UNIVERSITY OF OSLO

Plasma lenses for particle beams

A brief review

Carl A. Lindstrøm

Department of Physics, University of Oslo

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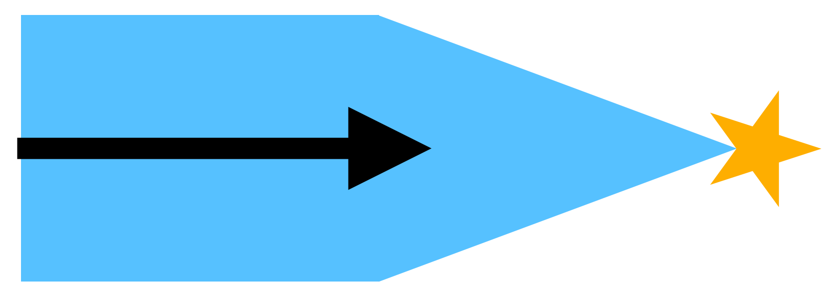
The motivation

> Many applications require small beam sizes
> (e.g., radiotherapy, FELs, particle colliders).



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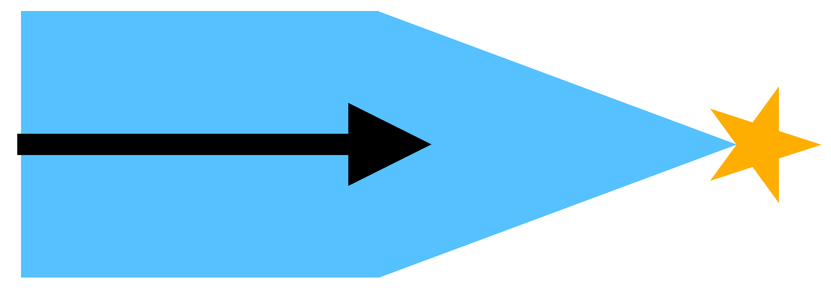

- Others require capture/collimation of highly diverging beams

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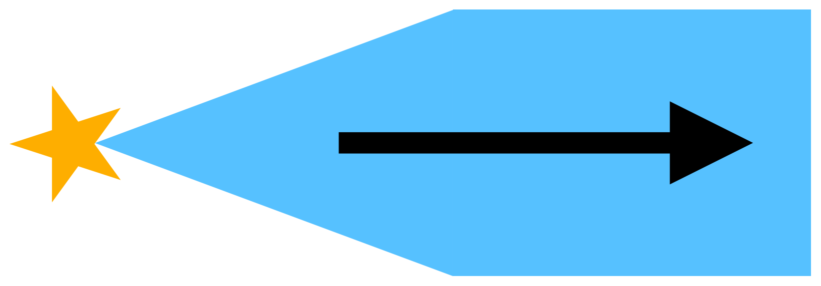

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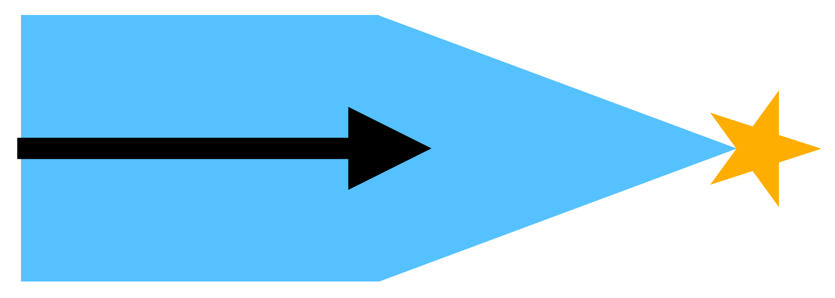

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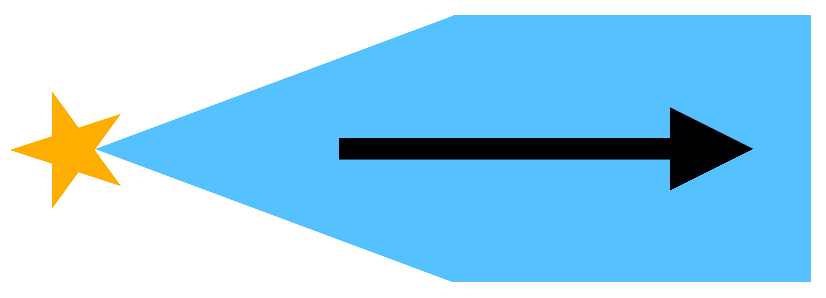

> Fortunately: we have thought about particle focusing for a century, and found many solutions…

Transverse beam dynamics

Some background and definitions

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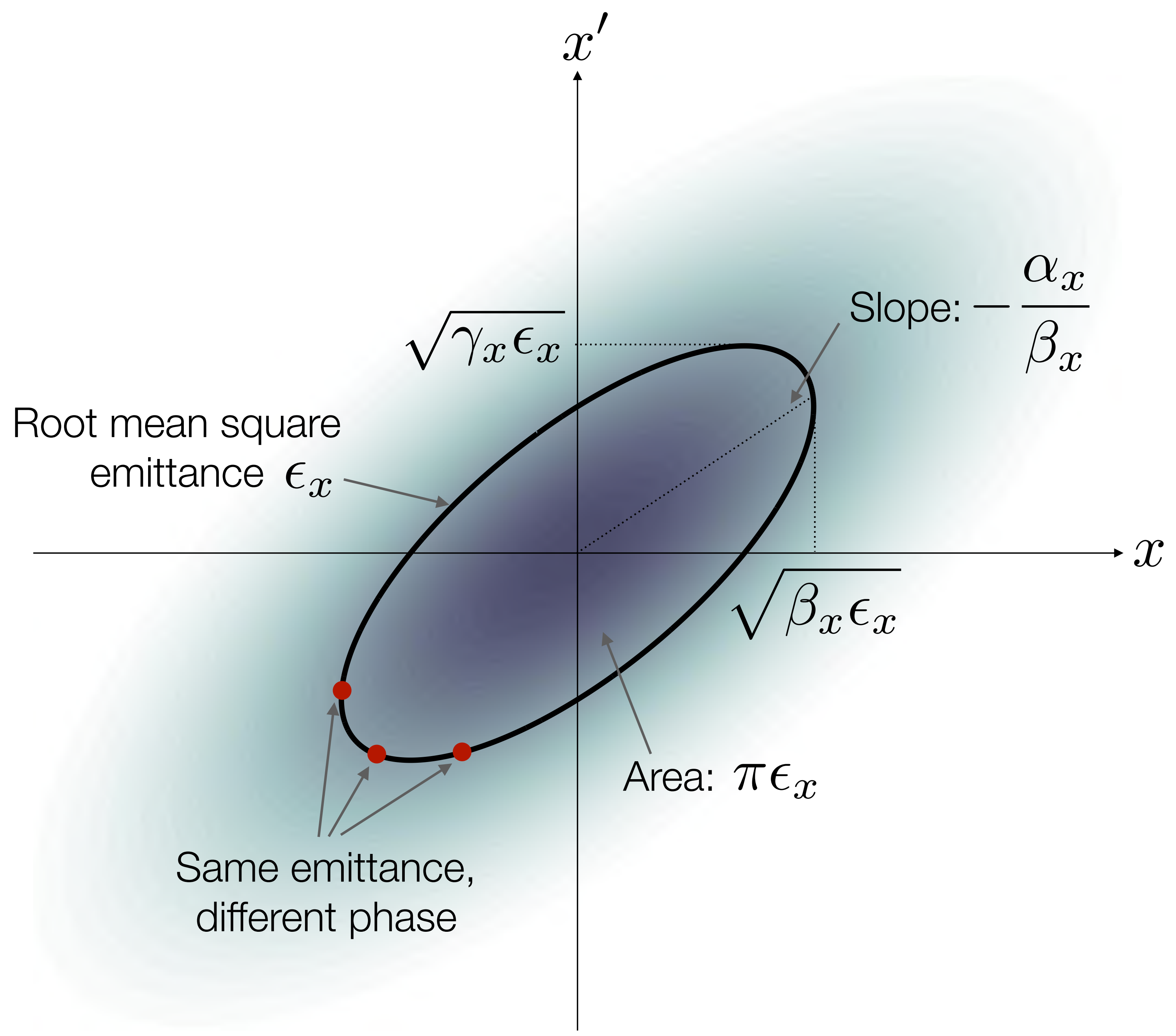

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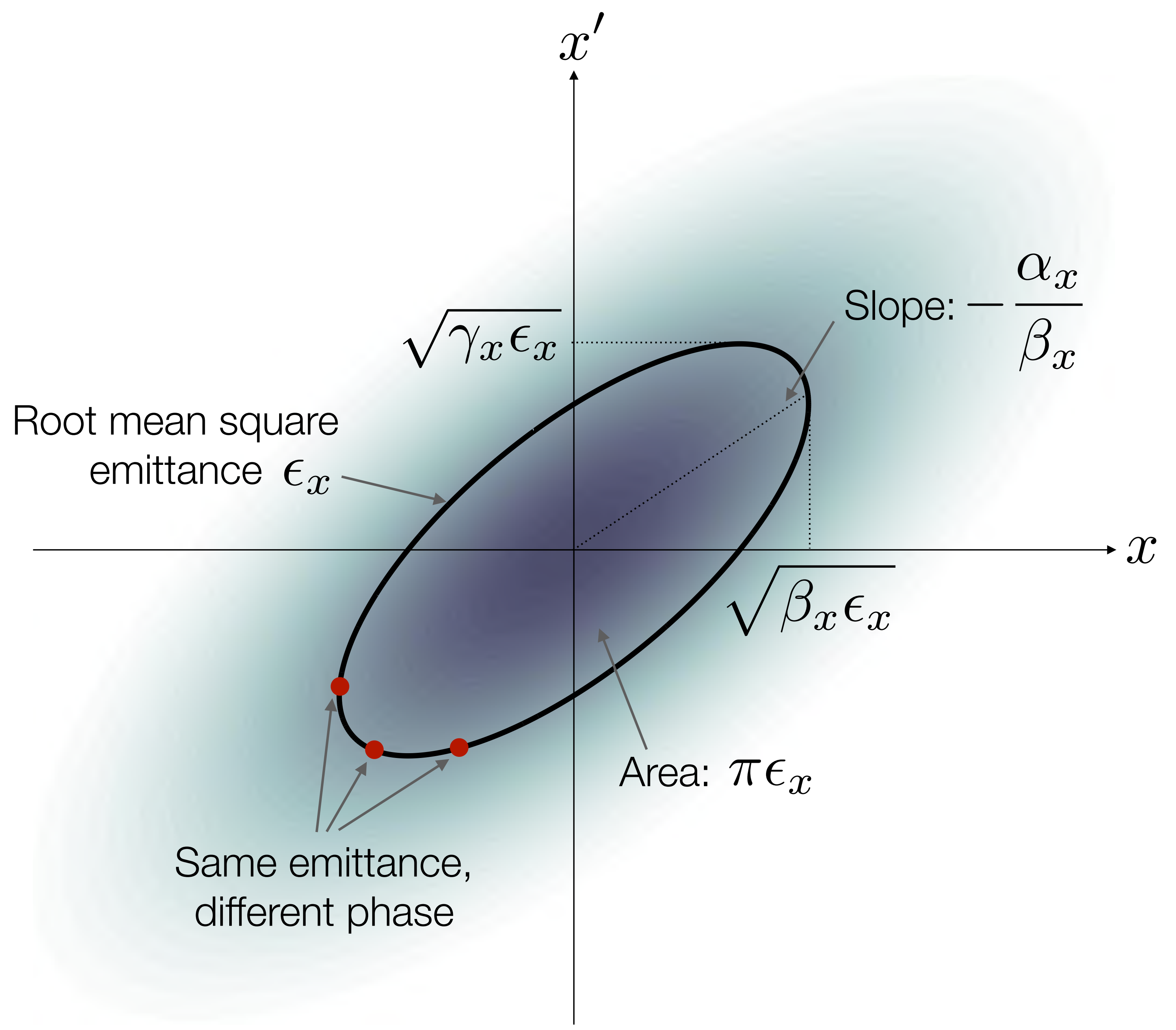

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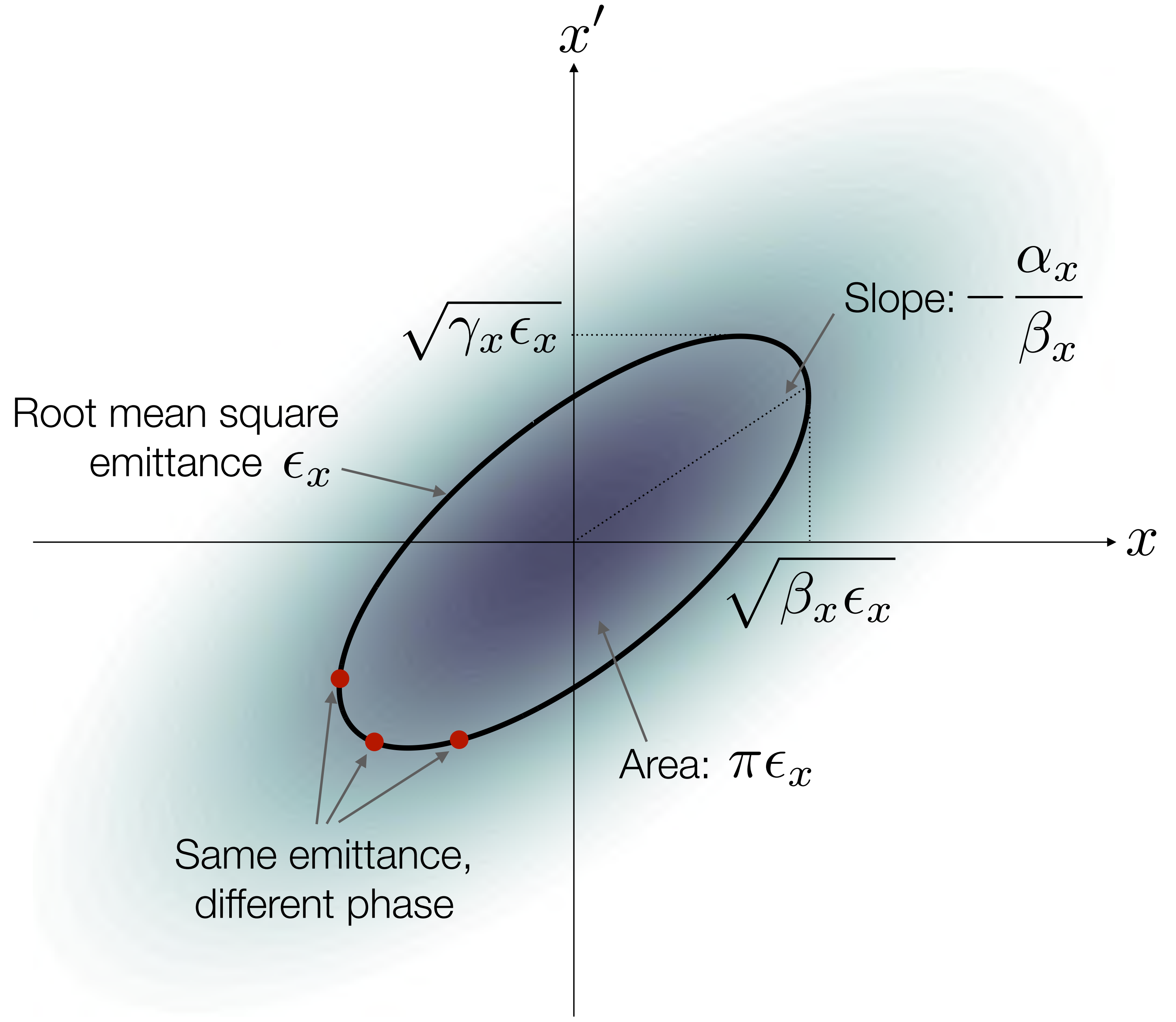

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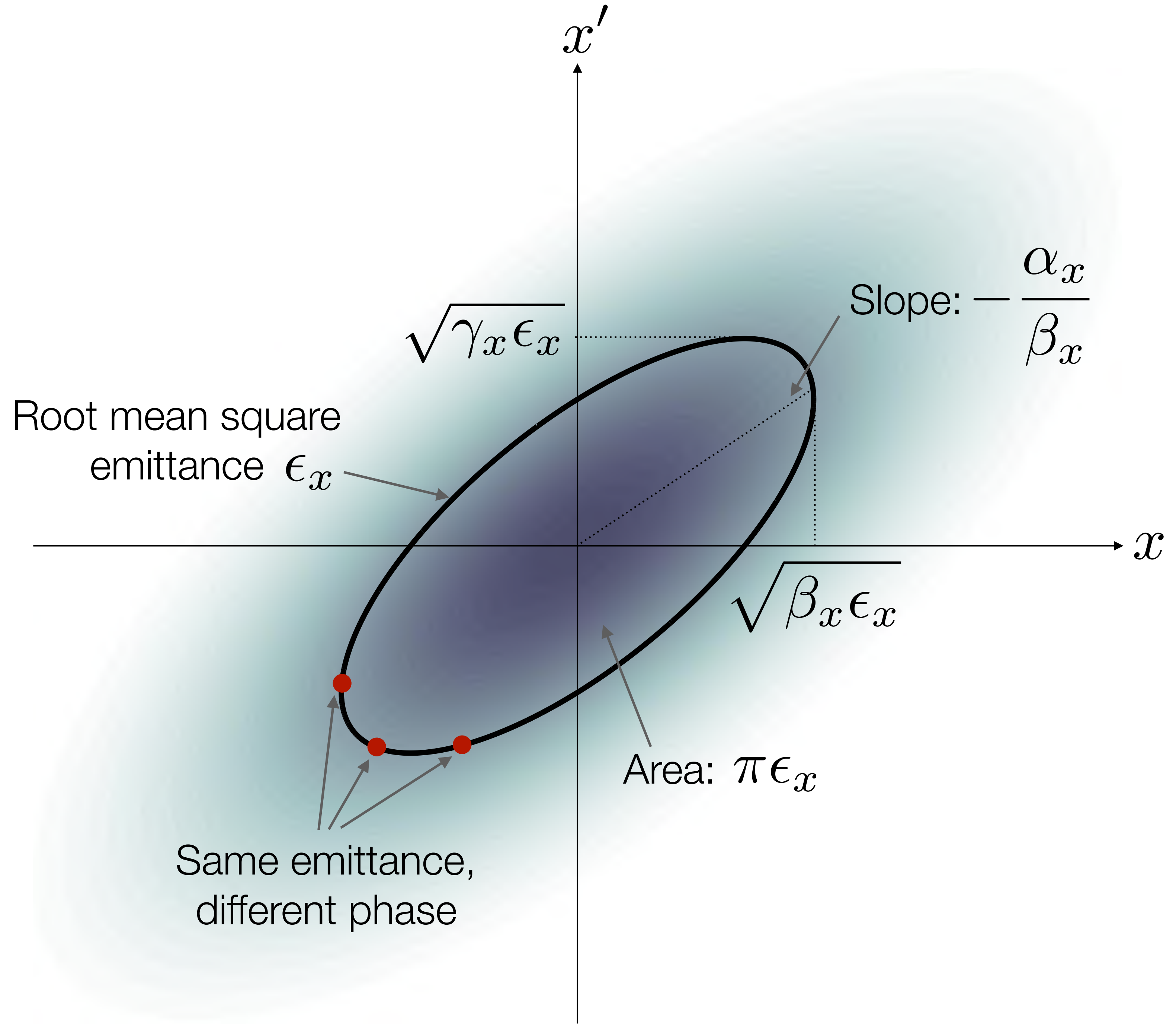

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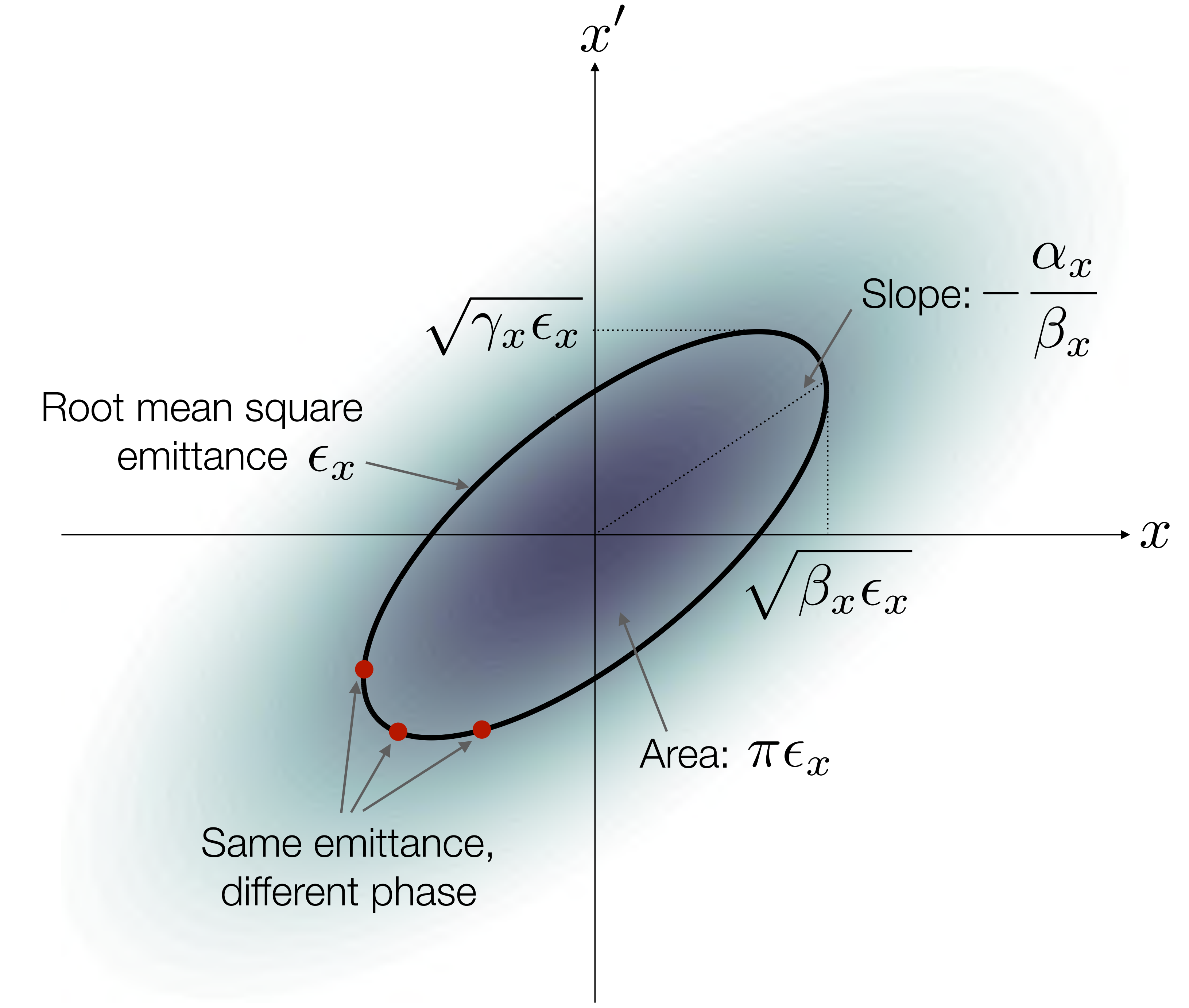
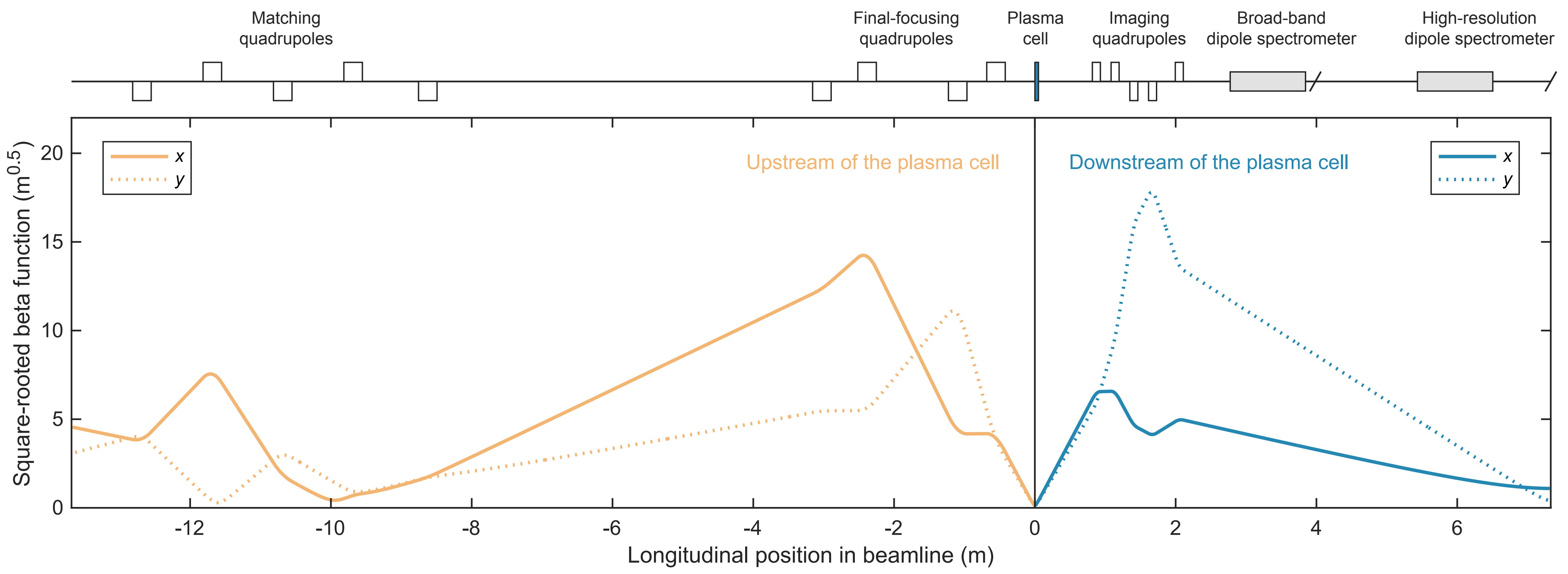
- > How do we manipulate particles in transverse phase space?





From Lindstrøm et al., Nat. Commun. 15,, 6097 (2024)

Magnetic optics elements

The traditional choice for high-energy particles

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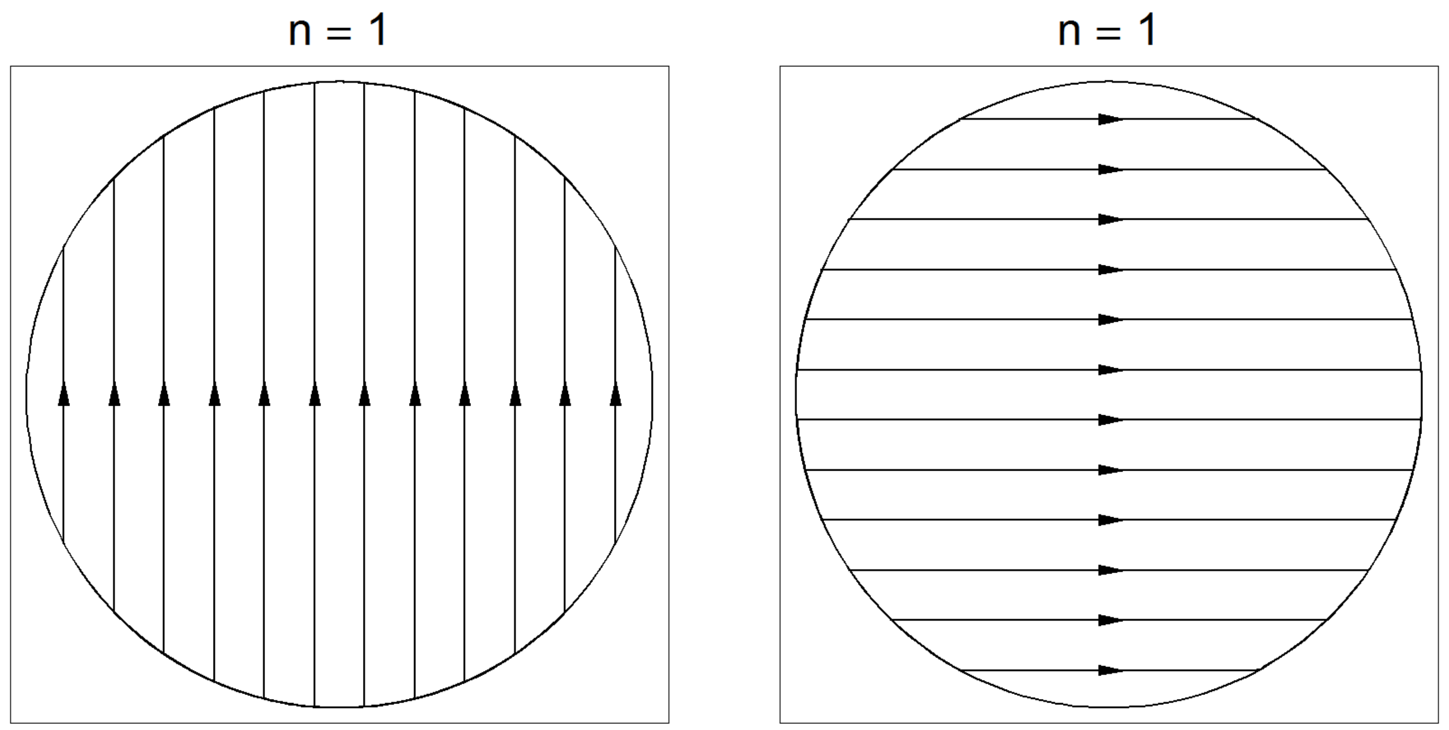

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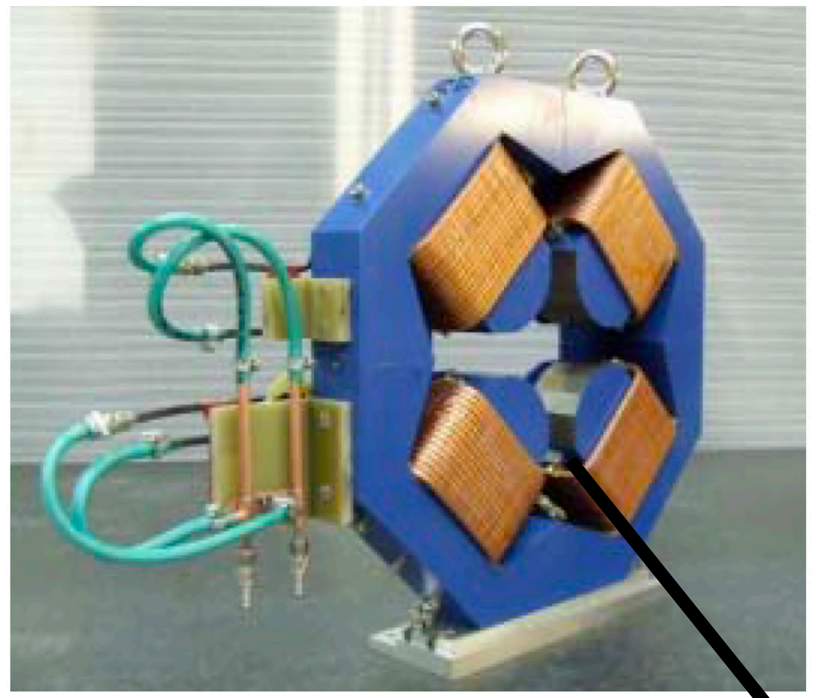

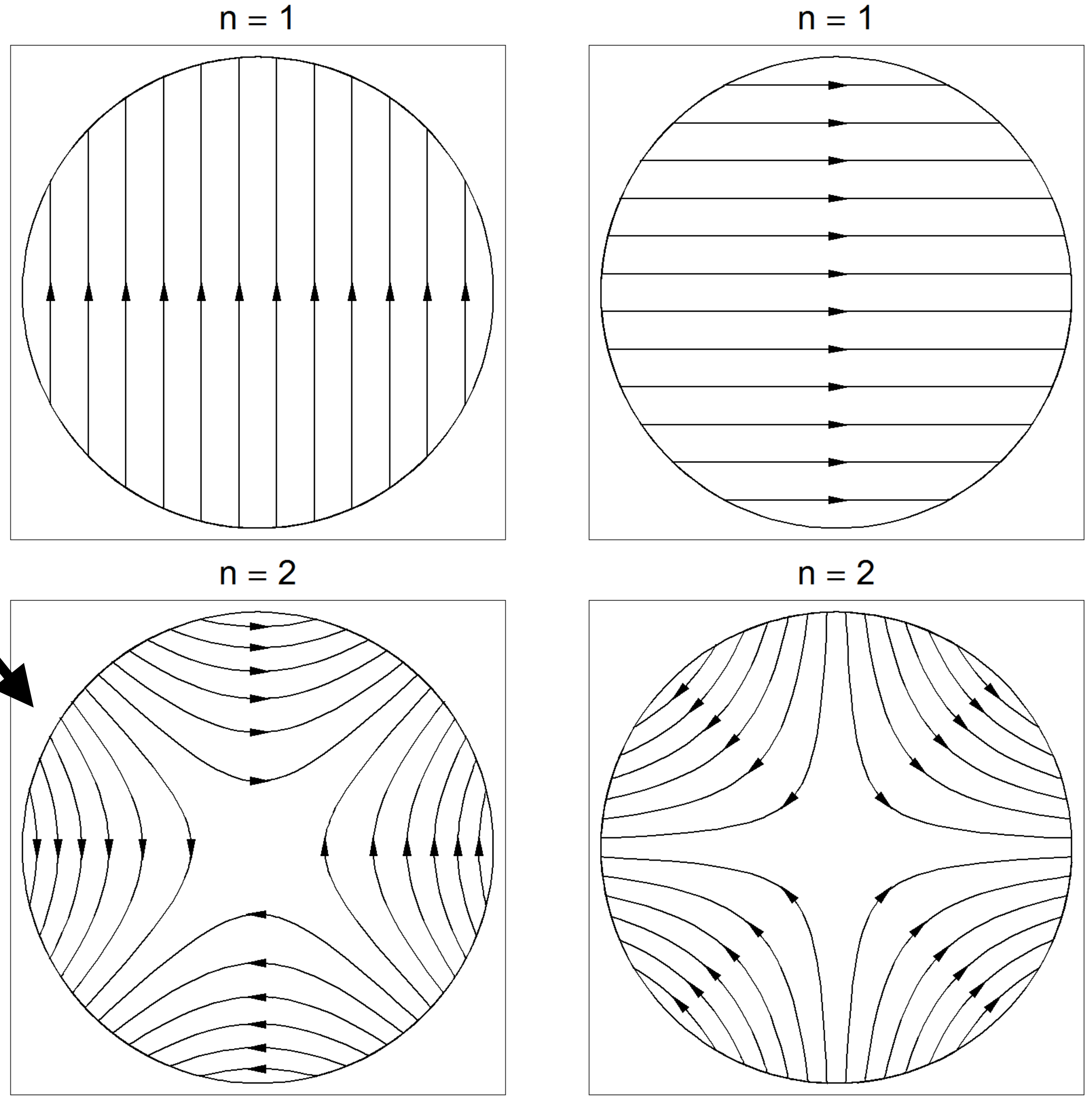

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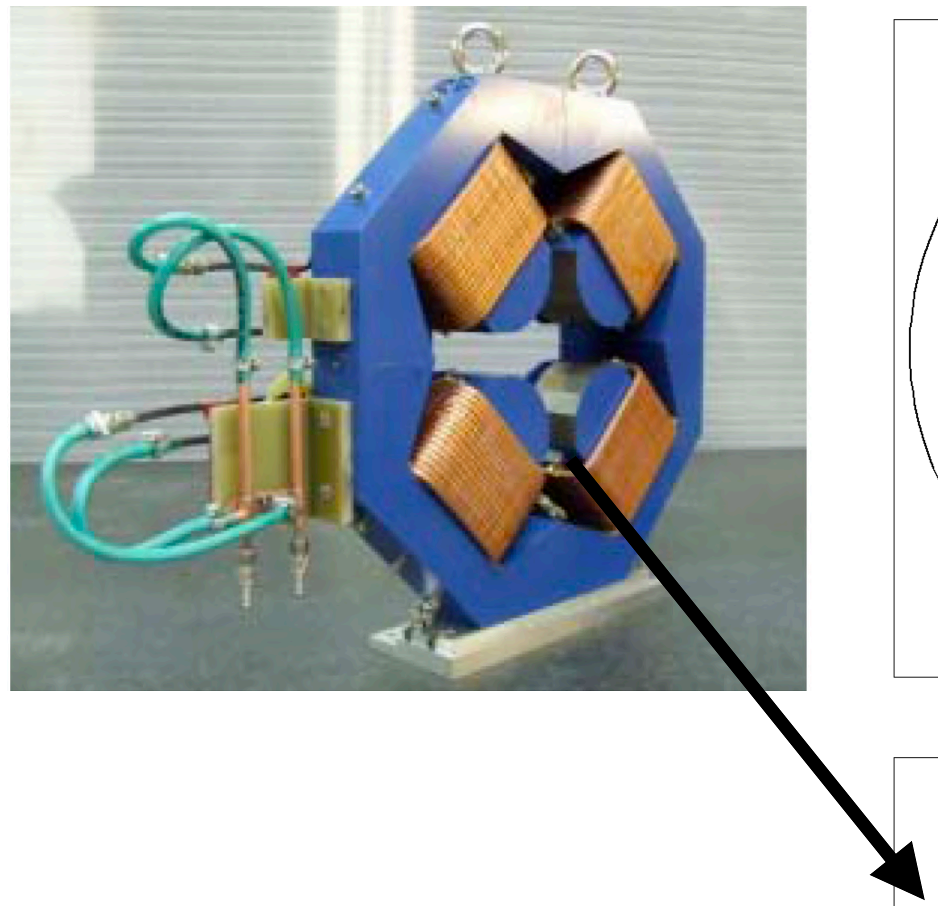

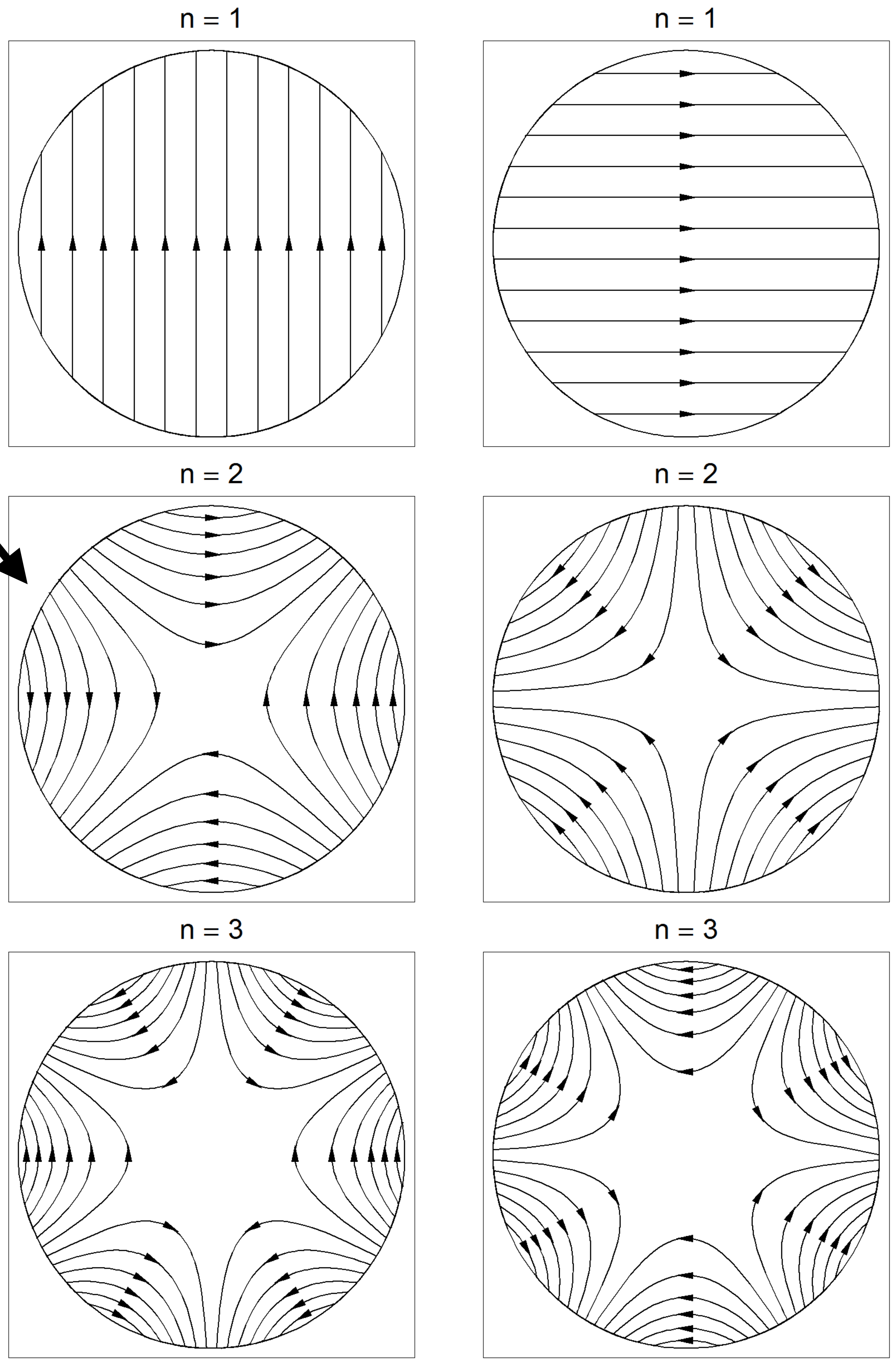

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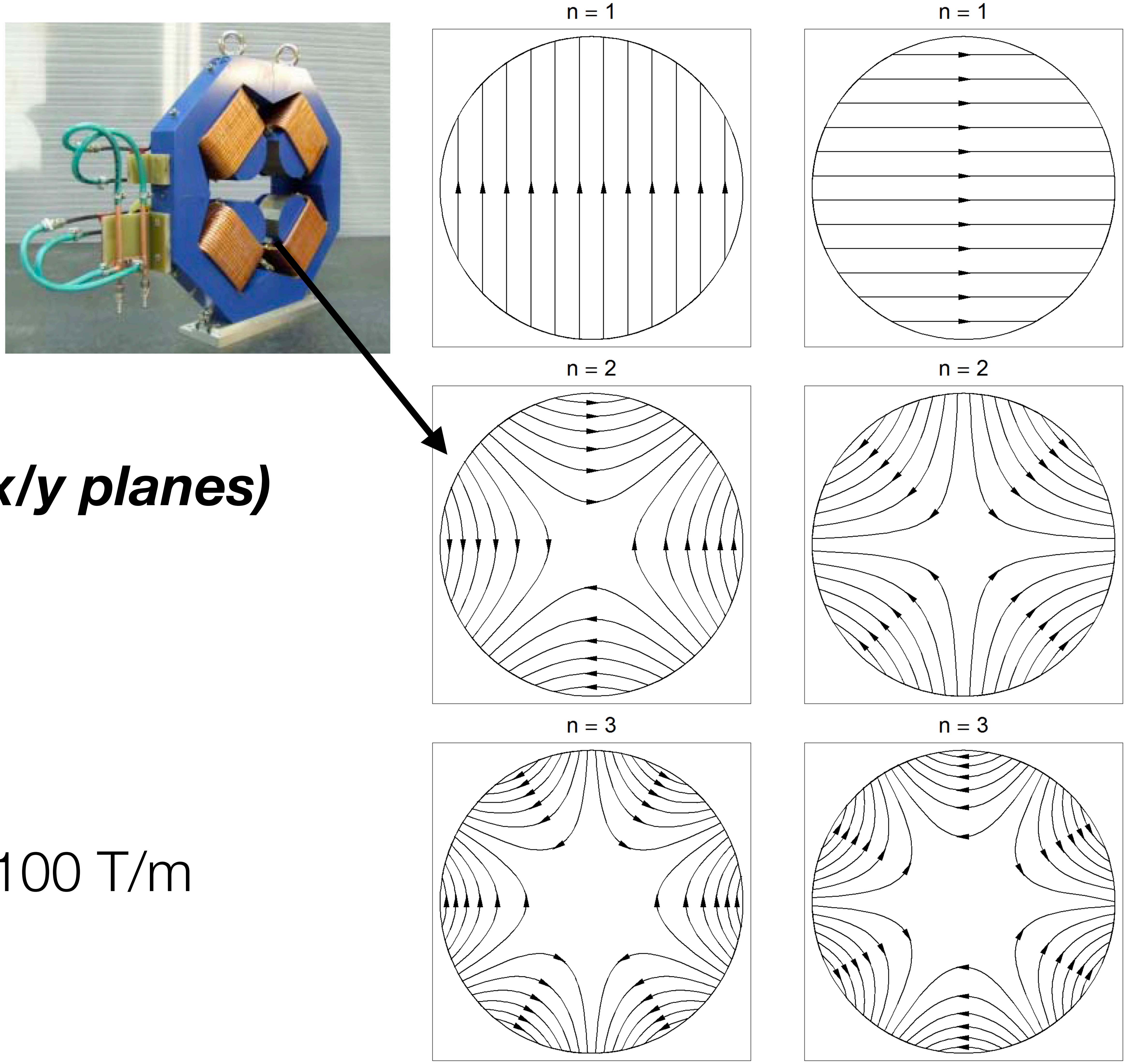

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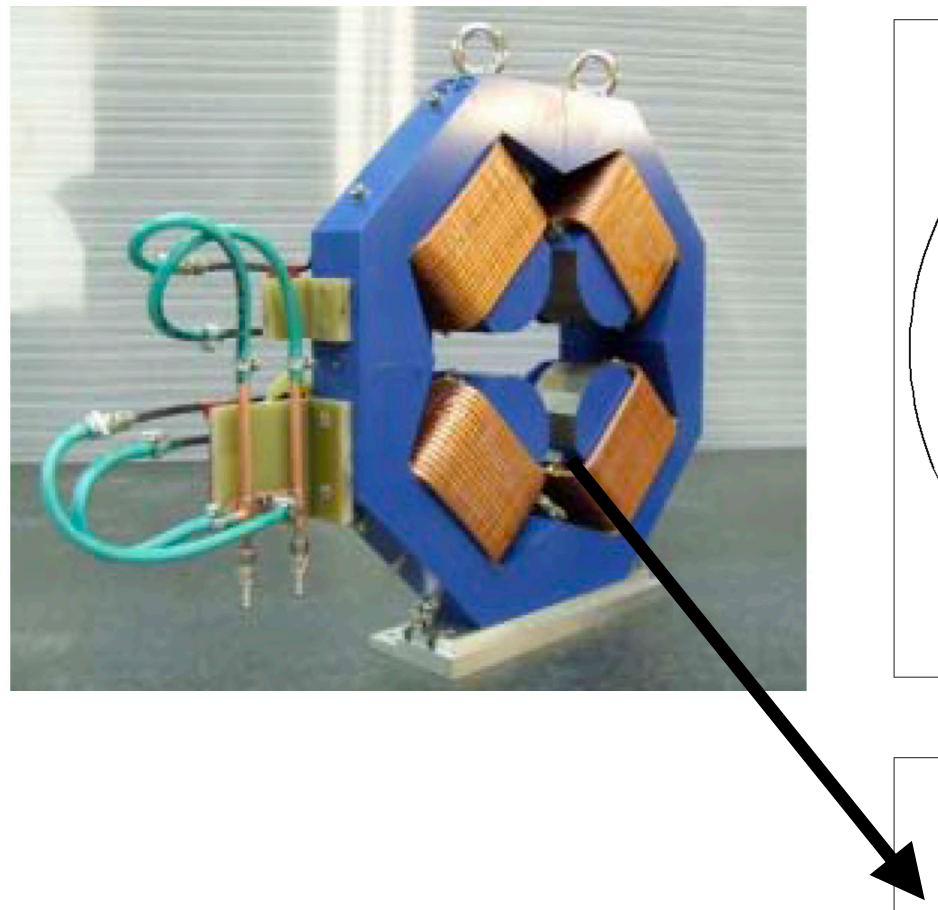

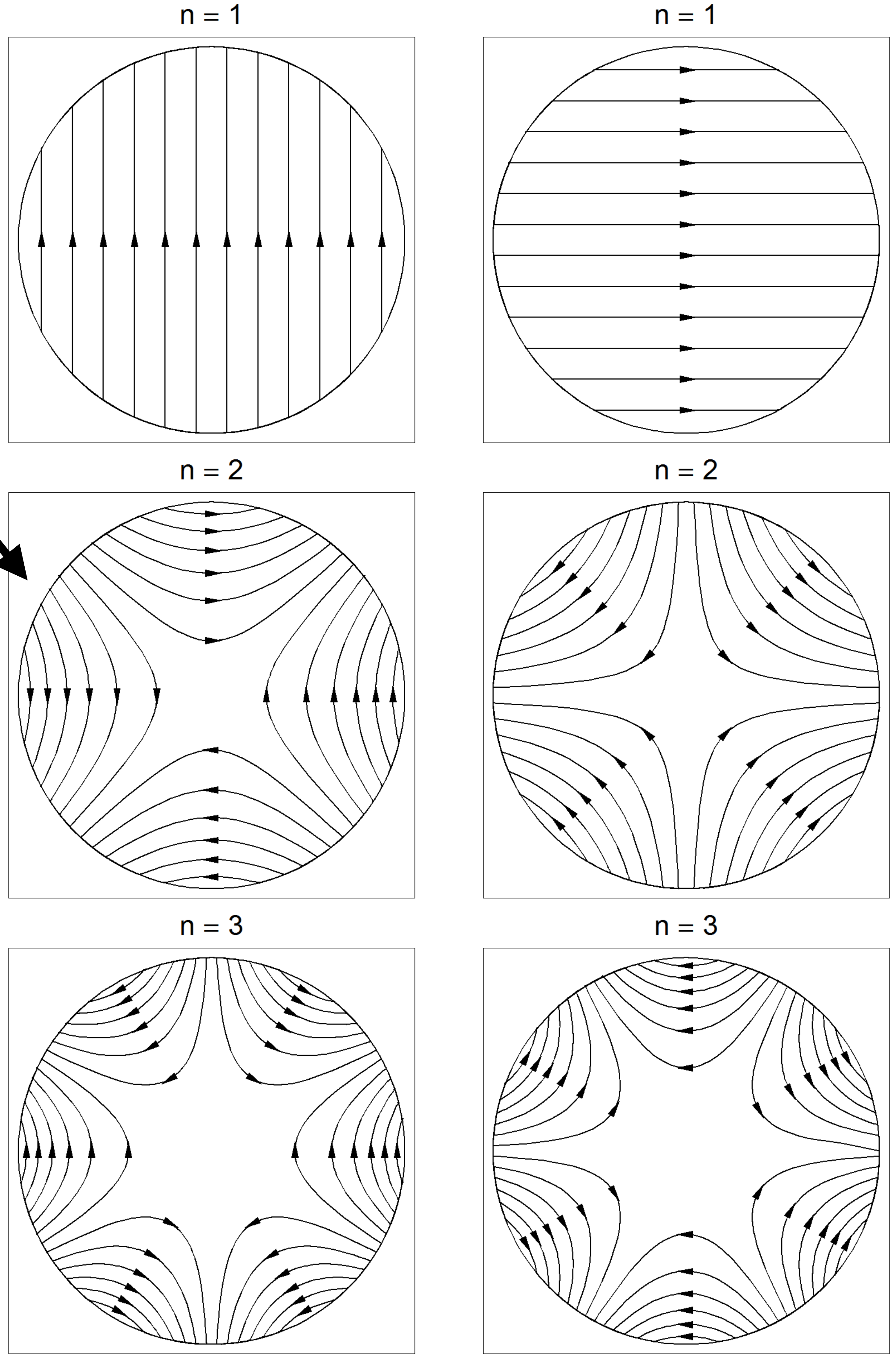

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  - Quad: 1–4 cm bore, 1 T tip field => 25–100 T/m
- **(Pulsed) solenoids** can also be used, but scale as $1/p^2$ (and not as $1/p$) – good for low momentum particles

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Focusing in both transverse planes at the same time

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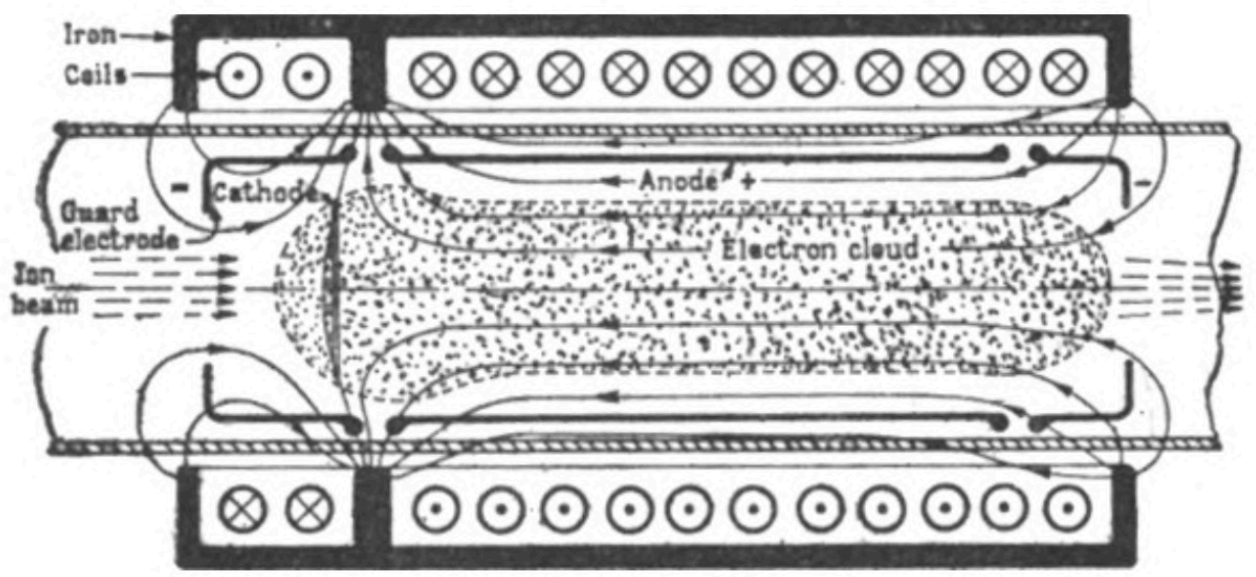

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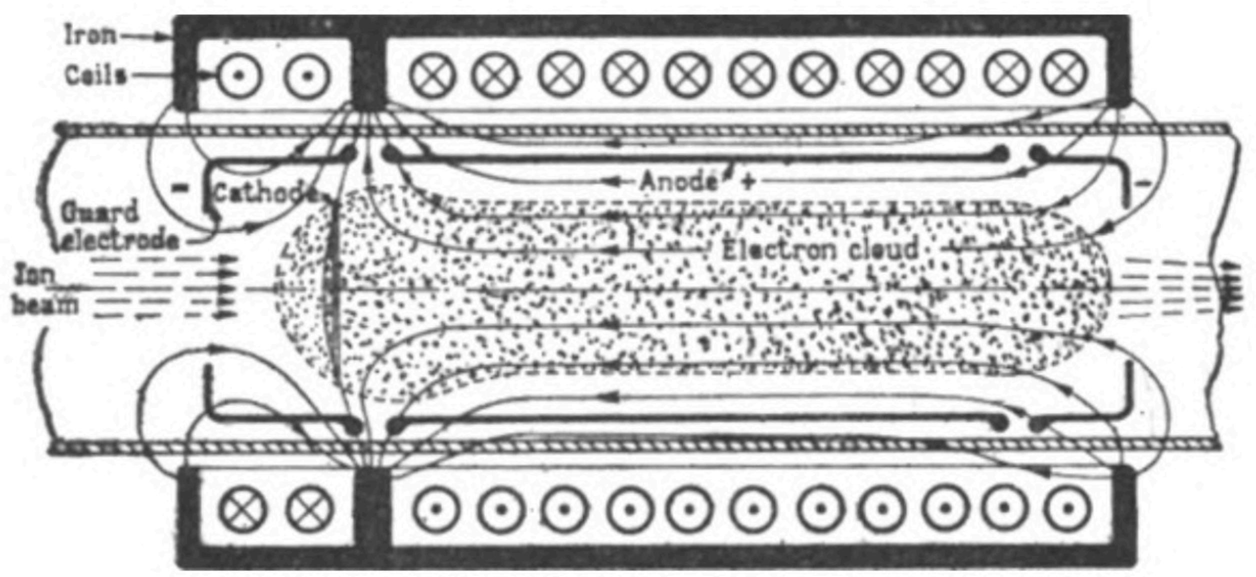

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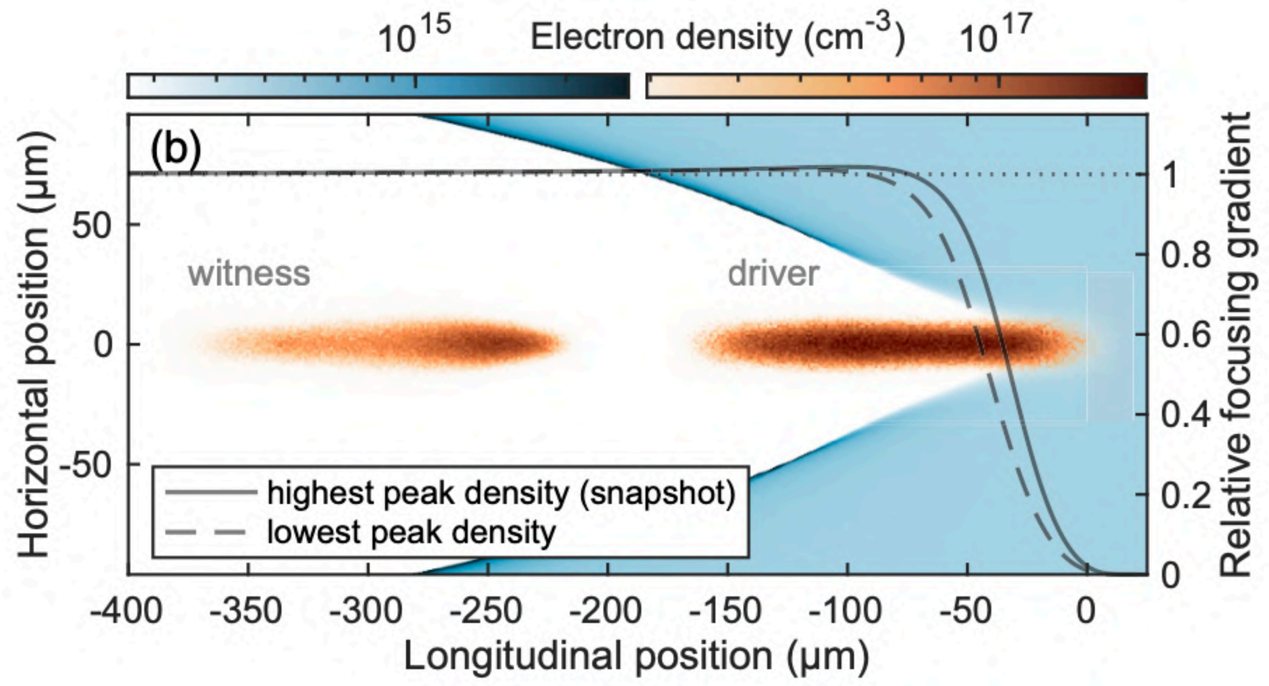

Björklund Svensson, PRR (2026)

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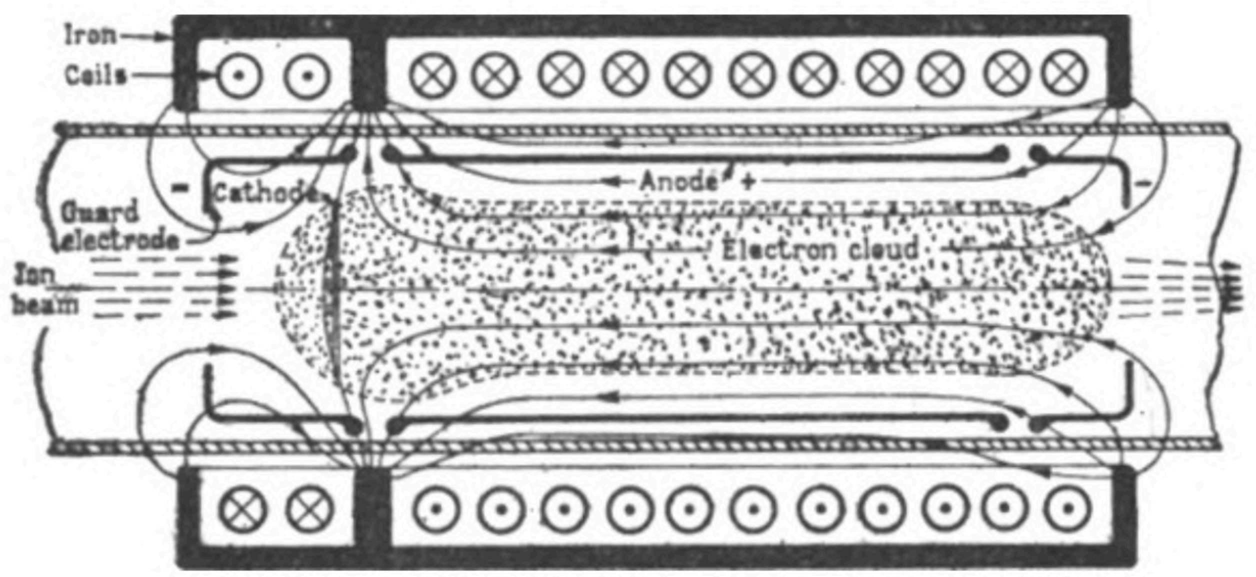

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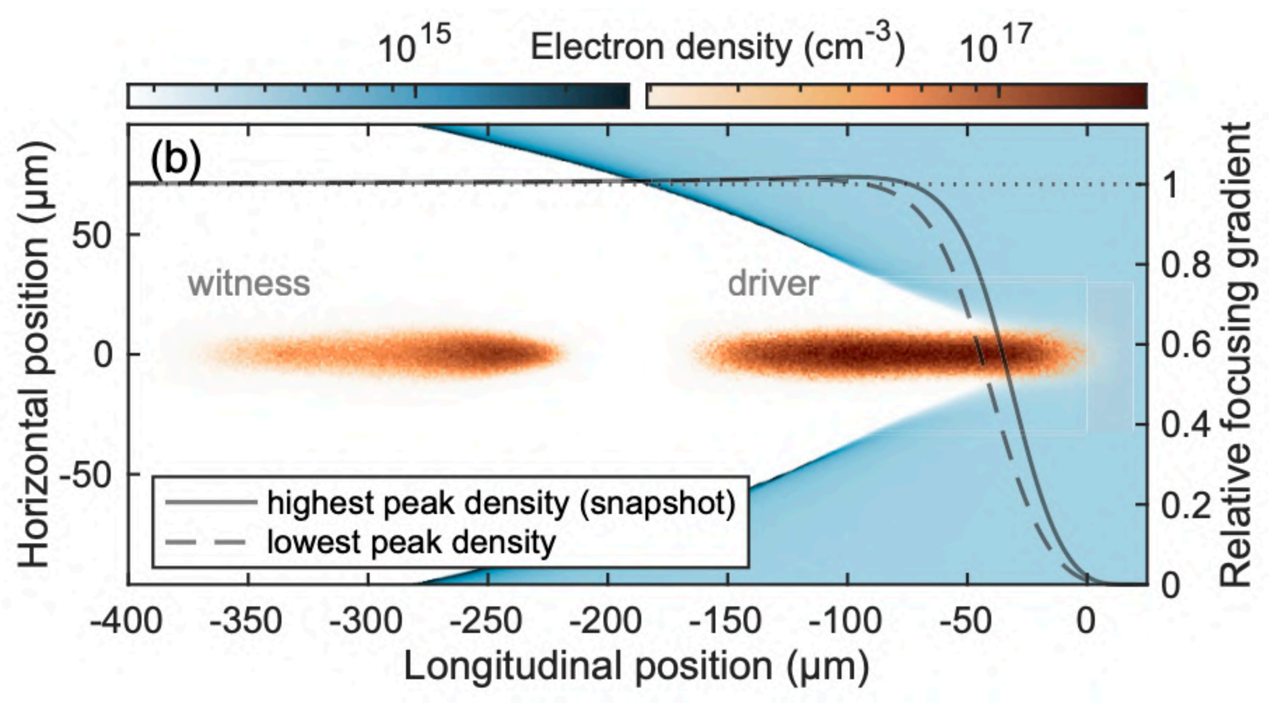

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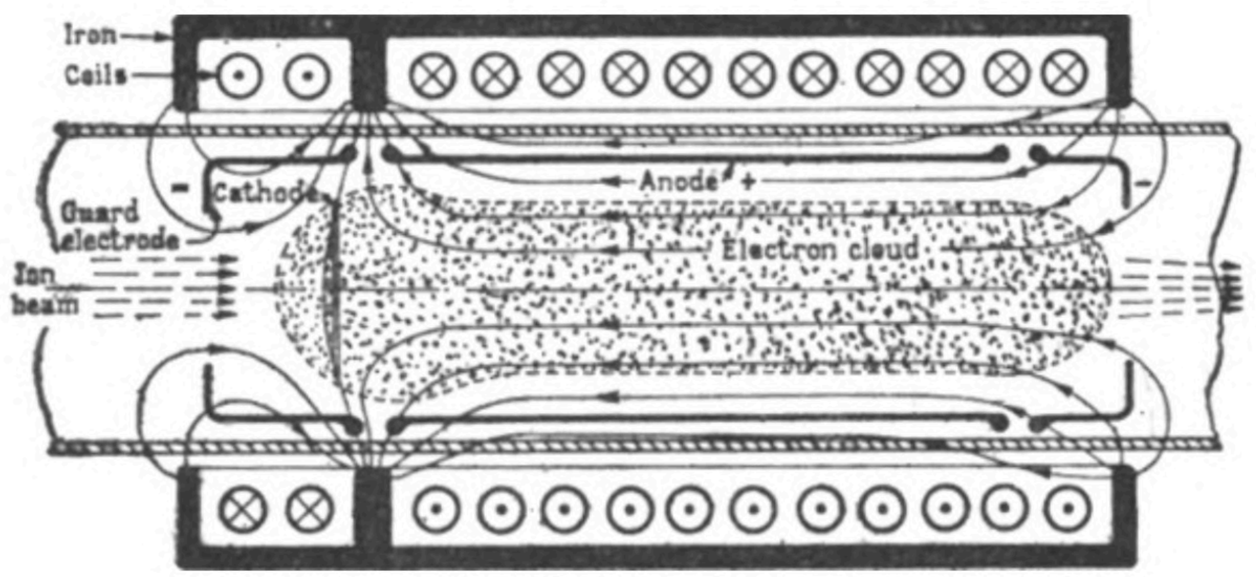

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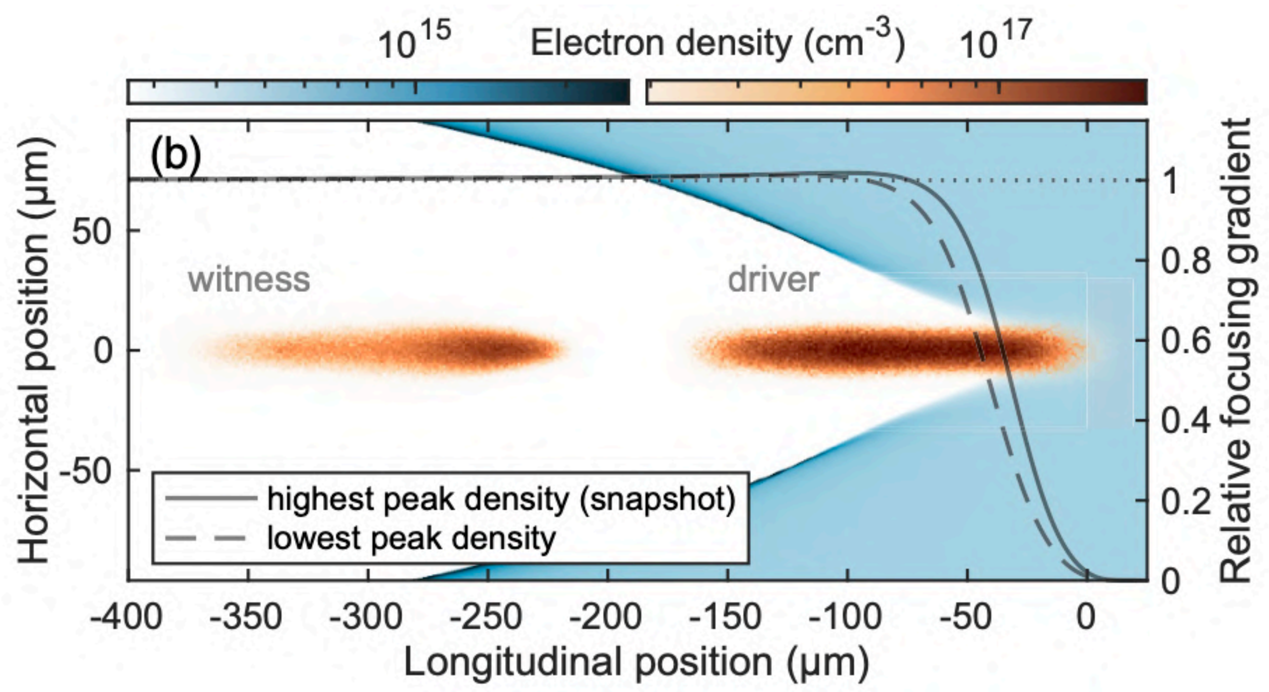

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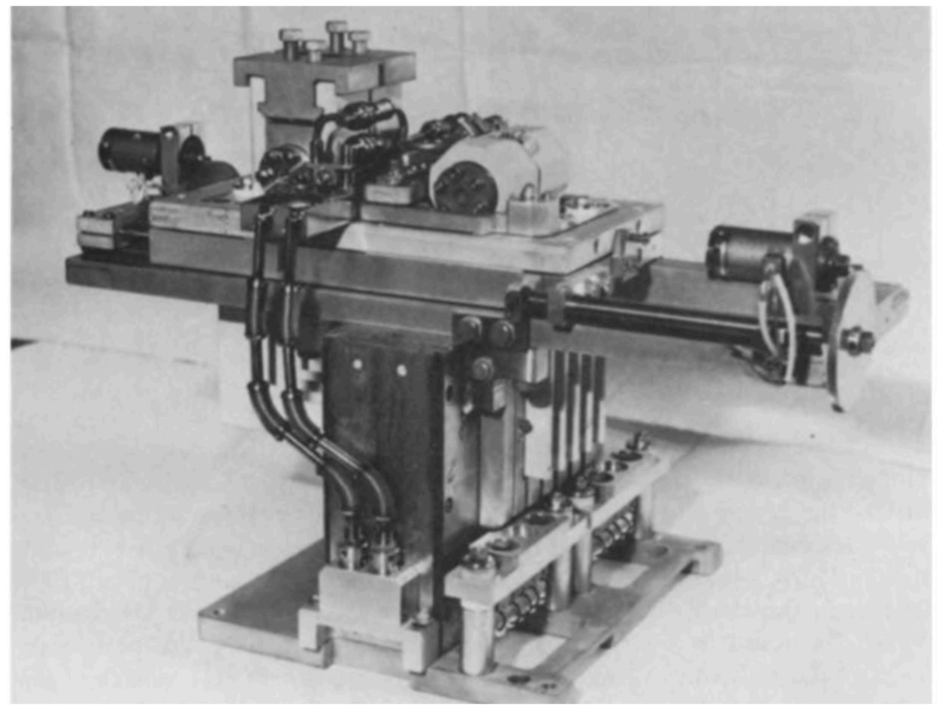

Bayanov et al., NIM 190, 9 (1981)

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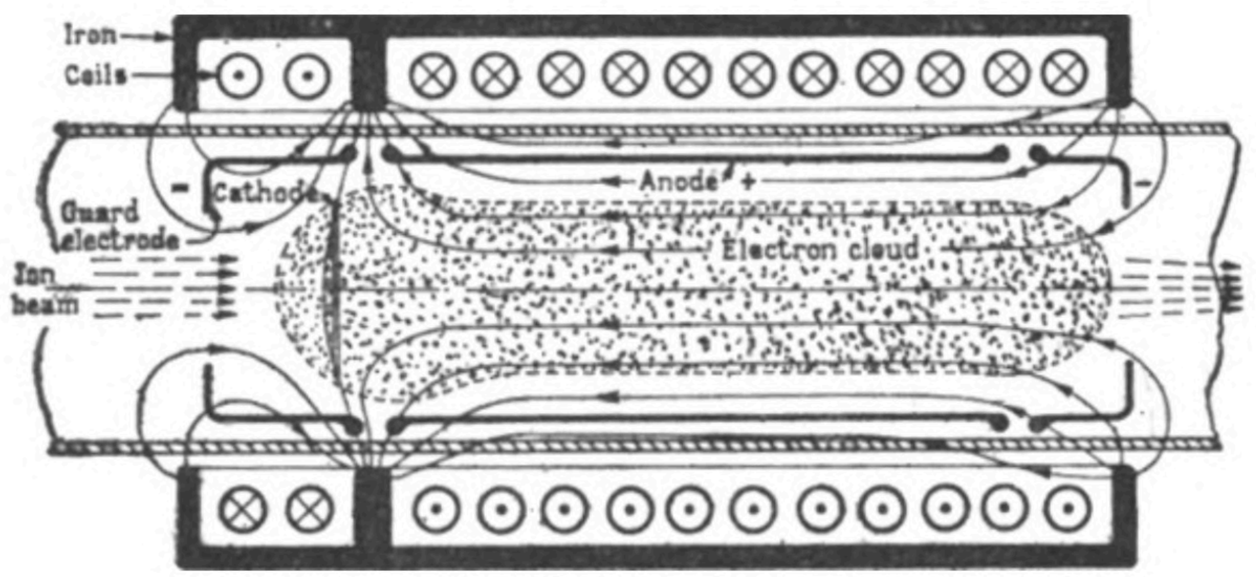
  - **Use the plasma as a conductor! (Active plasma lens)**



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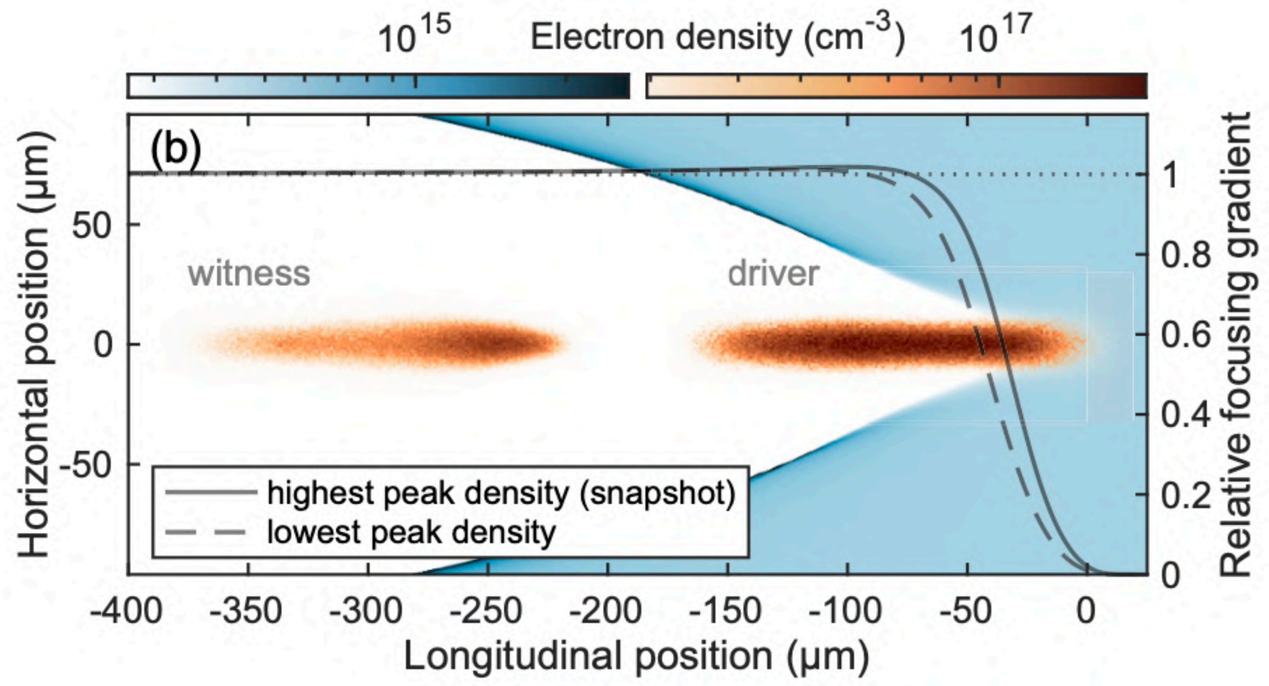

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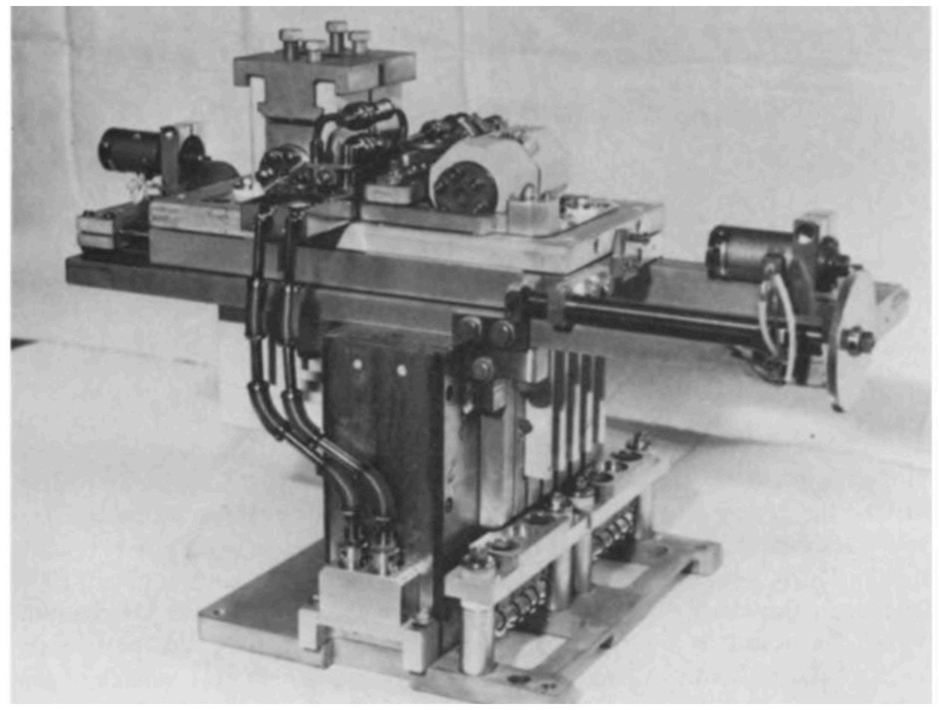

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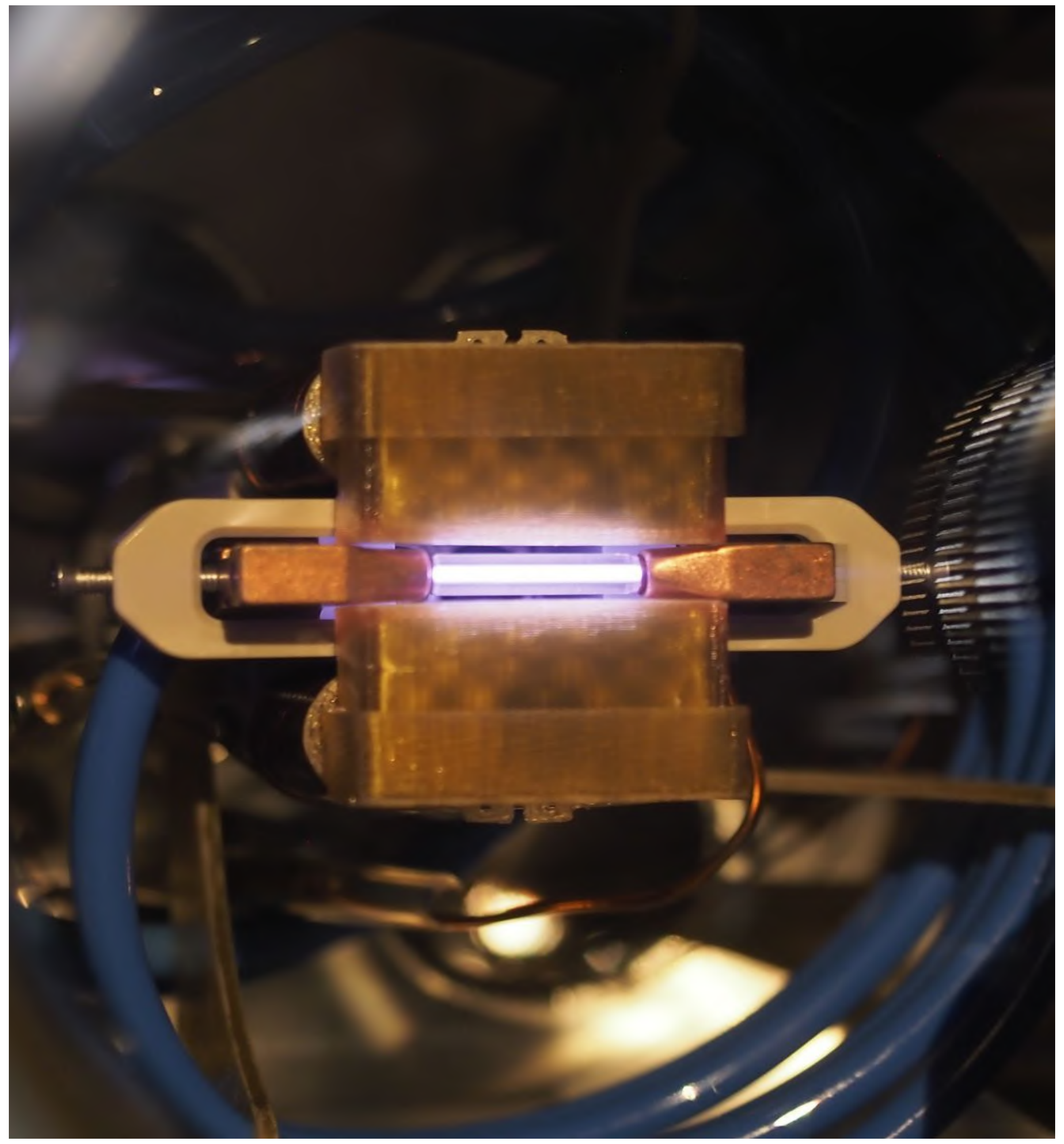
Active plasma lenses (APLs)

How do they work?

> High-voltage pulse (~10 kV, 0.1–1 μs, 0.1–1 kA) through a gas-filled tube



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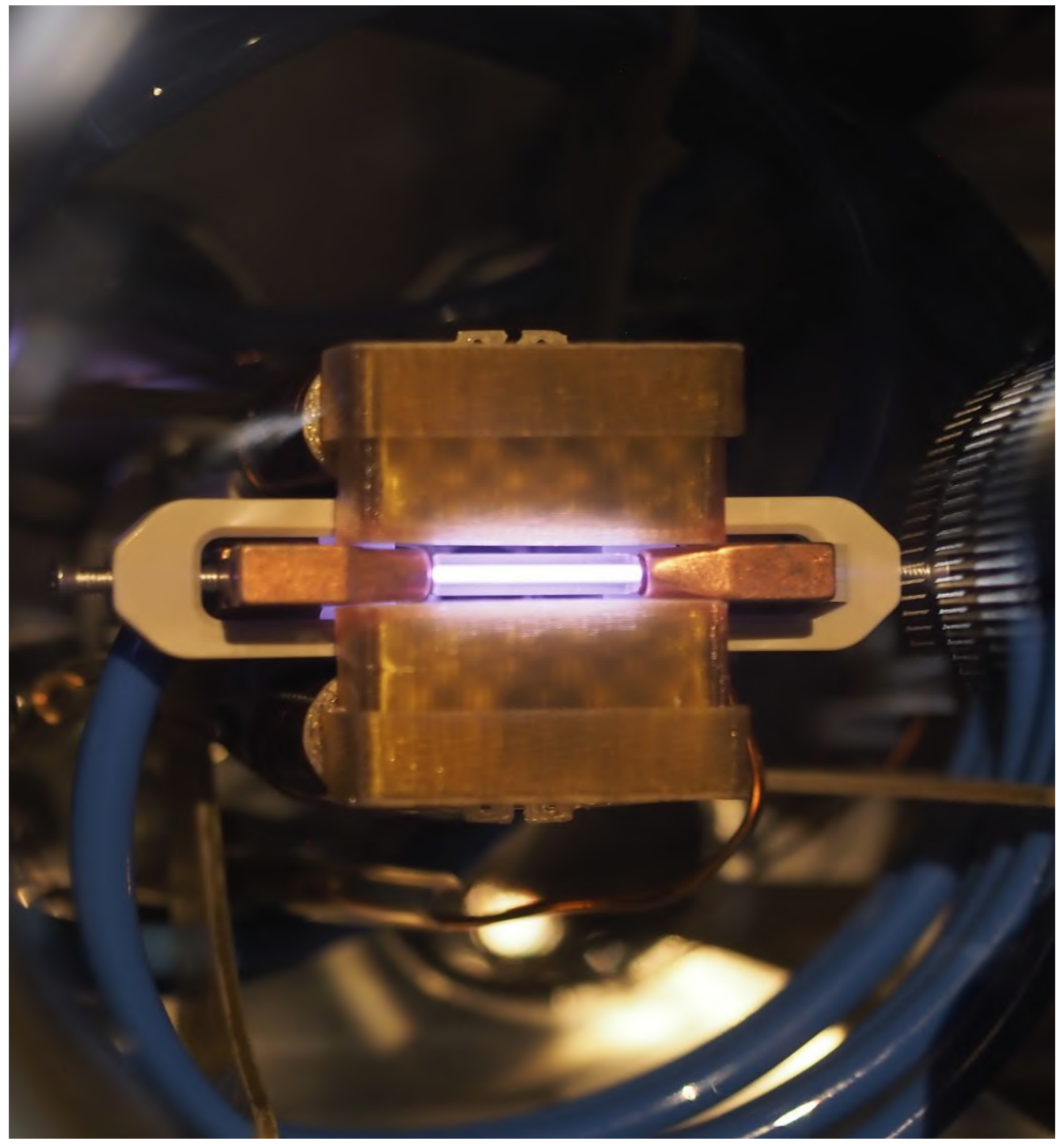

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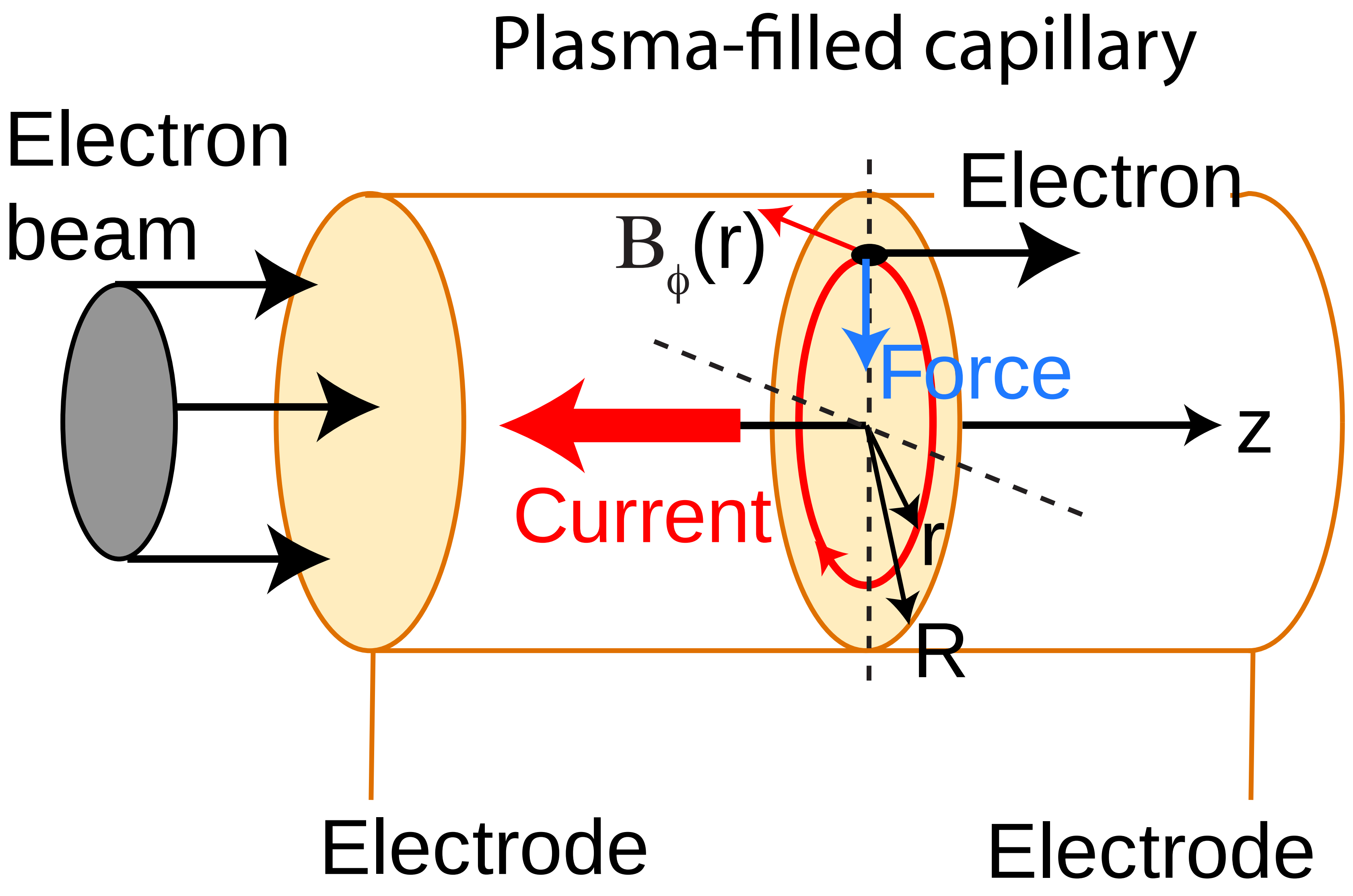

Image source: van Tilborg et al., Phys. Rev. Lett. 115, 184802 (2015).

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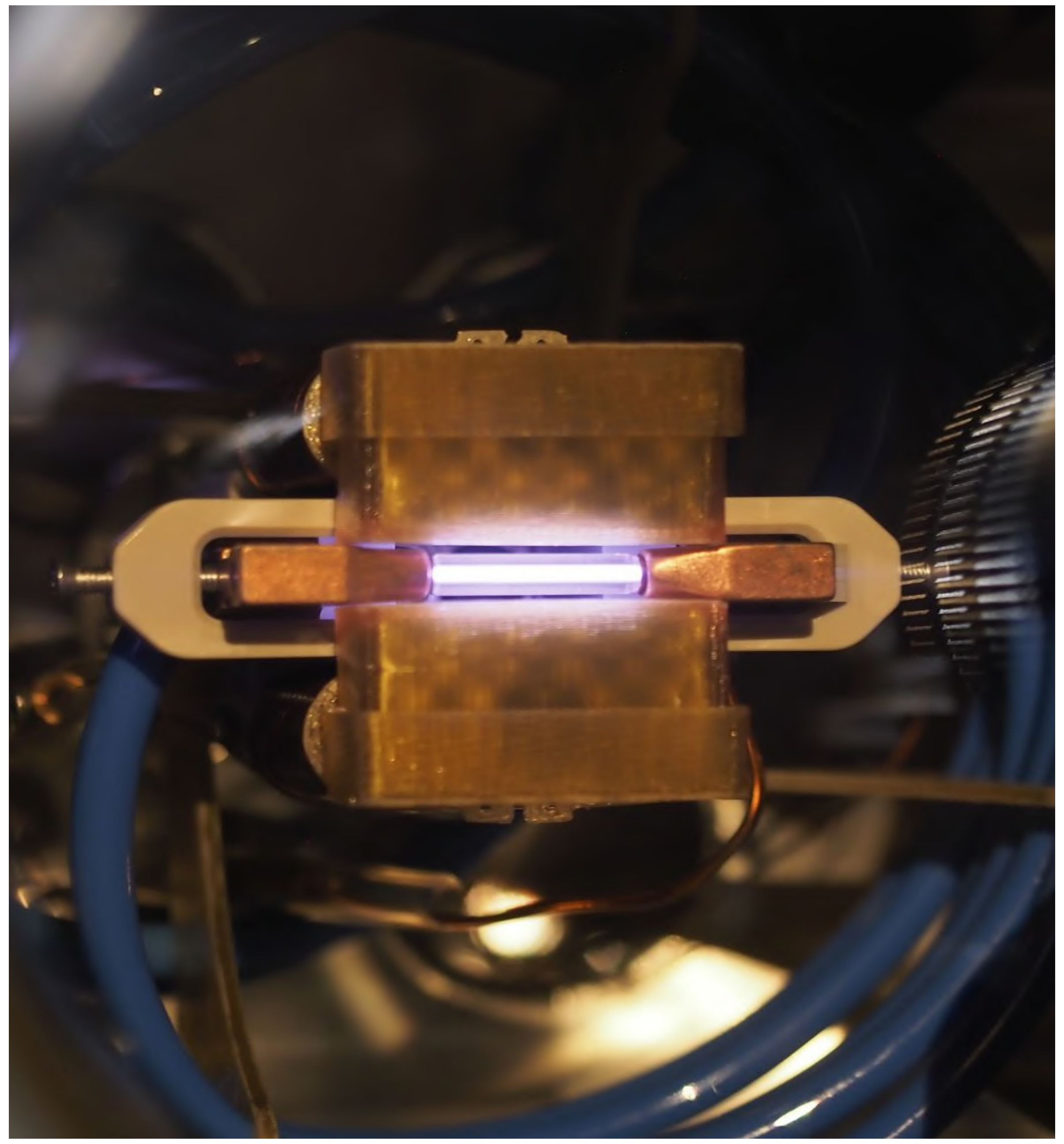
> Transversely uniform longitudinal current → azimuthal B-field varying linearly with radius



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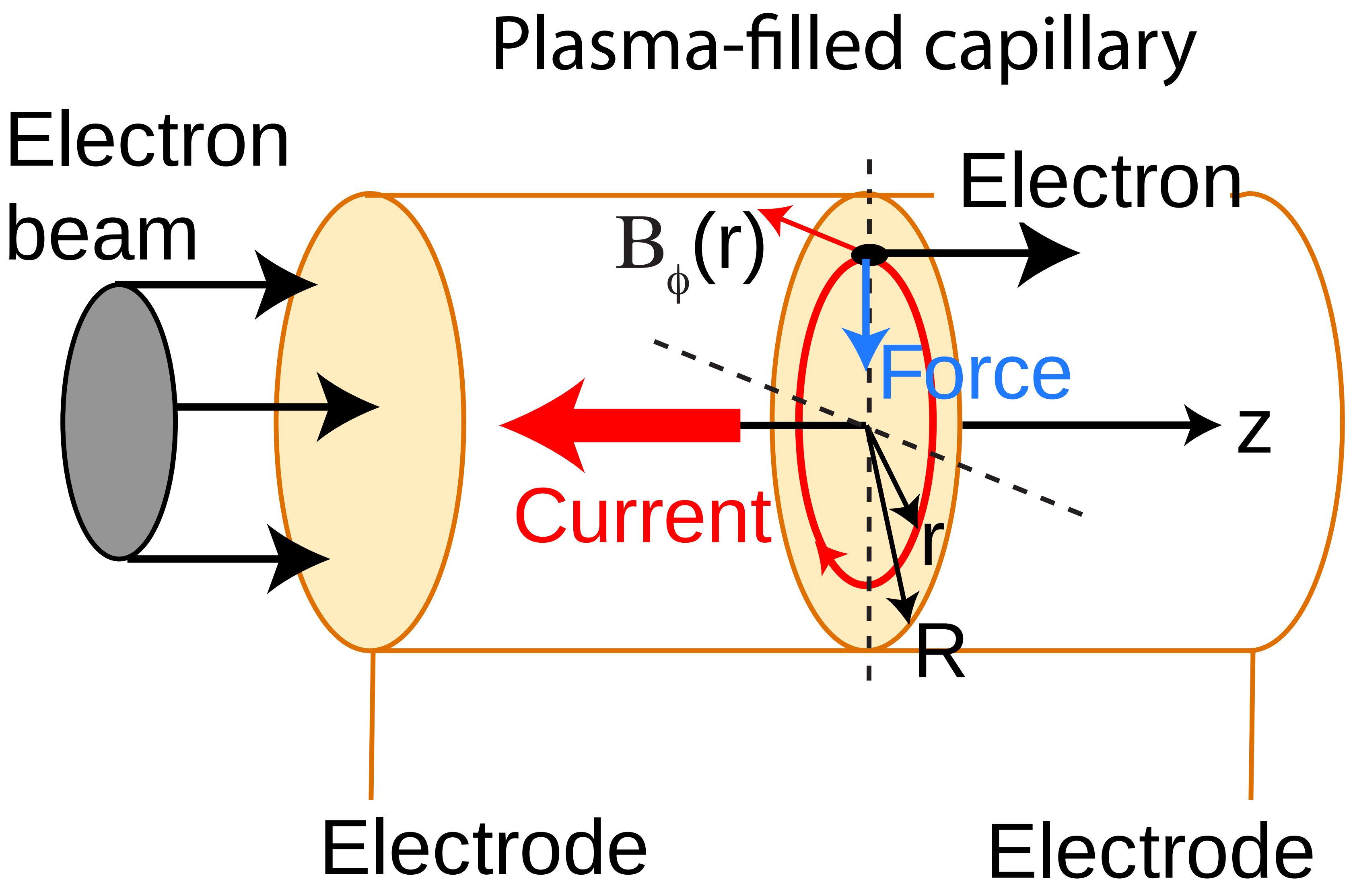

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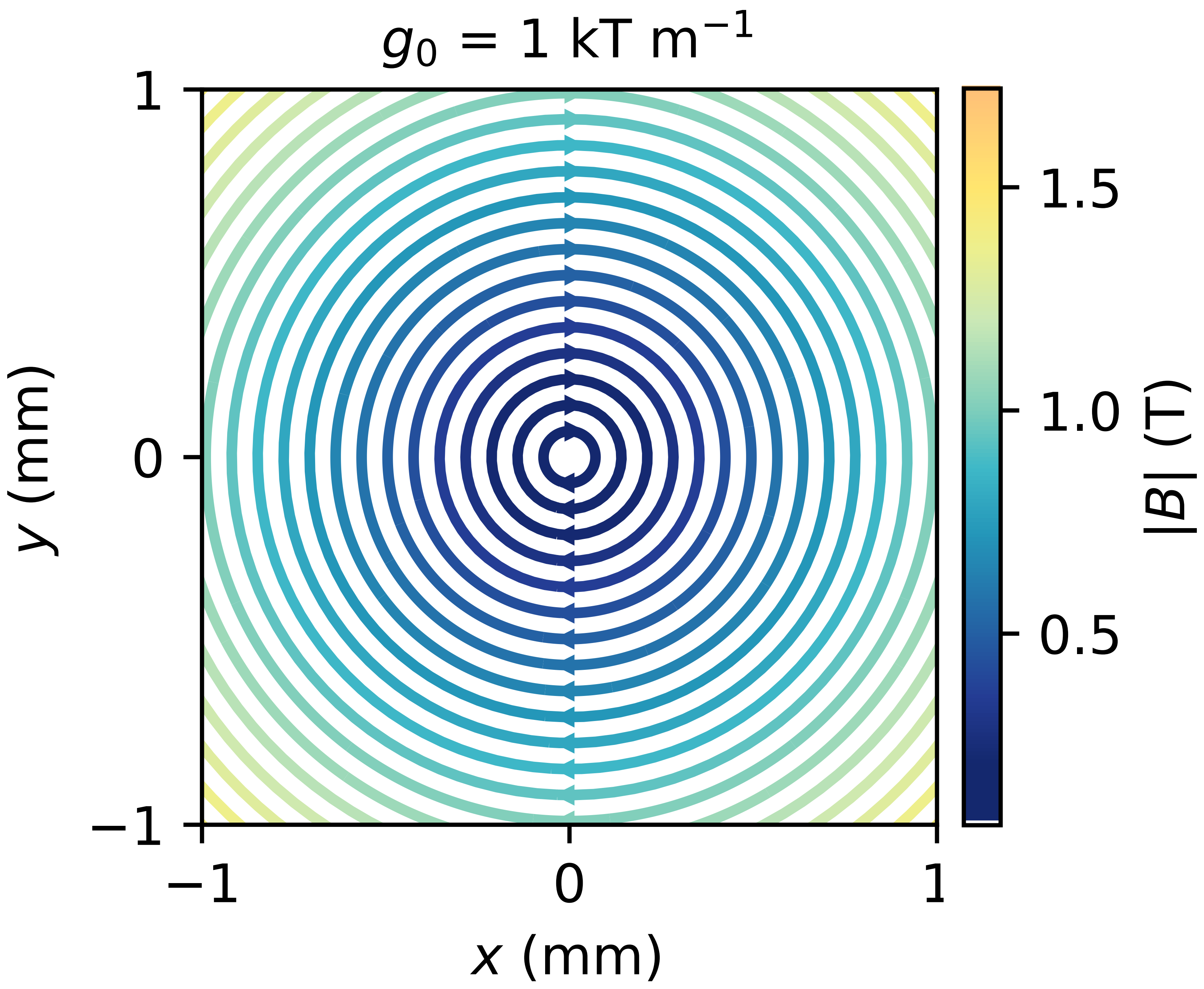

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More than 75 years of plasma lensing

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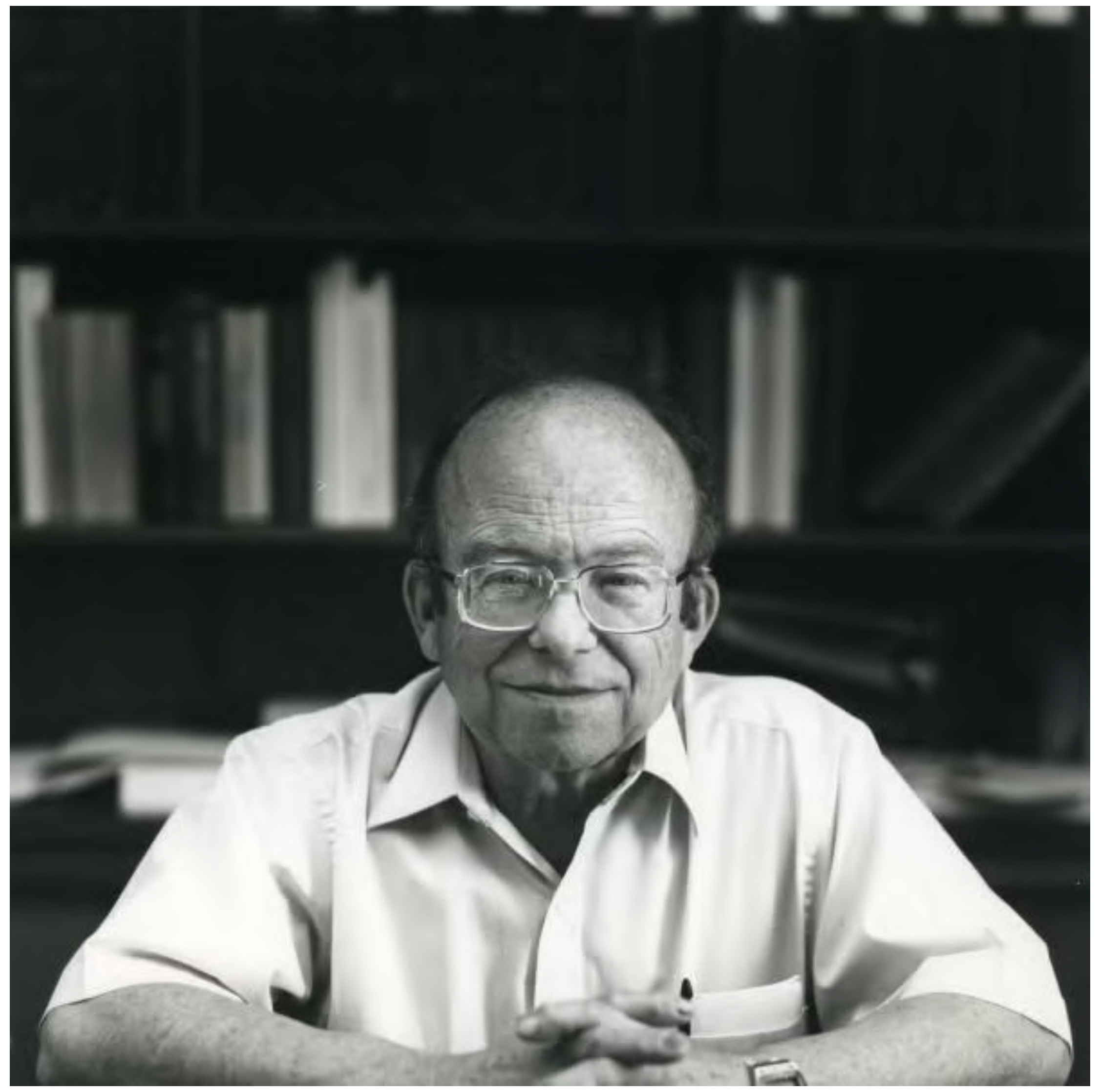

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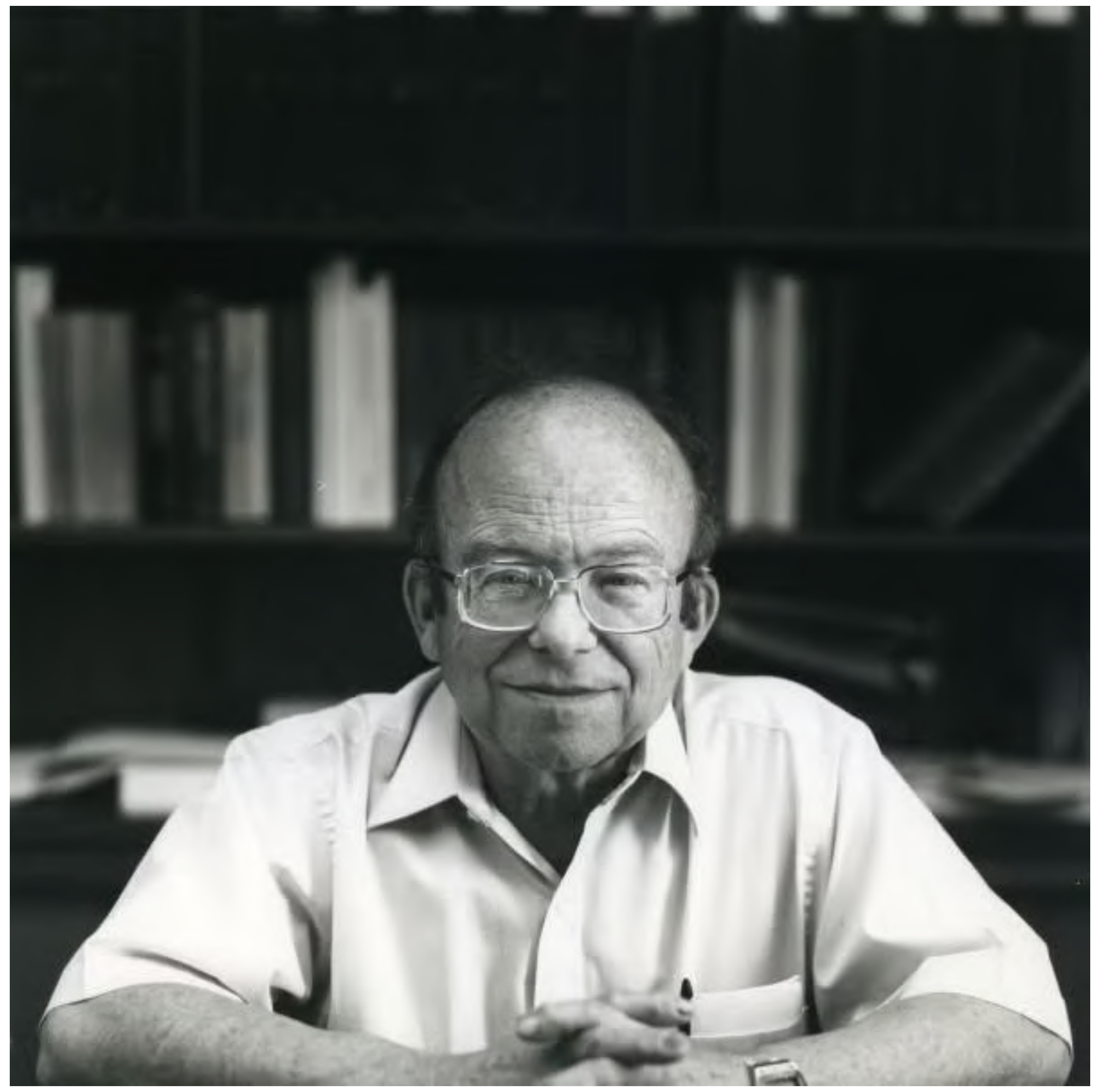

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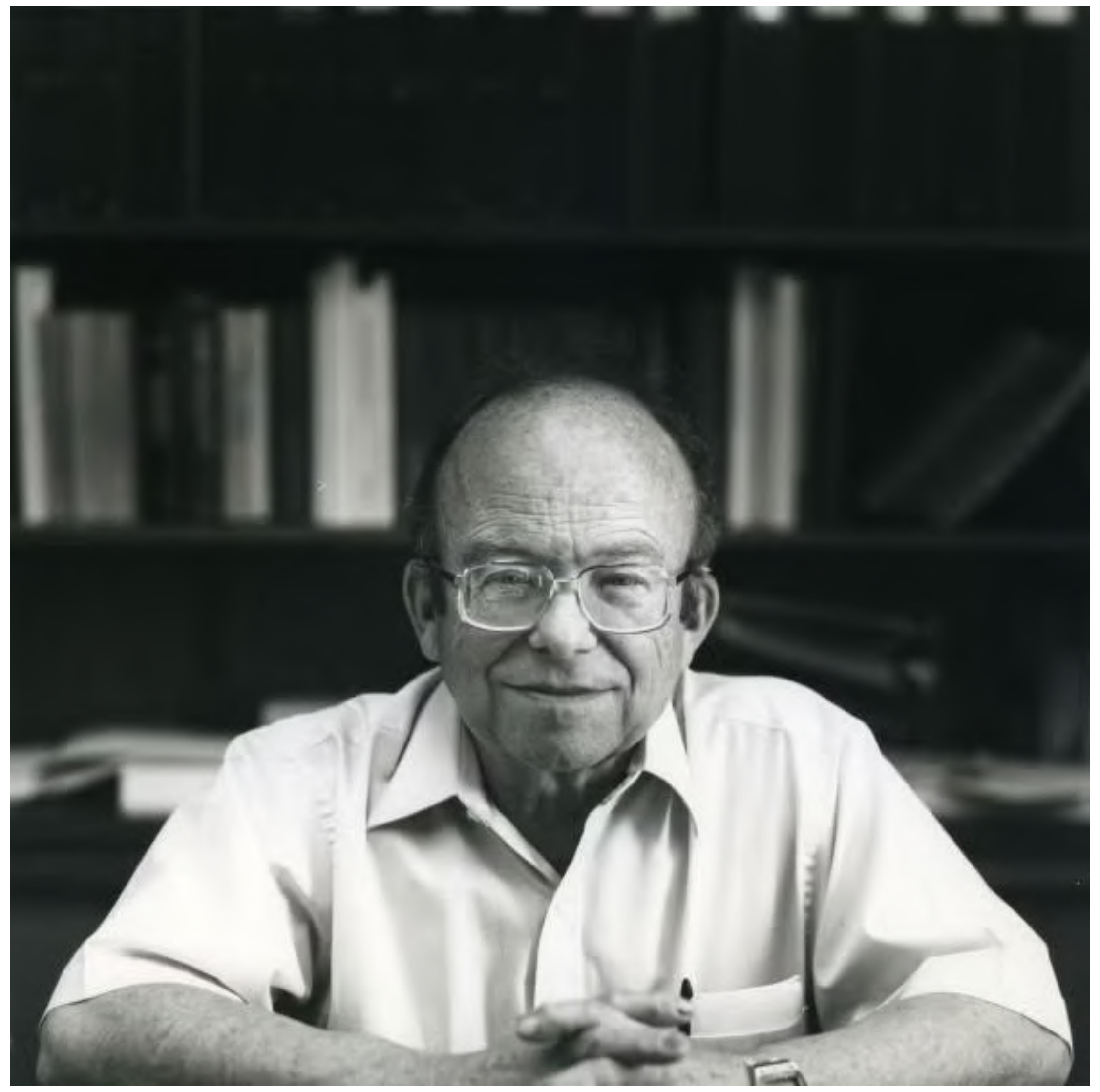

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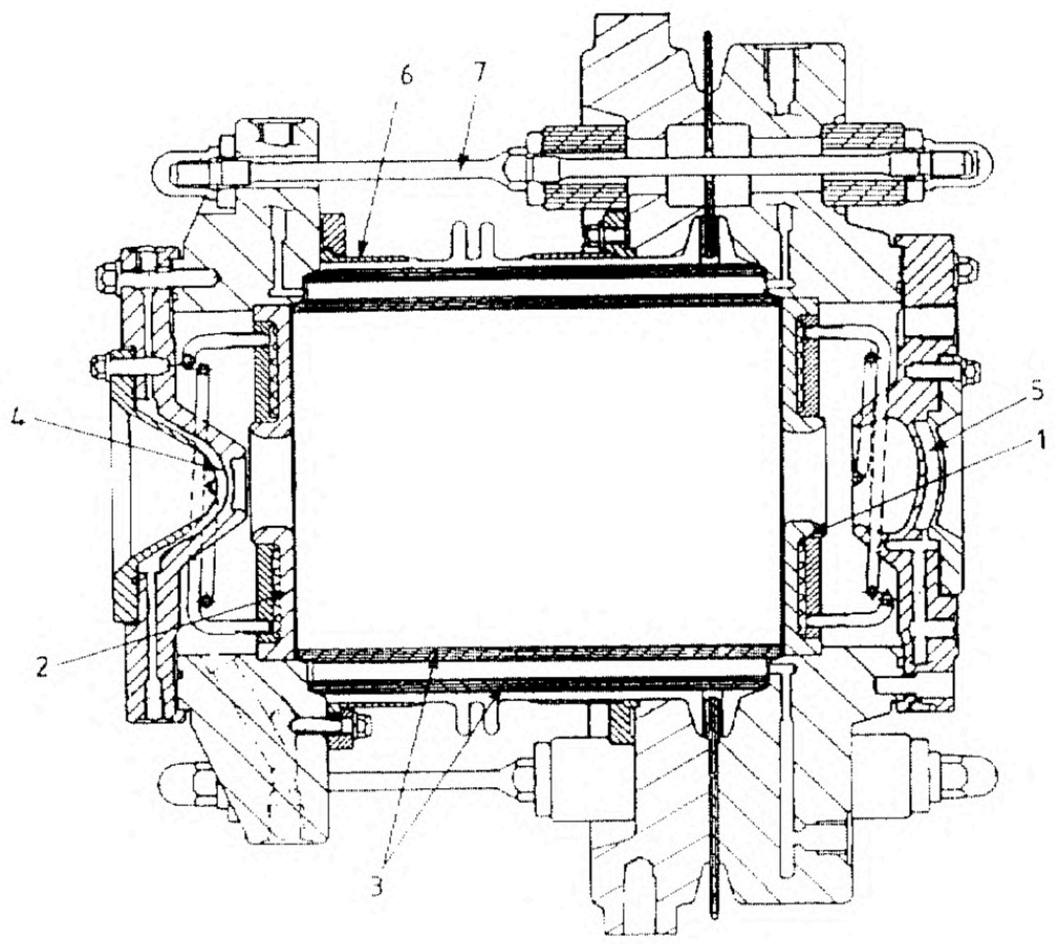

Le Dallic, Proc. EPAC 1990, p. 343

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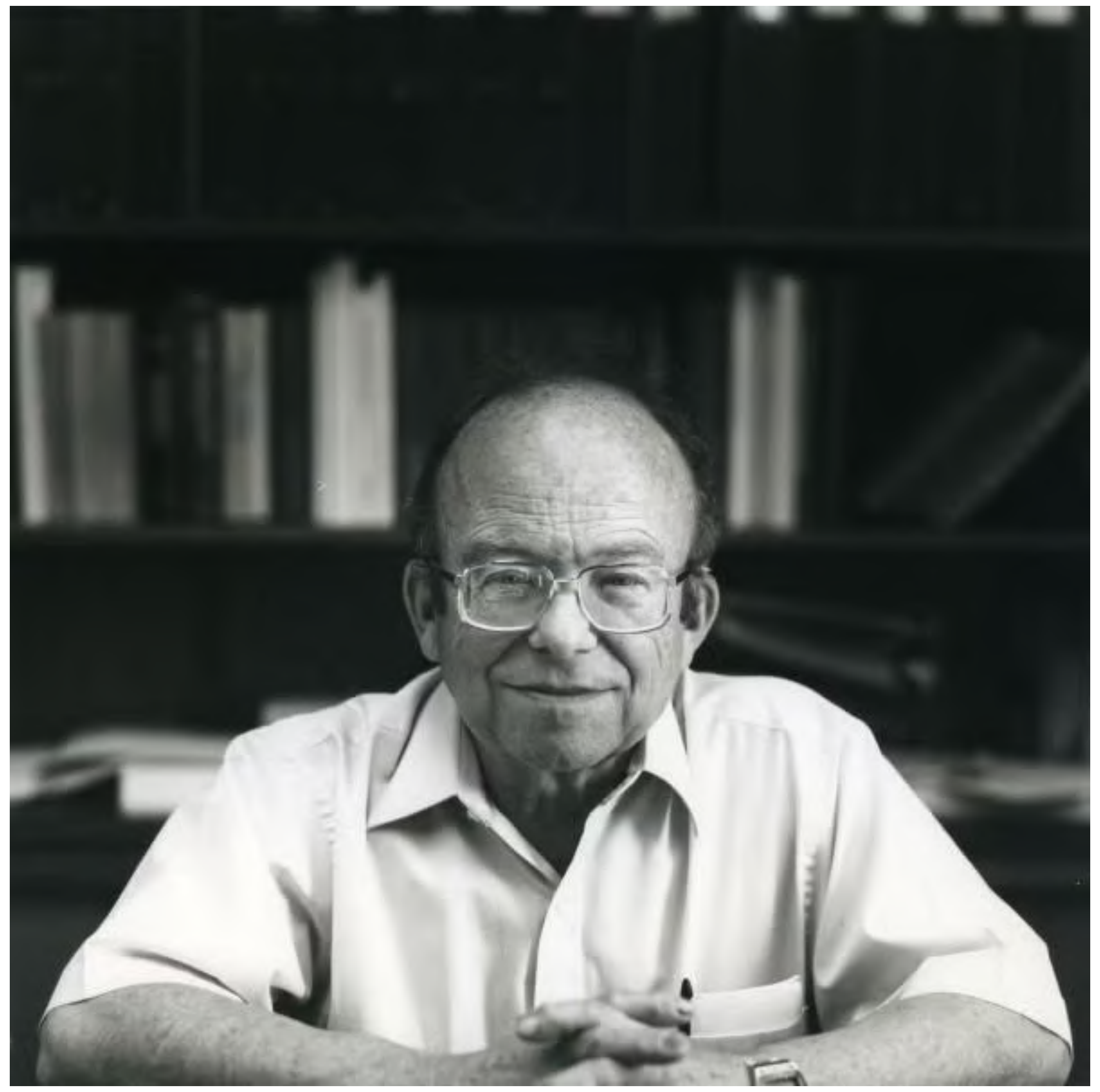

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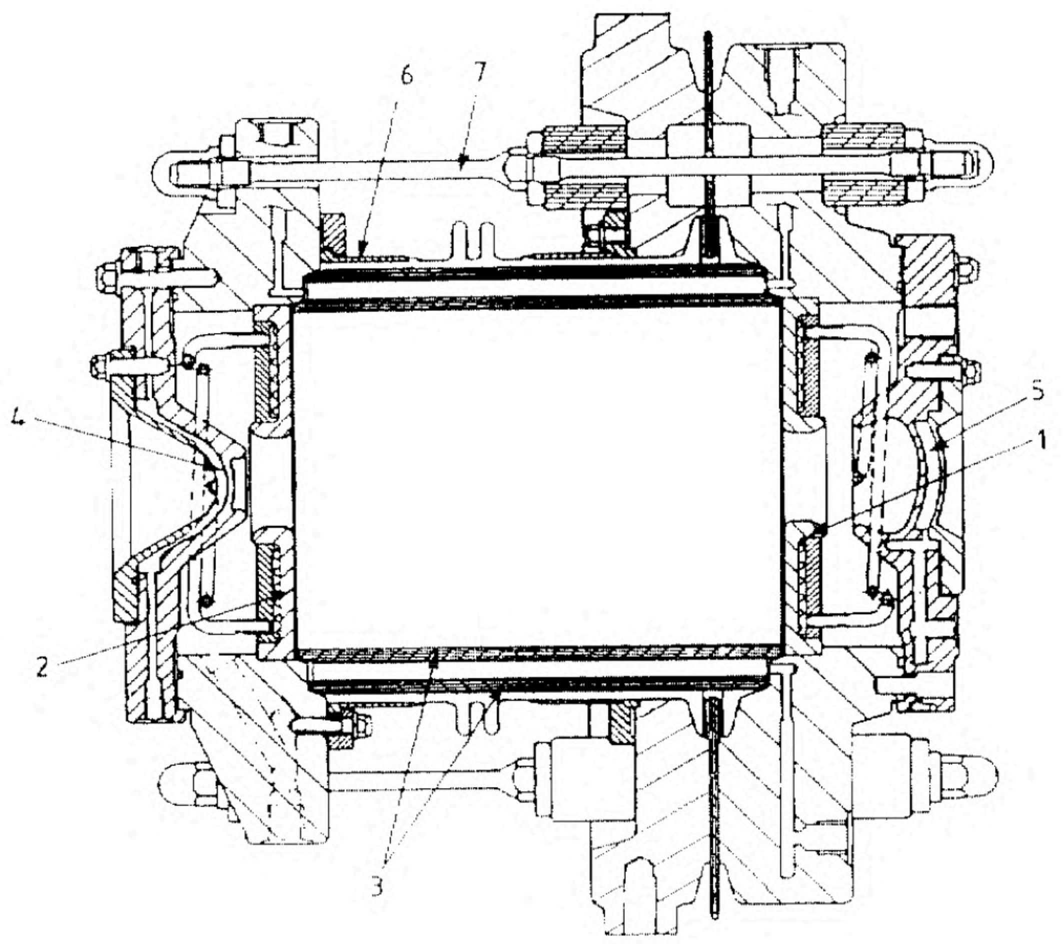

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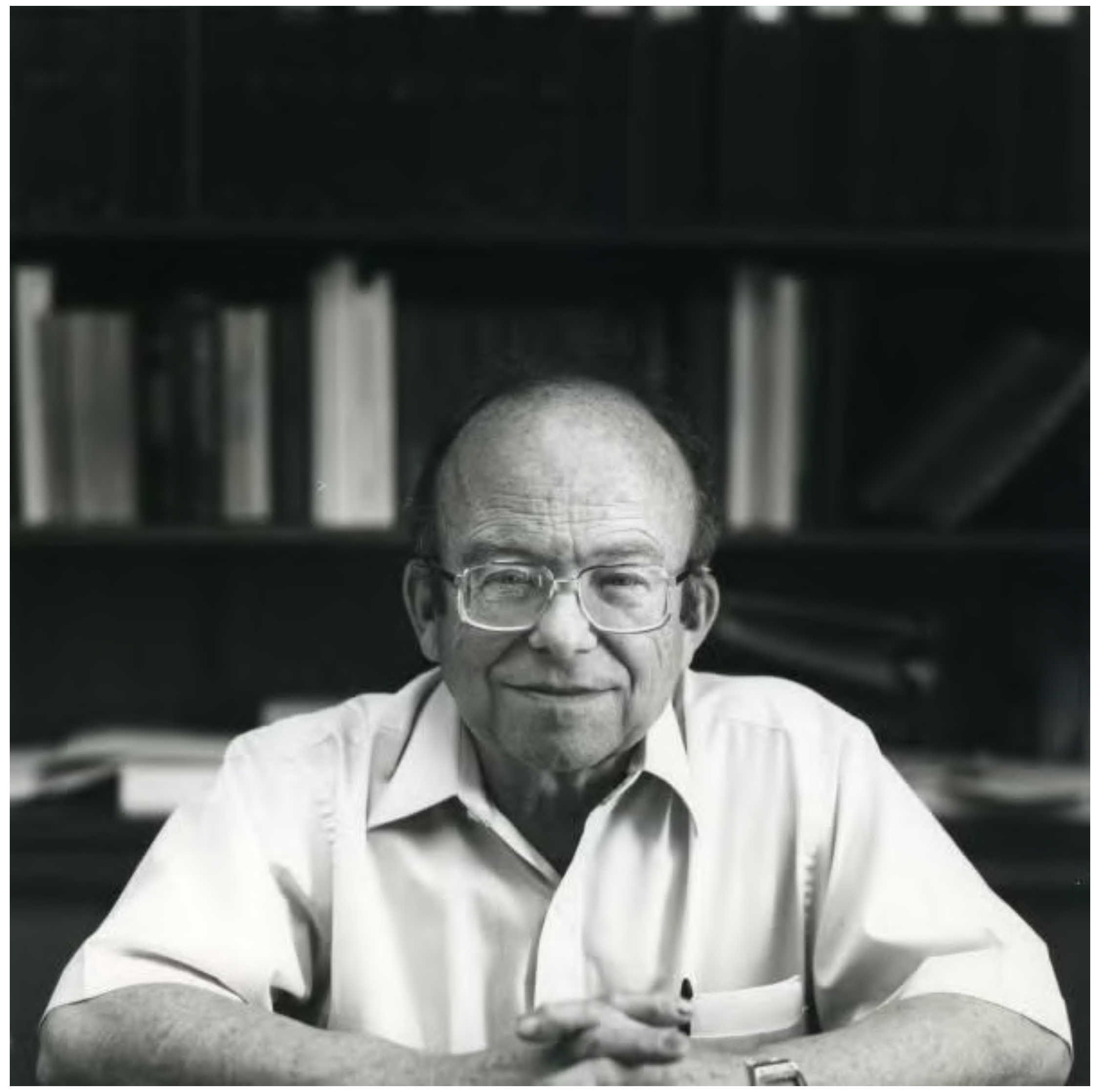
- **1992: Braun *et al.*** proposes using plasma lenses for positron capture (2x higher bandwidth than solenoids)



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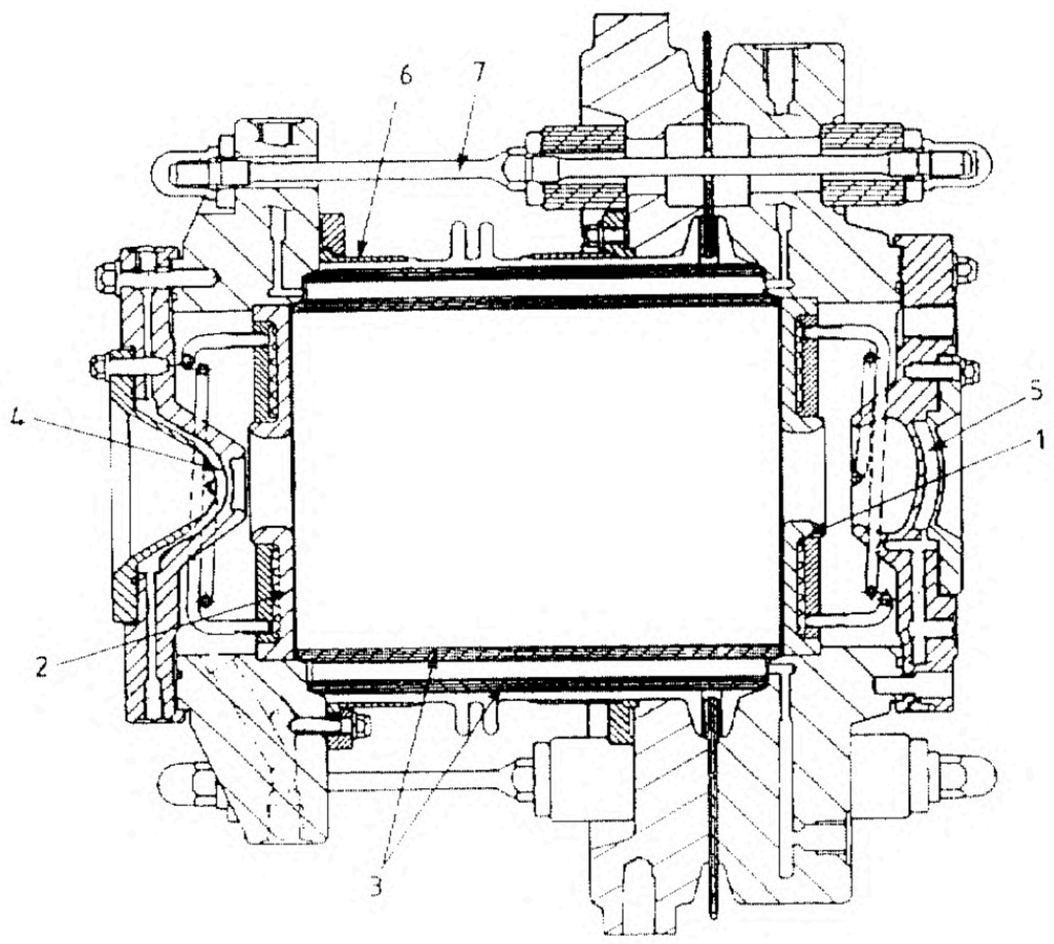

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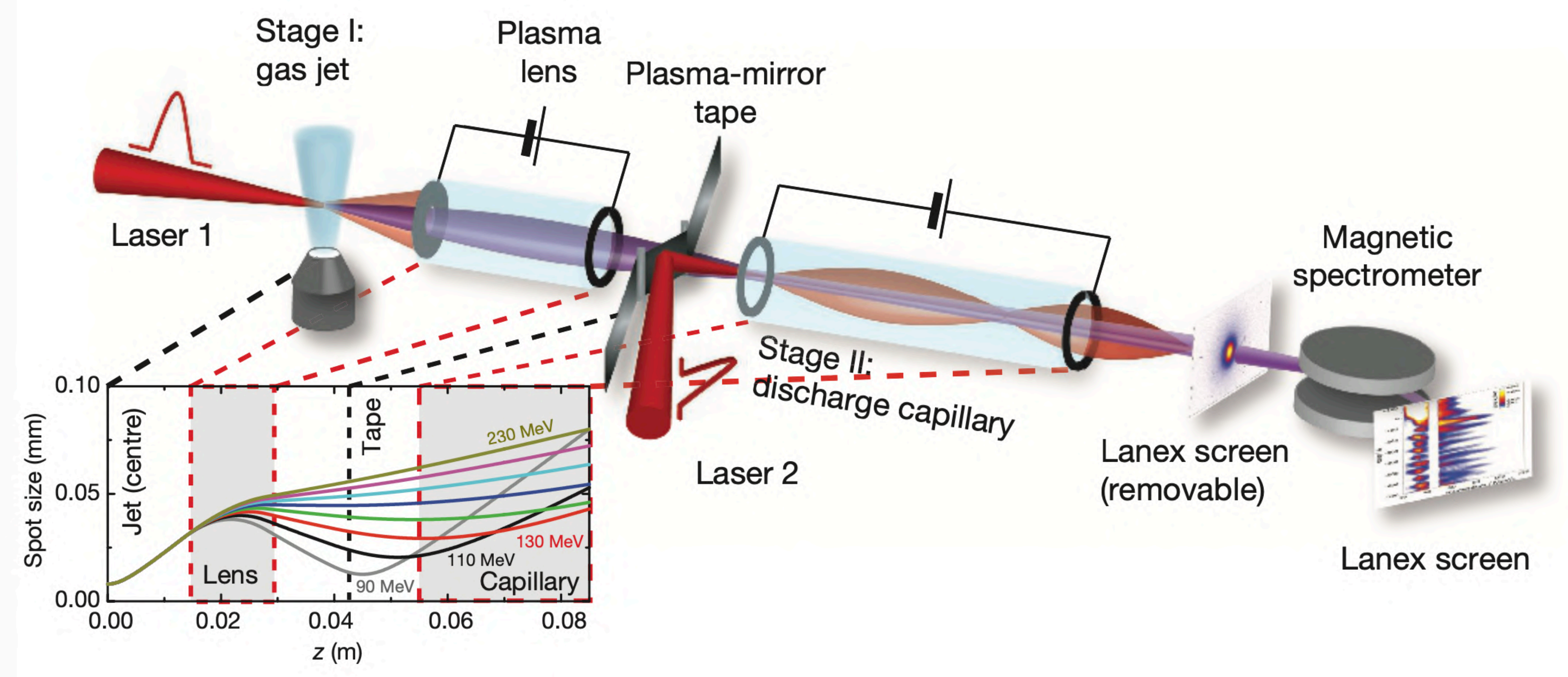

Steinke et al., Nature 530, 190 (2016)

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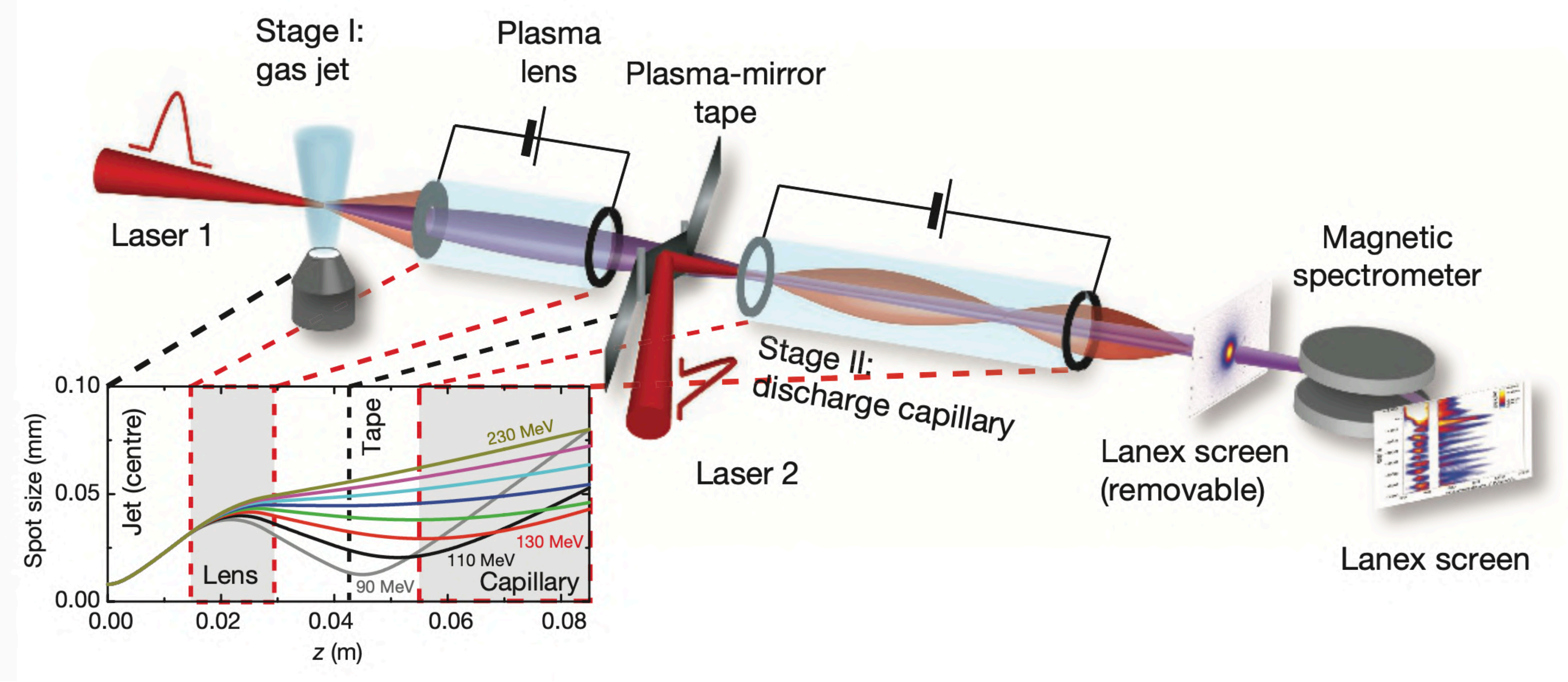
  - ***Reached field gradient of ~3.6 kT/m*** *(~100x stronger than typical quadrupoles)*
  - *Enabled the first plasma-accelerator staging experiment*
- Several other experiments followed:
  - *CLEAR at CERN (by Uni. Oslo et al.)*
  - *MAMI at Mainz (by DESY et al.)*
  - *SPARC_LAB at INFN*



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

Spherical aberrations and emittance preservation

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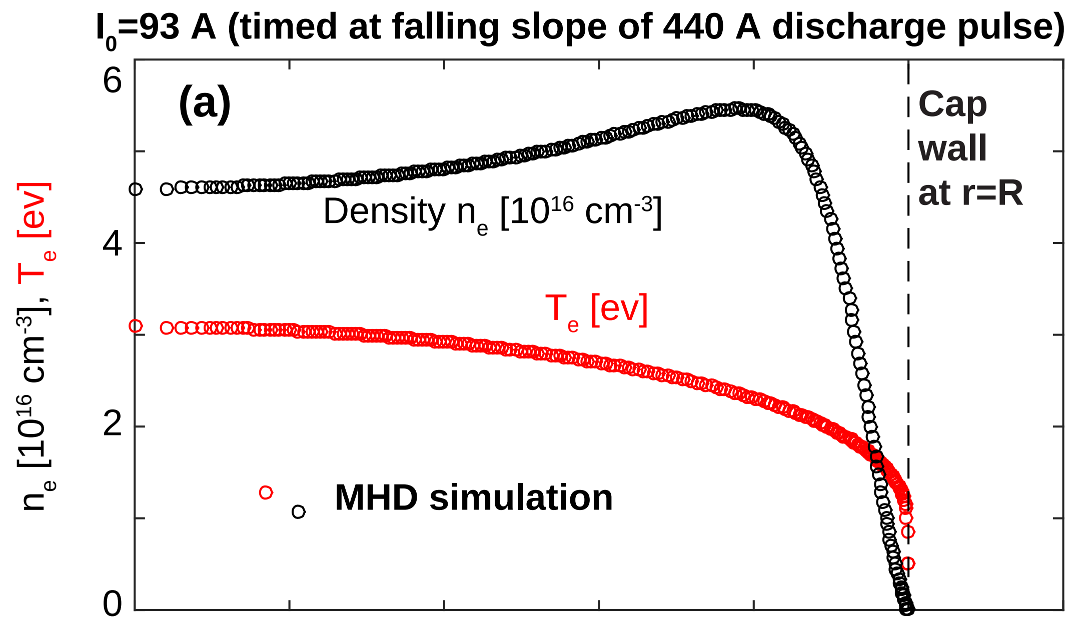

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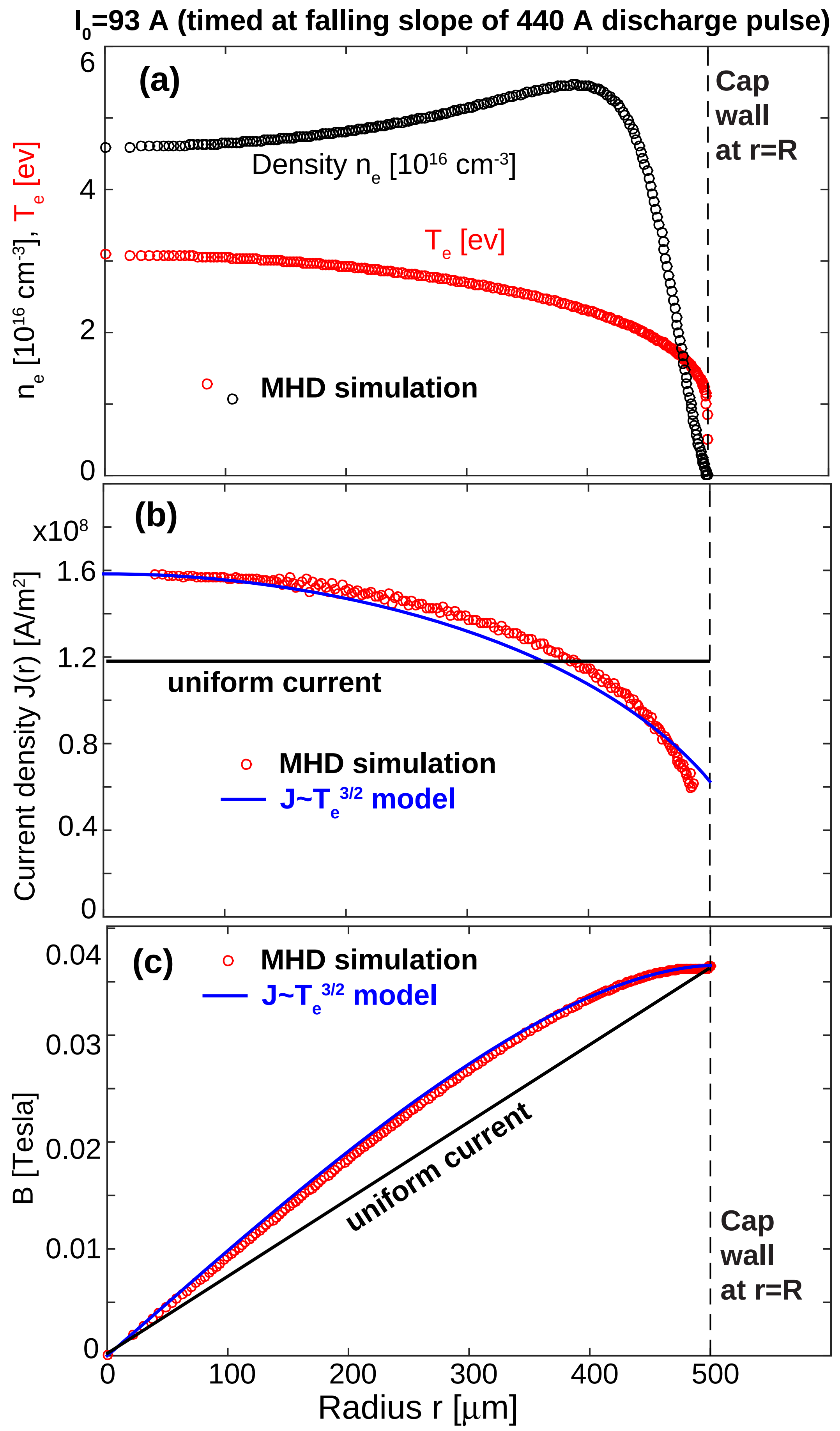

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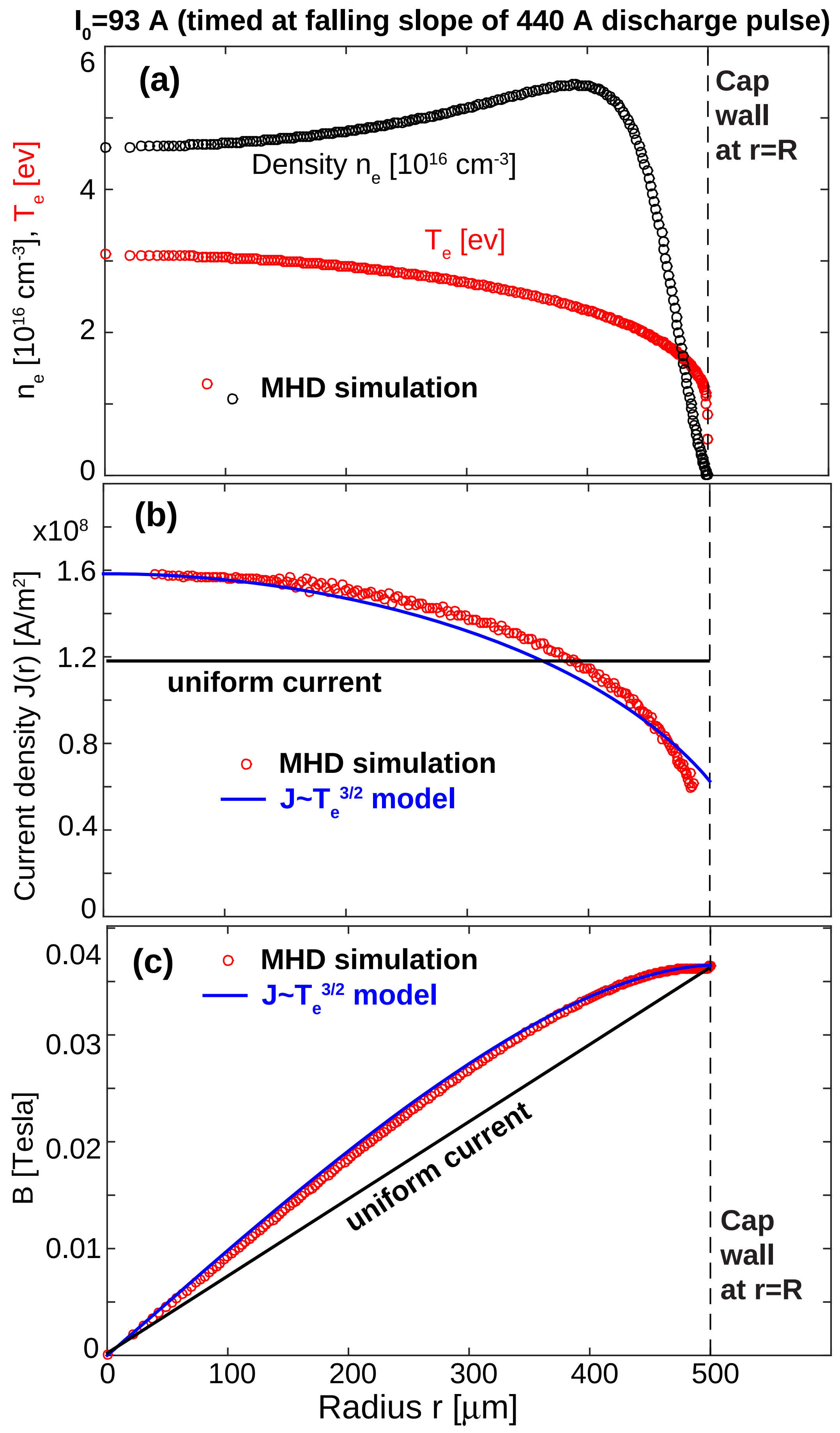

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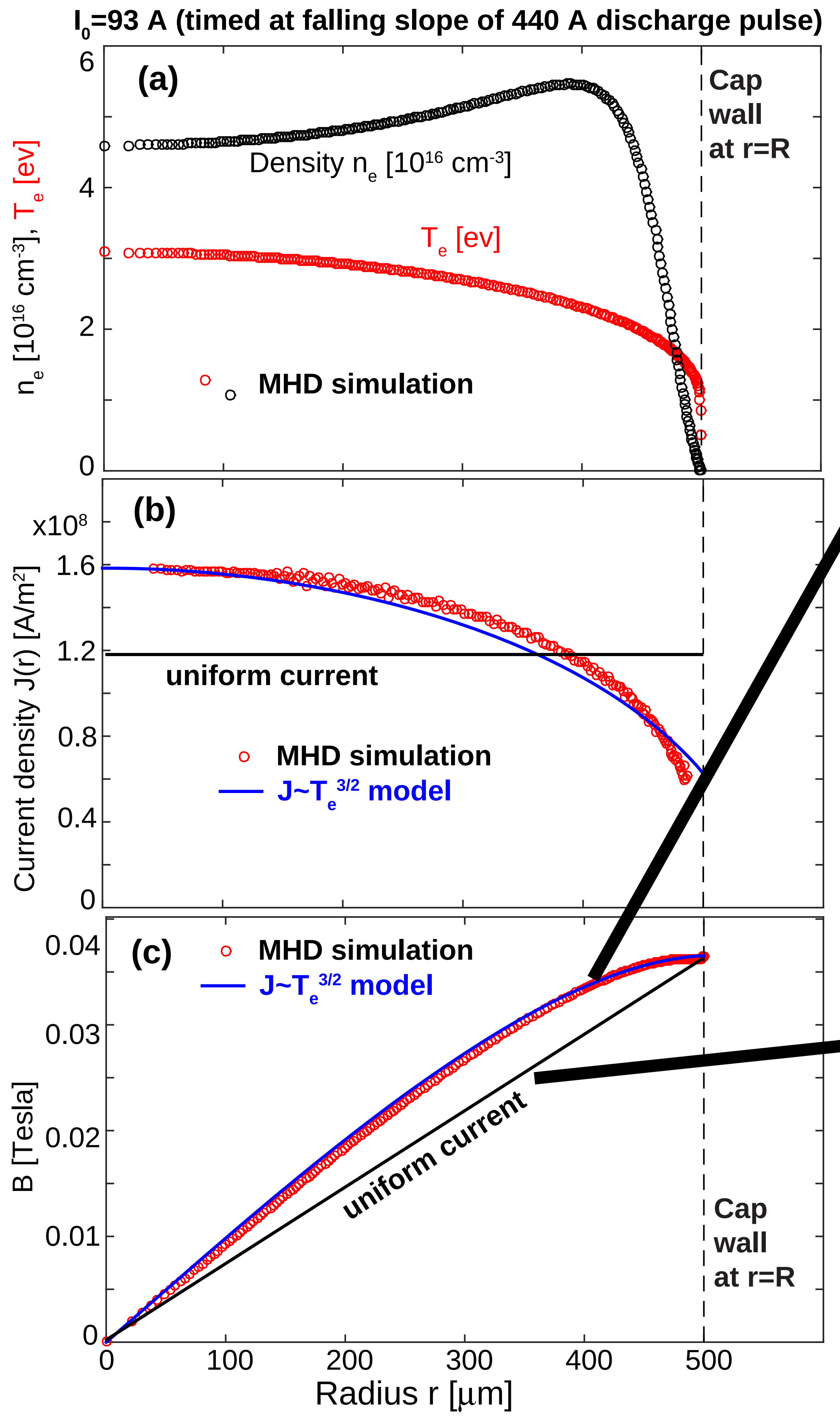

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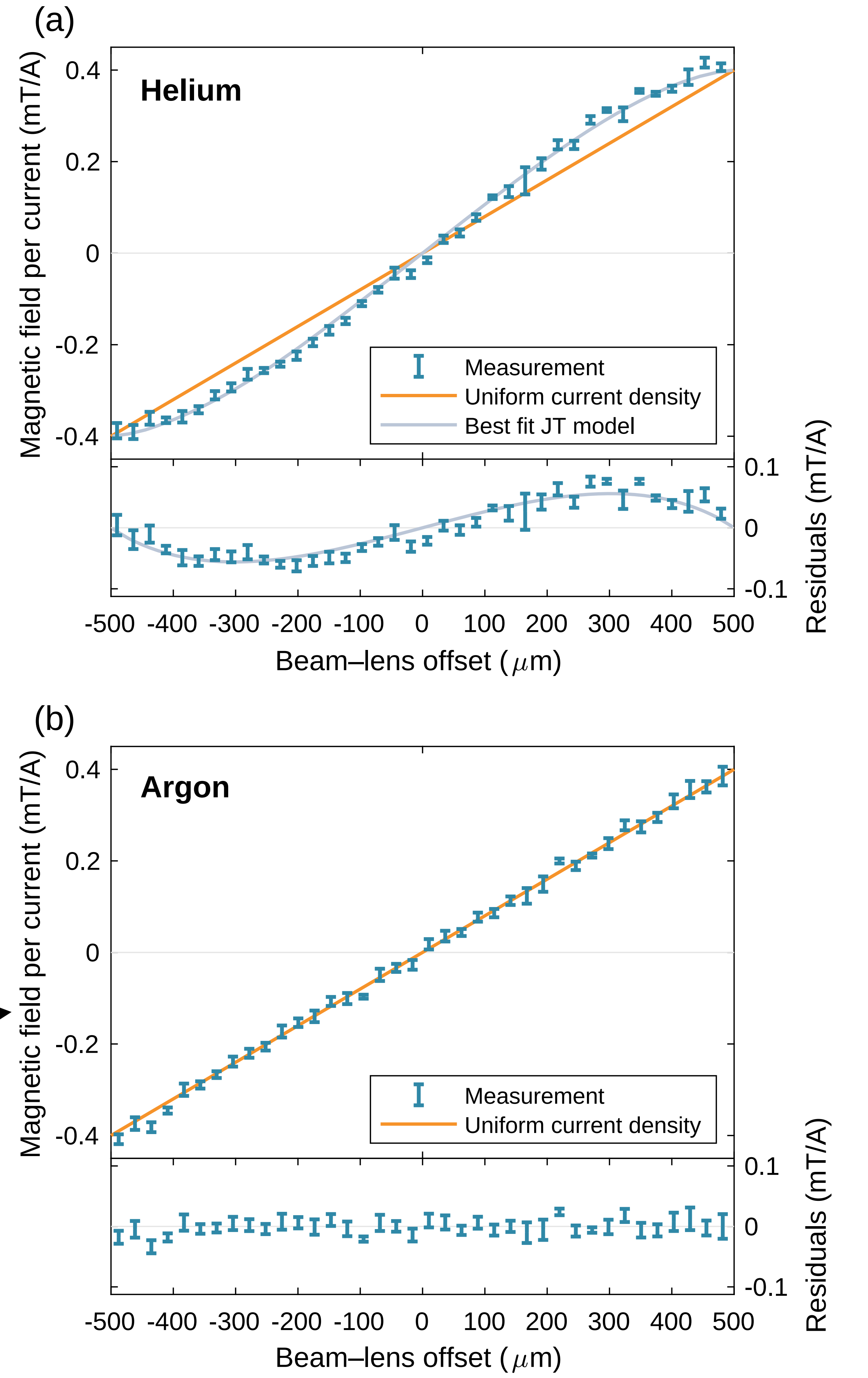

Lindstrøm et al., PRL 121, 194801 (2018)

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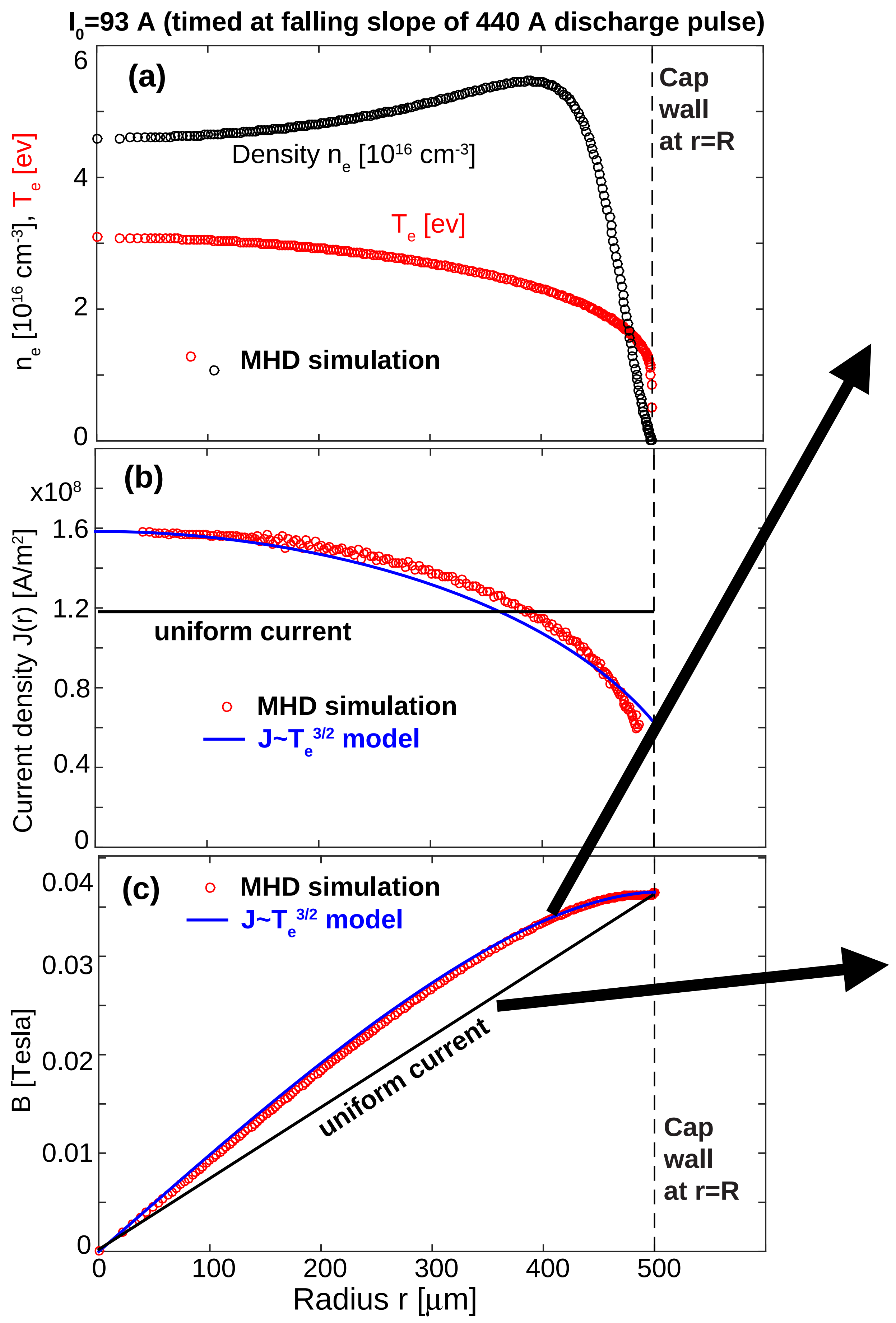

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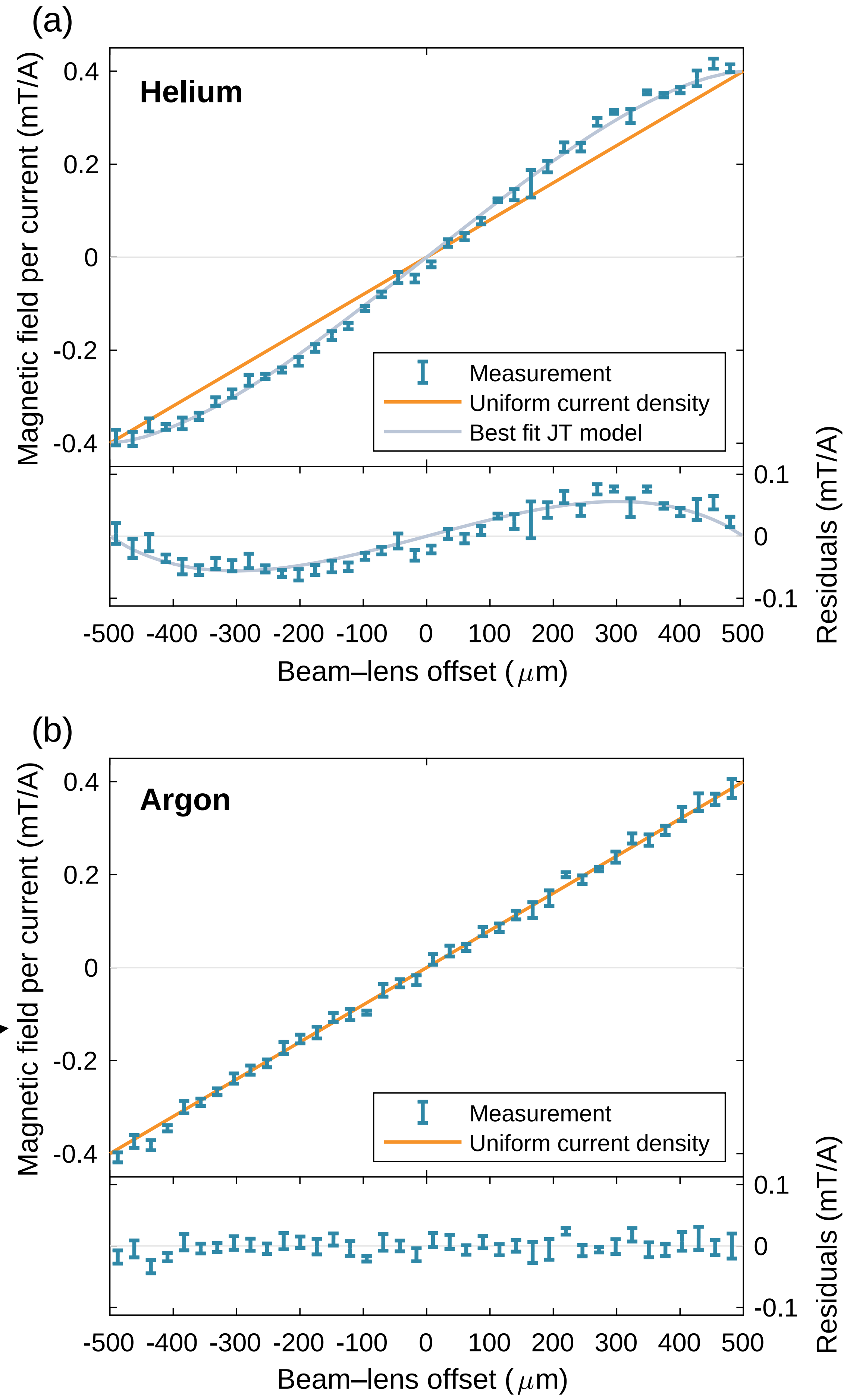

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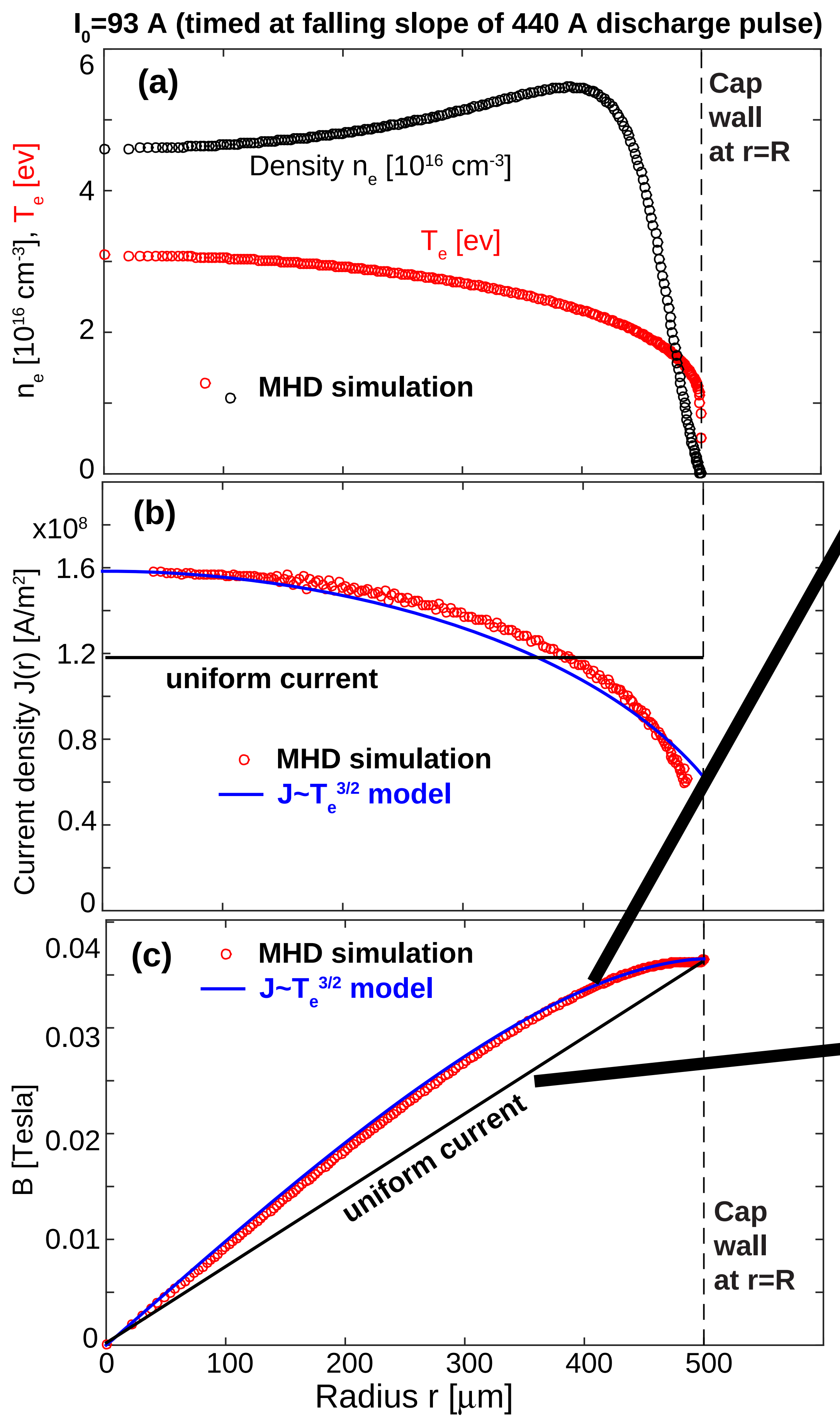
- Wakefields (passive plasma lensing) can also cause emittance growth



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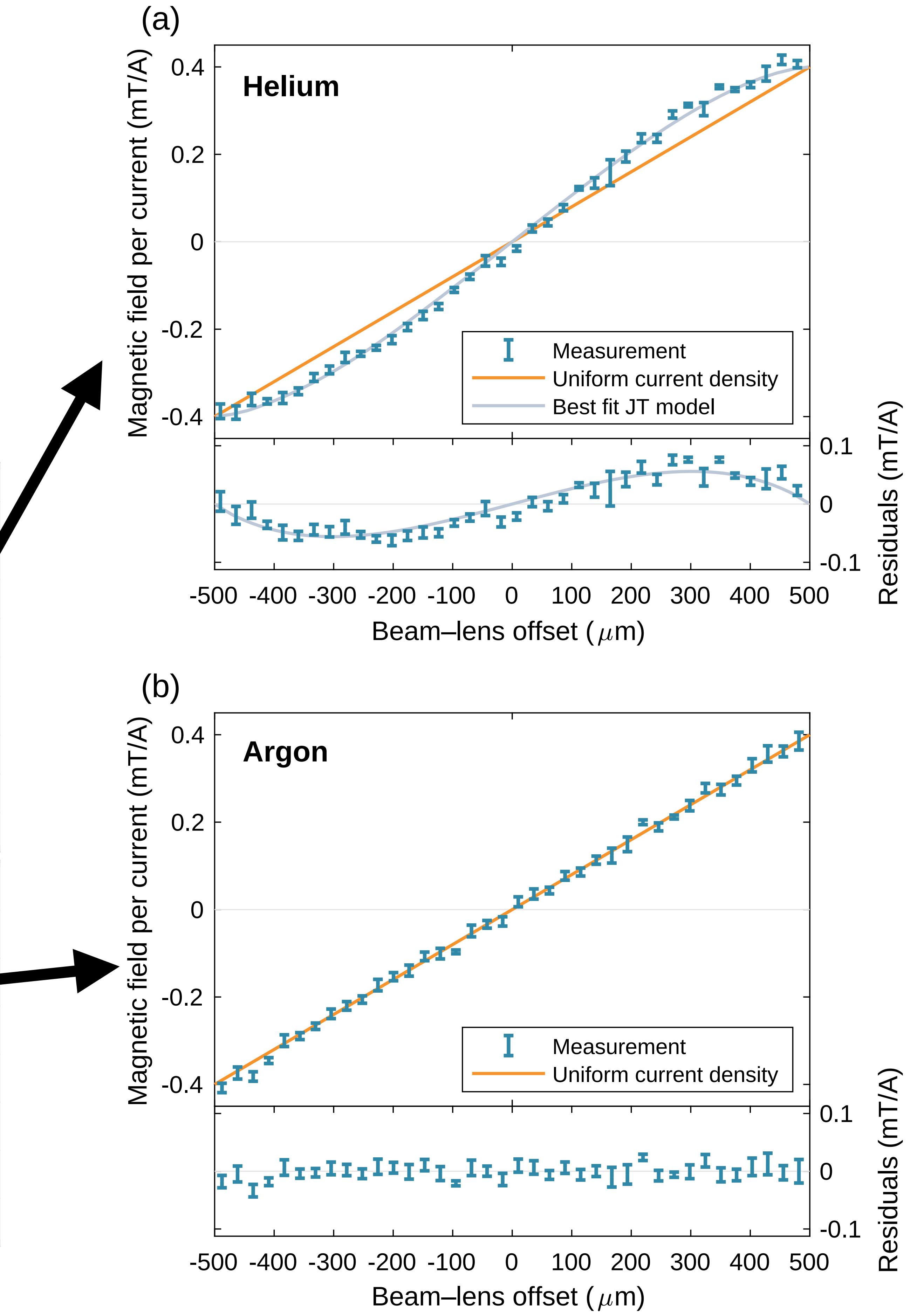

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Use with laser–proton beams

Recent progress in China

> Laser–protons have high energy spread and divergence

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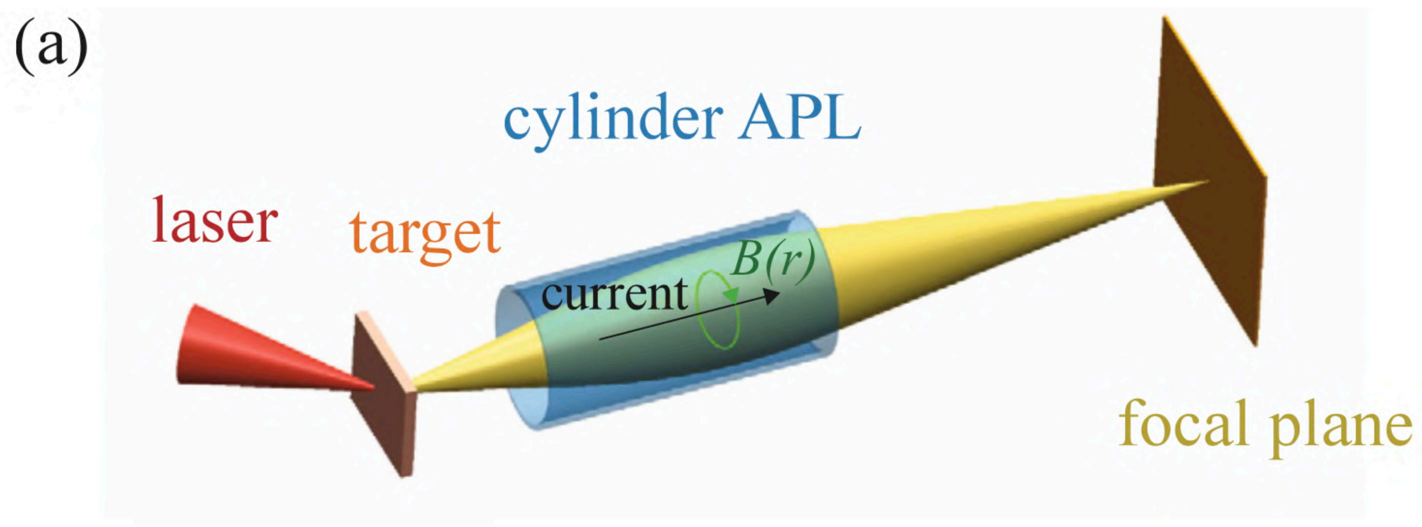

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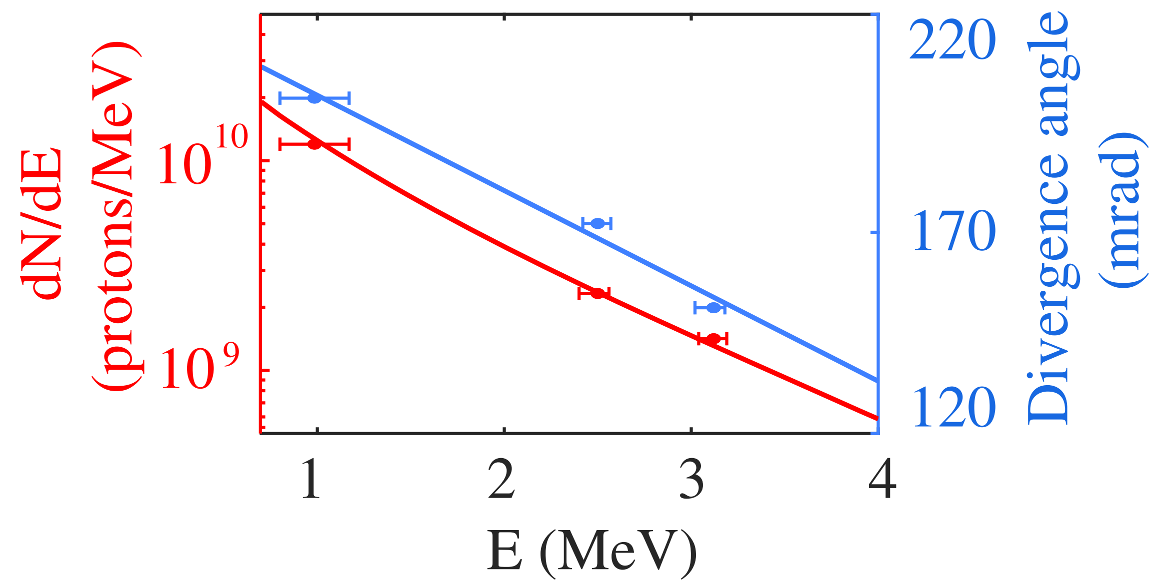

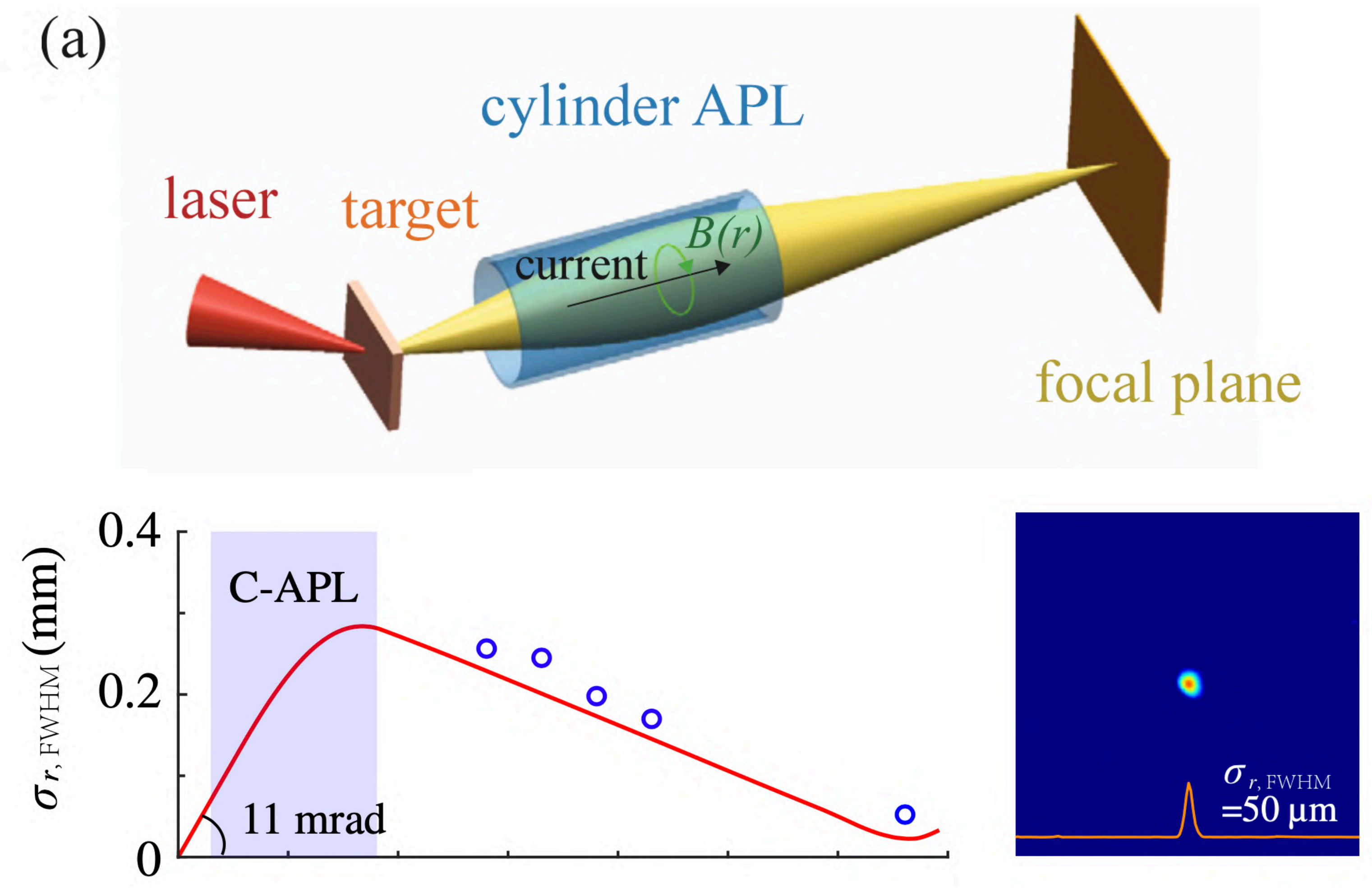

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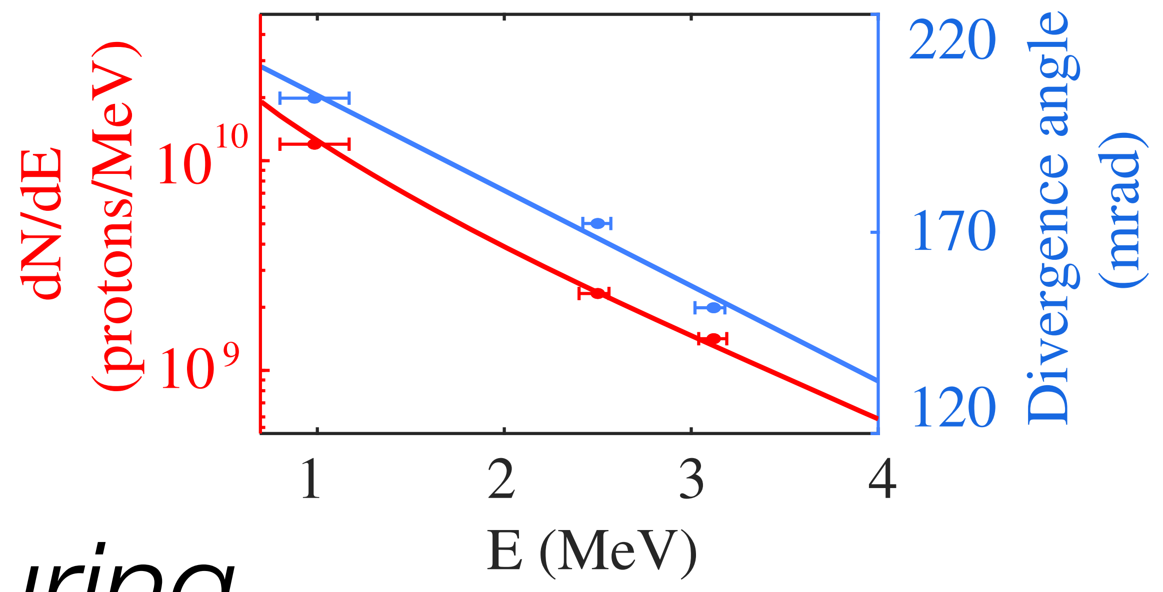
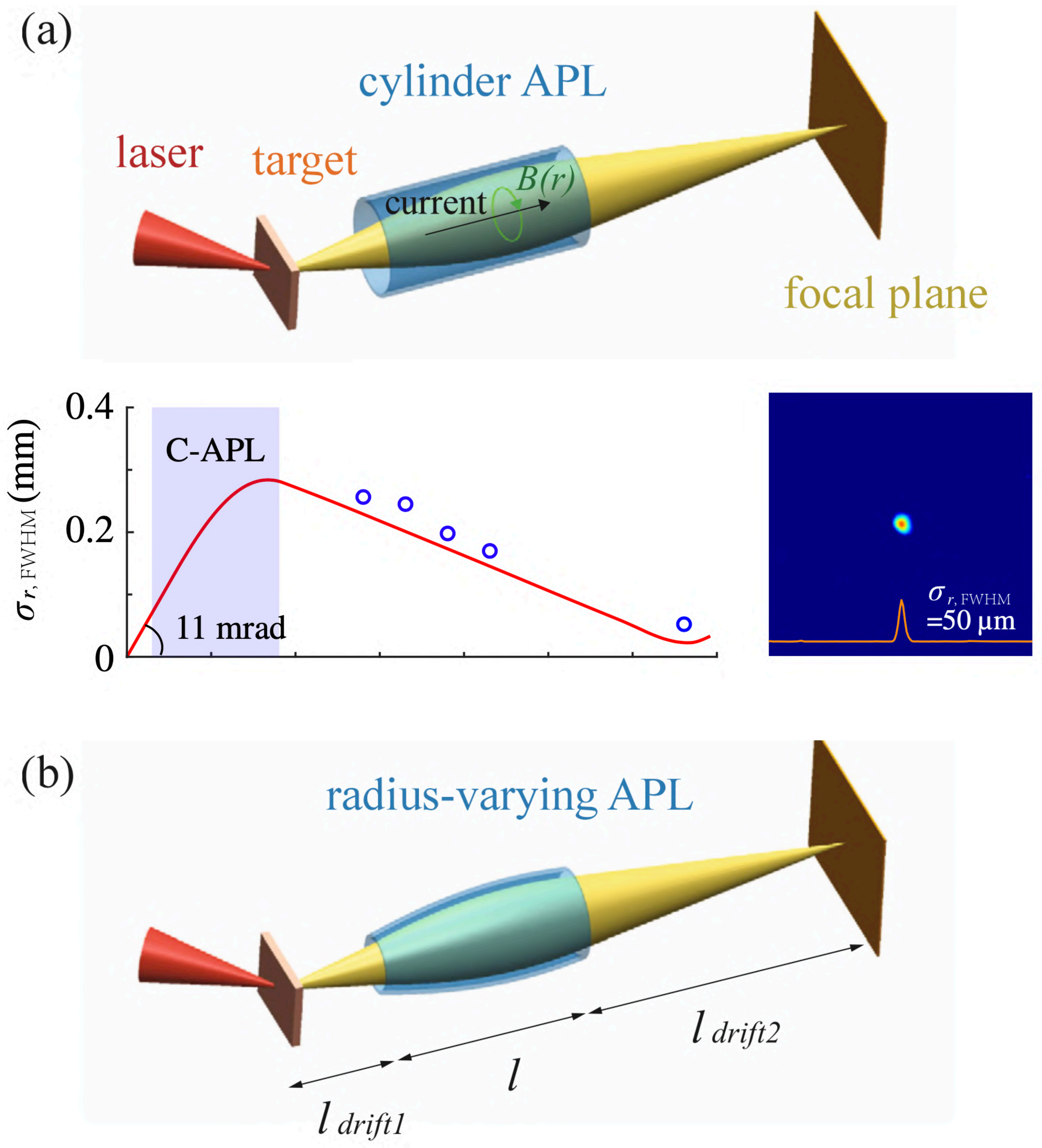
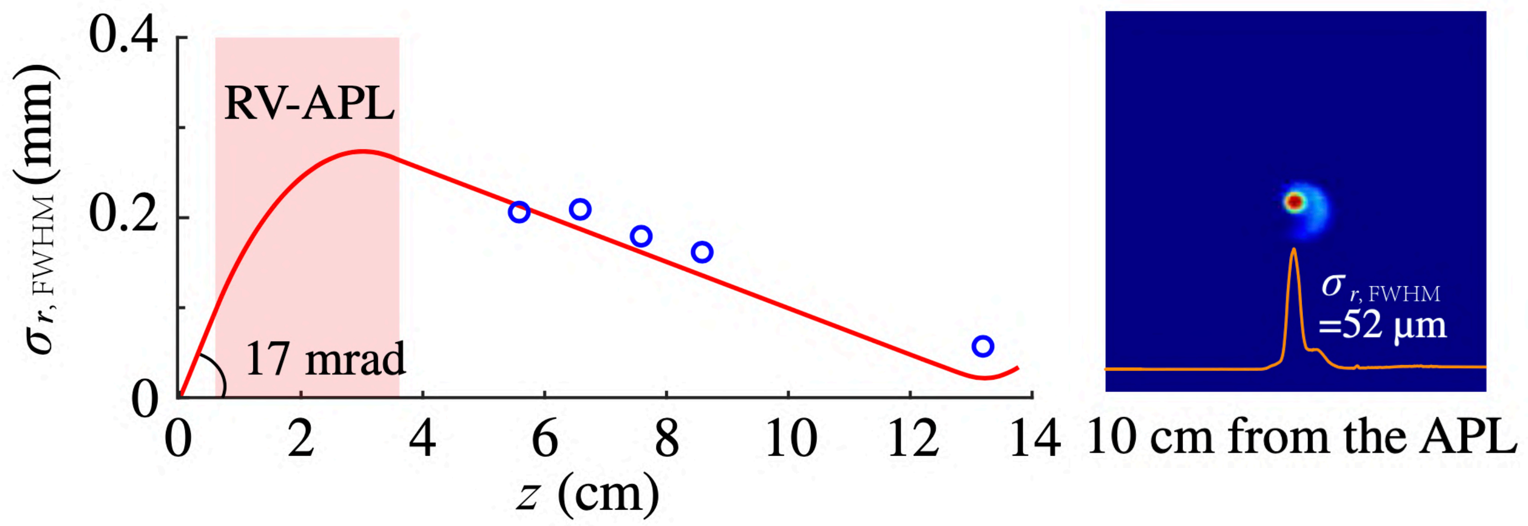




Yan et al., NIM A 1057, 168737 (2023)



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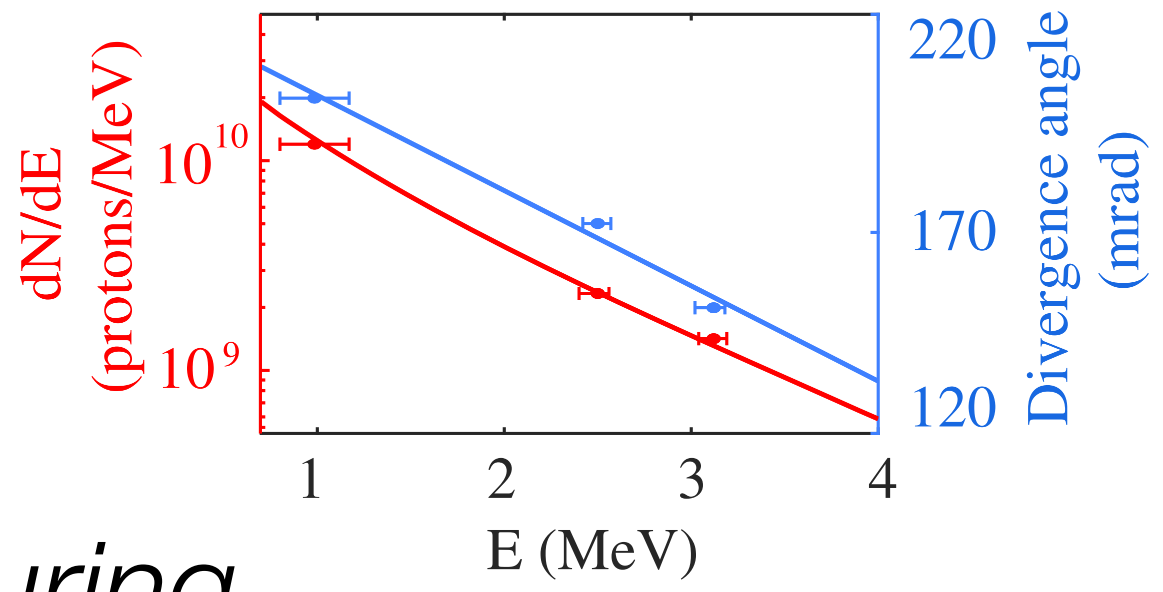
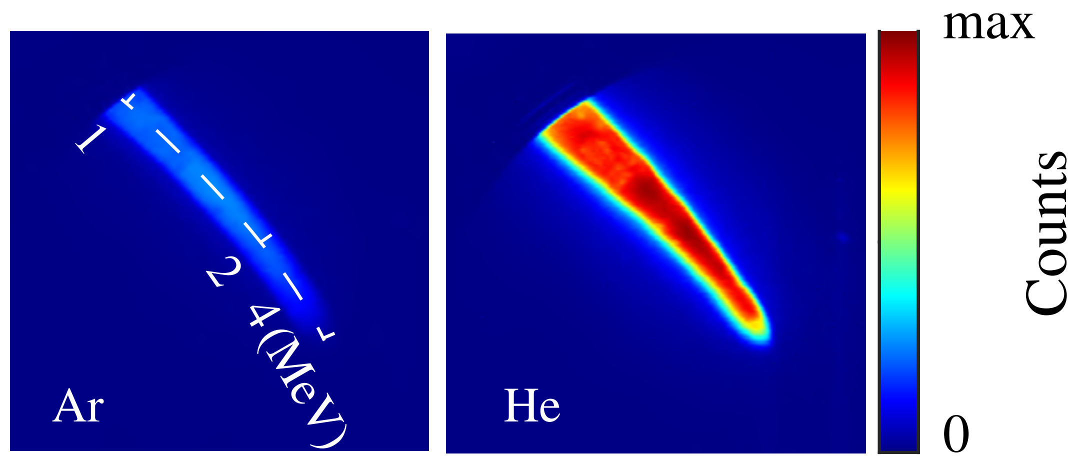
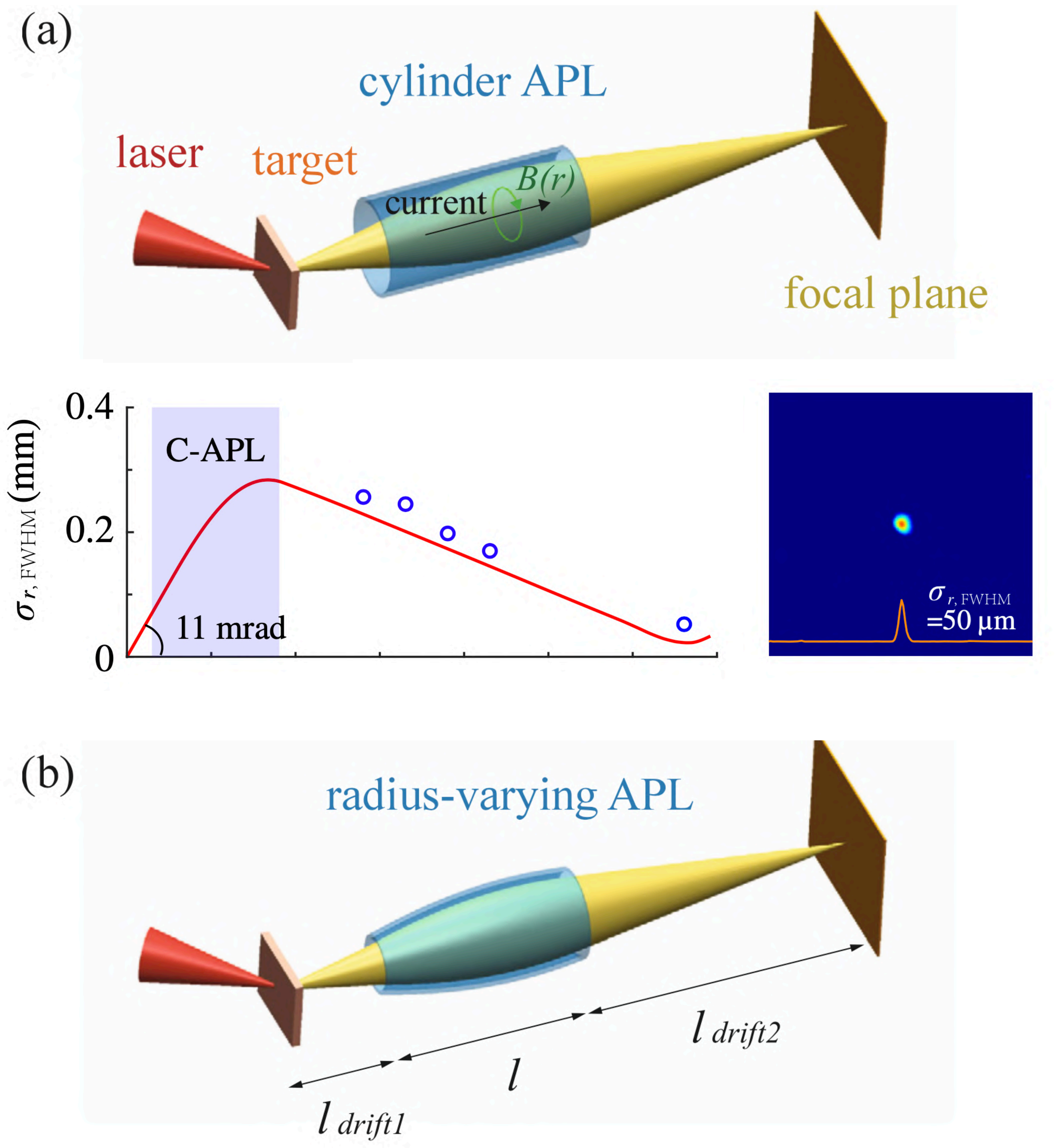
  - *Observed scattering from using heavy gases (Ar vs. He): beam density dropped by 3x for Ar.*







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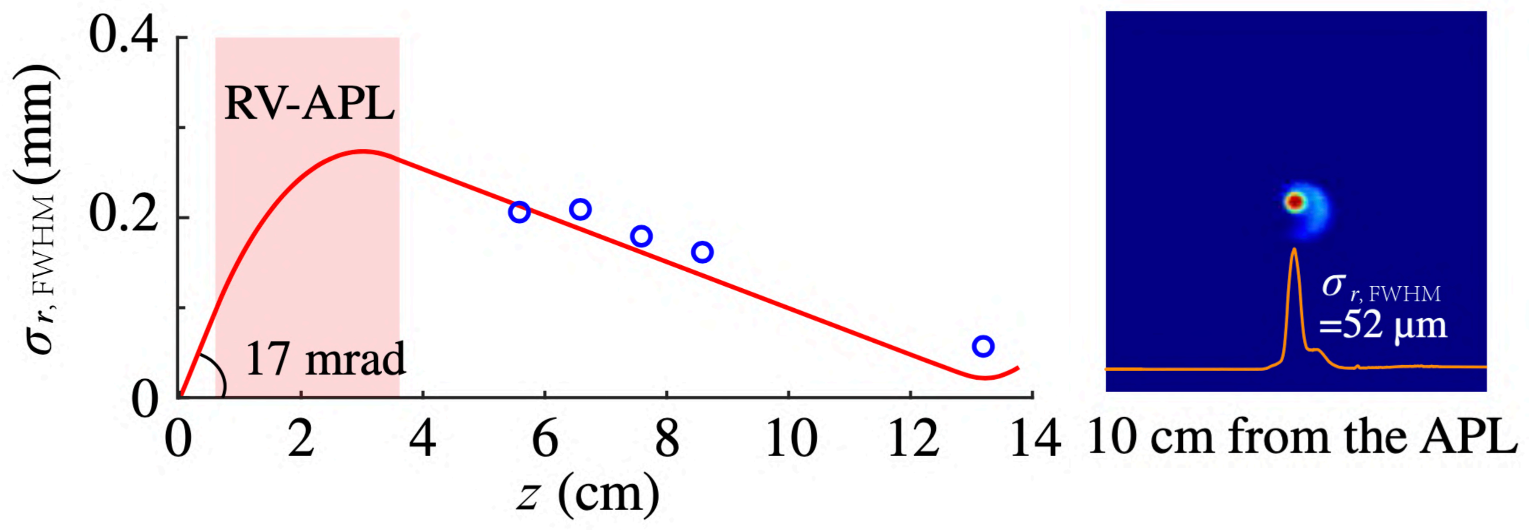

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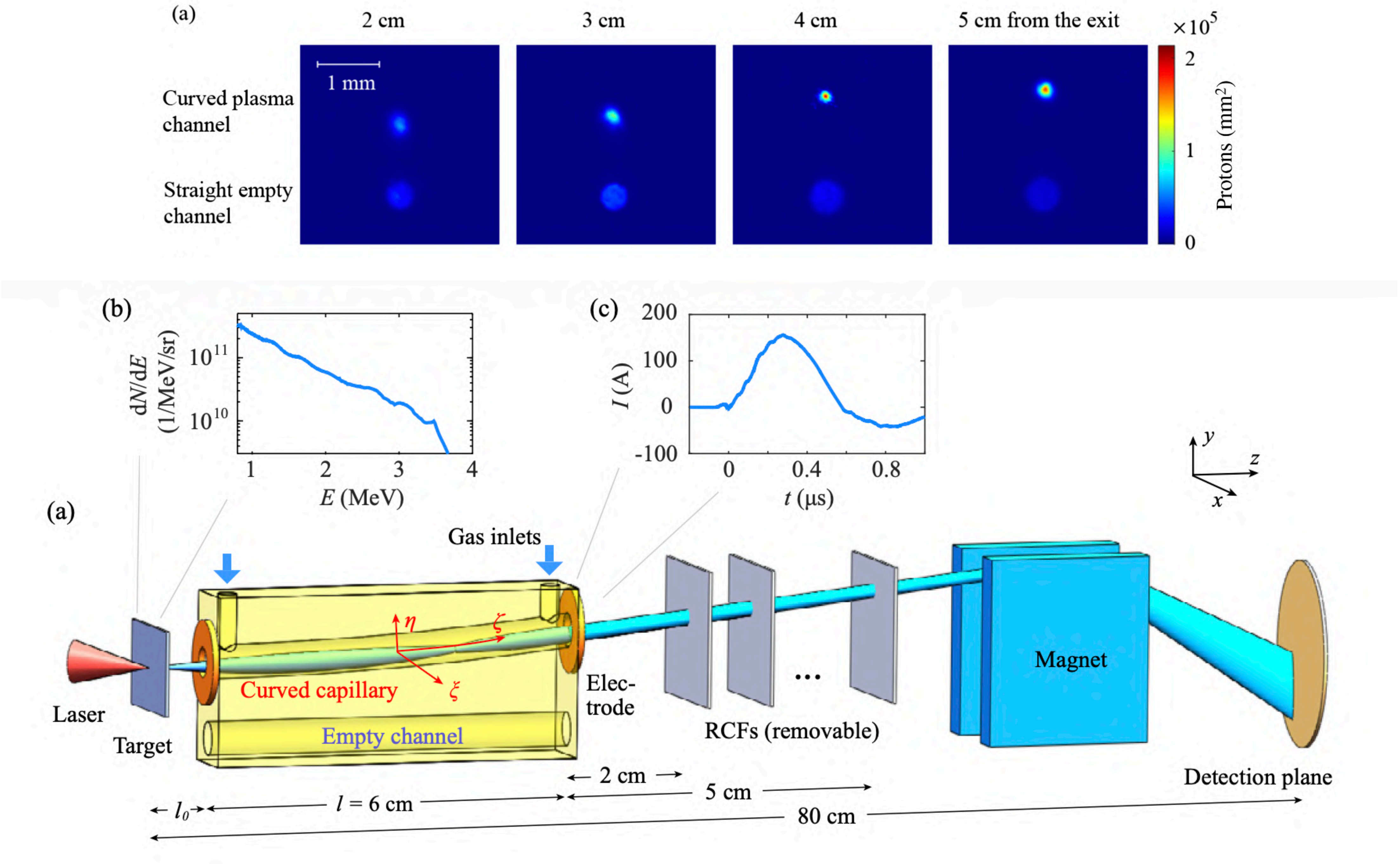
> Yan *et al. also* demonstrated use of bent capillaries (bending and guiding the beam) – idea introduced for electron beams by Pompili et al. (2018/2024)



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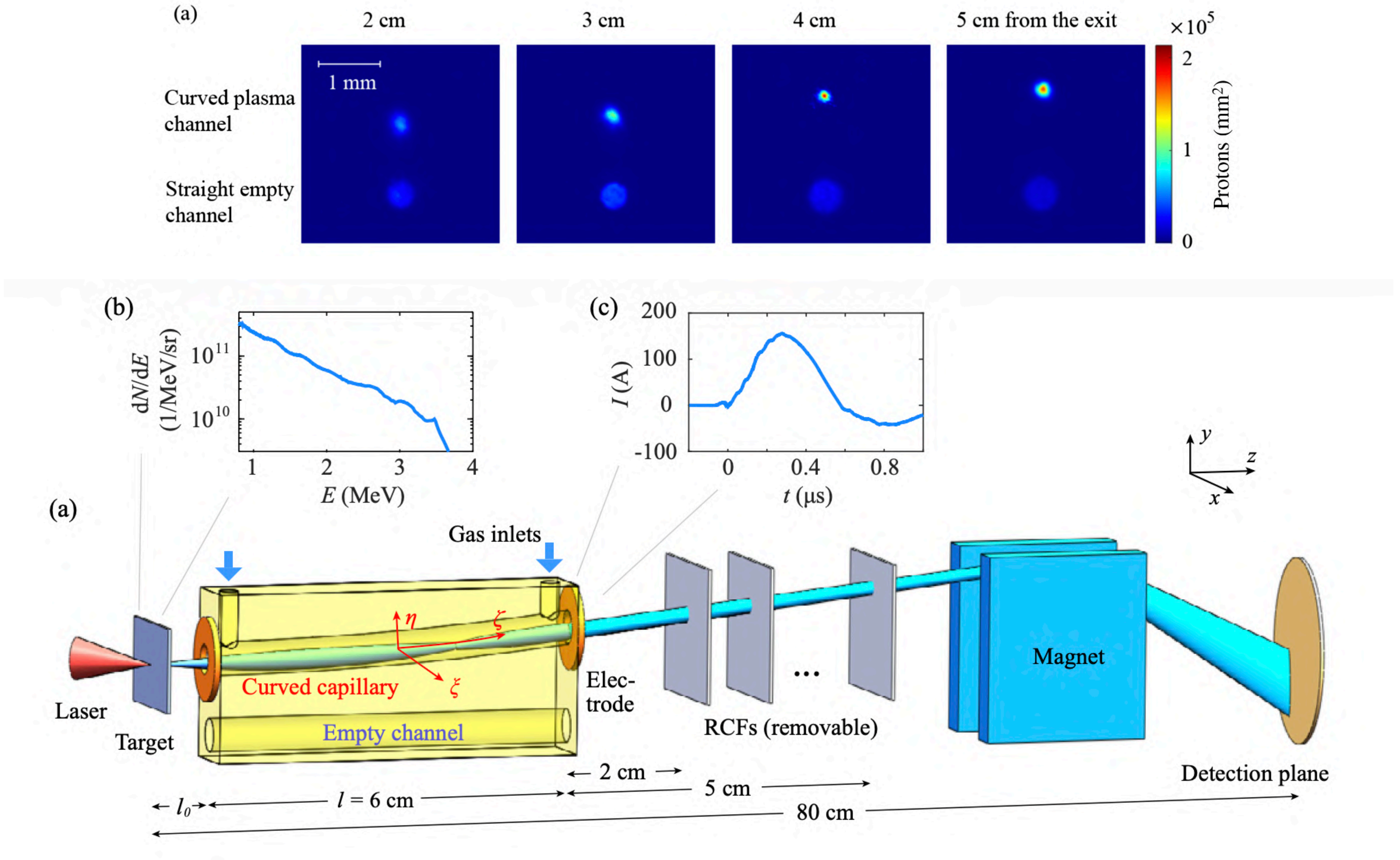
Use with laser–proton beams

- Yan *et al. also* demonstrated use of bent capillaries (bending and guiding the beam) – idea introduced for electron beams by Pompili et al. (2018/2024)
- Can be envisioned as part of a gantry setup for cancer treatment.



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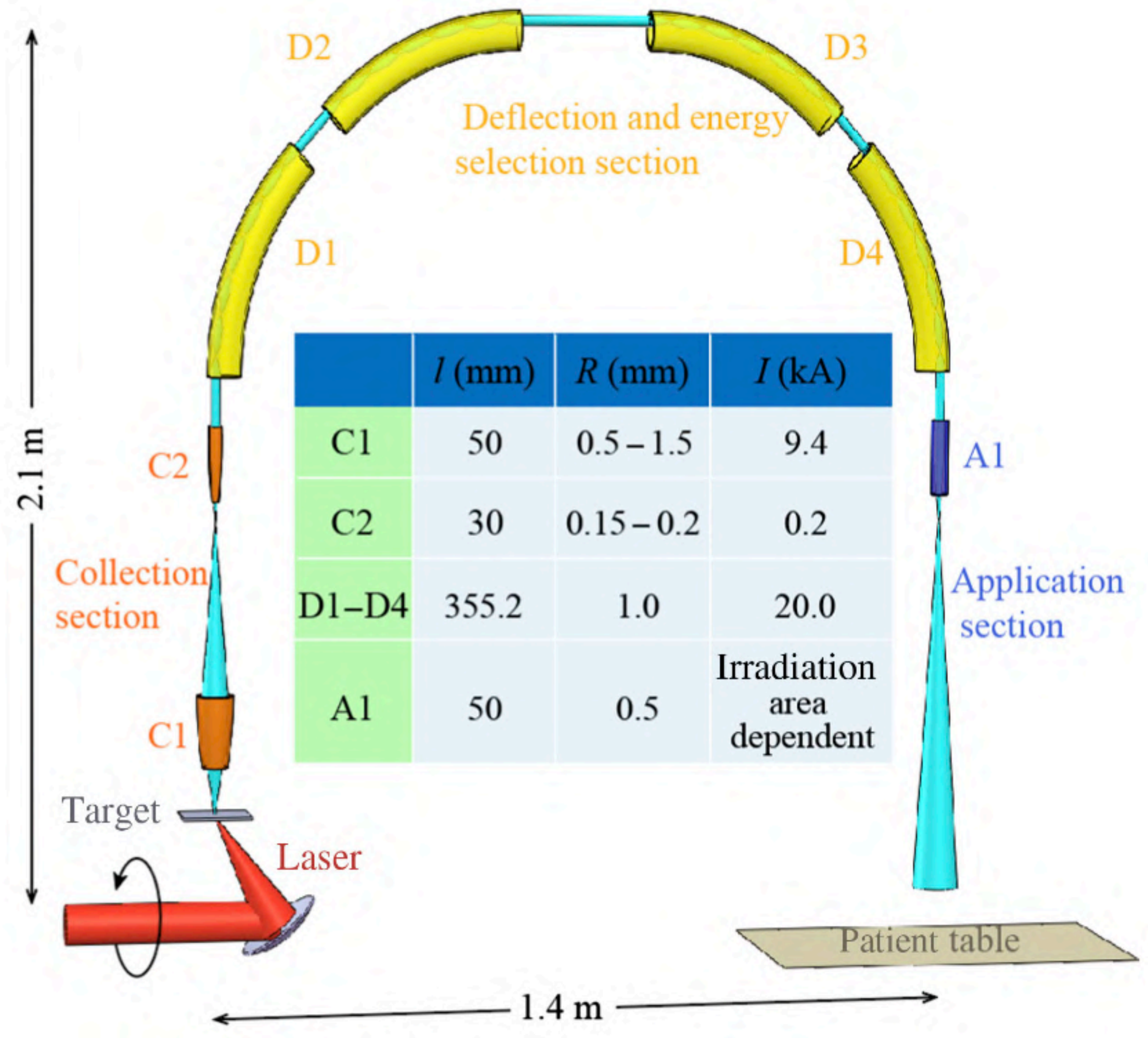
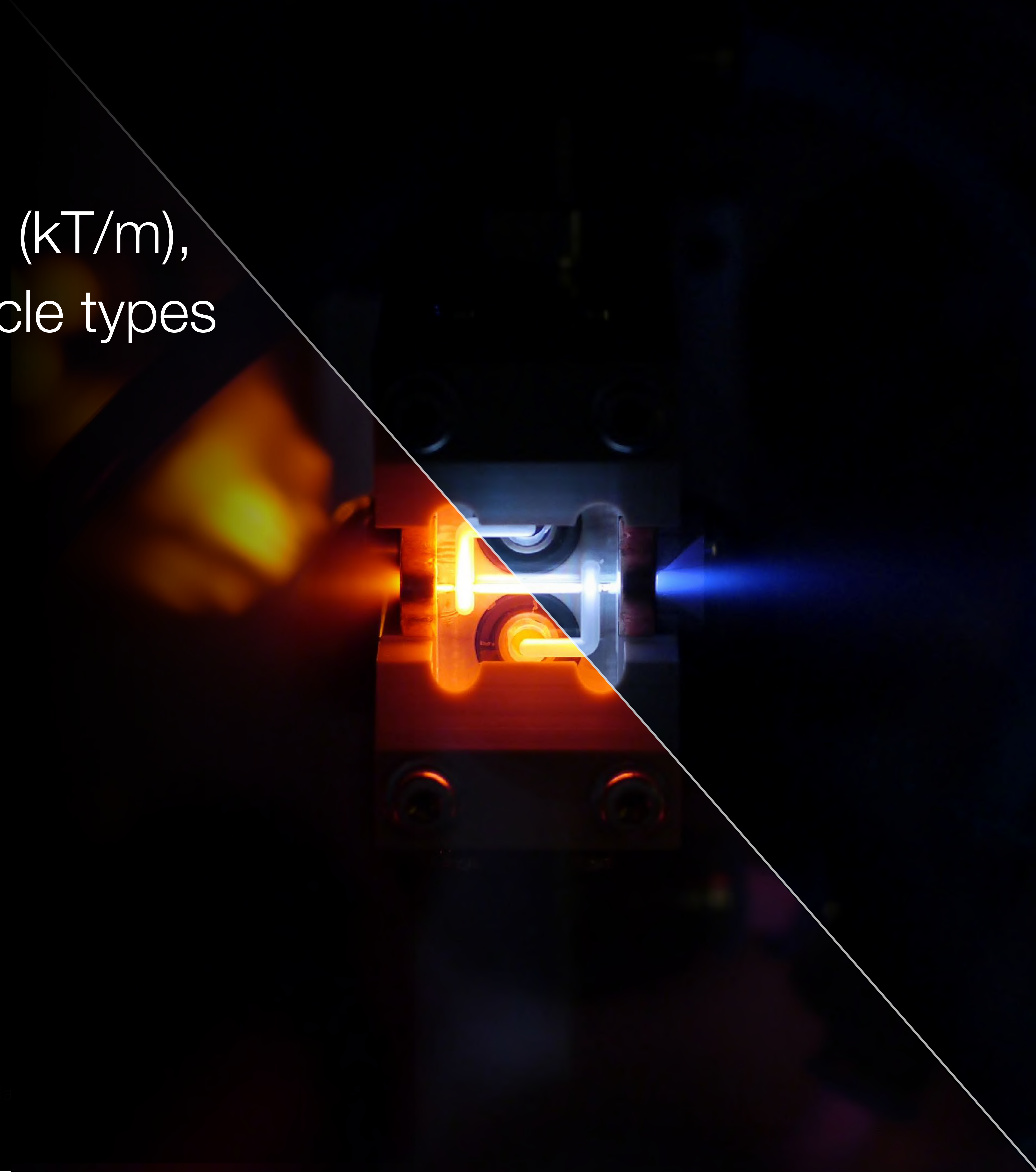


	l (mm)	R (mm)	I (kA)
C1	50	0.5 – 1.5	9.4
C2	30	0.15 – 0.2	0.2
D1–D4	355.2	1.0	20.0
A1	50	0.5	Irradiation area dependent

Conclusion

- > Active plasma lenses provide strong (kT/m), pulsed, uniform focusing for all particle types



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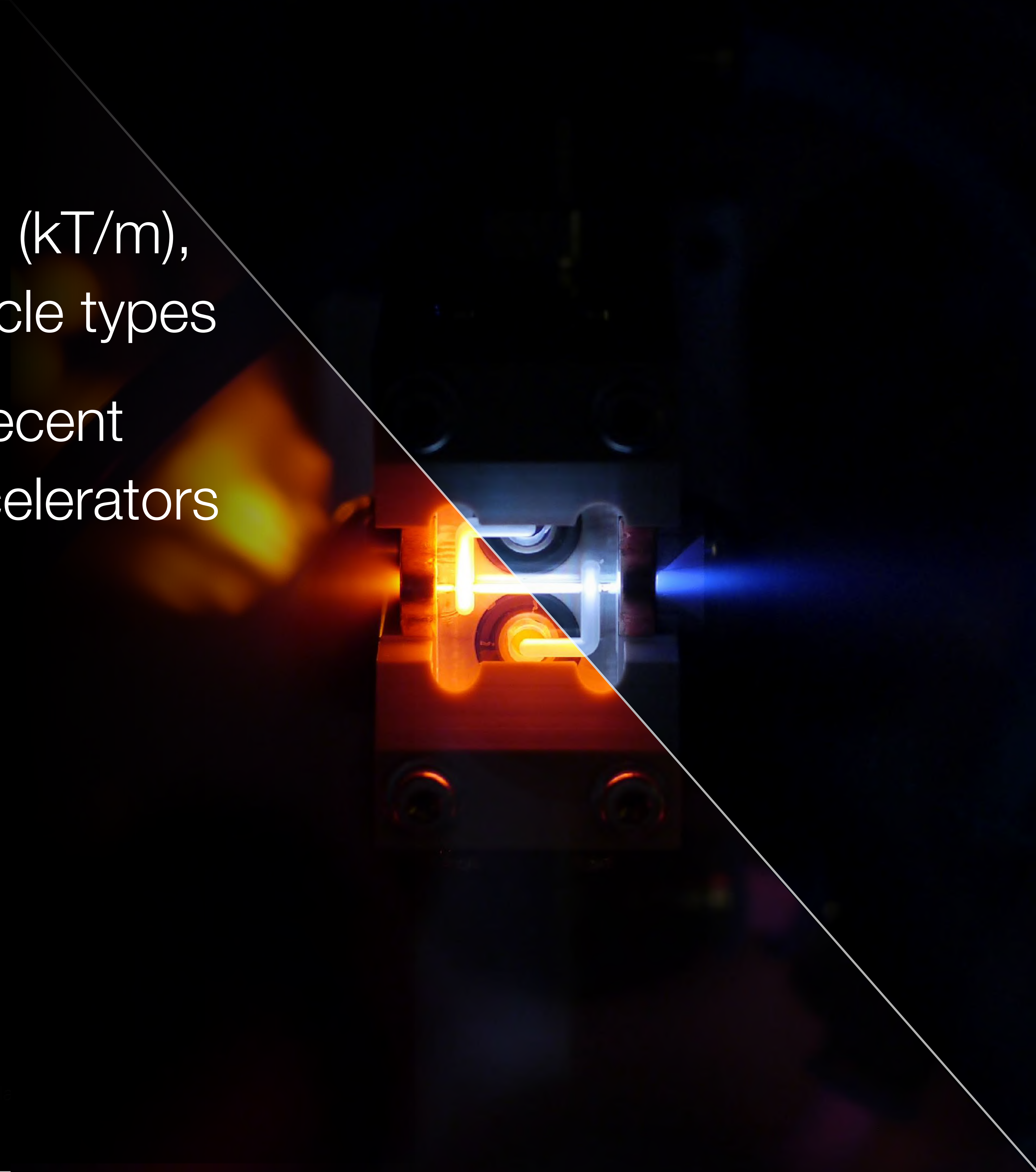

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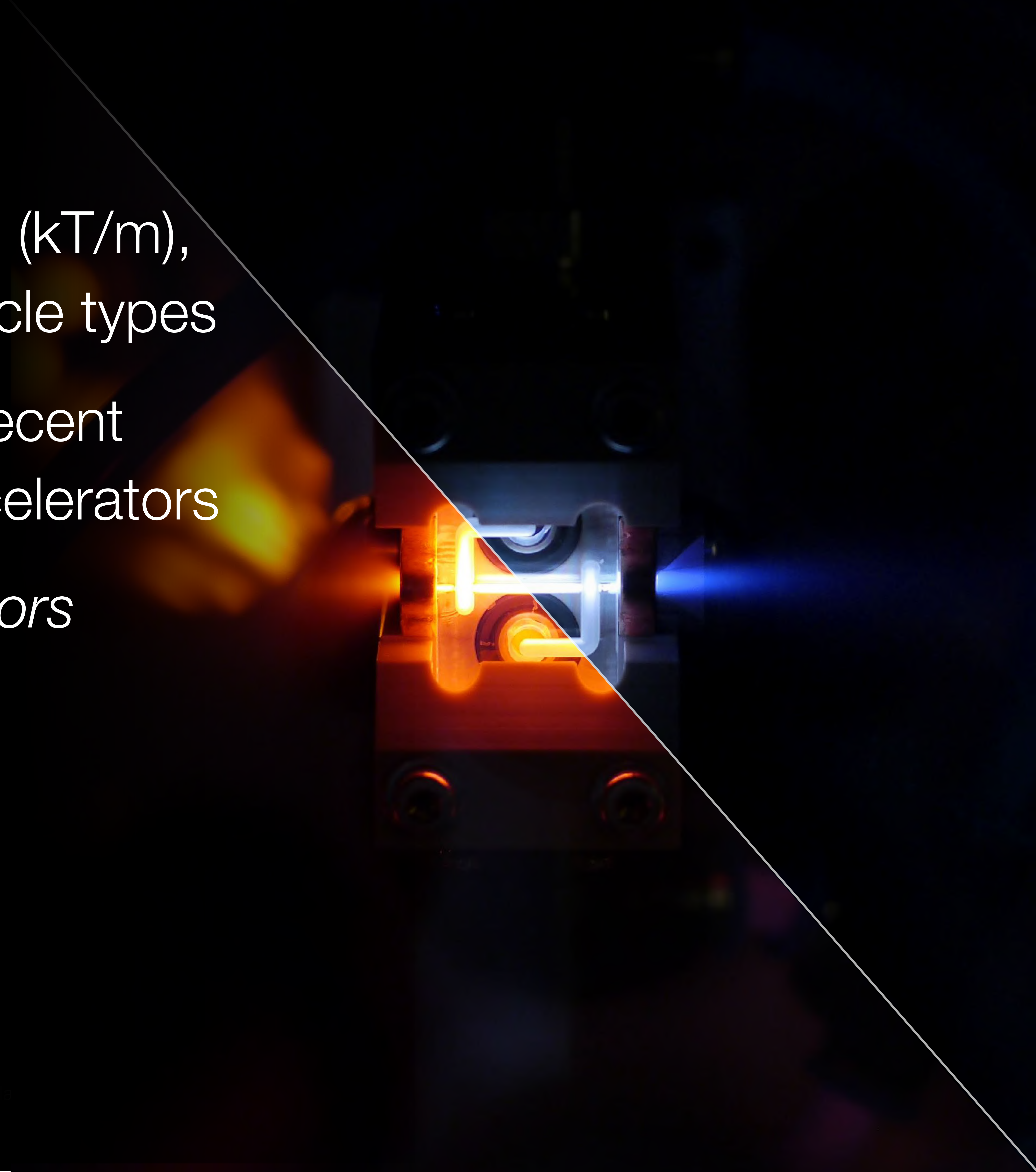

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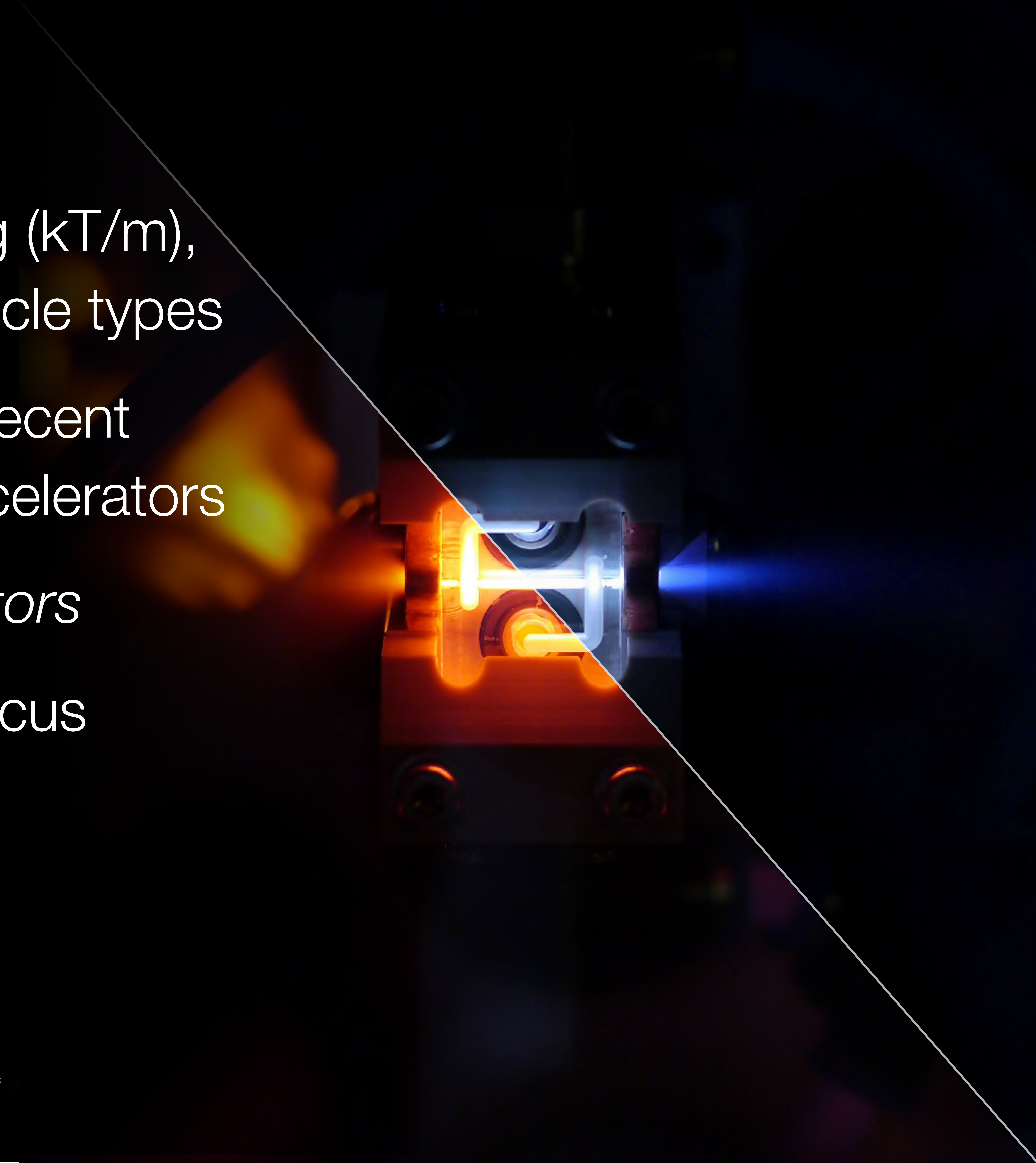

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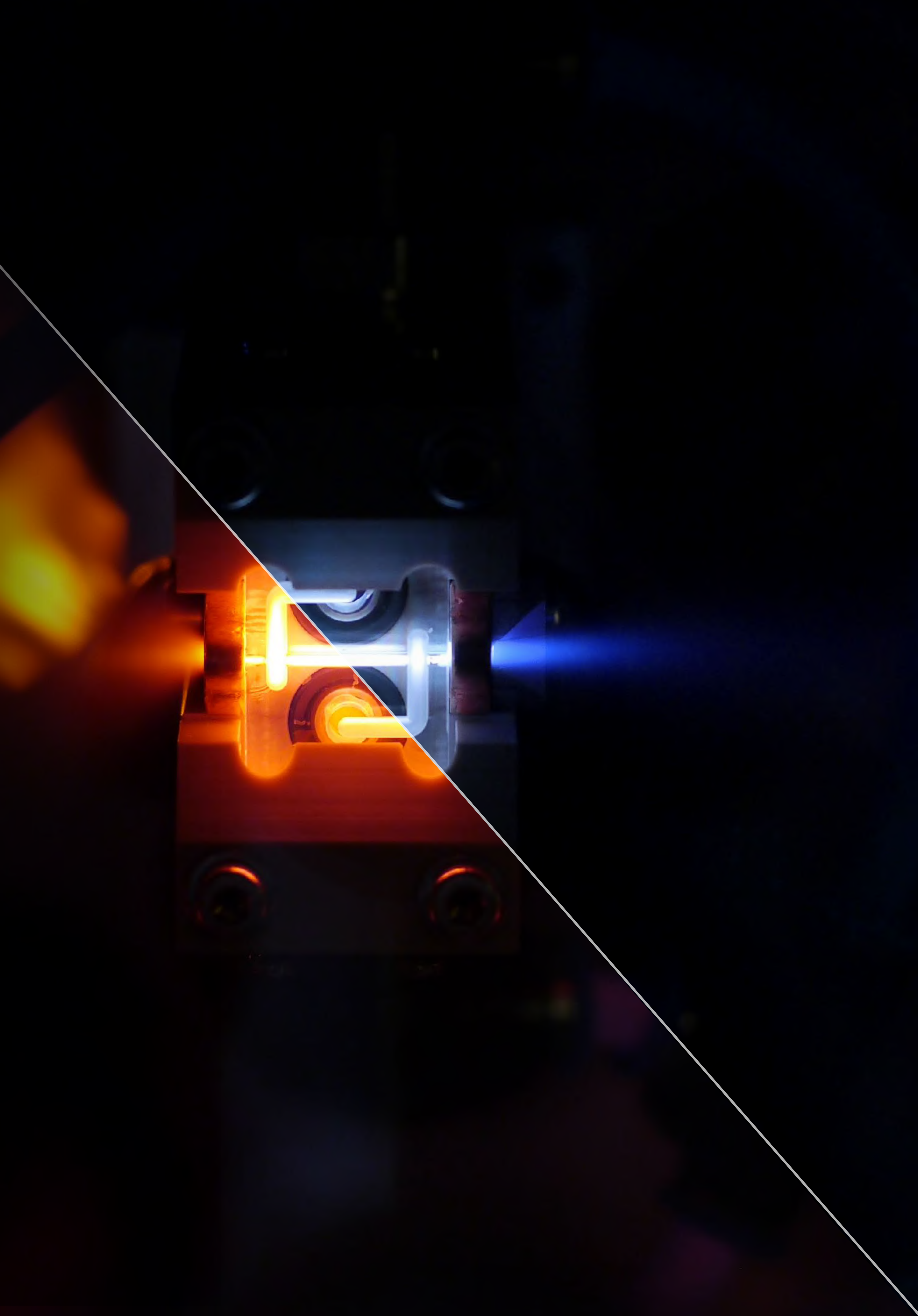
  - *Can we apply APLs to higher-energy proton/ion beams (~100 MeV)?*

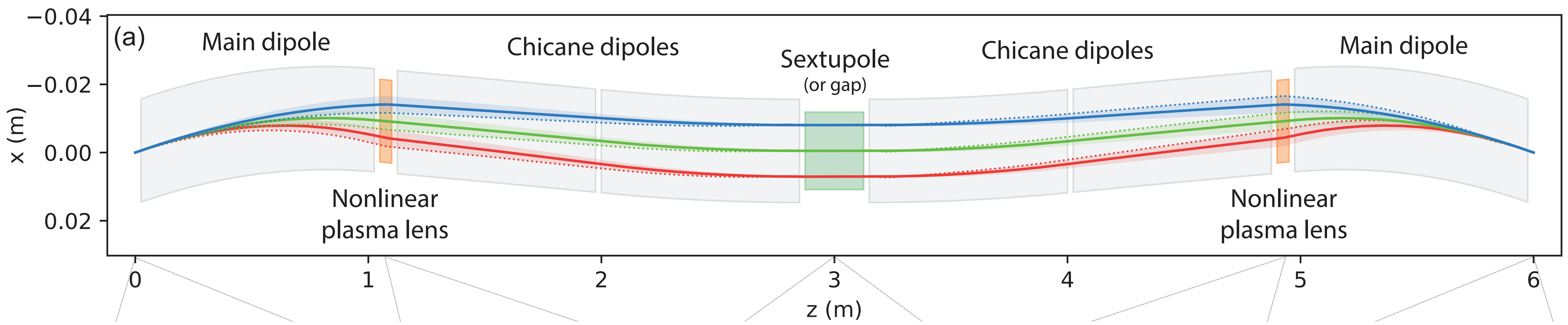


Extra slides

SPARTA: Novel achromatic staging optics

Solves staging (coupling plasma accelerators) with a new plasma lens

> *Inspiration:* chromaticity correction in collider final focusing



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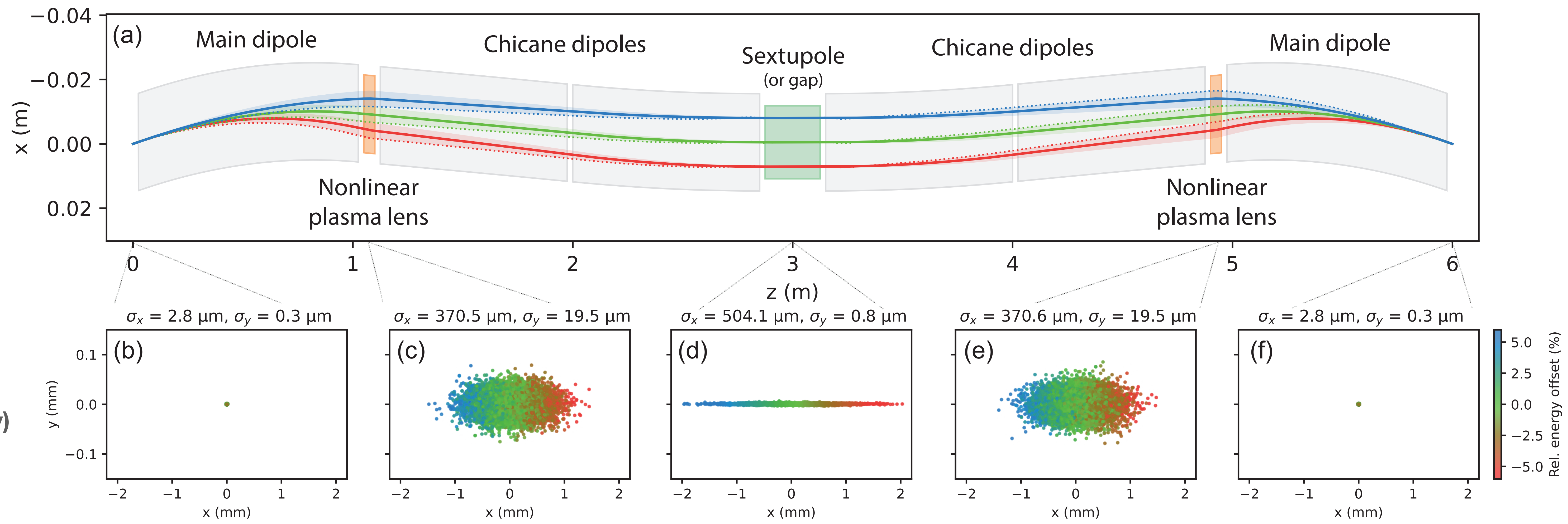
Evolution in transverse (x–y)



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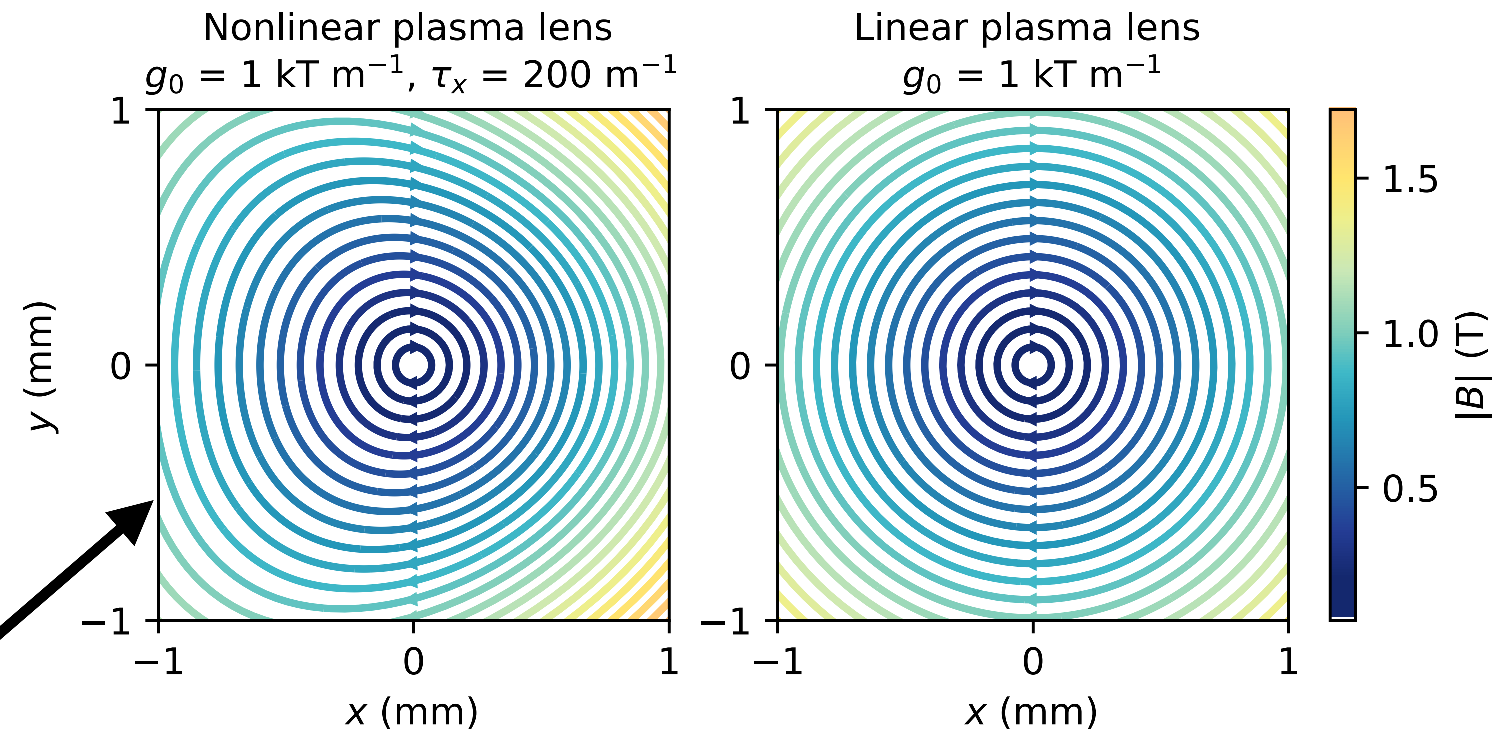

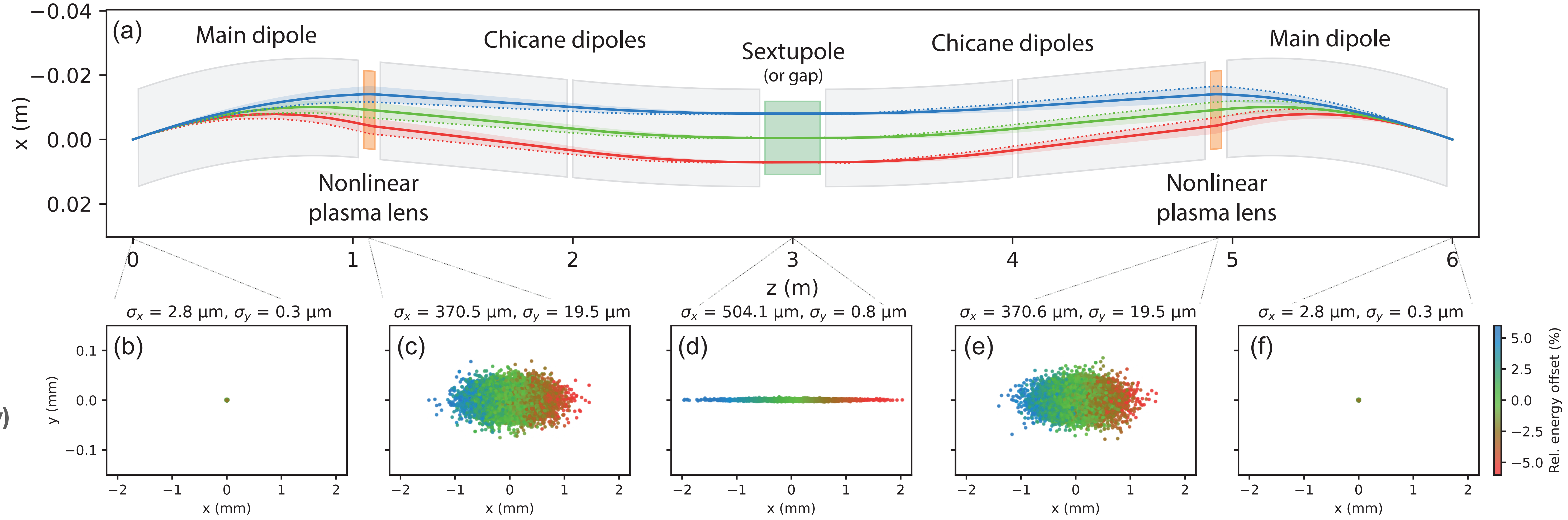

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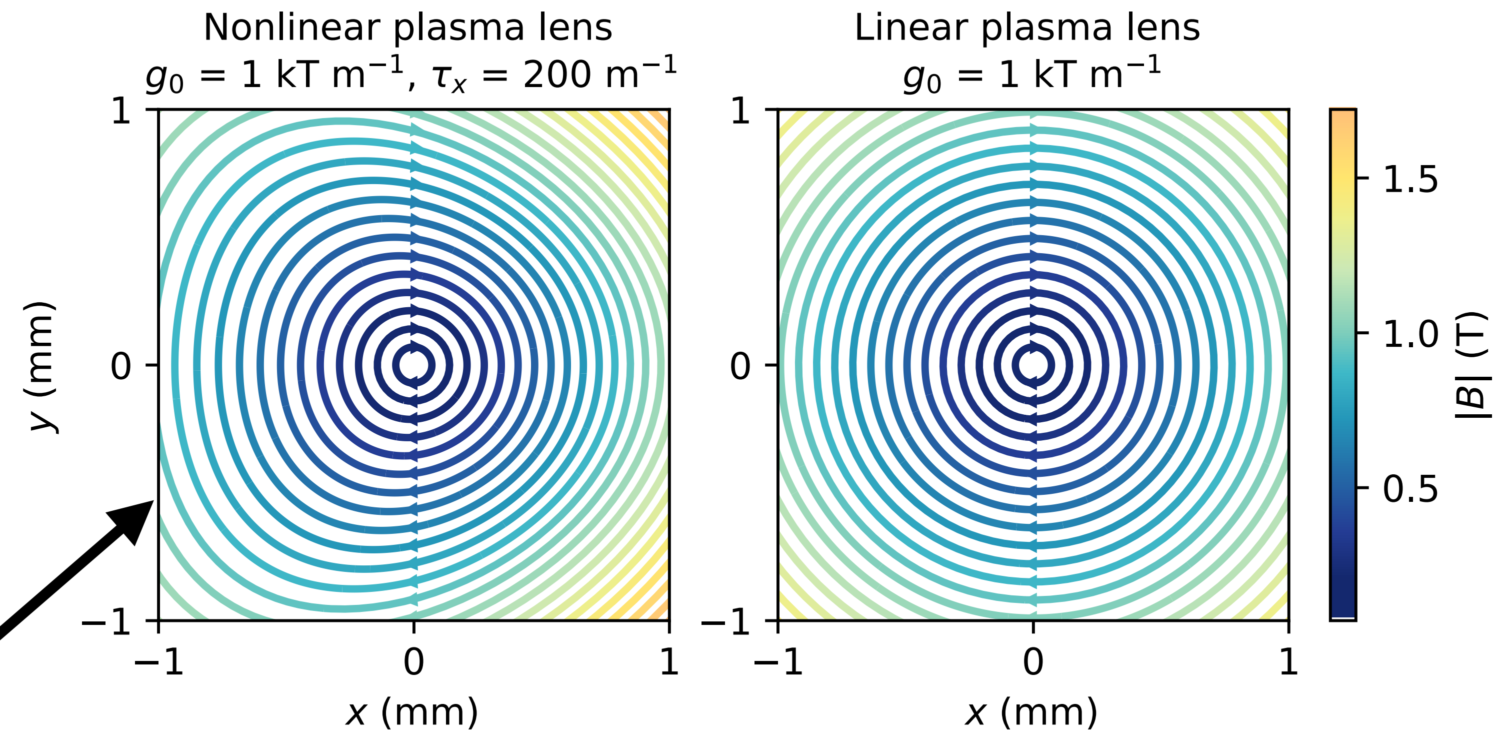

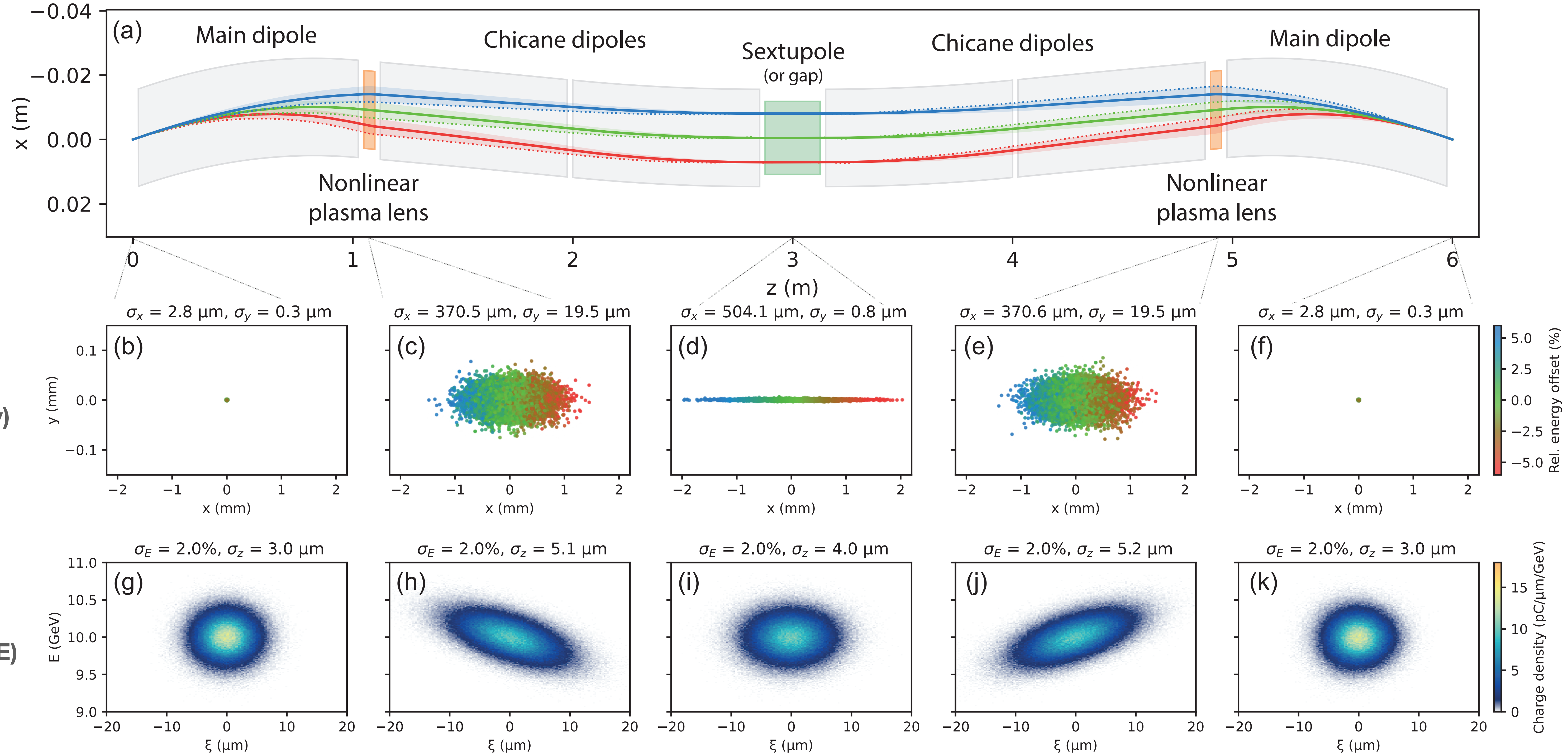

Evolution in transverse (x–y)

Evolution in longitudinal (z–E)

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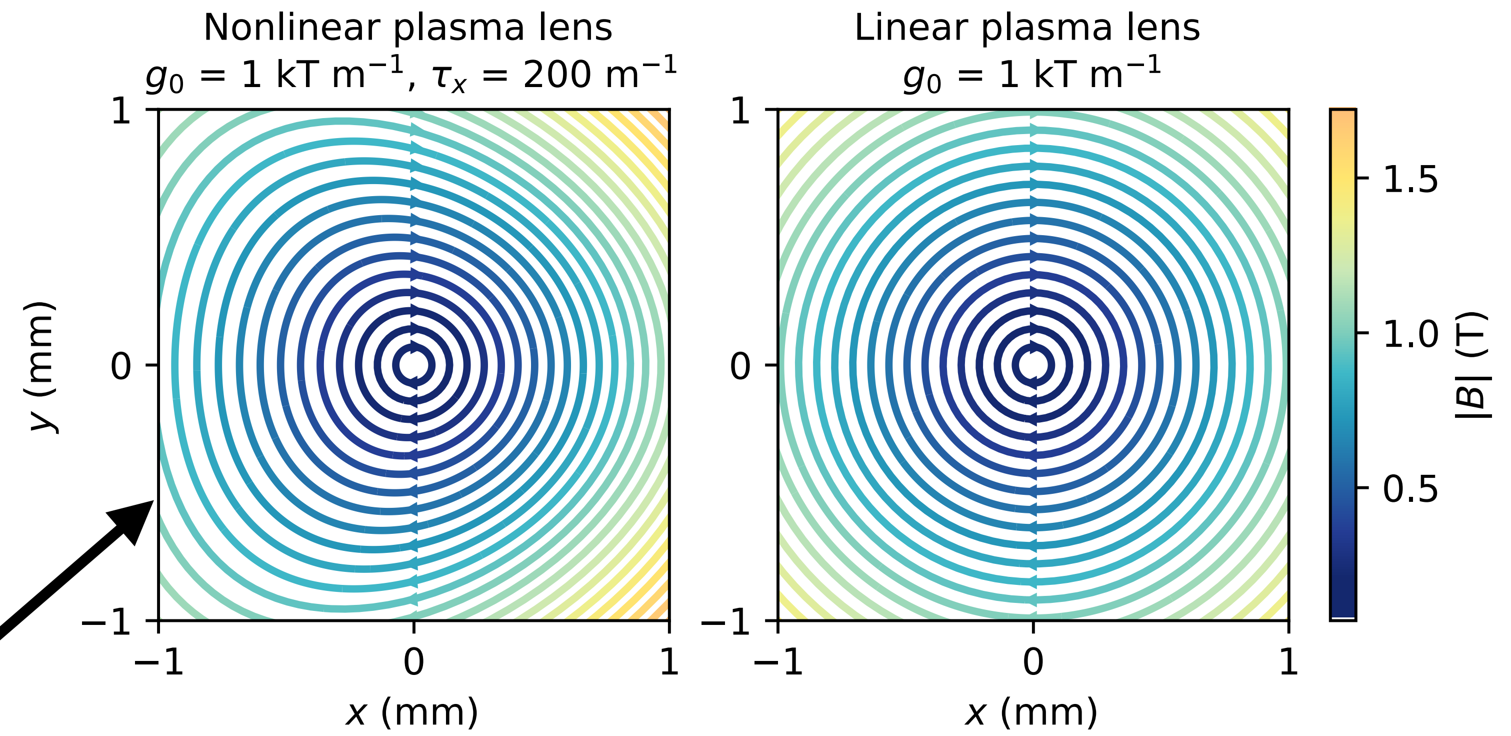

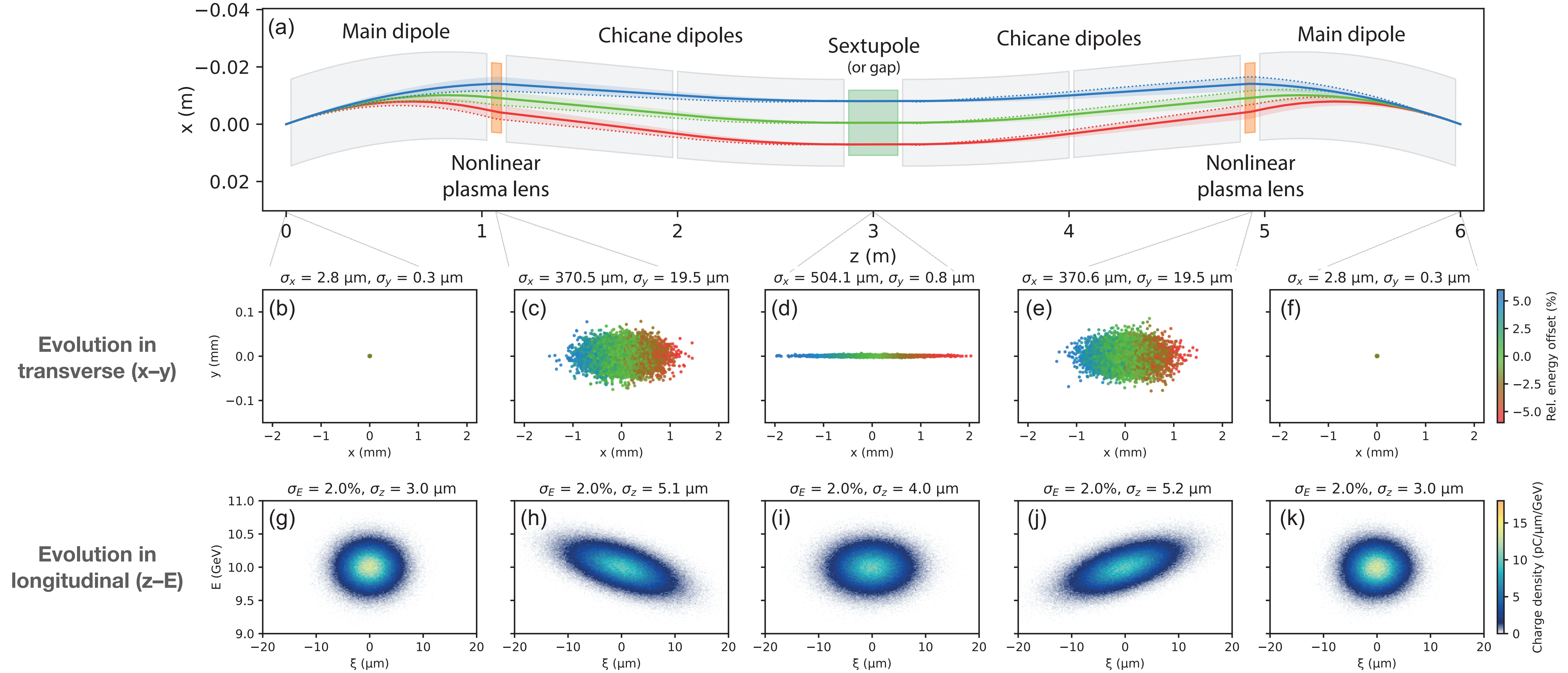

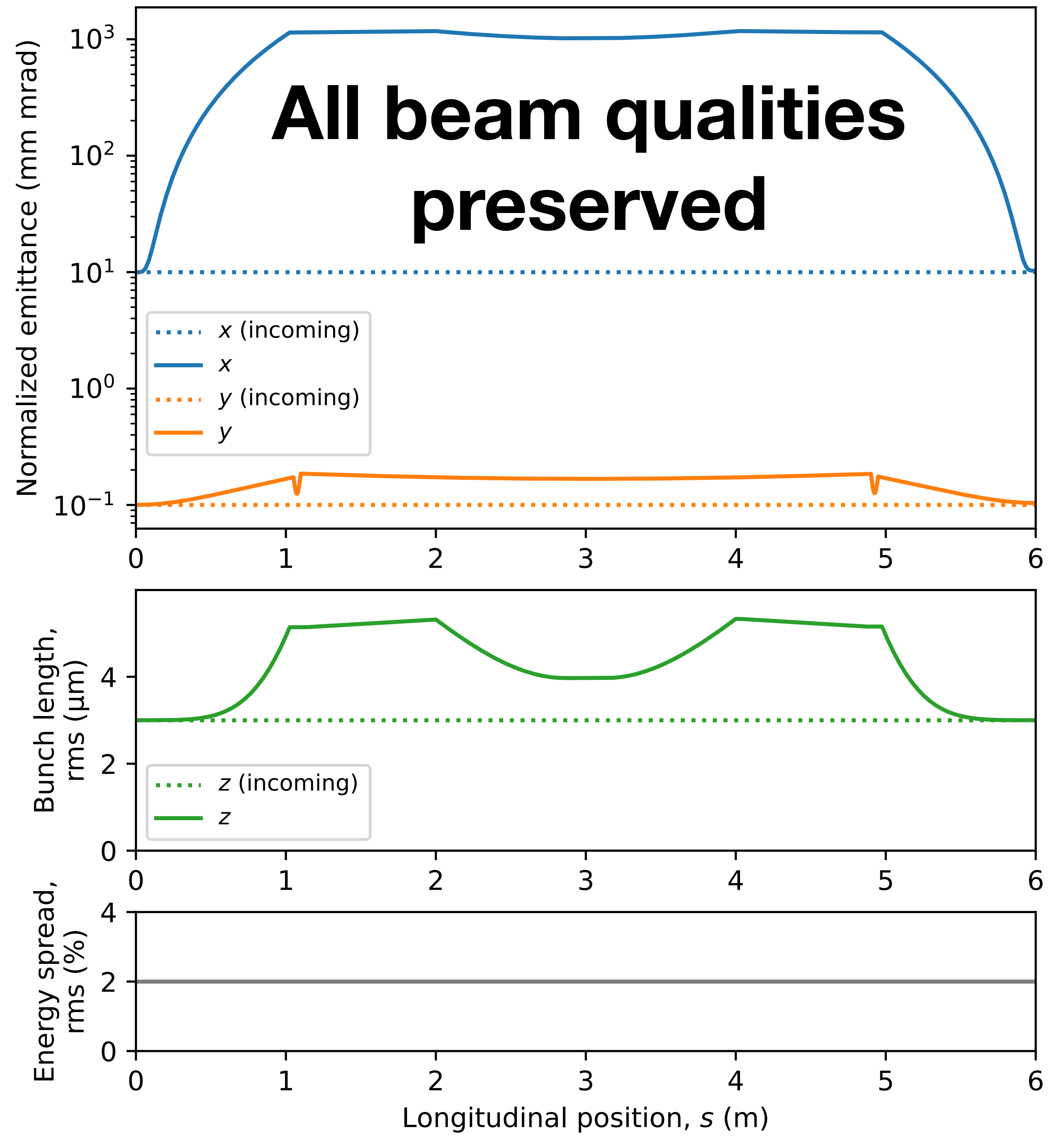

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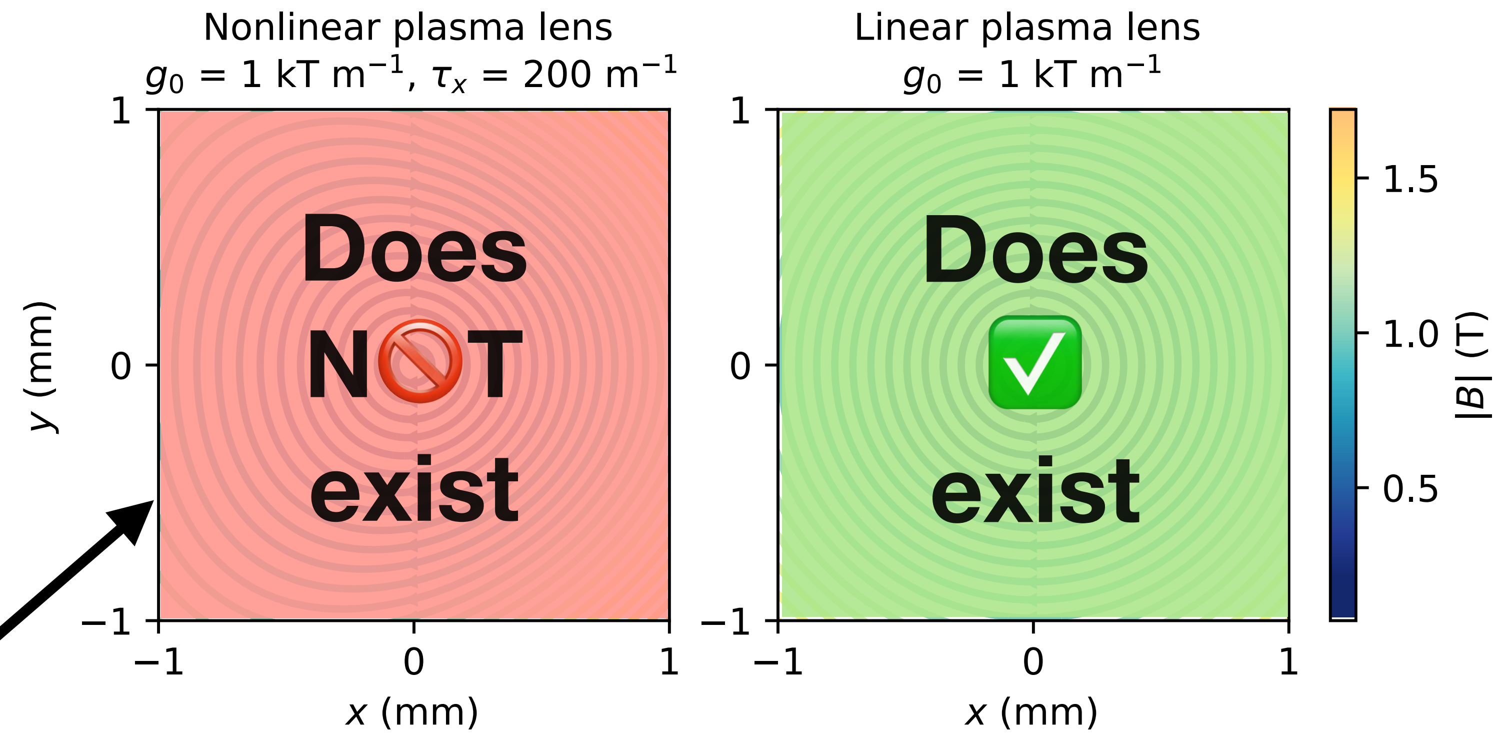
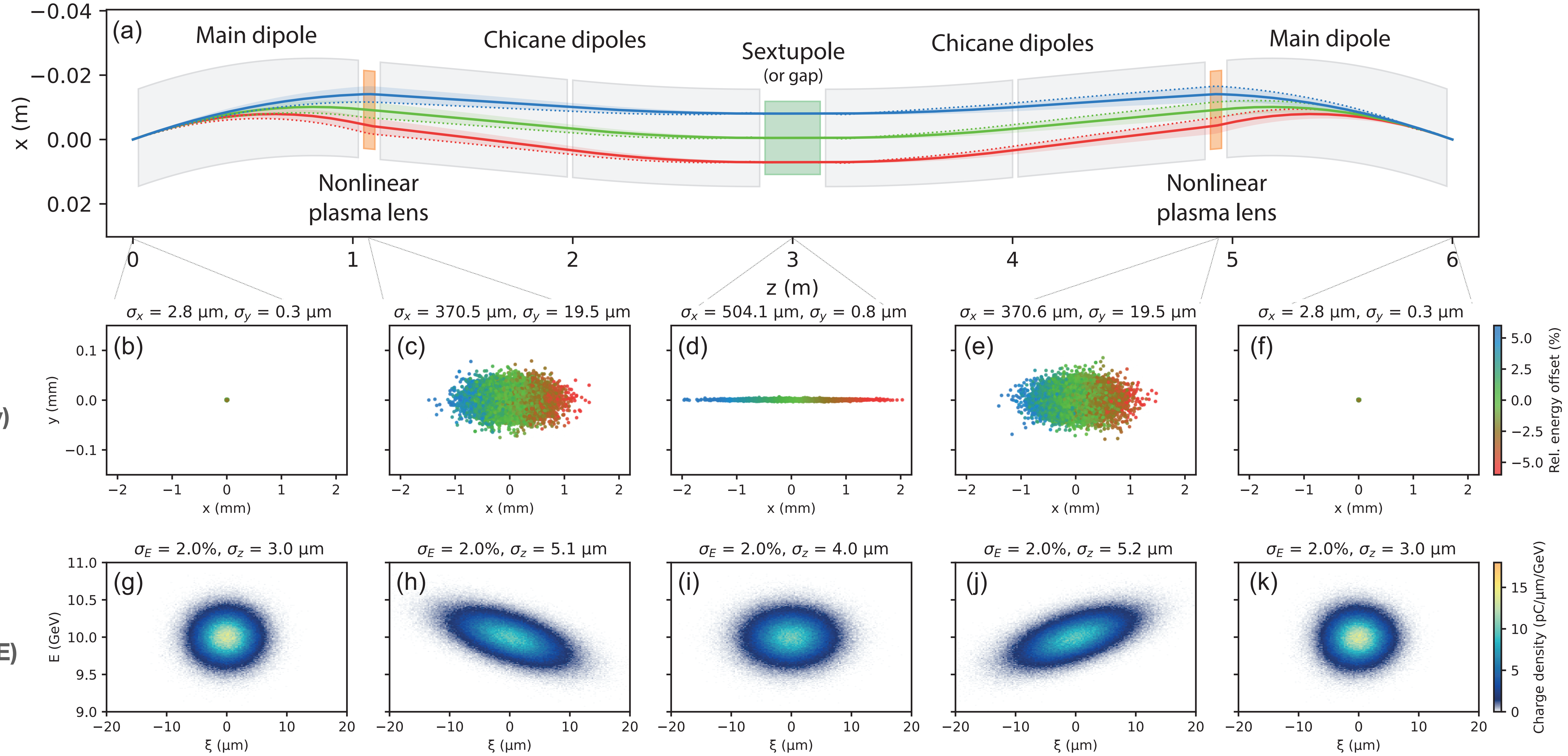
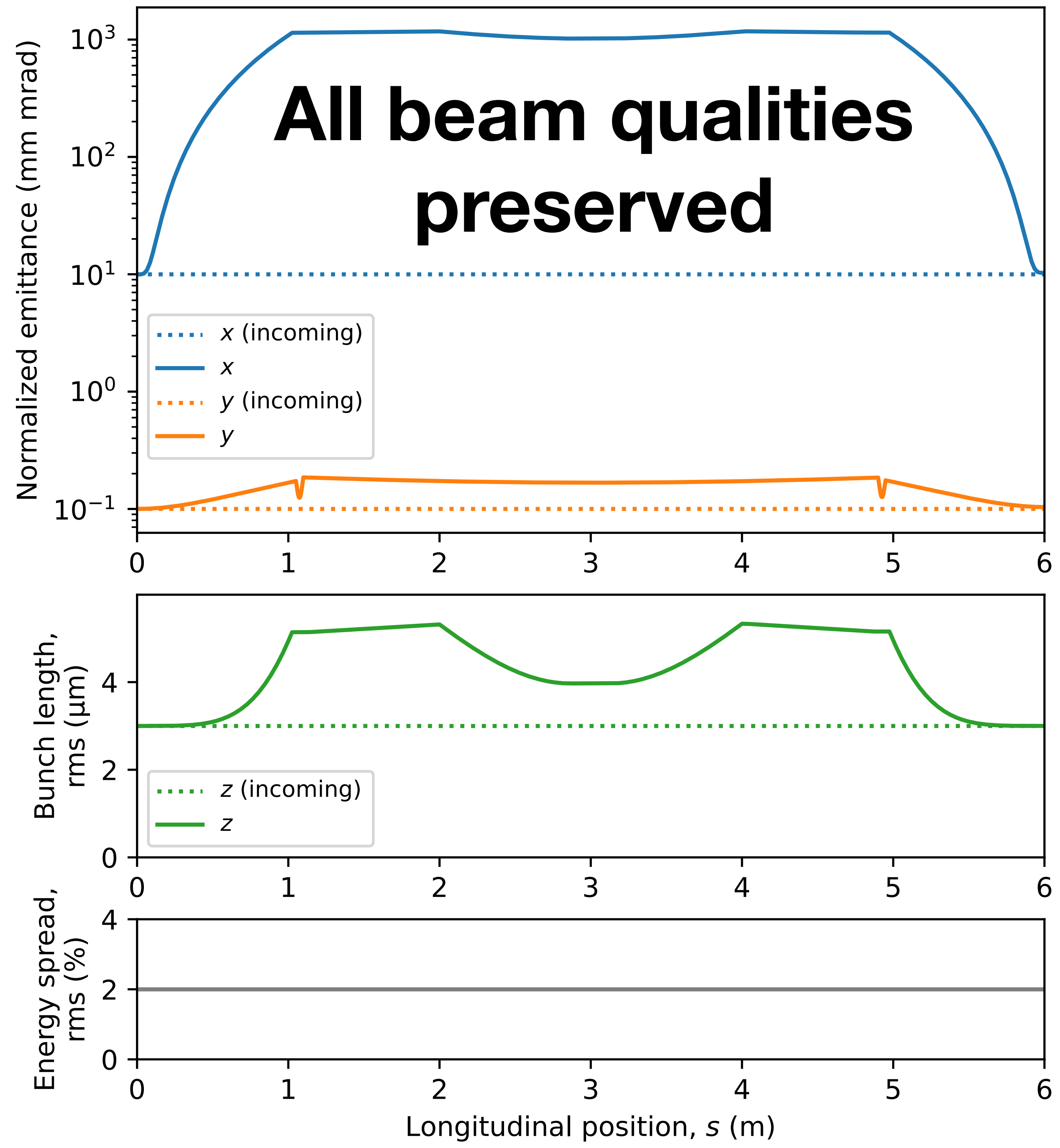
Development required!

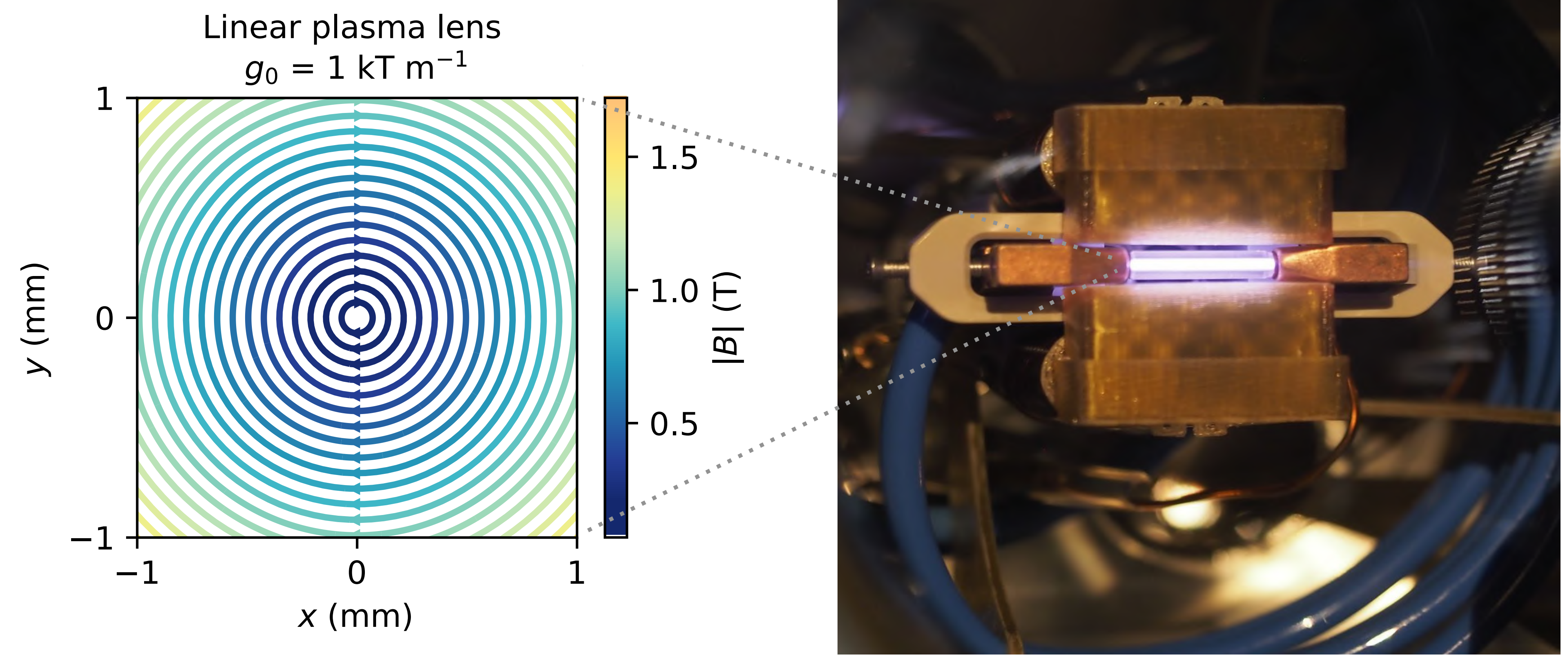






SPARTA: Development of a nonlinear plasma lens

Exciting a nonlinearity through the Hall effect



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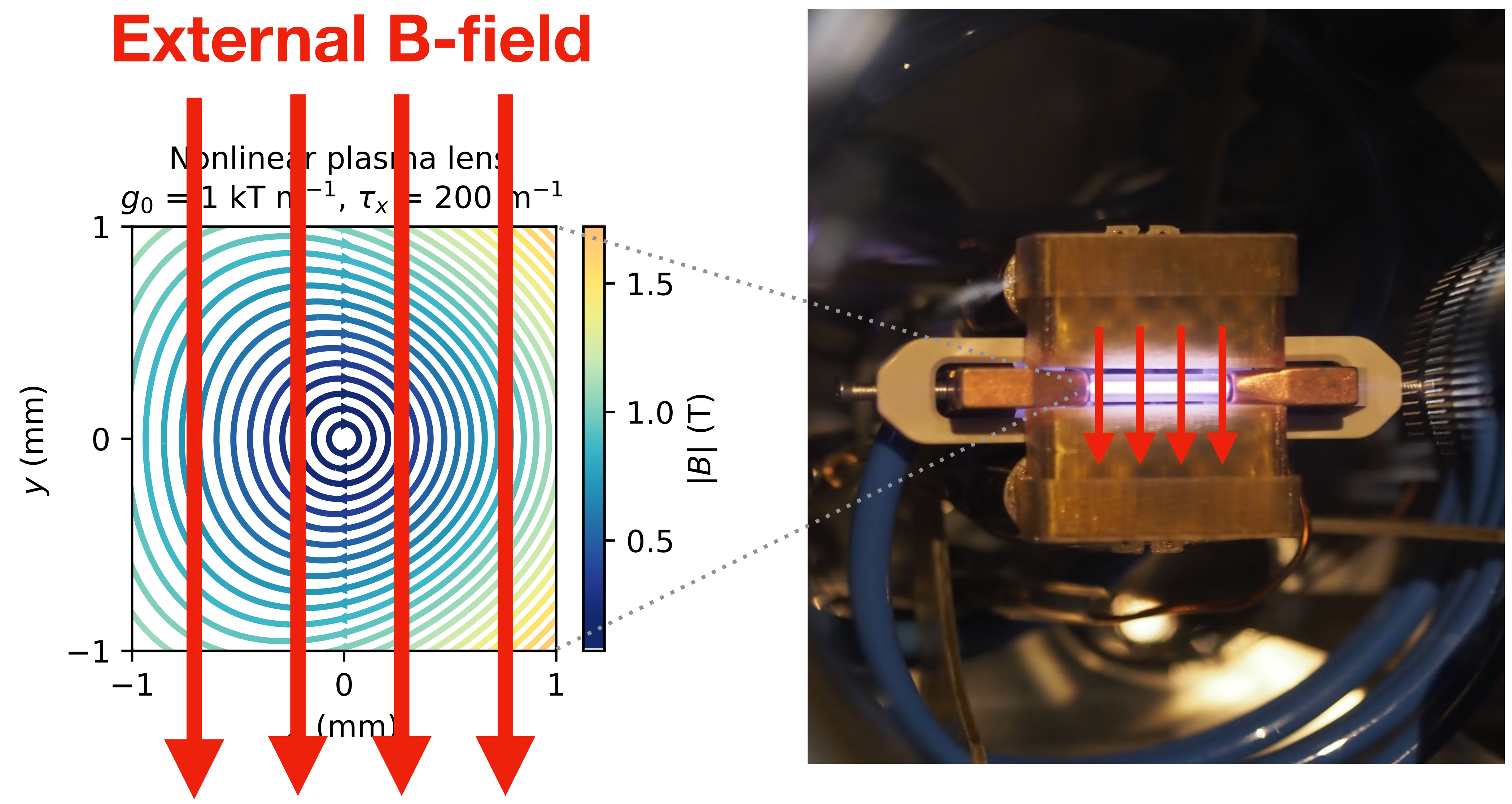

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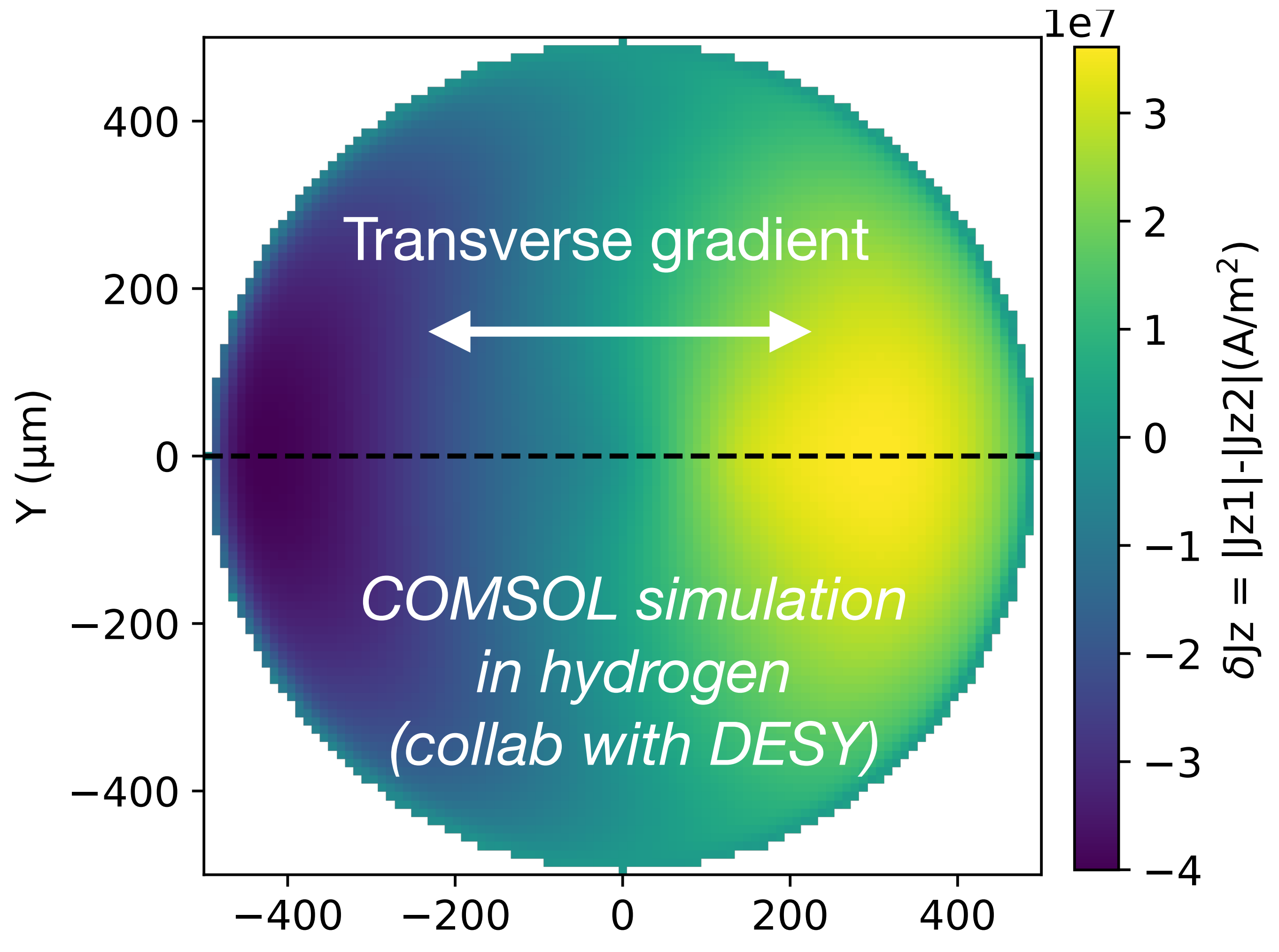
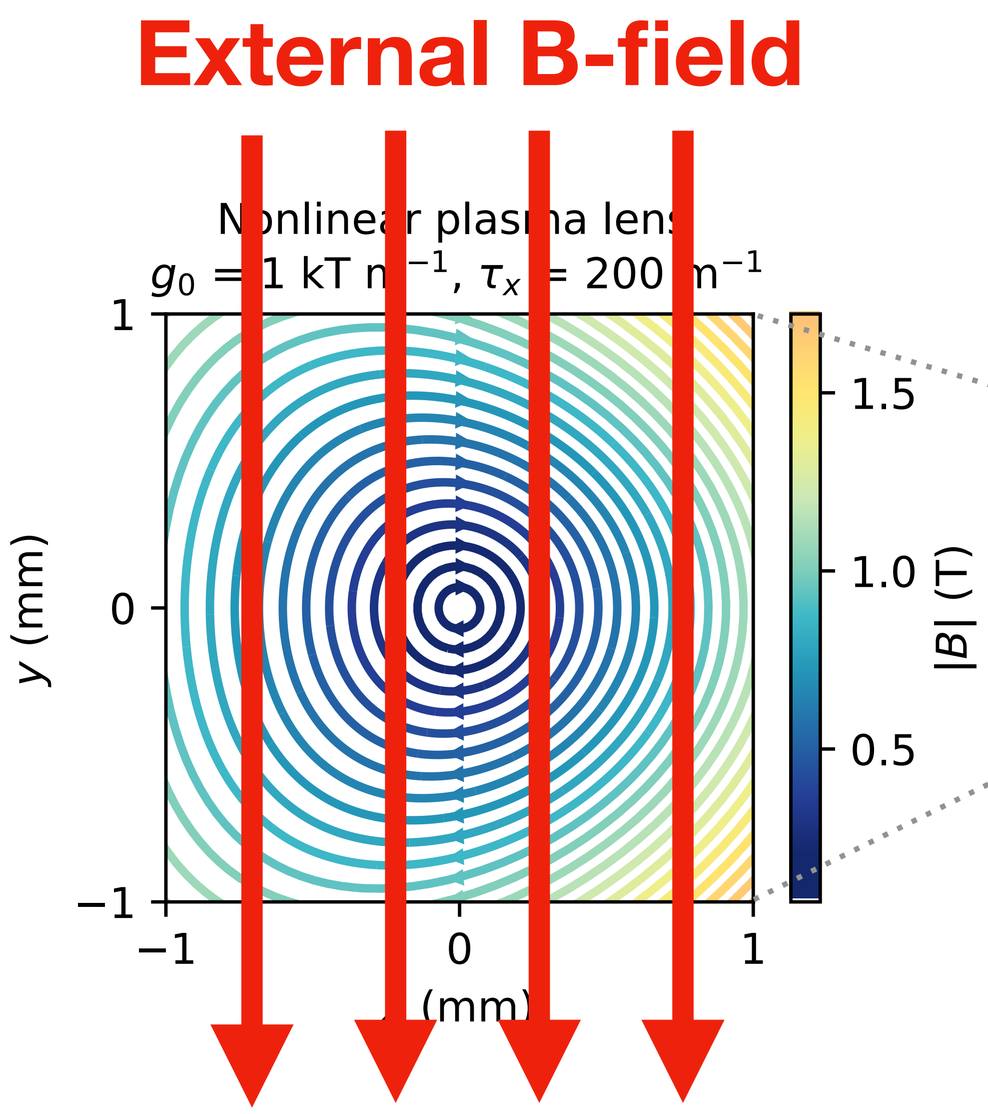
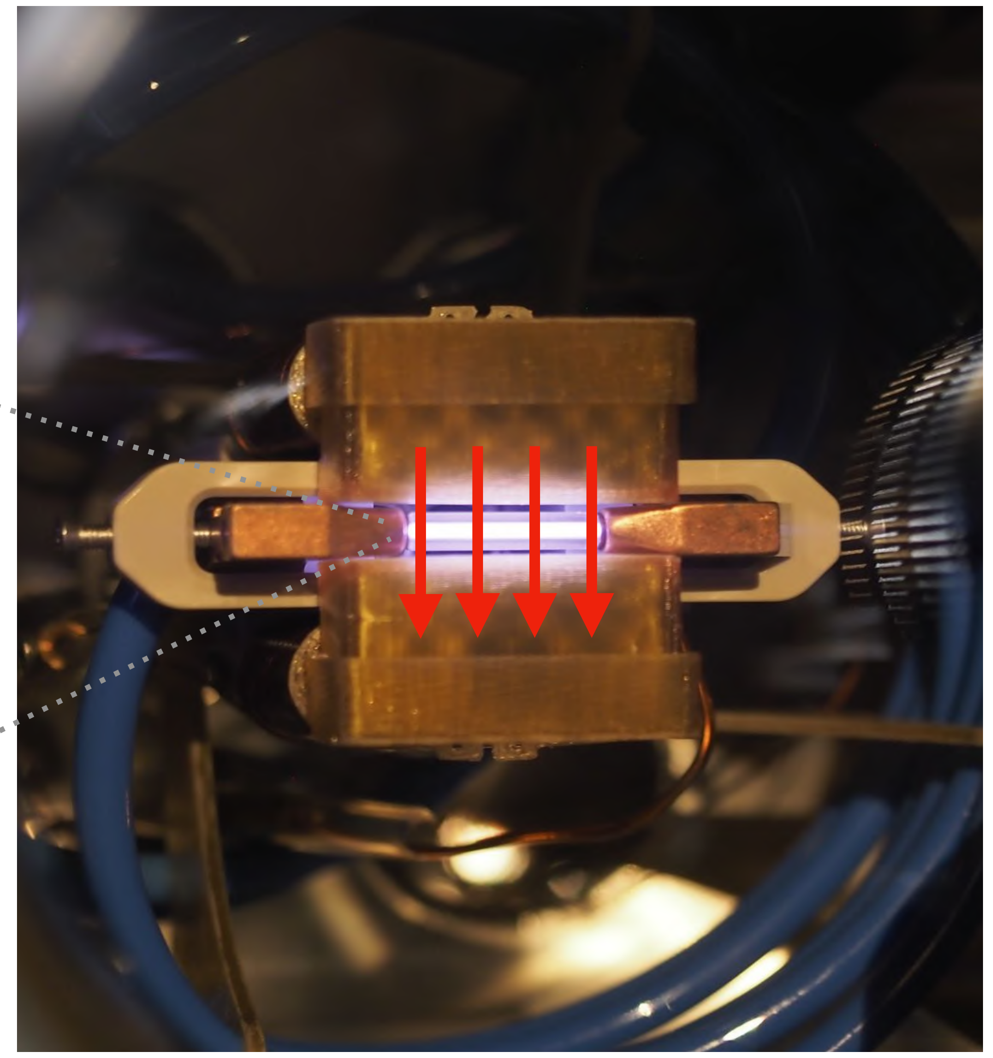


Source: P. Drobniak et al., Proc. IPAC (2025), p. 641





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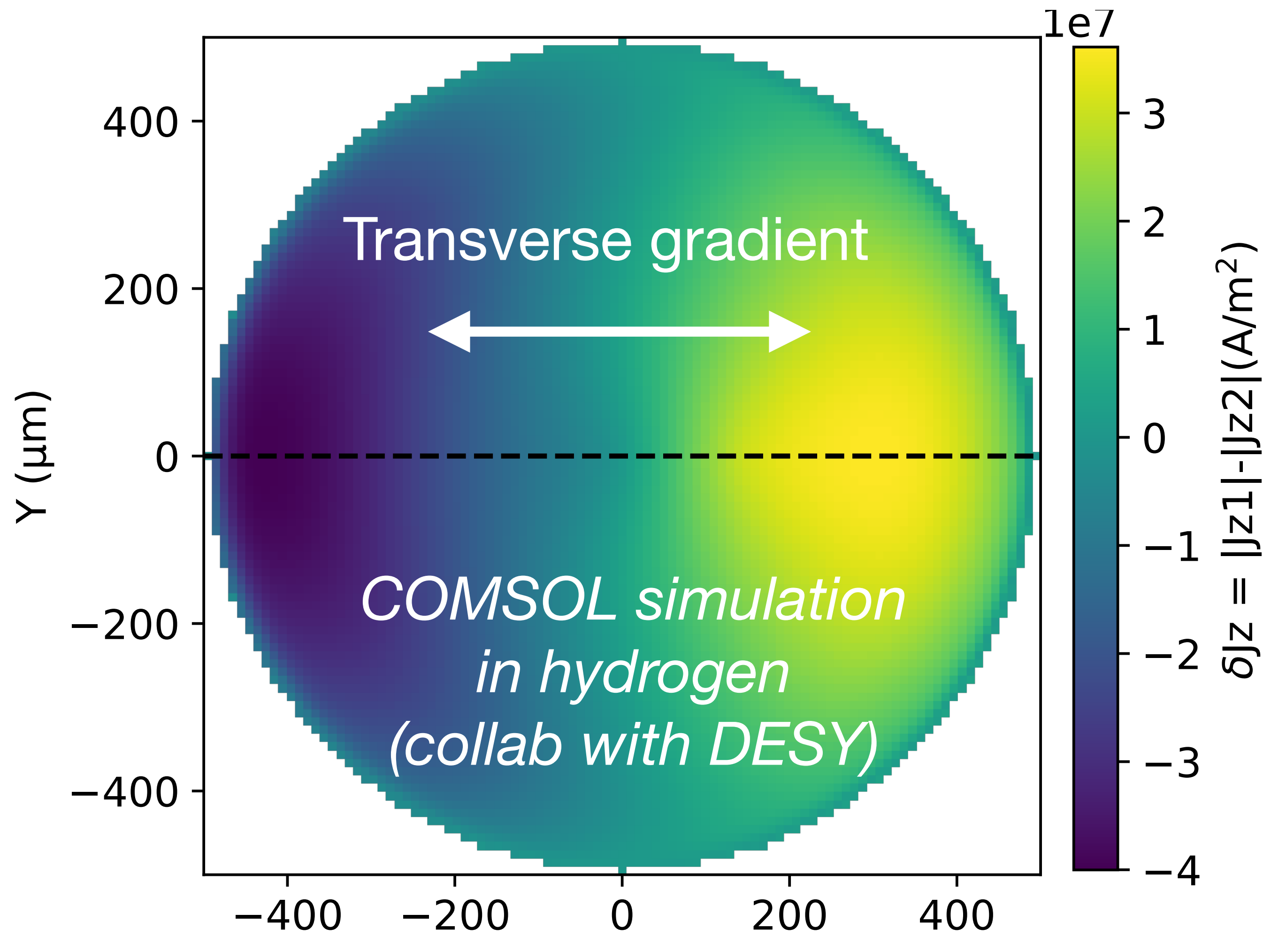

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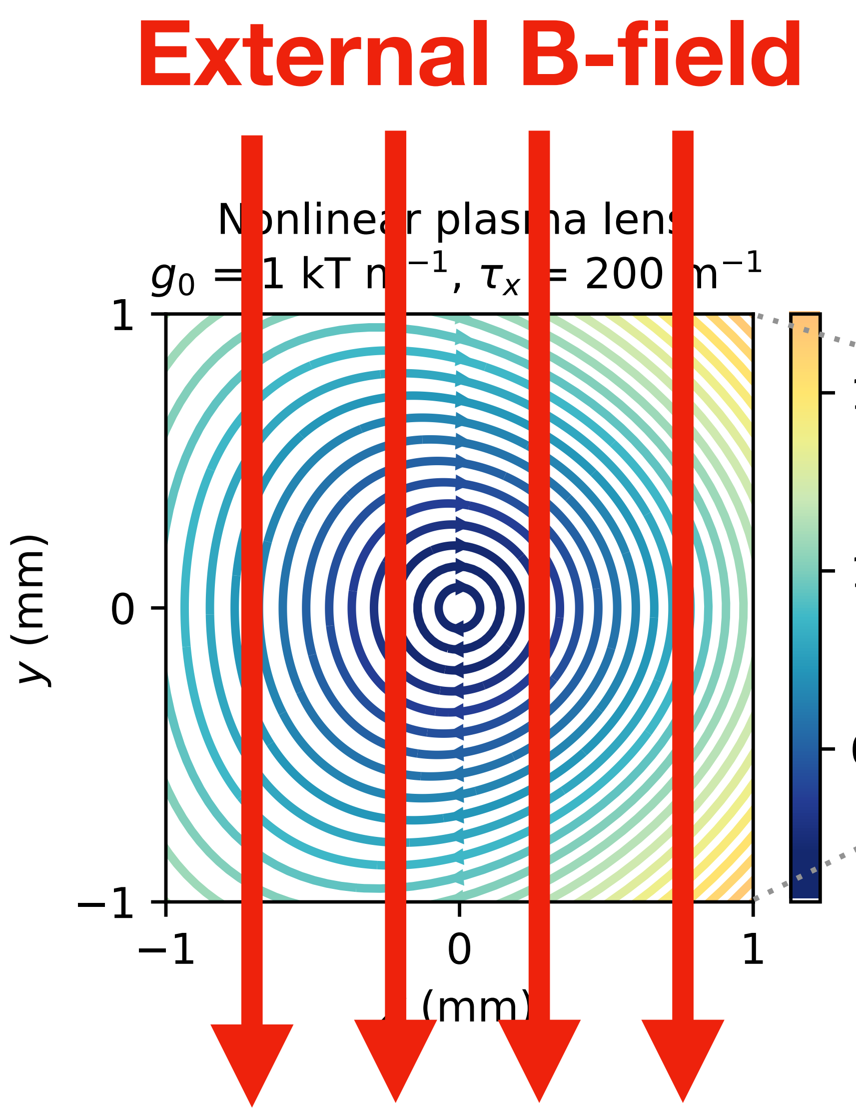

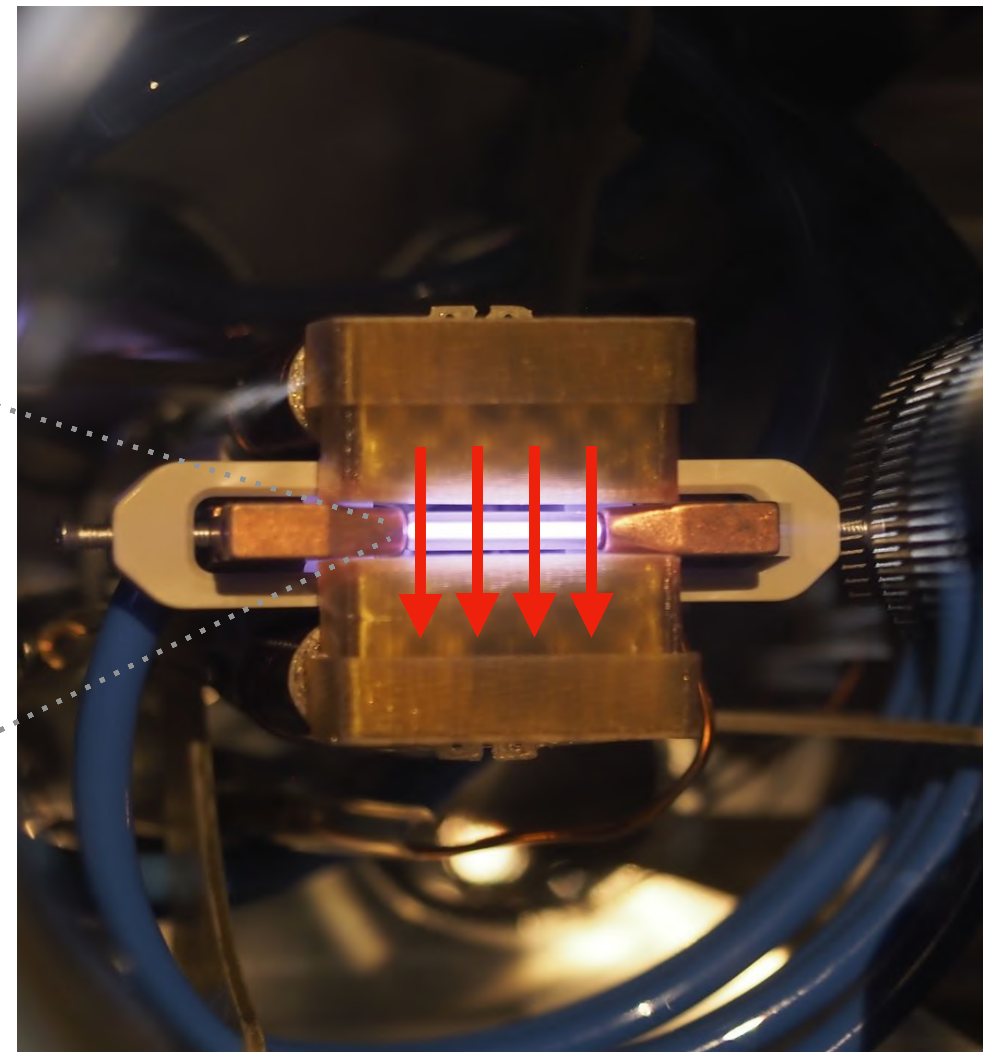

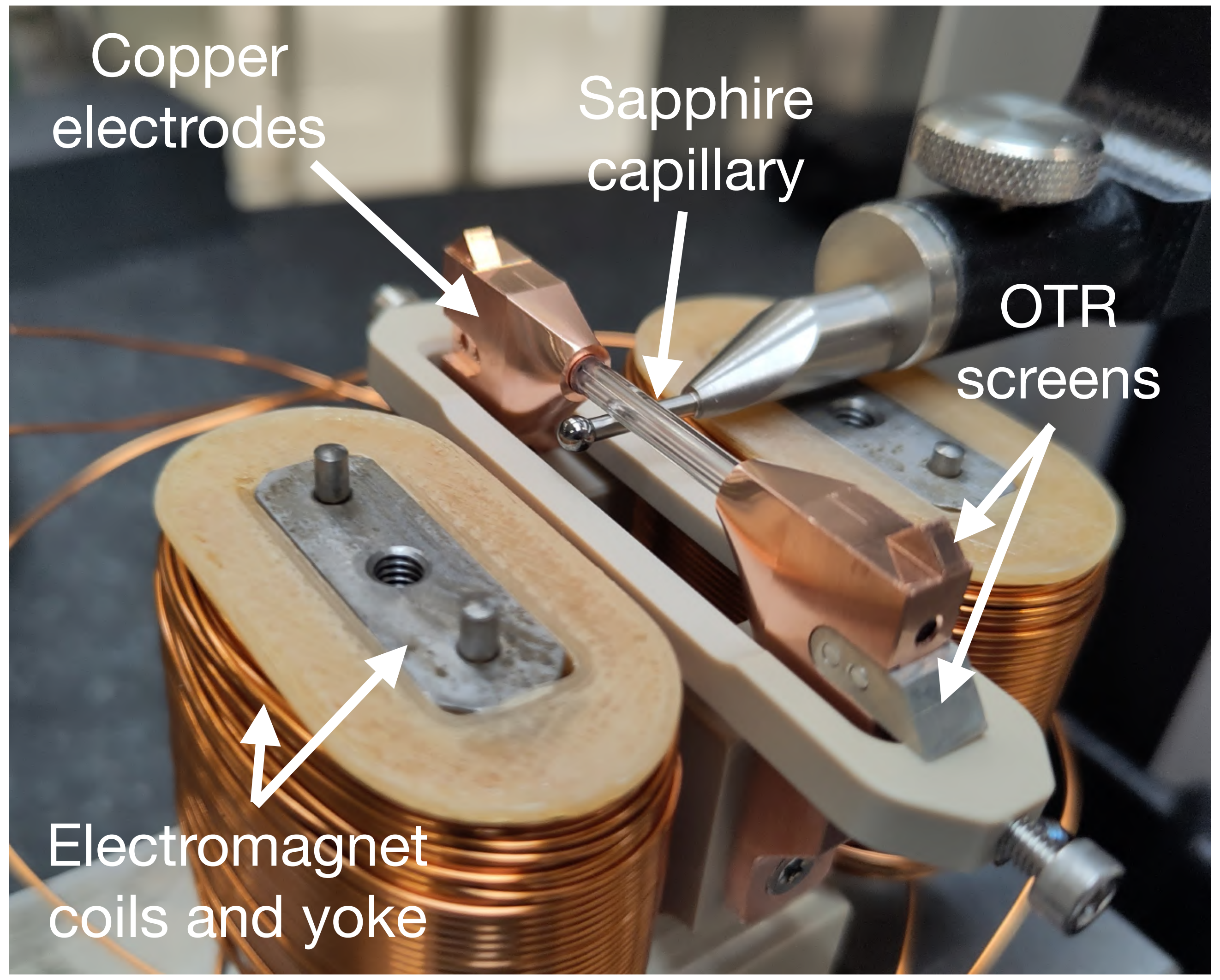

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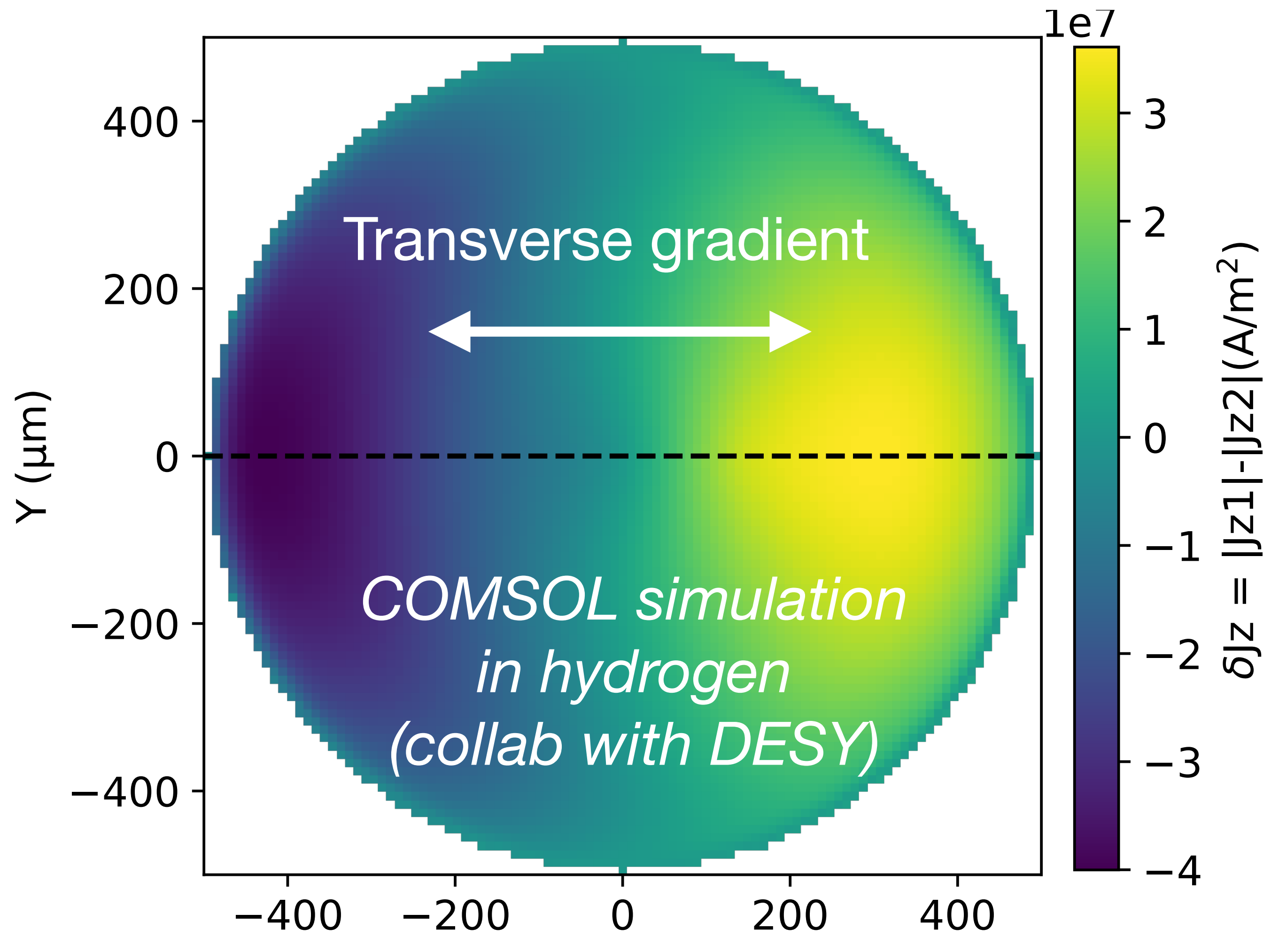
  - *Shifts the discharge current to one side*
- MHD simulations (COMSOL) indicates the principle works.
- Designed/manufactured at Uni. Oslo (P. Drobniak *et al.*).

SPARTA: Development of a nonlinear plasma lens

Exciting a nonlinearity through the Hall effect



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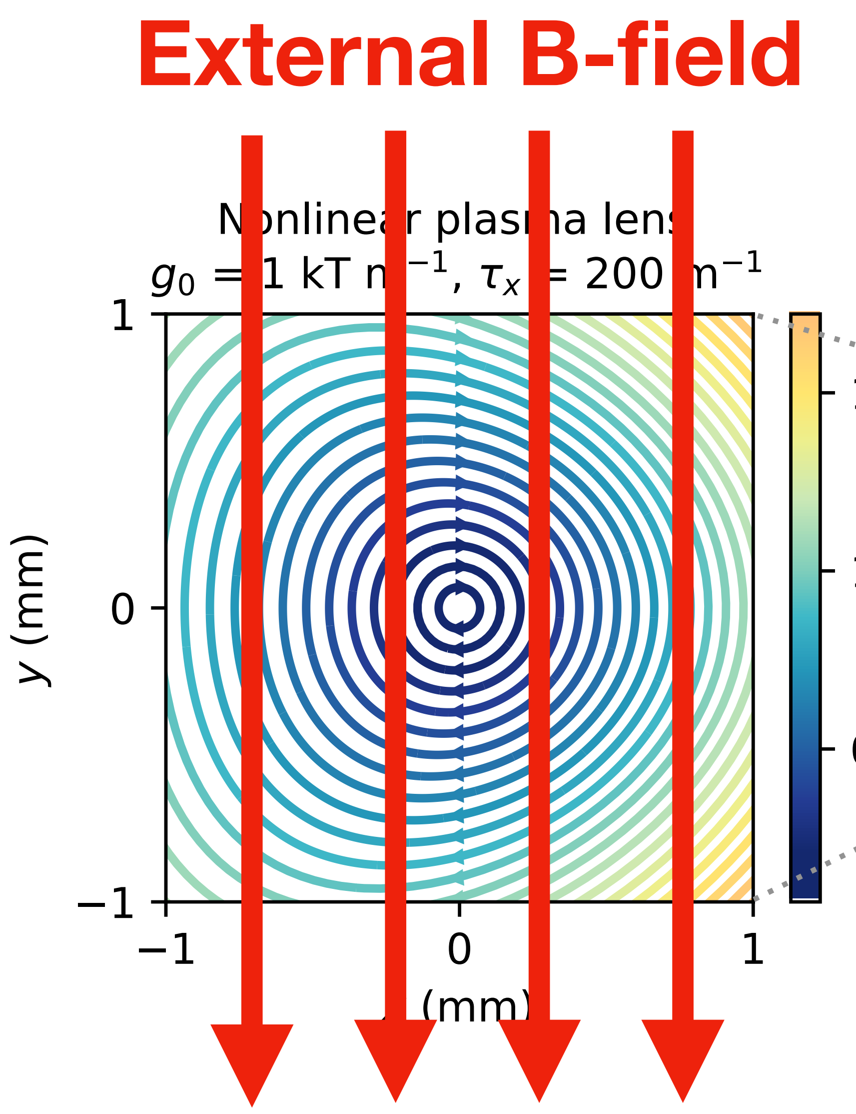
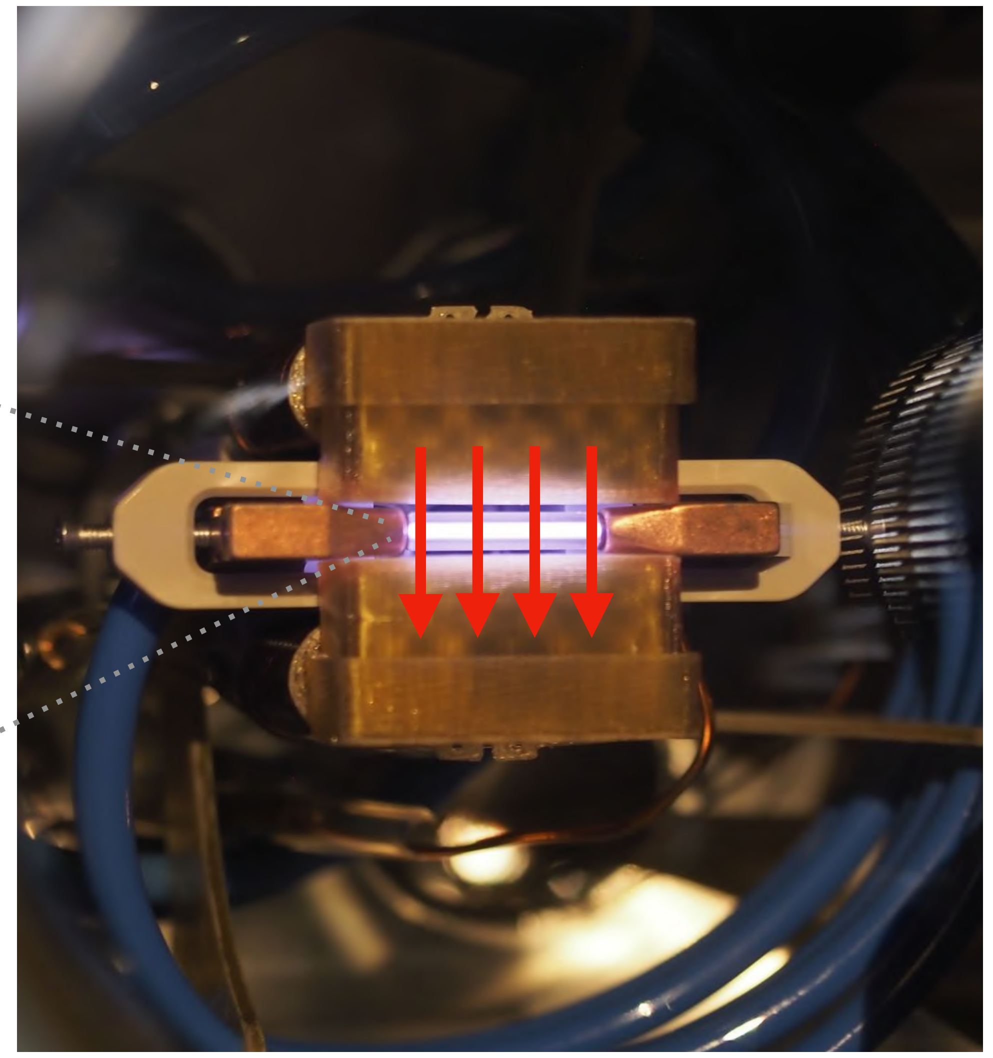
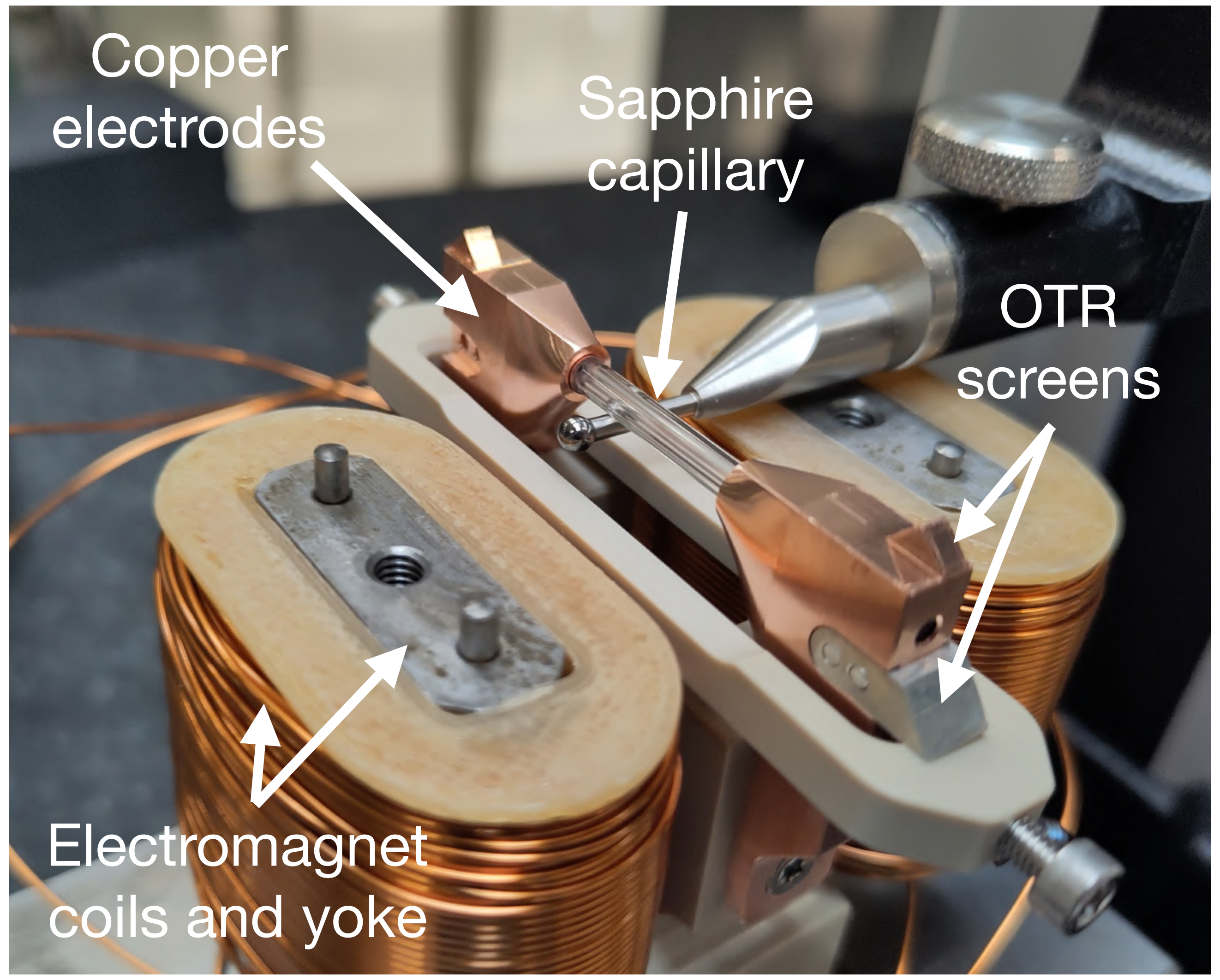
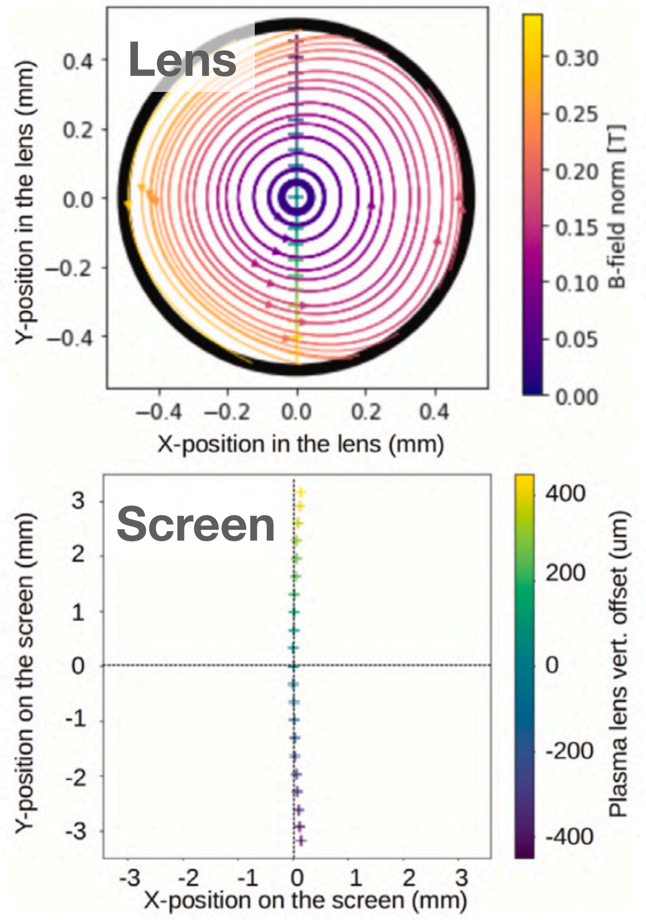
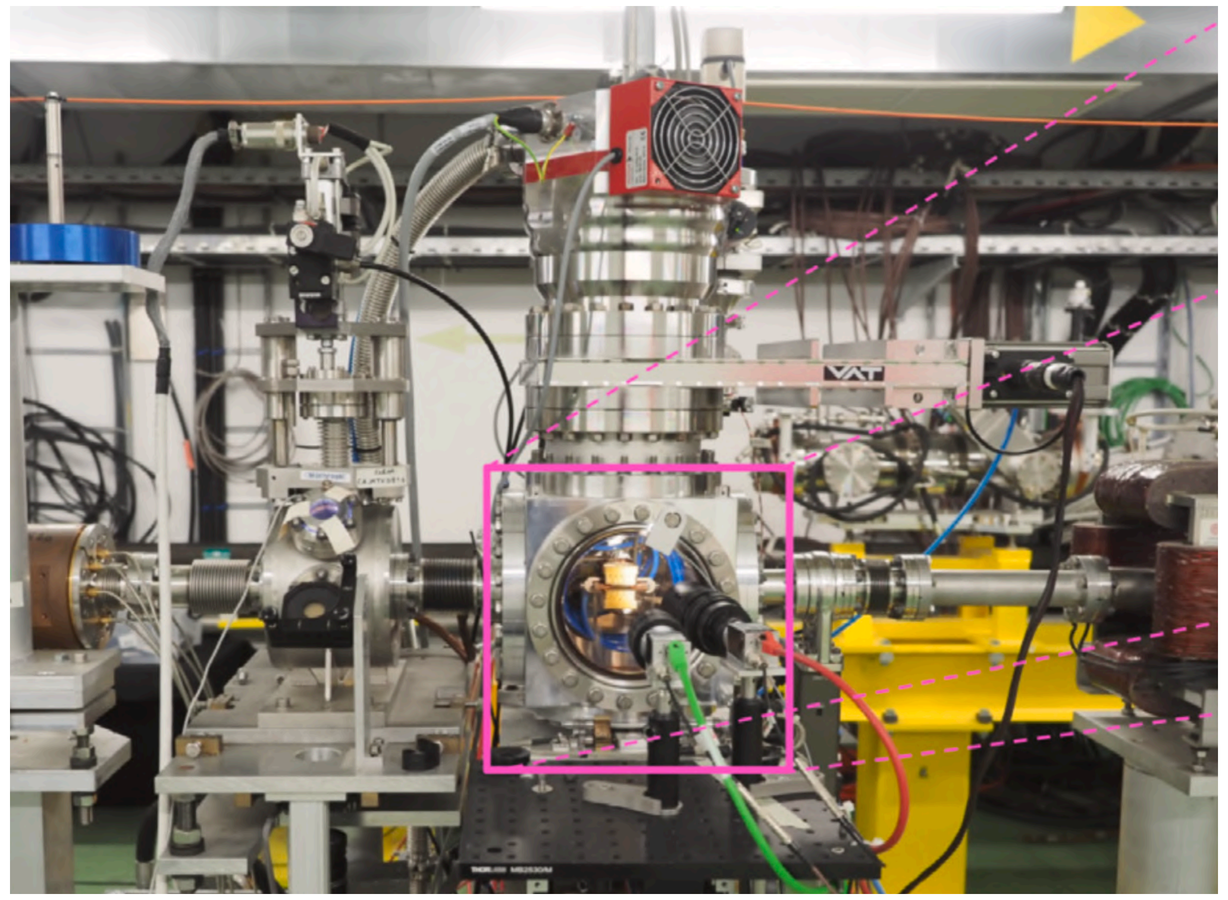






- Concept: apply an external B-field to induce Hall effect
  - *Shifts the discharge current to one side*
- MHD simulations (COMSOL) indicates the principle works.
- Designed/manufactured at Uni. Oslo (P. Drobniak *et al.*).
- Characterized with *e*-beam in CLEAR @ CERN (2024–2026).





P. Drobniak et al., NIM A 1072, 170223 (2025)

Radial vs. quadrupole focusing

$$g_{r,\text{quads}} \approx \frac{g_r}{10}$$

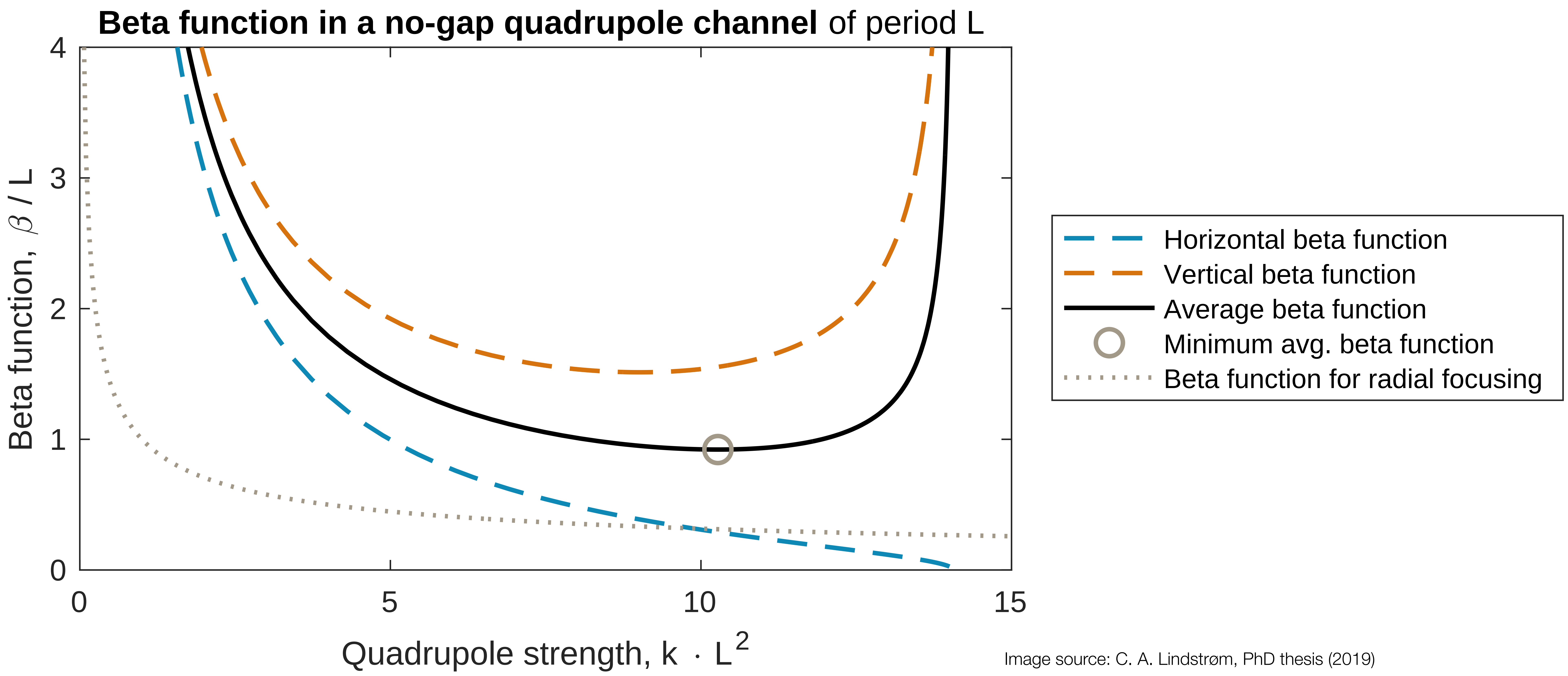


Image source: C. A. Lindstrøm, PhD thesis (2019)

Z-pinch

> **Current self-focuses due to strong B-fields** (magnetic pressure > "gas" pressure) — deforms uniform current

> Intensely studied in 1950s–60s as a path towards fusion (did not work out).

> Sets **limit to maximum current** (and therefore focusing gradient)

  > However, this effect takes some time to kick in:
  Example: 4 mbar argon, 500 μm radius, 5 A/ns ⇒ 200 ns

$$\tau_{\text{pinch}} \approx 1.5R \left(\frac{2\pi^2 n_0 A m_u}{\mu_0} \right)^{\frac{1}{4}} \left(\frac{dI}{dt} \right)^{-\frac{1}{2}}$$

> Being addressed in experiments at CLEAR

> Possible solution: Ultrafast current rise times (0-to-kA in ns or less)