

FLASHFORWARD>> INTO THE FUTURE

Challenges and Prospects for Plasma-Wave Acceleration

Jens Osterhoff

FLASHFORWARD>> | Research Group for Plasma Wakefield Accelerators
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Accelerator Research and Development, Matter and Technologies
Helmholtz Association of German Research Centres, Berlin, Germany



simulation by Alberto Martinez de la Ossa

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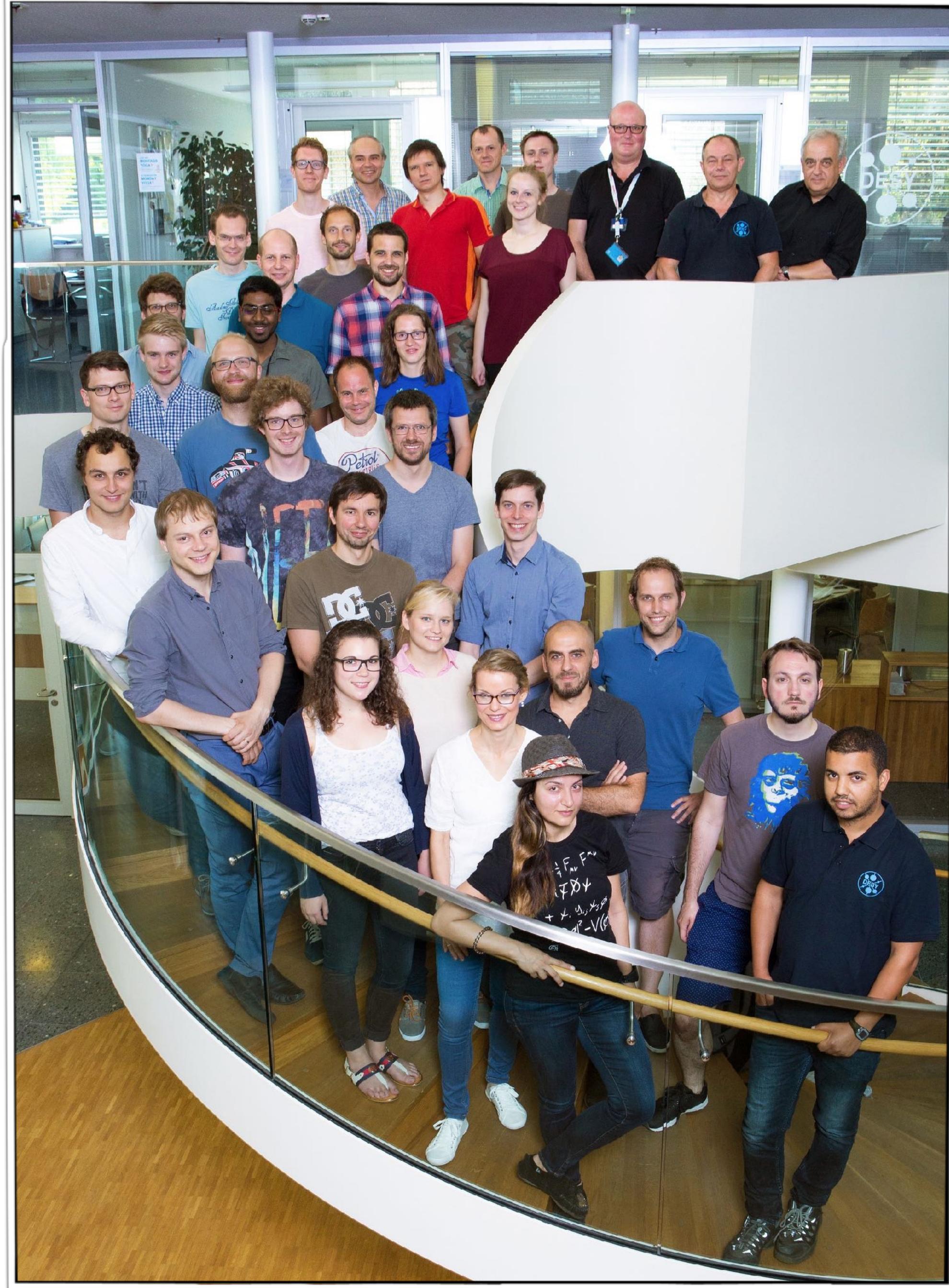
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> ...many DESY engineering & technical support groups

FLASHFORWARD► active collaboration partners

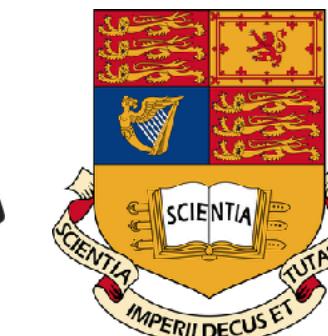
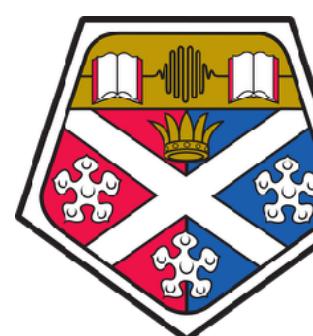
Helmholtz



Networks



Universities



National labs

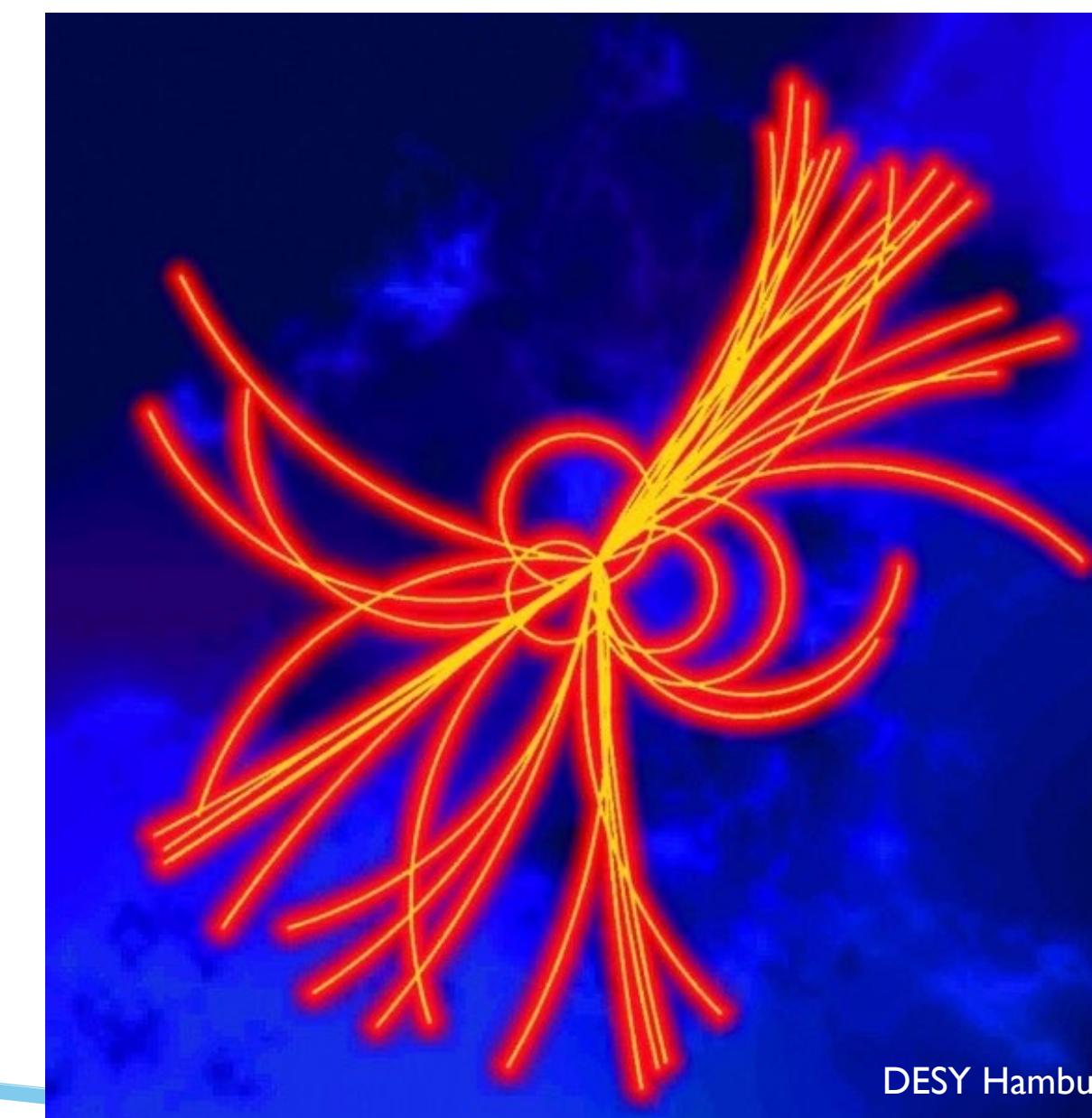
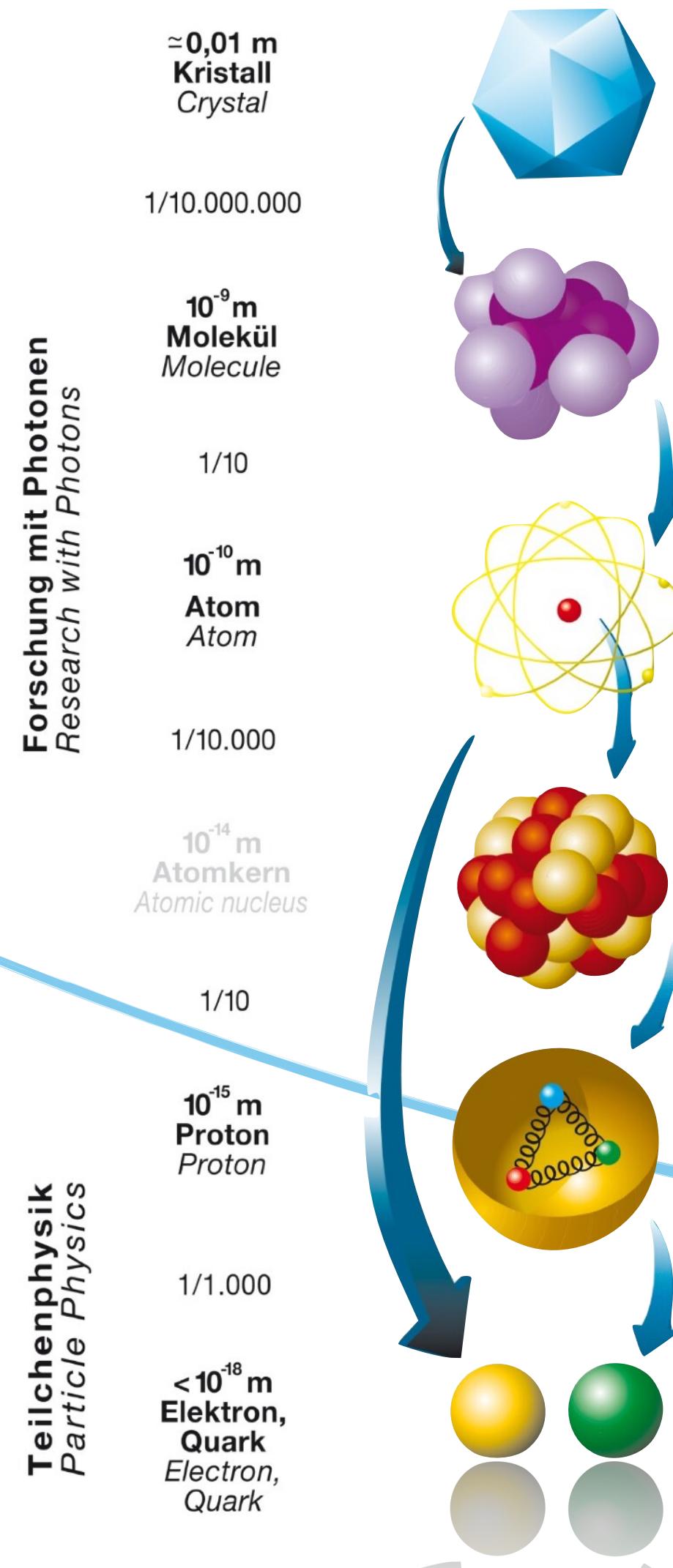


Science & Technology
Facilities Council



Accelerators are at the heart of high-energy photon sources and particle colliders

CUTTING-EDGE, HIGH-END SLOW-MOTION-CAMERAS AND MICROSCOPES TO STUDY **THE STRUCTURE OF MATTER**



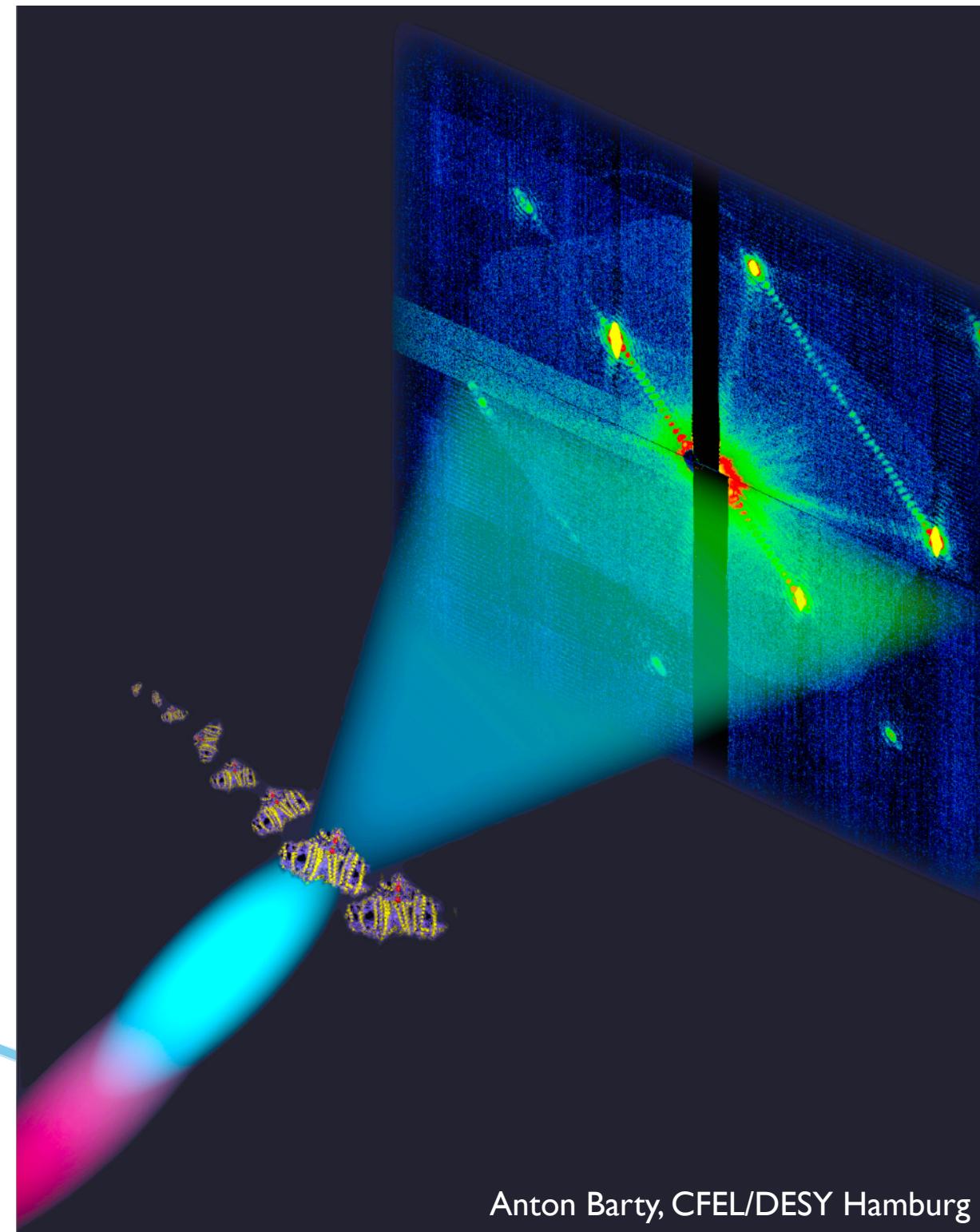
*Simulation of the decay of
a Higgs Boson (LHC, CERN)*

Particle colliders
investigation of the fundamental
forces and constituents of matter



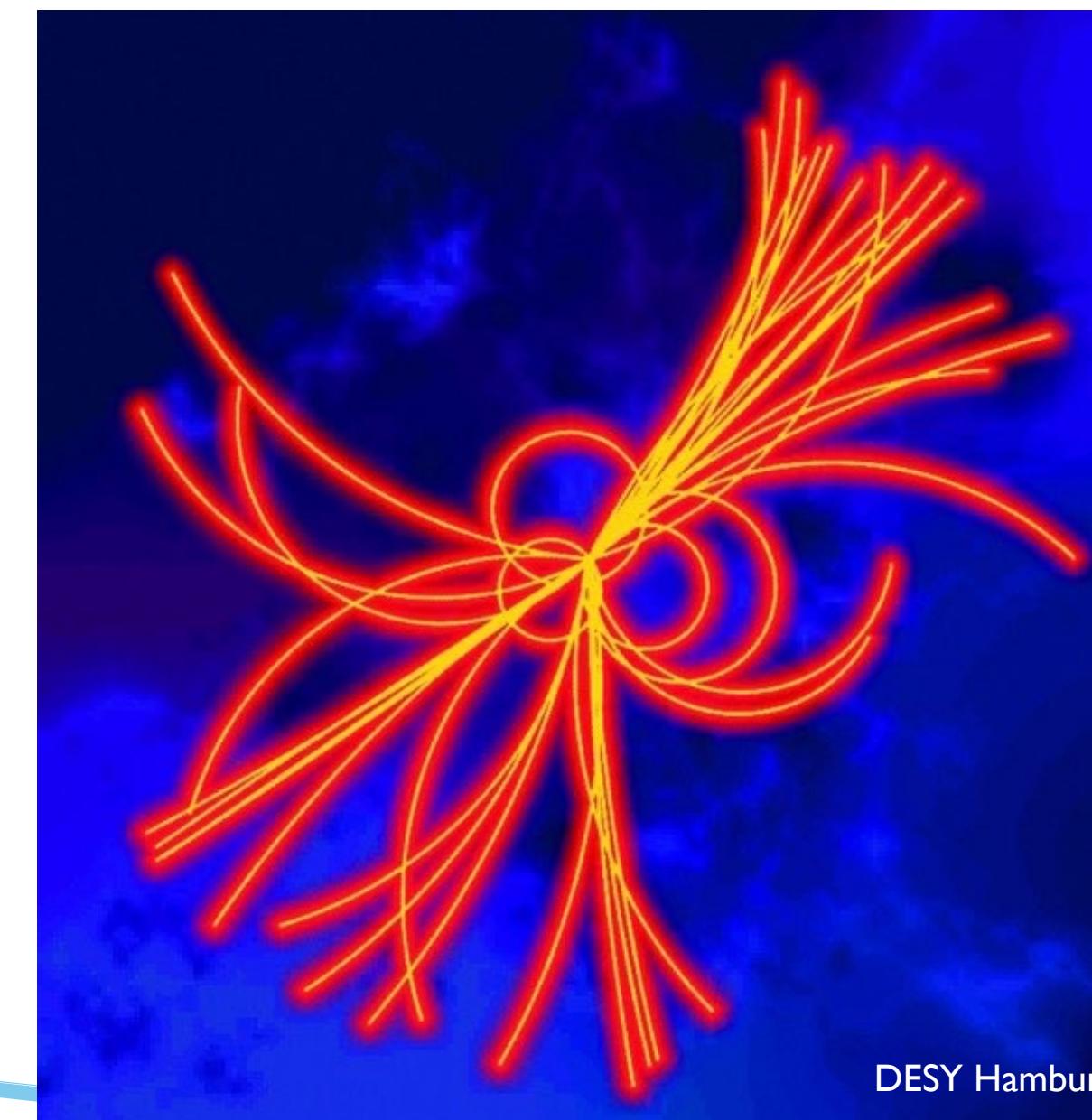
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*Illustration of an FEL-pulse
diffracting off a protein (XFEL, DESY)*

Synchrotron photon sources, e.g. Free-Electron Lasers (FELs)
investigation of processes on atomic and molecular scales



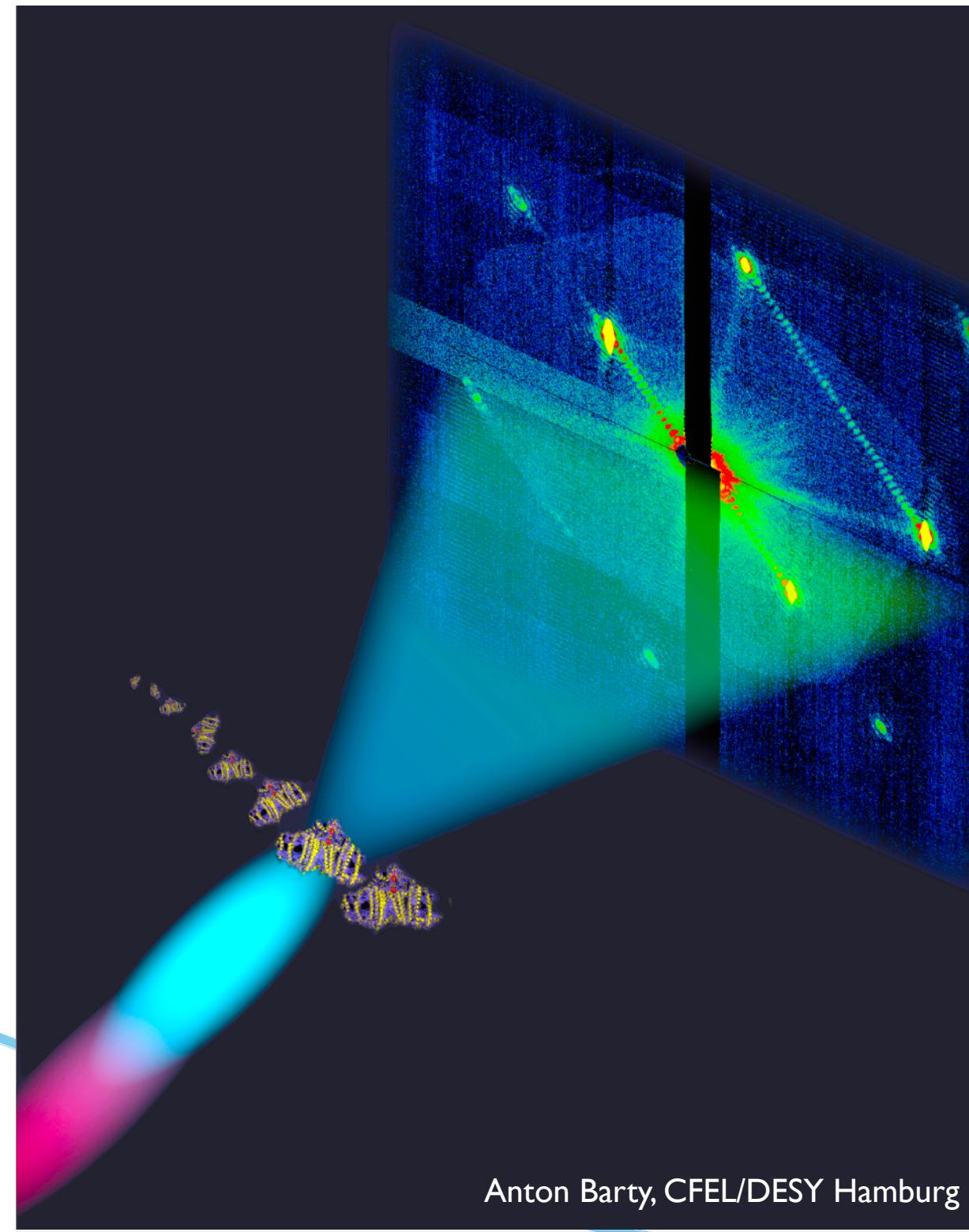
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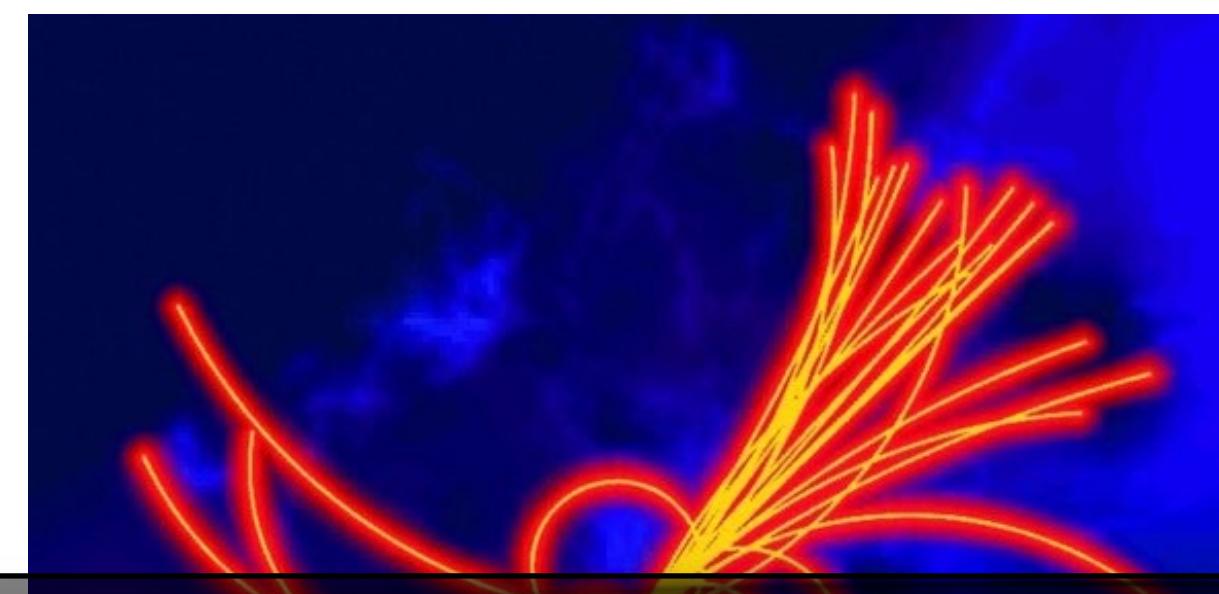
Accelerators are at the heart of high-energy photon sources and particle colliders

CUTTING-EDGE, HIGH-END SLOW-MOTION-CAMERAS AND MICROSCOPES TO STUDY **THE STRUCTURE OF MATTER**



*Illustration of an FEL-pulse
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Synchrotron photon sources, e.g. Free-Electron Lasers (FELs)
investigation of processes on atomic and molecular scales



Applications beyond matter

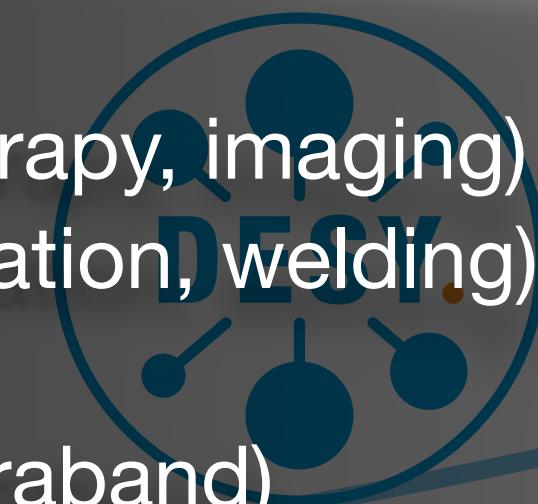
- medical accelerators (e.g. cancer therapy, imaging)
- material processing (e.g. food sterilization, welding)
- accelerator-driven reactors
- cargo scanning (e.g. for nuclear contraband)

DESY Hamburg

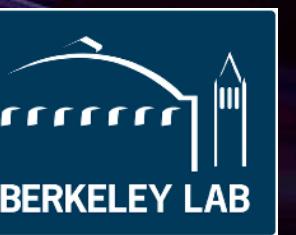
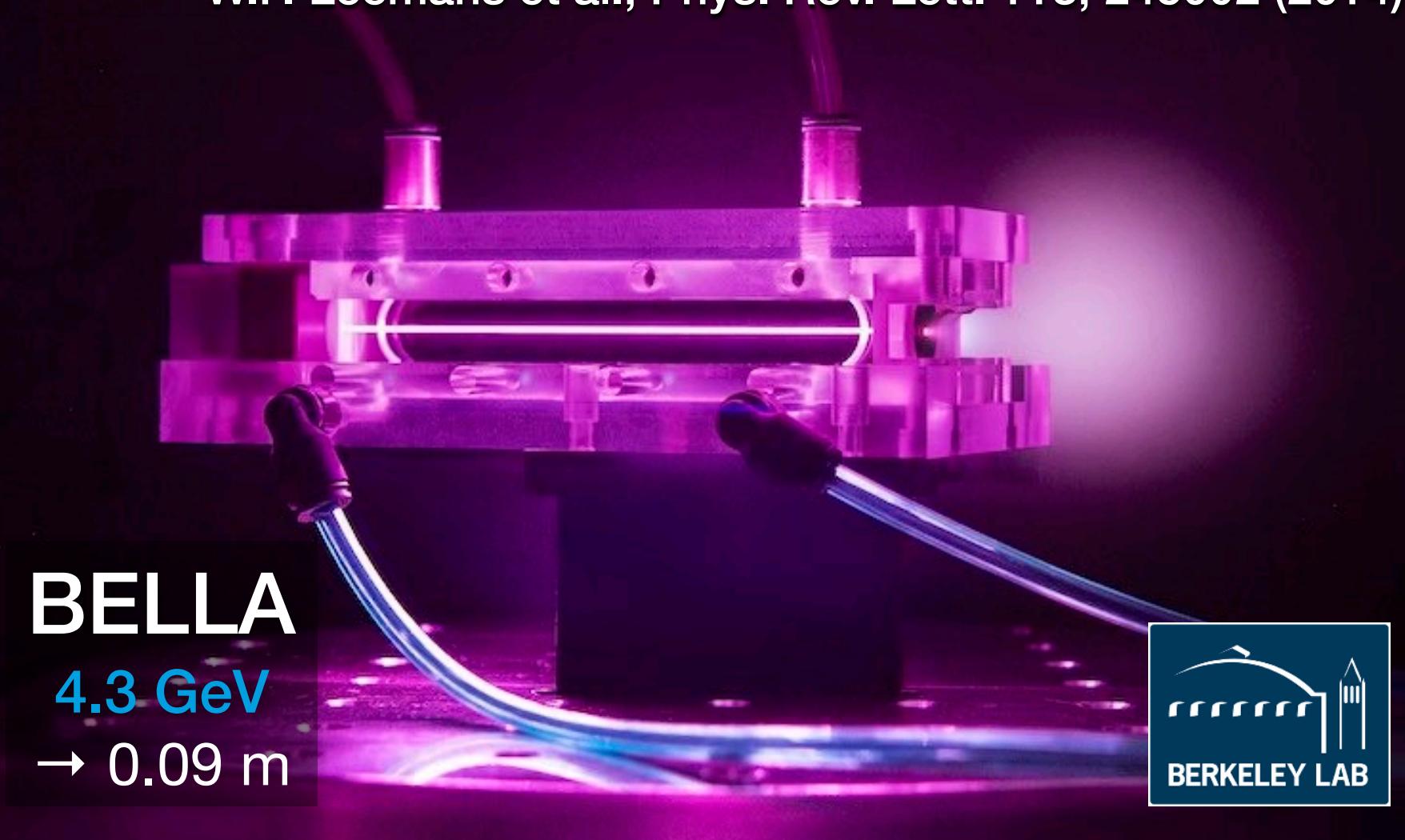
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Particle colliders

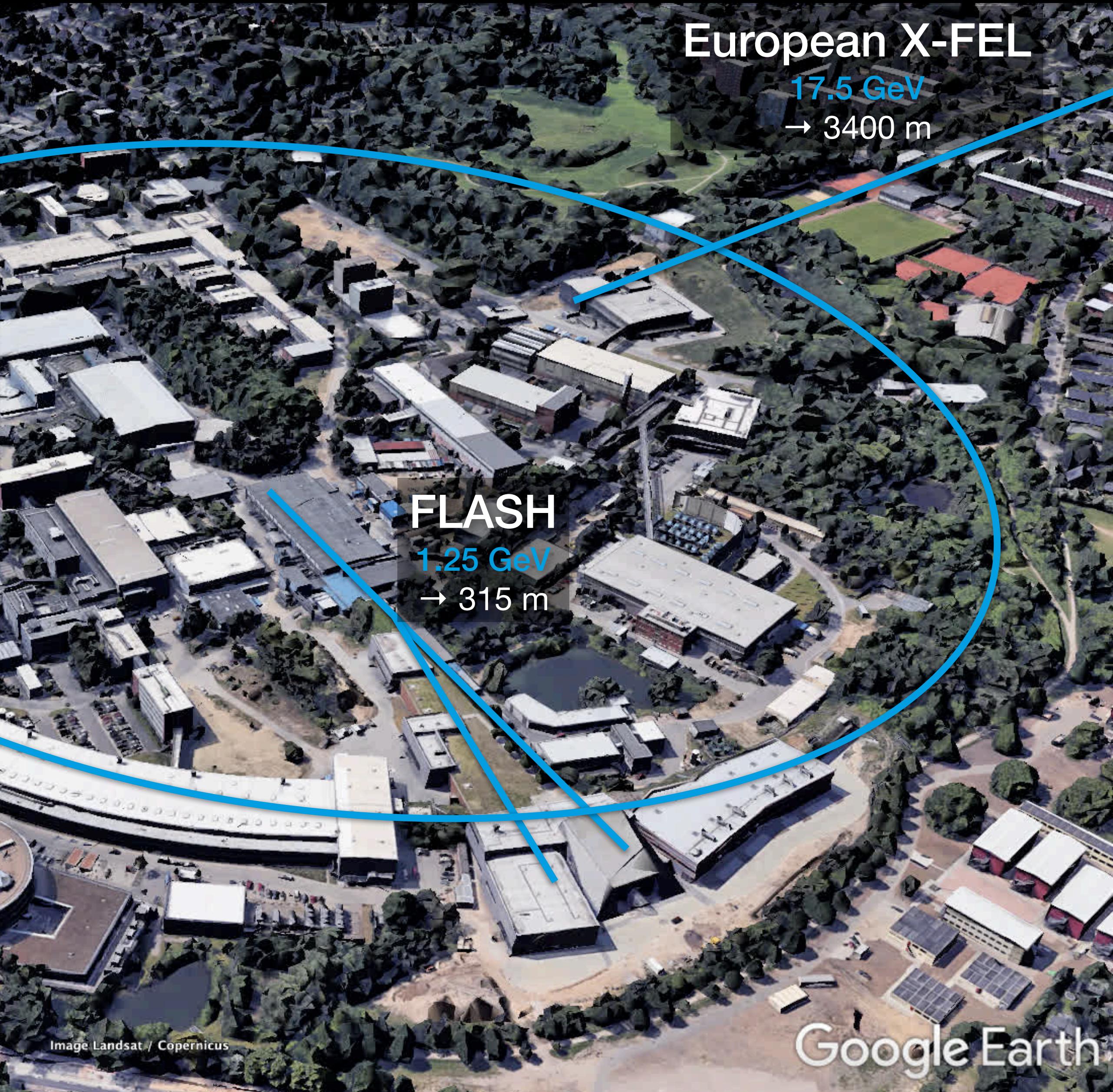
investigation of the fundamental
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W.P. Leemans et al., Phys. Rev. Lett. 113, 245002 (2014)

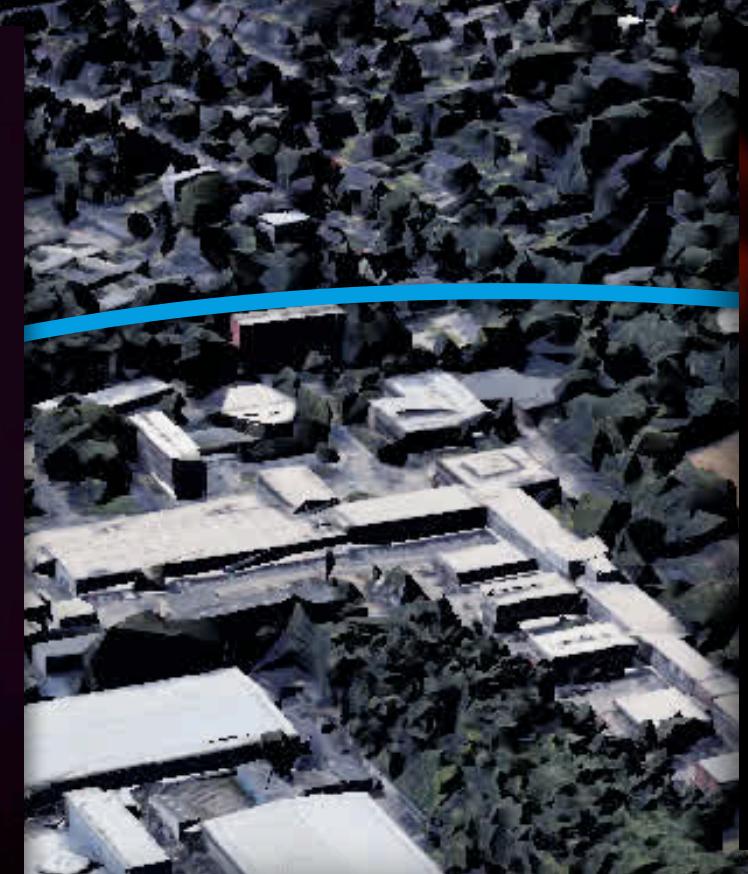
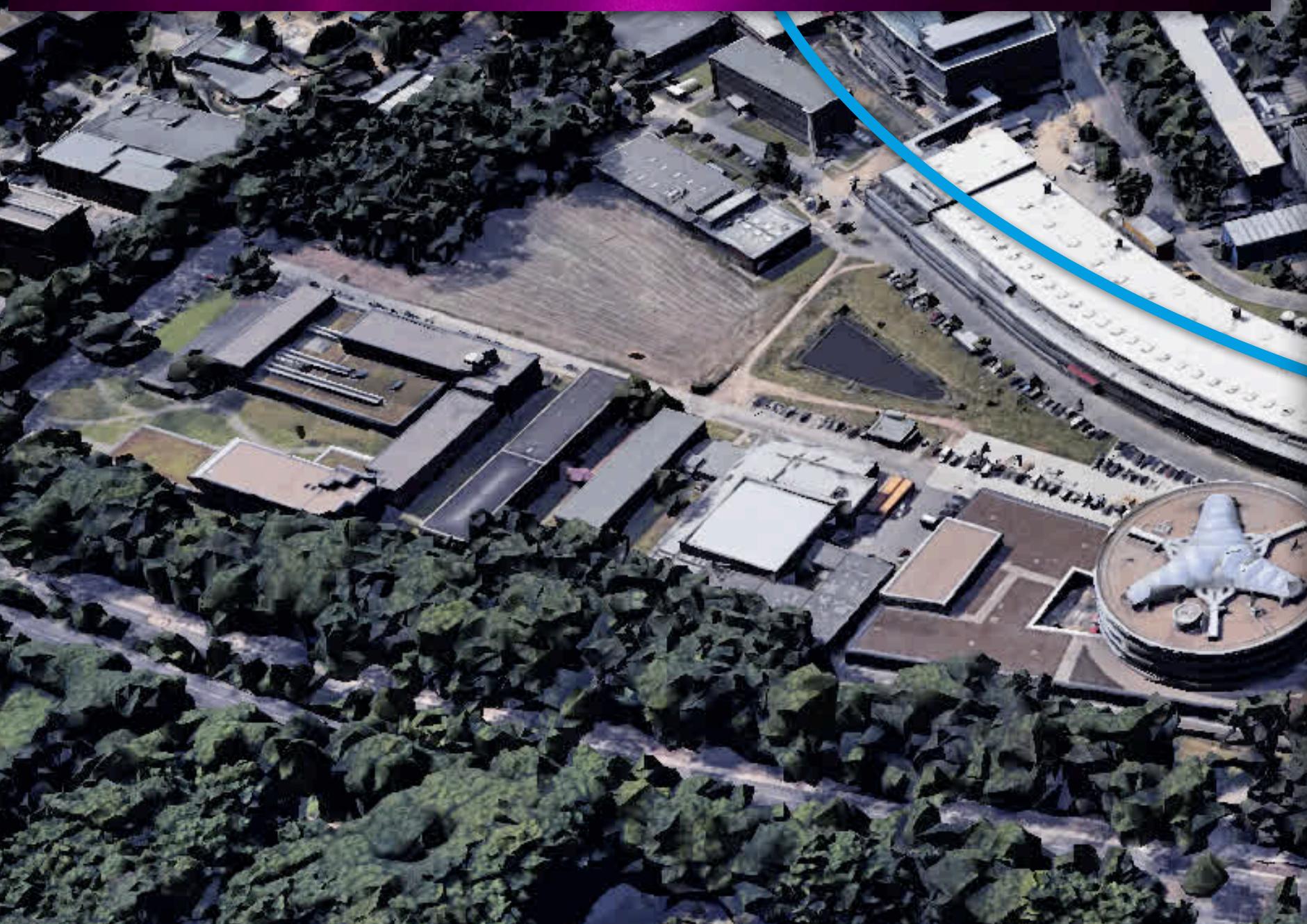


PETRA III
6 GeV
≈ 2300 m



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

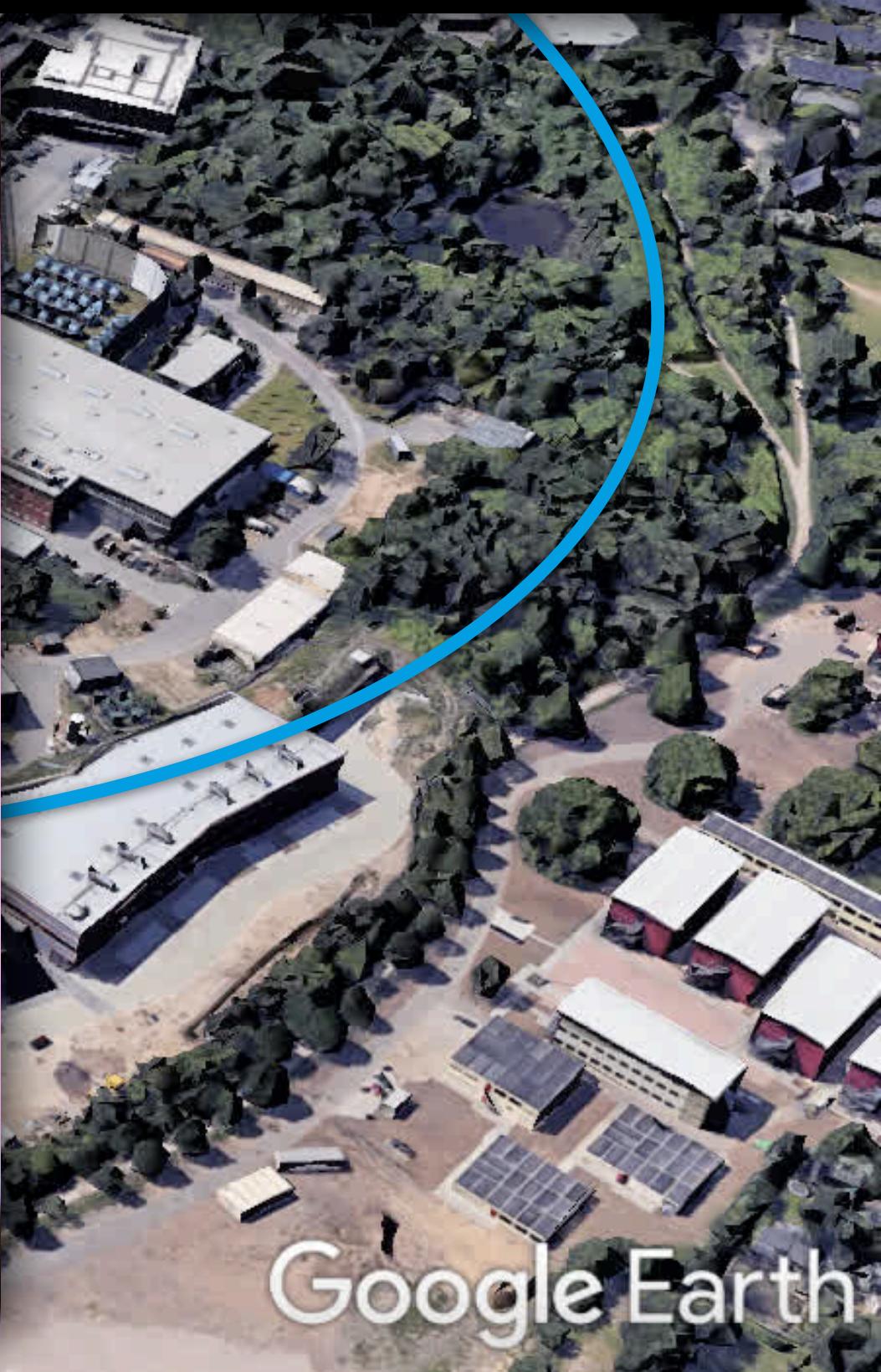
BELLA
4.3 GeV
 $\rightarrow 0.09 \text{ m}$



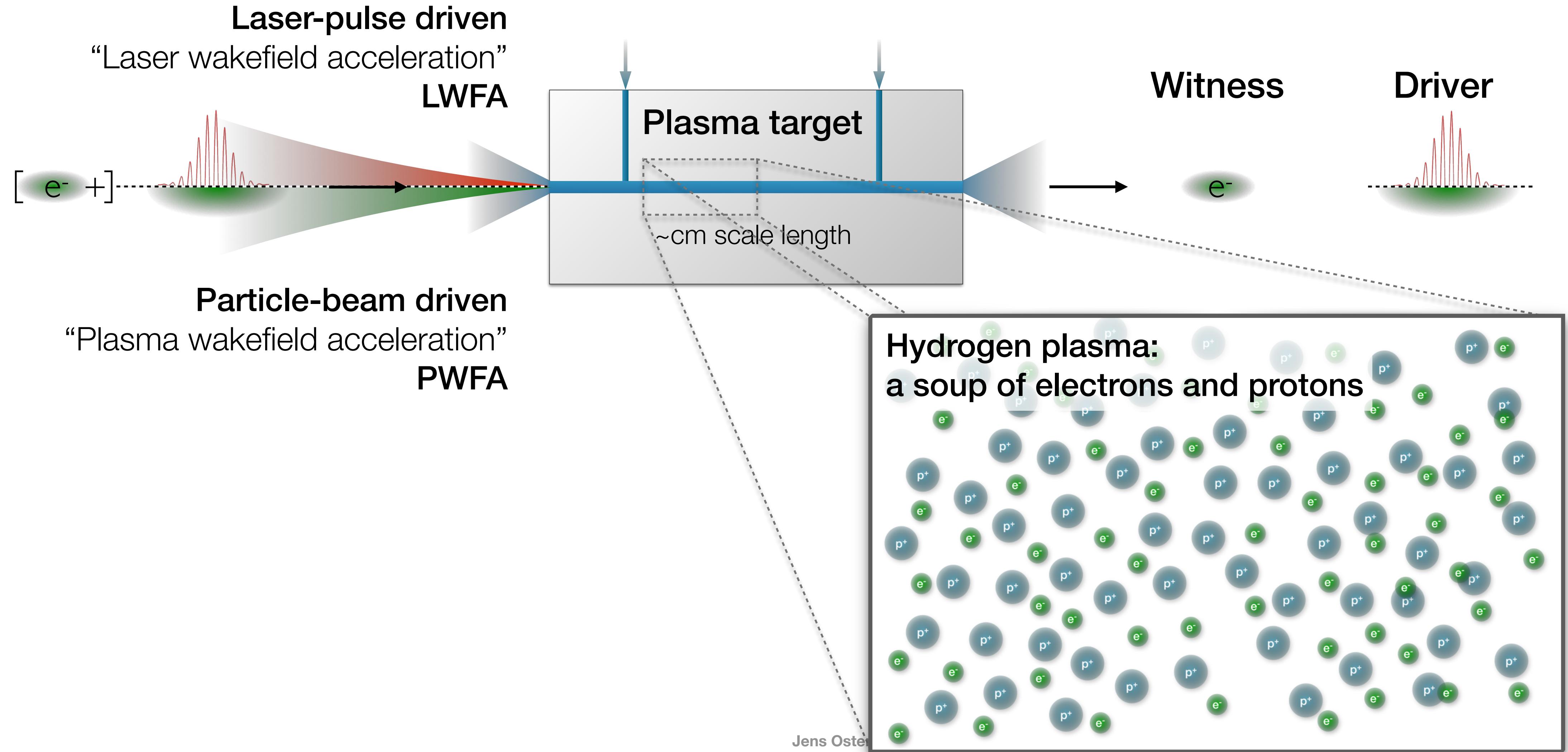
CLEAR
 kT/m plasma lens $\rightarrow 0.015 \text{ m}$



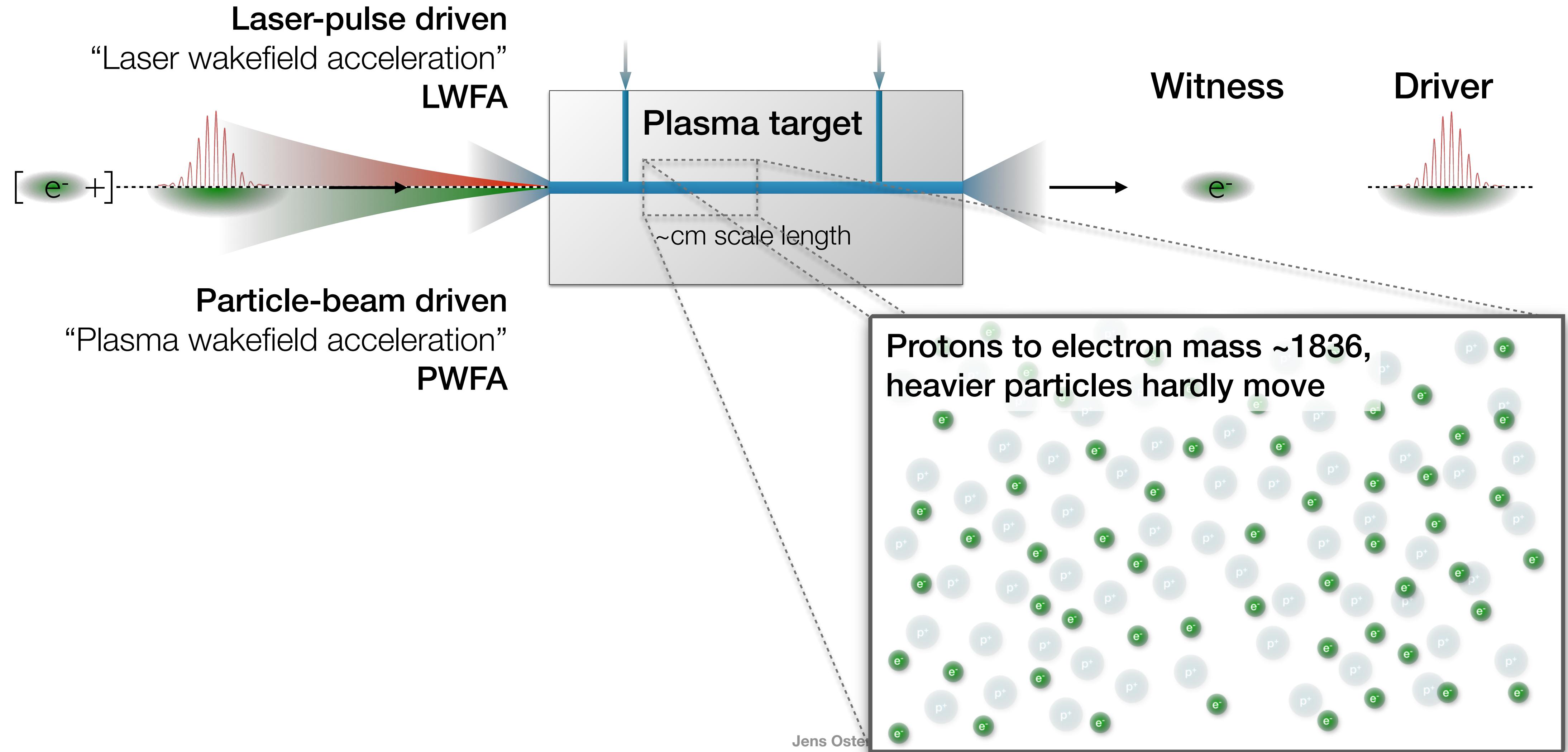
FLASHFORWARD▶▶
2.5 GeV (from simulation)
 $\rightarrow 0.03 \text{ to } 0.30 \text{ m}$



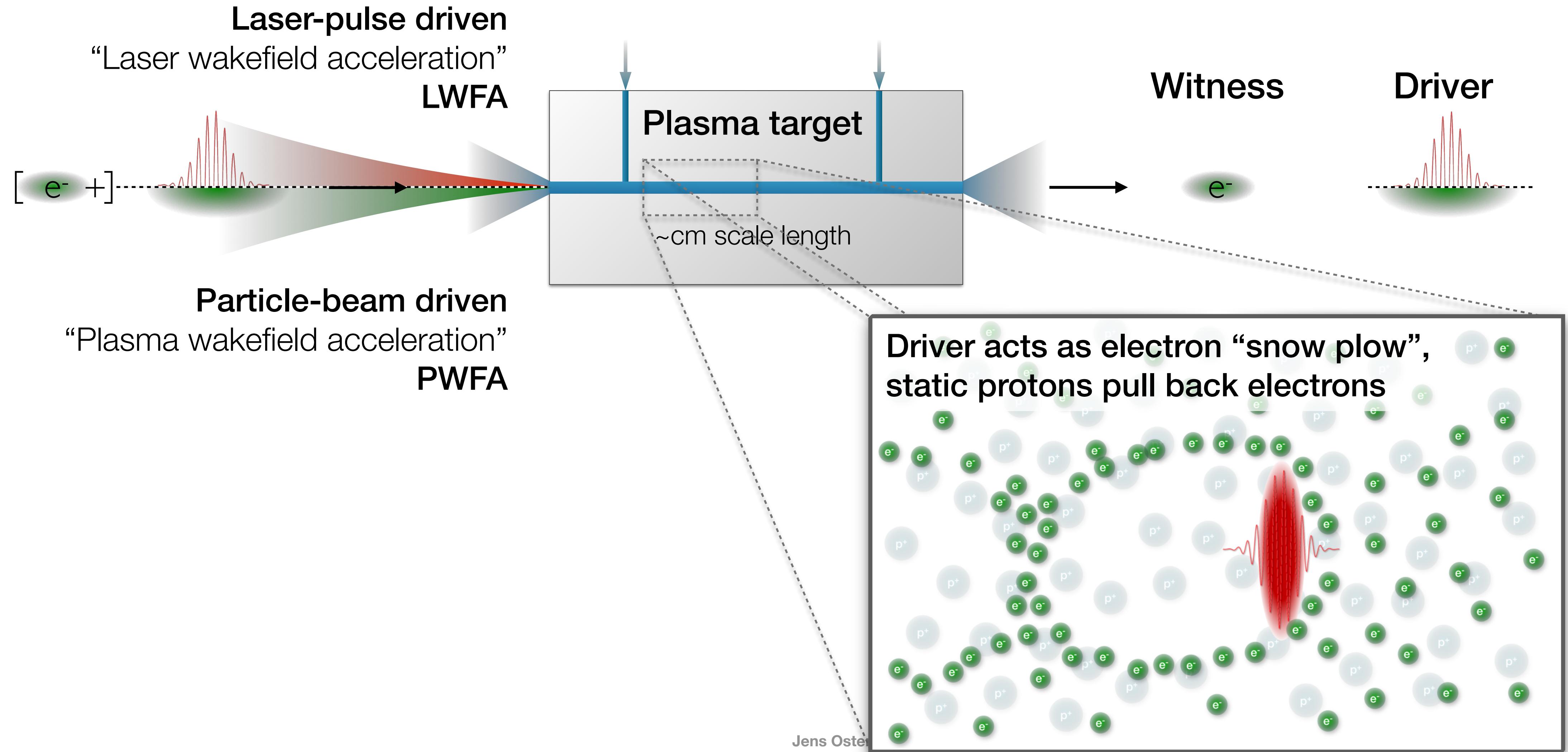
Plasma wakefield acceleration in a nutshell



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Plasma wakefield acceleration in a nutshell



Plasma wakefield acceleration in

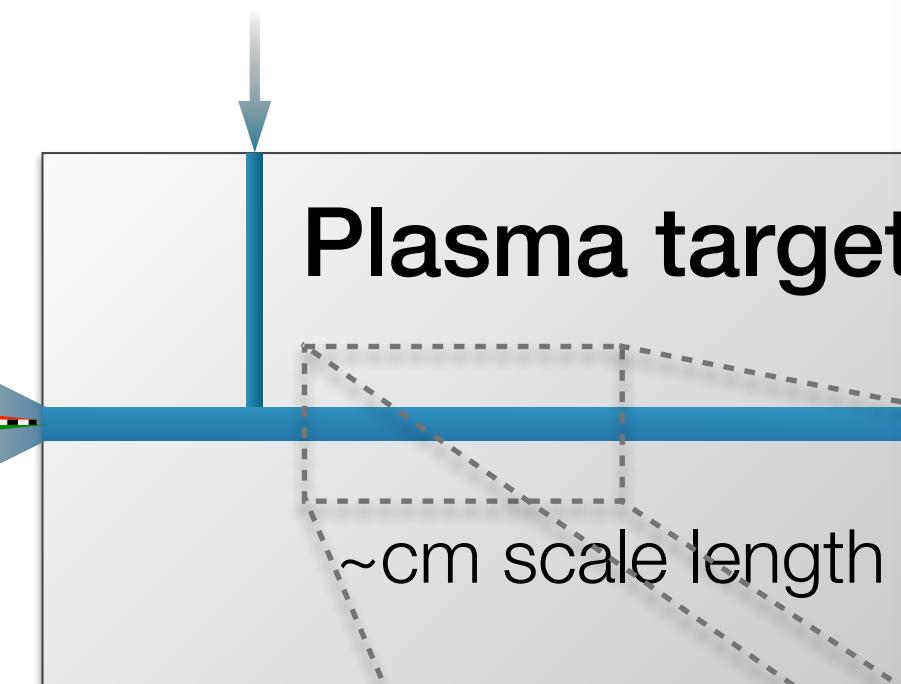
Laser-pulse driven
“Laser wakefield acceleration”

LWFA

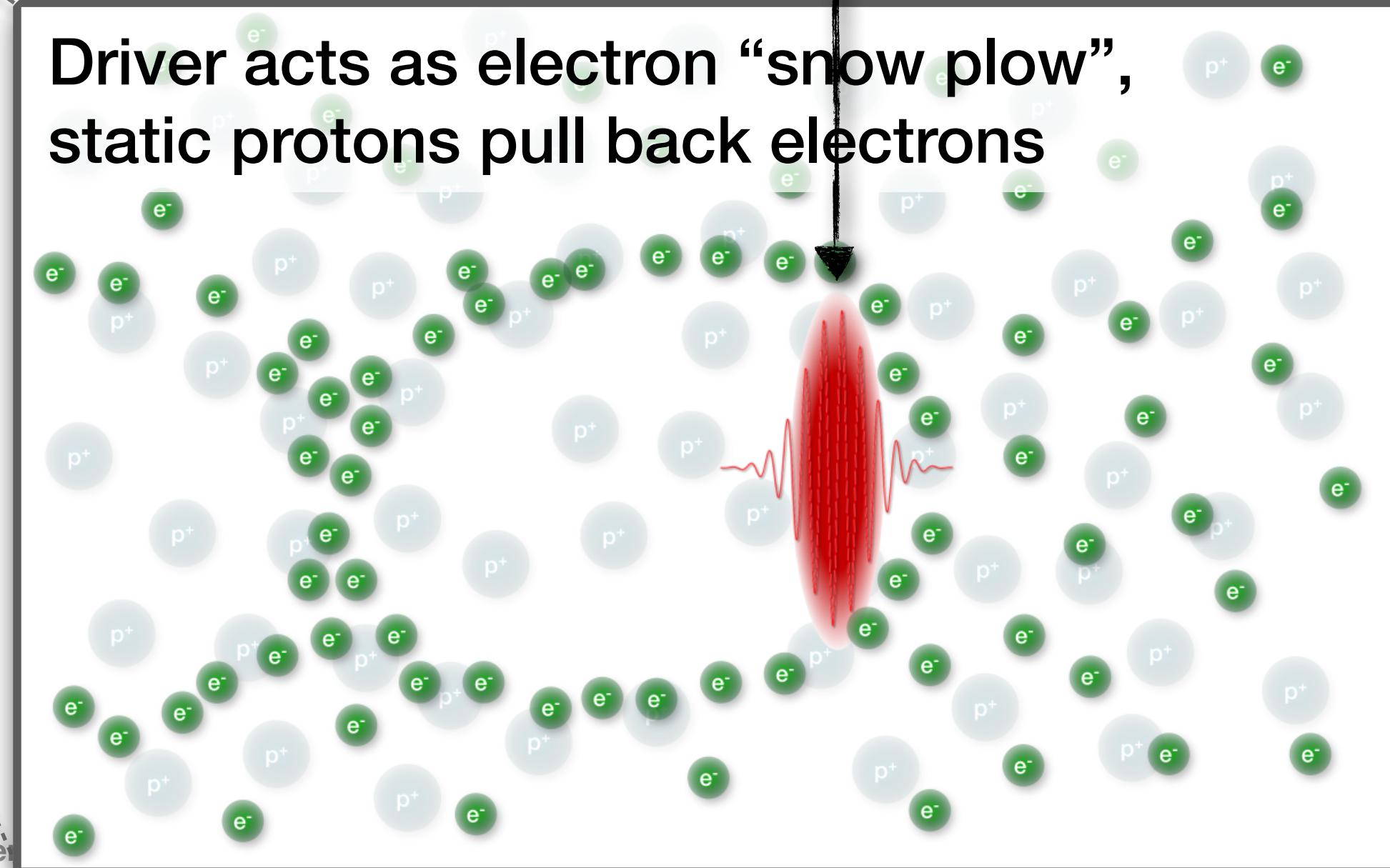
Particle-beam driven

“Plasma wakefield acceleration”

PWFA



Driver acts as electron “snow plow”,
static protons pull back electrons



Plasma wakefield acceleration in a nutshell



Particle-beam driven
“Plasma wakefield acceleration”
PWFA

Driver acts as electron “snow plow”,
static protons pull back electrons

Jens Oster

F



a nutshell

“Particle-beam driven
Plasma wakefield acceleration”

Bunch duration: fs

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

Size of structure

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

typically **$\lambda_p \approx 100 \mu\text{m}$** (for $n_e \approx 10^{17} \text{ cm}^{-3}$)

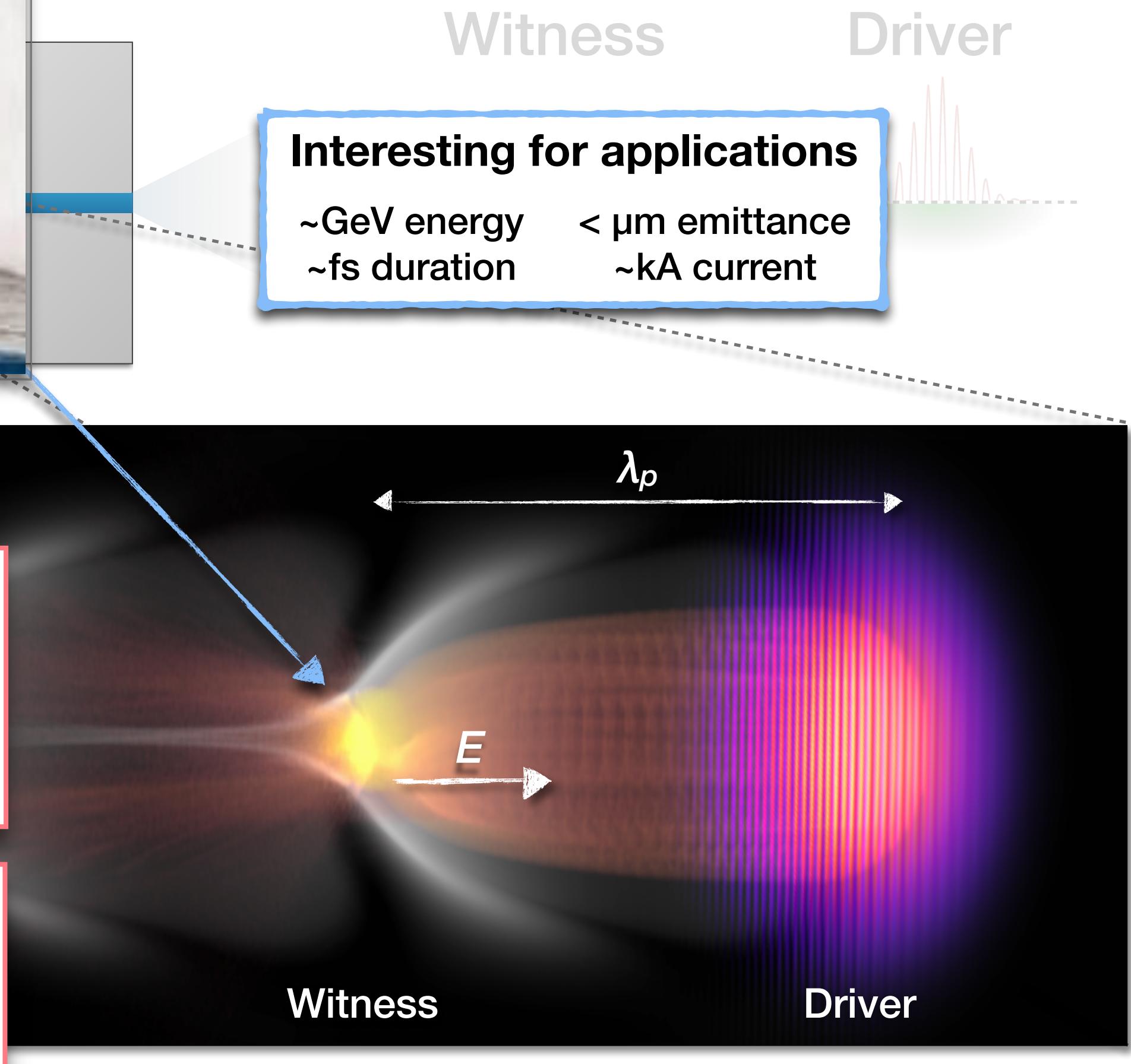
GeV energy gain over cm

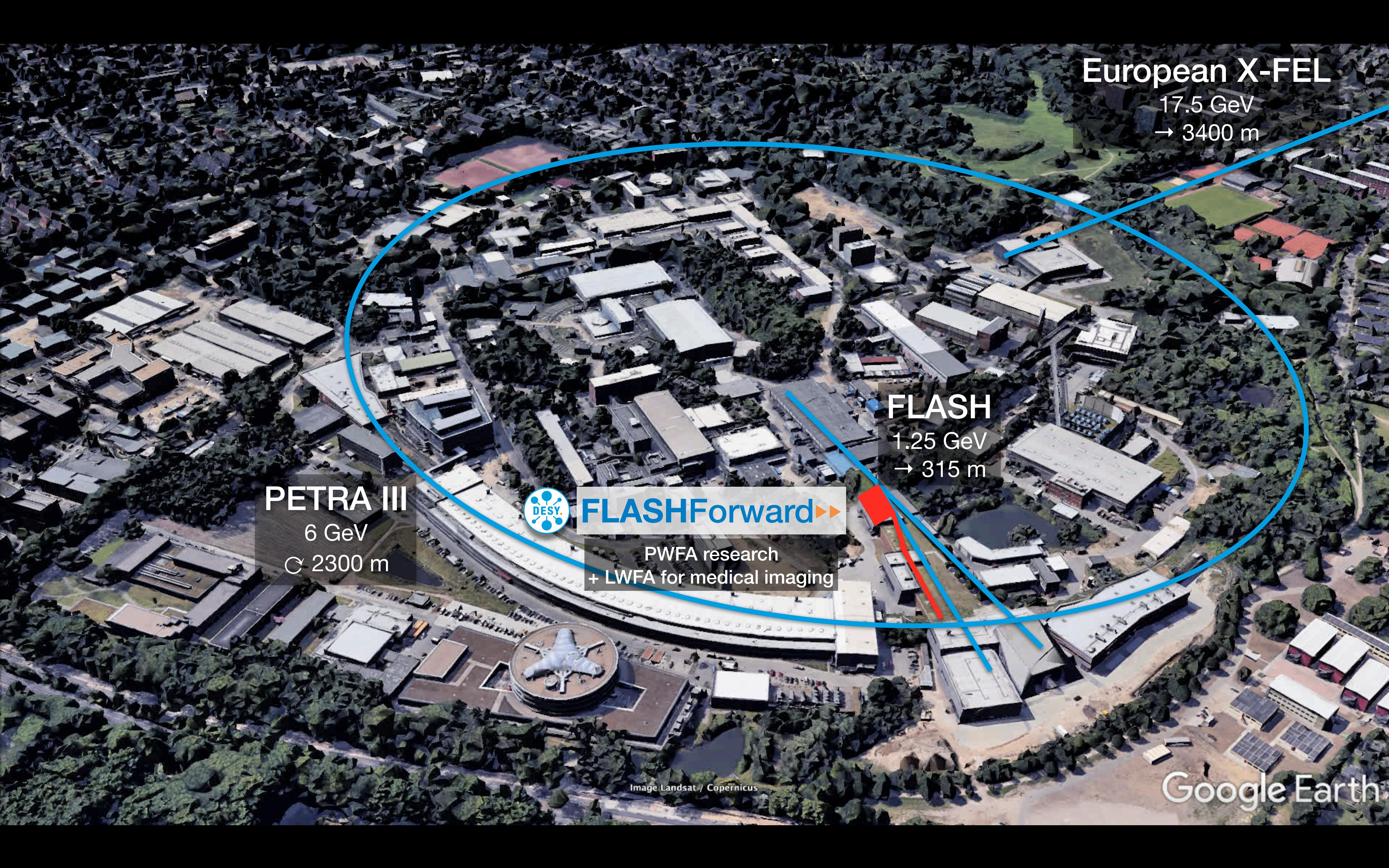
- W.P. Leemans et al.,
Nature Physics 2, 696 (2006)

Electric field strength

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

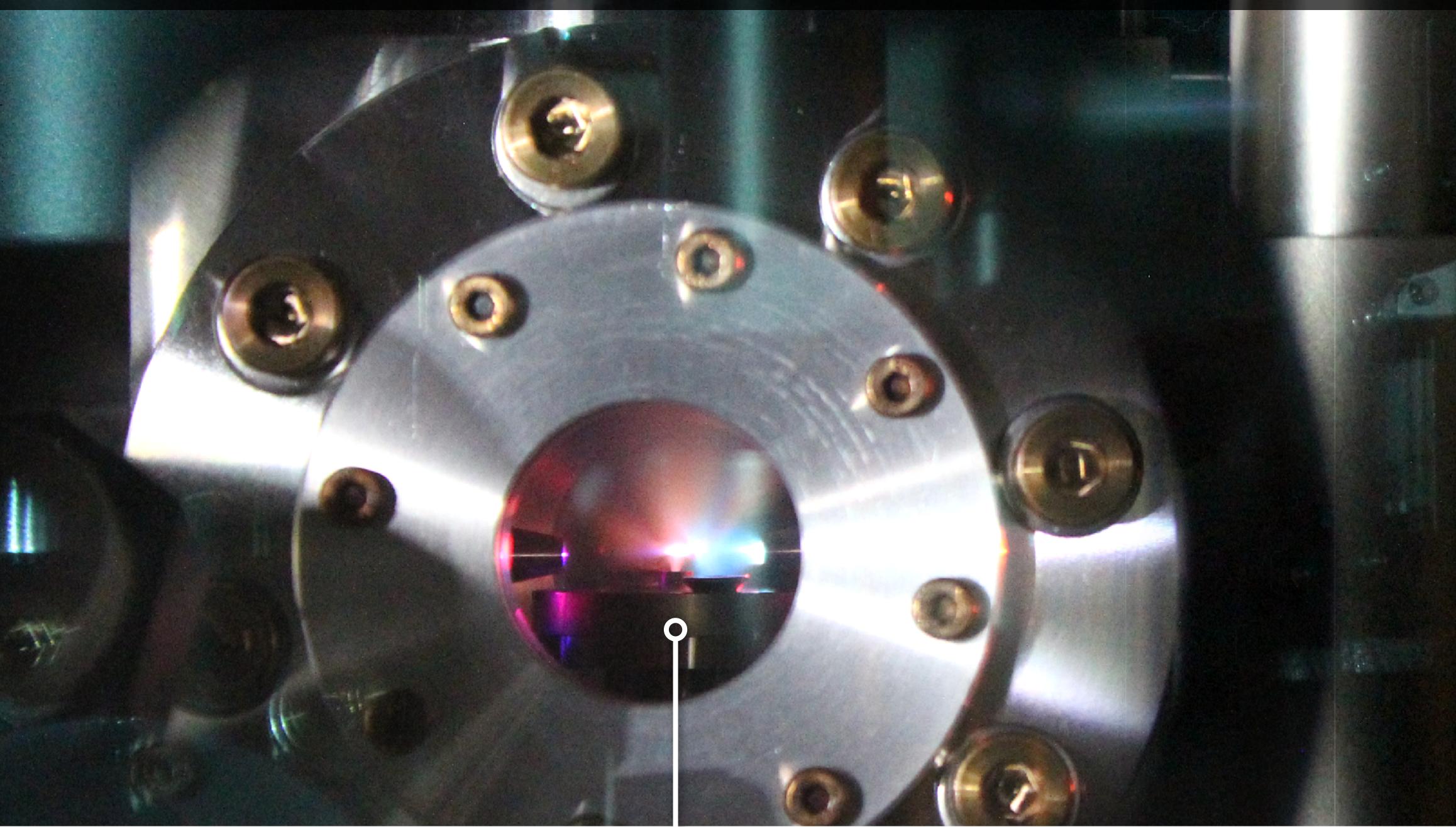
typically **$E \approx 33 \text{ GV/m}$** (for $n_e \approx 10^{17} \text{ cm}^{-3}$)





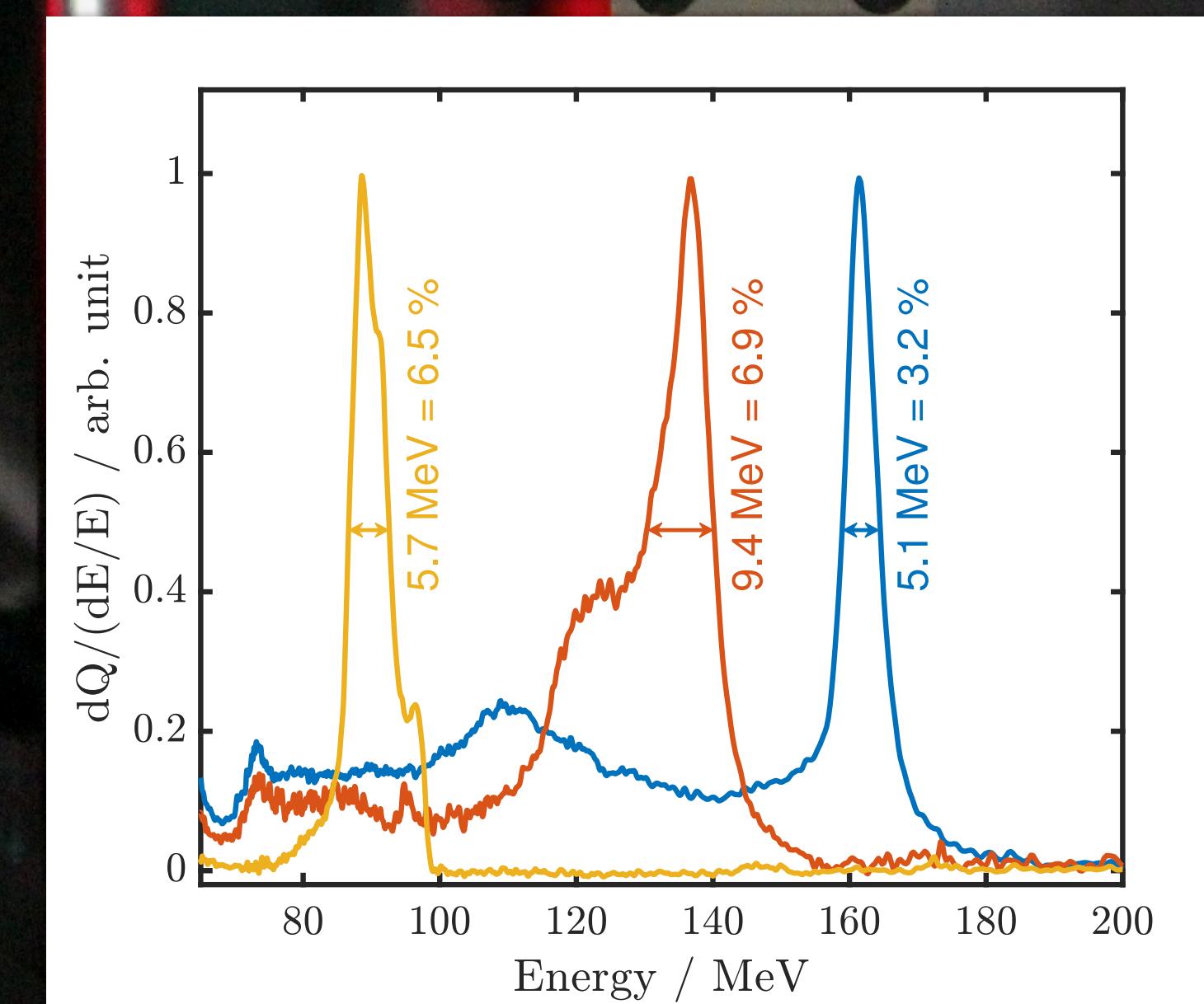
FLASHFORWARD ► laser-wakefield accelerator application

MEDICAL IMAGING PROTOTYPING



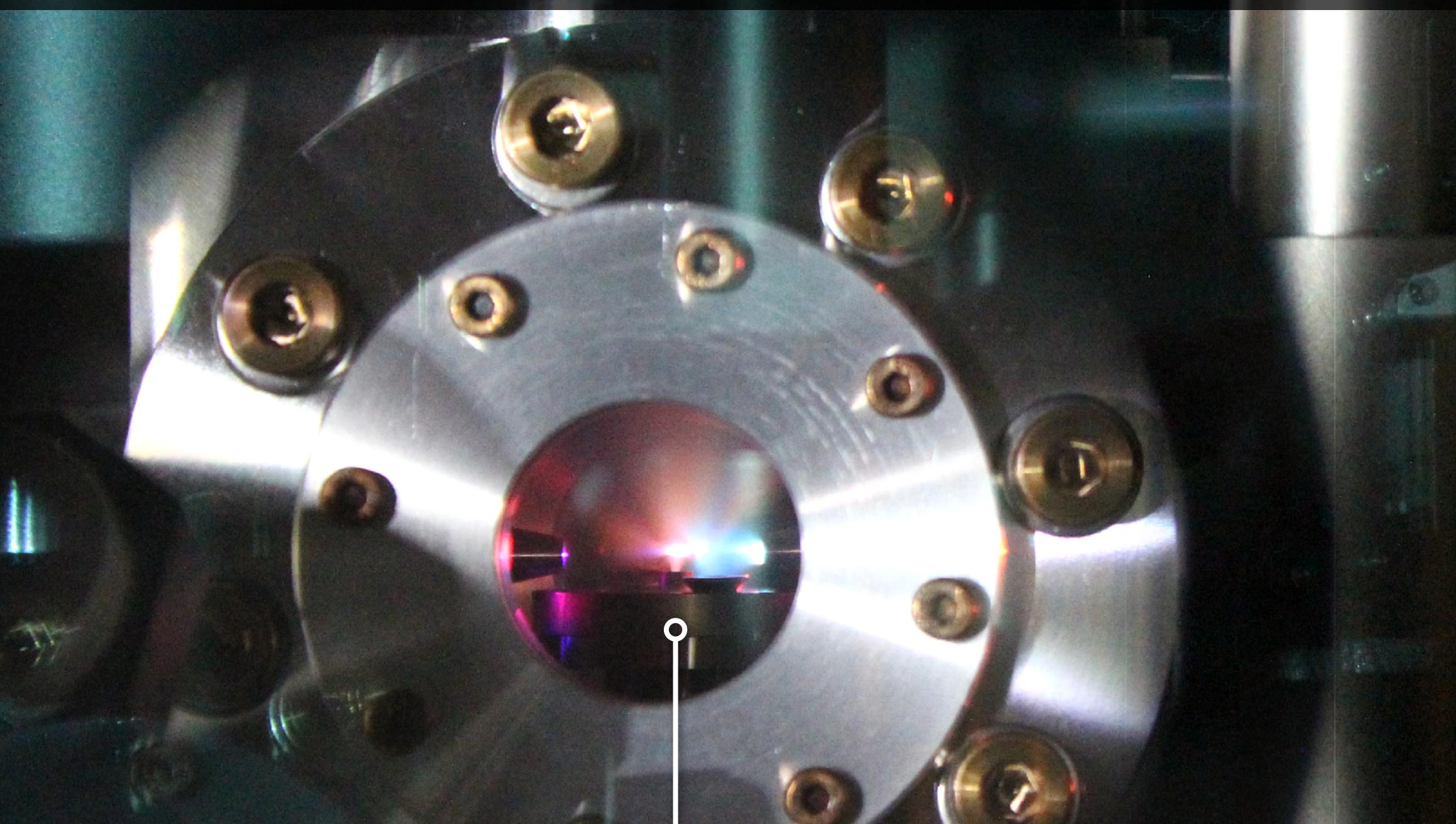
Plasma accelerator (2 mm long)

- ✓ driven by 25 TW Ti:sapphire laser
- ✓ *typical:* ionization injection at 1 Hz (up to 10 Hz):
~1 mrad divergence, ~1 mrad pointing stability from source,
~1 μm norm. emittance, $48 \pm 5 \text{ pC}$ of charge, energy up to 160 MeV



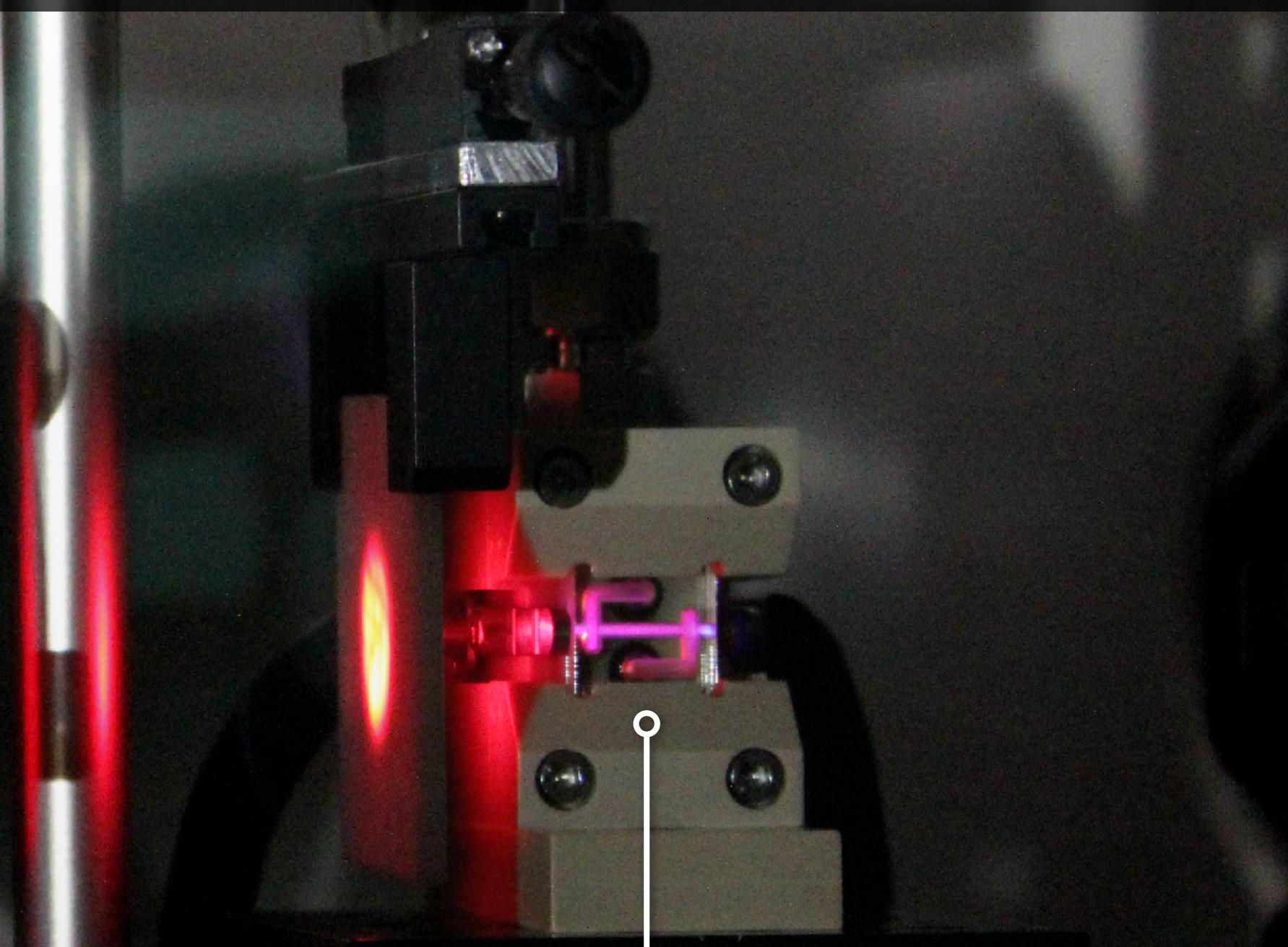
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MEDICAL IMAGING PROTOTYPING



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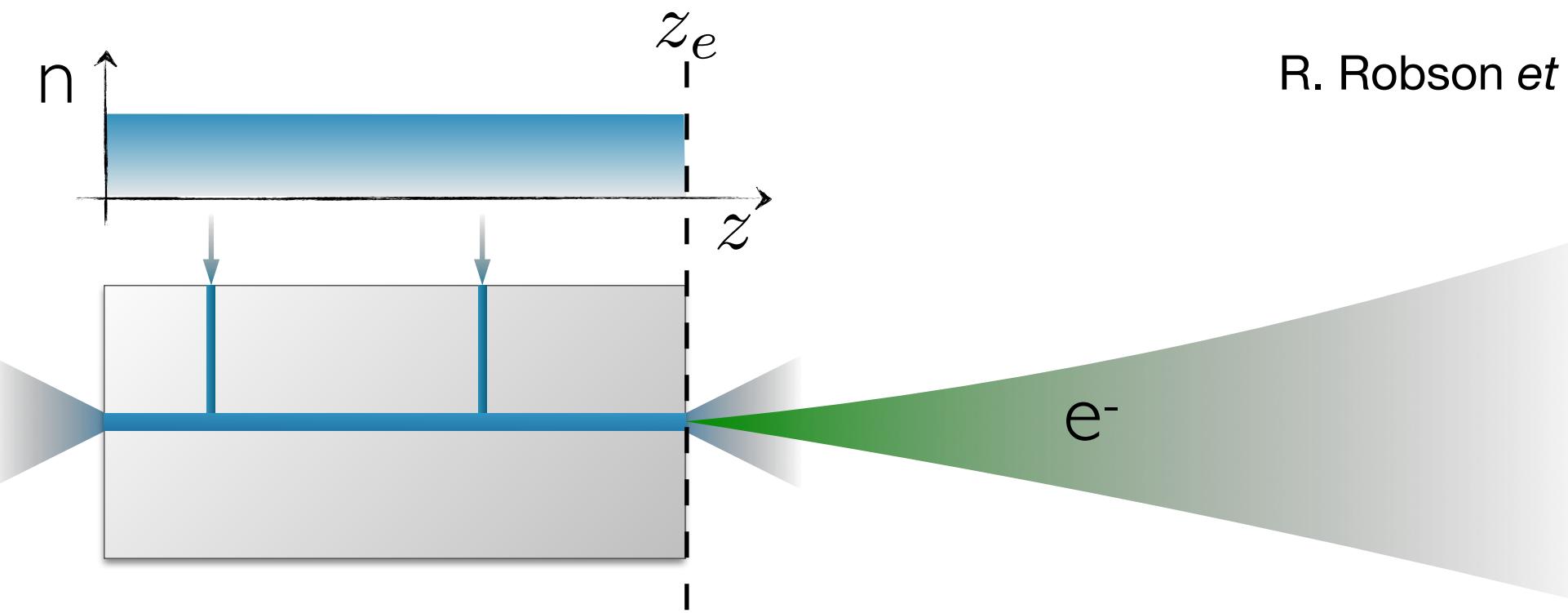
Active plasma lens (15 mm long)

- driven by 20 kV discharge
- radially symmetric, kT/m focussing optic

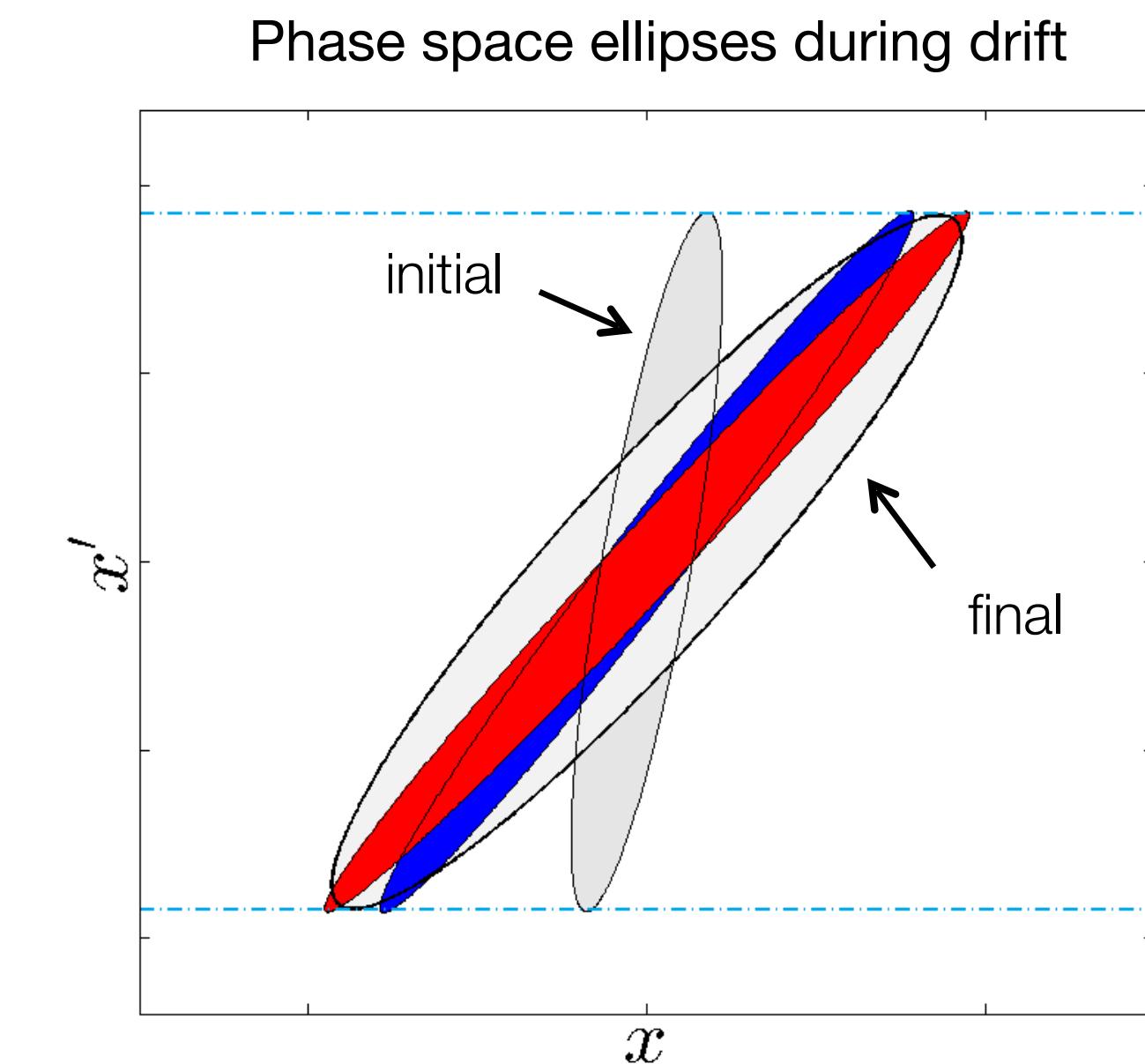
J.-H. Röckemann *et al.*, accepted at PRAB (2018)
C. A. Lindstrom *et al.*, Phys. Rev. Lett. 121, 194801(2018)

~0.2 m

Beam extraction from plasma with conservation of transverse normalized emittance



R. Robson et al., Annals of Physics **356**, 306 (2015); T. Mehrling et al., NIM A **829**, 367 (2016)

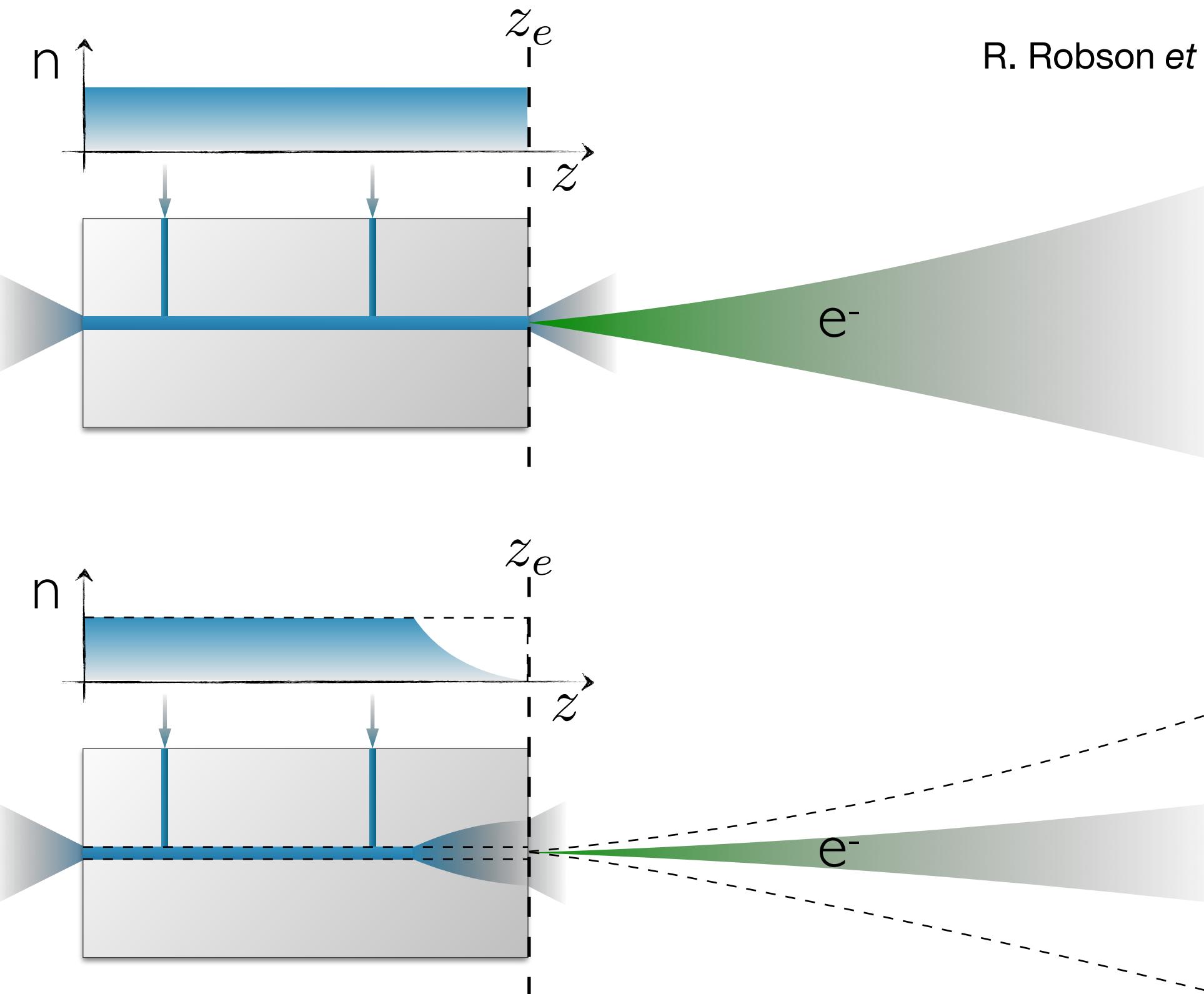


- beams at plasma exit:
 - ~% level energy spread
 - \lesssim mm beta function, ~mrad divergence
- leads to transverse emittance growth in free drift

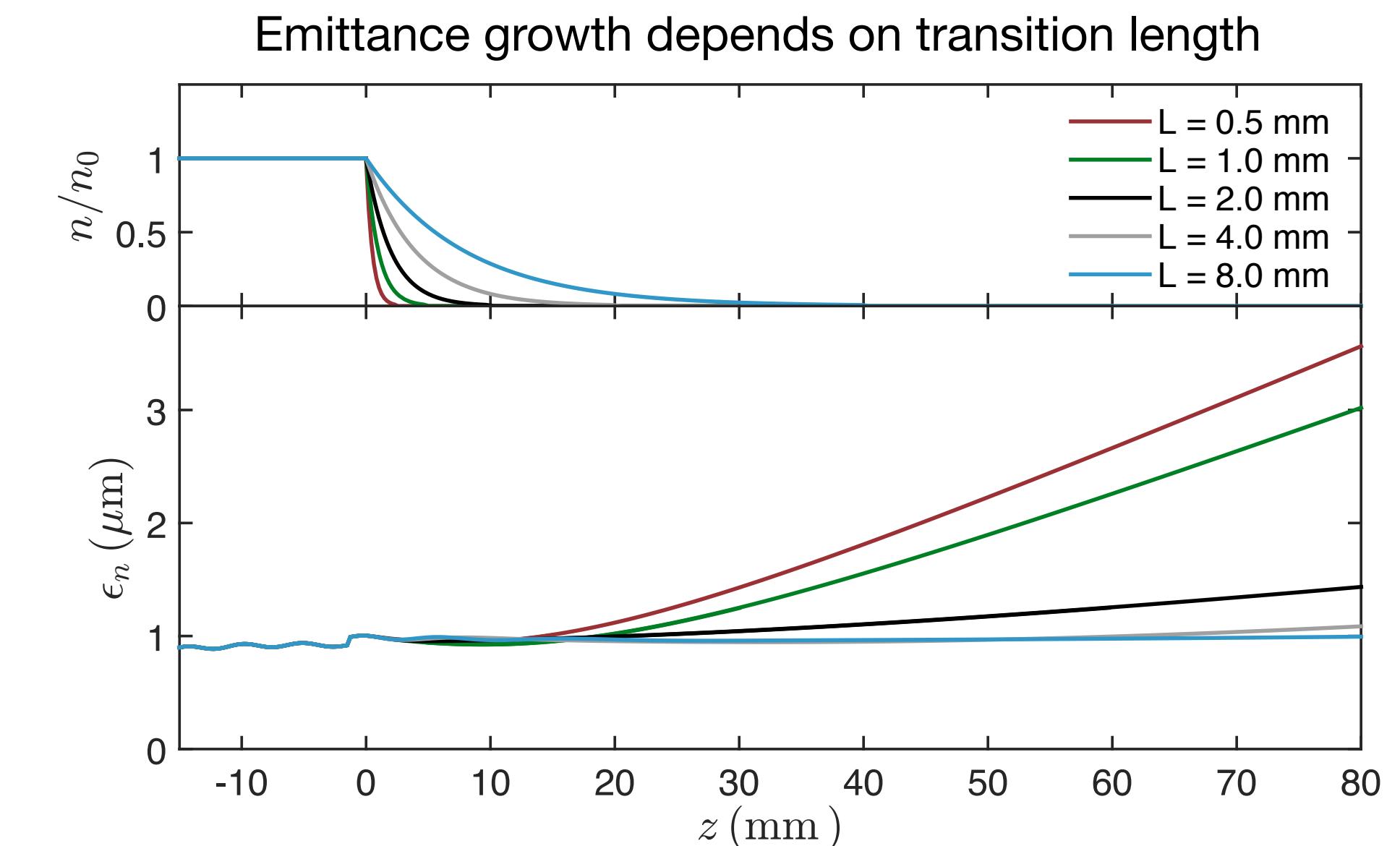
→ K. Floettmann, Phys. Rev. STAB 6, 034202 (2003)

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

Beam extraction from plasma with conservation of transverse normalized emittance



R. Robson et al., Annals of Physics **356**, 306 (2015); T. Mehrling et al., NIM A **829**, 367 (2016)



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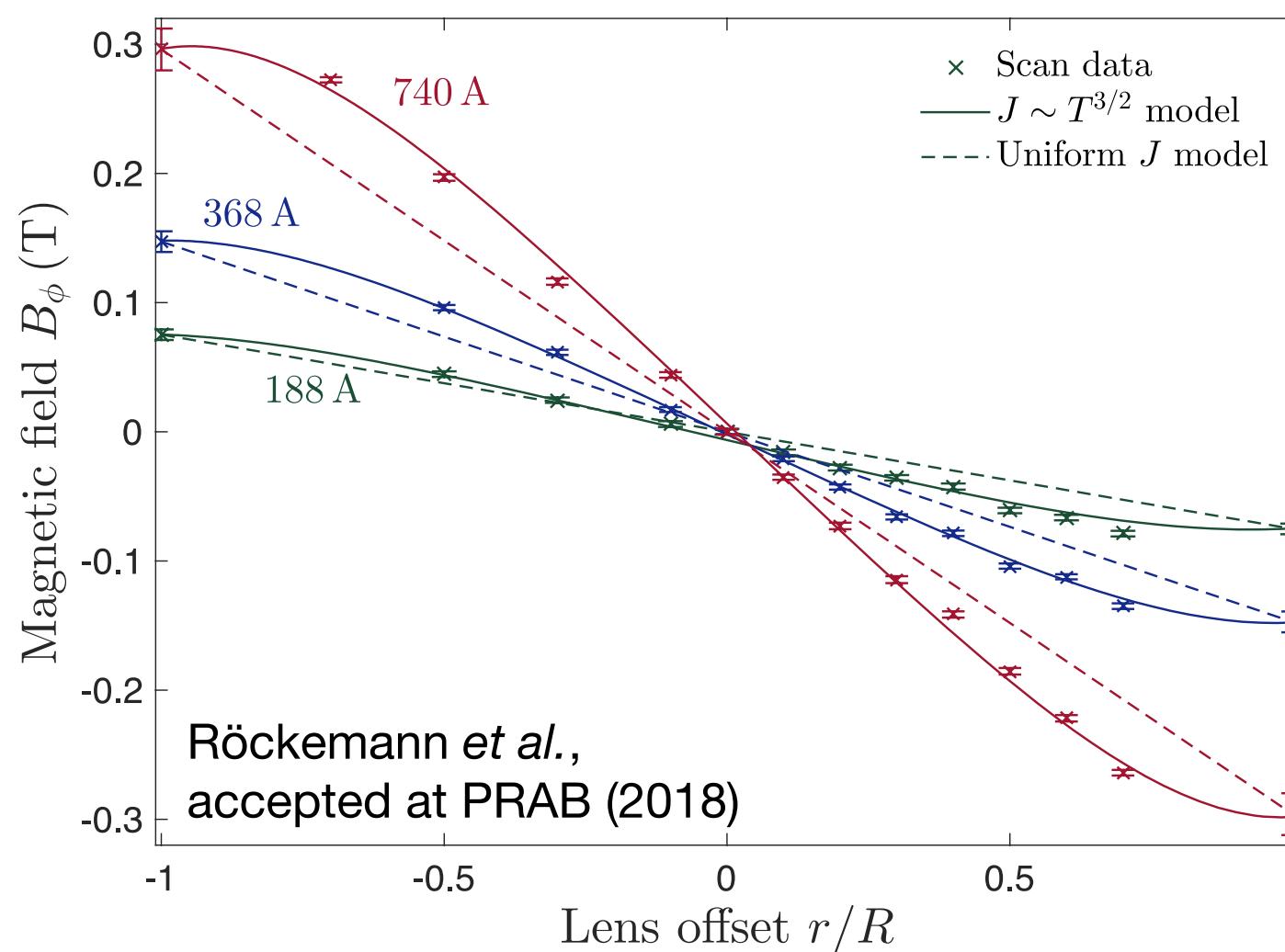
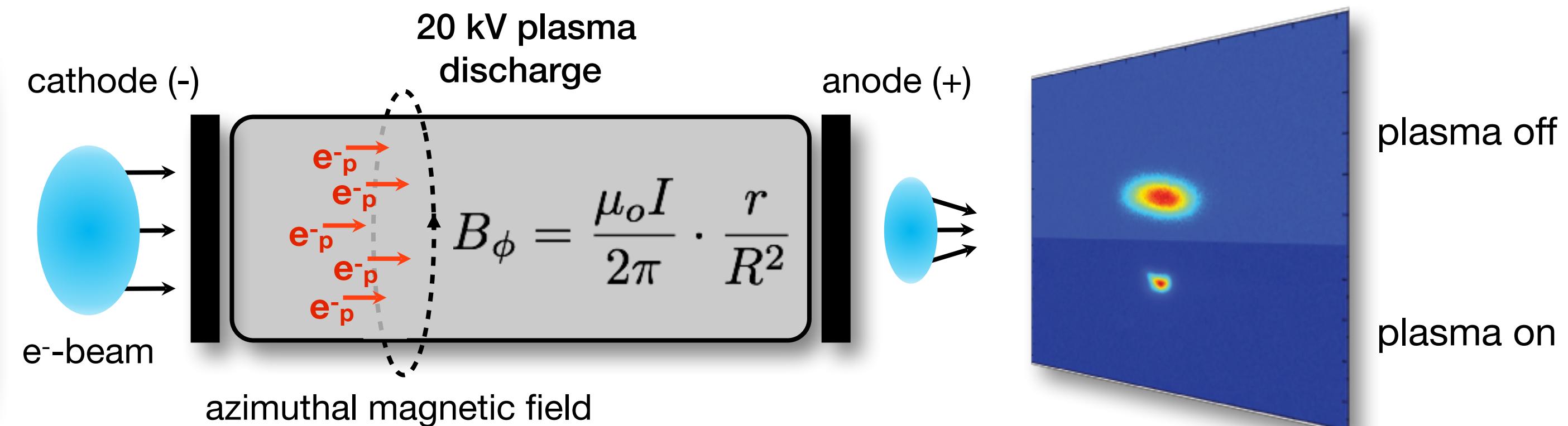
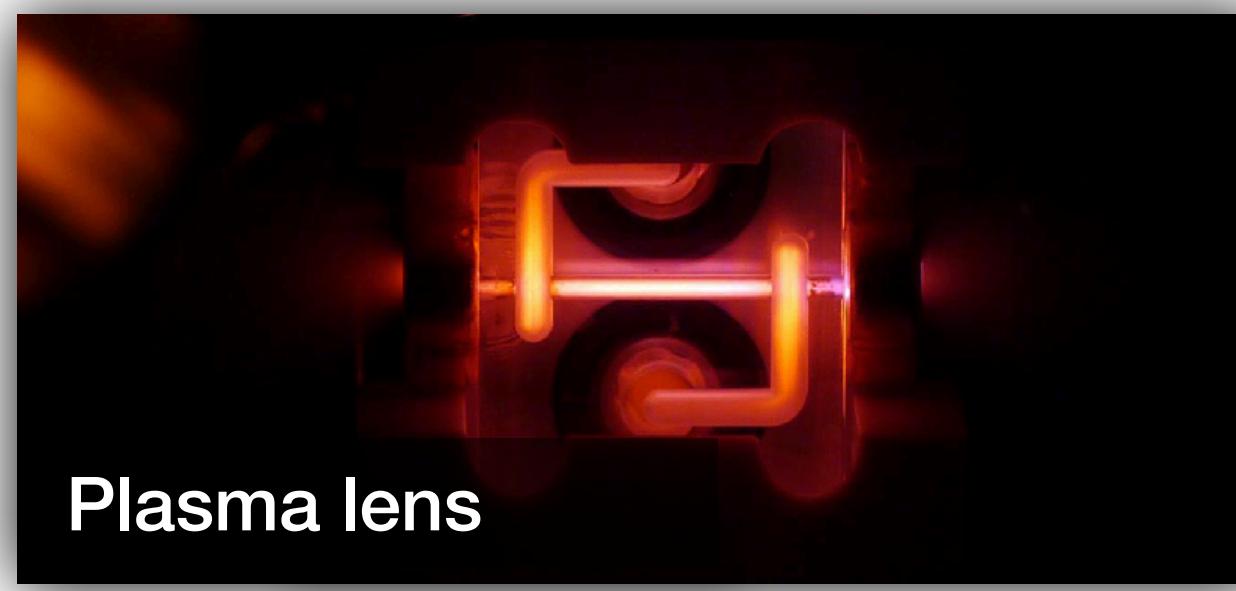
- Plasma-to-vacuum transition $\gg \beta$ for emittance preservation
- Strong quadrupoles for beam capturing required
Example: 1 GeV beam with 100 T/m quads fully captured only \sim 1 m behind plasma → emittance growth factor > 2



Prototype R&D: aberration-free active plasma lenses

FIRST MEASUREMENTS REVEAL NON-LINEAR FOCUSSING FIELDS

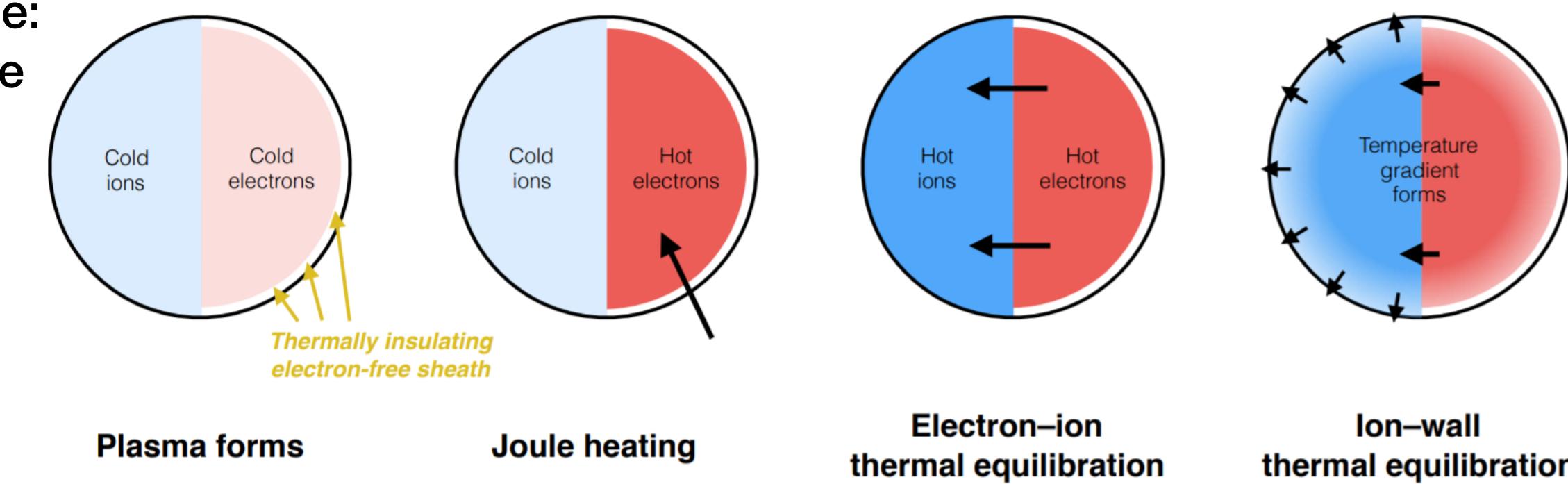
- > Strong focussing optics are desirable for emittance-preserving beam capturing after release into vacuum
- > Active plasma lenses are a promising technology providing up to 3 kT/m symmetric fields



$\mathbf{F} = \mathbf{I} \times \mathbf{B}$, tunable and symmetric focussing force for e-beam

J. van Tilborg et al.,
Phys. Rev. Lett. 115, 184802 (2015)

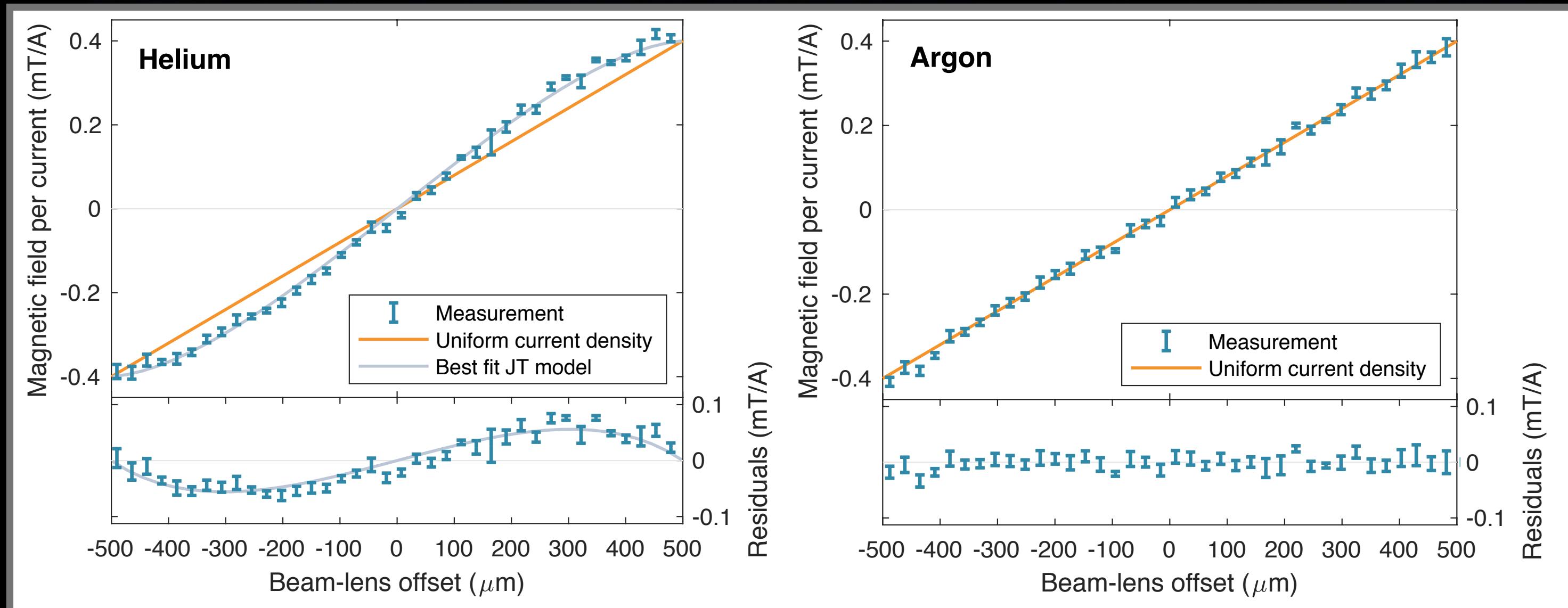
- > Field measurements reveal non-linearity consistent with measured emittance growth
- > Likely cause: temperature gradients





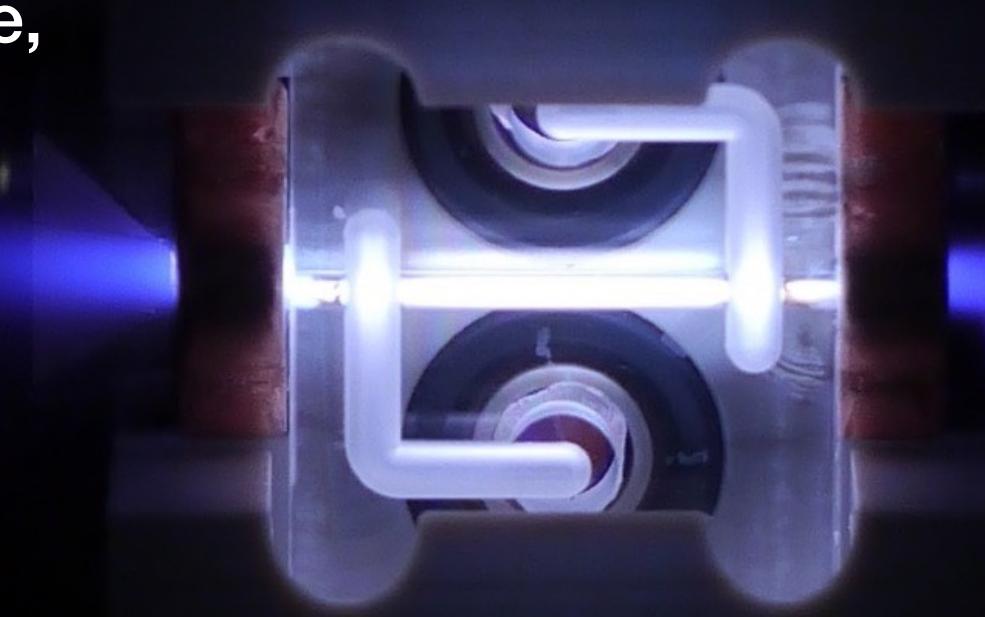
Prototype R&D: aberration-free active plasma lenses

EMITTANCE PRESERVATION REALIZED WITH HEAVY GAS SPECIES



C. A. Lindstrom *et al.*,
Phys. Rev. Lett. 121, 194801(2018)

- Idea: utilize APL before temperature equilibration can take place
- Substitute Hydrogen/Helium with Argon to extend timescale $\propto m_{\text{ion}}$
- Experiment at CLEAR, CERN: 216 MeV, 50 μm rms size, 3 μm trans. norm. emittance, 410 A current at 70 ns
- Argon: emittance conservation demonstrated
Helium: emittance not conserved



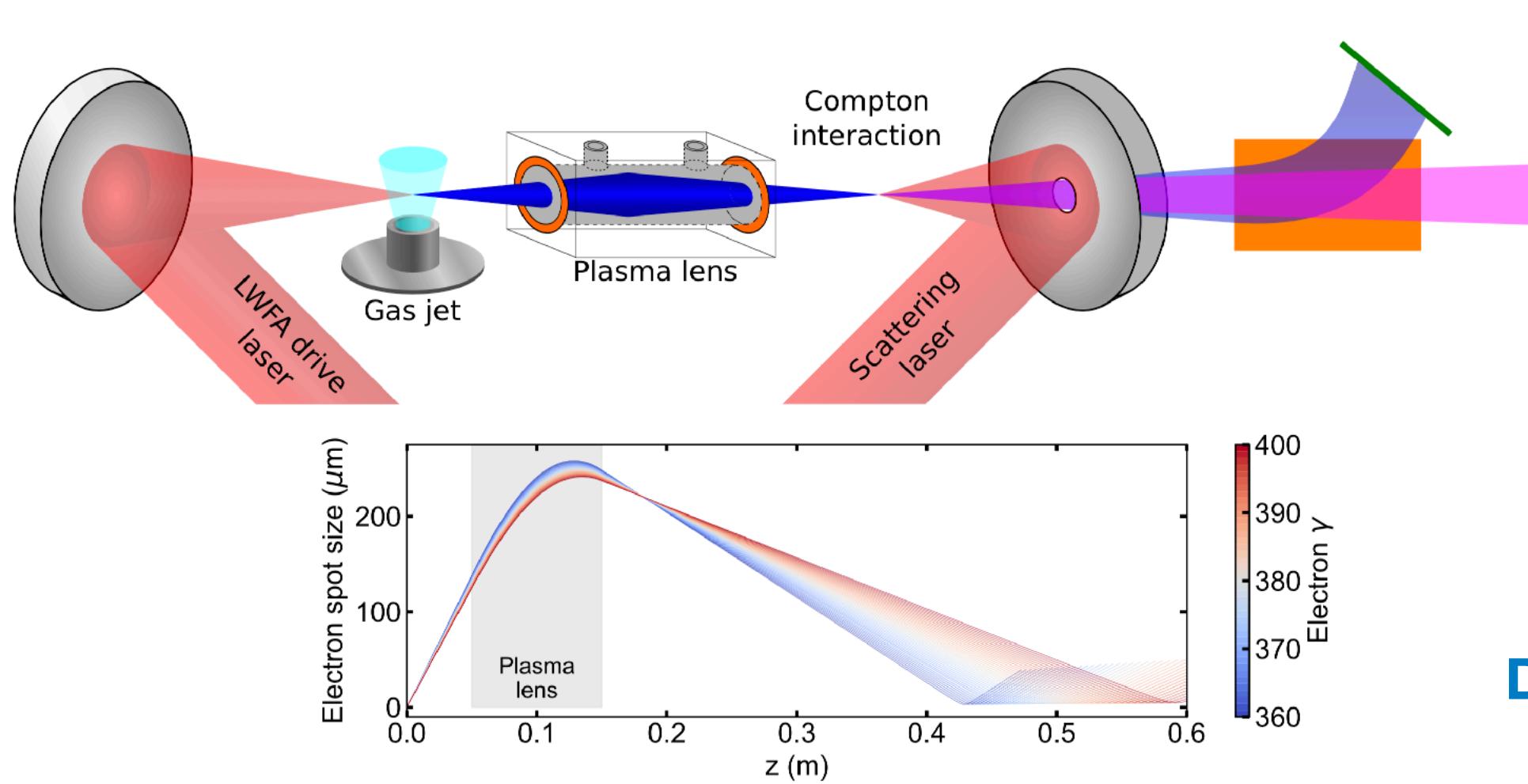
- Technology attractive for
 - beam capturing from plasma
 - positron capturing
 - adiabatic final focussing (Oide limit)

FLASHFORWARD ► laser-wakefield

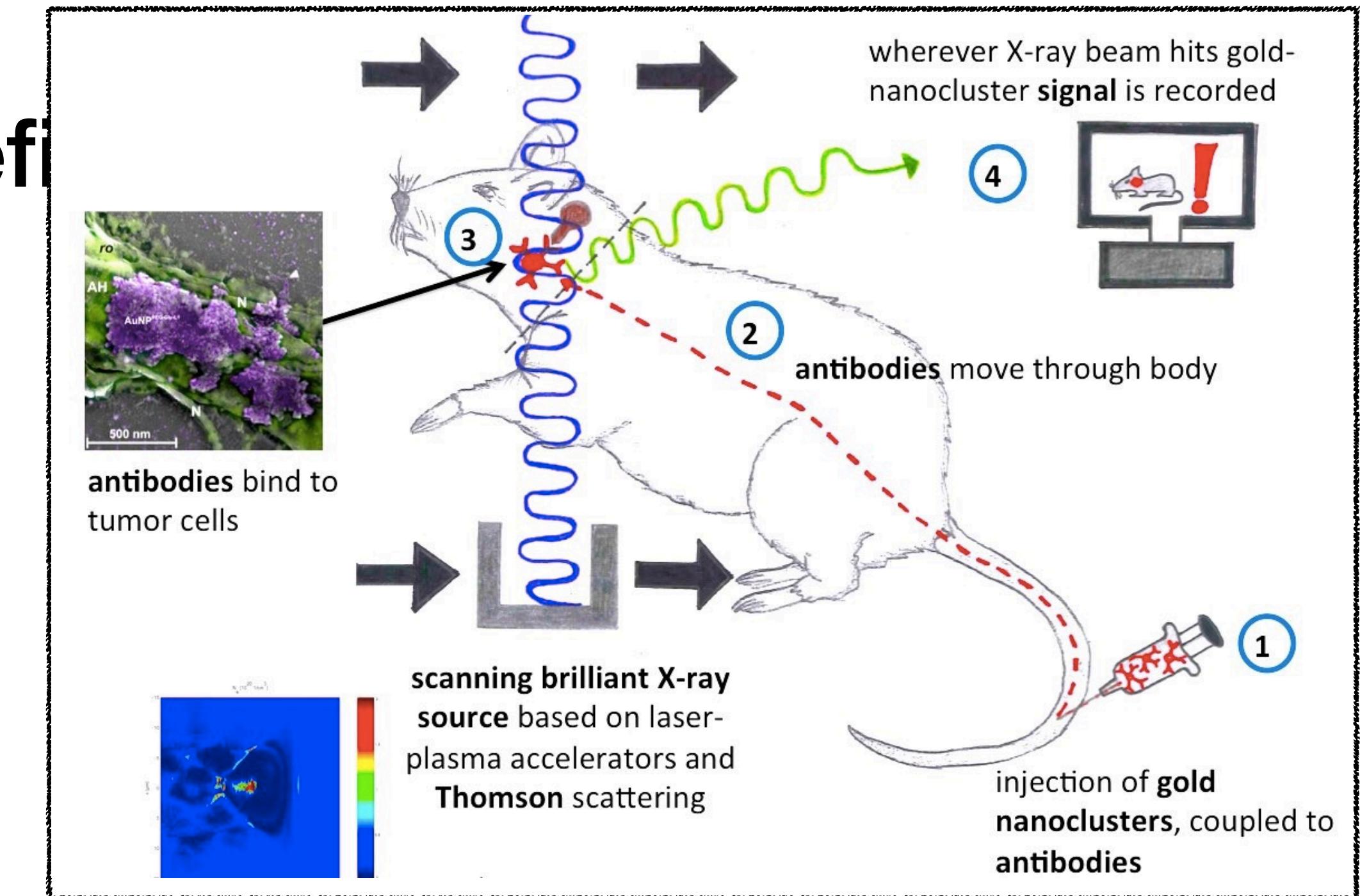
MEDICAL IMAGING PROTOTYPING

Scanning X-ray fluorescence imaging (XFI)

- imaging of gold-nanoclusters bound to anti-bodies (bound to tumors, ...)
- fluorescence signal excited by ~100 keV X-rays from Thomson scattering off LWFA electrons
- **2-year goal:** method proof-of-principle on isolated prostate tumor cells (end of 2019)
- **distant goal:** pharmacokinetics and high-resolution detection of tumors in-vivo



Supported by
DESY Strategy Fund



in collaboration between



Bundesministerium
für Bildung
und Forschung
Innovationspool



What about high average power applications with LWFAs?

EXAMPLE: PARTICLE COLLIDER → BACK-OF-THE-ENVELOPE POWER ESTIMATES REVEAL MAIN CHALLENGE

Required power per particle beam $P_b \approx 5 \text{ MW}$

Maximum power from the grid $P_{AC} \approx 200 \text{ MW}$

→ Need 5% wallplug efficiency

- > Efficiency laser to plasma wave ~50%
- > Efficiency plasma wave to beam ~30%

→ Expected laser-to-beam efficiency of 15%

→ Requires wallplug-to-laser efficiency of **33%**

confer C.B. Schroeder *et al.*, Phys. Rev. STAB 13, 101301 (2010)

confer B. Shadwick *et al.*, Phys. Plasmas 16, 056704 (2009)
from simulations

With 10 GeV LWFA stage ×50 and total energy per beam ~300 J

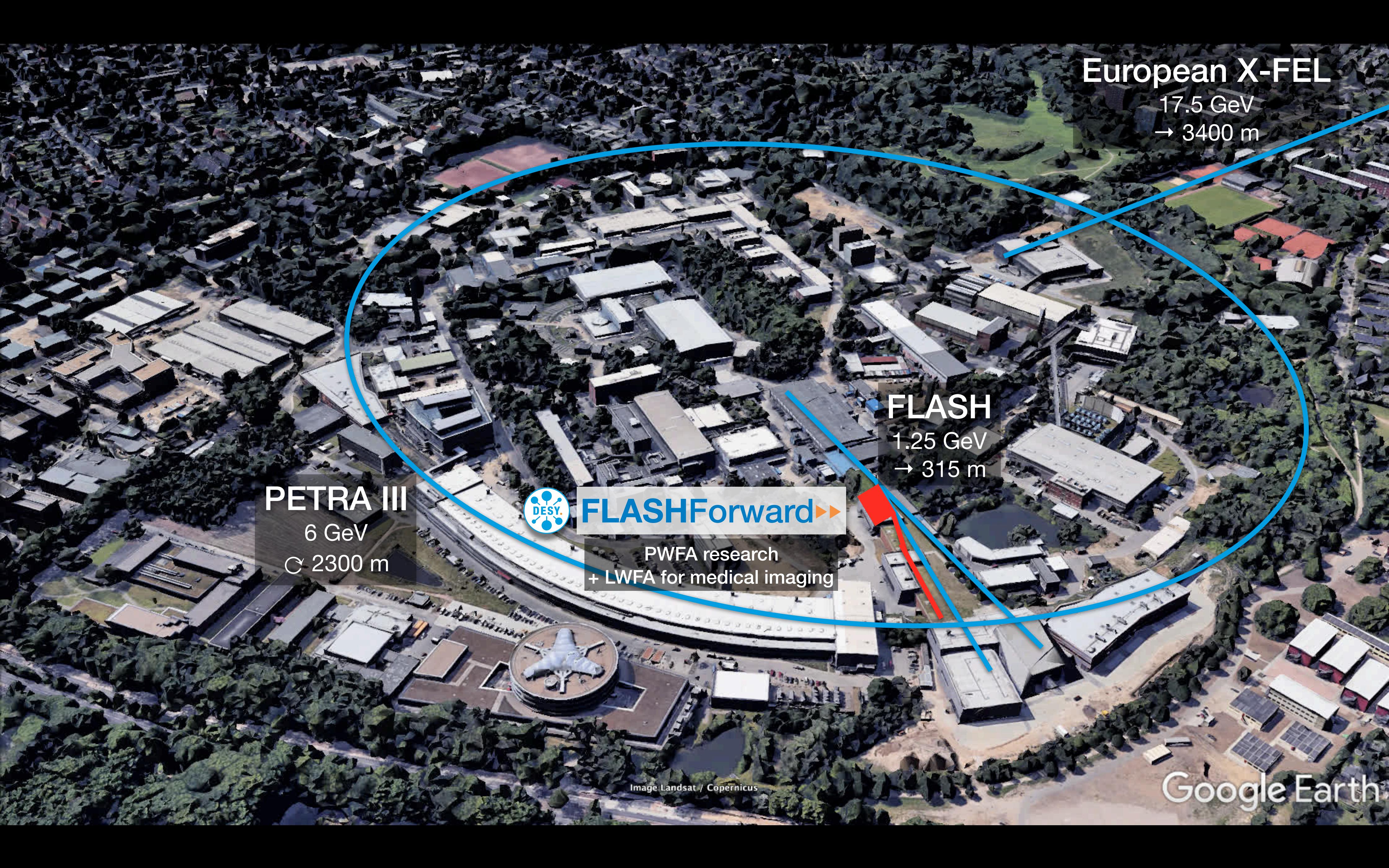
→ 6 J energy gain per module

→ 40 J laser energy per module at **~17 kHz** repetition rate

→ **680 kW** average laser power required

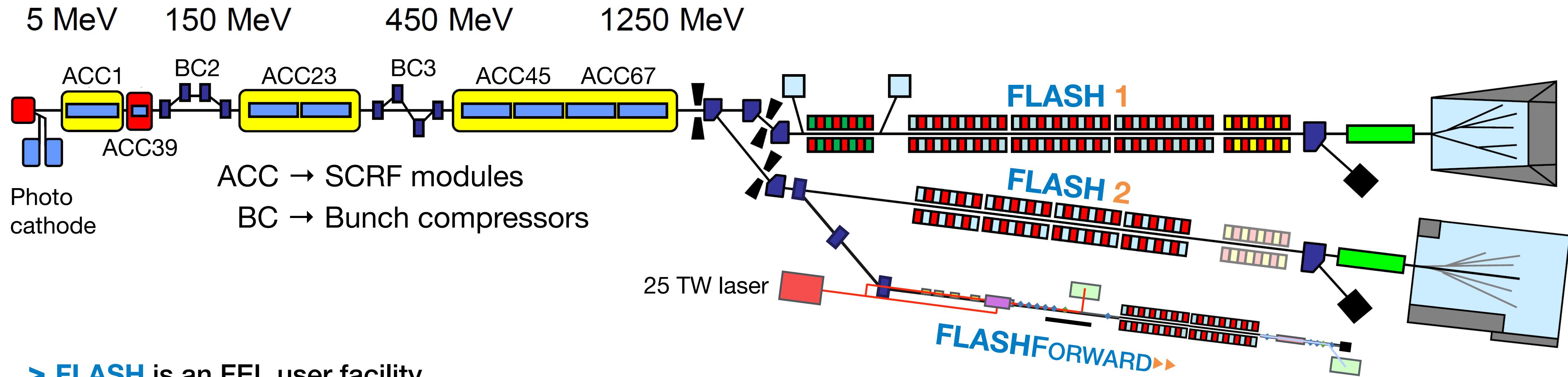
Modern 1 PW LWFA lasers: < 1% wallplug efficiency, **1 Hz** repetition rate, **~100 W** average power

→ **Laser tech revolution required. Current roadblock for LWFA colliders.**



FLASH drives free-electron laser and accelerator research

SUPERCONDUCTING, HIGH-AVERAGE POWER SYSTEM FEEDS MULTIPLE BEAM LINES SIMULTANEOUSLY



- > **FLASH** is an FEL user facility
 - 10% of beam time (750 h / year) dedicated to accelerator research
- > **FLASHForward**► is a beam line for PWFA research
- > Both share the same superconducting accelerator based on ILC/XFEL technology. Typical electron beam parameters:
 - ≤ 1.25 GeV energy with a few 100 pC at ~ 100 fs rms bunch duration
 - $\sim 2 \mu\text{m}$ trans. norm. emittance

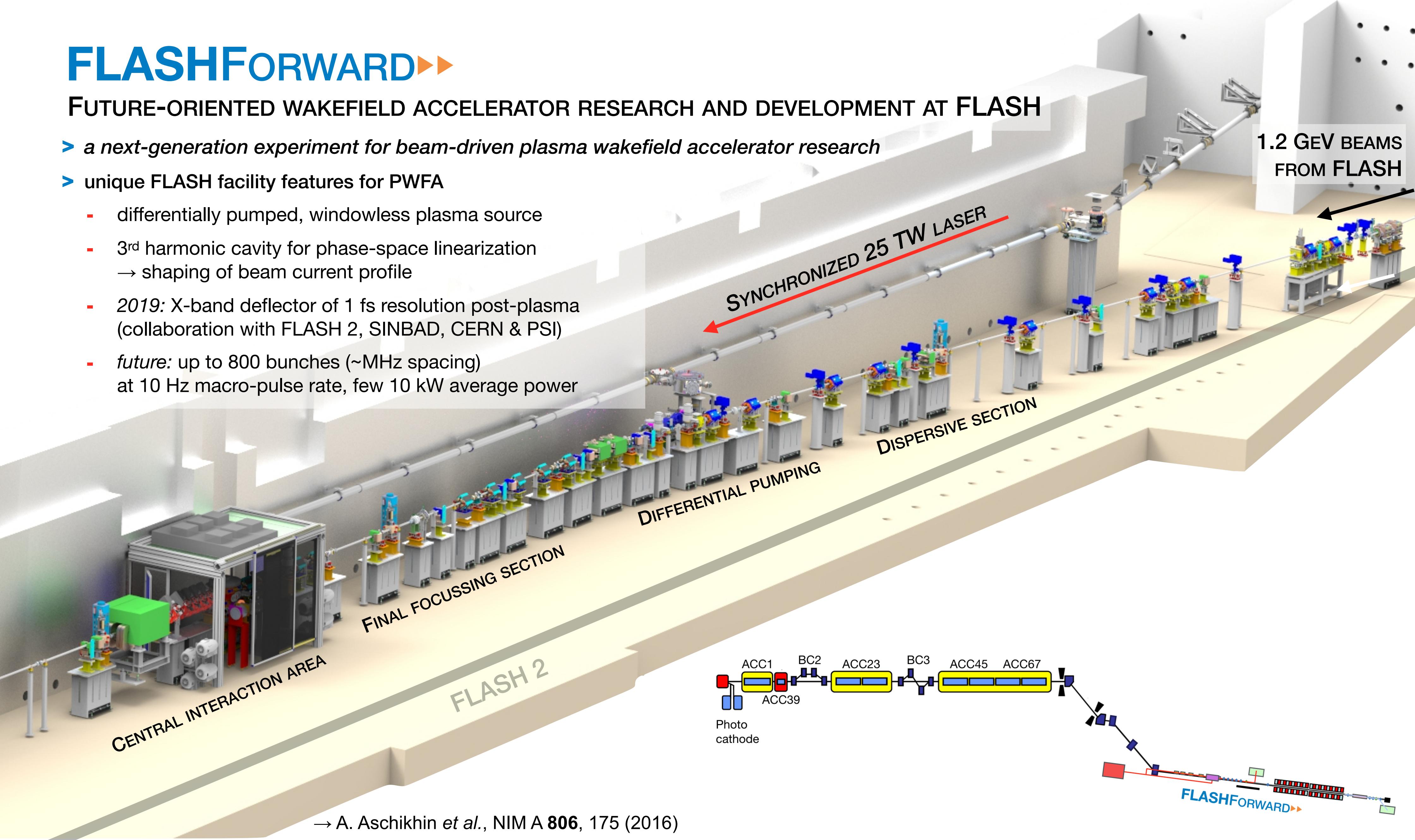
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FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

➢ *a next-generation experiment for beam-driven plasma wakefield accelerator research*

➢ **unique FLASH facility features for PWFA**

- differentially pumped, windowless plasma source
- 3rd harmonic cavity for phase-space linearization
→ shaping of beam current profile
- 2019: X-band deflector of 1 fs resolution post-plasma
(collaboration with FLASH 2, SINBAD, CERN & PSI)
- *future:* up to 800 bunches (~MHz spacing)
at 10 Hz macro-pulse rate, few 10 kW average power



First beam in FF► - August 31, 2017

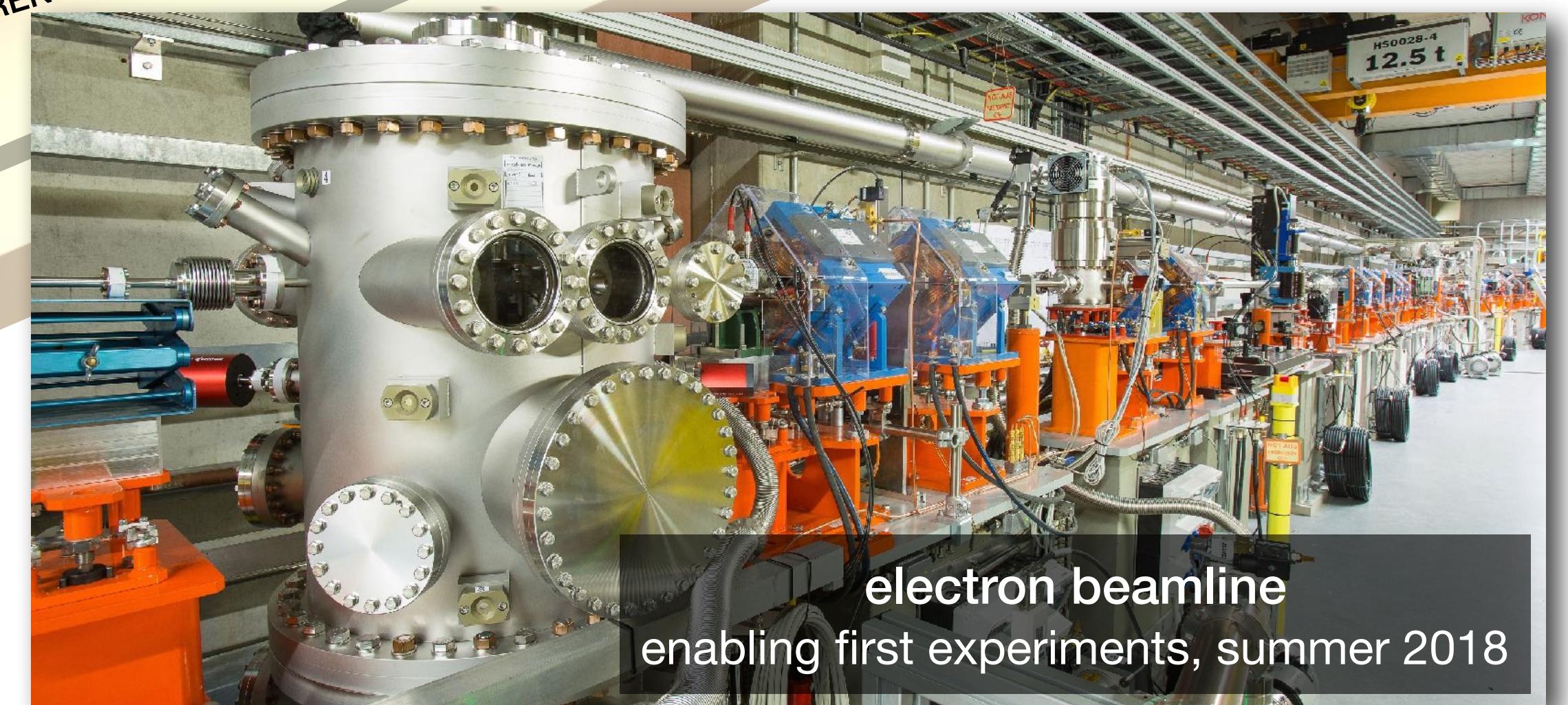
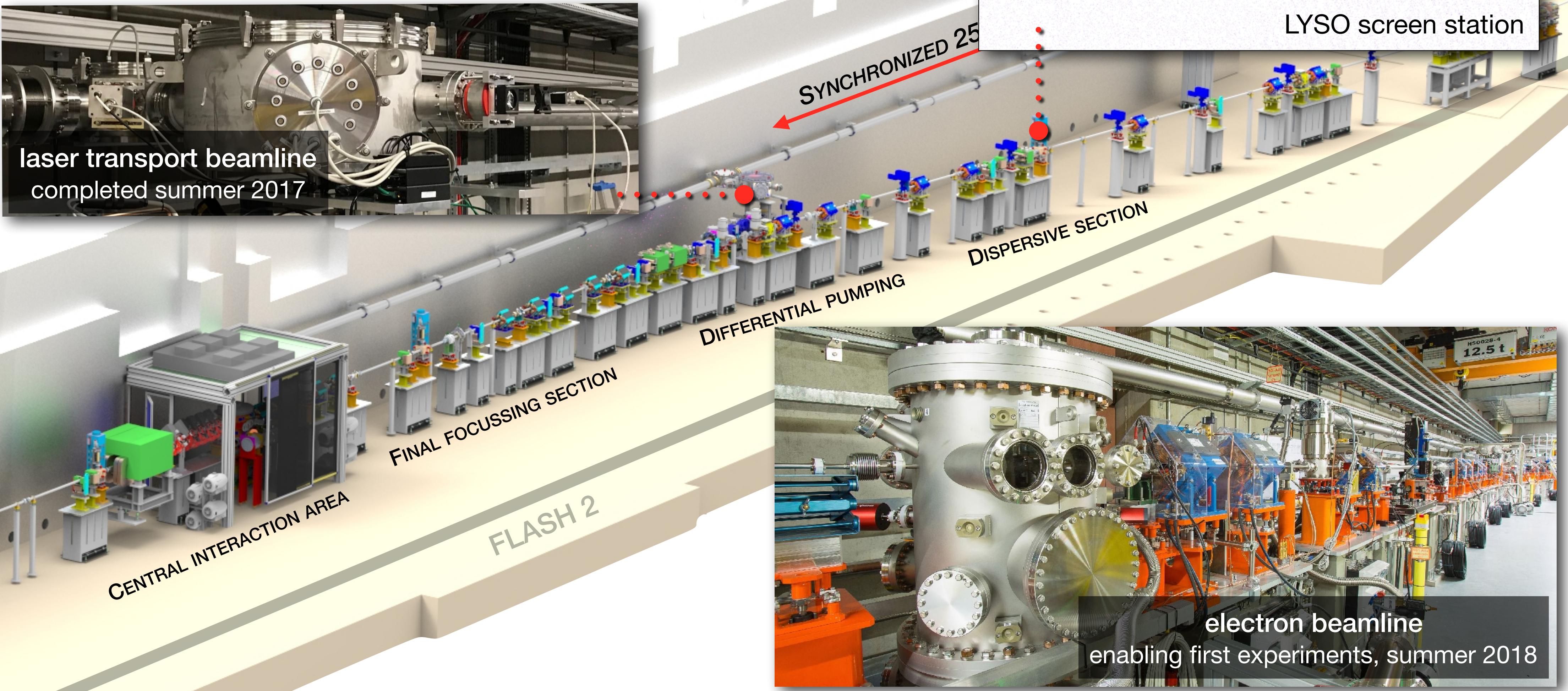
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FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT

- beamline commissioning August 30th, 2017 - June 30th, 2018
- experimentation started after July 15th, 2018



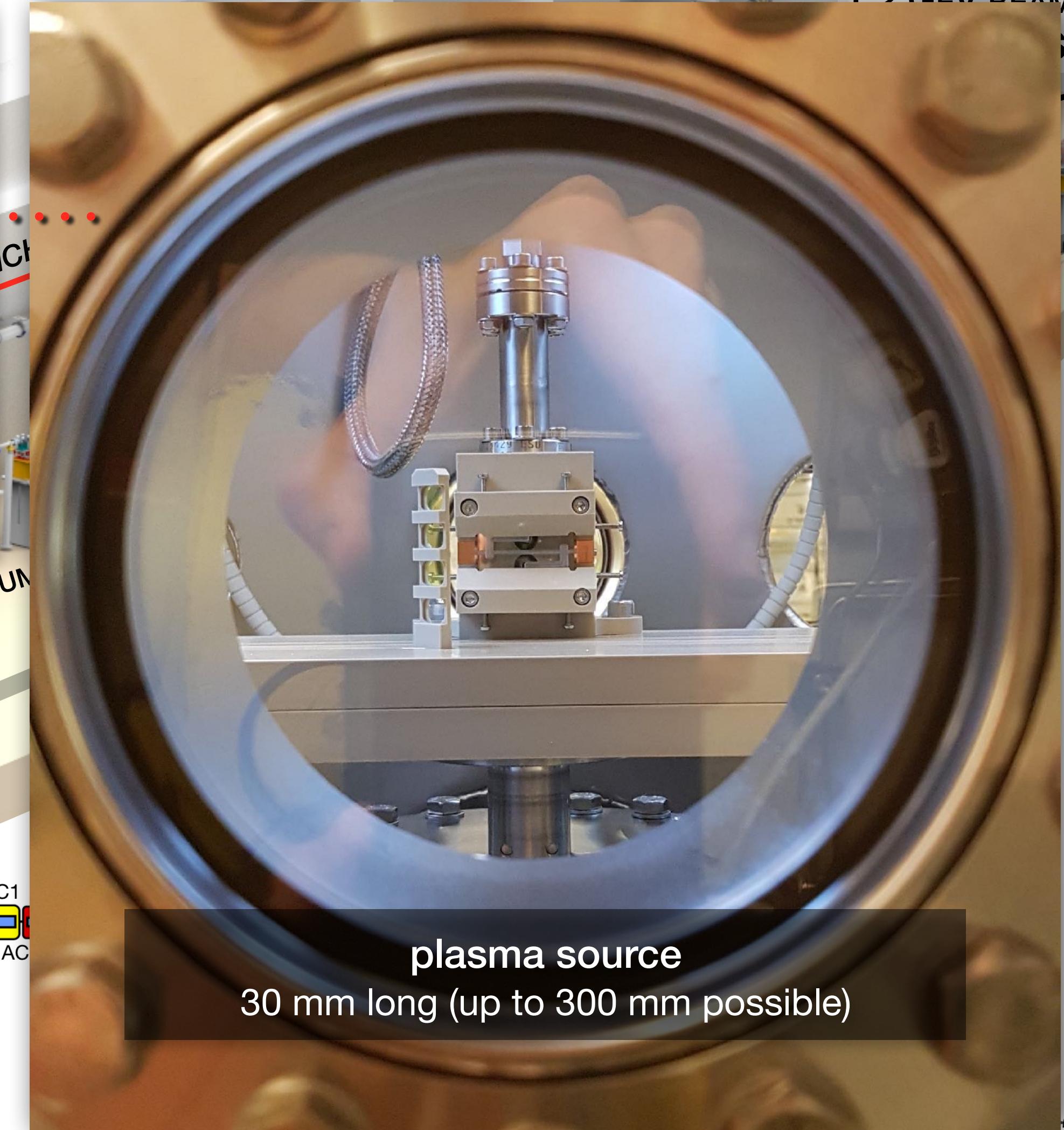
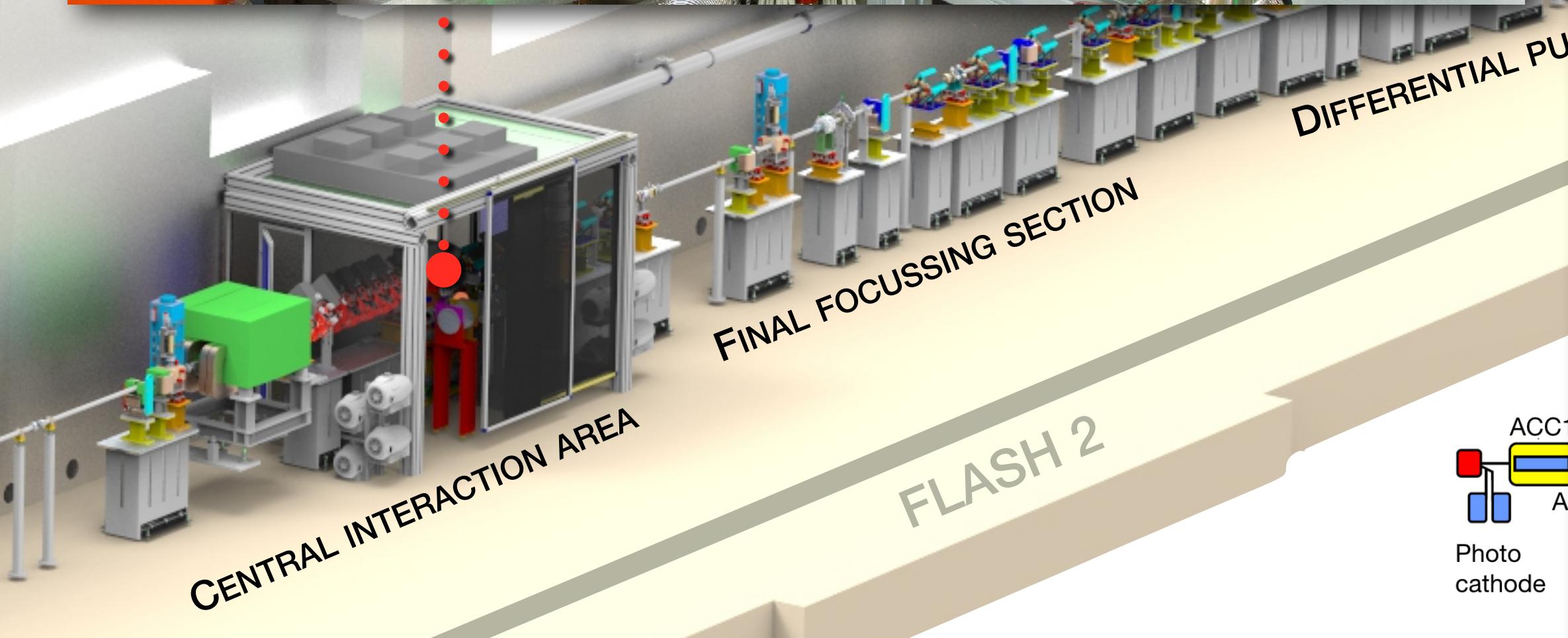
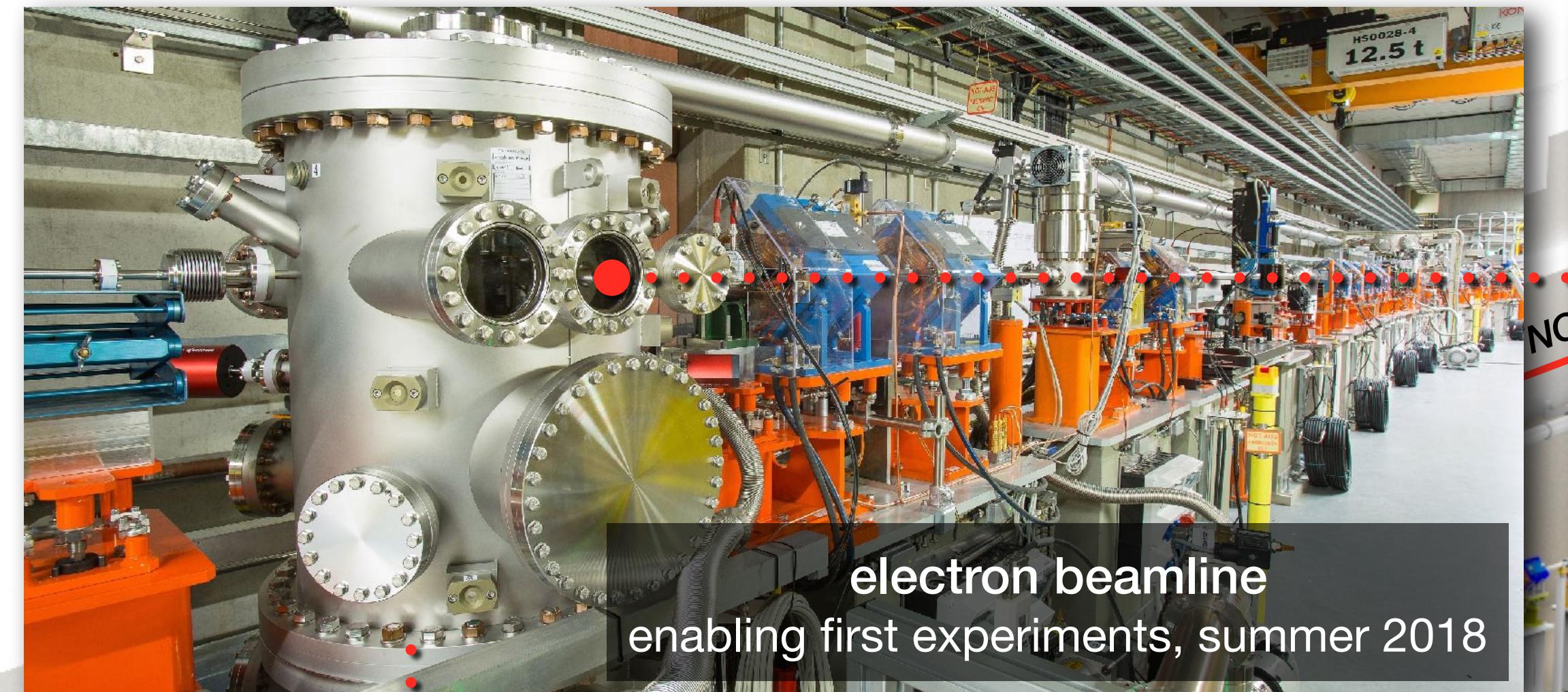
laser transport beamline
completed summer 2017



electron beamline
enabling first experiments, summer 2018

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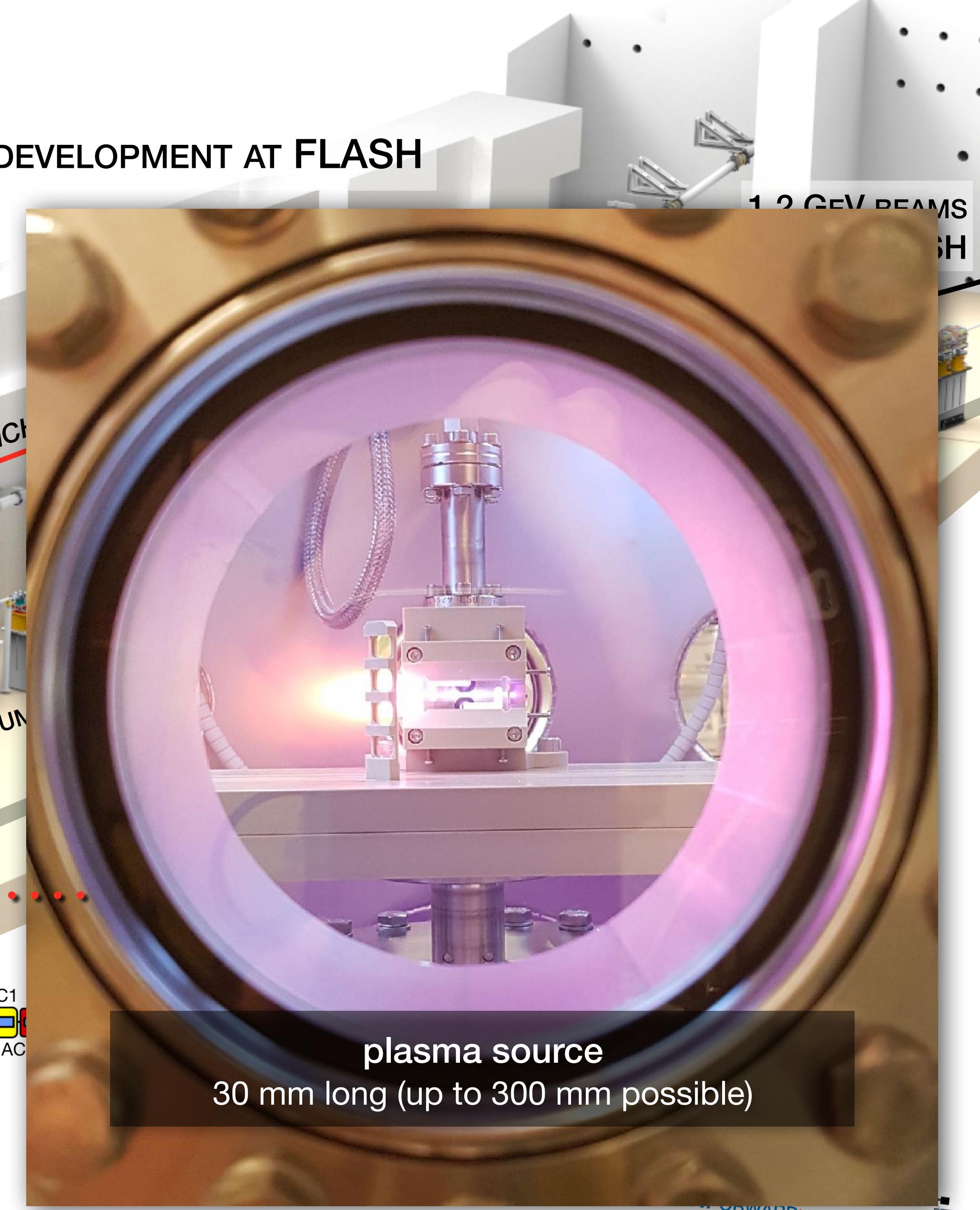
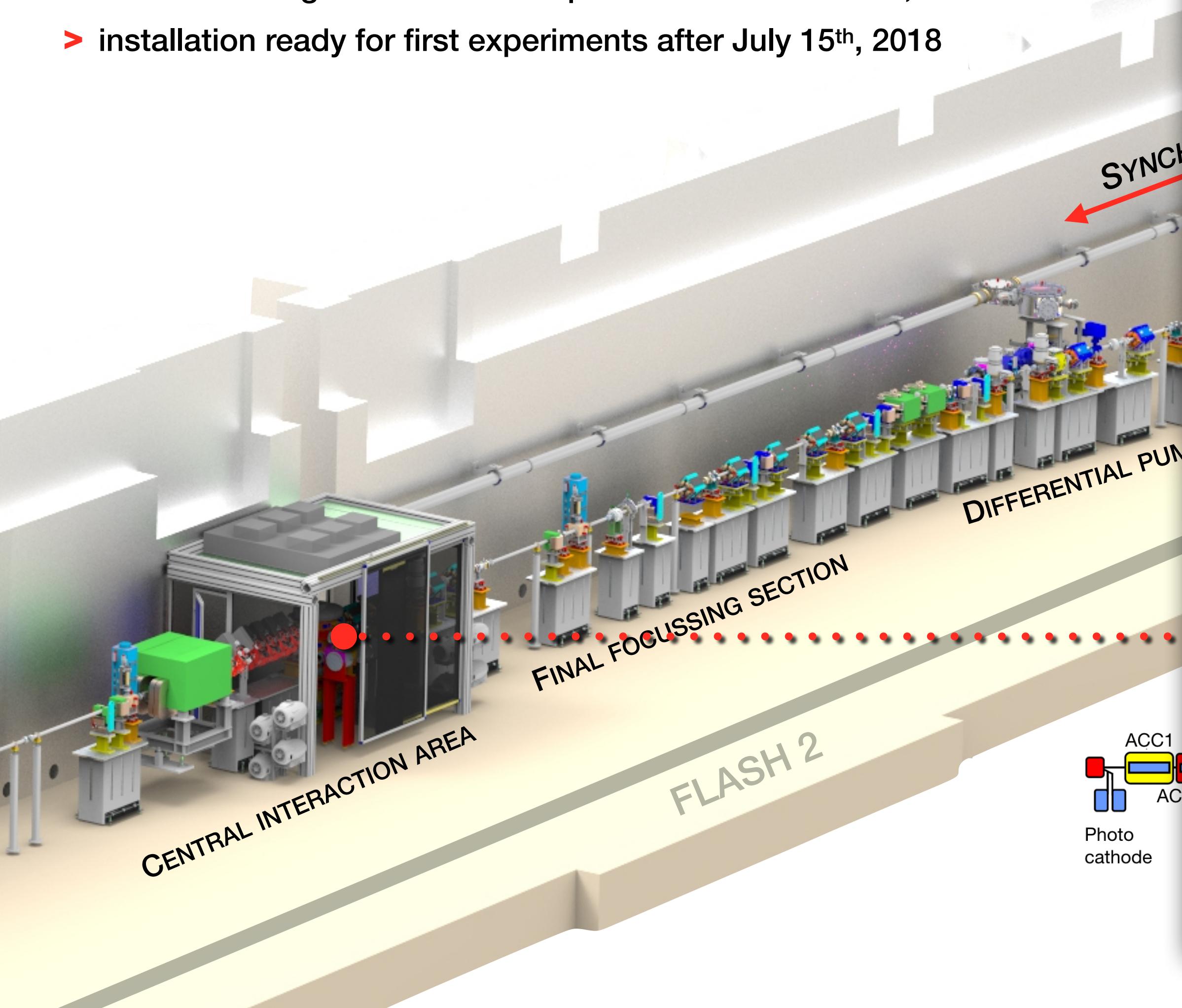
FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH



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FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

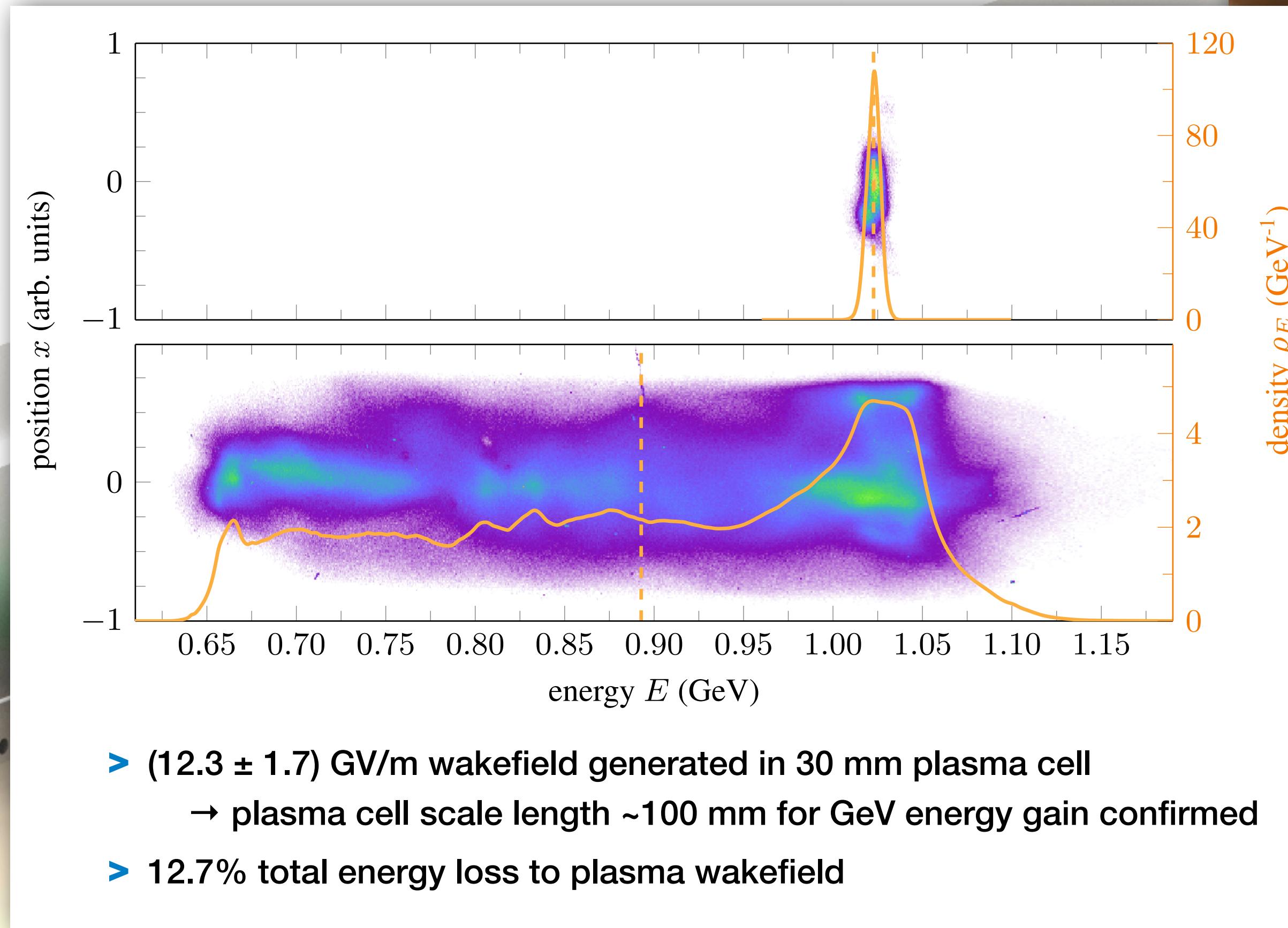
- first PWFA beam-plasma interaction on June 19th, 2018
- commissioning successful and quasi-finished June 30th, 2018
- installation ready for first experiments after July 15th, 2018



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FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

- first PWFA beam-plasma interaction on June 19th, 2018
- commissioning successful and quasi-finished June 30th, 2018
- installation ready for first experiments after July 15th, 2018



FLASHFORWARD► experimental programme

CORE EXPERIMENTAL STUDIES AND PROTOTYPING

Satellite studies for main experiments

CORE EXPERIMENTS	
X-1	Plasma Cathode ► PI: A. Knetsch (DESY)
X-2	Plasma Booster ► PI: V. Libov (U Hamburg)
X-10	Transformer Ratio ↑ ► PI: V. Libov (U Hamburg)
X-11	Hosing Studies ► PI: S. Wesch (DESY)
X-12	MHz PWFA ► PI: R. D'Arcy (DESY)
X-13	Beam (De-)chirping ► PI: R. D'Arcy (DESY)
X-14	Ion Motion Studies ► PI: t.b.d.
X-15	Ionization Studies ► PI: t.b.d.
X-100	FEL Gain ► PI: t.b.d.

Main FF► scientific goals

- > **X-1 Plasma cathode:** high-brightness beam generation (→ photon science)
> 1.25 GeV energy, trans. norm. emittance \sim 100 nm, current \geq 1 kA, \sim fs bunch duration
- > **X-2 Plasma booster:** wakefield module for post acceleration (→ staging, high-energy physics)
energy doubling, energy spread & emittance preservation, drive depletion ($>$ 10% efficiency)
- > **X-100 Investigate plasma-accelerated beams for FEL gain** (PHASE II, 2020+)

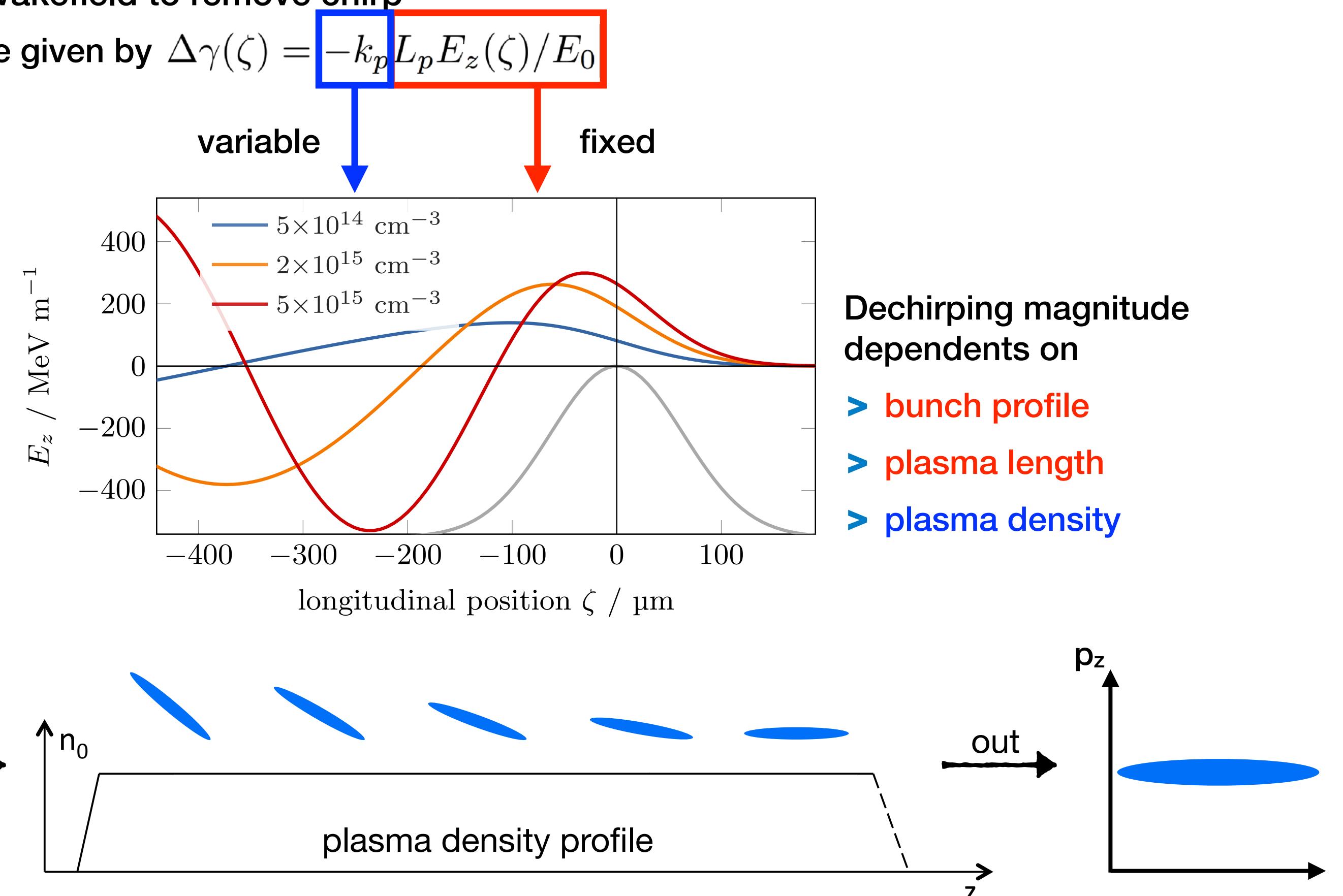
ADVANCED DIAGNOSTICS AND PROTOTYPES

P-1	TR Spectroscopy ► PI: B. Schmidt (DESY)	P-5	\perp Beam Probe ► PI: P. Niknejadi (DESY)	P-9	X-Deflector ► PI: R. D'Arcy (DESY)
P-3	Betatron Radiation ► PI: S.P.D. Mangles (ICL)	P-6	Pulsed Dipole ► PI: S. Wesch (DESY)	P-10	Laser-Beam Timing ► PI: A. Knetsch (DESY)
P-4	\perp Laser Probe ► PI: M. Kaluza (U Jena)	P-8	Active Plasma Lens ► PI: L. Schaper (DESY)	P-11	ICS Radiation Det. ► PI: S. Bohlen (DESY)

First study: a tunable plasma-based energy dechirper

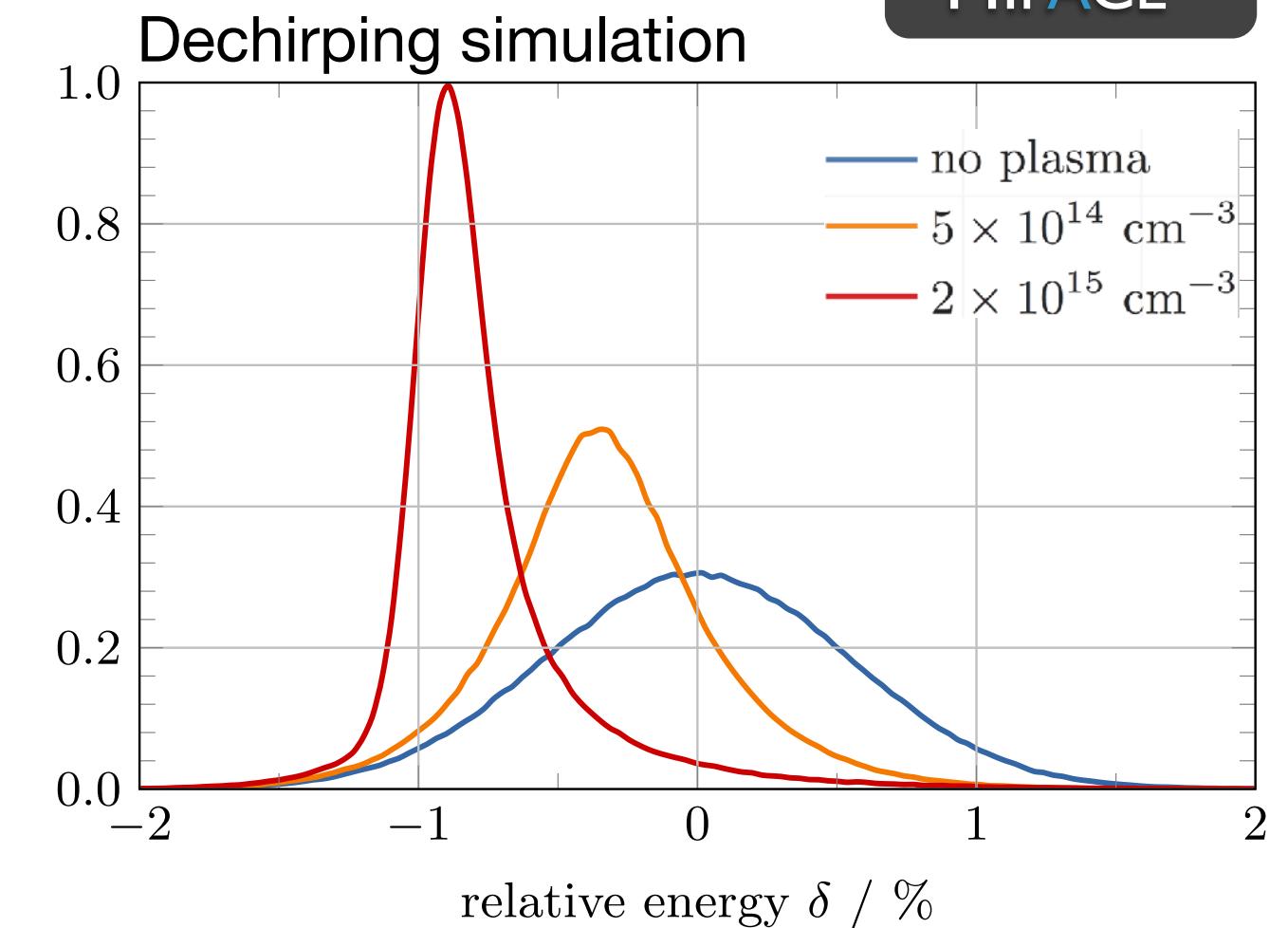
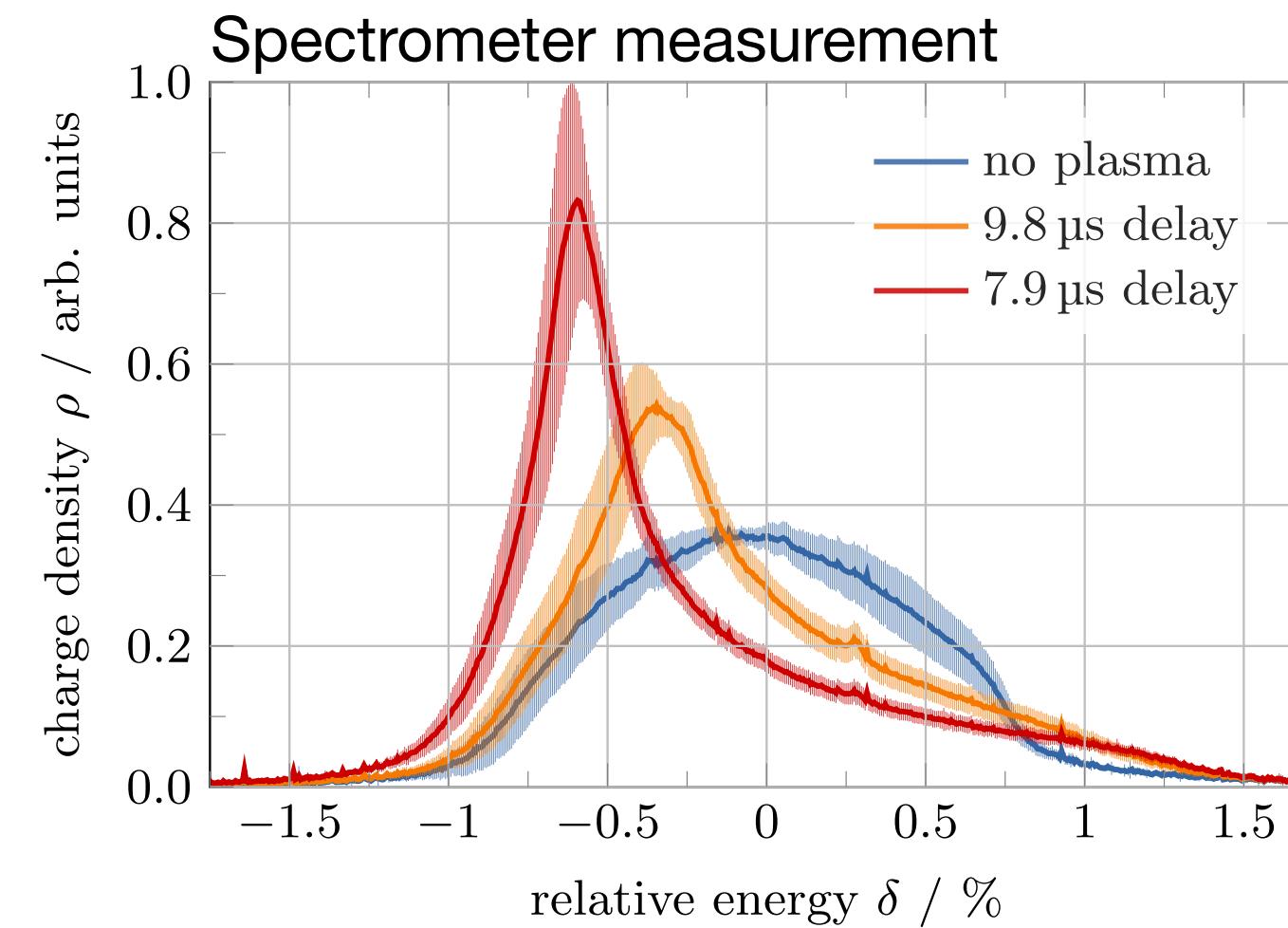
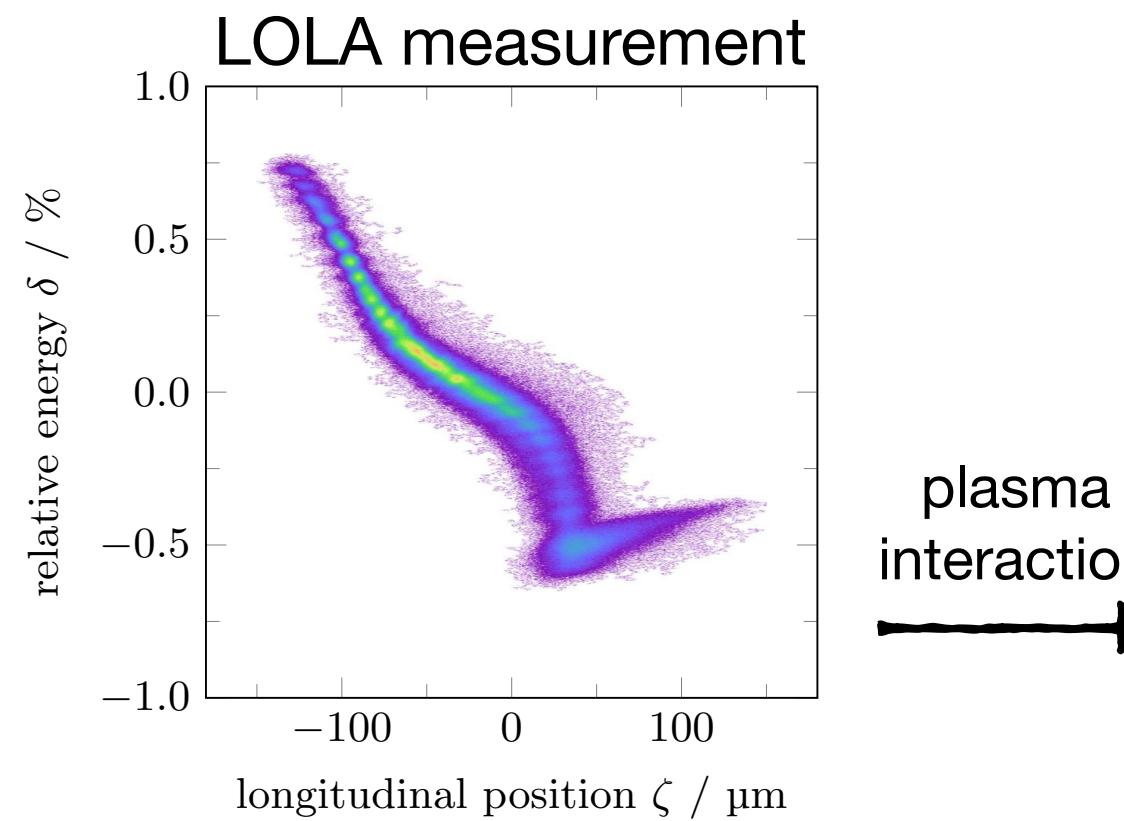
NOVEL TECHNOLOGY FOR REMOVING LONGITUDINAL ENERGY CORRELATION BY PLASMA WAKEFIELDS

- > Beams from plasma wakefield accelerators may feature large chirps of order 100 MeV/mm
- > Dechirping structures demonstrated up to 18 MeV/m/mm — insufficient
(e.g. K.L.F. Bane, G. Stupakov, NIM A 690, 106 (2012) or S. Antipov et al., Phys. Rev. Lett. 112, 114801 (2014))
- > The idea: utilize plasma wakefield to remove chirp
 - slice-energy change given by $\Delta\gamma(\zeta) = -k_p L_p E_z(\zeta)/E_0$



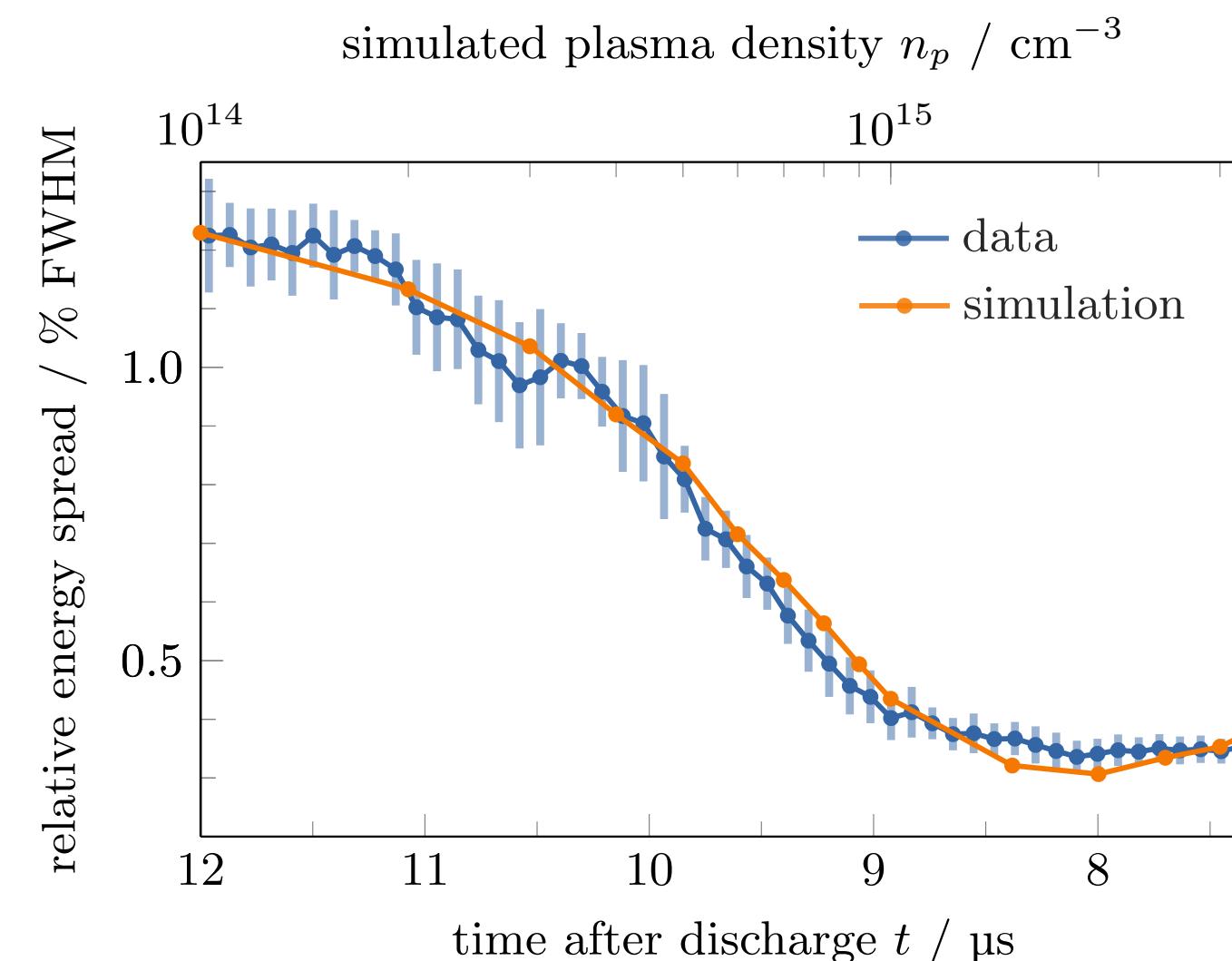
First study: a tunable plasma-based energy dechirper

PROOF-OF-PRINCIPLE EXPERIMENT TO REMOVE CHIRP OF FLASH BEAM IN PLASMA CELL



HiPACE

- Reduction of energy spread from 1.3% to 0.3% FWHM
- Experimental demonstration of 1.8 GeV/m/mm dechirping strength
- May dramatically improve applicability of PWFA beams

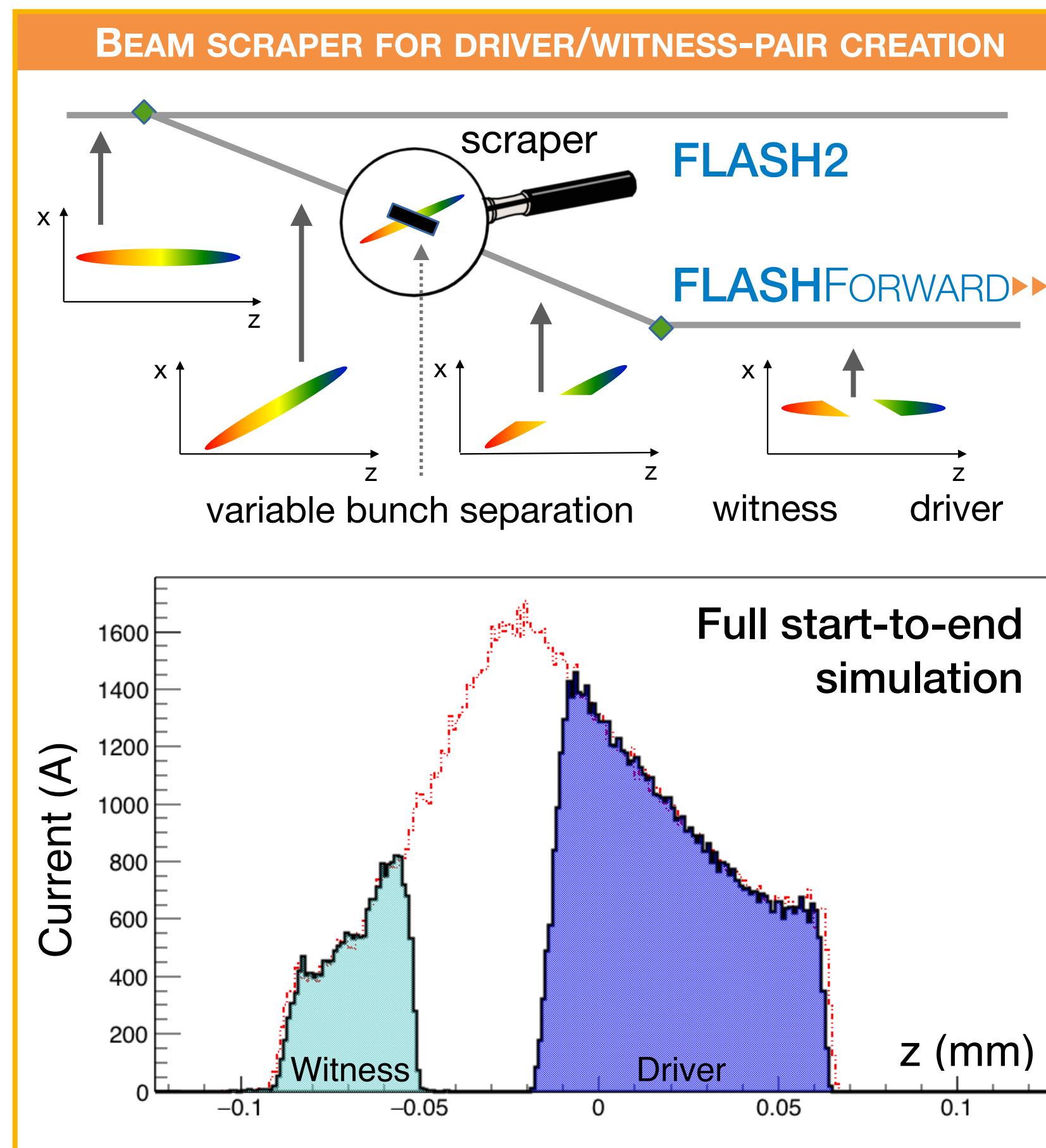


- PIC simulations fit very well
- Plasma process had no measurable impact on beam stability

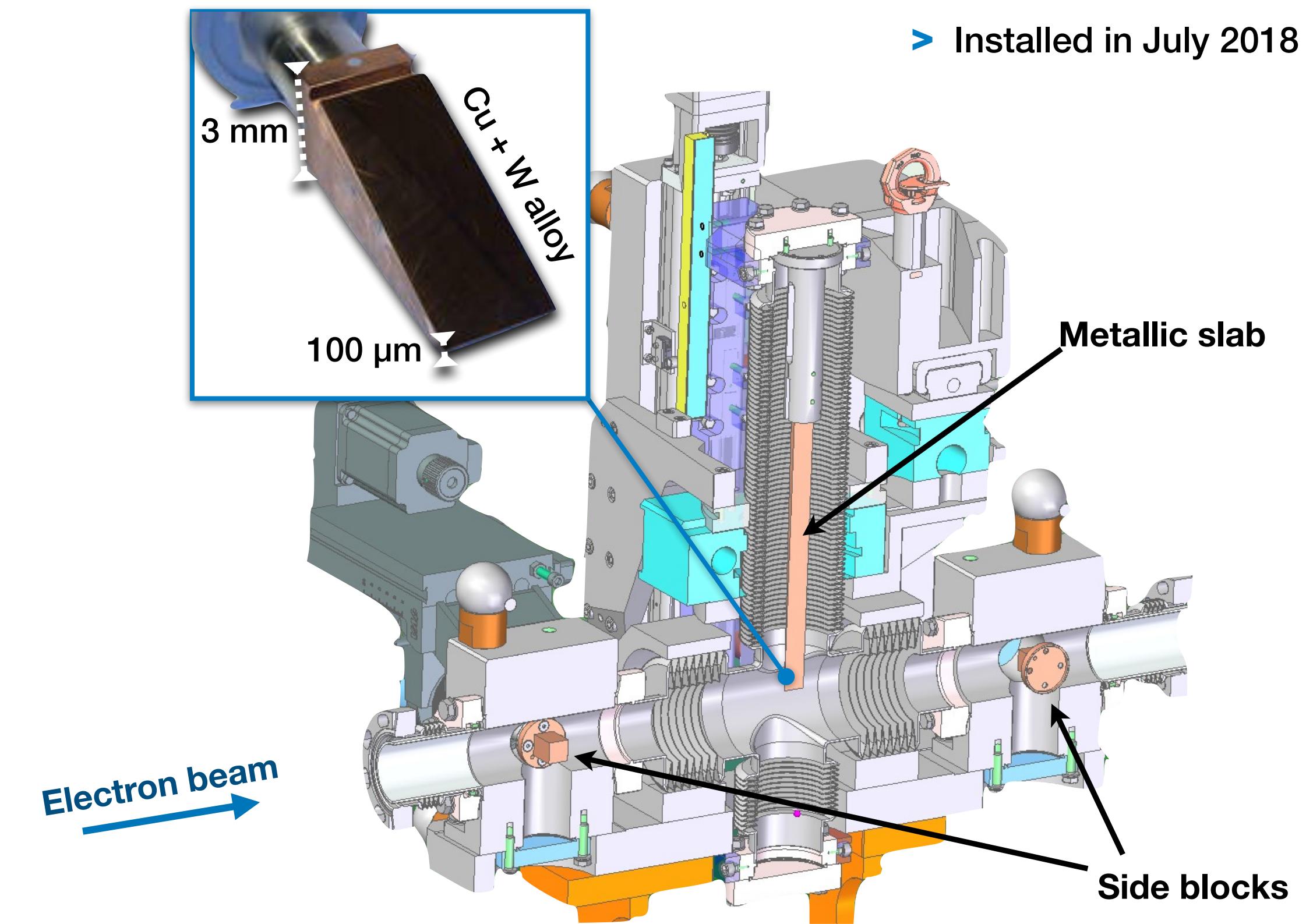
→ R. D'Arcy *et al.*, submitted (2018)

Core study: a plasma-based energy booster module

DRIVER/WITNESS-PAIR CREATION IN DISPERSIVE SECTION BY VARIABLE MASK

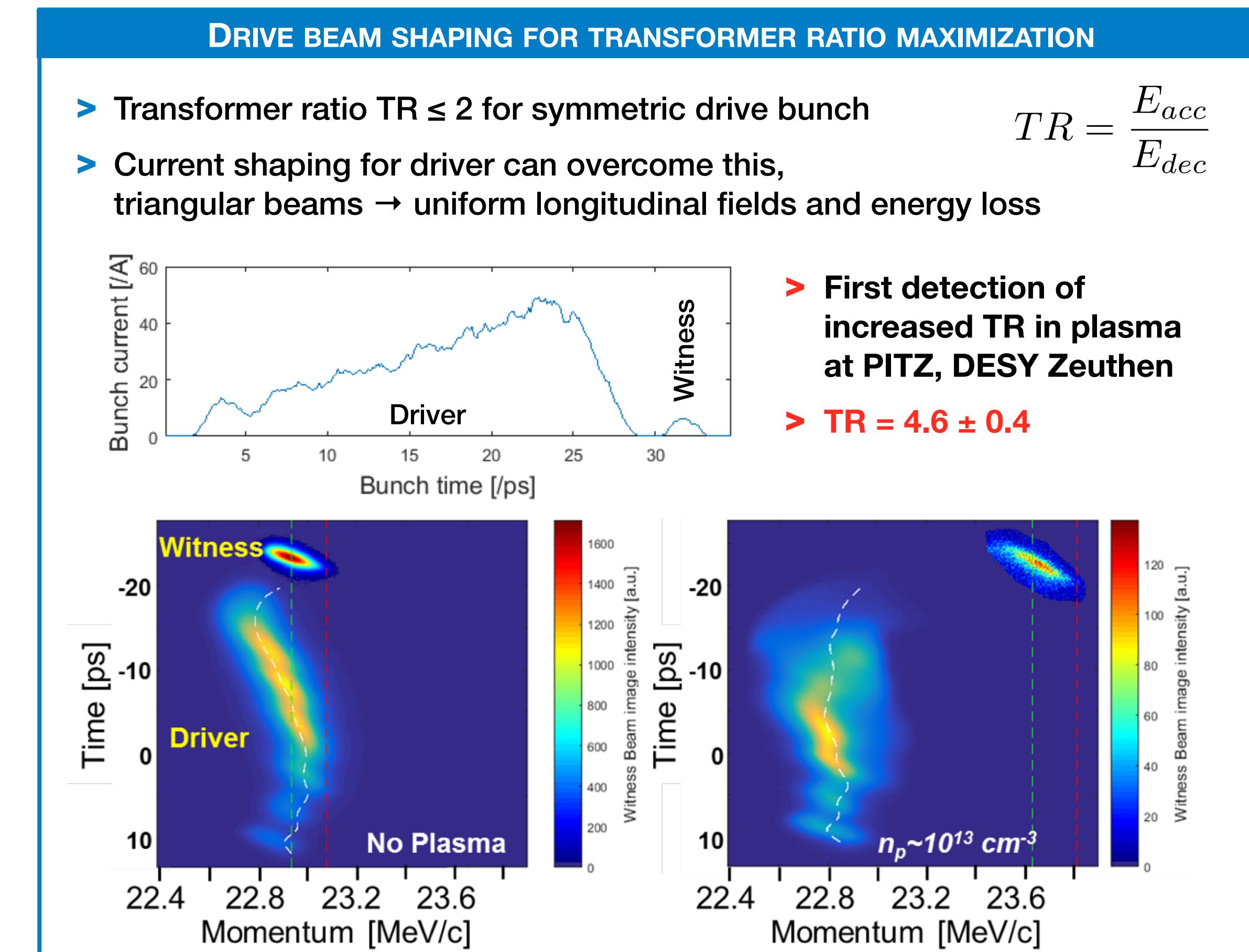
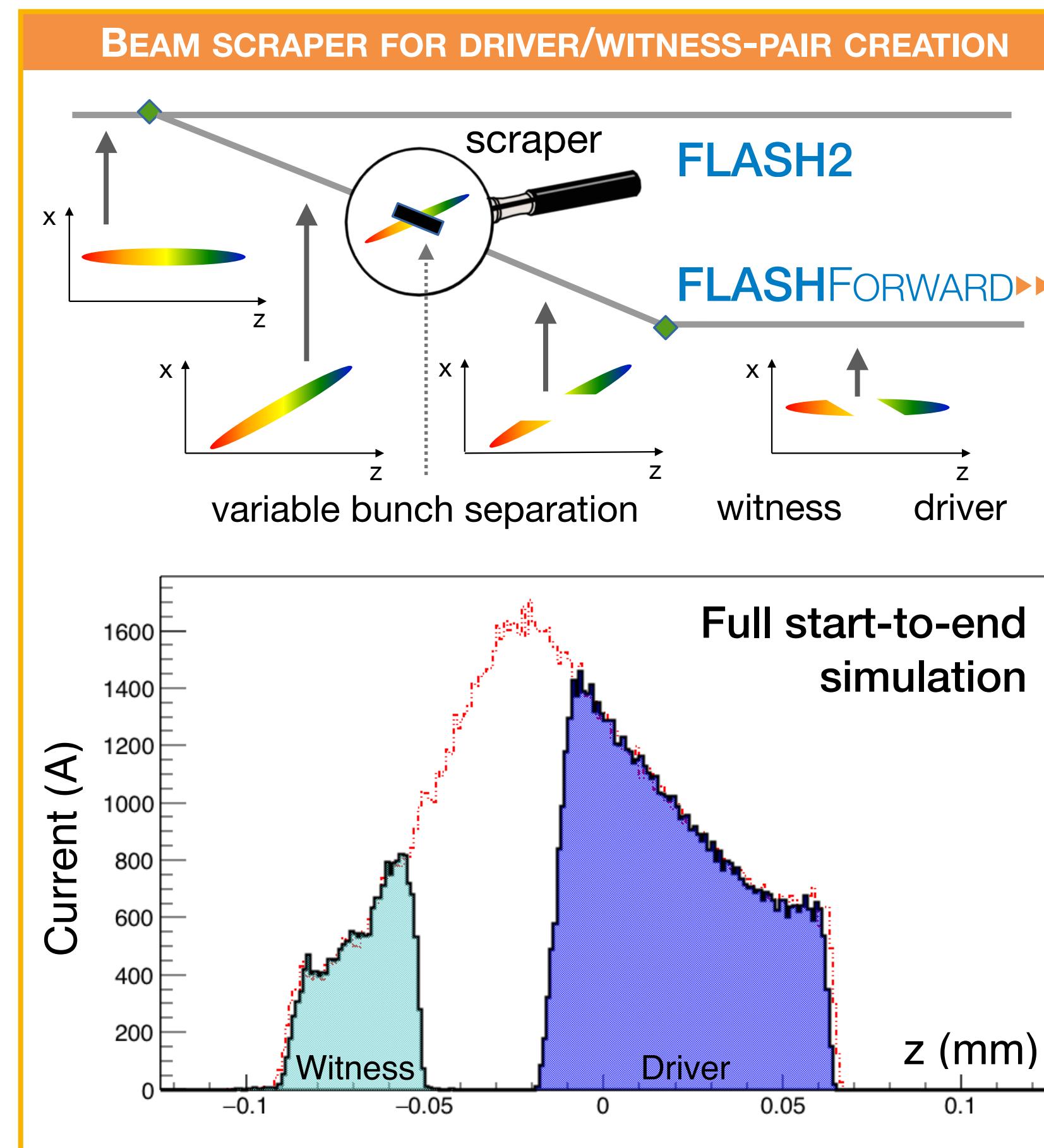


X-2 Plasma Booster
► PI: V. Libov (U Hamburg)



Core study: a plasma-based energy booster module

CURRENT-PROFILE SHAPING FOR TRANSFORMER RATIO MAXIMIZATION

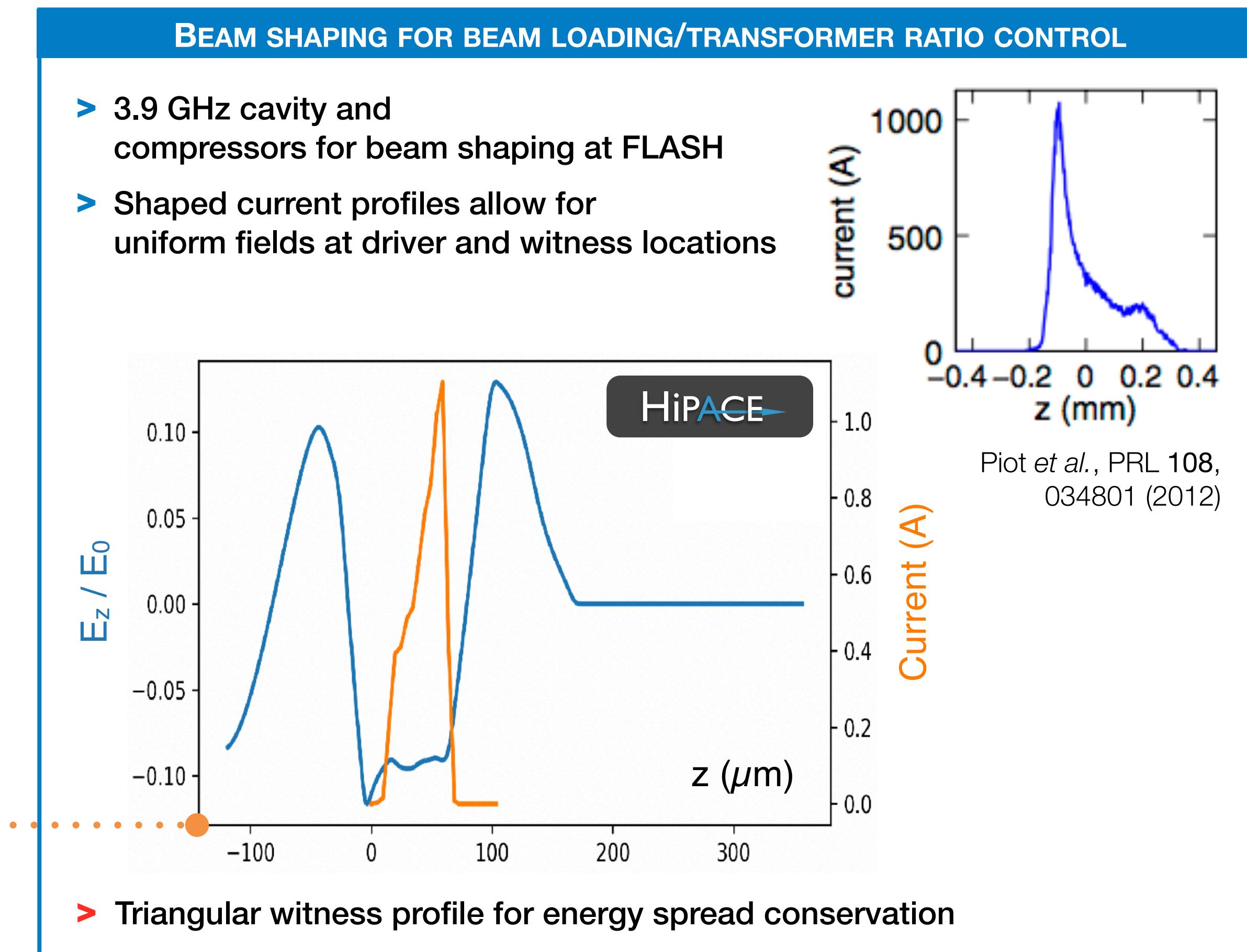
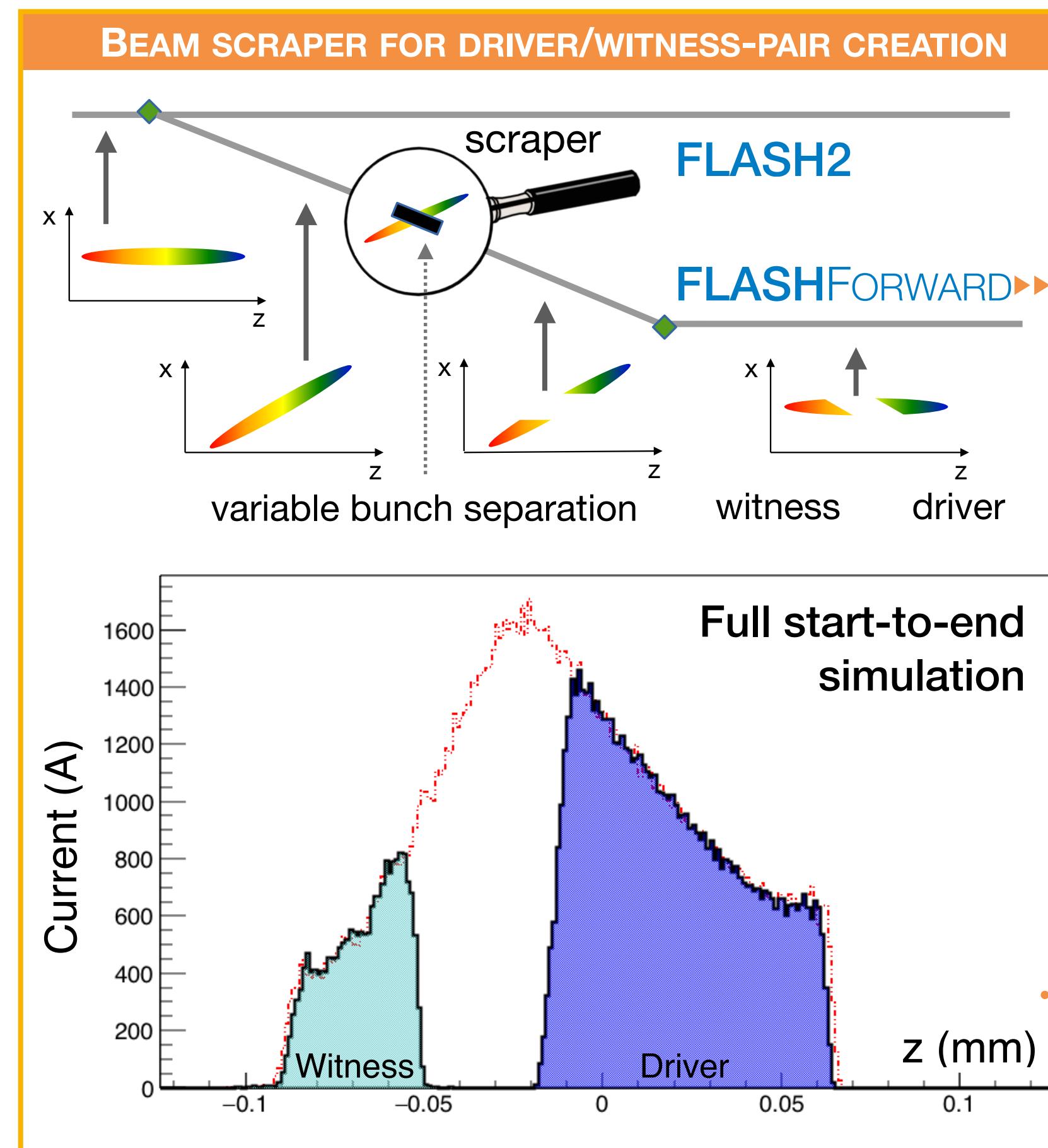


G. Loisch et al., Phys. Rev. Lett. 121, 064801 (2018)

X-2 **Plasma Booster**
► PI: V. Libov (U Hamburg)

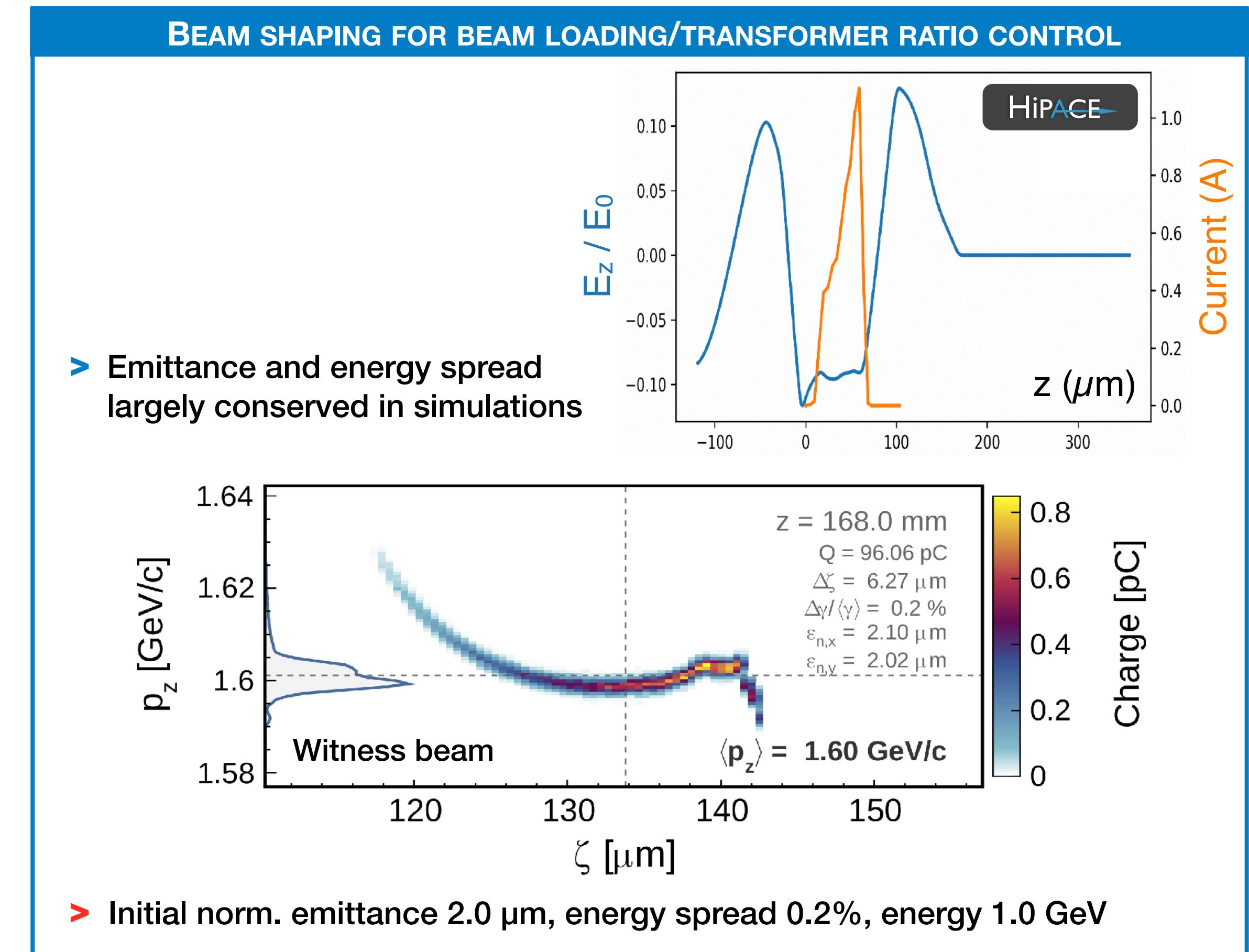
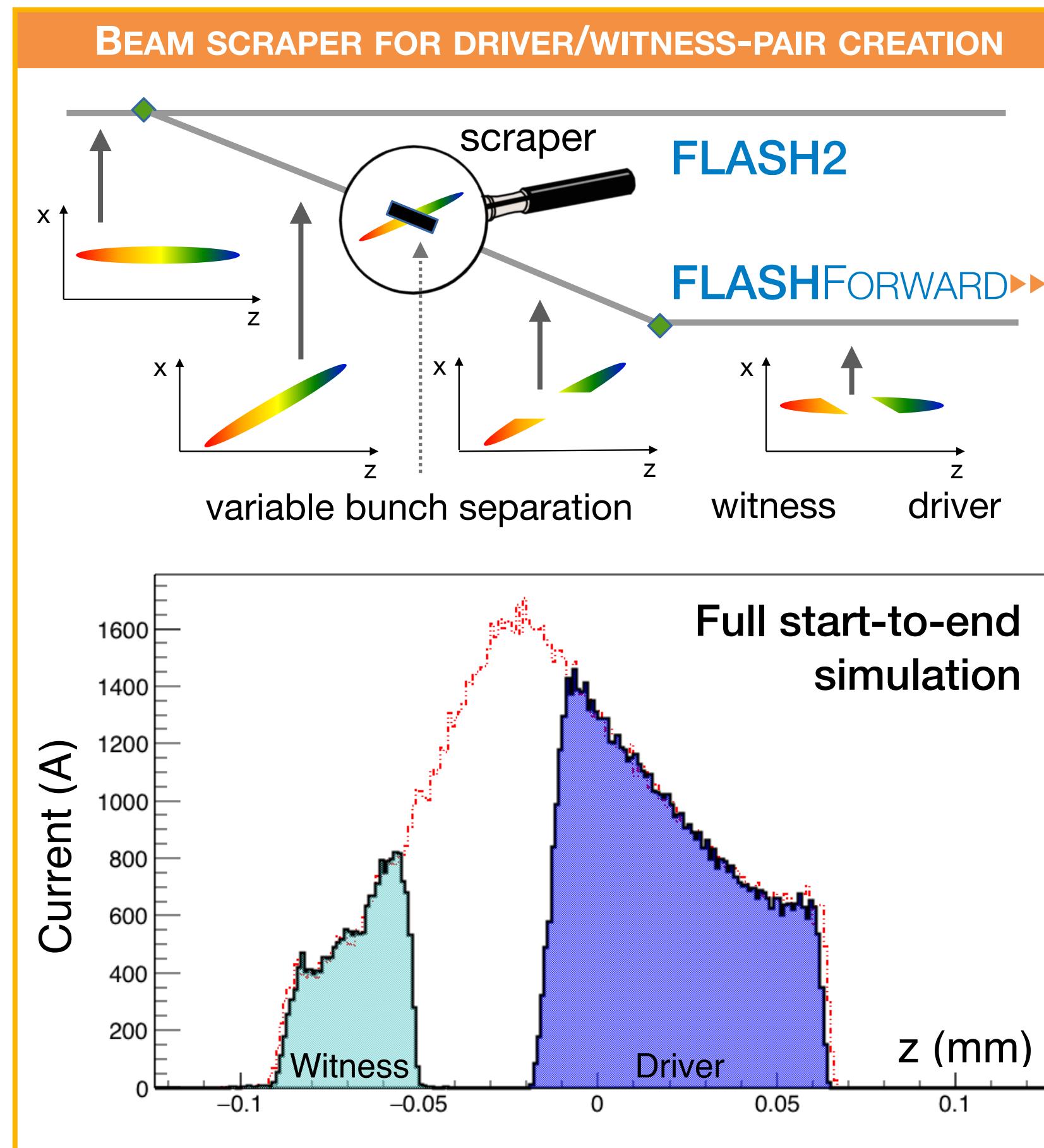
Core study: a plasma-based energy booster module

CURRENT-PROFILE SHAPING FOR ENERGY SPREAD AND EMITTANCE PRESERVATION



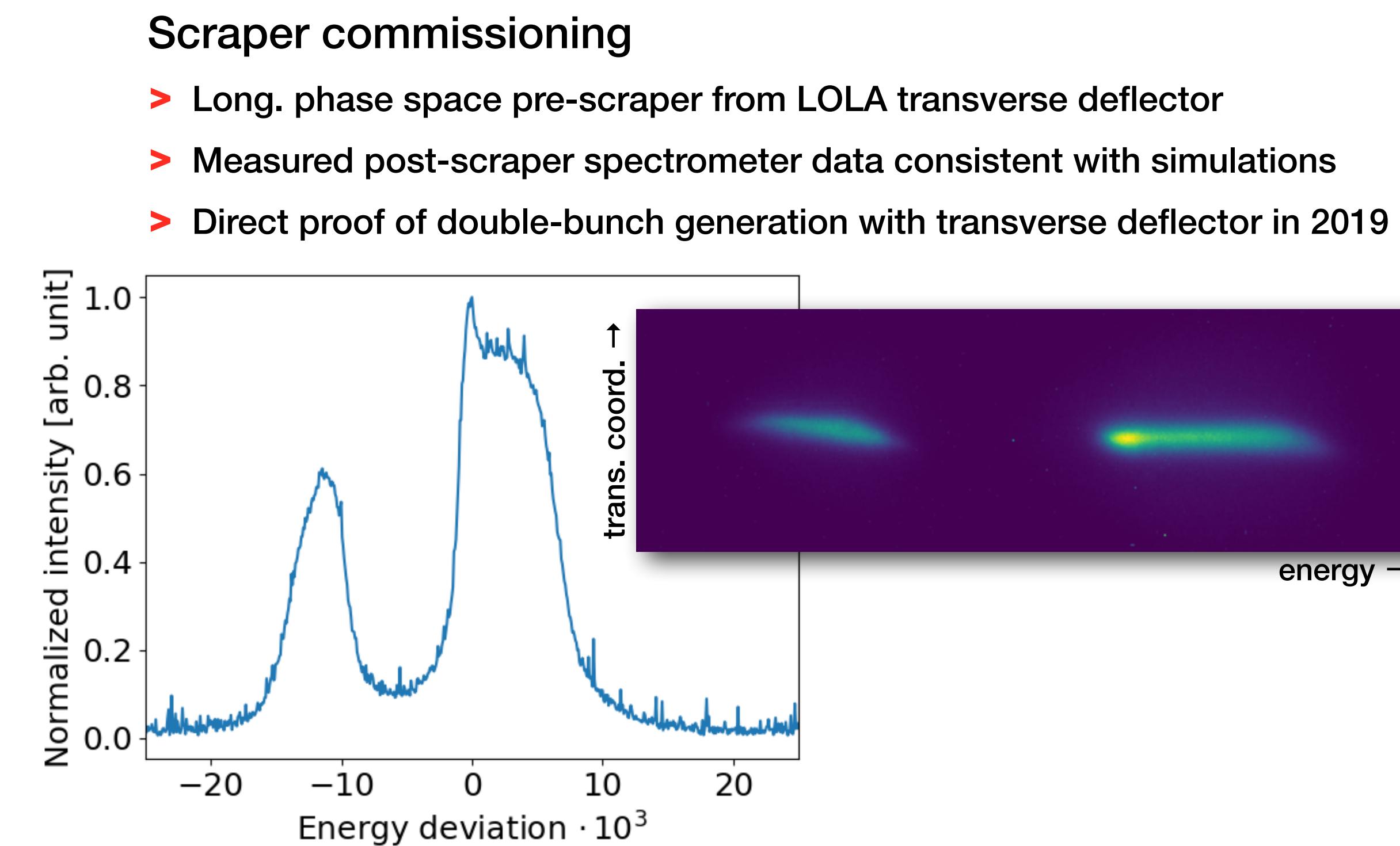
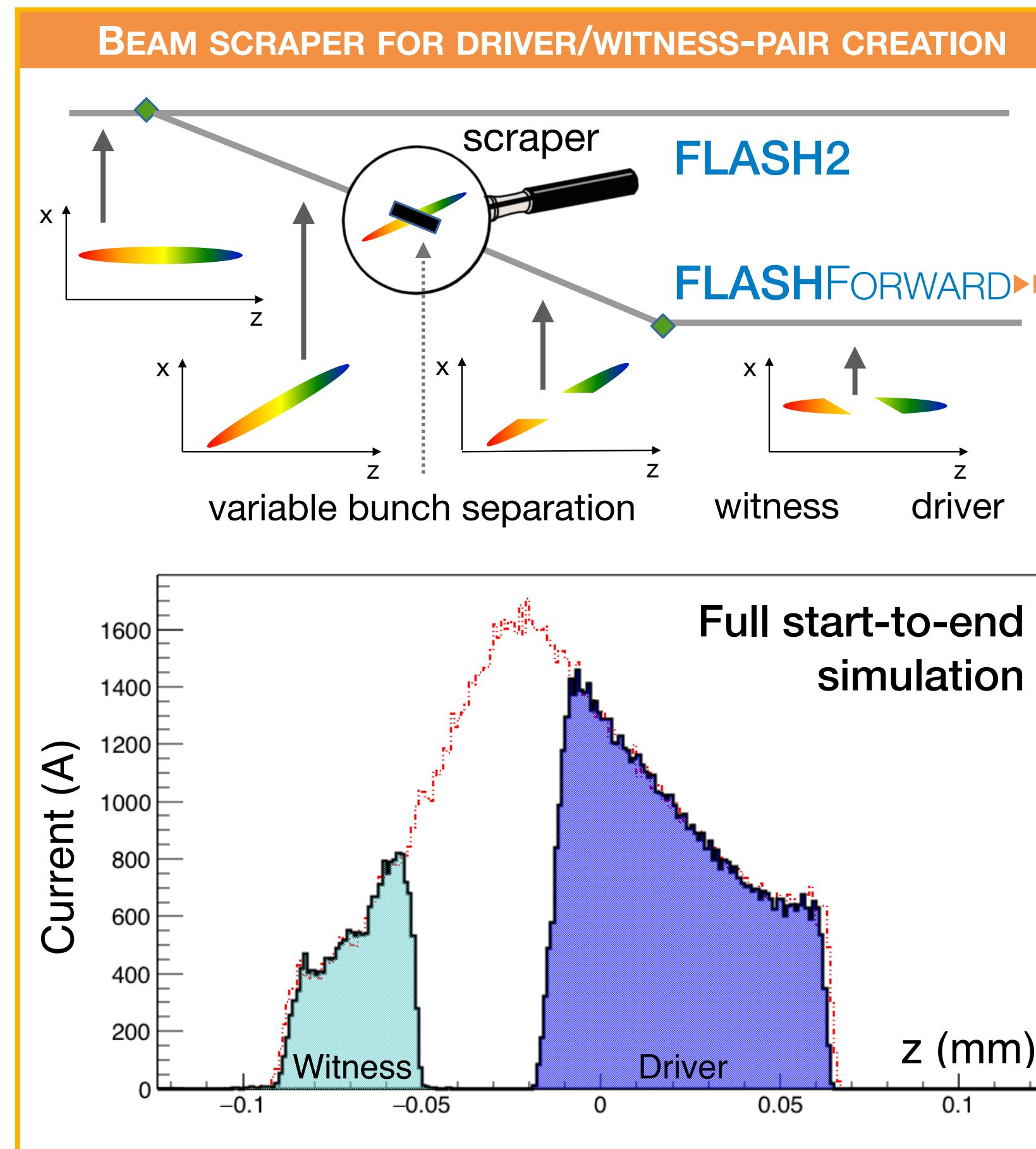
Core study: a plasma-based energy booster module

CURRENT-PROFILE SHAPING FOR ENERGY SPREAD AND EMITTANCE PRESERVATION



Core study: a plasma-based energy booster module

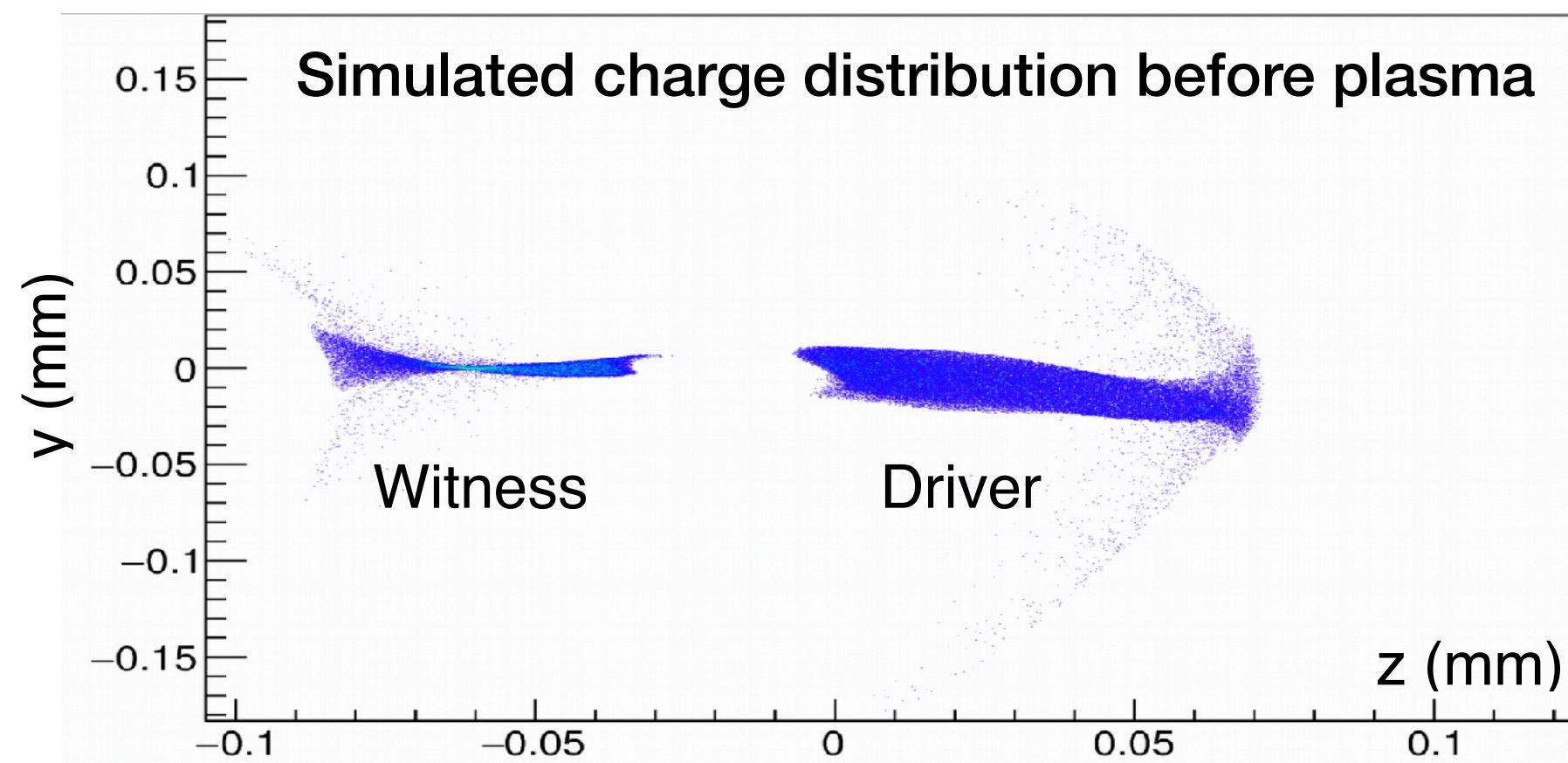
EXPERIMENTAL DRIVER/WITNESS CREATION



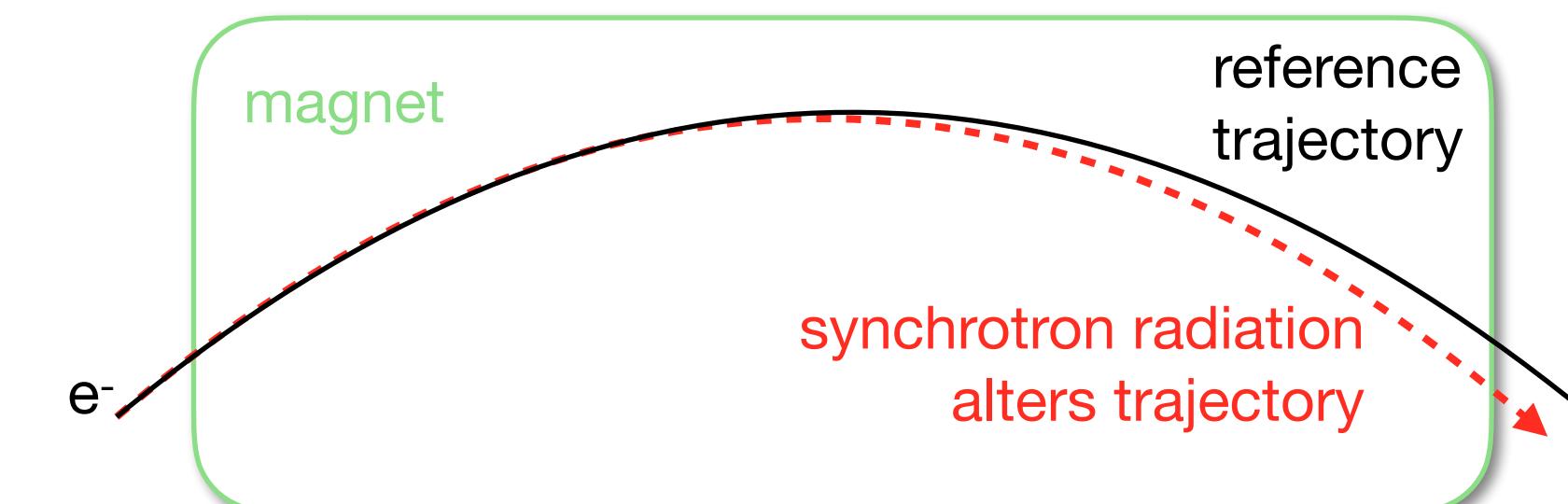
X-2 Plasma Booster
► PI: V. Libov (U Hamburg)

Future study: hosing growth rates and mitigation

START-TO-END SIMULATIONS SHOW EXCITATION OF THE HOSING INSTABILITY



- > Asymmetries in charge distribution and momentum expected, seed the hosing instability
- > Asymmetries caused by coupler kicks and CSR in bends

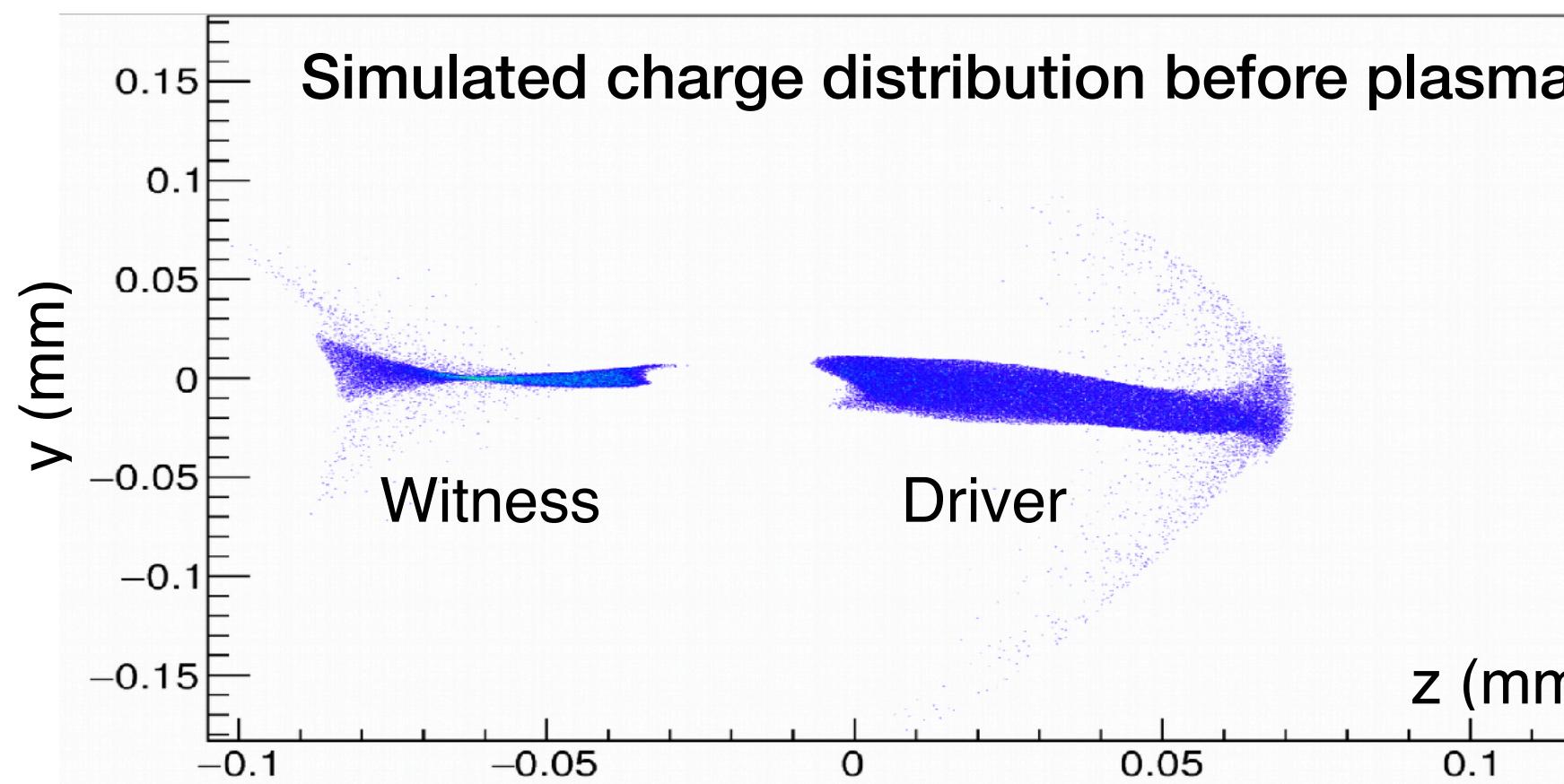


Formation of slice-centroid offsets in high-current bunches

- > emission of synchrotron radiation in dispersive element
→ causes energy loss → dispersion not closed
→ kick/offset w.r.t. reference orbit
- > energy loss/kick dependent on slice current
→ non-uniform along beam
- > emitted radiation acts back on beam

Future study: hosing growth rates and mitigation

START-TO-END SIMULATIONS SHOW EXCITATION OF THE HOSING INSTABILITY



in plasma

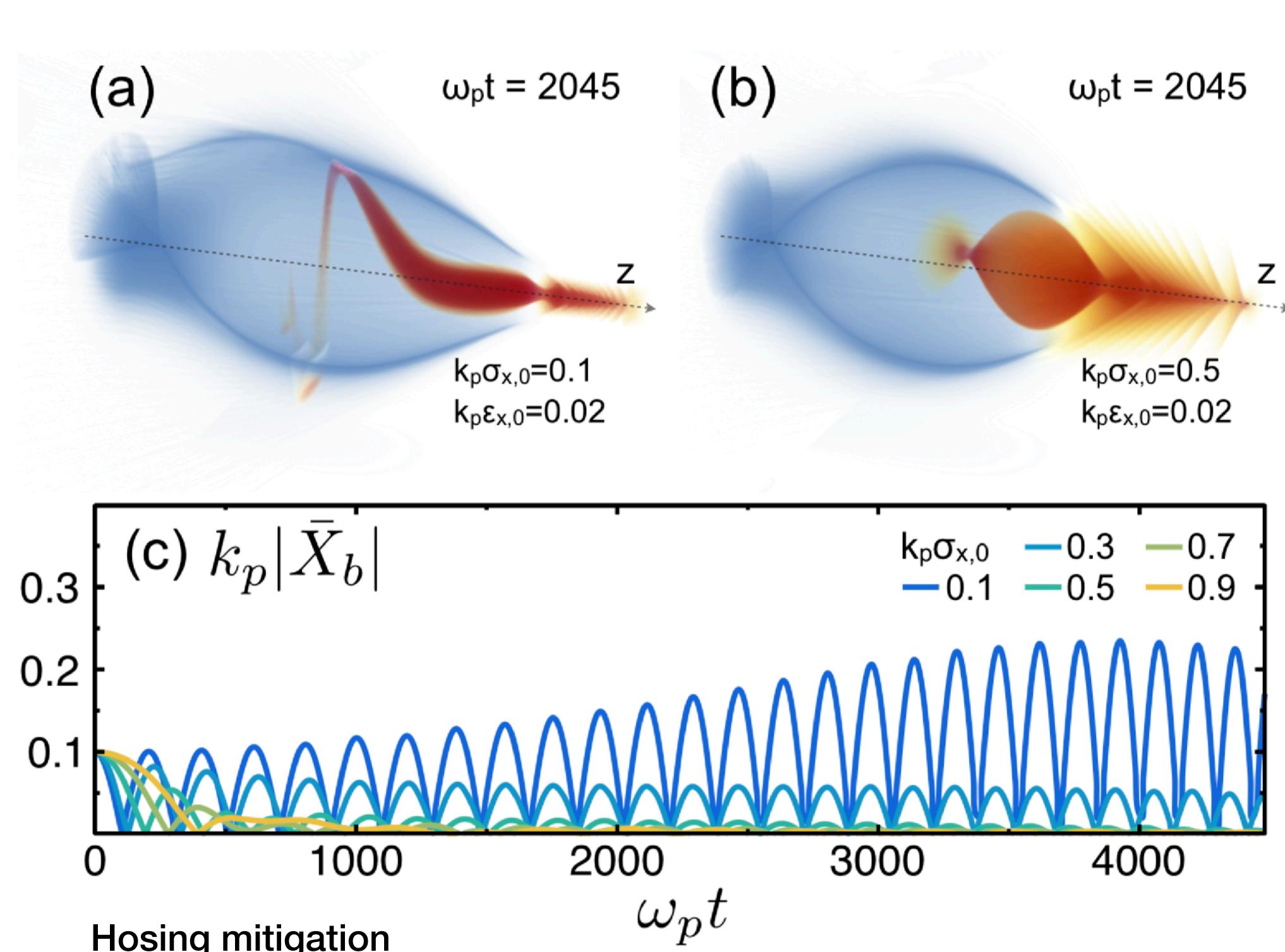


- > Asymmetries in charge distribution and momentum expected, seed the hosing instability
- > Asymmetries caused by coupler kicks and CSR in bends

- > Full start-to-end simulations incl. CSR predict hosing modes can be (easily) excited
- > Measurement of growth rates & hosing saturation vs. beam parameters one of next steps at FLASHForward

Future study: hosing growth rates and mitigation

START-TO-END SIMULATIONS SHOW EXCITATION OF THE HOSING INSTABILITY - EXPERIMENTS NOT YET



X-11 Hosing Studies
► PI: S. Wesch (DESY)

collaboration between DESY,
U Hamburg, and IST Lisbon

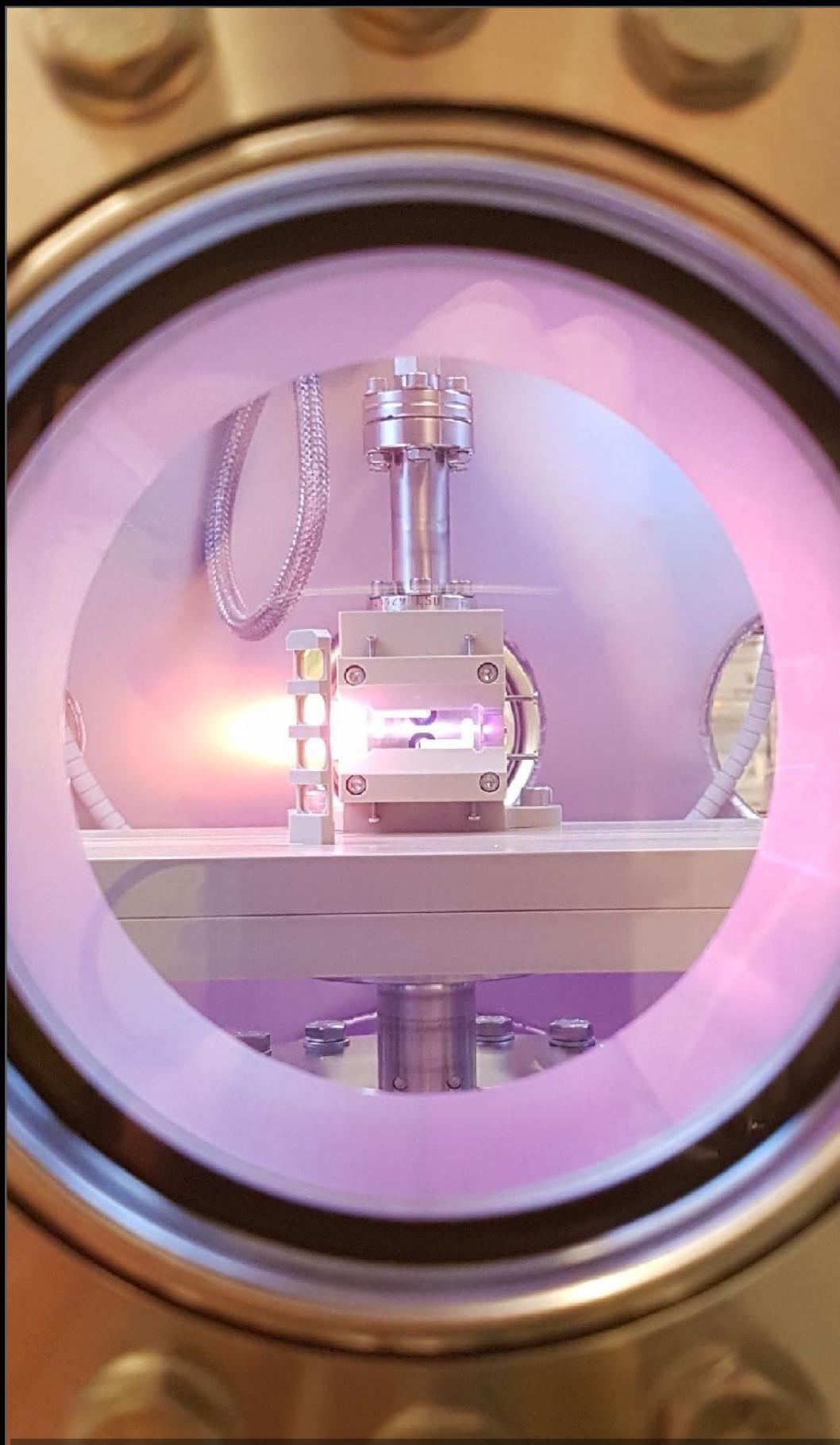


HiPACE

- Full start-to-end simulations incl. CSR predict hosing modes can be (easily) excited
- Measurement of growth rates & hosing saturation vs. beam parameters one of next steps at FLASHForward
- No sign of hosing so far in experiments
- Suppressed owing to large focal size?
(current diagnostic resolution limited at $\sim 20\mu\text{m}$...)

Plasma-based accelerator science at **FLASHFORWARD**►

SMALL IS BEAUTIFUL (AND USEFUL*)



Beam-driven wakefield acceleration
GeV energy booster, high-brightness beams

- > Plasma wakefield acceleration is an intriguing technology to radically miniaturize particle accelerators
- > First applications with laser drivers in photon science and medical imaging are within reach
- > High-average power applications are incompatible with current laser technology, will require particle beam drivers (for the foreseeable future)
- > **FLASHFORWARD**► is a unique, next-generation experiment toward high-brightness, high-quality, high-average power plasma accelerators
- > Experiments have started this summer. Exciting times are ahead!



Aberration-free active plasma lens
sym. kT/m focussing