasma of density $n_e \simeq 10^{13}$ cm^{-3}, and probed by a low-intensity 15-MeV witness pulse with a variable delay time behind the intense bunch. Accelerating and deflecting wake-field measurements are presented, and the results compared to theoretical predictions.

Argonne National Lab

Theoretical paper for beam driven PWFA 1985



VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[a]

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas

Department of Physics, University of California, Los Angeles, California 90024

(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^2 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

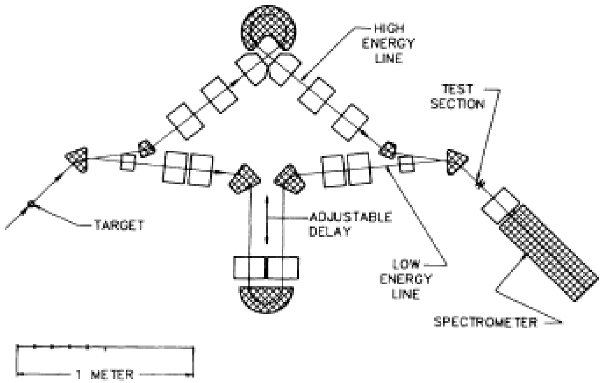


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

- Drive beam: 21 MeV, witness beam: 15 MeV $\sigma_z = \sigma_r = 2.4$mm, charge: 2-3nC
- DC plasma source, Argon, $n_e = 0.7\text{-}7\times10^{13}$cm^{-3}

Linear theory: $n_e = 8\times10^{12}$cm^{-3}

➔ Result: **Wakefields of order 1 MV/m**

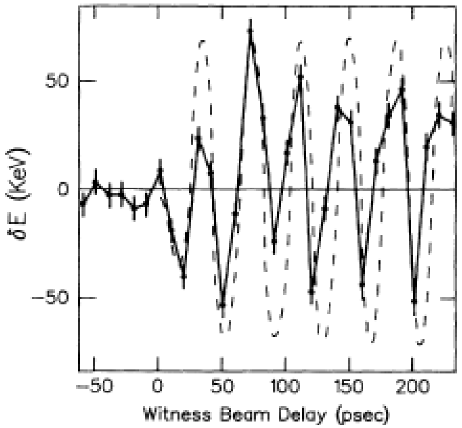


FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q = 2.1$ nC; plasma parameters $L = 28$ cm and $n_e = 8.6\times10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

Record Acceleration, at SLAC: 42 GeV

Final Focus Test Beam Facility, **FFTB** at SLAC

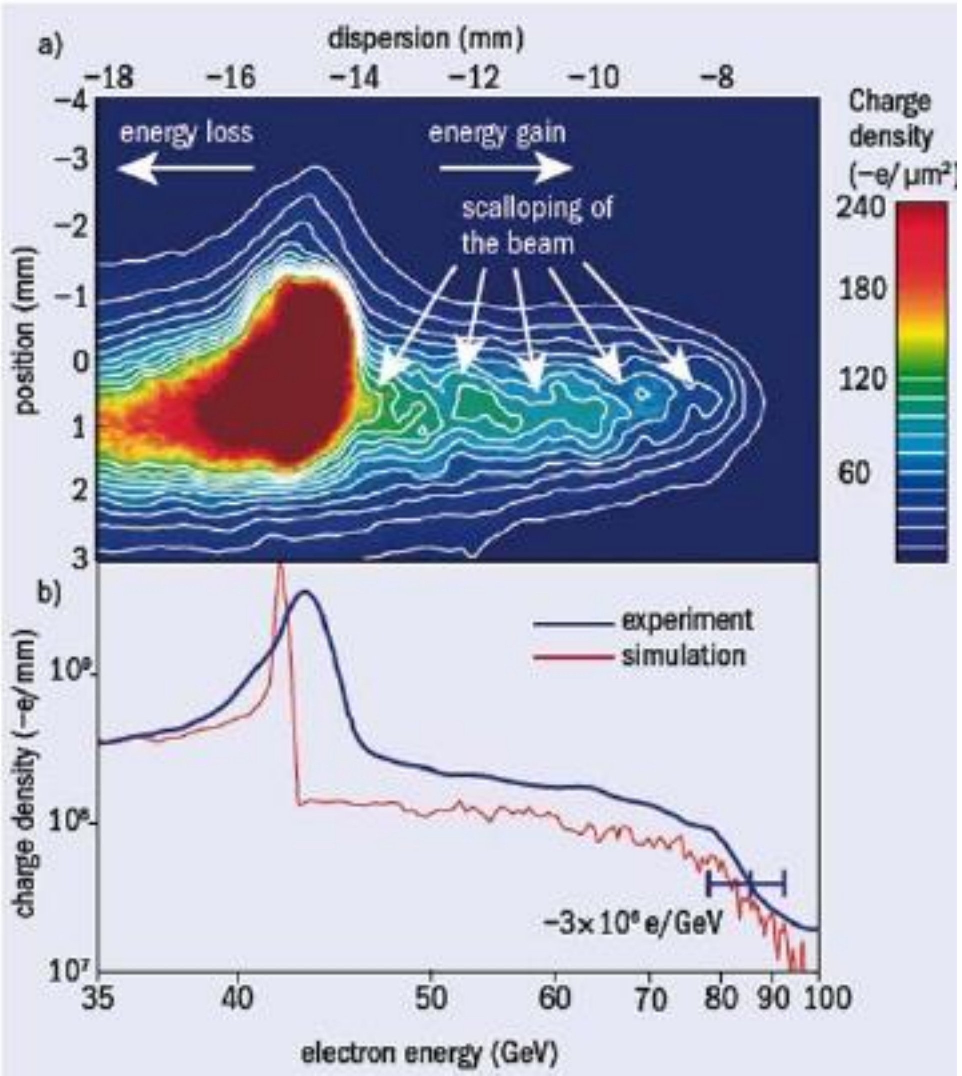
I. Blumenfeld et al, Nature 455, p 741 (**2007**)

Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, σ_x = 10µm, 50 fs

85cm Lithium vapour source, $2.7\text{x}10^{17}\text{cm}^{-3}$

➔ Accelerated electrons from 42 GeV to 85 GeV in 85 cm.

➔ Reached accelerating gradient of **52 GeV/m**



Facilities and Experimental Results of Key Challenges for PWFA

- Accelerating gradient
- Beam quality
- Transformer Ratio
- Positron acceleration
- Protons as drive beam

Metre-Scale Plasma Wakefield Accelerator Driven by a Matched Electron Beam, 2004

Muggli et al., PRL 93.014802, (2004)

Beam envelope dynamics described by an envelope model for the transverse beam size.

Match beam and plasma: if focusing force on the beam by the plasma compensates divergence coming from the beam emittance, then
→ beam focused at plasma entrance propagates along the plasma with a constant transverse size.

$$0 = \frac{d^2\sigma_r}{dz^2} = -K\sigma_r + \frac{\epsilon^2}{\sigma_r^3}$$

$K=\omega_p^2/2\gamma c^2$… plasma focusing strength

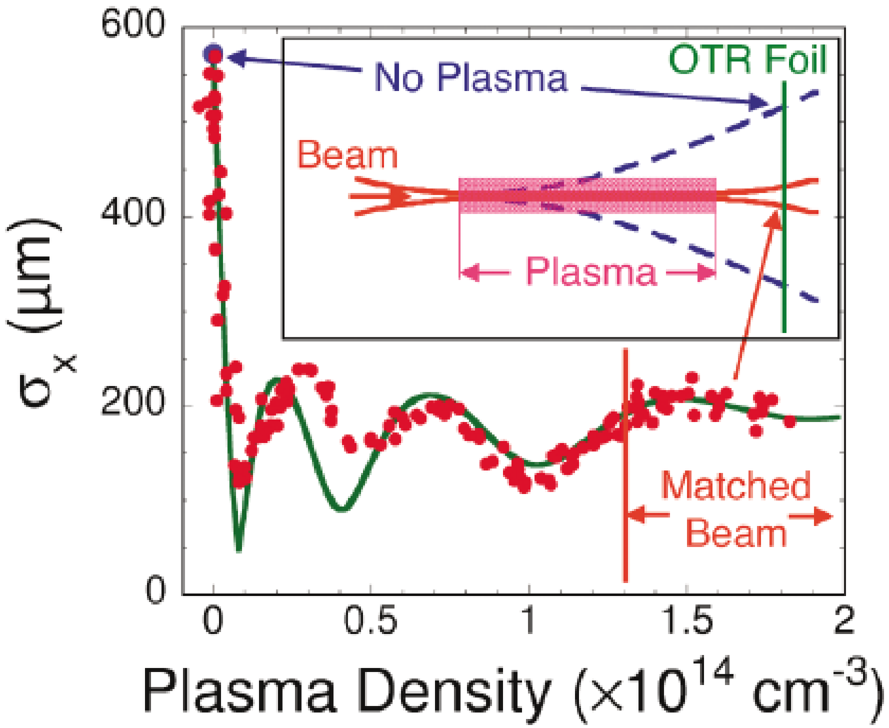


FIG. 2 (color). Transverse size σ_x of the beam (red points) in the x plane measured on the downstream OTR foil (see illustration inset) as a function of plasma density. The green line is the best fit to the data using a beam envelope model in which $\sigma_{x0} = 30\ \mu\text{m}$, $\epsilon_x = 9 \times 10^{-9}$ m rad, and $\beta_0 = 0.11$ m.

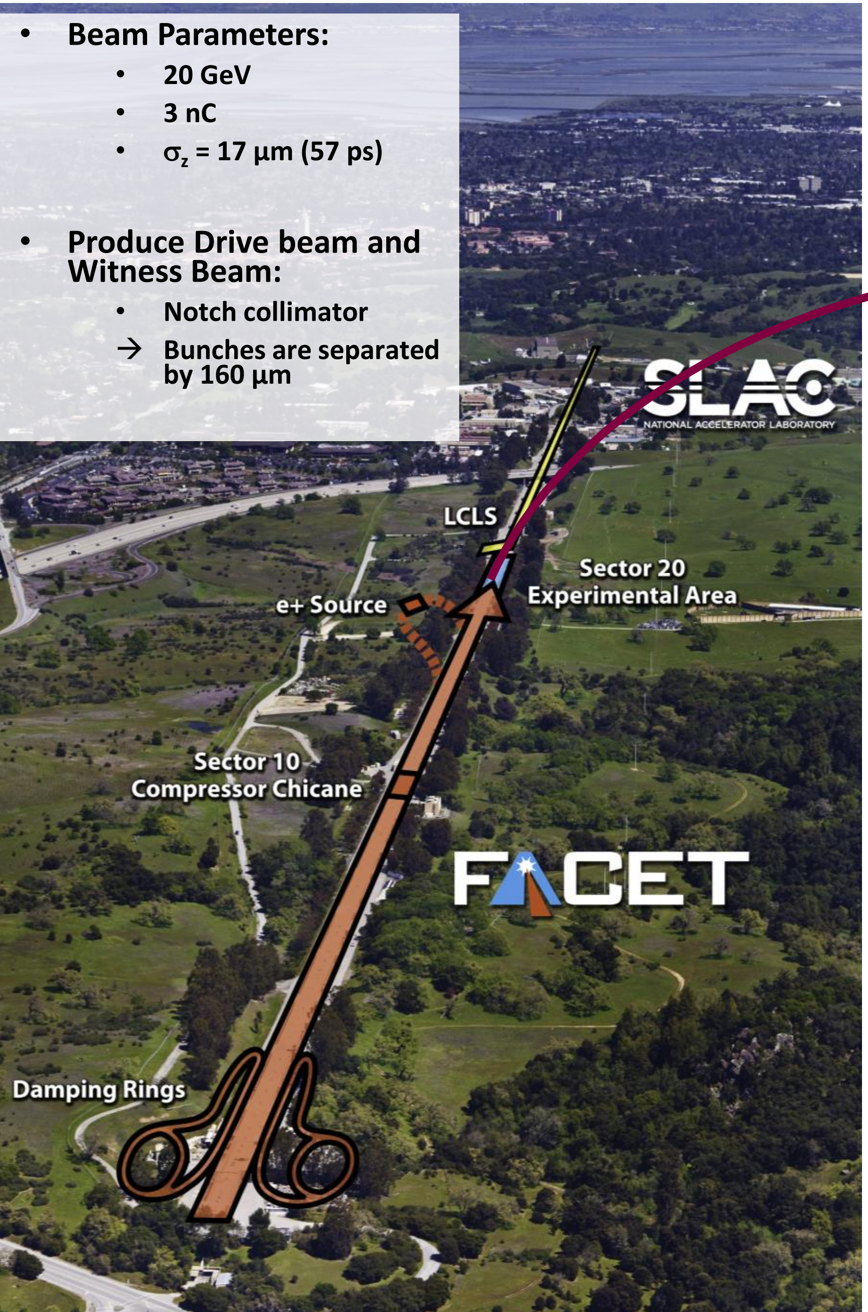
Experiment

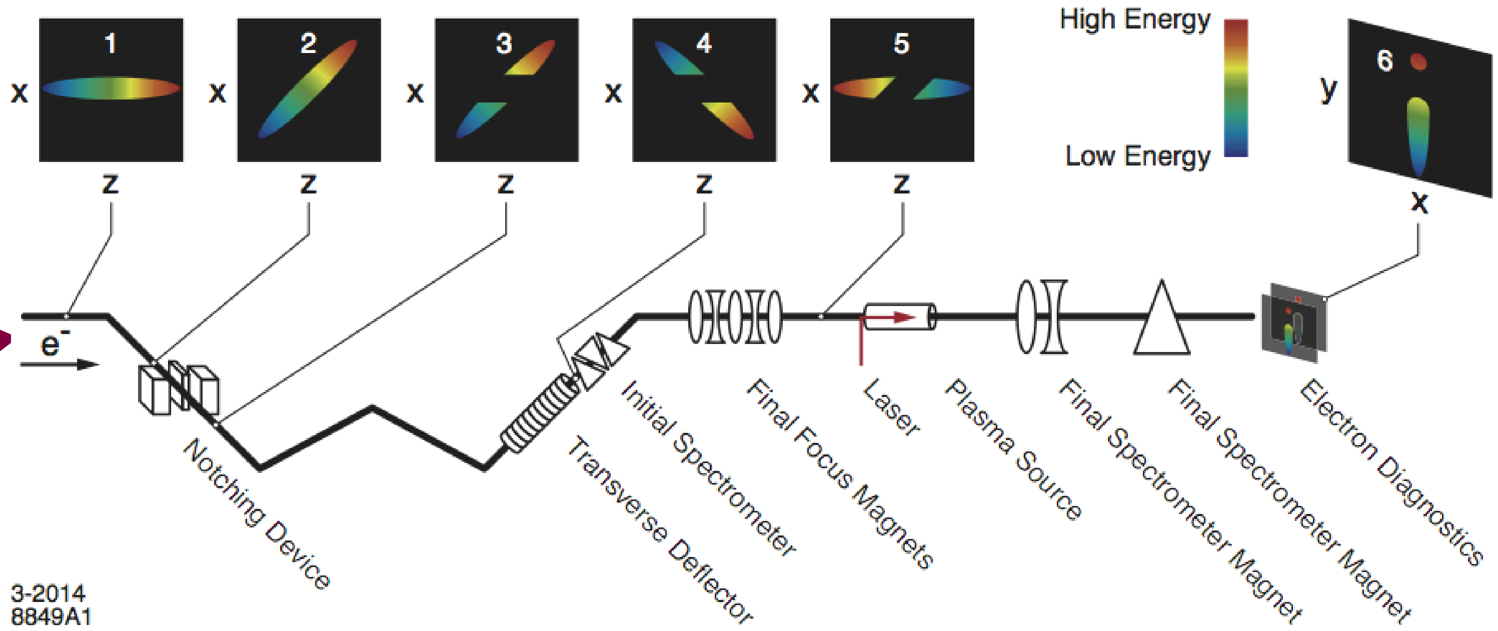
- 28.5 GeV, N= = $1.9\text{x}10^{10}$electrons, σ_z = 700µm , σ_{zr0} = ~30µm
- Lithium vapour source, 1.4m ,
- Matching conditions (blow-out regime) correspond to: n_e= $(1.2\text{-}2.5)\text{x}10^{14}\text{cm}^{-3}$

→ Emittance preserved for matched beam

SLAC FACET

- **Beam Parameters:**
  - **20 GeV**
  - **3 nC**
  - **σ_z = 17 µm (57 ps)**
- **Produce Drive beam and Witness Beam:**
  - **Notch collimator**
  - → **Bunches are separated by 160 µm**

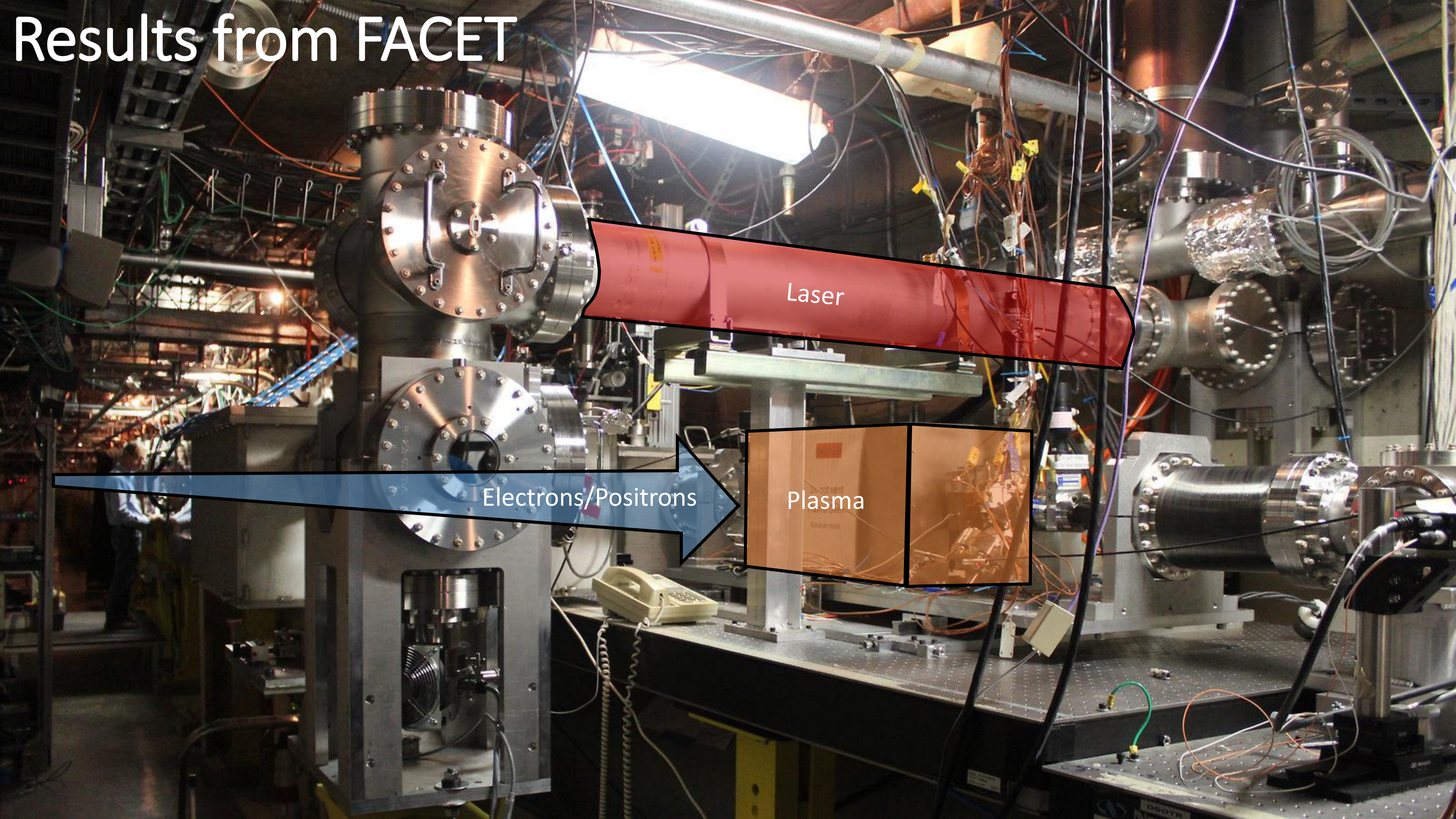




Facility for Advanced Accelerator Experimental Tests

- Demonstrate single-stage high-energy plasma accelerator for electrons
- Commissioning 2011, Experimental Program **2012-2016**:
- National User Facility: > 200 Users, 25 experiments, 8 months/yr operation
- First experiments with compressed positrons

Results from FACET



SLAC – FACET

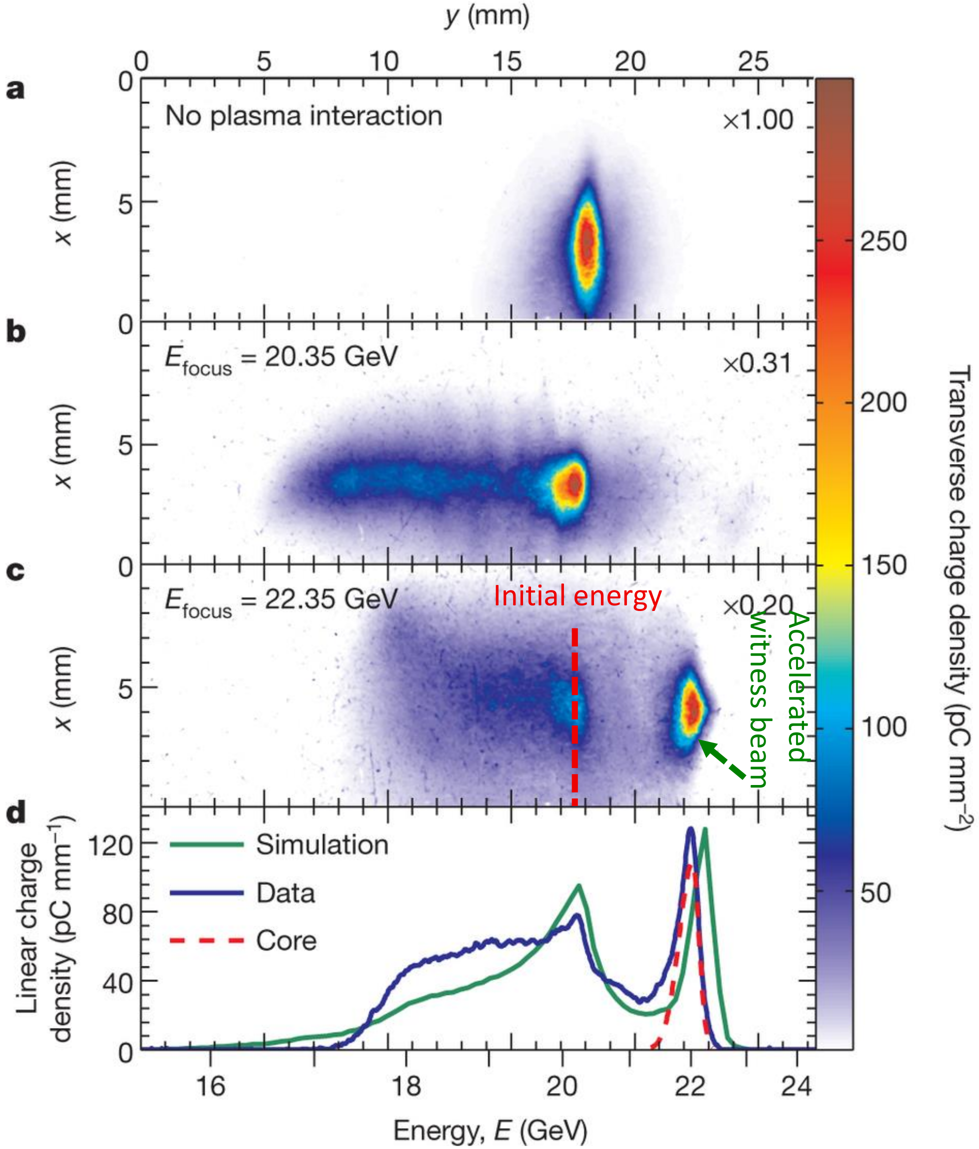
High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

M. Litos et al., doi, Nature, 6 Nov **2014**, 10.1038/nature 13882

- Laser ionized Lithium vapour plasma cell:
  - 36 cm long, Density: 5 10^{16} cm^{-3}, λ_π = 200 µm
- Drive and witness beam:
  - 20.35 GeV, D and W separated by 160 µm
  - 1.02nC (D), 0.78nC (W)

First demonstration of a high-efficiency, low energy-spread plasma wakefield acceleration experiment:

- 70 pC of charge accelerated
- 2 GeV energy gain
- 5 GeV/m gradient
- **Up to 30% transfer efficiency**
- ~2% energy spread



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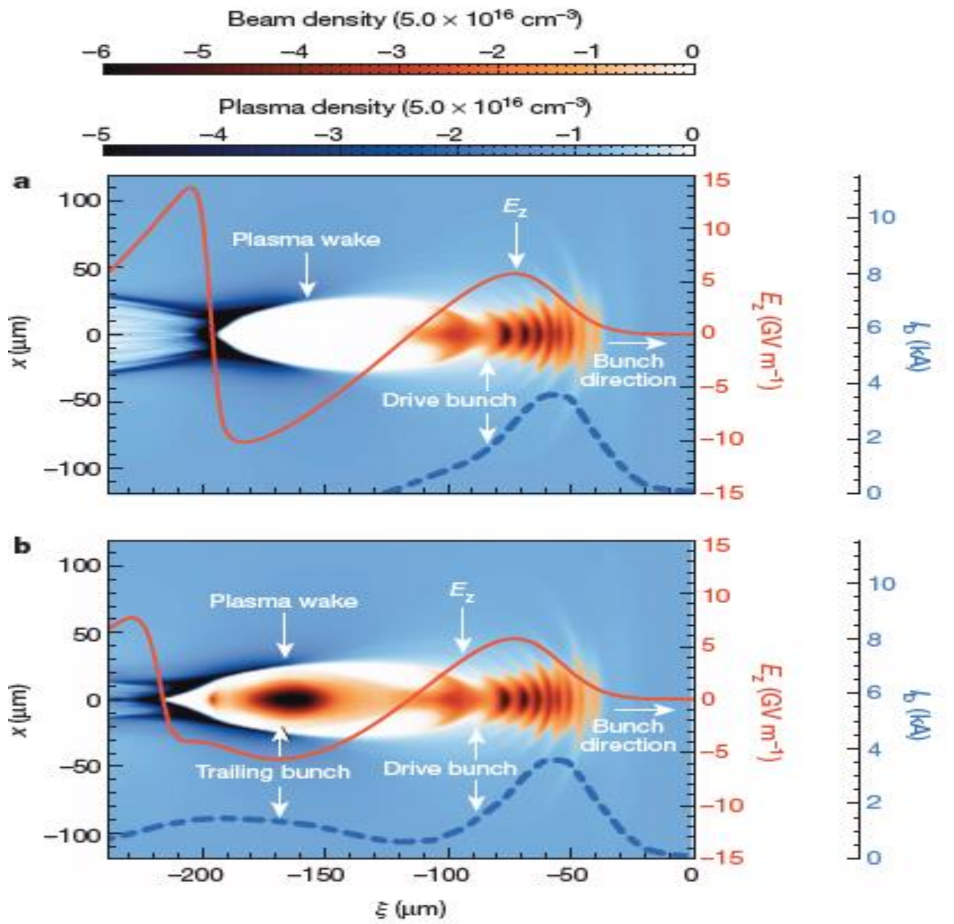

→ Electric field in plasma wake is **loaded** by presence of trailing bunch

→ Allows efficient energy extraction from the plasma wake

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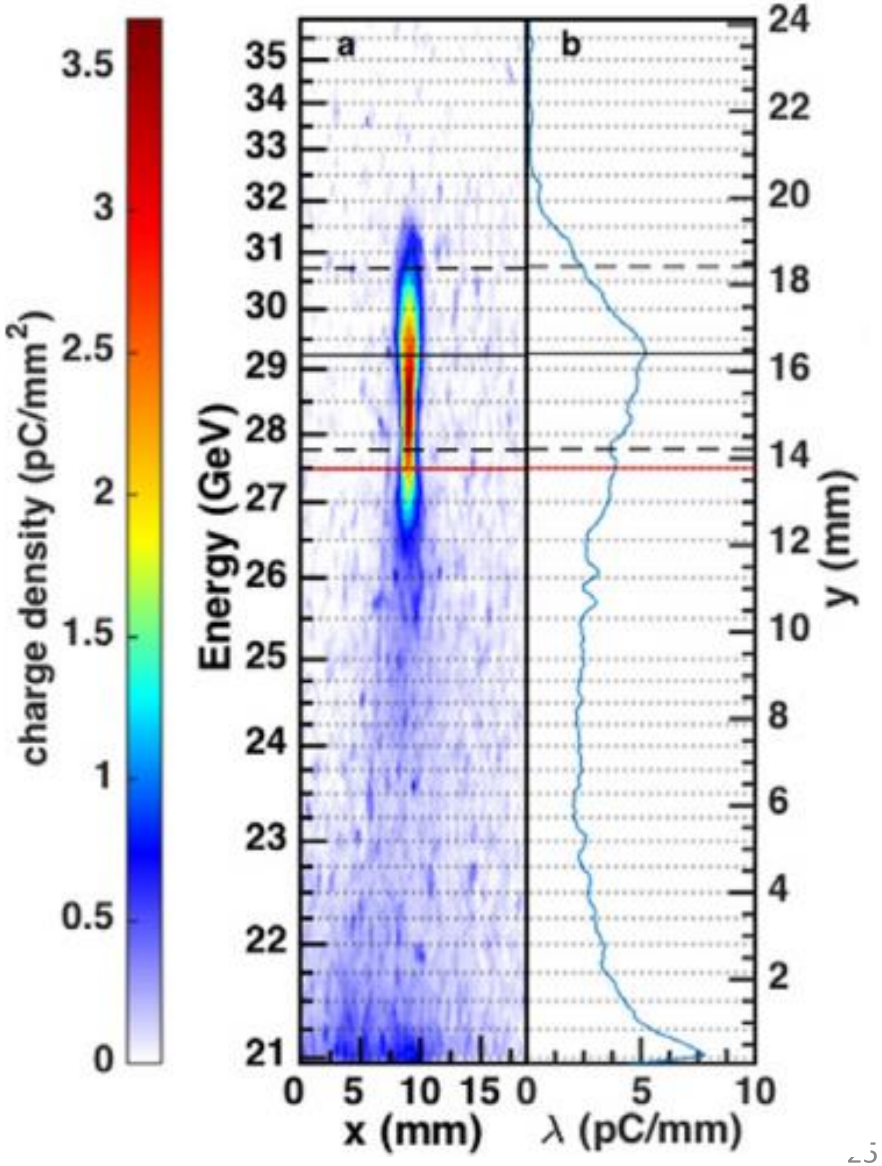
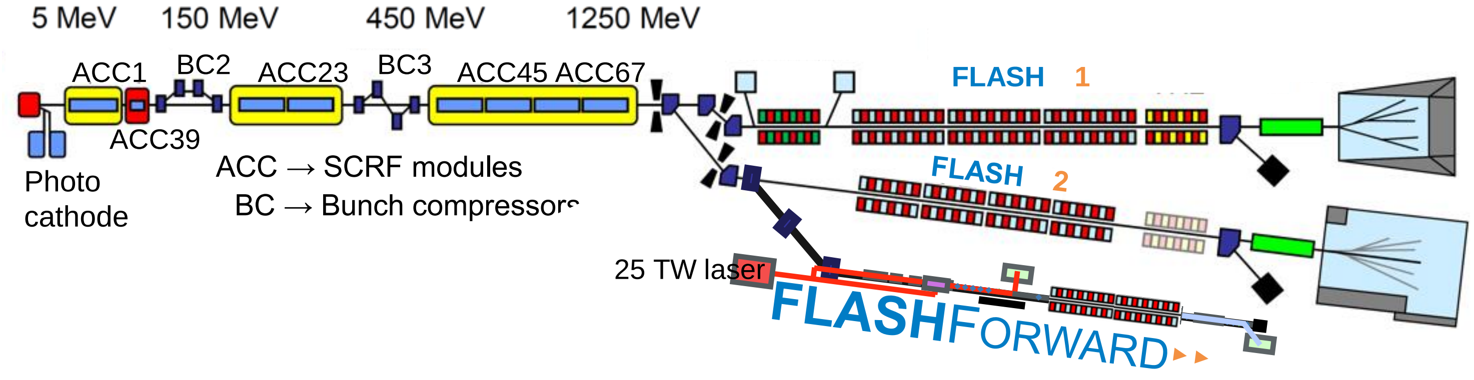
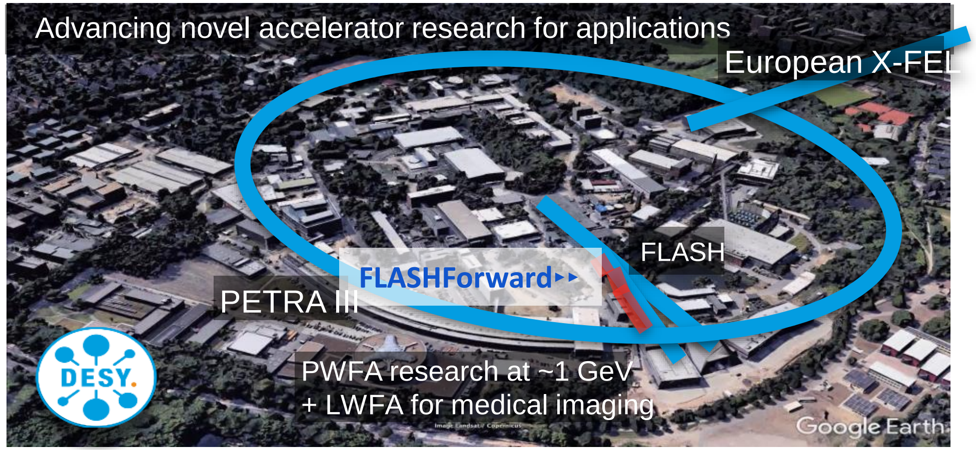


Later the plasma oven was extended from 0.3 to 1.3 meters long.

The accelerated beam had a spectral peak at **9 GeV energy gain.**

FLASH: Free Electron Laser and Accelerator Research





- → **FLASH** is an FEL user facility
  - 10% of beam time dedicated to generic accelerator research and development
- → **FLASH**Forward▸▸ is a beam line for PWFA research
- → Both share the same superconducting accelerator based on ILC/XFEL technology. Typical electron beam parameters:
  - $\lesssim$ **1.25 GeV energy** with a few **100 pC at ~100 fs** rms bunch duration
  - ~2 μm trans. norm. emittance

FLASHForward▸▸

Future-Oriented Wakefield Accelerator Research and Development at FLASH ▸▸

→ unique FLASH facility features for PWFA

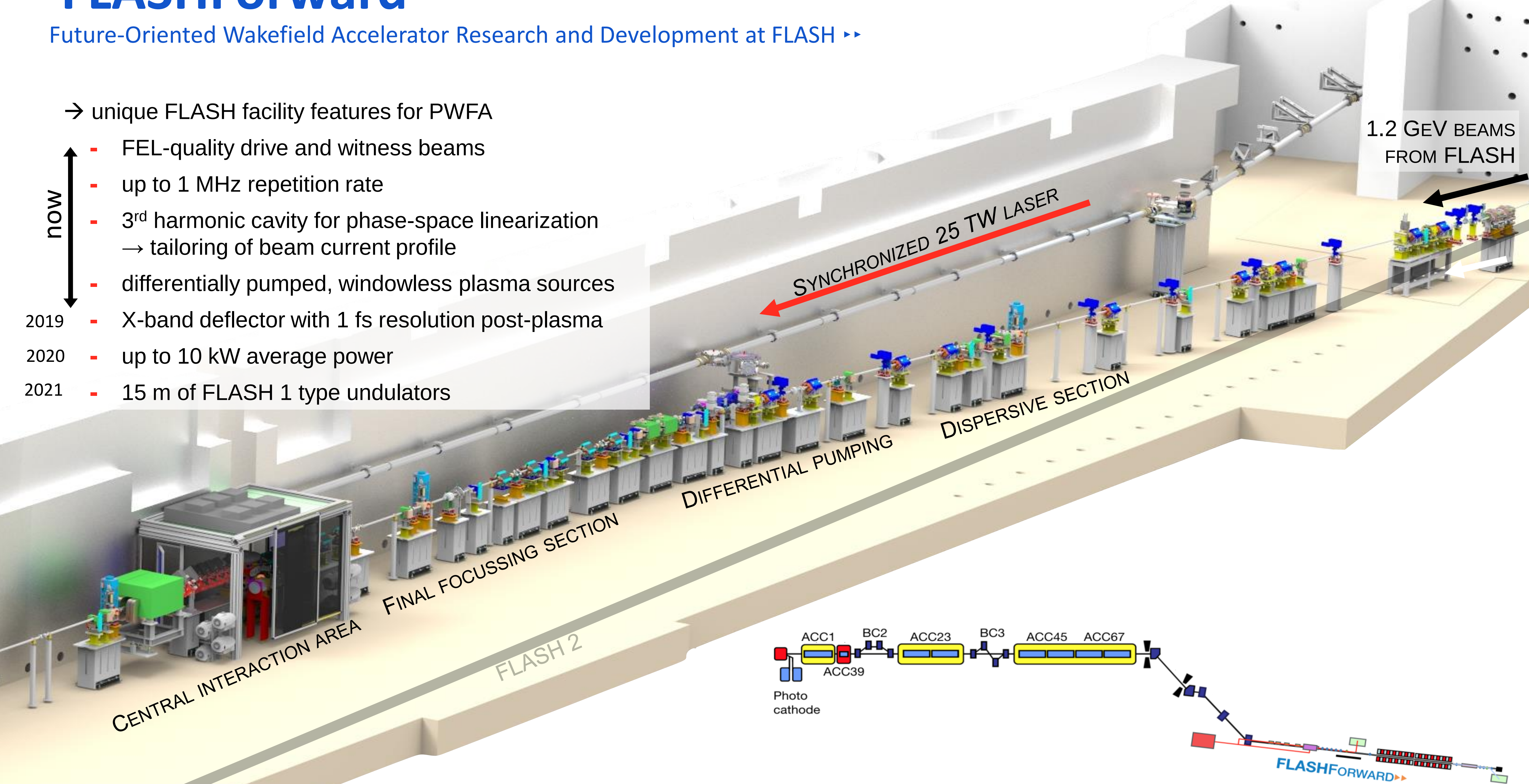
now

- FEL-quality drive and witness beams
- up to 1 MHz repetition rate
- 3rd harmonic cavity for phase-space linearization
  → tailoring of beam current profile
- differentially pumped, windowless plasma sources

2019 - X-band deflector with 1 fs resolution post-plasma

2020 - up to 10 kW average power

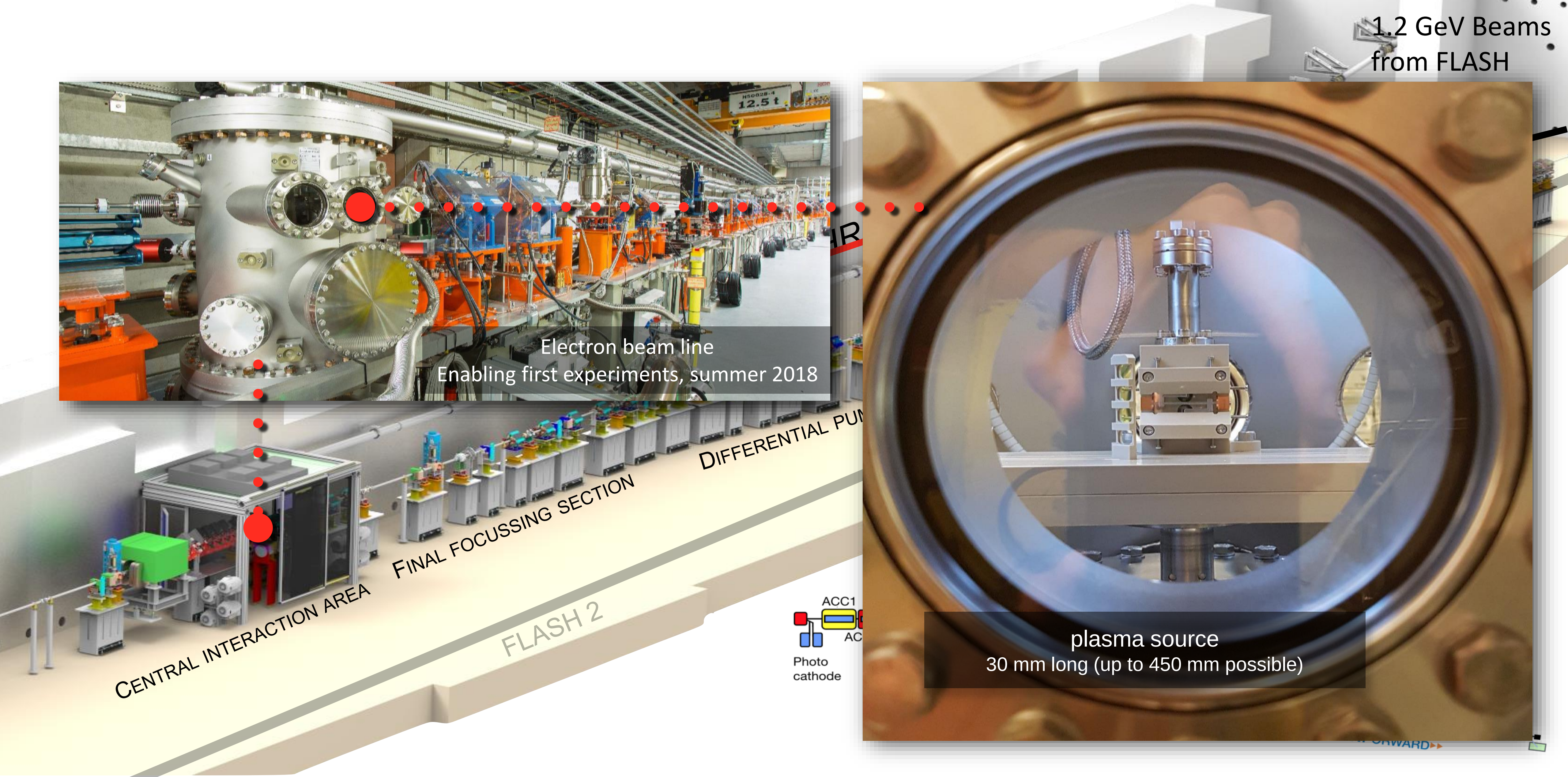
2021 - 15 m of FLASH 1 type undulators



→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)

FLASHForward▸▸

Future-Oriented Wakefield Accelerator Research and Development at FLASH ▸▸

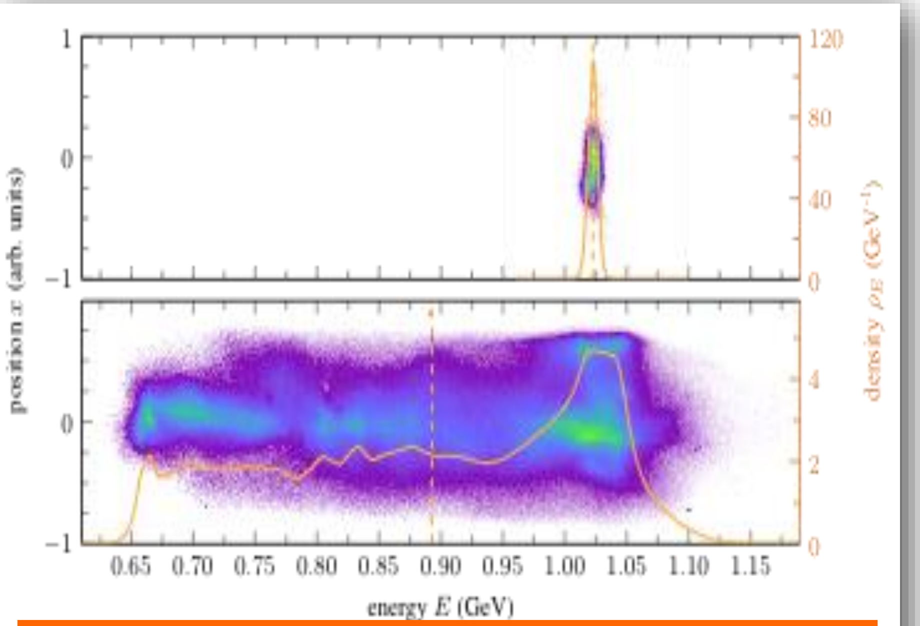


1.2 GeV Beams from FLASH

Electron beam line
Enabling first experiments, summer 2018

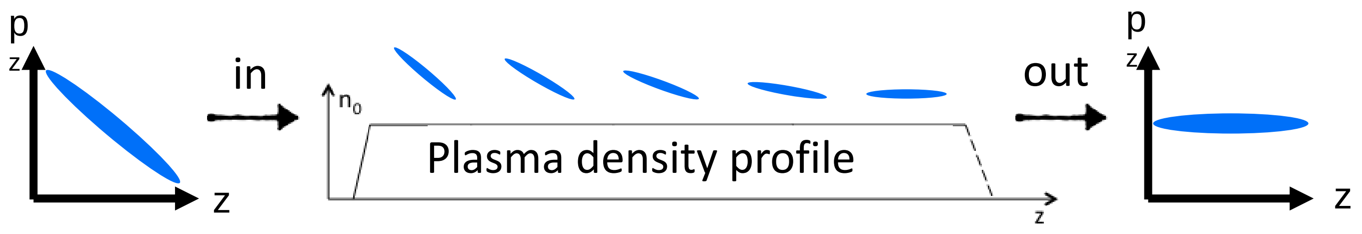
plasma source
30 mm long (up to 450 mm possible)

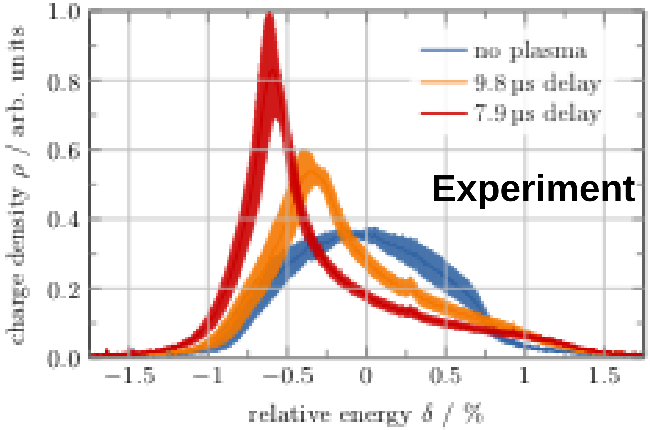
Overview of Recent FLASHForward▸▸ Results

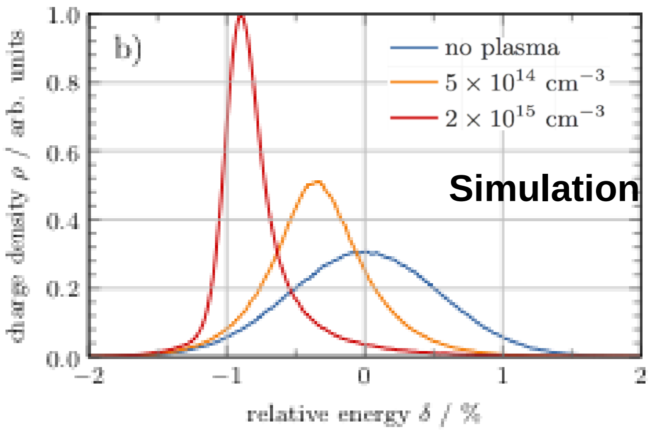


- → (12.3 ± 1.7) GV/m wakefield generated in 30 mm plasma cell
- → 12.7% total energy loss to plasma wakefield

Tunable plasma-beam dechirper with 1.8 GV/mm/m strength

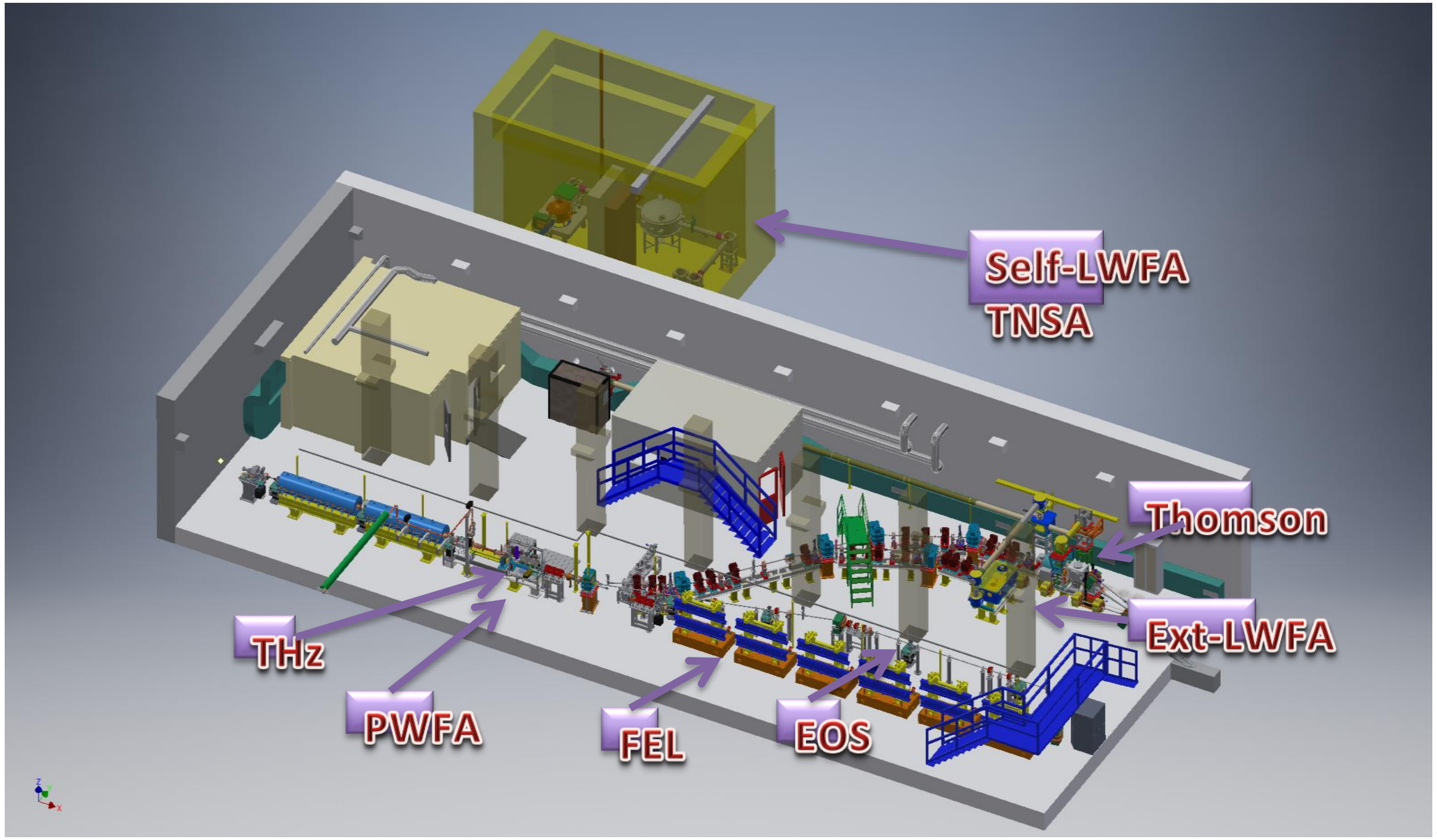


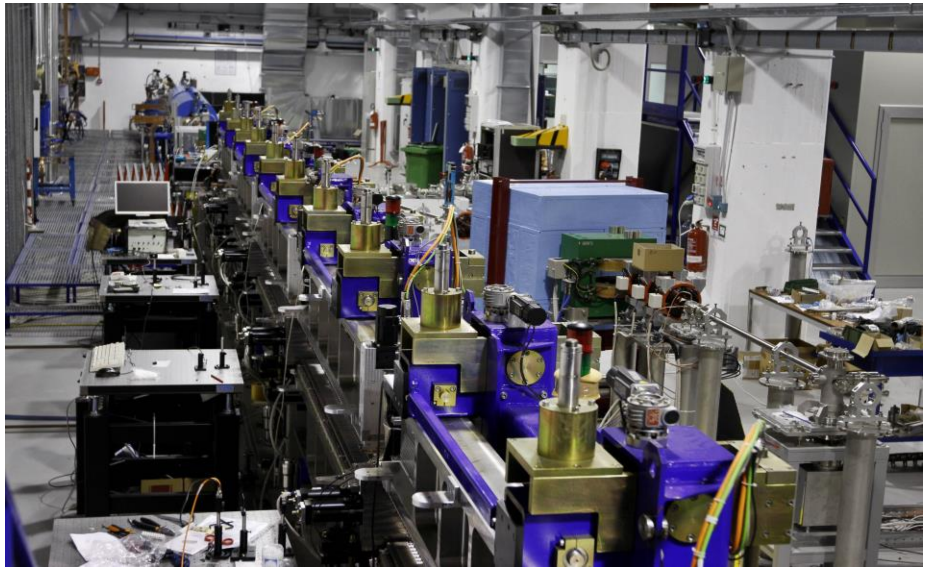




R. D’Arcy et al., PRL 122, 034801 (**2019**)

SPARCLAB, Frascati, Italy





- Resonant PWFA
- External injection on LWFA

- 150 MeV drive/witness beam

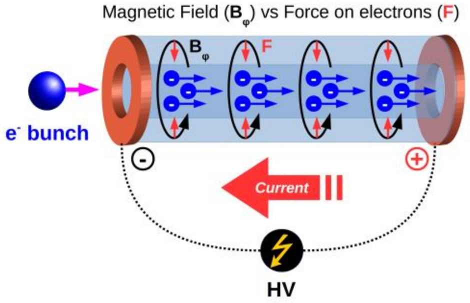
Plasma Lens Experiments:

Acceleration of high brightness beams and transport to the final application, while preserving the high quality of the 6D phase space

→ Want radially symmetric focusing gradient > kT/m, focusing field varying linearly with the radius

SPARCLAB, Plasma Lens Experiment

Plasma Lens



Beam focusing by azimuthal magnetic field generated by the discharge current density

$$B_\phi(r) = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$$

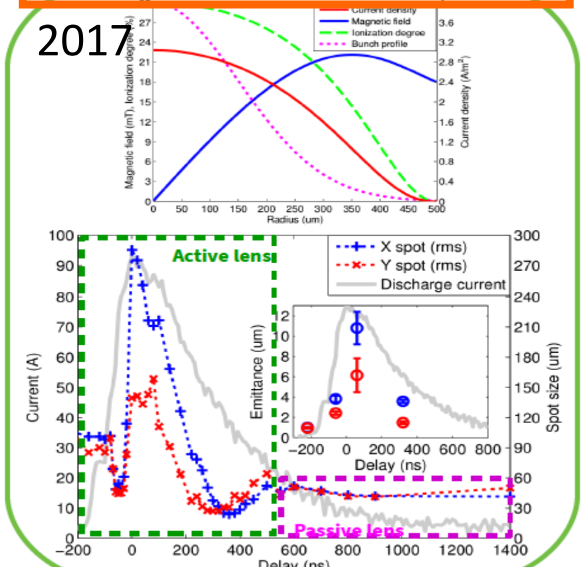
Experiment:

127MeV, 50pC, σt=1.3ps, ε_N= ~1 mm mrad, σ_x = 110µm.

Capillary discharge plasma cell, 3cm, R_0=500µm, I=100A, V=20kV, H_2 gas, n_e = 9×10^{16}cm^{-3},

→ Focusing is non-linear due to non-uniformity of the discharged current→ large growth of beam emittance

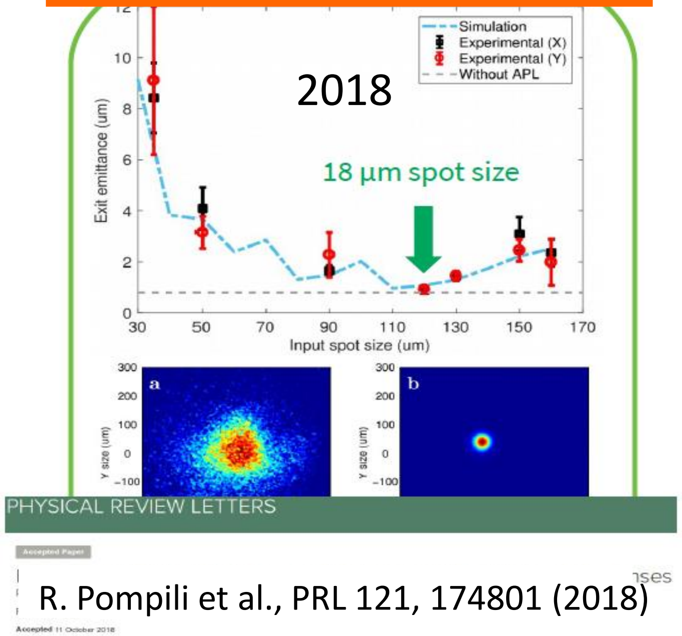
Demonstration of emittance growth



R. Pompili et al., Applied Physics Letters 110.10 (2017):104101
A. Marocchino et al., Applied Physics Letters 111.18(2017):184101

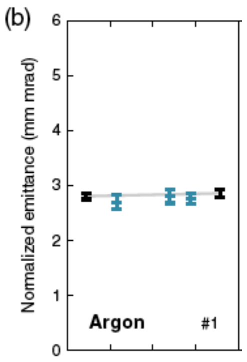
→ Change plasma discharge
→ Enhancing linearity of the focusing field.

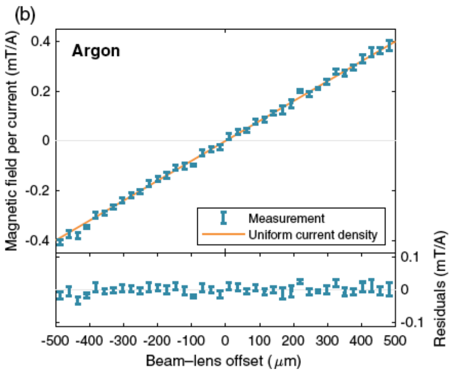
Demonstration of emittance preservation



R. Pompili et al., PRL 121, 174801 (2018)

➔ C. Lindstroem et al., Emittance Preservation in Aberration-Free Active Plasma Lens, PRL 121, 194801 (2018)





Facilities and Experimental Results of Key Challenges for PWFA

- Accelerating gradient
- Beam quality
- Transformer Ratio
- Positron acceleration
- Protons as drive beam

Transformer Ratio

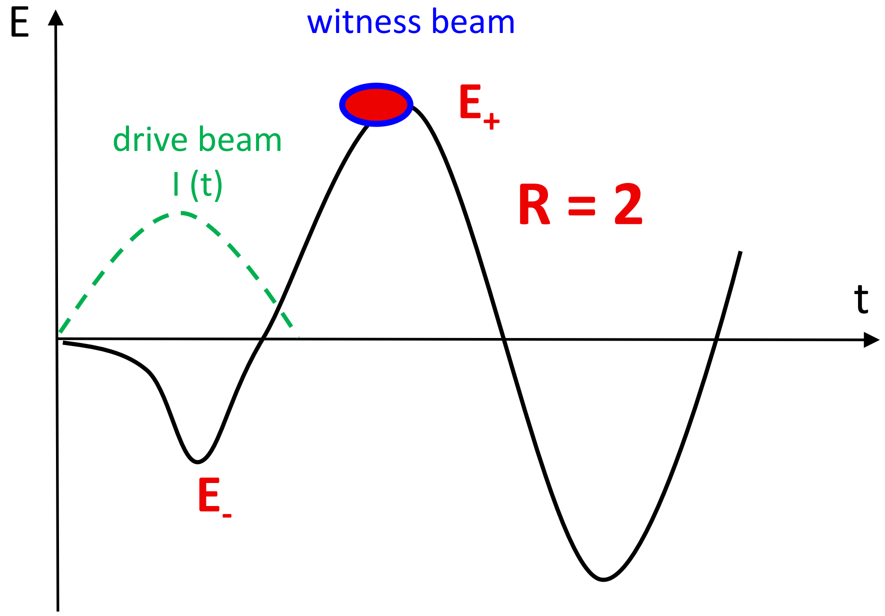
Would be fantastic to take a 1 GeV electron drive beam with 10^{11} electrons to accelerate 10^9 electrons by 100 GeV. Energy conservation is fulfilled.

BUT: not possible in reality

Limited by the **Transformer Ratio R ≤ 2**:

$$R = \frac{E_+}{E_-} = \frac{\text{Peak accelerating field behind the drive bunch}}{\text{Peak decelerating field within the drive bunch}}$$

(Short symmetric bunches)



Example:
Assume that E_- = 10 GV/m
With R = 2 ➔ E_+ = 20 GV/m

Drive beam (e^-) with **30 GeV** → decelerates 10GeV/m ➔ 3m total
Witness beam: gains 20 GeV/m ➔ gets **60 GeV** in 3m
Of course energy conservation must be fulfilled: $N_D = 3N_W$.

Increasing the Transformer Ratio

$$R = \frac{E_+}{E_-}$$

- Adjust the drive beam profile

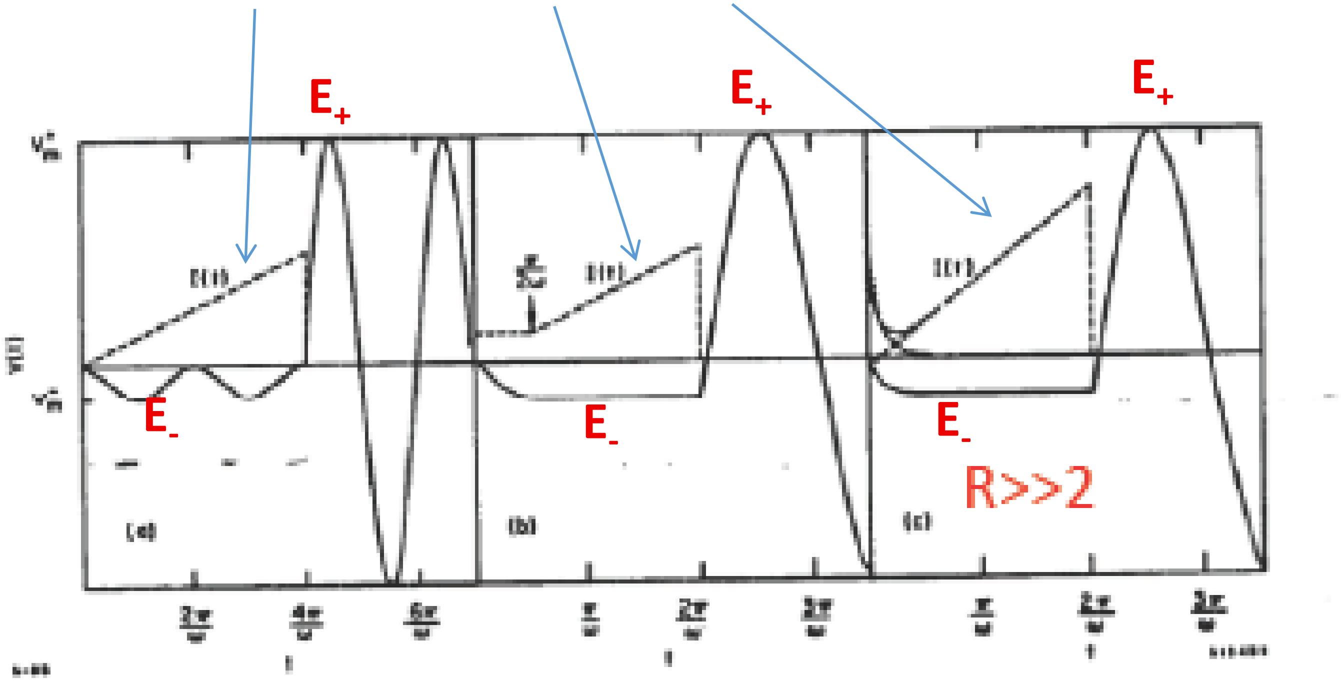
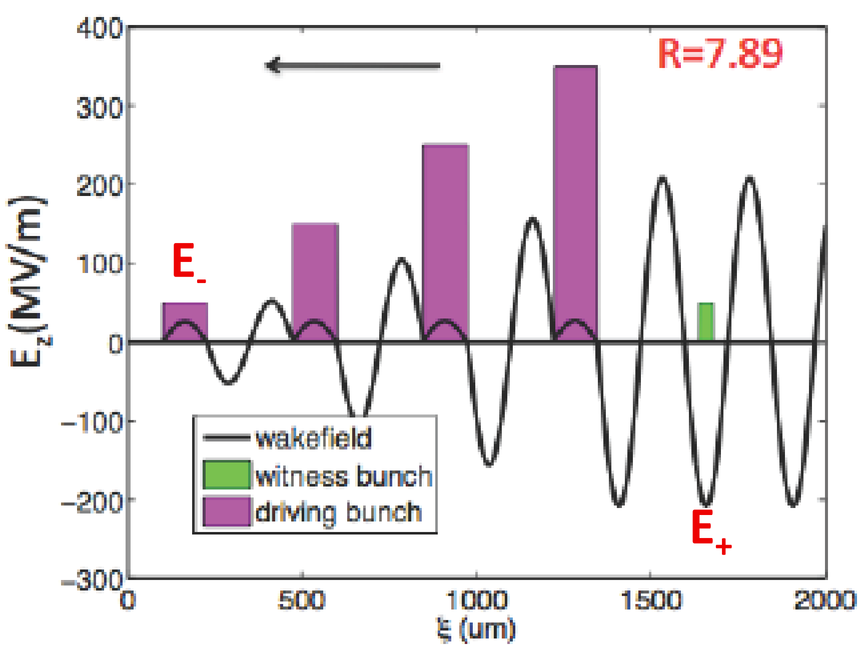


Figure 9. The voltage induced by three different asymmetric current distributions interacting with a single mode.

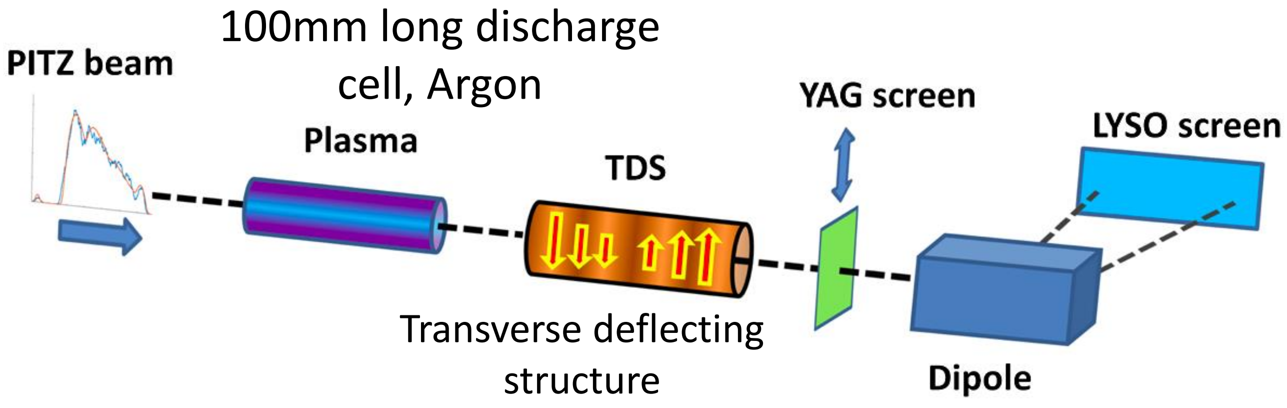
- Multiple drive beam bunches



Tzoufras, PRL 101, 145002 (2008)

DESY PITZ, 2018

- Photoinjector Test facility at DESY, Zeuthen (PITZ)
- 1.3GHz, 0.01-5nC, 25 MeV, ε_{norm} = 0.1 mmm rad
- Drive beam: 508 pC, 20ps
- Witness beam: 10 pC, 0.7ps, delay 10ps.



PITZ beam

100mm long discharge cell, Argon

Plasma

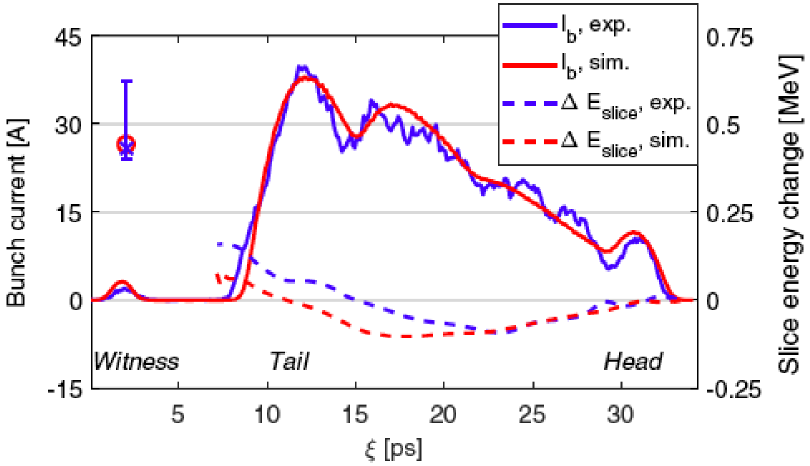
TDS

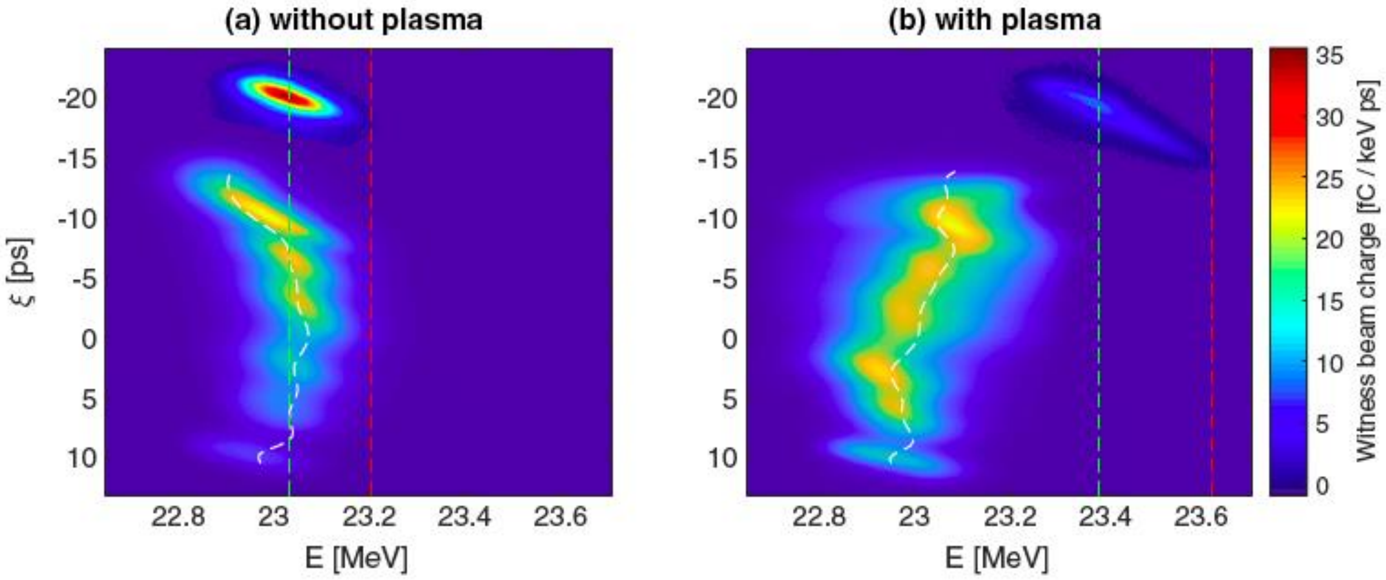
Transverse deflecting structure

YAG screen

Dipole

LYSO screen





G. Loisch et al., Observation of High Transformer Ratio Plasma Wakefield Acceleration, PRL **121,** 064801 (2018).

➔ Transformer Ratio:4.6 + 2.2/– 0.7

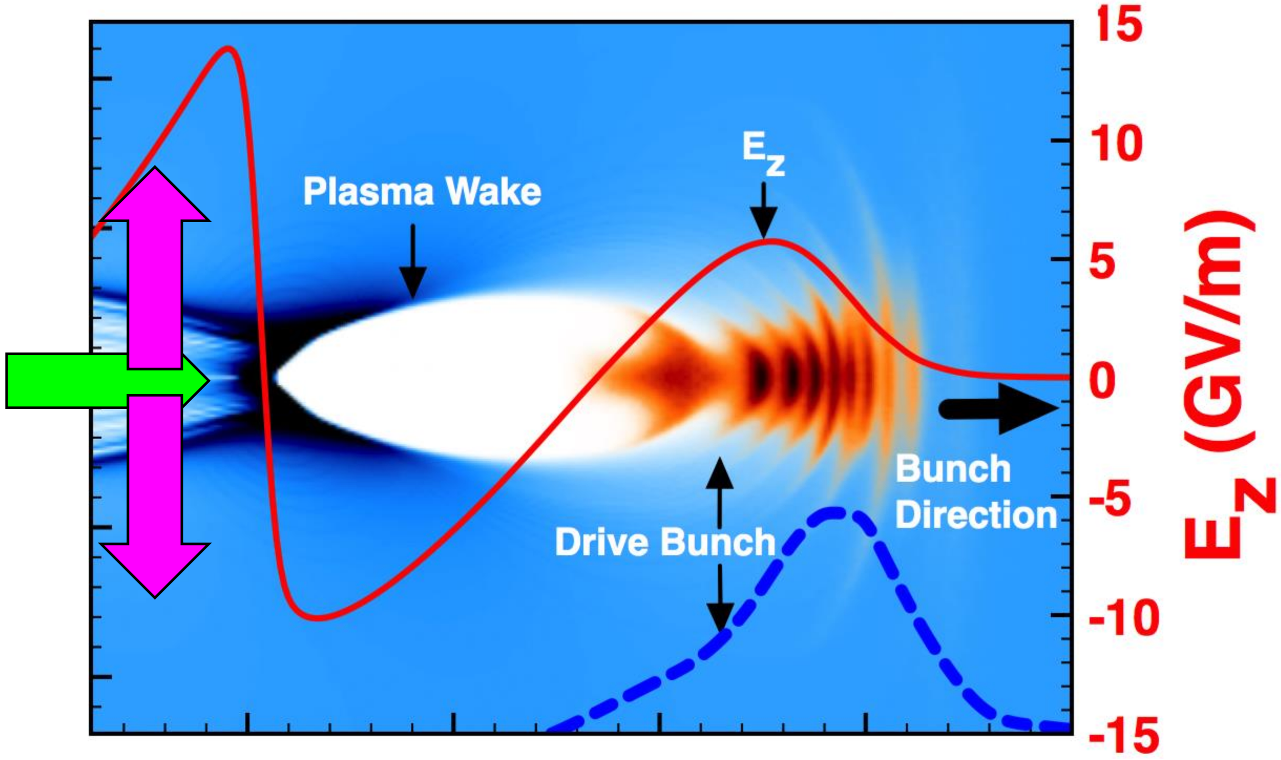
Facilities and Experimental Results of Key Challenges for PWFA

- Accelerating gradient
- Beam quality
- Transformer Ratio
- Positron acceleration
- Protons as drive beam

Positron Acceleration

- Interested in using positrons for high energy linear colliders:
  - Parameters for positrons: **high energy, high charge, low emittance**.

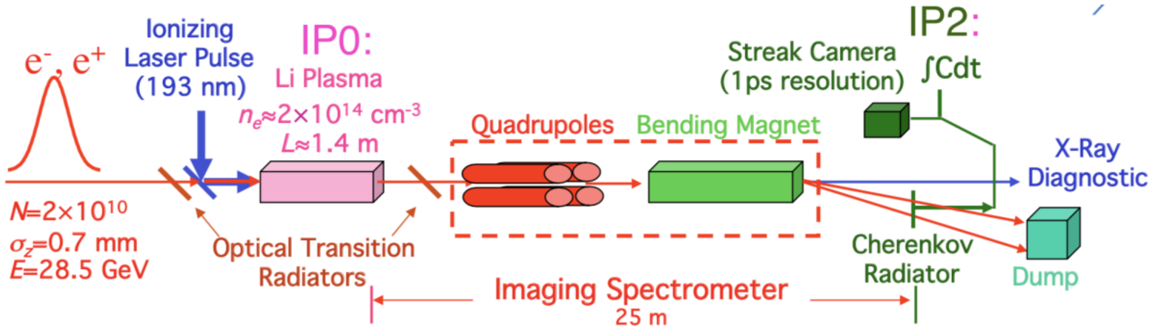
Electron-driven blowout wakes:



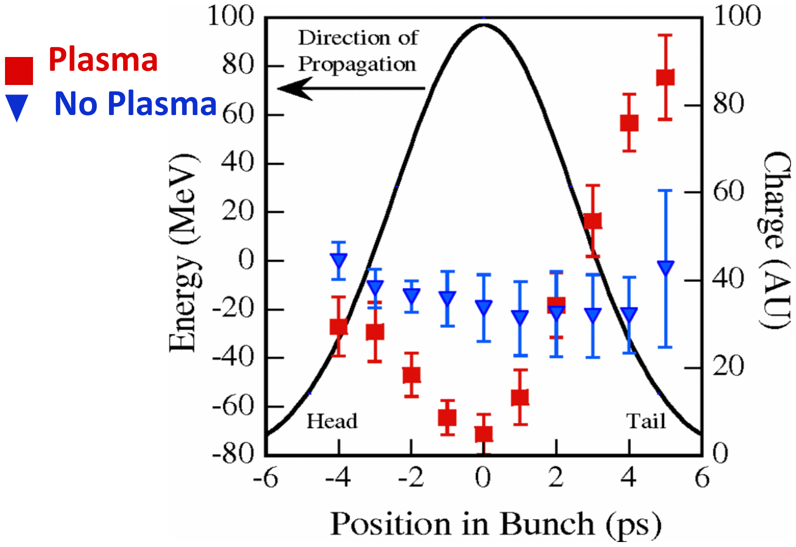
But the field is defocusing in this region.

Positron Beam at FFTB, 2003

- High-energy positron beam: E = 28.5 GeV
- Long positron bunch: σ_z = 700 µm
- Lithium heat pipe oven ionized by UV laser to produce plasma electron densities from 0-2 × 10^{14} cm^{-3}



The E162 experiment operated in the linear regime and a streak camera was used to measure the time-resolved energy spectrum.



→ First demonstration of positron acceleration in plasma!

→ A large, non-gaussian, beam halo is observed → large emittance. Simulations show that the emittance grows rapidly along all longitudinal slices of the beam.

B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (2003)
M. J. Hogan et. al. *Phys. Rev. Lett.* 90 205002 (2003).
P. Muggli et. al. *Phys. Rev. Lett.* 101 055001 (2008).

Positron Beam at FACET, 2015

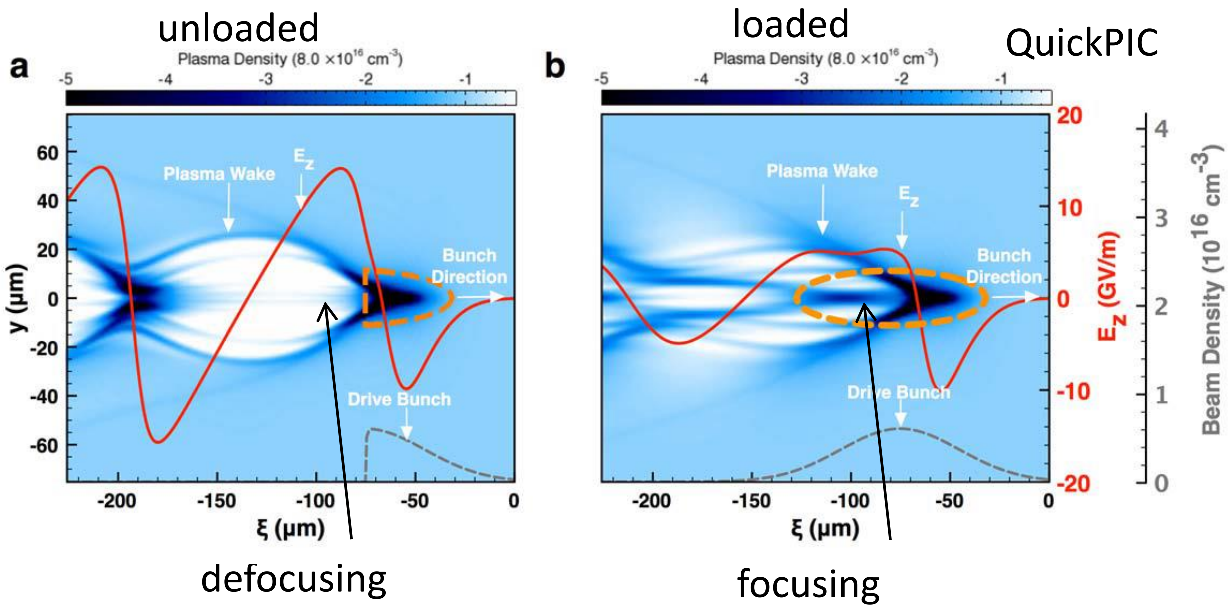
High-density, compressed positron beam for non-linear PWFA experiments.

1.3m plasma cell, 20 MeV beam.

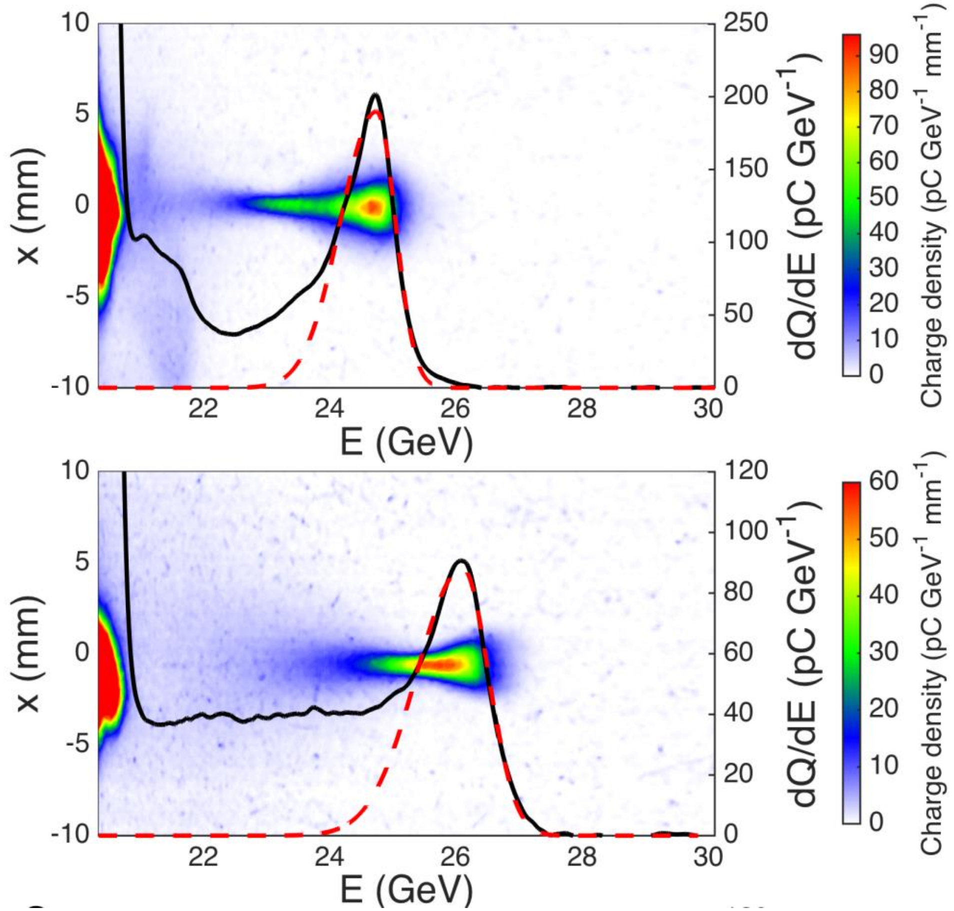
New observations:

- Accelerated positrons form a spectrally-distinct peak with an **energy gain of 5 GeV**.
- Energy **spread can be as low as 1.8%** (r.m.s.).

But emittance blow-up!



➔ Beam loading affects transverse fields for positron driven wakes!

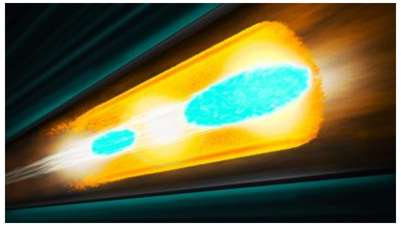


S. Corde *et al.*, Nature **524**, 442 (2015)

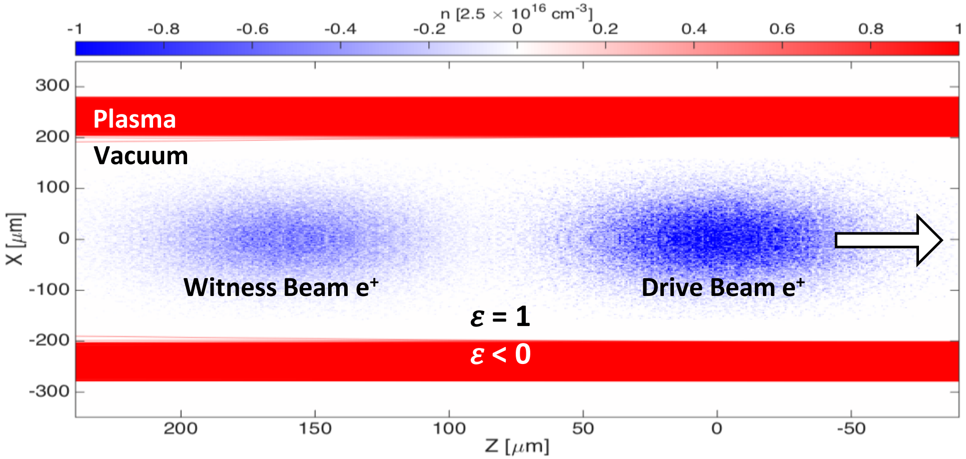
S. Doche *et al.*, Nat. Sci. Rep. 7, 14180 (2017)

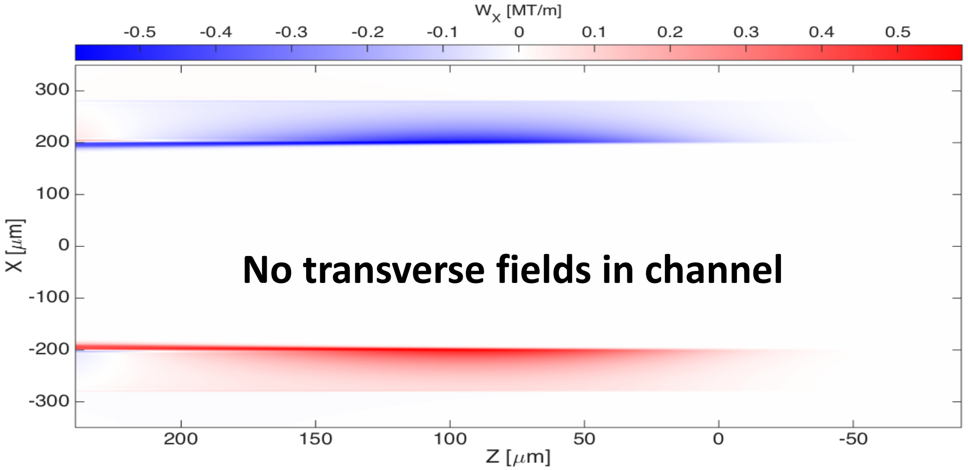
Two-bunch positron beam: First demonstration of controlled beam in positron-driven wake

Positron Acceleration in Hollow Channel at FACET

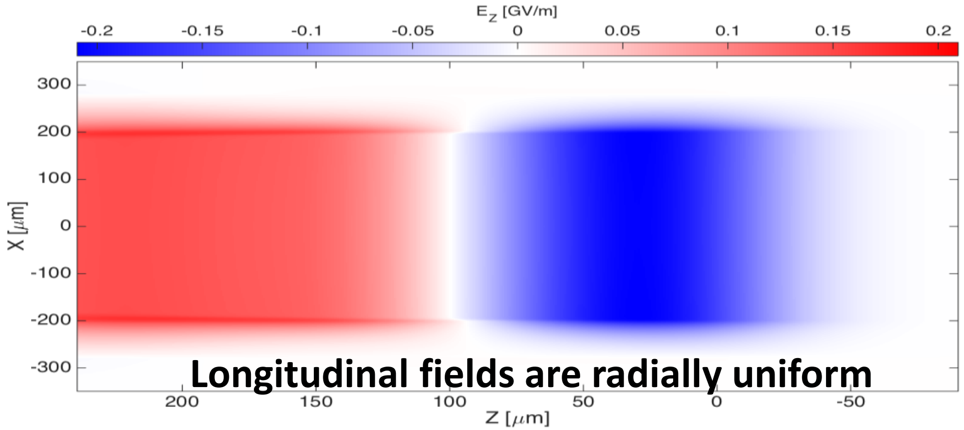


- There is no plasma on-axis, and therefore no complicated forces from plasma electrons streaming through the beam.
- Treat the plasma as dielectric





No transverse fields in channel

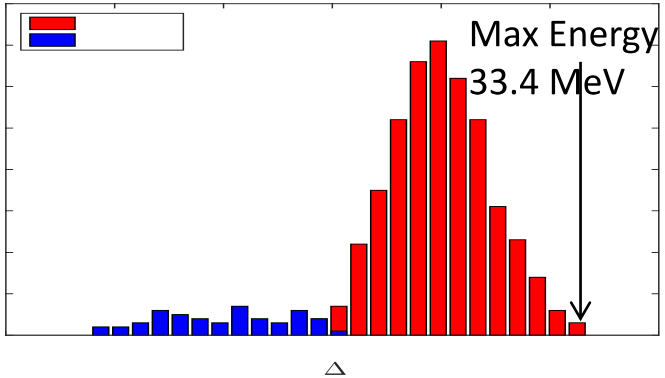


Longitudinal fields are radially uniform

Positron Acceleration in Hollow Channel at FACET, 2016, 2018

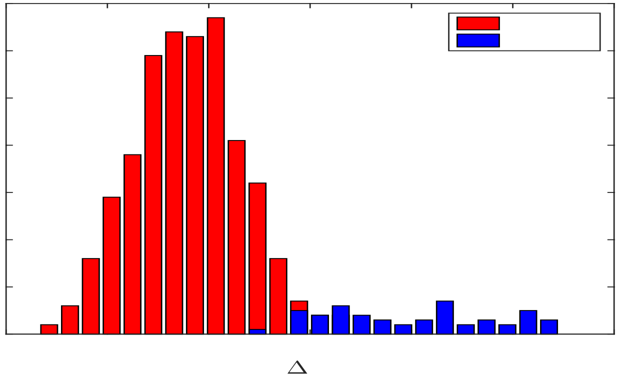
First Demonstration of Acceleration in Hollow channel

Mean <ΔE> = 19.9 MeV



Witness beam gains energy from the wake.

Mean <ΔE> = -11.0 MeV



Drive beam transfers energy to witness beam.

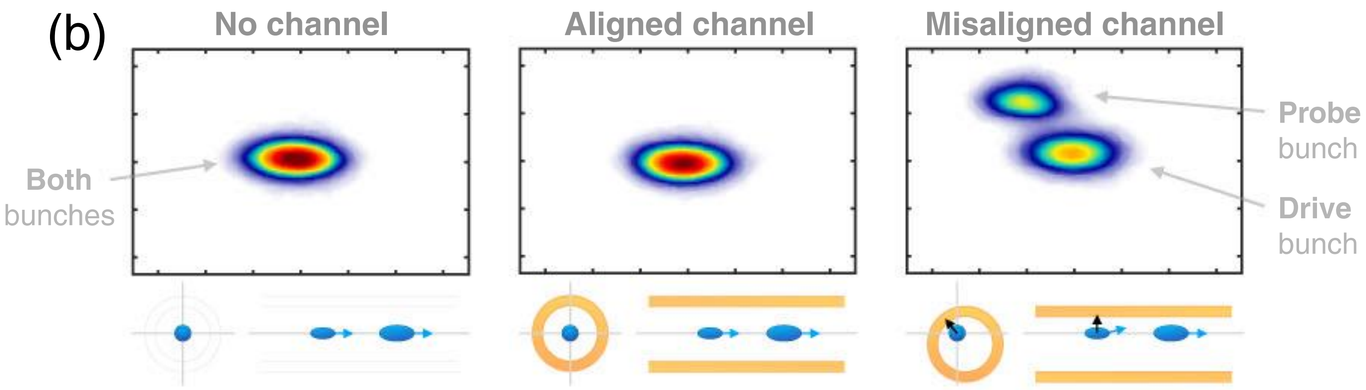
S. Gessner et. al. *Nat. Comm.* 7, 11785 **(2016)**

Measurement of transverse wakefields in hollow channel

→ the result agrees with theoretical calculation:

10^6 V/(pC m mm)

Or about **10,000 times stronger than the wakefields in CLIC!**



C. A. Lindstrøm et. al. *Phys. Rev. Lett.* 120 124802 (**2018**).

Facilities and Experimental Results of Key Challenges for PWFA

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Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

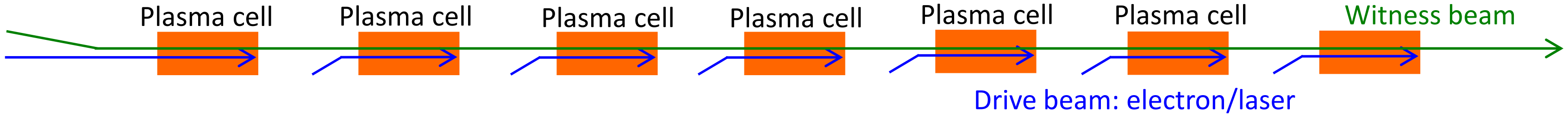
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

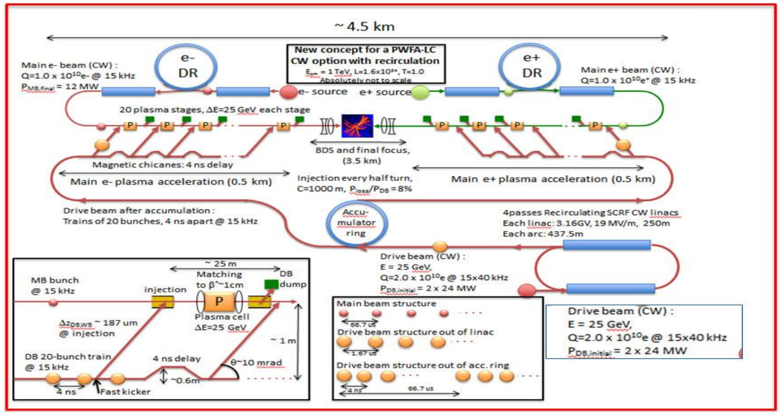
Witness beams:

Electrons: 10^{10} particles @ 1 TeV ~few kJ

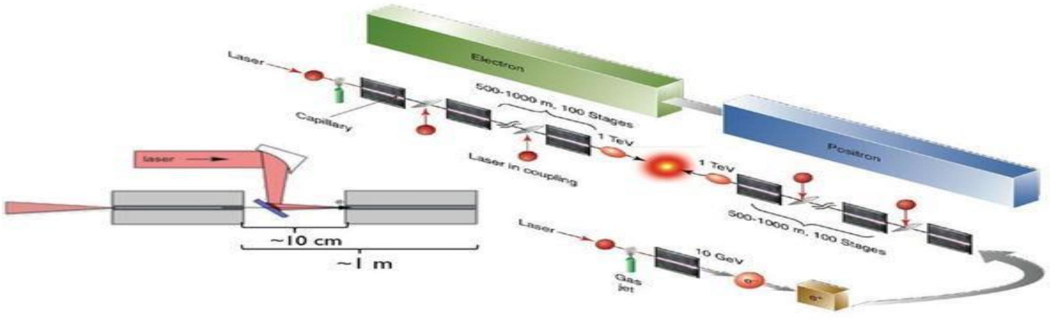
To reach TeV scale:

- **Electron/laser driven PWA**: need several stages, and challenging wrt to relative timing, tolerances, matching, etc…
  - effective gradient reduced because of long sections between accelerating elements….





E. Adli *et. al*.,arXiv:1308.1145 [physics.acc-ph]



C. B. Schroeder *et. al*. Phys. Rev. ST Accel. Beams **13**, 101301

Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:

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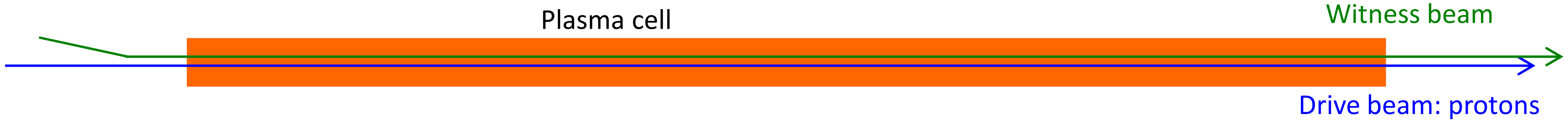
Electron drive beam: 30 J/bunch

Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:

Electrons: 10^{10} particles @ 1 TeV ~few kJ

- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.



Plasma cell

Witness beam

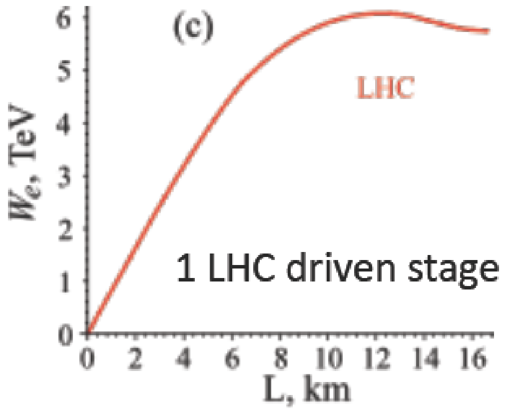
Drive beam: protons

Dephasing: $\delta = \dfrac{\pi L}{\lambda_p} \dfrac{1}{\gamma^2}$

SPS: ~70 m

LHC: ~few km

FCC: ~ ∞



Seeded Self-Modulation of the Proton Beam

In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.

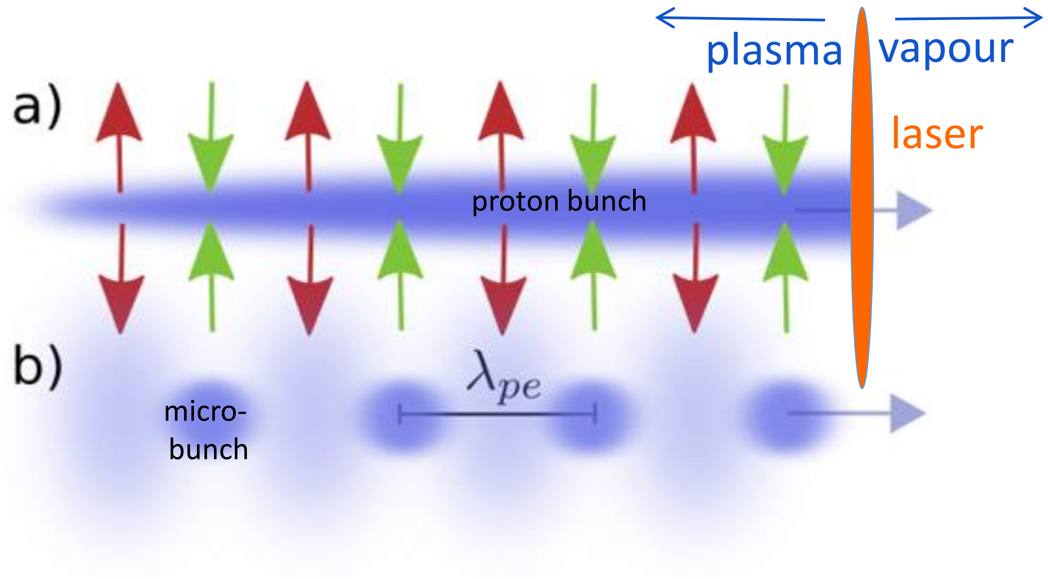
CERN SPS proton bunch: very long! (**σ_z = 12 cm**) → much longer than plasma wavelength (**λ = 1mm**)

N. Kumar, A. Pukhov, K. Lotov,
PRL 104, 255003 (2010)

Self-Modulation:

a) Bunch drives wakefields at the initial seed value when entering plasma.
  - **Initial wakefields act back** on the proton bunch itself. → On-axis dens is modulated. → Contribution to the wakefields is $\propto n_b$.

b) Density modulation on-axis → **micro-bunches**.
  - Micro-bunches separated by plasma wavelength λ_{pe}.
  - drive wakefields resonantly.

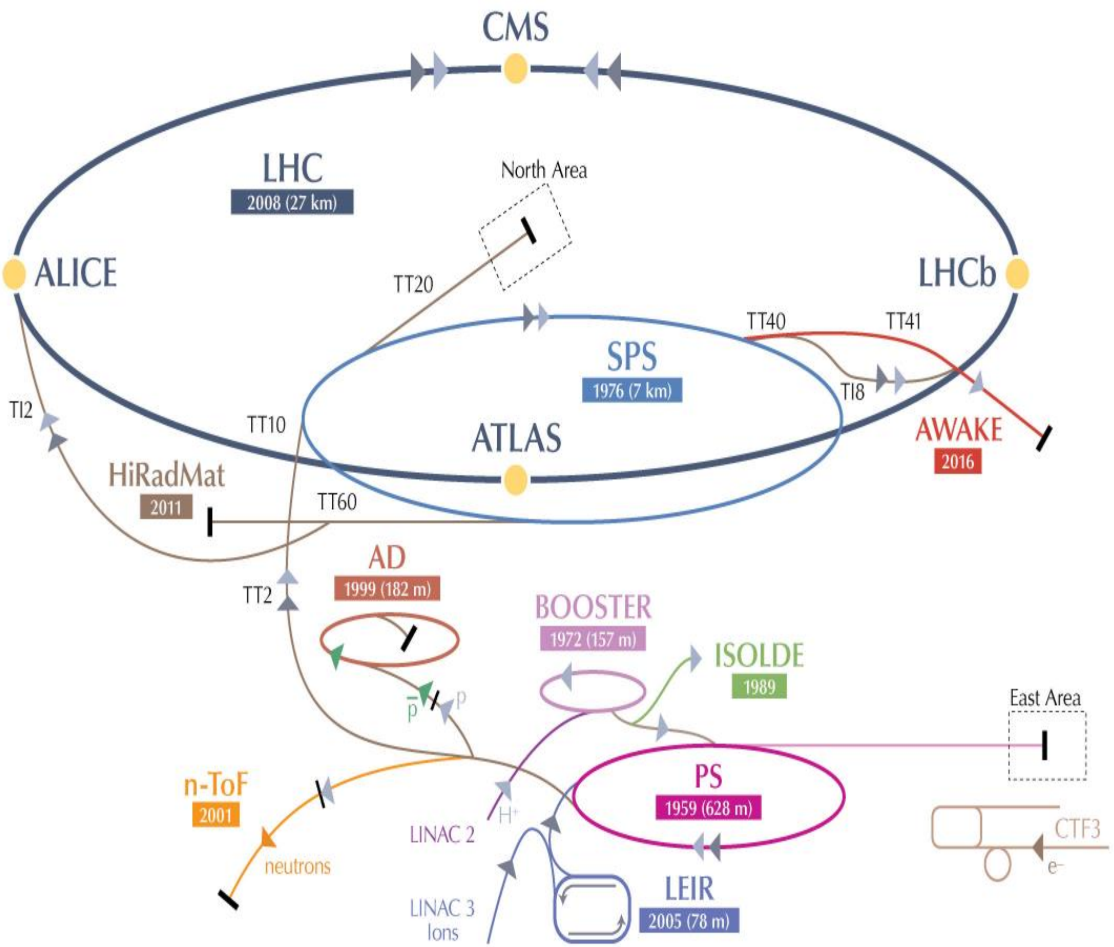


→ Seeded Self-Modulation

AWAKE: Seeding of the instability by

- Placing a laser close to the center of the proton bunch
- Laser ionizes vapour to produce plasma
- Sharp start of beam/plasma interaction
- → Seeding with ionization front

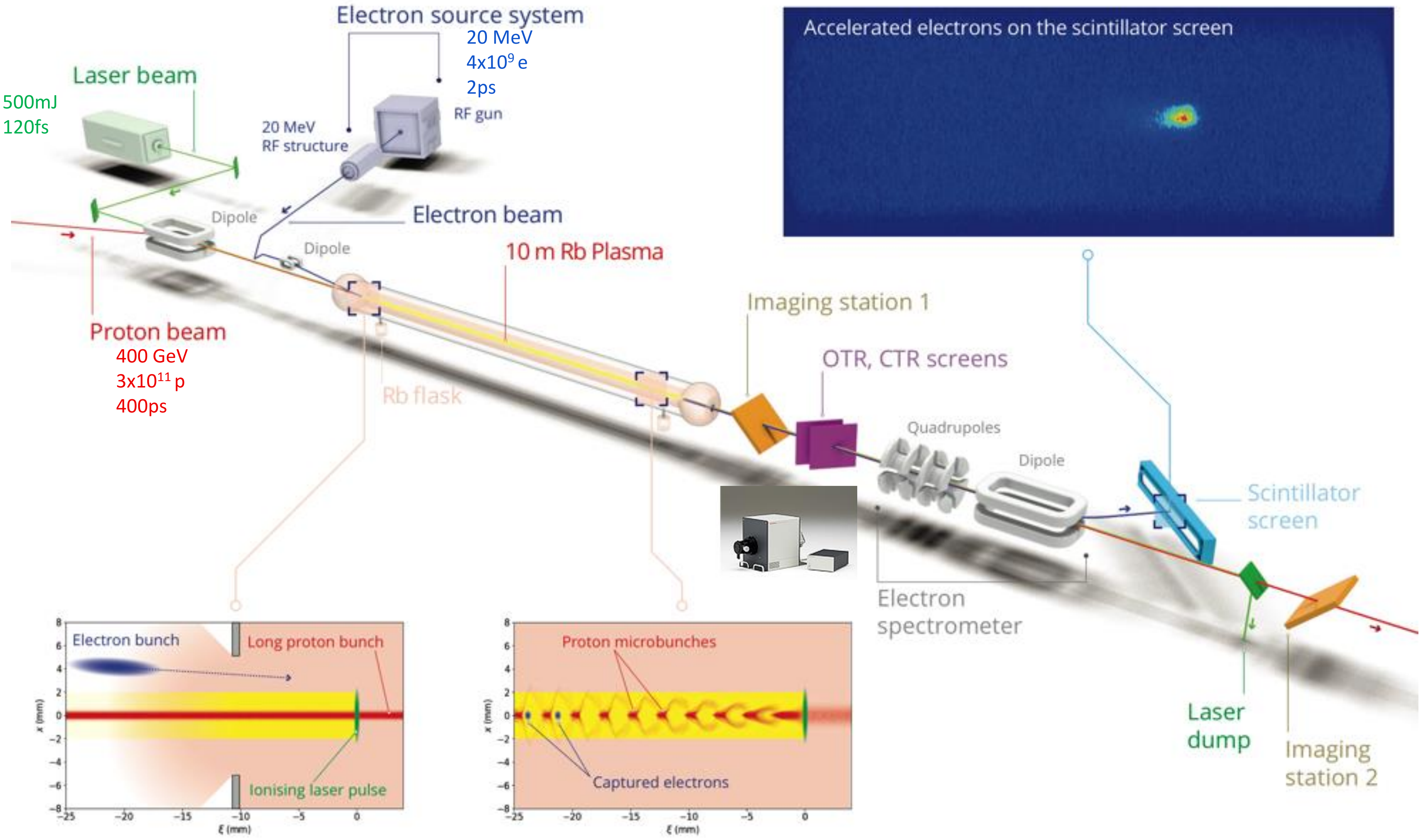
AWAKE at CERN



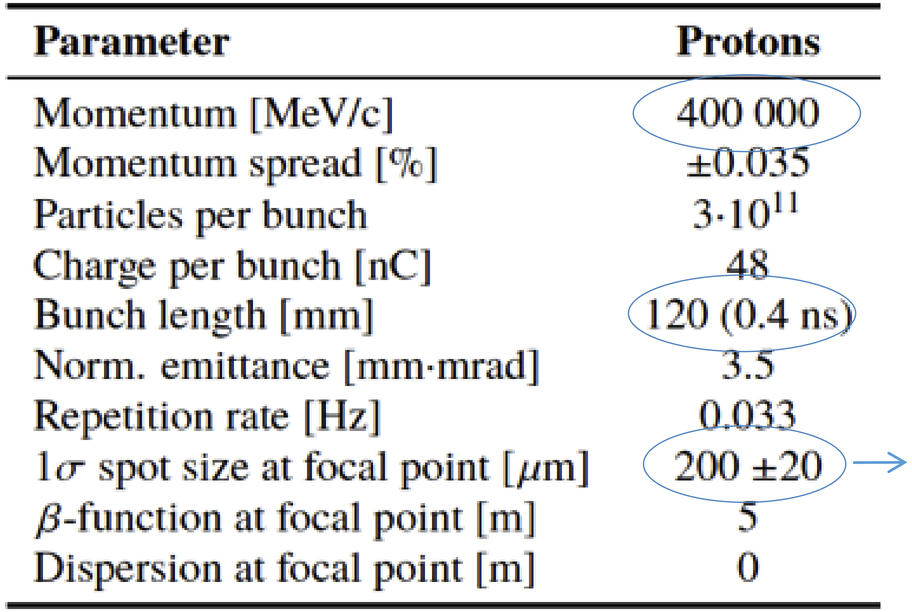
Advanced WAKEfield Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Approved in August 2013
- First beam end 2016

AWAKE Experiment



AWAKE Proton and Laser Beam Line



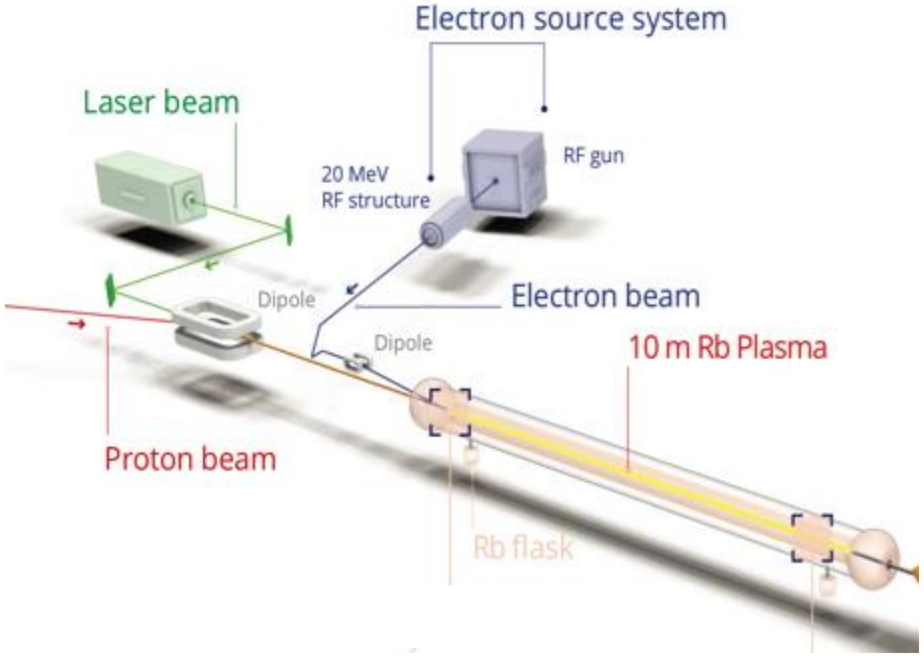
Parameter	Protons
Momentum [MeV/c]	400 000
Momentum spread [%]	±0.035
Particles per bunch	$3 \cdot 10^{11}$
Charge per bunch [nC]	48
Bunch length [mm]	120 (0.4 ns)
Norm. emittance [mm·mrad]	3.5
Repetition rate [Hz]	0.033
1σ spot size at focal point [μm]	200 ±20
β-function at focal point [m]	5
Dispersion at focal point [m]	0

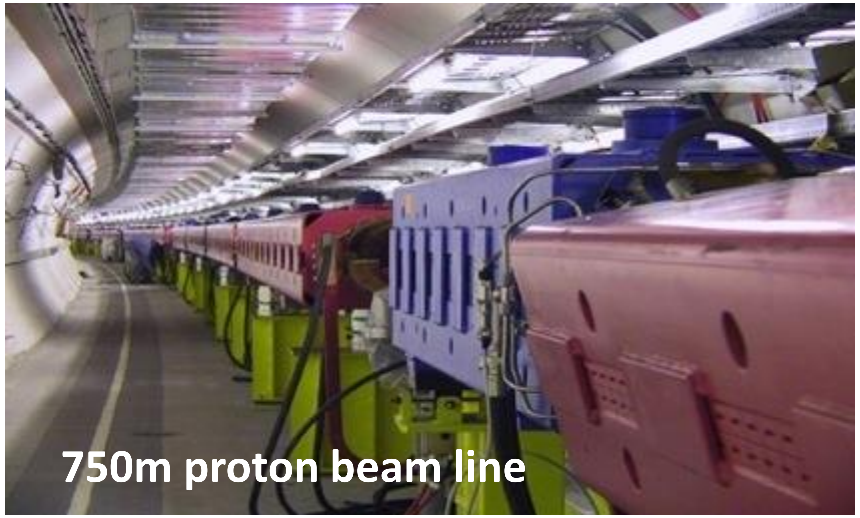
Plasma linear theory: $k_{pe}\,\sigma_r \leq 1$

With $\boldsymbol{\sigma_r}$ **= 200 µm**

$k_{pe} = \omega_{pe}/c = 5\ \mathrm{mm}^{-1}$

➔ $\mathbf{n_{pe} = 7x10^{14}\ cm^{-3}}$





750m proton beam line

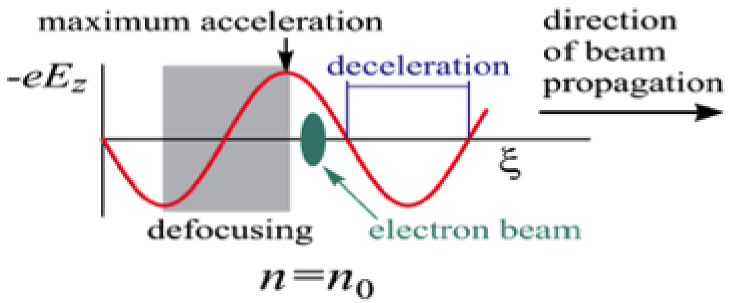
The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment.

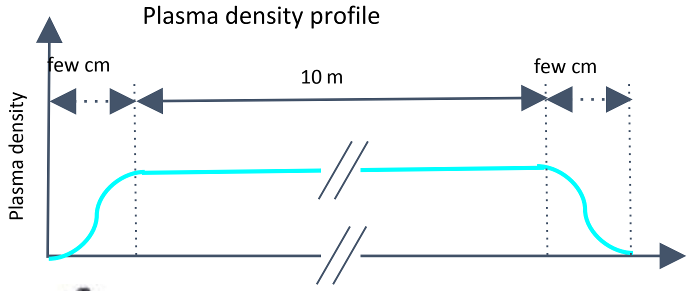
The proton beam must be steered around a mirror which **couples a terawatt class laser (Ti:Saph, 500mJ, 120fs)** into the beamline.

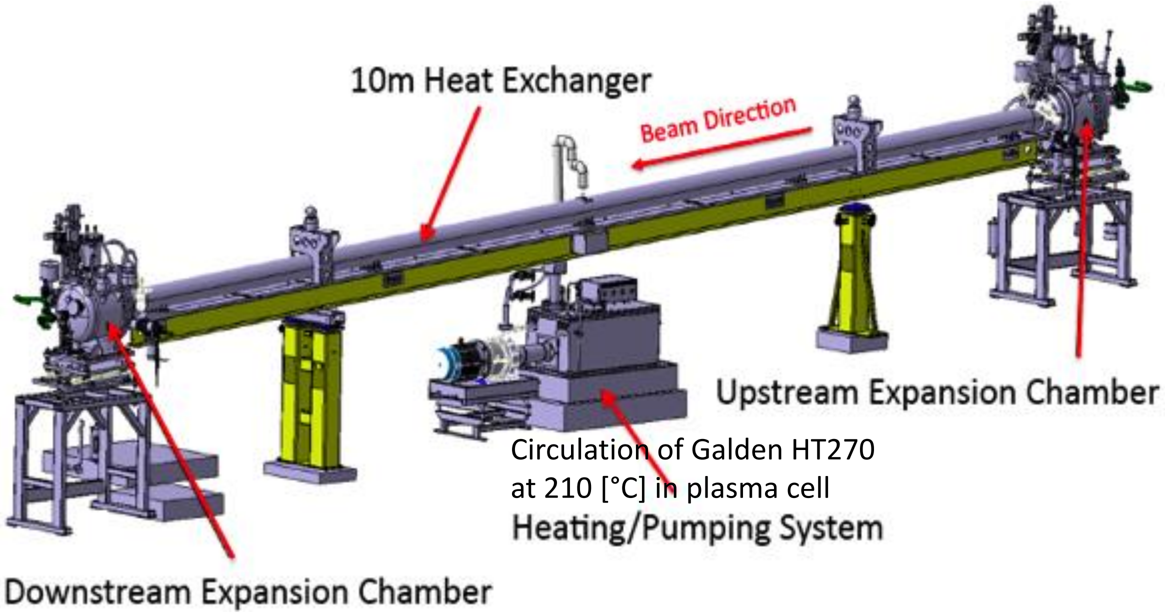
Further downstream, a **trailing electron beam** will injected into the same beamline.

AWAKE Plasma Cell

- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from $10^{14} - 10^{15}$ cm^{-3} ➔ **7x 10^{14} cm^{-3}**
- Requirements:
  - **density uniformity better than 0.2%**
    - Fluid-heated system (~220 deg)
    - Complex control system: 79 Temperature probes, valves
  - **Transition between plasma and vacuum as sharp as possible**



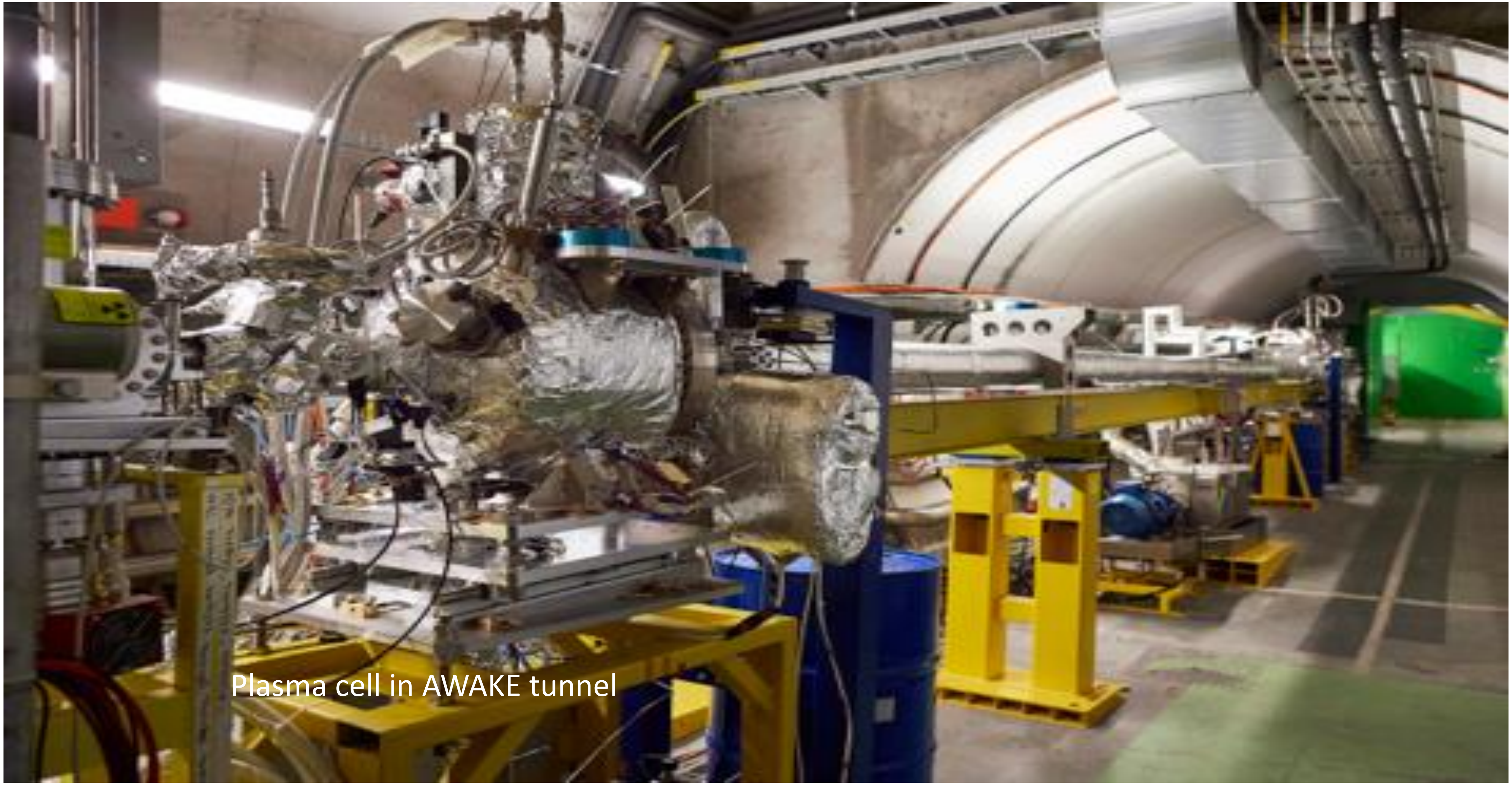




Circulation of Galden HT270 at 210 [°C] in plasma cell

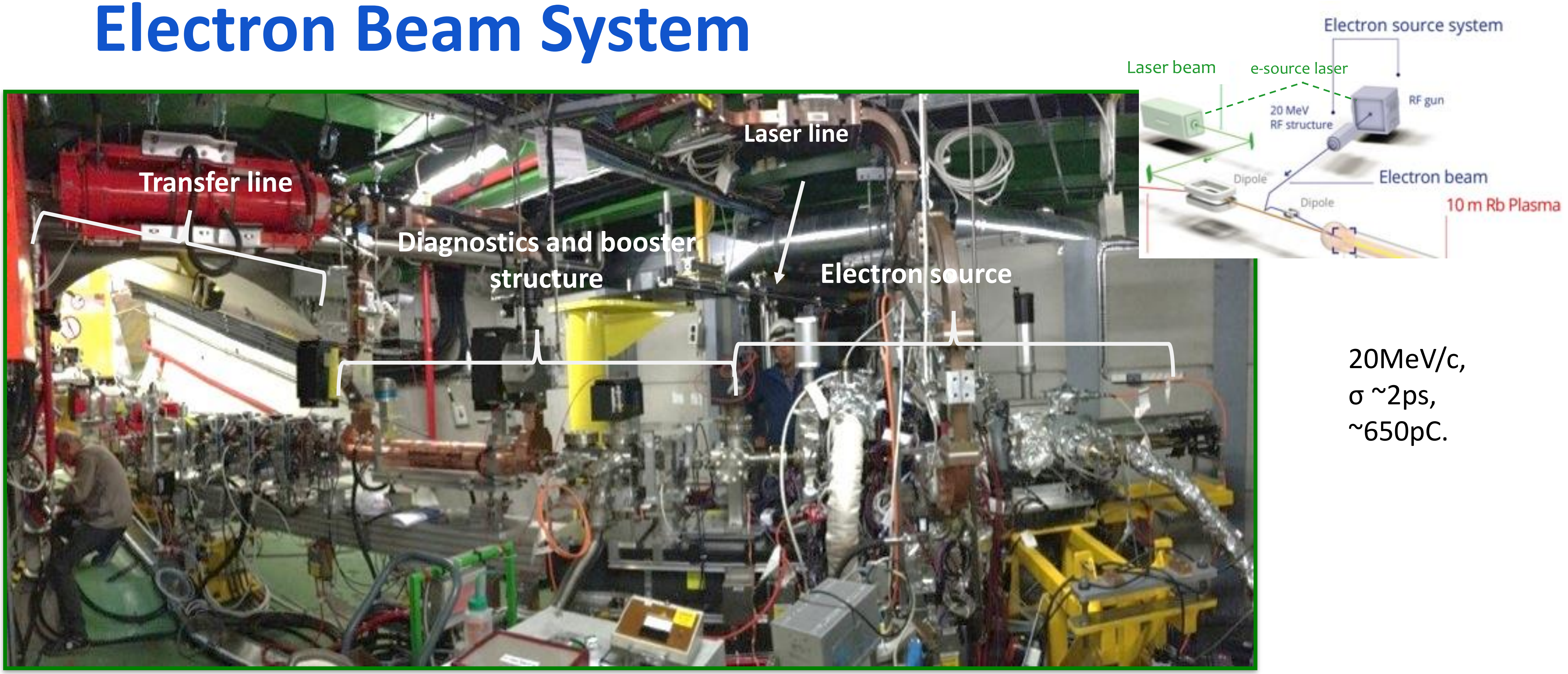
E. Öz et al., NIM A 740(11), 197 (2014)
E. Öz et al., NIM A829, 321 (2016)
F. Batsch et al., NIM A, 909, 359 (2018)

AWAKE Plasma Cell



Plasma cell in AWAKE tunnel

Electron Beam System

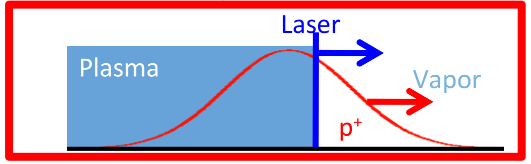


20MeV/c,
σ ~2ps,
~650pC.

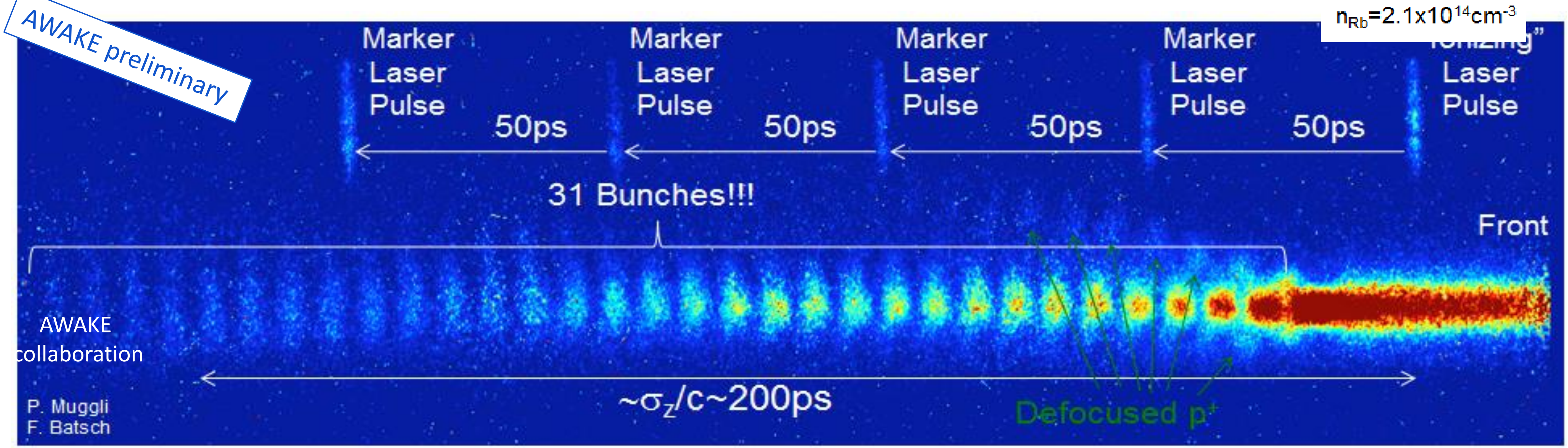
A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**
A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

Challenge: cross the electron beam with the proton beam inside the plasma at a precision of ~100 µm.

Results: Direct Seeded Self-Modulation Measurement, 2018



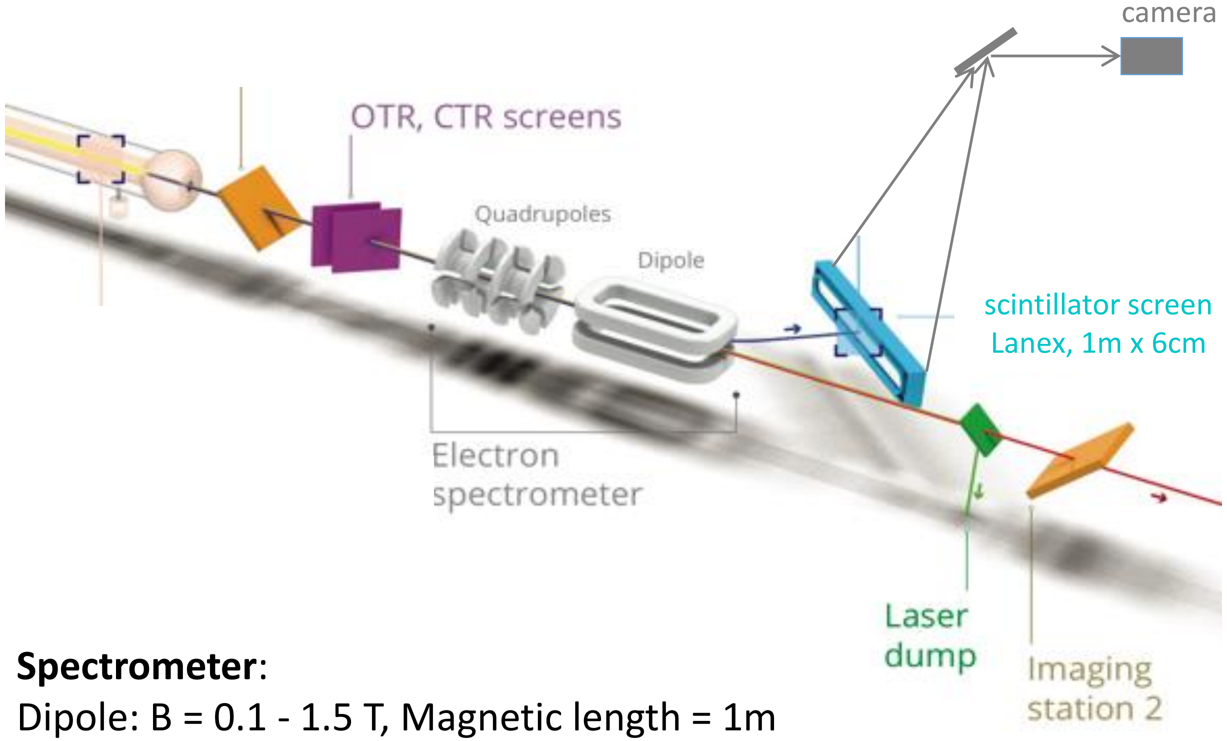
n_{Rb}=2.1x$10^{14}$$cm^{-3}$



- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the µ-bunch process against bunch parameters variation
- **Phase stability** essential for e^- external injection.

AWAKE Collaboration, 'Experimental observation of proton bunch modulation in a plasma, at varying plasma densities'. **Phys. Rev. Lett. 122, 054802 (2019).**
M. Turner et al. (AWAKE Collaboration), 'Experimental observation of plasma wakefield growth by the seeded self-modulation of a proton bunch', **PRL, 122, 054801 (2019).**

Electron Acceleration Diagnostics

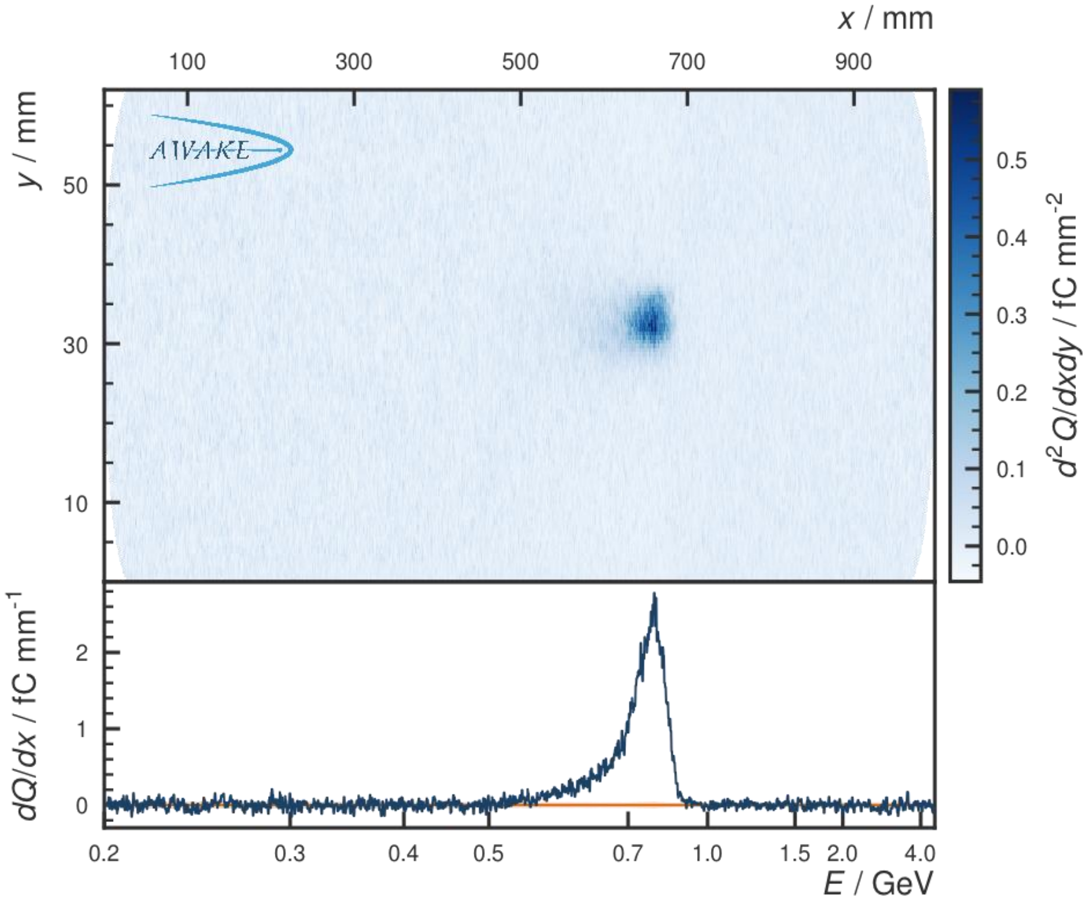


Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

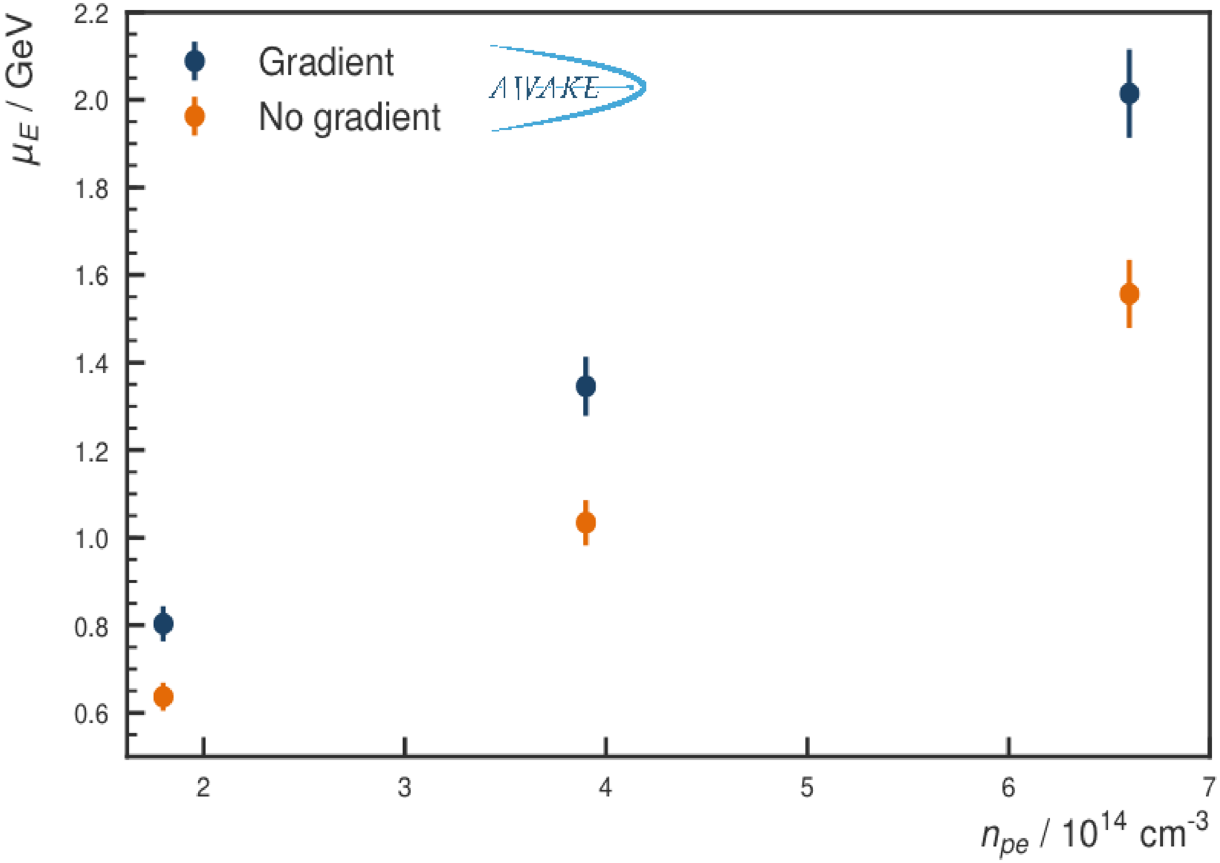
Electrons will be accelerated in the plasma. To measure the energy the electrons pass through a **dipole spectrometer and the dispersed electron impact on the scintillator screen.**
The resulting light is collected with an intensified CCD camera.

Electron Acceleration Results, 2018

Results from **May 2018 Run**



Event **at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m** density gradient.



➔ **Acceleration up to 2 GeV** has been achieved.

AWAKE Collaboration, Nature, doi:10.1038/s41586-018-0485-4 (2018)

Status of Today and Goals for Collider Application

	Current	Goal
Charge (nC)	0.1	1
Energy (GeV)	9	10
Energy spread (%)	2	0.1
Emittance (um)	>50-100	$<10^{-1}$
Staging	single	single/multiple
Efficiency (%)	20	40
Rep Rate (Hz)	1-10	10^{3-4}
Acc. Distance (m)	1	1-5

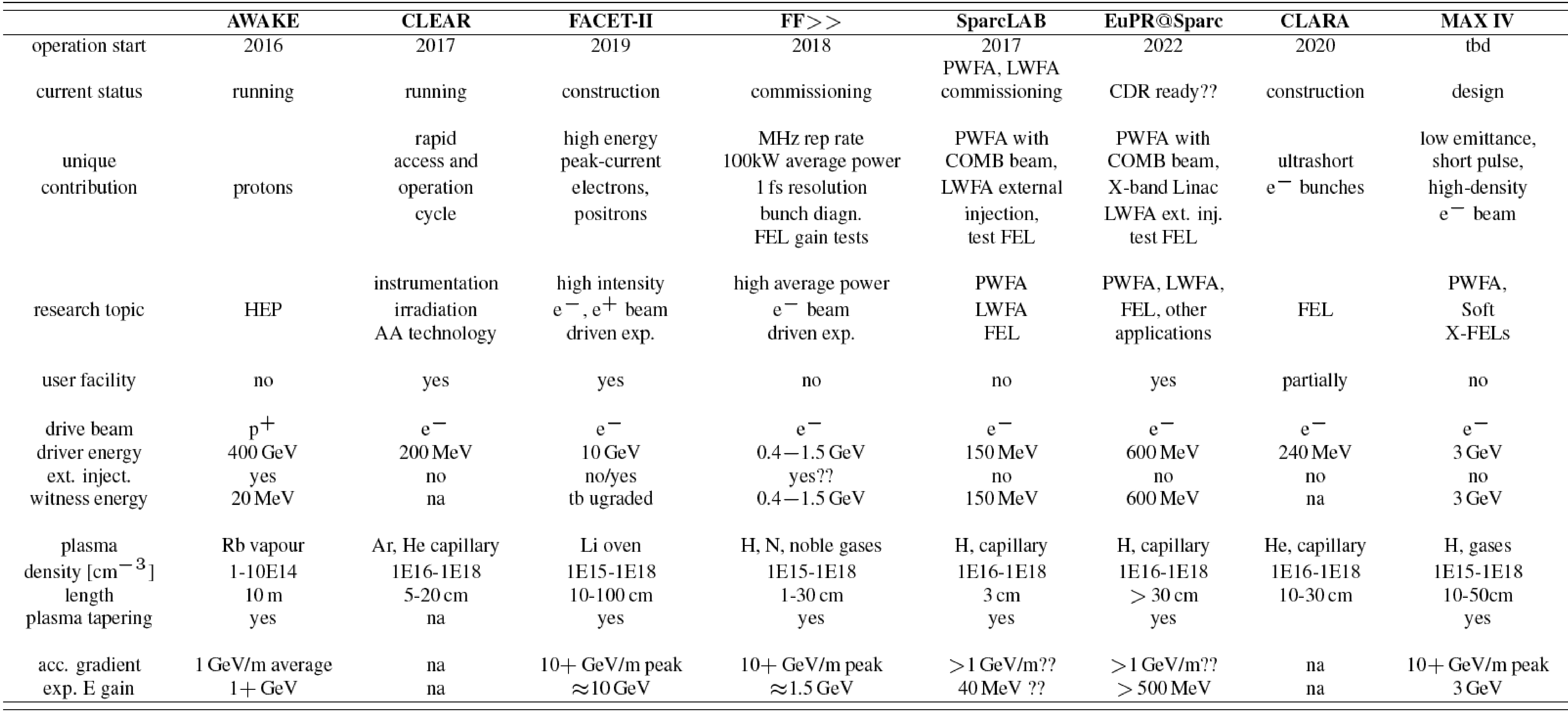
C. Joshi, AAC2018 Talk

- ✦ Positron acceleration: first limits, but no clear process for Collider Applications
- ✦ Use of Proton Drive Beam to reach GeV electrons, beam quality not yet shown.

Challenges not yet Demonstrated

- Acceleration with GV/m average gradient
- Generation/acceleration of nC charge, ultra-low emittance beams
- Emittance preservation
- Stability and reproducibility of the accelerated beam
- Independently shaped drive and witness beam
- Beam matching in and out of a plasma stage
- Positron acceleration
- Staging
- Technology readiness
- Plasma sources
- New diagnostics
- ….

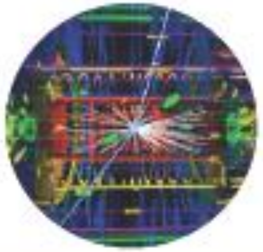
Future Facilities



	AWAKE	CLEAR	FACET-II	FF>>	SparcLAB	EuPR@Sparc	CLARA	MAX IV
operation start	2016	2017	2019	2018	2017	2022	2020	tbd
current status	running	running	construction	commissioning	PWFA, LWFA commissioning	CDR ready??	construction	design
unique contribution	protons	rapid access and operation cycle	high energy peak-current electrons, positrons	MHz rep rate 100kW average power 1 fs resolution bunch diagn. FEL gain tests	PWFA with COMB beam, LWFA external injection, test FEL	PWFA with COMB beam, X-band Linac LWFA ext. inj. test FEL	ultrashort e^- bunches	low emittance, short pulse, high-density e^- beam
research topic	HEP	instrumentation irradiation AA technology	high intensity e^-, e^+ beam driven exp.	high average power e^- beam driven exp.	PWFA LWFA FEL	PWFA, LWFA, FEL, other applications	FEL	PWFA, Soft X-FELs
user facility	no	yes	yes	no	no	yes	partially	no
drive beam	p^+	e^-	e^-	e^-	e^-	e^-	e^-	e^-
driver energy	400 GeV	200 MeV	10 GeV	0.4−1.5 GeV	150 MeV	600 MeV	240 MeV	3 GeV
ext. inject.	yes	no	no/yes	yes??	no	no	no	no
witness energy	20 MeV	na	tb ugraded	0.4−1.5 GeV	150 MeV	600 MeV	na	3 GeV
plasma	Rb vapour	Ar, He capillary	Li oven	H, N, noble gases	H, capillary	H, capillary	He, capillary	H, gases
density [cm^{-3}]	1-10E14	1E16-1E18	1E15-1E18	1E15-1E18	1E16-1E18	1E16-1E18	1E16-1E18	1E15-1E18
length	10 m	5-20 cm	10-100 cm	1-30 cm	3 cm	> 30 cm	10-30 cm	10-50cm
plasma tapering	yes	na	yes	yes	yes	yes		yes
acc. gradient	1 GeV/m average	na	10+ GeV/m peak	10+ GeV/m peak	>1 GeV/m??	>1 GeV/m??	na	10+ GeV/m peak
exp. E gain	1+ GeV	na	≈10 GeV	≈1.5 GeV	40 MeV ??	> 500 MeV	na	3 GeV

FACET-II, SLAC

A National User Facility Based on High Energy Beams and Their Interaction with Plasmas and Lasers



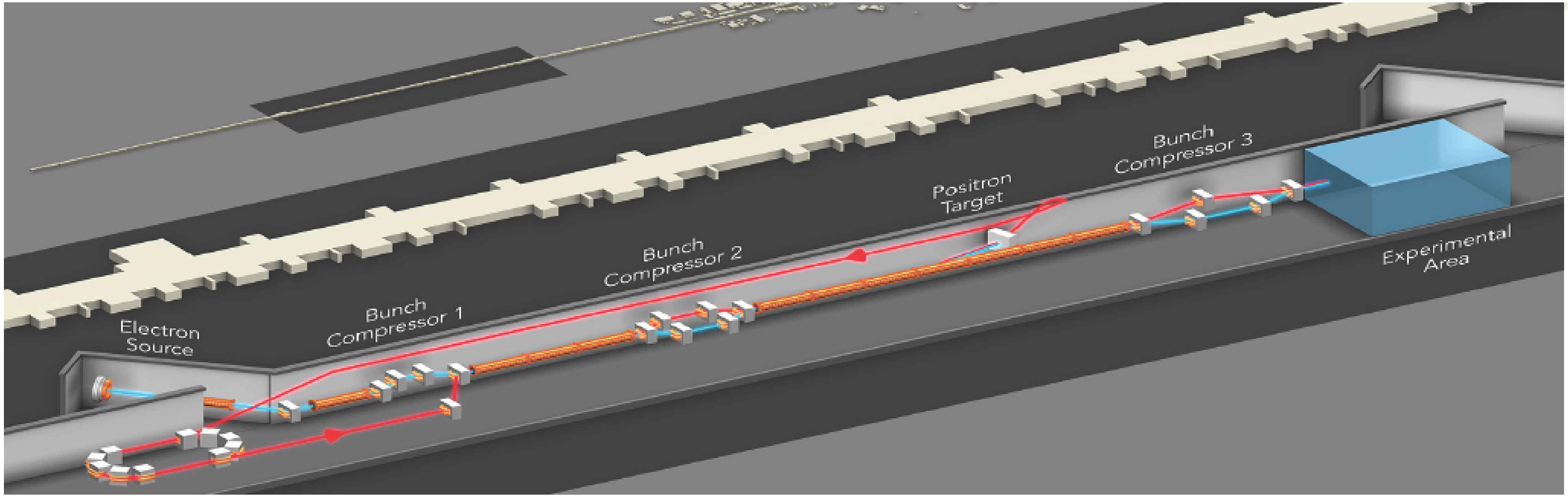
Advance the energy frontier
for future colliders

Develop brighter X-rays
for photon science

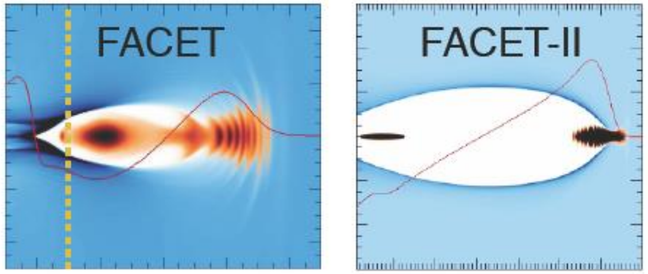
10 GeV e^- & e^+ beams, 2nC/1nC @ 30/5Hz, ~μm emittance, Ipk > 10kA

- Start of RF Gun: 2018
- Commissioning: 2019
- User programs: 2019 – 2026

FACET-II: Stage 1 (2019-2022)



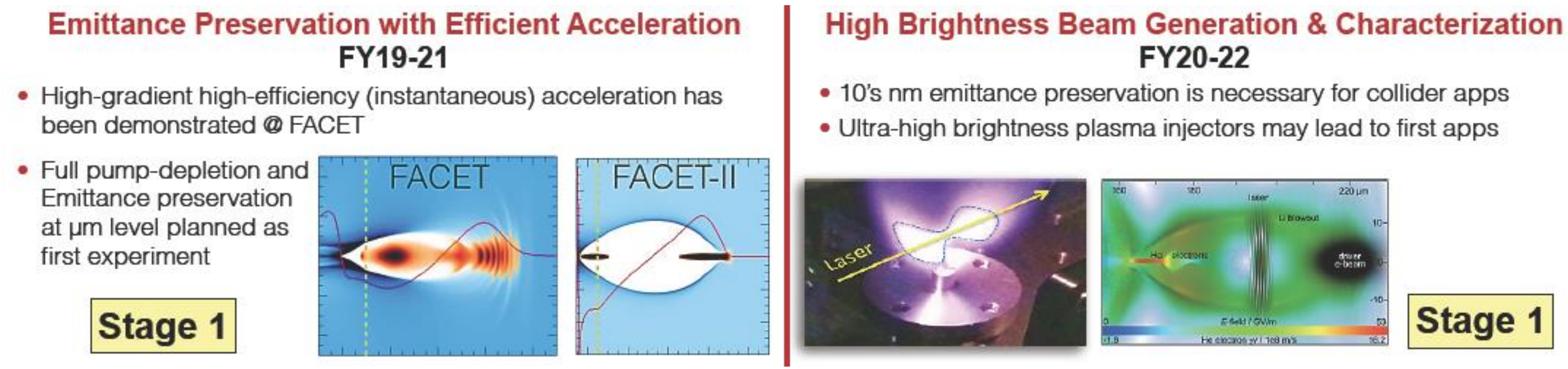
Electron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	2	0.7-5
Repetition Rate [Hz]	30	1-30
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]	4.4, 3.2	3-6
Spot Size at IP $\sigma_{x,y}$ [μm]	18, 12	5-20
Min. Bunch Length σ_z (rms) [μm]	1.8	0.7-20
Max. Peak current I_{pk} [kA]	72	10-200



Key upgrades:

- Photoinjector beam
- Plasma source with matching ramps
- Differential pumping
- Single shot emittance diagnostics

FACET-II Program



Emittance Preservation with Efficient Acceleration

FY19-21

- High-gradient high-efficiency (instantaneous) acceleration has been demonstrated @ FACET
- Full pump-depletion and Emittance preservation at µm level planned as first experiment

Stage 1

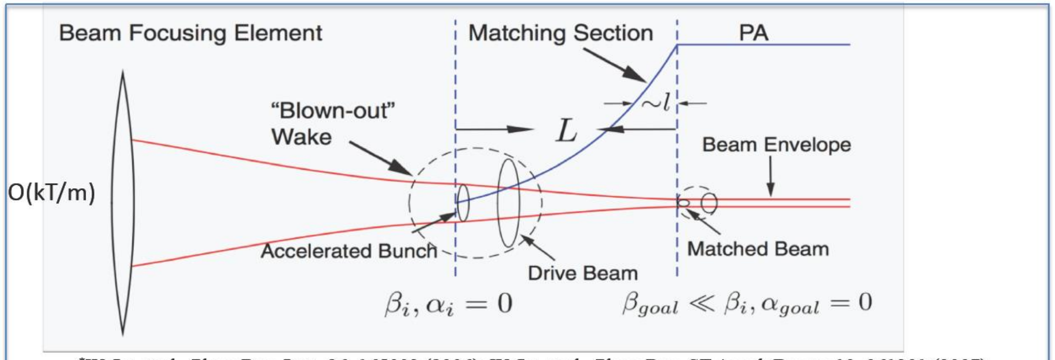
High Brightness Beam Generation & Characterization

FY20-22

- 10's nm emittance preservation is necessary for collider apps
- Ultra-high brightness plasma injectors may lead to first apps

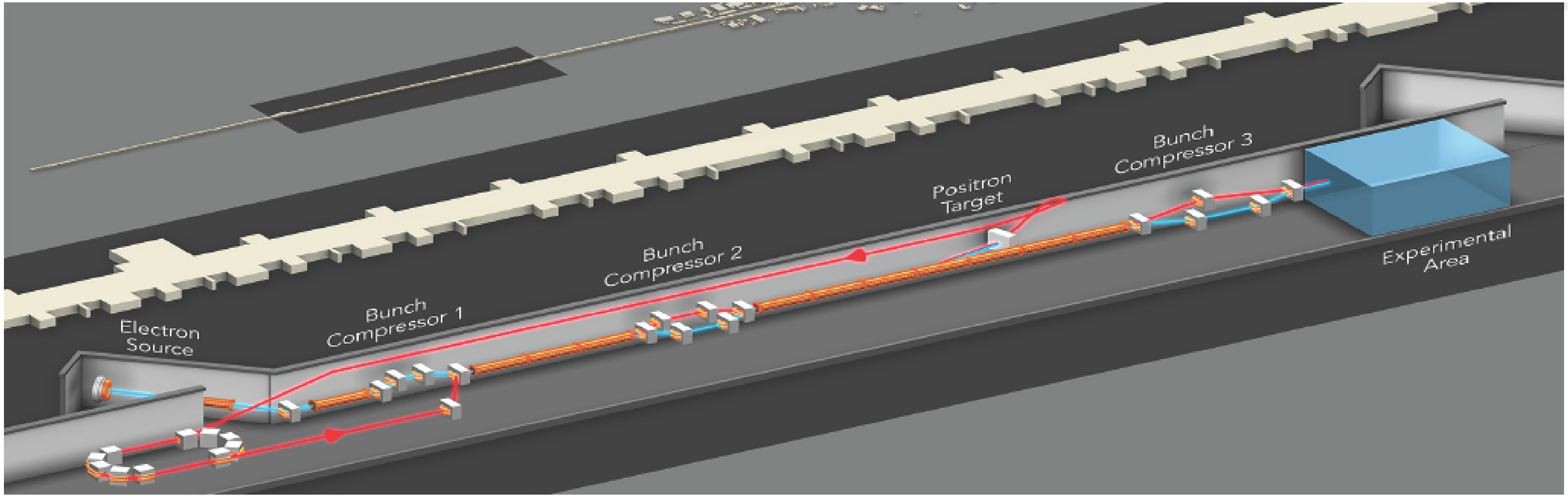
Stage 1

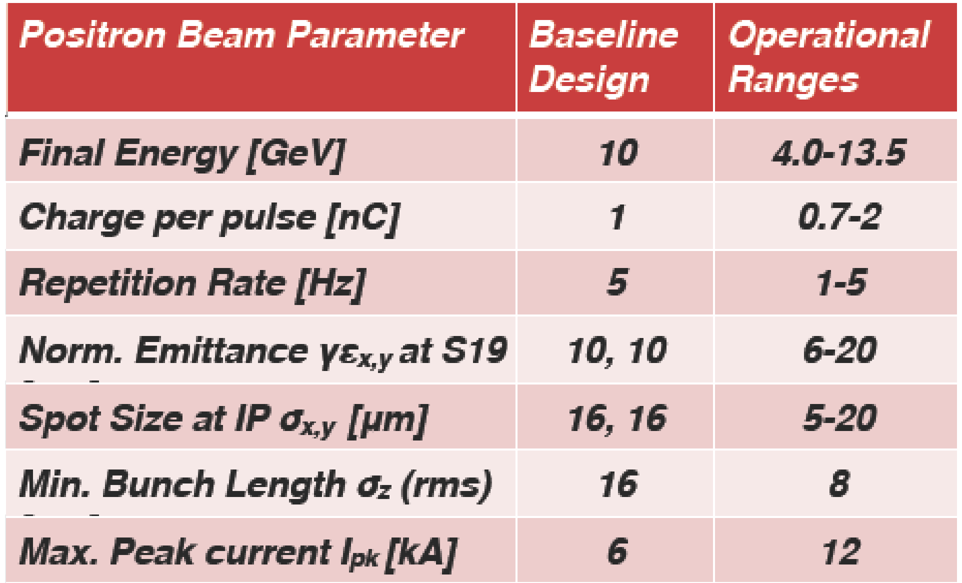
- Energy doubling of the witness beam.
- Minimize energy spread of the witness bunch.
- High energy extraction efficiency with minimum energy spread → requires optimized beam loading
- Emittance preservation of the witness beam and determine factors causing emittance growth.
- Alignment tolerance between drive and witness beam.
- Beam matching in and out of the plasma → critical to staging.



*W. Lu et al., Phys. Rev. Lett. 96, 165002 (2006); W. Lu et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007).

FACET-II: Stage 2, 3 (2021-2025)





Positron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	1	0.7-2
Repetition Rate [Hz]	5	1-5
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19	10, 10	6-20
Spot Size at IP $\sigma_{x,y}$ [µm]	16, 16	5-20
Min. Bunch Length σ_z (rms)	16	8
Max. Peak current I_{pk} [kA]	6	12

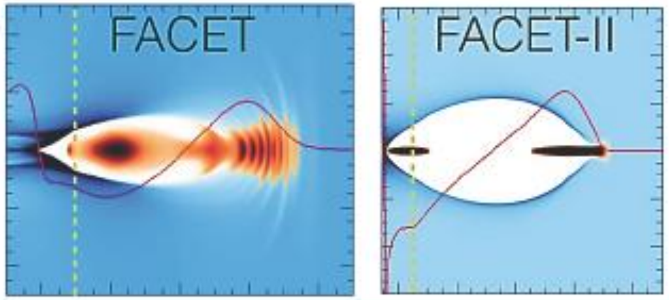
FACET-II Program

Emittance Preservation with Efficient Acceleration

FY19-21

- High-gradient high-efficiency (instantaneous) acceleration has been demonstrated @ FACET
- Full pump-depletion and Emittance preservation at μm level planned as first experiment

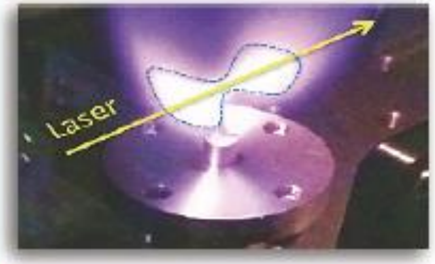
Stage 1

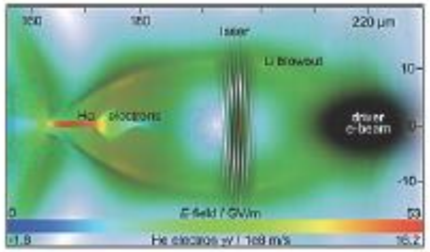


High Brightness Beam Generation & Characterization

FY20-22

- 10's nm emittance preservation is necessary for collider apps
- Ultra-high brightness plasma injectors may lead to first apps





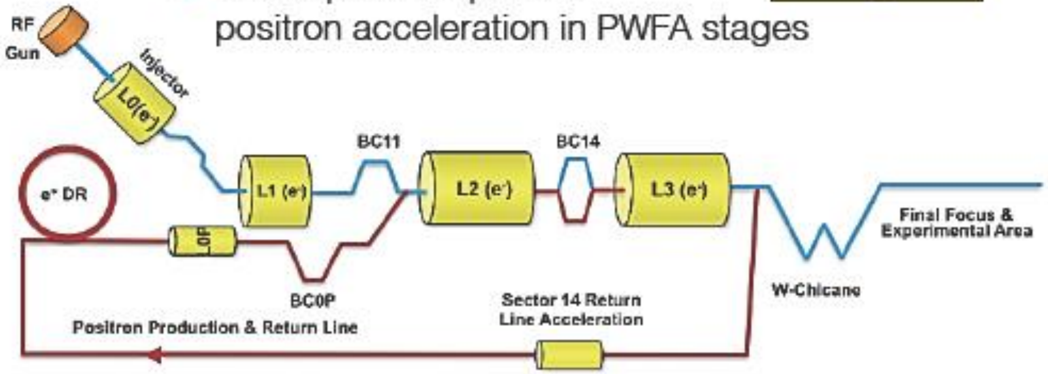
Stage 1

Positron Acceleration

FY21-24

- Only high-current positron capability in the world for PWFA research will be enabled by Phase II
  - Develop techniques for positron acceleration in PWFA stages

Stage 2

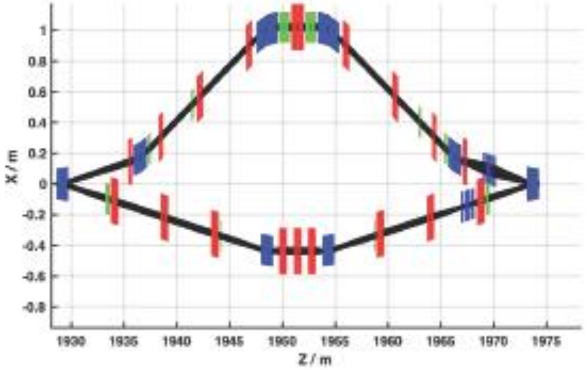


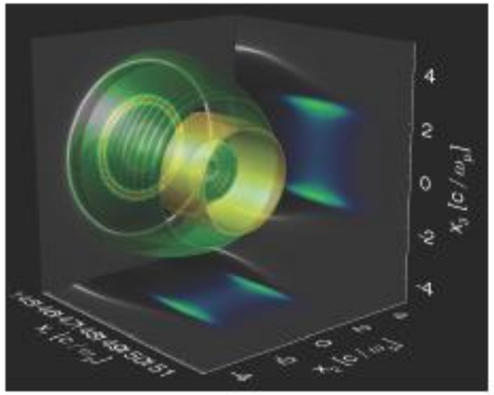
Simultaneous Deliver of Electrons & Positrons

FY22-25

- Positron Acceleration on Electron Beam Driven Wakefields

Stage 3



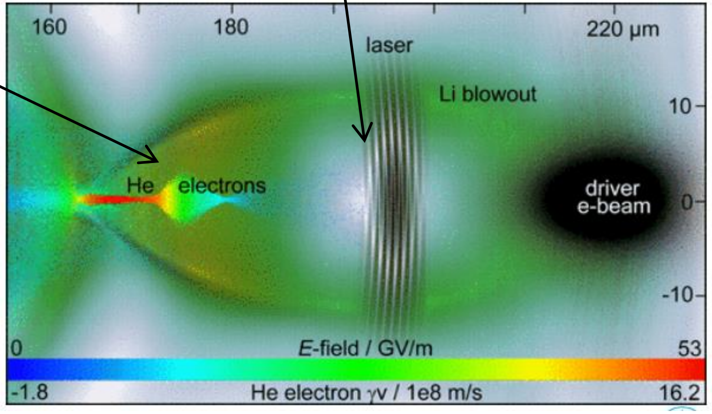


Example of FACET-II Experiment ‘Trojan Horse’: High Brightness Beam

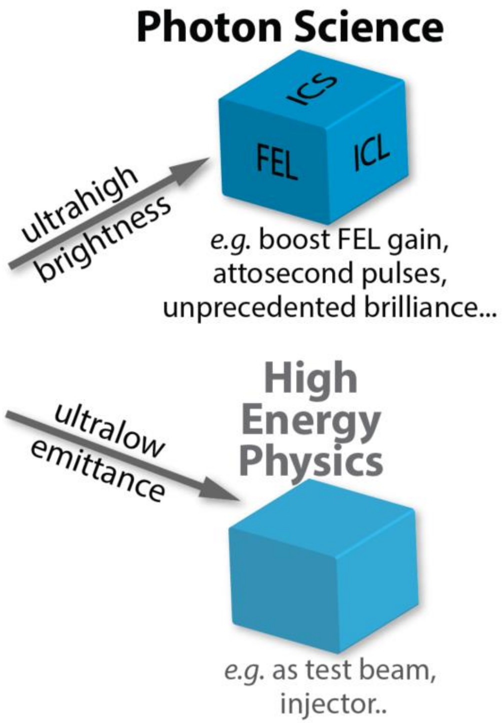
Plasma photocathode: Tunable production of electron bunches of ultrahigh quality by laser release from higher ionization threshold inside the electron-driven plasma wave

Released electrons are rapidly accelerated and form bunch with ultralow emittance

Synchronized laser pulse tunnel ionizes in focus and releases ultracold electron population



B. Hidding et al., PRL 108, 035001 (2012)



Two plasma components:

- Beam-driven plasma wakefield using low-ionization-threshold gas such as Li
- Laser-controlled electron injection via ionization of high-ionization threshold gas such as He

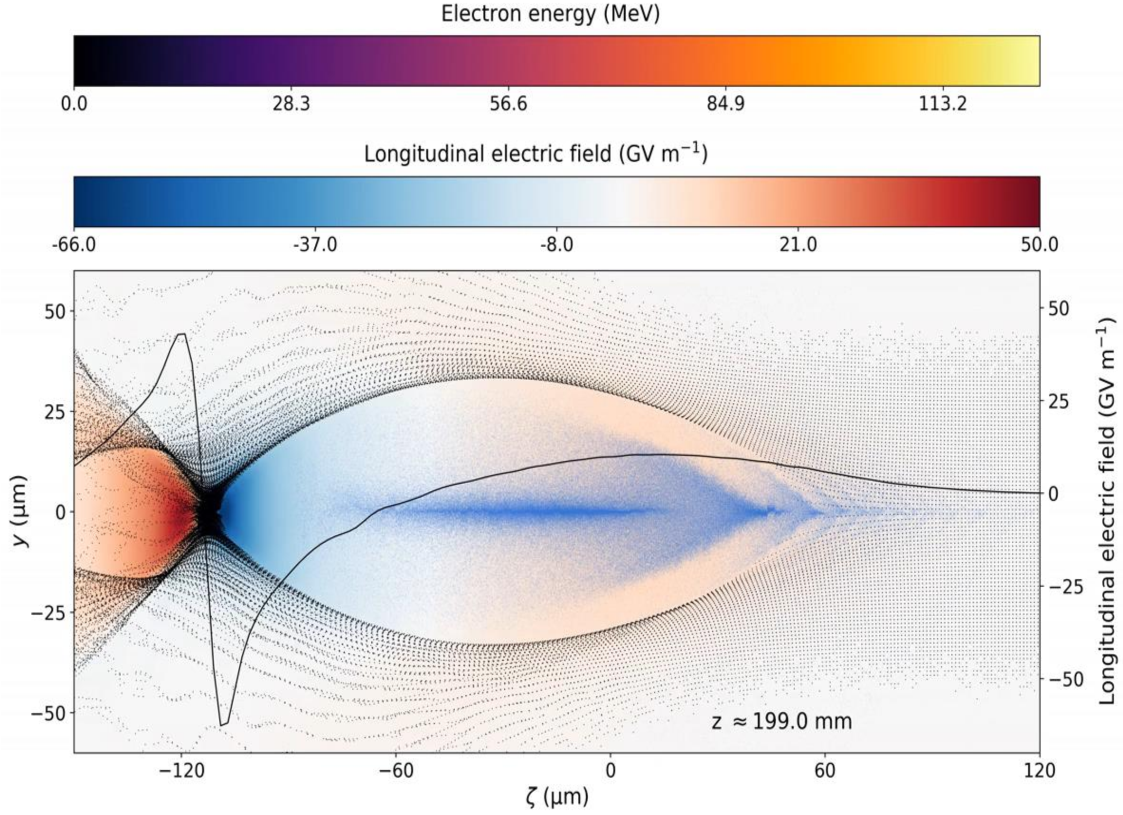
Ultra-high brightness beams:

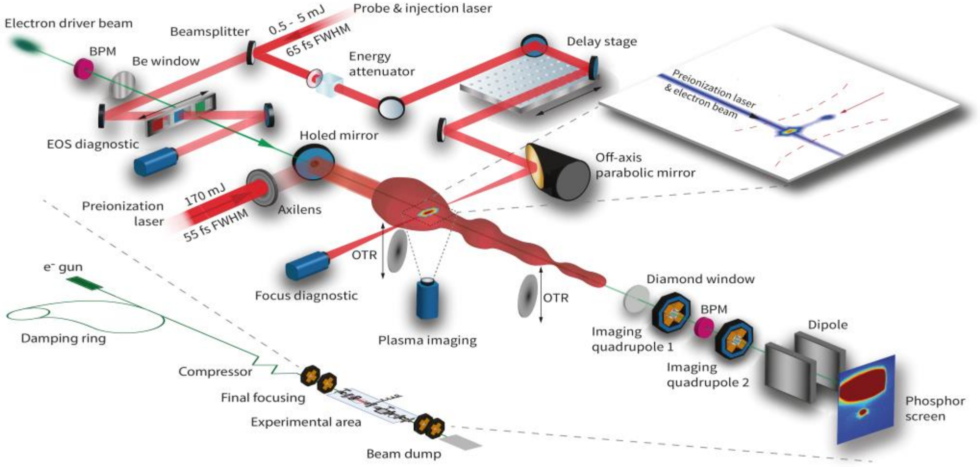
- Sub-µm spot size
- fs pulses
- Small emittance (nm mrad)

$$B_{6D} = \frac{\overset{\text{current}}{I}}{\underset{\text{emittance}}{\epsilon_n^2} \cdot 0.1\%\sigma_W}\ \text{energy spread}$$

Trojan Horse at FACET, 2016

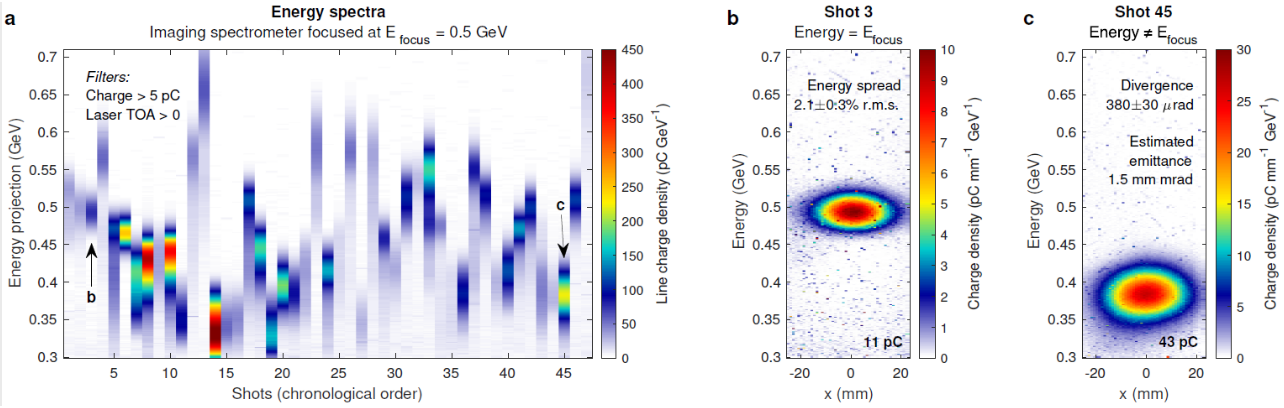
Laser-based plasma cathodes in 90° geometry



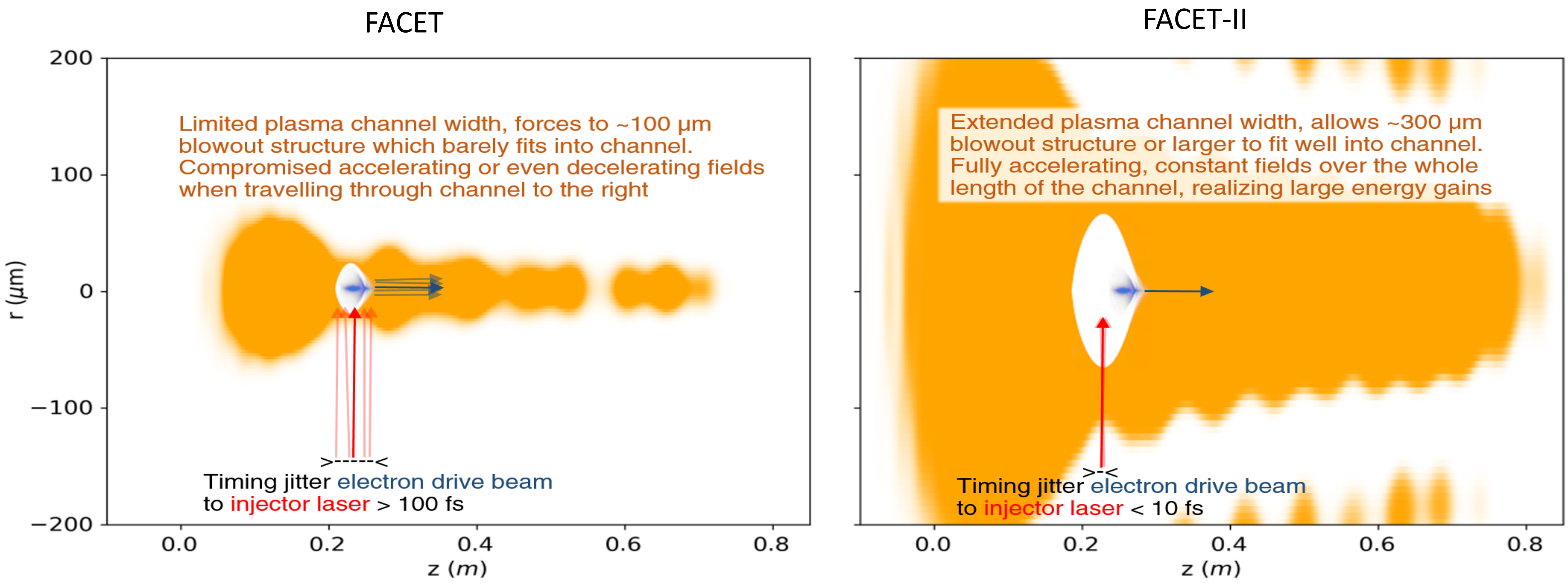


Challenges during FACET run:

- Pre-ionized plasma channel width
- Jitter of incoming laser and e-beam



Trojan Horse at FACET-II, 2019+


FACET

Limited plasma channel width, forces to ~100 µm blowout structure which barely fits into channel. Compromised accelerating or even decelerating fields when travelling through channel to the right

>-----<

Timing jitter electron drive beam to injector laser > 100 fs

FACET-II

Extended plasma channel width, allows ~300 µm blowout structure or larger to fit well into channel. Fully accelerating, constant fields over the whole length of the channel, realizing large energy gains

>-<

Timing jitter electron drive beam to injector laser < 10 fs

Program:

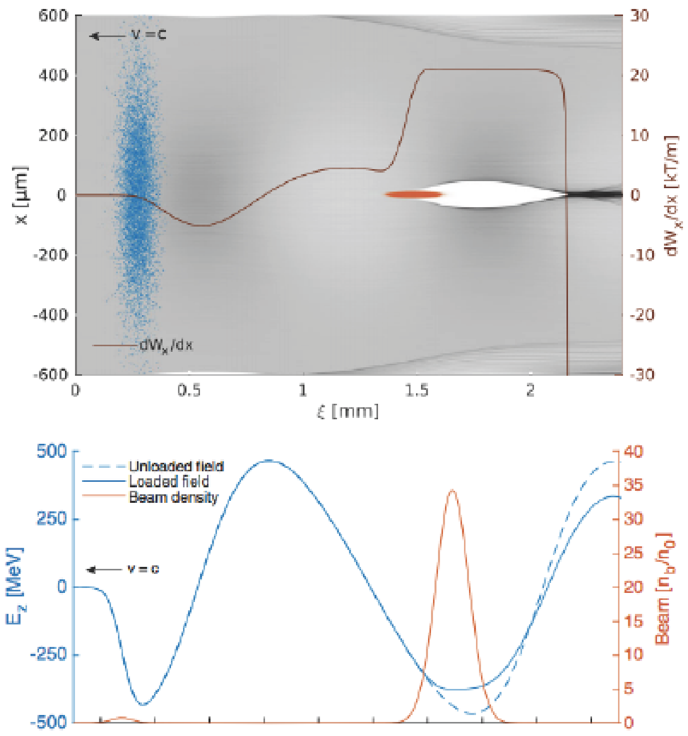
1. Re-establish 90 deg Trojan Horse with more stable beams, jitter and larger blowouts
2. Realize at different angles, e.g. 45 deg
3. Realize in collinear geometry for nm rad emittance values, test different gases, tune beams

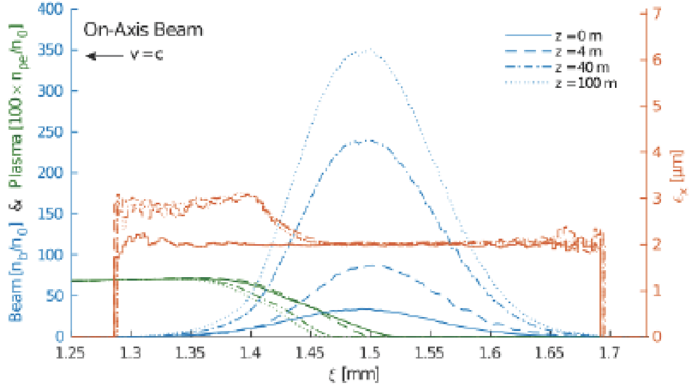
AWAKE Run 2

Proposing Run 2 for 2021 after CERN Long Shutdown 2

✧Acceleration of an externally injected e⁻ bunch with small final ε and ΔE/E @ GeV

OLSEN, ADLI, and MUGGLI PHYS. REV. ACCEL. BEAMS **21,** 011301 (2018)





Typical parameters:

σ_z=60μm

σ_r=5.25μm

(matched for ε_N=2mm-mrad, n_e=7x10^{14}cm^{-3}, ~$\varepsilon_N^{1/4}$)

Q=100pC

Blow-out and beam loading

~73% charge with $\Delta\varepsilon_N/\varepsilon_N$<5%, ΔE/E~%

- AWAKE Run 1: Proof-of-Concept
- AWAKE Run 2: Accelerate electron beam to high energy while preserving beam quality so that it can be used for first physics application.

✧Challenging parameters to produce with low energy particles (σ_r,σ_z)

✧Challenging to measure (σ_r)

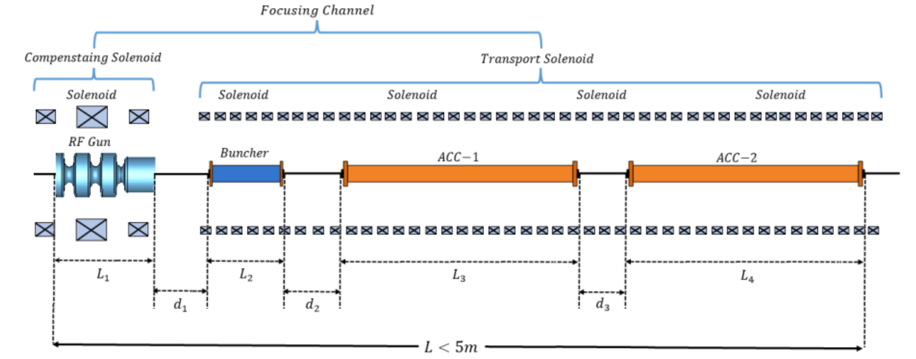
AWAKE Run 2

Proposing Run 2 for 2021 after CERN Long Shutdown 2

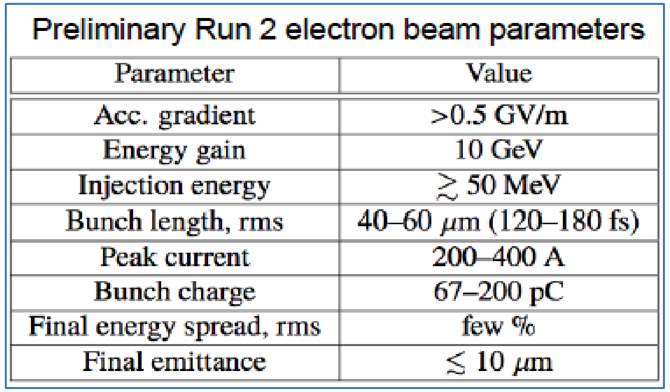
Goals:

- **Accelerate an electron beam to high energy** (gradient of 0.5-1GV/m)
- **Preserve electron beam quality** as well as possible (emittance preservation at 10 mm mrad level)
- **Demonstrate scalability** of the AWAKE concept (R&D plasma sources)

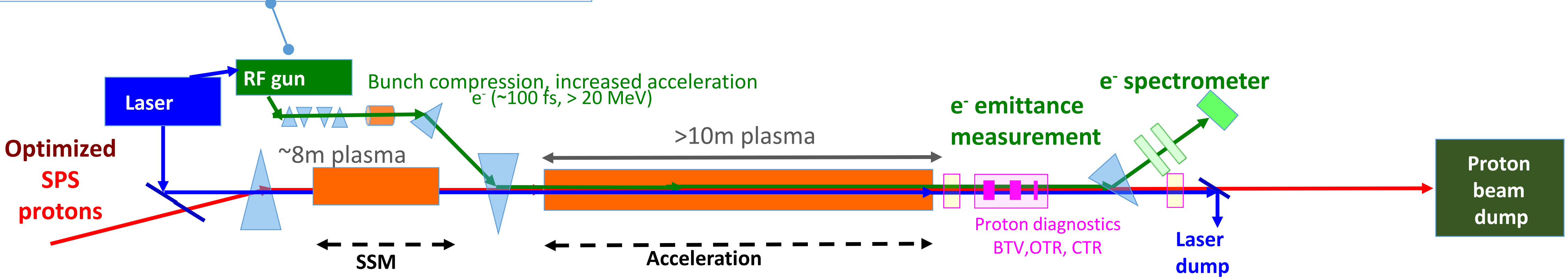
Proposal: X-band electron source



Preliminary Run 2 electron beam parameters



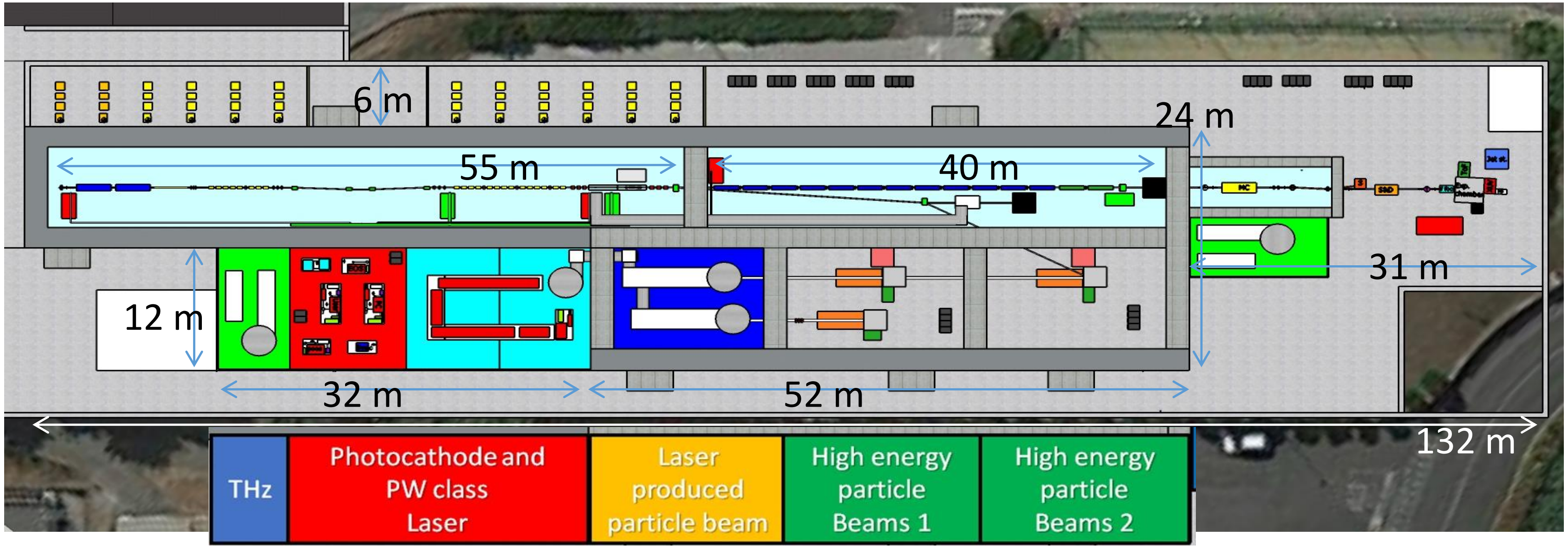
Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm



E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

EuPRAXIA@SPARC_LAB

- EuPRAXIA:
  - EuPRAXIA Design Study started in November 2015, 4 years, 3MEuros
  - Goal: Engineering of a high quality, compact plasma accelerator, 5 GeV electron beam for 2020’s, demonstrate user readiness, Pilot users from FEL, HEP, medicine
- SPARC_LAB: EuPRAXIA Site for beam driven plasma accelerator




INFN
Istituto Nazionale di Fisica Nucleare

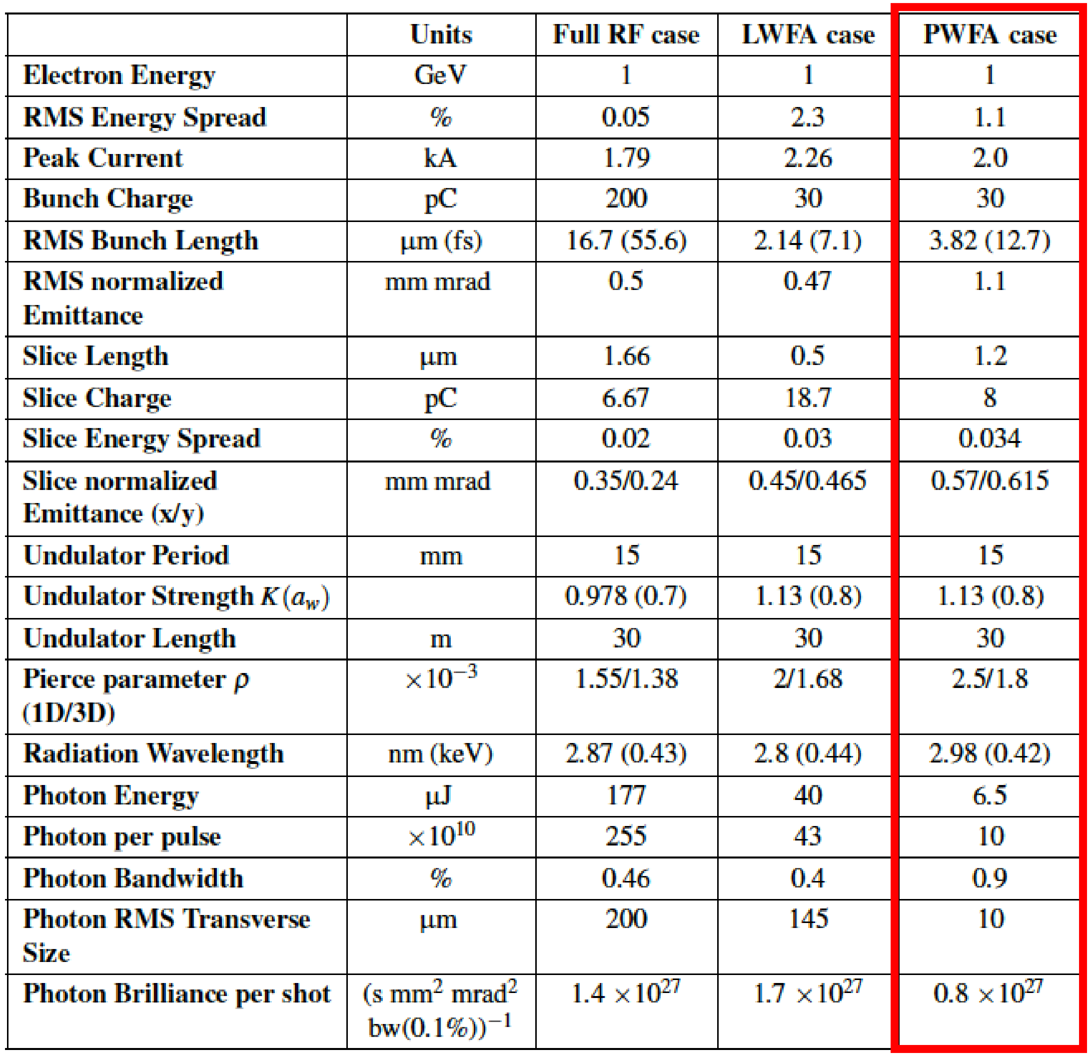
LNF–18/03
May 7, 2018

EuPRAXIA@SPARC_LAB

Conceptual Design Report

CDR ready

EuPRAXIA@SPARC_LAB



	Units	Full RF case	LWFA case	PWFA case
Electron Energy	GeV	1	1	1
RMS Energy Spread	%	0.05	2.3	1.1
Peak Current	kA	1.79	2.26	2.0
Bunch Charge	pC	200	30	30
RMS Bunch Length	μm (fs)	16.7 (55.6)	2.14 (7.1)	3.82 (12.7)
RMS normalized Emittance	mm mrad	0.5	0.47	1.1
Slice Length	μm	1.66	0.5	1.2
Slice Charge	pC	6.67	18.7	8
Slice Energy Spread	%	0.02	0.03	0.034
Slice normalized Emittance (x/y)	mm mrad	0.35/0.24	0.45/0.465	0.57/0.615
Undulator Period	mm	15	15	15
Undulator Strength $K(a_w)$		0.978 (0.7)	1.13 (0.8)	1.13 (0.8)
Undulator Length	m	30	30	30
Pierce parameter ρ (1D/3D)	$\times 10^{-3}$	1.55/1.38	2/1.68	2.5/1.8
Radiation Wavelength	nm (keV)	2.87 (0.43)	2.8 (0.44)	2.98 (0.42)
Photon Energy	μJ	177	40	6.5
Photon per pulse	$\times 10^{10}$	255	43	10
Photon Bandwidth	%	0.46	0.4	0.9
Photon RMS Transverse Size	μm	200	145	10
Photon Brilliance per shot	(s mm^2 mrad^2 bw(0.1%))$^{-1}$	1.4×10^{27}	1.7×10^{27}	0.8×10^{27}

Table 4.1: Beam parameters from start-to-end simulations for full RF and for plasma wakefield acceleration cases with electron (PWFA) or laser (LWFA) driver beam

Start to end simulations of the witness beam

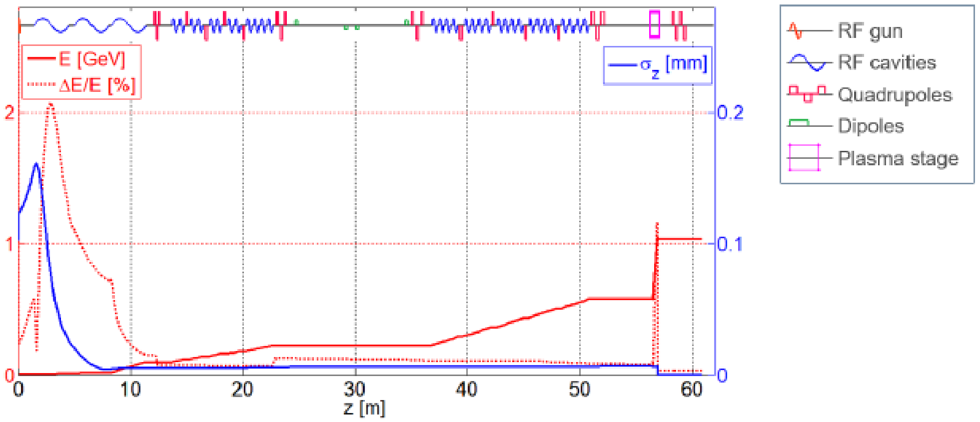


Figure 4.5: Start to end simulation results for the trailing bunch for the PWFA case: evolution along the injector of the energy (E red line) and energy spread ($\Delta E/E$ red dotted-line) and longitudinal bunch length (σ_z blue line).

CLARA

Compact Linear Accelerator for Research and Applications

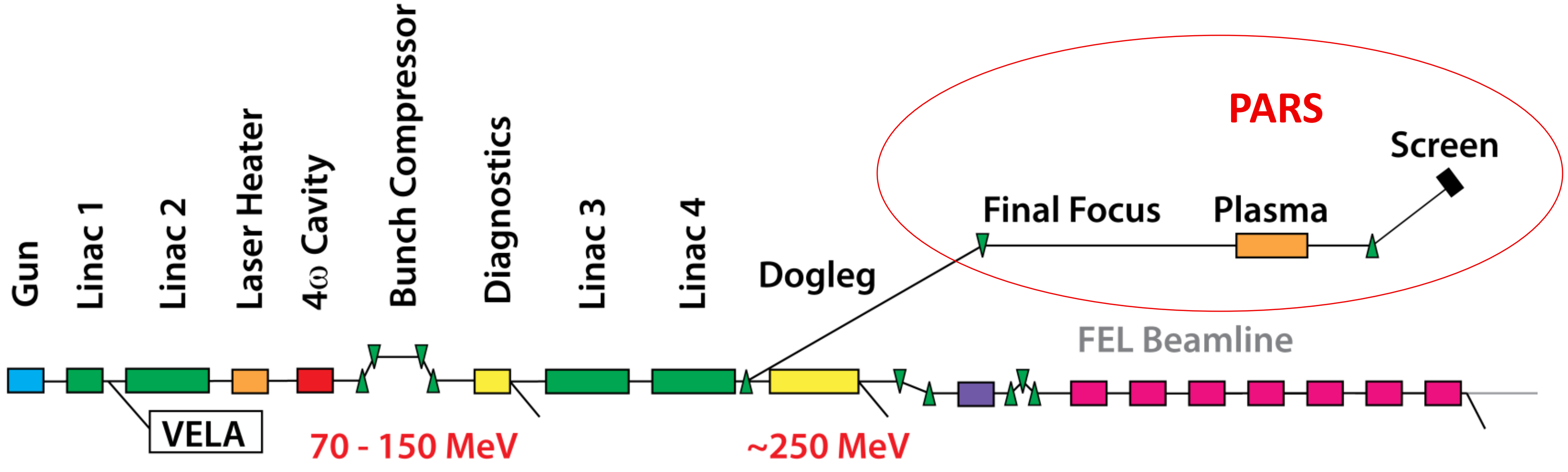
→upgrade of existing VELA Photoinjector Facility at Daresbury Laboratory to a 250 MeV Free-Electron Laser Test Facility.

- proof of principle demonstration of novel FEL concepts with emphasis on Ultra-Short Pulse Generation.

- → Propose a Plasma Accelerator Research Station, PARS

Status:

- VELA and CLARA frontend (50 MEV): exists since 2015
- CLARA 150MeV: approved, under construction
- CLARA 250MeV: needs approval



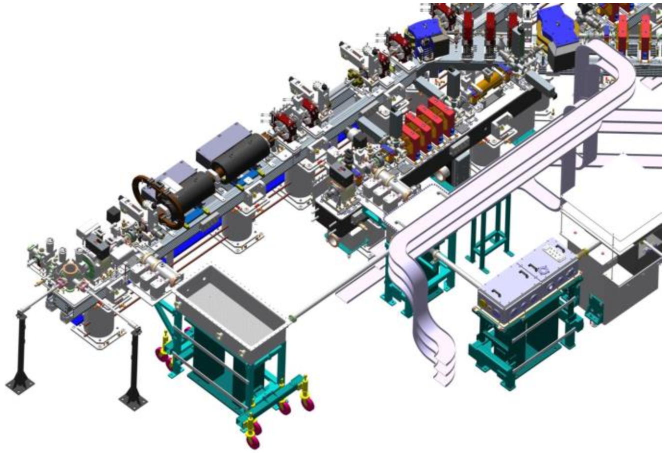
ASTeC
Strathclyde
INFN Frascati
SwissFEL
DLS
Oxford
Liverpool
Manchester
Imperial

PWFA at CLARA

CLARA Front-end beam available

Phase 1 parameters:

Max Energy	~50 MeV
Max Charge	250 pC
Norm. Emitt.	<1 mm mrad
Min Bunch Length	50fs (rms), (10 MeV)
Max Peak Current	2kA
Bunches/RF pulse	1
Pulse Rep Rate	10 Hz (400Hz later)

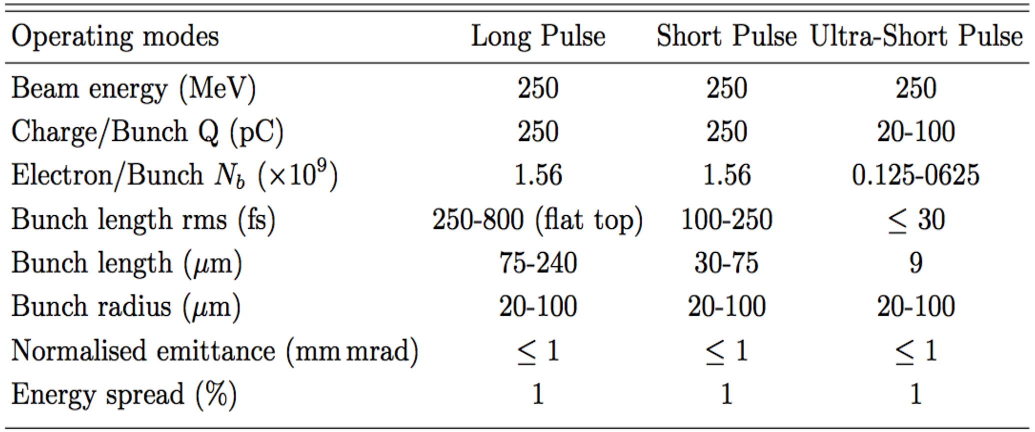


Existing VELA RF photoinjector facility

Proposed program for Plasma Accelerator Research Station:

- Two bunch experiment
- Beam quality preservation
- Plasma lens focusing effect (first experiment done in 2015)
- Beam loading effect for PWFA
- Hybrid wakefield acceleration/plasma photocathode injector
- High transformer ratio
- Plasma beam dump experiment
- …

CLARA operation modes



Operating modes	Long Pulse	Short Pulse	Ultra-Short Pulse
Beam energy (MeV)	250	250	250
Charge/Bunch Q (pC)	250	250	20-100
Electron/Bunch N_b ($\times 10^9$)	1.56	1.56	0.125-0625
Bunch length rms (fs)	250-800 (flat top)	100-250	≤ 30
Bunch length (μm)	75-240	30-75	9
Bunch radius (μm)	20-100	20-100	20-100
Normalised emittance (mm mrad)	≤ 1	≤ 1	≤ 1
Energy spread (%)	1	1	1

Summary

- Remarkable progress in the last decades in beam driven plasma wakefield acceleration.

- Much progress needs to be made to reach realistic collider beam parameters.
  - Many facilities will offer new potential for meeting the challenges.

➔ Lots of opportunities for young students and scientists!!