UNIVERSITY OF OSLO

Simon van der Meer Early Career Award in Novel Accelerators

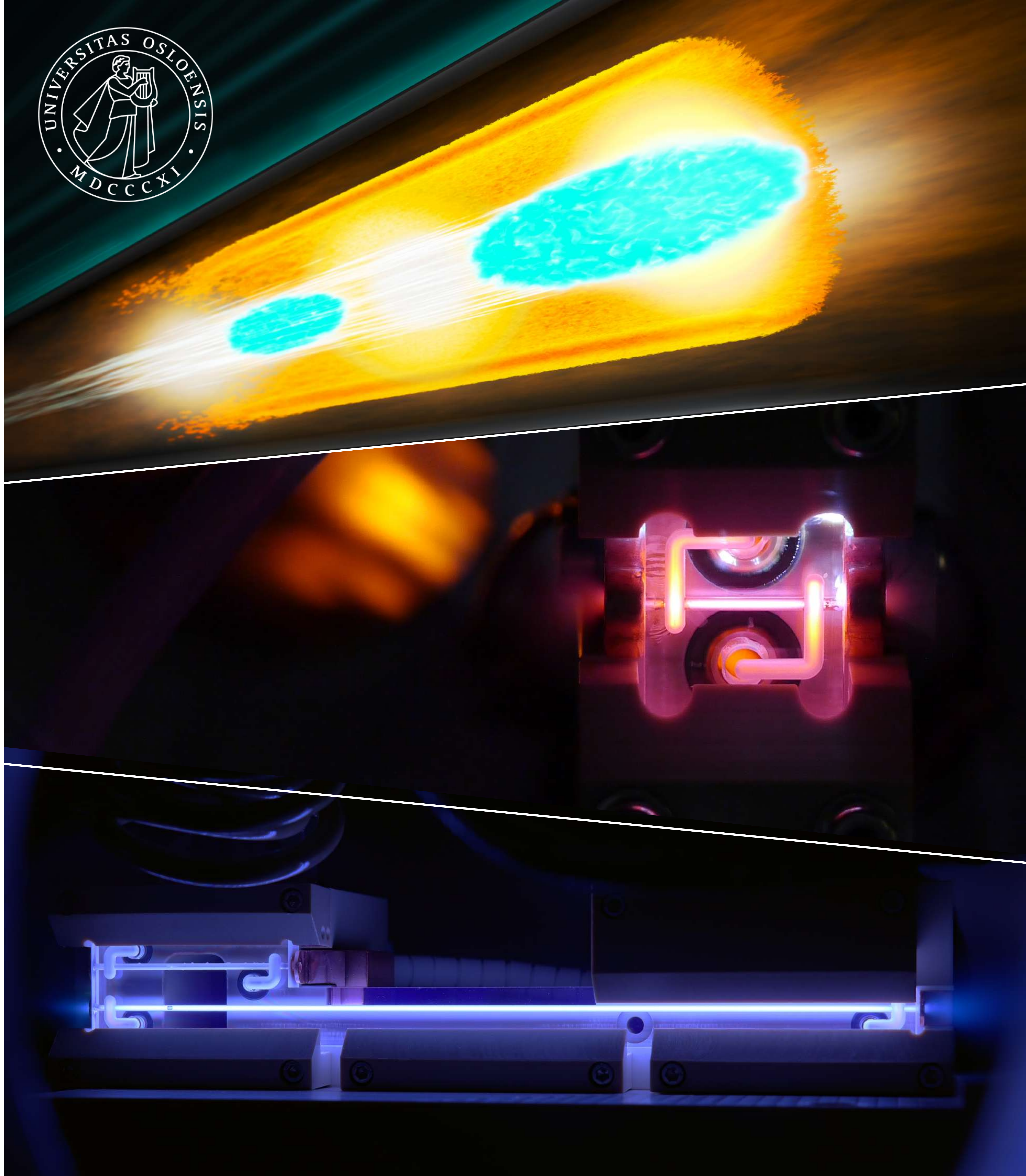
Teamwork makes the beam work

Dr. Carl A. Lindstrøm

Postdoctoral Fellow

Dept. of Physics, University of Oslo

22 Sep 2022 | EuroNNAc workshop | Elba, Italy



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Petition details   Comments   Updates

Make the CERN slogan “Teamwork makes the beam work”.

42 have signed. Let’s get to 100!

At 100 signatures, this petition is more likely to be **featured in recommendations!**

First name

The CERN slogan is not currently “Teamwork makes the beam work”, and this (we feel) is a problem.

Email

Yes! Tell me if this petition wins, and how I can help other relevant petitions

No. I do not want to hear about this petition's progress or other relevant petitions.

Sign this petition

Do not display my name and comment on this petition

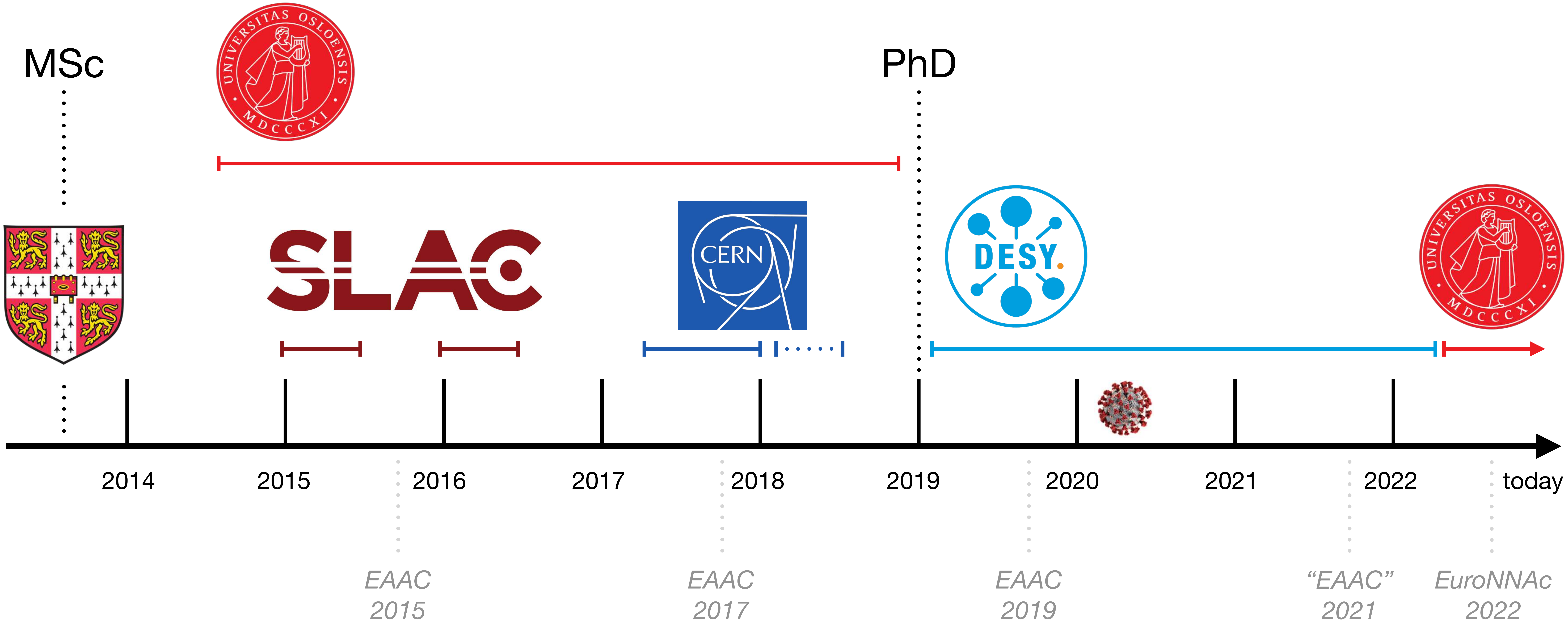
George Tsikas started this petition to CERN

The CERN slogan is not currently “Teamwork makes the beam work”, and this (we feel) is a problem. CERN represents an absolutely incredible level of collaboration and cooperation between nations. From the ashes of post-world-war-II Europe, science proved among the most effective means to reunite people, and inspire a vision of common interest and achievable, shareable progress. This dream has been vindicated by the emergence of a truly international

CERN

https://www.change.org/p/cern-make-the-cern-slogan-teamwork-makes-the-beam-work

A tale of **three labs**



Three messages

Highlight exciting **experimental results**

Highlight the large **team effort** behind the results

Highlight good **mentorship** and **supervision**

Part 1:

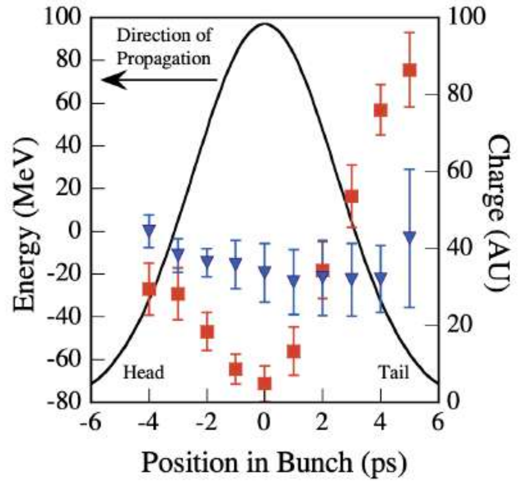
SLAC

Positron acceleration

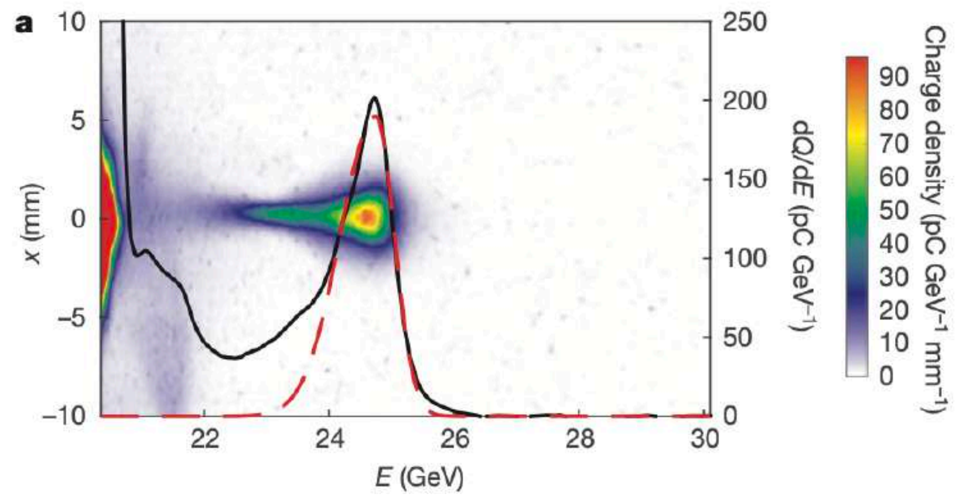
(2015–2016)

Getting motivated: **Compact particle colliders**

- A future goal for high-energy physics is a precision machine, such as an **electron–positron collider.**
- Plasma-wakefield acceleration of **electrons** is **very promising**.
- **Positron** plasma acceleration has been demonstrated experimentally, however the **beam quality is not good enough** (high emittance, high energy spread).

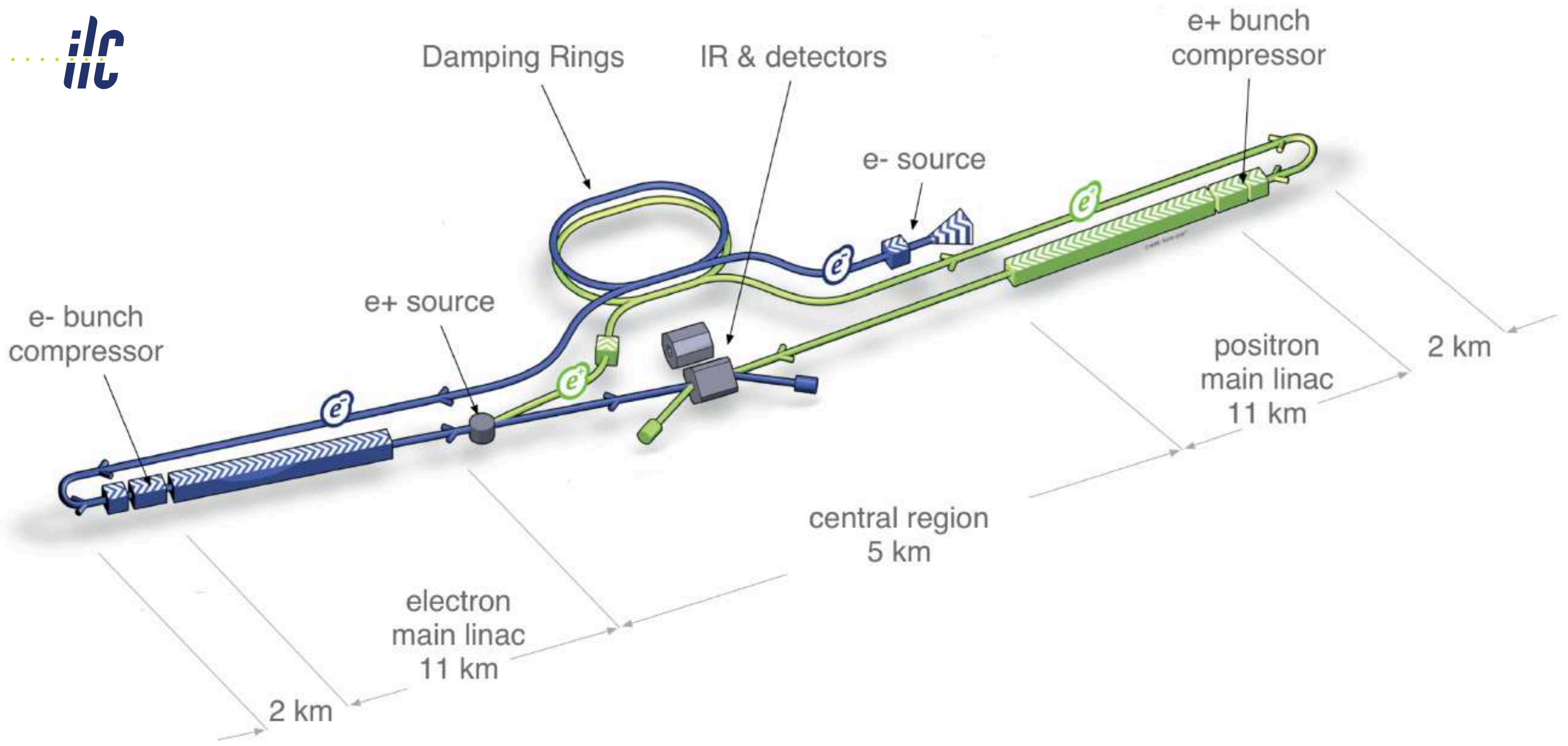


Source: Blue et al., PRL 90, 214801 (2003)

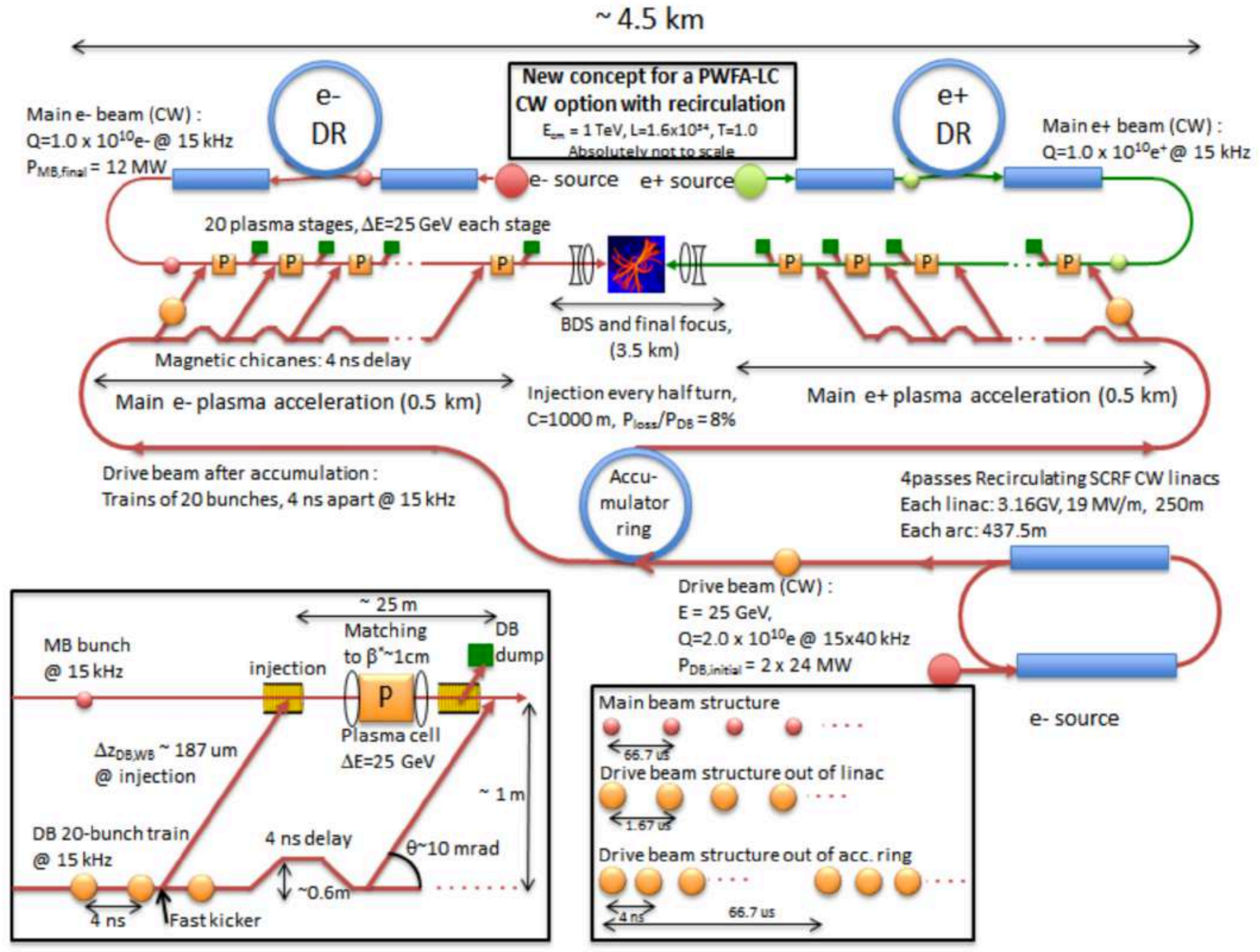


Source: Corde et al., Nature 442, 524 (2015)

Can we accelerate positrons in a plasma, while also maintaining beam quality?



Source: ILC TDR (2013)



Source: Adli et al., Proc. Snowmass (2013)

Erik Adli

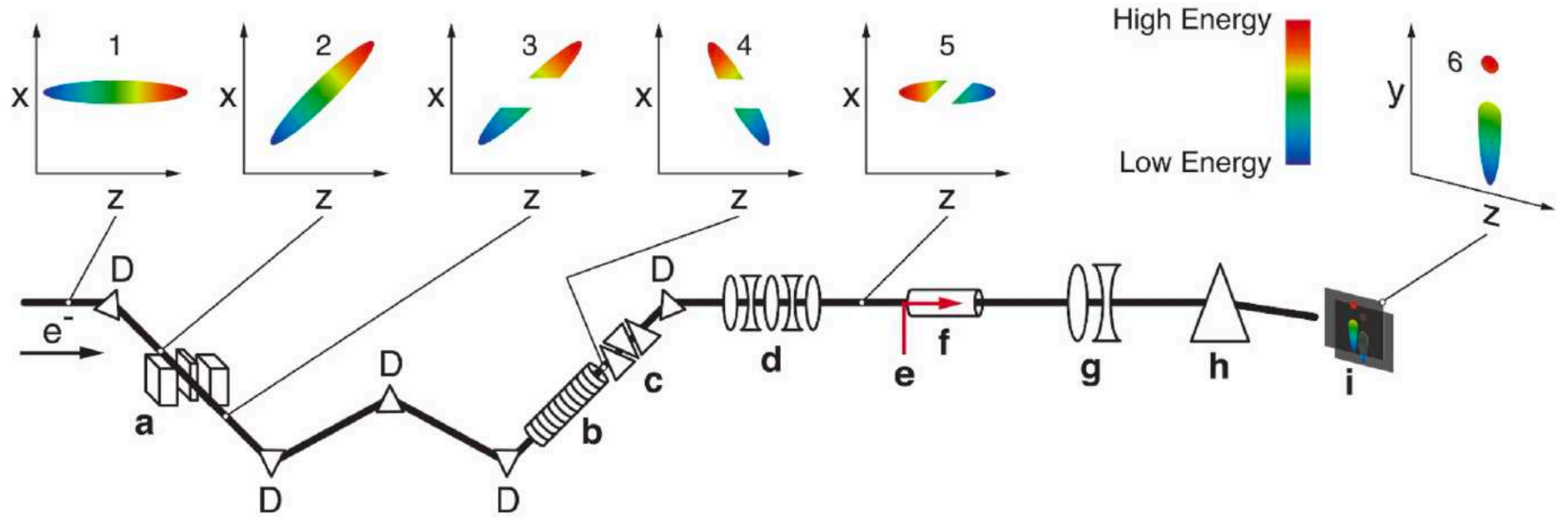
The importance of **trust**

Mark Hogan

The importance of **motivation**

Thrown in at the deep end: **The FACET facility**

- **Beam-driven** plasma-wakefield accelerator research
- **20 GeV** beams (2 km of the SLAC linac)
- The **only facility to provide positrons** for plasma accelerator research
  - Positron target, return line, damping ring
- **Double-bunch** generation
  - Chirped bunch, notch collimator



Source: Litos et al., Nature 515, 92 (2014)

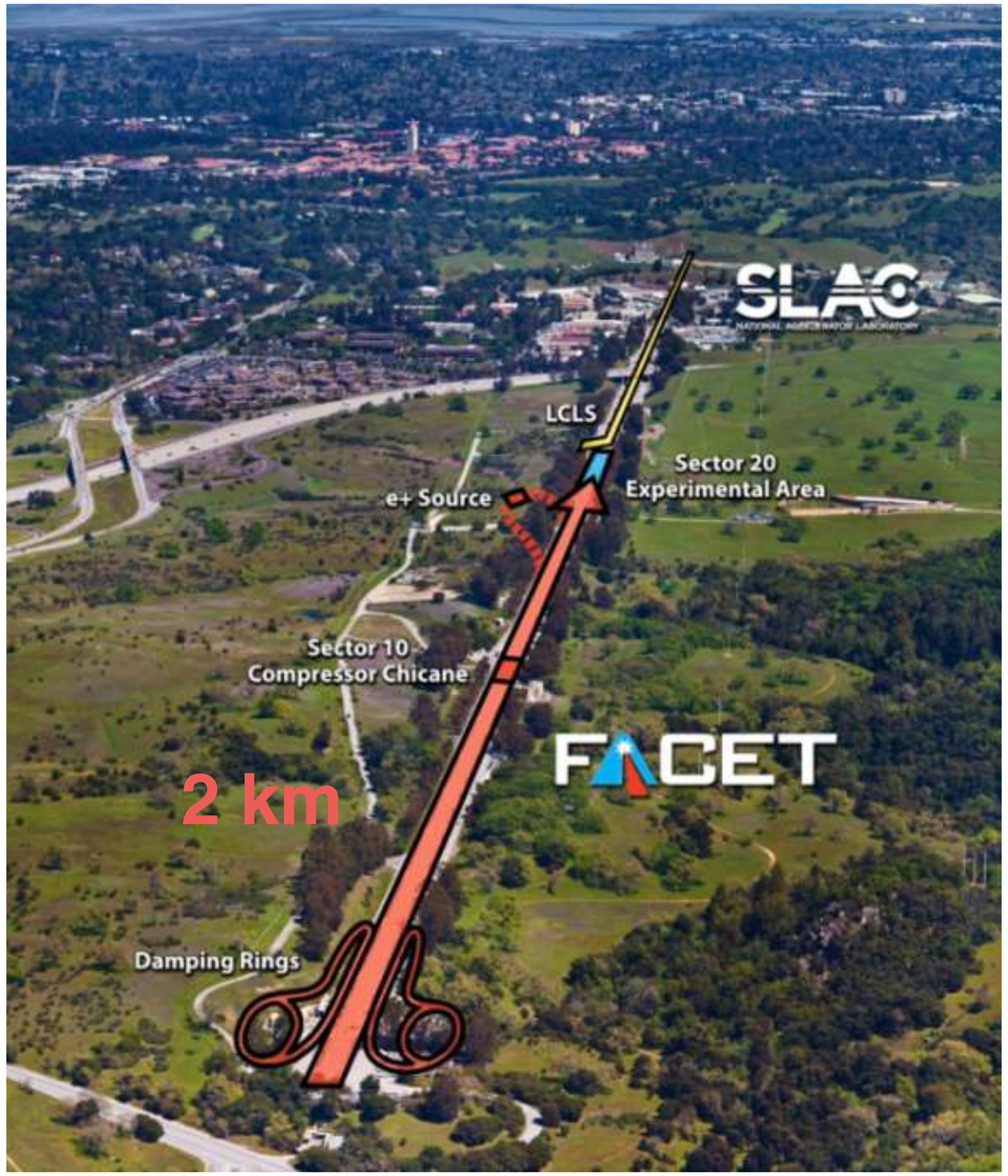
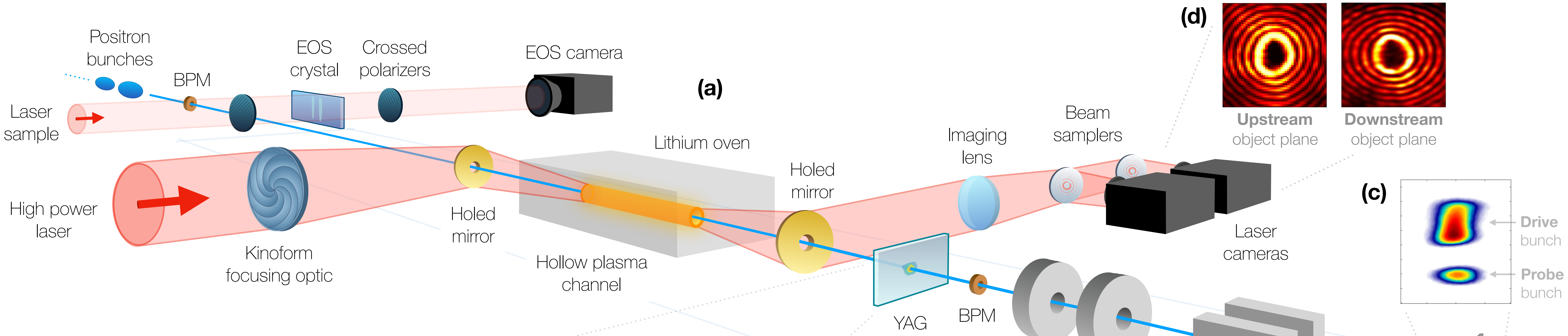
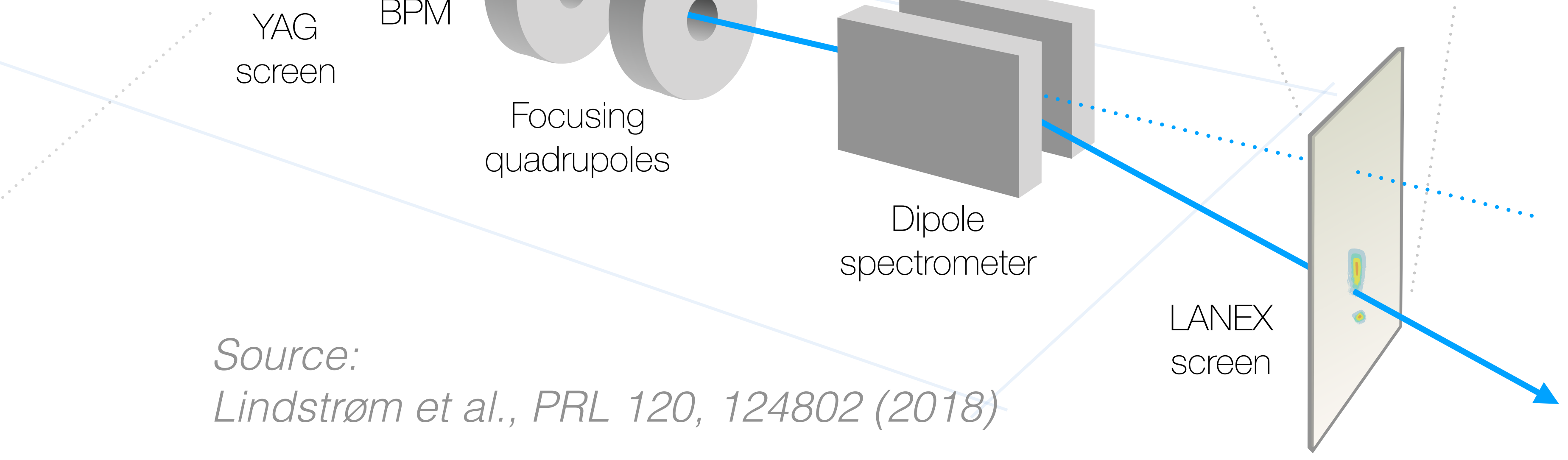


Image source: SLAC

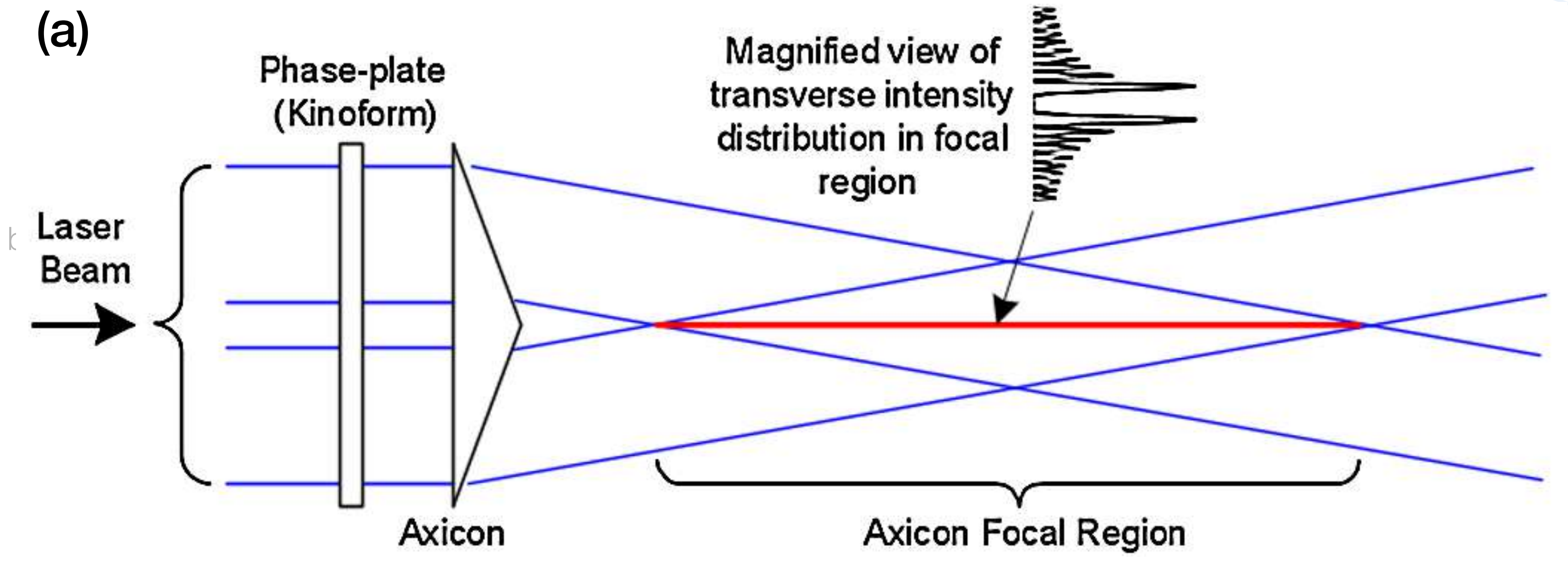
Mike Litos

The importance of **patience** and **hard work**

Finding a niche: **Hollow channel plasma accelerators**

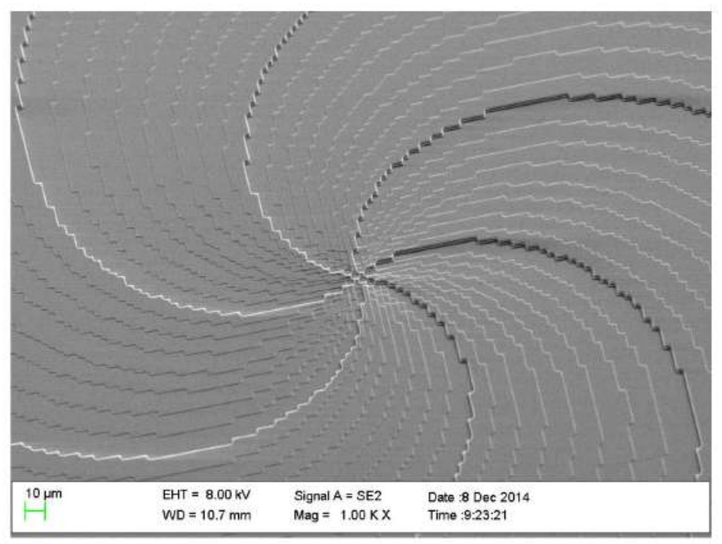



Source: Lindstrøm et al., PRL 120, 124802 (2018)



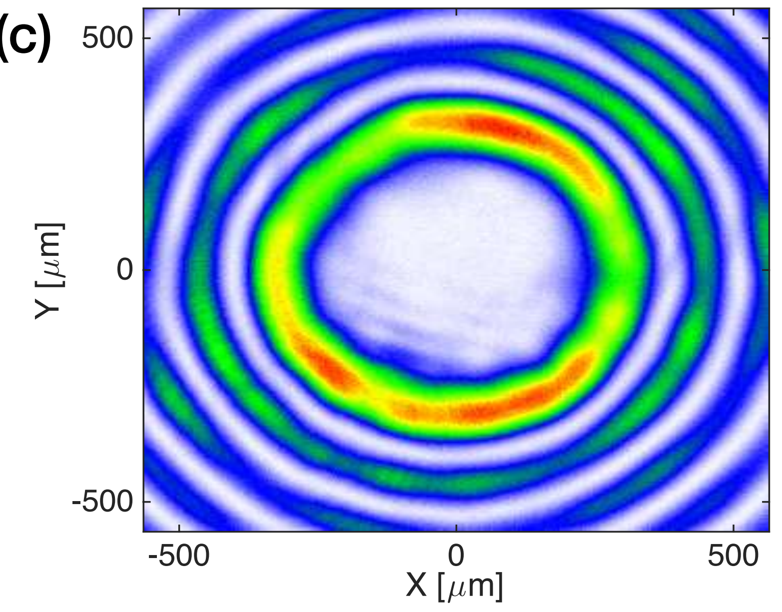
Source: Kimura et al., PRSTAB 14, 041301 (2011)

(b)



Source: NIL Technology ApS

(c)



Source: Gessner, PhD thesis (2016)

- Why: **Keeping the accelerating fields, but avoid on-axis focusing fields** (to preserve the emittance).
- How: Laser ionization with a “**kinoform**”.
- Who: Project **lead by Spencer** [Gessner et al., Nat. Commun. 7, 11785 (2016)]

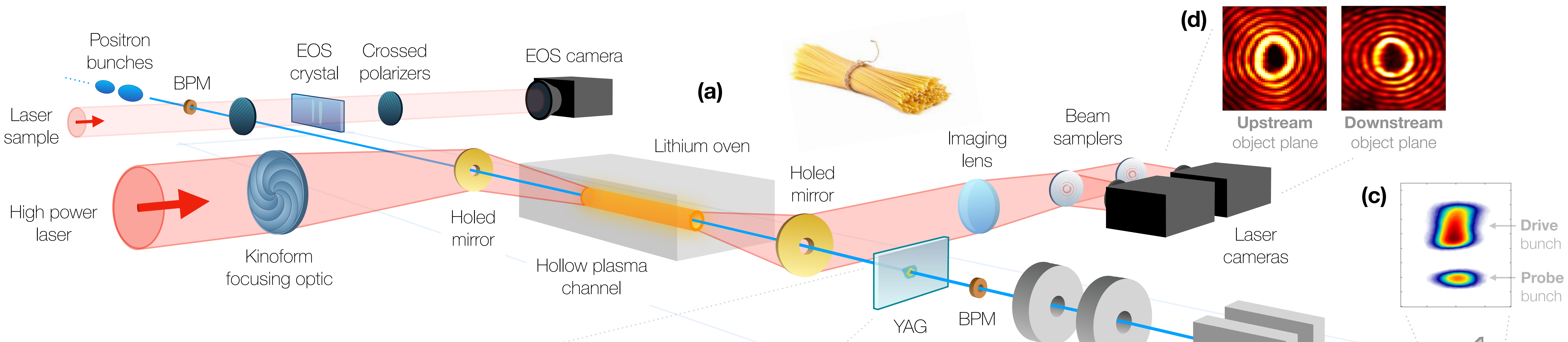
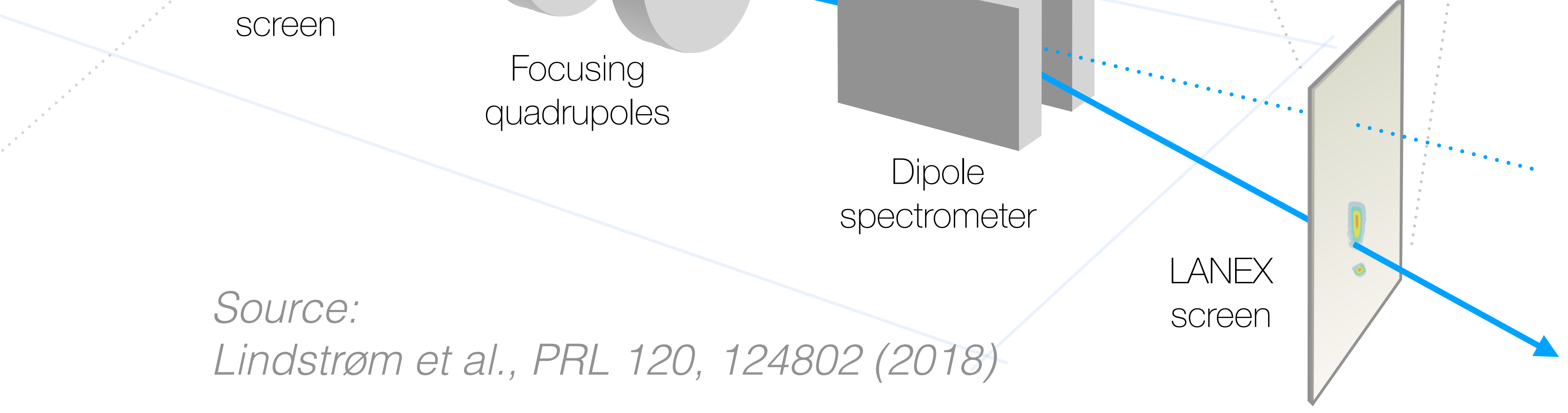
Spencer Gessner

The importance of **openness** and **sharing**

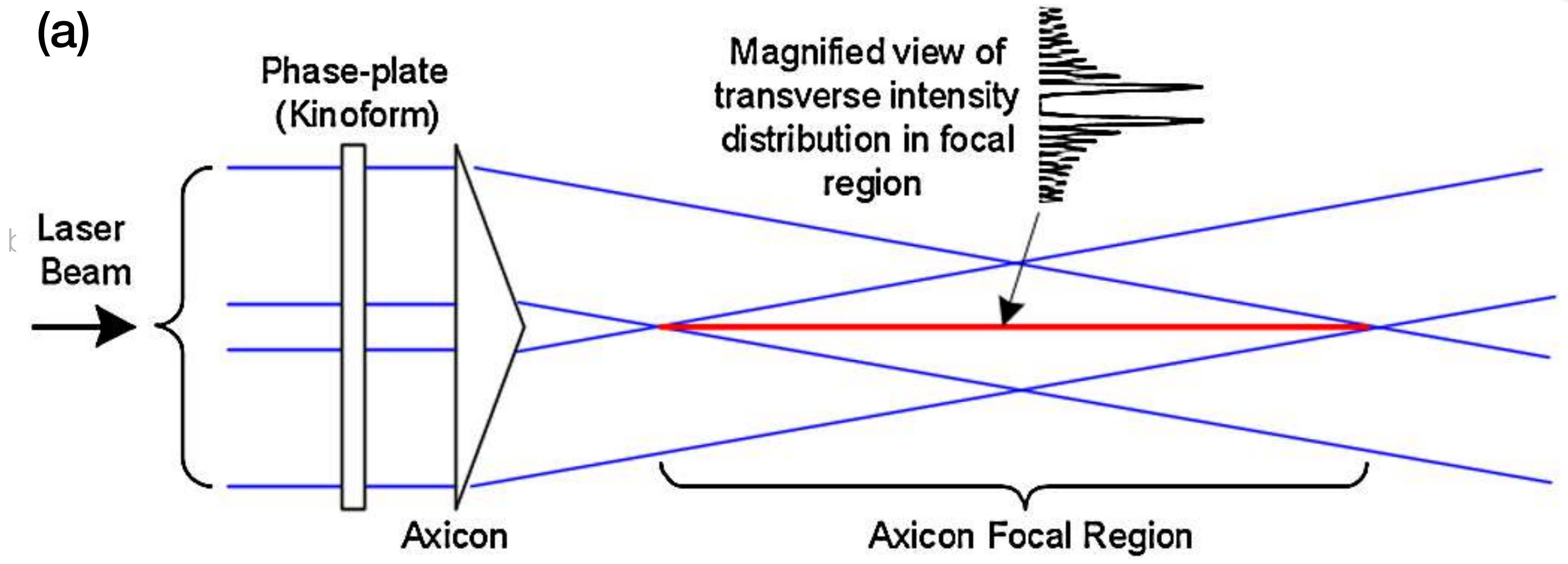
Sebastien Corde

The importance of **clear thought**

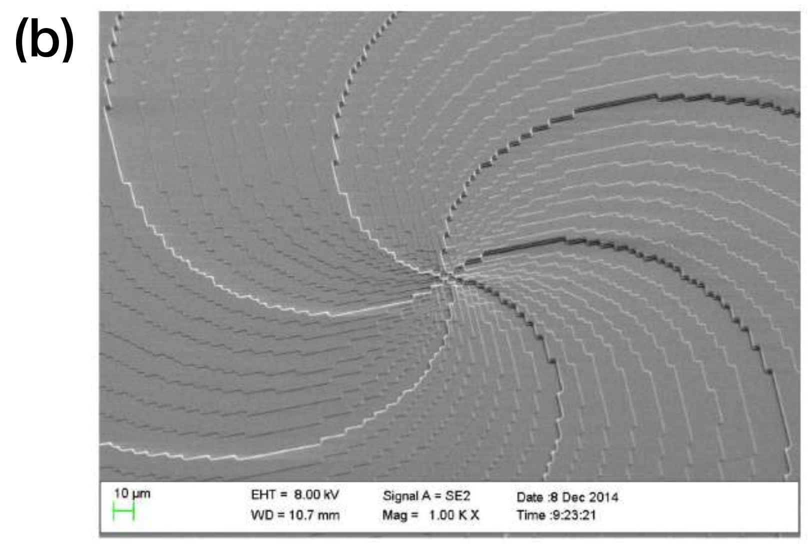
Finding a niche: **Hollow channel plasma accelerators**

Source: Lindstrøm et al., PRL 120, 124802 (2018)



Source: Kimura et al., PRSTAB 14, 041301 (2011)



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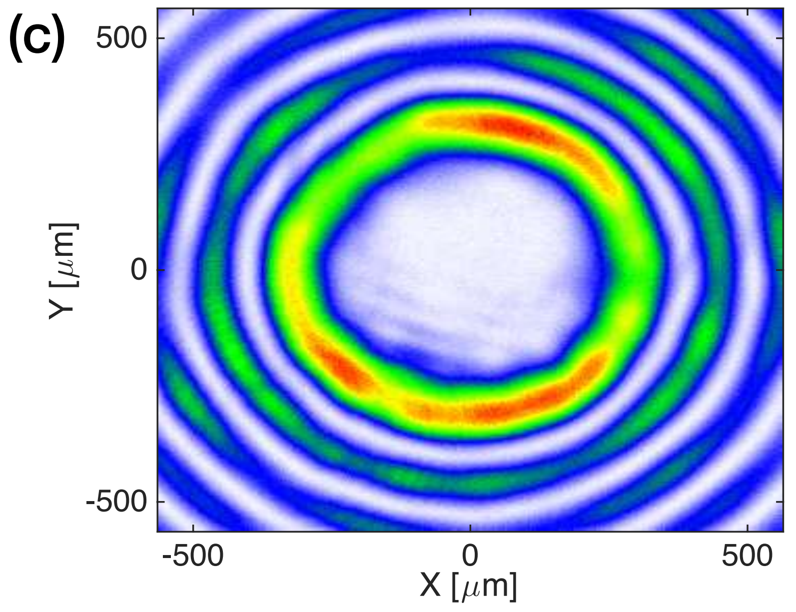

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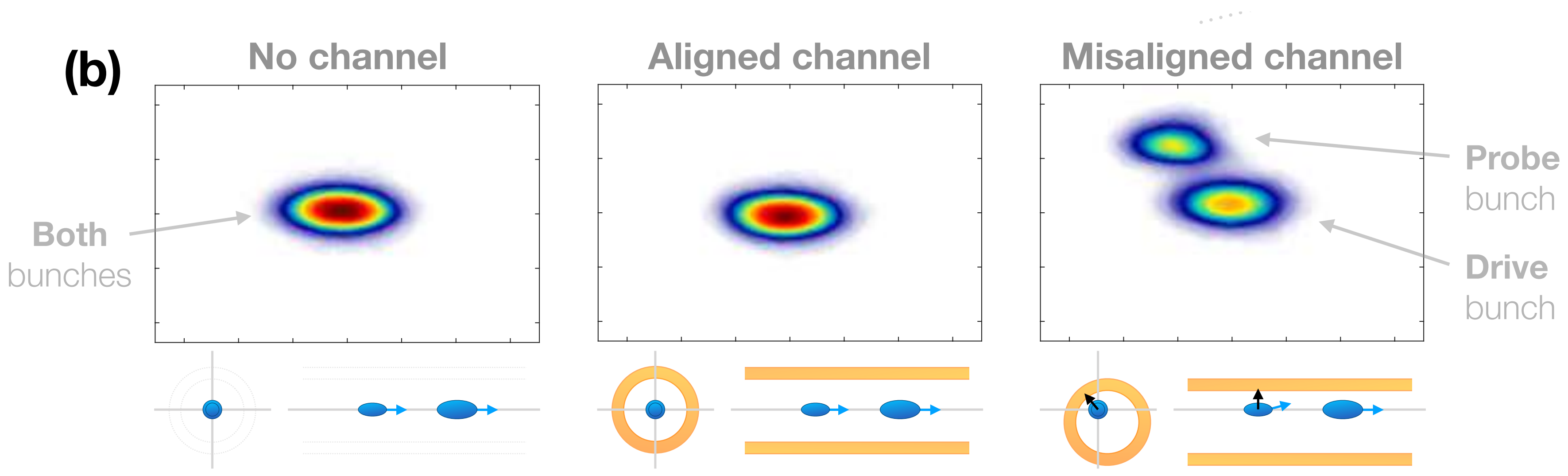
Spencer Gessner

The importance of **openness** and **sharing**

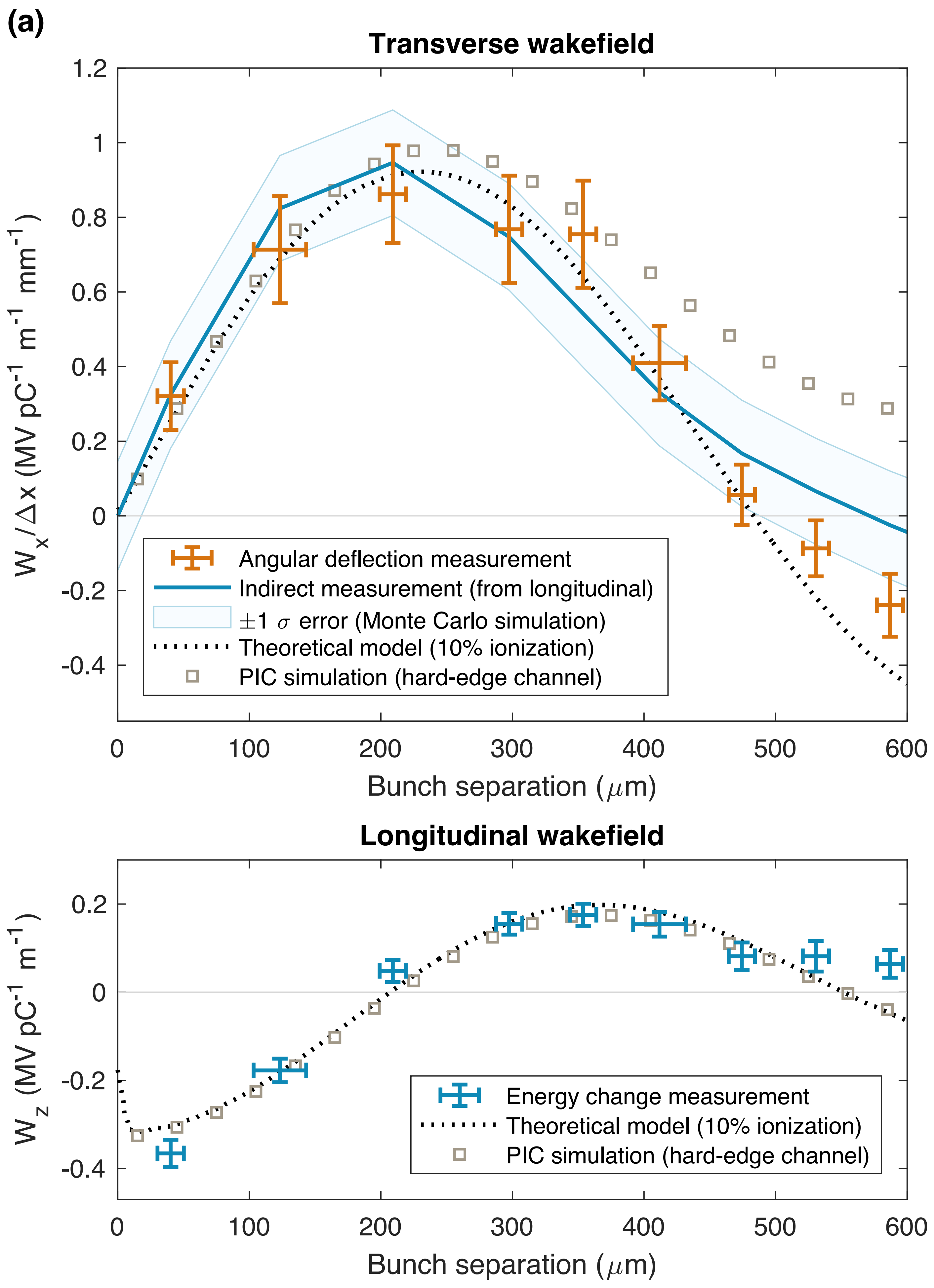
Sebastien Corde

The importance of **clear thought**

An inconvenient truth: **Debilitating transverse instabilities**



- An off-axis beam "exposes" more ions in the channel wall, leading to stronger attraction in that direction (a transverse instability)
- The **transverse wakefield** (force per charge per offset) varies with bunch separation.
- **Measured in two ways** (in agreement):
  - Directly: correlating hollow-channel offsets to beam deflection angle.
  - Indirectly: measuring the acceleration and using the Panofsky–Wentzel theorem
- **Good agreement with theory.**



Source: **Lindstrøm et al., PRL 120, 124801 (2018)**

Chan Joshi

The importance of **narrative**

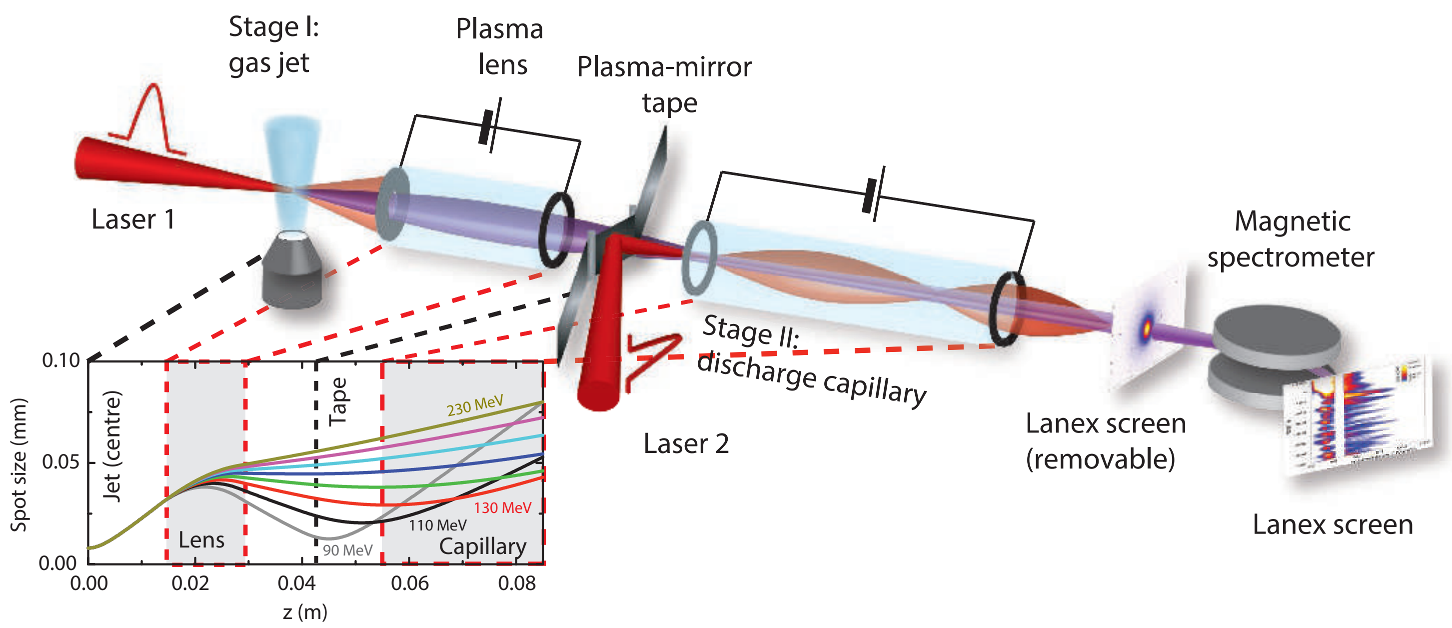
Part 2:

Active plasma lenses (2017–2018)

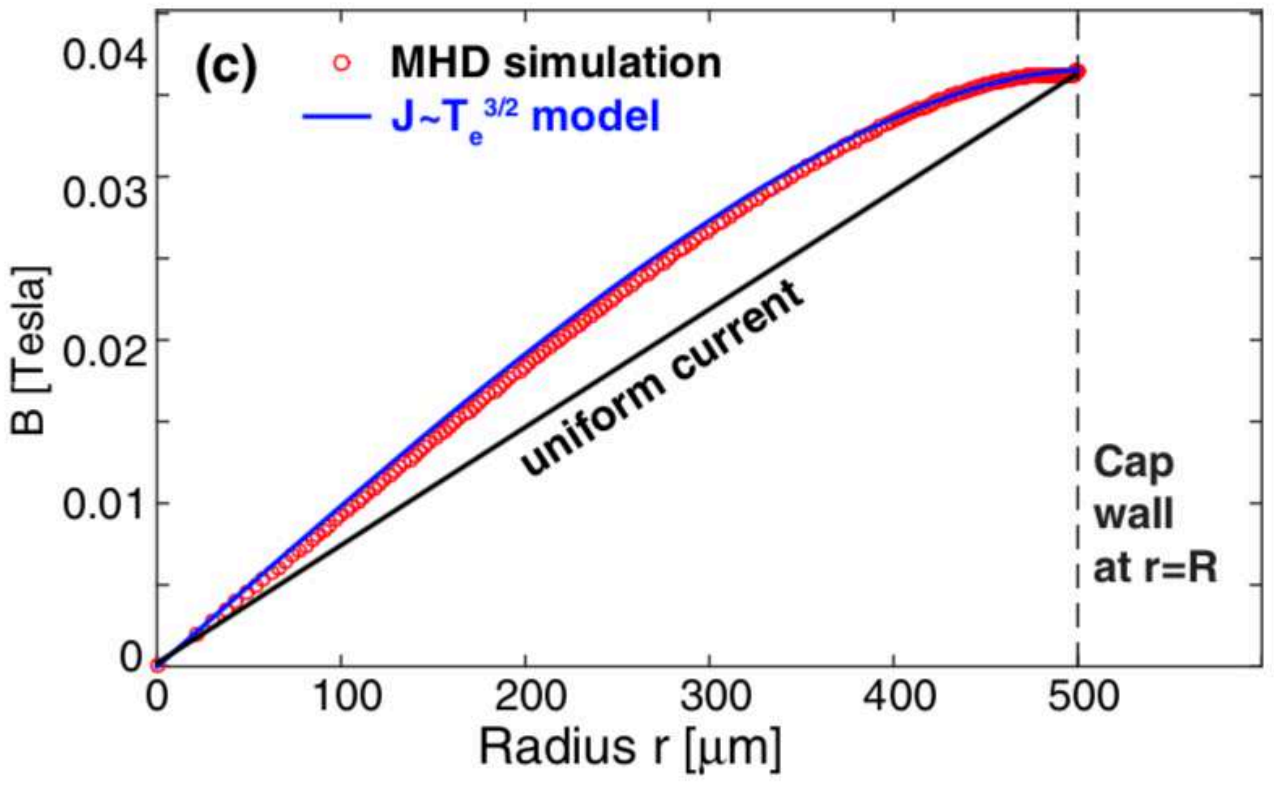
New opportunities: **Characterizing an active plasma lens**

- **Active plasma lenses (APLs) promise large focusing gradients (kT/m)**
  - Can be used for compact staging of plasma accelerators
  - Proof-of-principle demonstrated at LBNL
- However, APLs can have an **aberration** caused by a **temperature non-uniformity**:
  - Higher current density on axis
  - Nonlinear fields (spherical aberration)
  - Leads to **emittance growth**
- A collaboration of **Uni. Oslo, Uni. Oxford, DESY and CERN** formed to do an experiment:

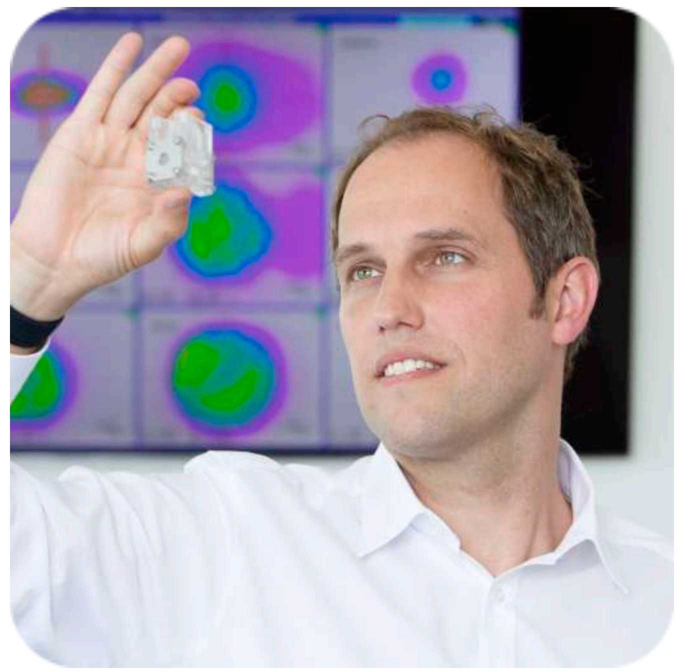
Can we experimentally verify this aberration? And, can we suppress it?



Source: Steinke et al., Nature 530, 190 (2016).



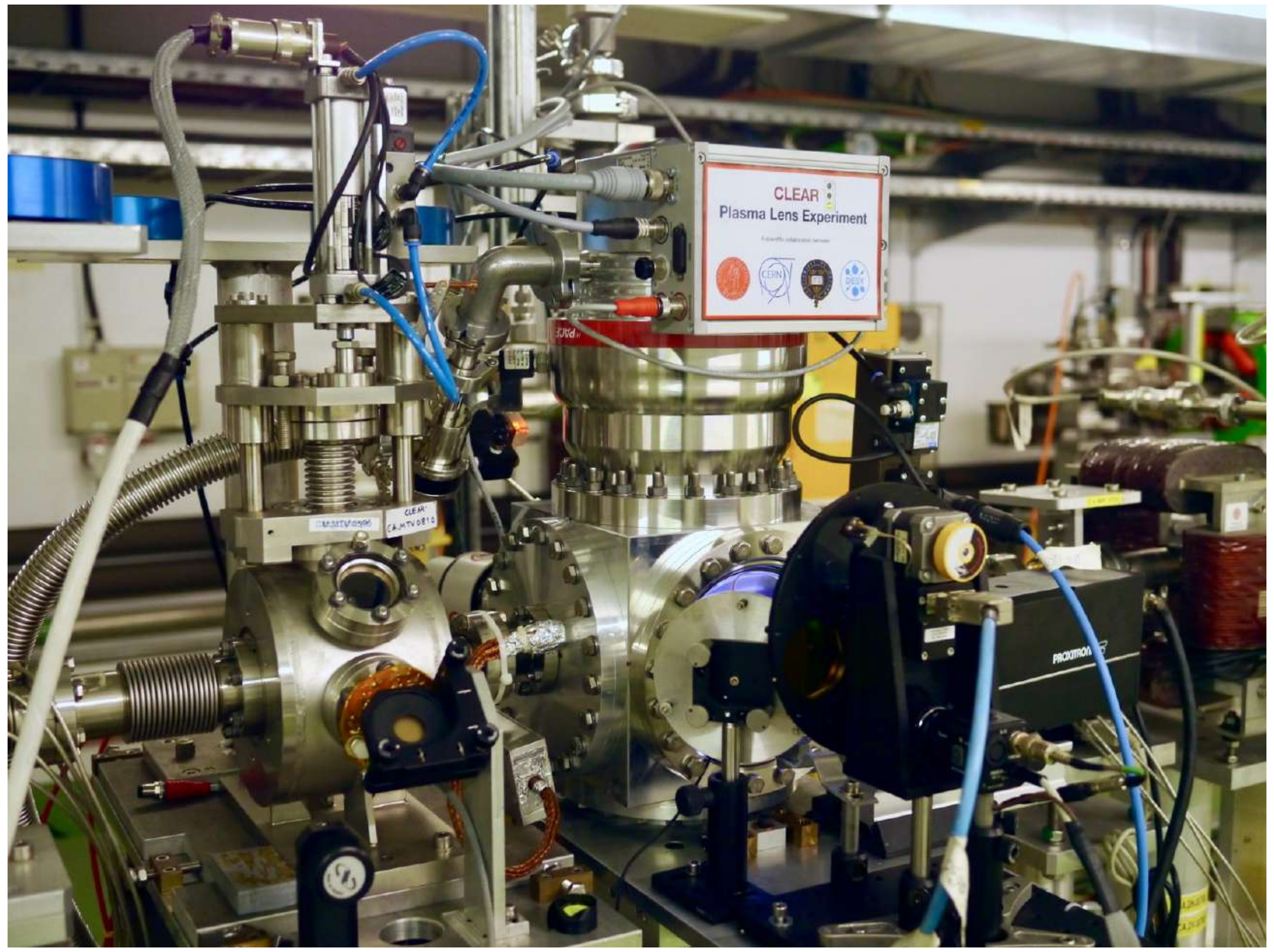
Source: van Tilborg et al., PRAB 20, 032803 (2017)



Jens Osterhoff

The importance of **collaboration**

A year at CLEAR: **Building a plasma lens from scratch**



Source: Lindstrøm et al., NIM A 909, 379 (2018)

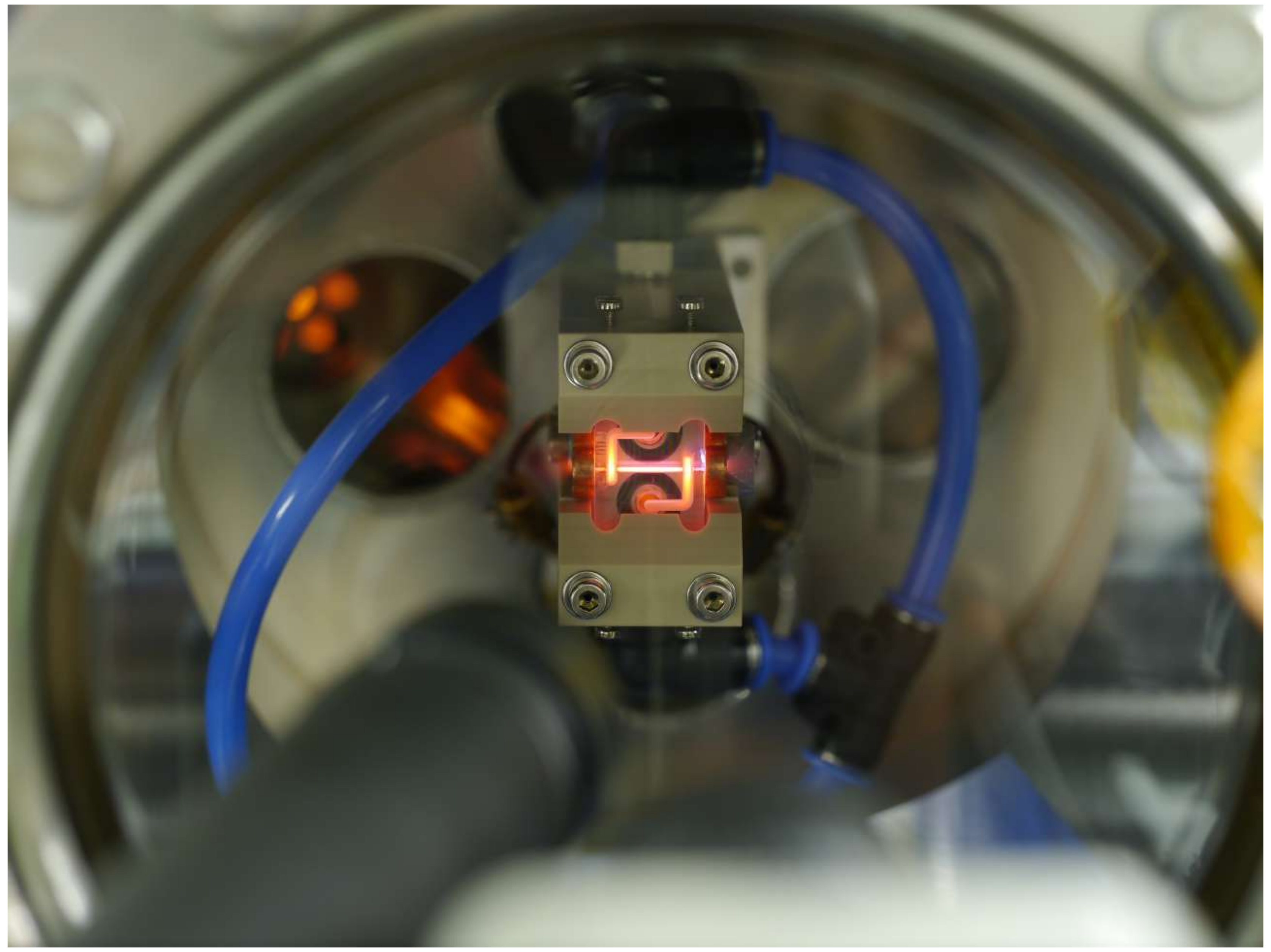


Photo by Kyrre N. Sjøbæk

- CLEAR: CERN Linear Electron Accelerator for Research (**200 MeV electron bunches**)
  - Plasma lens experiment build at the end of the beam line.
  - APL: **Sapphire capillary,** 15-mm long, 1-mm diameter **(built by DESY)**
  - HV current source: **compact Marx Bank (built by Oxford)**

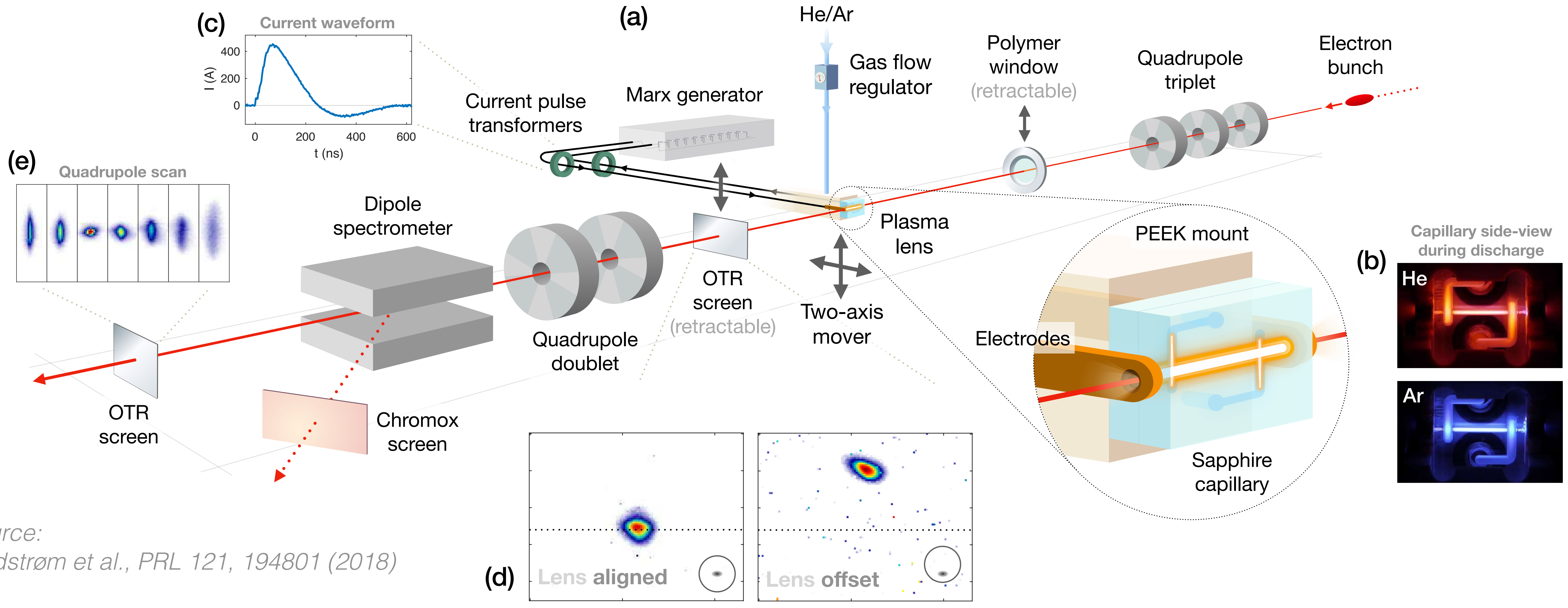
Kyrre N. Sjøbæk

The importance of
attention to detail

Anthony Dyson

The importance of
enthusiasm

Developing a method: **Beam-based field measurement**



Source: Lindstrøm et al., PRL 121, 194801 (2018)

- Measuring the magnetic-field profile:
  - Tightly focus the beam (local probing)
  - **Scan the transverse lens offset**
  - Measure the electron **beam deflection** (scales with B-field)

Beam time at CLEAR (March 2018)

Wilfrid Farabolini

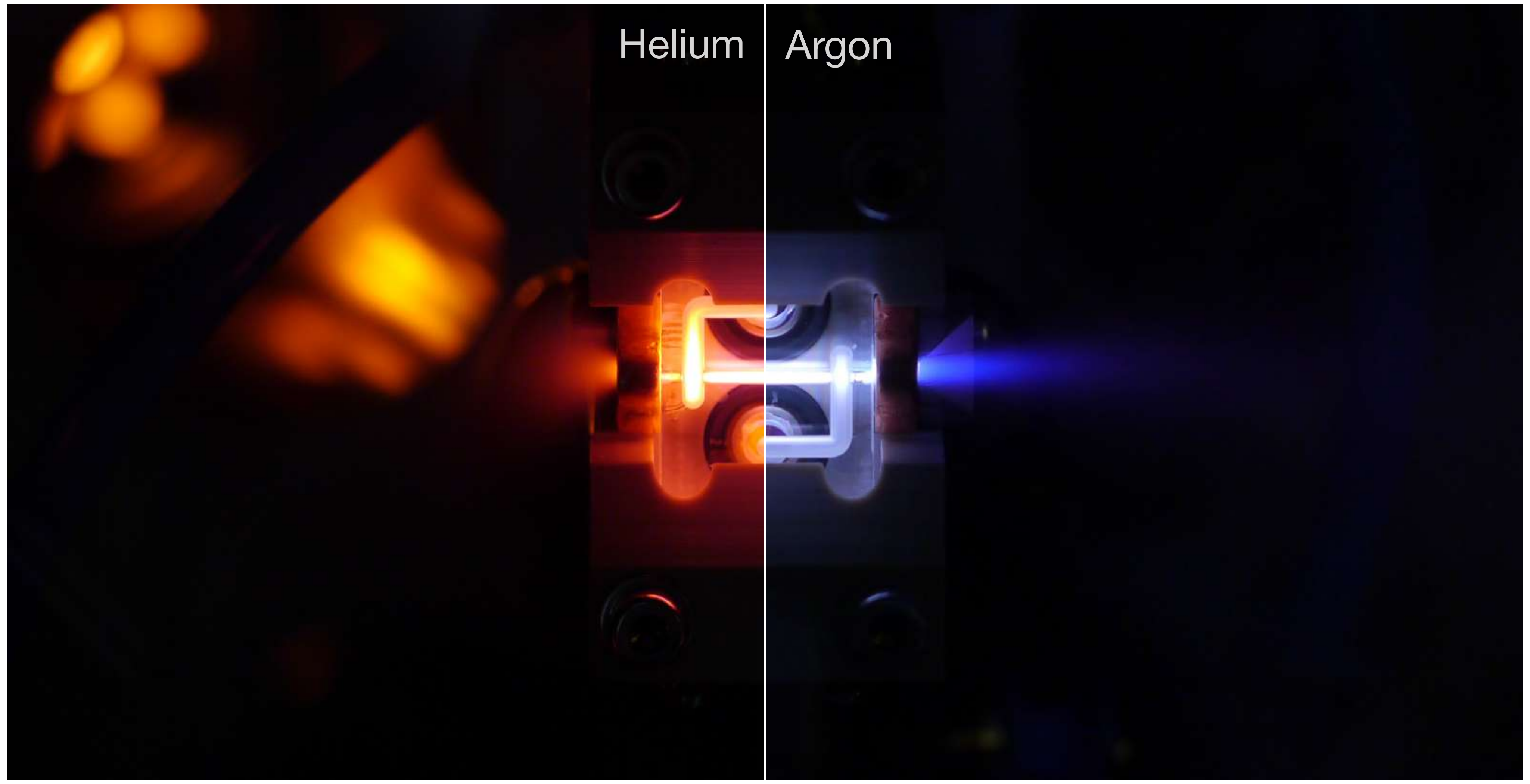
The importance of **good engineering**

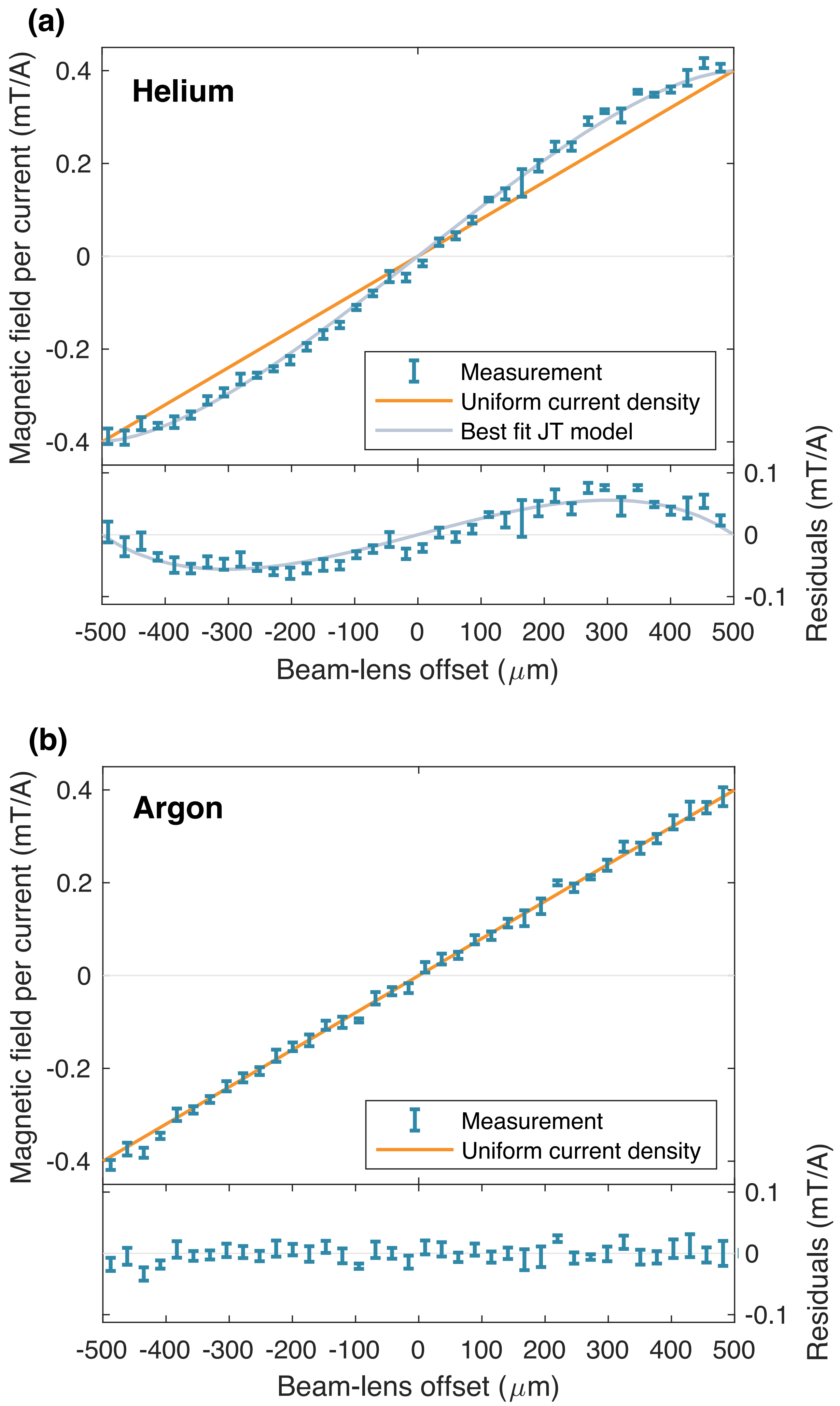
Davide Gamba

The importance of **wholistic machine understanding**

A small discovery: **Argon gas suppresses the aberration**

- Result #1: **Helium-filled APL has the predicted spherical aberration.**
- Result #2: **Argon-filled APL has no aberration!**
  - Found after initial difficulties with helium, causing a switch to argon (easier to ionise)
- Corroborated by measurement of **emittance preservation** in argon APL.





Source: **Lindstrøm et al., PRL 121, 194801 (2018)**

Simon Hooker

The importance of **combining great knowledge with great humanity**

A crazy week in September 2018

Friday: PRL accepted

PHYSICAL REVIEW LETTERS **121,** 194801 (2018)

Emittance Preservation in an Aberration-Free Active Plasma Lens

C. A. Lindstrøm,[1,*] E. Adli,[1] G. Boyle,[2] R. Corsini,[3] A. E. Dyson,[4] W. Farabolini,[3] S. M. Hooker,[4,5] M. Meisel,[2] J. Osterhoff,[2] J.-H. Röckemann,[2] L. Schaper,[2] and K. N. Sjobak[1]

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[2]*DESY, Notkestraße 85, 22607 Hamburg, Germany*
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(Received 10 August 2018; published 7 November 2018)

Active plasma lensing is a compact technology for strong focusing of charged particle beams, which has gained considerable interest for use in novel accelerator schemes. While providing kT/m focusing gradients, active plasma lenses can have aberrations caused by a radially nonuniform plasma temperature profile, leading to degradation of the beam quality. We present the first direct measurement of this aberration, consistent with theory, and show that it can be fully suppressed by changing from a light gas species (helium) to a heavier gas species (argon). Based on this result, we demonstrate emittance preservation for an electron beam focused by an argon-filled active plasma lens.

DOI: 10.1103/PhysRevLett.121.194801

Advances in high gradient acceleration research [1–4] promise significantly more compact particle accelerators, key to next-generation free-electron lasers (FELs) [5] and linear colliders [6]. However, advances in high gradient acceleration must be matched by a similar miniaturization of beam focusing devices. Active plasma lensing [7] is one promising technique that provides compact, strong focusing in both planes simultaneously, by passing a large longitudinal current through a thin plasma-filled capillary [8,9], ideally creating an azimuthal magnetic field proportional to the distance from the axis. While the concept dates back to the 1950s [10] and was used for fine focusing of heavy ion beams [11], active plasma lenses (APLs) have recently gained attention based on their application to advanced accelerator research, such as beam capture and staging of laser plasma accelerators [12].

Although APLs provide kT/m focusing fields, orders of magnitude stronger focusing compared to conventional quadrupole magnets, they can suffer from aberrations that increase the emittance of the beam being focused [13,14]. One such aberration is caused by plasma temperature gradients in the capillary (colder plasma closer to the wall), which leads to a radially nonlinear magnetic field distribution [15,16] with enhanced focusing closer to the axis. This spherical aberration has been indirectly demonstrated in both helium [17] and hydrogen [18], by measurements of on axis field gradient enhancement and the formation of ring-shaped beams.

In this Letter, we show that this aberration can be fully suppressed by changing from a light gas species (helium) to a heavier gas species (argon). This discovery was made possible by the first complete characterization of the radial magnetic field distribution in an APL, in an experiment performed at the CERN Linear Electron Accelerator for Research (CLEAR) User Facility [19,20]. The beam emittance was subsequently measured using quadrupole scans, resulting in the first demonstration of emittance preservation in an APL.

The experimental setup [21], shown in Fig. 1, consisted of a 1 mm diameter and 15 mm long capillary milled from two sapphire blocks, mounted in the CLEAR beam line to allow passage of an electron beam. The capillary was filled with 1–100 mbar of gas through internal gas inlets, connected to an external flow regulator and a buffer volume. The gas escaping into the surrounding chamber was pumped out by a large turbo pump, which together with a 3 μm polymer (Mylar) window [22] preserved the ultrahigh vacuum in the upstream accelerator line. Holed copper electrodes on the up- and downstream side of the capillary were connected to a compact Marx bank [23], providing short 20 kV discharge pulses with a tunable 410–450 A peak current after 80 ns and a duration of 145 ns full width at half maximum (FWHM) [see Fig. 1(c)], as measured by in- and outgoing wideband current pulse transformers. A two-axis mover [24] was used to displace the capillary horizontally and vertically relative to the beam, with a 1 μm step resolution and an approximate range of 10 mm.

0031-9007/18/121(19)/194801(6) 194801-1 Published by the American Physical Society

A crazy week in September 2018

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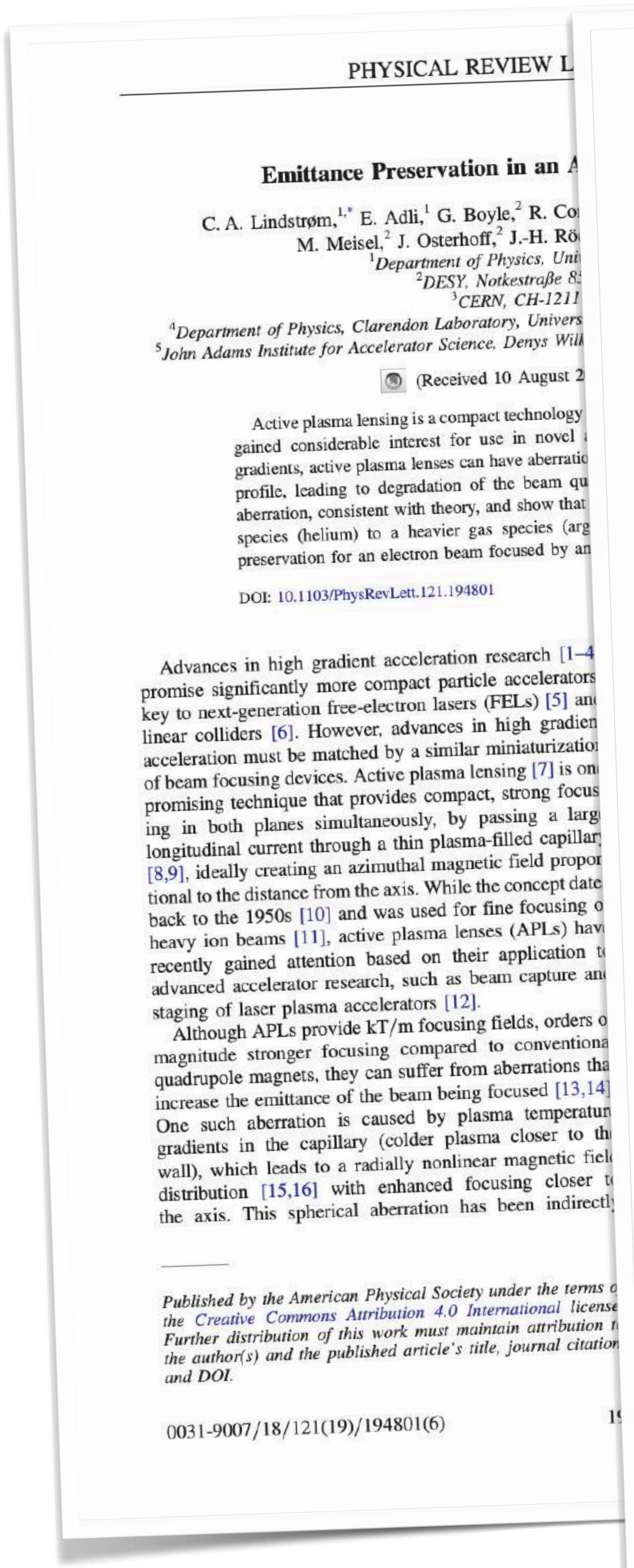
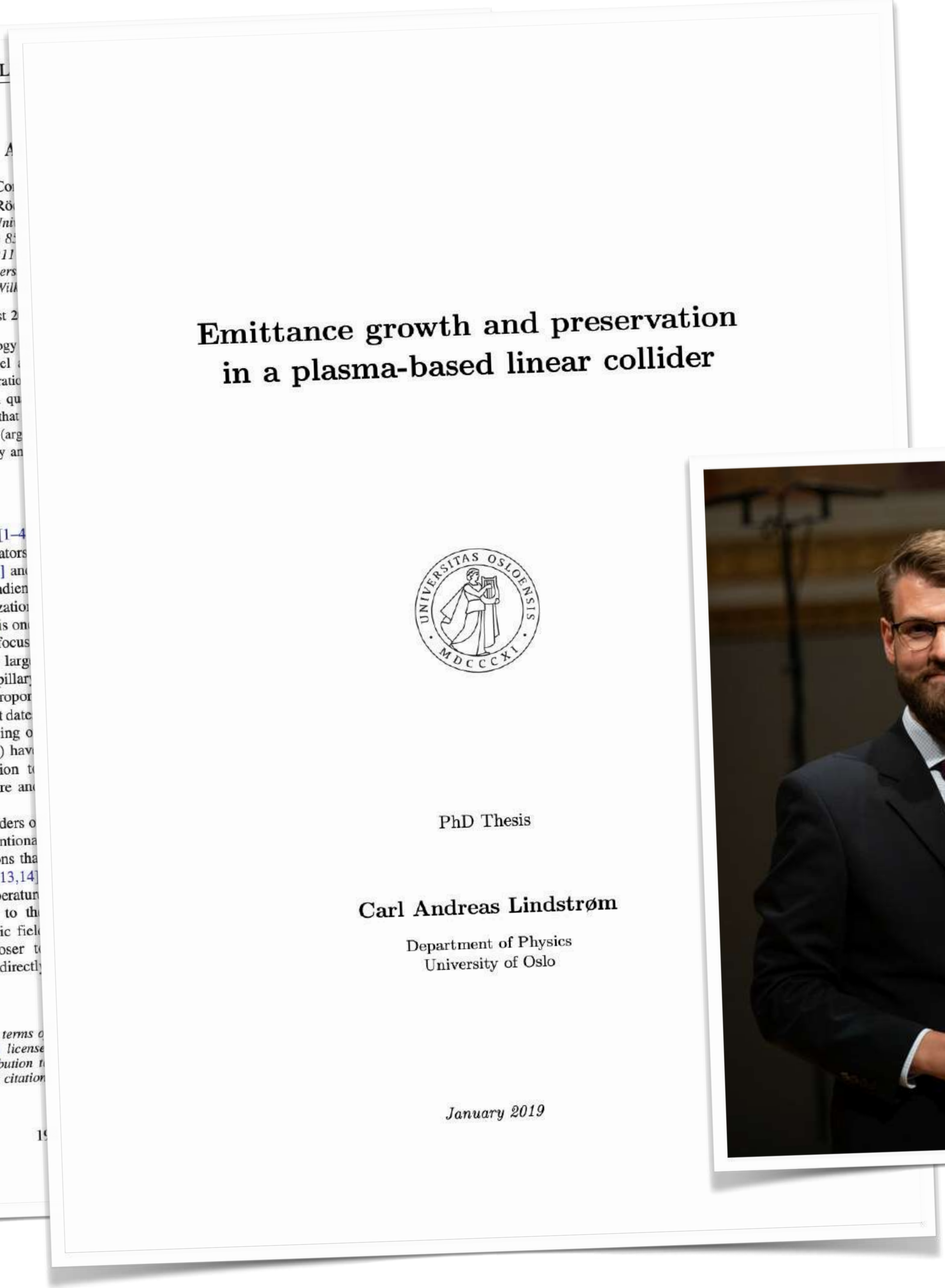
Also Friday: Handed in PhD thesis





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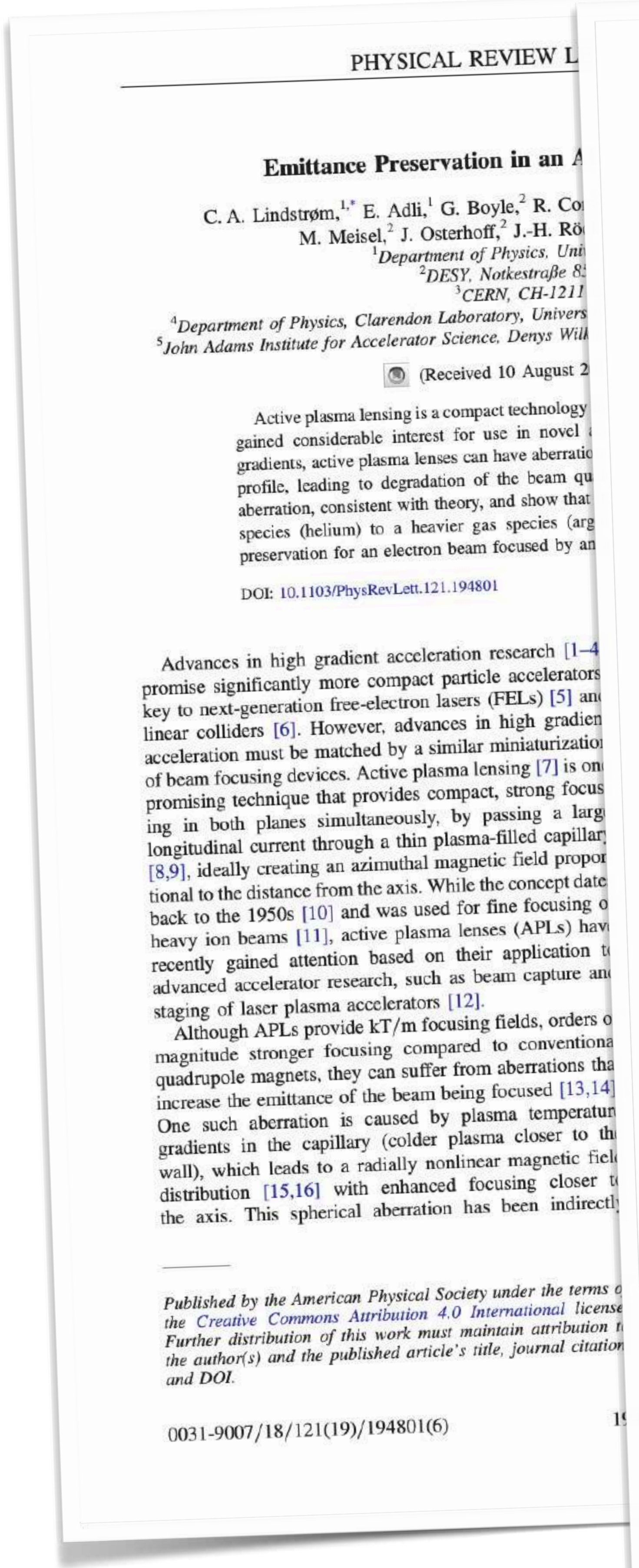

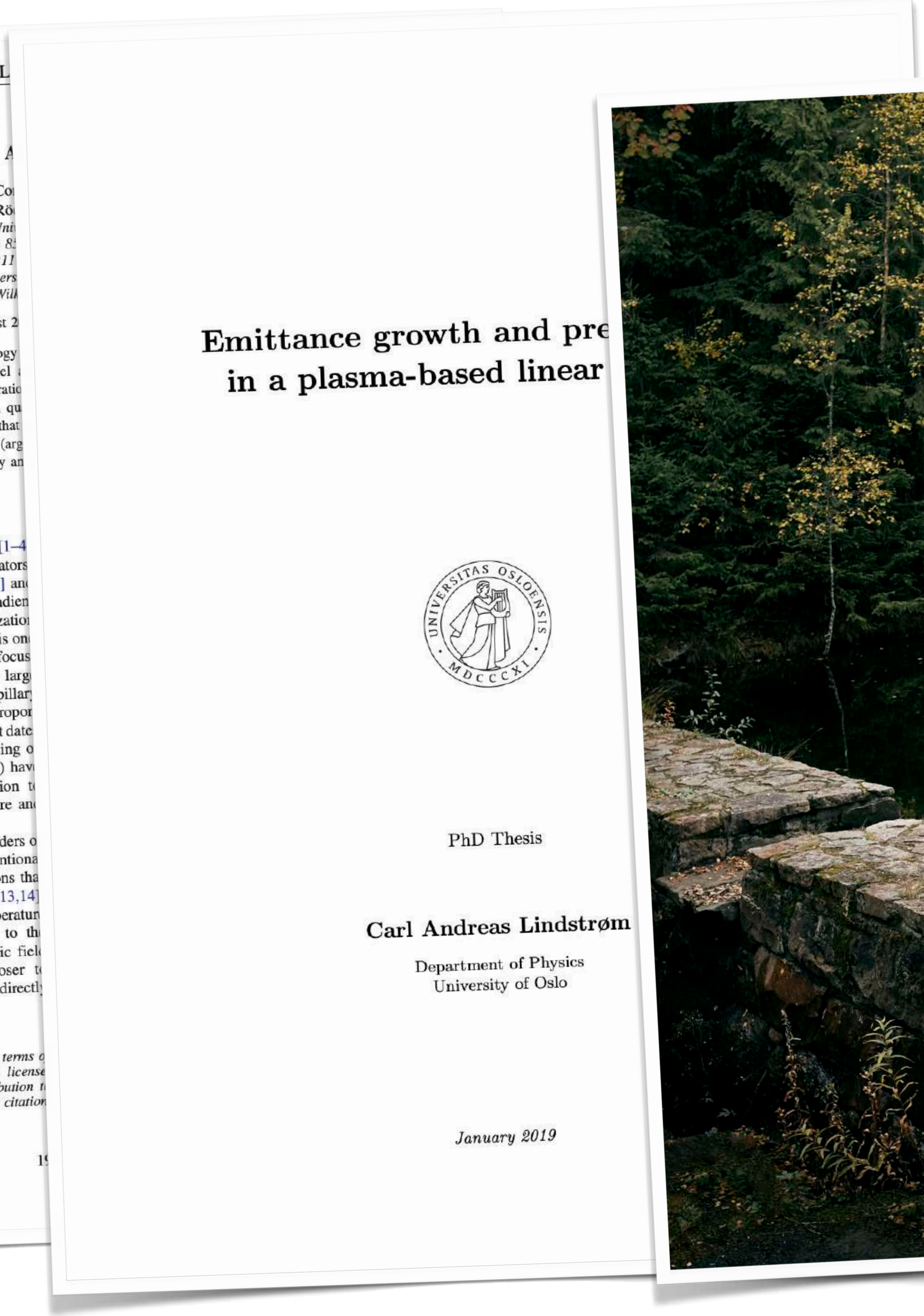

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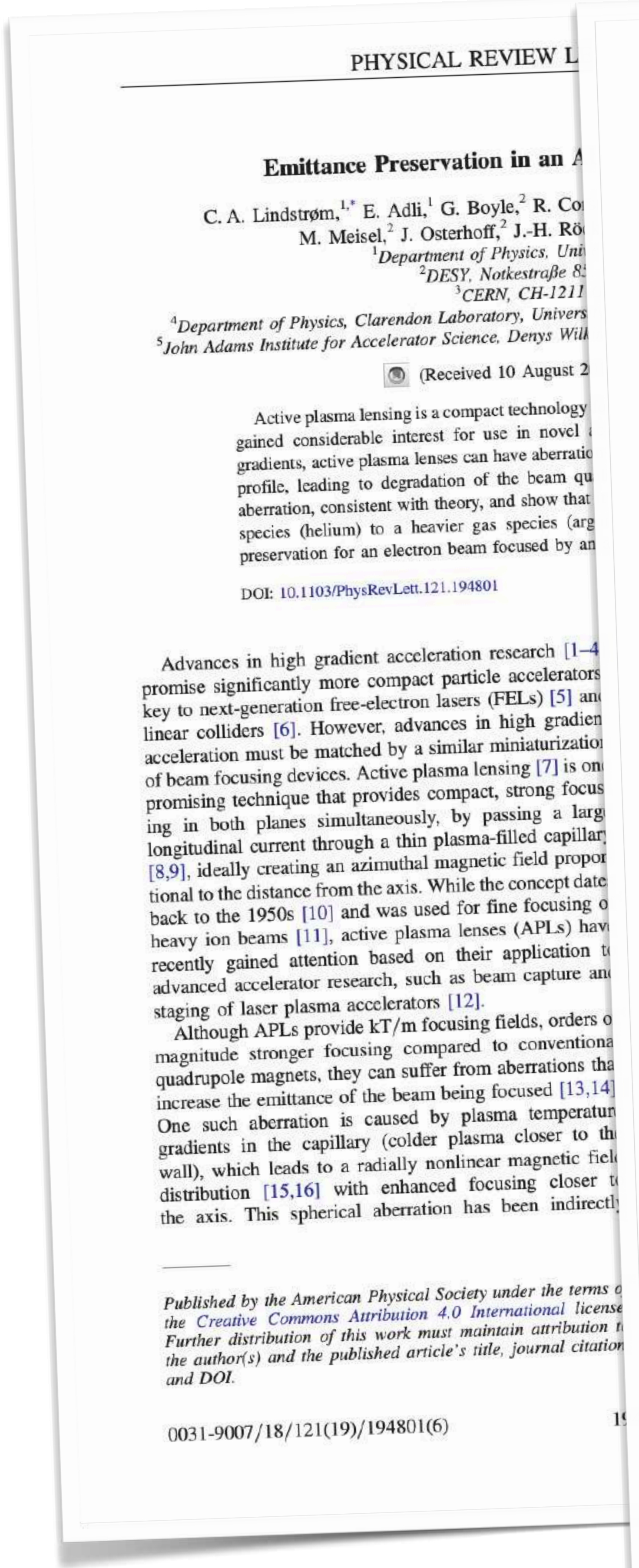
PHYSICAL REVIEW L

Emittance Preservation in an A

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(Received 10 August 2

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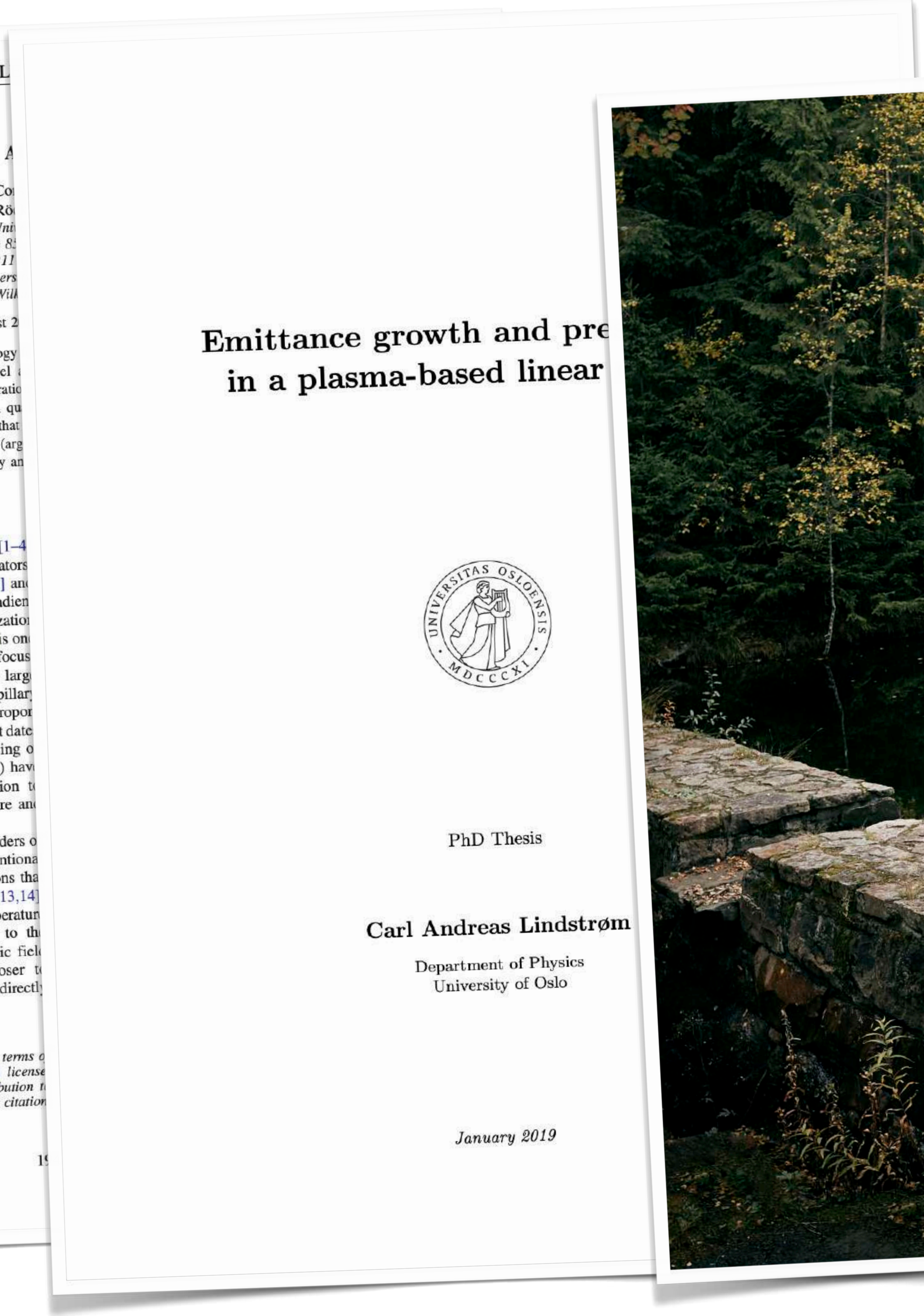

Emittance growth and pre
in a plasma-based linear

PhD Thesis

Carl Andreas Lindstrøm

Department of Physics
University of Oslo

January 2019

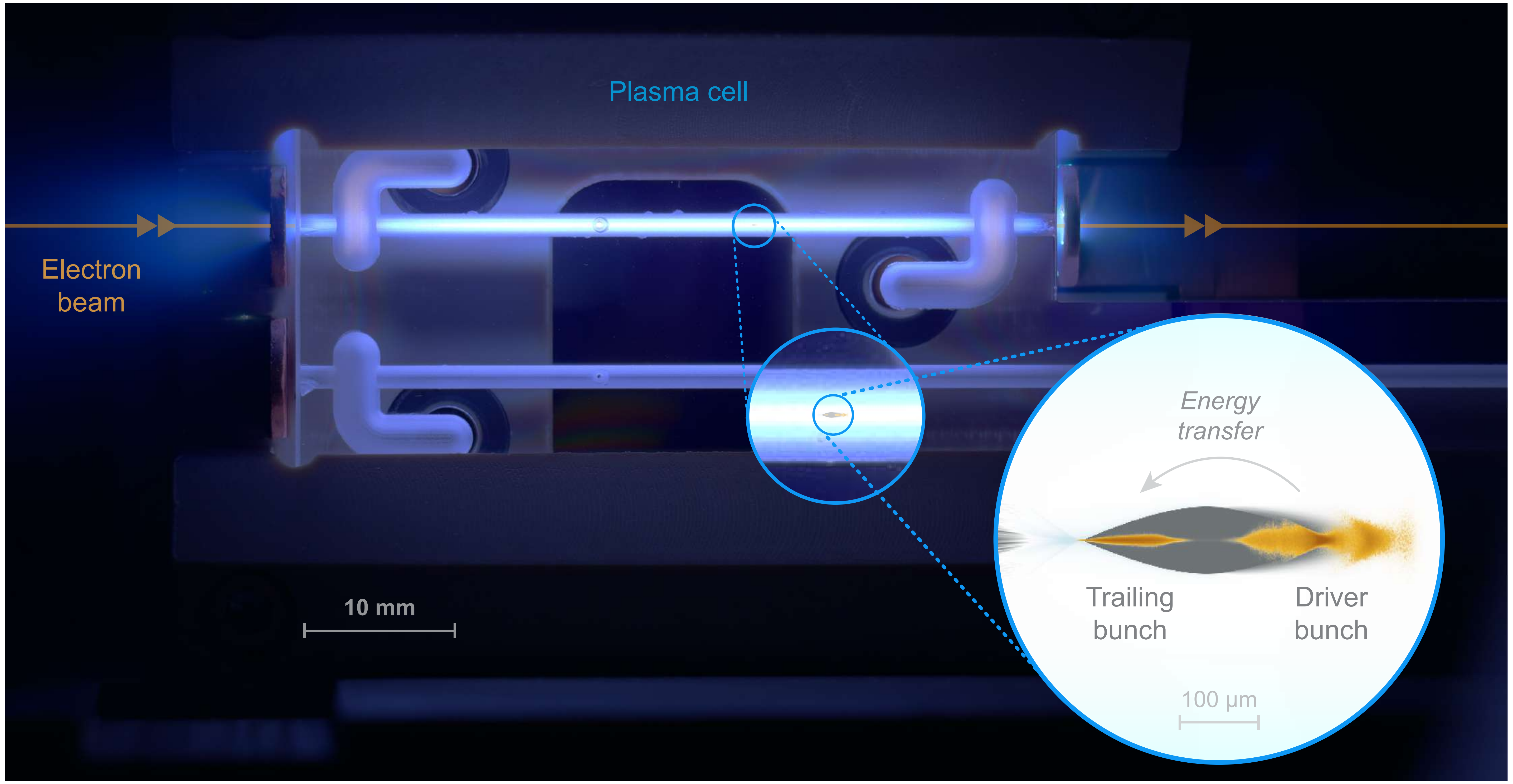
A crazy week in September 2018

Friday: PRL accepted | **Also Friday**: Handed in PhD thesis | **Saturday**: Got married | **Tuesday**: Moved out | **Wednesday**: Honeymoon (South Pacific)

Part 3:

Beam-quality preservation (2019–2022)

A new vision: **the FLASHForward X-2 experiment**



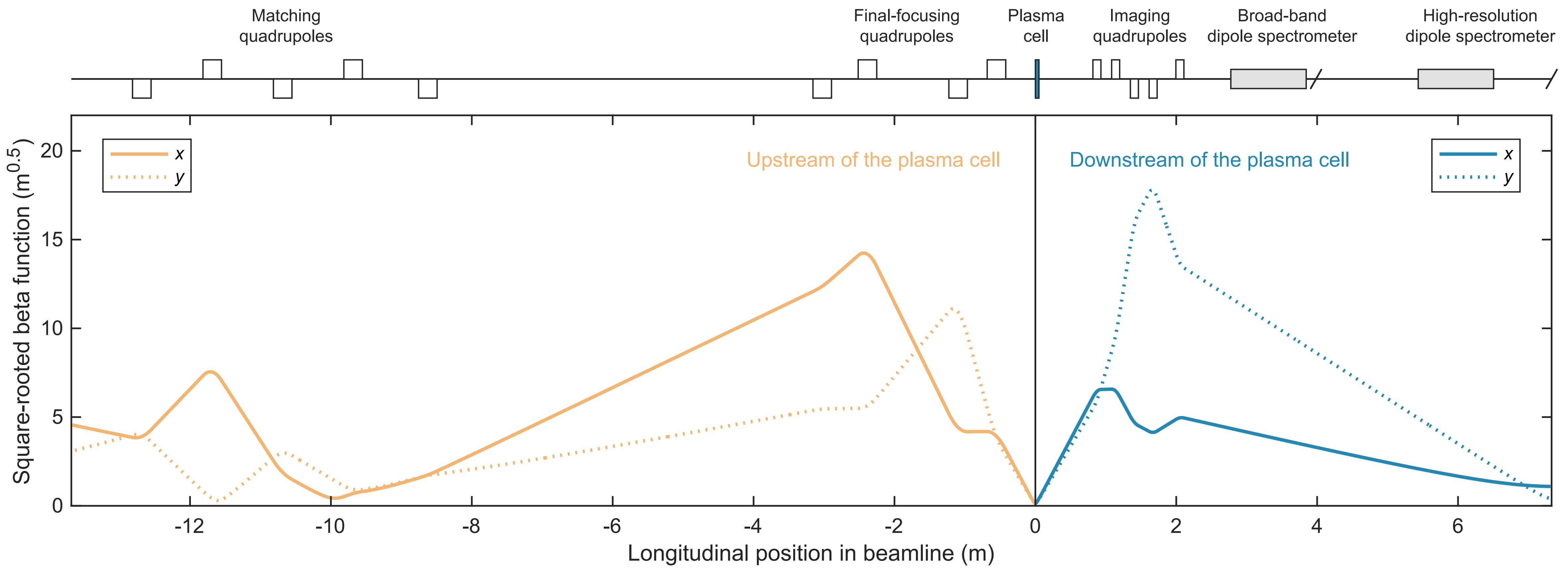
- Energy efficiency and beam quality are both key to applications (FELs, colliders).
- FLASHForward: 1 GeV beams, high stability/quality, 50+ mm plasma cell (discharge)

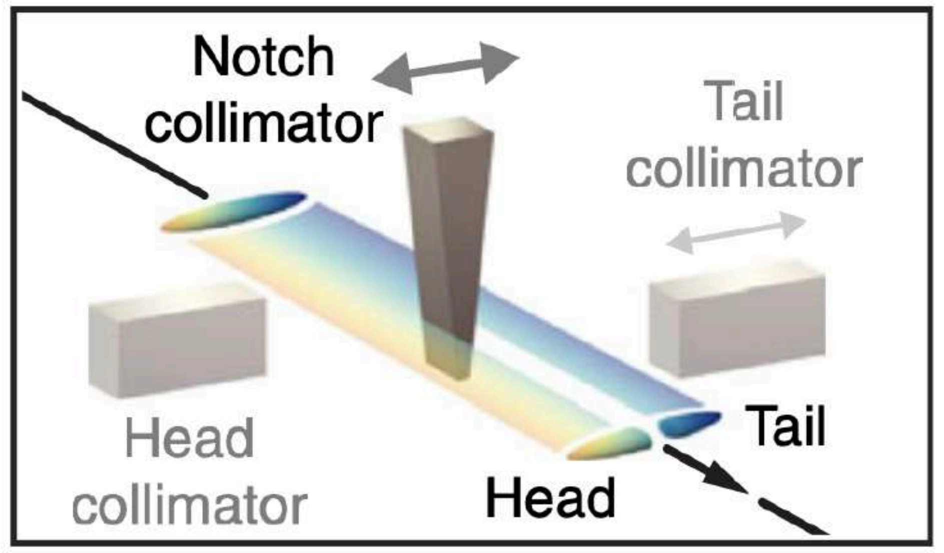
Goal: **demonstrate simultaneous high efficiency** and **beam-quality preservation (charge, energy spread, and emittance)** in a beam-driven plasma accelerator stage.

Richard D’Arcy

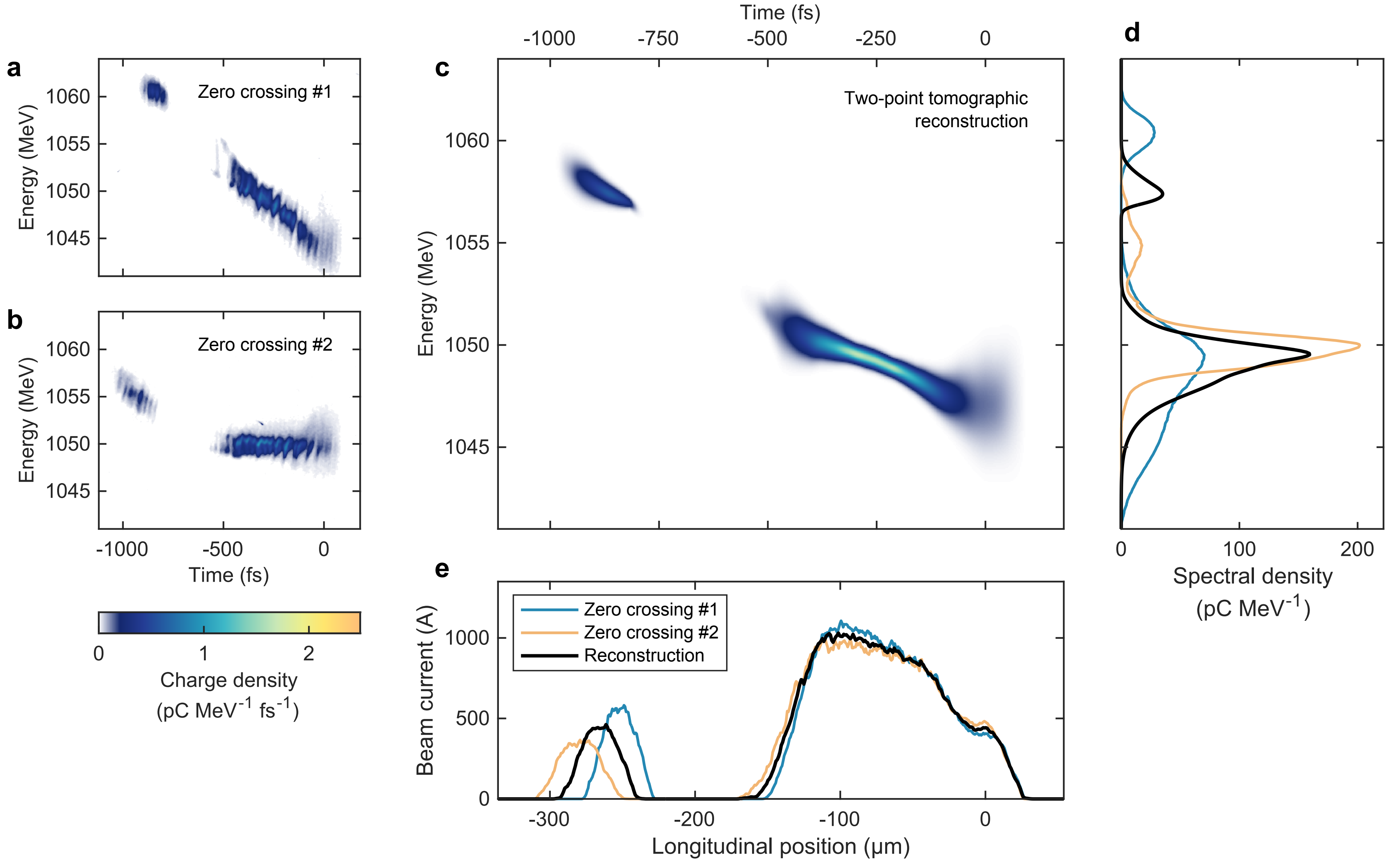
The importance of **project coordination**

Understanding the machine: **Precision plasma acceleration**





- High-precision control and high stability:
  - Strong **beam optics** (~10 mm beta functions at focus)
  - **Current profile shaping** (notch collimator + 3rd order RF cavity)
  - **Plasma-density profile**
- Diagnostics: X-band **TDS** (8 fs resolution), high-resolution **screens** (6 μm rms), cavity-based **BPMs** (1 μm)

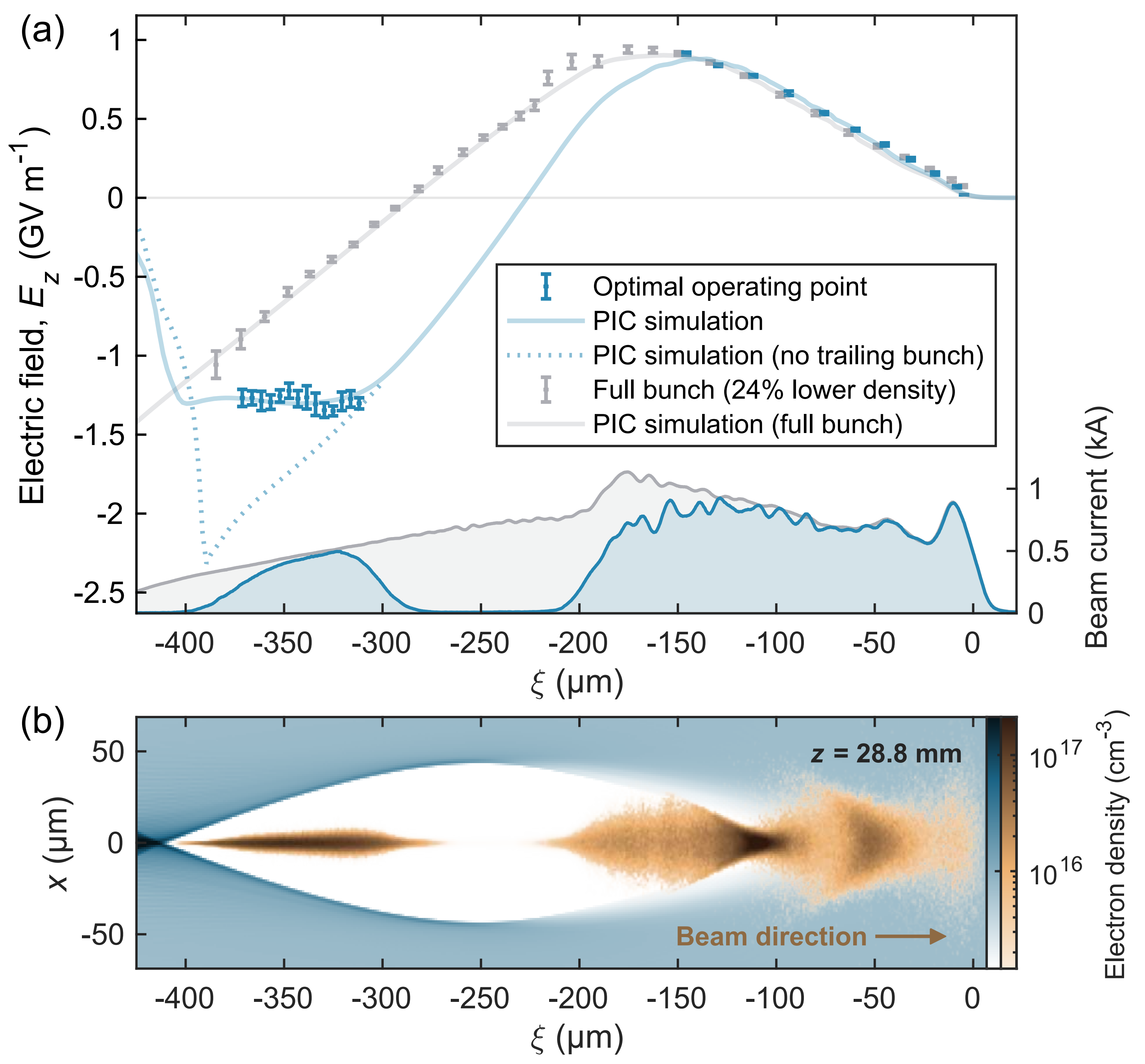


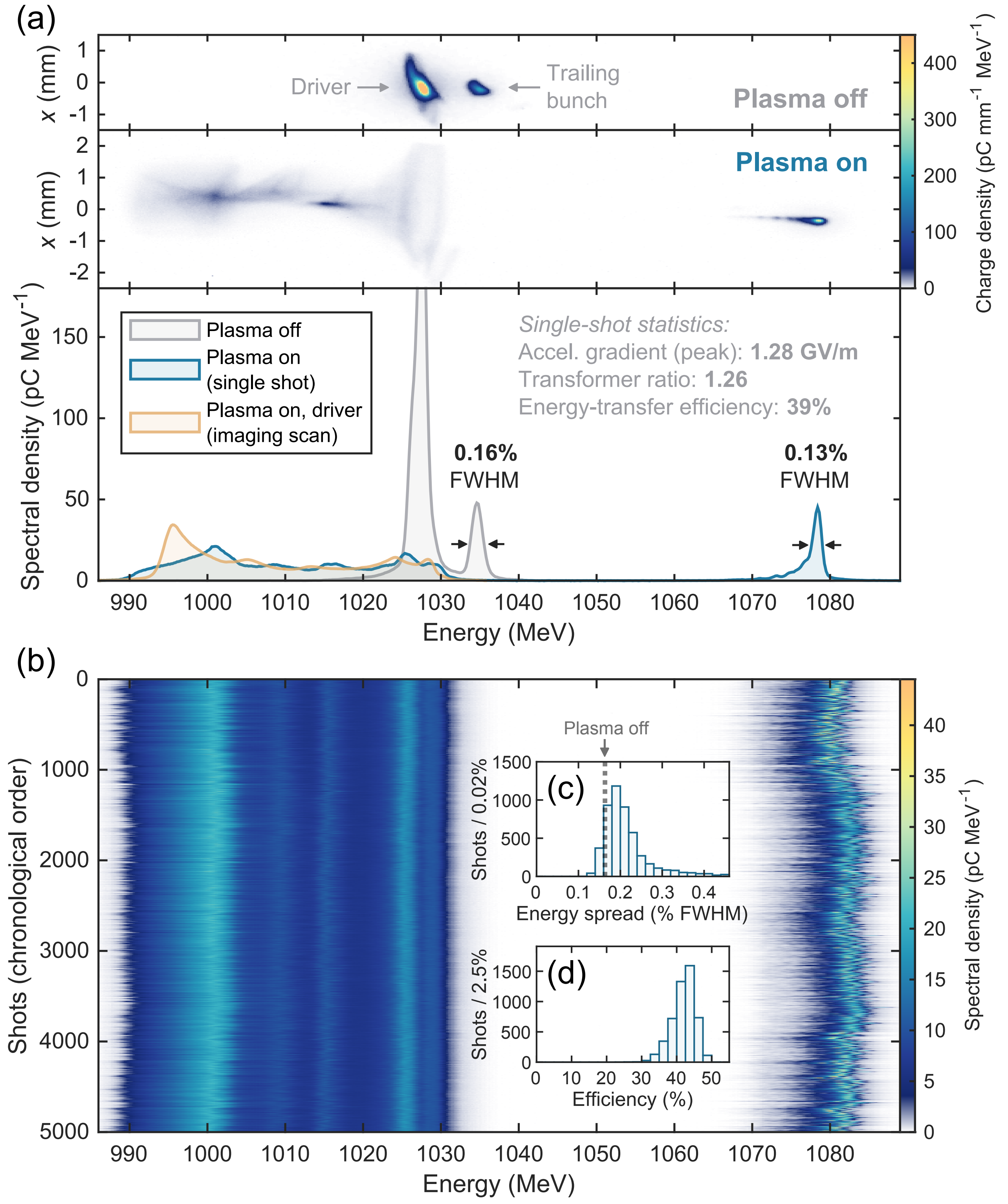
Longitudinal phase space measured with PolariX transverse deflection structure (TDS).

Pau Gonzalez Caminal

The importance of **never giving up**

Preserving beam quality: **Energy-spread and charge preservation**





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

Sarah Schröder

The importance of **questioning assumptions**

> Achieved “optimal” beam loading:
> > Flattened field: **preserved energy spread** at ~0.1% FWHM (and preserved 100-pC charge)
> > Strongly loaded: **(42 ± 4)% energy-transfer efficiency**
> > Wakefield **measured with 10-fs resolution** [Schröder *et al.*, Nat. Commun. 11, 5984 (2020)]

Preserving beam quality: **Emittance preservation (teaser)**

- 400 pC driver, plasma-density profile peaking at ~1.2 x 10^{16} cm^{-3}
- Stable working point: **40 MeV gain** in a 50 mm plasma cell (**22% transfer efficiency, 1.4 GV/m estimated peak field**)
- **Preserved charge** of 40 pC (41% of shots)
- **Preserved**/reduced **energy spread** of 0.12% FWHM (62% of shots)

Brian Foster

The importance of
good writing

Matthew Wing

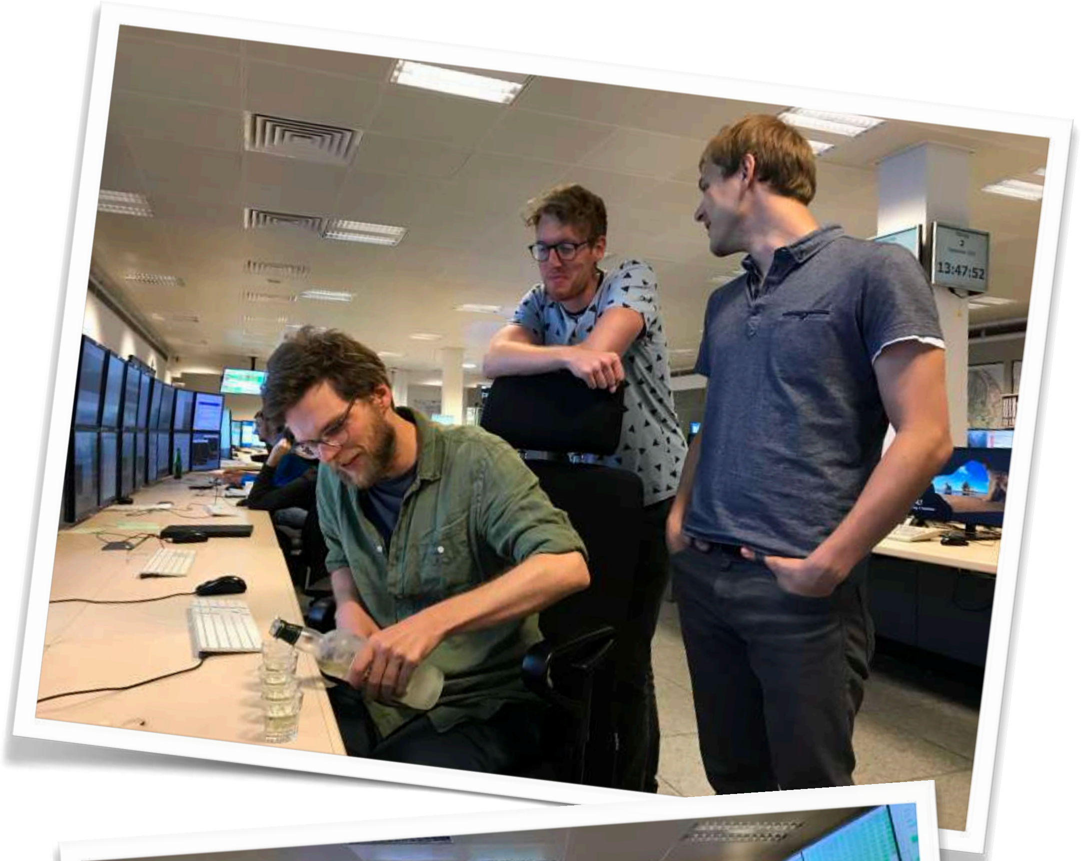
The importance of
sound statistics

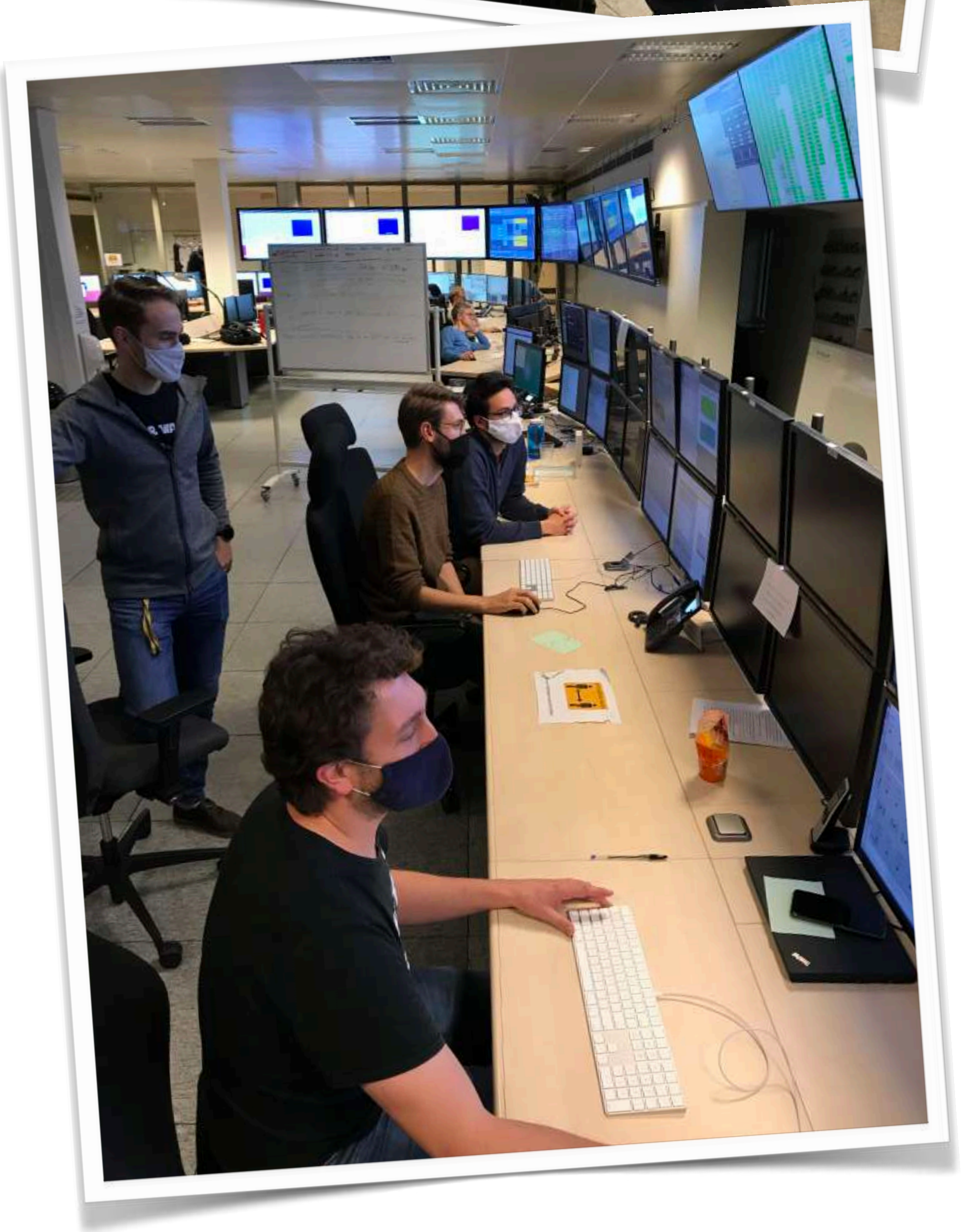
Preserving beam quality: **Emittance preservation (teaser)**

Lindstrøm et al., *submitted* (2022)

- Object-plane scans (quad scans) comparing plasma cell extracted and inserted.
- Result: **<u>Projected emittance preserved</u> at 2.8 mm-mrad within 3% measurement error.**
  Simultaneous charge and energy-spread preservation, high efficiency, and high gradients.
- Measurements show that **misalignment** (< 0.1 mrad) and **mismatching** (waist location beyond ±5 mm) causes significant **emittance growth**: ~880° of phase advance / **~5 betatron envelope oscillations** (simulation estimate)

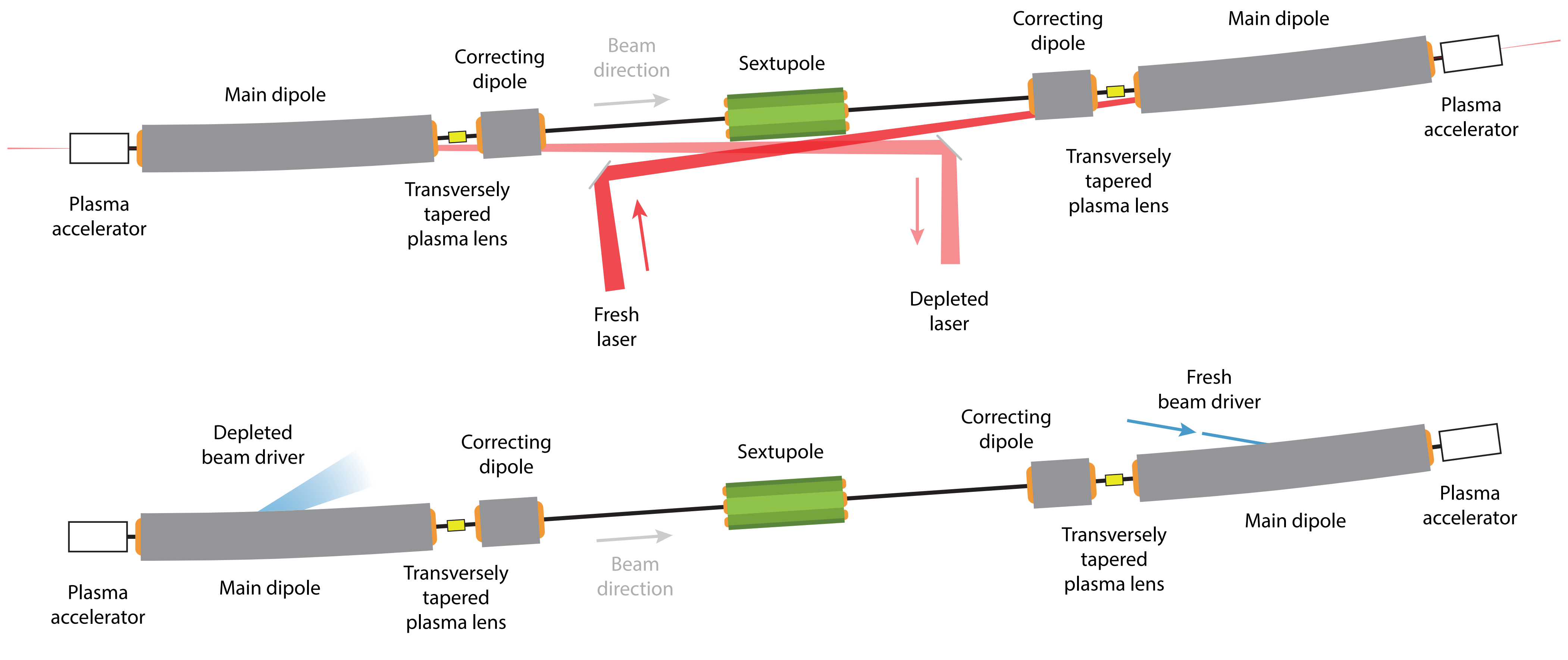
The FLASHForward Beam Team



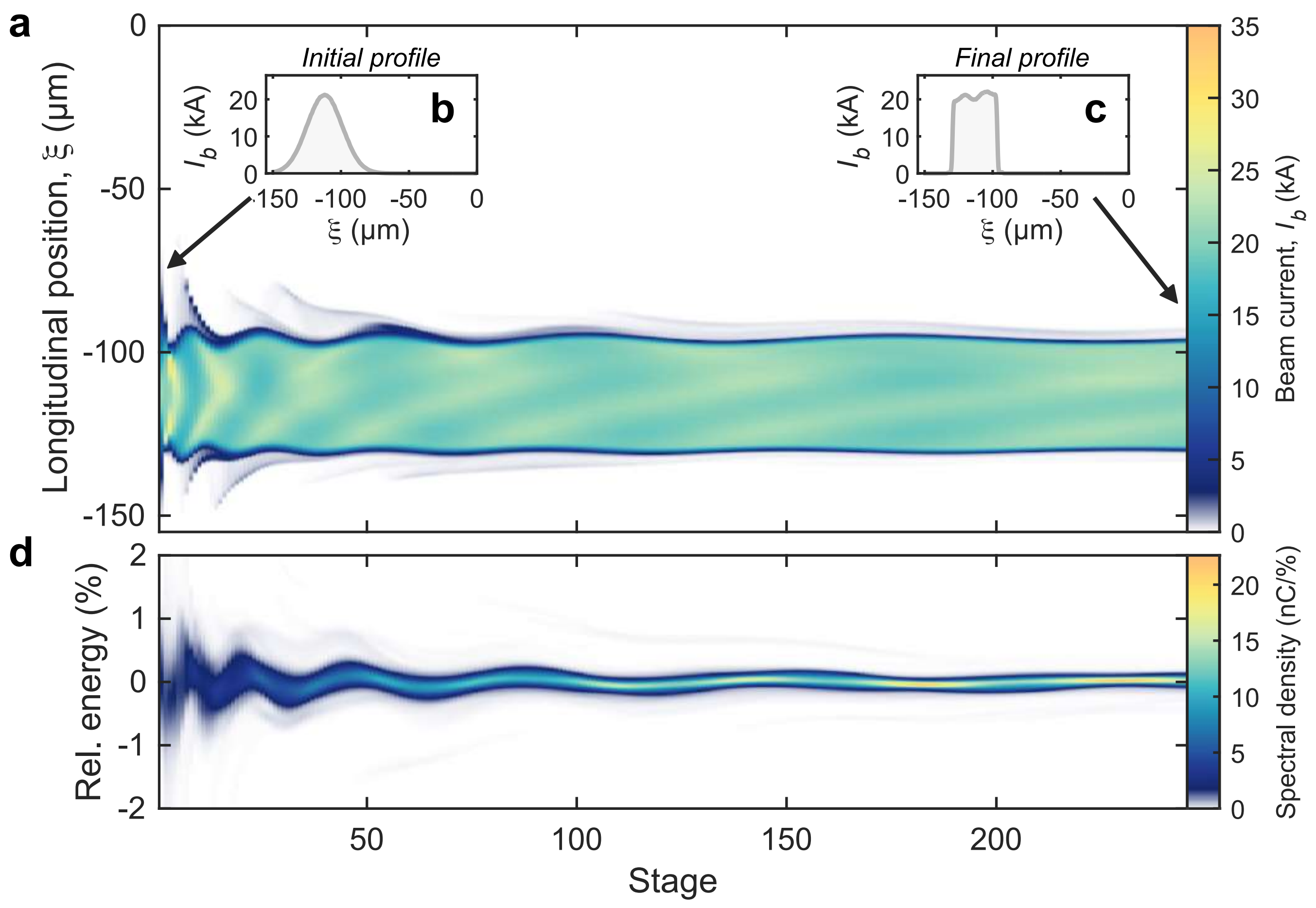


Last shift of 2021 (smiling, but exhausted)

Looking to the future: **Staging and self-correction**



See talk at Thursday 11:40



Source: Lindstrøm, arXiv:2104.14460 (2021)

> **Nonlinear (transversely tapered) plasma lenses** can provide **achromatic transport** between stages, if combined with dipoles and sextupoles.

> > Enables **emittance preservation between stages** (+ driver in- and out-coupling).

> Multiple stages separated by **bunch compressors** (e.g., achromatic lattice) leads to a **self-correction in the longitudinal phase space** (i.e., current profile self-optimises).

> Goal: a **multistage facility** to provide stable, high-energy beams (for nonlinear QED?)

Wim Leemans

The importance of **long-term vision**

Conclusions

> Some **exciting results**:
  > Acceleration of **positrons** in hollow plasma channels suffers from a strong **transverse instability**.
  > Active **plasma lenses** (filled with argon) can be made **aberration-free**, preserving emittance.
  > Simultaneous **preservation of emittance**, energy spread, and charge, at high efficiency and gradient.
  > **Staging** with emittance preservation and longitudinal self-correction may be possible (with **nonlinear plasma lenses**).

> Take-aways:
  > Beam work is **teamwork**.
  > I worked with a lot of **great people** along the way.
  > Good **mentorship** and **supervision** is important.