UNIVERSITY OF OSLO

Plasma lenses for particle beams

A brief review

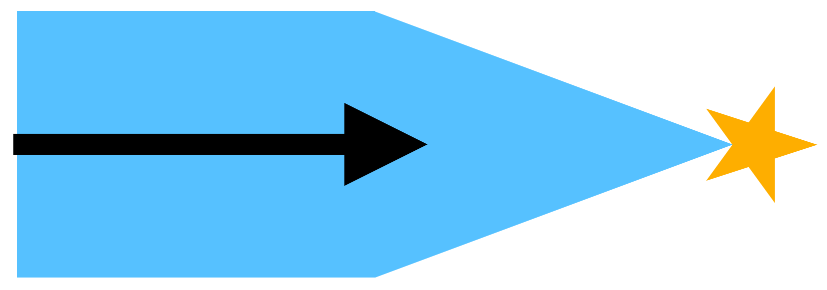
Carl A. Lindstrøm
Department of Physics, University of Oslo

11 Sep 2026 | IoP Workshop | London, UK

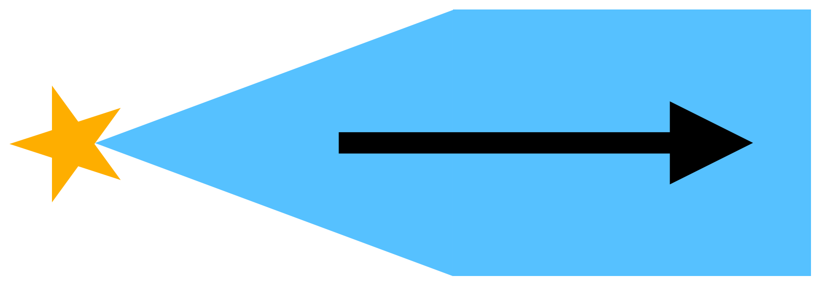
erc
SPARTA
ERC project
The Research Council of Norway

The motivation

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



> Others require capture/collimation of highly diverging beams
> (e.g., particle sources, plasma accelerators).



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

Transverse beam dynamics

Some background and definitions

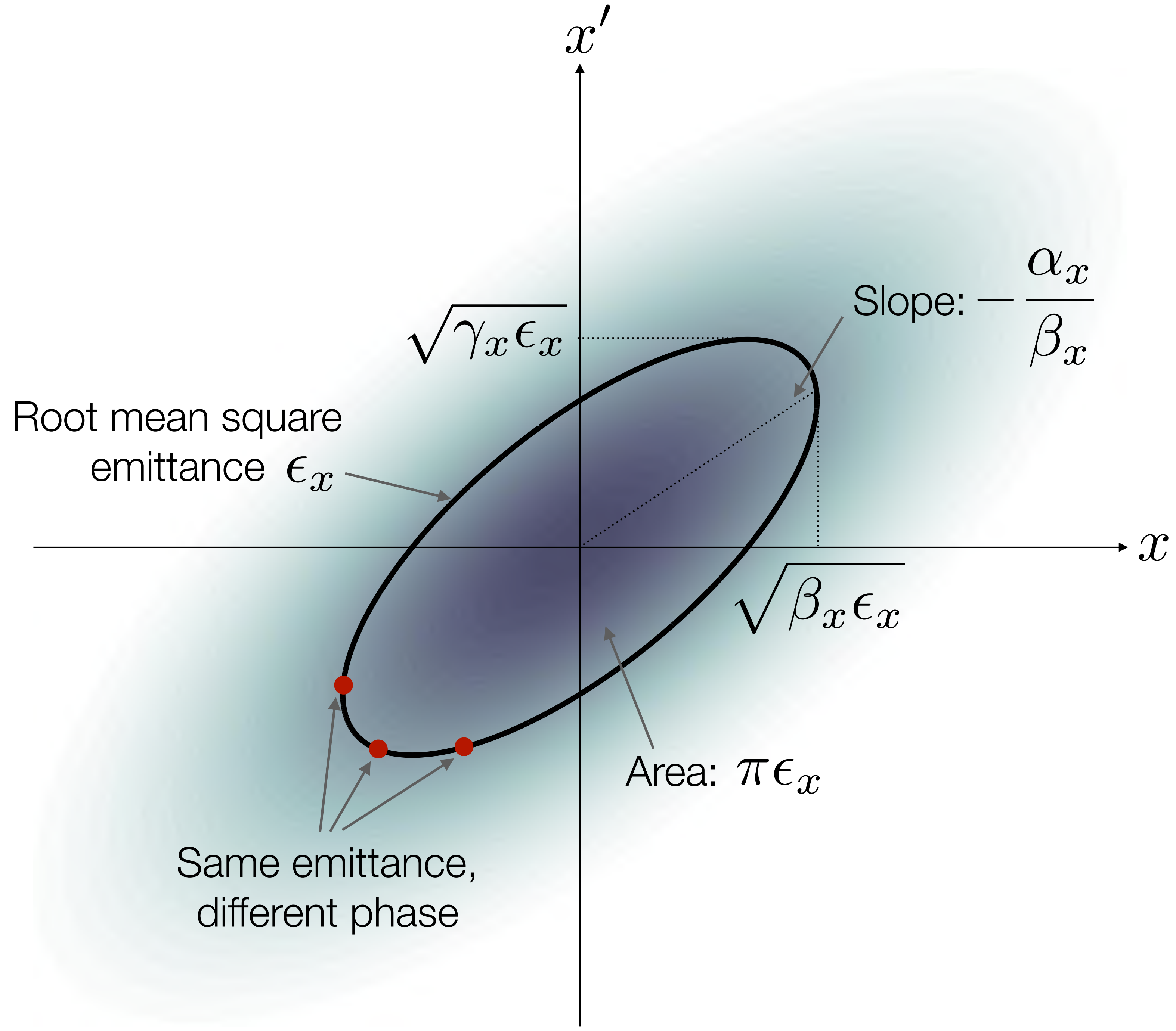
> Transverse phase space (x, p_x/mc)

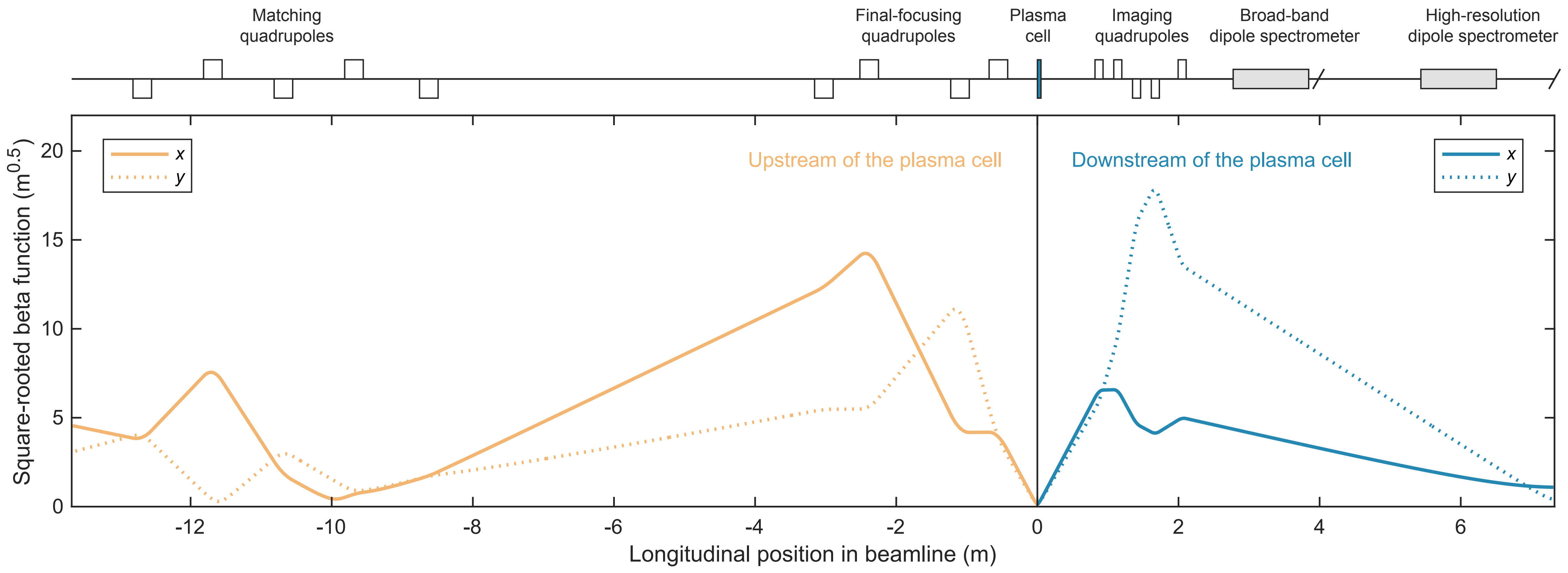
> **Emittance** = "transverse beam quality" or "focusability" = area in phase space (invariant)

> **Twiss parameters** quantify the shape in phase space

> The evolution is determined by the Twiss parameters and the **optical elements** (but is independent of emittance)

> How do we manipulate particles in transverse phase space?

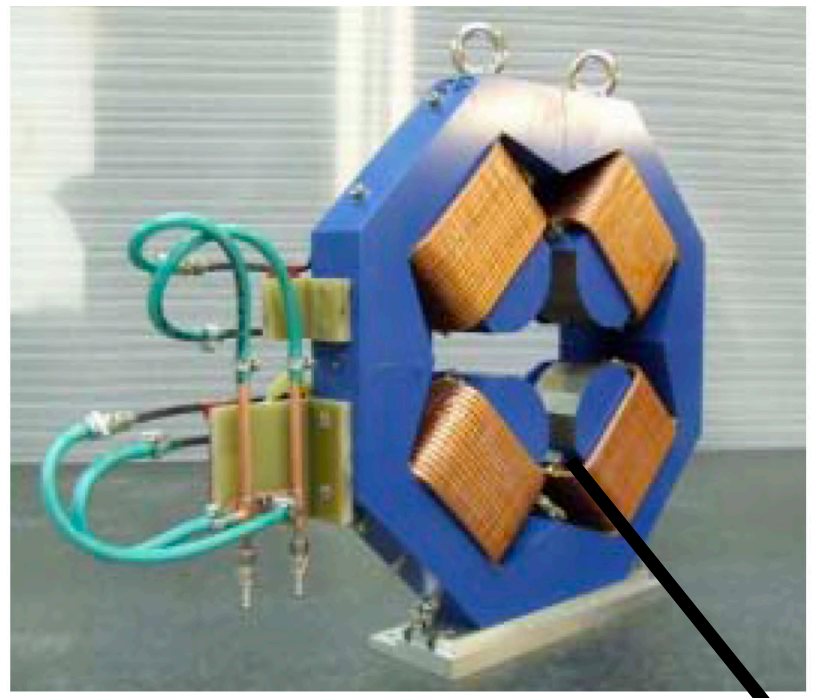


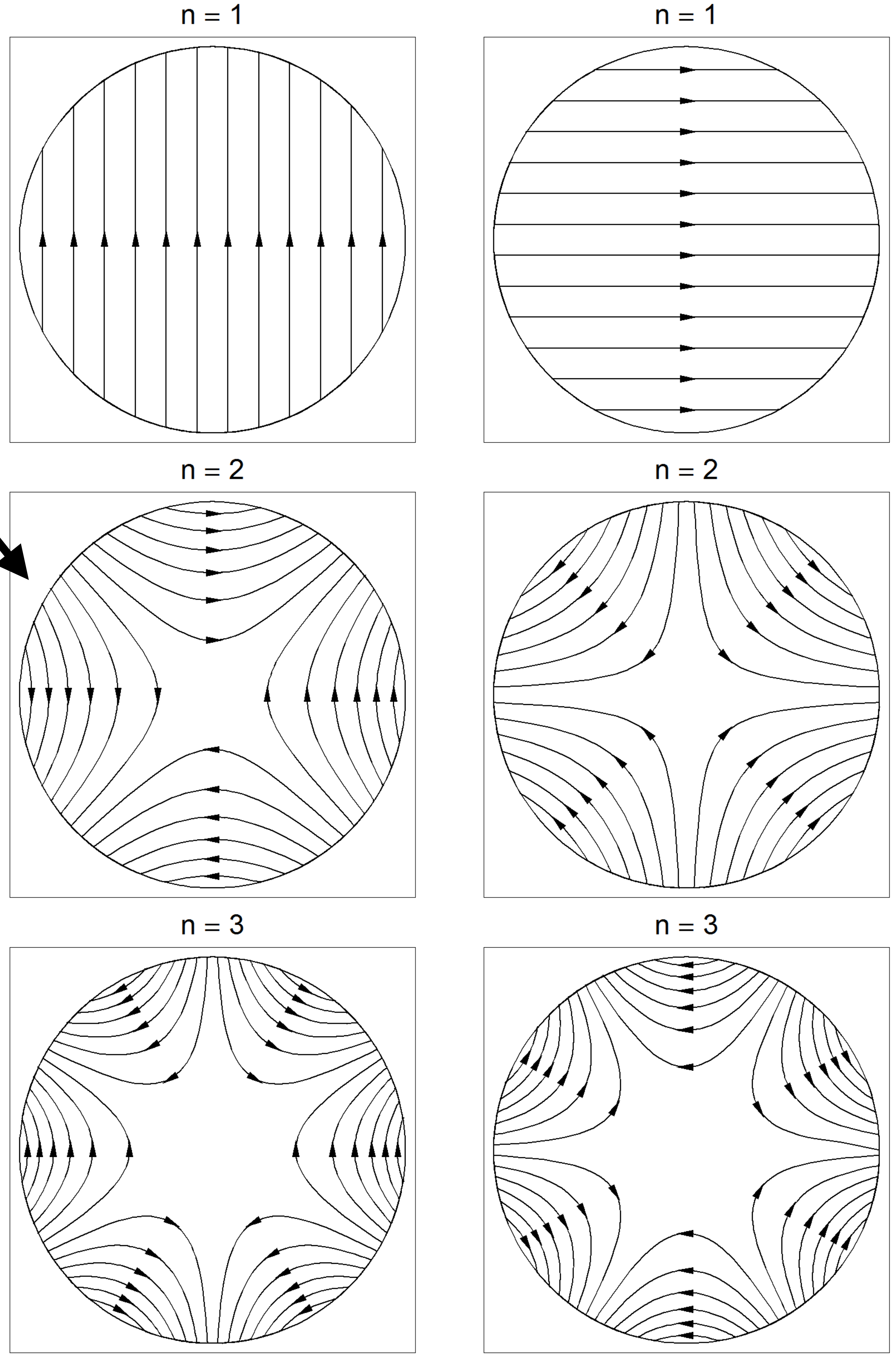


From Lindstrøm et al., Nat. Commun. 15,, 6097 (2024)

Magnetic optics elements

The traditional choice for high-energy particles





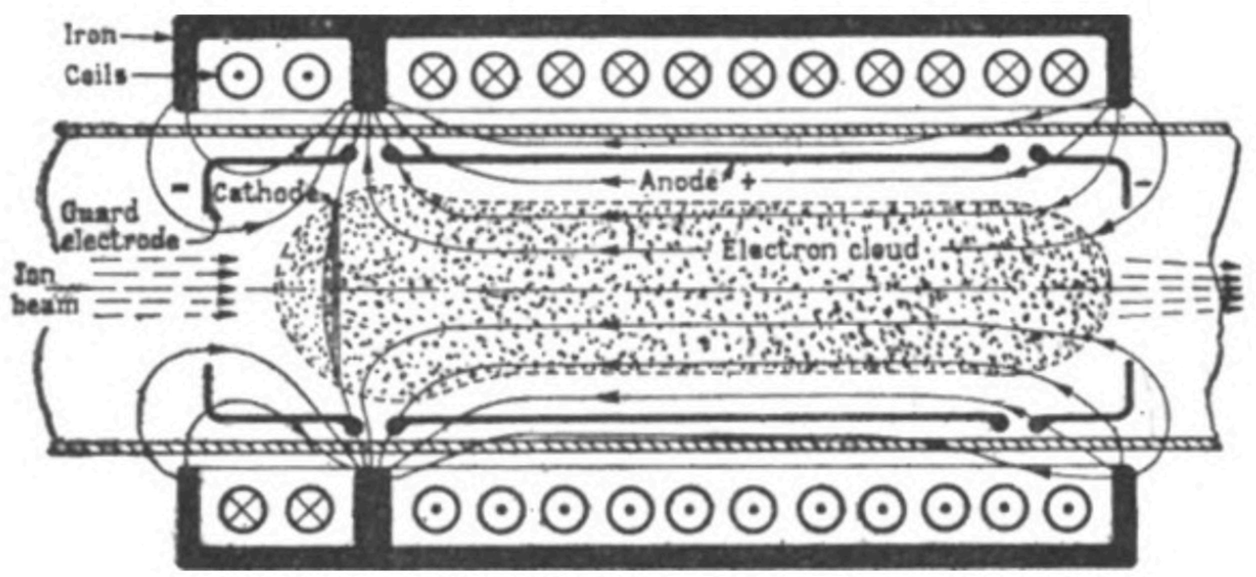
From Wolski (2019), arXiv:1103.0713

- Dipoles
  - *For bending the orbit*
- **Quadrupoles**
  - ***For focusing (focuses/defocuses in x/y planes)***
- Sextupoles
  - *For chromatic correction*
- Limited in field (typically by the pole-tip field)
  - 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

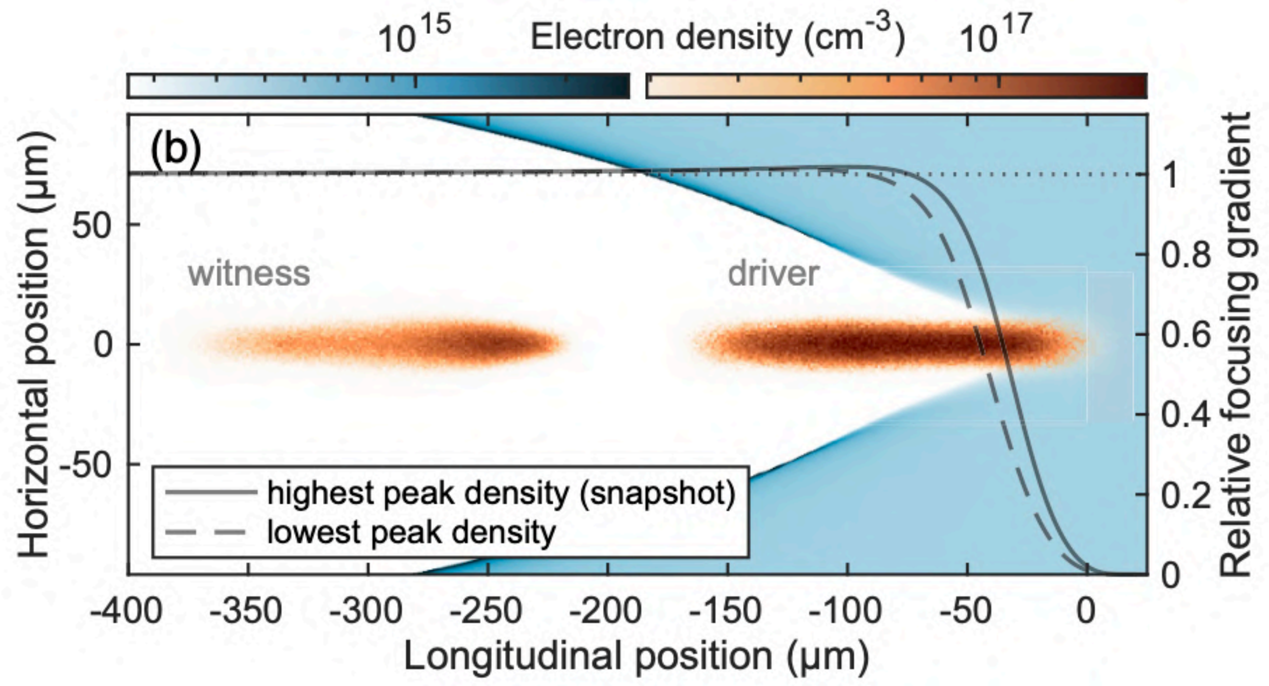
Achieving radial focusing

Focusing in both transverse planes at the same time

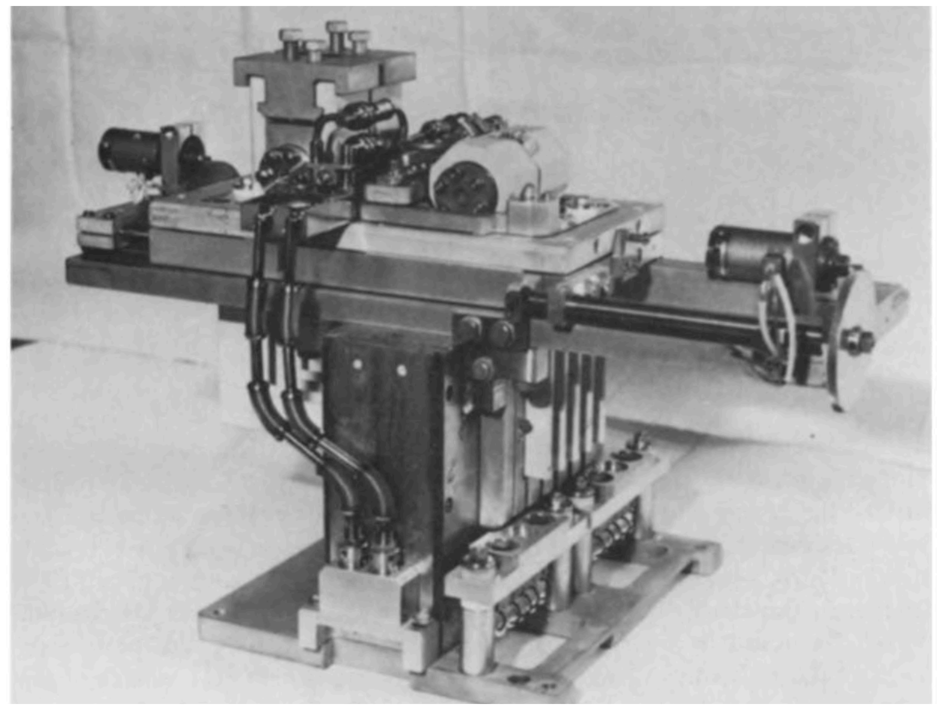
- Only two fields can radially focus a beam: E_r *and* B_ϕ
  - *Radial focusing "worth" ~10x in focusing strength.*
- Electrostatic lenses (E_r) require on-axis charge:
  - Can use an electron cloud (Gabor lenses),
    — *Low charge density*
  - Use a short plasma accelerator! (Passive plasma lens)
    — *Very strong (MT/m), but needs a driver to be uniform*
- Magnetic lenses (B_ϕ) require on-axis current:
  - Can use a metal (Lithium lenses),
    – *Problem with scattering*
  - **Use the plasma as a conductor! (Active plasma lens)**



Gabor, Nature 160, 89 (1947)



Björklund Svensson, PRR (2026)



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

Active plasma lenses (APLs)

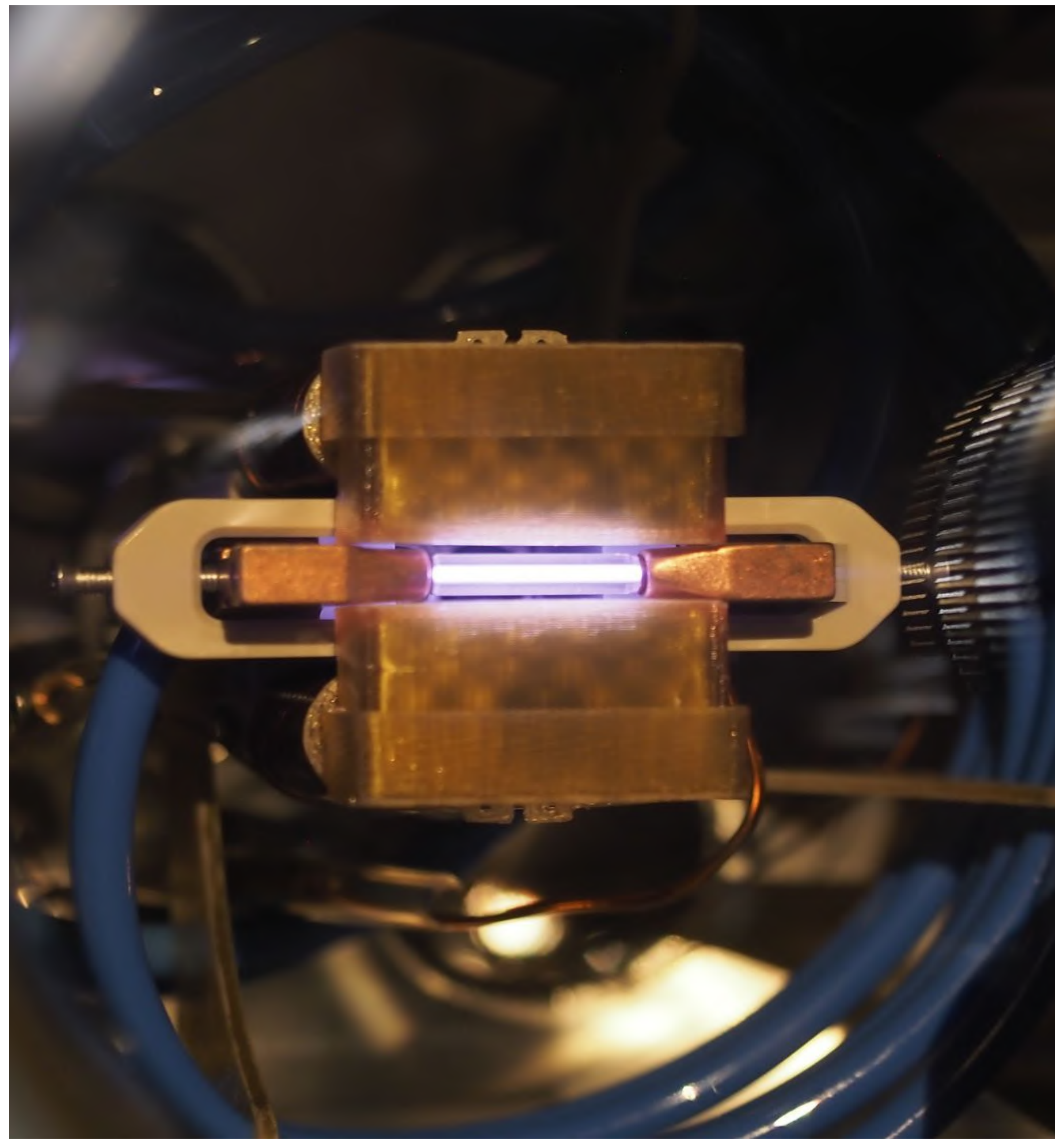
How do they work?

Focusing gradient:

$$g_r = \frac{\mu_0 I}{2\pi R^2}$$

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

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



The Oslo plasma lens design

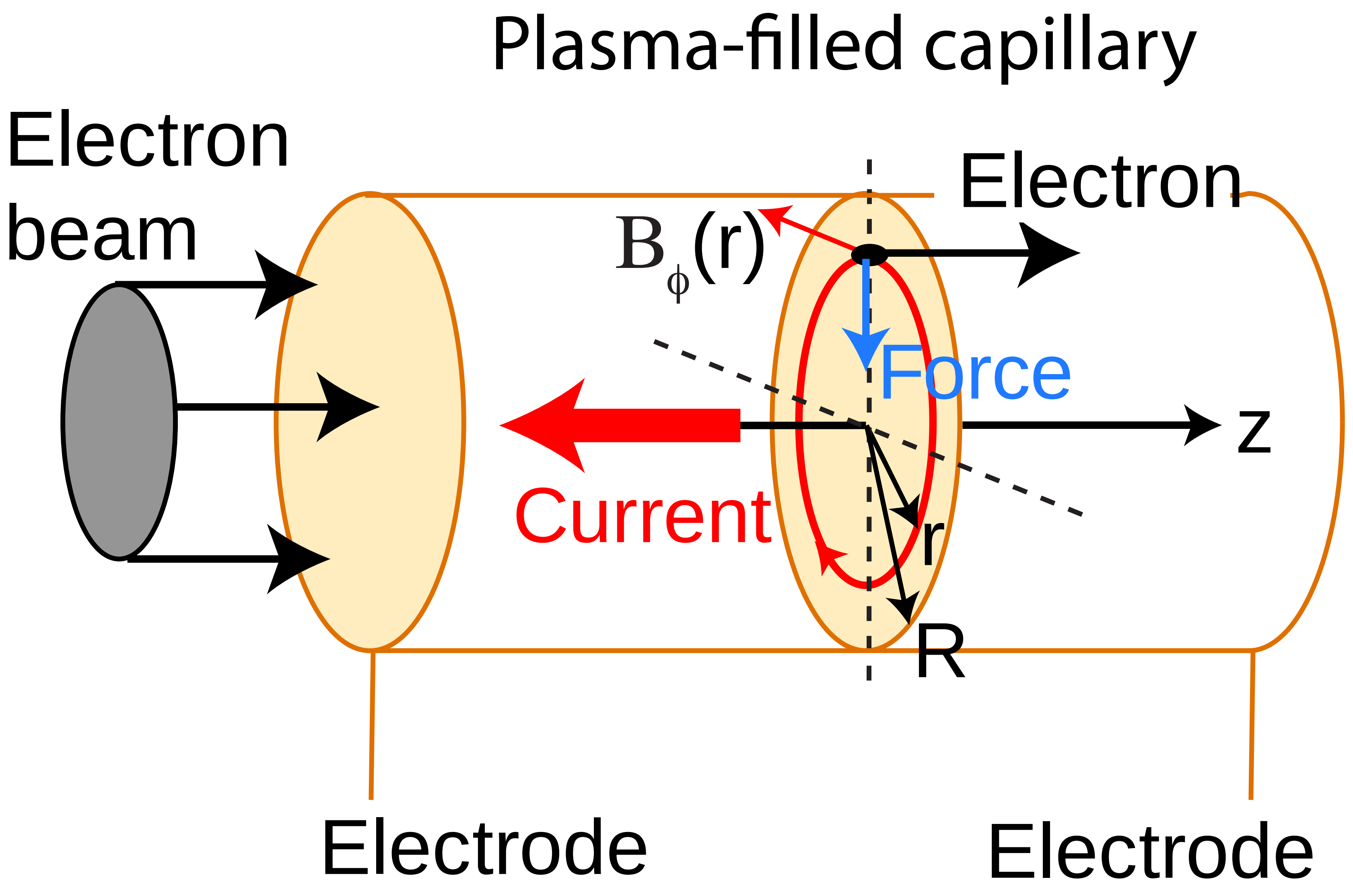
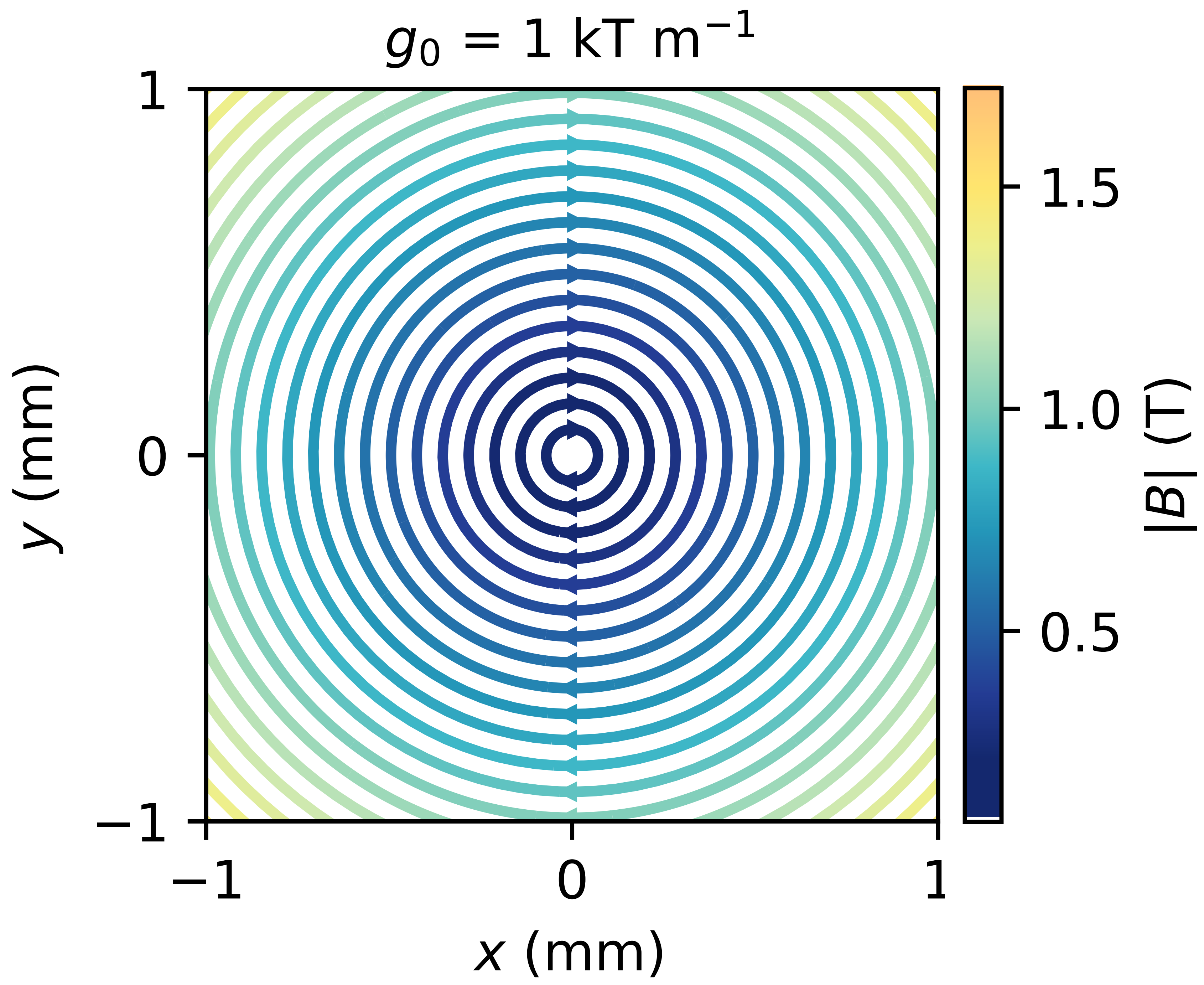


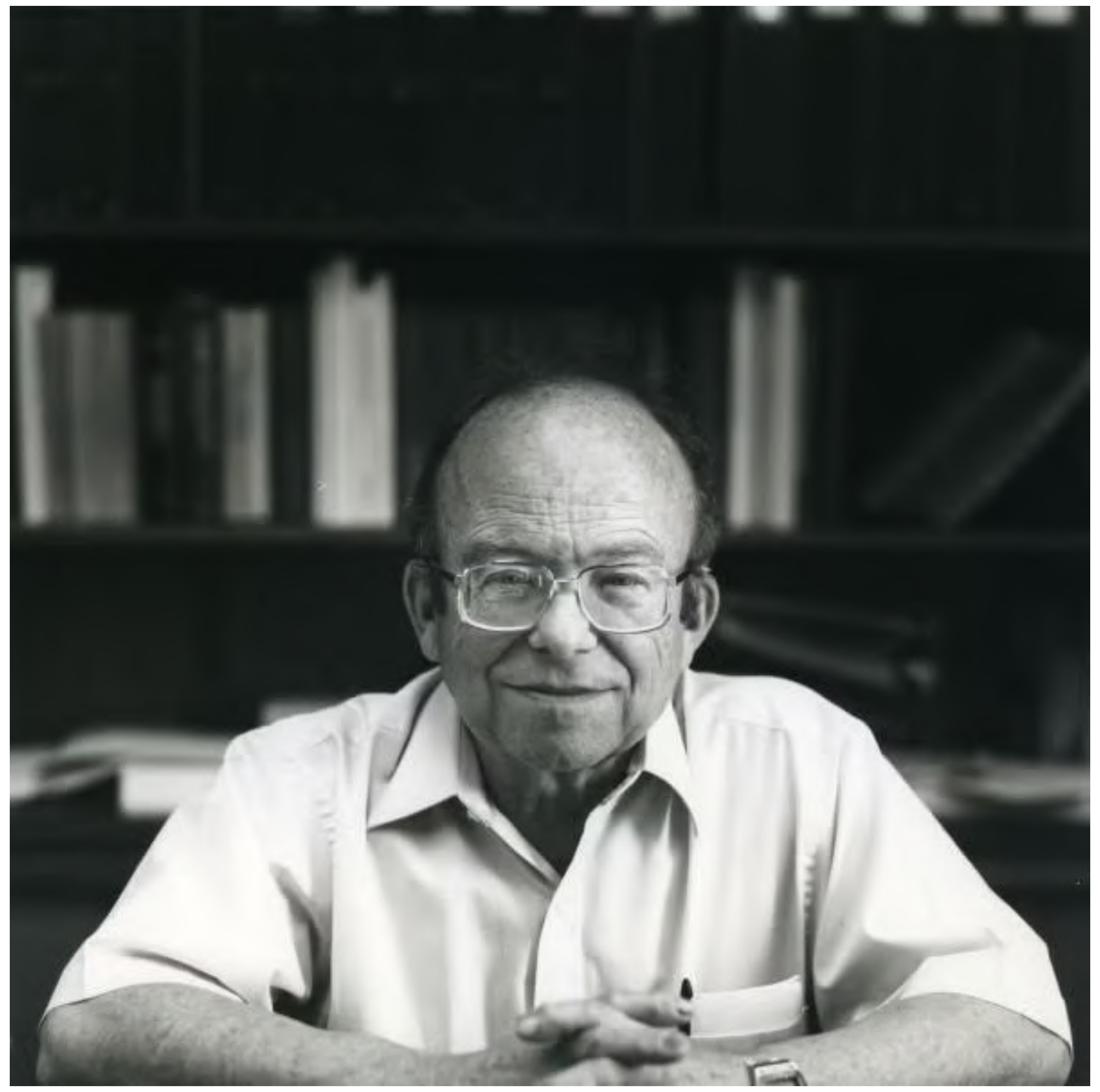
Image source: van Tilborg et al., Phys. Rev. Lett. 115, 184802 (2015).



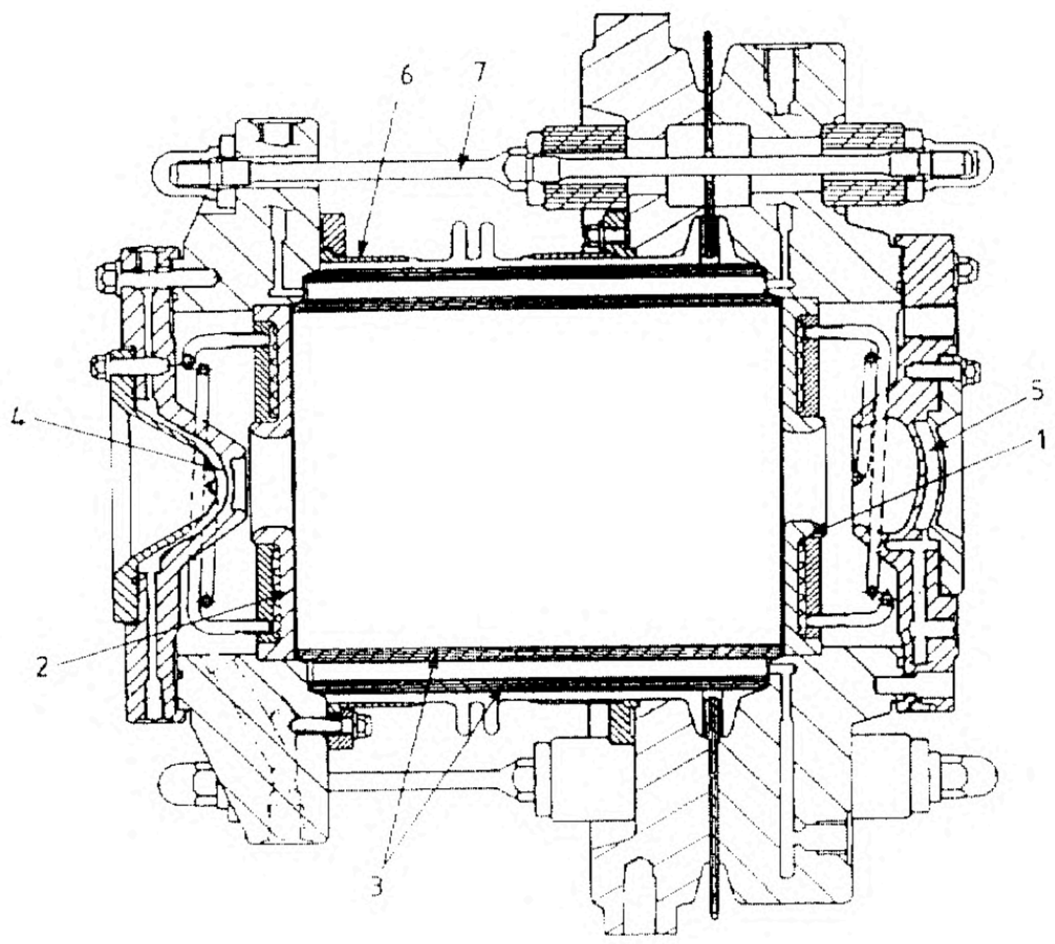
History of active plasma lenses

More than 75 years of plasma lensing

- **1950: Panofsky and Baker** – "arc lens" for proton beams from the 184-inch cyclotron at the Berkeley Rad Lab.
- **1965: Forsyth *et al.*** use a "z-pinch" plasma lens to increase neutrino yield from protons at Brookhaven National Lab
- **1990s: Le Dallic/Kowalewicz *et al.*** develop a plasma lens for antiproton capture at CERN
- **1990s: Boggasch and Stetter *et al.*** develop a "wall-stabilized" lens for heavy-ion beams at UNILAC at GSI
- **1992: Braun *et al.*** proposes using plasma lenses for positron capture (2x higher bandwidth than solenoids)



Wolfgang Panofsky, SLAC Director

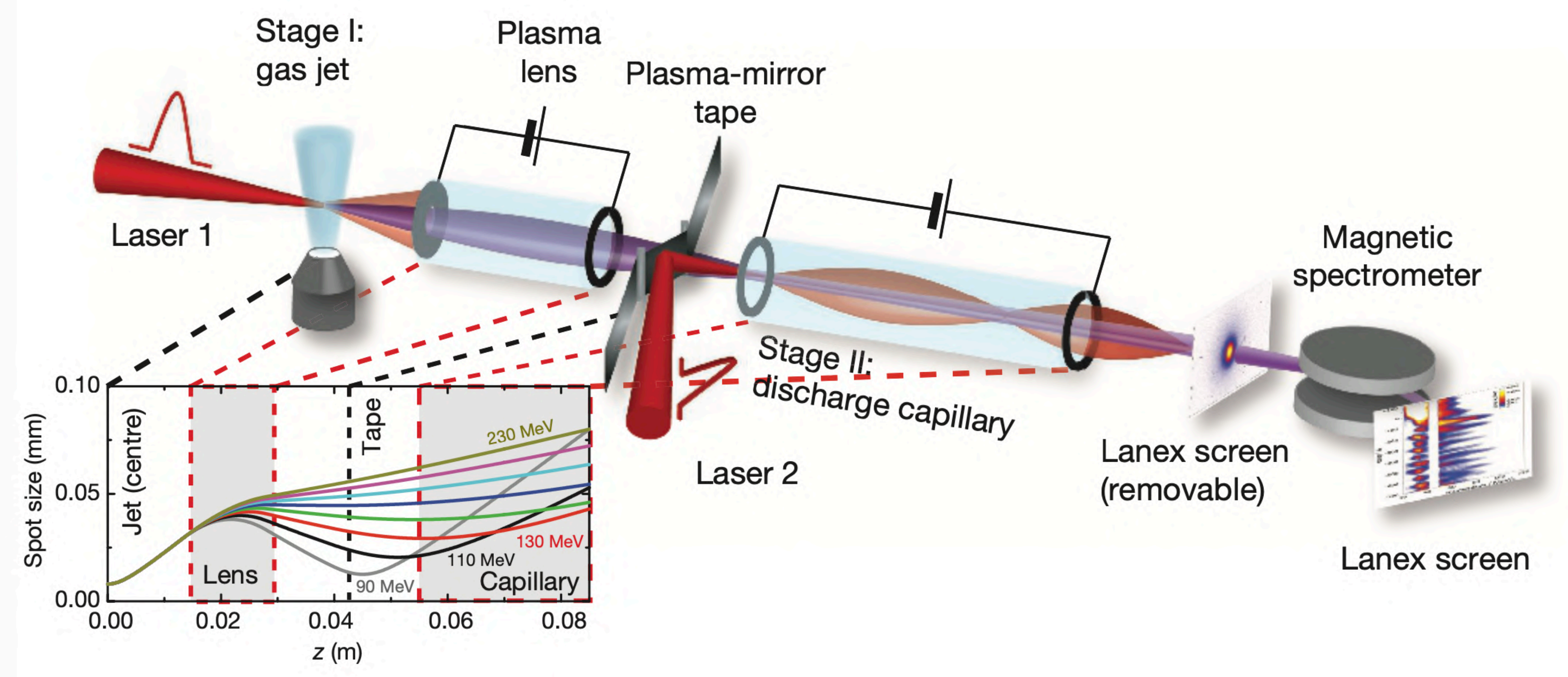


Le Dallic, Proc. EPAC 1990, p. 343

APL revival and modern use with electrons

The Berkeley Lab strikes again

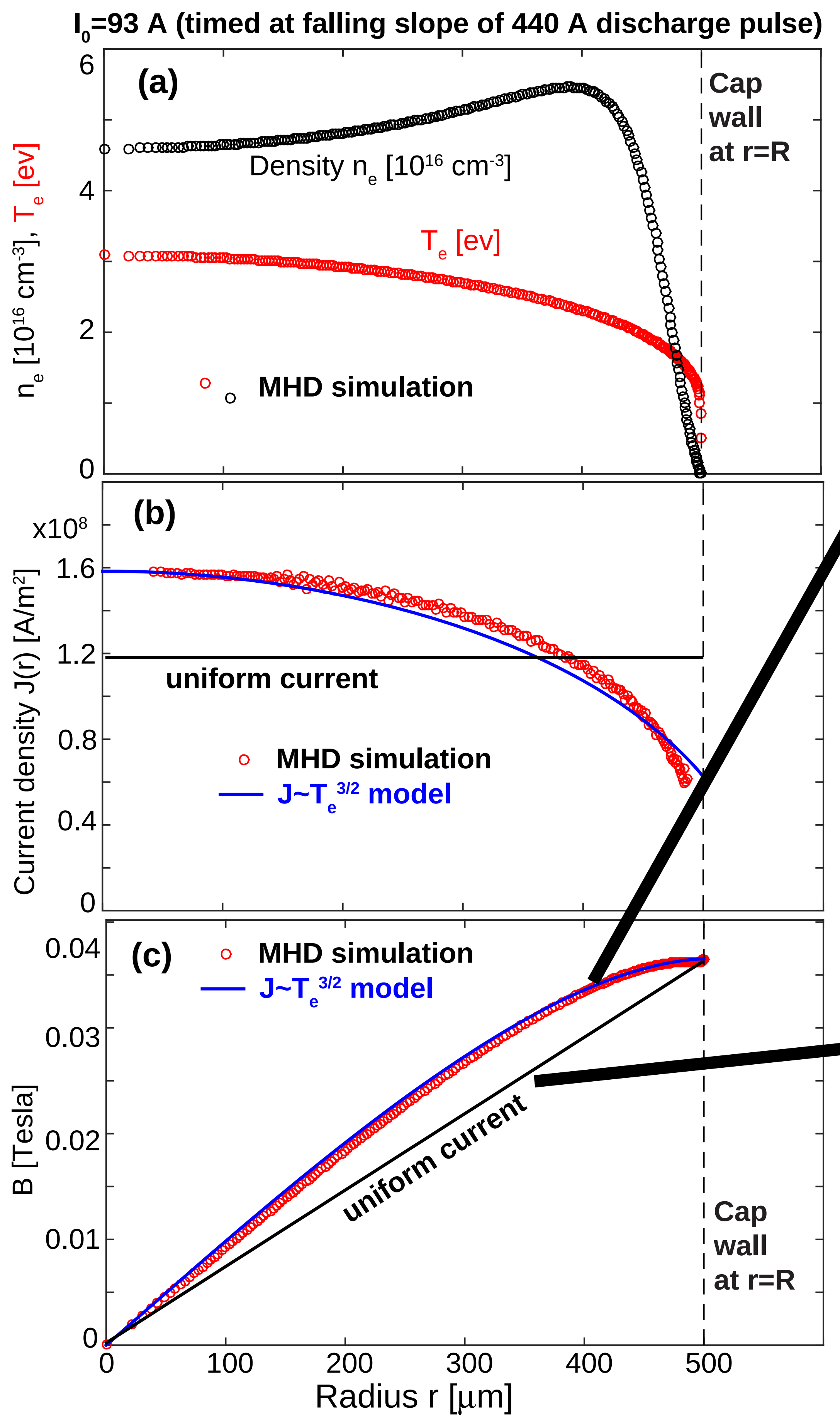
- In 2015, van Tilborg *et al.* brought it back to life
  - ***Reached field gradient of ~3.6 kT/m*** *(~100x stronger than typical quadrupoles)*
  - *Enabled the first plasma-accelerator staging experiment*
- Several other experiments followed:
  - *CLEAR at CERN (by Uni. Oslo et al.)*
  - *MAMI at Mainz (by DESY et al.)*
  - *SPARC_LAB at INFN*



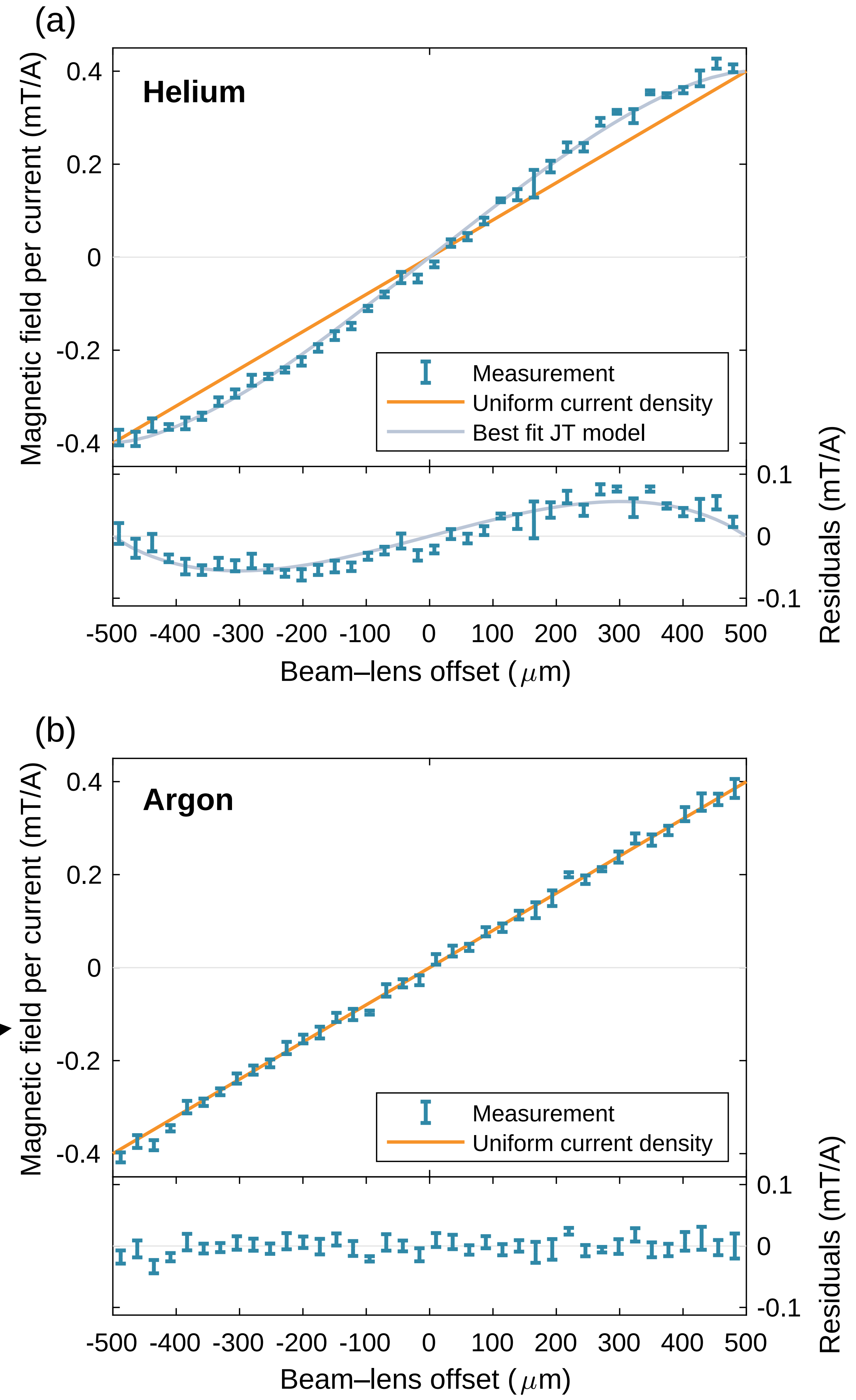
Steinke et al., Nature 530, 190 (2016)

Spherical aberrations and emittance preservation

- Found spherical aberration to be an issue
  - *Caused by wall cooling*
  - *Modeled by Bobrova et al. (JT model)*
- Solved by changing to heavy gas (Ar)
  - *Linear focusing (preserves emittance)*
  - *Emittance preservation demonstrated in an experiment at CLEAR, CERN*
- Beam–gas scattering can however be an issue for heavy gases ($\Delta\varepsilon_n \sim Z^2$)
- Wakefields (passive plasma lensing) can also cause emittance growth



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

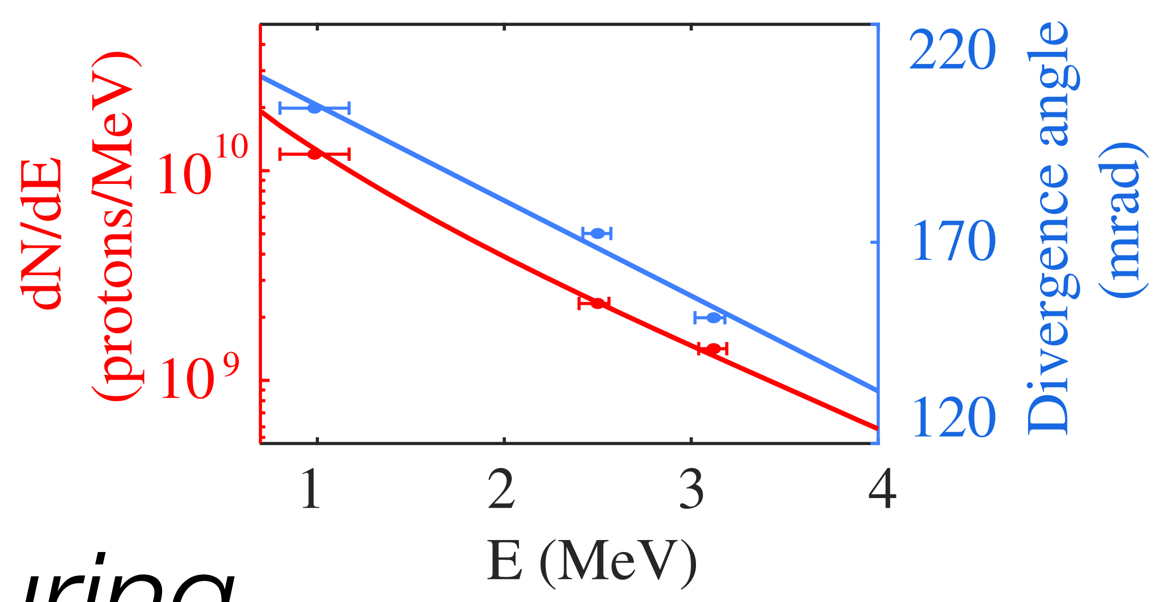


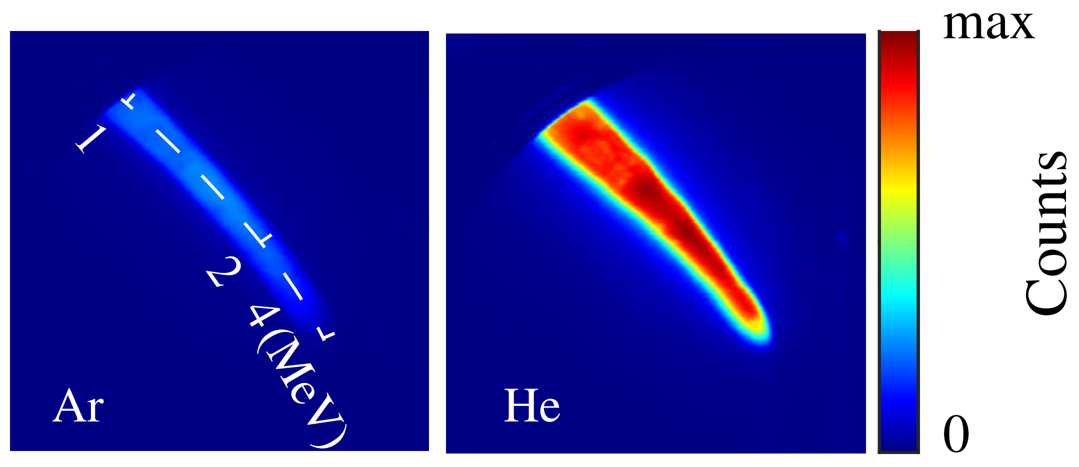
Lindstrøm et al., PRL 121, 194801 (2018)

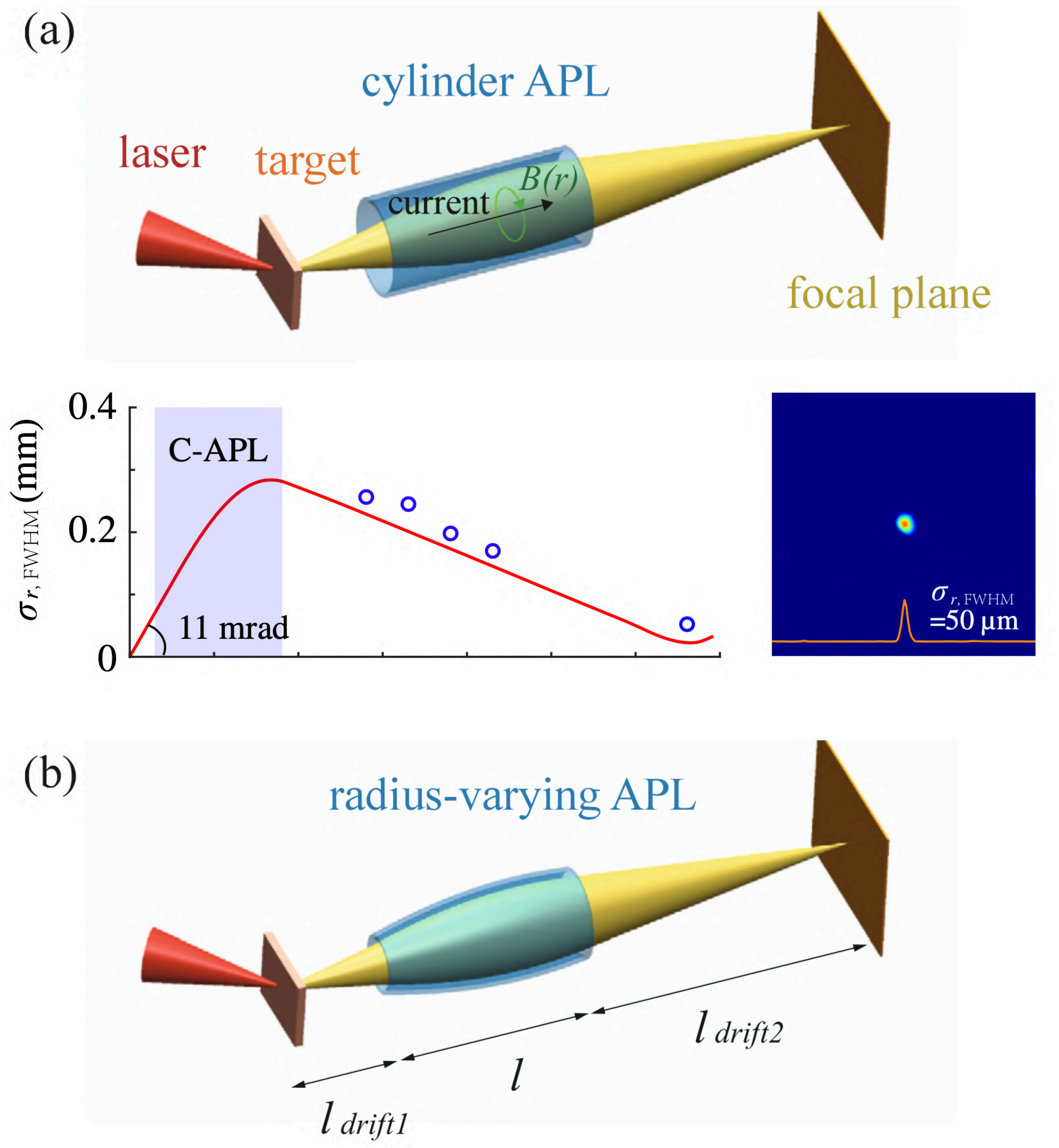
Use with laser–proton beams

Recent progress in China

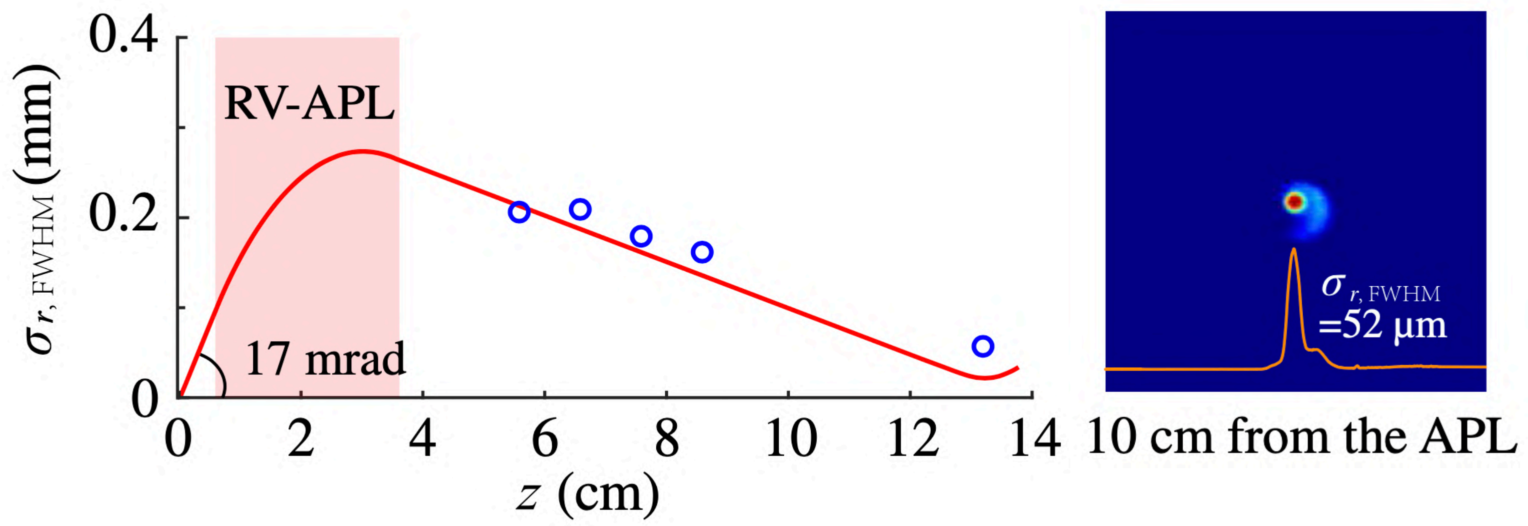
- Laser–protons have high energy spread and divergence
- Yan *et al.* (CLAPA, Peking University, China) have recently applied APLs to this problem:
  - *Experiment using laser–proton beams (TNSA; up to 3.5 MeV)*
  - *Used a radius-varying lens, capturing ~50% higher divergences (~2x more charge) compared to a constant-radius lens*
  - *Observed scattering from using heavy gases (Ar vs. He): beam density dropped by 3x for Ar.*







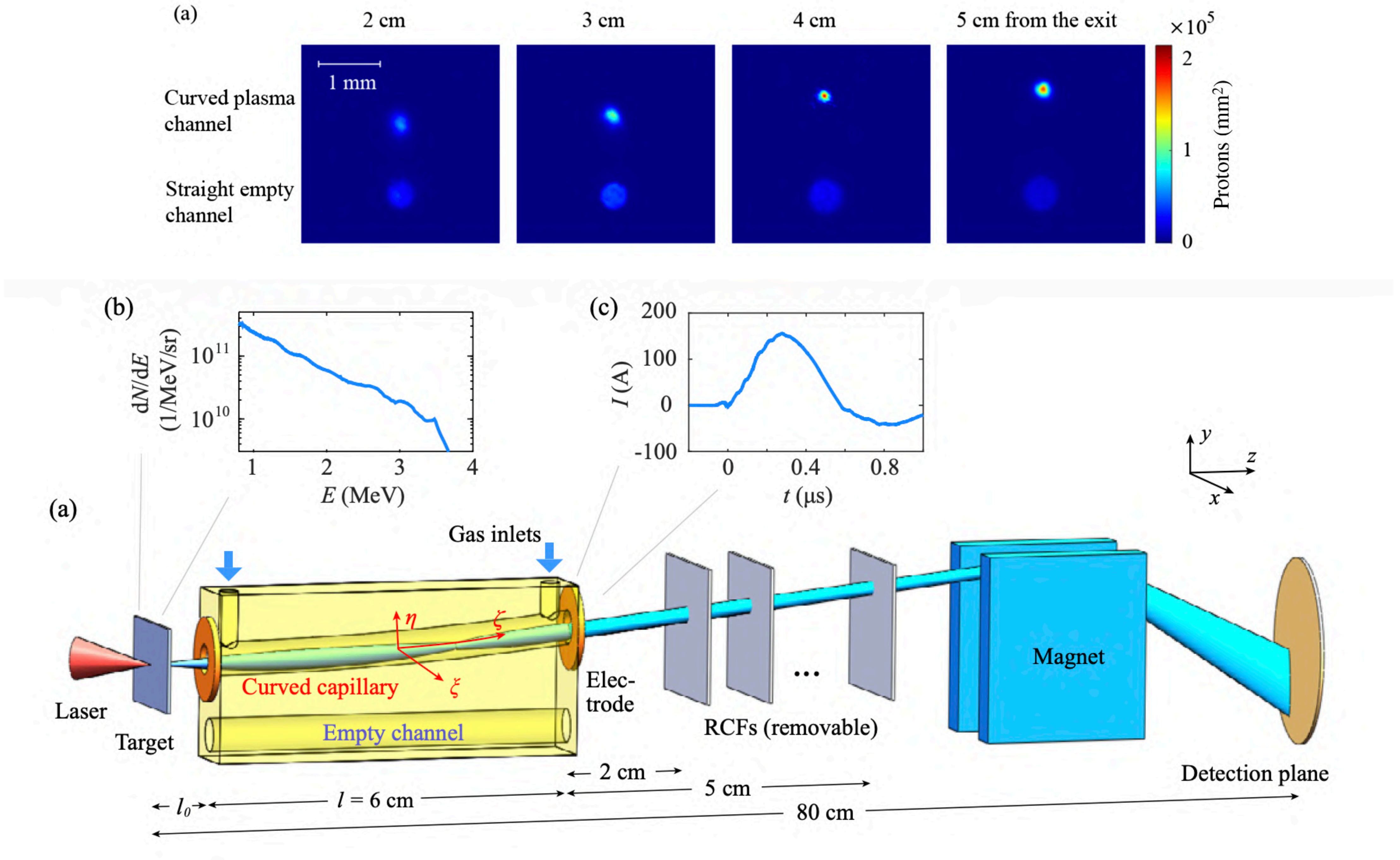
Yan et al., NIM A 1057, 168737 (2023)



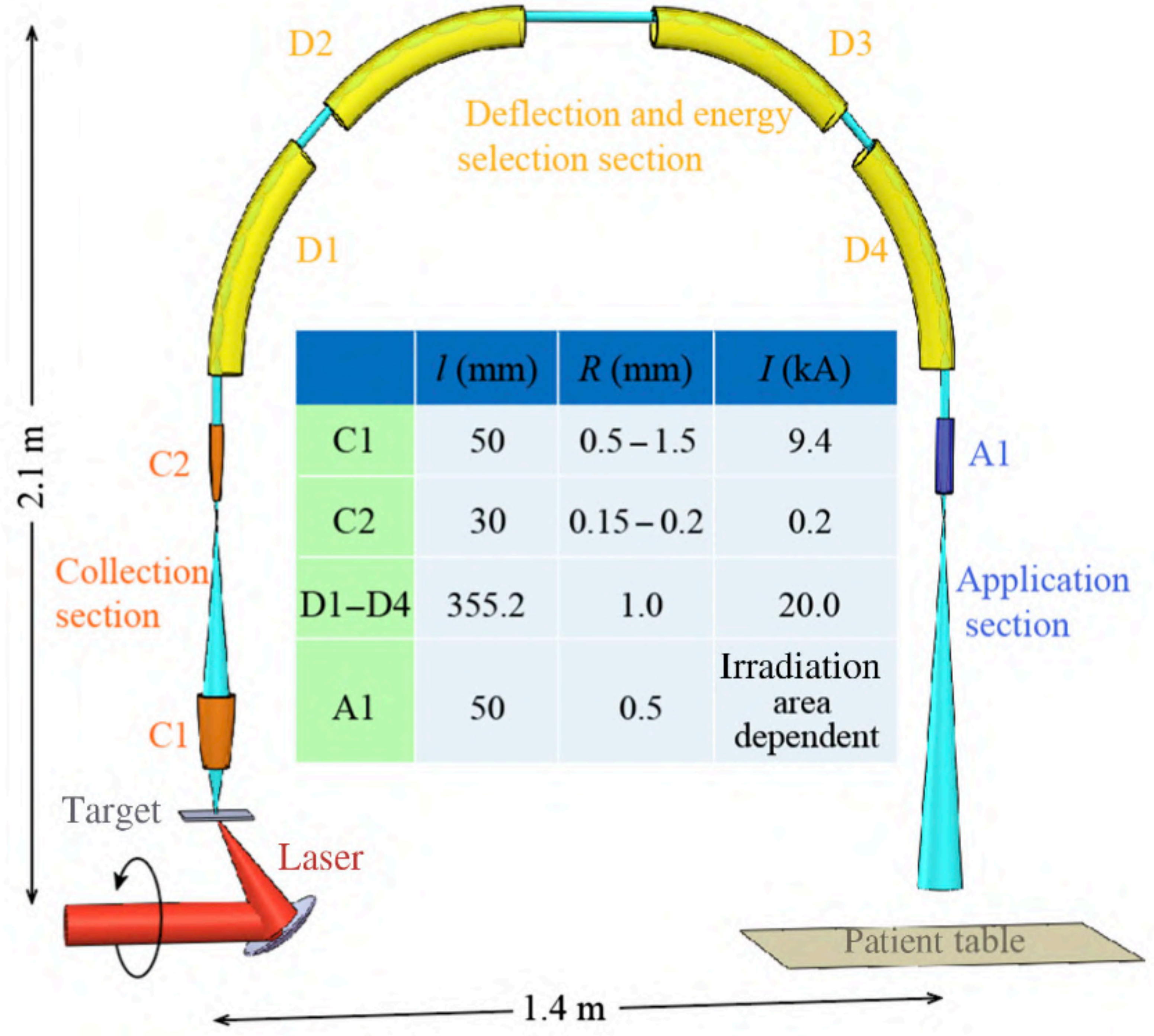
Y. Yan et al., Phys. Rev. Accel. Beam 27, 052802 (2024)

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.

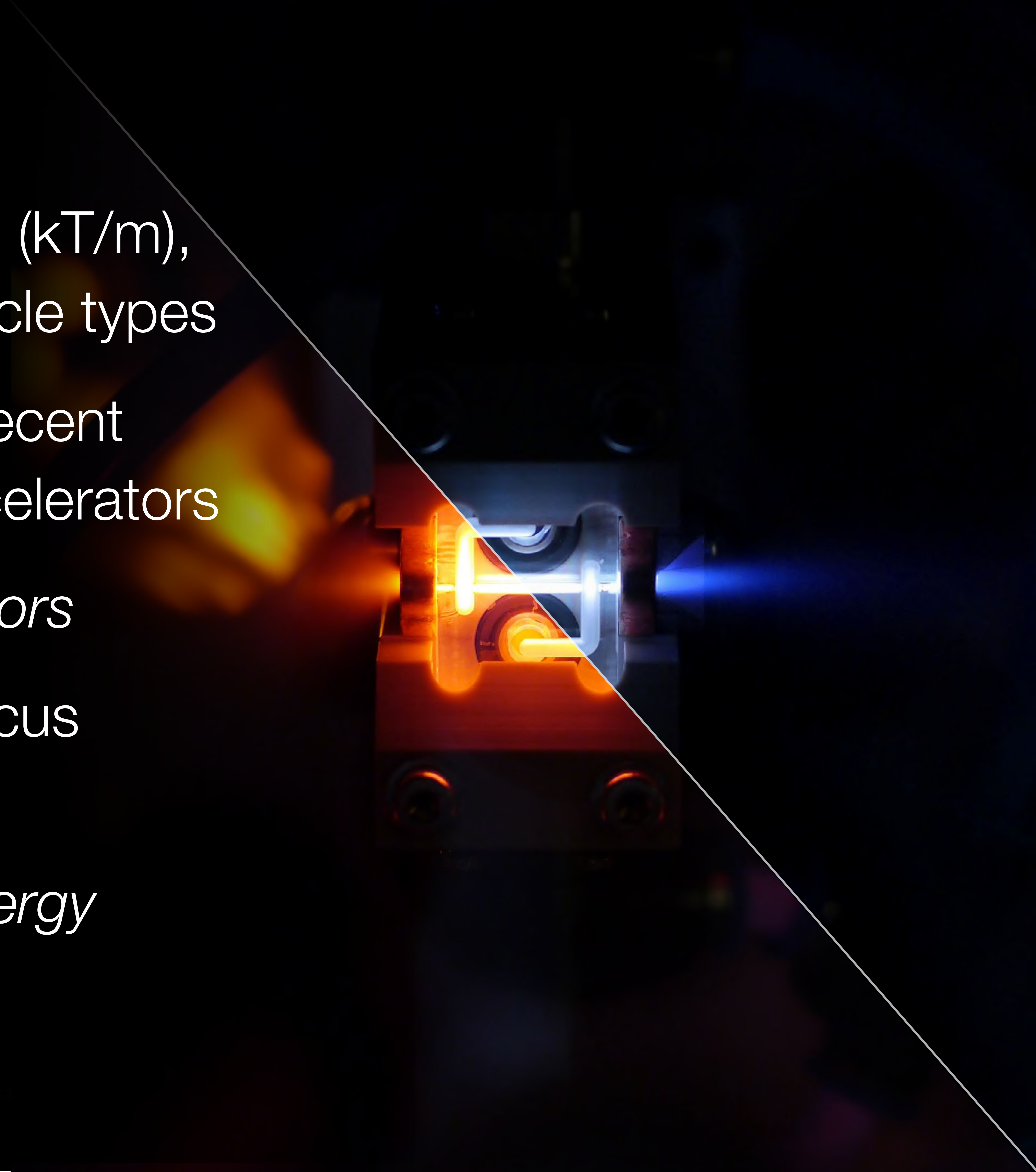


Y. Yan et al., Phys. Rev. Accel. Beam 28, 032801 (2025)



Conclusion

- Active plasma lenses provide strong (kT/m), pulsed, uniform focusing for all particle types
- Long history starting in 1950, with recent surge of interest from advanced accelerators
  - *Key for staging plasma accelerators*
- APLs have recently been used to focus ~3 MeV laser–proton beams
  - *Can we apply APLs to higher-energy proton/ion beams (~100 MeV)?*



Extra slides

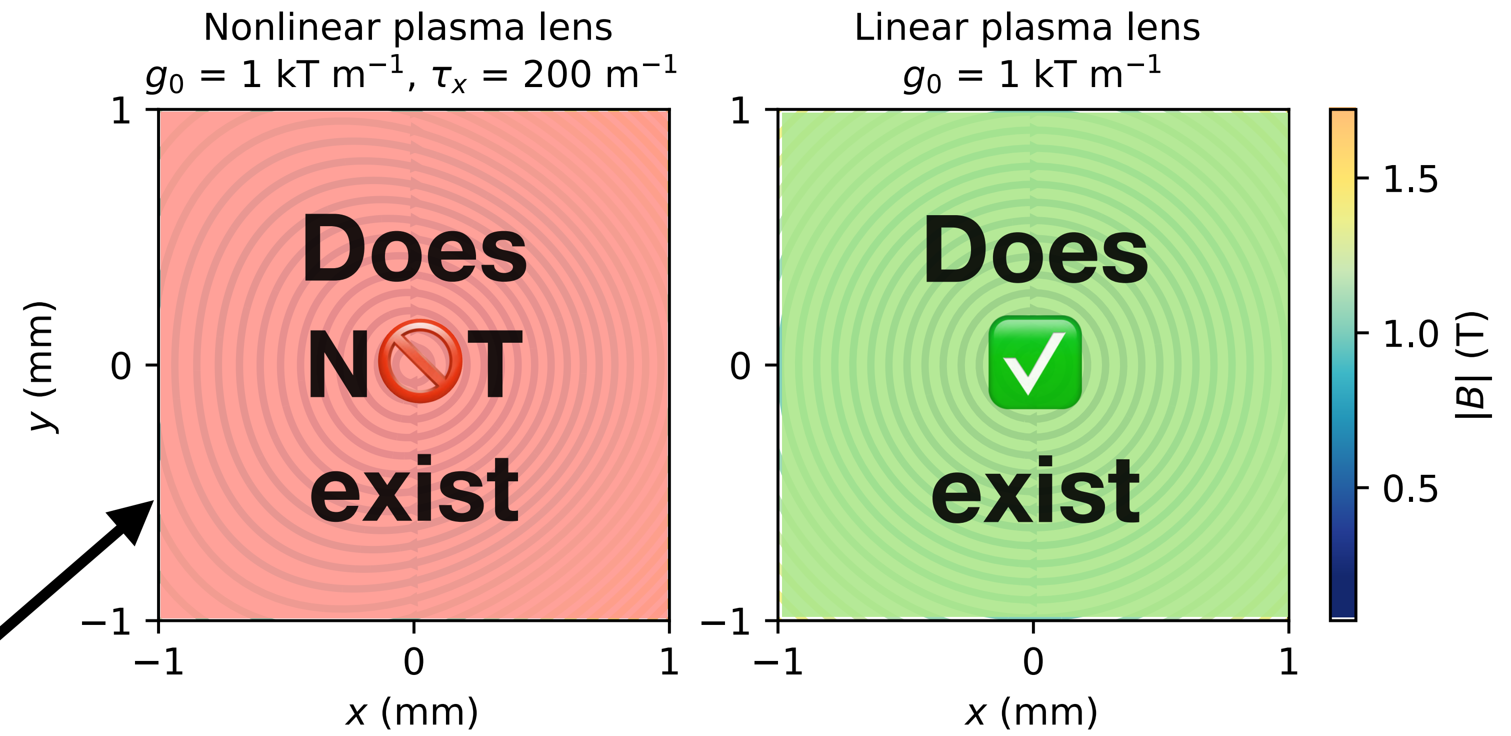
SPARTA: Novel achromatic staging optics

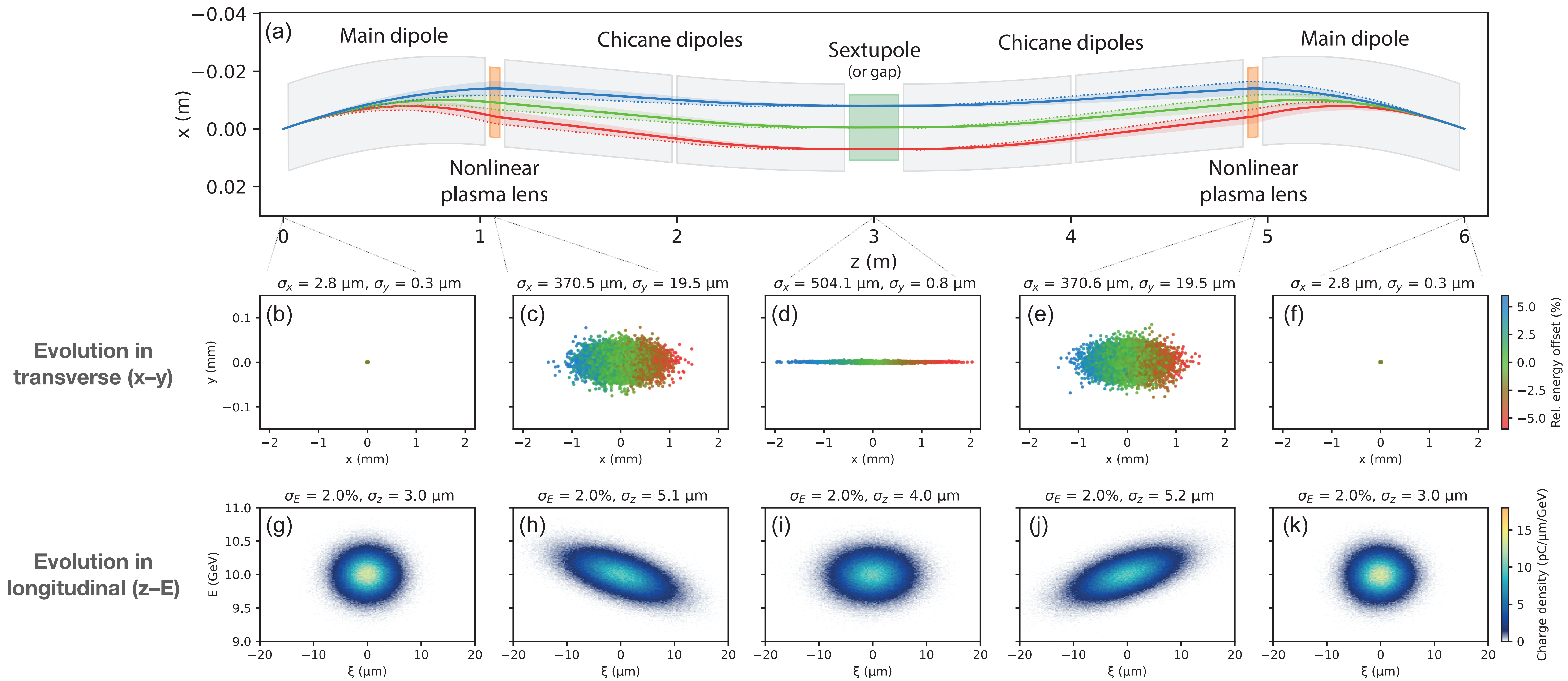
Solves staging (coupling plasma accelerators) with a new plasma lens

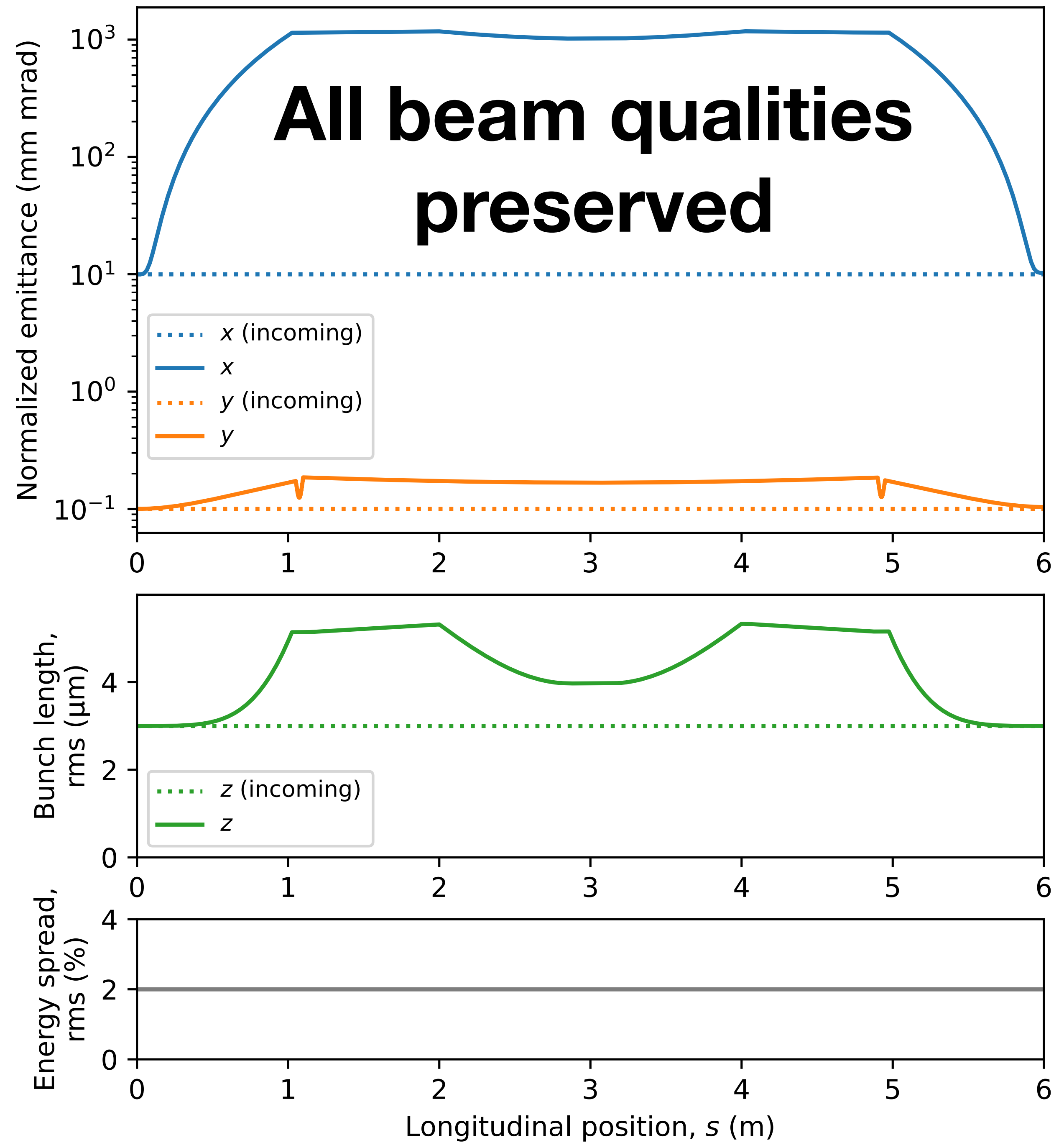
> *Inspiration:* chromaticity correction in collider final focusing
  > *Disperse, apply stronger focusing for higher energies (+ vice versa)*

> Compact and achromatic (~10% BW) using a **nonlinear plasma lens**

Development required!

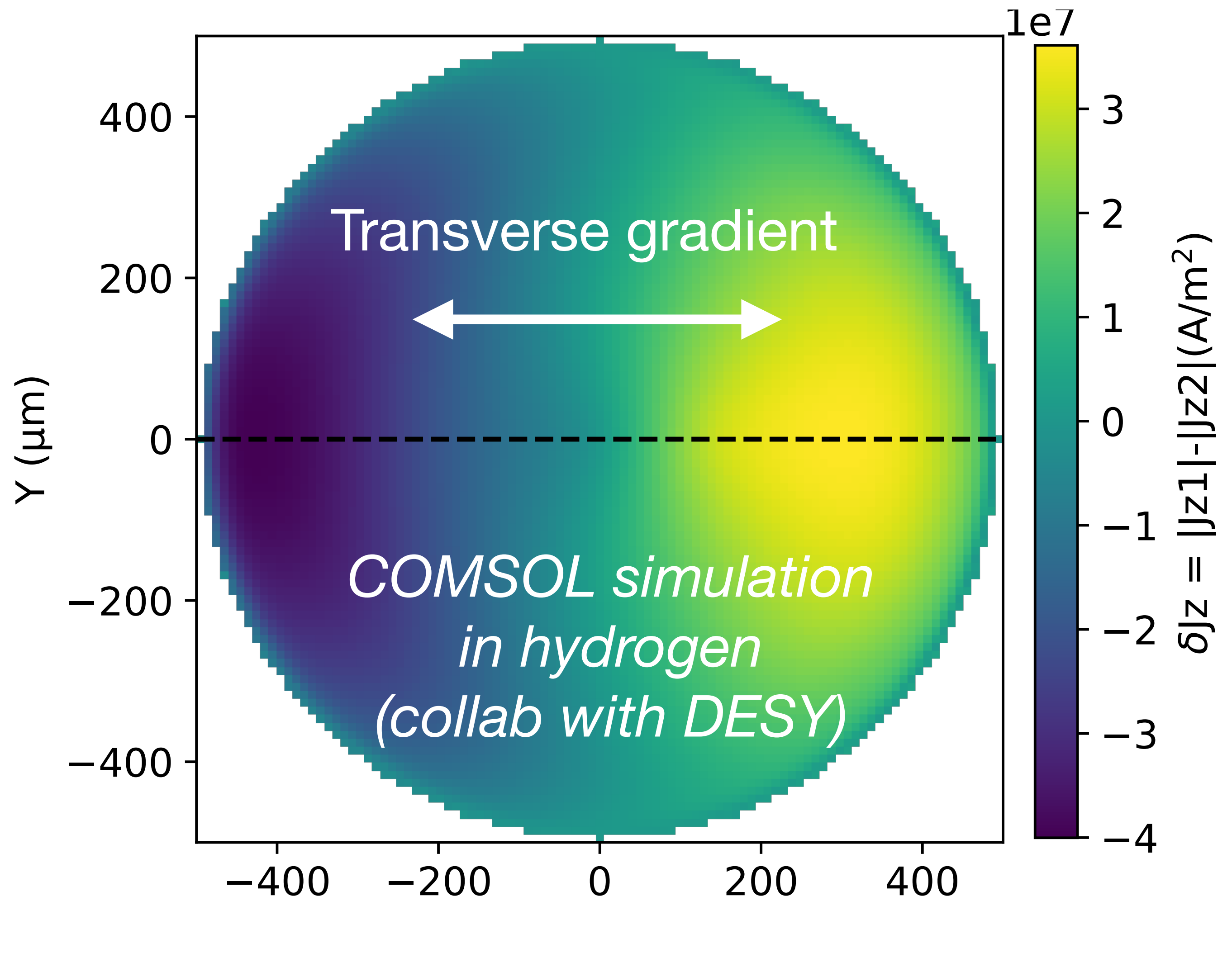




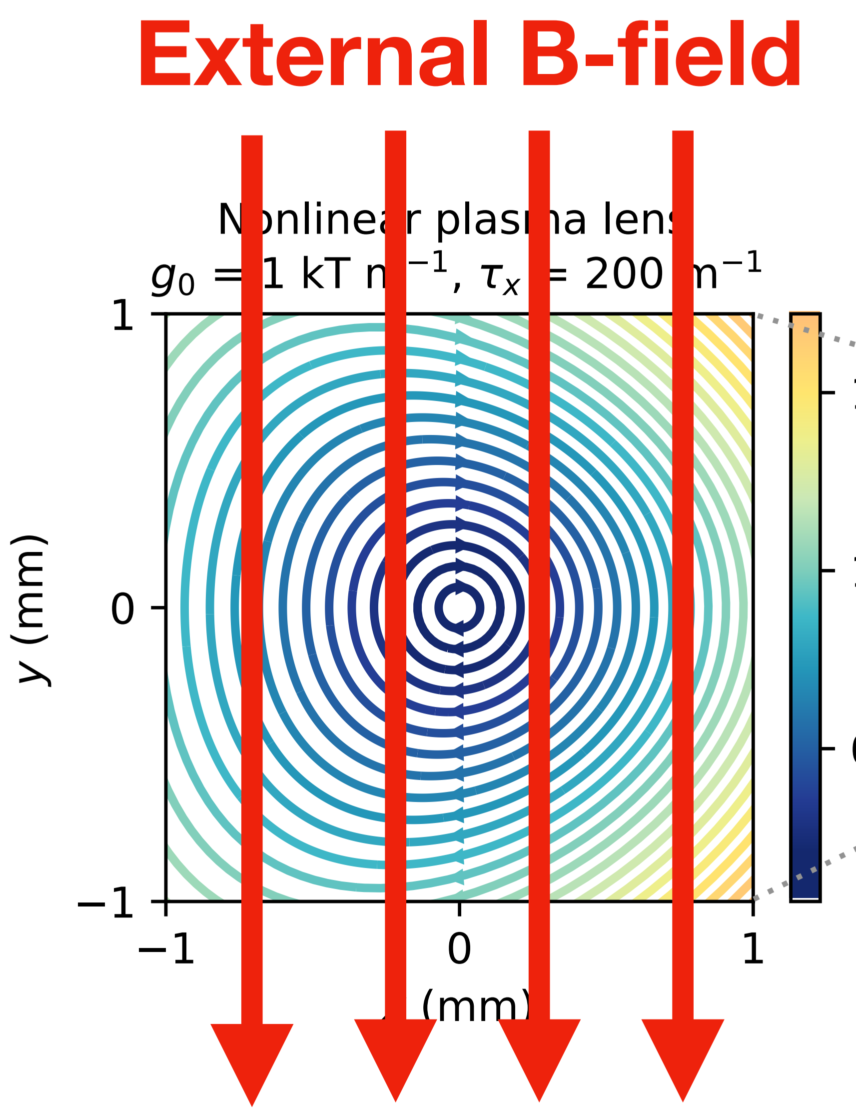


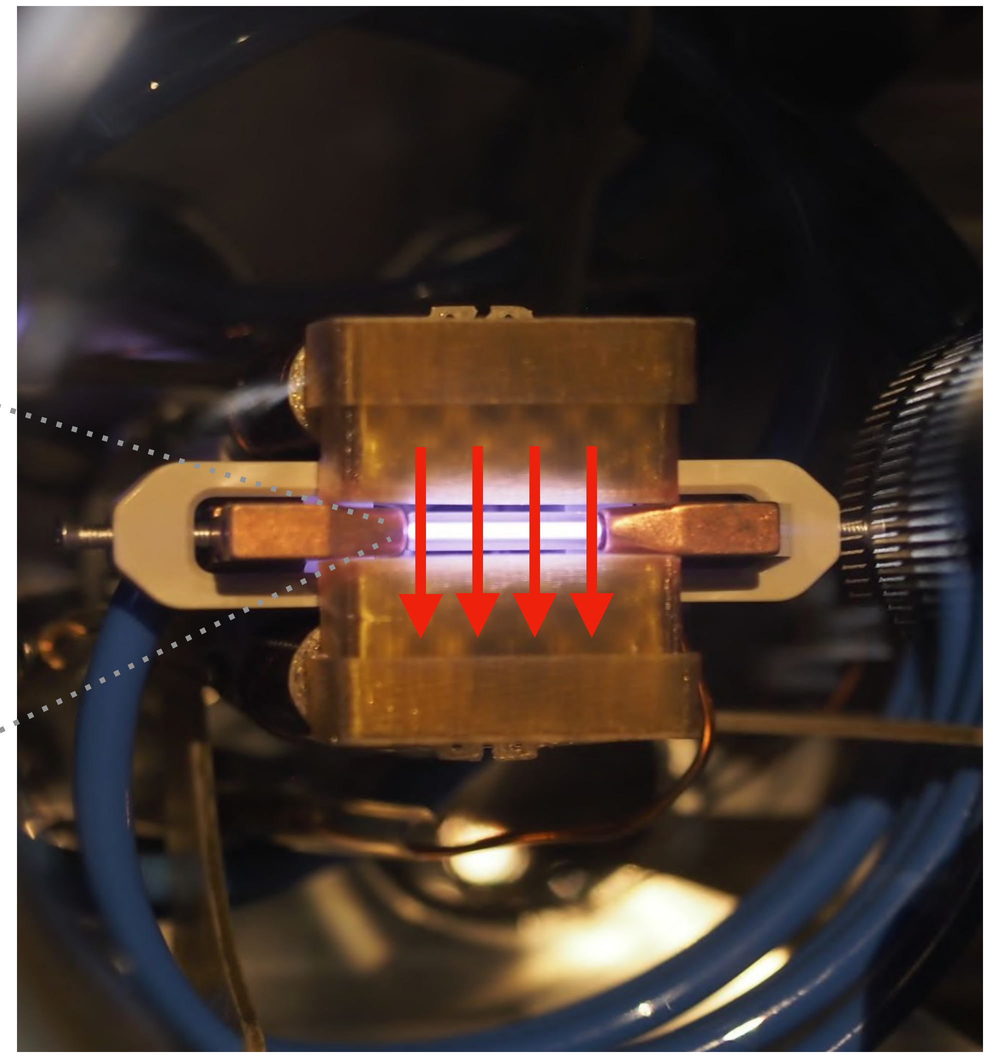
SPARTA: Development of a nonlinear plasma lens

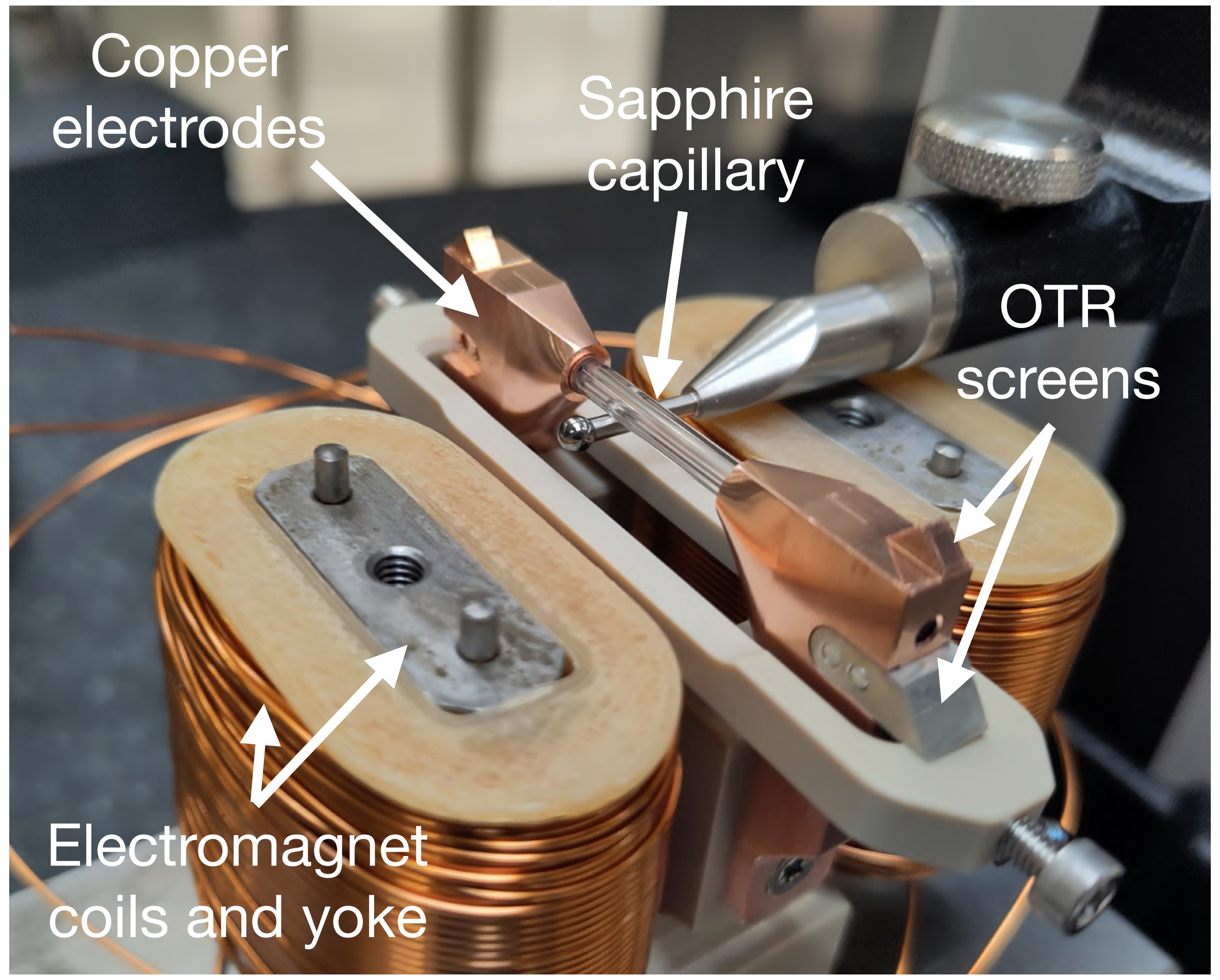
Exciting a nonlinearity through the Hall effect



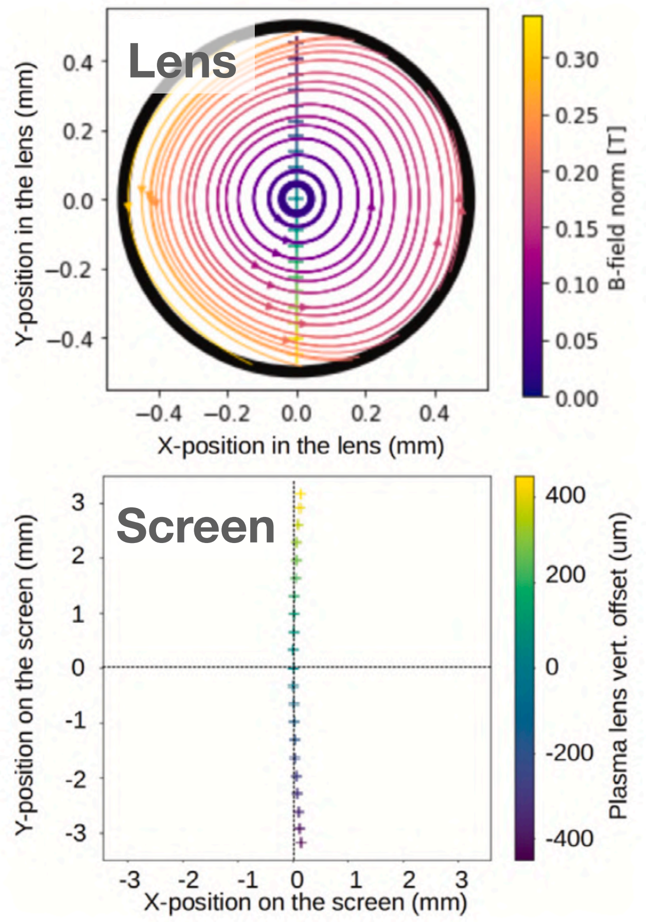
Source: P. Drobniak et al., Proc. IPAC (2025), p. 641

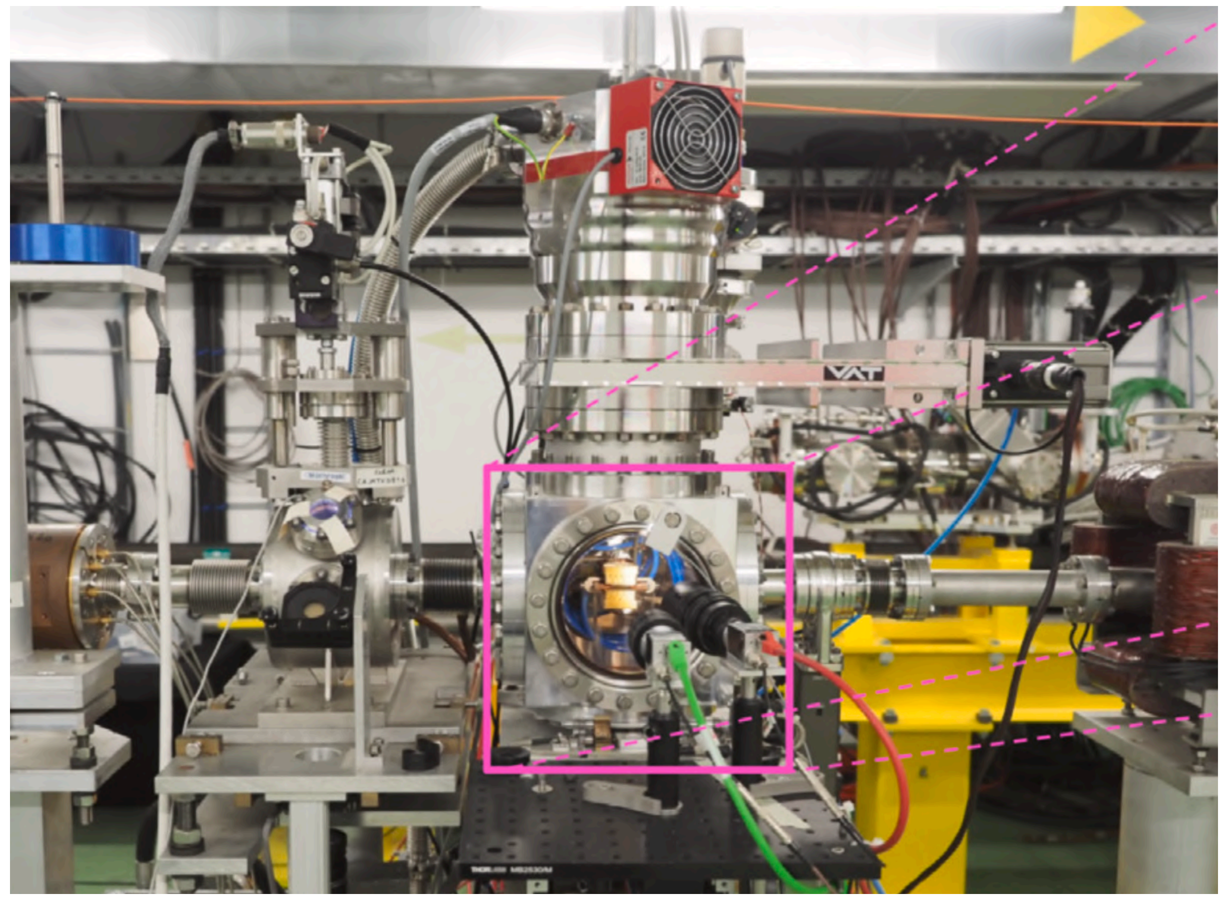






> Concept: apply an external B-field to induce Hall effect
  > *Shifts the discharge current to one side*
> MHD simulations (COMSOL) indicates the principle works.
> Designed/manufactured at Uni. Oslo (P. Drobniak *et al.*).
> Characterized with *e*-beam in CLEAR @ CERN (2024–2026).





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

Radial vs. quadrupole focusing

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

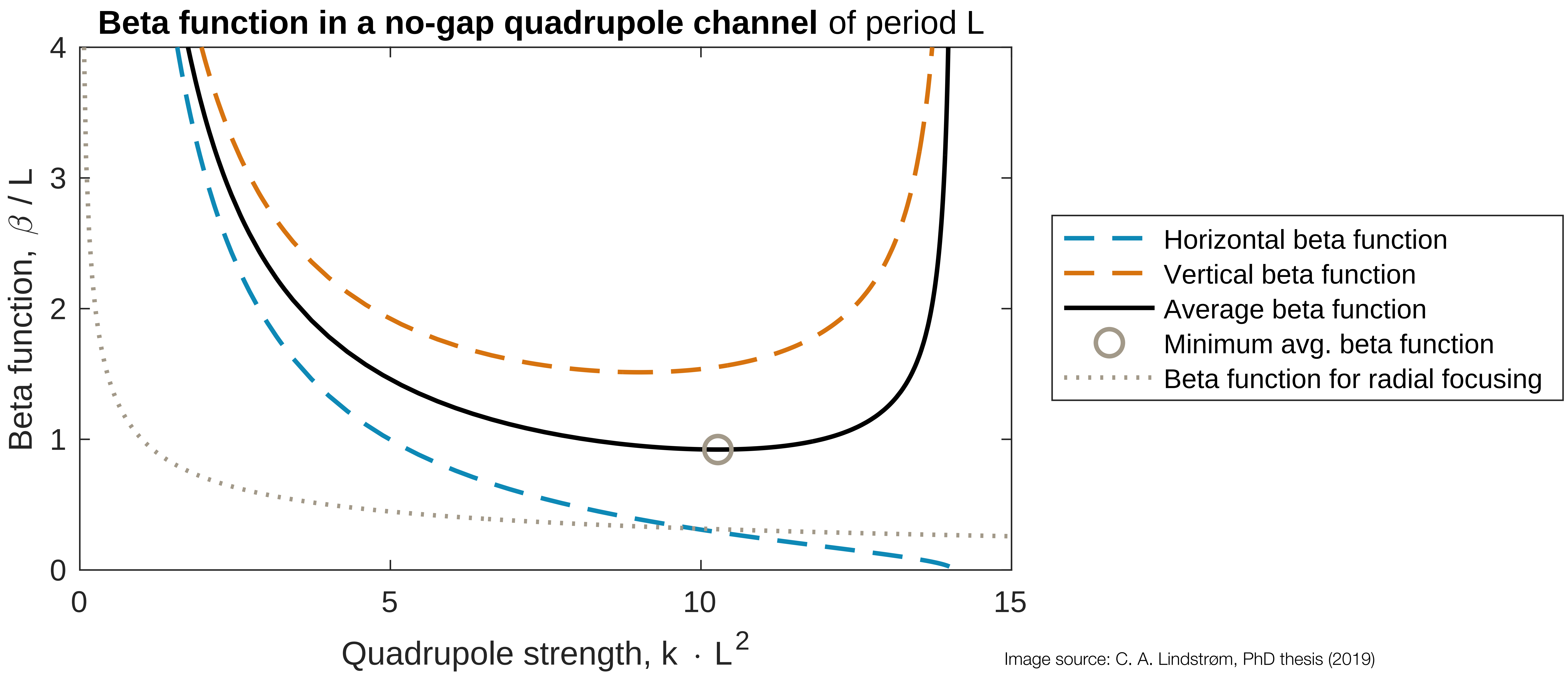


Image source: C. A. Lindstrøm, PhD thesis (2019)

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

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

> Being addressed in experiments at CLEAR

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