Matching beams to plasma accelerators

EAAC Workshop 2015

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CFEL SCIENCE

LAOLA. is a collaboration of UHH DESY

LUX Junior Research group

Junior Research group at CFEL and Hamburg University

commission & operate 200 TW ANGUS laser system

build and operate the LUX beamline for laser-plasma driven undulator radiation

lux.cfel.de


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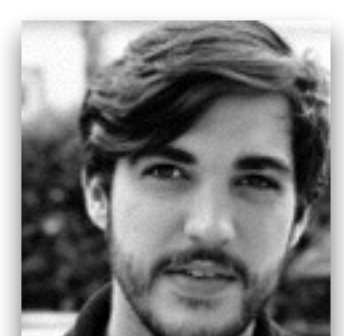
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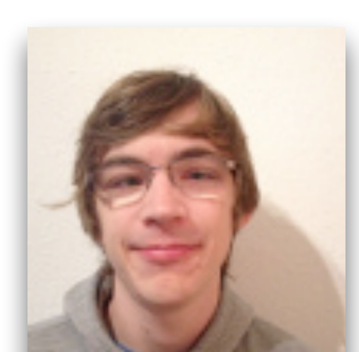
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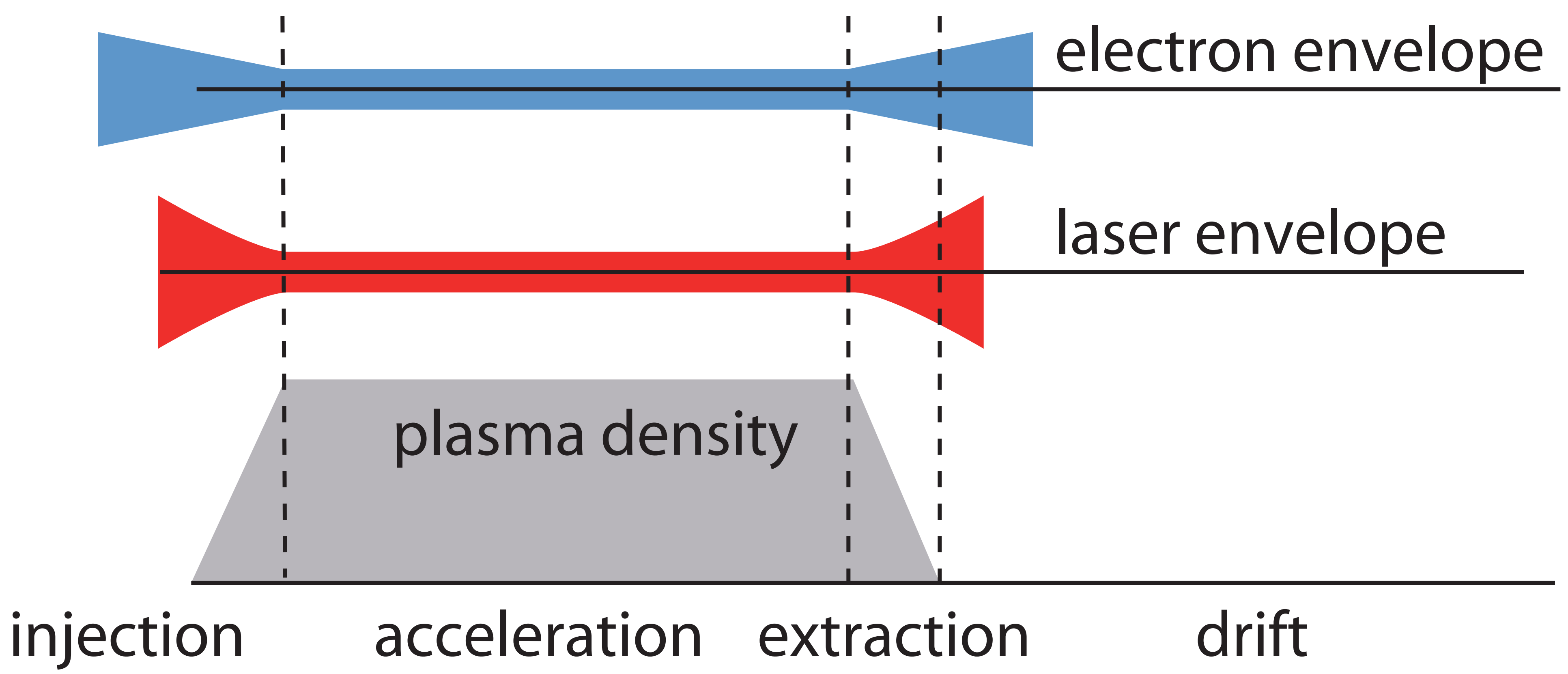
why should you care?

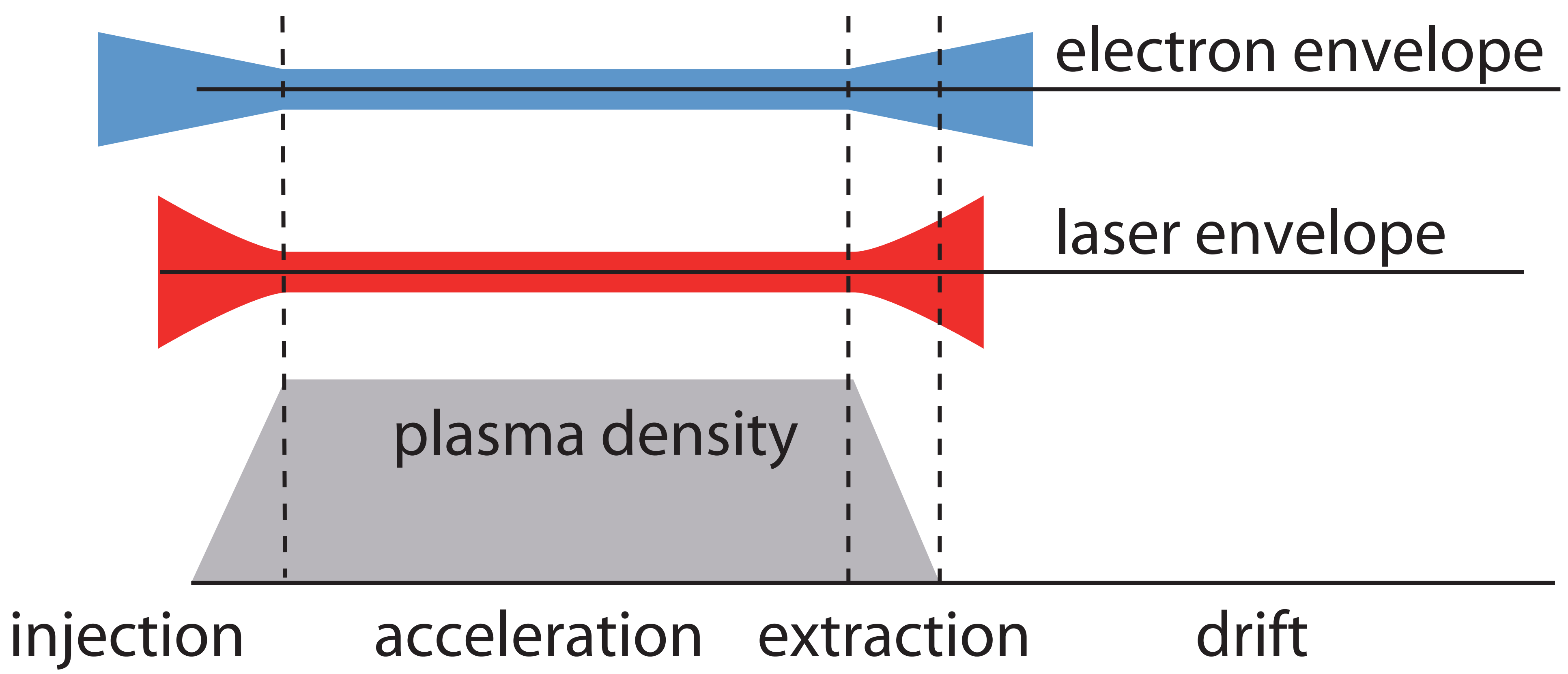


injection
> external injection schemes at INFN, REAGE, SINBAD
> staged acceleration

acceleration
> clear…

extraction
> applications req. good emittance, low divergence

our model



our main concern here is the transverse beam quality -> look at focusing forces

linear wakefield

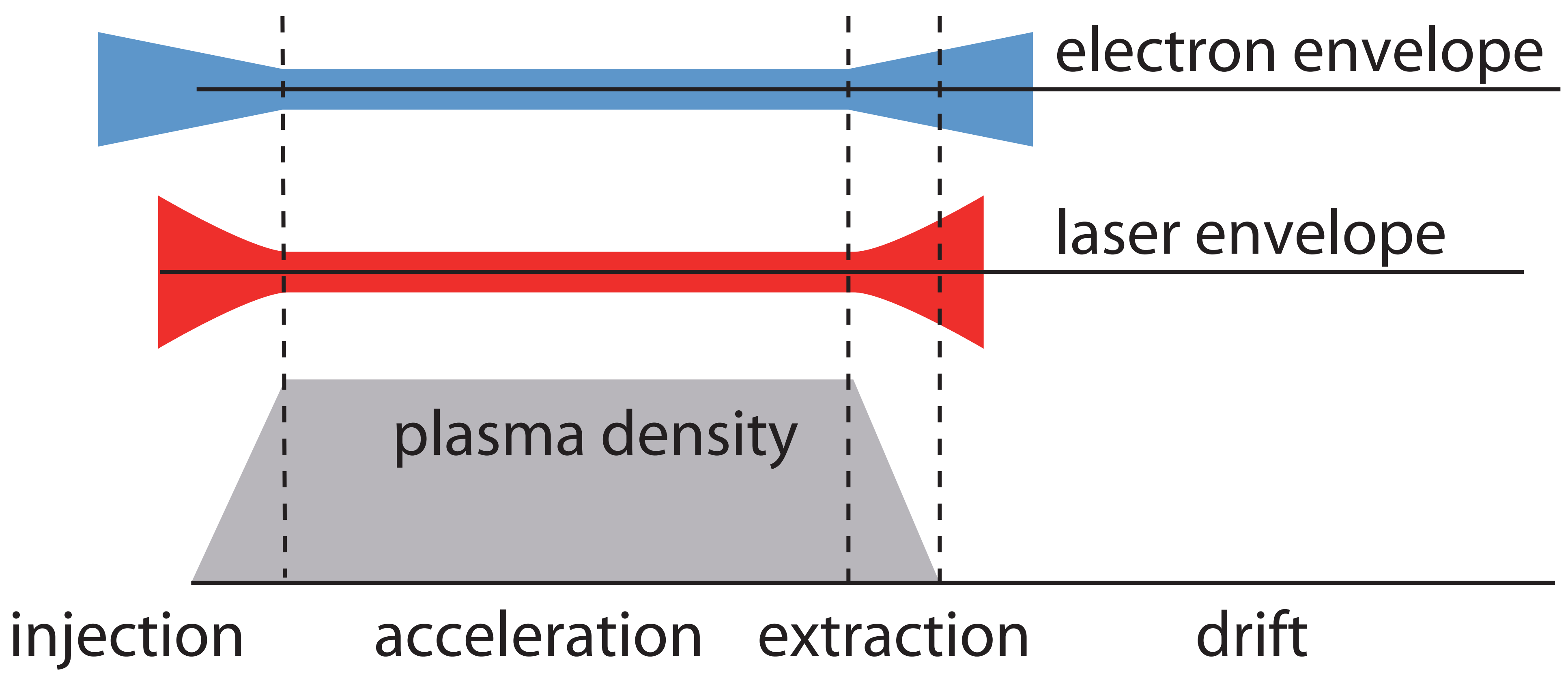
$$K \propto -\frac{a^2 k_p}{w^2} \exp\left(k_p^2 \sigma_z^2 / 2\right) \sin\left(\Psi\right)$$

focusing forces depend on density profile AND laser profile

K	focusing
a^2, w	laser
$k_p, \Psi = k_p \zeta$	density

there are many knobs to turn…

our model



we will now go through all sections step by step

we use an analytical description together with simulations: ASTRA, WARP3D, and FBPIC

reference case:

plasma $n_e = 10^{17}\,\mathrm{cm}^{-3}$,

laser $a_0 = 0.8$,

electrons $E = 100\,\mathrm{MeV}$,

$\epsilon_n = 1\,\mathrm{mm.mrad}$,

$\sigma_z = 1\,\mu\mathrm{m}$

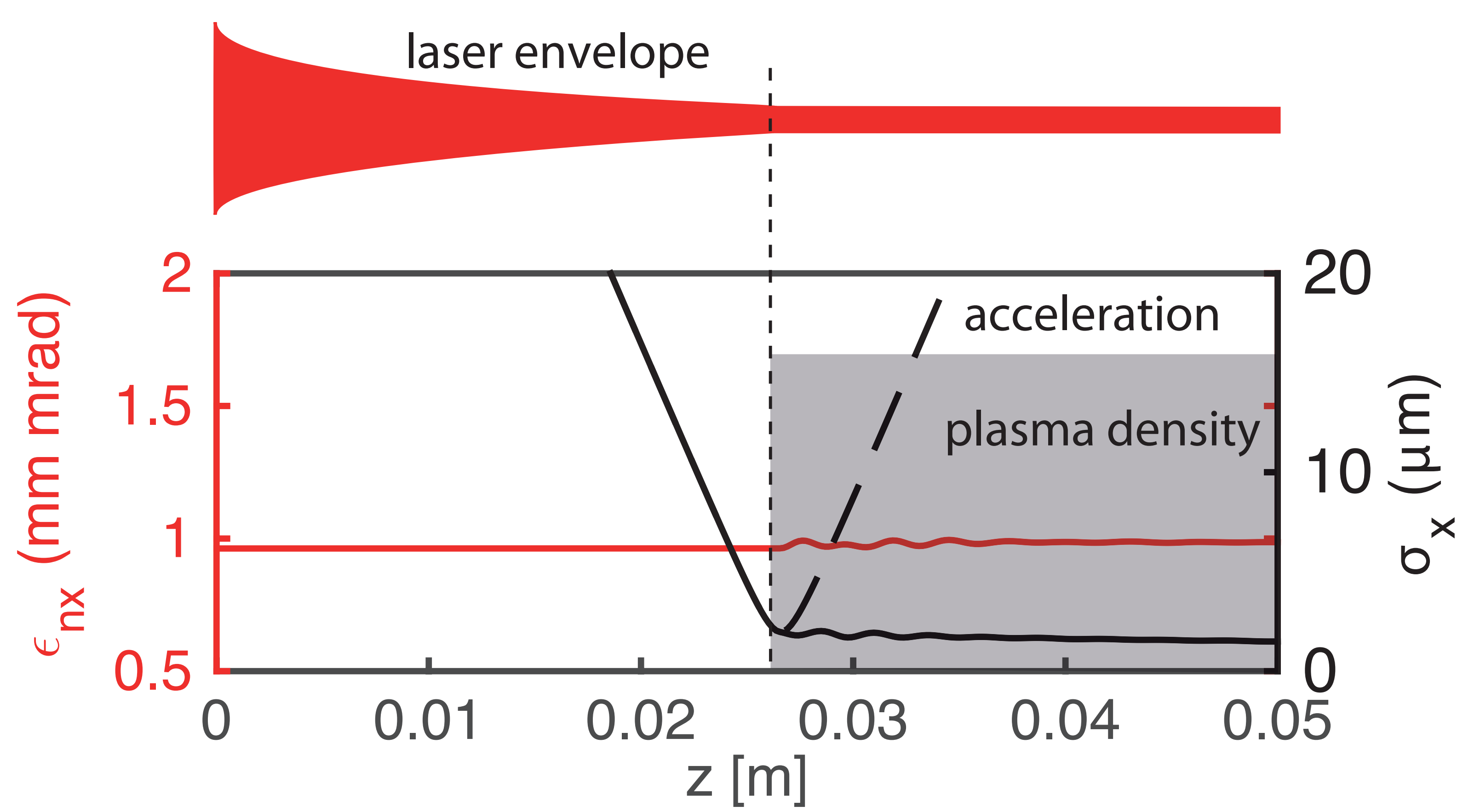
references

> T. Mehrling et al., PRST-AB 15, 111303 (2012)
> R. Assmann et al., NIM A 410, 544 (1998)
> P. Antici et al., J. Appl. Phys. 112, 044902 (2012)
> M. Migliorati et al., PRST-AB 16, 011302 (2013)
> K. Floettmann, PRST-AB 17, 054402 (2014)
> R. Lehe et al., PRST-AB 17, 121301 (2014)
> I. Dornmair et al., PRST-AB 18, 041302 (2015)

beam injection

relevant for external injection, and staged schemes

external injection w/ sharp transition



matched beam size: $\beta \propto K^{-1/2}$

doing the numbers: $\sigma_x = 2\,\mu\mathrm{m},$

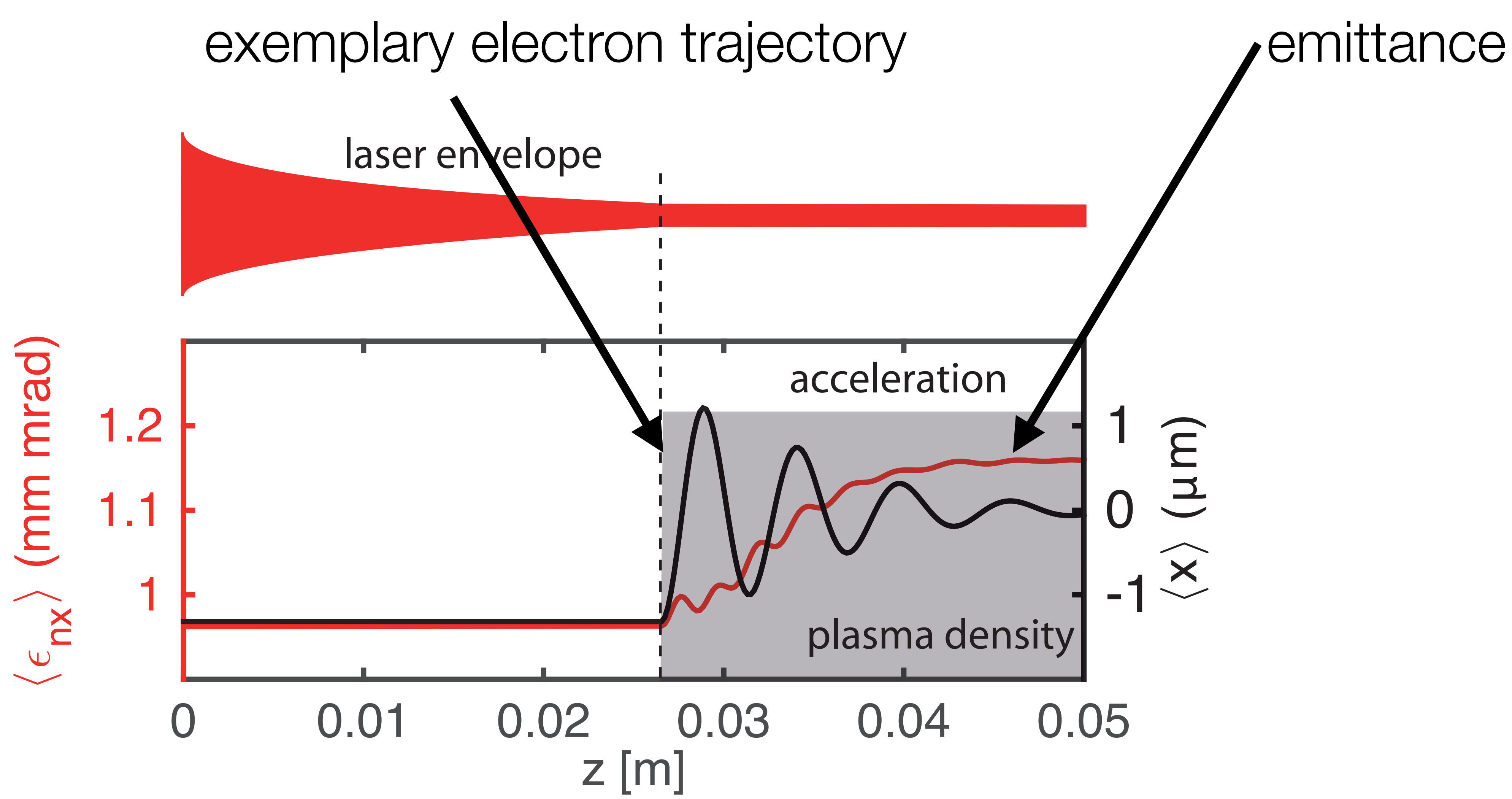
$$\beta = 0.8\,\mathrm{mm}$$

extreme focusing forces cause ***very*** small matched beam size

> hard to get with beam optics

> very sensitive to positioning jitters

external injection w/ sharp transition



example: do 3000 runs with 10% rms laser and electron position jitter

> emittance growth by 20 %

matched beam size: $\beta \propto K^{-1/2}$

doing the numbers: $\sigma_x = 2\,\mu\mathrm{m},$

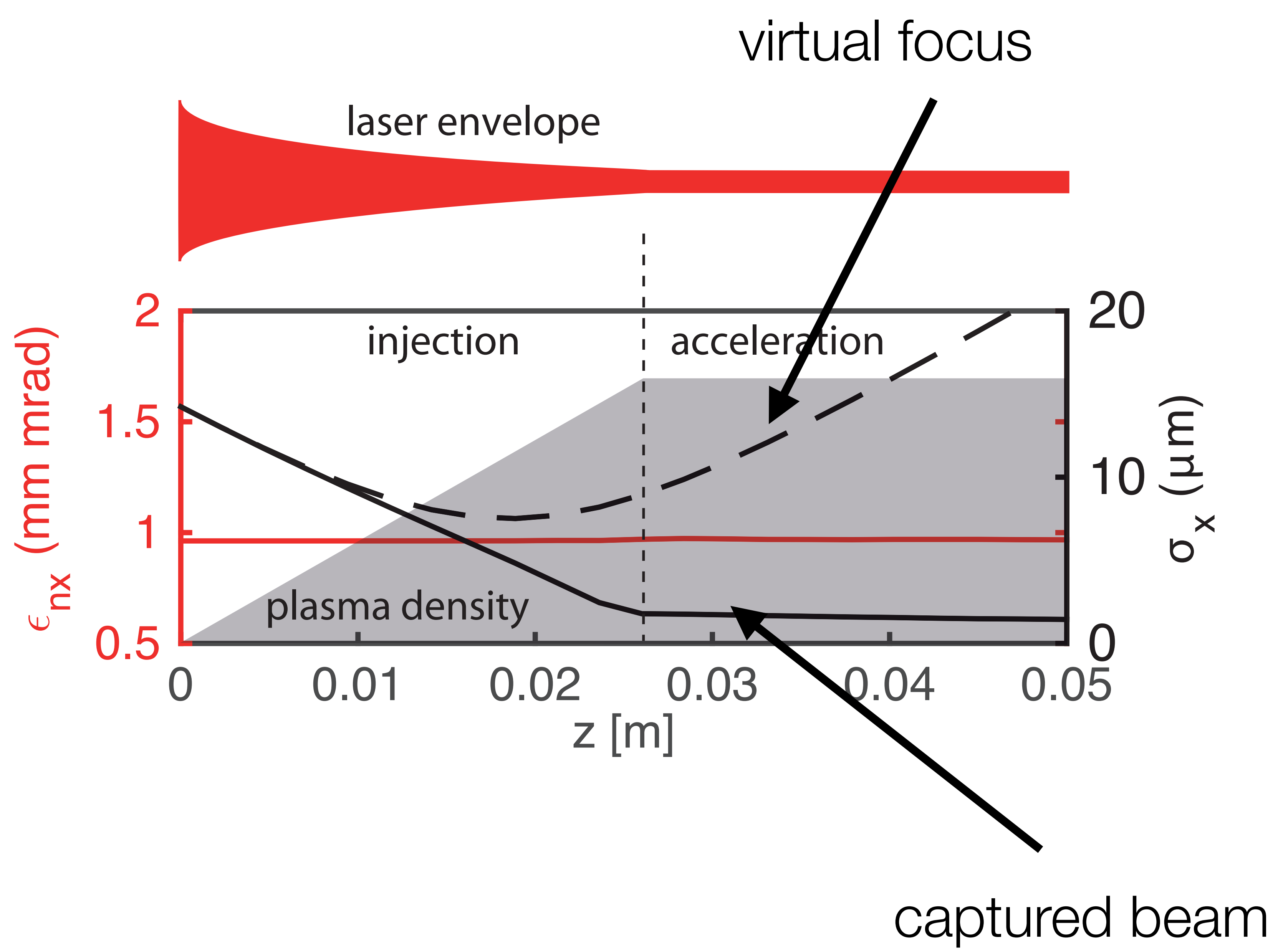
$$\beta = 0.8\,\mathrm{mm}$$

extreme focusing forces cause ***very*** small matched beam size

> hard to get with beam optics

> very sensitive to positioning jitters

external injection w/ smooth transition



relaxed requirements: $\sigma_x = 8\,\mu\mathrm{m},$

$\beta = 12\,\mathrm{mm}$

> add a smooth transition

> now you have to solve

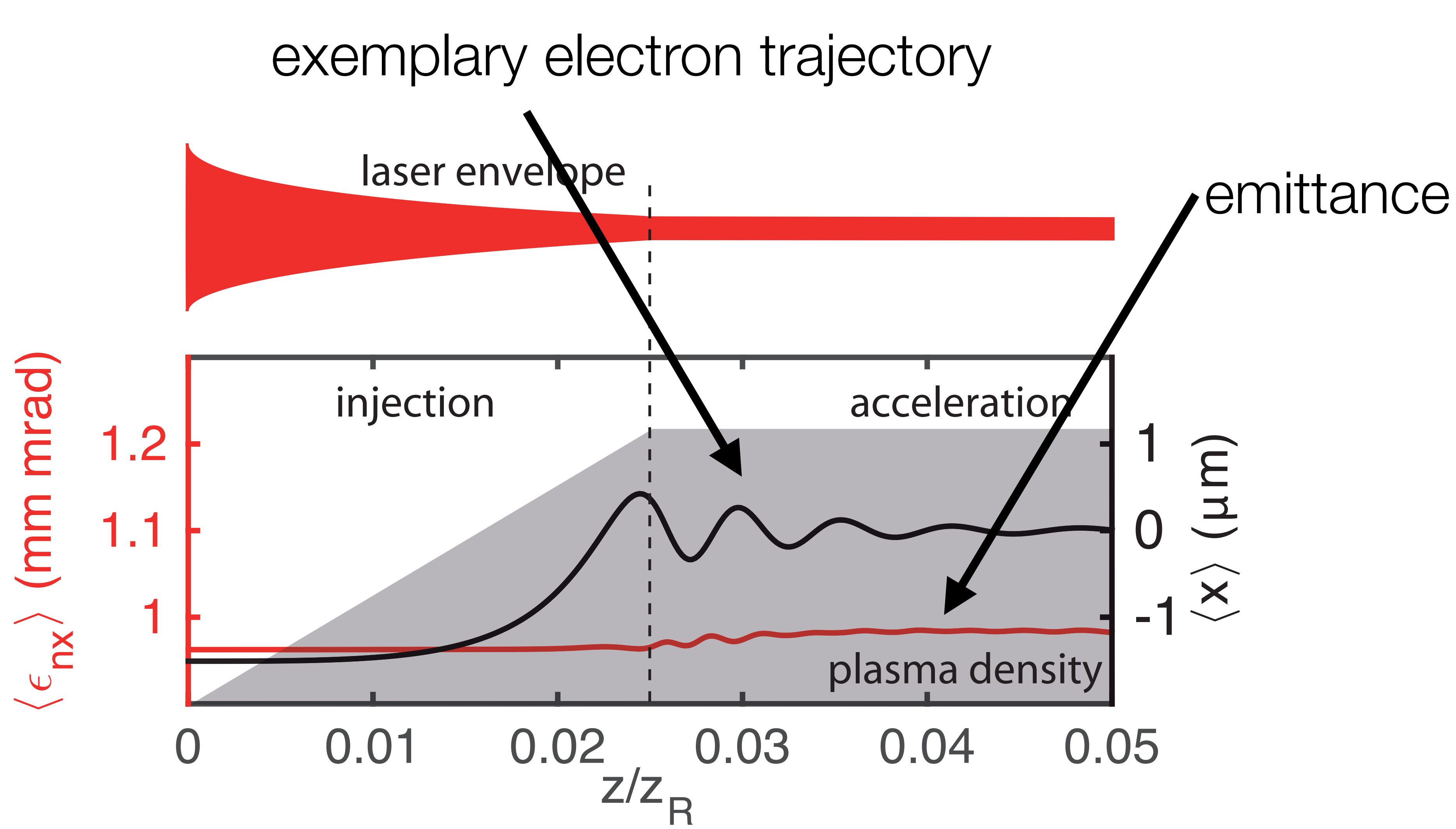
$$x'' = -K(z)x$$

with *K(z)* a function of the density upramp

> set electron beam optics to a ***virtual focus***

> the upramp captures the beam

external injection w/ smooth transition



example: do 3000 runs with 10% rms laser and electron position jitter

> emittance growth by only 2 %

take home message:

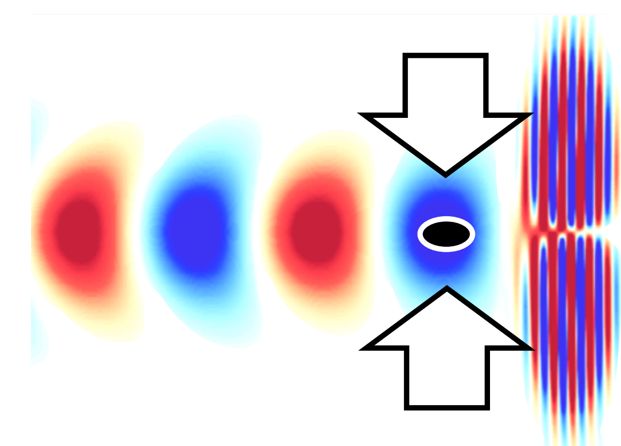
add a smooth transition

relaxed requirements: $\sigma_x = 8\,\mu\mathrm{m},$

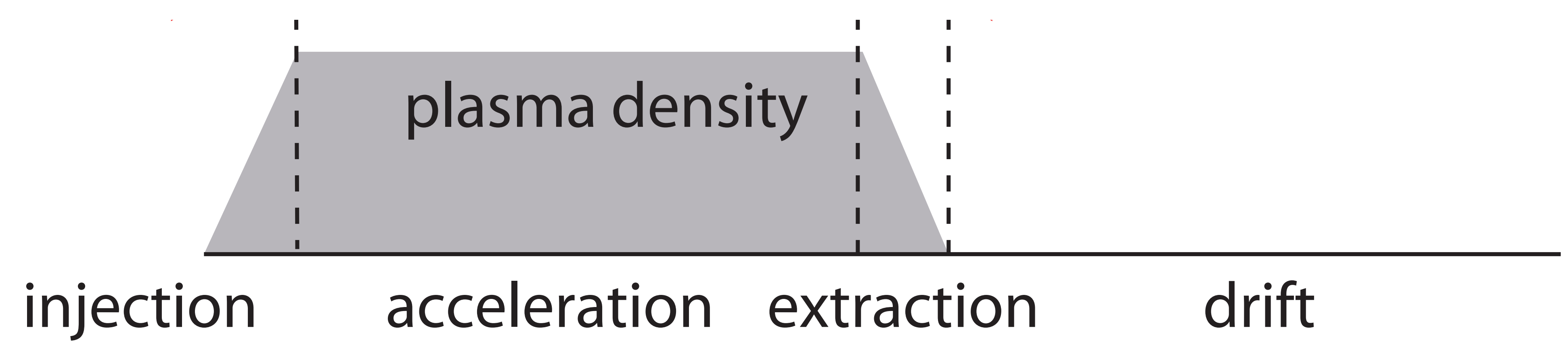
$\beta = 12\,\mathrm{mm}$

acceleration

effects during acceleration



$$x'' = -Kx$$



inside the plasma

> constant K

> you want to be matched to K

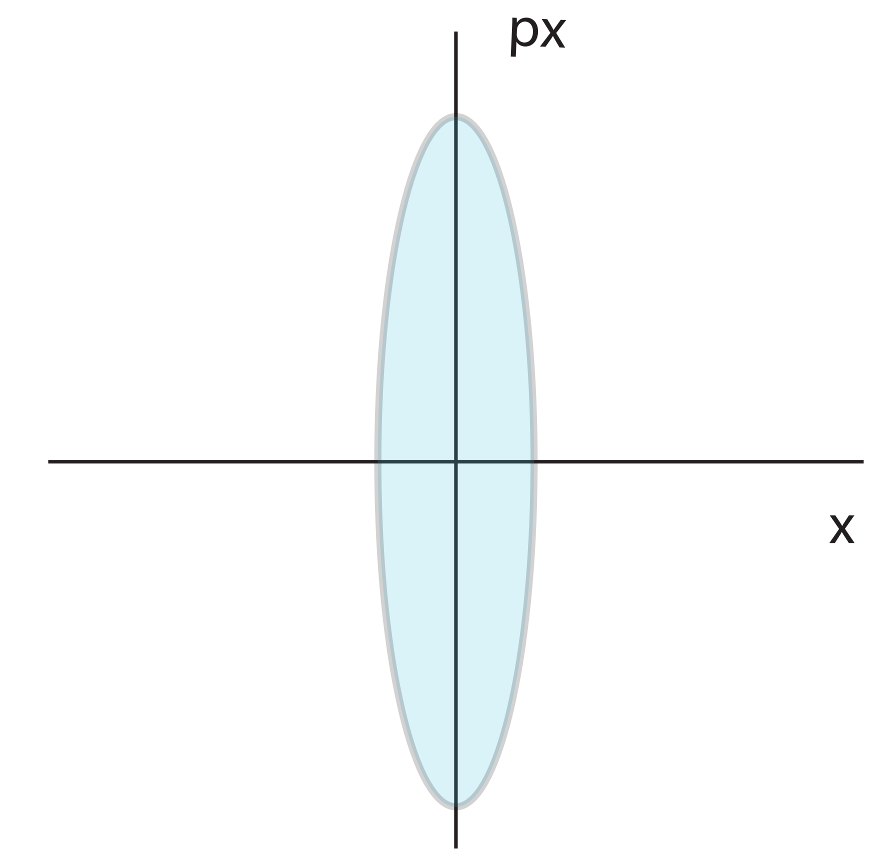
> i.e. have the right spot size

if you ***ARE*** matched

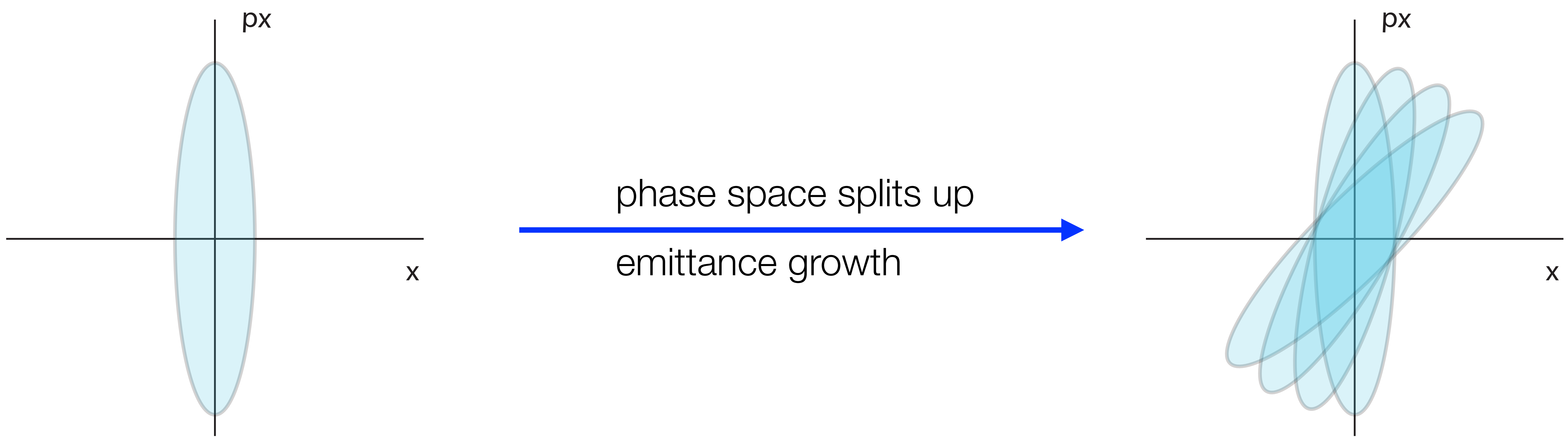
> constant beam size

> electrons of different energies rotate with different betatron frequencies

> but phase space ellipse stays upright



effects during acceleration



if you are ***NOT*** matched

> „beam breathing"

> two possible sources of emittance growth

1. energy spread
2. bunch length

energy spread

> phase space splits up

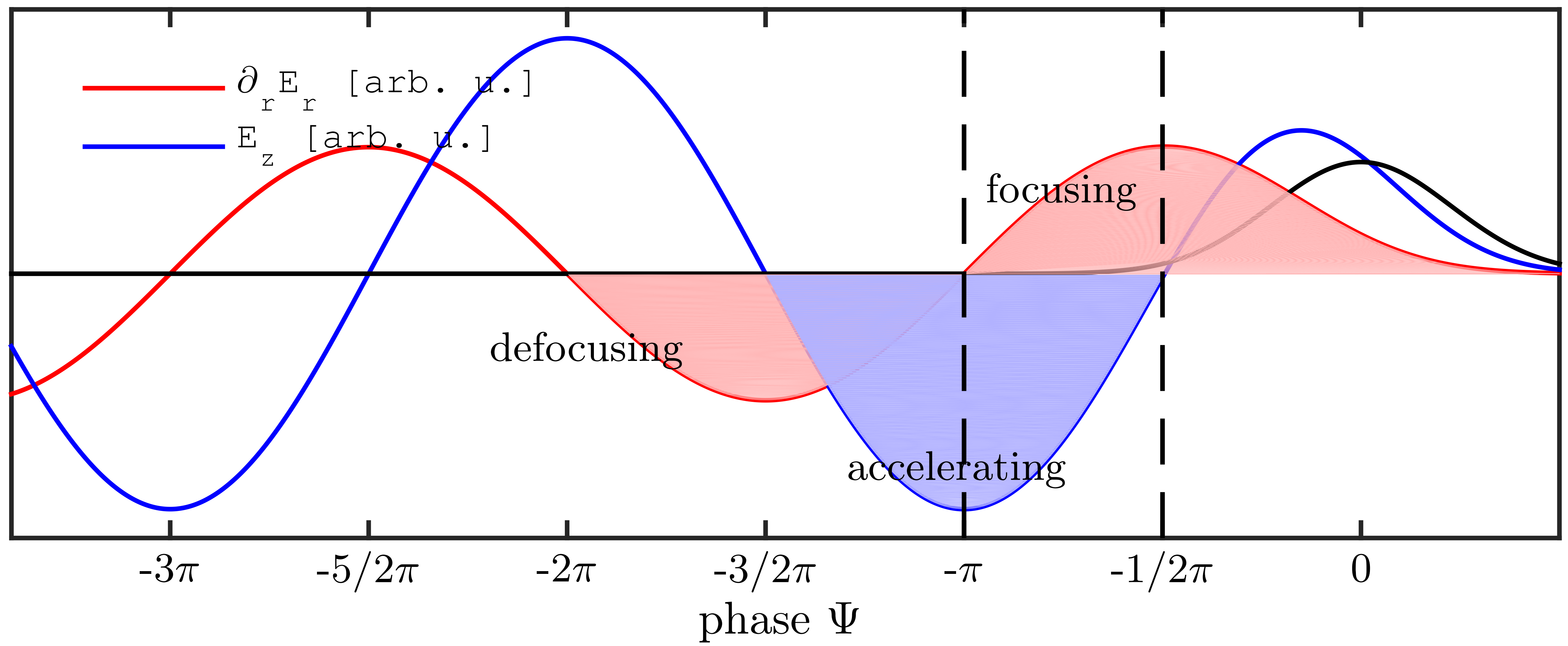
> different energies rotate w/ different frequency

bunch length

> K can vary along the bunch

> again, ellipsoid rotate w/ different frequencies

effects during acceleration



> accumulate energy chirp during acceleration

> makes things worse if you are not matched

effects during acceleration

good news

> self-injection: always matched

> external injection: you added the upramp anyway…

take home message:

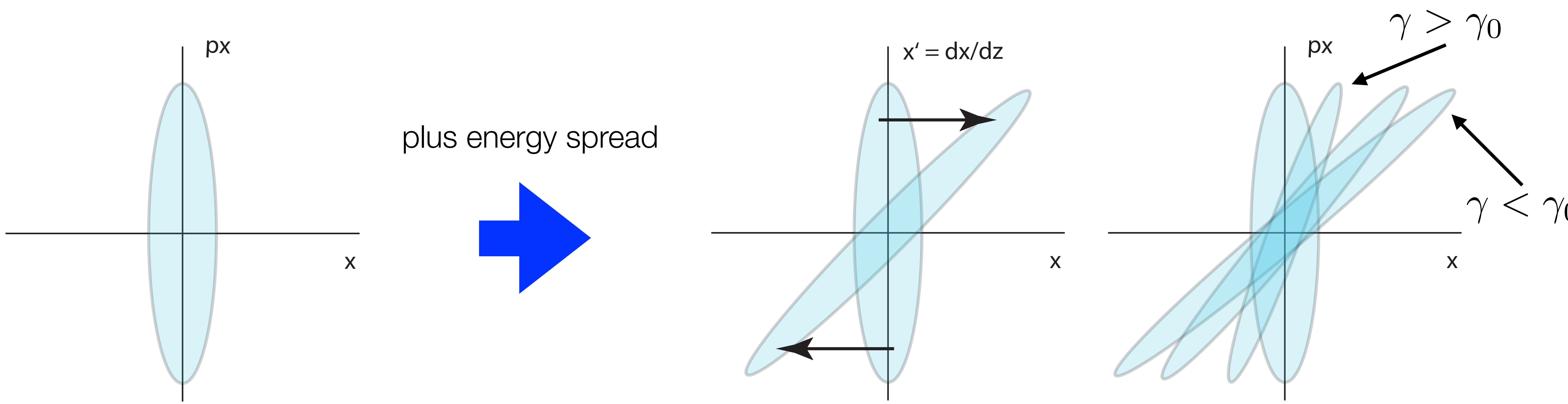
don’t worry too much,

but take care

beam extraction

caring about applications?

extraction



trace space

phase space

remember: in the plasma

> small beam size

> ***large*** divergence

remove focusing forces instantaneously

and beam explodes

emittance growth in phase space

extraction

adiabatic
- deform phase space
- change of K per betatron frequency is slow, i.e. large phase advance per change in K

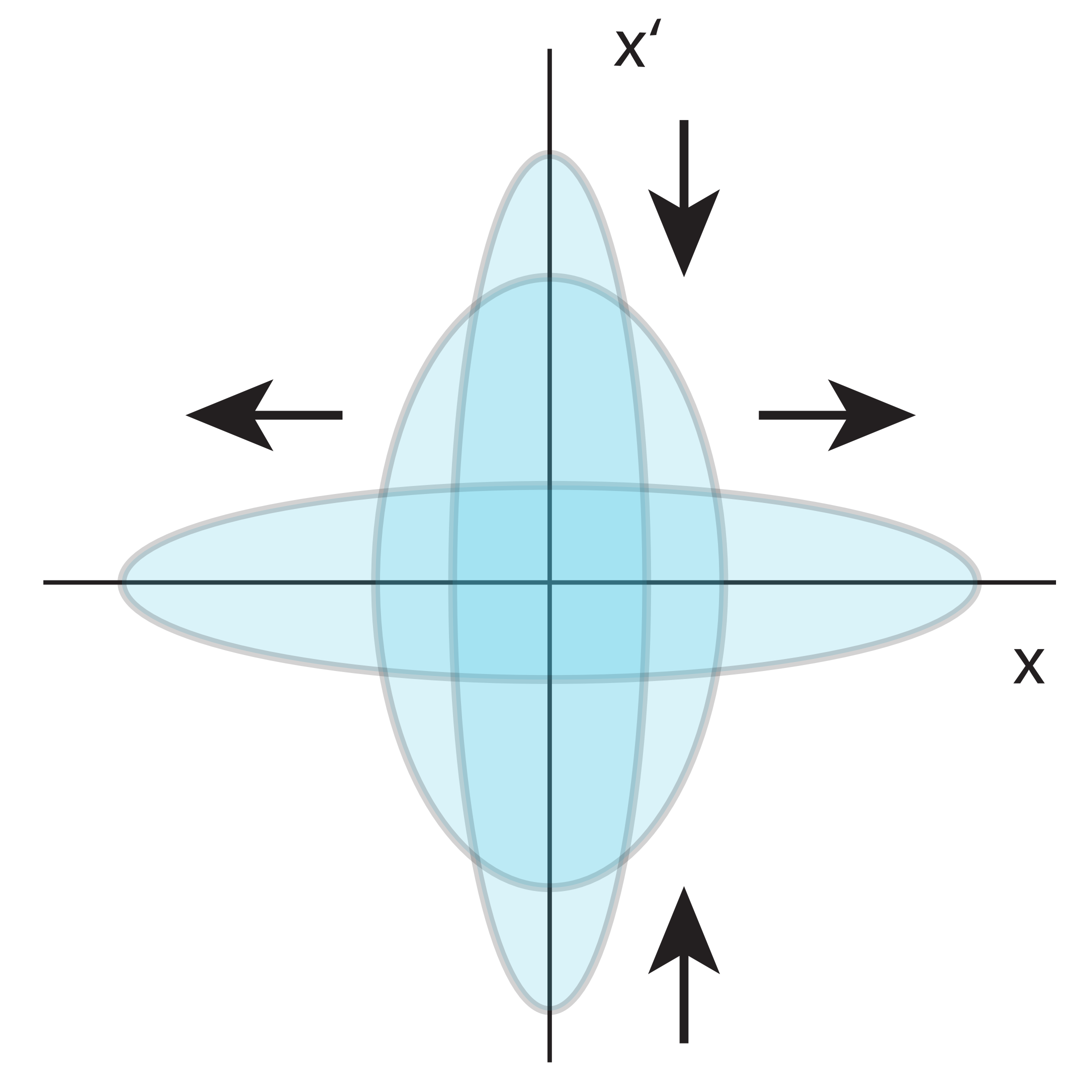
we find, the shortest K profile which is adiabatic and minimizes divergence is

$$K(z) \propto \frac{1}{(1+gz)^4}$$

adiabaticity parameter and adiabatic for

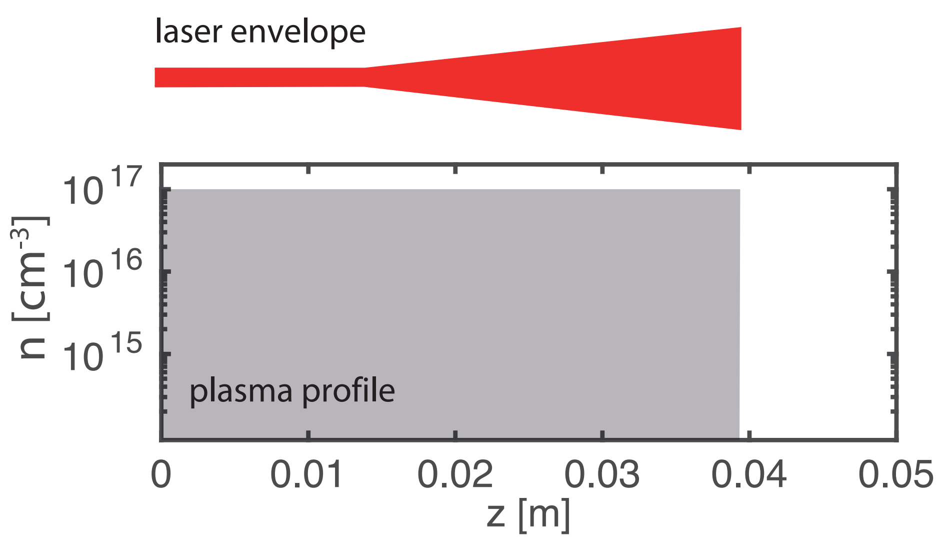
$$g\beta_0 \ll 1$$

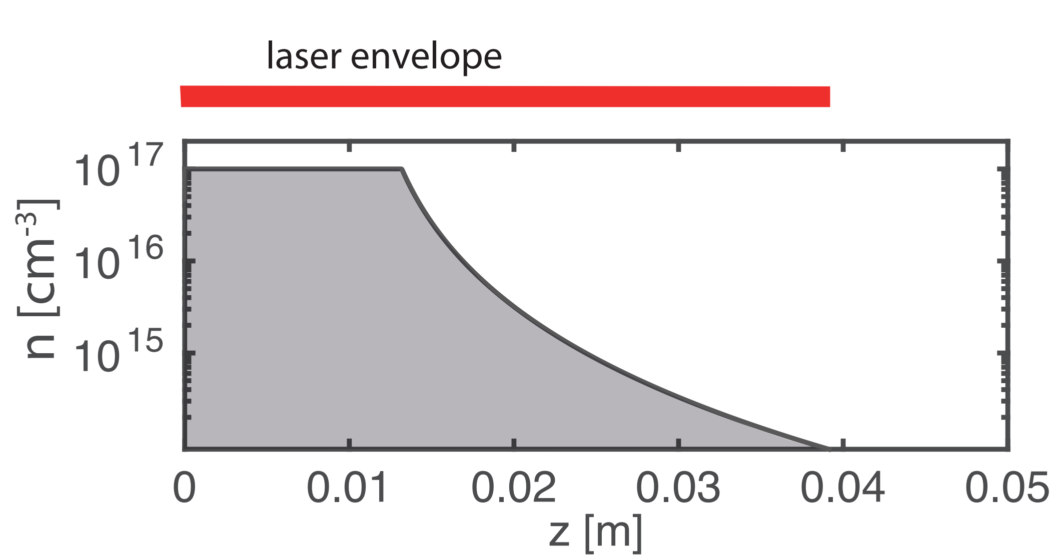
better:
- deform, do not shear
- reduce focusing adiabatically
- large focal spot means low divergence



extraction

$$K(z) \propto \frac{1}{(1+gz)^4}$$





- in terms of laser and density profiles:

$$K \propto -\frac{a^2 k_p}{w^2} \exp\left(k_p^2 \sigma_z^2/2\right) \sin\left(\Psi\right)$$

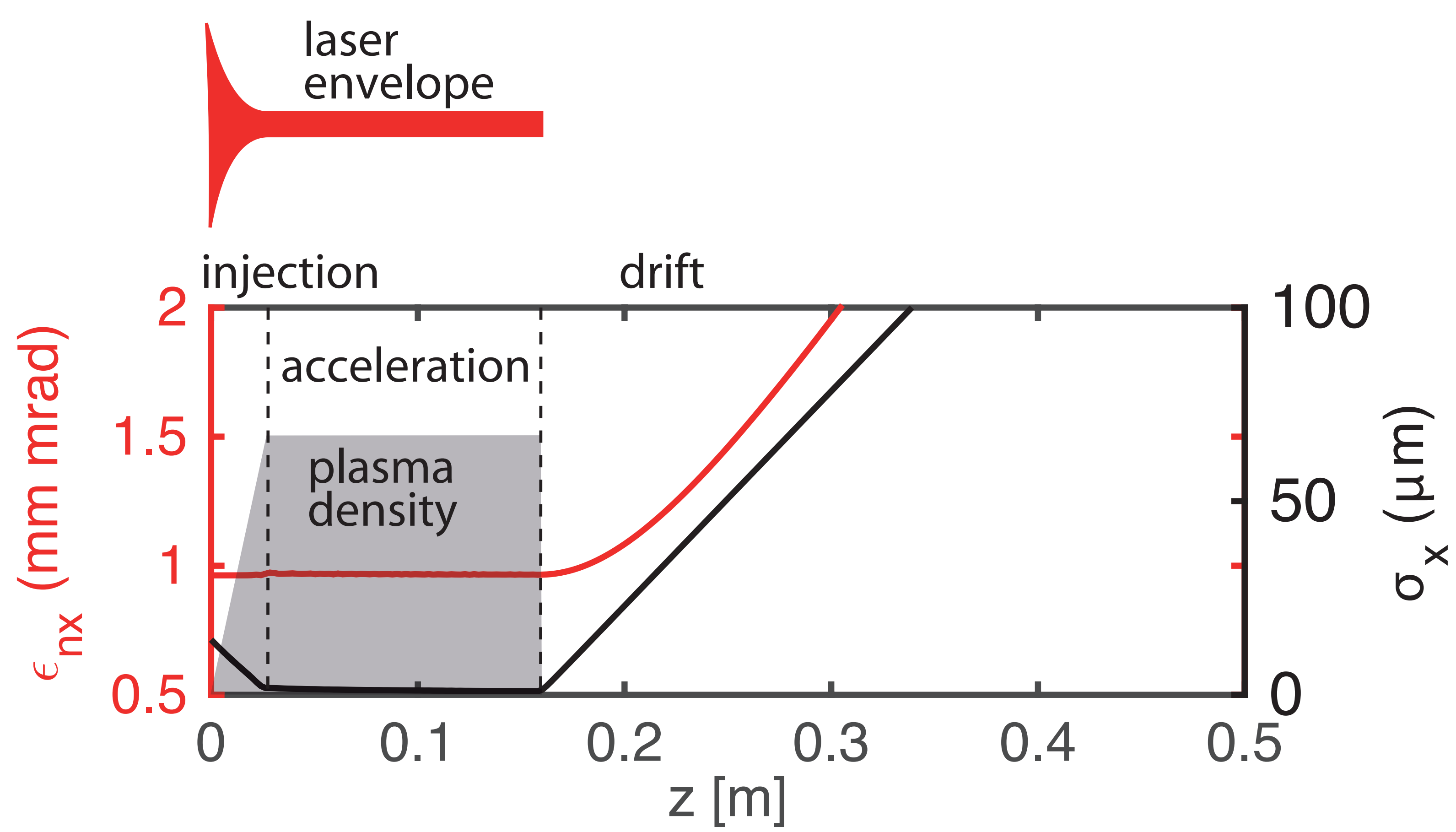
- assume constant density:

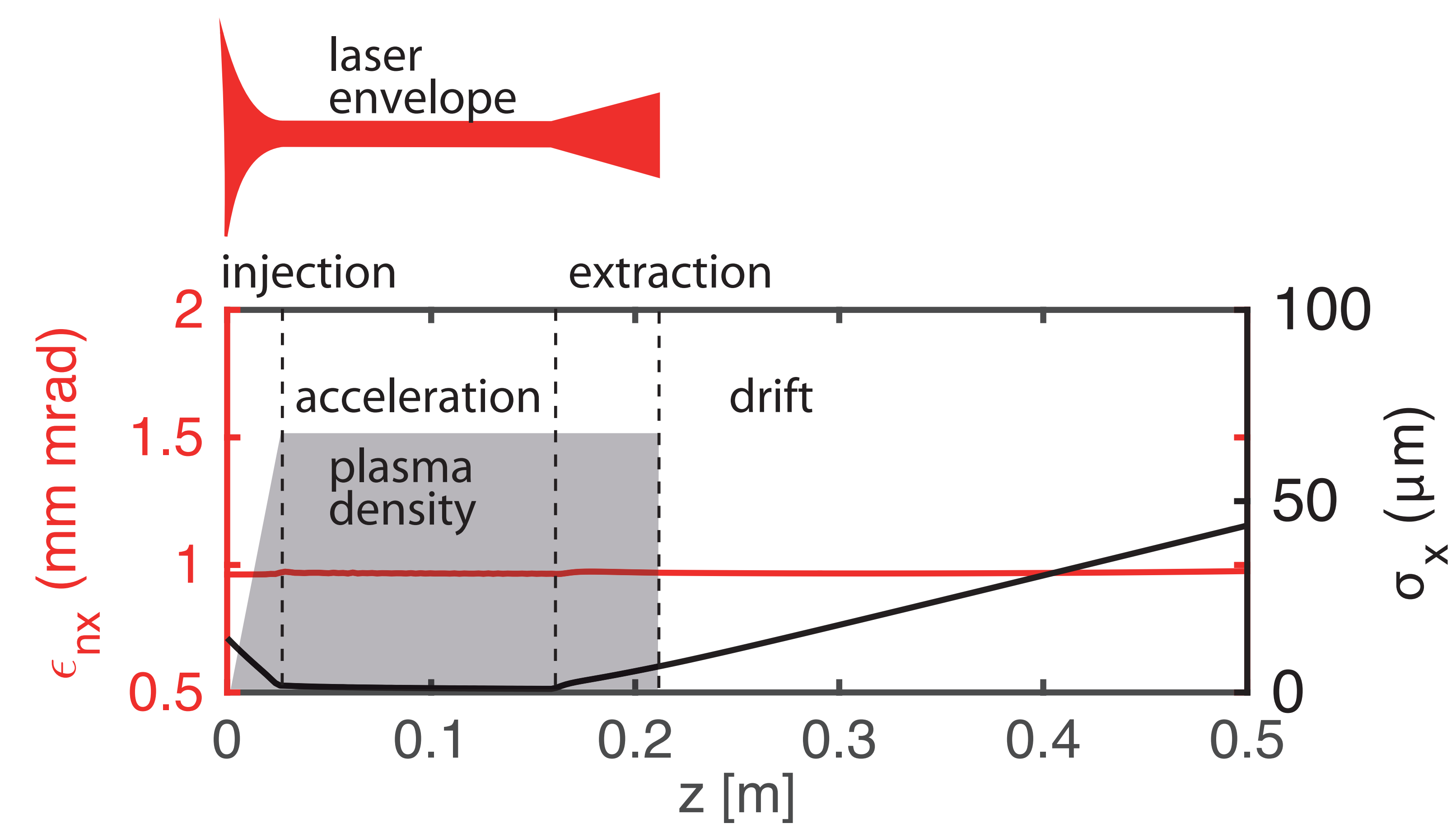
$$w(z) \propto 1 + gz$$

- assume constant laser

$$n(z) \propto \frac{1}{(1+agz+bg^2z^2)^2}$$

example





> sharp plasma-vacuum transition

> large divergence

> emittance growth

> slowly decrease *K(z)*

> smaller divergence

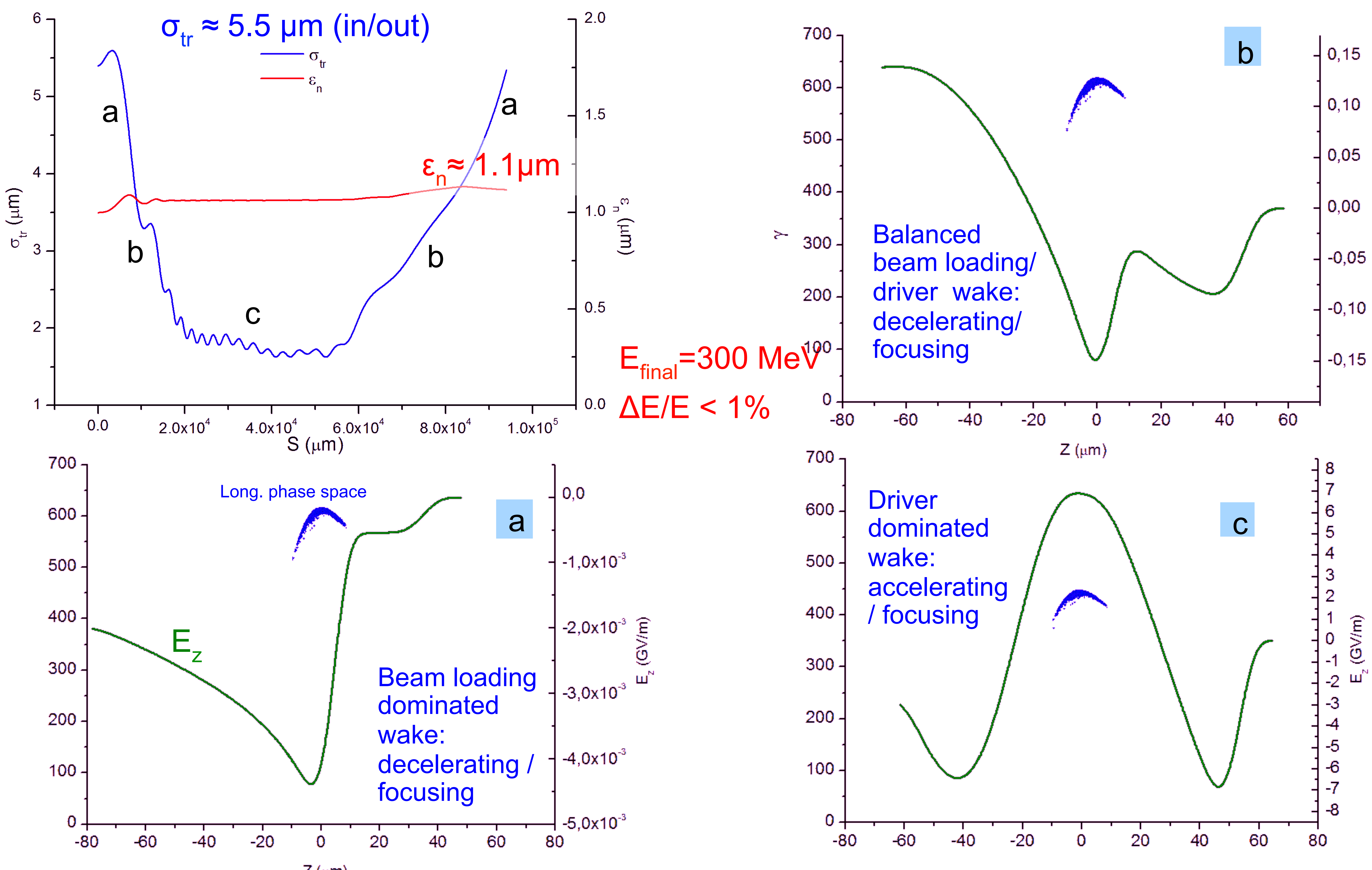
> ~ constant emittance

beam loading & the plasma lens

thanks to A. Rossi (INFN) and R. Lehe (LBNL) for discussions, and slides…

thanks to Andrea Rossi for slides

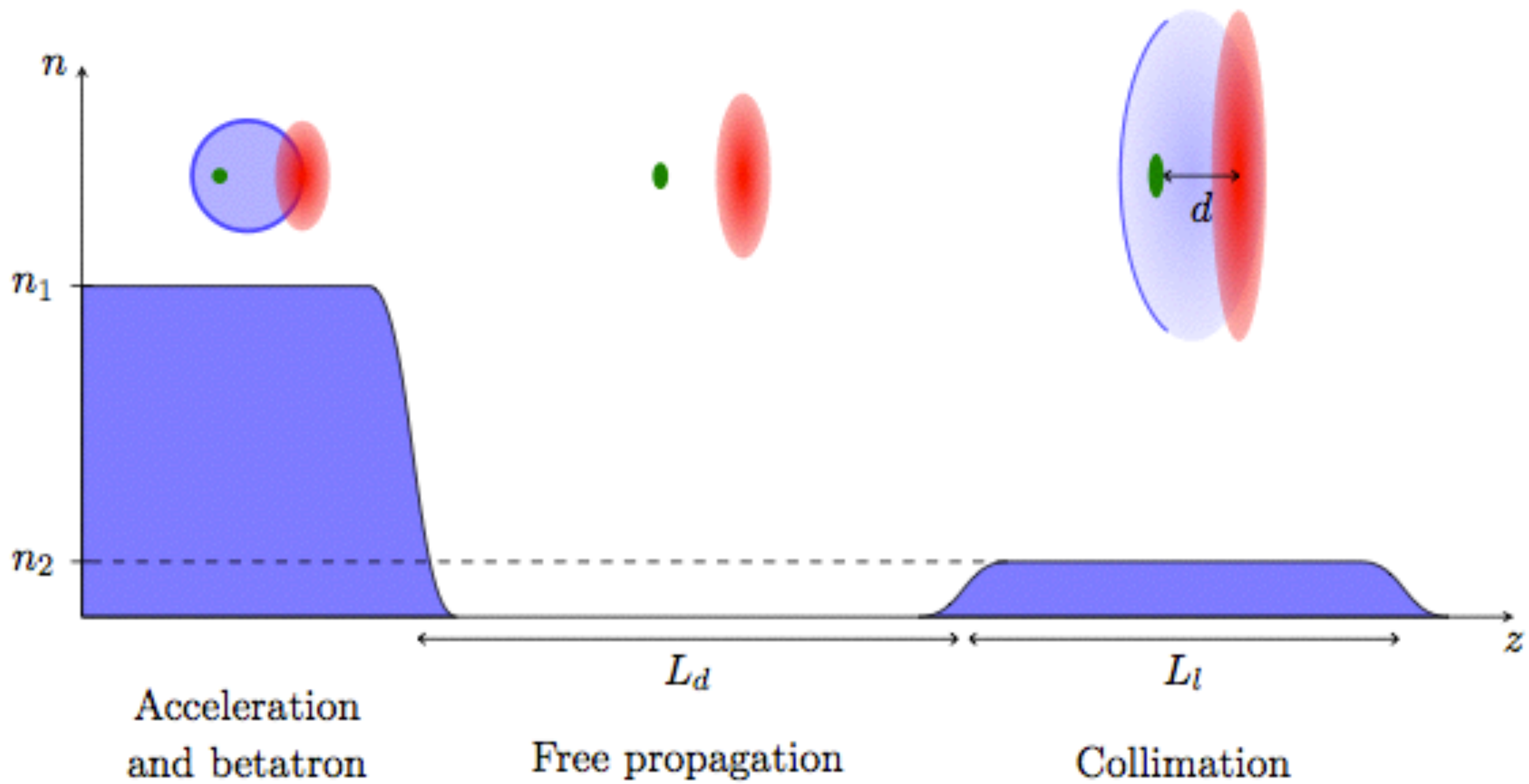
adding beam loading



Andrea R. Rossi

2nd European Advanced Accelerator Concepts, September 15th 2015, La Biodola, Italy thanks to Remi Lehe for slides

the laser-plasma lens

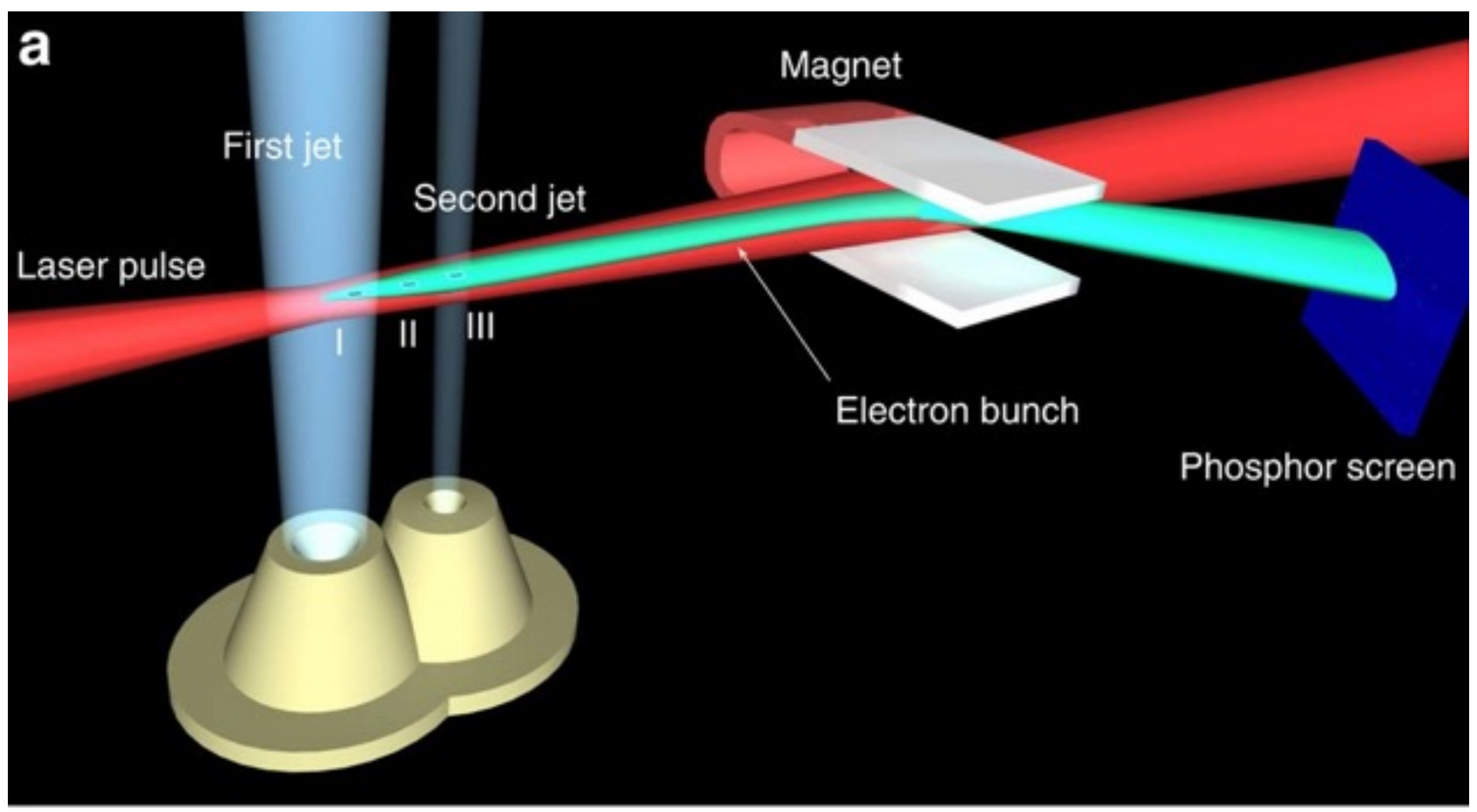


- **2 gas jets, 1 laser pulse**
- **Free propagation** for the laser and the bunch, after the accelerator (stretches the phase space)
- **Focusing laser-wakefield** in the second jet (rotates the phase space, results in a low θ_x)
- Requires **tuning** of the parameters of the setup (L_d, L_l, n_2) for **collimation** (proper amount of rotation)
- $\neq$ **plasma lens** (i.e. no laser) In a plasma lens, only the tail of the bunch is focused, whereas both head and tail are focused here.

First proposed and demonstrated at LOA (France)

the laser-plasma lens

- **In experiments**

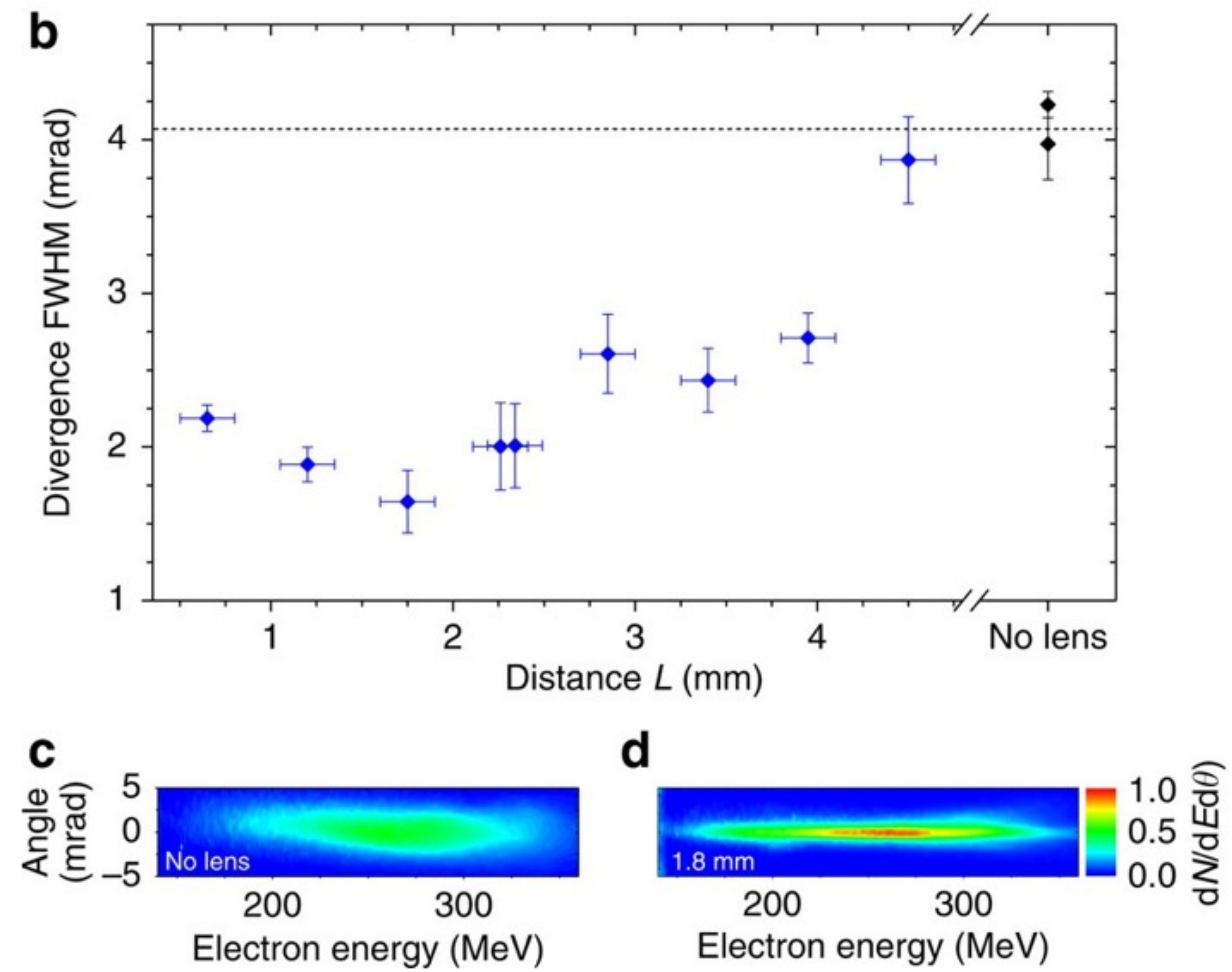


2.5x reduction of the divergence over a wide energy distribution

C. Thaury et al., Nat. Comm. **6**, 6860 (2014)

R. Lehe et al., PRSTAB **17**, 121301 (2014)

Tuning of the lens with respect to the distance L between the two jets



conclusion

conclusion

- proper injection, and extraction is important
- (unless you do not want to use the beam)
- precise control over the density profile (and the laser) becomes more and more important
- we have to do more experiments to validate results, and compare regimes
- and have to think about fundamental limitations
- (by the way, energy spread is still an issue)

references

- T. Mehrling et al., PRST-AB 15, 111303 (2012)
- R. Assmann et al., NIM A 410, 544 (1998)
- P. Antici et al., J. Appl. Phys. 112, 044902 (2012)
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- R. Lehe et al., PRST-AB 17, 121301 (2014)
- I. Dornmair et al., PRST-AB 18, 041302 (2015)

please see also references within those papers for credits of previous work (sometimes even decades ago)

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