FLASHForward▸▸

Future-oriented wakefield-accelerator research and development at FLASH

DESY

Future accelerator technologies

– Plasma-wakefield acceleration –

Outline:

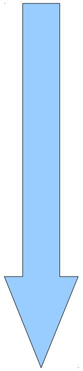
- Limits of current accelerator technology
- Plasma-wakefield acceleration
- **FLASHForward** facility at DESY

Vladyslav Libov,
DESY (Hamburg)

Diffractive and Electromagnetic Processes at High Energies
Bad Honnef, Germany, August 17-21, 2015

Accelerators in particle physics

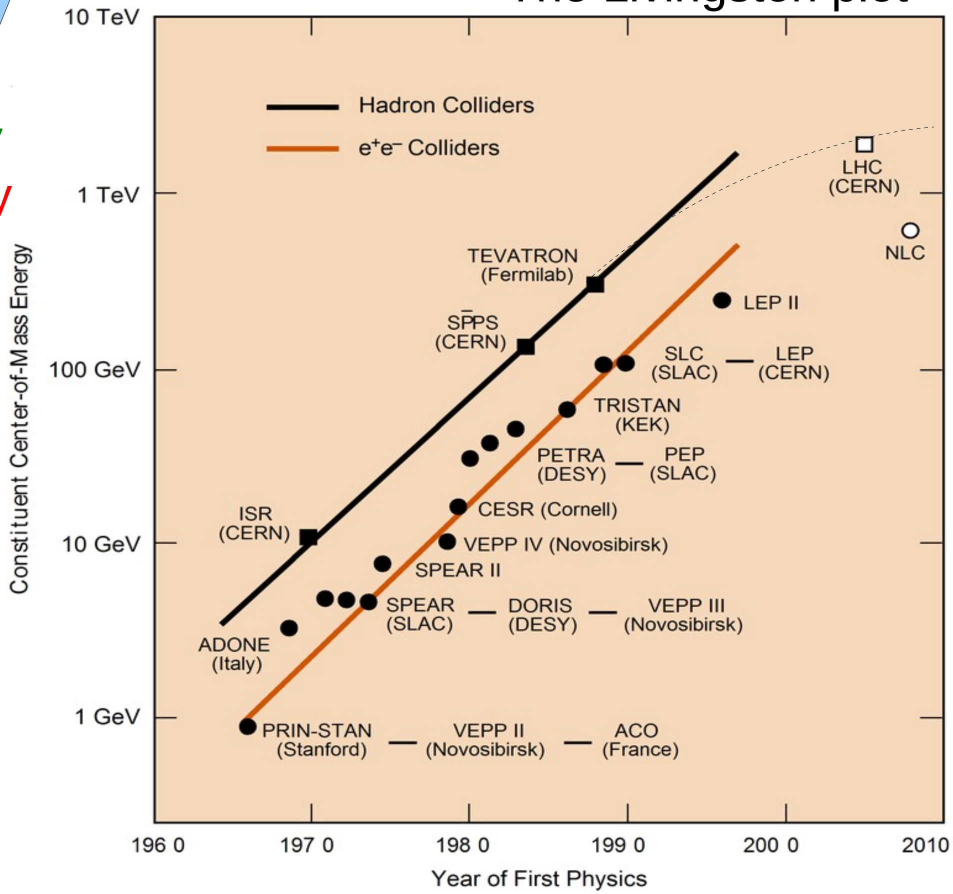
- **Accelerator** is a **discovery driver**
  - → AGS/SPEAR: c-quark (J/Ψ) (1974)
  - → SPS: W/Z-Bosons (1983)
  - → HERA: proton structure (1992)
  - → Tevatron: t-quark (1995)
  - → LHC: Higgs Boson (2012), … ?



Energy, luminosity

Cost, construction time, complexity

The Livingston plot



Nearly exponential growth in energy

Accelerators in particle physics

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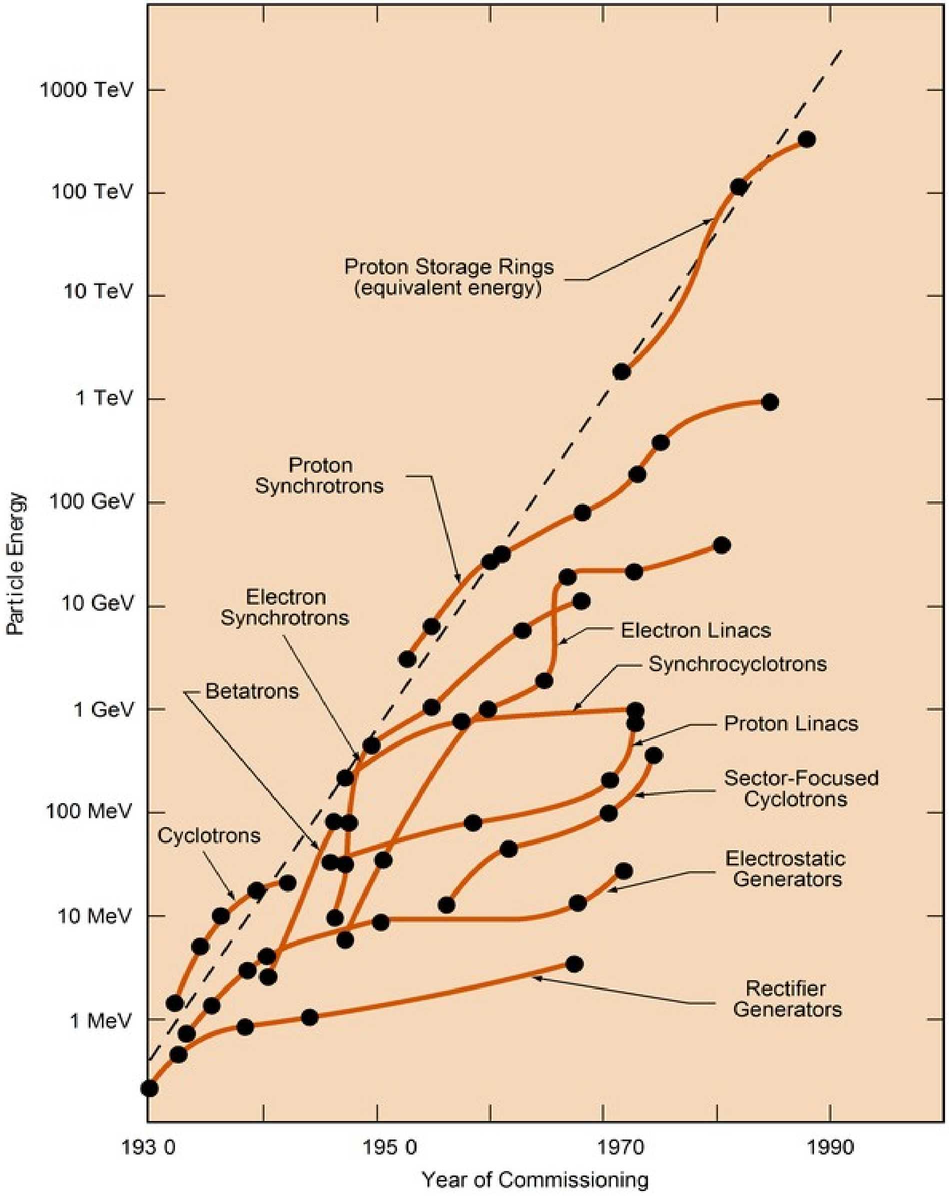


Can we maintain/go beyond the exponential energy growth?

What limits the beam energy?

I. Dipole magnetic field ↔ bending radius (circular hadron)

$$B=\frac{p}{e\,R}$$

Particle momentum

Bending radius (given by the tunnel)

HE-LHC: 17 TeV

FCC-pp: 50 TeV, 20 T, 80 km

LHC: 7 TeV*, 8.4 T, 27km

II. Bending radius (circular electron)

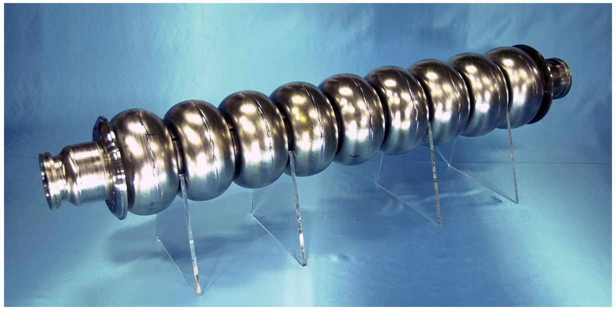
Synchrotron losses ~ $\frac{E^4}{R\,m}$

LEP: 100 GeV, 27km

III. Accelerating gradient ↔ length (linear)

Superconducting radio-frequency (RF) technology ~ 100 MeV/m

ILC: 250-500 GeV, 50 MeV/m, 30-50 km



Need new accelerator technologies if want to maintain exponential growth/keep size (=cost) reasonable

* all energies per beam

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Plasma-based acceleration

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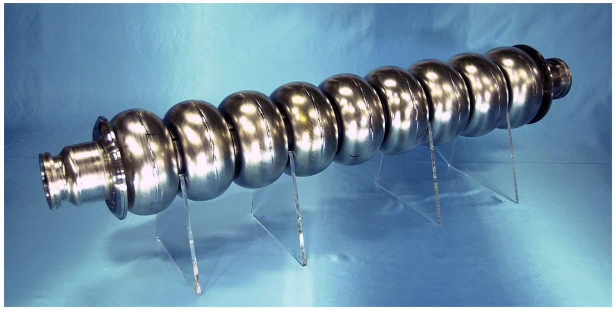

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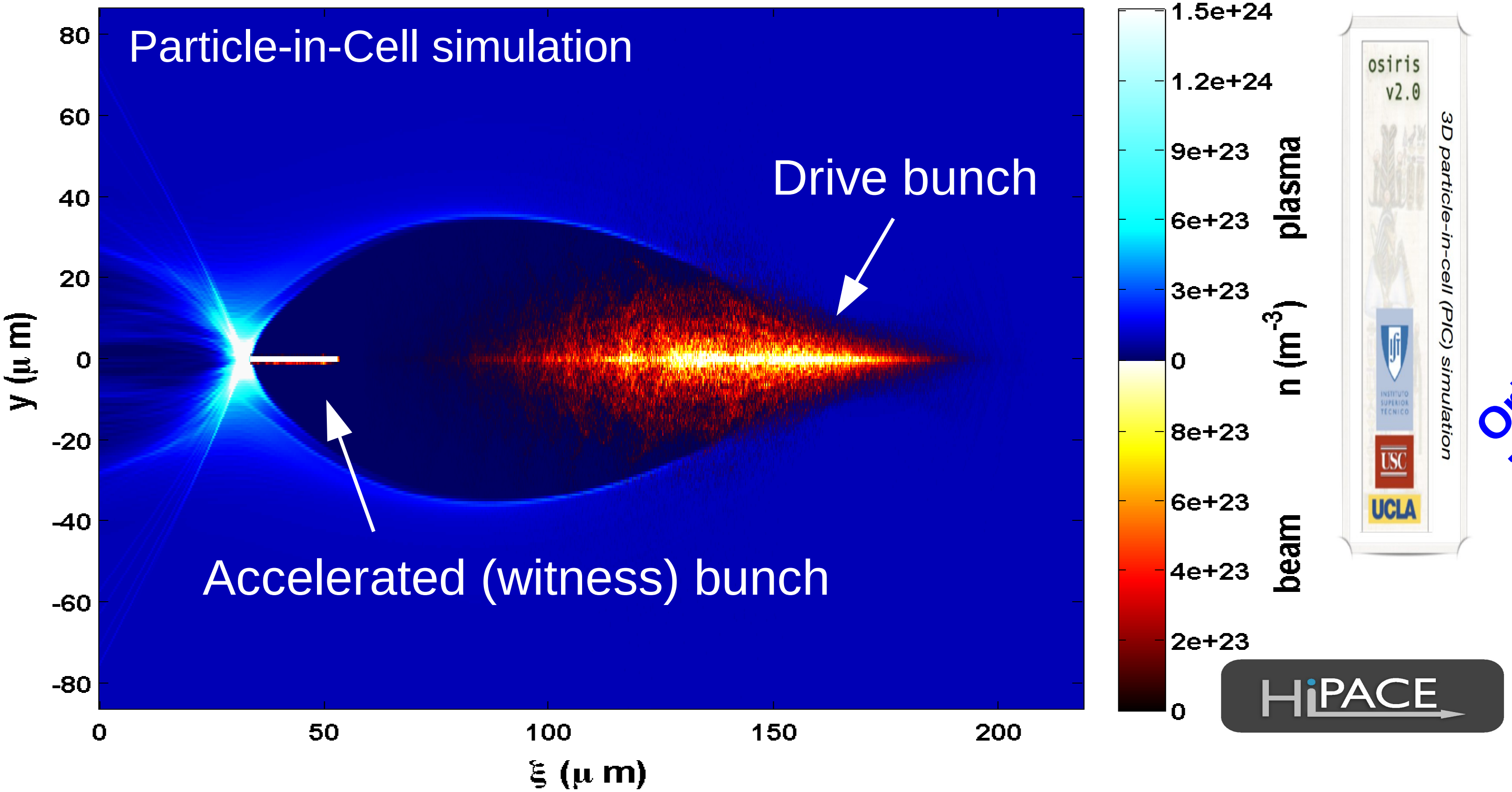
Plasma-based acceleration: basic idea



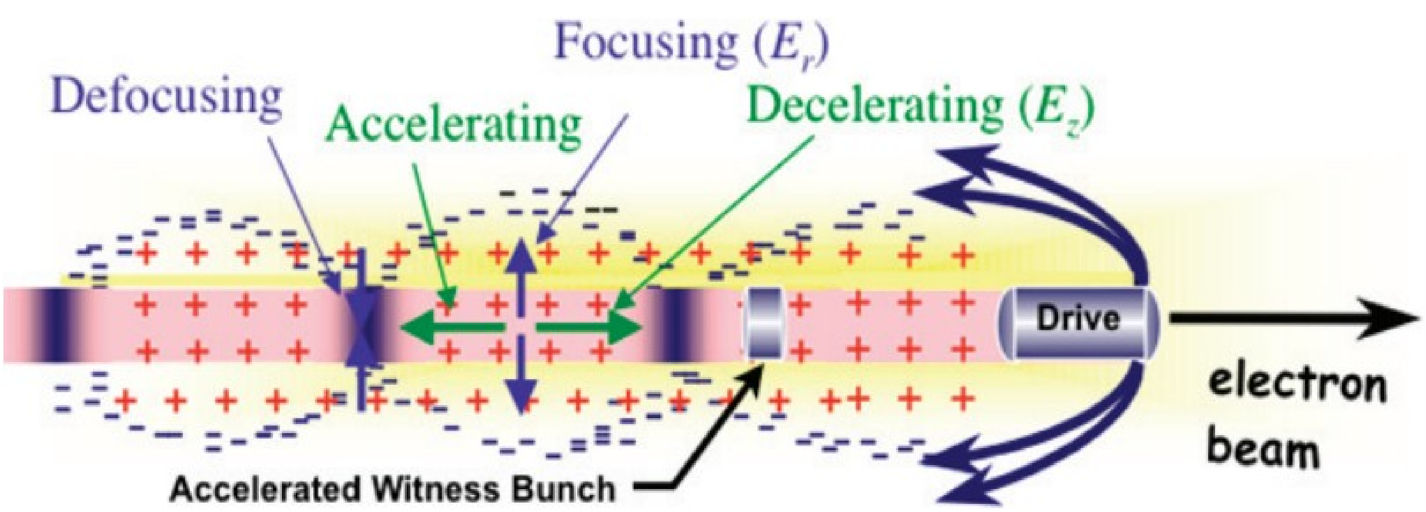
Original idea (1979): T. Tajima and J. Dawson [1]

- Driver expels plasma electrons and leaves an ion cavity behind
- Attracted by the positive ions, electrons start to oscillate
- Wakefields (co-propagating the driver) emerge
- Electrons with a proper phase relationship to the driver are accelerated by the wakefields
  → *injection* mechanisms: *internal*, *external*

Laser Wakefield Accelerator, **LWFA**: driven by a *laser pulse*
Plasma Wakefield Accelerator, **PWFA**: driven by a *charged particle beam*

[1] Phys. Rev. Lett. **43**, 267 (1979)

Fields in the cavity



Longitudinal field in the *linear regime*:

$$eE_{\mathrm{linear}} \cong 100\,\mathrm{GeV/m}\left(\frac{N}{2\times 10^{10}}\right)\left(\frac{20}{\sigma_z(\mu\mathrm{m})}\right)^2 \ln\sqrt{\frac{2.5\times 10^{17}(\mathrm{cm}^{-3})}{n_\mathrm{p}}\,\frac{10(\mu\mathrm{m})}{\sigma_r}}$$

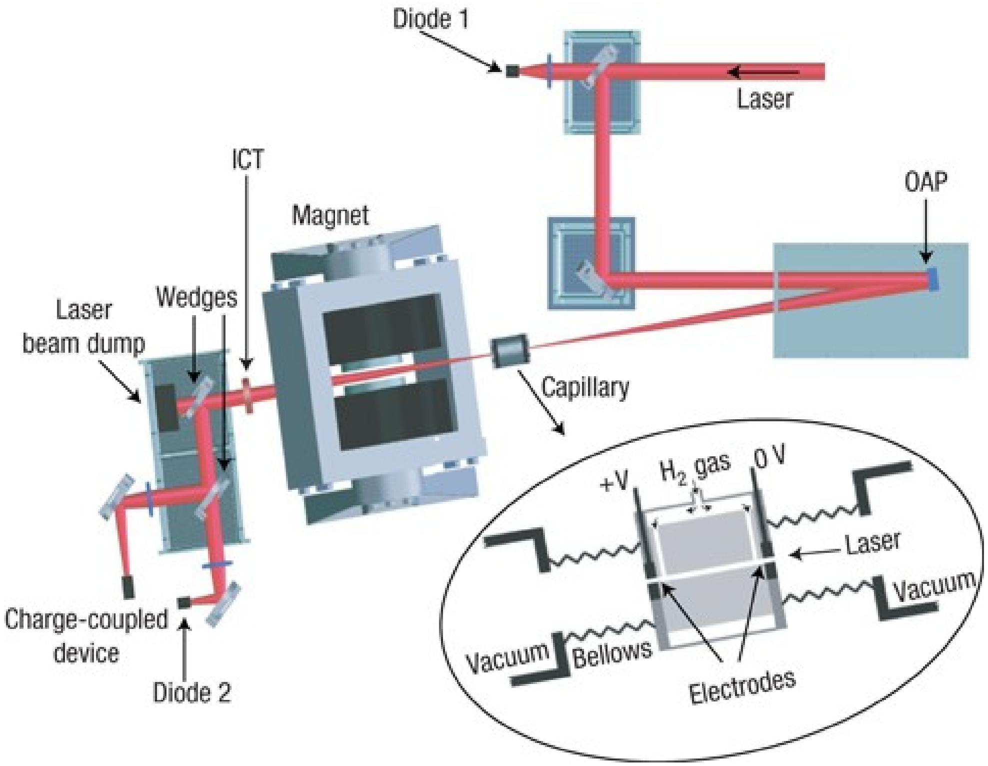
Assume:
$N=0.3\times10^{10}$ (0.5 nC)
$\sigma_z=15\mu m$ (50 fs)
$\sigma_r=10\mu m$
$n_p=10^{17}$ cm^{-3}

$$e\,E_{\mathrm{linear}} = 13\ \mathrm{GeV/m}$$

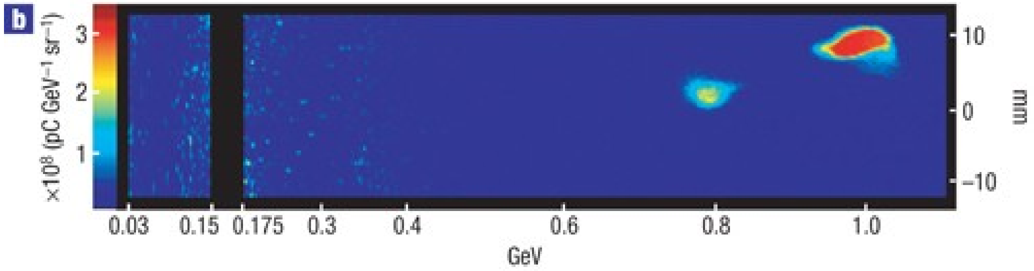
The accelerating gradient is 3 orders of magnitude greater than in conventional RF cavities
→ could lead to compact accelerators!

M. Hogan et al., New J. Phys. **12**, 055030 (2010)

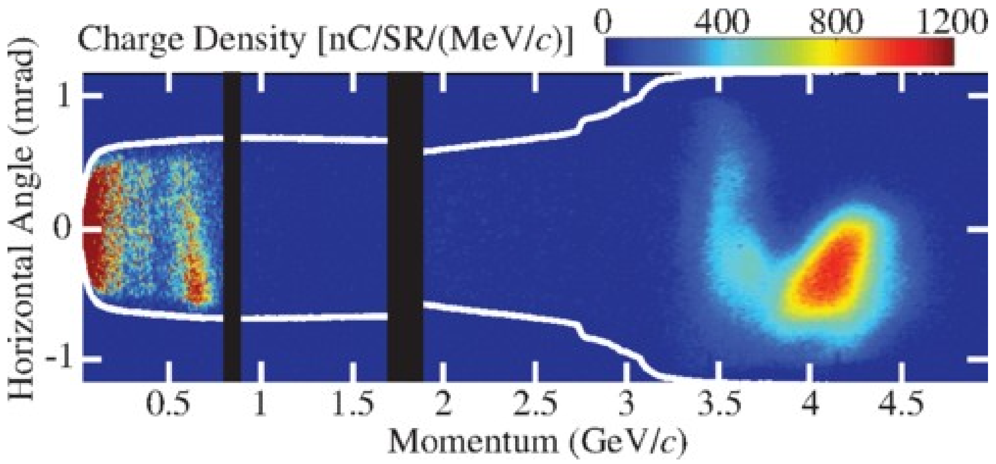
Laser-driven wakefield



2006



2014



> 4GeV electrons!

9-cm plasma capillary
→ gradient **> 44 GeV/m!**

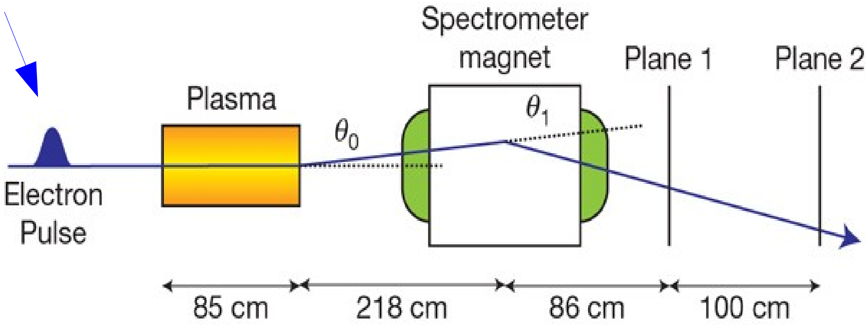
W. P. Leemans et al., Nat. Phys. **2**, 696 - 699 (2006)

W. P. Leemans et al., Phys. Rev. Lett. **113**, 245002 (2014)

Beam-driven acceleration proof-of-principle

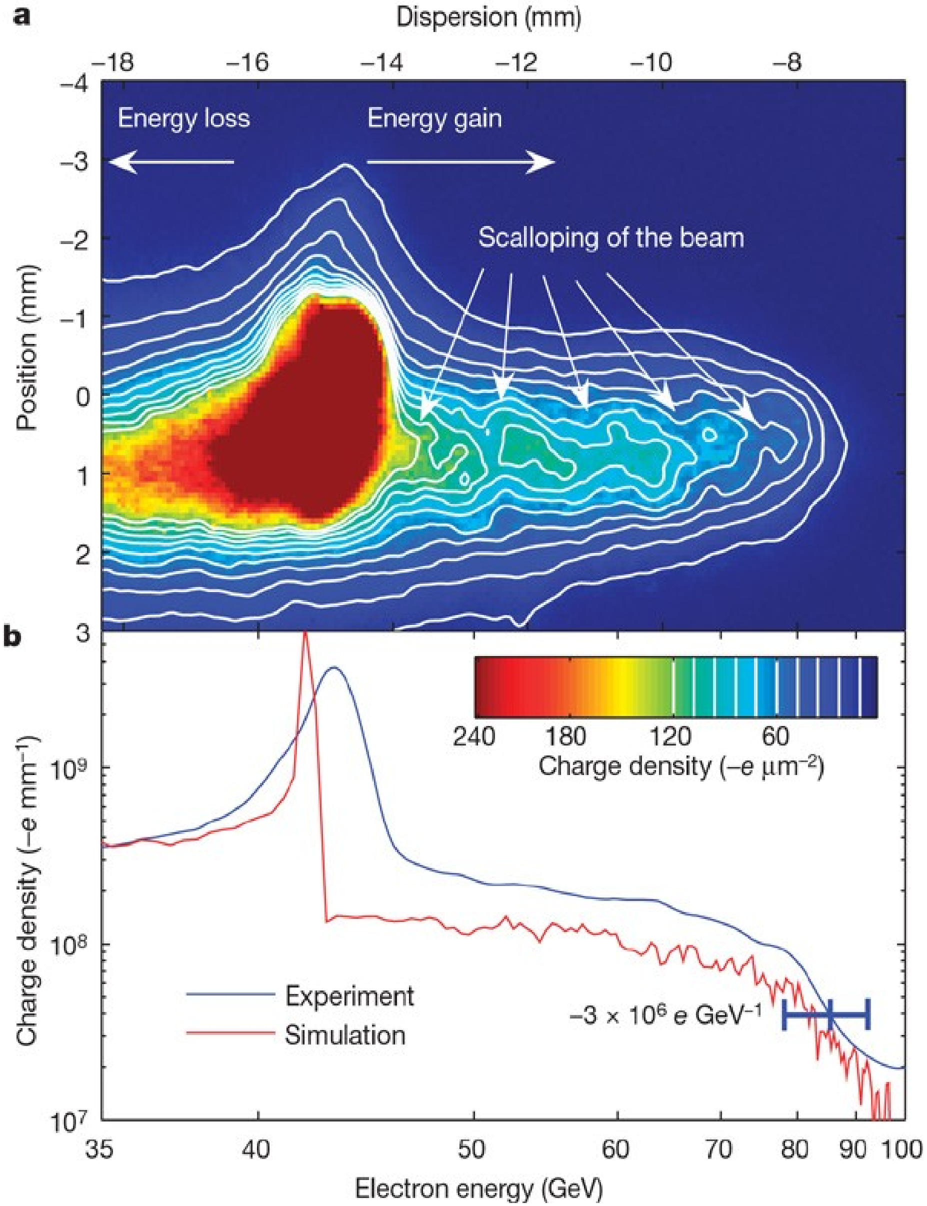
2007

Electorn beam from 3 km SLAC accelerator



- Energy doubling (42 GeV gain) within a plasma column of ~ 1m

→ eE=90 GeV/m

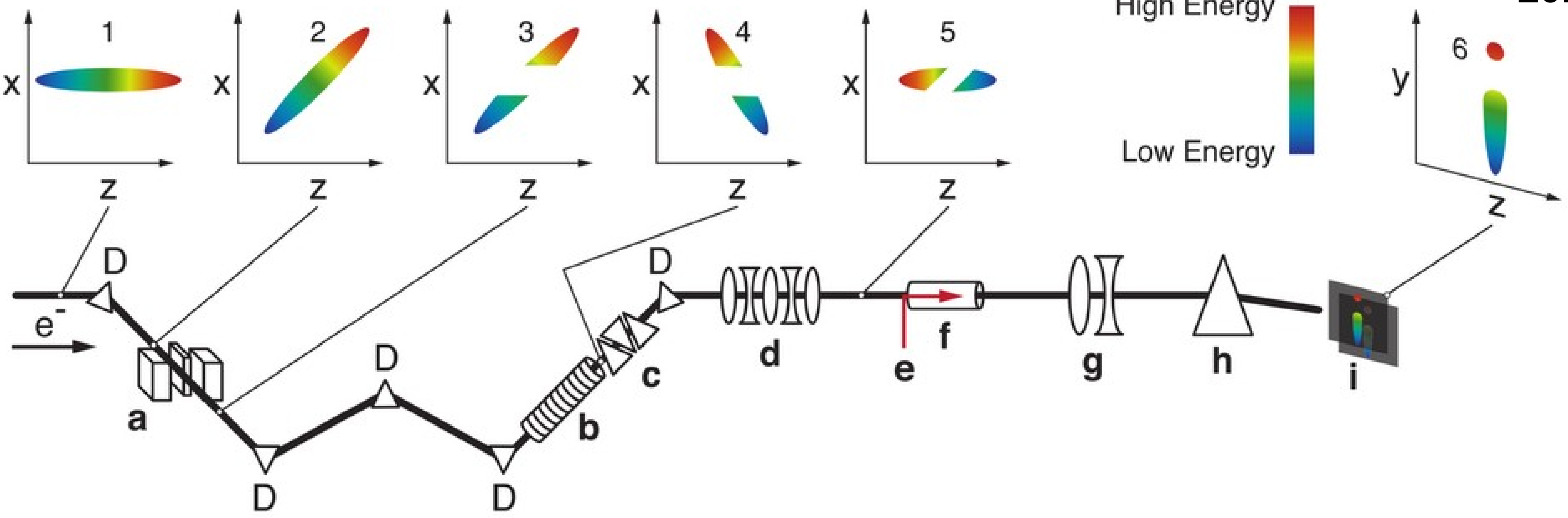


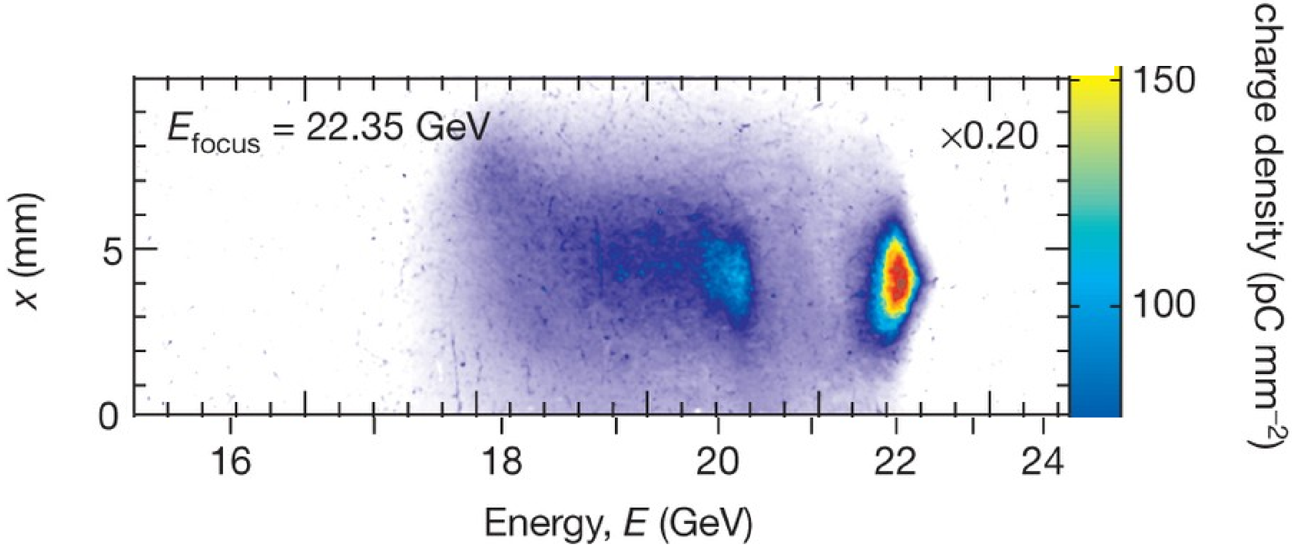
I. Blumenfeld et al., *Nature* **445,** 741 (2007)

External injection demonstration

Splitting a single e^- beam into driver/witness

2014





1.6 GeV energy gain (4 GeV/m)
~1% energy spread

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

So are we ready for applications?

The concept works! but can we built a collider? Not yet...

- LWFA already demonstrated
  → GeV-class electron beams (record: 4.5 GeV)
  → quasi-monoenergetic spectra (~1% energy spread)

- Limitations of LWFA
  → *diffraction:* laser expands and stops driving the wakefield
  → *dephasing*: $v^{group} < c$ → electrons outrun the wake
  → *depletion*: pulse gives all its energy to the wake
  → shot-to-shot pulse variations (few %)
  → low wall-plug efficiency / low average power

Limits the energy

Limits the quality

Limits the average power

- PWFA offers a promising alternative to LWFA, however good quality to be demonstrated yet
  → limited availability of specialized accelerators
  → insufficient control over the electron injection so far

FLASHForward at DESY aims to overcome some of the PWFA problems
→ Extensive R&D program using FLASH free-electron laser
→ Under construction, expected to operate in 2016

FLASHForward goals

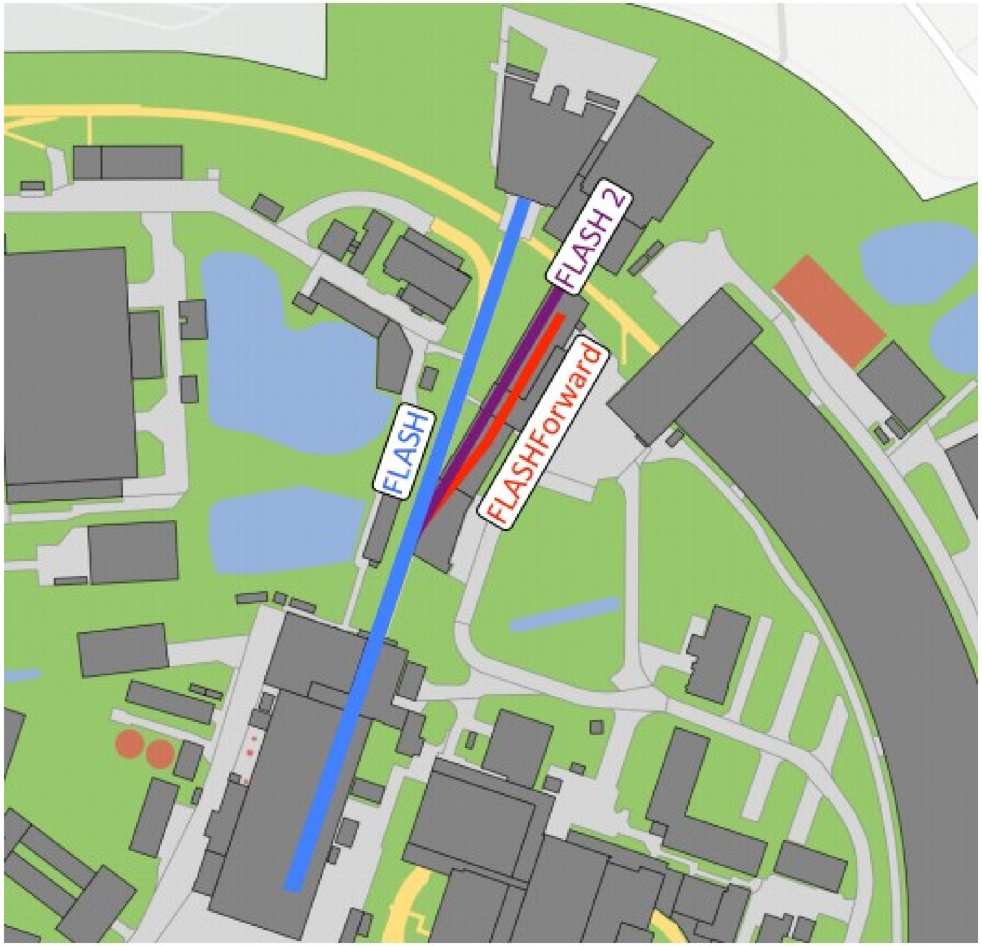
Physics goal is to advance the field of PWFA

- Demonstrate high-quality beams
  → internal injection (small emittance, high current)
  → external injection (needed for staging)
  → controlled release and capture of accelerated beams (quality preservation)

- Systematically analyse bunch parameters for various injection techniques (emittance, bunch length, energy spread, etc.)

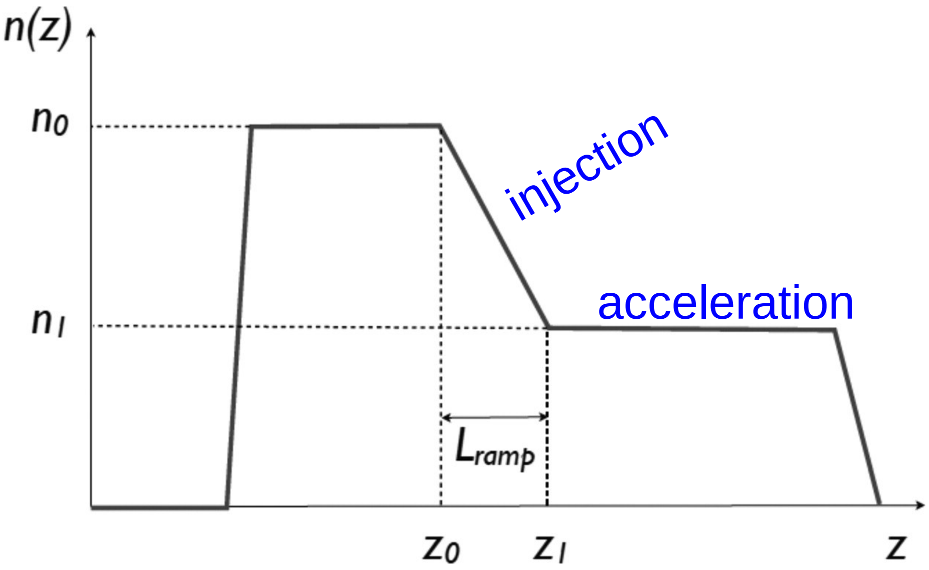
- Achieve transformer ratios greater than 2
  → possible with ramped current profiles of FLASH

- Demonstrate for the first time FEL lasing of plasma-accelerated electron beams



Phase I: generation of high quality beams (2016-2018)
Phase II: usage of these beams to drive FEL (2018-2020)

Density-downramp injection - idea



- Internal injection mechanism, based on the tailored plasma density profiles
- z-dependent plasma density
  → plasma wavenumber depends on z
  → wake phase velocity v_p differs from c
- dn/dz<0 → v_p<c (wake slows down)
- This reduces the velocity which plasma electrons need to achieve in order to be trapped

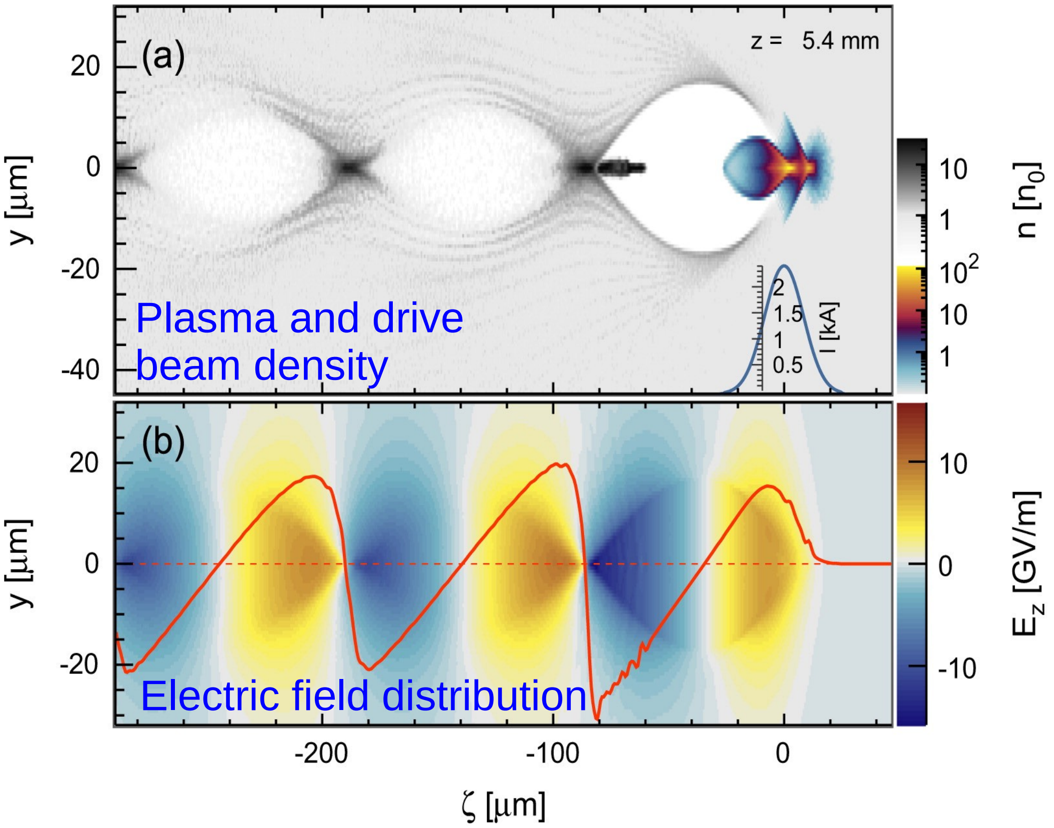
The technique was demonstrated in LWFA but not PWFA

Assume for Particle-in-Cell simulations (next slide)
n_0=10x10^{17} cm^{-3}
n_1=1 x10^{17} cm^{-3}
L_{ramp} = 60 µm

J. Grebenyuk *et al.*, NIM A **740**, 246 (2014)

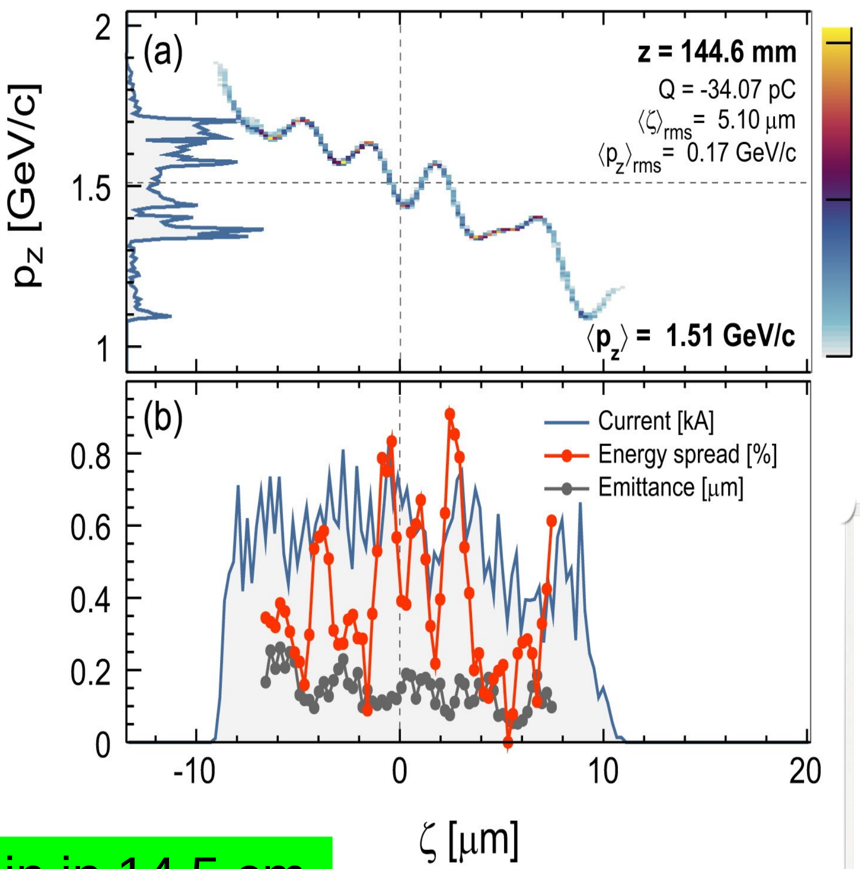
Density-downramp injection - simulations

- Full 3D Particle-in-Cell (PIC) simulation with OSIRIS



Plasma and drive beam density

Electric field distribution

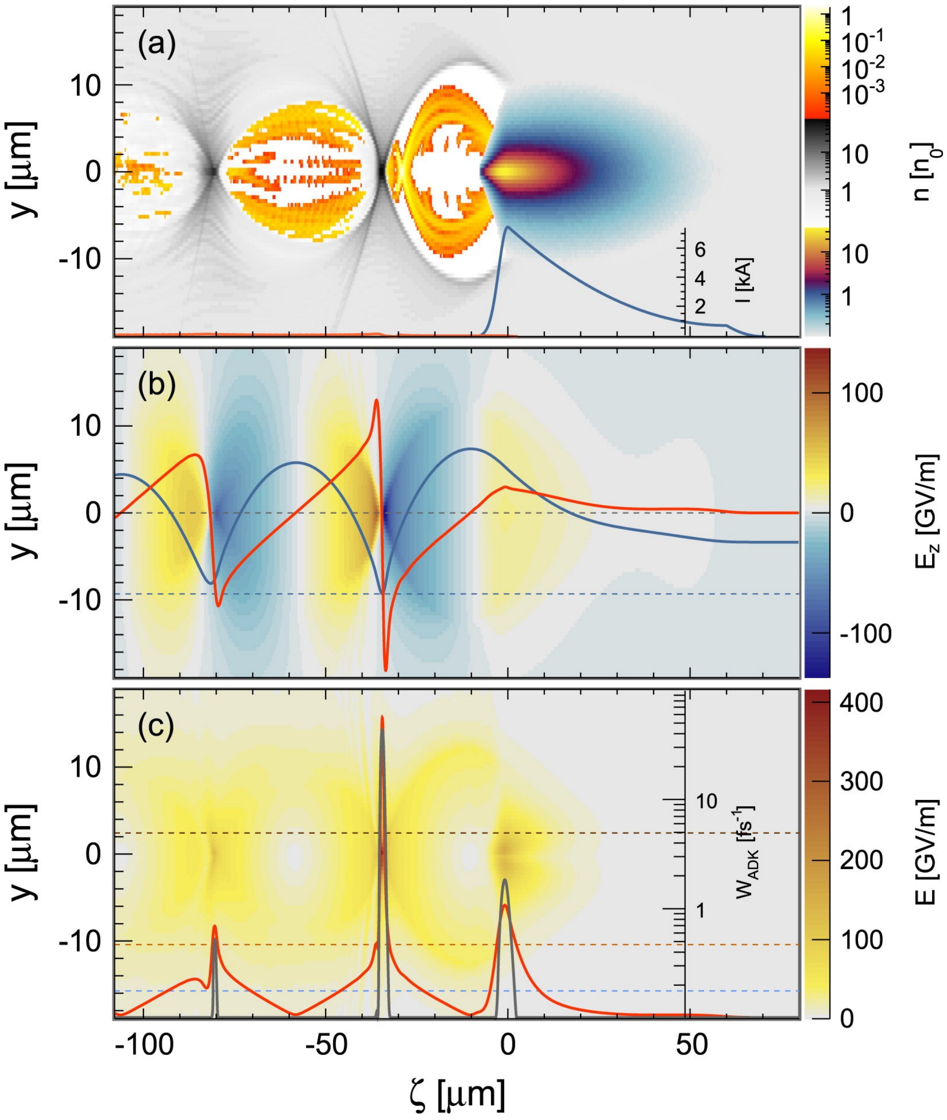


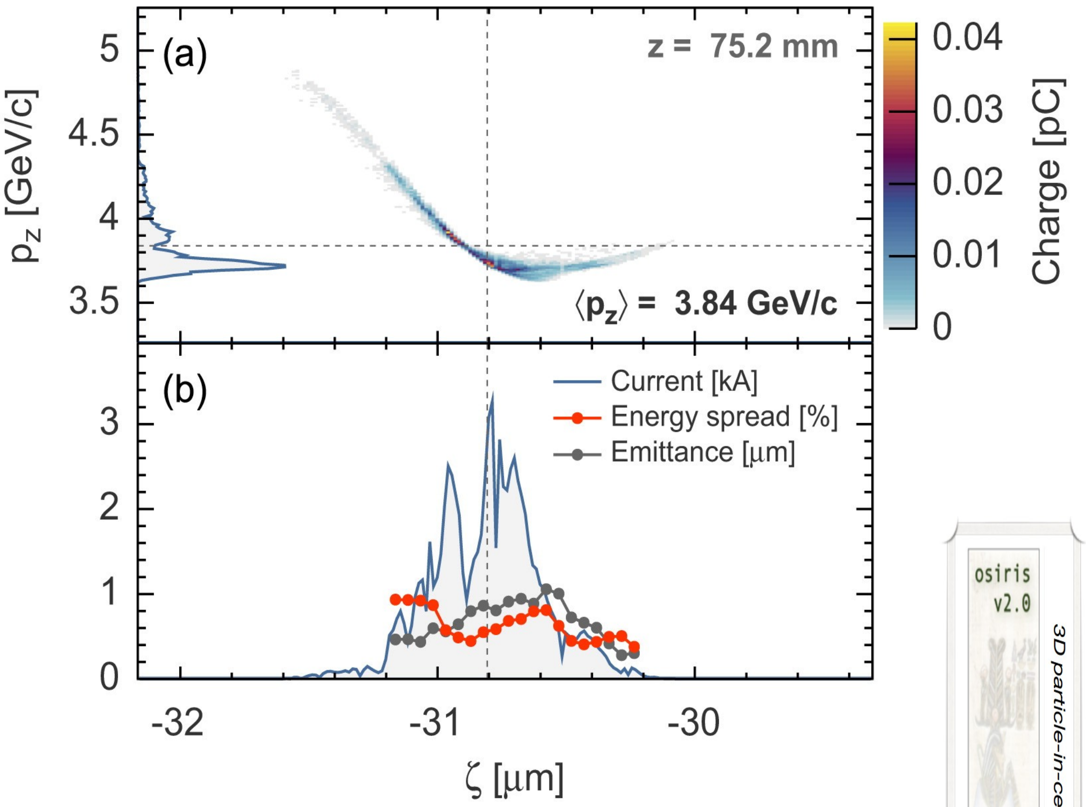
1.5 GeV energy gain in 14.5 cm
Slice energy spread < 1%
Emittance 0.2 μm
Length 20 μm (60fs)
Charge 34 pC

J. Grebenyuk *et al.*, NIM A **740**, 246 (2014)

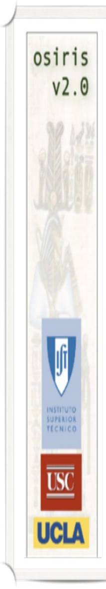
Ionisation injection - simulations

- Plasma electrons are injected by means of beam-induced ionisation of a **dopant gas** (He)





3.84 GeV energy
Slice energy spread ~1%
Emittance ~1 μm
Length 1 μm (3fs)



3D particle-in-cell (PIC) simulation

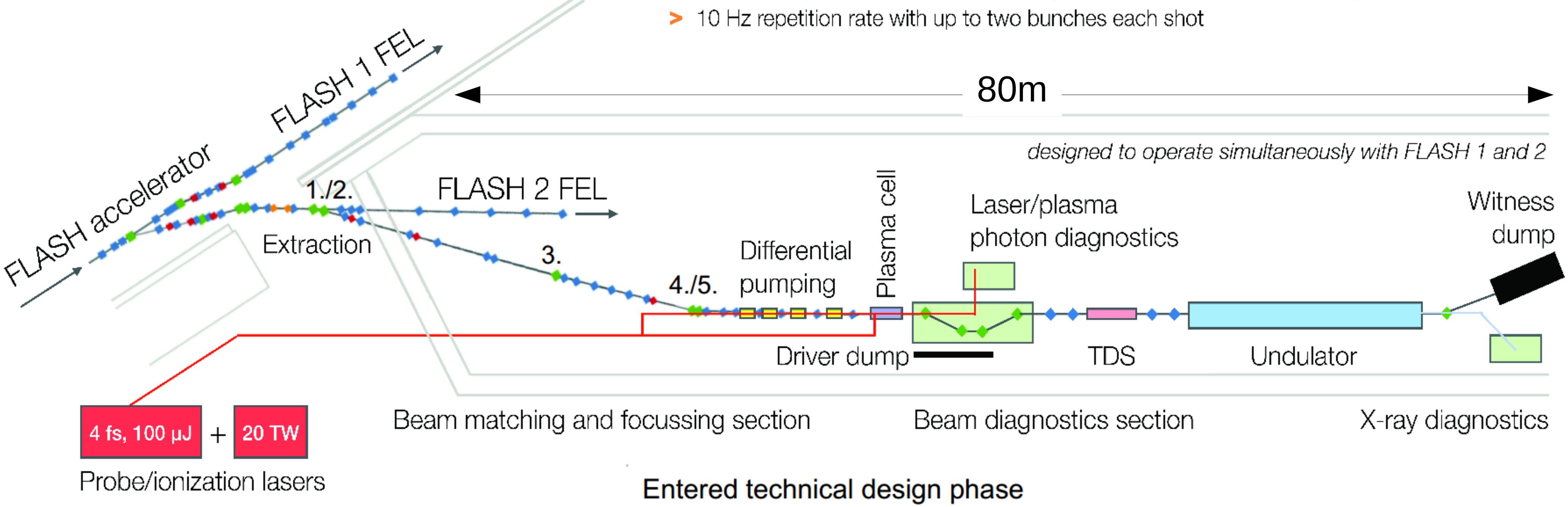
A. Martinez de la Ossa *et al.*, NIM **A 740**, 231 (2014)

FLASHForward

- FLASHForward is **PWFA** facility being designed/constructed at DESY
- The science motivation is to overcome current PWFA limitations
- High-quality electron beams from FLASH will drive the wakefields

Driver-beam parameters

- FEL quality, ≤ 1.6 GeV, 0.1% energy spread, 1 μm transverse emittance, **current up to 10 kA**
- variable longitudinal beam shape (triangular, Gaussian), 20 to 500 fs long, ~20 pC to 500 pC
- 10 Hz repetition rate with up to two bunches each shot

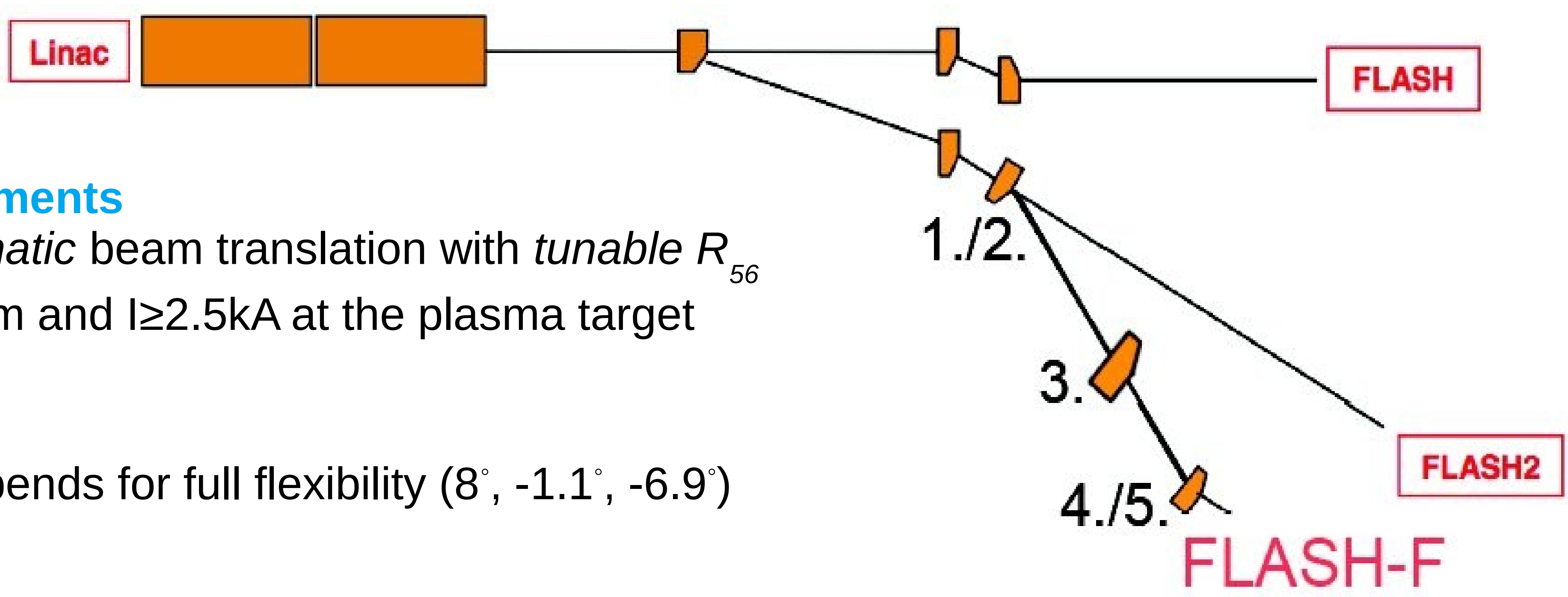


Entered technical design phase

Experiments to start early 2016, run for 4 years+

Submitted to Nucl. Instr. Meth. A
arXiv:1508.03192

Extraction from FLASHII to FLASHForward



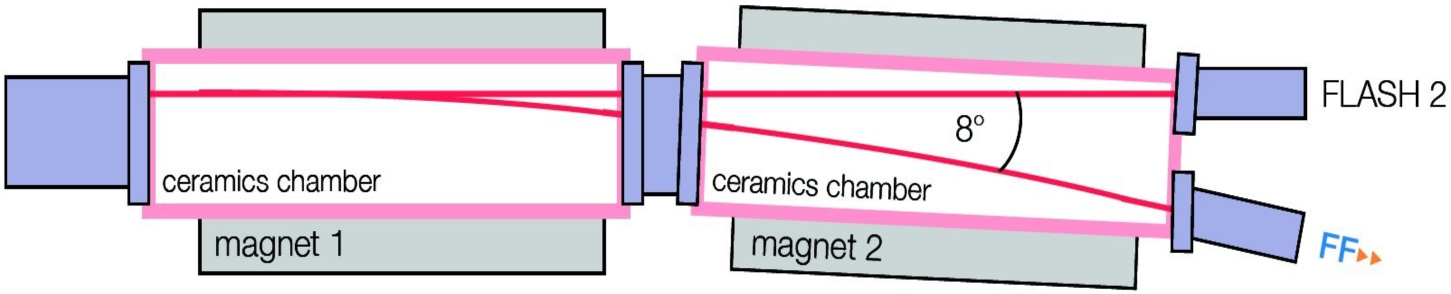
Requirements

- *Achromatic* beam translation with *tunable* R_{56}
- $\sigma_{x,y} \leq 7\mu m$ and $I \geq 2.5 kA$ at the plasma target

Solution

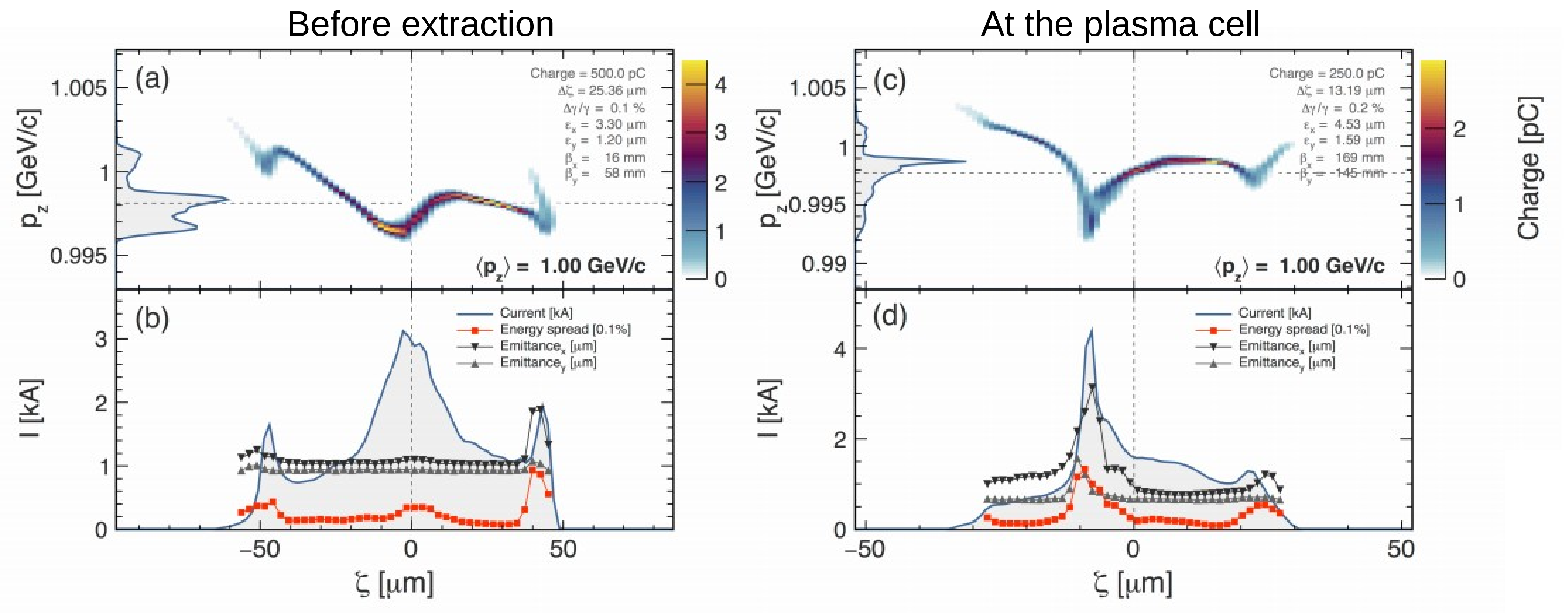
- Three bends for full flexibility (8°, -1.1°, -6.9°)

→ Fast pulsers (rise time 111.5 μs) to kick FLASH2 bunches to FLASHForward
→ One pulser per magnet



Extraction: beam dynamics

- Start-to-end simulations (RF Gun → plasma)

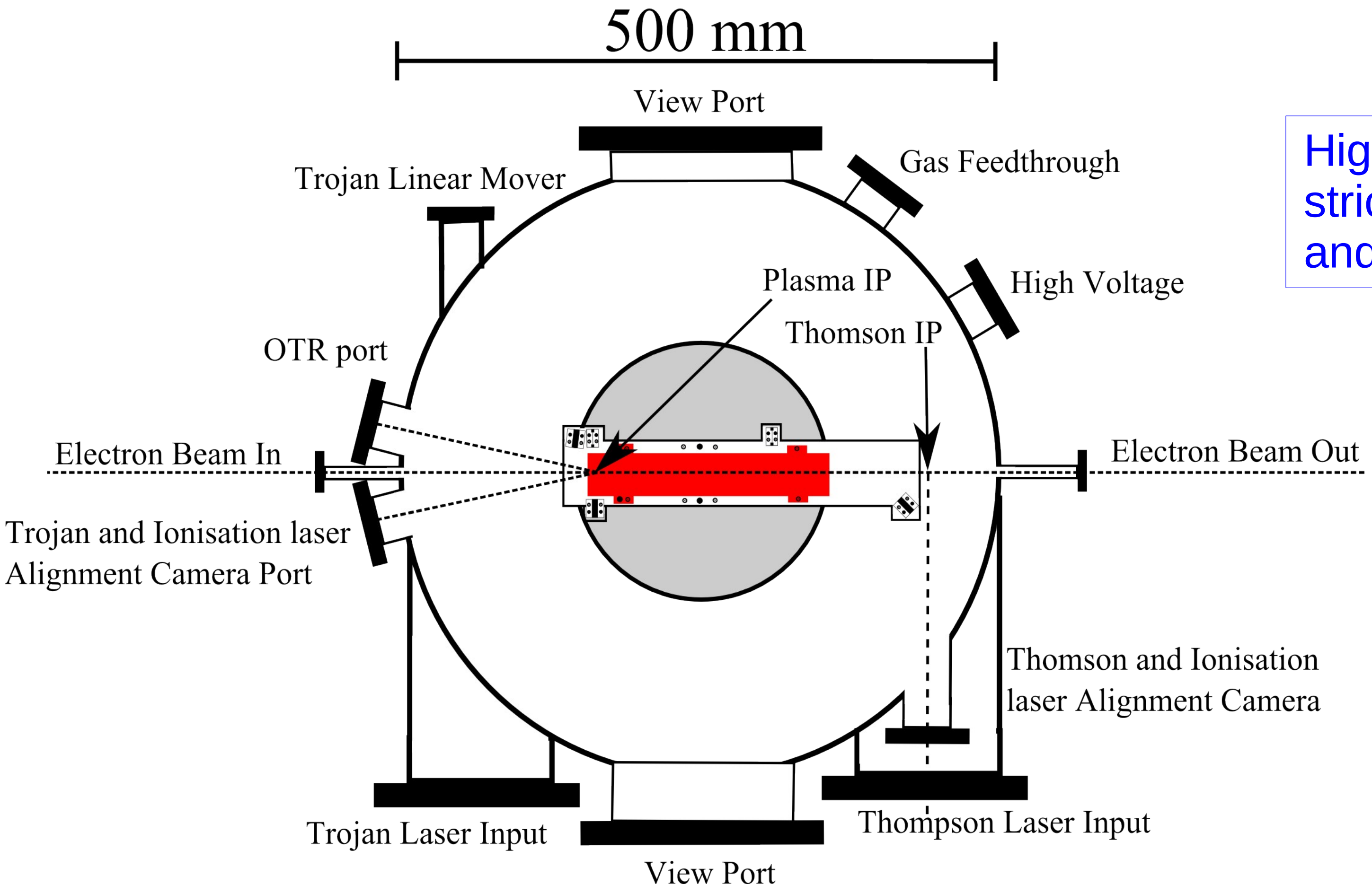

Before extraction

At the plasma cell

Note:

Current after extraction 4 kA (values up to 10kA are possible)
→ suitable for plasma experiments
→ Linac parameters not yet optimised

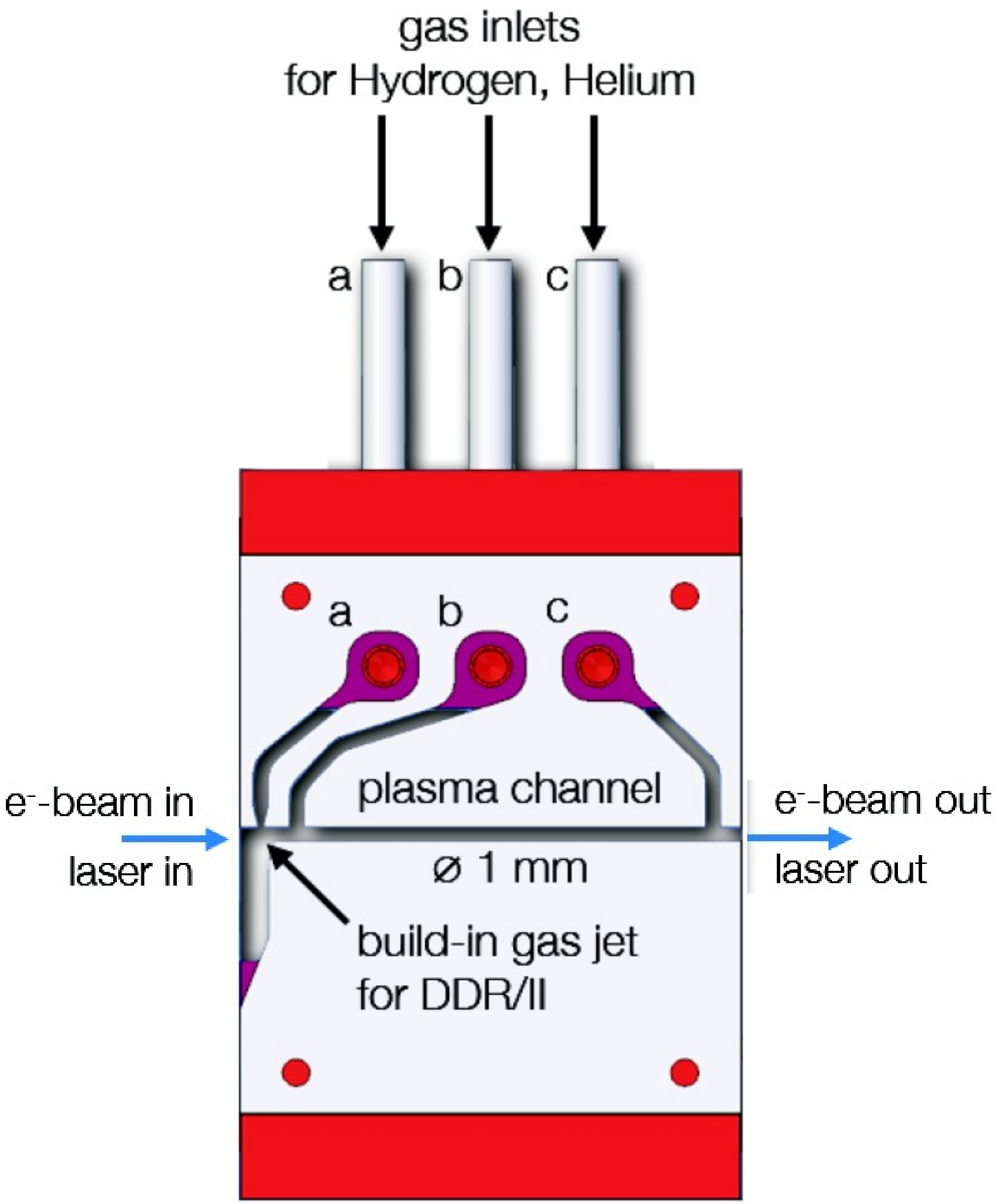
Experimental chamber



Highly challenging because of strict vacuum requirements and experimental constraints

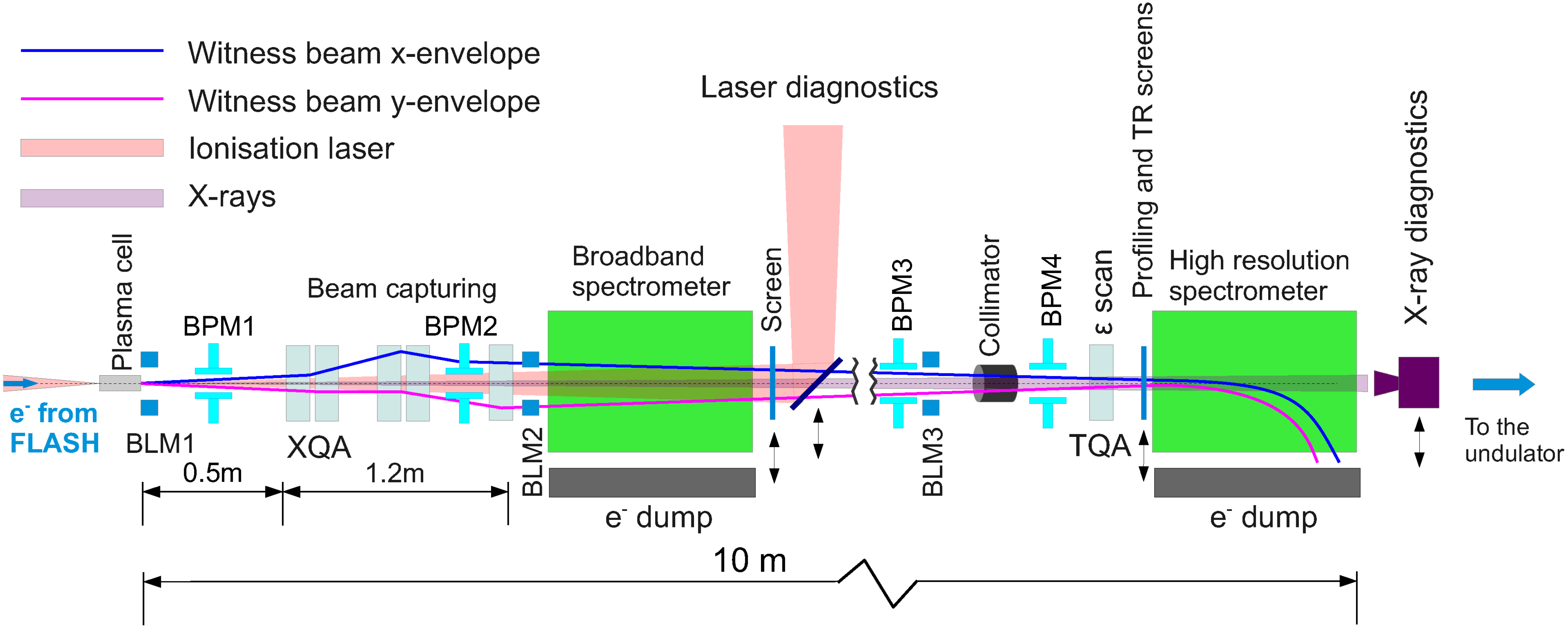
- Capability to move the plasma cell in 6D in ultra-high (10^{-9} mbar) vacuum
- Alignment and diagnostics of the incoming electron and laser beams
  → wires, knife edges, OTR screens, scintillator screens, multiple cameras
- Possibility to study laser-controlled injection (“Trojan Horse”) and Thomson scattering

Gas target



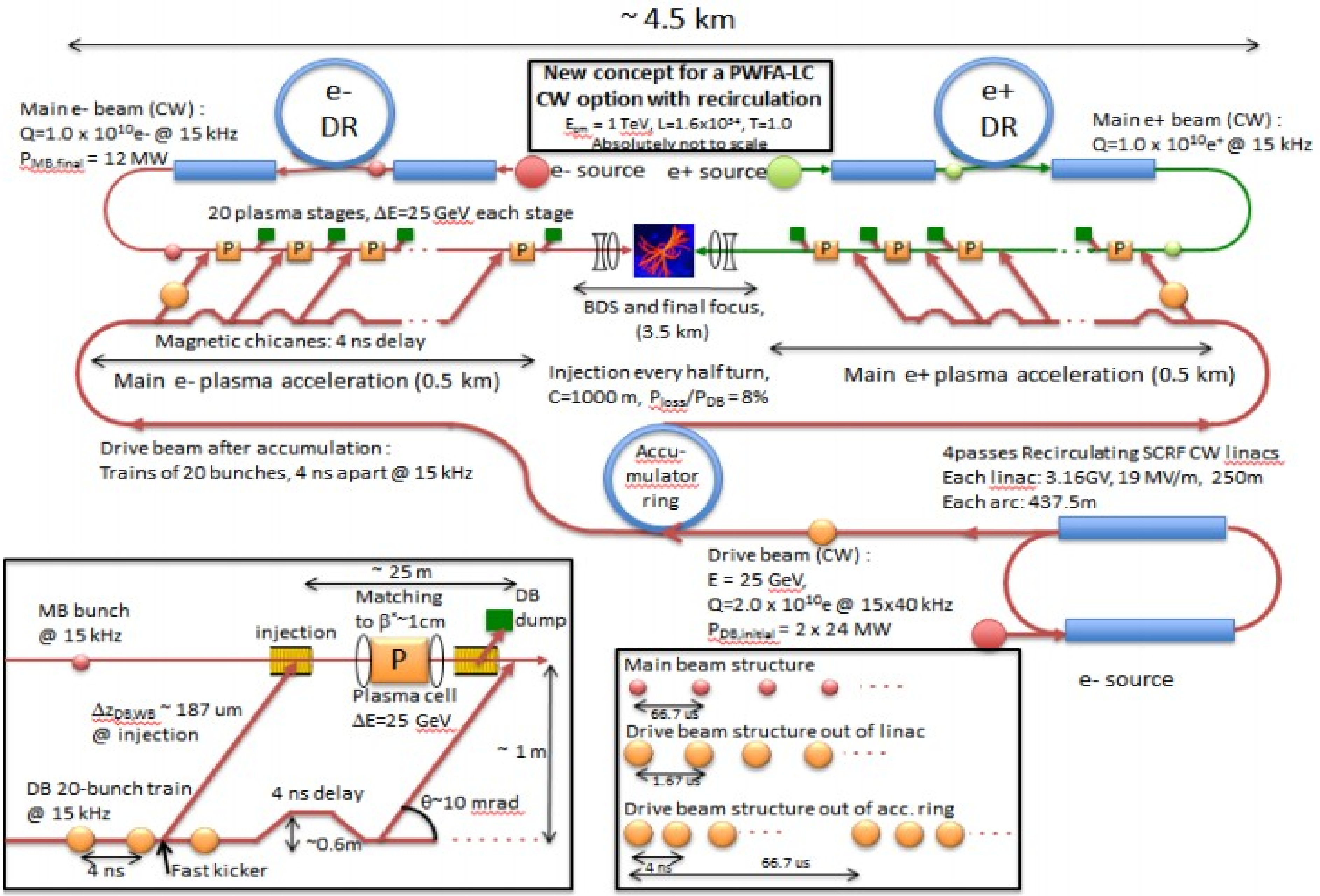
- Window-less to aviod emittance growth
- Plasma creation by laser, electron beam or discharge is possible
- Plasma of $1x10^{16}$ – $5x10^{17}$ cm^{-3}
- Tailored plasma density profiles are possible → essential for density downramp injection
- Diagnostics: full transverse access

Post-plasma beam line



- Challenging due to large divergence and large energy spread
- Driver is dispersed by quadrupoles and dumped into the collimator
- Energy measurement with dipole magnets
- Longitudinal profile measurement with transition radiation
- Transverse emittance determination with a single quardupole scan

Outlook: 1 TeV PWFA Linear Collider



E. Adli et al., SLAC-PUB-15426 (2013)

Summary

- We are reaching the limits of current accelerator technology
  → need new ideas to maintain the exponential energy growth

- Plasma-based acceleration is a promising candidate
  → provides gradients of 10-100 GeV/m (demonstrated experimentally)

- Great progress in the last decade, the field is gaining momentum

- FLASHForward at DESY aims at improving the beam quality and stability of beam-driven plasma accelerators
  → paving the way to applications in FEL and HEP

FLASHForward team

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