Plasma Lenses for Collider Beams

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Motivation: Staging requires strong focusing

> High gradient accelerators require strong focusing during acceleration

> > Inherent in plasma wakefields

> > Needed (in any accelerator) to stop beam breakup from transverse wakefields

> Result: **highly divergent beams** at the exit/re-entry

> Focal length arguments dictate a **minimum staging length** given by the energy (E) and focusing gradient (g_r):

> > Example: g_r = 10 T/m, E = 100 GeV ⇒ L_{min} = 23 m
> > (with an 11.5 m long focusing channel)

> In a plasma accelerator, the **relative emittance growth between each stage** will be approximately:

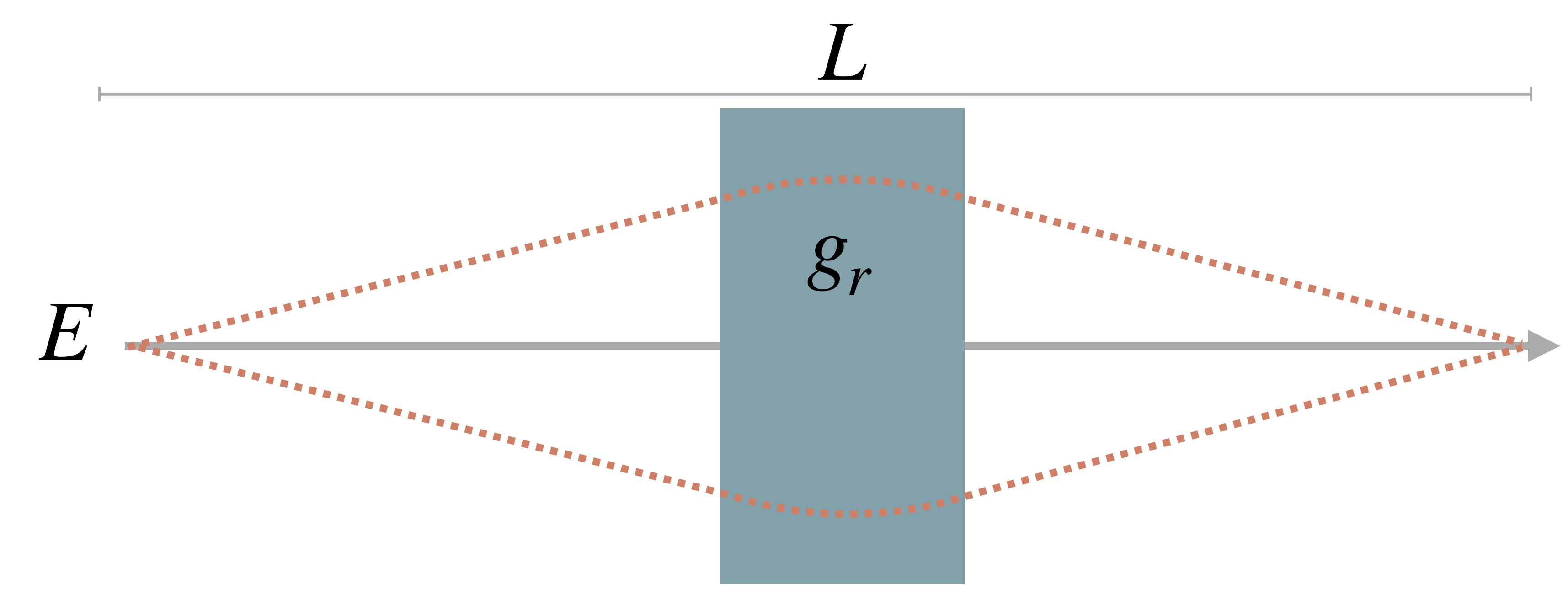
> > Example: g_r = 10 T/m, $n_0 = 10^{15}$ cm^{-3}, σ_δ = 1%
> > ⇒ ~100% emittance growth

> > Favours low energy spread (bad for beam breakup instability)

> > Favours low plasma density (bad for high gradient acceleration, unless using plasma density ramps)

> > **Favours high focusing gradients**

> > Another option: final focus-style chromaticity correction (very long)



$$L_{\mathrm{min}} \approx 4\sqrt{\frac{E}{g_r e c}}$$

$$\frac{\Delta \epsilon_n^2}{\epsilon_n^2} \approx \frac{2 n_0 e \sigma_\delta^2}{g_r \epsilon_0 c}$$

* For derivations, please see C. A. Lindstrøm, PhD thesis (2019) or the recent CERN Accelerator School staging lecture

RADIAL FOCUSING AND QUADRUPOLES

> Very strong/very small quadrupoles — permanent (~500 T/m) or microelectromechanical* (multi-kT/m?)

> What is the equivalent radial focusing gradient (g_r) for a lattice of quadrupoles?

> **A quadrupole channel has to be ~10 times stronger than a radial focusing channel with the same gradient.**

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

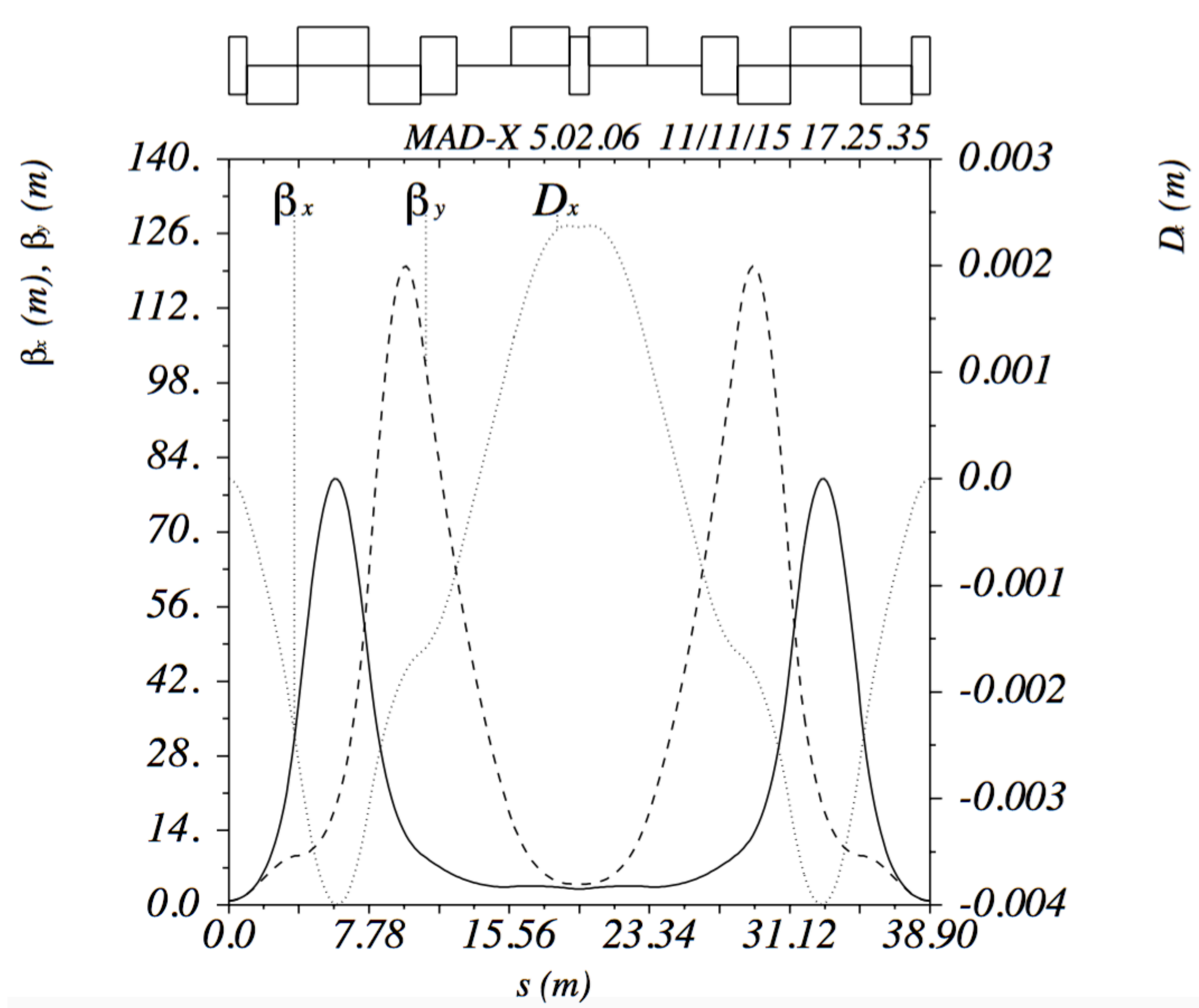


Image source: C. A. Lindstrøm et al., NIM A 829, 224–228 (2016)

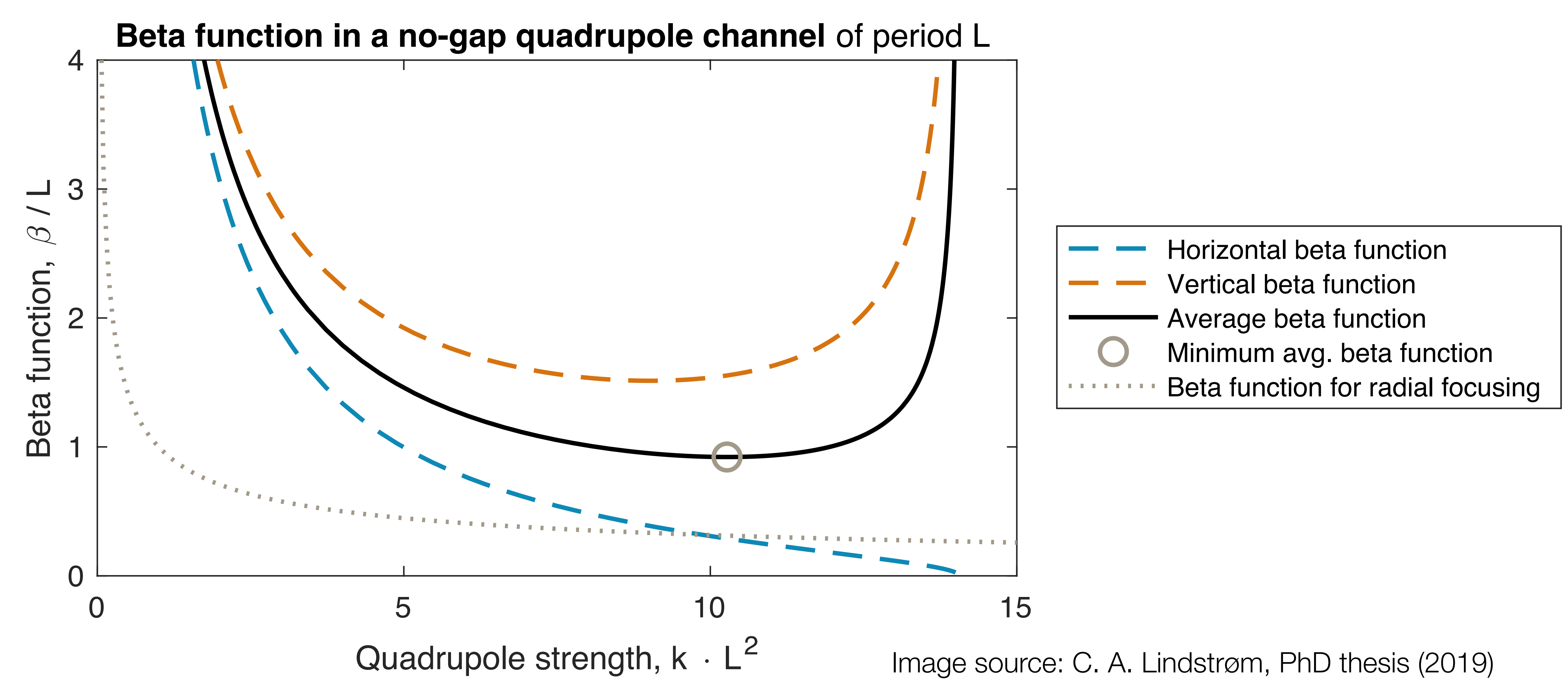


Image source: C. A. Lindstrøm, PhD thesis (2019)

* J. Harrison, et al., Phys. Rev. ST Accel. Beams 18, 023501 (2015).

Is it possible to do radial focusing in vacuum?

> Only two fields can radially focus a beam: E_r and B_ϕ

> Seemingly three options:

> 1. E_r from a charge density
> 2. B_ϕ from a current density
> 3. B_ϕ from a displacement current (rapidly changing E_z)

> Only option 3 could be done in vacuum — but turns out to be fundamentally impossible:

> Rapidly varying E_z-fields (at zero crossing) sets up E_r-fields (Gauss' law) which cancels out (to $1/\gamma^2$) any overall focusing from the induced B_ϕ across the cavity.

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \left(\vec{J} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right)$$

> **Conclusion: Radial focusing requires an on-axis material**

> To reduce scattering, we must maximize exposed charge or conductivity per density

⇒ **Use a plasma**

> Two categories:

> **Passive** plasma lenses (electrostatic, E_r)

> **Active** plasma lenses (magnetic, B_ϕ)

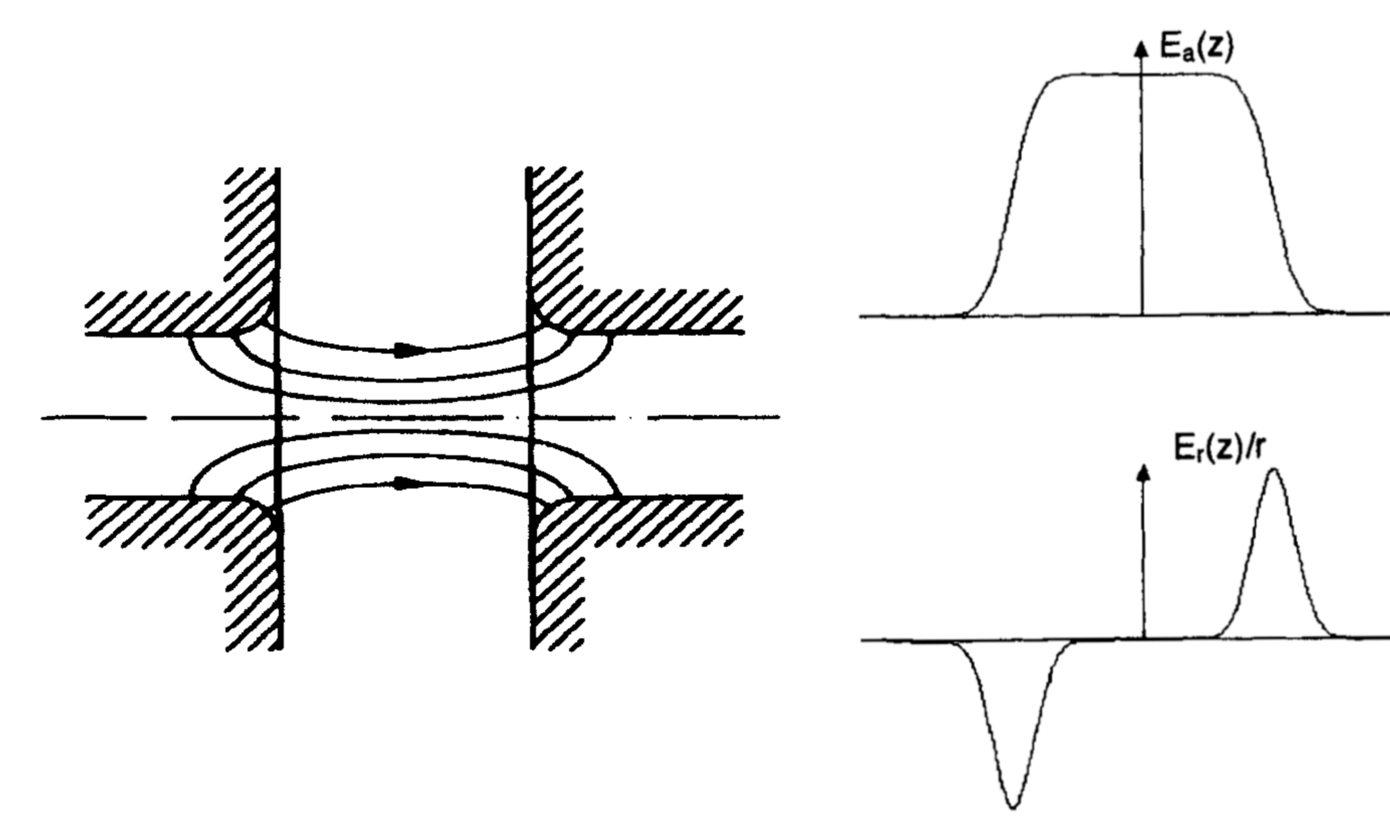


Image source: Thomas P. Wangler, RF Linear Accelerators, (Wiley, Weinheim, 2008), pp. 201–207.

PASSIVE PLASMA LENSING — HISTORY (1922–2019)

- "Ancient" history:
  - 1922: Electrostatic focusing of a continuous 300 eV electron beam in a cathode ray tube by Johnson from an excess of on-axis positive ions.
  - 1934: Bennett proposes magnetically self-focused electron streams, where the electric space-charge field of the stream is neutralized by a plasma, leaving only magnetic focusing fields.
  - 1947: Gabor proposes to use an electron cloud for focusing low energy ion beams.
  - 1966: Magnetically self-focused electron streams are observed by Graybill and Nablo
  - 1969: Gabor lensing is experimentally demonstrated for the first time by Zhukov et al.
- Modern history:
  - **1987: Chen proposes to use the strong transverse electrostatic fields of beam-driven PWFAs for the final focus of a linear collider**
  - 1990: Self-pinching of a 21 MeV electron beam by (overdense) plasma wakefields is observed at Argonne by Rosenzweig et al.
  - 2001: 28.5 GeV positrons focused by a 3 mm passive plasma lens at FFTB by Ng et al.
  - 2010: Thompson et al. demonstrates a low-aberration plasma lensing at the underdense (blowout) threshold at Fermilab.
  - 2015: Laser-driven passive plasma lensing demonstrated by Thaury et al. at LOA.

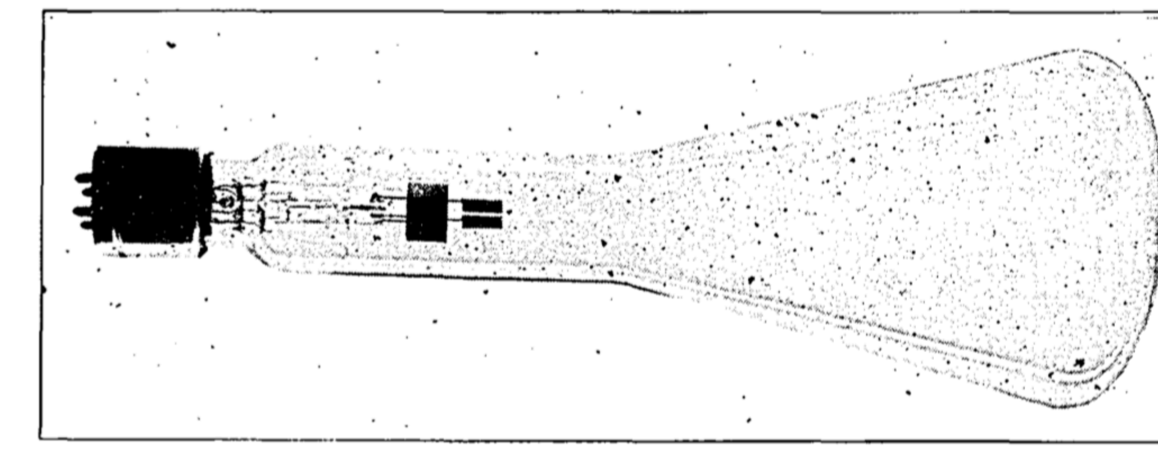


Image source: John B. Johnson, J. Opt. Soc. Am. 6, 701 (1922).

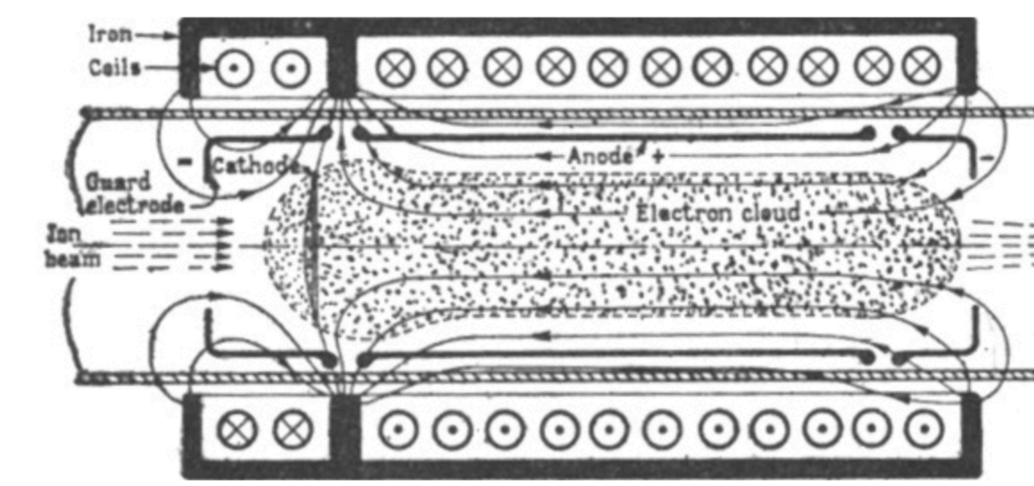


Image source: Dennis Gabor, Nature 160, 89 (1947).

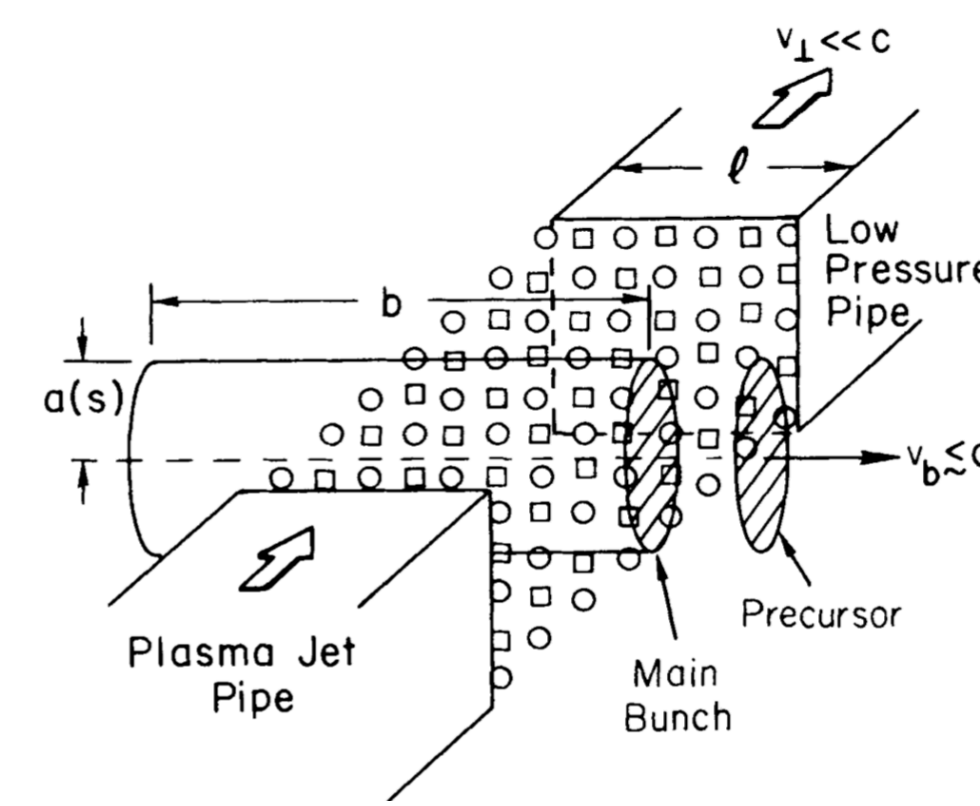


Image source: Pisin Chen, Part. Accel. 20, 171 (1987).

Passive plasma lensing

> Electrostatic focusing by an ion column — using a plasma wakefield accelerator for focusing only

> Provides **very strong focusing gradients**:

Maximum focusing gradient: $$g_r = \frac{en_0}{2c\epsilon_0}$$

> Example: $n_0 = 10^{17}$ cm^{-3} $\Rightarrow$ $g_r = 3$ MT/m

> Only works for intense bunches (self-driven or with a driver)

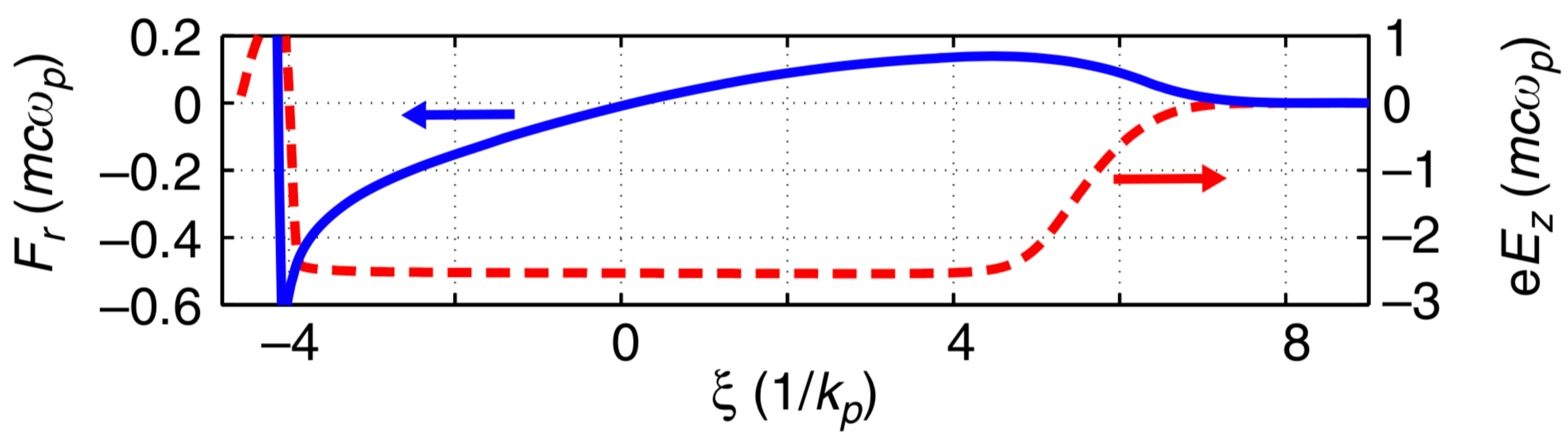


Image source (adapted): C. E. Clayton et al., Nat. Commun. 7, 12483 (2016)

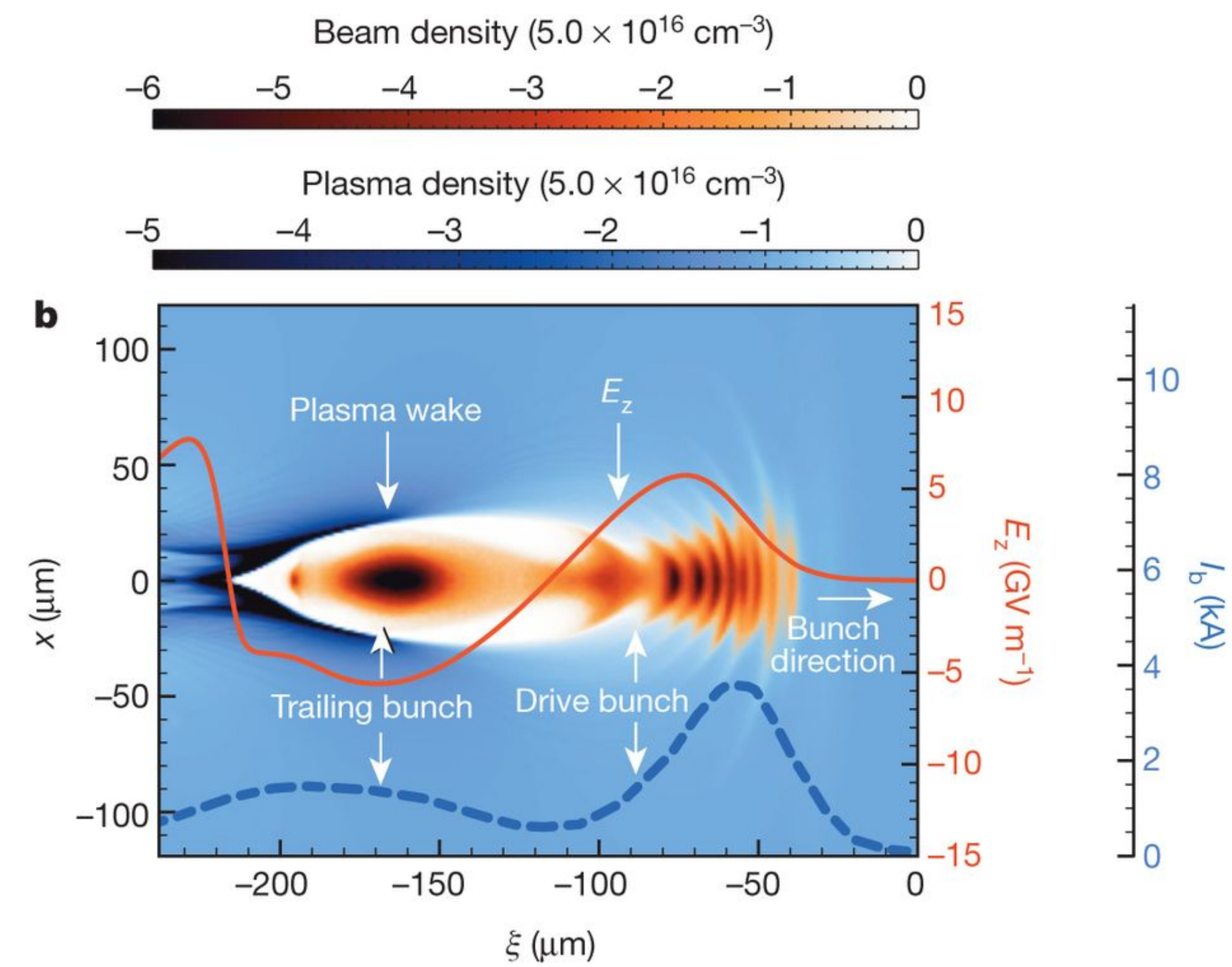


Image source: M. Litos et al., Nature 515, 92–95 (2014)

PASSIVE PLASMA LENSING — PLASMA DENSITY RAMPS

> Main direction of research in plasma lenses today: tailored plasma density ramps

> Able to **significantly increase matched beta functions** before exiting the plasma

> Two classes:

  > **Adiabatic** (slow, matched beta throughout) — long, good for chromaticity

  > Non-adiabatic (fast, not matched beta throughout) — short, good for monochromatic beams

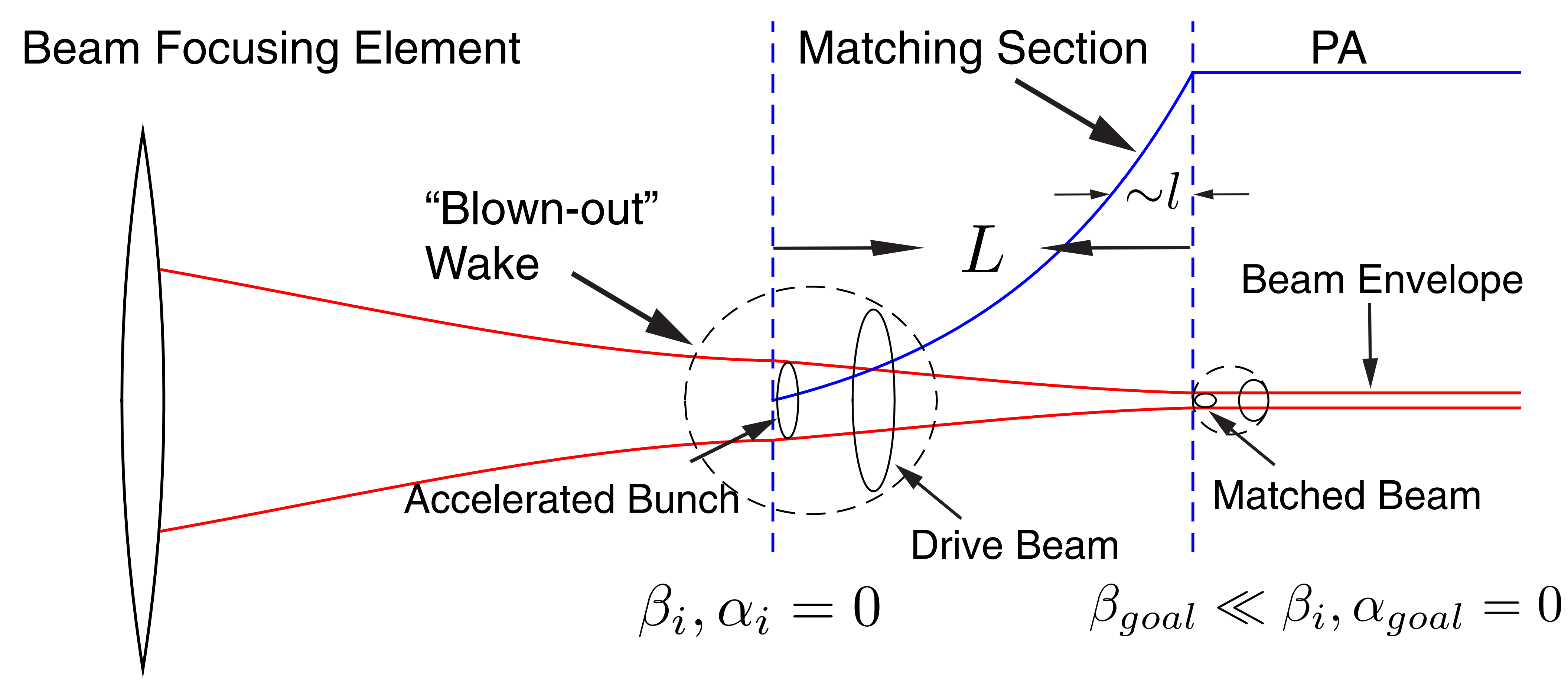


Image source: X. Xu et al., Phys. Rev. Lett. 116, 124801 (2016) [10]

Passive plasma lensing — Problems for collider beams

> Non-uniformity / need for driver

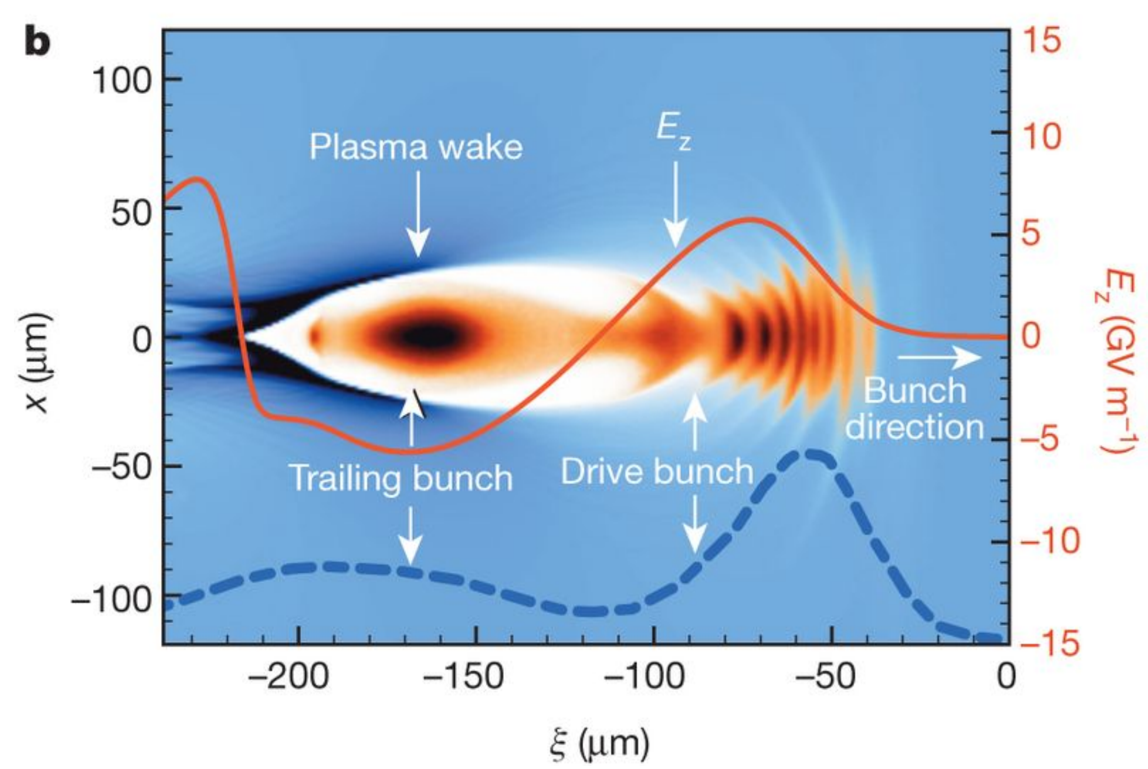


Image source: M. Litos et al., Nature 515, 92–95 (2014)

> Positron focusing

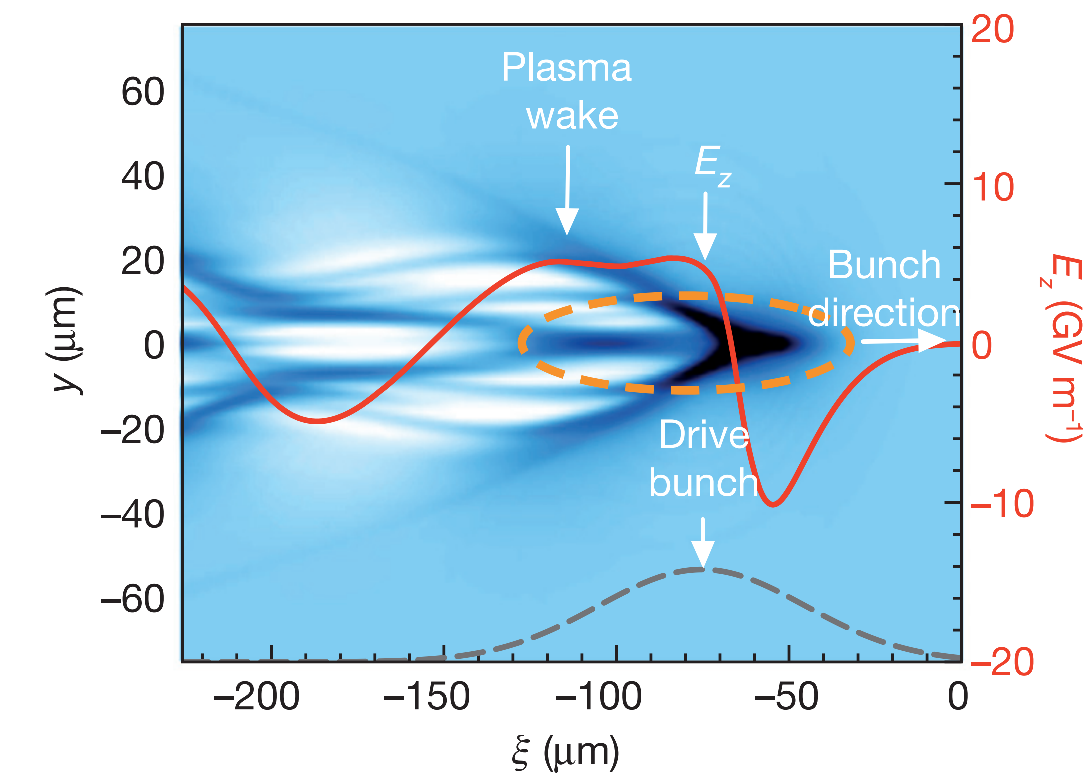
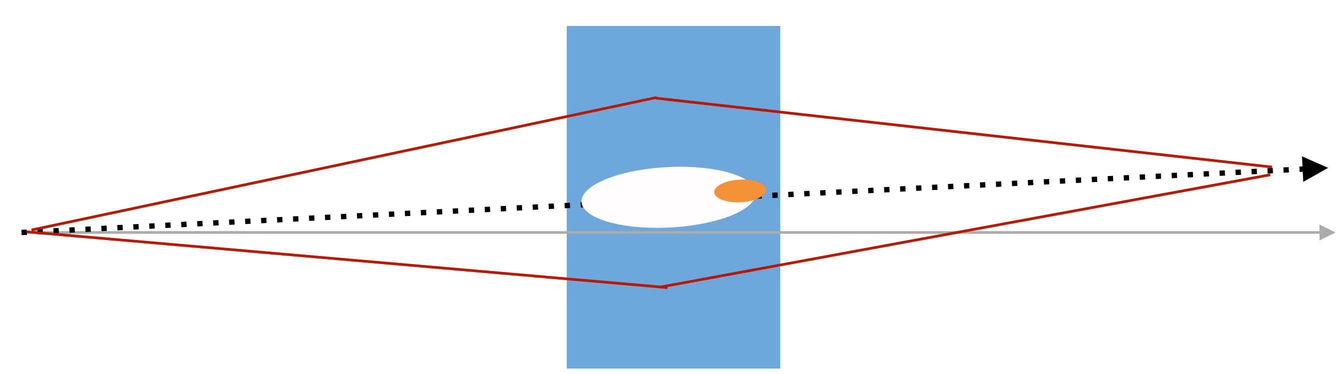


Image source: S. Corde et al., Nature 524, 442 (2015).

> Driver/self-misalignments



$R_{12} \neq R_{34} \neq 0$
unless driven by on-axis beam

> Ion motion

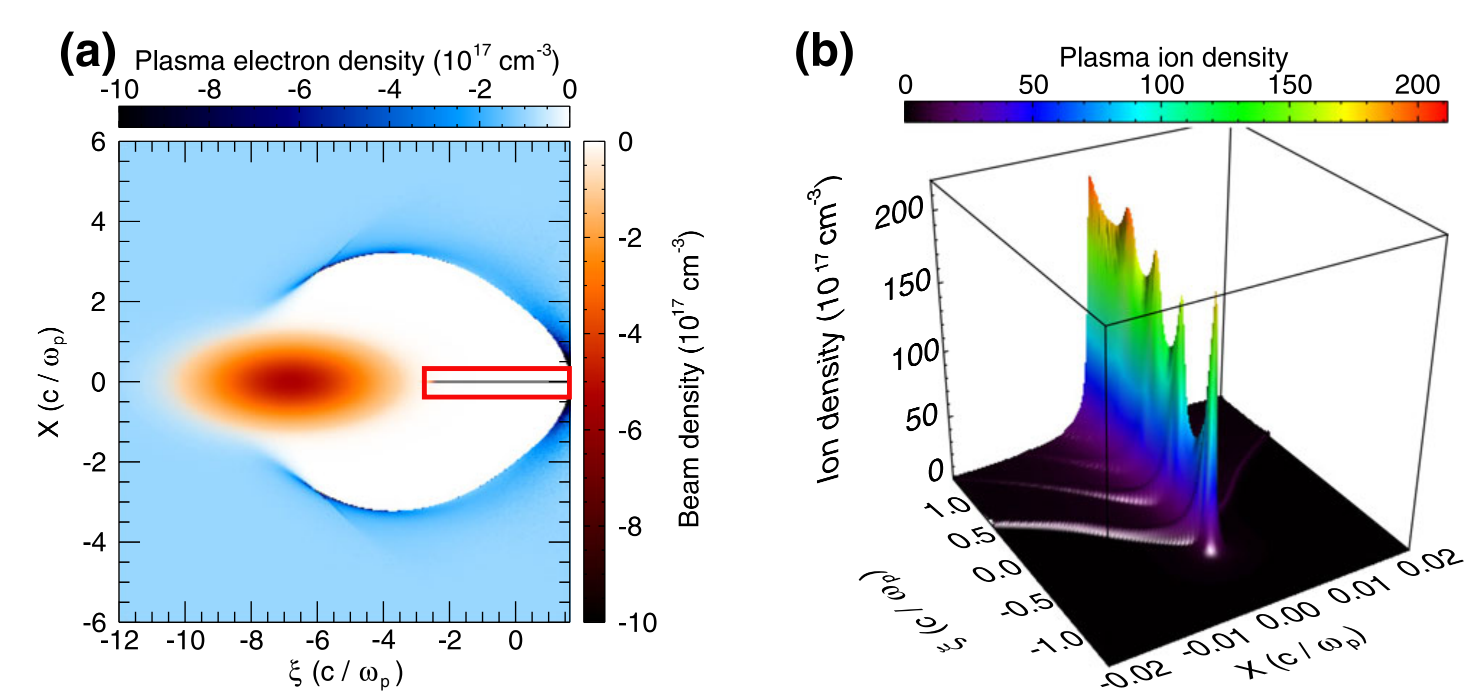


Image source: W. An et al., Phys. Rev. Lett. 118, 244801 (2017).

Active plasma lensing — Working principle

> Magnetic fields from a uniform current density
> Strong focusing fields ~kT/m (~3 kT/m demonstrated at BELLA)
> Uniform focusing fields, longitudinally and transversely (ideally)
> Misalignments not beam-based – can do imaging.

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

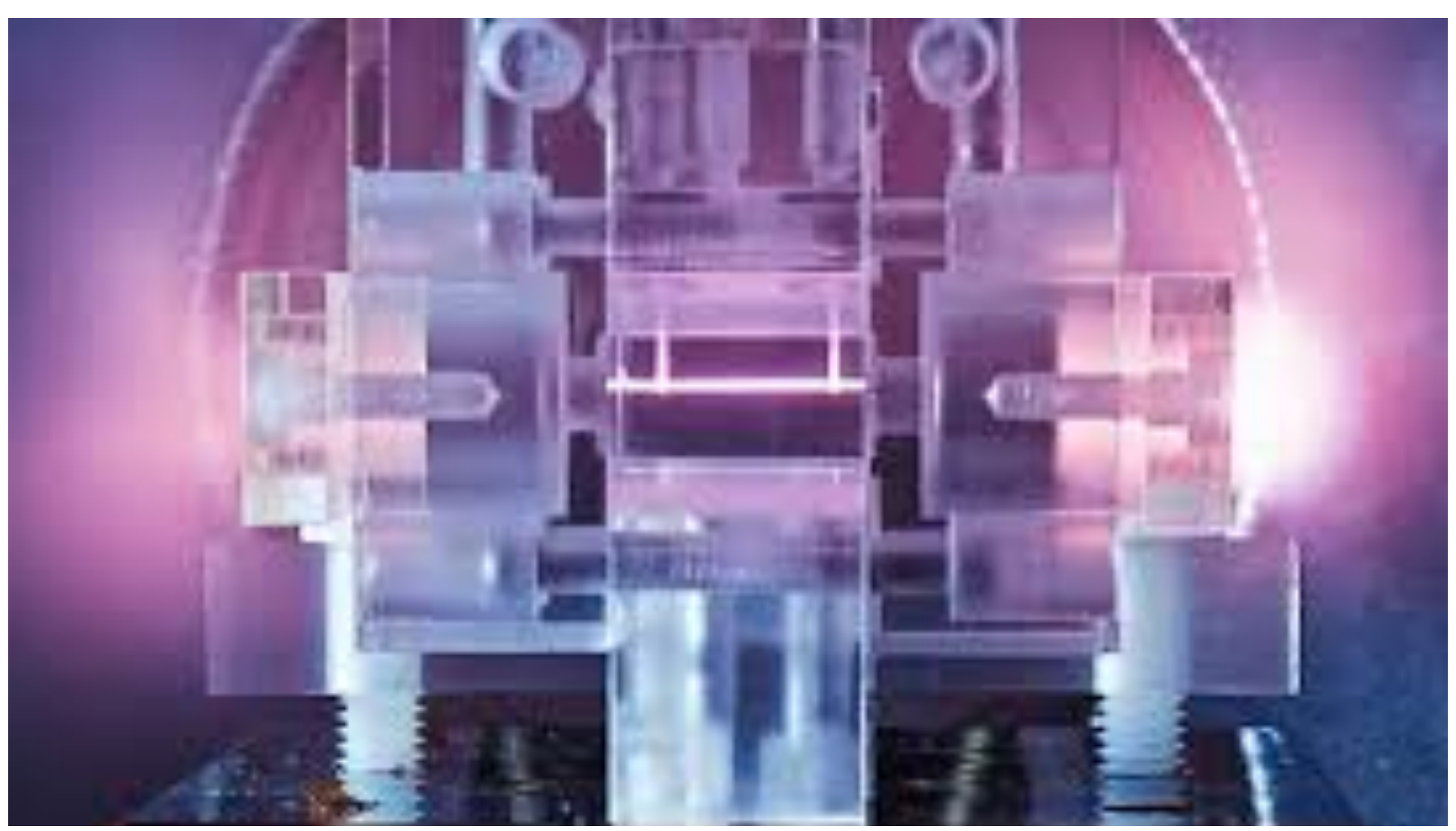


Image source: DESY Mainz plasma lens experiment

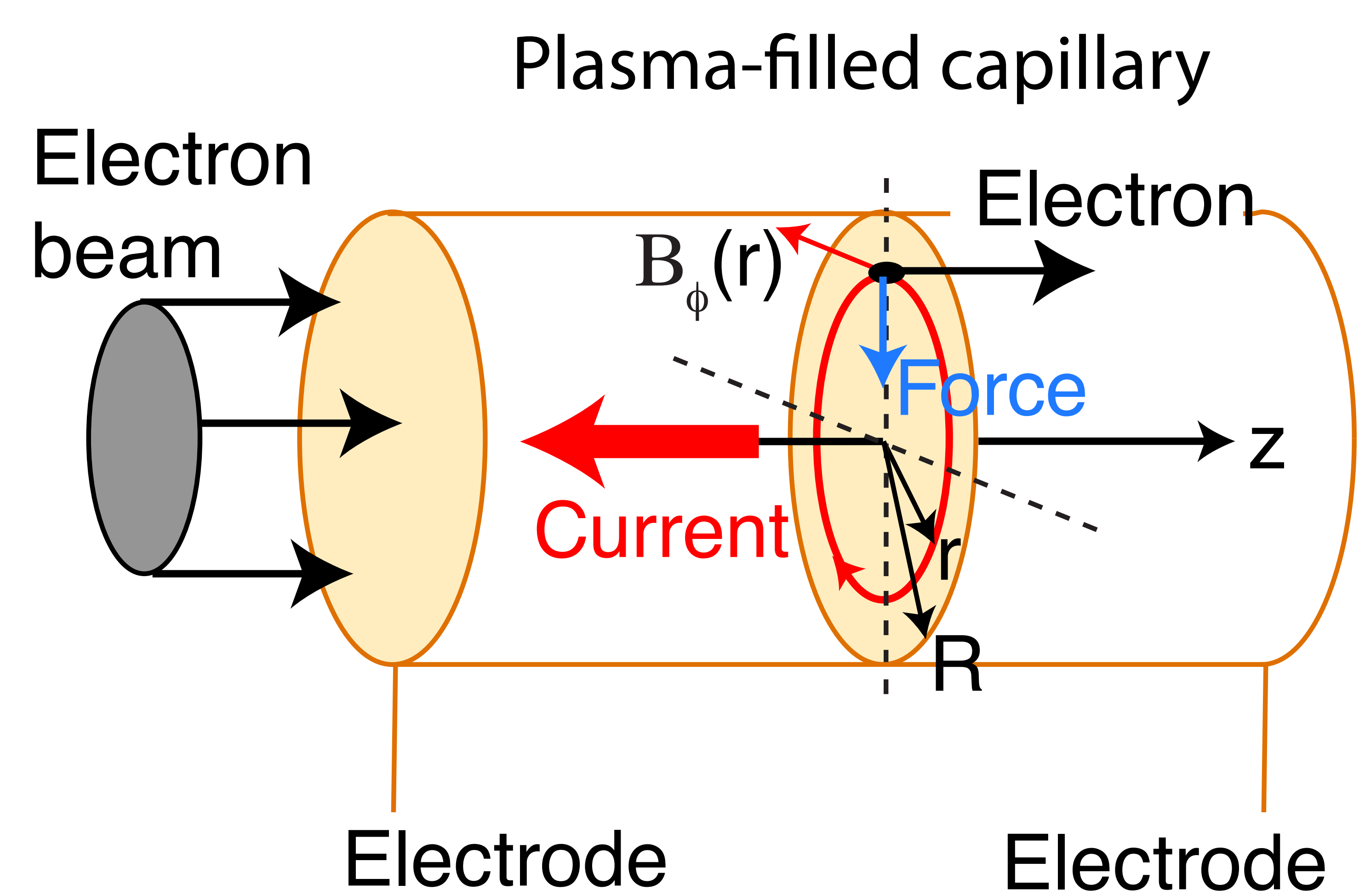


Image source: van Tilborg et al., Phys. Rev. Lett. 115, 184802 (2015).

ACTIVE PLASMA LENSING — HISTORY (1950–2019)

> "Ancient" history:

  - **1950: Panofsky and Baker construct an "arc lens" with an externally driven current to focus their 350 MeV ion beam in the 184-inch cyclotron at the Berkeley Rad Lab.**
  - 1965: A similar lens is build at Brookhaven by Forsyth et al. to increase the neutrino yield in a spark chamber experiment.
  - 1991: z-pinch plasma lensing is used for focusing heavy-ion beams in the SIS accelerator at GSI-Darmstadt by Boggasch et al.
  - 1992: Braun proposes active plasma lensing for more efficient positron capture.
  - 1992: Wall-stabilized, unpinched active plasma lensing of heavy ions in UNILAC, GSI-Darmstadt by Boggasch and Stetter et al.

> Modern history:

  - **2015 Discharge capillary-based (unpinched) active plasma lenses are used for strong (3000 T/m) focusing of laser-wakefield accelerated beams in BELLA at Lawrence Berkeley National Lab by van Tilborg et al..**
  - 2016: The BELLA plasma lens is used by Steinke et al. to demonstrate staging of two laser plasma accelerators.
  - 2017: Van Tilborg et al. presents indirect evidence of the nonuniform current density in helium, by observation of ring-shaped beams and an enhanced focusing gradient.
  - 2017: Experiments at INFN by Pompili et al.
  - 2018: Experiments at Mainz Microtron (by DESY) by Röckemann et al.
  - 2018: Experiments at CLEAR, CERN by Lindstrøm et al — aberration suppression and emittance preservation

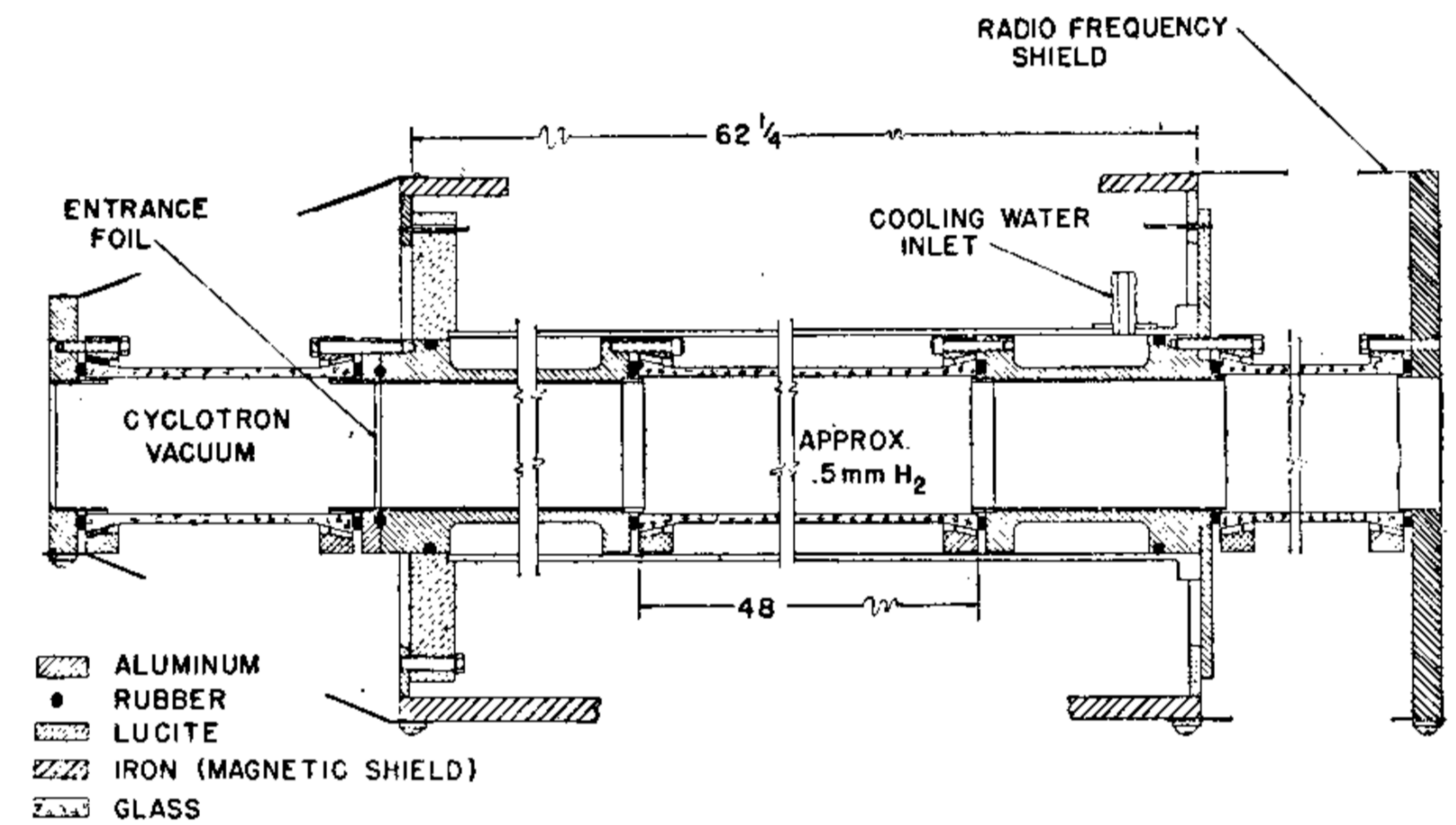


Image source: W. K. H. Panofsky and W. R. Baker, Rev. Sci. Instrum. 21, 445 (1950).

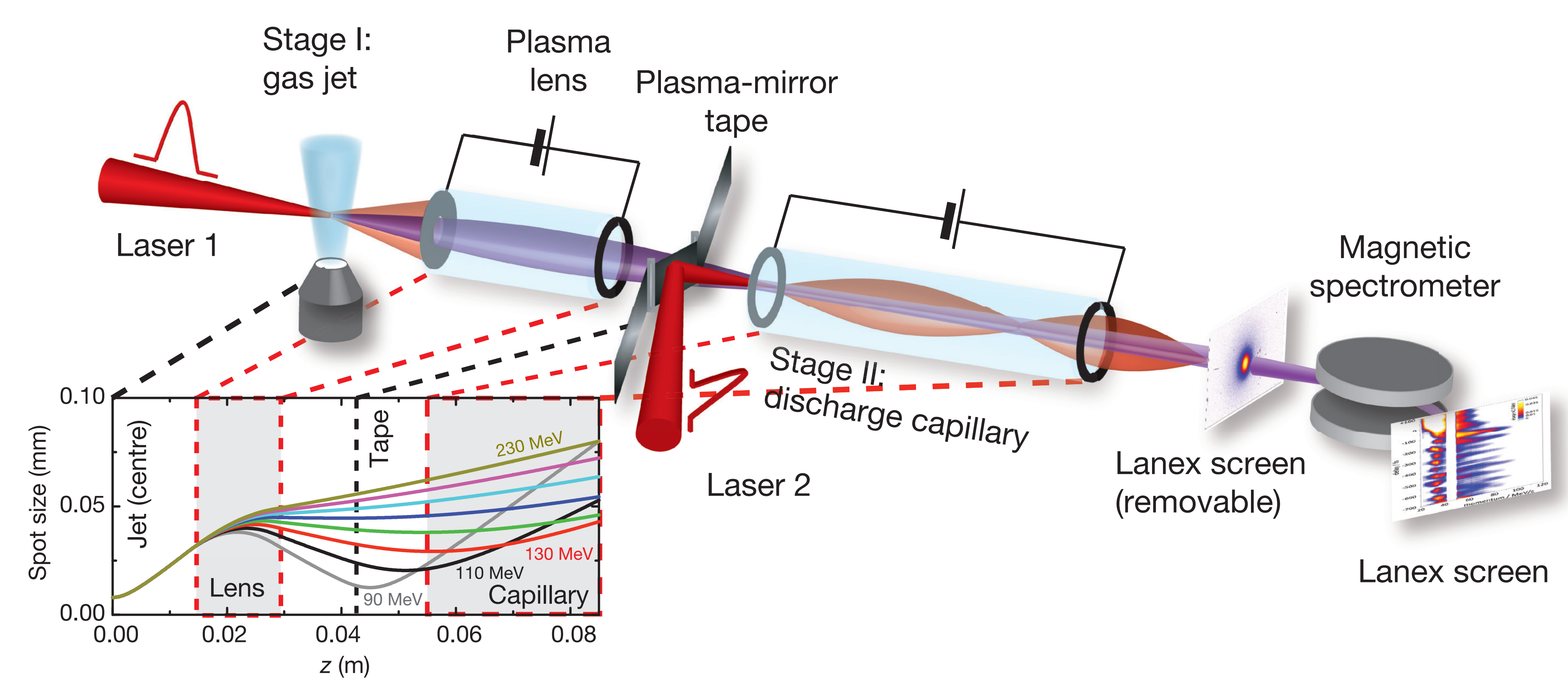


Image source: S. Steinke et al., Nature 530, 190–193 (2016)

ACTIVE PLASMA LENSING — PROBLEM 1: TEMPERATURE NON-UNIFORMITIES

> Radial temperature non-uniformity – leads to nonlinear magnetic field profile

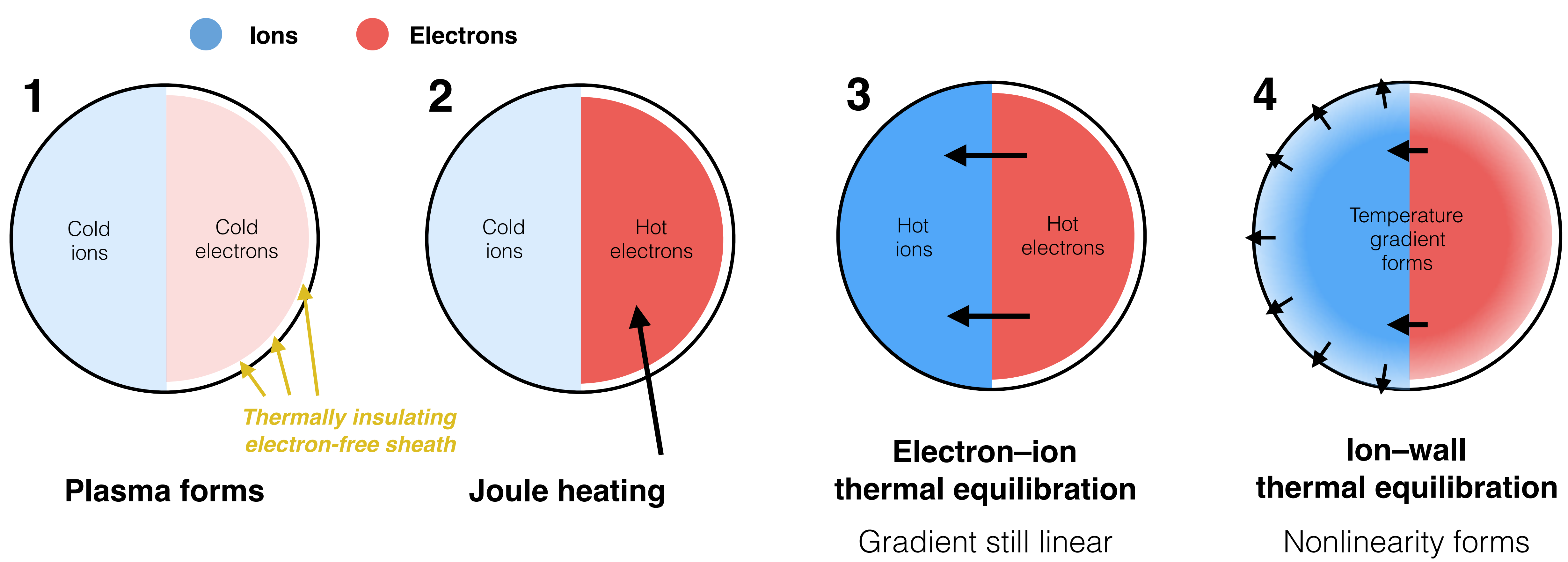
⇒ Emittance growth or reduced aperture

> Can be solved using a high-Z gas species (argon instead of hydrogen/helium)

> However, high-Z gases lead to increased gas scattering:

> Can reduce scattering by using shorter, stronger lenses

$$\frac{d\epsilon_n}{ds} = \frac{4\pi r_e^2 n_0 \beta_x}{\gamma}\left(Z_i^2 \ln\left(\frac{\lambda}{R_a}\right) + 1.64Z(Z+1)\ln\left(\frac{287}{\sqrt{Z}}\right)\right)$$



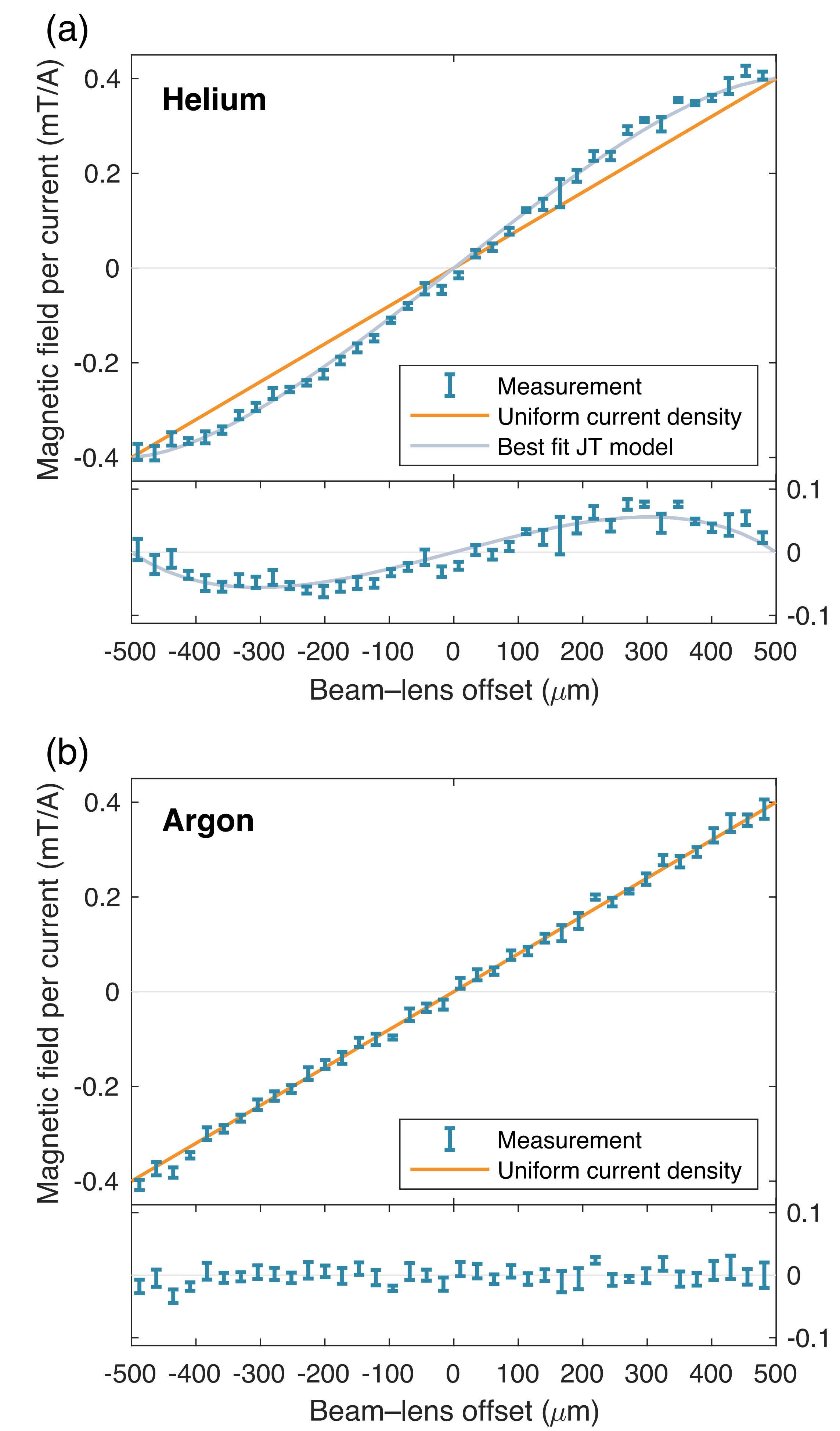


Image source: C. A. Lindstrøm et al., Phys. Rev. Lett. 121, 194801 (2018)

ACTIVE PLASMA LENSING — Z-PINCHING

> **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).

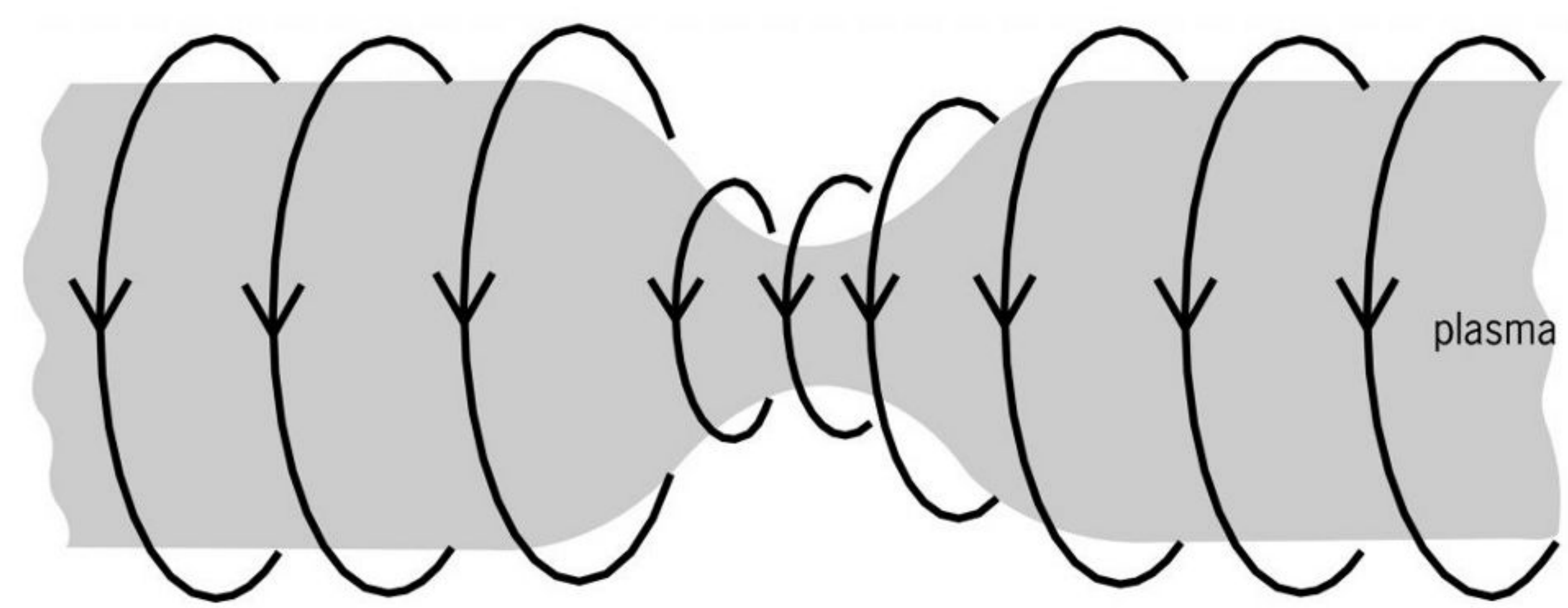
> Sets **limit to maximum current** (and therefore focusing gradient)

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

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

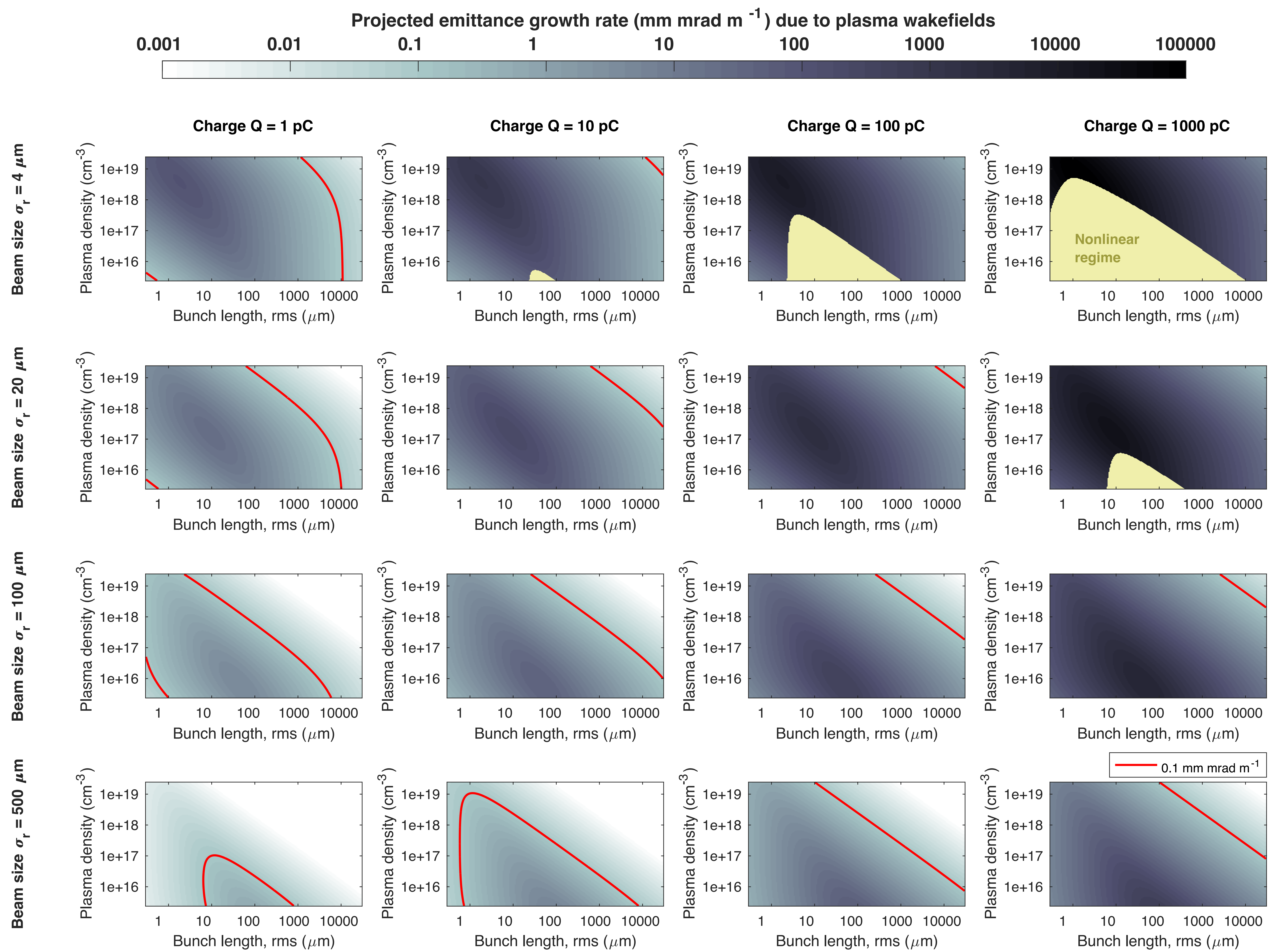
> Being addressed in experiments at CLEAR

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

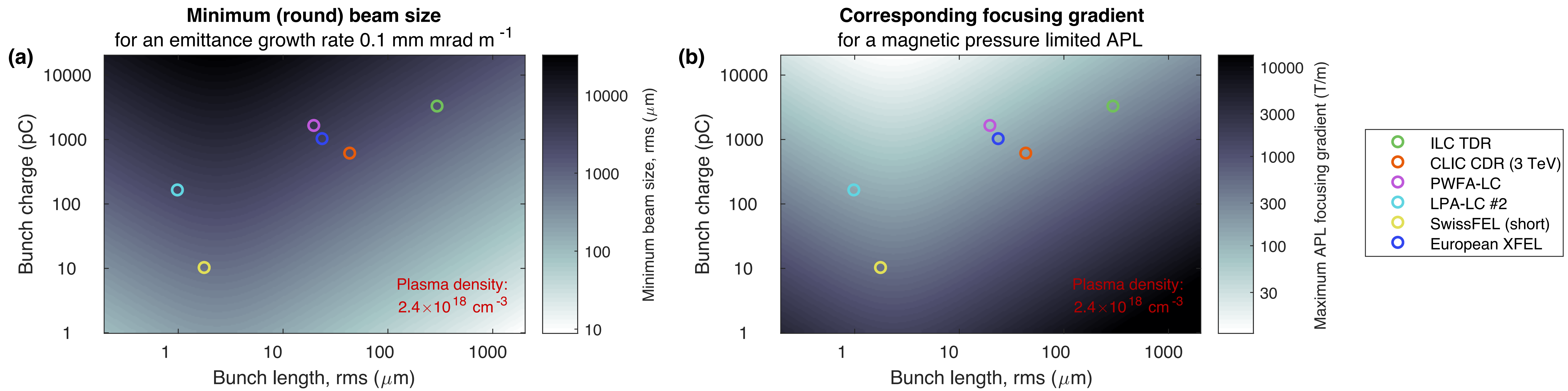


$$\frac{B_\phi^2}{2\mu_0} < n_0 k_B T$$

ACTIVE PLASMA LENSING — PASSIVE PLASMA LENSING DISTORTIONS



Active plasma lensing — Passive plasma lensing distortions



Machine	ILC TDR	CLIC CDR	PWFA-LC 1 TeV	LP-LC Ex. 1	SwissFEL CDR	XFEL TDR	LHC 13 TeV
Final beam energy (GeV)	250	1500	1500	500	5.8	20	6500
Charge per bunch (pC)	3200	595	1600	160	10	1000	18400
Bunch length, rms (μm)	300	44	20	1	1.8	24	7.6×10^4
Normalized emittance, x/y (μm rad)	10/0.035	0.66/0.02	10/0.035	1/0.01	0.25	1.4	3.75
Considerations for a magnetic pressure limited active plasma lens with a minimum diameter 250 μm							
Beam size (μm) for 10% m^{-1} emit. growth in y	524	2270	1440	2420	1400	2740	16.4
Corresponding APL gradient (T/m)	650	150	236	140	243	124	13600
Vertical beta function at final energy (m)	3.8×10^6	7.6×10^8	1.7×10^8	5.7×10^8	8.9×10^4	2.1×10^5	1.0

Source: Lindstrøm and Adli, arXiv:1802.02750 (2018)

> Linear colliders: intense beams — short bunches, high charge per bunch

> Plasma density can be chosen at will — high density more optimal for bunches longer than ~1 μm

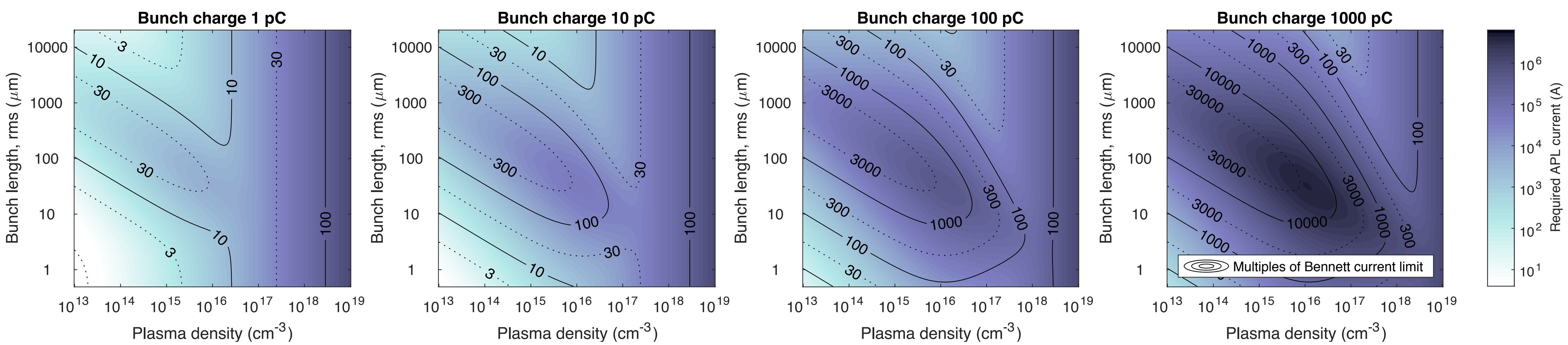
> To avoid large emittance growth, the beam size must be increased (see Figure)

> **Conclusion: For all machines, the required minimum beam size is FAR TOO LARGE (huge beta functions)**

> Possible solutions: Ultra-strong/fast discharges (short lenses). Multi-bucket bunch trains of lower intensity? Ultra-short beams?

ACTIVE PLASMA LENSES — ALIC APPLICATIONS BEYOND STAGING

> **Low chromaticity final focusing** (radial focusing can significantly increase energy acceptance)
⇒ May shorten final focus significantly, and allow larger energy spread required for BNS damping



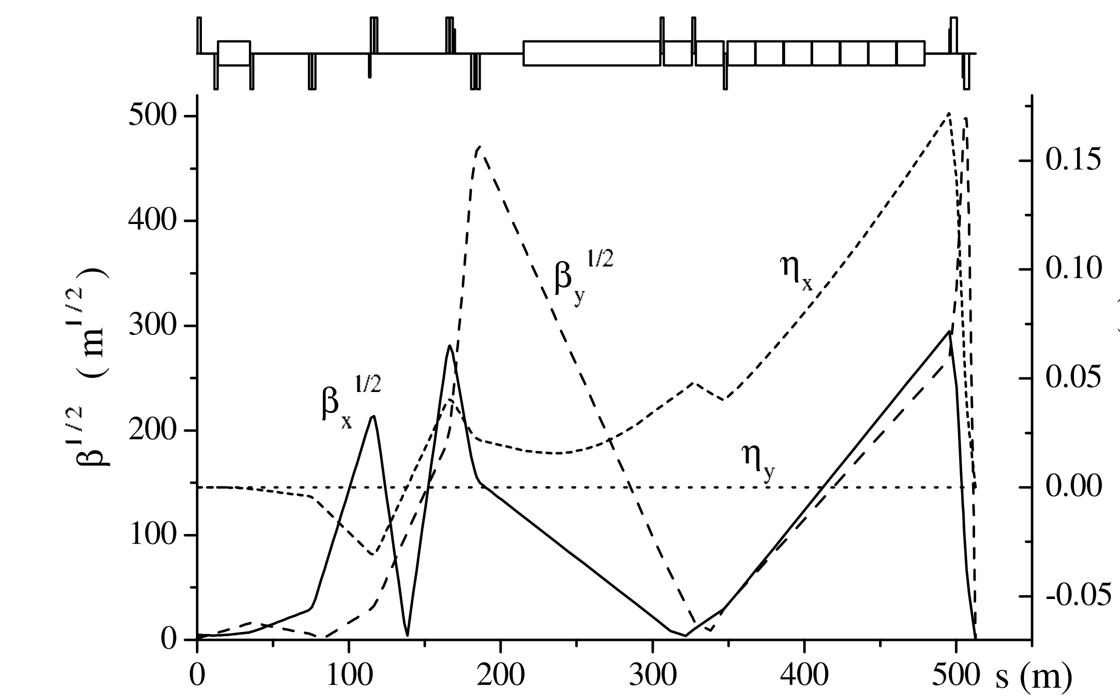
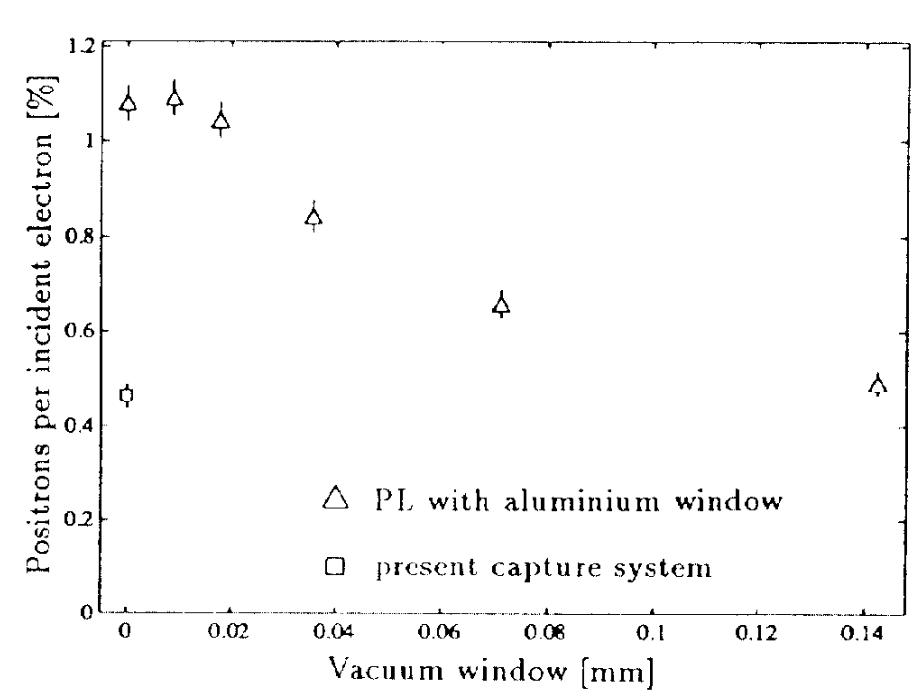


Image source: C. A. Lindstrøm, PhD thesis (University of Oslo, 2019)

Image source: P. Raimondi and A. Seryi, Phys. Rev. Lett. 86, 3779 (2001)

> **High-yield positron sources** (very compact, double energy acceptance, electron filtering, low phase slippage)
⇒ Mentioned as an important goal for ALEGRO – could be done at CLEAR or eSPS



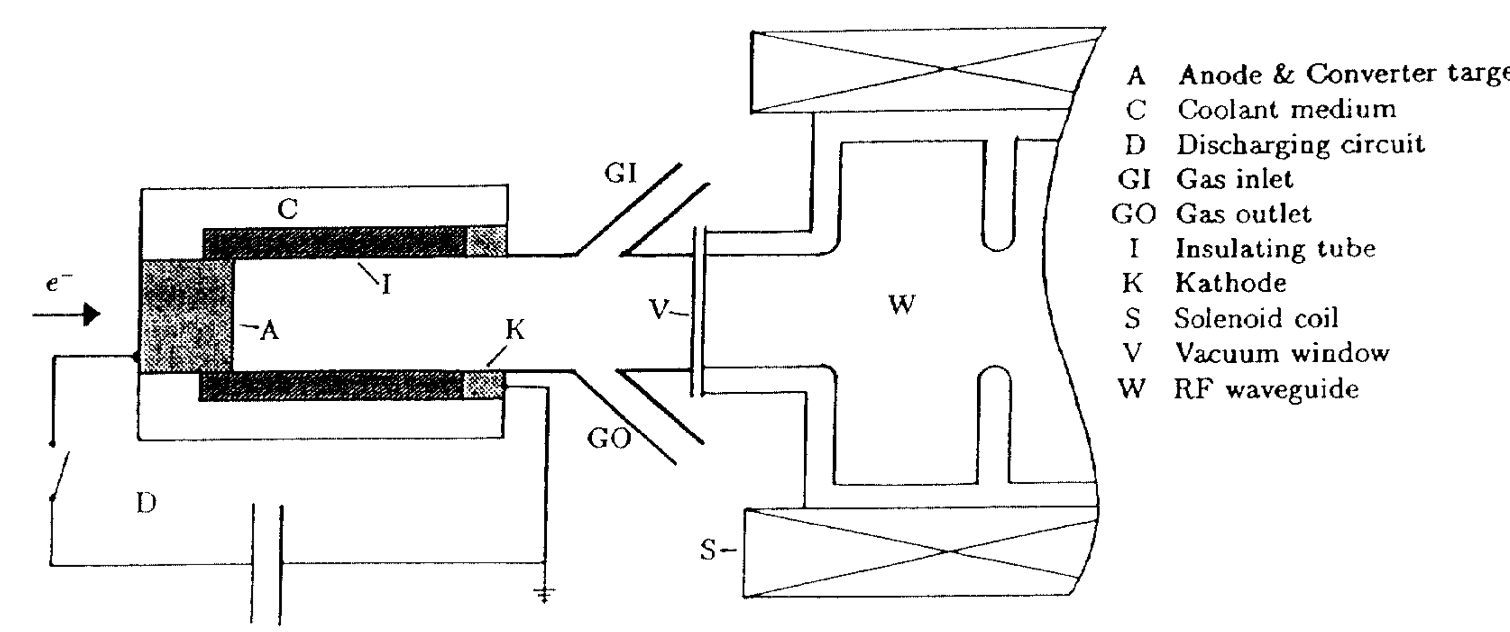


Image source: Braun et al., Proceedings of EPAC1992 (1992), p. 1650.

Fundamental question: Plasma lenses and ALIC

> **Strong focusing** and non-negligible energy spread/chirp **is needed in any high gradient accelerator** to avoid transverse wakefields and beam breakup

> Avoiding significant divergence of the beam to **avoid emittance growth from chromaticity** in staging – requires **strong lensing**

> Requires: Ultra-strong (small-scale) quadrupoles, or ideally **radial focusing** = plasma lensing

> Fundamentals problem with **passive plasma lenses**:

  > Emittance growth from **longitudinally/transversely nonuniform focusing** — unless in a blowout with a driver

  > Ion column does not work for **positrons**, suck-in regime leads to transverse beam loading for efficient beams

  > Beam-based: Not suitable for systems with few nm-level misalignment tolerances

> Fundamental problem with **active plasma lenses**:

  > **Intense bunches in the accelerator + no significant divergence** (no chromaticity) = Intense bunches in APL

  > **Drives wakefields**: no longer functions as an active plasma lens (see passive plasma lens problems above)

> **Conclusion: Active/passive plasma lensing is technologically promising, but face fundamental issues related to ALIC.**

> Is there any way around this problem?   No staging? Fewer, longer stages? Low intensity bunch trains?

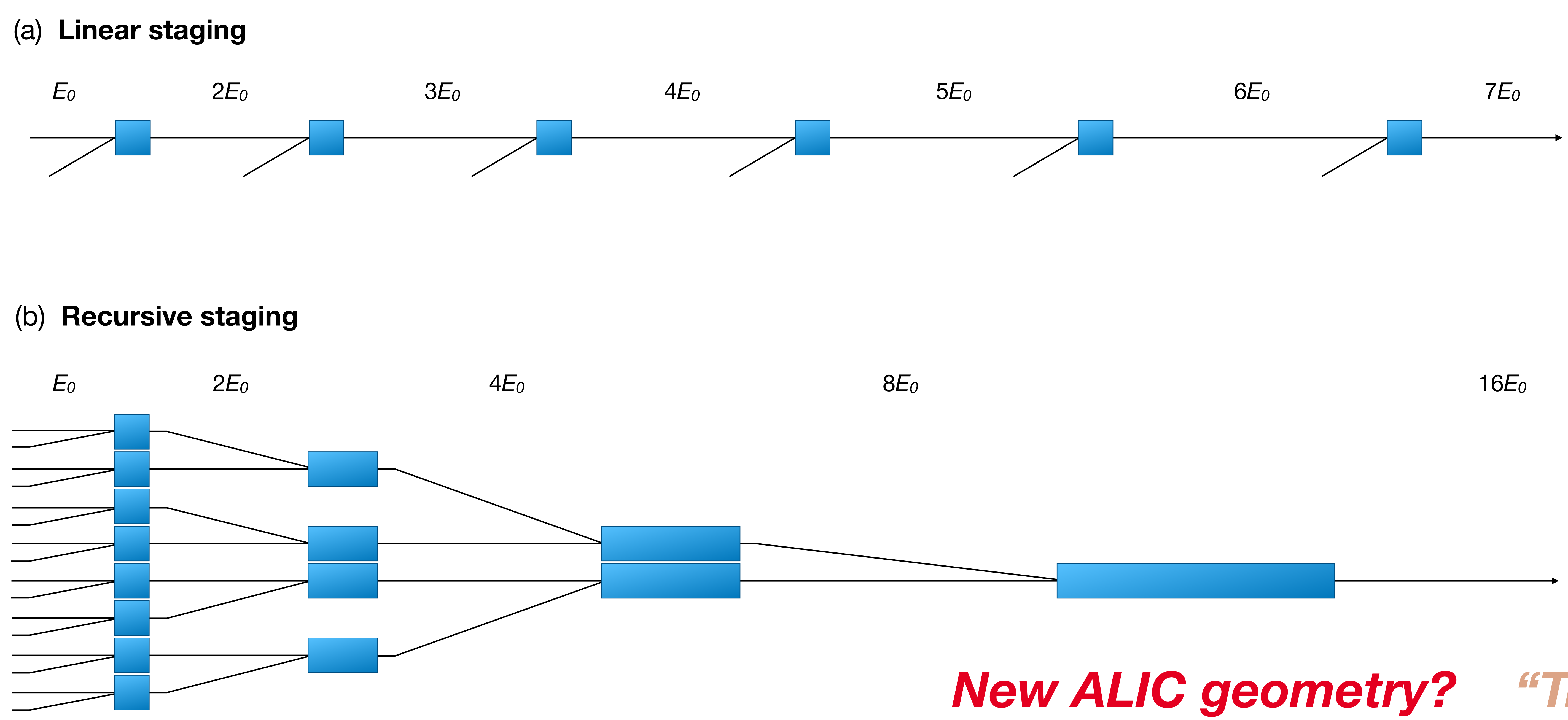
Possible direction for fewer, longer stages — Recursive staging

> Use PWFA recursively for increasing driver energy — fewer, longer accelerator cells (allows longer interstages)

> A solution for staging-limited accelerators (= high-gradient accelerators?) — not for length, but for emittance growth

> **Important requirement: high driver-to-witness energy and efficiency.**

> Limits transformer ratio = 1? Only possible for beam driven accelerators?



New ALIC geometry? “Tree collider”?


THANKS FOR LISTENING!