ALEGRO Workshop
Oxford | March 27th, 2018

Staging and coupling of plasma accelerators

in WG4 - laser-driven wakefield acceleration

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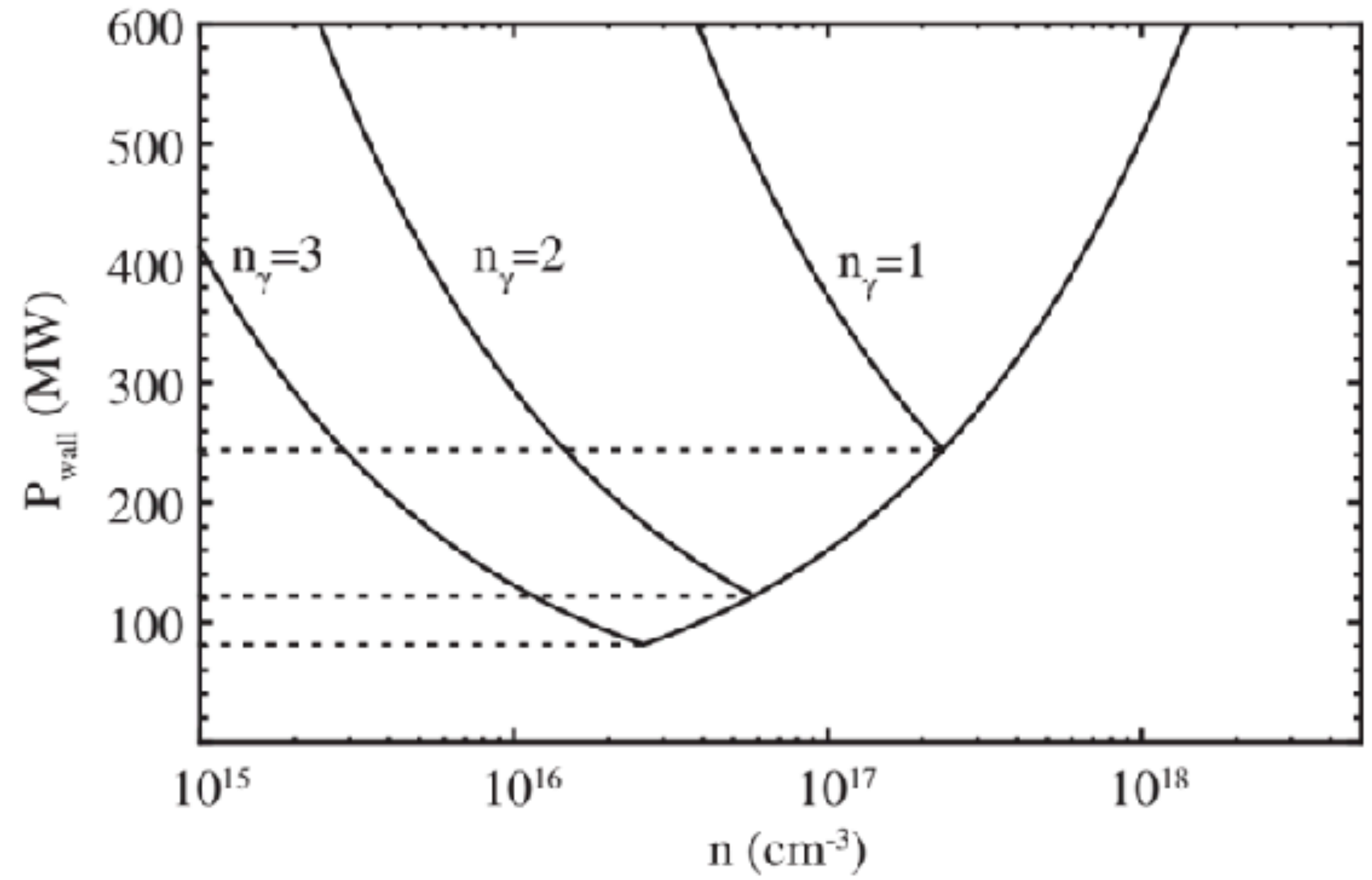
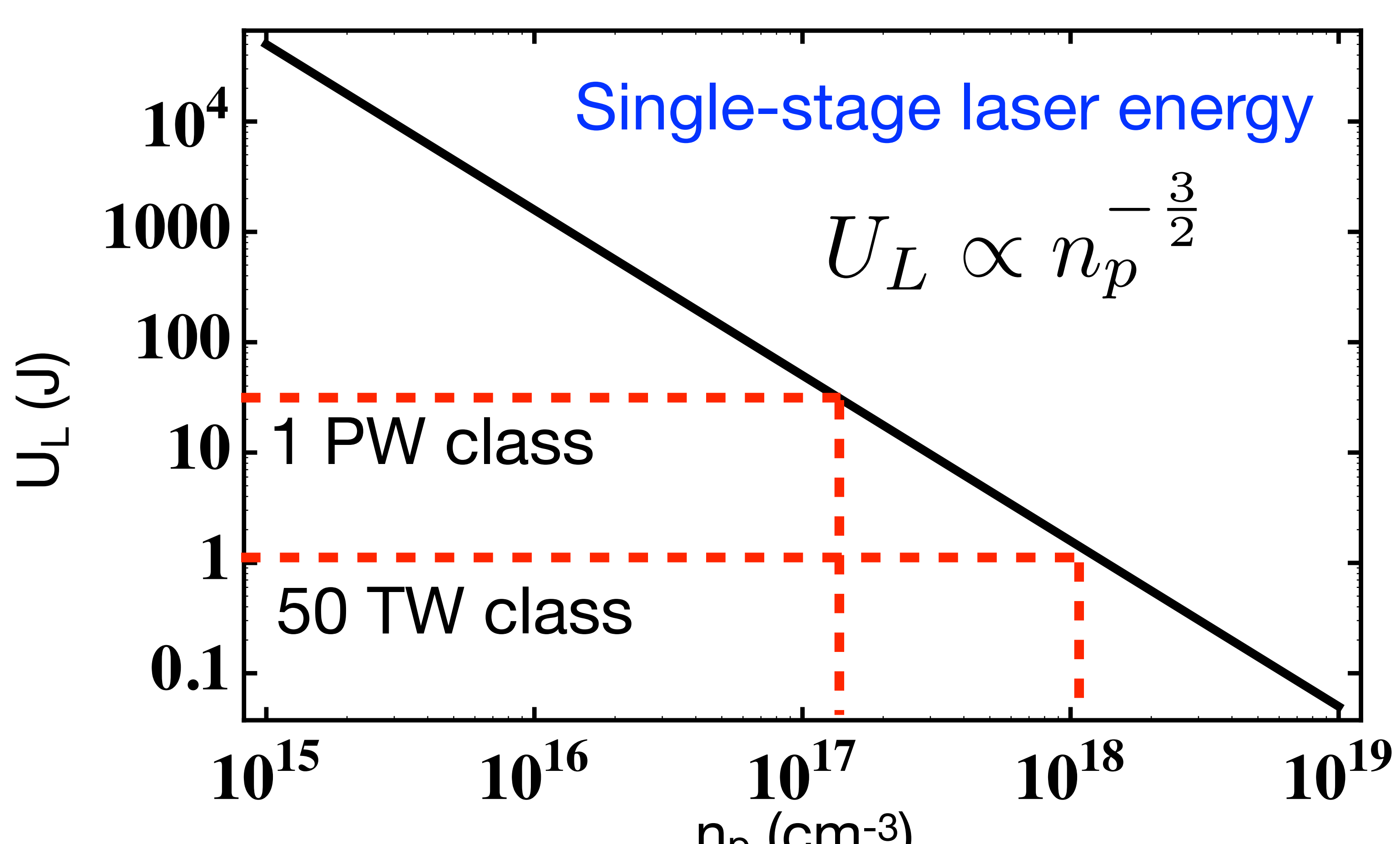
Energy gain per LWFA stage limited by depletion

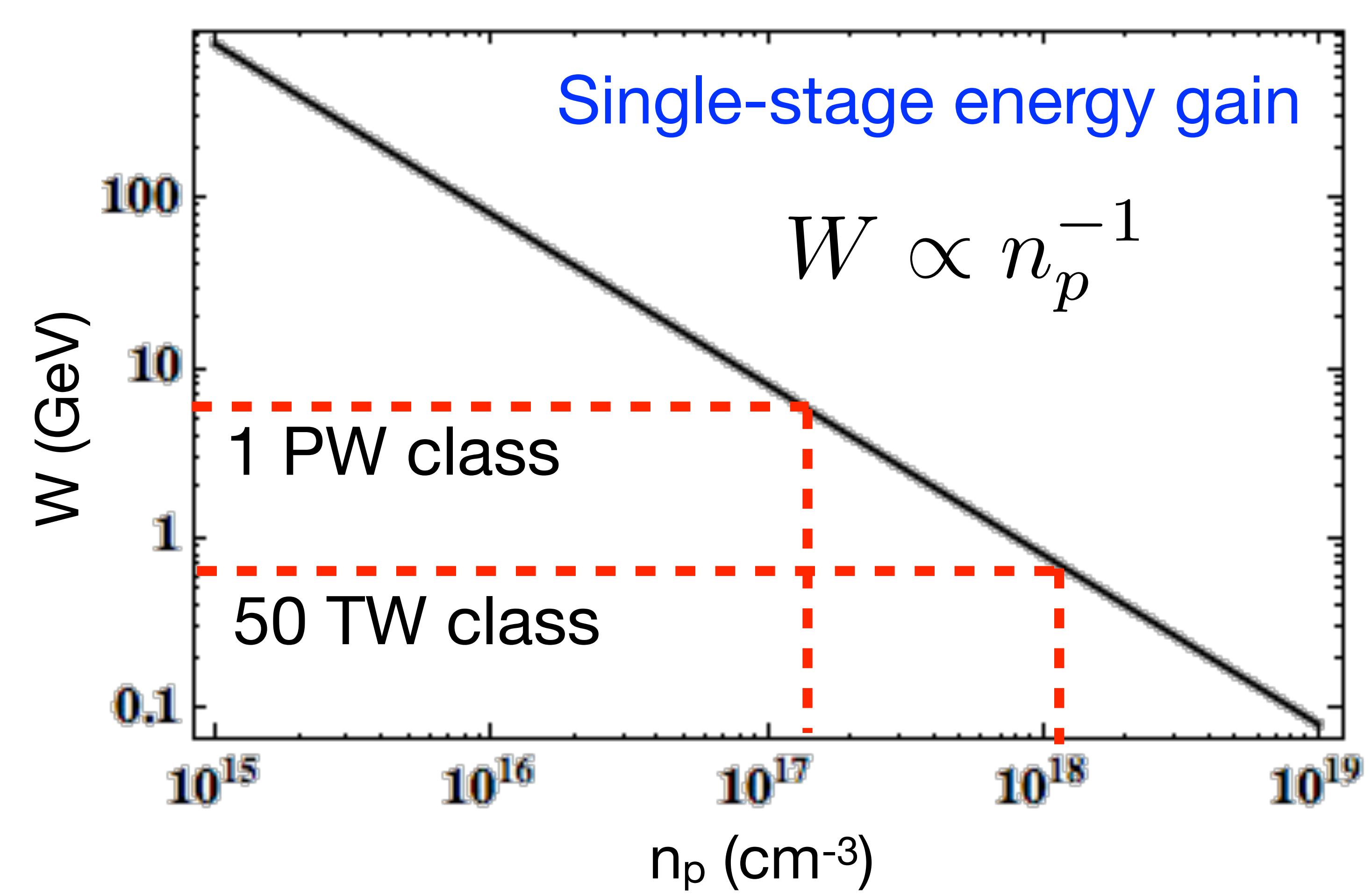
STAGING REQUIRED TO GO BEYOND ENERGY RANGE OF ORDER 10 GEV (WITH MODERN LASER TECHNOLOGY)



10 GeV energy gain per stage seems good compromise, will use collider parameters from

→ C.B. Schroeder *et al.*, Phys. Rev. STAB **15**, 051301 (2012)



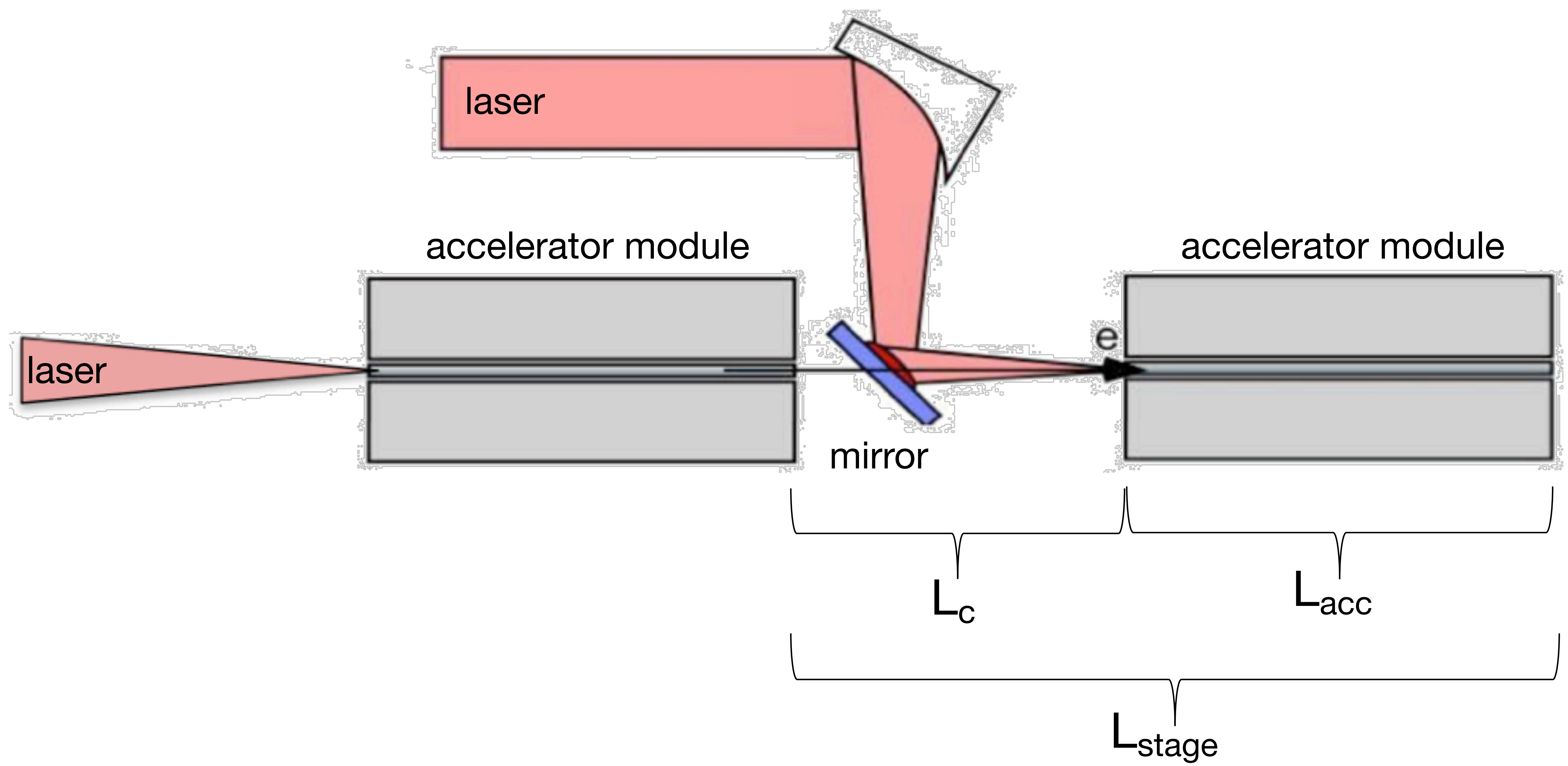


Coefficients determined from simulations in the quasi-linear regime ($a_0 = 1.5$)

by courtesy of C.B. Schroeder

Definition of staging

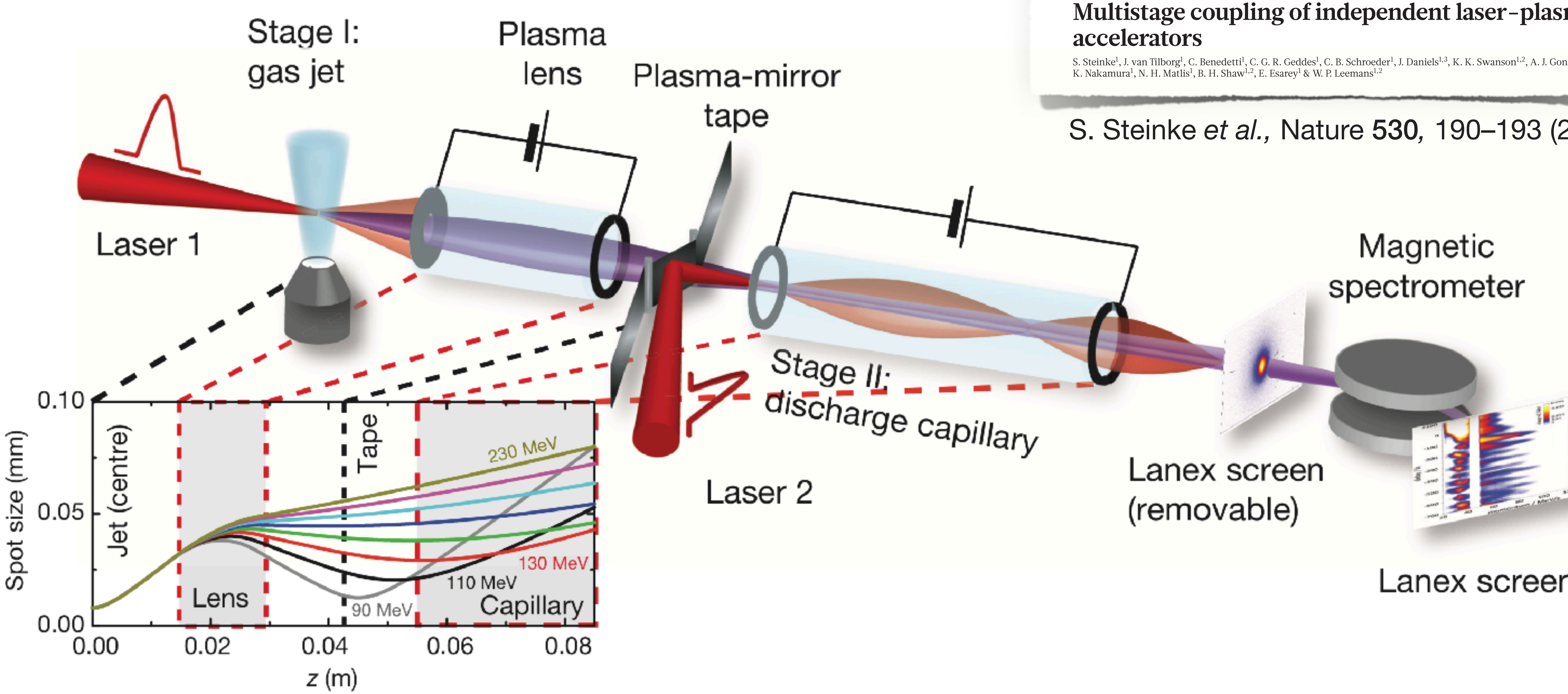
STAGING REQUIRES A FRESH WAKEFIELD DRIVER PER STAGE



This presentation will (mostly) focus on what happens between the accelerator modules…

Staging concept demonstrated at Berkeley Lab

Deployed setup contains all crucial ingredients, needs further refinement for collider application




LETTER

doi:10.1038/nature16525

Multistage coupling of independent laser–plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]

S. Steinke *et al.*, Nature **530**, 190–193 (2016)

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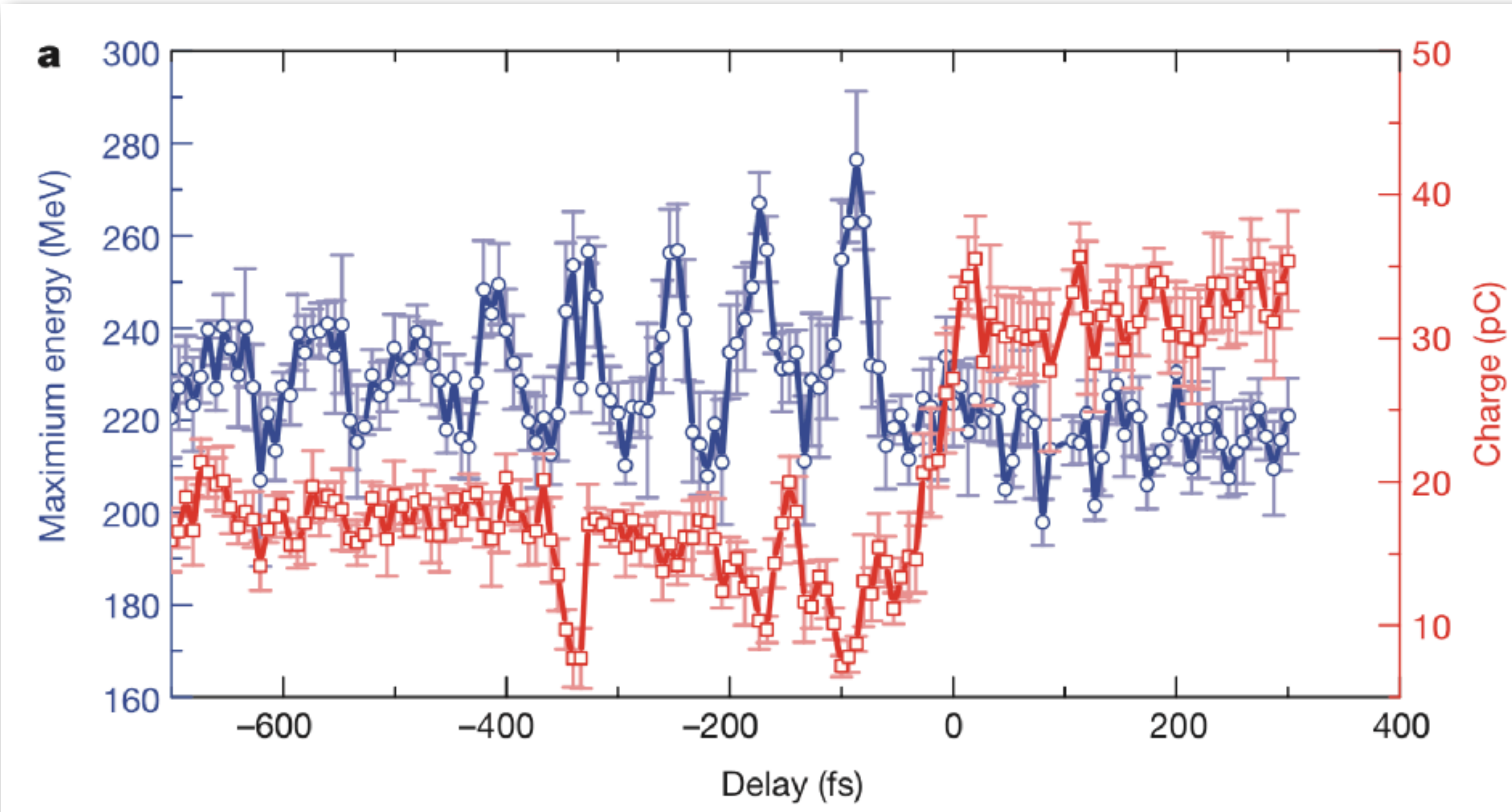


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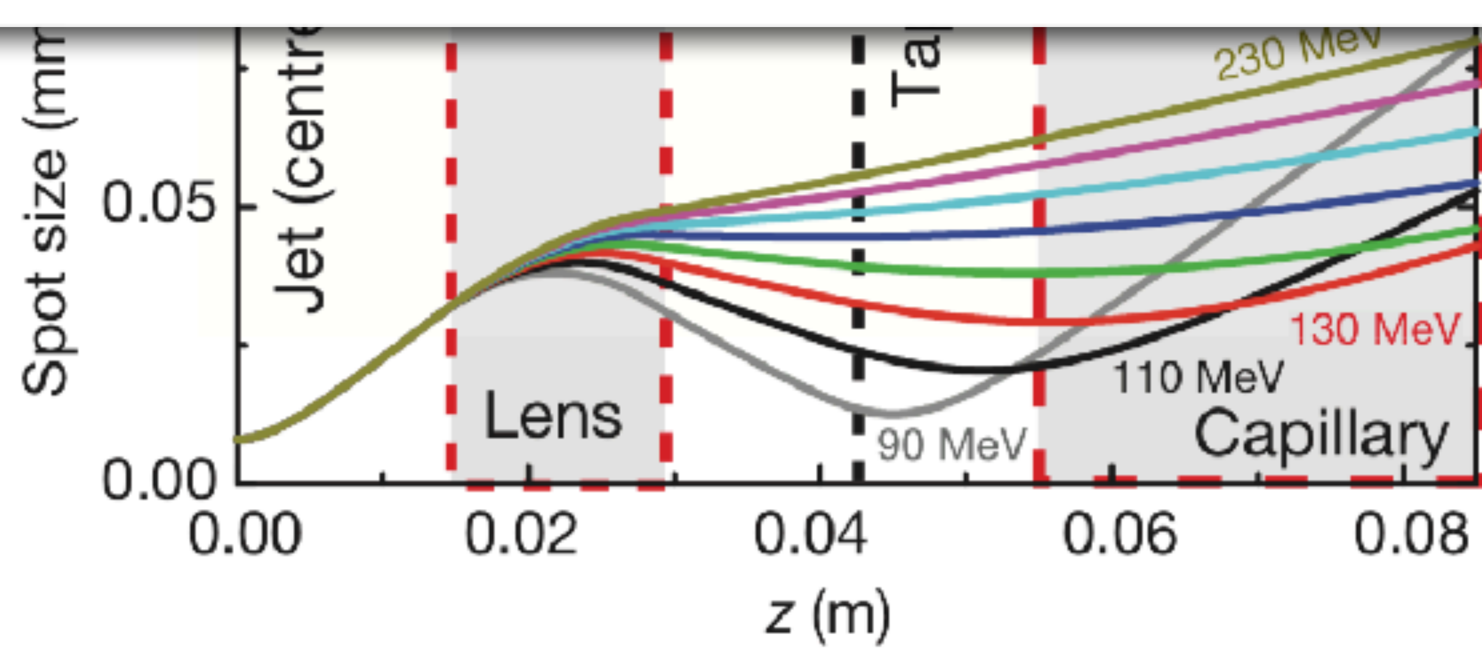
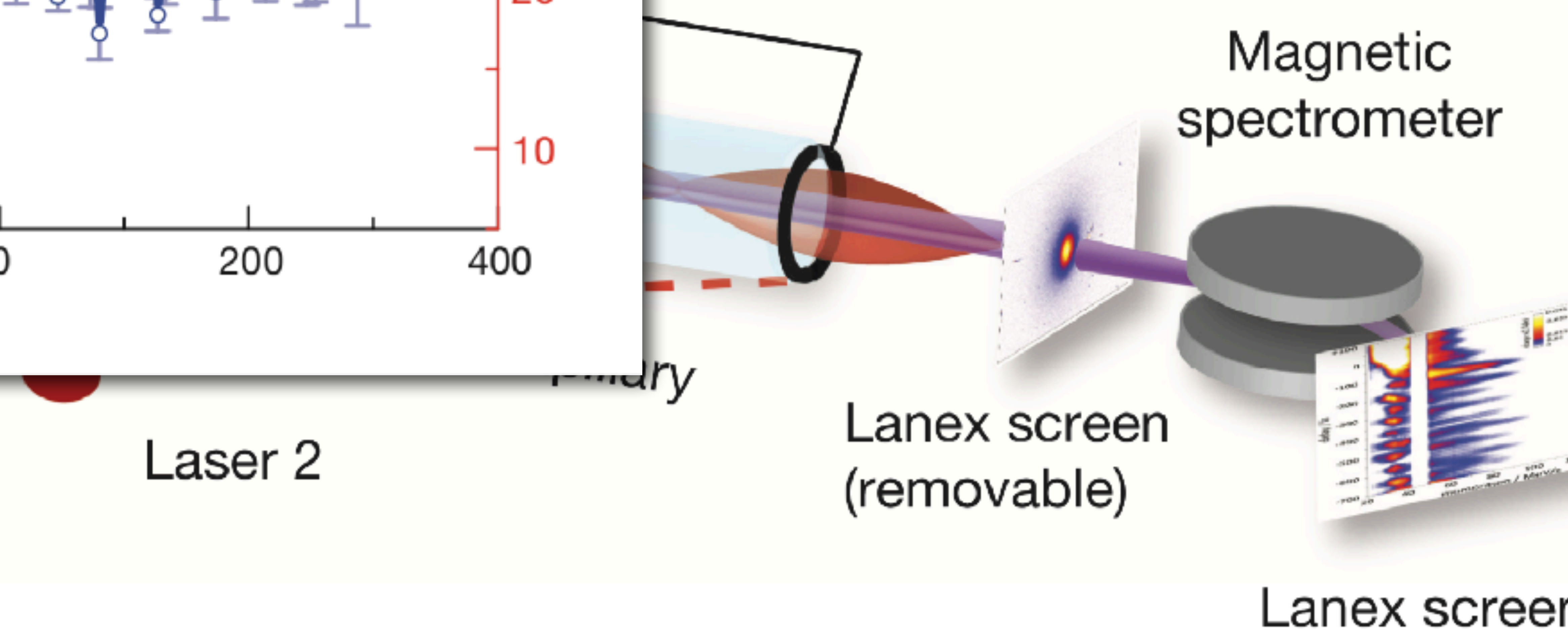




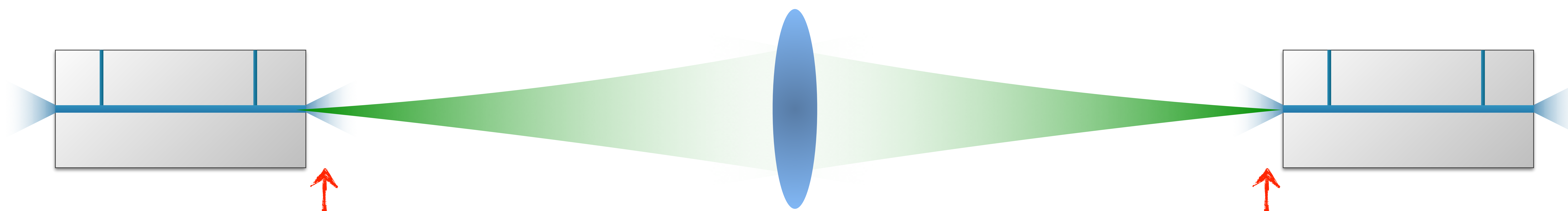
Staging demands for collider application

GOING BEYOND WHAT HAS BEEN DEMONSTRATED

- Preservation of bunch charge → efficiency → operation cost
- Preservation of normalized transverse emittance on ~10 nm level → spot size at IP → luminosity
- Operation at high repetition rate and average power → luminosity
- Limited inter-stage distance to keep effective gradient > 1 GV/m, implying < 1 km/TeV → construction cost

Compact, emittance-conserving interstage beam transport

I. Particle beam transport



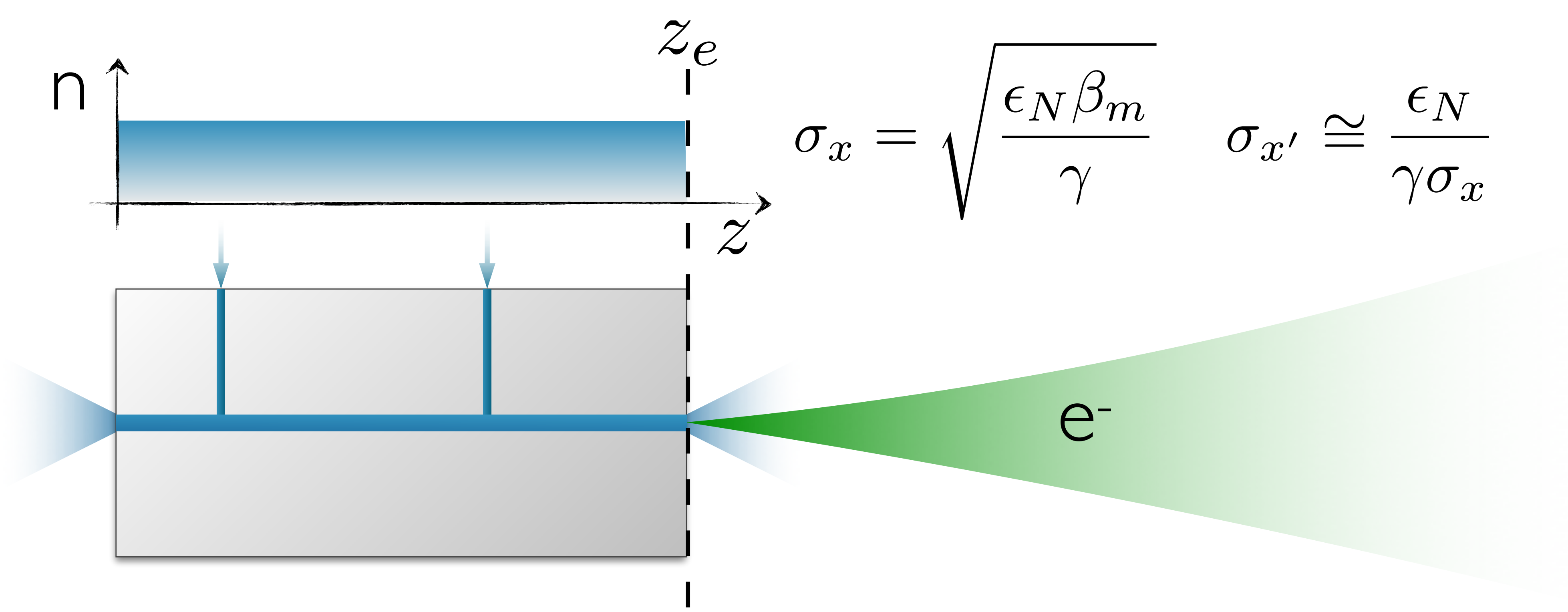
Beam release
- chromatic emittance growth in drift

Beam injection
- matching for emittance conservation

Beam optics
- nonlinear fields → emittance growth
- field gradient × length → coupling distance

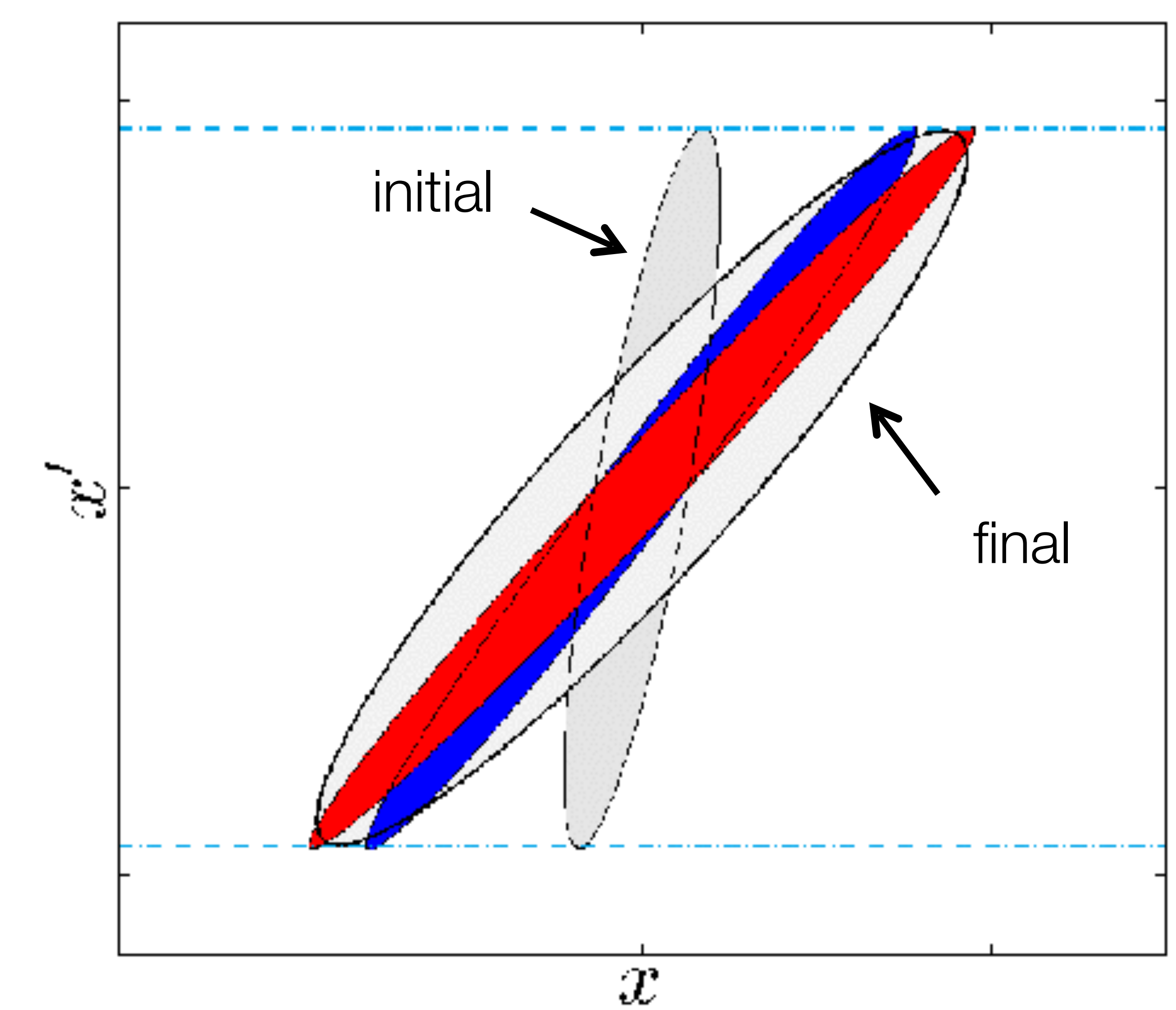
Beam release from plasma

I. PARTICLE BEAM TRANSPORT



$$\sigma_x = \sqrt{\frac{\epsilon_N \beta_m}{\gamma}} \qquad \sigma_{x'} \cong \frac{\epsilon_N}{\gamma \sigma_x}$$

Phase space ellipses during drift



- beams at plasma exit
  - finite energy spread
  - finite emittance and matched β → finite divergence
- leads to growth of transverse emittance in free drift

$$\epsilon_N^{*\,2}(z) \cong \epsilon_N^2 + \gamma^2 \frac{\sigma_p^2}{p^2} \sigma_{x'}^4 z^2$$

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

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

Beam release from plasma

I. Particle beam transport

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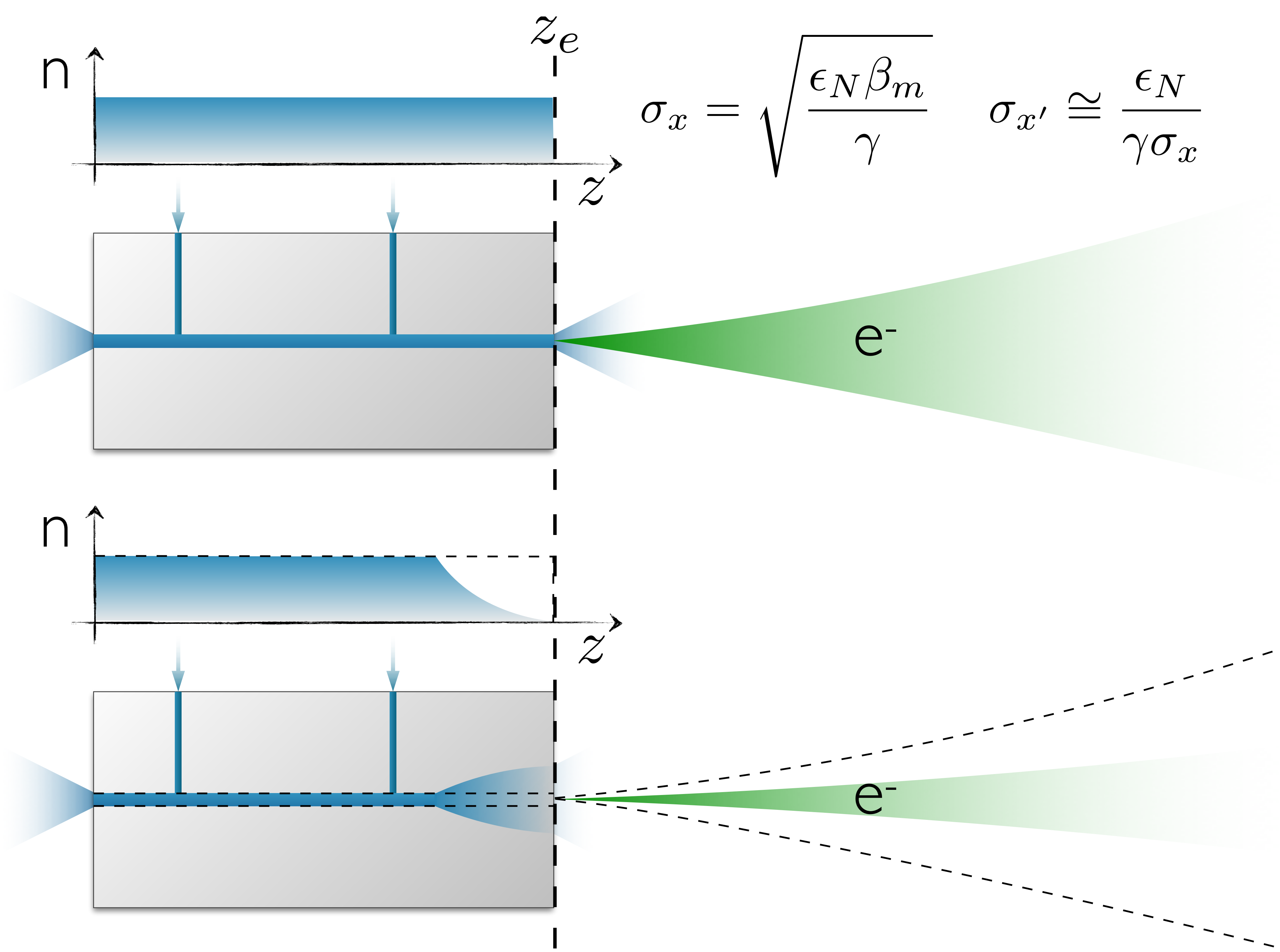
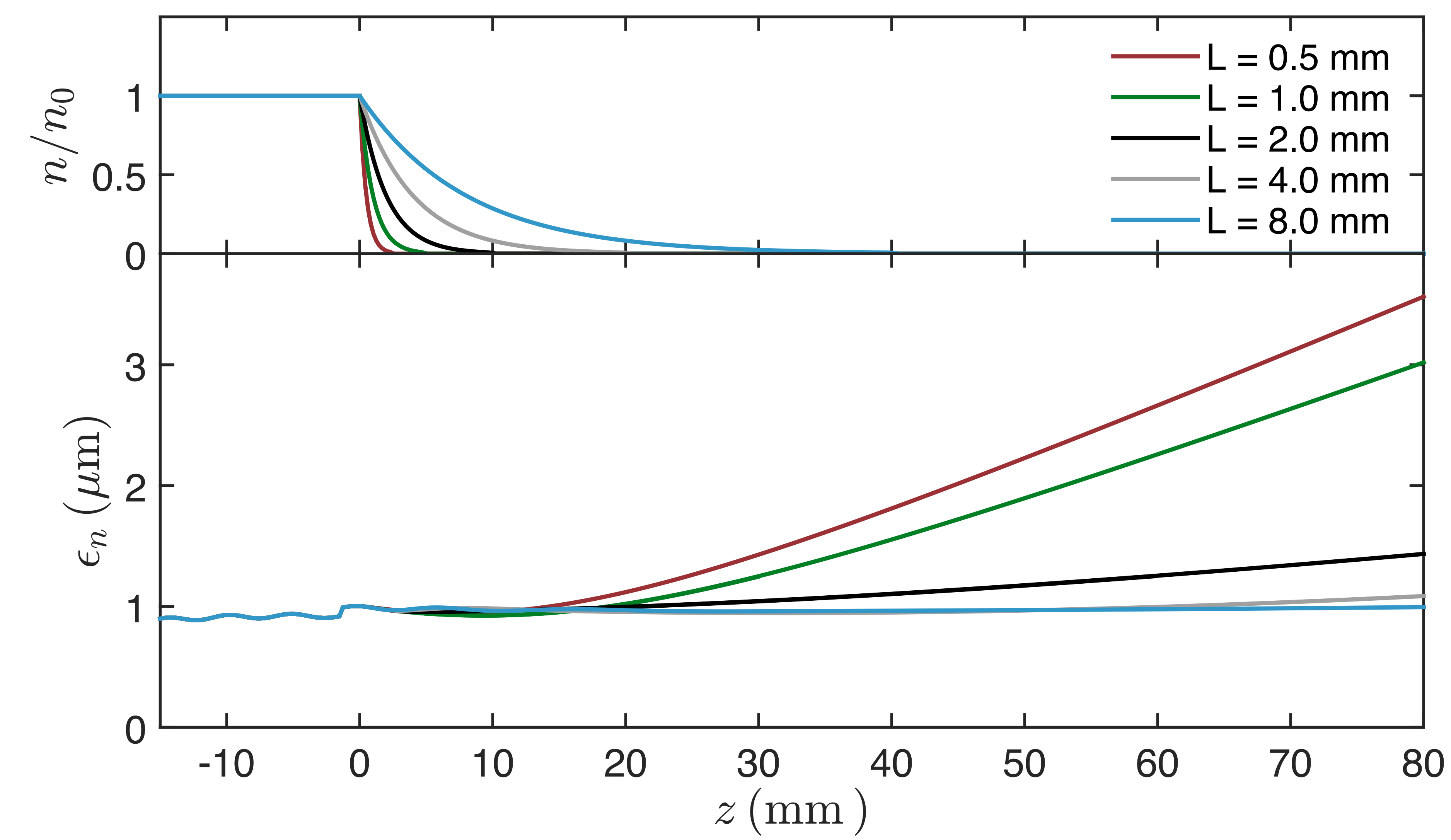


Emittance growth depends on transition length



- Plasma-to-vacuum transition » β for adiabatic release
- Strong focussing for beam capturing required

$$\epsilon_N^{*\,2}(z) \cong \epsilon_N^2 + \gamma^2 \frac{\sigma_p^2}{p^2} \sigma_{x'}^4 z^2$$

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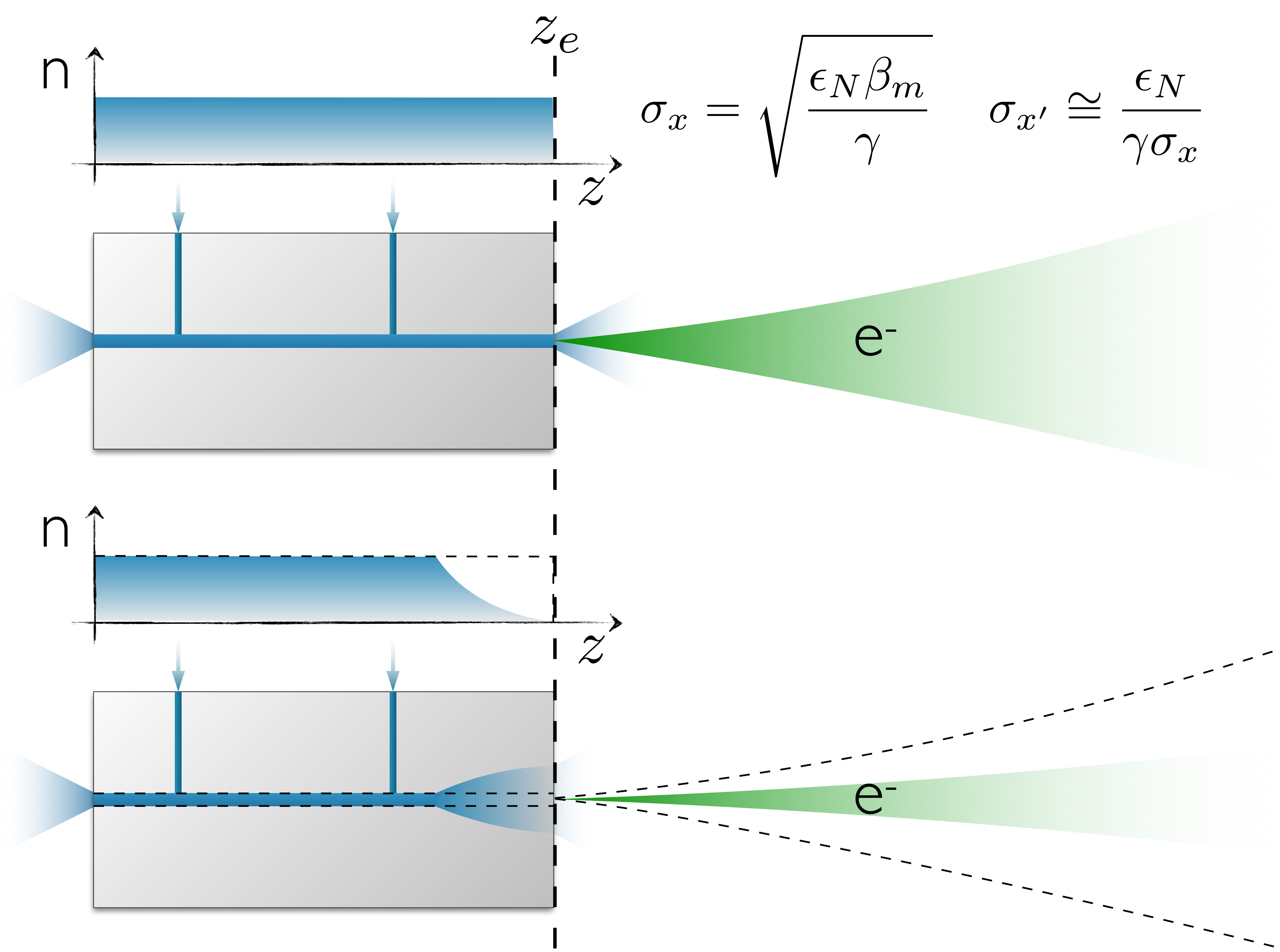

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Case: $n_e = 10^{17}$ cm^{-3}, ϵ_N = 10 nm, σ_p/p = 0.5%

- **10 GeV stage**
  - → $\beta_m \approx$ 3 mm, $\sigma_x \approx$ 40 nm, $\sigma_{x'} \approx$ 10 μrad
  - → **10 nm / m emittance growth in drift**
- **1 TeV stage**
  - → $\beta_m \approx$ 30 mm, $\sigma_x \approx$ 10 nm, $\sigma_{x'} \approx$ 0.3 μrad
  - → **1 nm / m emittance growth in drift**

$$\epsilon_N^{*\,2}(z) \cong \epsilon_N^2 + \gamma^2 \frac{\sigma_p^2}{p^2} \sigma_{x'}^4 z^2$$

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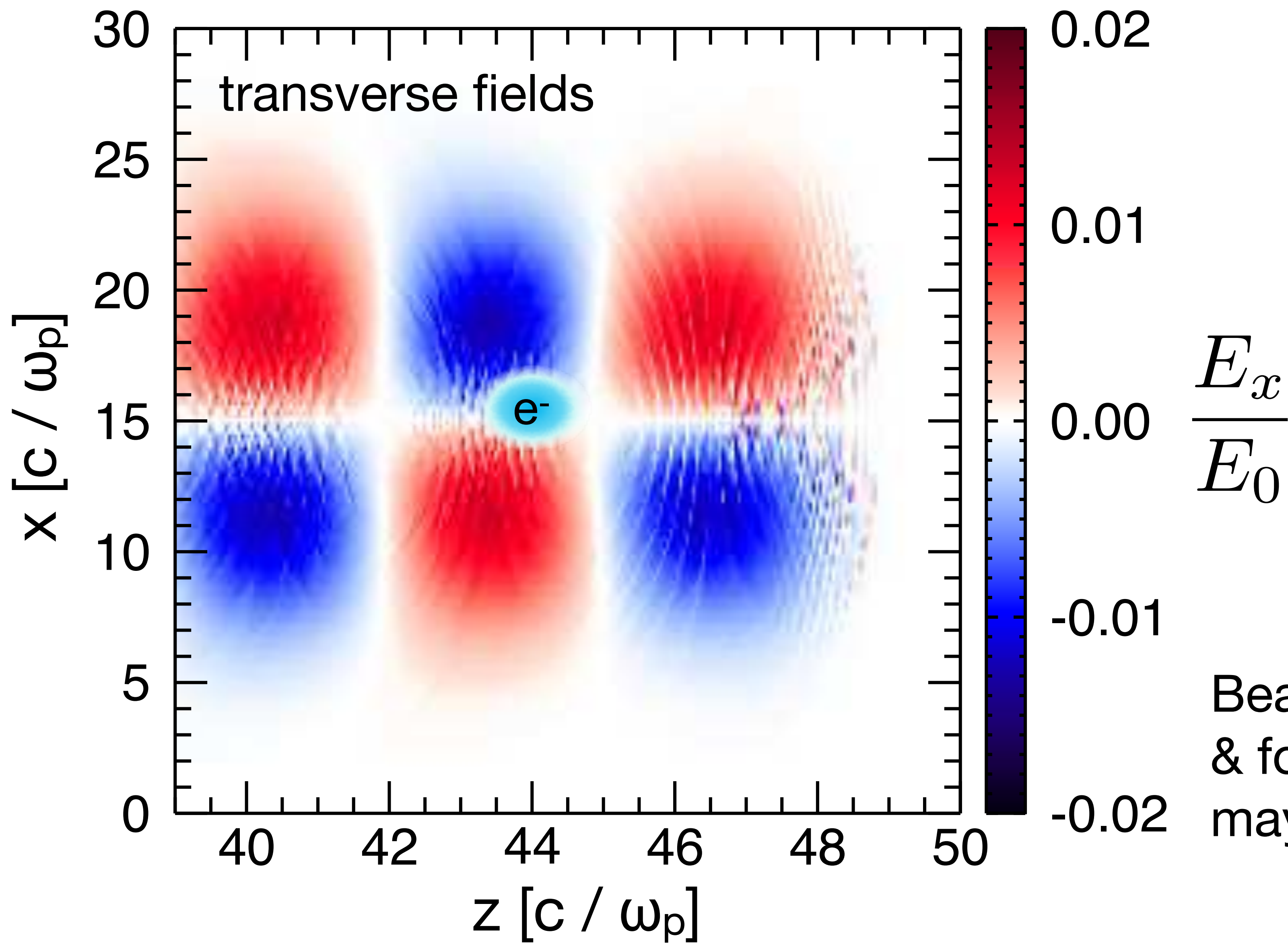
Beam matching into plasma

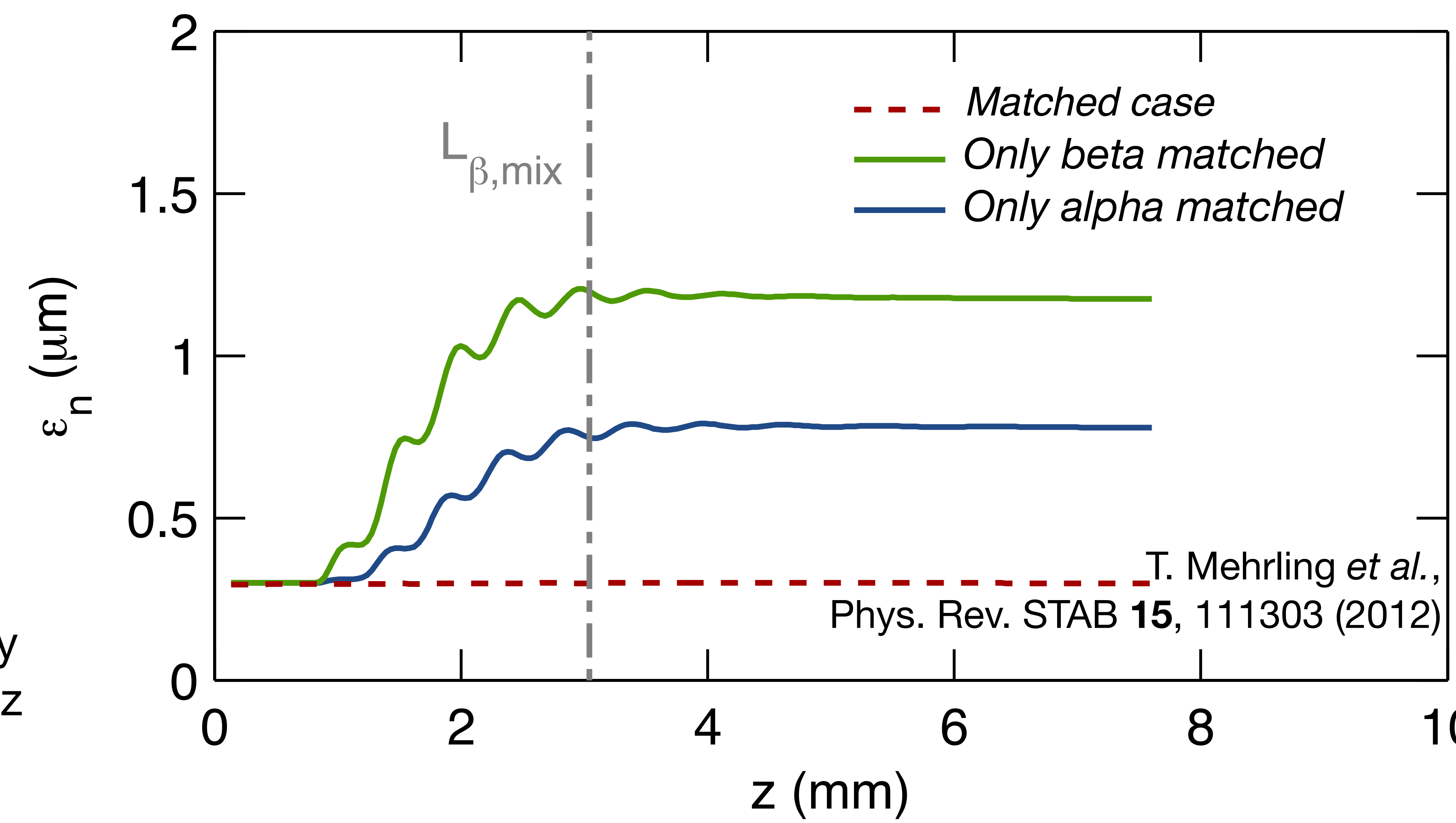
I. Particle beam transport



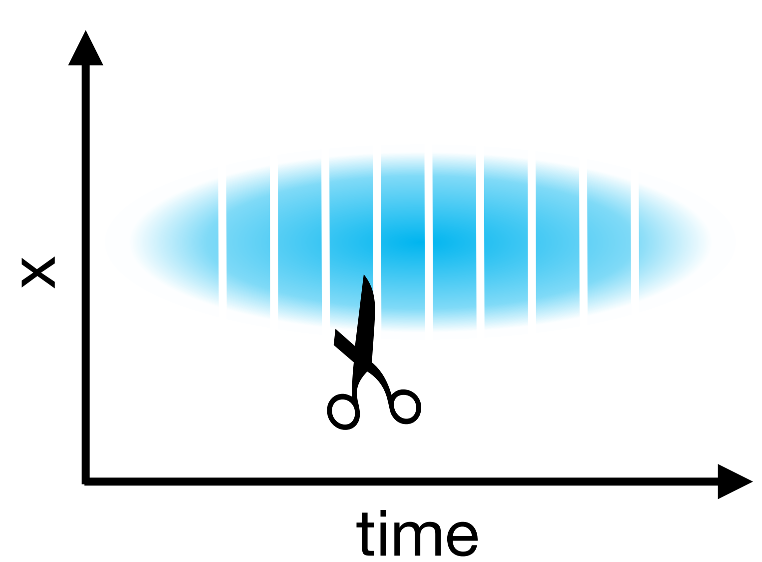
Beam particle energy & focusing forces in z may vary in plasmas

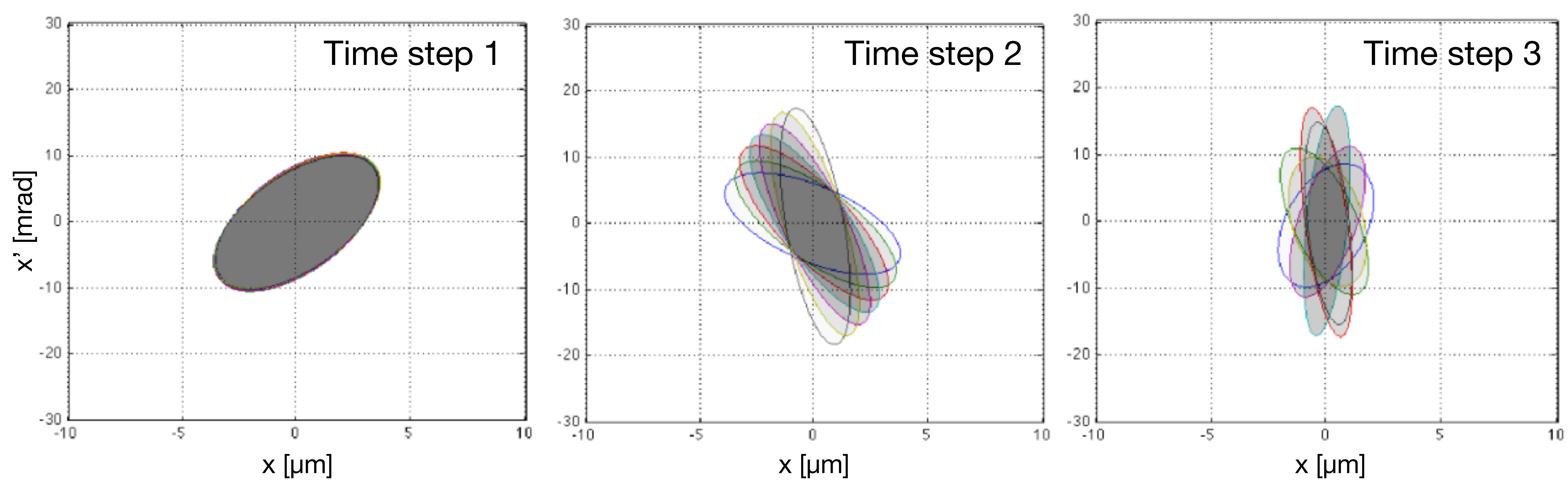
Matching conditions

$$\alpha_m = 0 \qquad \beta_m \simeq \frac{c}{\omega_\beta} \qquad \omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$



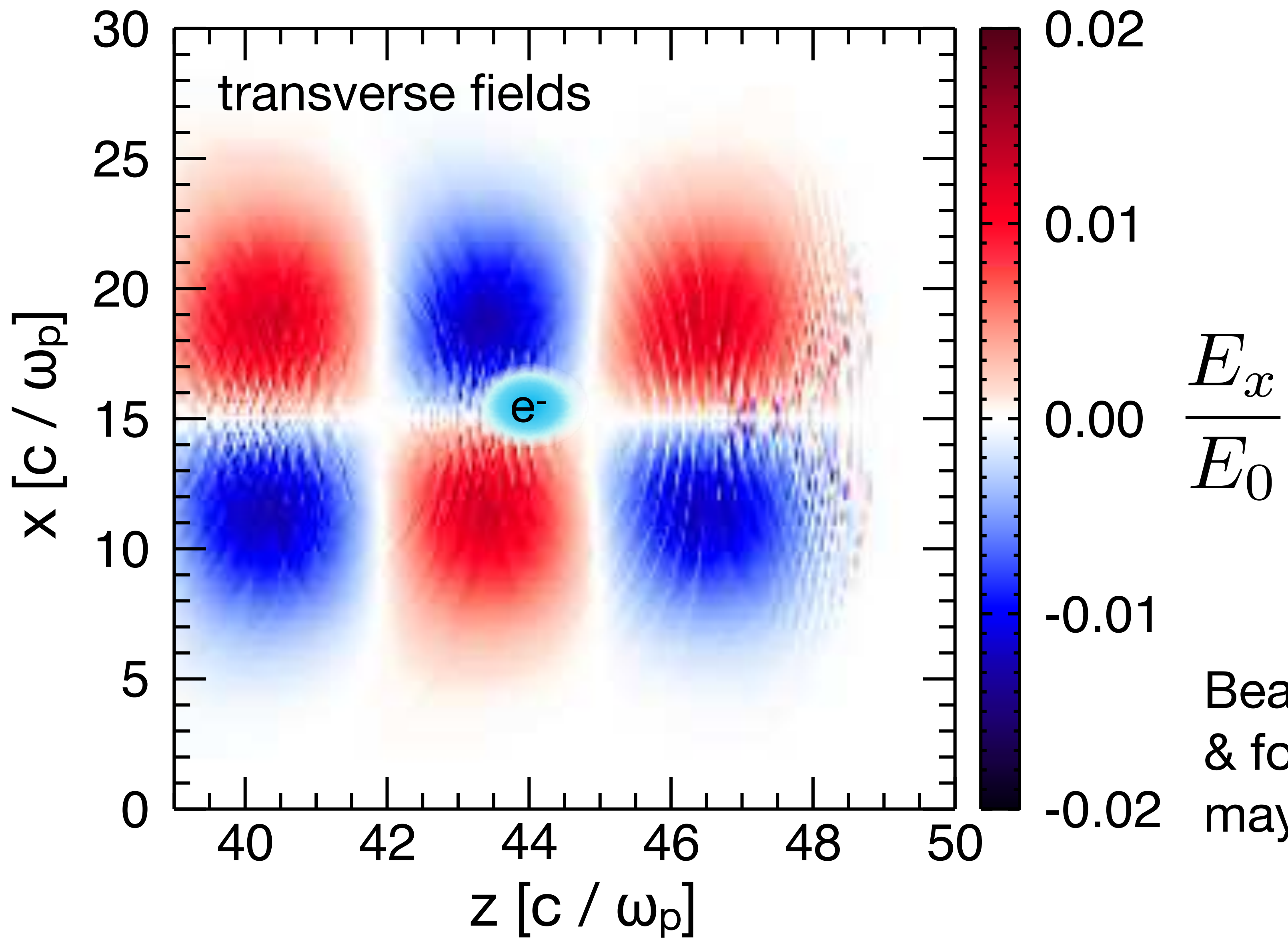
Slice rotation speeds vary along electron bunch





Beam matching into plasma

I. PARTICLE BEAM TRANSPORT



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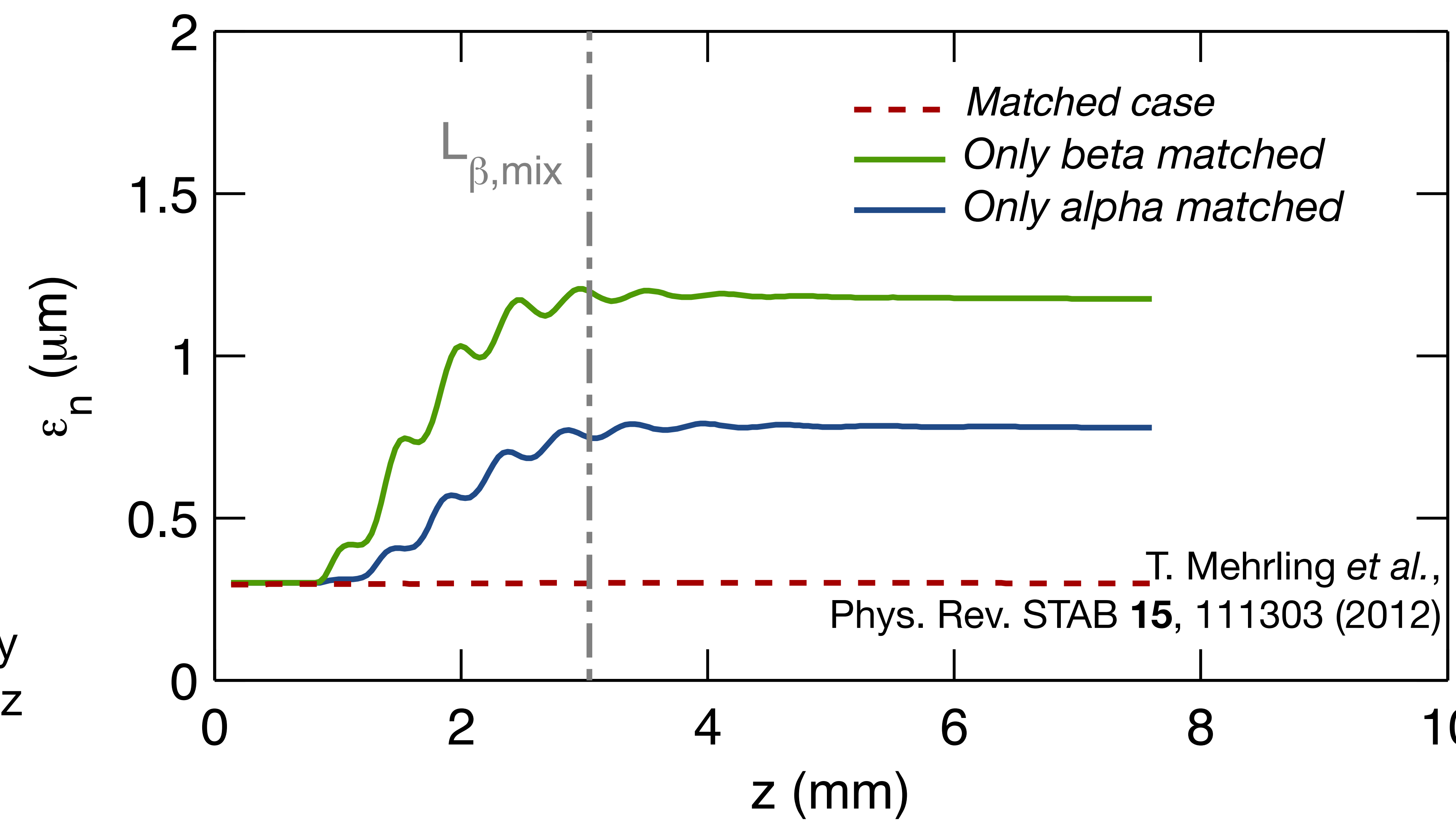


> Do we need matching even at high energies?

$$\epsilon_{n,\mathrm{fin}} = \frac{\epsilon_{n,\mathrm{init}}}{2}\left(\frac{1+\alpha^2}{\beta^*} + \beta^*\right) \quad \text{with} \quad \beta^* = \beta/\beta_m$$

and $\alpha(z) = -\frac{z}{\beta_m} \qquad \beta(z) = \beta_m + \frac{z^2}{\beta_m}$

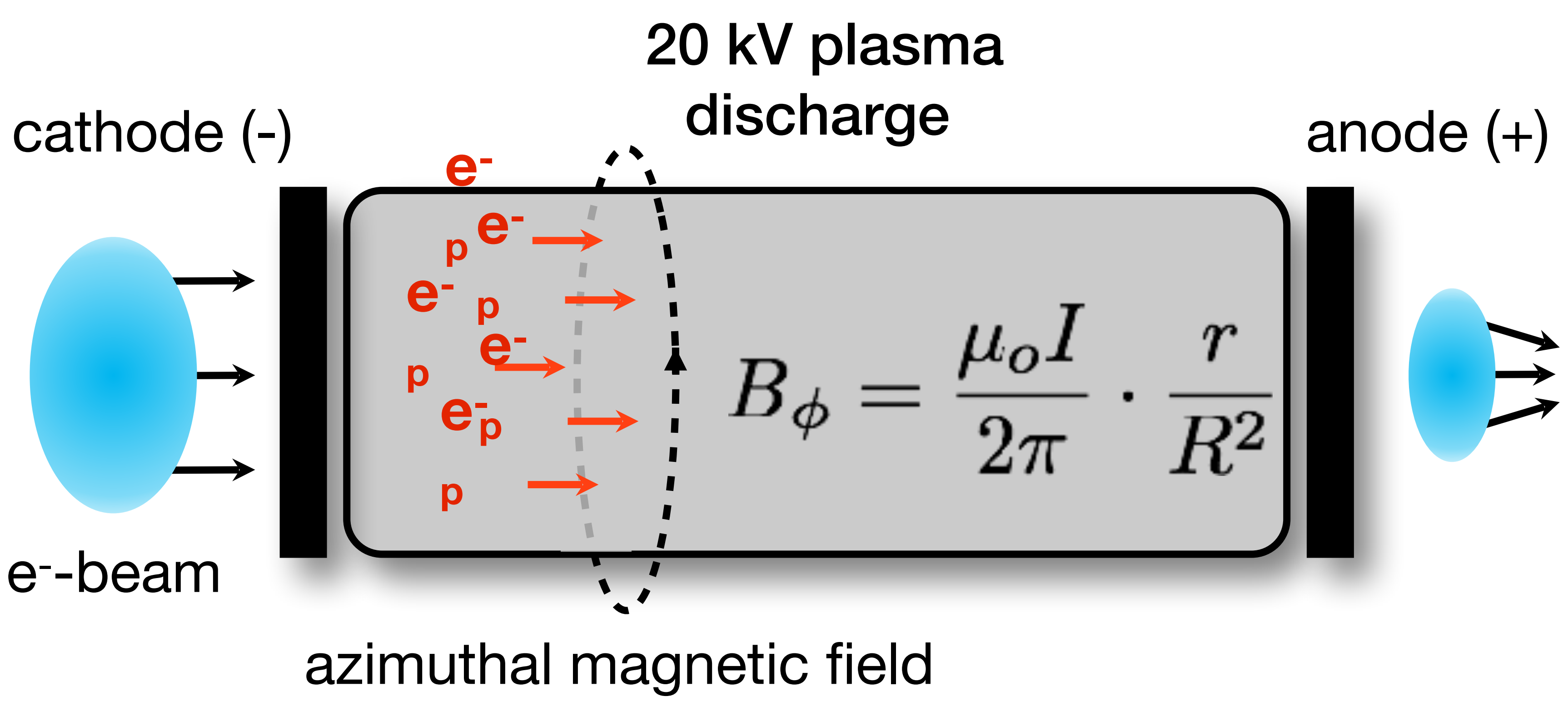
$$\rightarrow \epsilon_N^* = \epsilon_N\left(1 + \frac{z^2}{2\beta_m^2}\right)$$

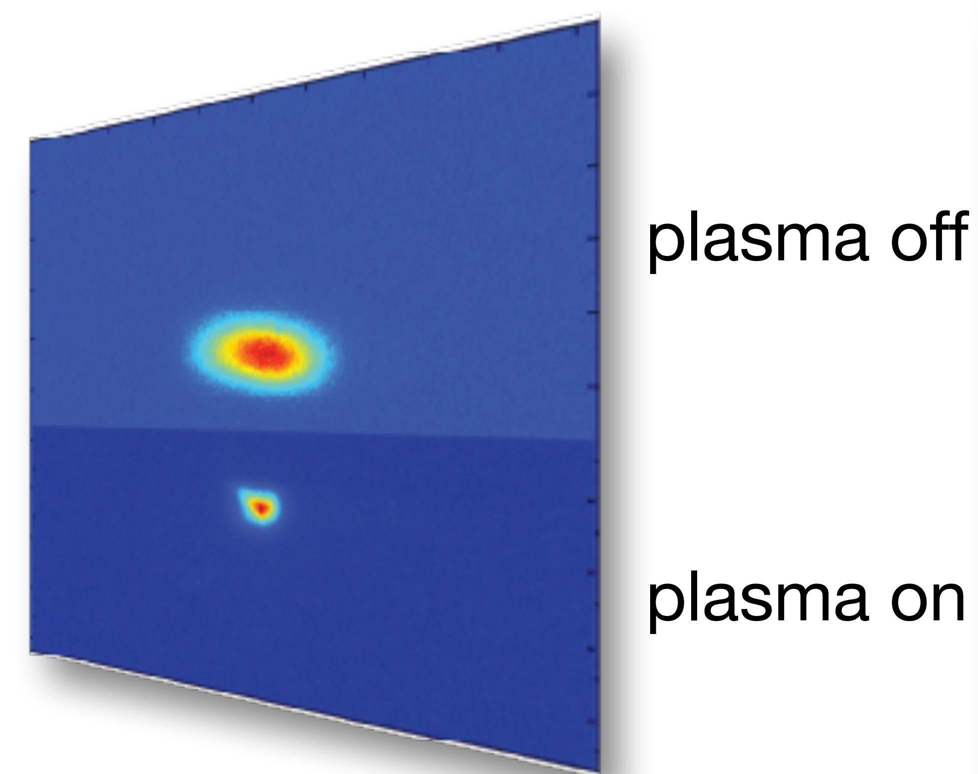
> **for z = β_m emittance grows by 50% w/o matching ($\beta_m \approx$ 33 mm for 1 TeV)**

Strong beam optics options: active plasma lenses

I. Particle beam transport

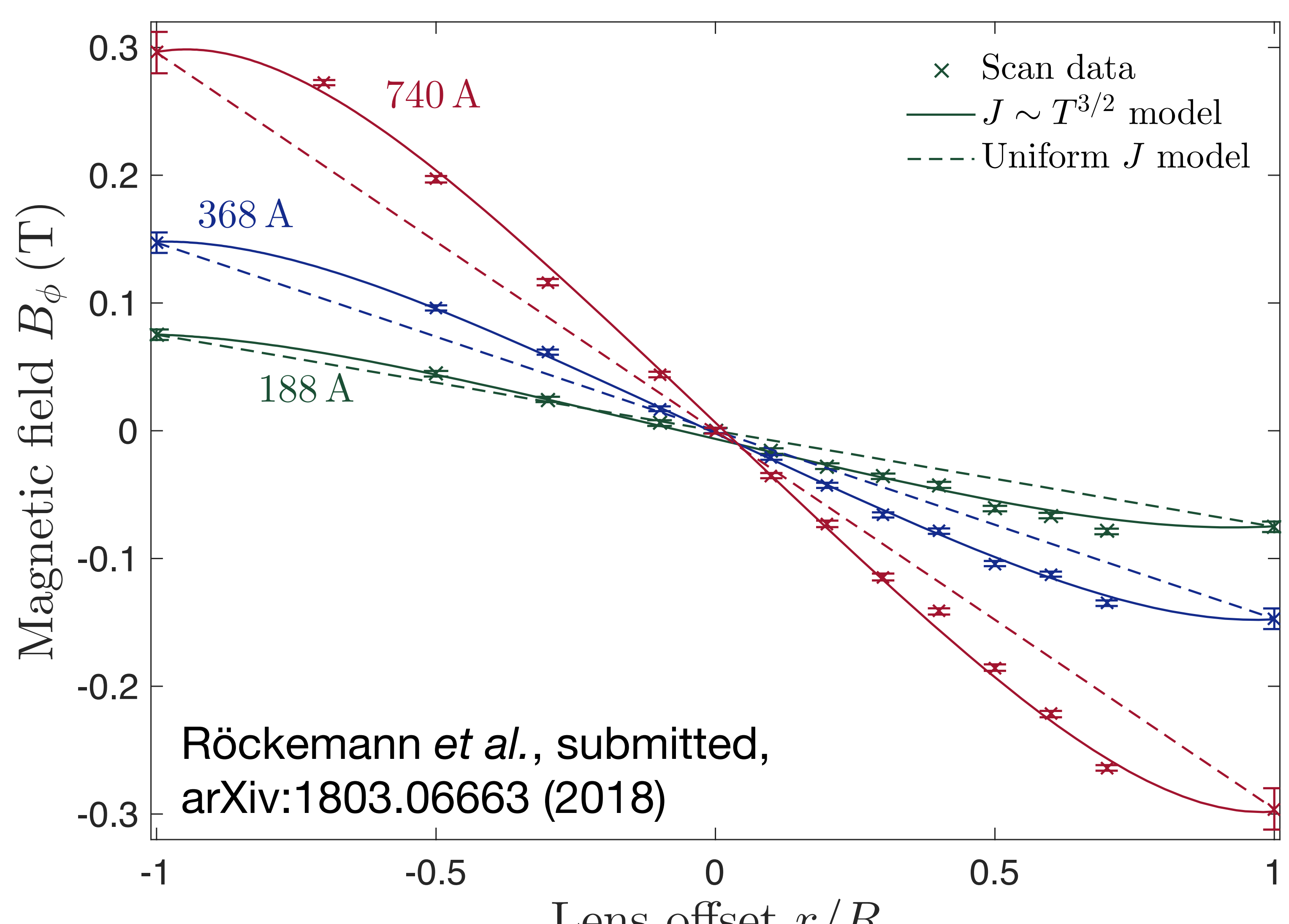
in collaboration between





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

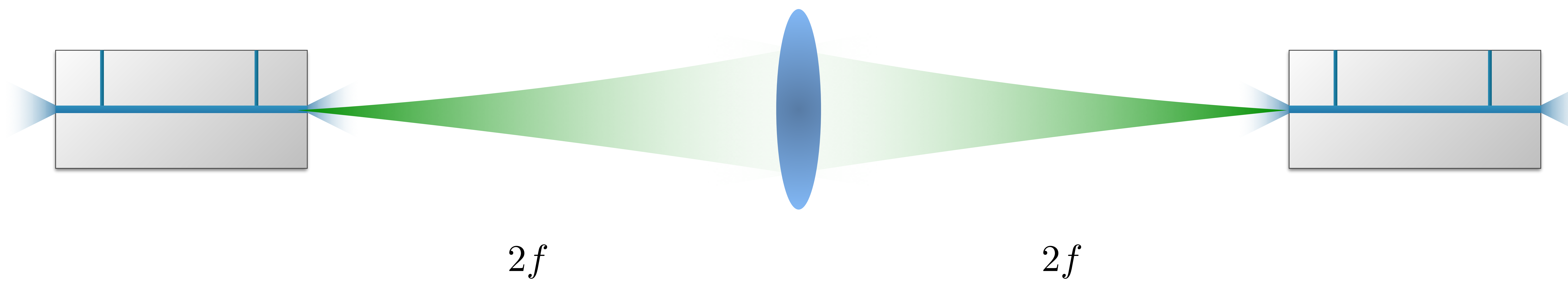
J. van Tilborg et al., Phys. Rev. Lett. ***115****, 184802 (2015)*



- **direct field measurements** with 855 MeV beam at Mainz Microtron
- **transverse offset scan**, measure kick to beam
  → **no measurable effect on pointing** / position stability observed
- **(non-)linear field gradients ≤ 823 ± 1 T/m detected, scalable to mult-kT/m** (~order of magnitude stronger focusing than conventional EM-quadrupoles)
- **measured emittance evolution** of beam in line with gradient measurements
- **kT/m-lens applications:** beam matching into plasma wake & high-field generation, compact beam capturing and transport with emittance conservation

Scaling of coupling distances

I. Particle beam transport



Coupling distance L_c

- 1:1 point-to-point imaging of beam with $\alpha=0$ and $\beta=\beta_m$ at exit cell n and entrance cell $n+1$, thin lens approximation…

$$L_c = 4f \quad \text{with} \quad f = (kL_{lens})^{-1} \qquad k[m^{-2}] = \frac{0.3 \cdot g[T/m]}{p[GeV/c]}$$

- aim at $L_c = L_{acc}$ with $L_{acc} \approx$ 1m
- **L_{lens} = 0.13m for 10 GeV beam with g = 1kT/m**

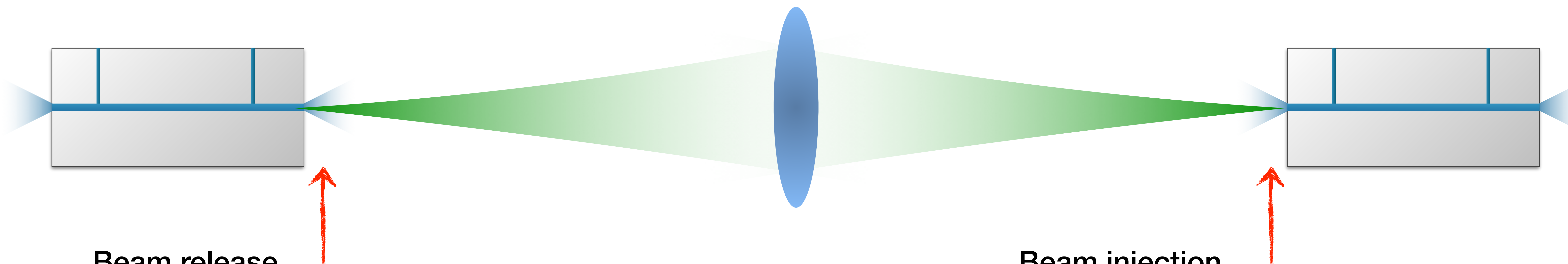
$$L_{lens} f = \frac{p}{0.3 \cdot g}$$

→ **solution for 1 TeV with fixed g: L_{lens} = 1.3m mit L_c = 10m**

But: beam size in lens!
6 µm for 10 GeV
2 µm for 1 TeV

Summary of interstage beam transport

I. Particle beam transport



Beam release
- want small energy spread
- want plasma density tailoring for adiabatic release

Beam injection
- need beam matching even at TeV energies

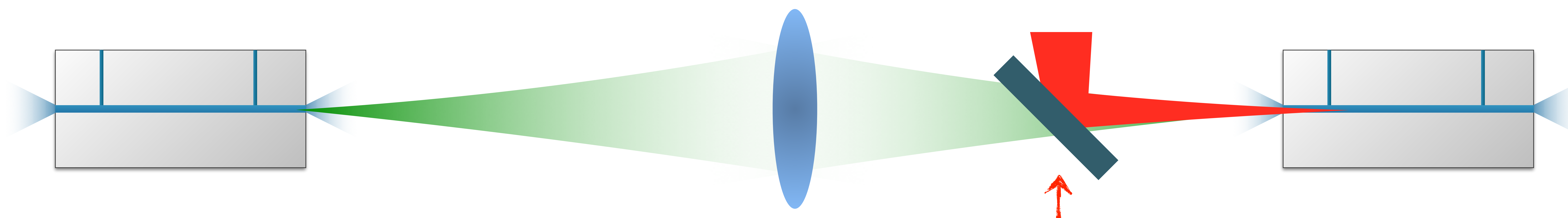
Beam optics
- want 1 kT/m × 1 m scale focussing optics to conserve emittance and keep coupling distances in range 1 to 10 L_{acc}
- plasma-based lenses may not work owing to generated wakefields

Compact laser in-coupling

II. Laser beam transport

Challenge: jitter/pointing tolerances

- jitter in timing
  → jitter in energy + energy bandwidth (beamloading)
- **pointing fluctuations** must be less than matched
  $\sigma_x \approx$ 10 nm (compare to laser spot size of ~λ_p)
  → emittance degradation
  cf. R. Assmann and K. Yokoya, NIM A 410, 544 (1998)



Laser in-coupling

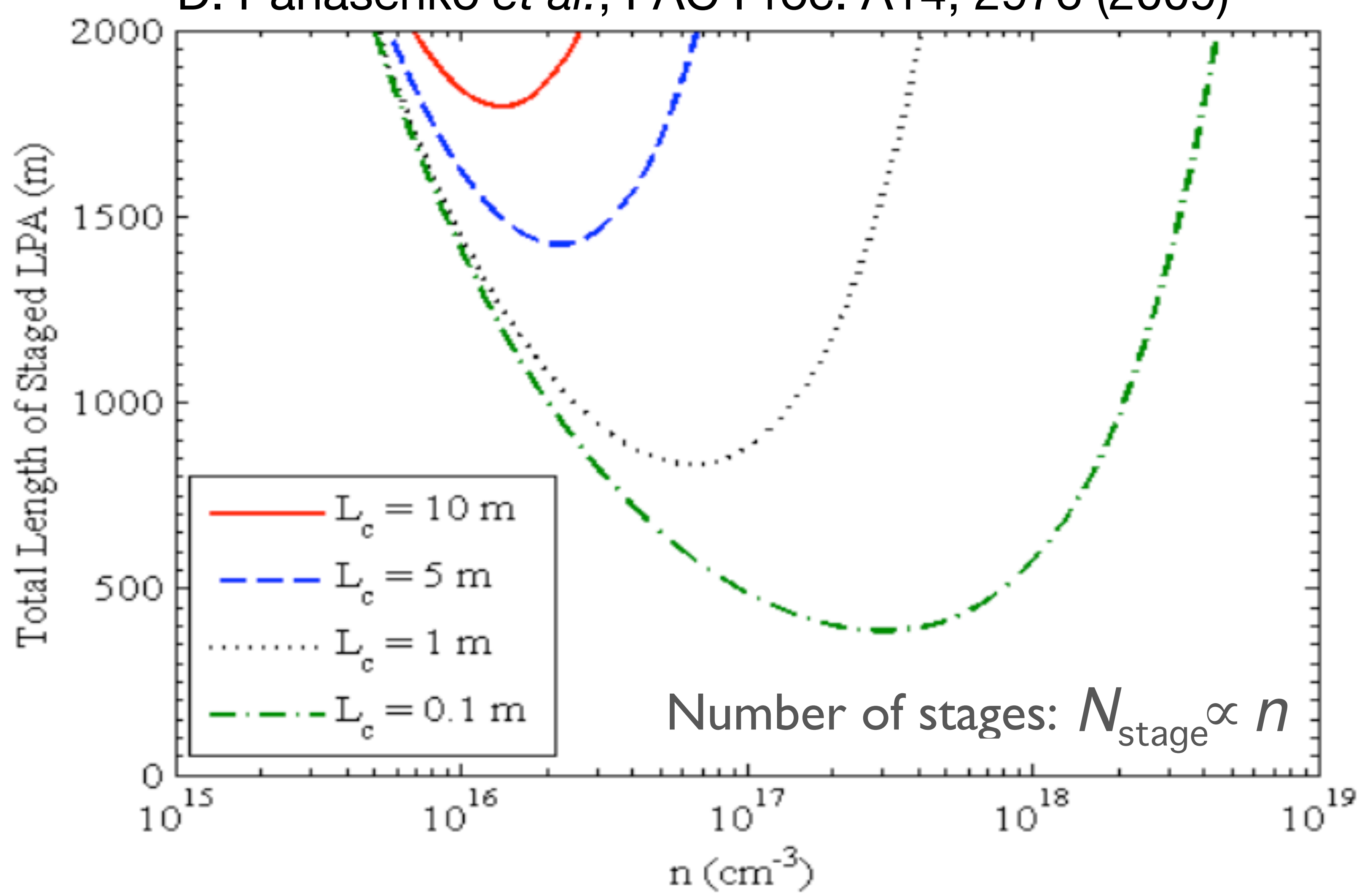
- mirror technology for short coupling distances

> conventional mirrors require ~10 m distance from focal point to prevent damage (for PW-class lasers and required f-number)

> degradation of effective accelerating field strength by > 1 order of magnitude acceptable?

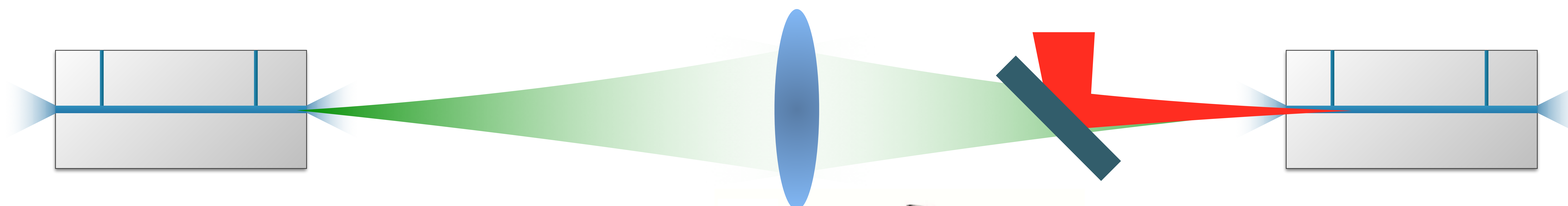
> L_c may dictate multi-stage accelerator length for $L_{acc} \approx$ 1 m

D. Panasenko *et al.*, PAC Proc. A14, 2976 (2009)



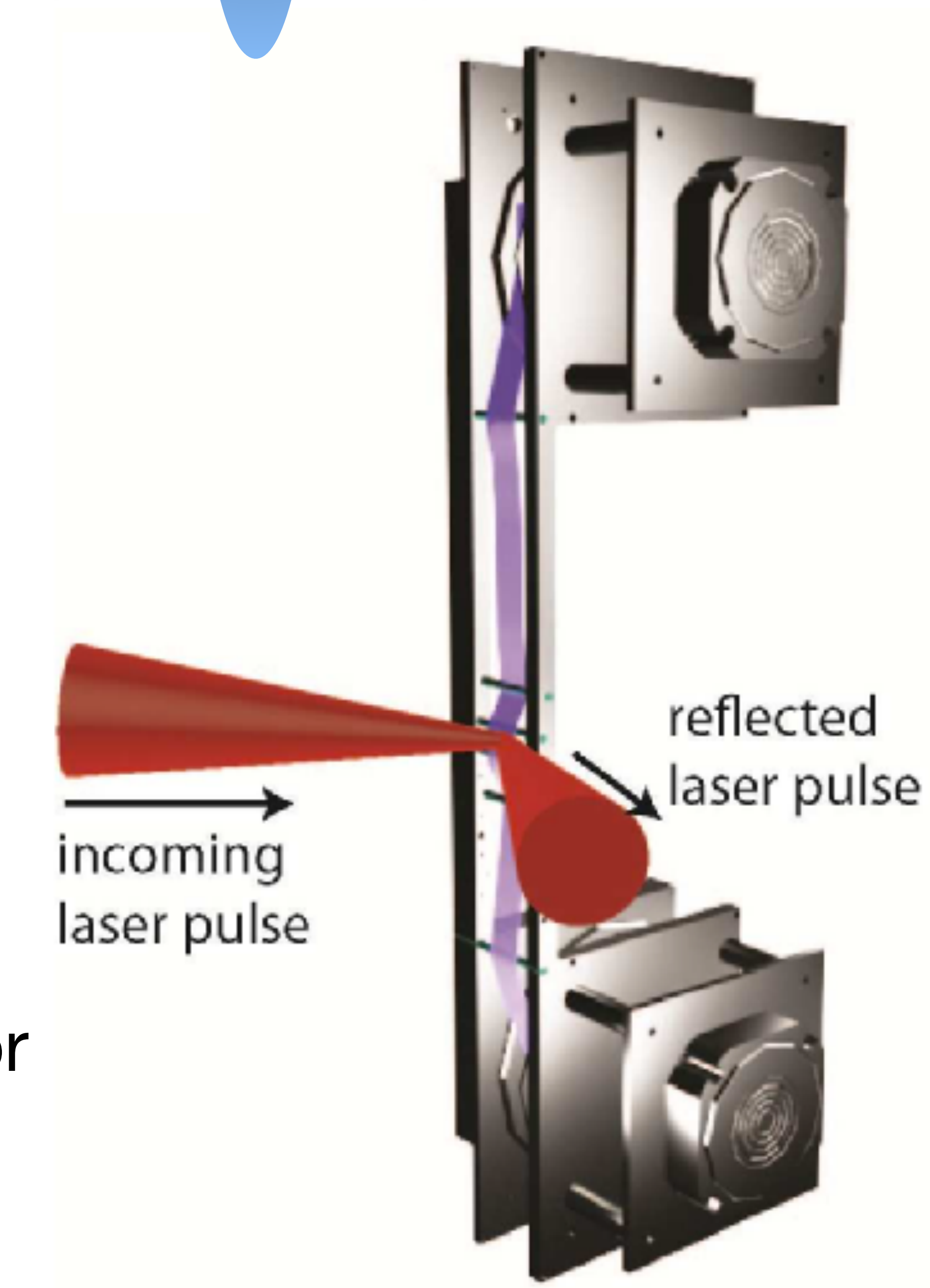
Compact laser in-coupling

II. Laser beam transport



Option: plasma mirror

- based on liquid jet
  → D. Panasenko *et al.*, PAC Proc. A14, 2976 (2009)
- based on tape drive
  → T. Sokollik *et al.*, AIP Conf. Proc. 1299, 233 (2010)



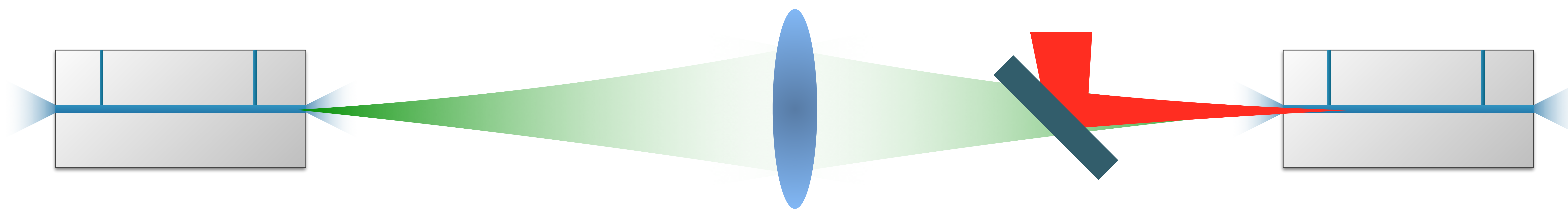
High laser intensity (~10^{16} W/cm^2) generates an optically flat, critical-density plasma surface
→ minimizes L_c to cm-scale

Challenge

- emittance growth due to beam scattering in mirror & collective plasma effects?
- impact on efficiency? reflectivity ~80%

Emittance growth to multiple small-angle scattering

II. Laser beam transport



Minimum mirror thickness → order of plasma skin depth (efficiency, do not want to waste laser energy)

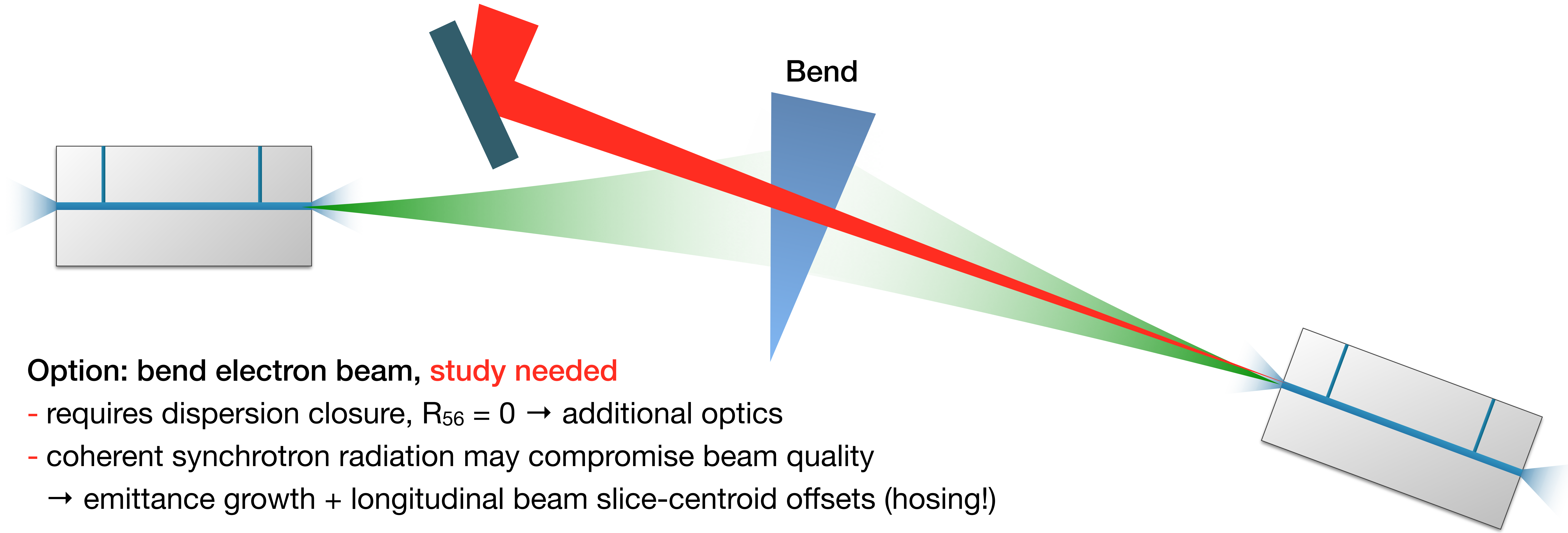
- skin depth ~50 nm for 10^{22} cm^{-3} plasma
- scattering angle $$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$
- x/X_0 is mirror thickness in radiation lengths
- z is charge number of incident particle
- *example:* thin water-jet with X_0 = 36 cm

→ θ_0 (10 GeV) = 1.3 μrad (compare to $\sigma_{x'}$ = 10 μrad, ~13%/stage)

→ θ_0 (1 TeV) = 0.013 μrad (compare to $\sigma_{x'}$ = 0.3 μrad, ~4%/stage)

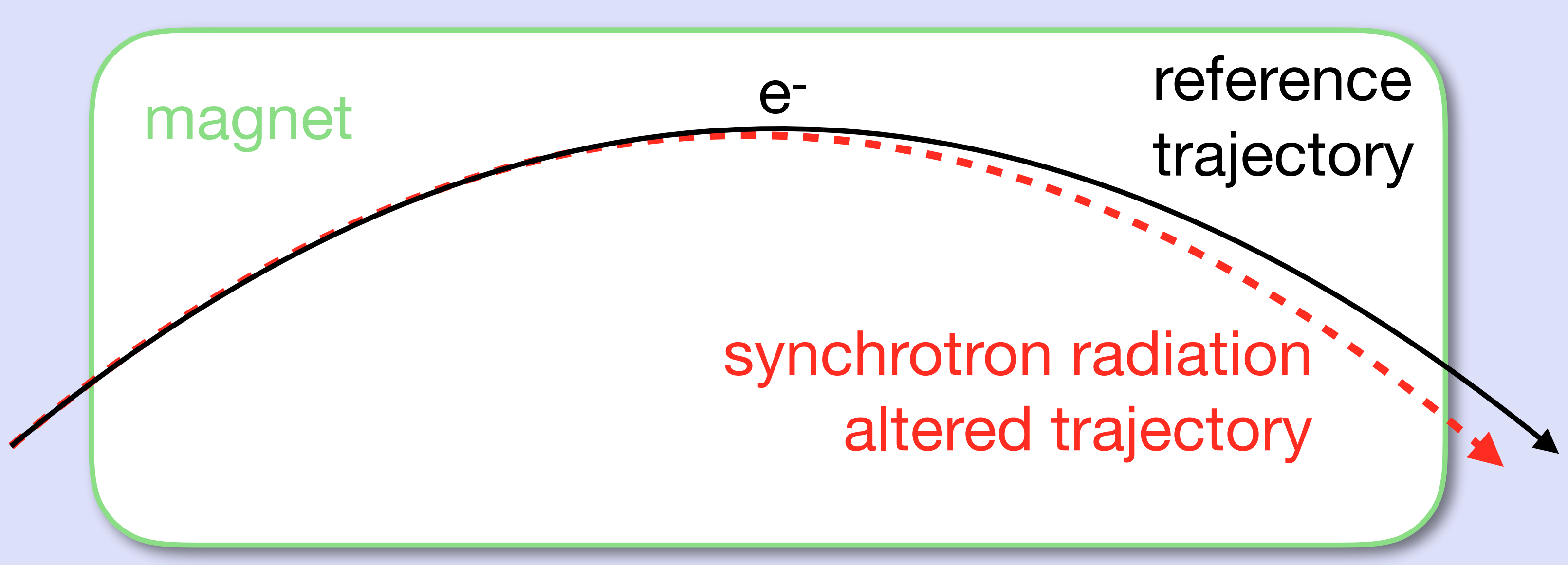
Alternatives to straight solutions?

II. LASER BEAM TRANSPORT



Option: bend electron beam, study needed

- requires dispersion closure, $R_{56} = 0$ → additional optics
- coherent synchrotron radiation may compromise beam quality
  → emittance growth + longitudinal beam slice-centroid offsets (hosing!)



→ talk by S. Libov in WG5

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

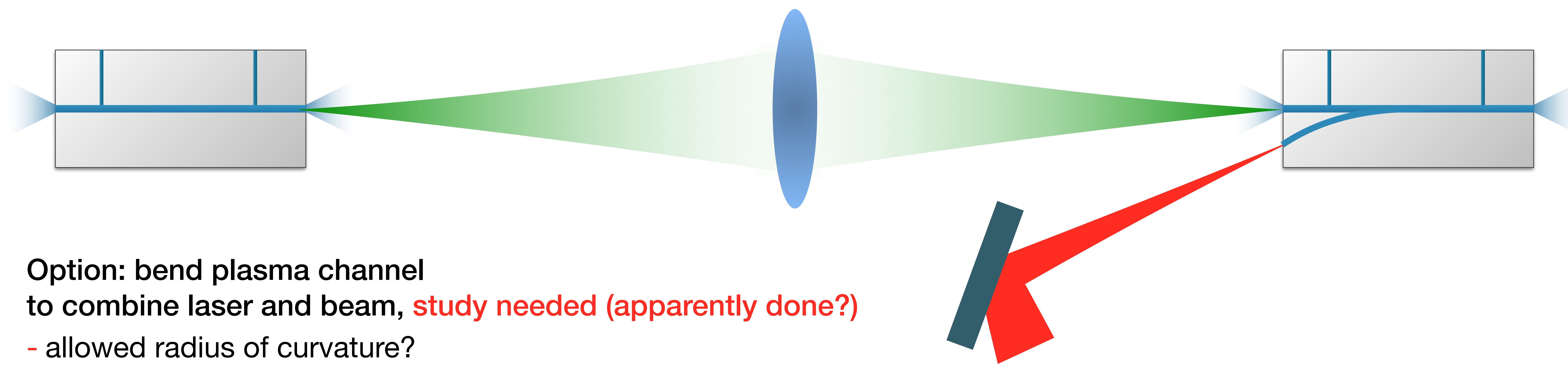
> energy loss/kick dependent on slice current
  → non-uniform along beam

> emitted radiation acts back on beam

Alternatives to straight solutions?

II. Laser beam transport

Bend plasma channels
Y. Ehrlich *et al.*, Phys. Rev. Lett. **77,** 4186 (1996)
M. Chen *et al.*, Light: Science & Applications **5** (2016)



Option: bend plasma channel
to combine laser and beam, study needed (apparently done?)

- allowed radius of curvature?
- effects at combination point?

Alternatives to straight solutions?

II. Laser beam transport

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Y. Ehrlich *et al.*, Phys. Rev. Lett. **77,** 4186 (1996)
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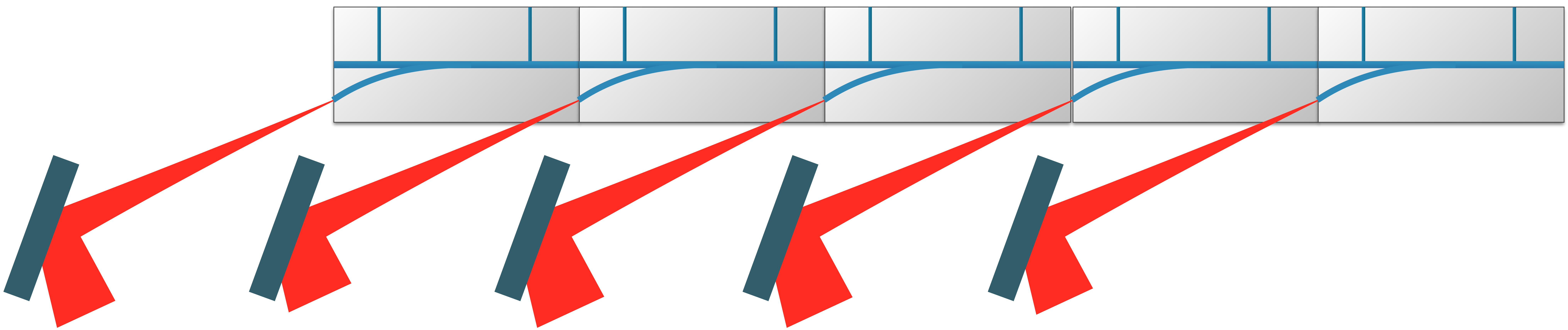
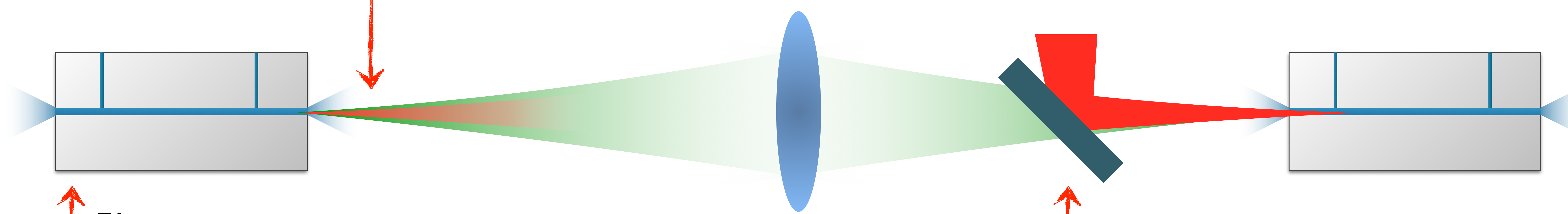


Scalability to multi-10 kHz rep. rate and high avg. power

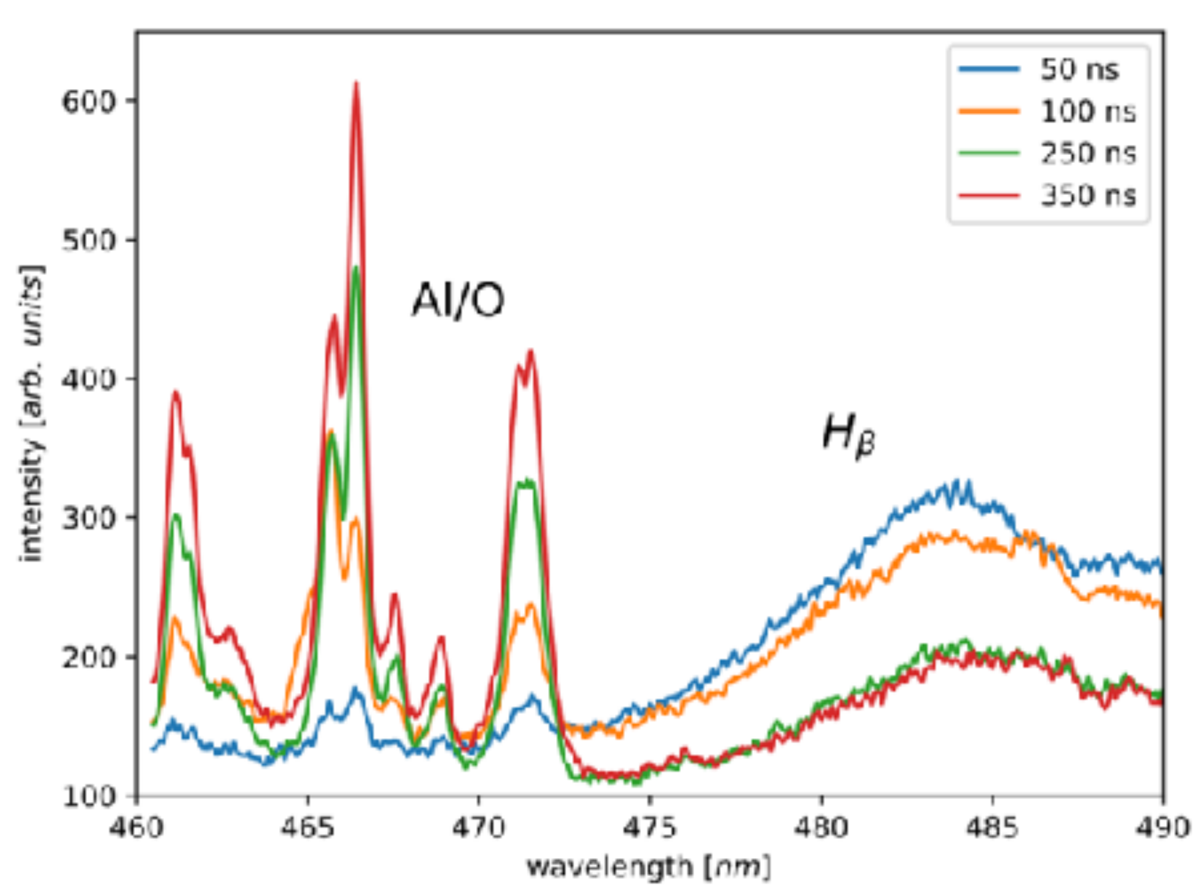
III. High-average power operation

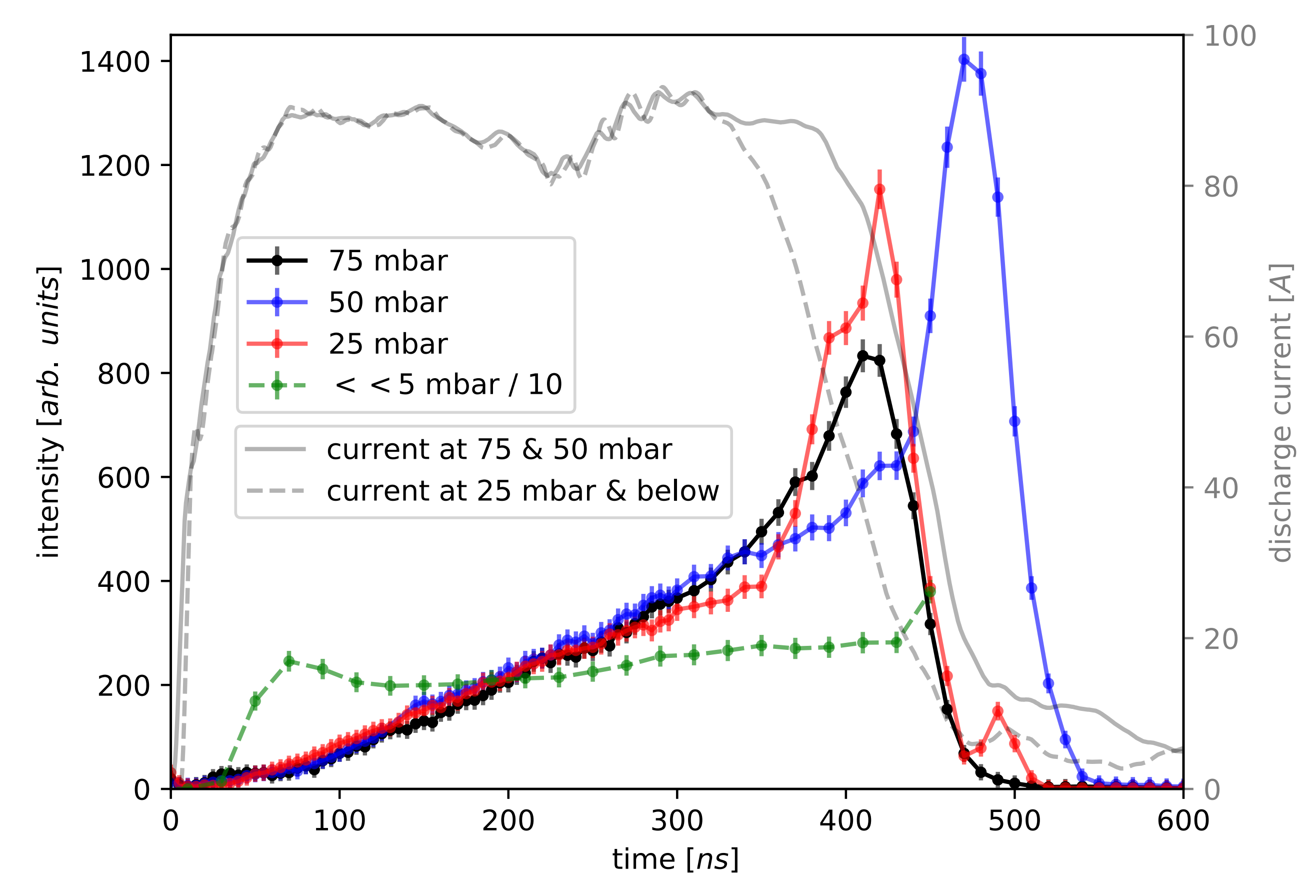
Depleted laser
- needs compact ~100 kW dump/recycling



Plasma source
- etching of wall at multi-10 kHz rep. rate, life time of device?
- heat management (losses of ~100 kW per L_{acc})

Plasma mirror
- replenish surface at multi-10 kHz rep. rate





L. Goldberg, PhD thesis (2018)

Summary

- **Staging is unavoidable for LWFA-based collider designs**
- Basic scheme has been demonstrated → S. Steinke *et al.*, Nature 530, 190–193 (2016)
- Emittance conservation on 10-nm level is a challenge
- **Technology wishlist**
  - plasma sources with shaped boundaries
  - kT/m scale, emittance conserving focussing optics
  - highly stable alignment between laser and electron beam
- **Needed studies**
  - alternatives to co-linear laser-electron-beam coupling? (study must be done for PWFA staging…)
  - scalability of technologies to high repetition rate and high average power
- **The community should work on a detailed conceptual collider-ready staging design**
- **It's tough, but no principal showstopper**