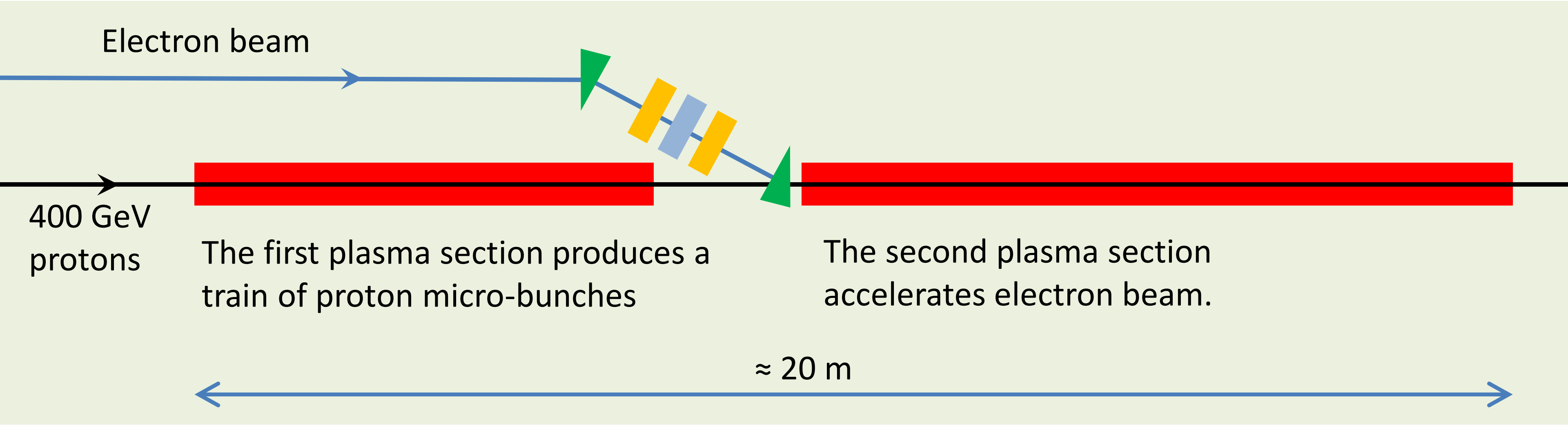
Details of electron injection for RUN 2

A. Petrenko, A. Pukhov, K. Lotov, A. Gorn, A. Sosedkin

August 27, 2018. Run-2 meeting at CERN.

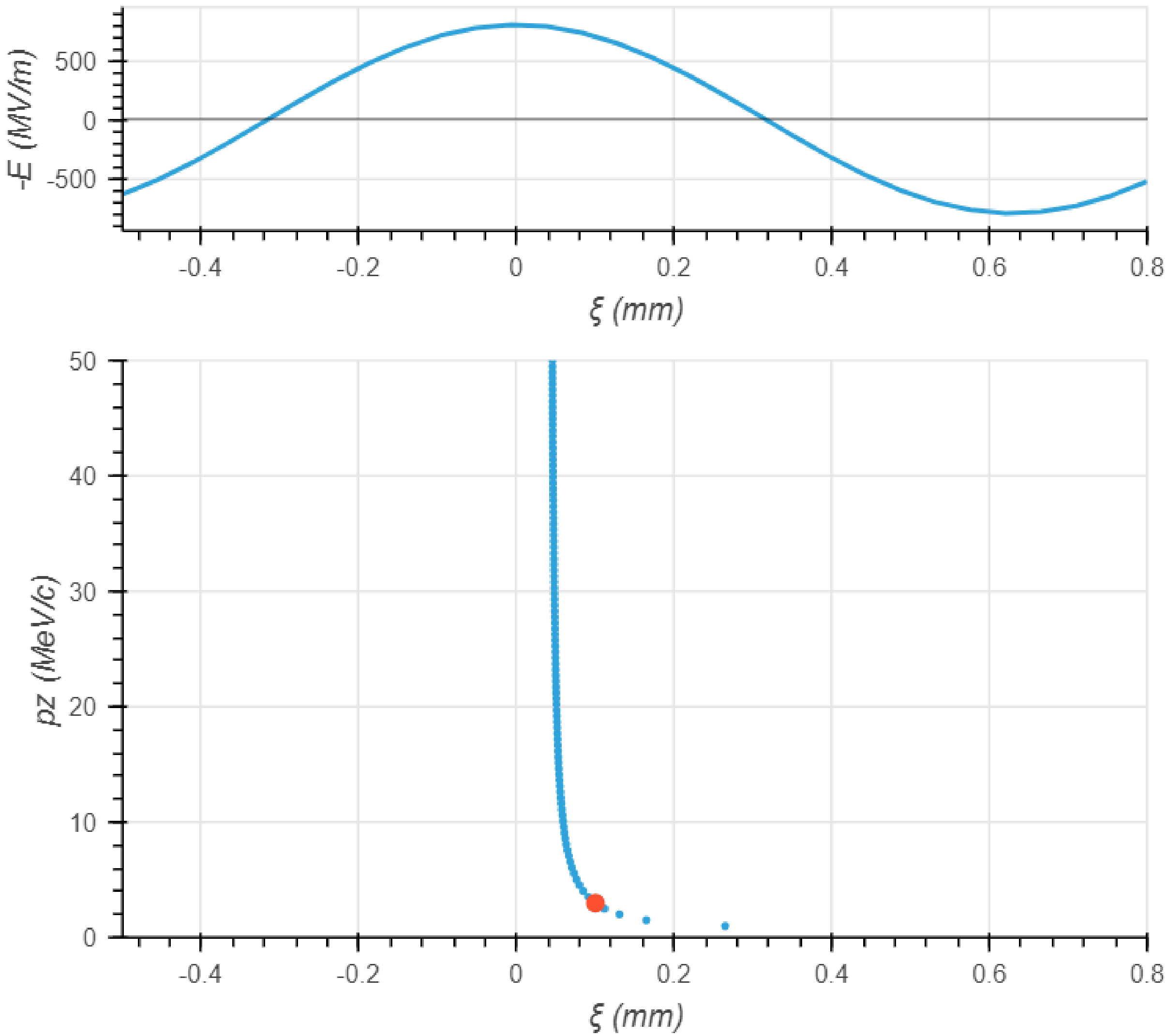


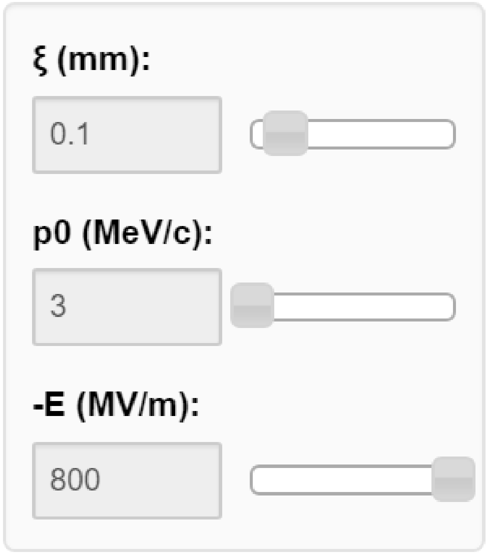
Plasma density $\boldsymbol{n_p = 7 \cdot 10^{14}}$ **1/cm³** (plasma wave length λ_p = 1.2 mm).

The SPS proton beam is assumed to be compressed longitudinally by a factor of two ($\sigma_z \approx$ 6 cm, $\boldsymbol{I_{peak} \approx}$ **100 A**) – feasible according to the "Prospects for improved SPS p+ bunch parameters for AWAKE" by A. Lasheen, J. Repond, E. Shaposhnikova.

What is the electron energy suitable for Run-2 injection?

Longitudinal e-beam dynamics can be described with simple analytics:





For more details see: https://anaconda.org/petrenko/1d_e-inj

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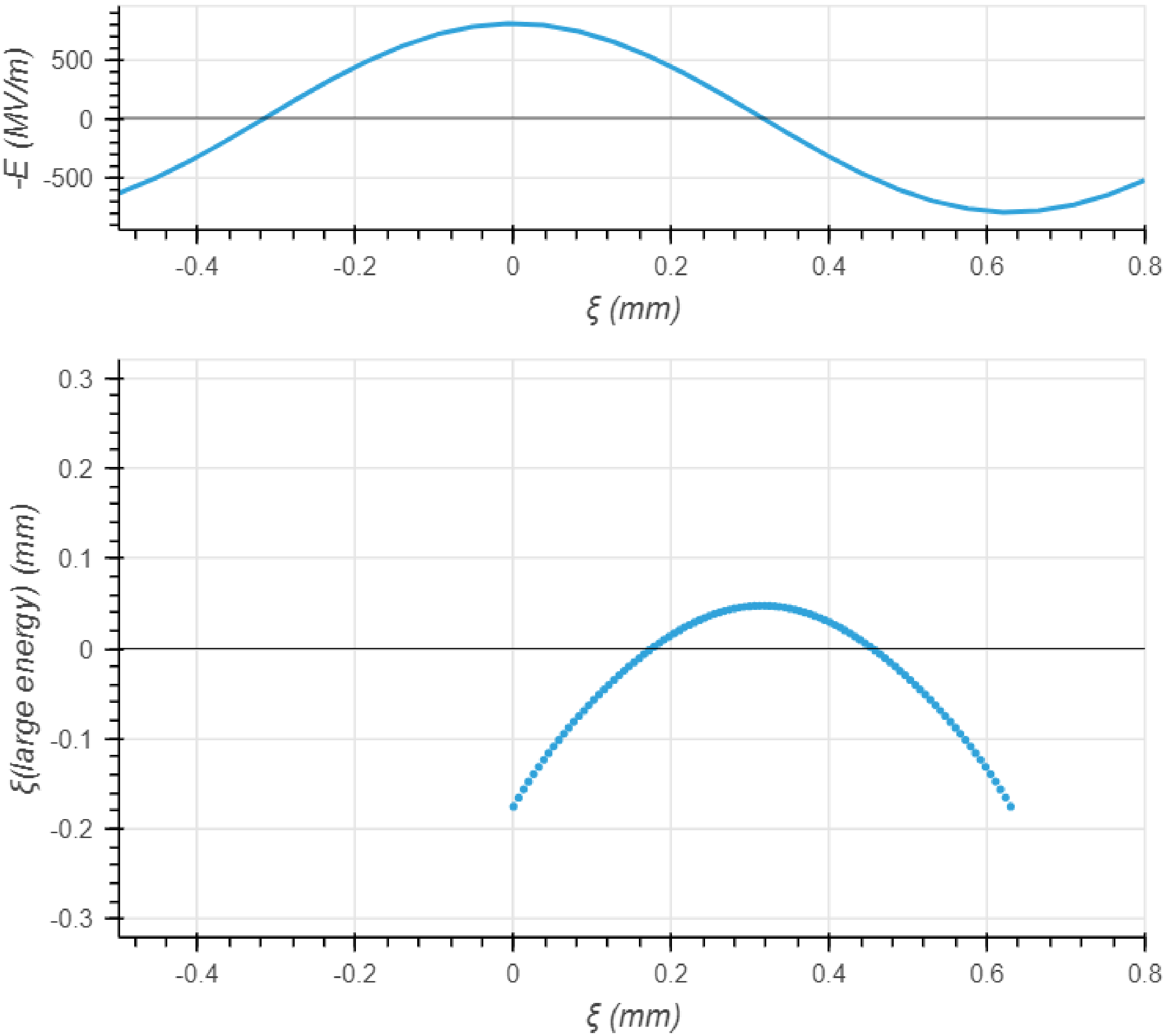

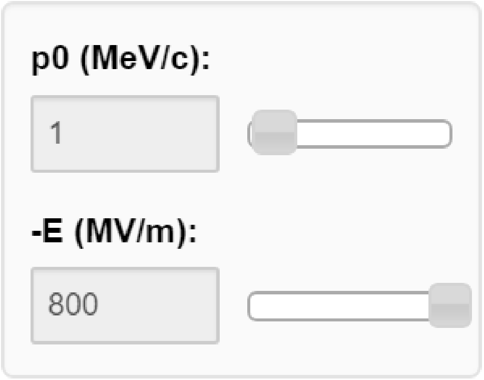

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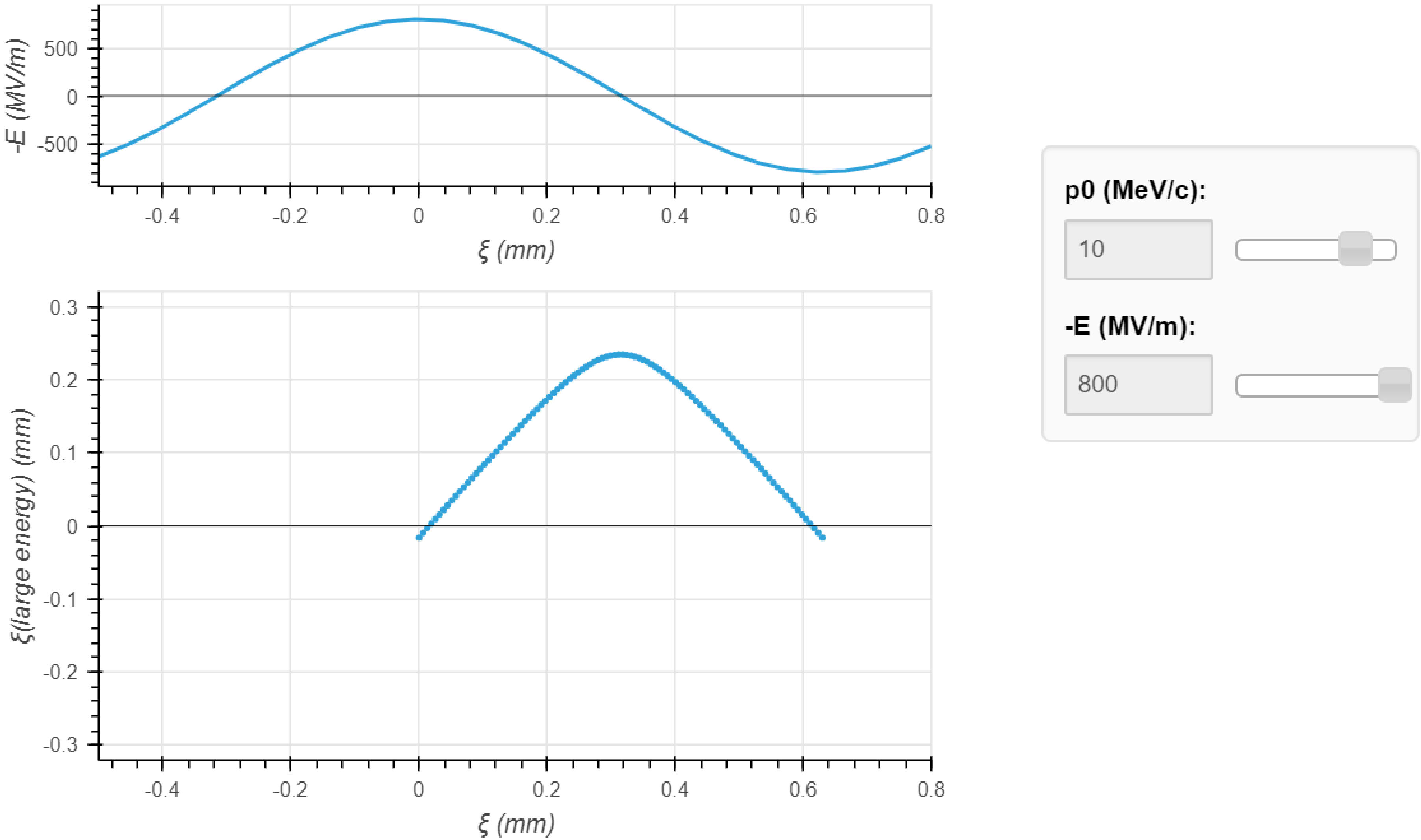

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Preserving the emittance of electron beam

[V. K. Berglyd Olsen, E. Adli, and P. Muggli Phys. Rev. Accel. Beams **21**, 011301 (2018)](#)

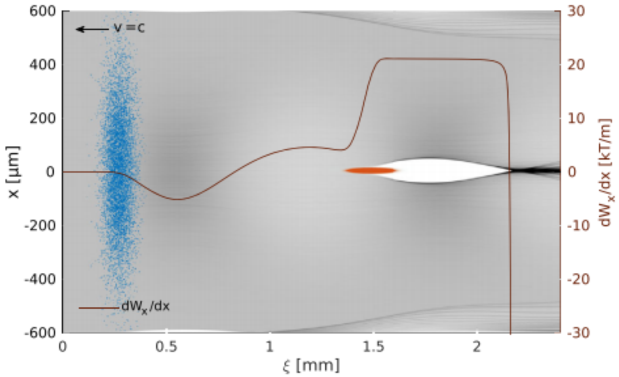


FIG. 2. QuickPIC simulation results showing the initial time step for the single proton drive beam and witness beam setup. Plasma electron density is shown in grey with the drive beam (blue) and the witness beam (red) superimposed. The line plot indicates the transverse wakefield gradient dW_x/dx where $W_x = E_x - v_b B_y$, evaluated along the beam axis. Beams move to the left.

spread as well as emittance growth, we consider a witness beam matched to the plasma density. The matched beam transverse size [29] is

$$\sigma_{x,y,eb} = \left(\frac{2c^2\epsilon_N^2 m_e \epsilon_0}{n_{pe} e^2 \gamma}\right)^{1/4}. \qquad (1)$$

We assume an initial normalized emittance of $\epsilon_N = 2\ \mu$m. This emittance is possible to produce with a standard rf-injector, while at the same time yielding a sufficiently narrow beam.

Beam loading by a short witness beam is sensitive to its position relative to the electric field [30] as well as, at low energy, to its dephasing with respect to the wakefields. To eliminate dephasing of the witness beam, the initial beam energy is set such that $\gamma_{eb} = \gamma_{pb} = 426.3$, giving an energy of 217 MeV. A lower initial energy is likely to be sufficient for AWAKE Run 2 injection.

Equation (1) yields a transverse size $\sigma_{x,y,eb}$ of 5.25 μm, which is narrow compared to the drive beam $\sigma_{x,y,pb} = 200\ \mu$m. The bunch length was set to $\sigma_z = 60\ \mu$m based on earlier beam loading studies [22]. The charge is adjusted to 100 pC for optimal beam loading, as discussed in the next section. We refer to the defined drive beam and

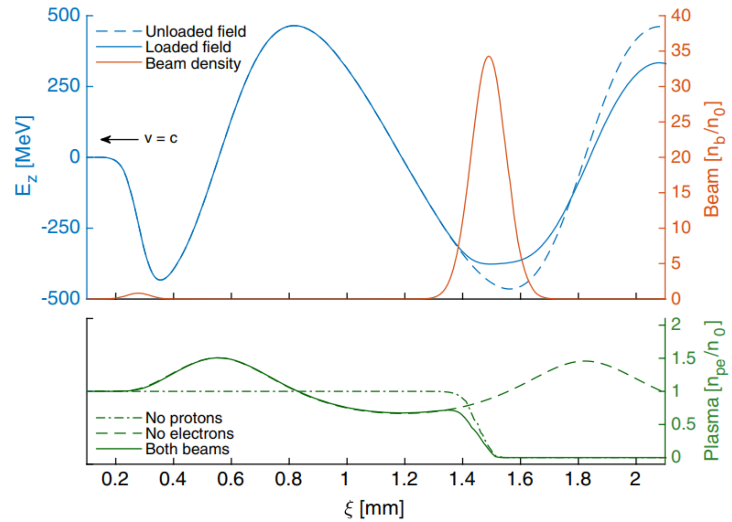
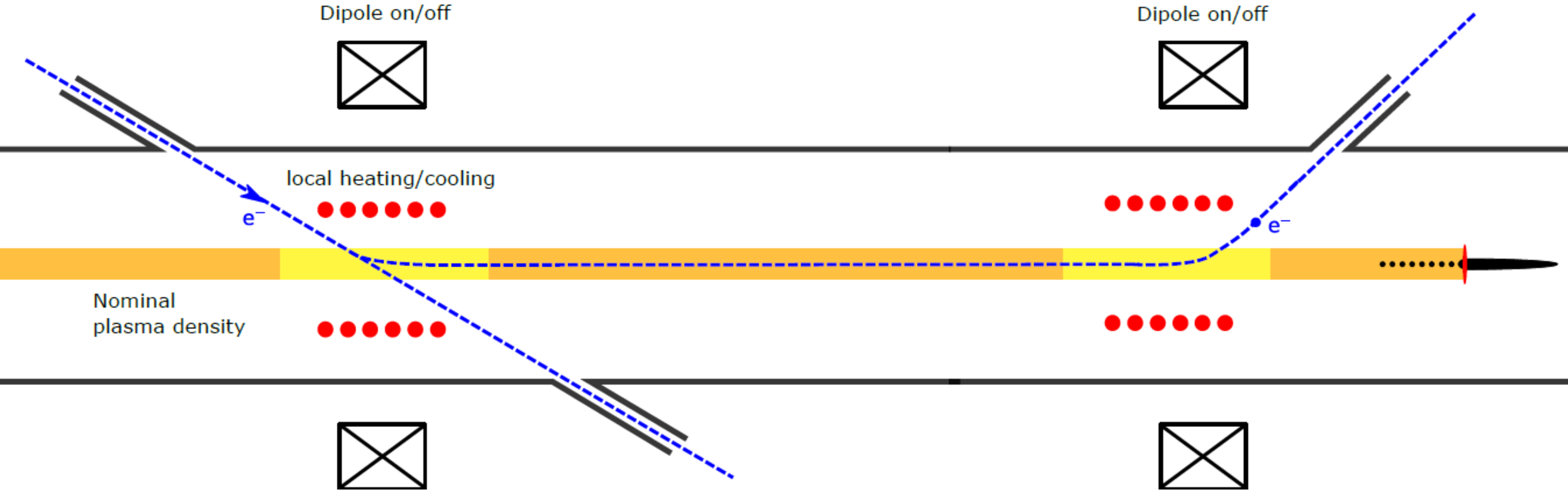


FIG. 3. Top plot: Unloaded longitudinal electric field with no witness beam (dashed blue line) and loaded field (whole blue line) along the beam axis. The beam density along the axis for both beams are shown in red. Bottom plot: Plasma densities along the beam axis for a drive beam with no witness beam (dashed green line), witness beam with no drive beam (dash-dotted green line), and both beams present (continuous green line). The position in the simulation box $\xi = z - tc$, moving toward the left. The plots show the initial time step.

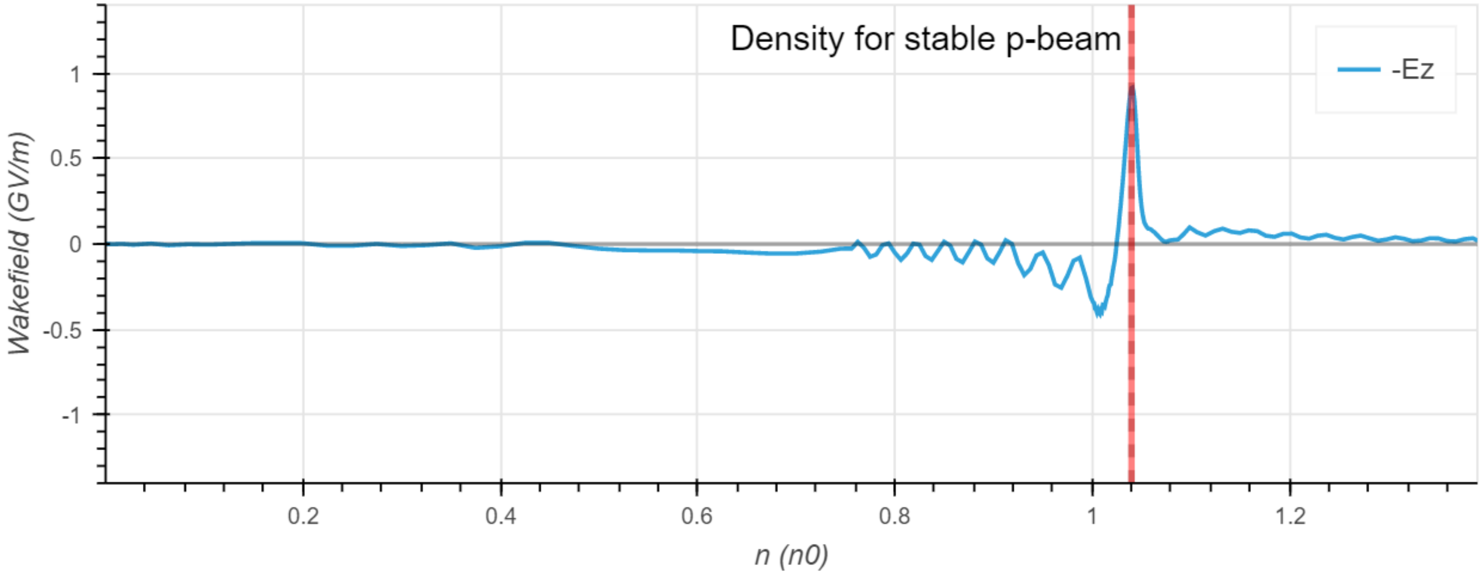
The main question is what minimum e-beam energy is needed to reach such a regime? The requirements on initial beam energy end emittance are probably more relaxed than in Eq. 1 because electron beam is gaining energy quickly and its size is decreasing adiabatically.

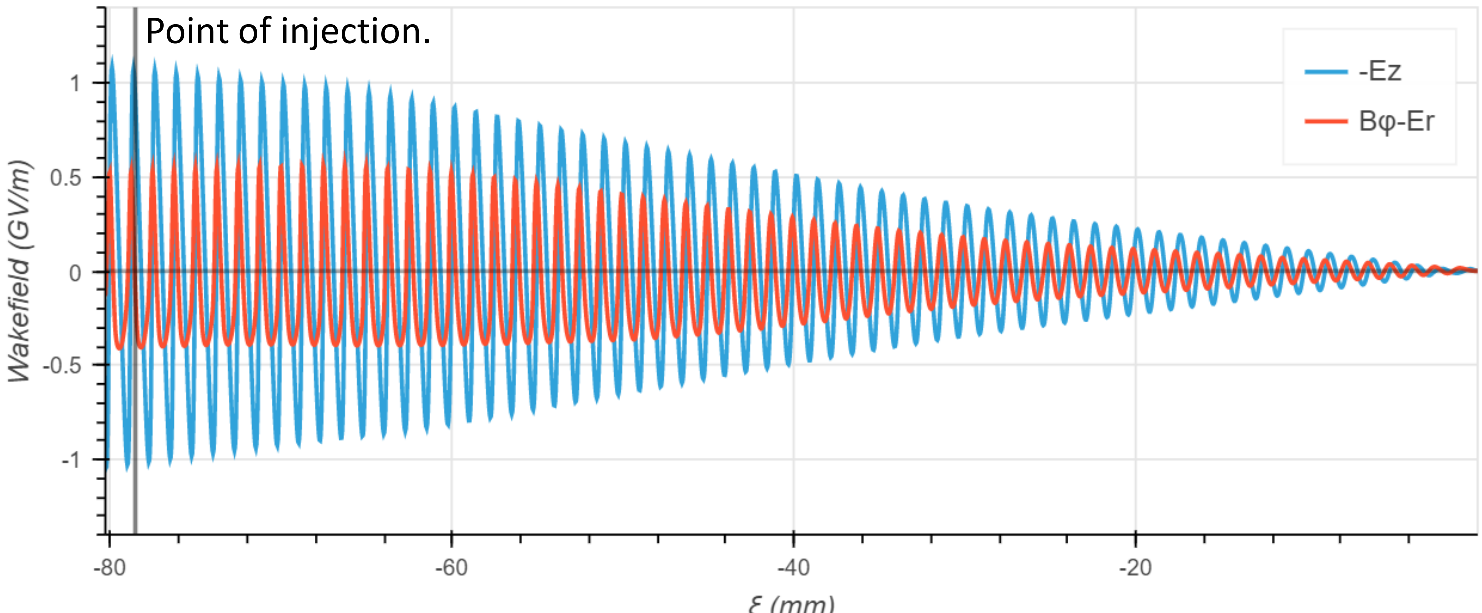
What are the technical details of this injection scheme?



Wakefield amplitude vs plasma density

-Ez at the point of injection.





See interactive plots (+2D fieldmaps) for more details.

Wakefield amplitude vs plasma density

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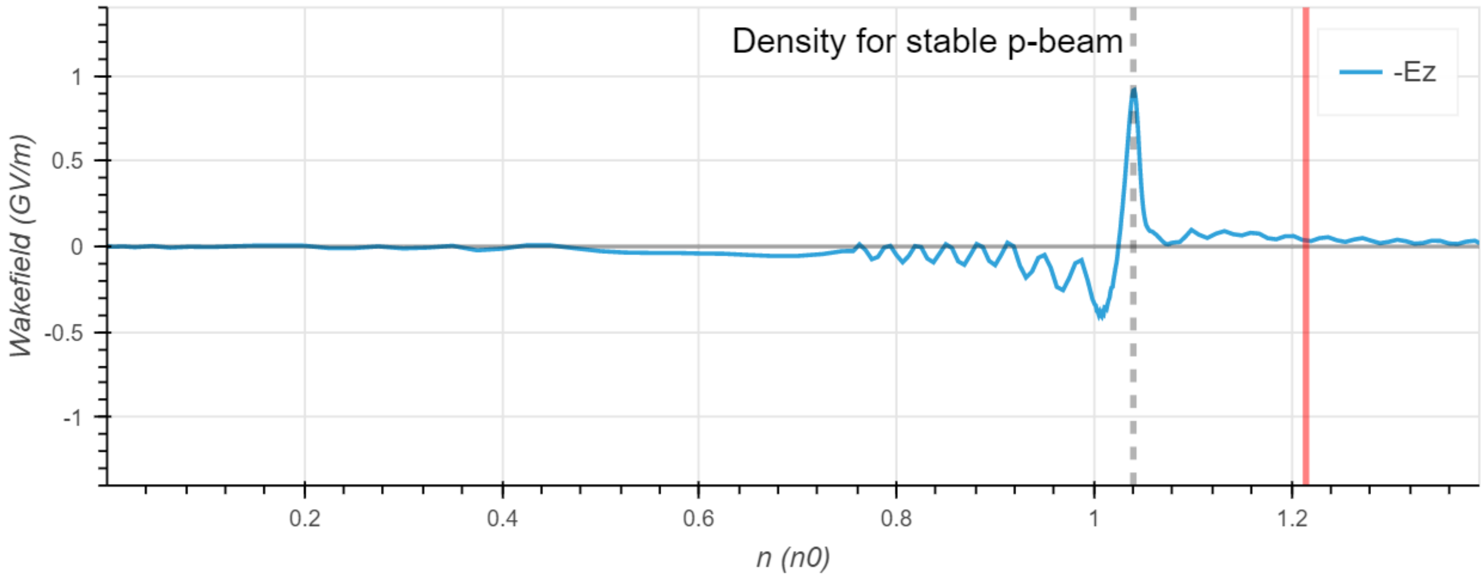

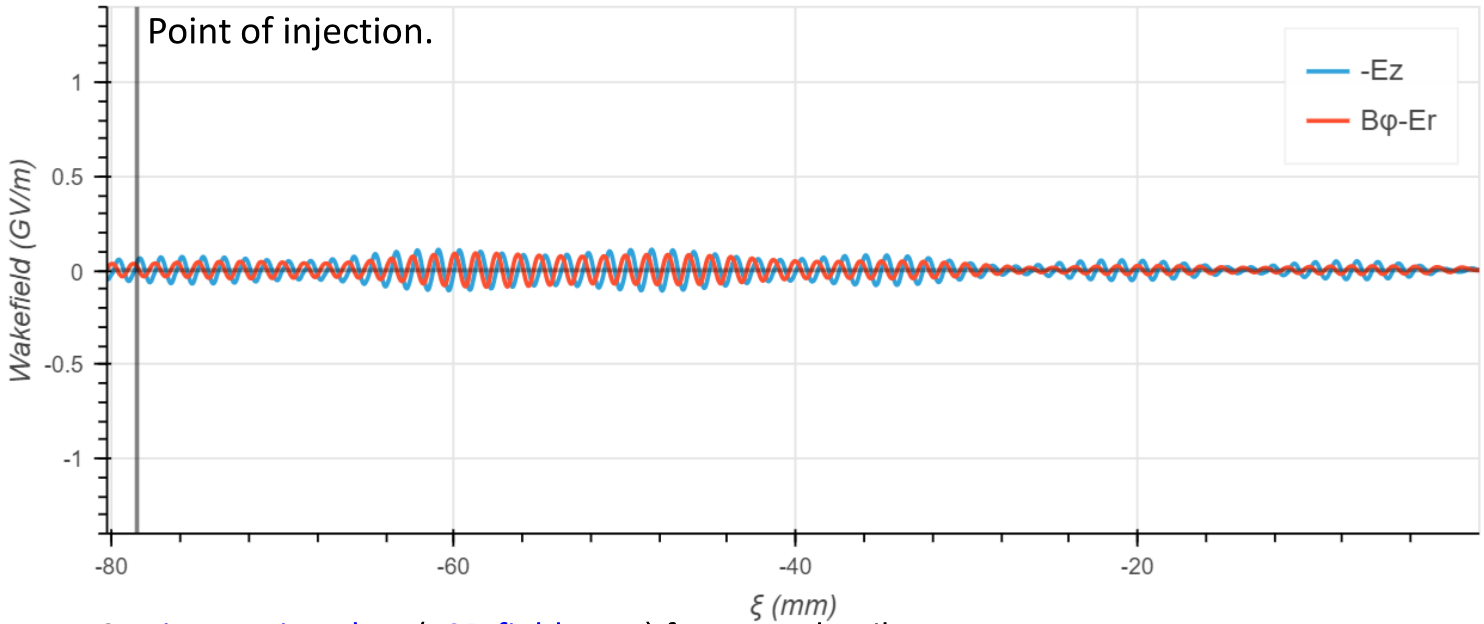

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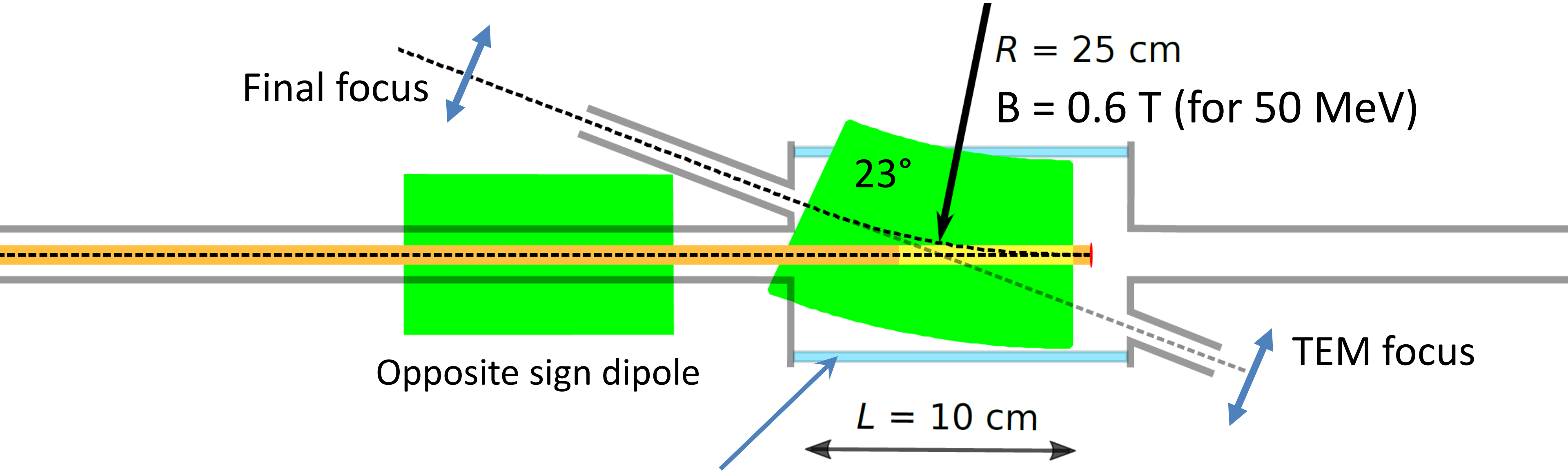
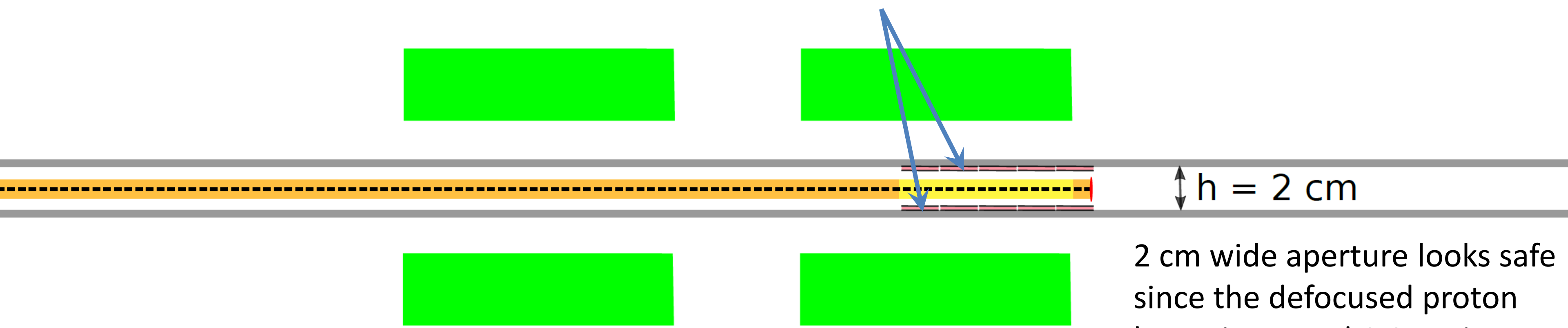
Possible design for the injection region:



Long and narrow glass window (or several round windows)

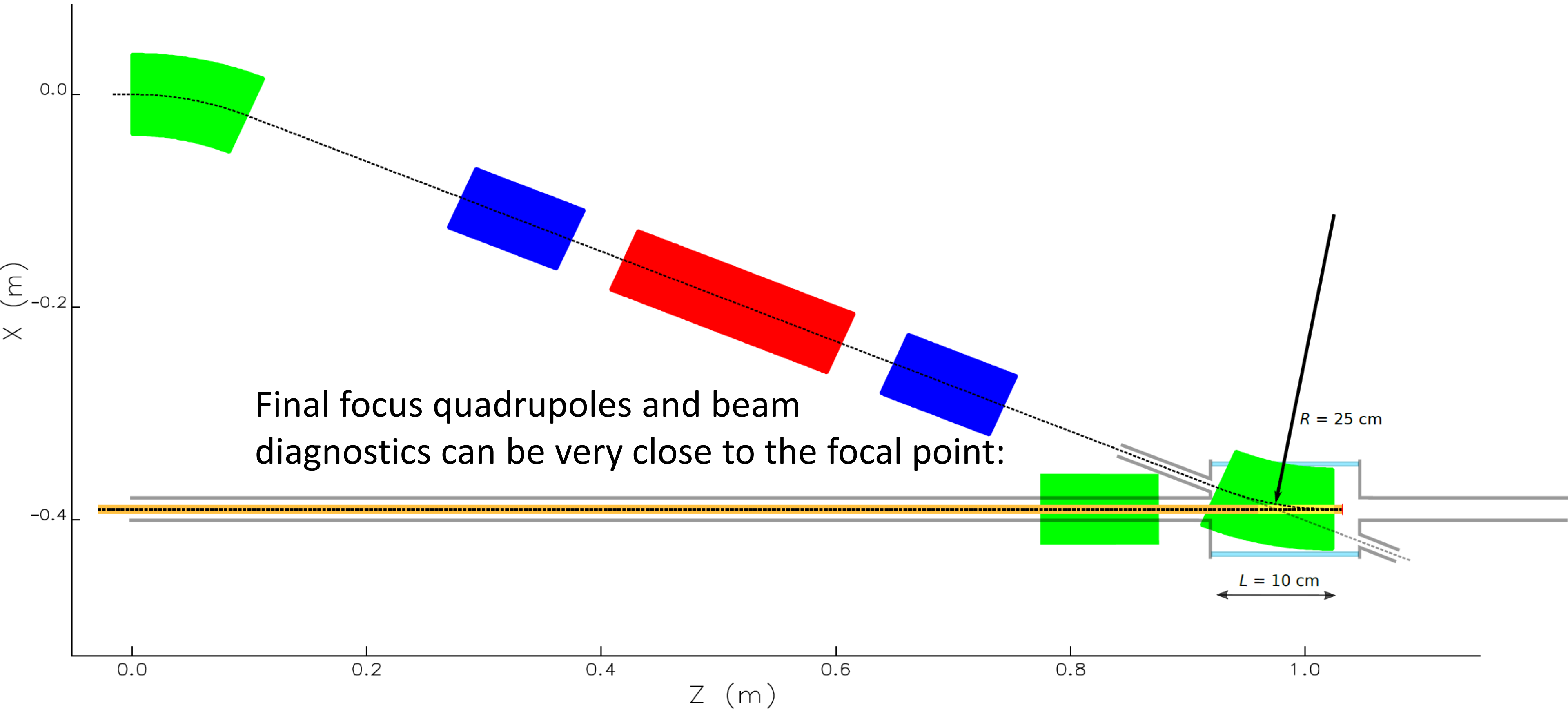
Wide heating/cooling cm-long segments (Pipes with oil? Peltier elements?)



2 cm wide aperture looks safe since the defocused proton beam is around 1.1 cm in diameter here.

Probably vacuum thermal insulation should be used.

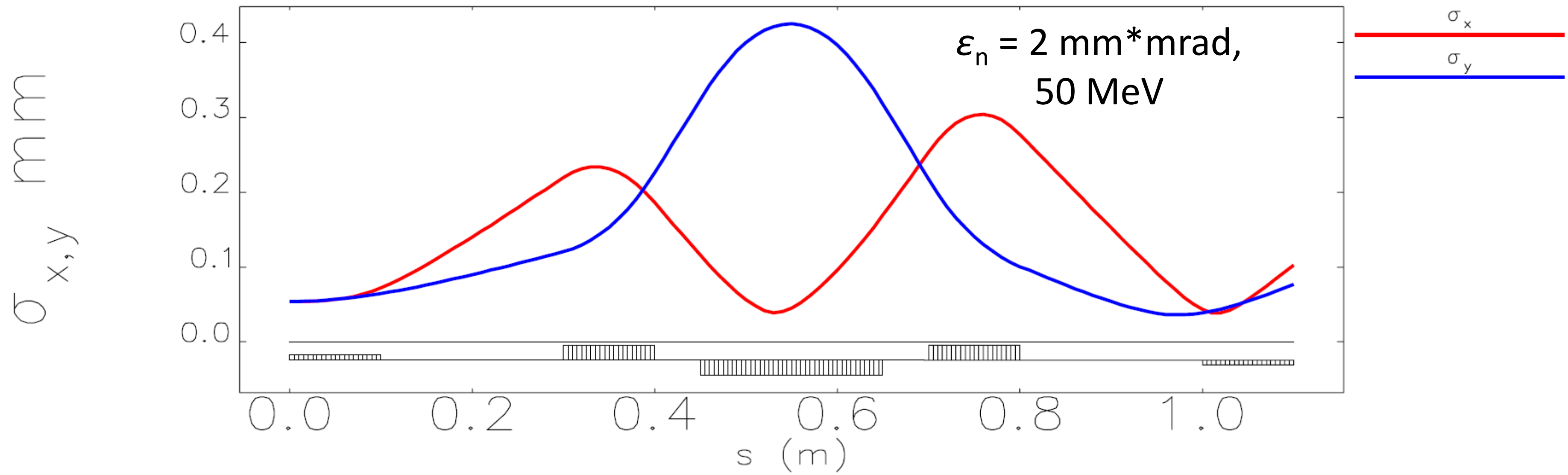
Example final focus:



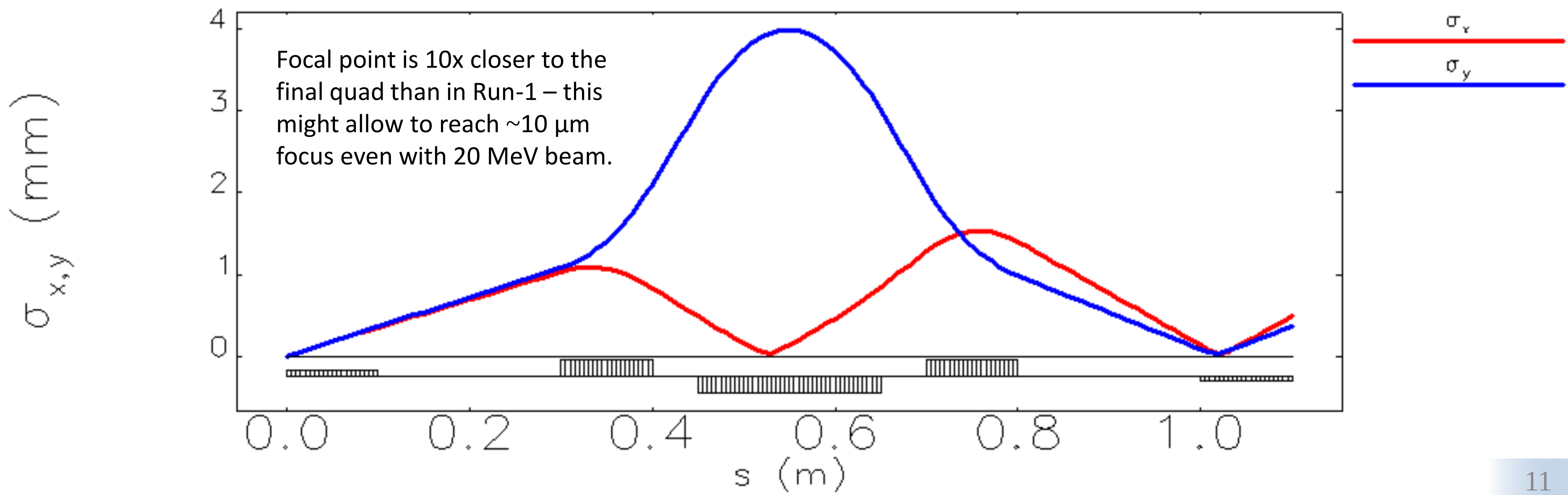
Final focus quadrupoles and beam diagnostics can be very close to the focal point:

Example final focus:

50 µm focus (mm-size aperture quads, $K_{1,max}$ = 100 m^{-2}, G = 0.17 T/cm):

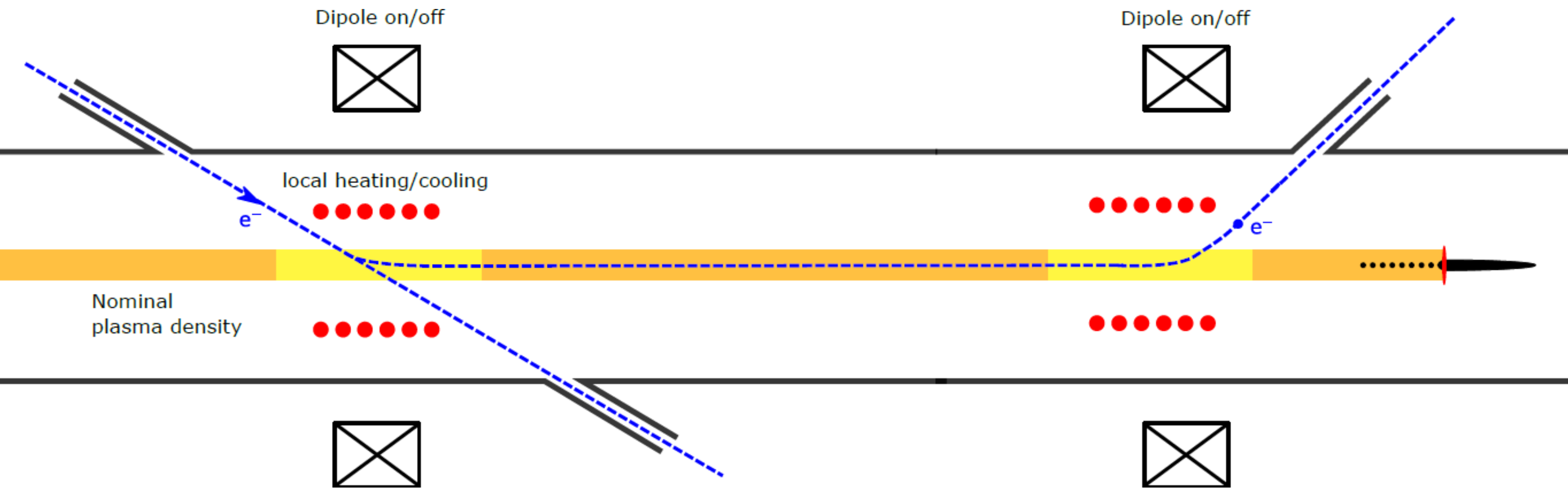


5 µm focus (cm-size aperture quads with exactly the same gradient):



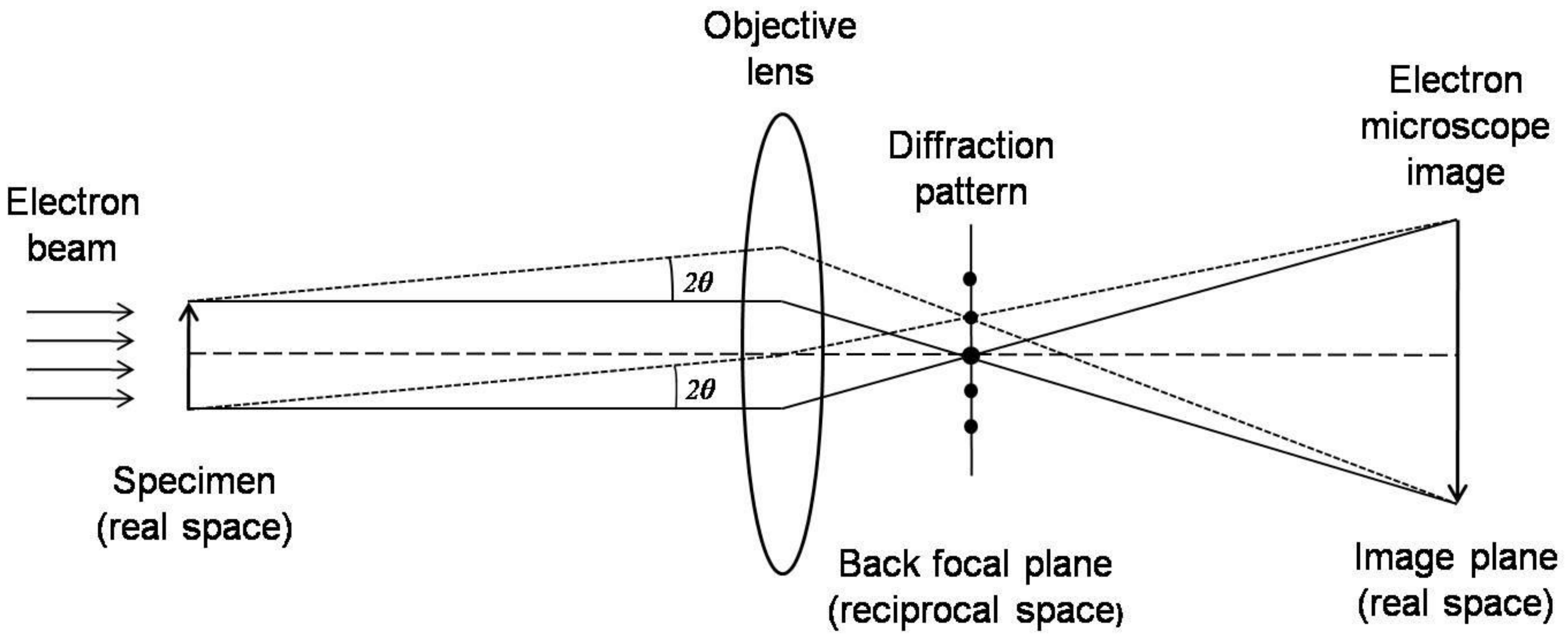
There are ways to measure electron beam and plasma wake parameters:

Similar hot/cold spot can be used to get the electron beam out of the wakefield:



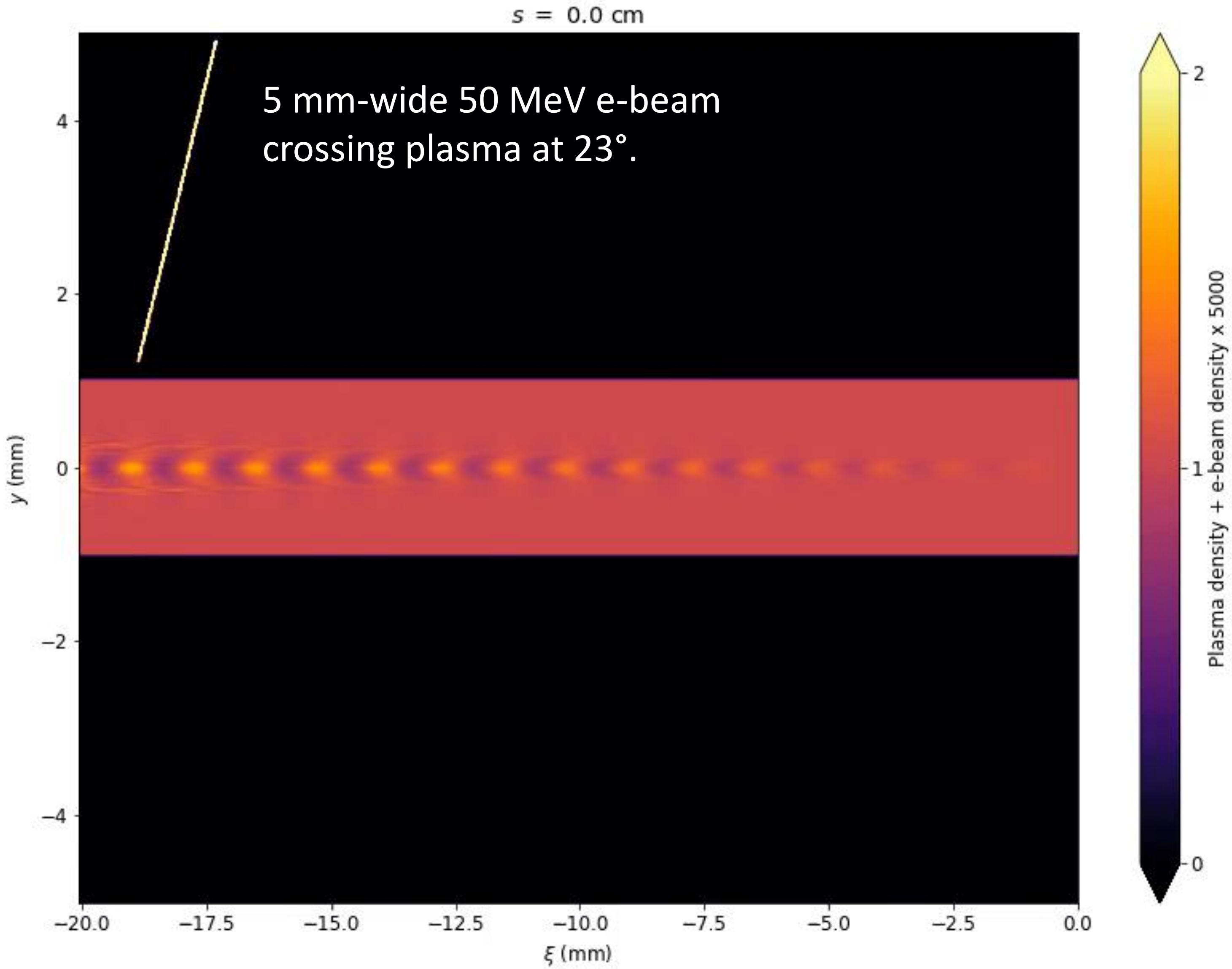
This can significantly improve the experimental control over e-injection. It can be possible to observe e-injection decoupled from long acceleration process. Electron injection into the plasma wakefield can be tuned precisely.

Transmission Electron Microscopy:



By adjusting the lenses (changing their focal lengths), both electron microscope images and DP can be observed. Thus, both observation modes can be successfully combined in the analysis of the microstructures of materials. For instance, during investigation of DPs, an electron microscope image is observed. Then, by inserting an aperture (selected area aperture), adjusting the lenses, and focusing on a specific area that we are interested in, we will get a DP of the area. This kind of observation mode is called a *selected area diffraction*. In order to investigate an electron microscope image, we first observe the DP. Then by passing the transmitted beam or one of the diffracted beams through a selected aperture and changing to the imaging mode, we can get the image with enhanced contrast, and precipitates and lattice defects can easily be identified.

Transmission Electron Microscopy of plasma wave (QV3D simulation):



QV3D is a fully kinetic quasi-static 3D code developed by A. Pukhov. For details see:
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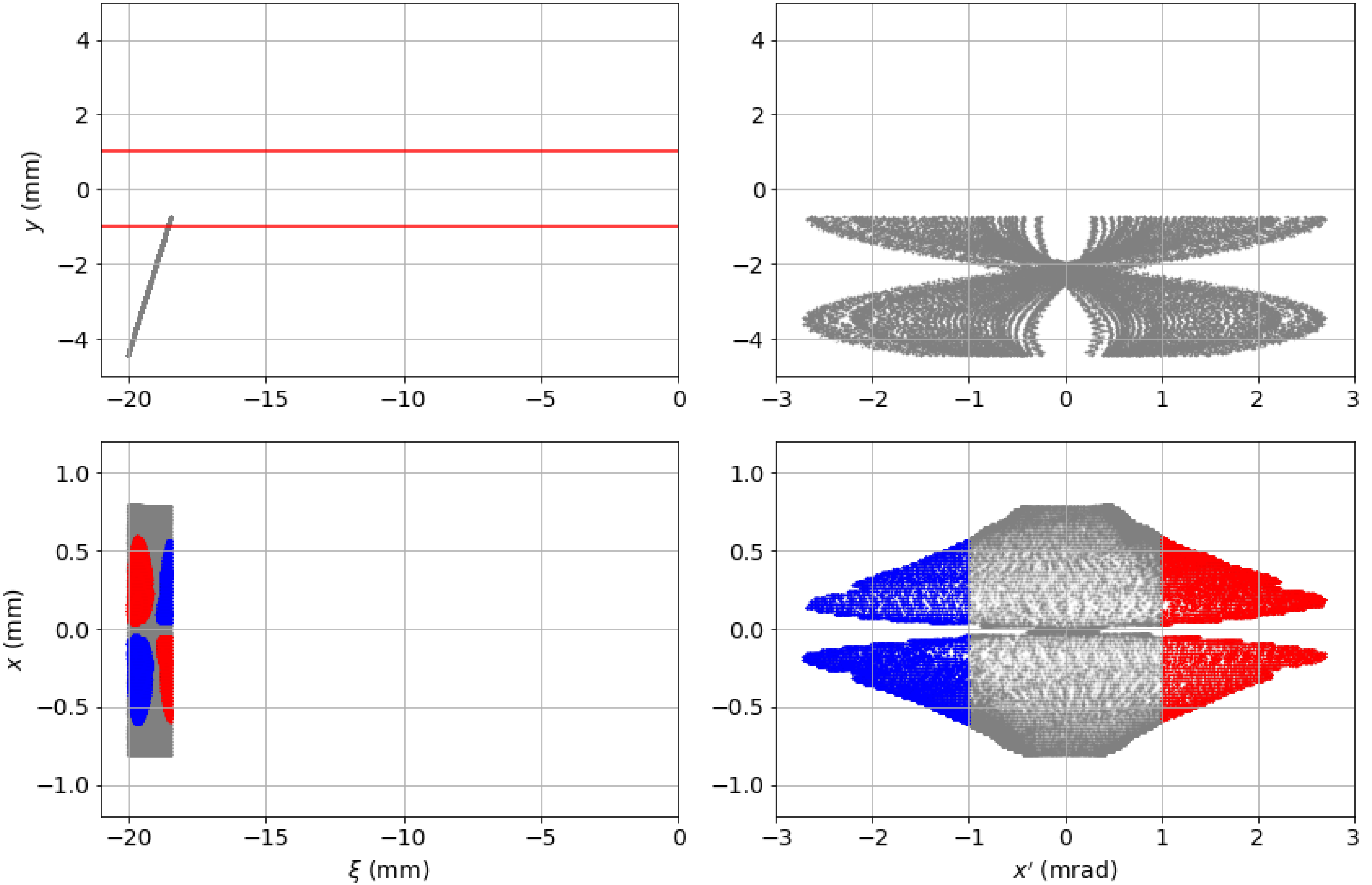
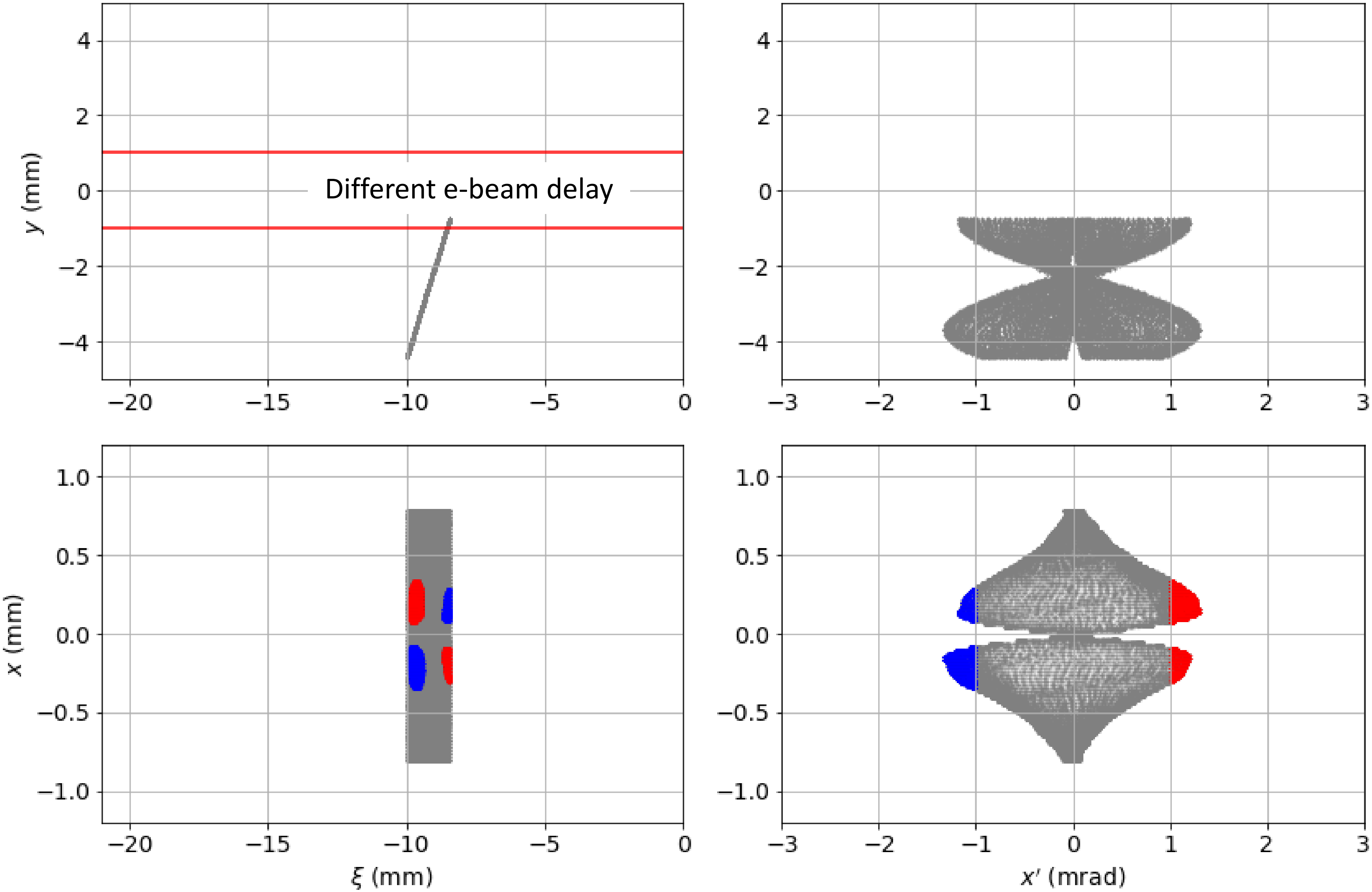


Longitudinal wakefields can be imaged with a vertical collimation!

Angular acceptance can be varied using aperture at the focal plane.

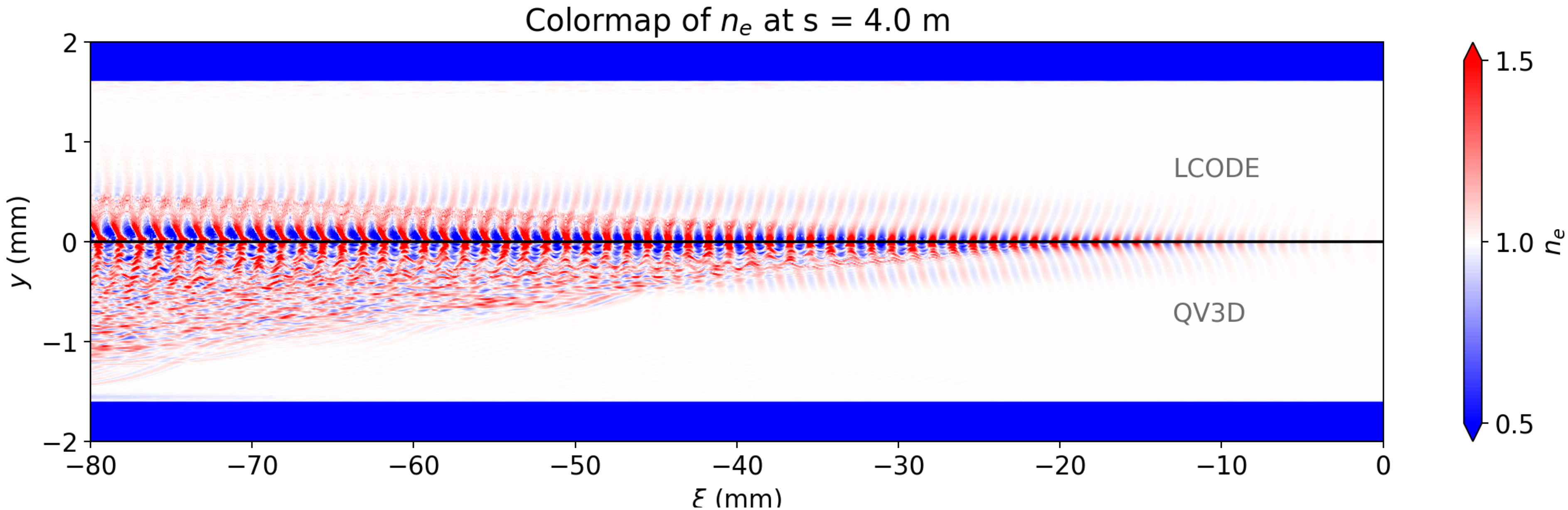
Transmission Electron Microscopy of plasma wave (QV3D simulation):

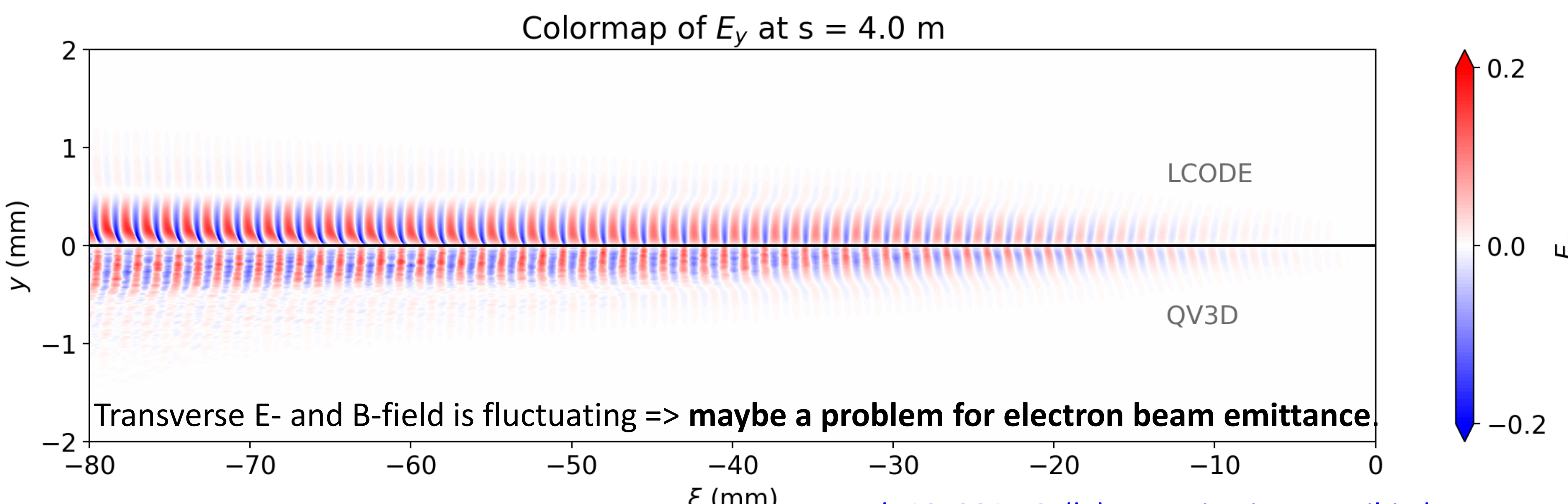


Precise time/space-resolved image of the plasma wakefield amplitude!

Angular acceptance can be varied using aperture at the focal plane.

QV3D (3D) vs LCODE (2D)

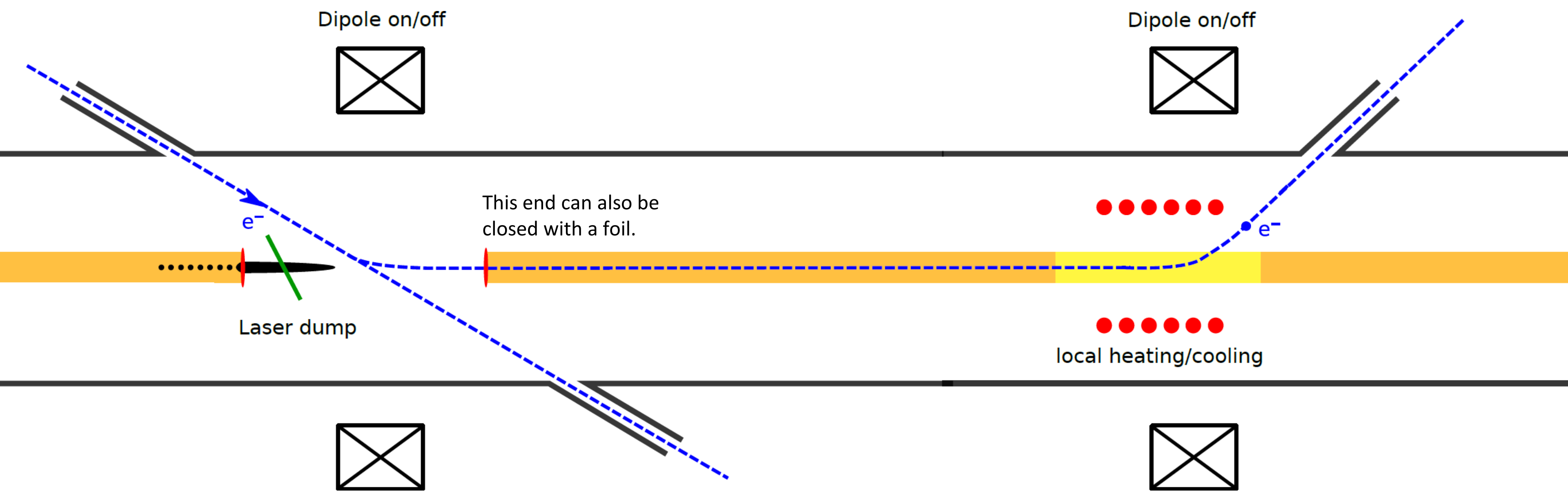


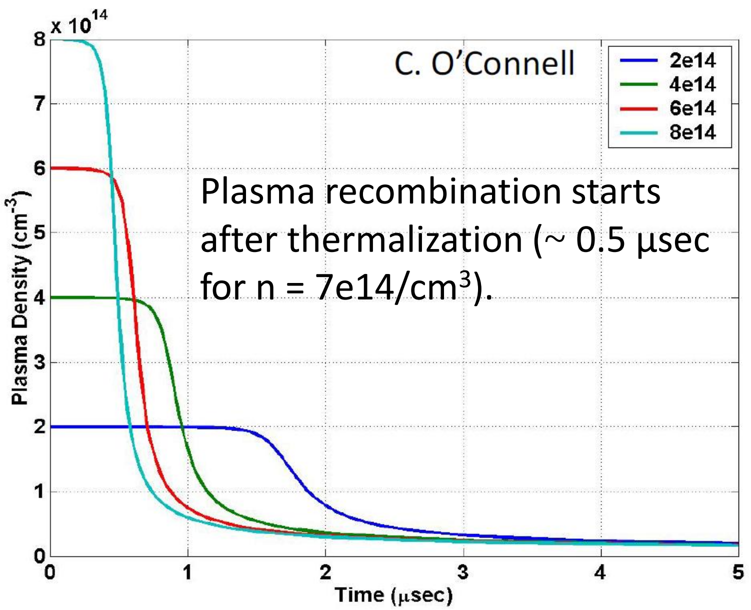


Transverse E- and B-field is fluctuating => **maybe a problem for electron beam emittance**.

March 10, 2017 Collab. Meeting in Novosibirsk.

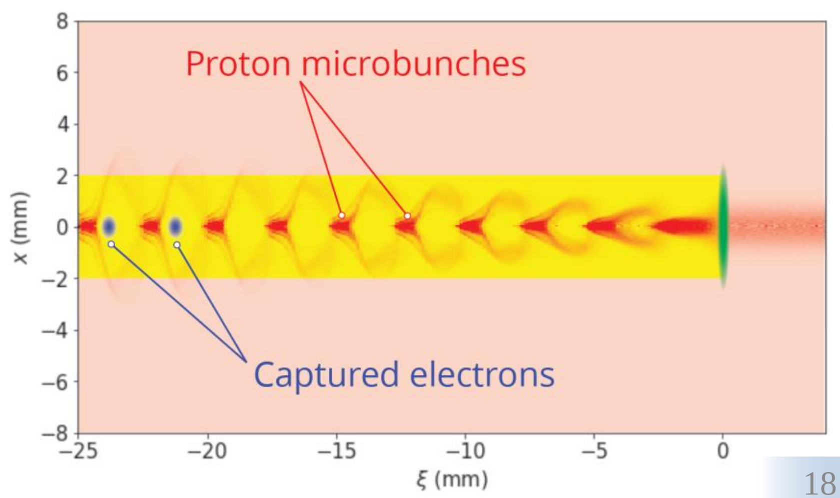
Possible upgrdate of this system with a pre-ionized plasma:



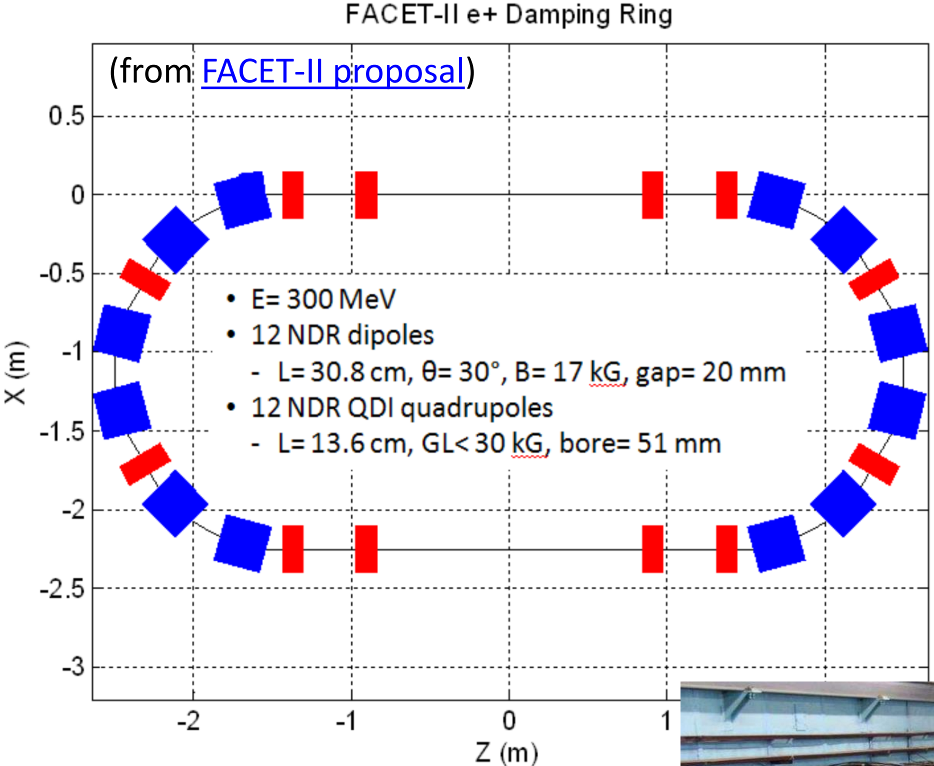


From Spencer's [PEB slides (June. 22, 2018)]

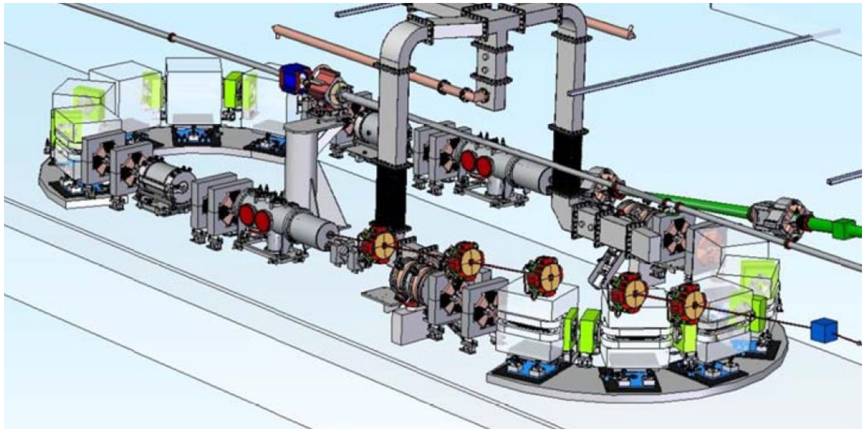
How important is the p-beam head interaction with plasma for micro-bunch stability?



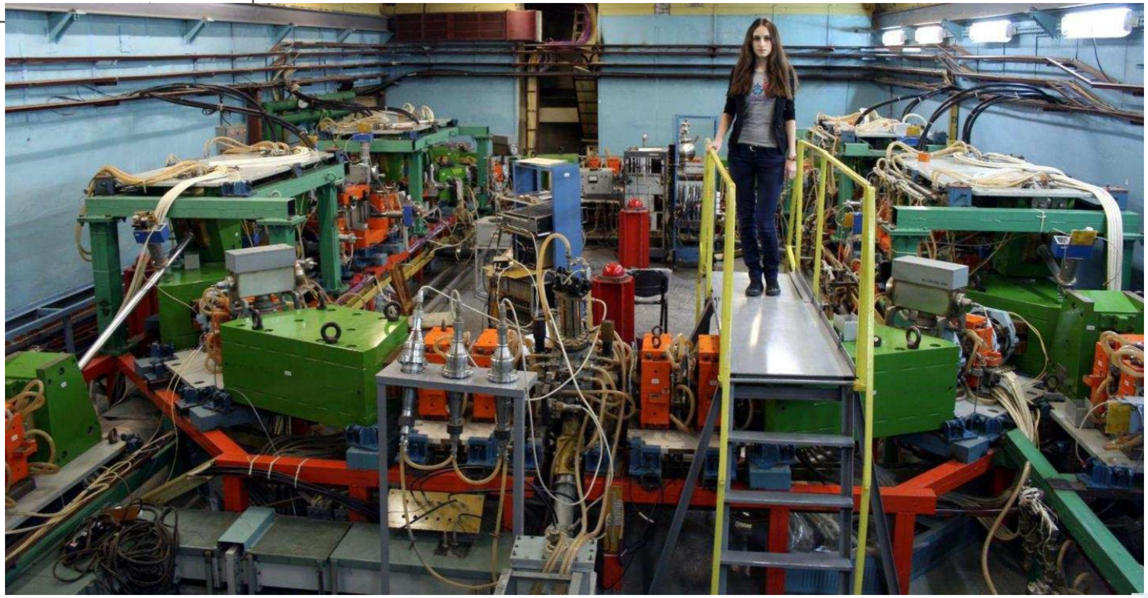
Examples of small positron damping rings:



TDR: https://doi.org/10.2172/1340171



500 MeV Damping Ring in Novosibirsk:



Can be also used as a replacement for AWAKE Run-II injector.

ALEGRO Workshop, Feb. 9, 2018

Conclusions

What can be studied with the current e-beam (E < 20 MeV):

- Testing all injection schemes at low e- peak current (no beam loading).
- Velocity bunching at low injection energy (~1-5 MeV).
- Transmission electron microscopy of wakefields below few 100s of MV/m.
- Testing e-beam extraction with low-energy spectrometer and emittance diagnostics.

Higher e-energy is needed to produce more dense e-beams with high peak current:

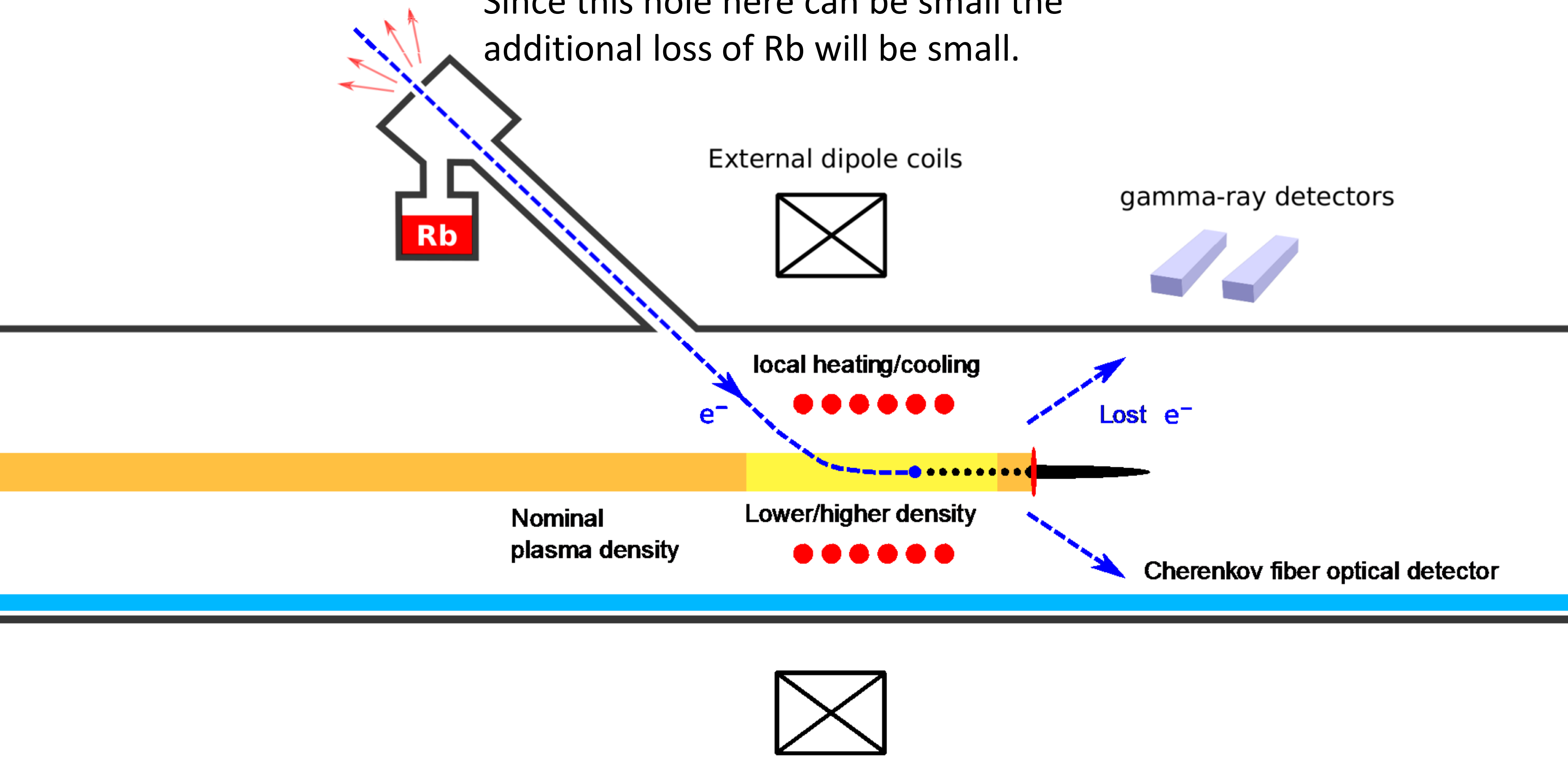
- Load wakefield with e-beam.
- Reach minimum equilibrium emittance.
- Transmission electron microscopy of high-amplitude wakefields.

To make further progress in simulations it would be very helpful to define a realistic final focus/bending electron beamline with realistic beam parameters for different electron beam energies.

Back-up slides

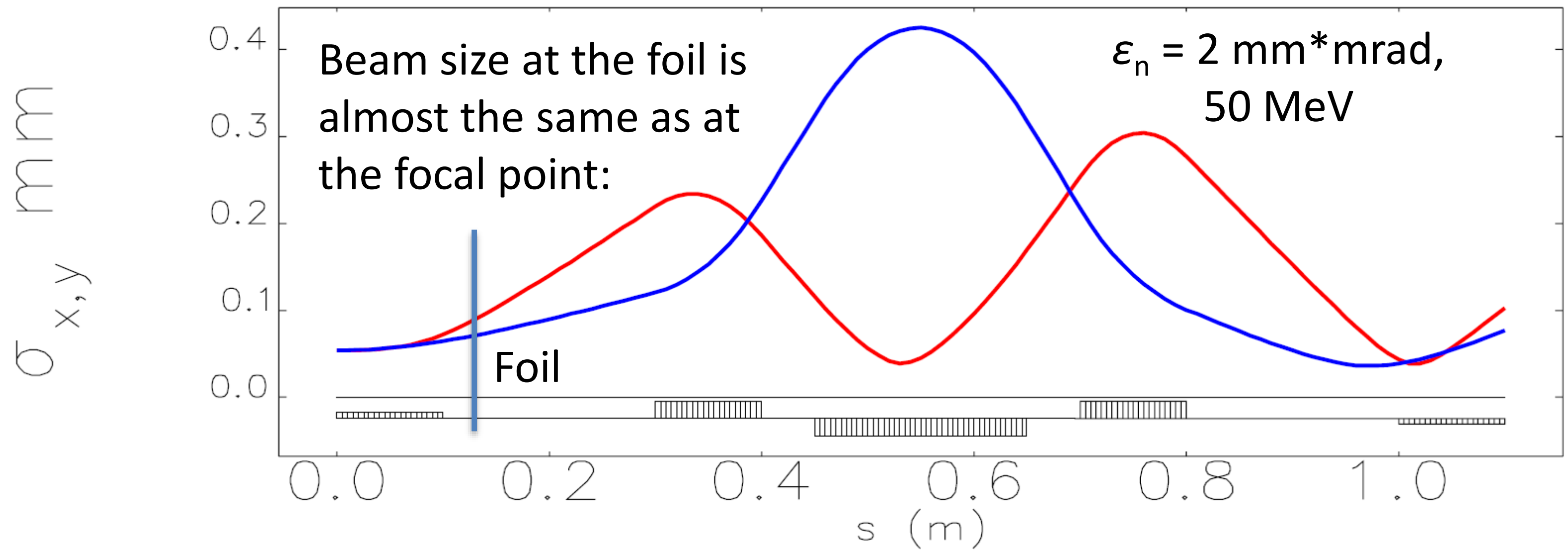
Solution without any foil

Since this hole here can be small the additional loss of Rb will be small.



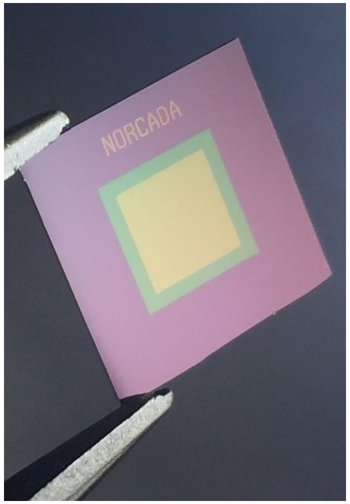
What kind of optics and foil is possible?

Not fully optimized optics (maybe it's a good to make the achromat symmetric)



Elegant simulation

Few years ago Allen suggested using ultra-thin silicon membranes:



Flat Ultrathin Silicon Membrane on 500µm Thick Silicon Frame					
Part Number	Si Mem Thick	Si Mem Area	Window Area	Frame Size	Price/Pack
CUF1065D	200nm	5mm dia.	6x6mm	10x10mm	$650
SUF1054D	200nm	4x4mm	5x5mm	10x10mm	$600
SUF1054E-	340nm	4x4mm	5x5mm	10x10mm	$550
SUF743D	200nm	3x3mm	4x4mm	7.5×7.5mm	$340

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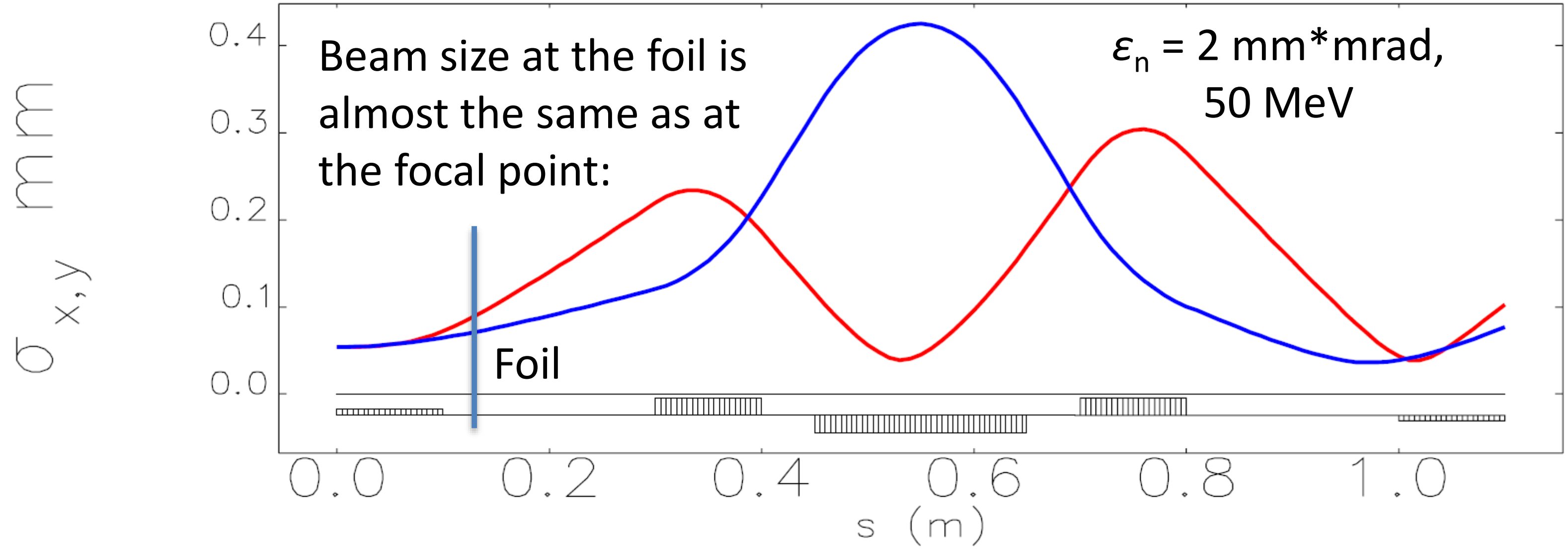
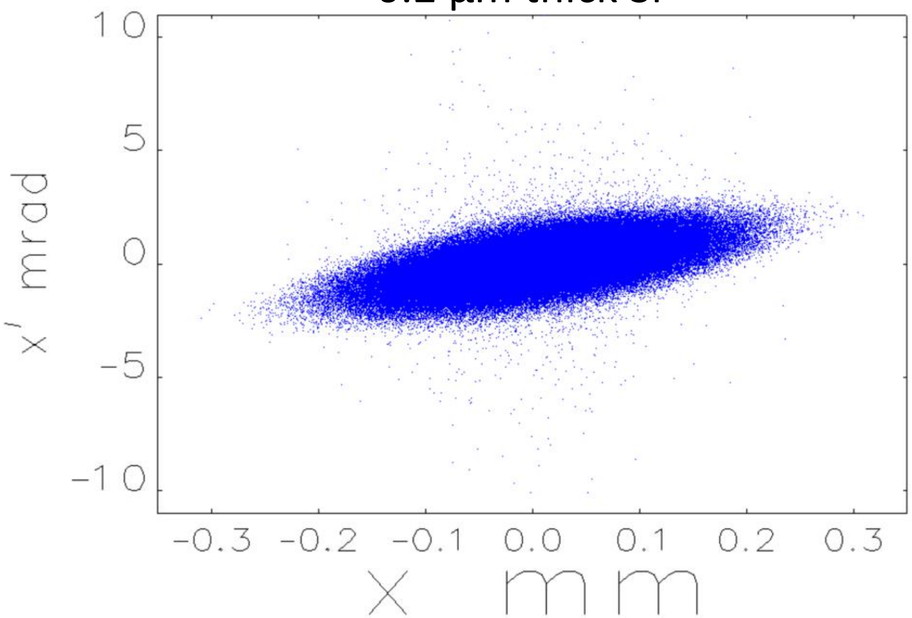
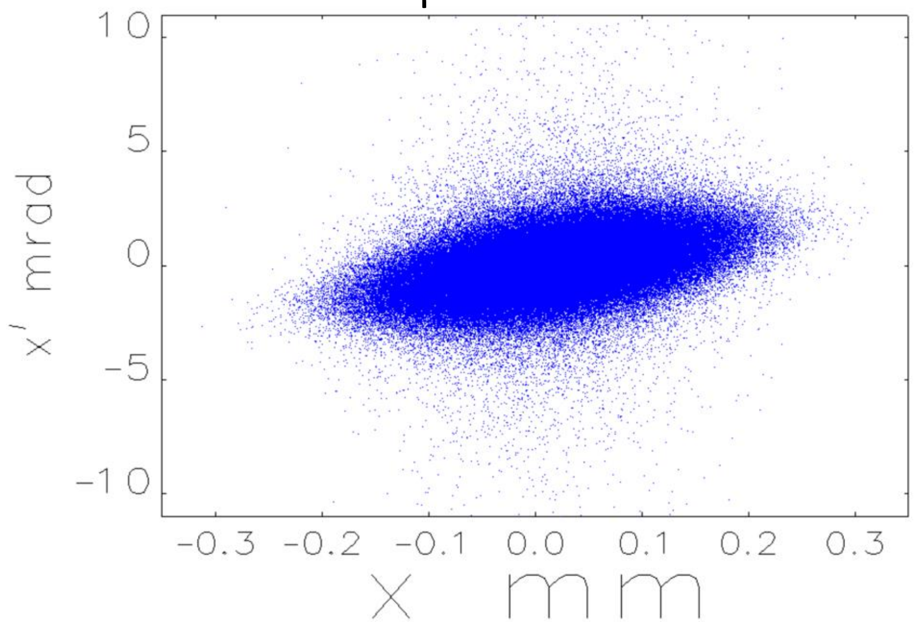


[Elegant](#) simulation

0.2 µm thick Si

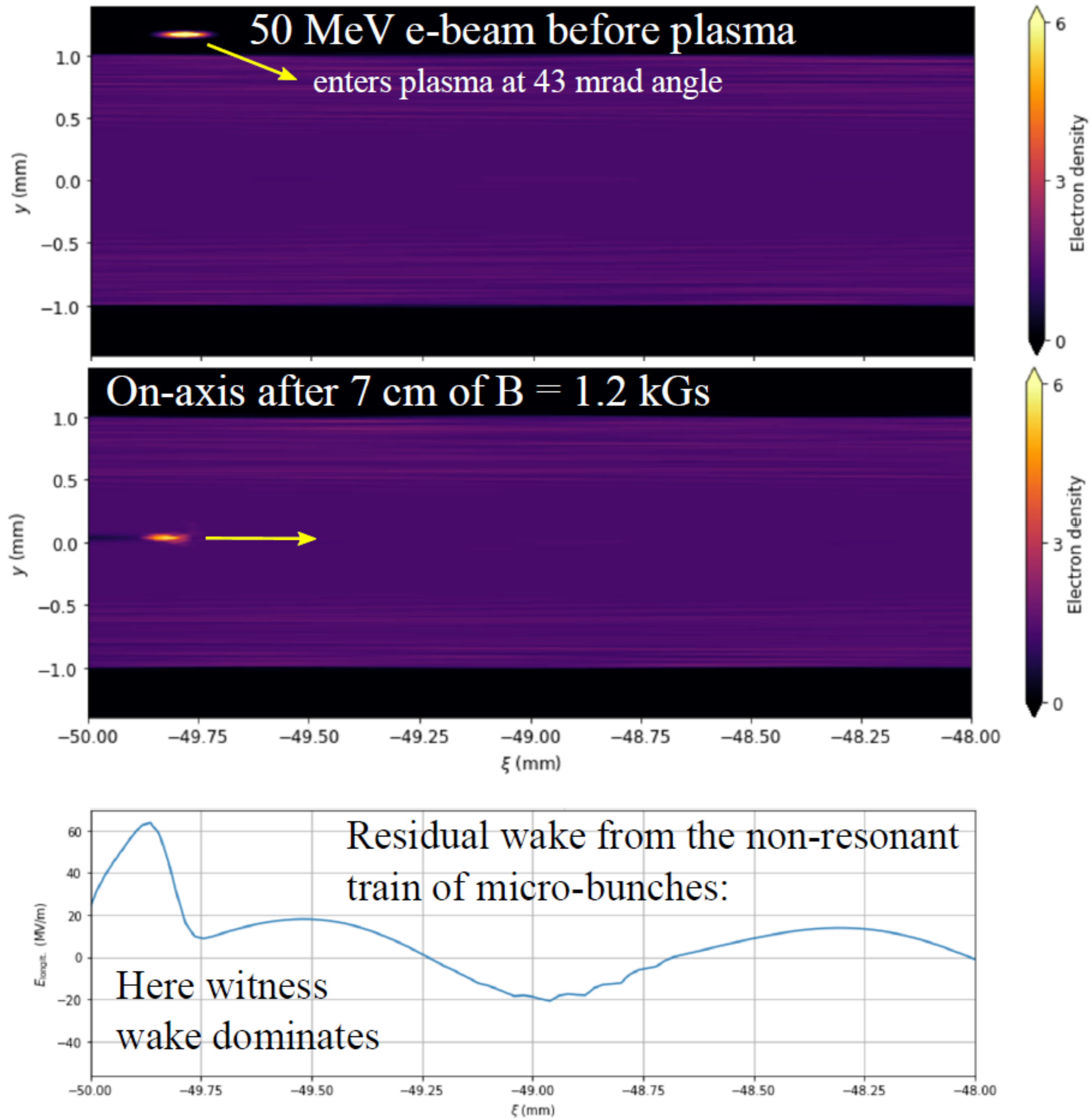


2 µm thick Si

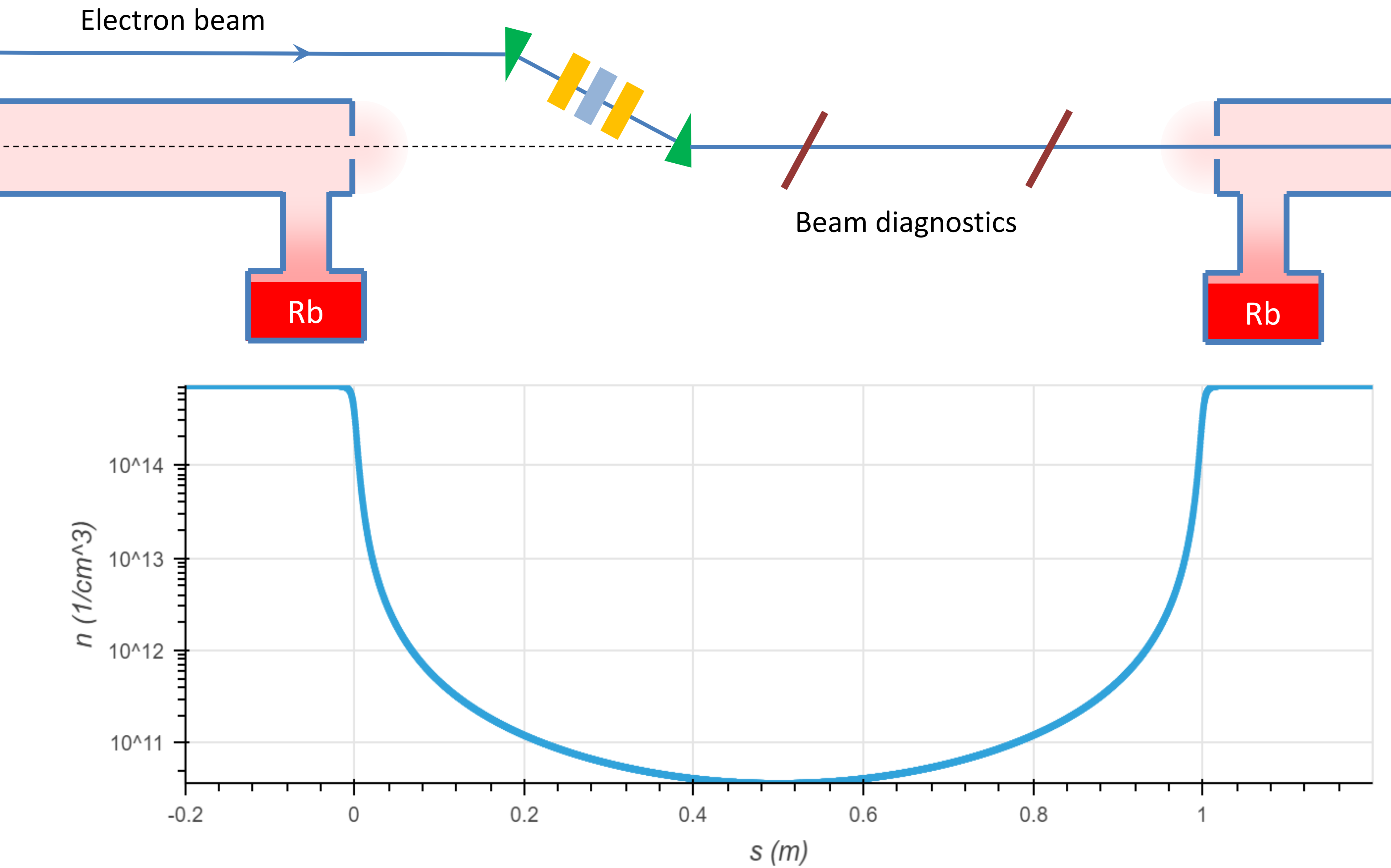


QV3D simulations of this scheme:

n_{plasma} is 25% higher than resonant value:



Why on-axis injection through low-density plasma does not work?



See Gennady's report for details (EDMS 1611560, arXiv:1708.08280, notebook).

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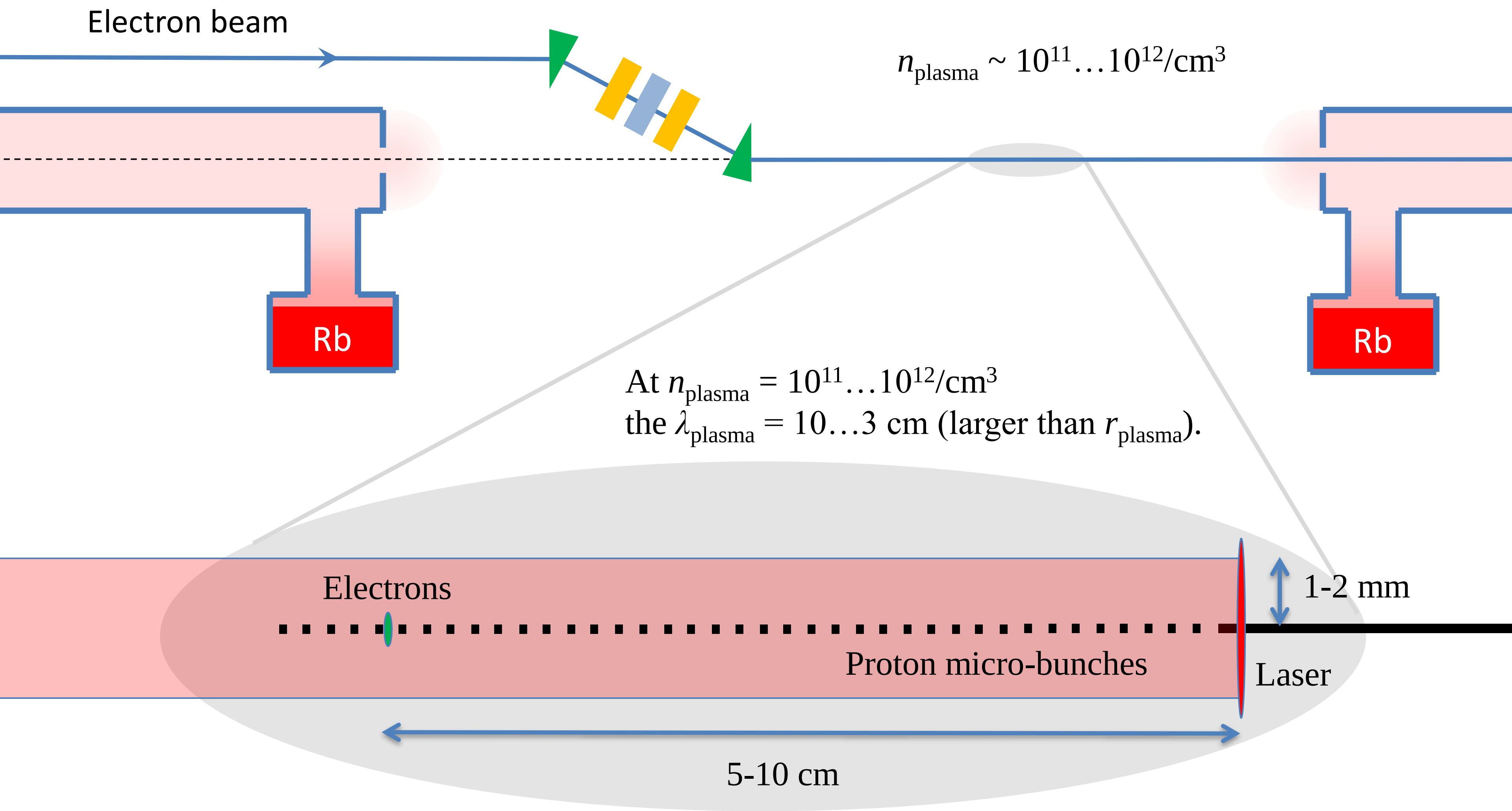
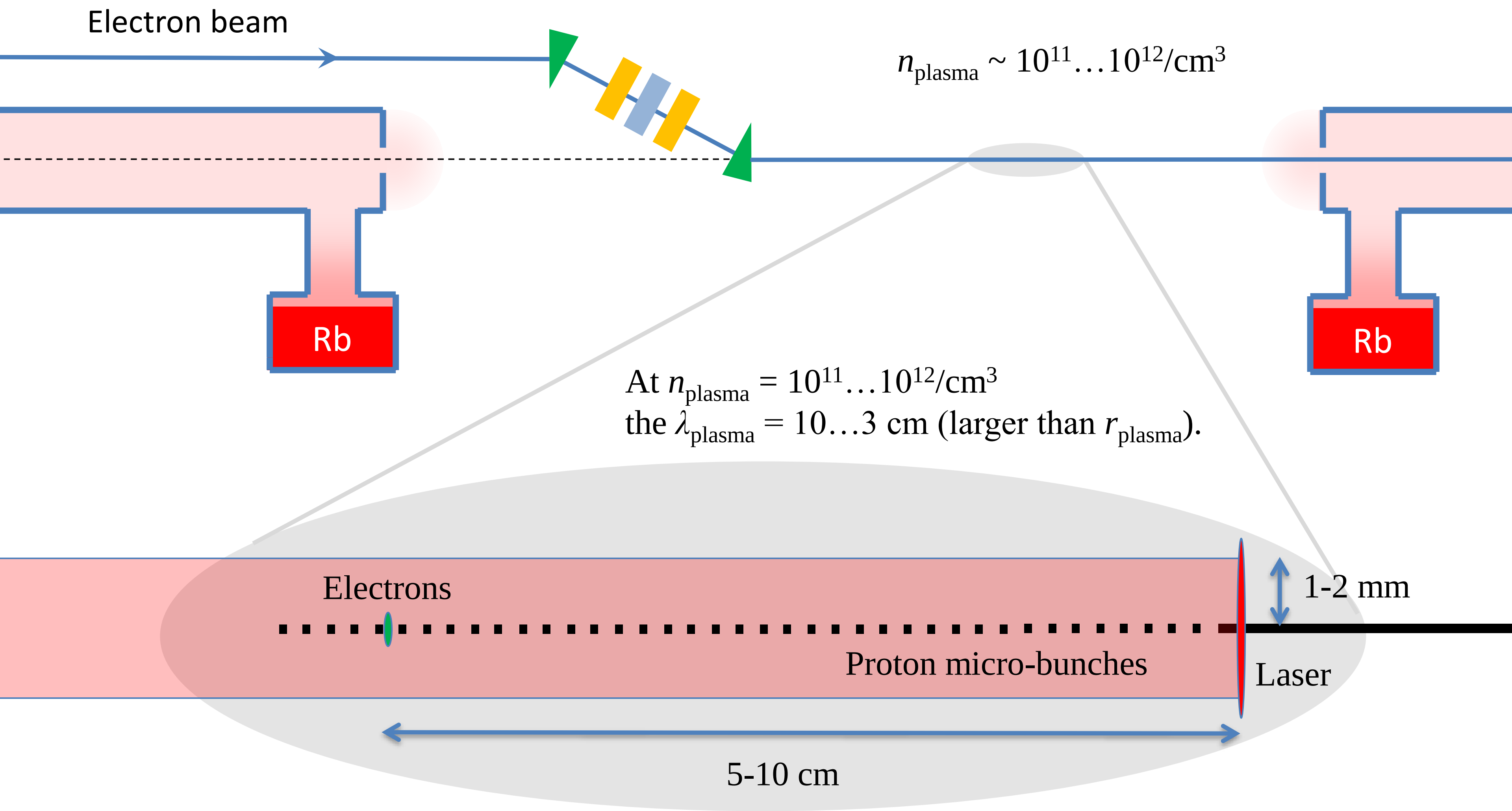


The number of protons remaining in the micro-bunches $N_p \sim 3{\cdot}10^{11} / 2 / 3 = 5{\cdot}10^{10}$ is comparable to the amount of charge in the surrounding ionized vapour at $n \sim 10^{11}/cm^3$:
$N_{plasma\ e} \sim V \cdot 10^{11}/cm^3 = 5\ cm \cdot \pi \cdot (0.2\ cm)^2 \cdot 10^{11}/cm^3 = 6{\cdot}10^{10}$. It means that the plasma-induced fields will be similar to the fields of p-beam average current (e.g.: **1 mm away from a 30 A wire B = 60 Gs**).

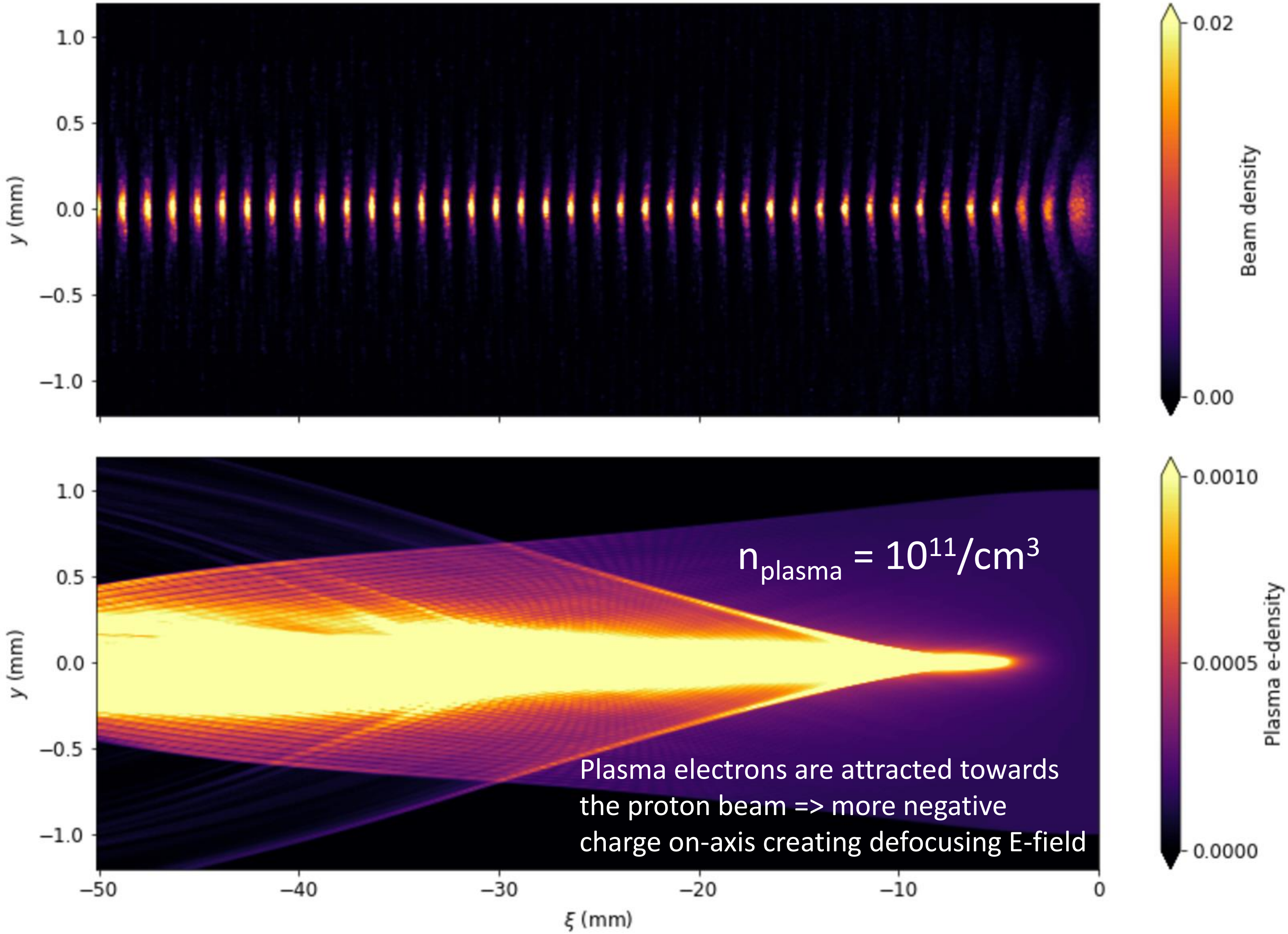
Why on-axis injection through low-density plasma does not work?



1 mm away from a 30 A wire *B* = 60 Gs:
The bending radius of a 50 MeV electron in 60 Gs field is 30 m. Already over 10 cm of travel distance the kick from such wakefield will be ~ 10 cm / 3000 cm = 3 mrad. The mrad-level kicks over few 10s of cm distance will result in significant uncontrolled beam size distortion ~ 1 mm – not acceptable for us.

What happens in low-density plasma (QV3D simulation):

Proton beam distribution is from earlier QV3D simulations



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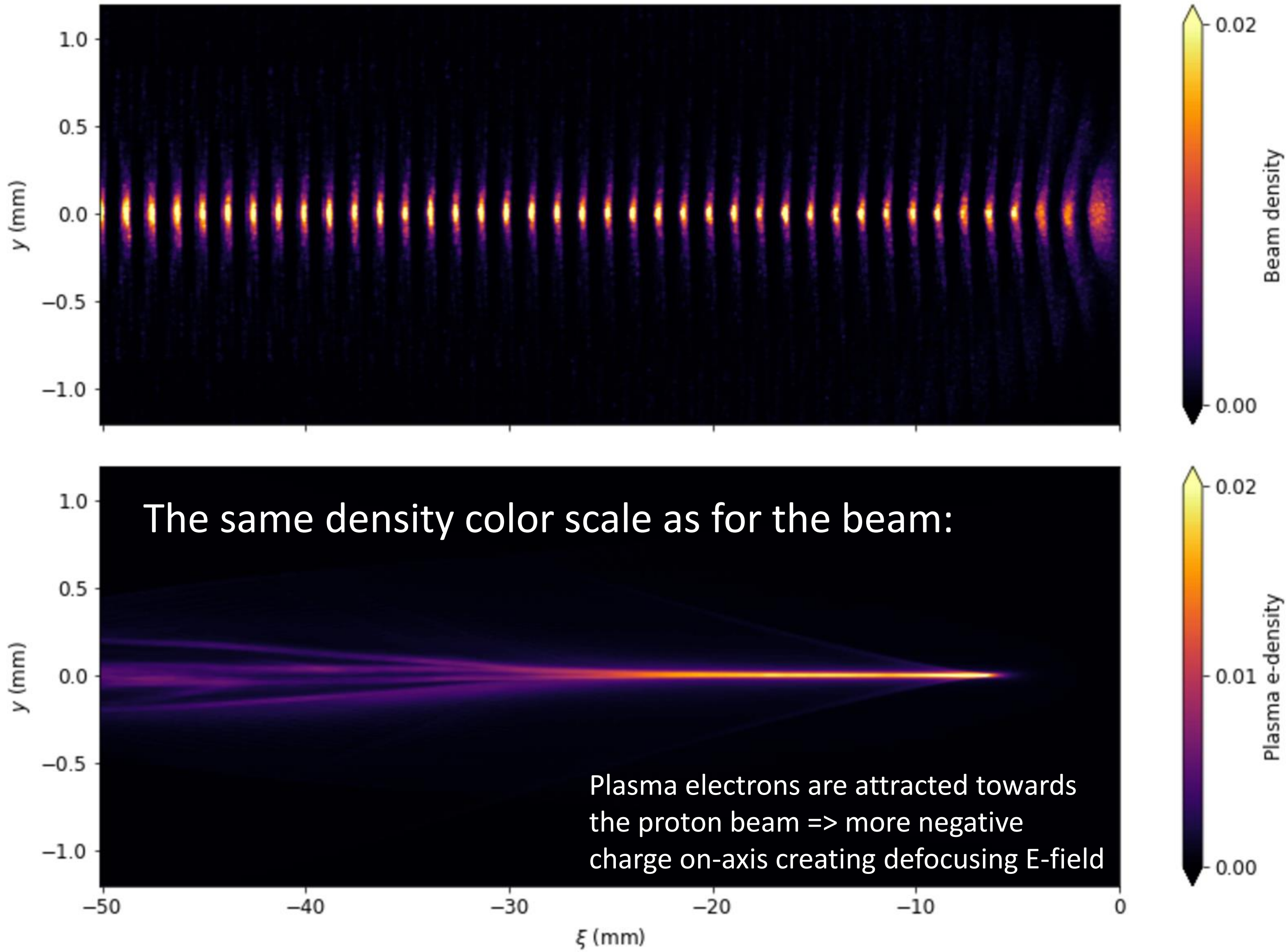

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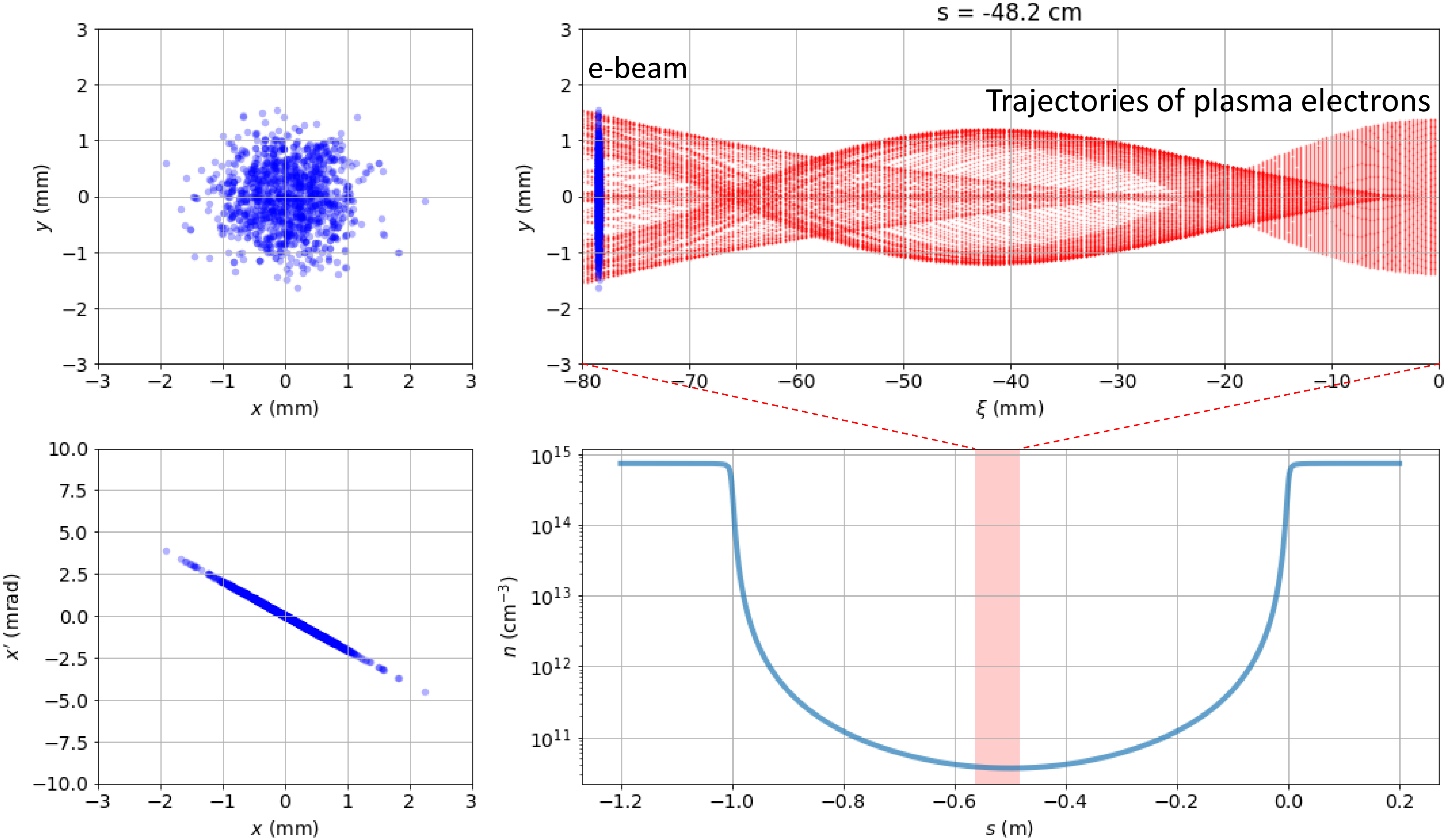
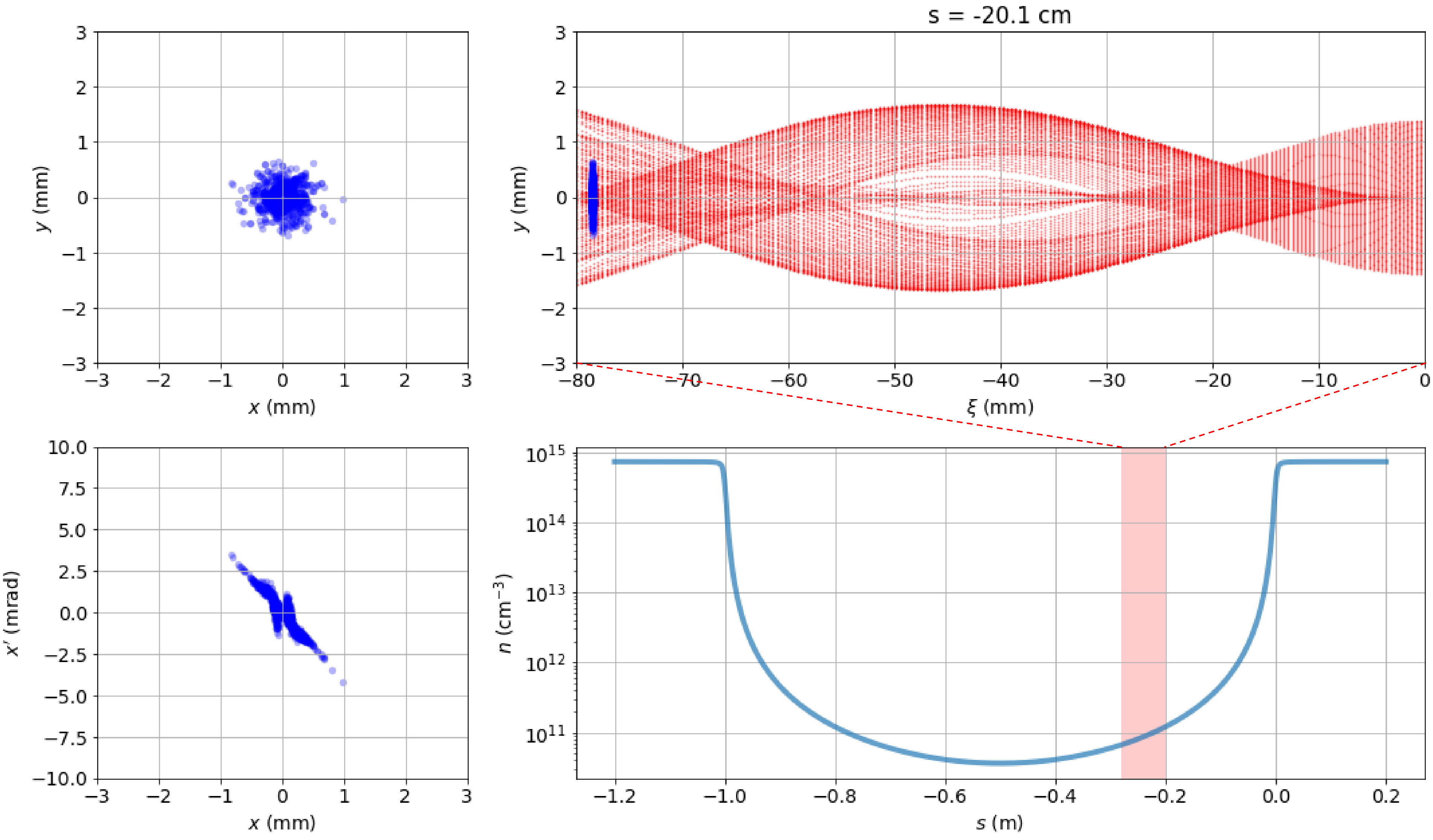
On-axis injection of 50 MeV beam (ε_n = 1 mm·mrad) through such density profile:
(LCODE simulation)



e-beam is designed to arrive to 2nd plasma section with equilibrium size (σ_x = 10 mkm).

On-axis injection of 50 MeV beam (ε_n = 1 mm·mrad) through such density profile:
(LCODE simulation)



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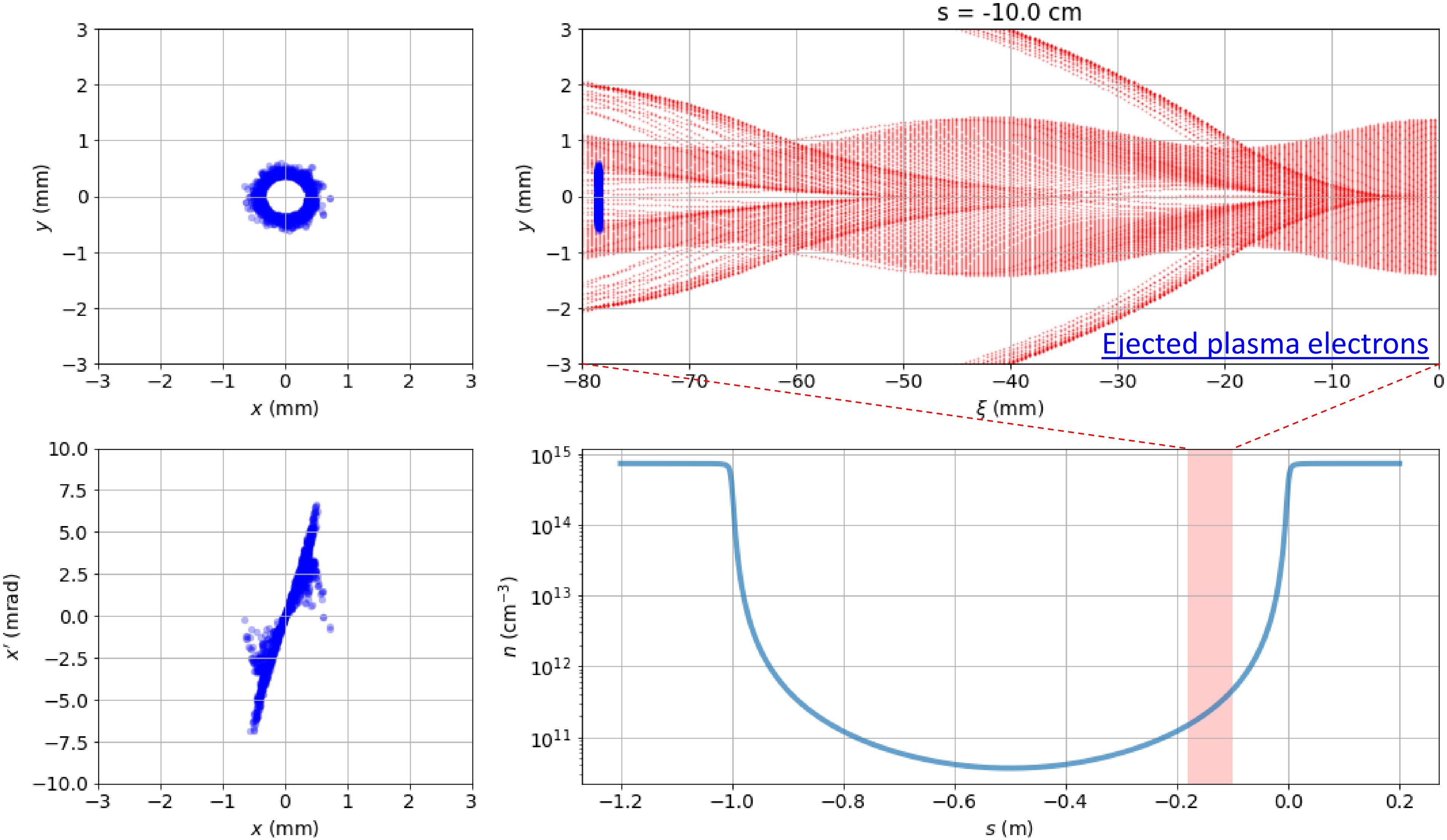

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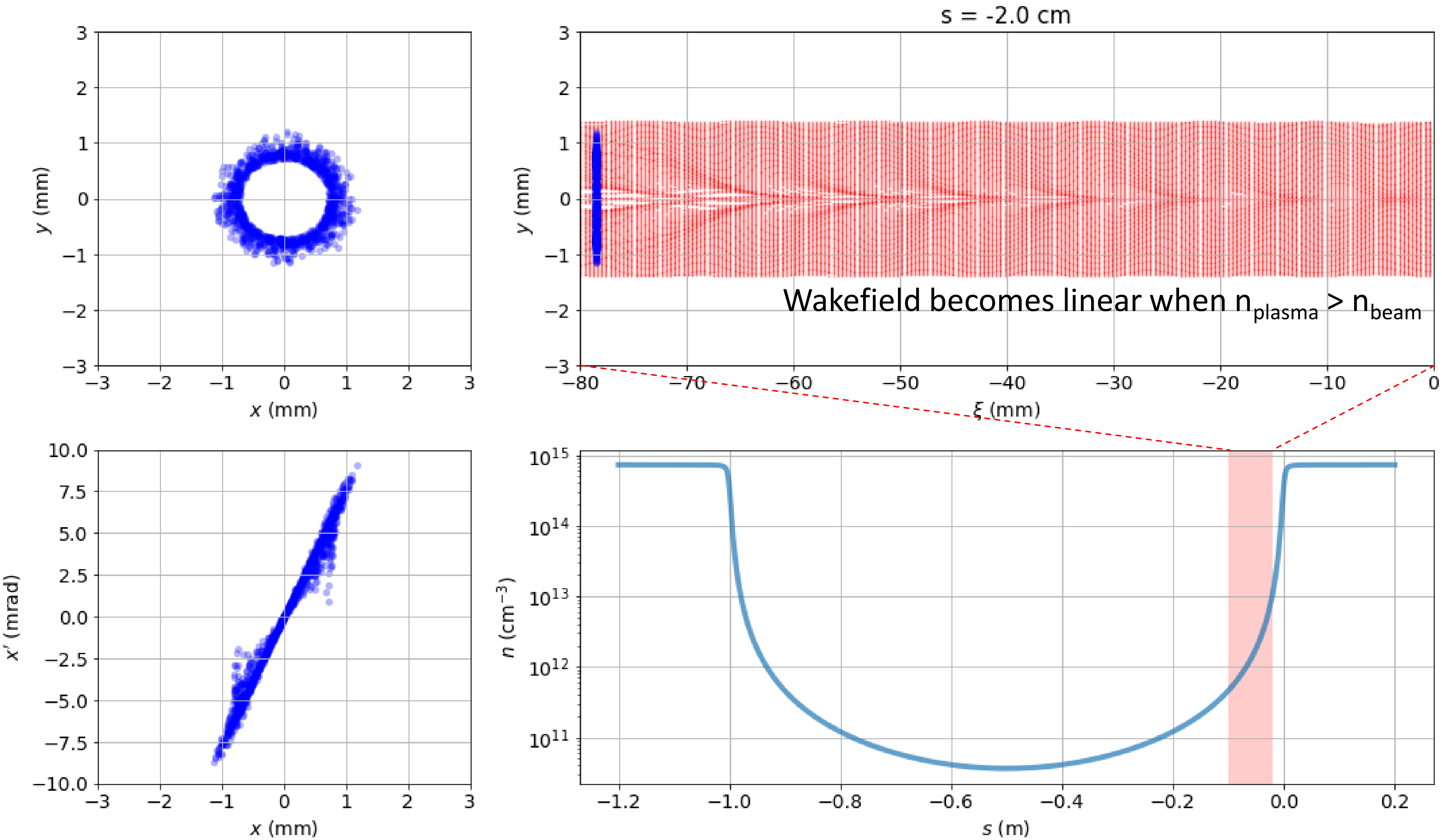

Unfortunately low-density plasma completely defocused all electrons injected on-axis.
Beam dynamics with and without laser and protons will be completely different!

With realistic (asymmetric) transverse plasma profile the kicks will be asymmetric:
(QV3D simulation**)**