PRC Meeting
Hamburg | March 21st, 2017

Plasma Wakefield Acceleration

in the DESY Particle Physics Division (and beyond…)

Jens Osterhoff

FLASHForward | Research Group for Plasma Wakefield Accelerators
Deutsches Elektronen-Synchrotron DESY, Particle Physics Division, Hamburg, Germany

Accelerator Research and Development, Matter and Technology
Helmholtz Association of German Research Centres, Berlin, Germany

Team members and collaboration partners

Core team

Engineers and technicians

Maik Dinter
Kai Ludwig
Sven Karstensen
Frank Marutzky
Amir Rahali
Andrej Schleiermacher

Postdocs

Richard D'Arcy
John Dale
Alexander Knetsch
Laura di Lucchio
Vladyslav Libov
Alberto Martinez de la Ossa
Timon Mehrling
Pardis Niknejadi
Kristjan Põder
Lucas Schaper
Stephan Wesch

Staff scientists

Jens Osterhoff
Bernhard Schmidt

PhD students

Alexander Aschikhin
Simon Bohlen
Jan-Hendrik Röckemann
Lars Goldberg
Olena Kononenko
Sarah Schröder
Jan-Patrick Schwinkendorf
Bridget Sheeran
Gabriele Tauscher
Paul Winkler

Students

Paul Pourmoussavi
Martin Quast
Jelto Thesinga

DESY technical groups

Collaborating institutes and labs

HELMHOLTZ ASSOCIATION
VIRTUAL INSTITUTE
VH-VI-503

Universität Hamburg, Germany
John Adams Institute, UK
Lawrence Berkeley National Laboratory, US
Stanford Linear Accelerator Center, US
James Cook University, Australia
Max Planck Institute for Physics, Bavaria
CERN, Switzerland
Laboratori Nazionali di Frascati, Italy
University of California Los Angeles, US
Instituto Superior Técnico Lisboa, Portugal

Bundesministerium für Bildung und Forschung
Verbundforschung

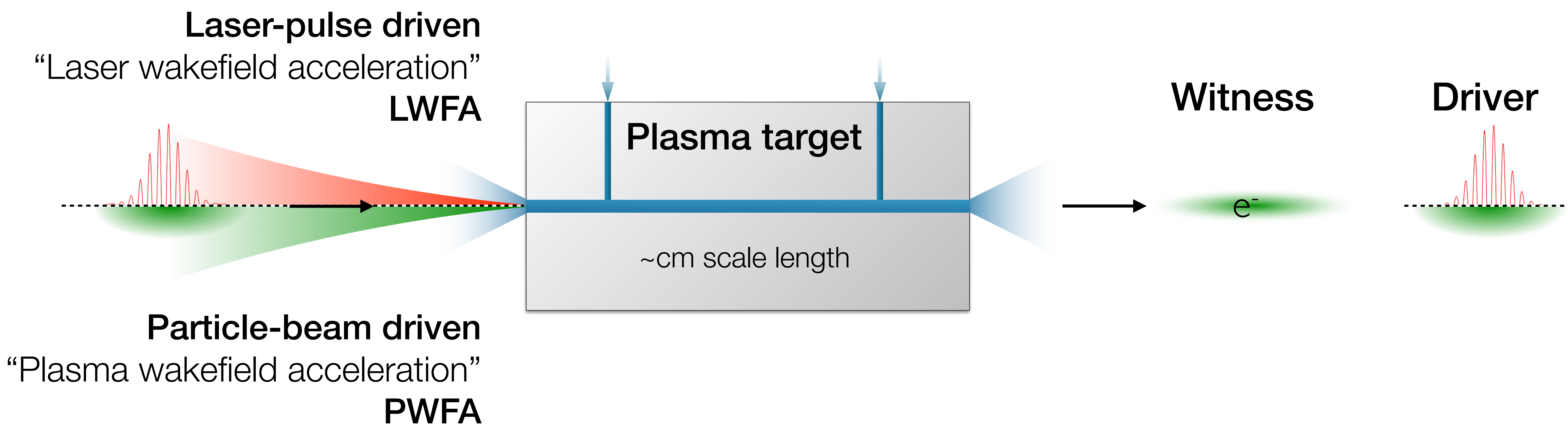
Friedrich-Schiller-Universität Jena, Germany
Heinrich-Heine-Universität Düsseldorf, Germany

FLASH FEL facility

315 m long with ~100 m 1.2 GeV SRF accelerator

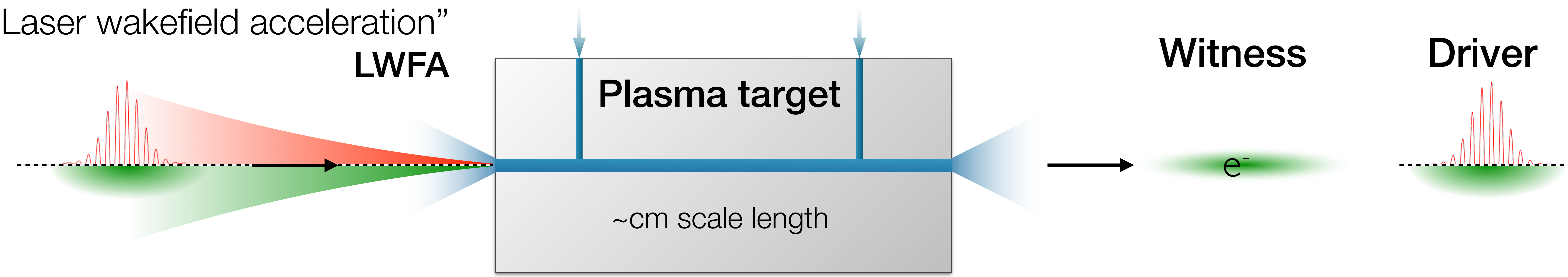

FLASHFORWARD▸▸
Plasma wakefield accelerator
0.03 m
delivers ~1 GeV, a similar energy as FLASH
→ Leemans et al., Nature Physics 2, 696 (2006)
DESY

Plasma wakefield acceleration in a nutshell



Plasma wakefield acceleration in a nutshell

Laser-pulse driven
"Laser wakefield acceleration"
LWFA

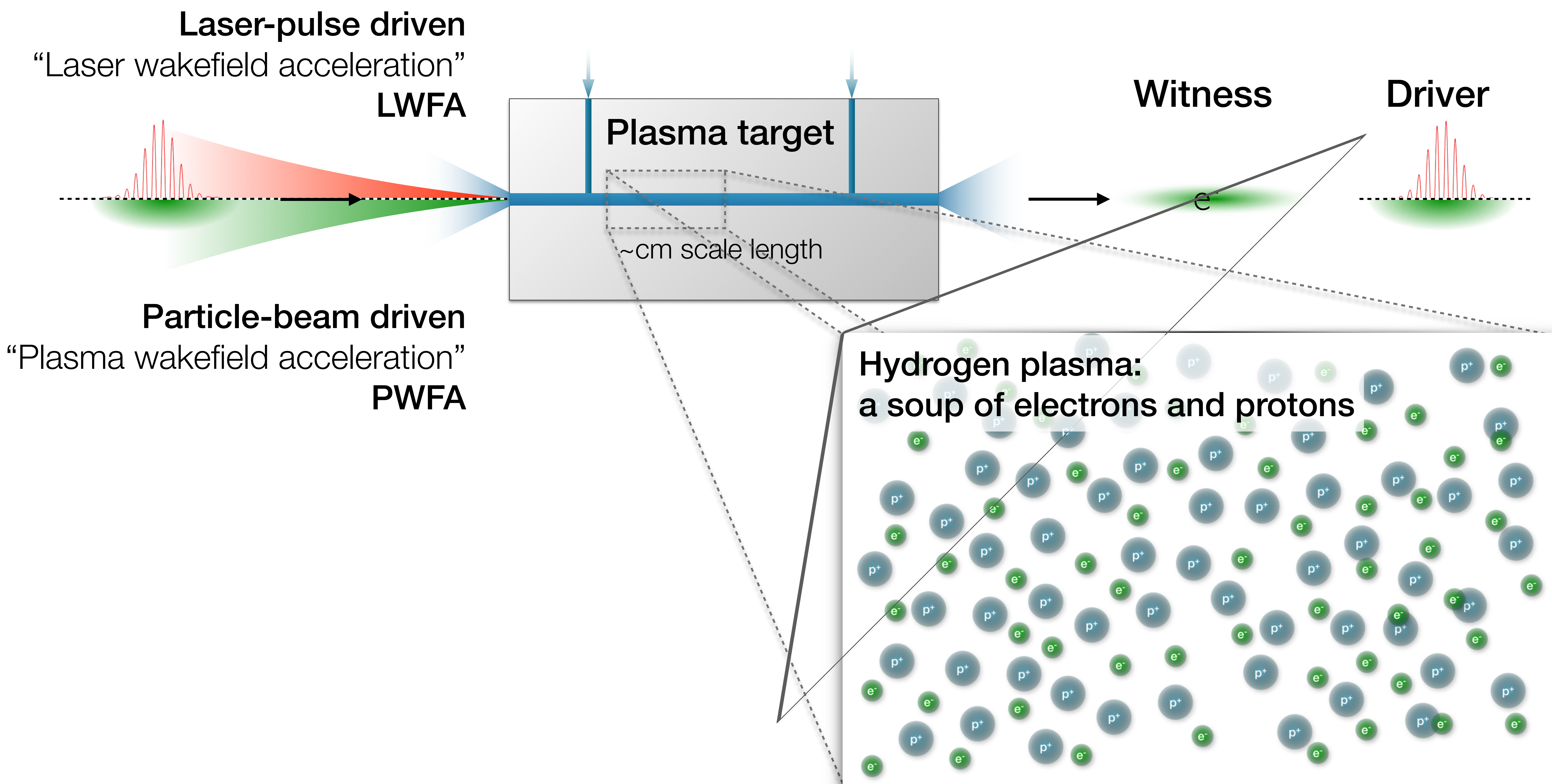


Particle-beam driven
"Plasma wakefield acceleration"
PWFA (vs. LWFA)

- average power of up to MW (vs. ~100 W)
- wall-plug efficiency of ~10% (vs. < 0.1%)

→ beam-driven wakes (currently) the only viable solution for high-average-power applications

Plasma wakefield acceleration in a nutshell



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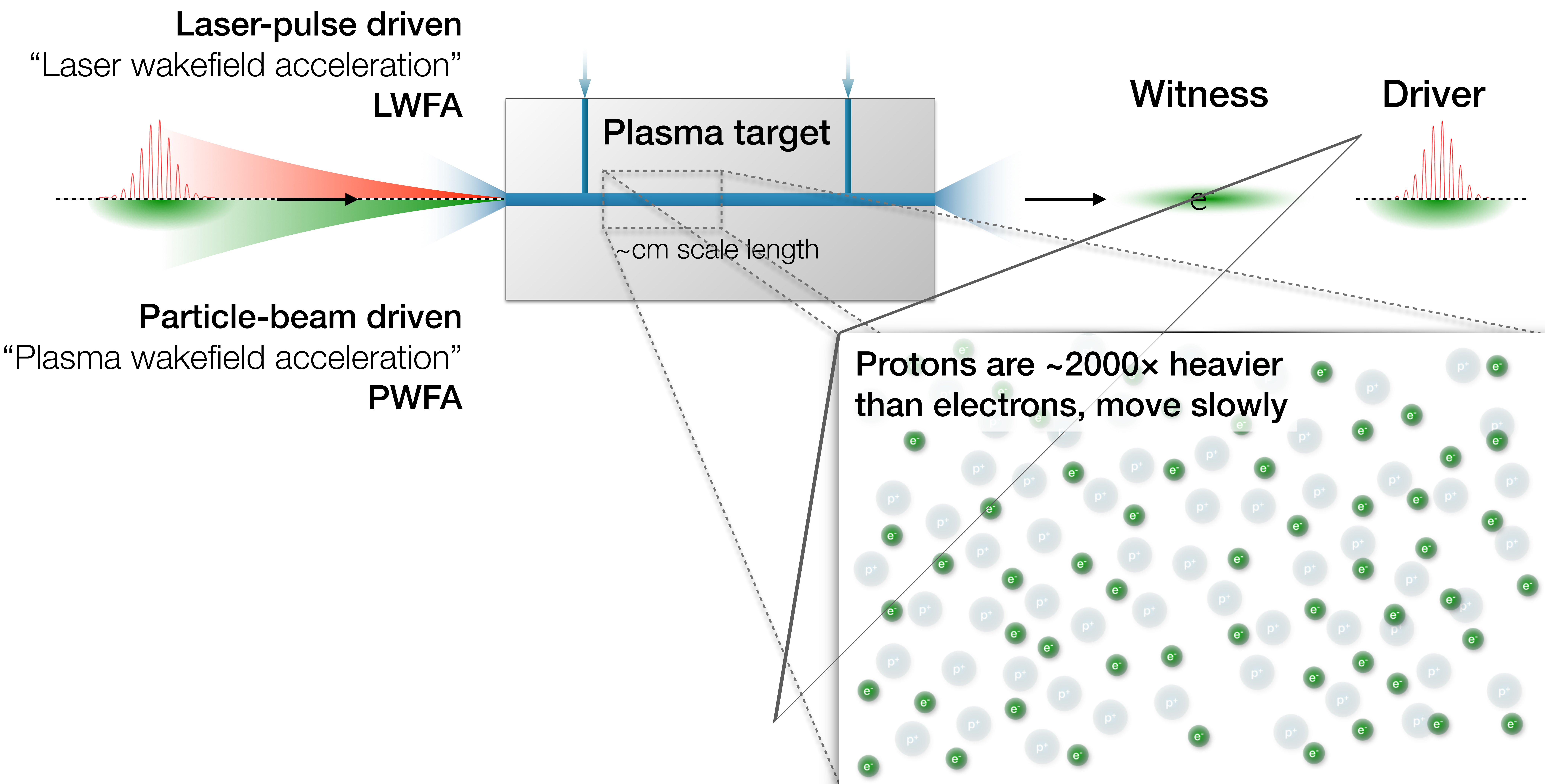

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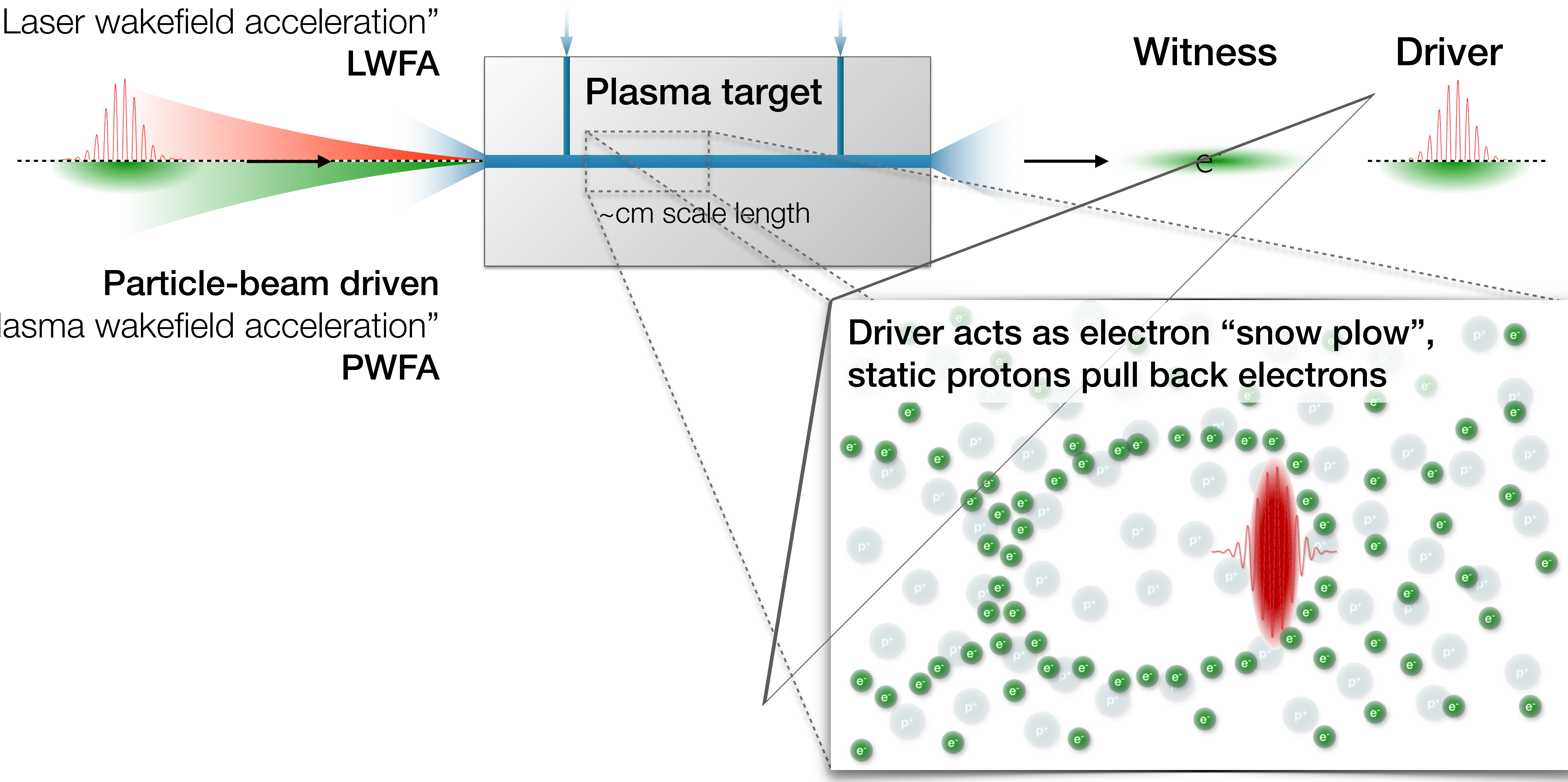

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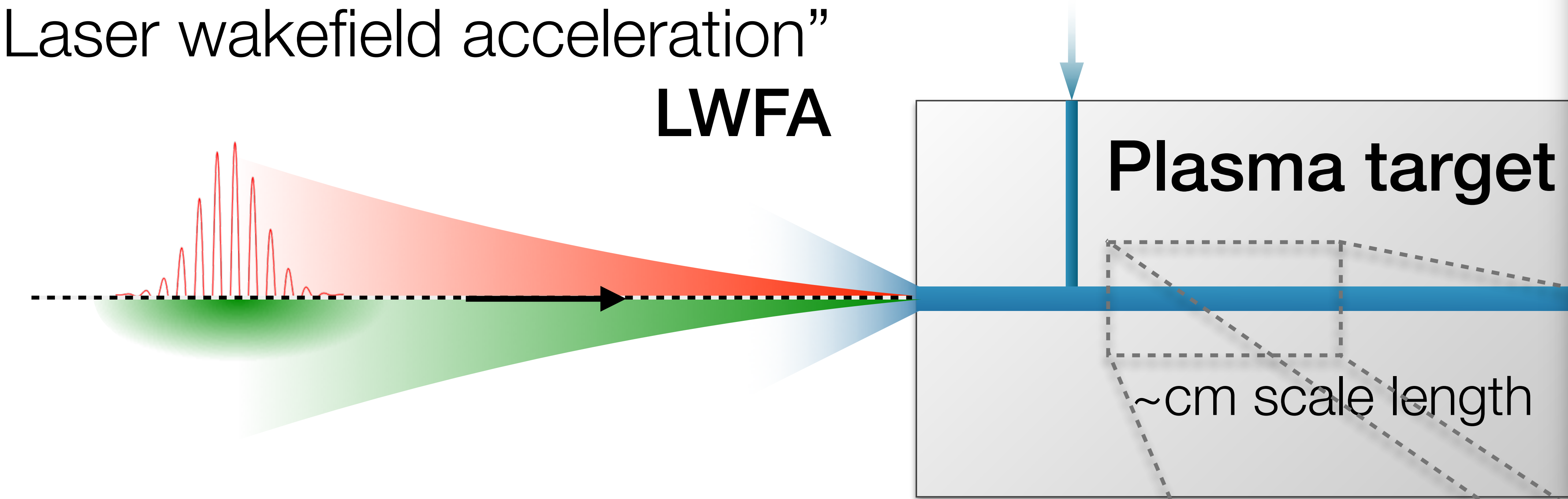

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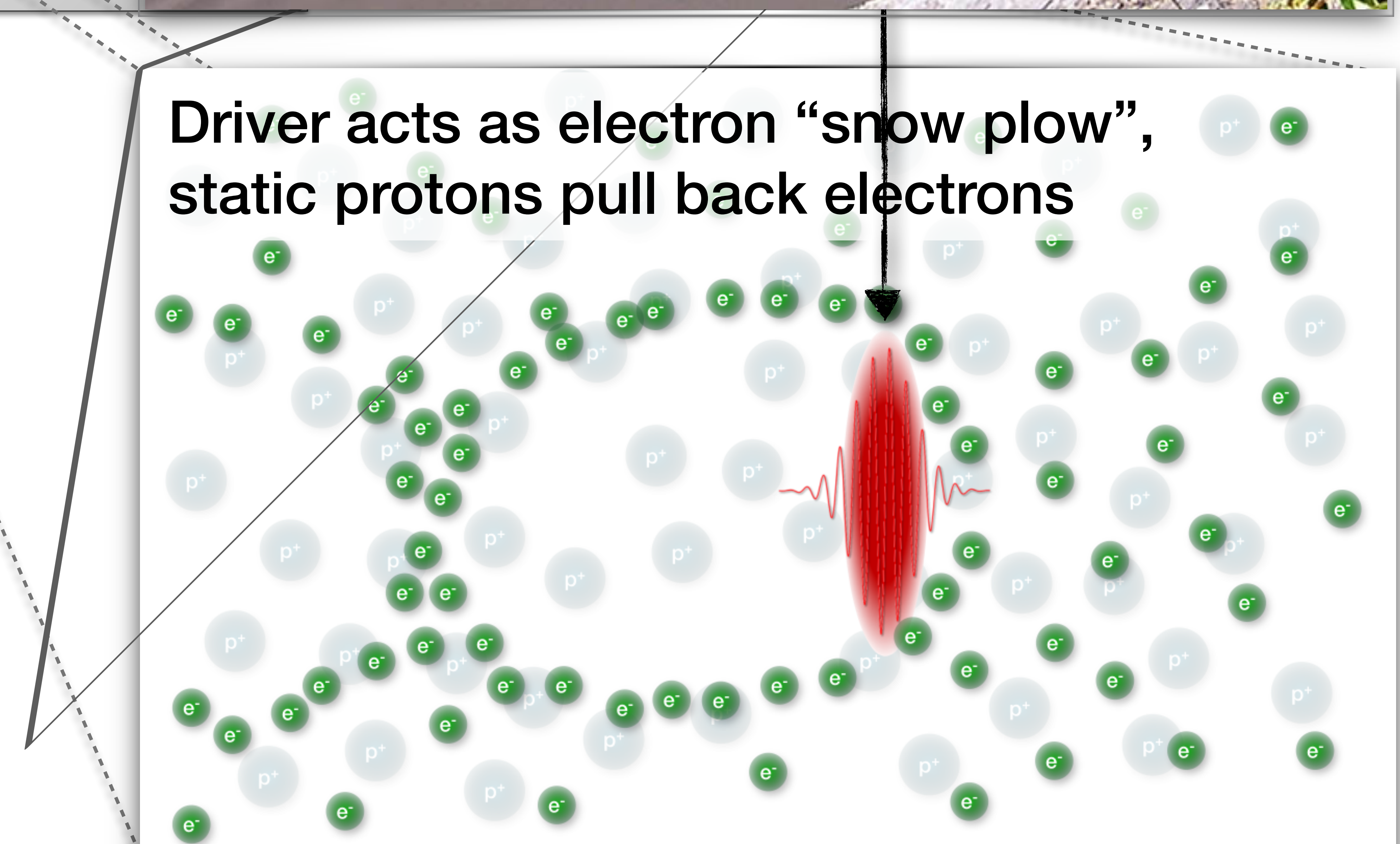

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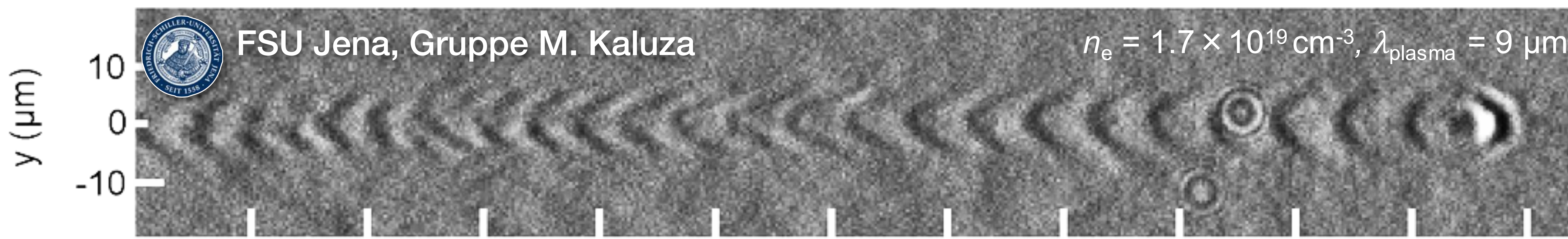

M. Schnell *et al.*, Nat. Comm. 4, 2421 (2013)

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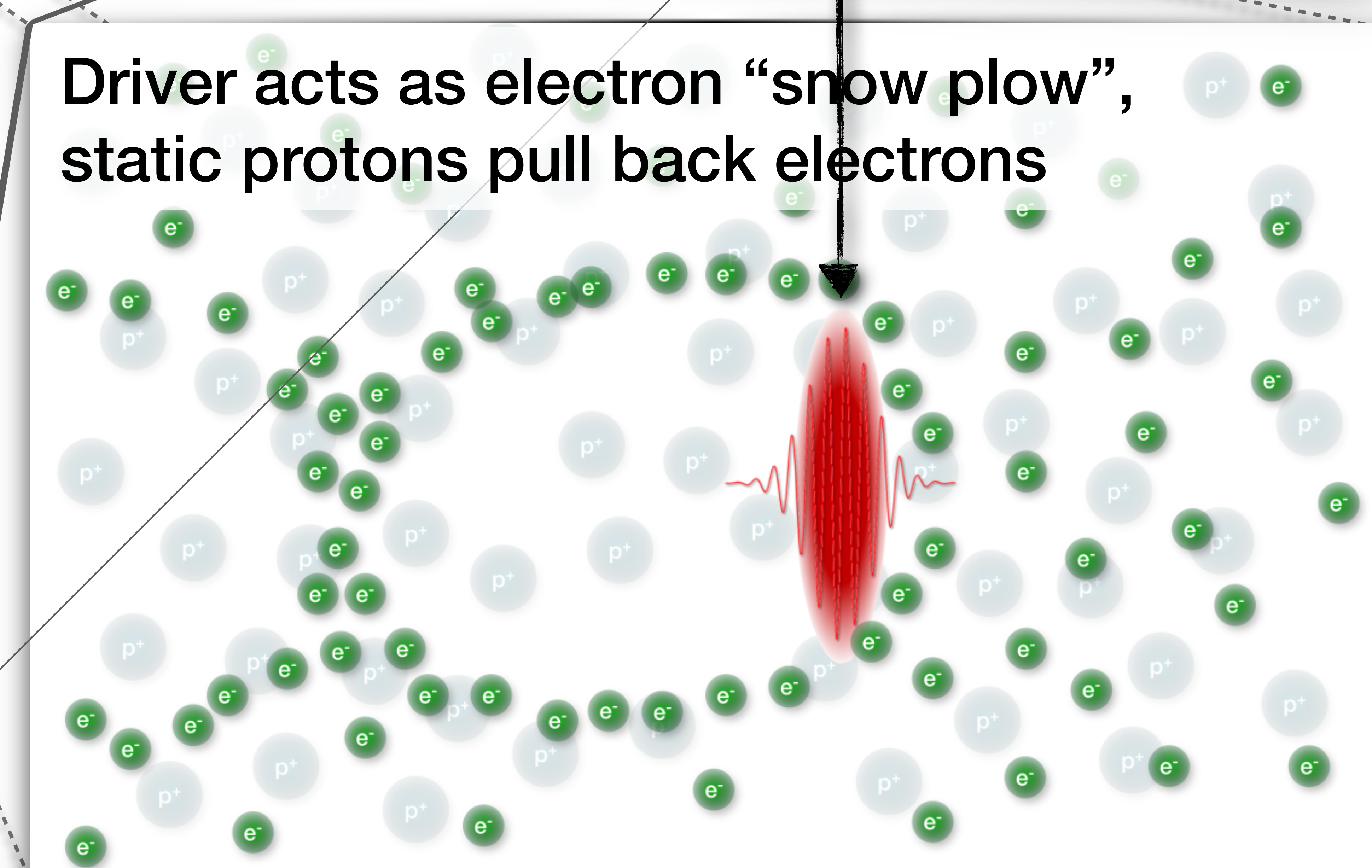

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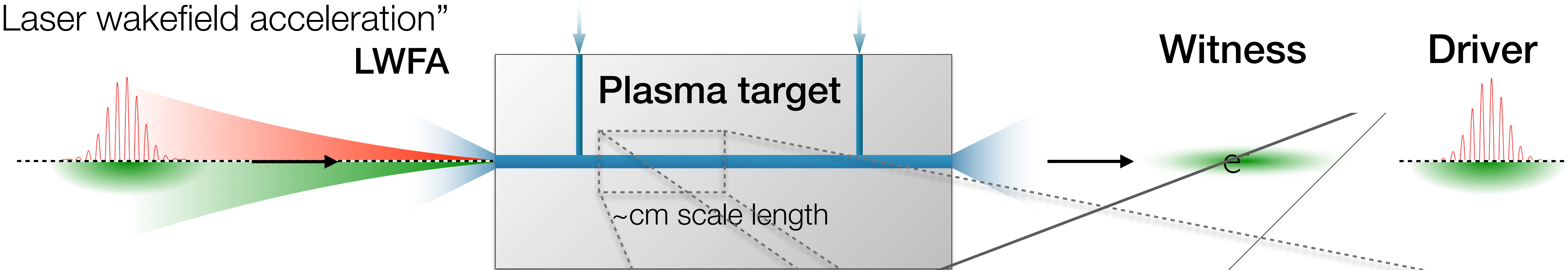

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"Plasma wakefield acceleration"
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Bunch duration: fs

→ O. Lundh *et al.*, Nature Physics 7, 219 (2011)
→ A. Buck *et al.*, Nature Physics 7, 543 (2011)

GeV energy gain over cm

→ W.P. Leemans *et al.*, Nature Physics 2, 696 (2006)

Size of structure

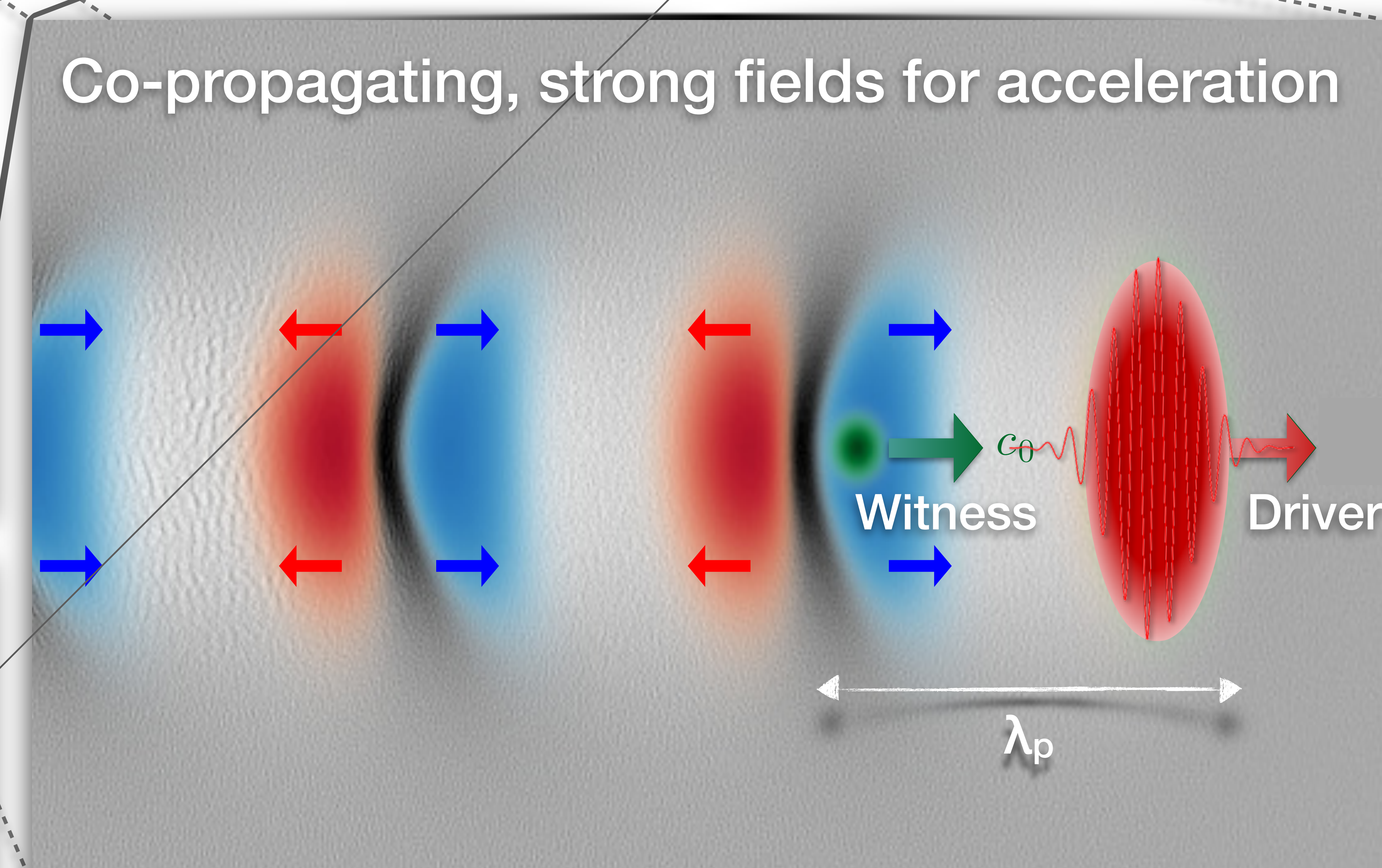
$$\lambda_p \approx \frac{2\pi c}{\omega_p} \approx (33\ \text{km})\sqrt{n_e^{-1}[\text{cm}^{-3}]}$$

typically $\boldsymbol{\lambda_p \approx 33\ \mu m}$ (for $n_e \approx 10^{18}$ cm^{-3})

Electric field strength

$$E \approx \frac{mc\omega_p}{e} \approx (96\ \text{V/m})\sqrt{n_e[\text{cm}^{-3}]}$$

typically $\boldsymbol{E \approx 100}$ **GV/m** (for $n_e \approx 10^{18}$ cm^{-3})



Plasma wakefield acceleration in a nutshell

Interesting for applications

~GeV energy   < µm emittance
~fs duration   ~kA current

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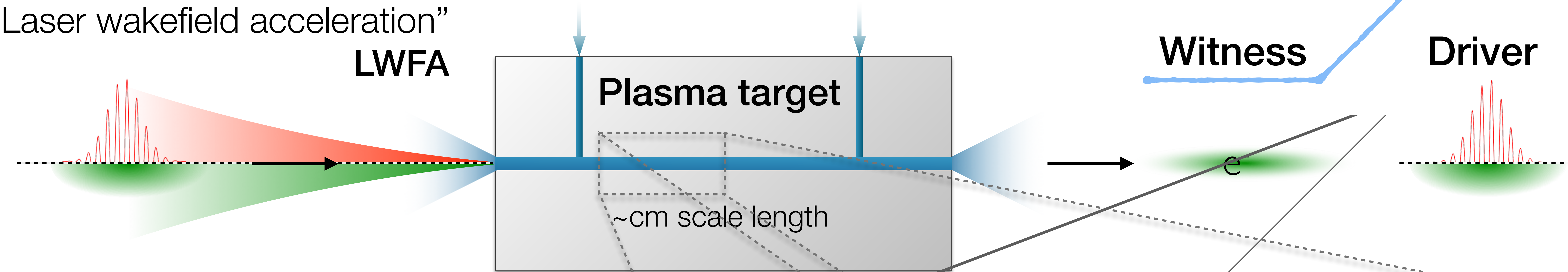

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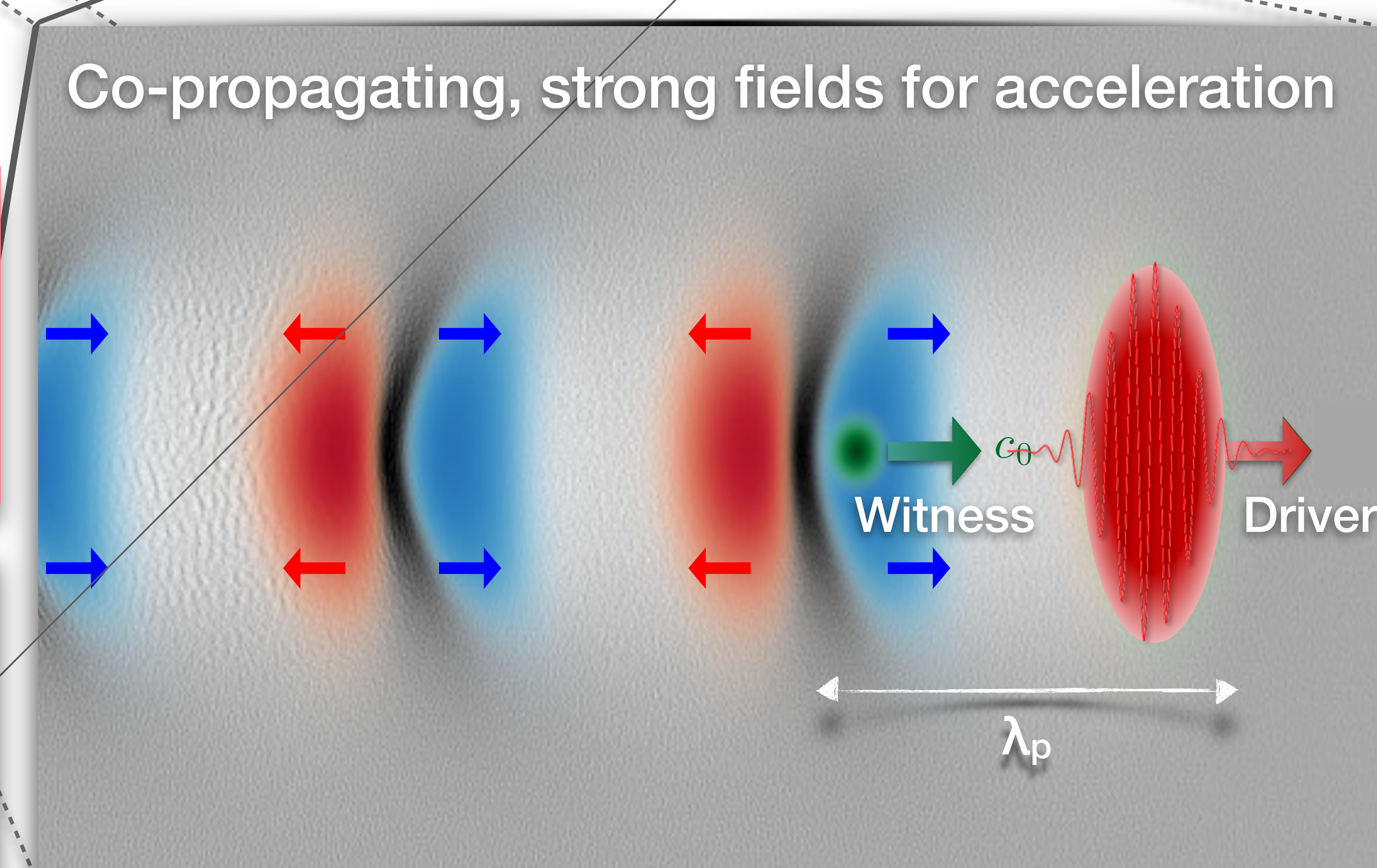
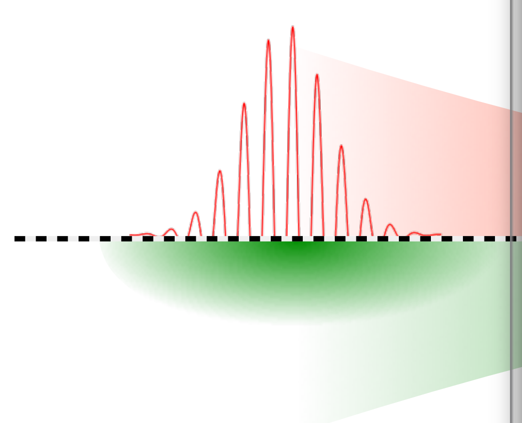


Plasma w

Lase
“Laser wakefiel



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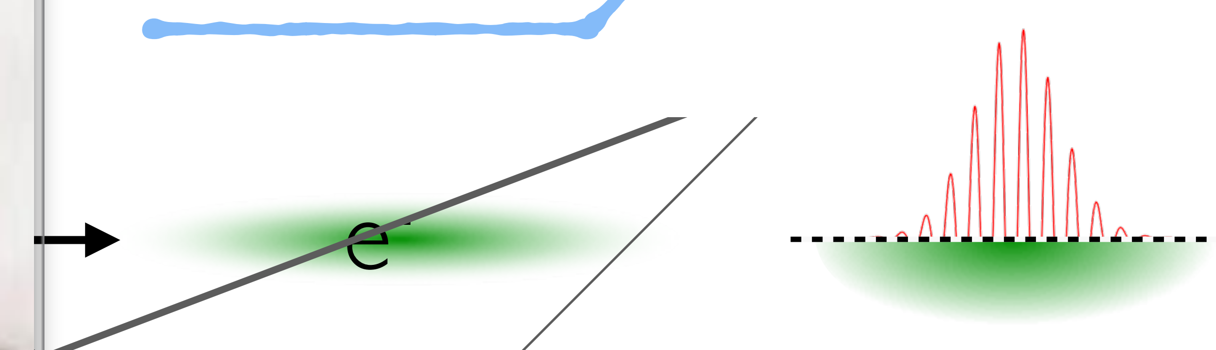

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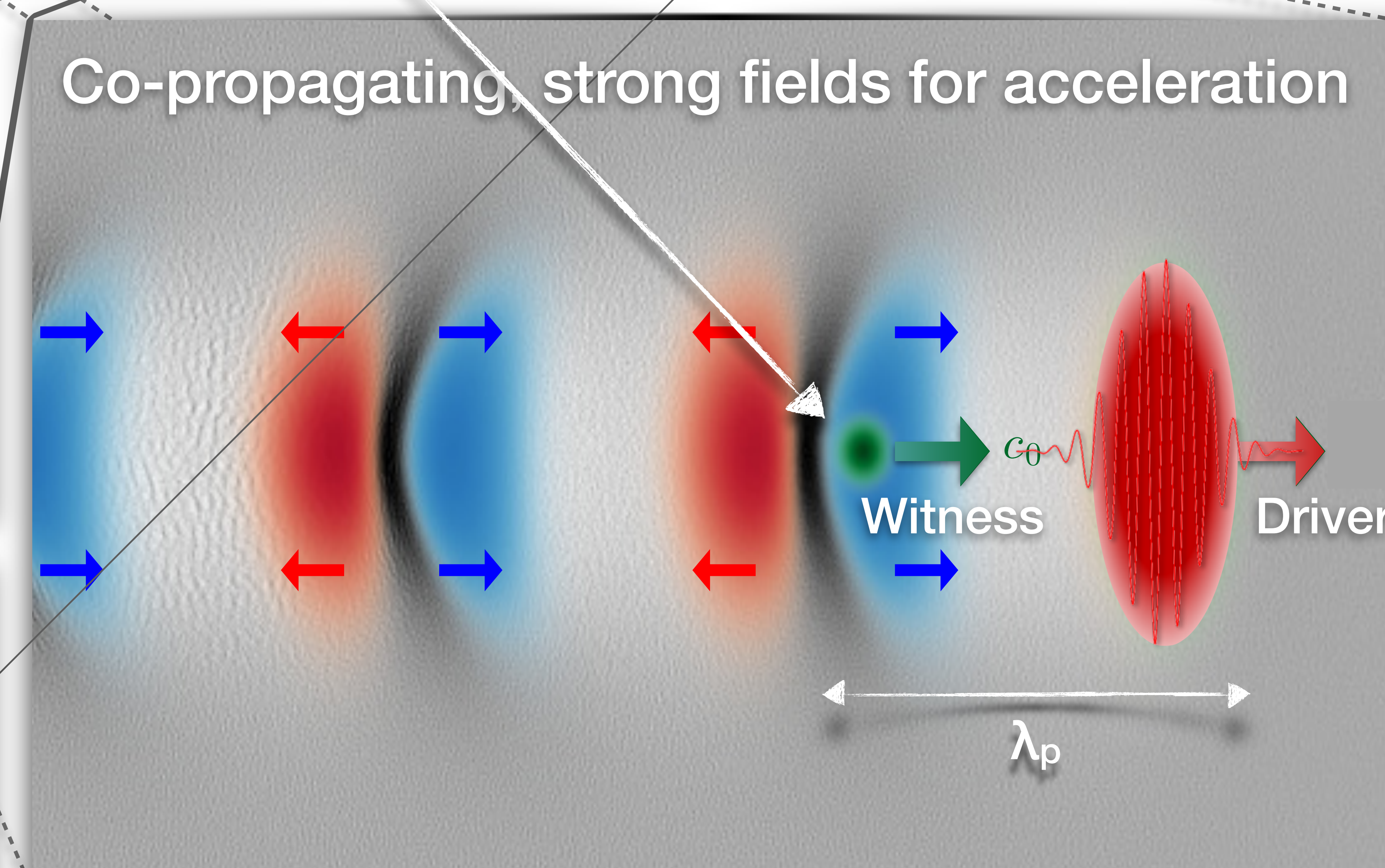
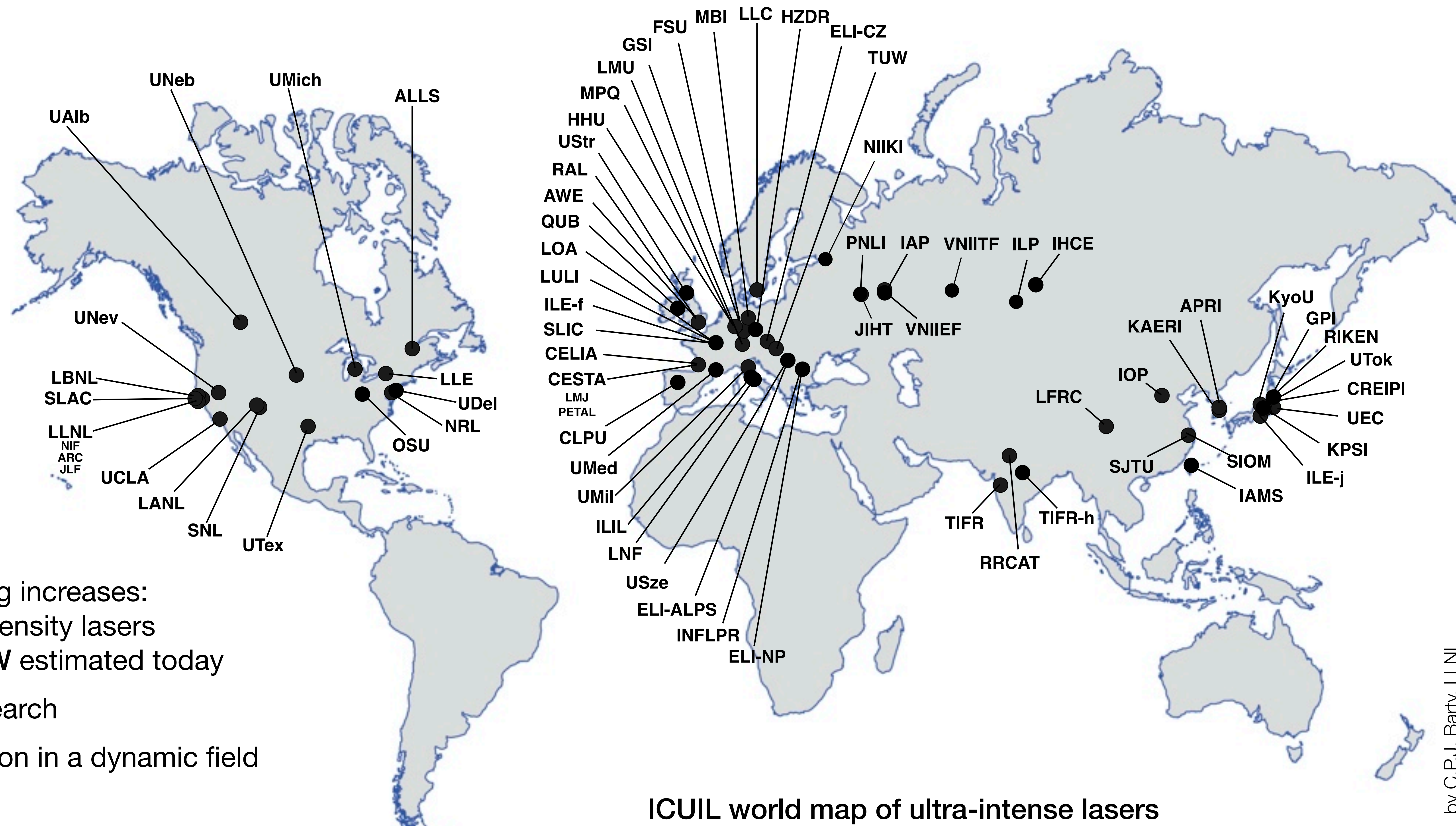


Activities in plasma wakefield acceleration quickly growing

Disclaimer: no guarantee for completeness



ICUIL world map of ultra-intense lasers

- Worldwide activity and funding increases: total peak intensity of high-intensity lasers in 2010 **~11.5 PW → ~127 PW** estimated today
- Most sites support LWFA research
- Strong international competition in a dynamic field

by C.P.J. Barty, LLNL

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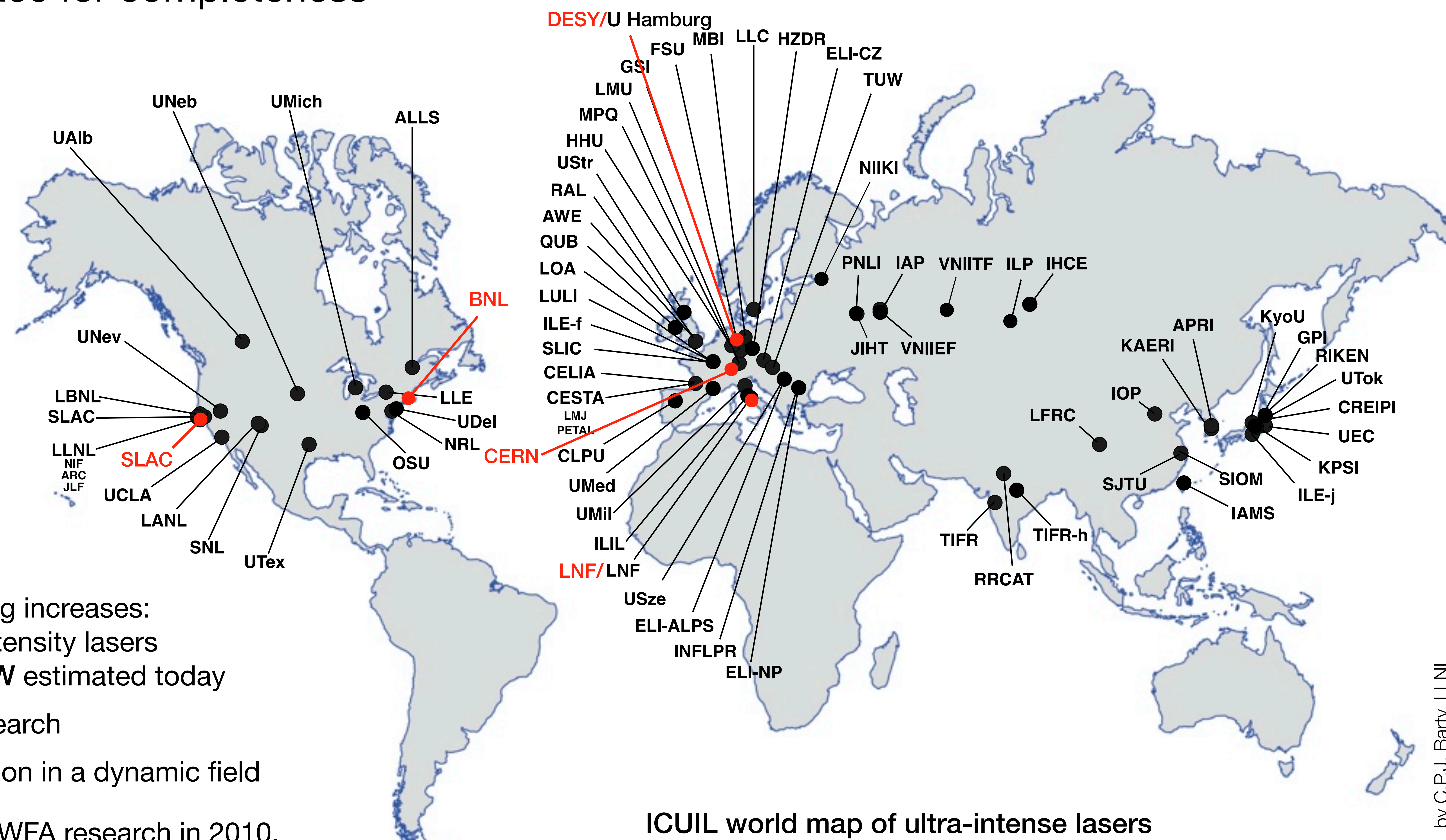

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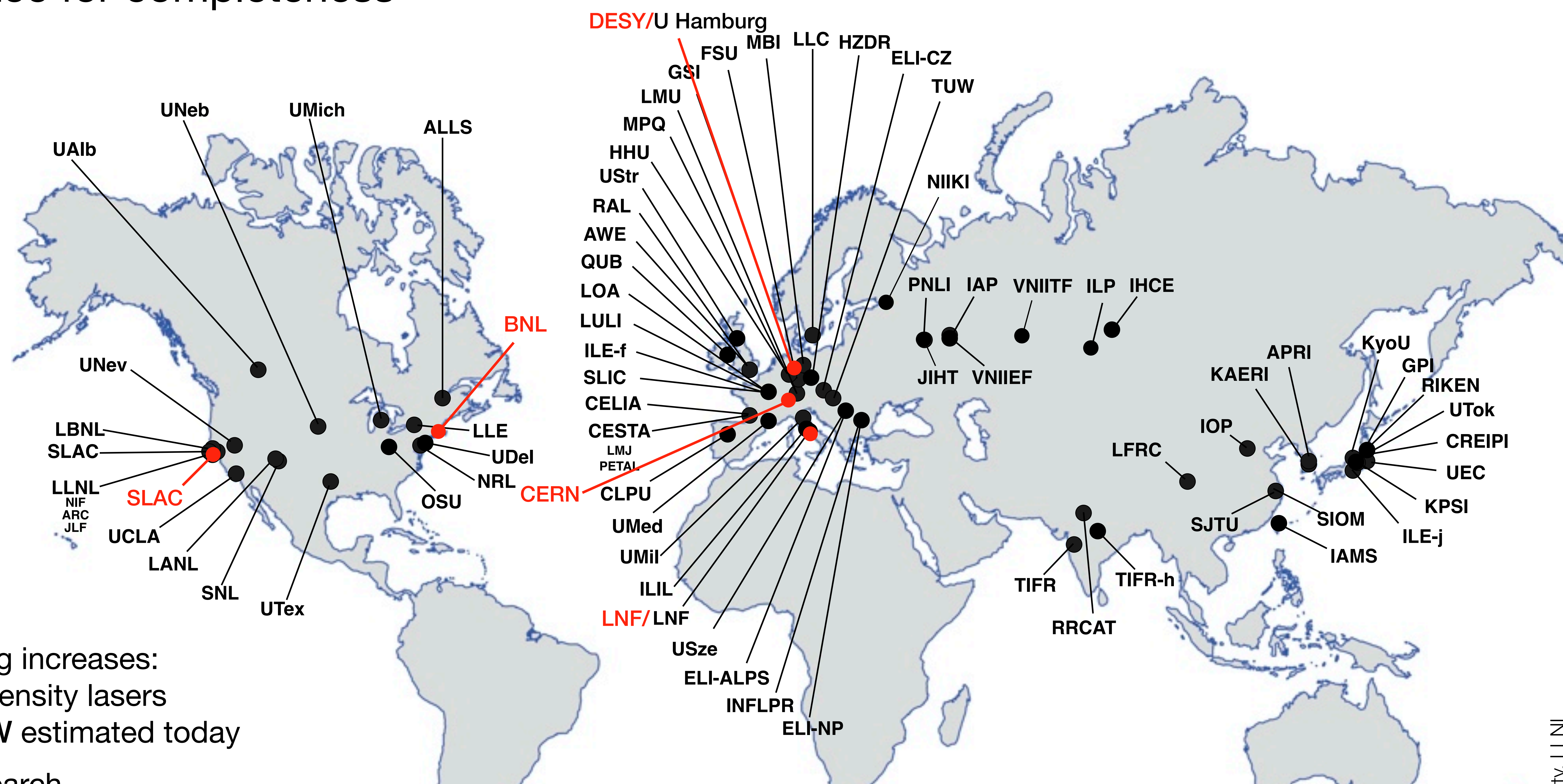

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Overarching goal:

Plasma accelerator research → usable plasma accelerators

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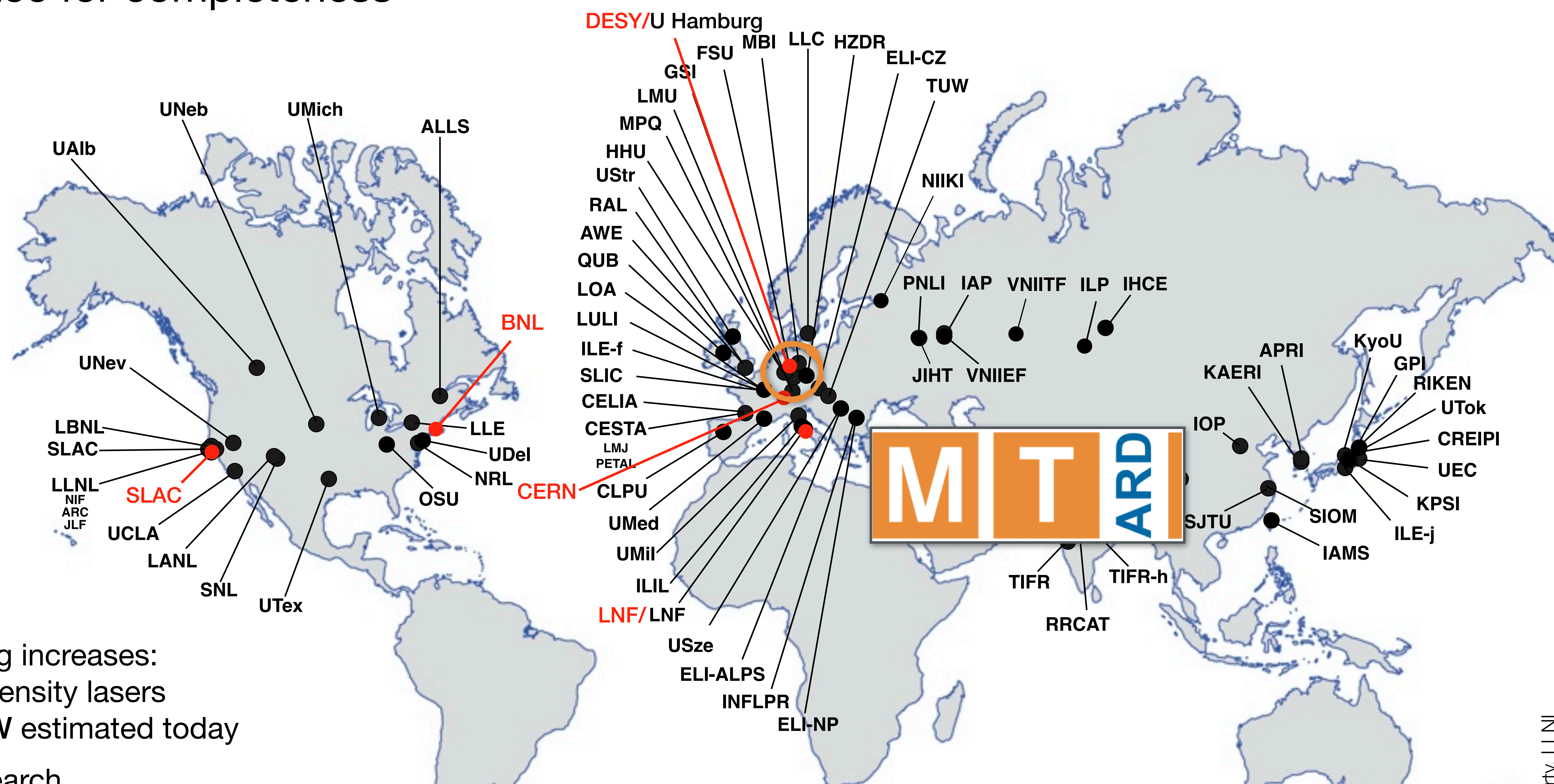

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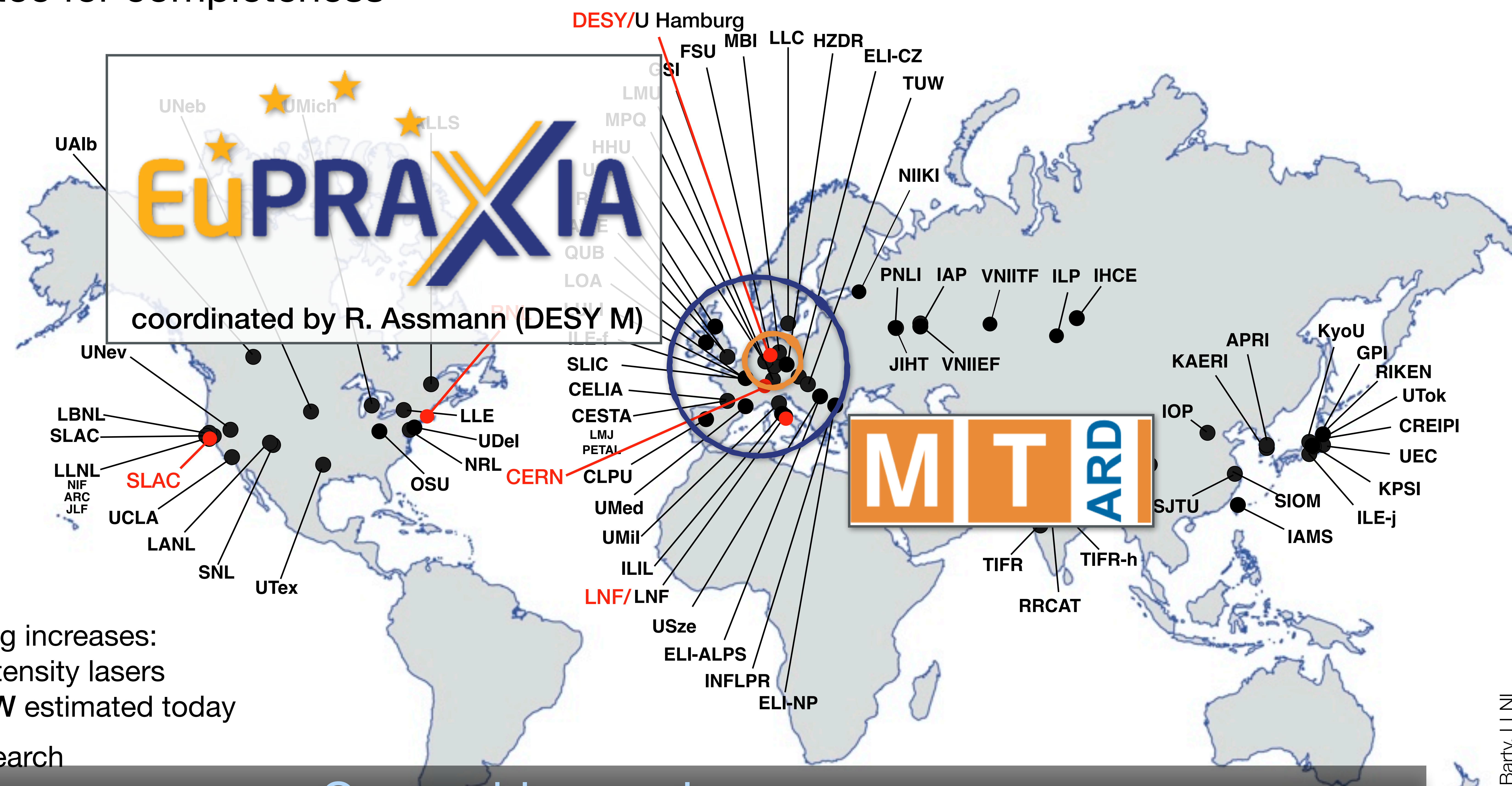

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DESY is building a unique environment for novel accelerator research & development

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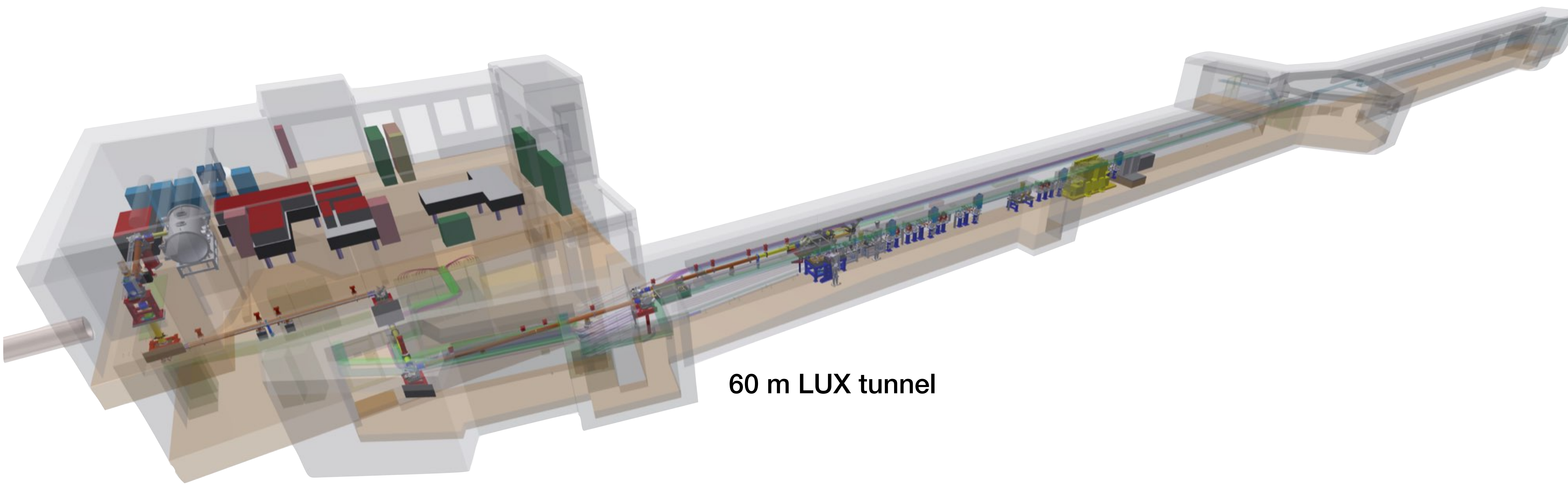
LUX - Laser-driven plasma accelerator research in Hamburg

Project coordinator:
Andreas R. Maier (UHH, CFEL)
→ http://lux.cfel.de/



LUX - Laser-driven plasma

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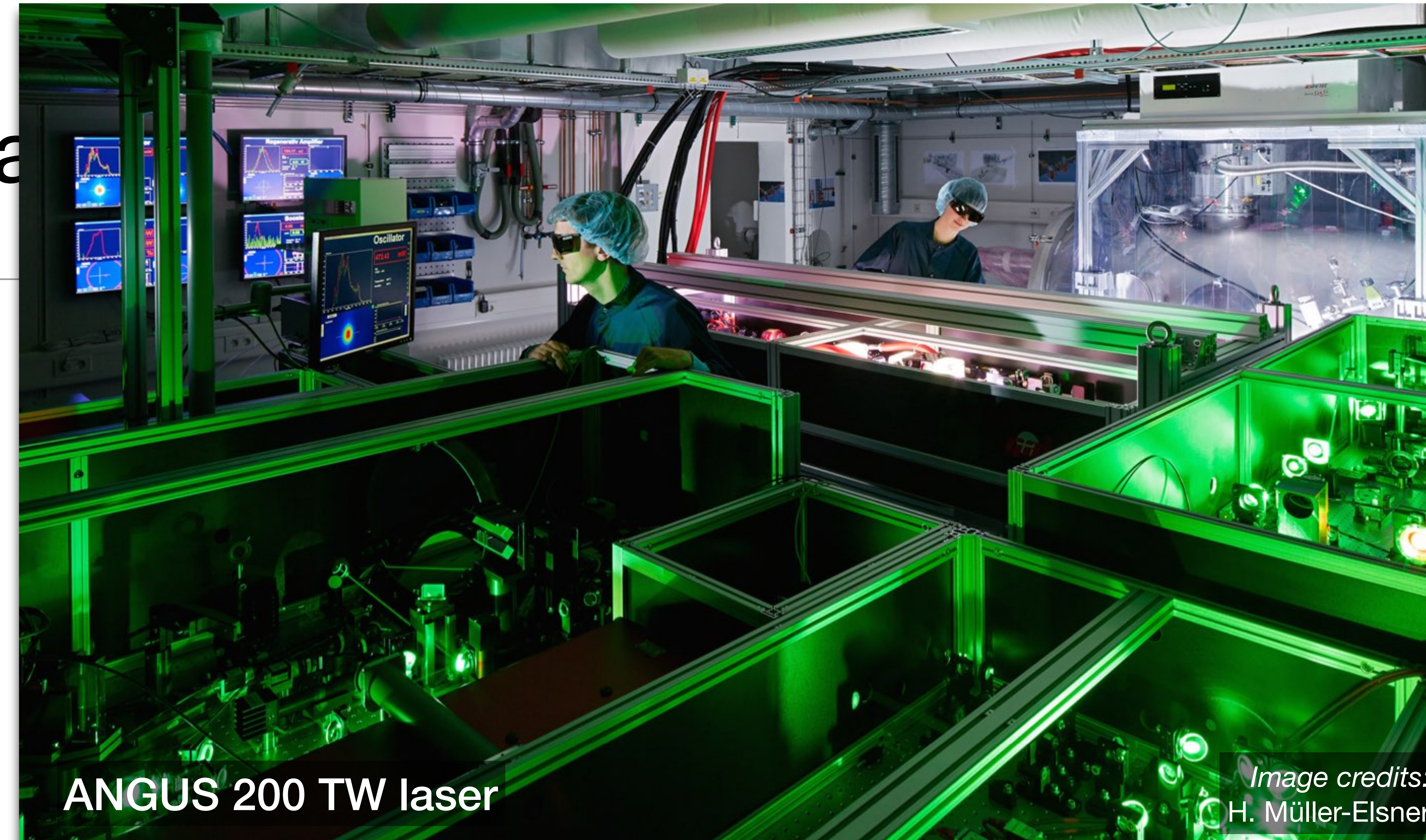

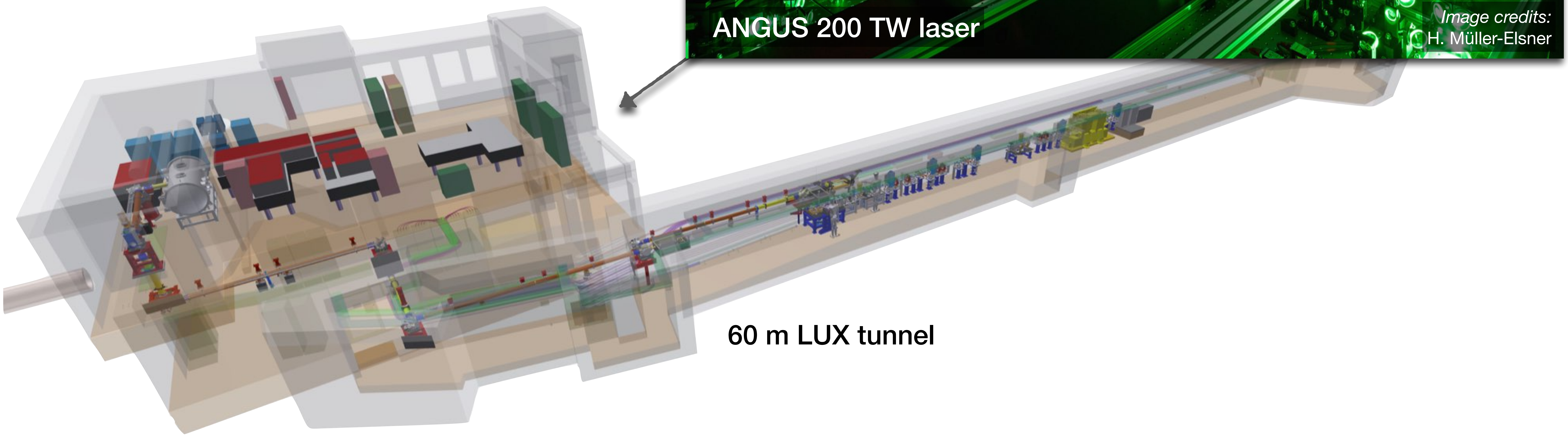

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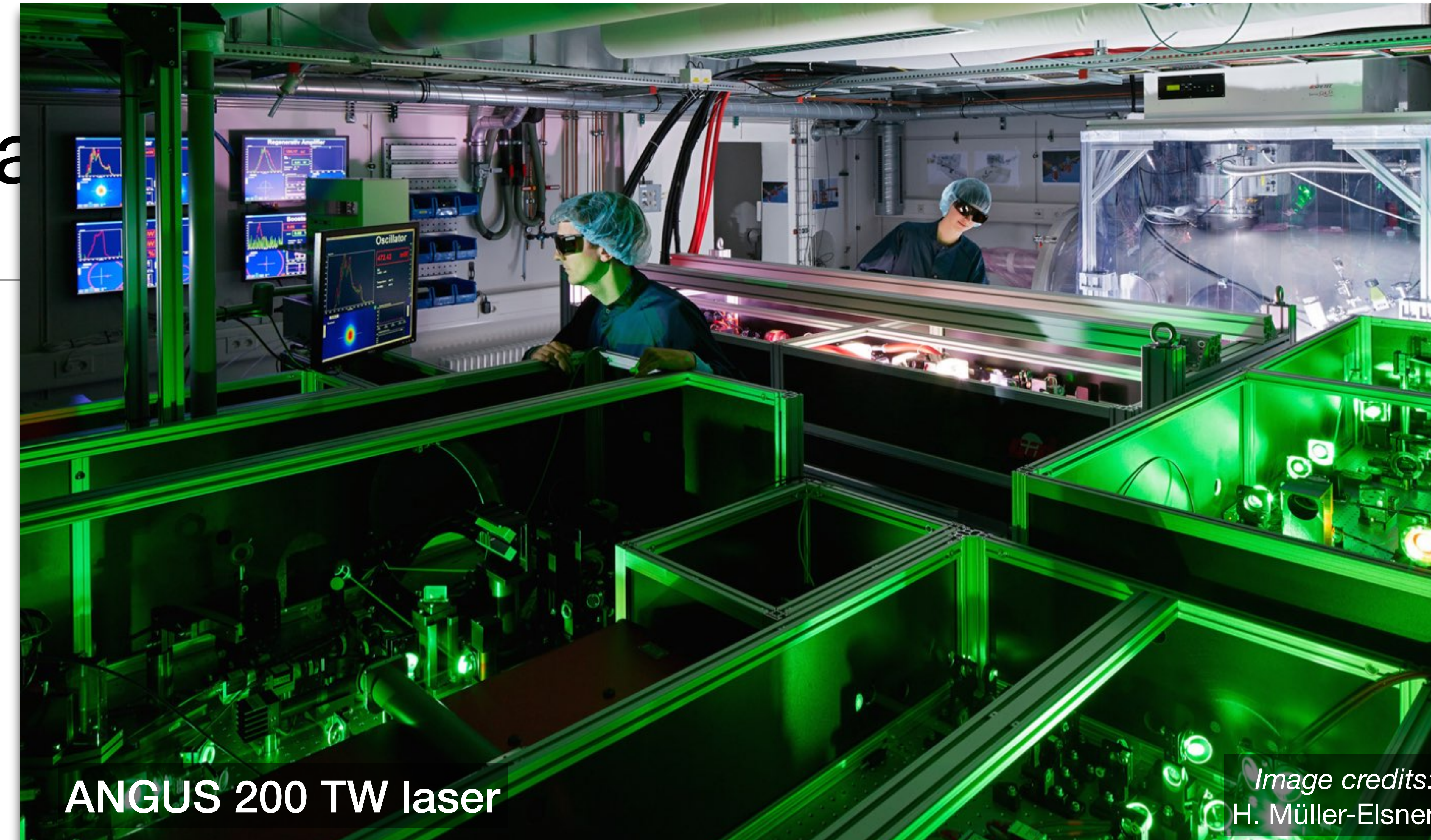
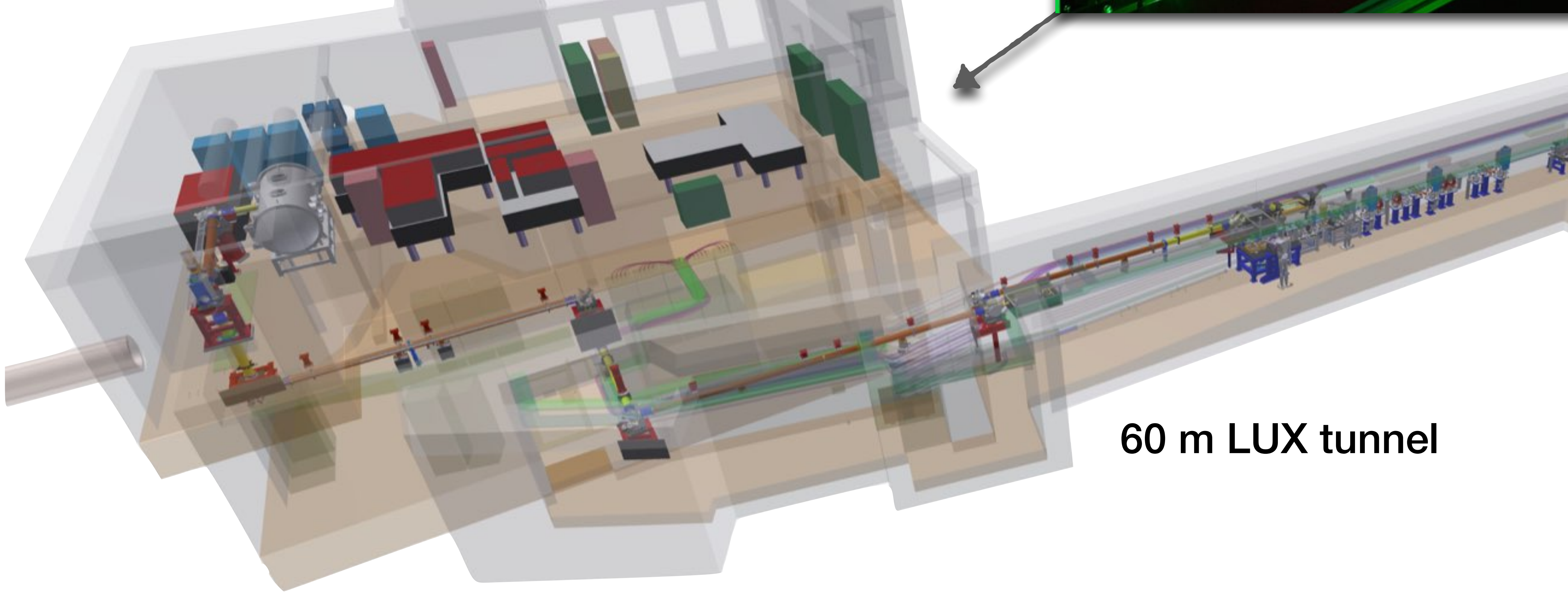
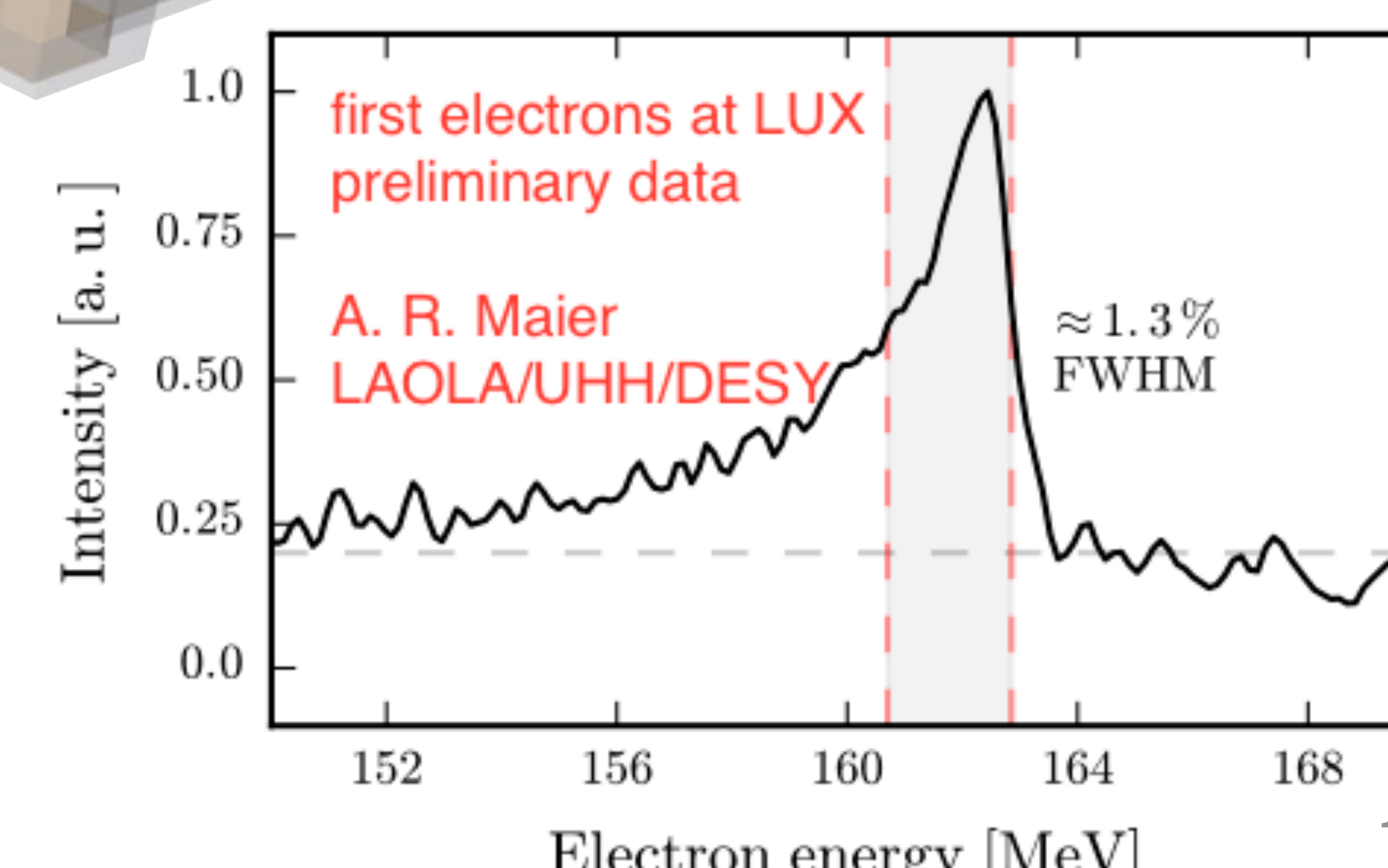




60 m LUX tunnel



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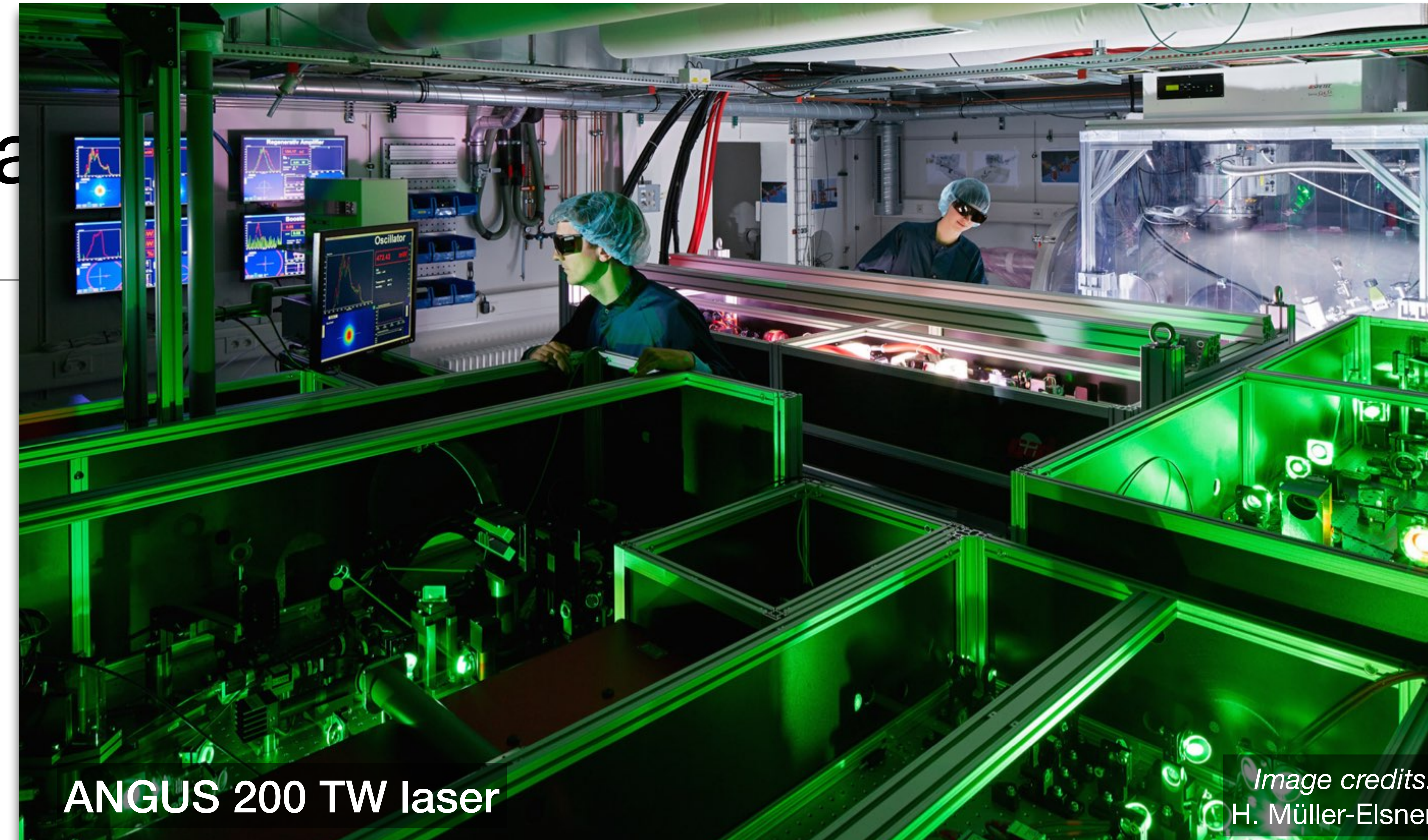
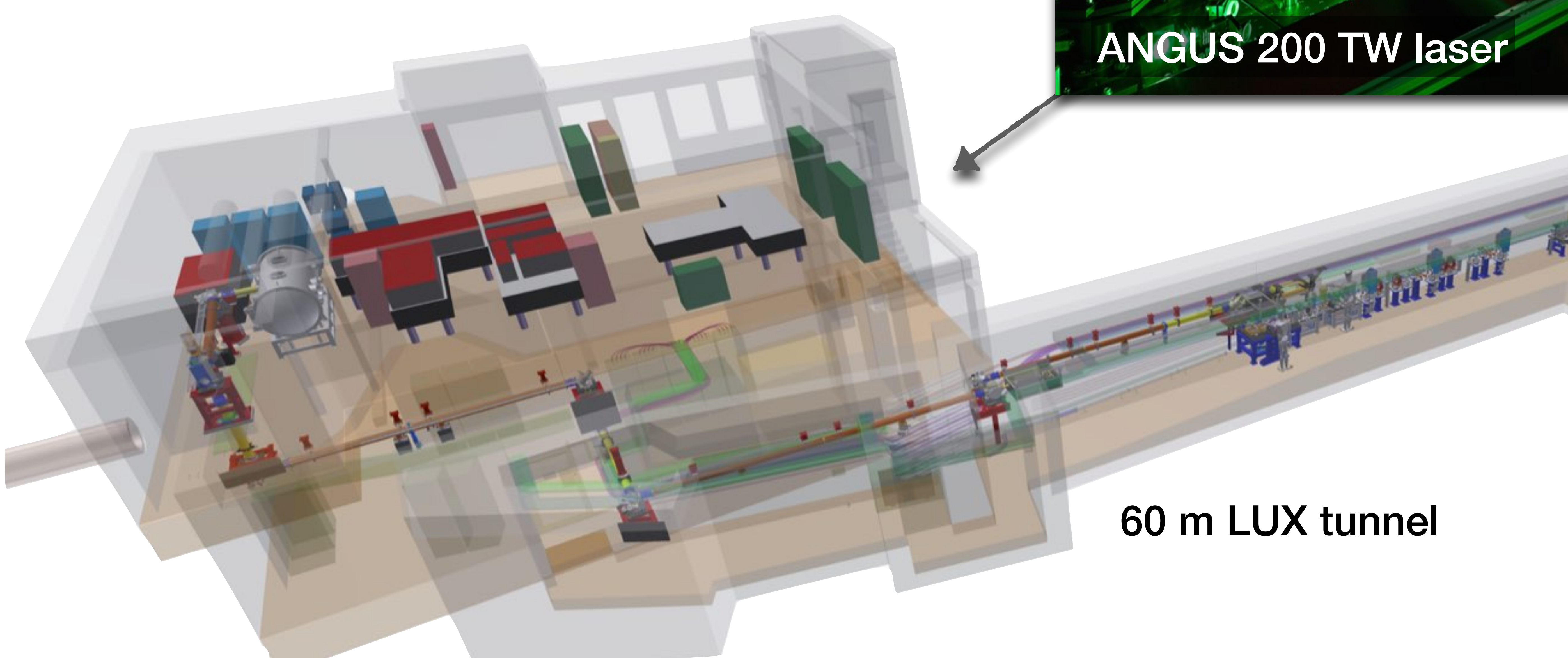
- **First electron acceleration experiments up to 400 MeV at 5 Hz in summer 2016**





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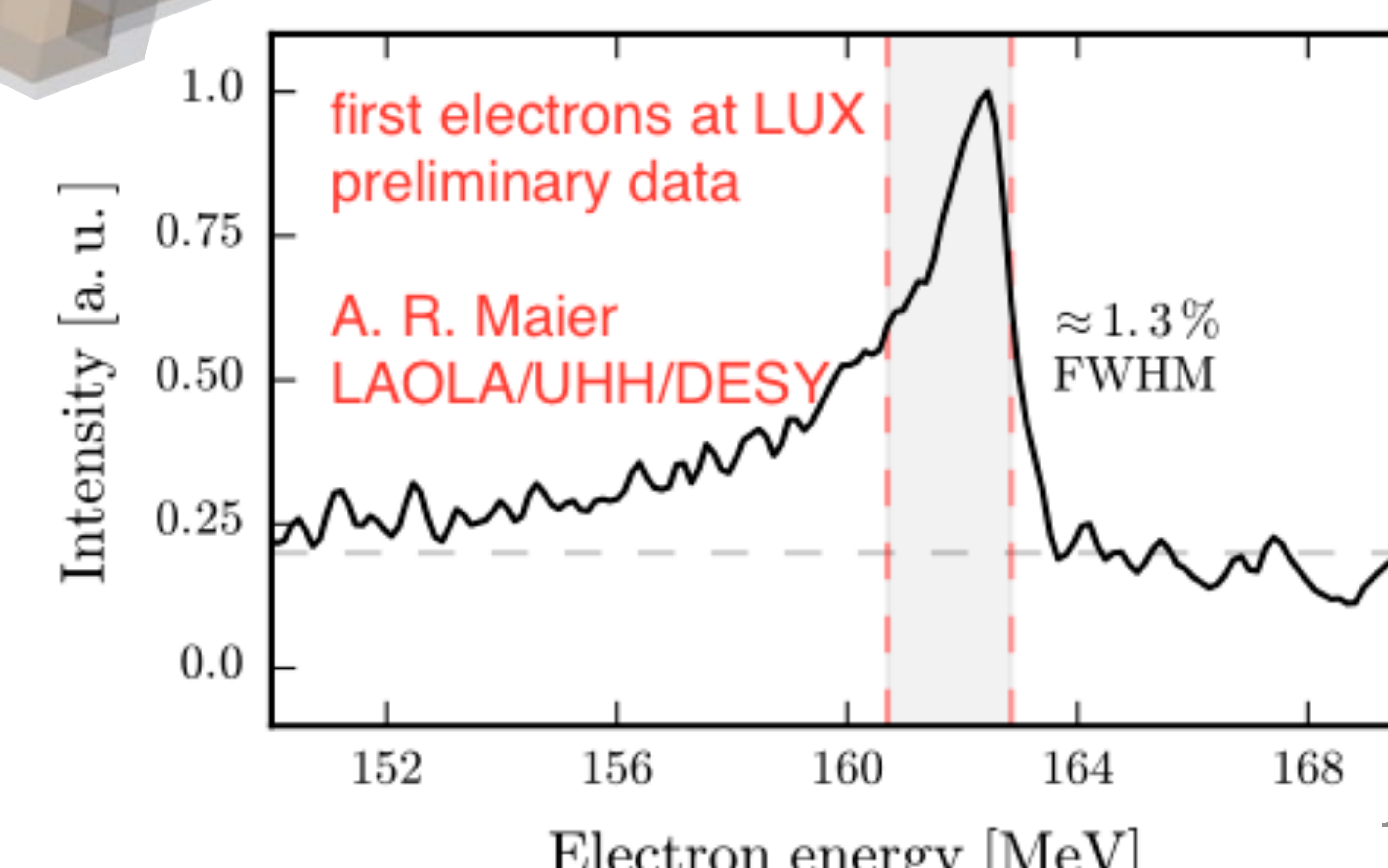

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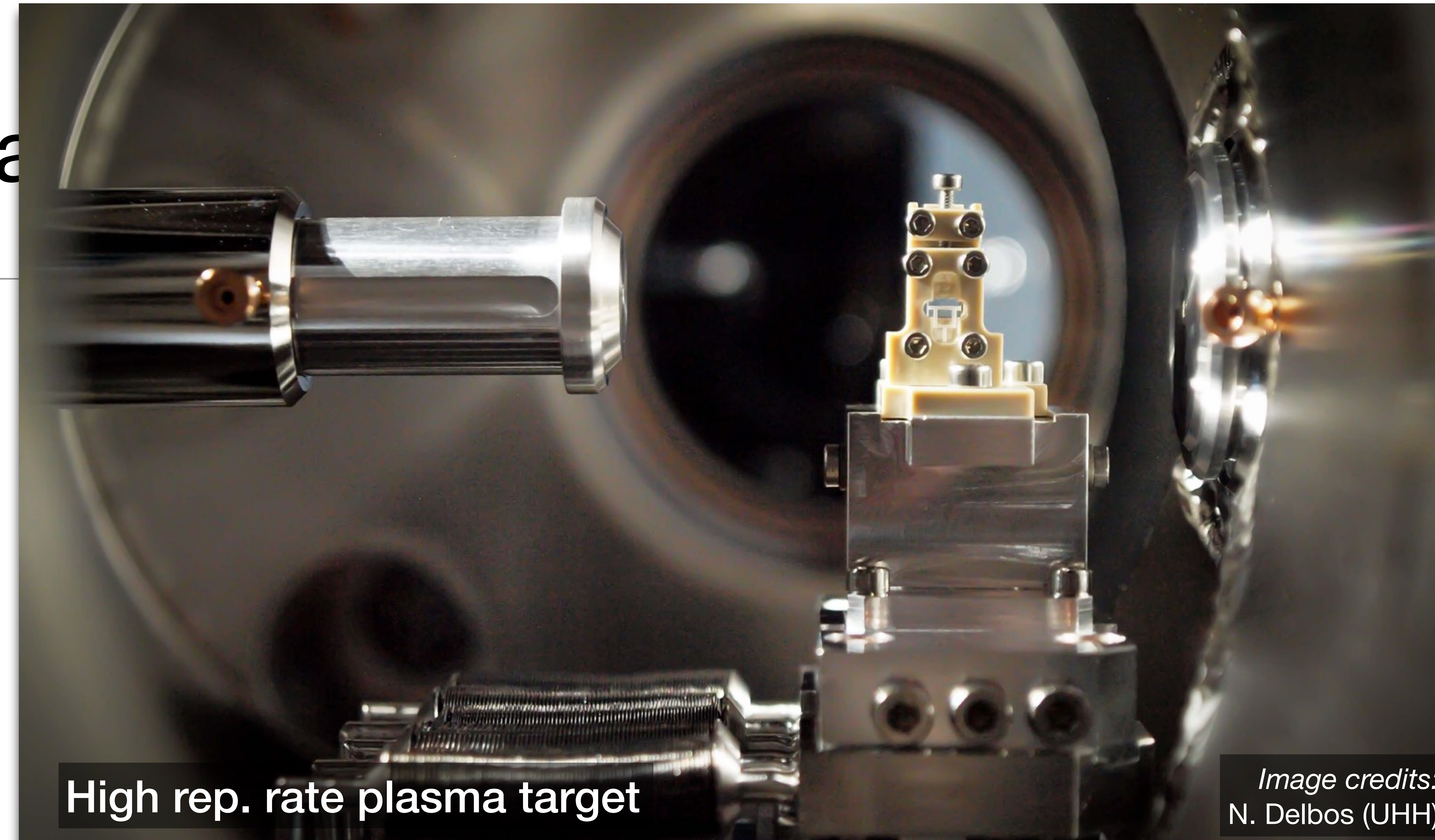

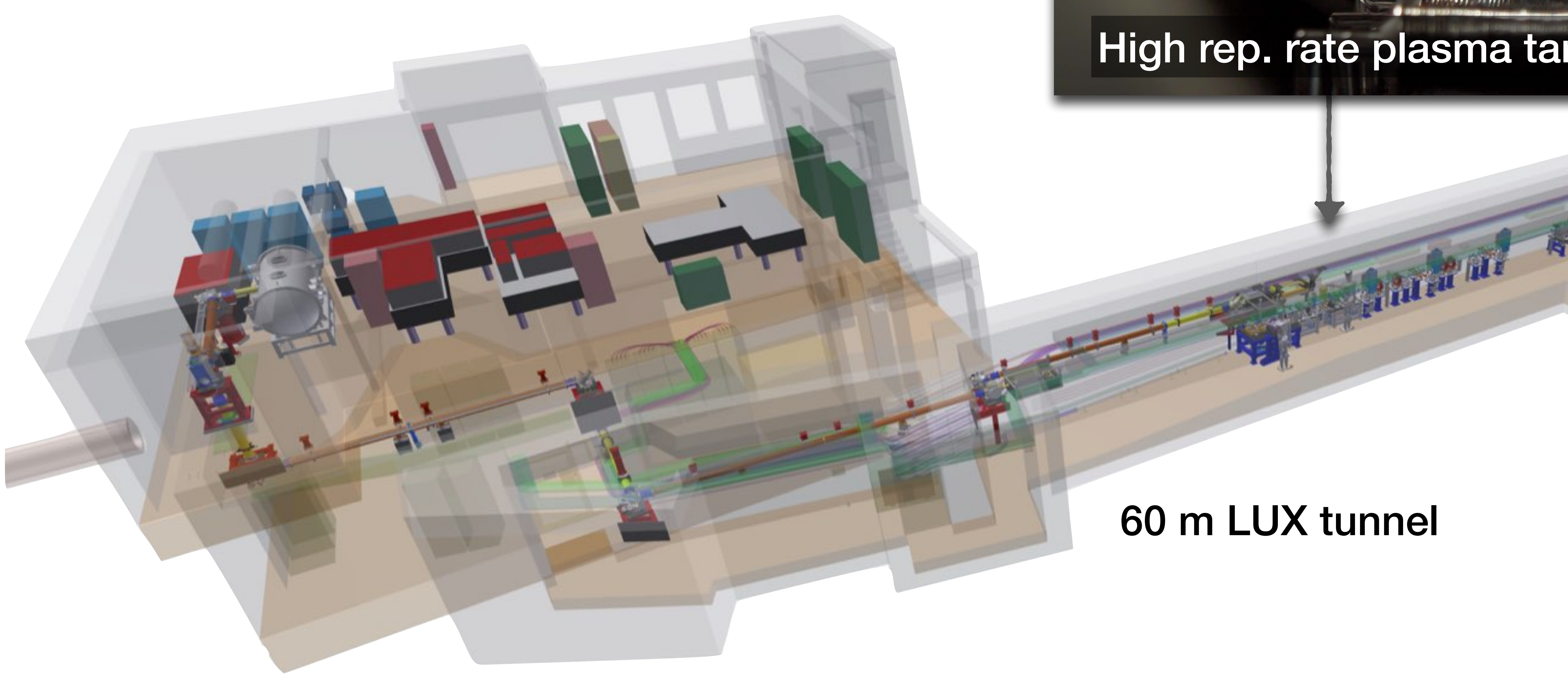

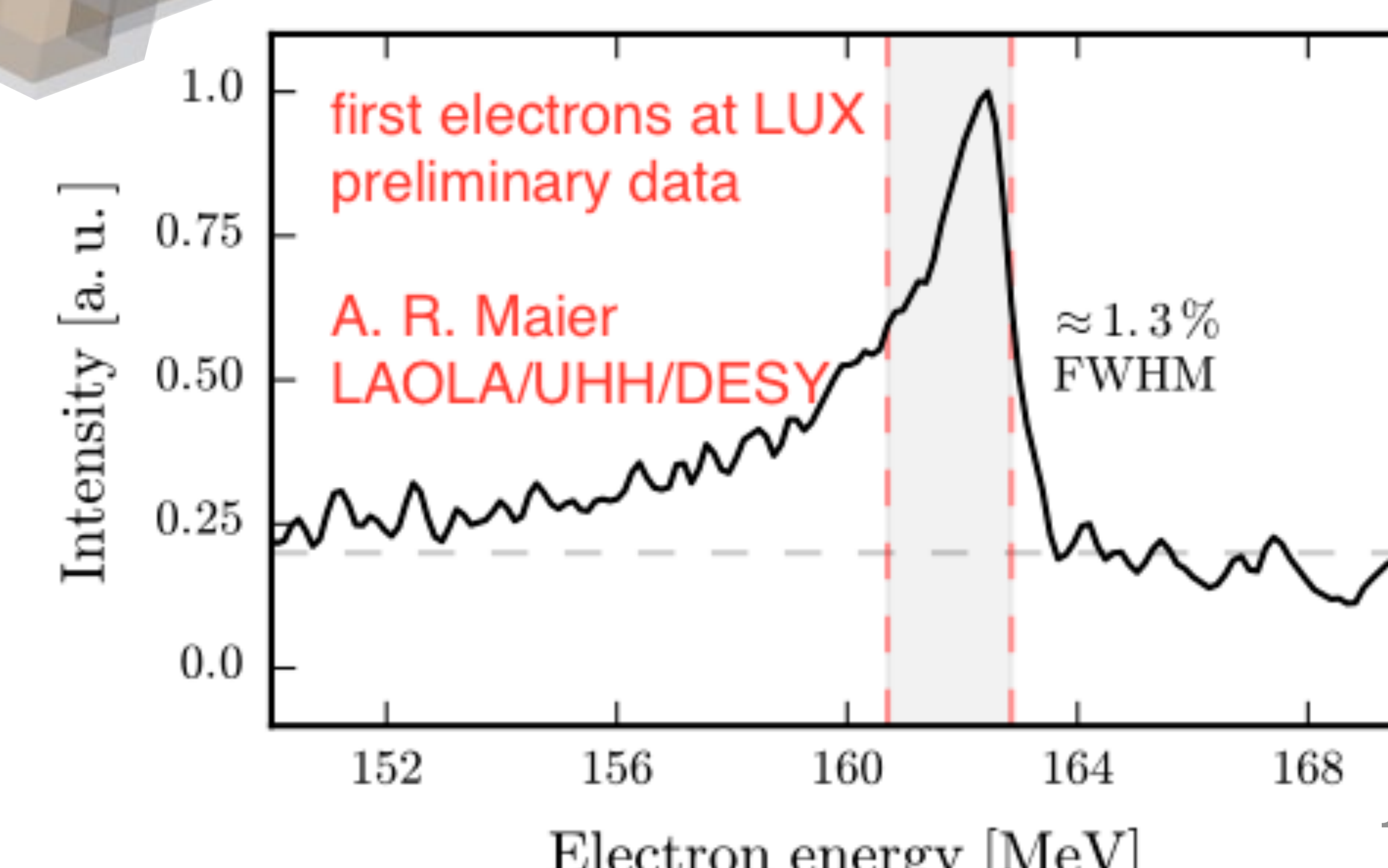

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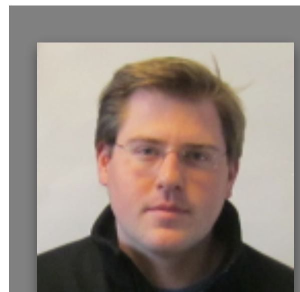

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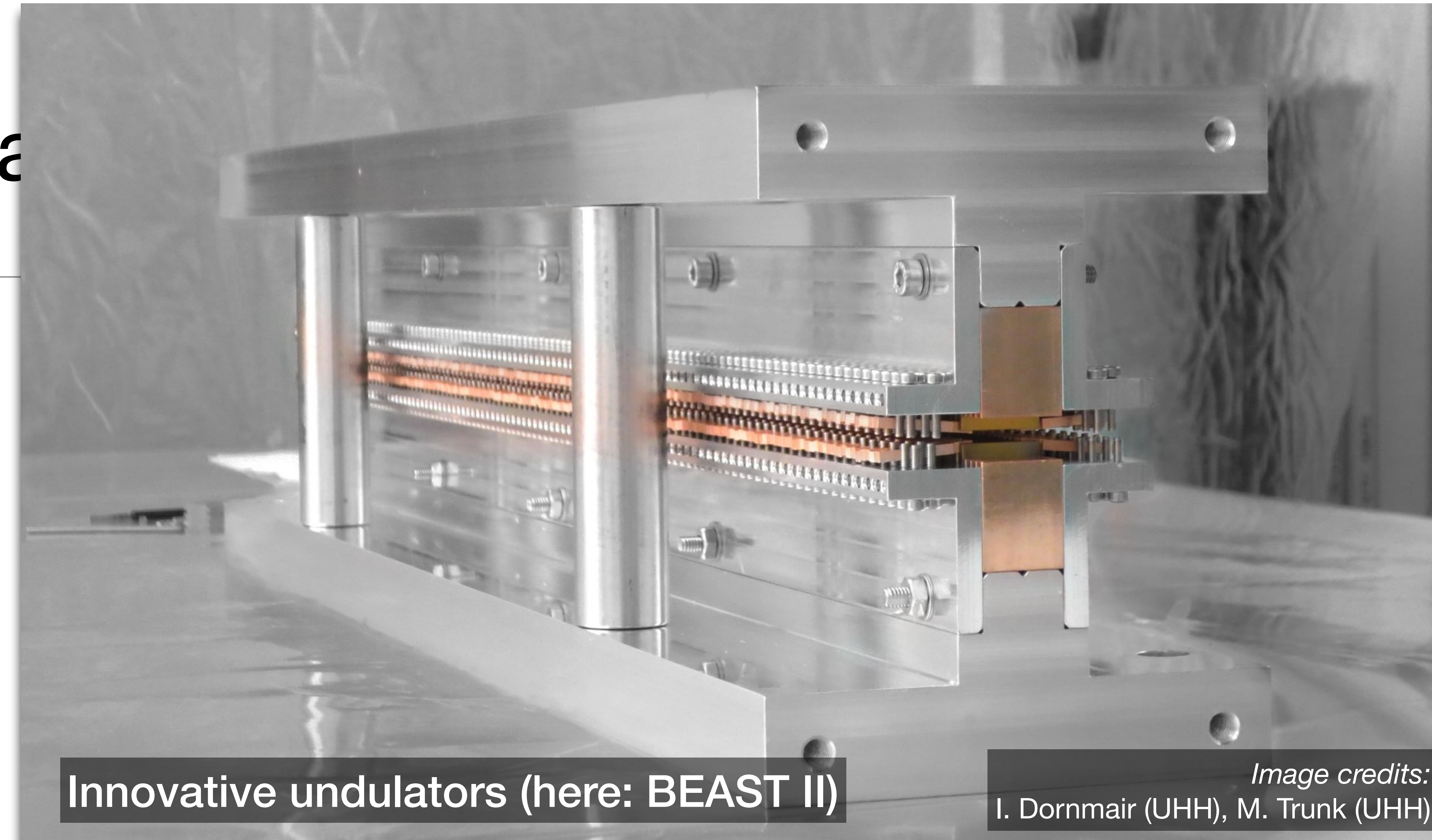

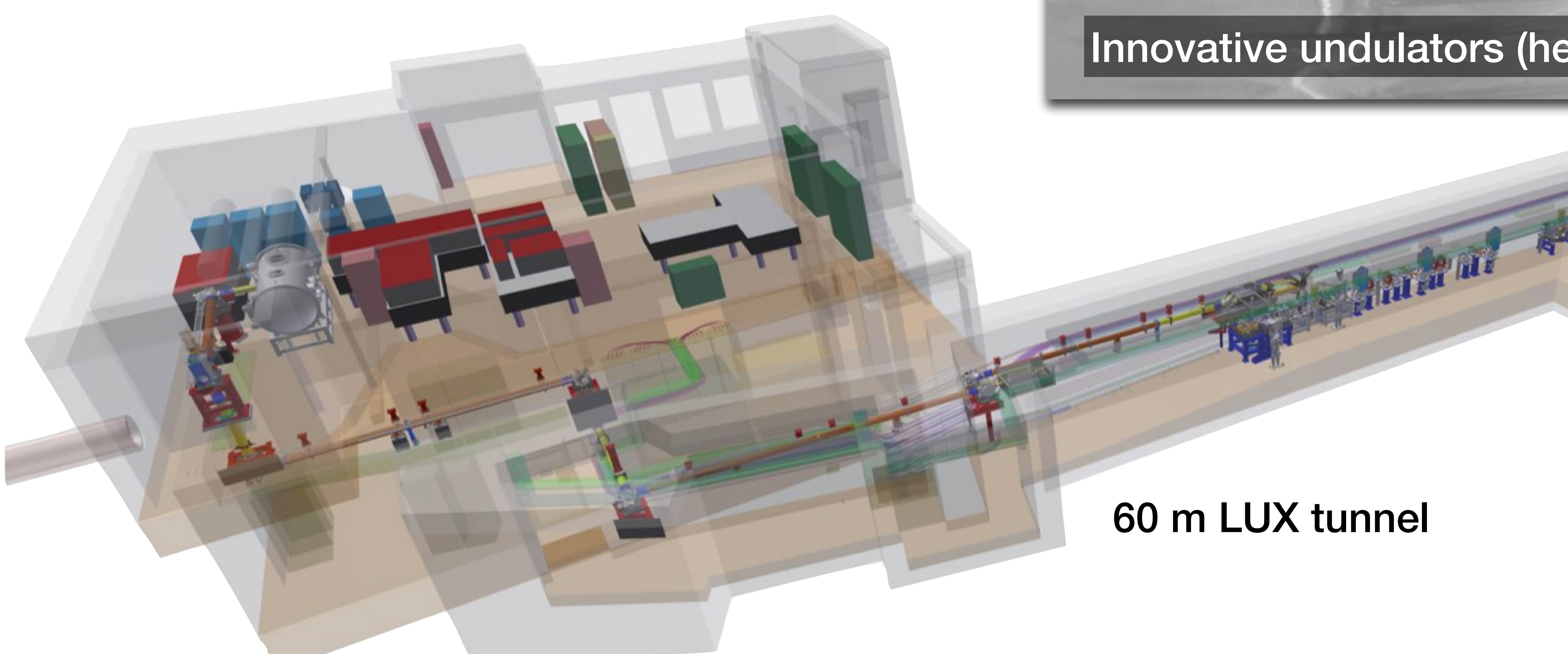

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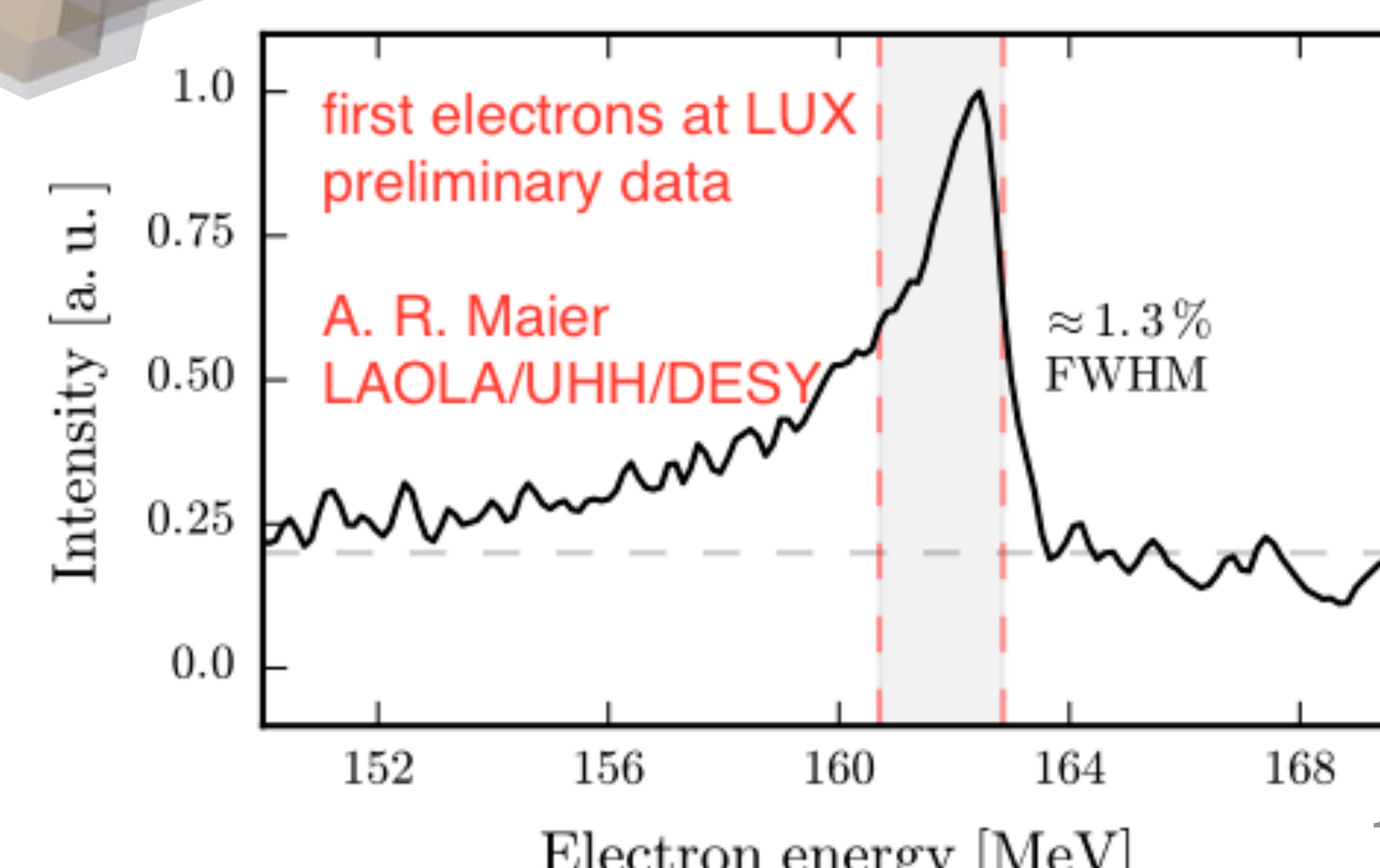

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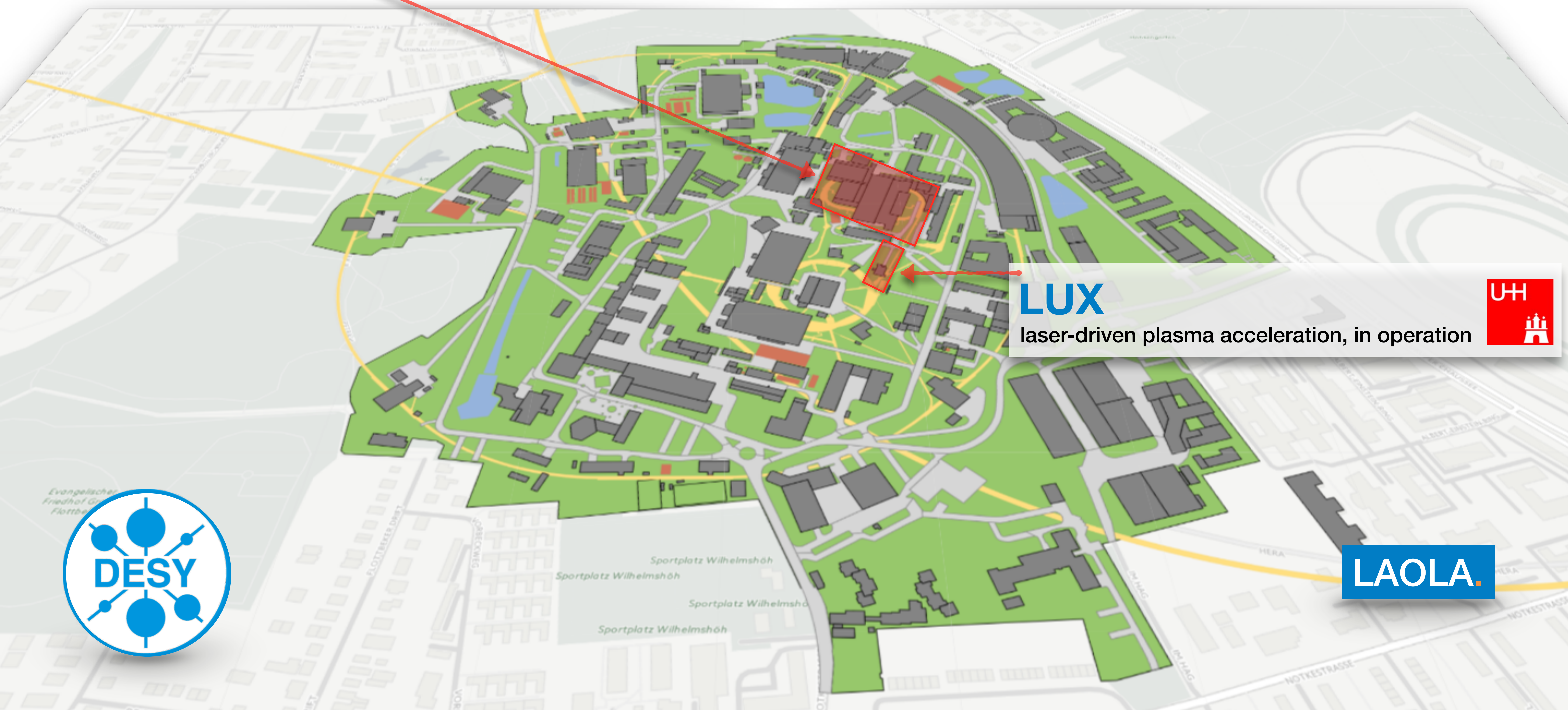
ATHENA$_{e-}$

Helmholtz infrastructure, plasma accelerator test facility, 2020+



LUX

laser-driven plasma acceleration, in operation

LAOLA.

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ATHENAe-

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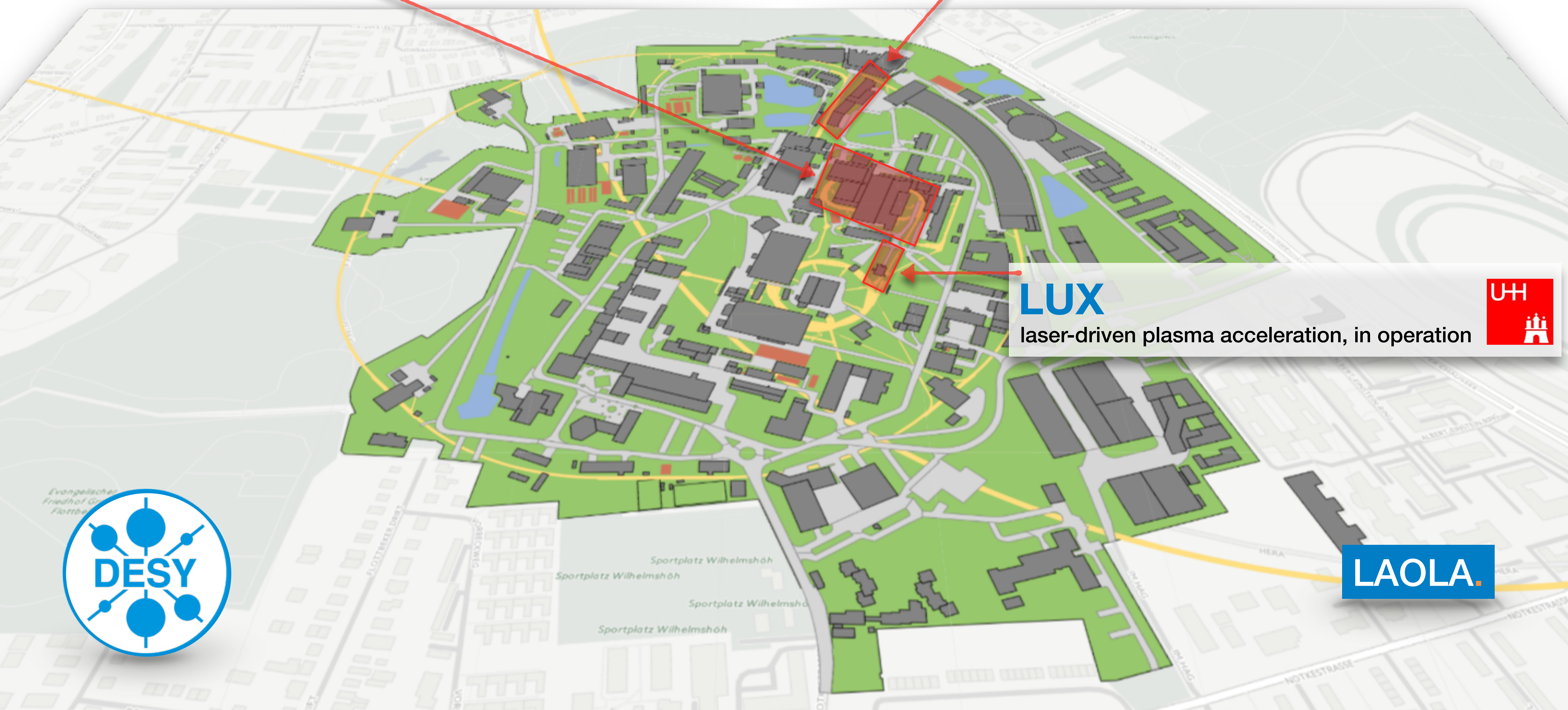
beam-driven plasma acceleration, 2017+



LUX

laser-driven plasma acceleration, in operation

LAOLA.

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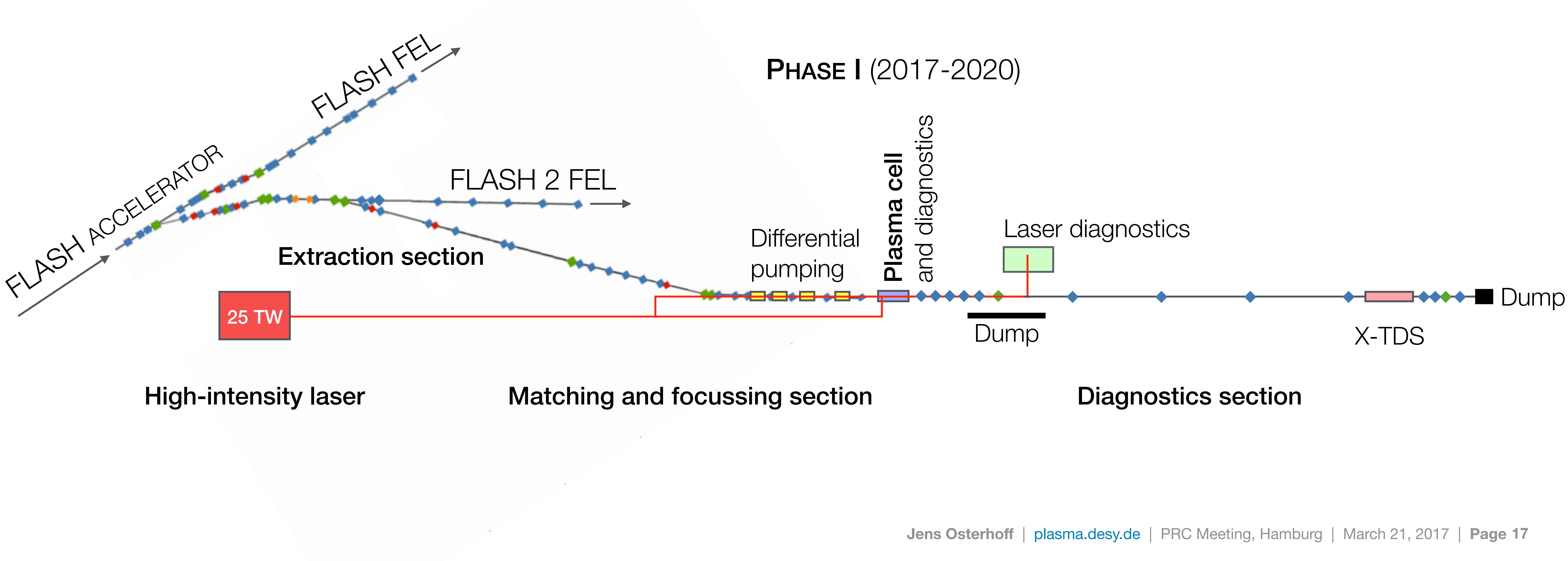
FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

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

- an extension beam line to the FLASH 1.2 GeV superconducting RF FEL facility
- ***a next-generation experiment for beam-driven plasma wakefield accelerator research***



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Future-oriented wakefield accelerator research and development at FLASH

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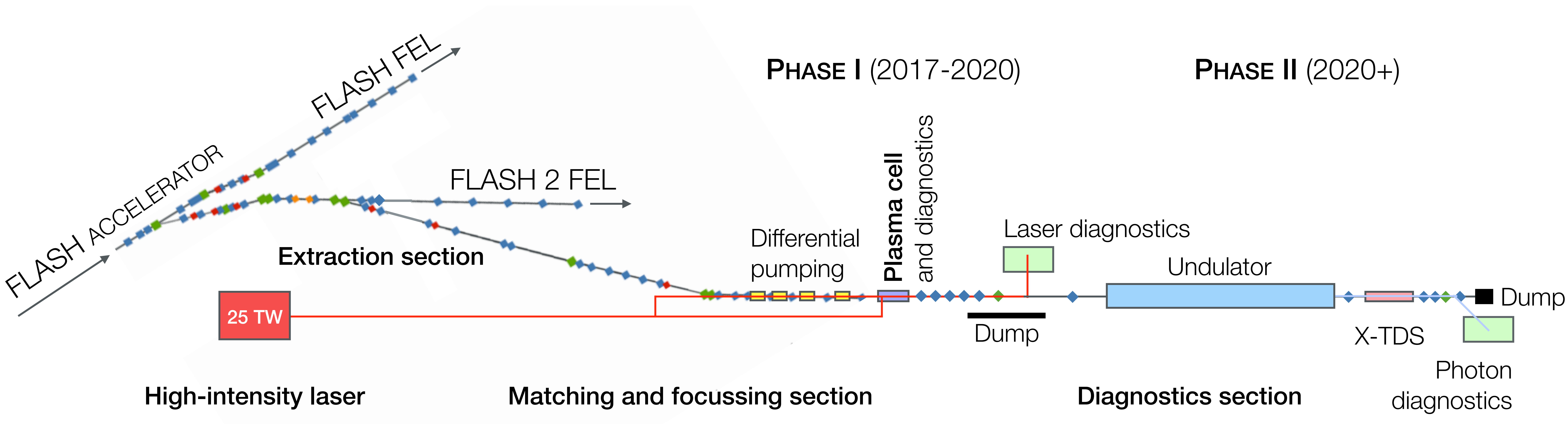
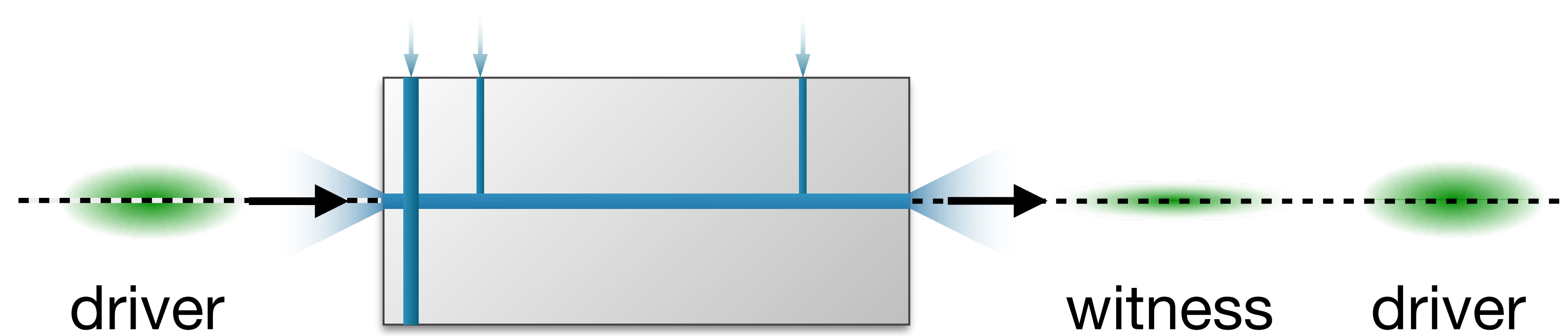


FLASHForward▸▸ - scientific goals

Future-oriented wakefield accelerator research and development at FLASH

Phase I (2017 - 2020)

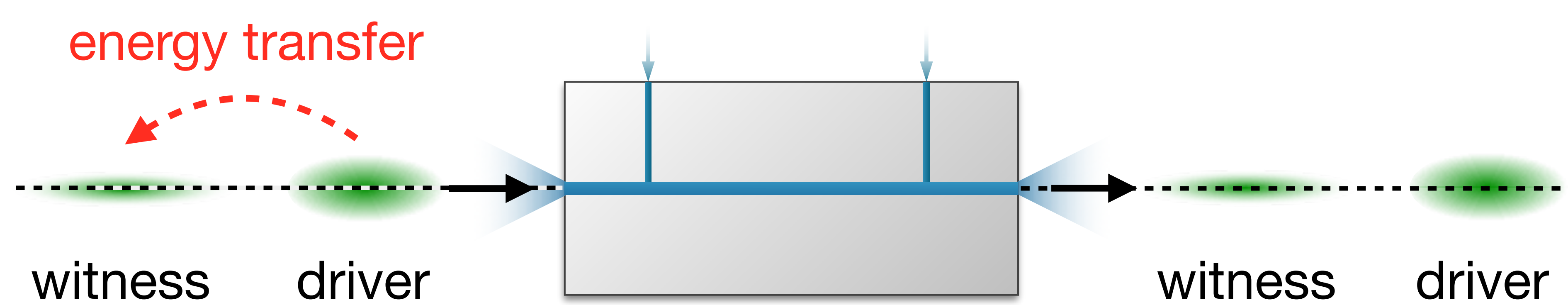
Core Study I: High-brightness beams



Goals:
- 1 GeV energy gain of in-plasma injected beam
- transverse normalized beam emittance ~ 100 nm
- peak current ≳ 1 kA
- femtosecond bunch duration

> Beam generation for photon science applications

Core Study II: Beam-quality conservation



Goals:
- 1 GeV energy gain
- conserve beam energy spread
- conserve beam normalized transverse emittance
- deplete drive beam energy
- 20% energy extraction efficiency from drive to witness

> Stage towards high-energy physics applications

FLASHForward▸▸ - scientific goals

Future-oriented wakefield accelerator research and development at FLASH

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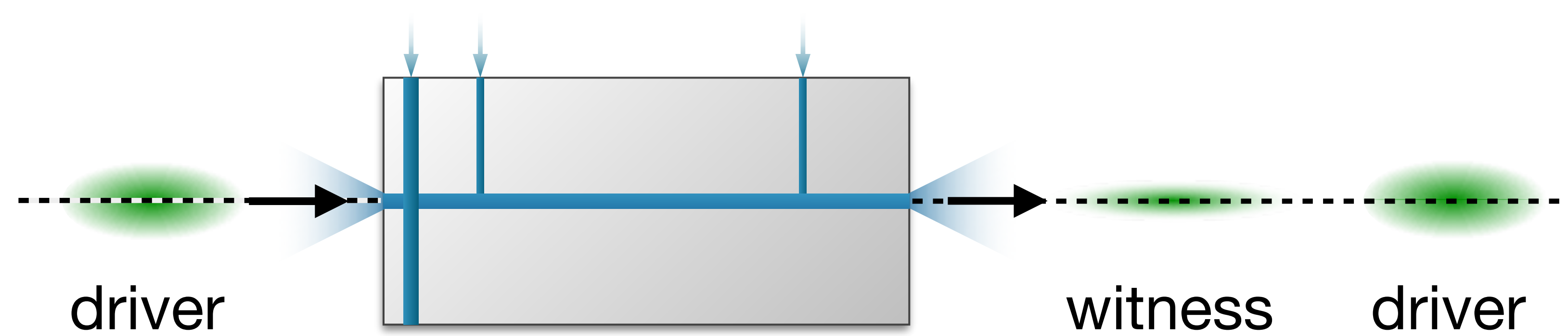

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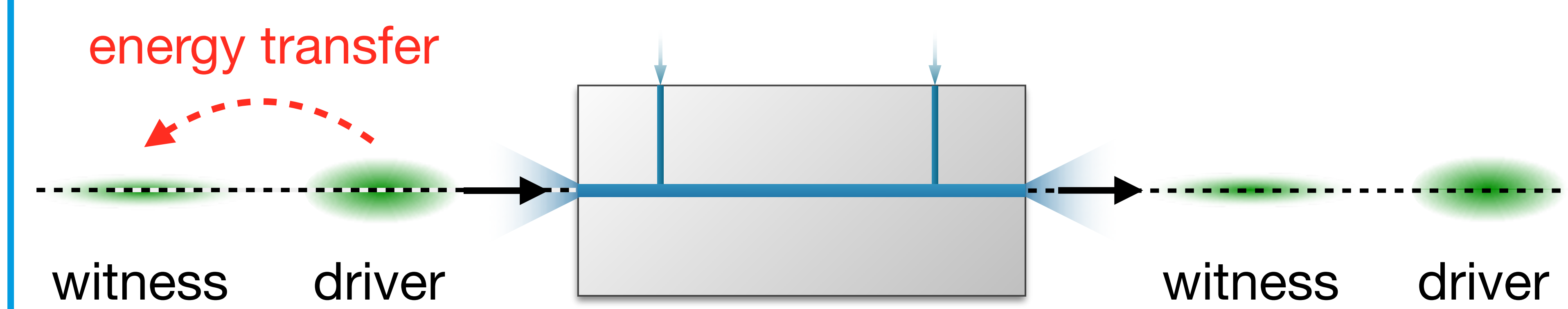


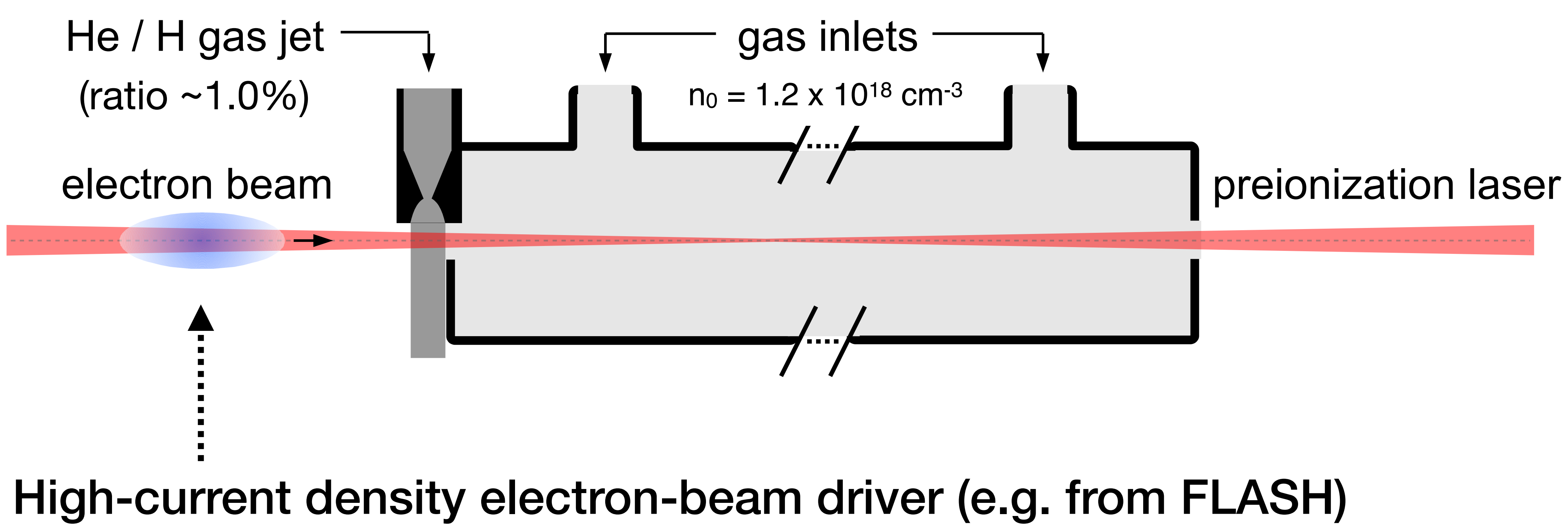
Goals:
- 1 GeV energy gain
- conserve beam energy spread
- conserve beam normalized transverse emittance
- deplete drive beam energy
- 20% energy extraction efficiency from drive to witness

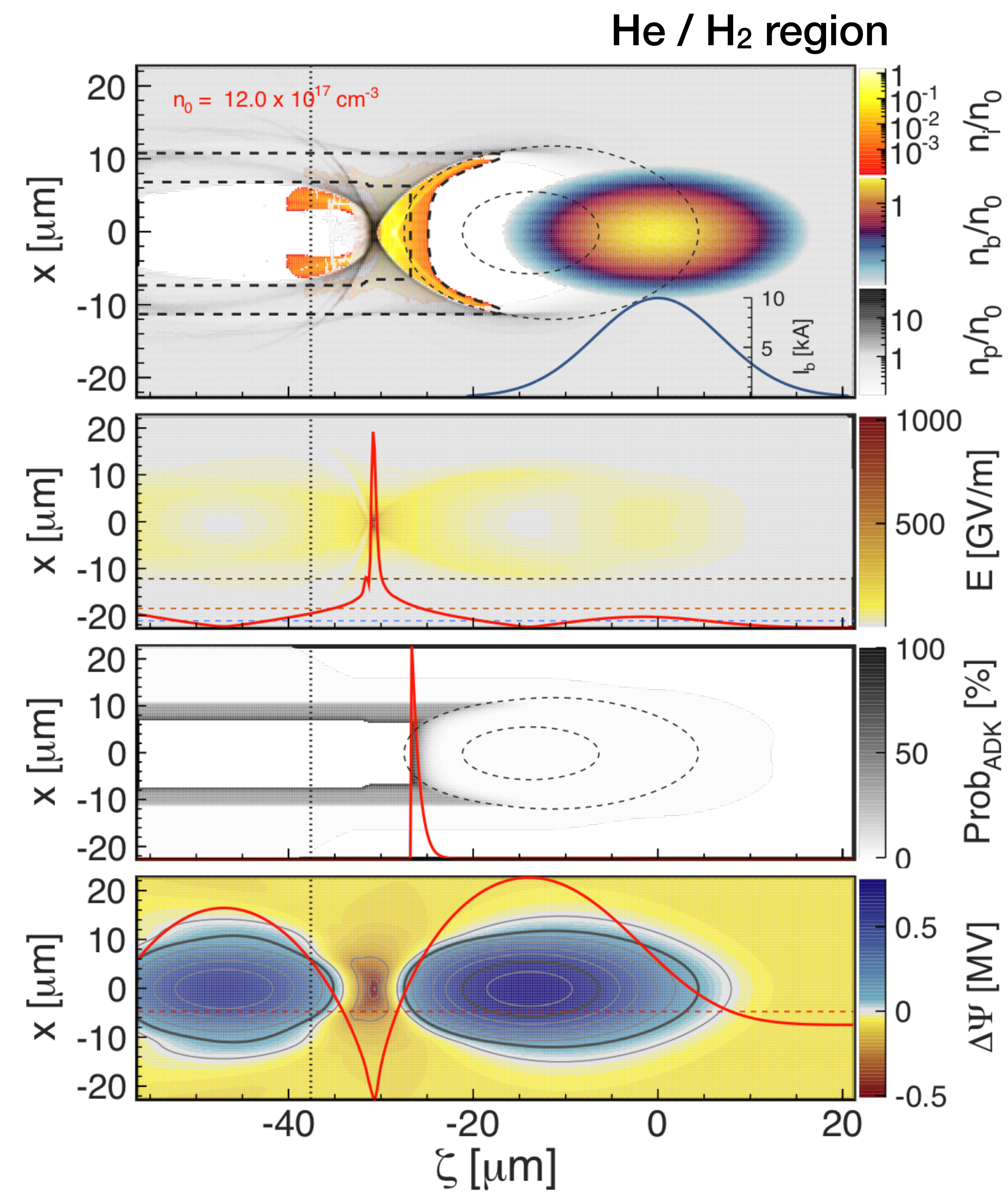
> Stage towards high-energy physics applications

Phase II (2020+)

Core Study III: FEL-gain

High-brightness, attosecond, multi-GeV electron beam generation





> **Wakefield-induced ionization injection**

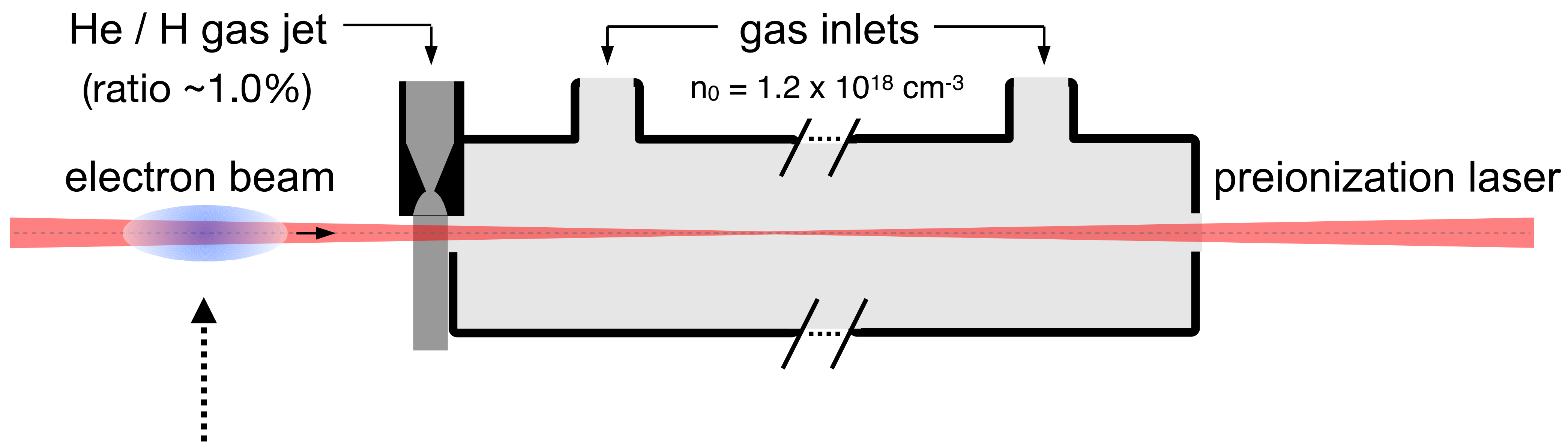
A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)
A. Martinez de la Ossa et al., Phys Plasmas 22, 093107 (2015)

High-brightness, attosecond, multi-GeV electron beam generation

osiris v2.0

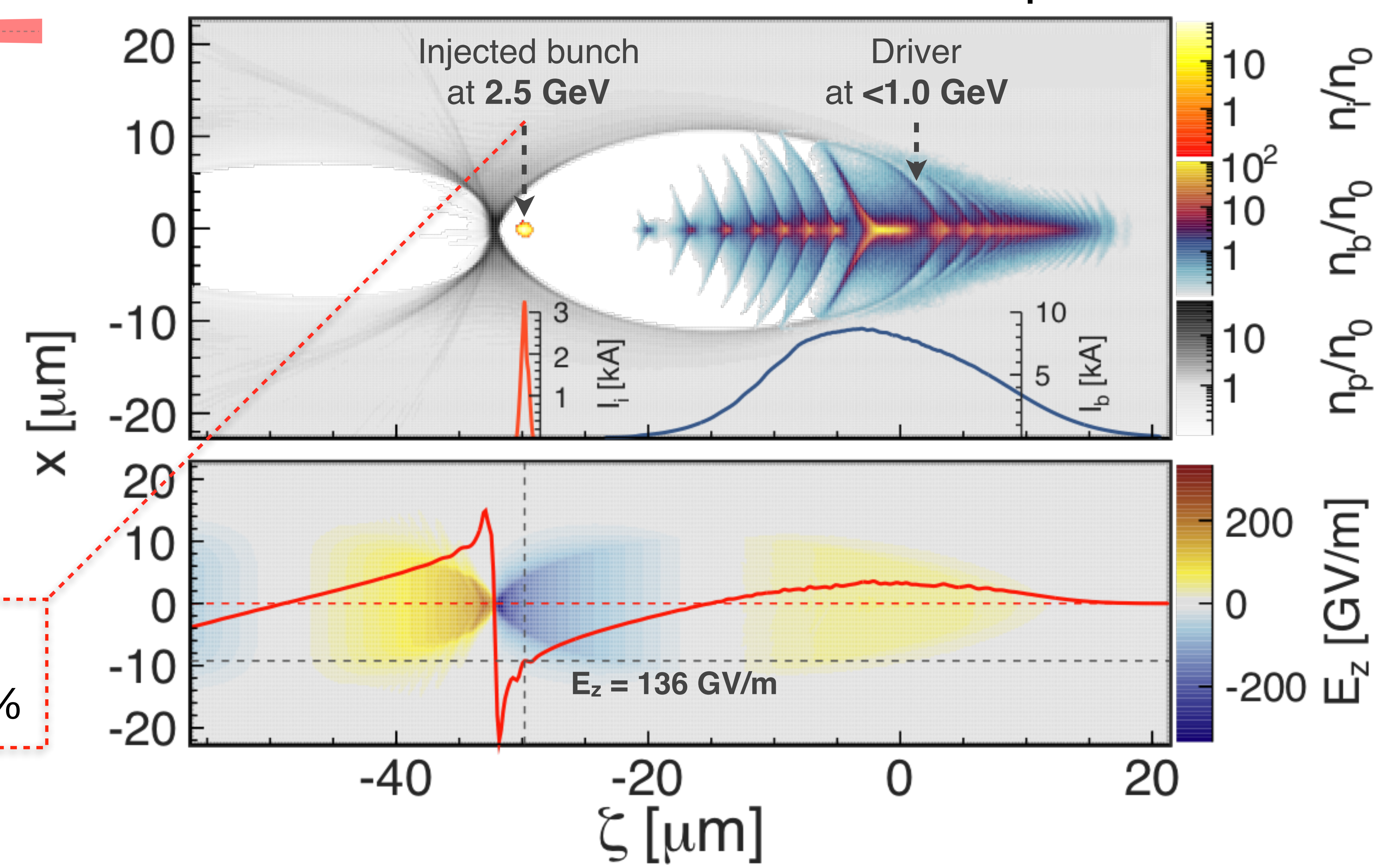
3D particle-in-cell (PIC) simulation

JÜLICH FORSCHUNGSZENTRUM



High-current density electron-beam driver (e.g. from FLASH)

Driver and witness bunch after 14.6 mm in plasma



- Duration: 770 as rms
- Peak current: 5 kA
- Normalized emittance: 300 nm
- Uncorrelated energy spread: < 1%

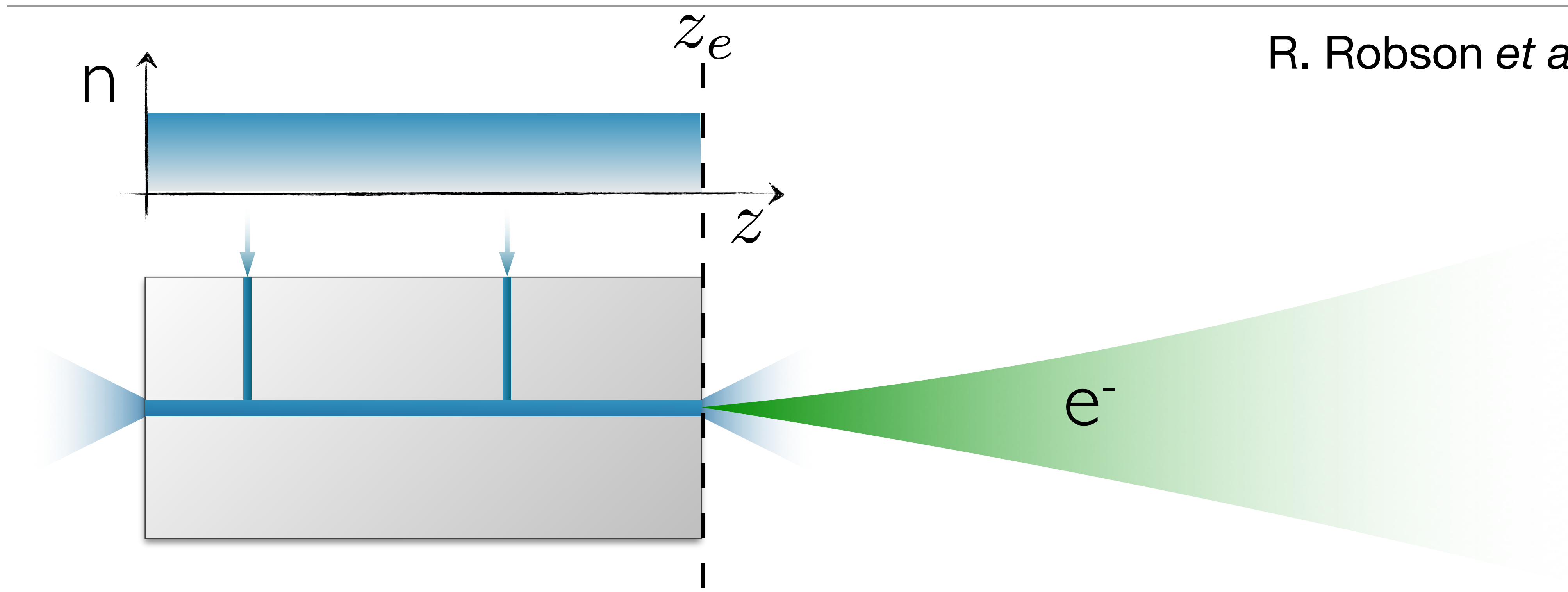
DESY

- Wakefield-induced ionization injection

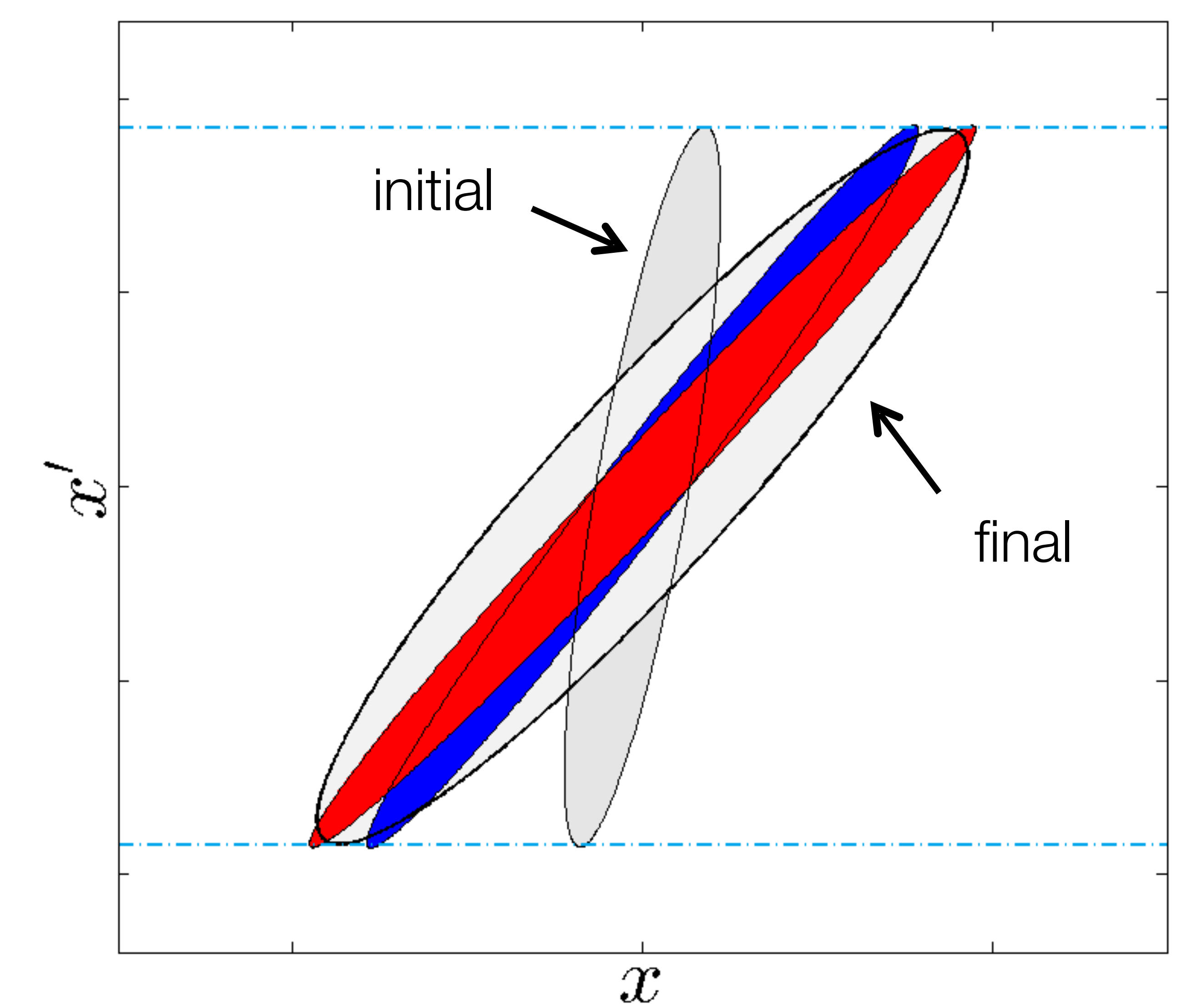
A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)
A. Martinez de la Ossa et al., Phys Plasmas 22, 093107 (2015)

Tailored plasma-to-vacuum transition to mitigate emittance growth

R. Robson *et al., Annals of Physics* **356,** 306 (2015); T. Mehrling *et al.*, NIM A, in press (2016)



Phase space ellipses during drift



- beams at plasma exit:
  - ~% level energy spread
  - small beta function, mrad divergence
- leads to transverse emittance growth in free drift

$$\varepsilon_n{}^2 \cong \langle\gamma\rangle^2 \cdot (\sigma_E{}^2 \sigma_{x'}{}^4 s^2 + \varepsilon^2)$$

→ K. Floettmann, Phys. Rev. STAB 6, 034202 (2003)

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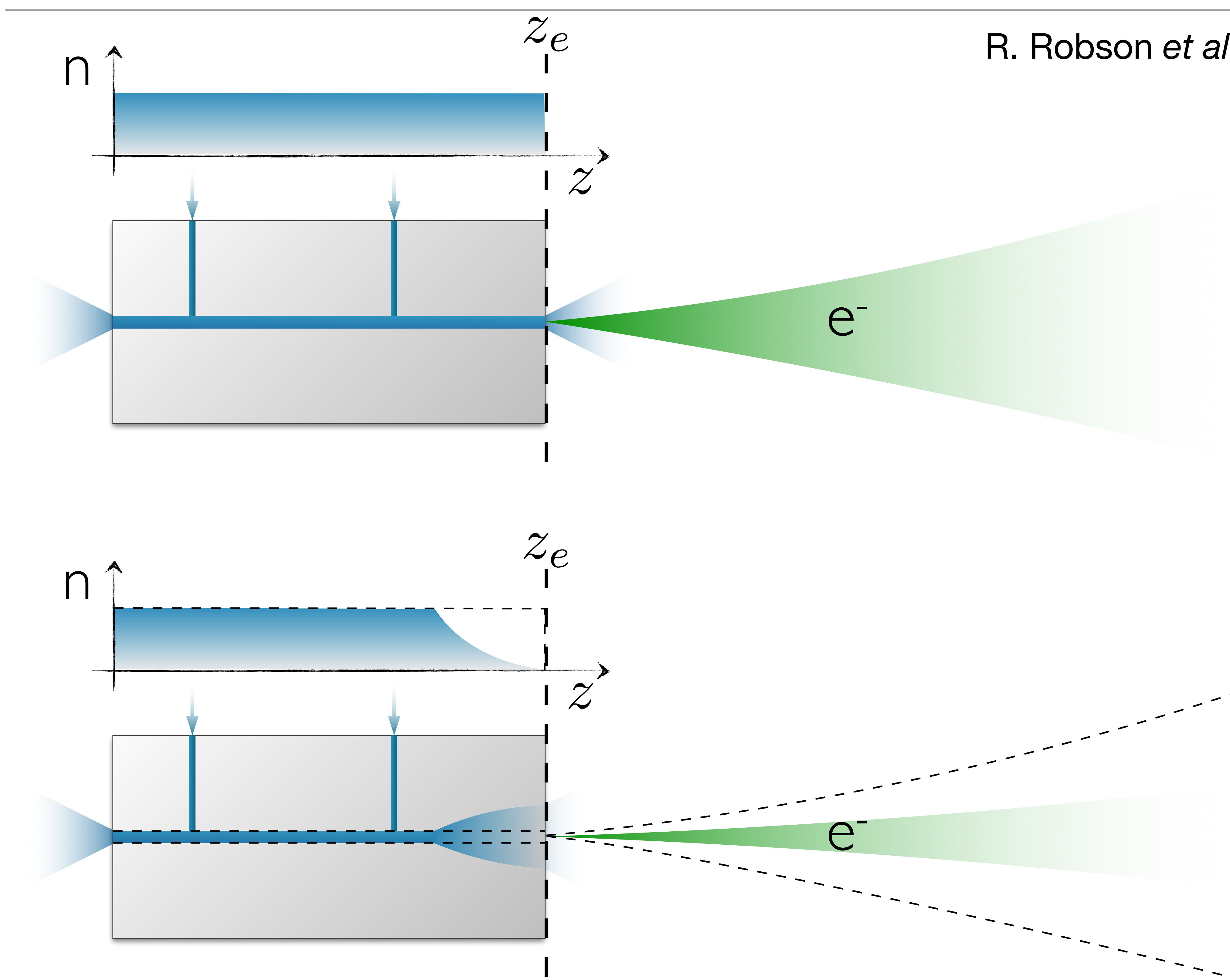

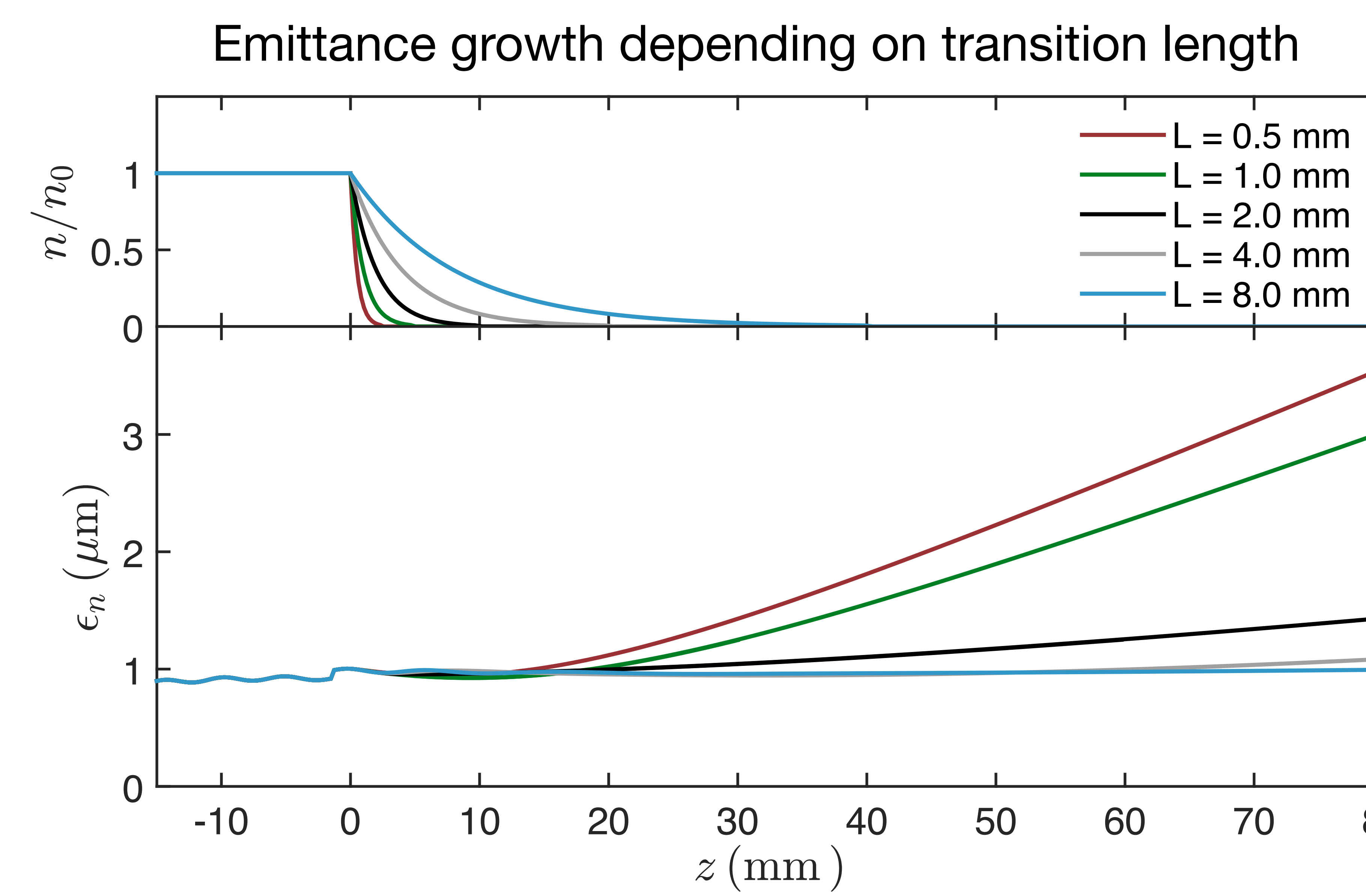

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  - small beta function, mrad divergence
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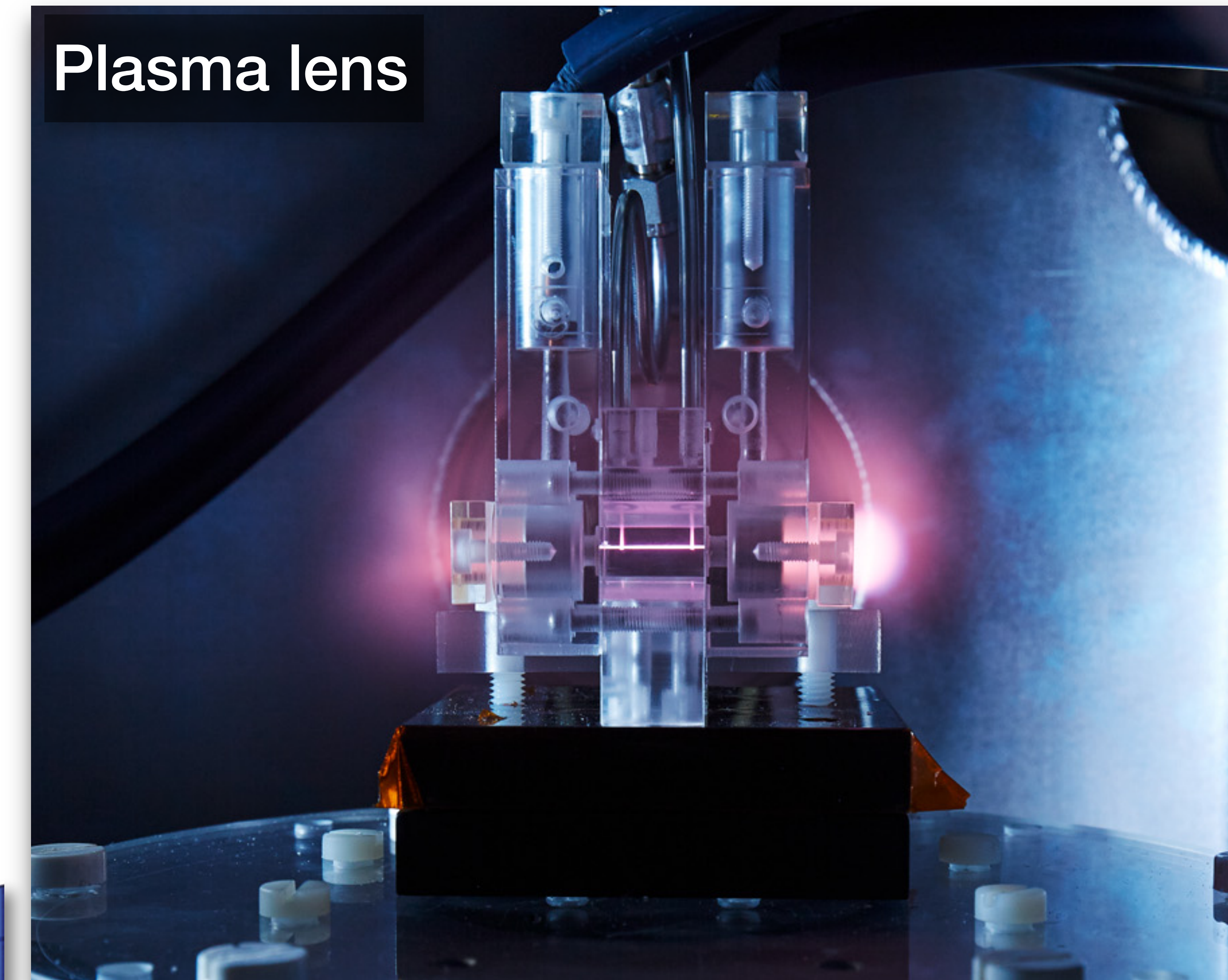
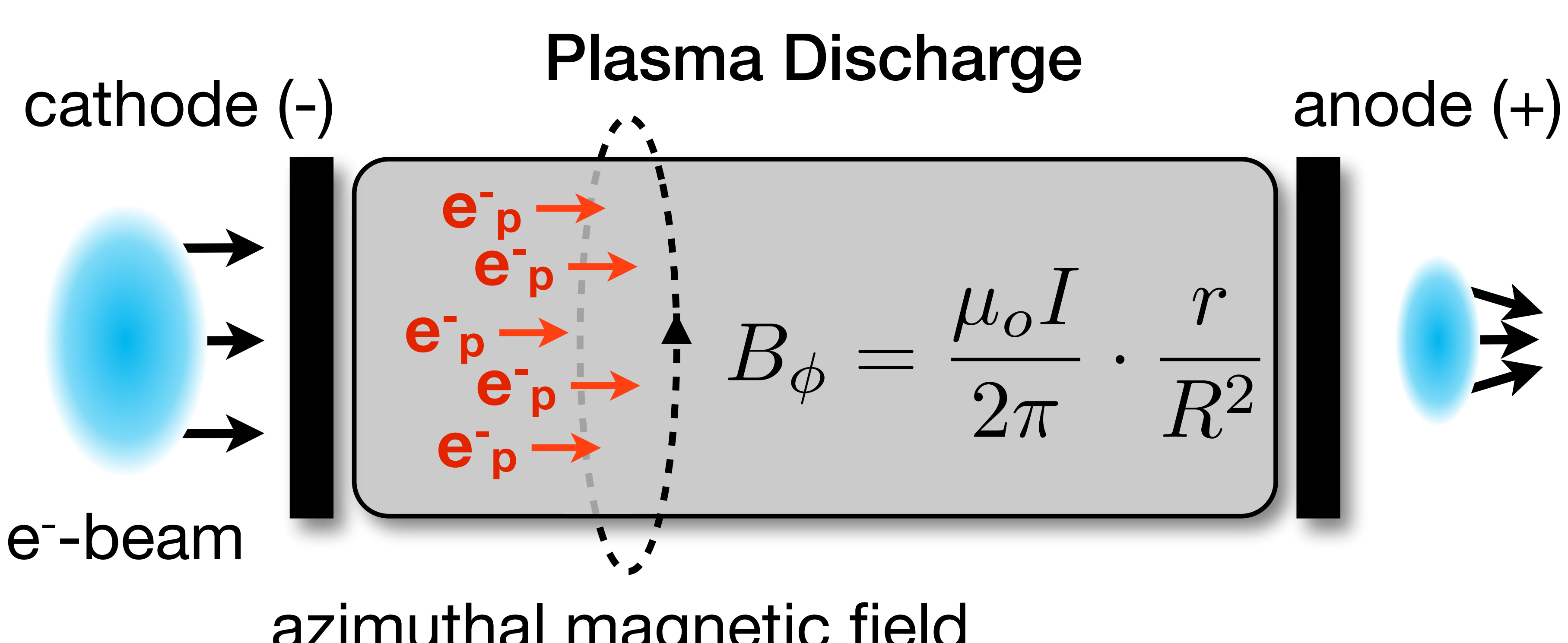
→ K. Floettmann, Phys. Rev. STAB 6, 034202 (2003)

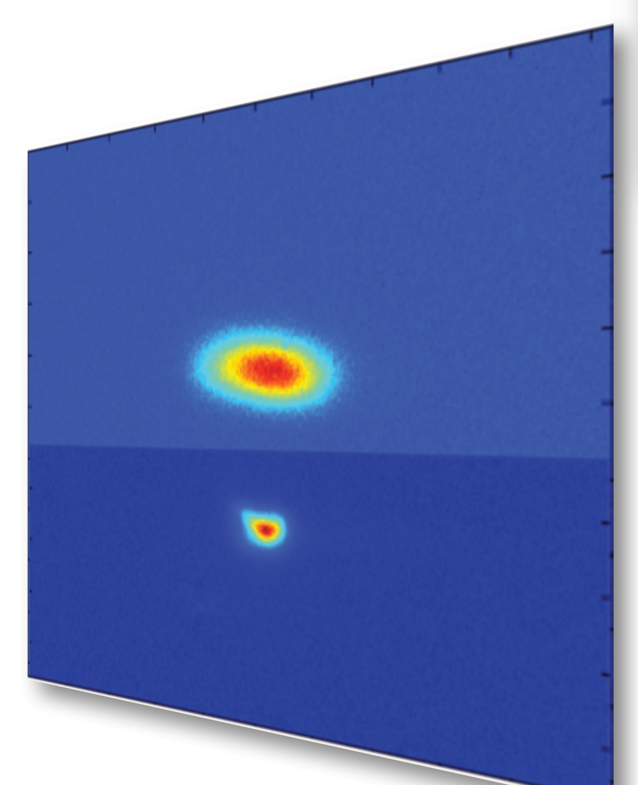
- Plasma-to-vacuum transition » beta for emittance preservation
- Strong quadrupoles for beam capturing required

Active plasma lenses with kT/m magnetic field gradients

in collaboration between
DESY, U Hamburg, U Mainz, and LBNL







plasma off

plasma on

→ **F = I x B**, tunable and symmetric focussing force for e^--beam

W. K. H. Panofsky and W. R. Baker, Rev. Sci. Instrum. ***21****, 445 (1950)*

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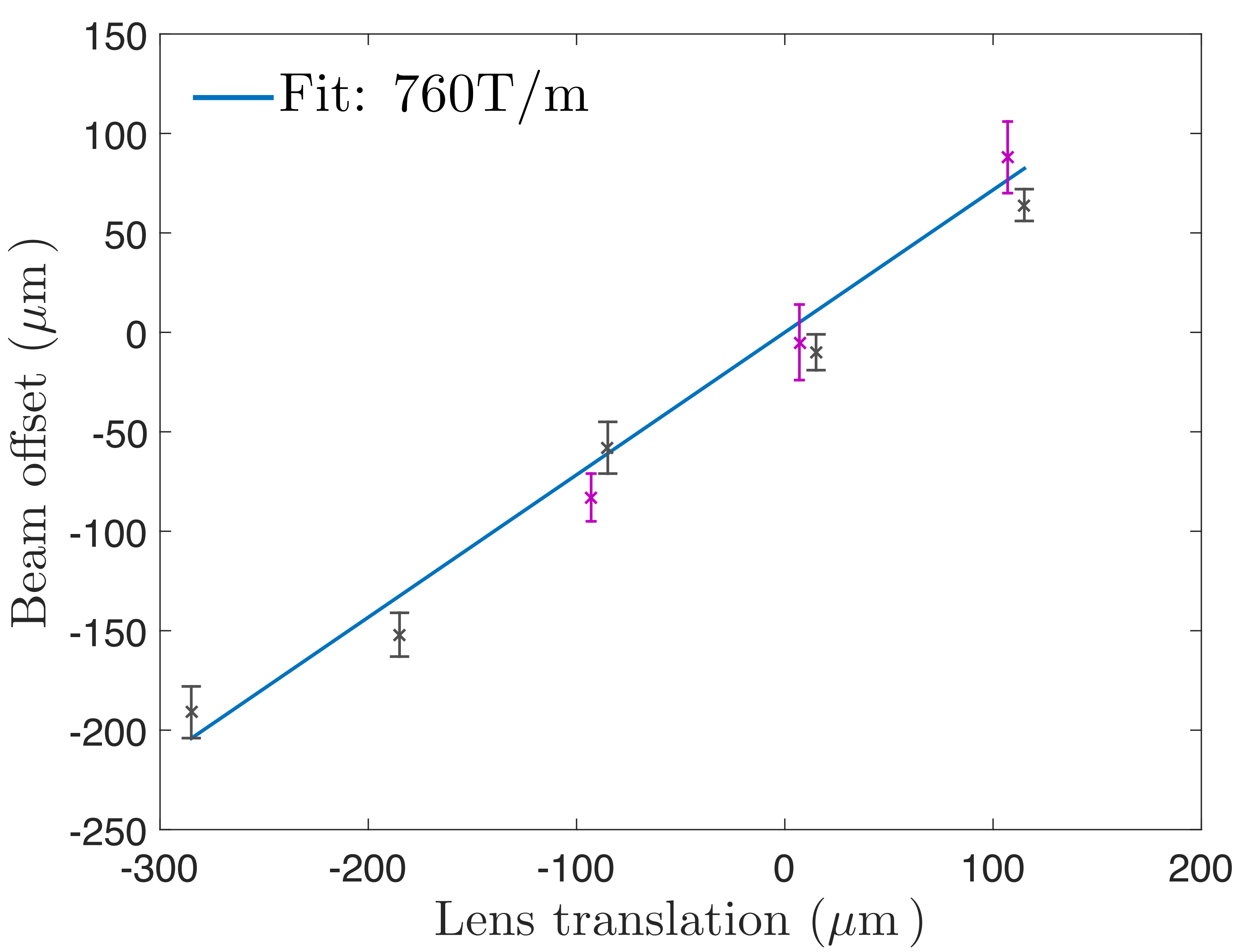
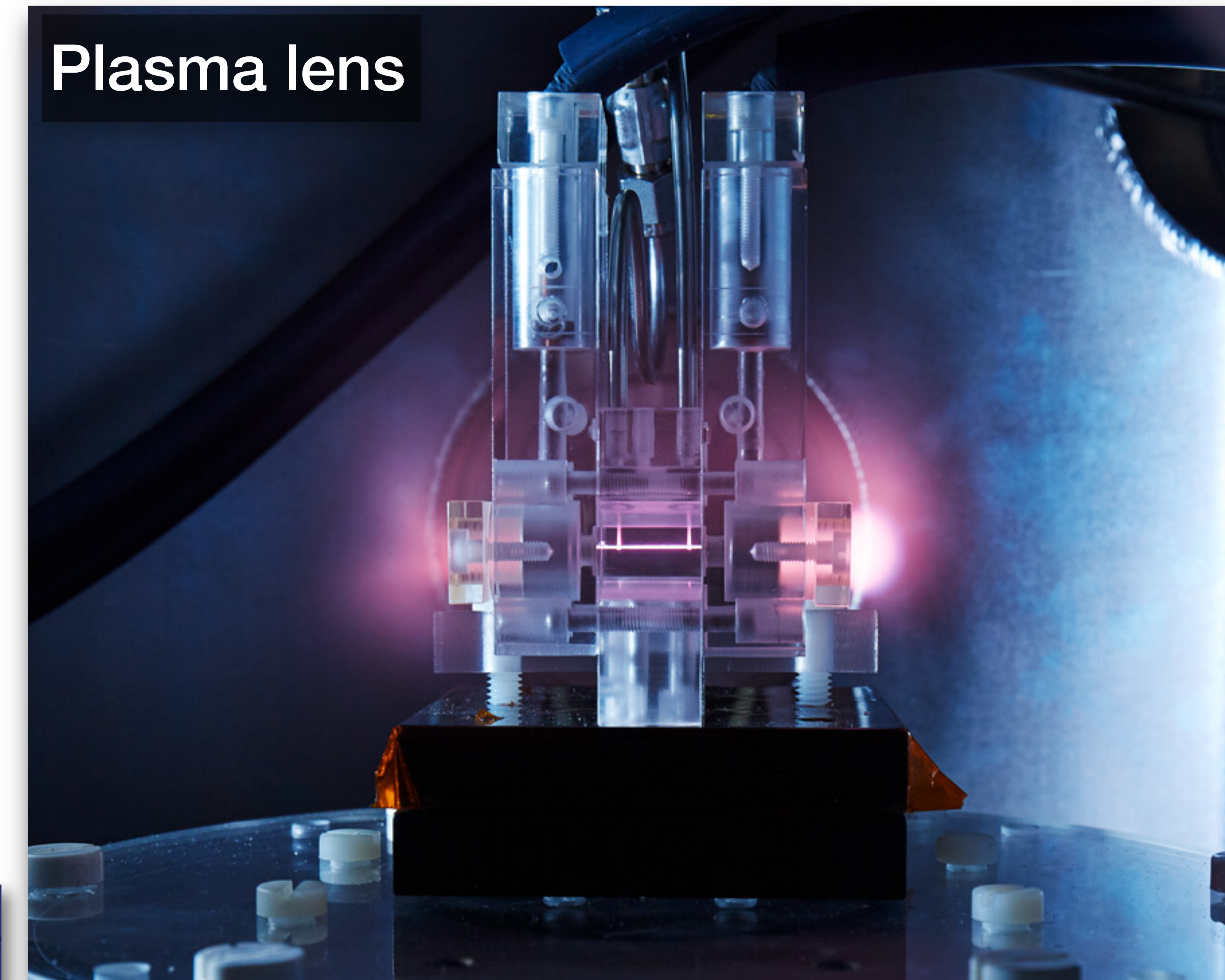
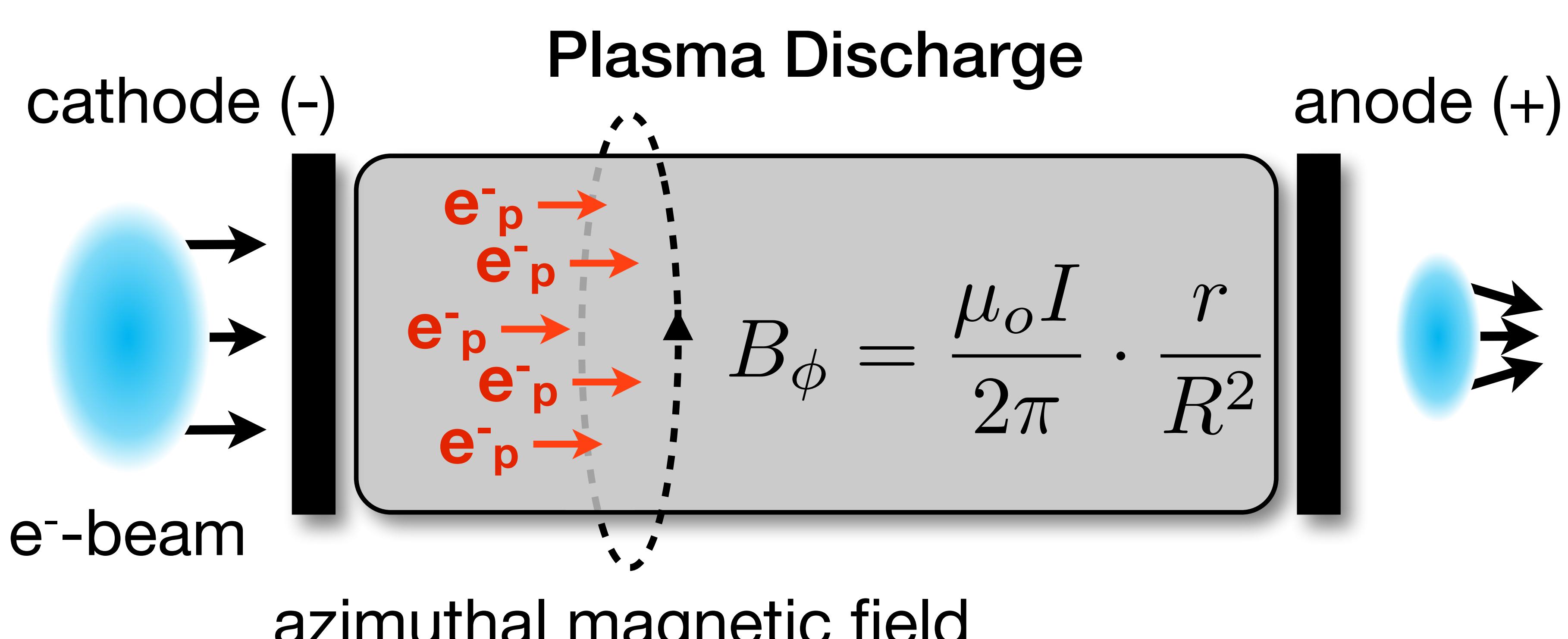
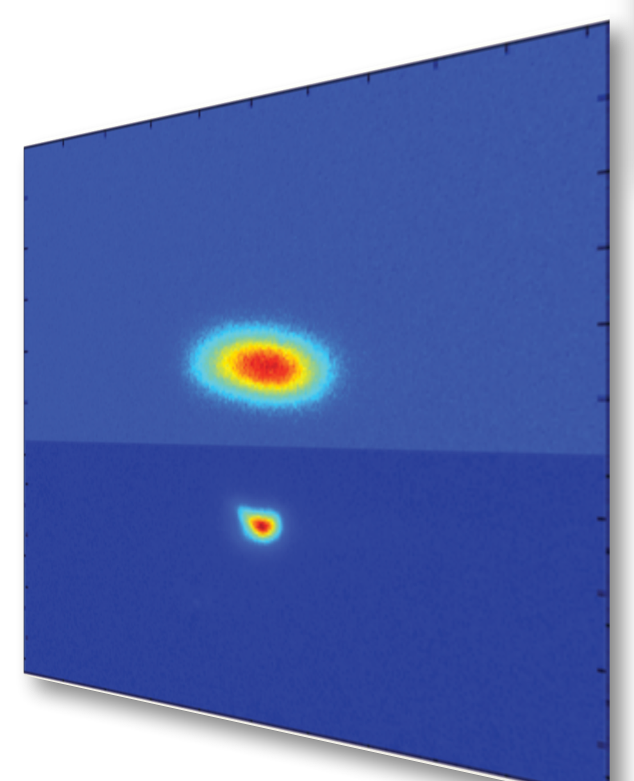


- experiments performed at MaMi in Mainz with 855 MeV beam
- gradient scalable to multi-kT/m
- applications
  - beam matching into plasma
  - beam capturing from plasma







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→ **F = I x B**, tunable and symmetric focussing force for e⁻-beam

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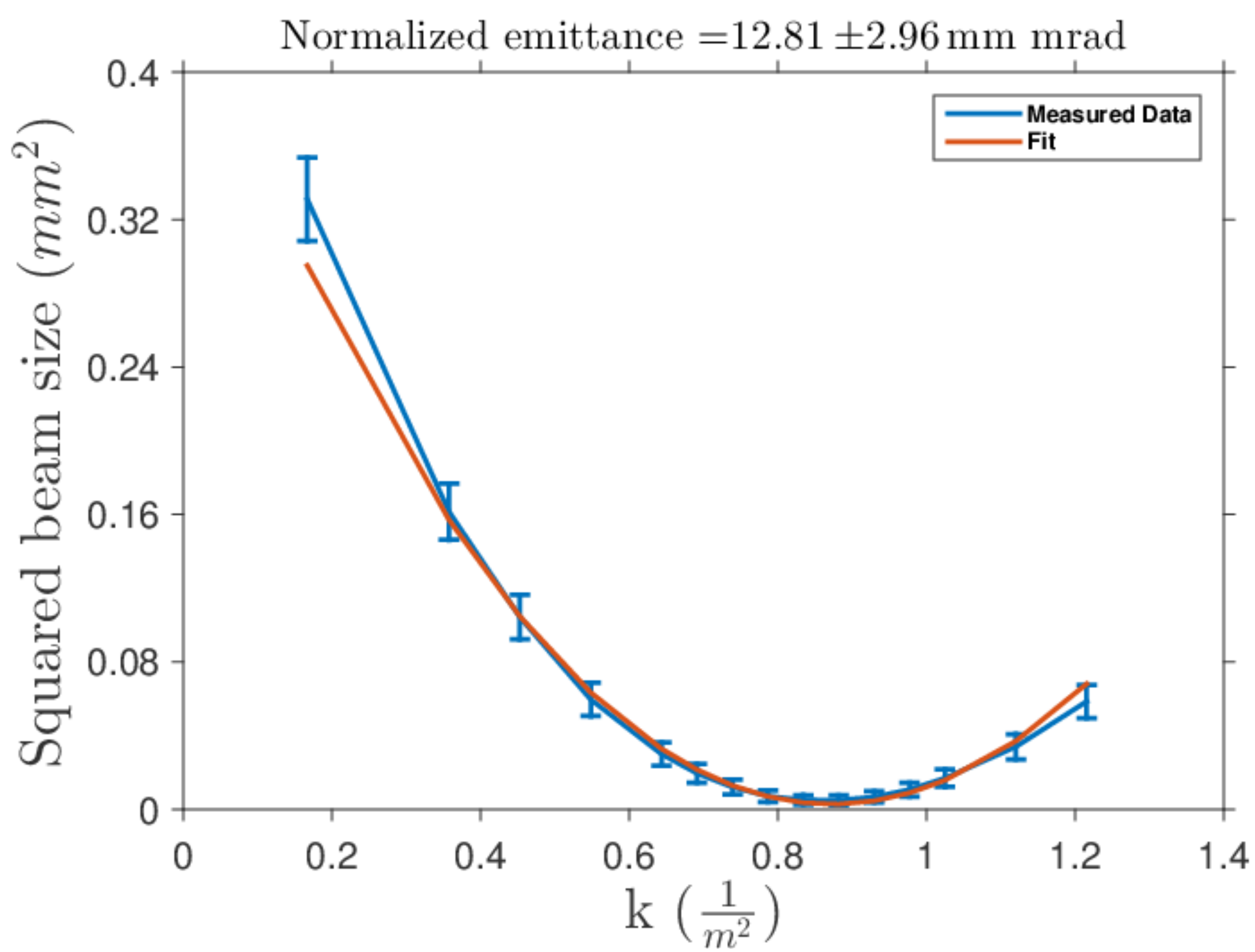
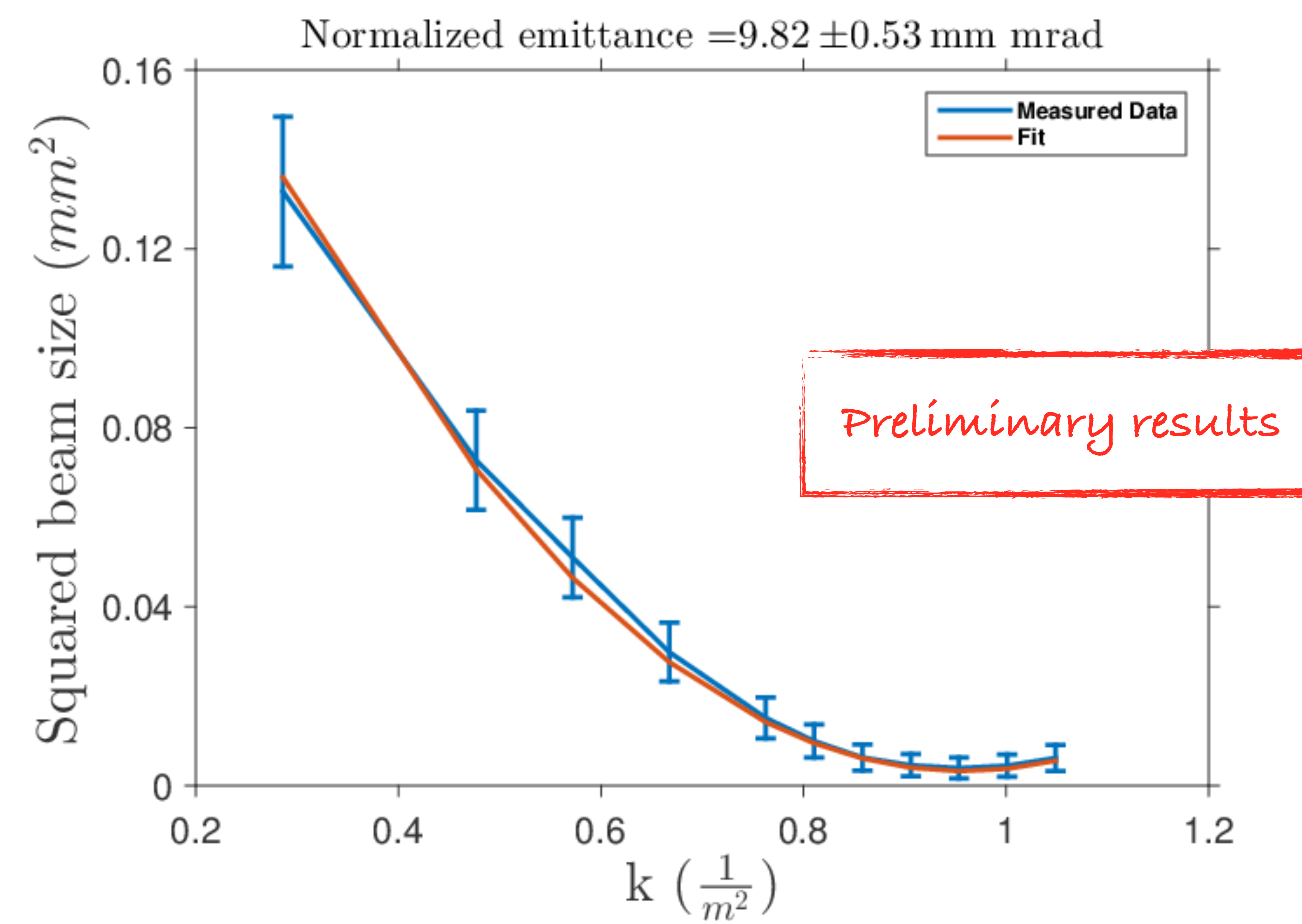




Without plasma lens

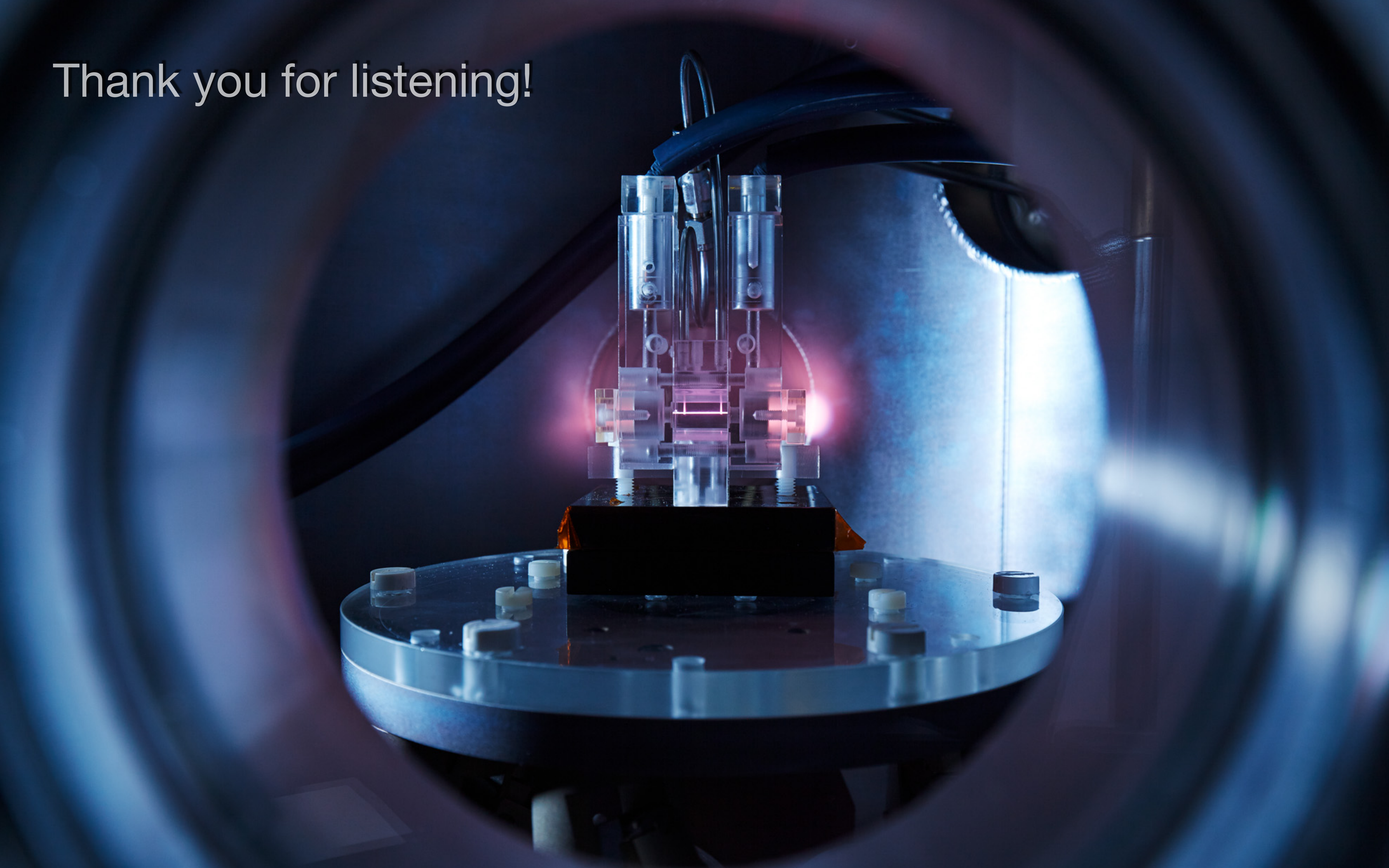
- full beam measured
- in agreement with MaMi specs

With plasma lens

- only core of beam measured
- new experiment in April for full characterization

Summary

- **Today, accelerators are large-scale, cutting-edge tools for high energy physics, photon science, cancer therapy, …**
- **Plasma technology offers a promising path to miniaturize accelerators by a thousandfold**
- **Hope:** miniaturization of accelerators leads to
  - significant cost reduction
  - widespread proliferation of compact accelerator technology → universities, hospitals, developing countries…
  - beams with new and extreme properties
- **Overarching goal:**
  - plasma accelerator research → usable plasma accelerators
- **Staged approach to get there:**
  - First (~10 year frame): demonstrate controlled, stable single stage → sufficient for most of applications (except HEP)
  - Then (>> 10 years): scale technology to energy frontier
- **DESY research facilities: LWFA at LUX/ATHENA, PWFA at FLASHForward▸▸**
- **Needs close, international collaboration between universities (for basic research), national labs (for research and engineering resources), and industry (e.g. laser engineering)**
- **If we do this right, plasmas may have a revolutionary impact on future accelerator applications**


Thank you for listening!