Evaluation of the proton fluxes captured and transmitted by plasma lenses (and solenoids) in LhARA

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LhARA fortnightly Meeting
25th April 2023

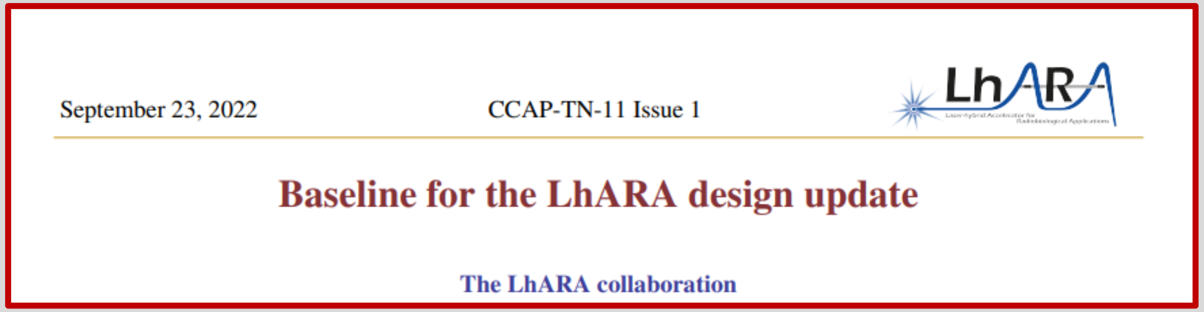
Motivation

1. No previous investigation of the capability of the front-end LhARA beam-line to capture protons without collimators
   - No direct comparison of the beam losses for the case of using plasma lenses vs. solenoids

2. Significant impact of vacuum nozzle on transmission of protons from source to first lens
   - Previous optimisation of energy and momentum collimators, but not of the nozzle

3. Full energy spectrum of more realistic protons produced by TNSA available
   - from 3-D particle-in-cell simulations (WP2)

Studies presented here are based on the **baseline design of LhARA** Stage 1 (Sep 2022)

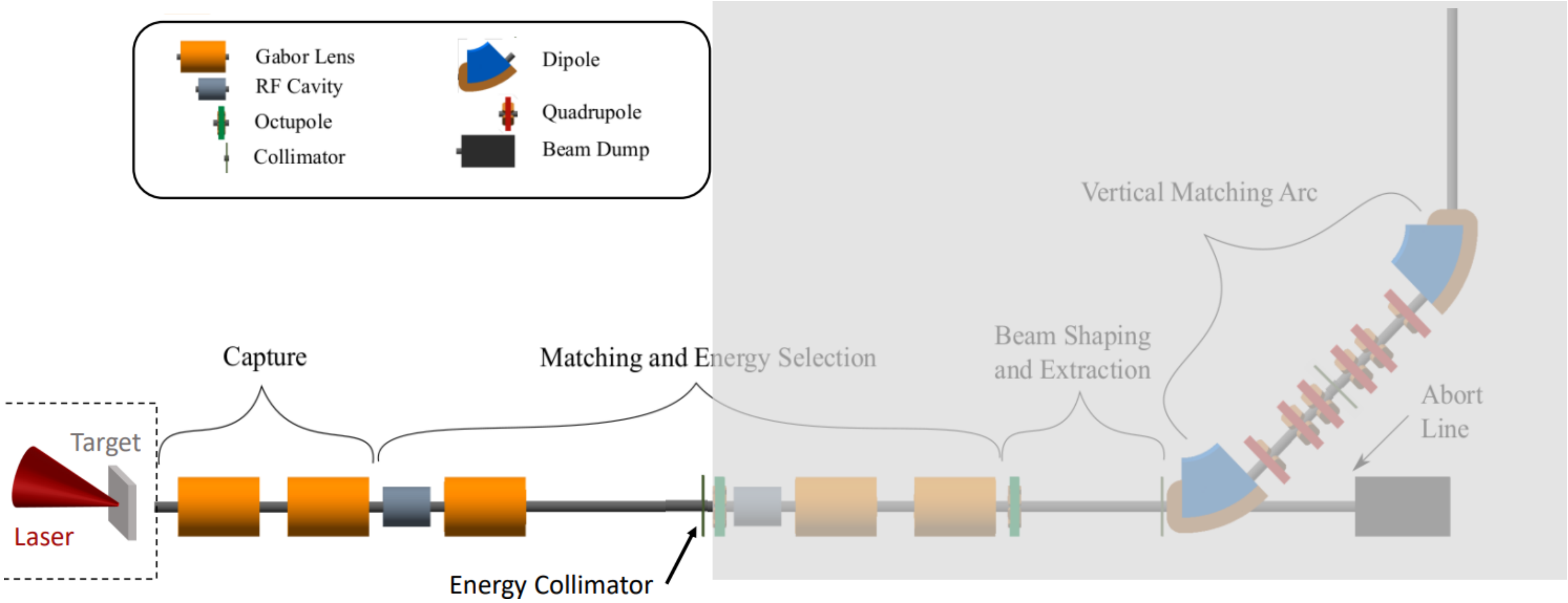

September 23, 2022 CCAP-TN-11 Issue 1

Baseline for the LhARA design update

The LhARA collaboration

1. **Proton capture efficiency (without beam collimators)**
2. Protons loss due to beam collimators

Model only the front-end of LhARA Stage 1



- Protons tracked with GPT
  - first 5 cm from source without space-charge (due to comoving electrons)
  - with space-charge for the rest of the beam-line
- Plasma lenses modelled as field maps

Protons at the source

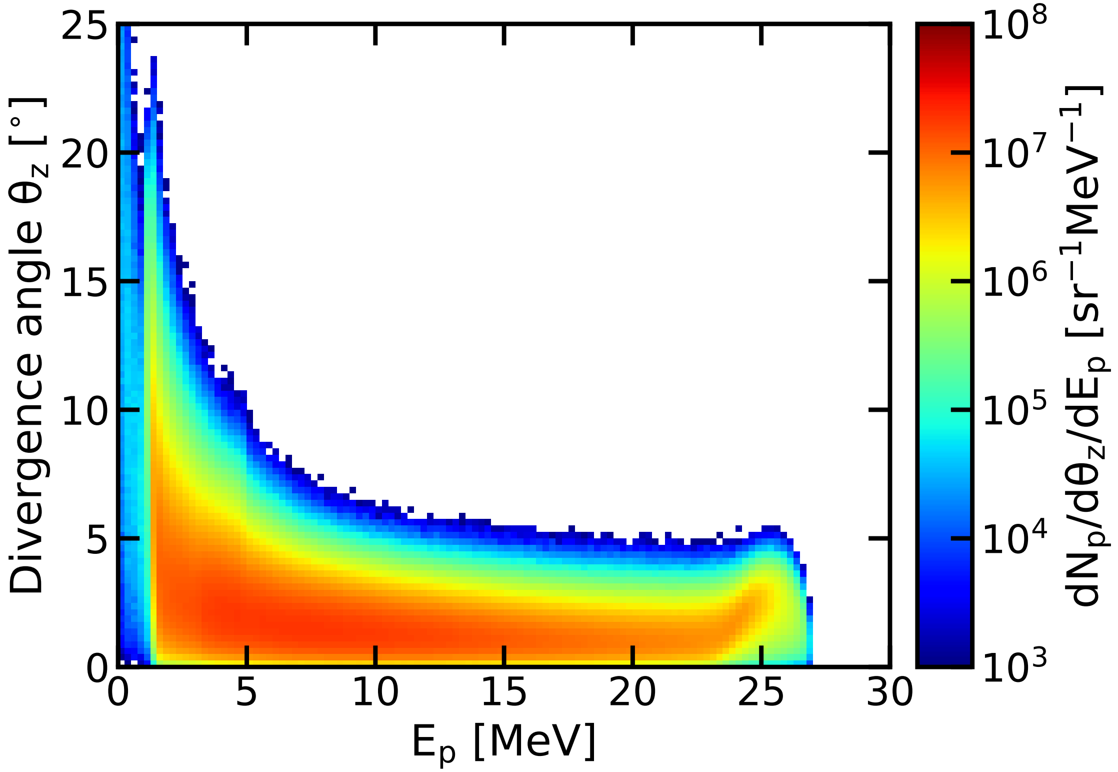
- 3-D particle-in-cell simulation of SCAPA-like laser hitting a solid tape target
  - TNSA regime
  - work of E. Boella described in the ITRF/LhARA 6M Progress Report

Key figures

full energy spectrum $\sim 10^{10}$ protons

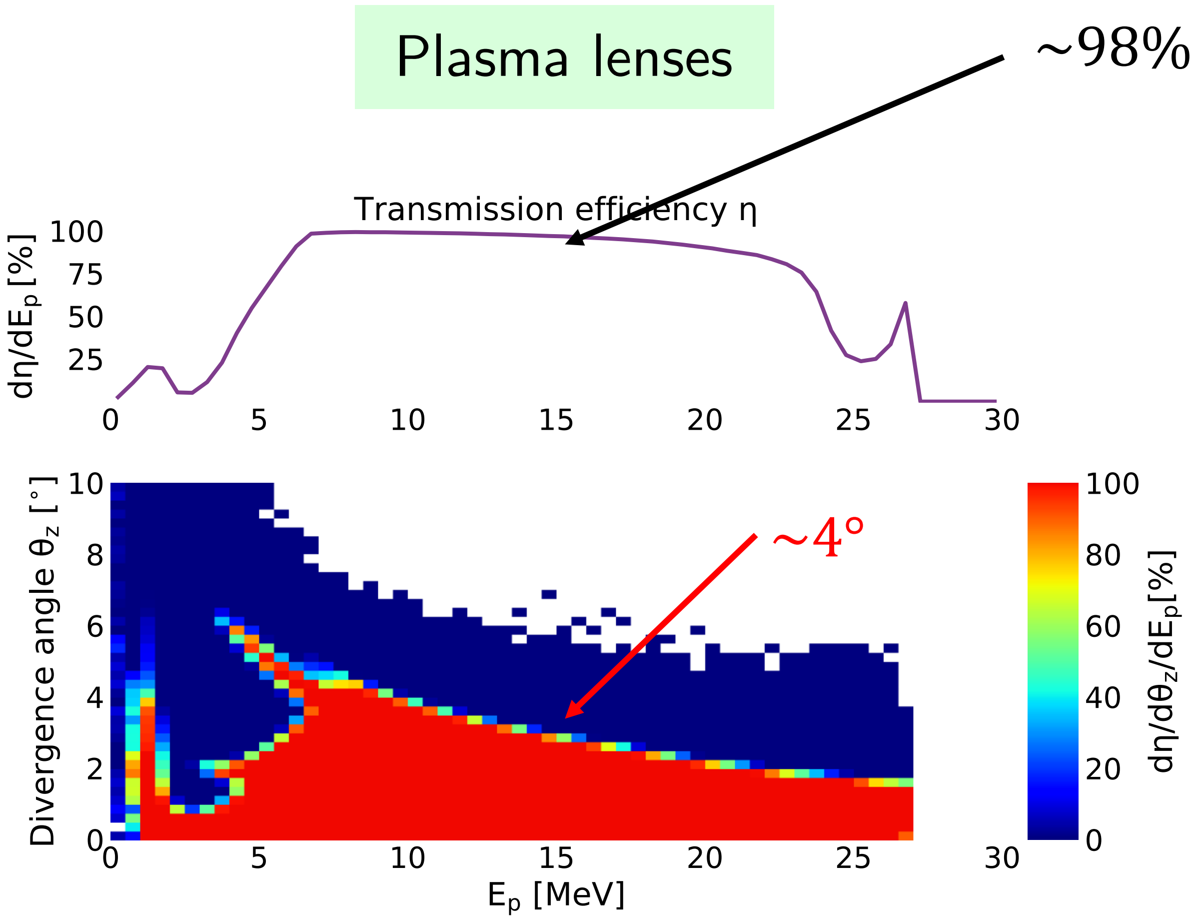
nominal energy band $\sim 2 \times 10^{9}$ protons
$(15\ \text{MeV} \pm 2\%)$

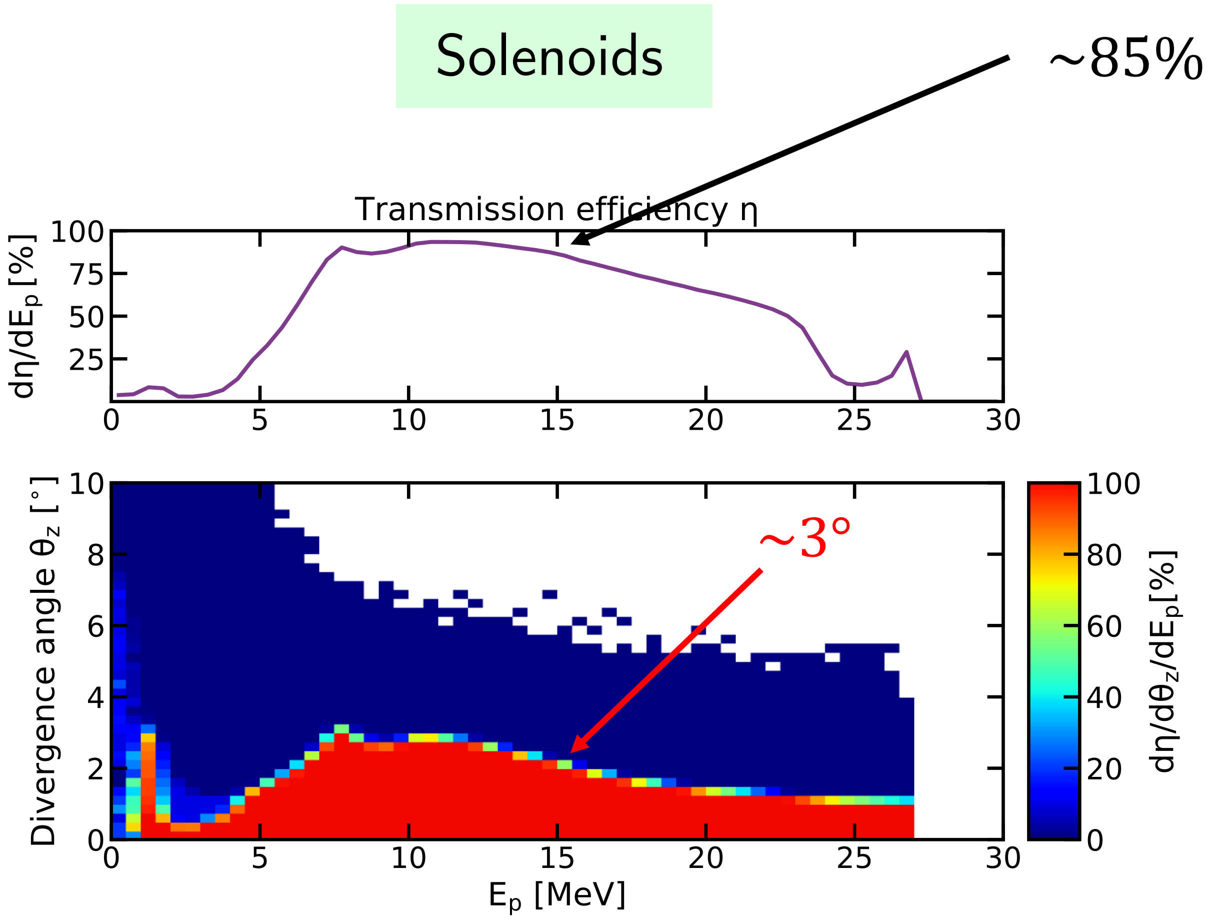
RMS divergence angle $\sim 1°$
(around nominal energy)



Transmission from source to first beam focus

- No vacuum nozzle, no energy collimator
  - Protons lost in the beam-pipe + inner walls of the solenoids/lenses

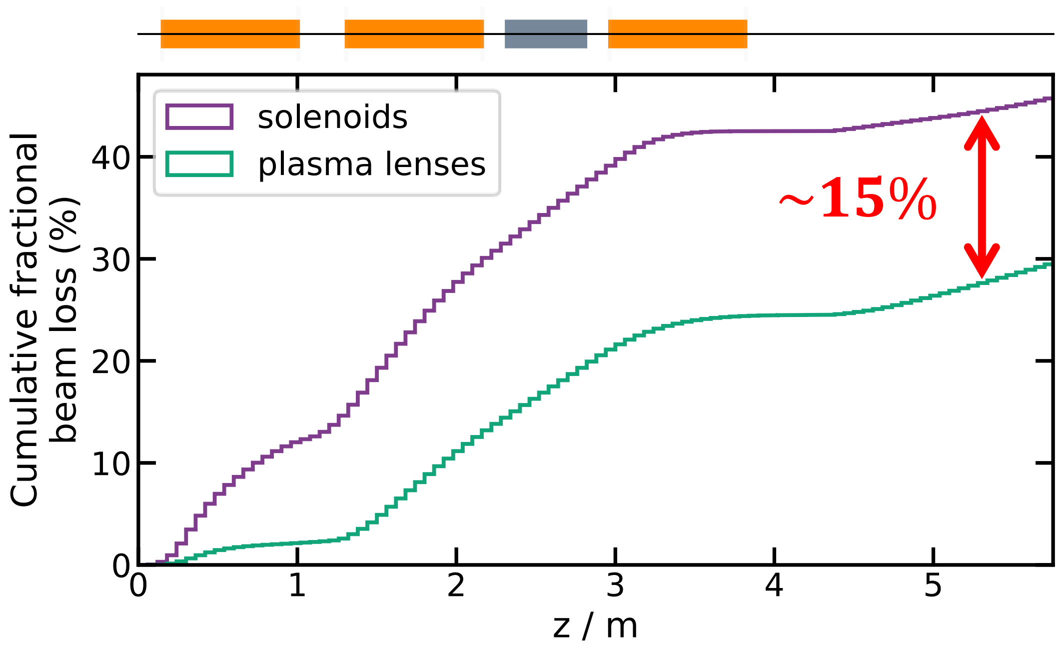




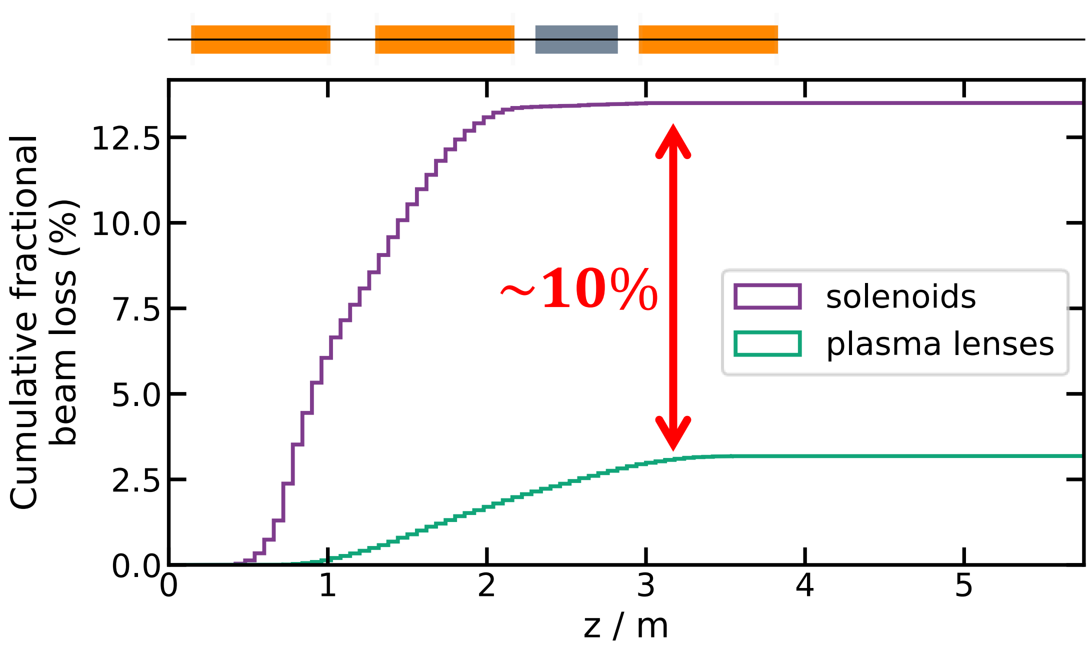
Beam loss integrated over angle and energy

- Beam loss calculated as fraction of number of protons produced at the source

- Full energy spectrum



- Nominal energy band

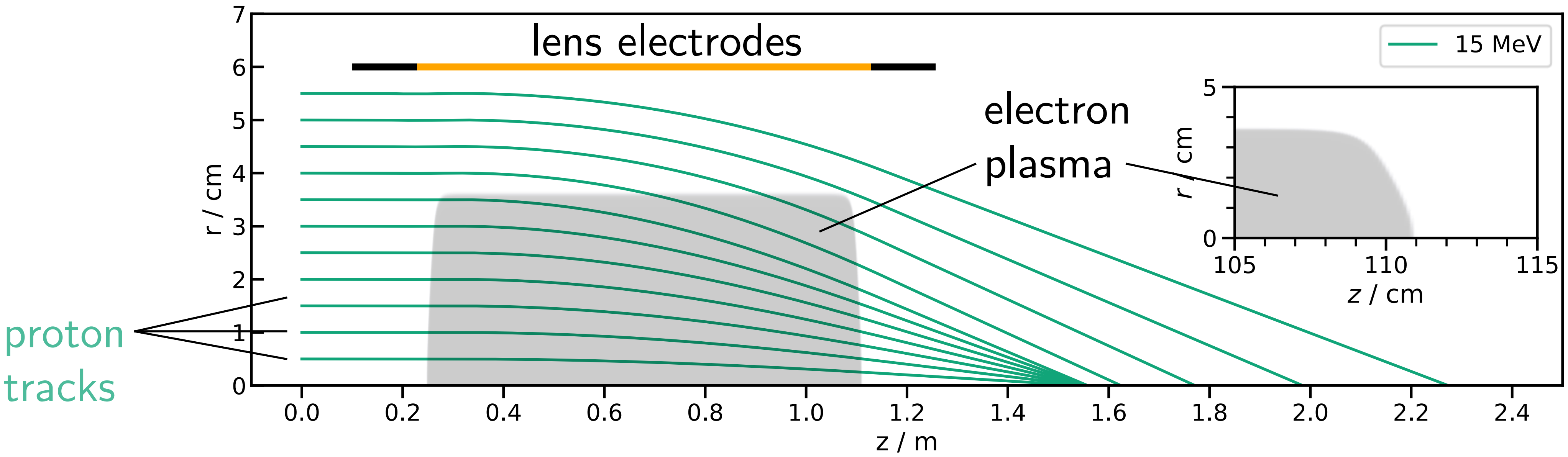


Geometrical acceptance of Gabor lenses vs. solenoids

- Cost of large aperture of a solenoid is large overall size and mass
  - from preliminary design for normal-conducting solenoid for LhARA

- Plasma lenses generate additional focusing outside of the plasma
  - Non-linear focusing

- Plasma lenses should provide larger physical aperture
  - For diameter of the plasma identical to diameter of solenoid

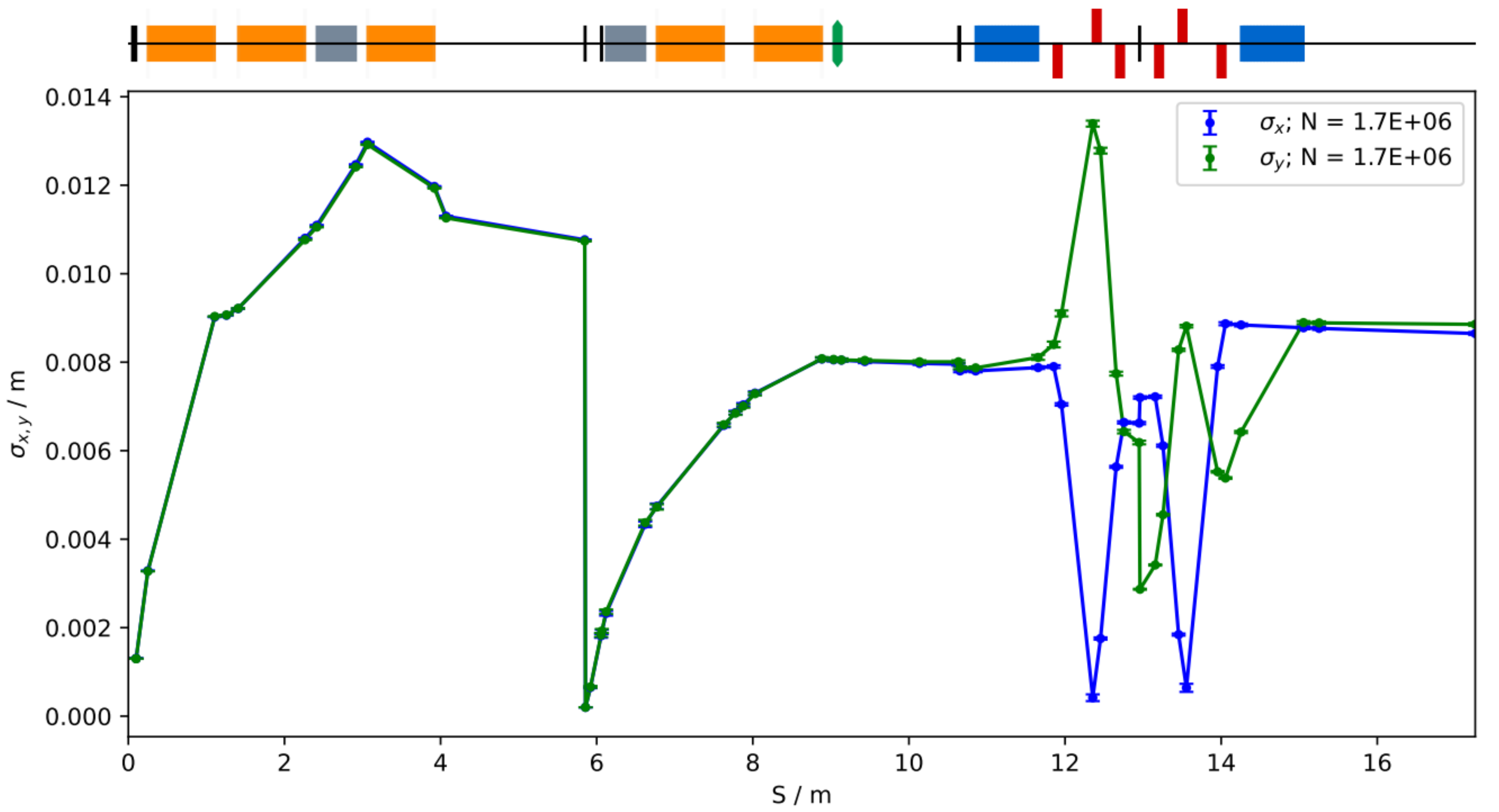


1. Proton capture efficiency (without beam collimators)

2. **Protons loss due to beam collimators**

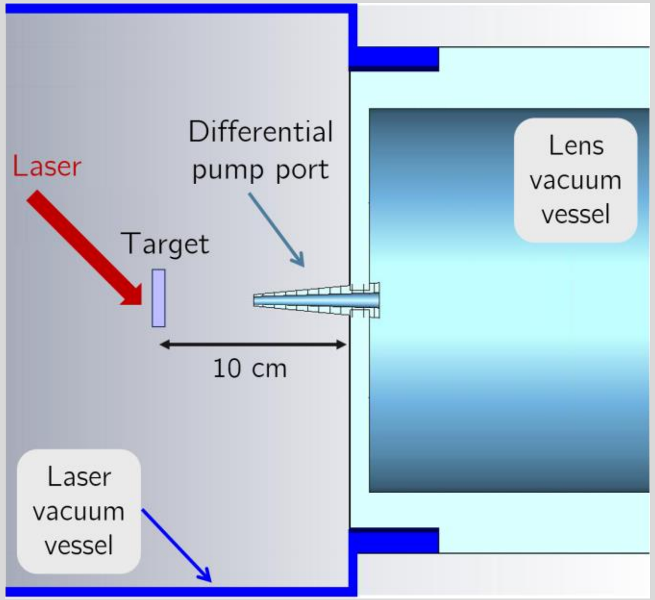
Model verification

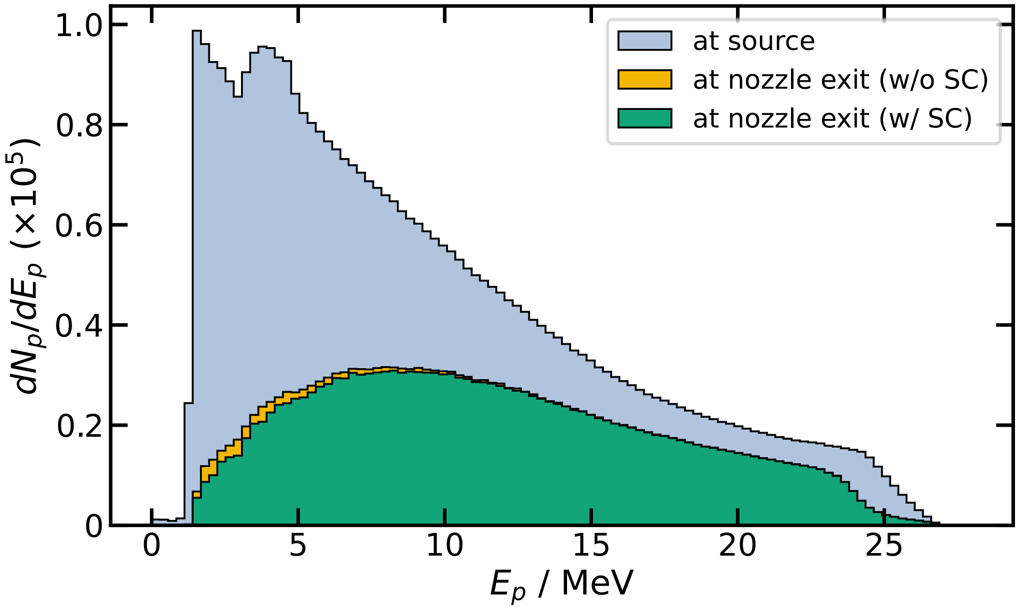
- Protons with full energy spectrum
- Complete Stage 1 beam-line
- Hard-edge field maps for the Gabor lenses
- GPT for the first 10 cm, of which the last 5 cm with space-charge
- BDSIM for the rest of the beam-line, without space-charge

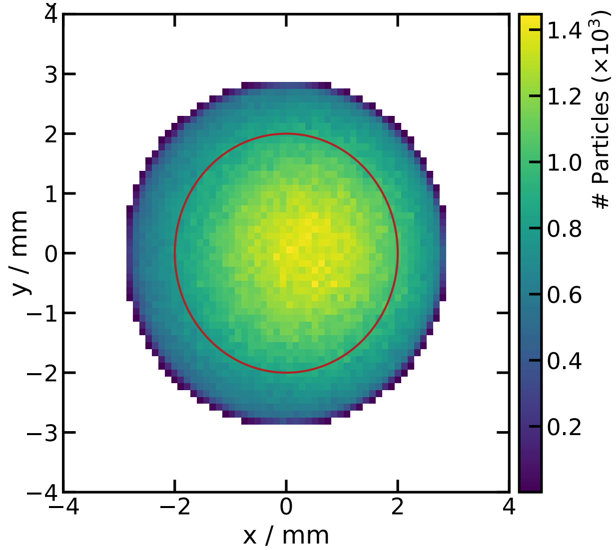


First significant reduction in proton flux

- At the interface between the source and the first lens
- Conical nozzle
  - 1° half-angle
  - 2 mm entrance radius



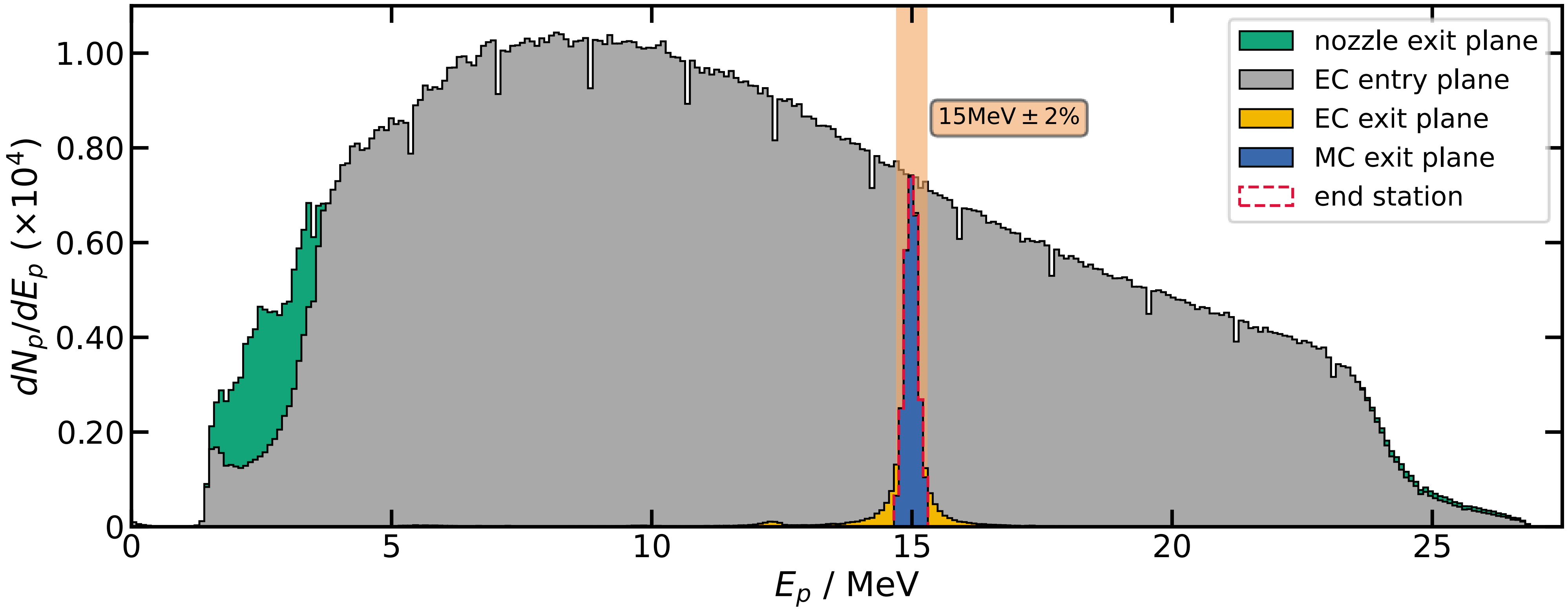


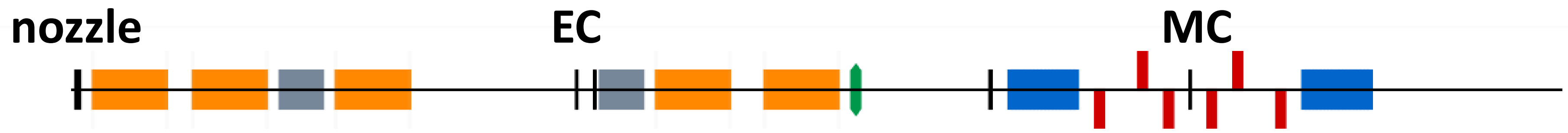


Validation of the energy-selection scheme

With solenoids

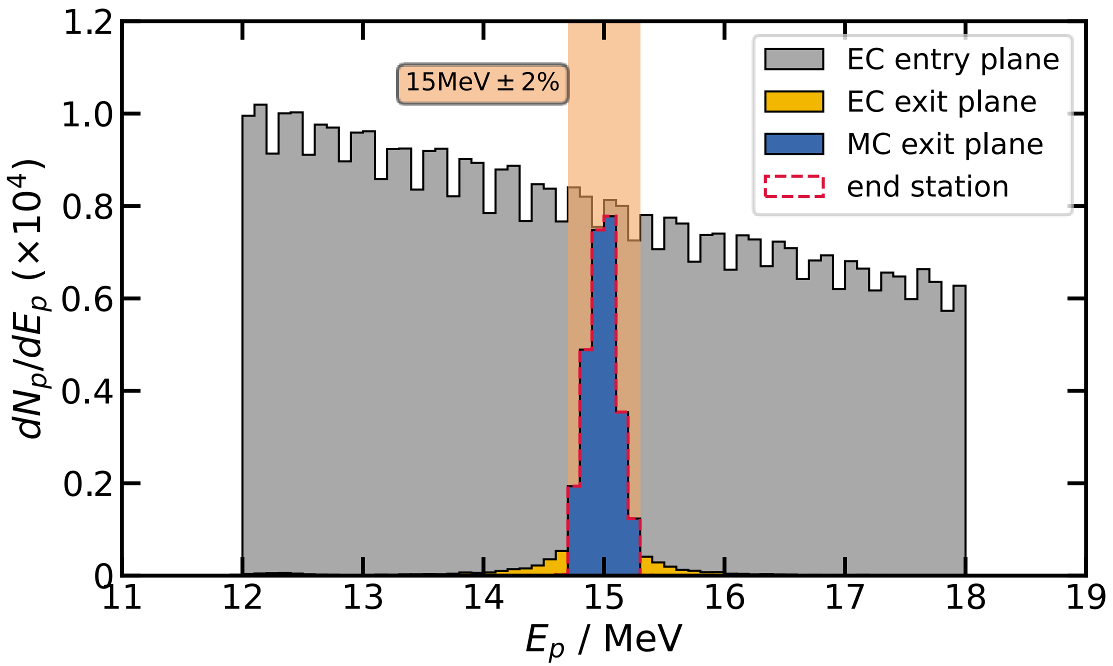
56% transmission from nozzle exit to end station



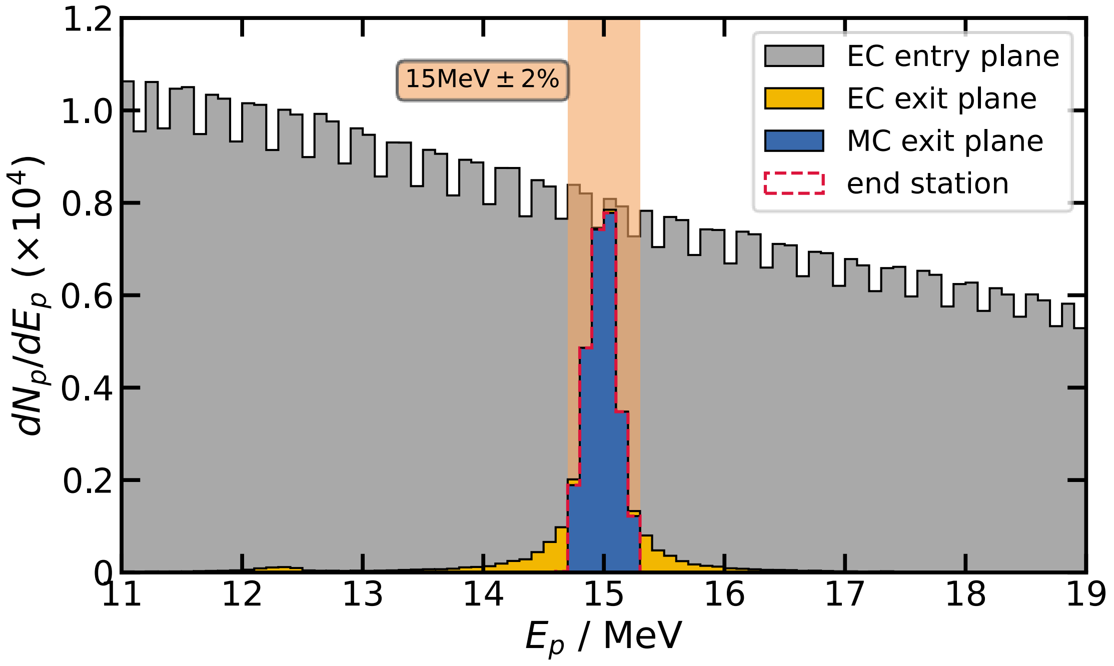


Identical energy selection with plasma/magnetic focusing

Plasma lenses



Solenoids



- 56% vs. 57% proton transmission within the nominal energy range from the nozzle

Conclusions

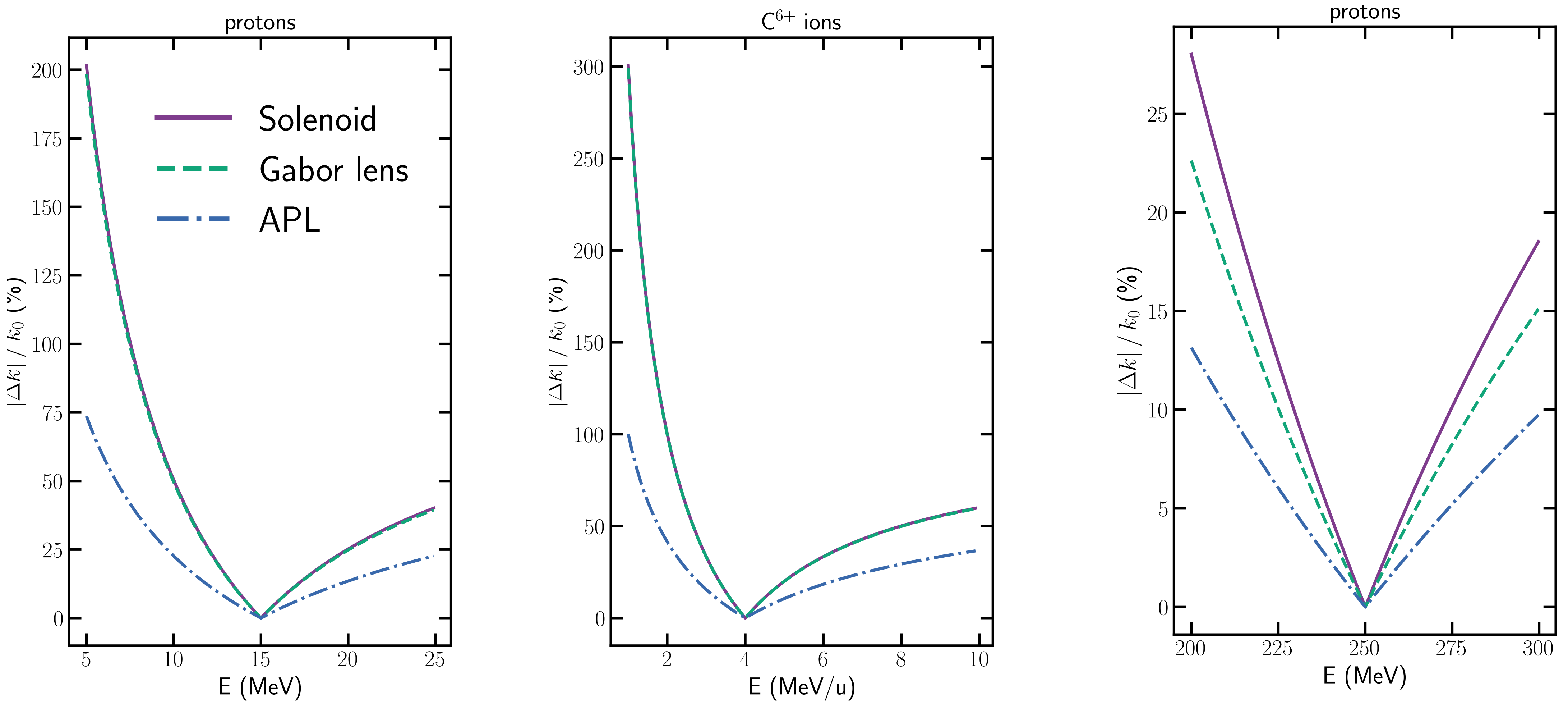
- In the absence of beam collimators, the capture section of LhARA transports a larger number of protons from the source when using plasma lenses compared to solenoids
- For the complete Stage 1 beam-line (baseline design, multiple collimators): identical fractions of protons reach the end station from the source with the use of solenoids or plasma lenses
  - within the nominal energy spread
- The superior capture efficiency of the plasma lenses compared to solenoids is suppressed by the limited angular acceptance of the nozzle situated downstream of the target
- Future optimisation of the nozzle should take into account
  - Beam-envelope size and divergence for protons within the nominal energy range from source
  - The full transport efficiency of the capture section of the LhARA beam-lines

Back-up slides

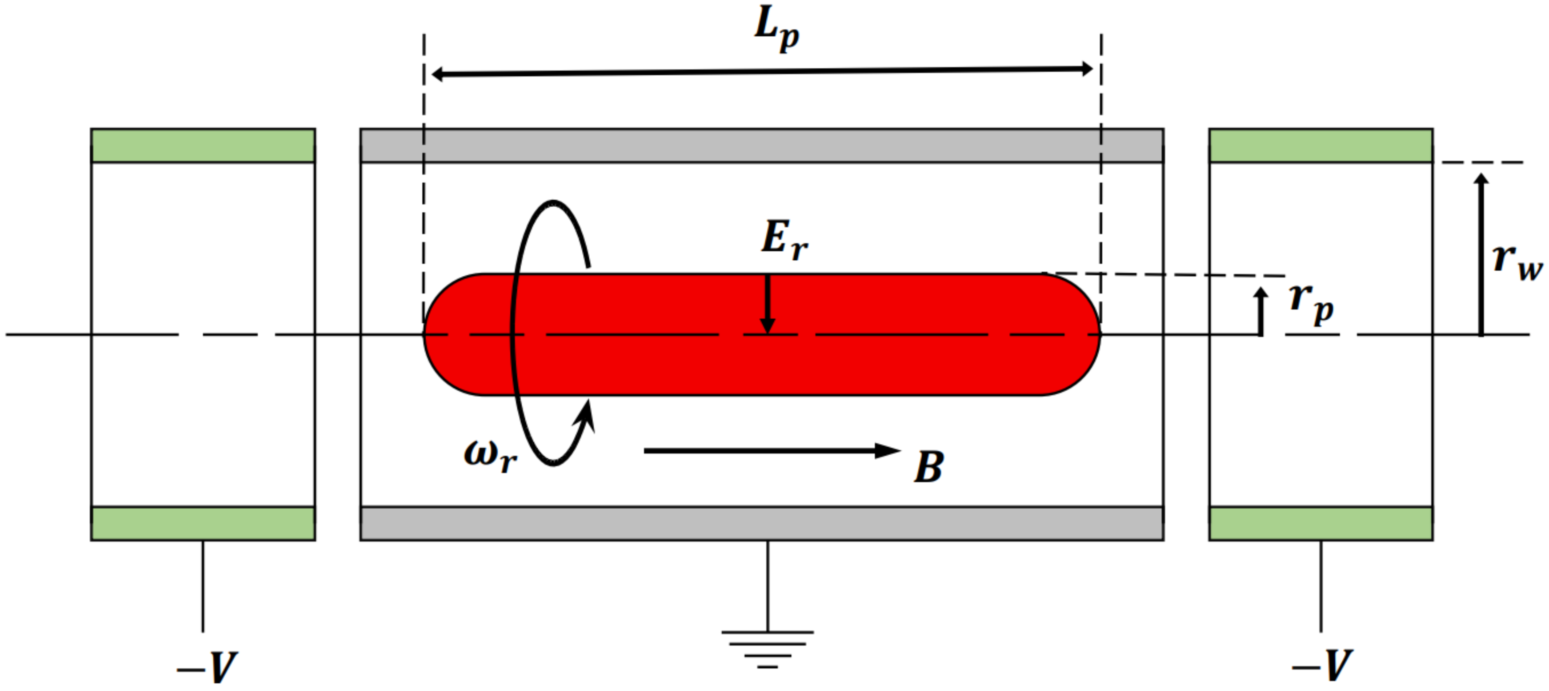
Single-particle motion through a lens

- Focusing strength parameter, $k \sim \frac{1}{f}$:

$$k_{\mathrm{GL}} \sim \frac{\gamma_0}{P_0^2} \qquad k_{\mathrm{solenoid}} \sim \frac{1}{P_0^2}$$



Electron plasma (Gabor) lens

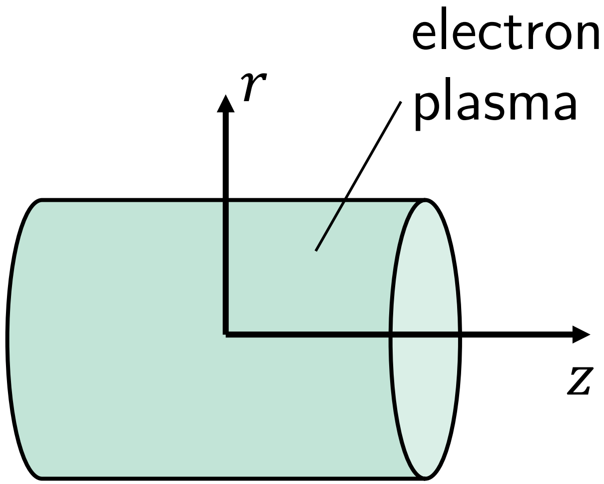


Field map of lenses with edge effects

[*] DOI: 10.1103/RevModPhys.87.247

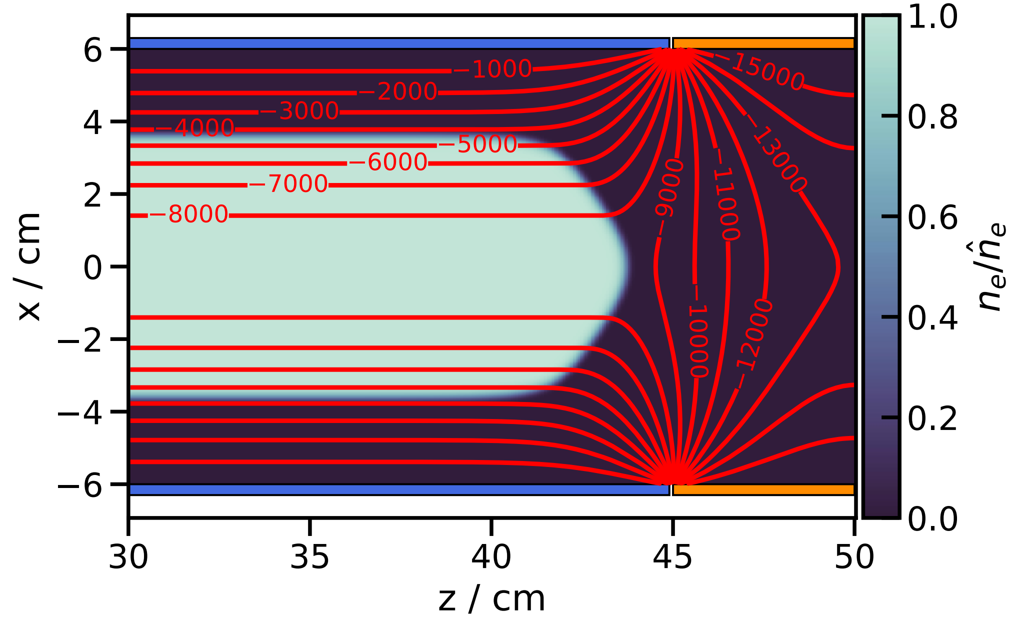
- Field map for each lens calculated separately
  - Plasma in global thermal equilibrium + rigid rotation
  - 2-D cylindrically symmetric numerical solution to Poisson-Boltzmann equations [1]

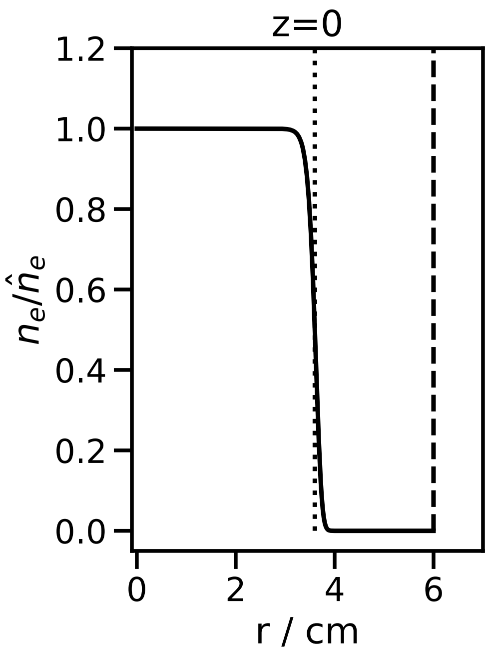
Hard-edge plasma (ideal lens)



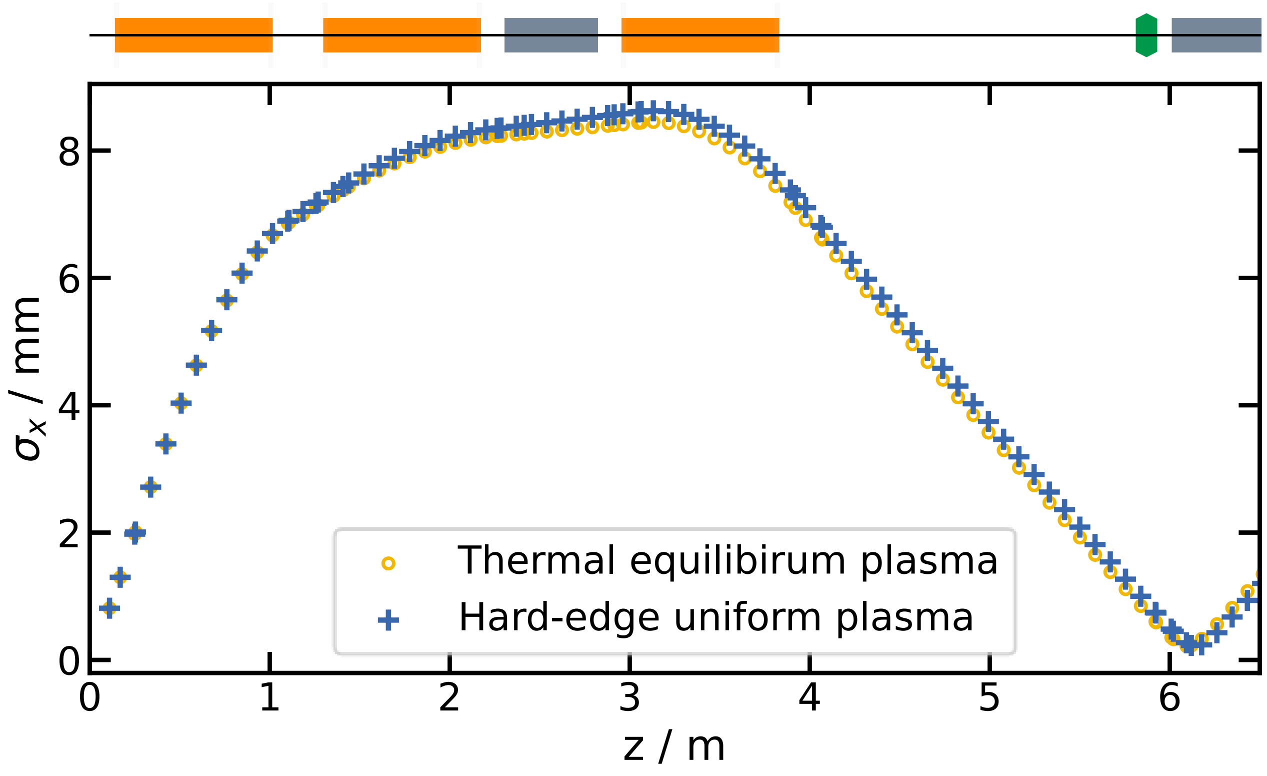
- uniform electron density
- infinitely long plasma

More realistic plasma shape





Contribution of edge-effects in beam-tracking



- Negligible differences between the two models of the lens
  - Preference for the hard-edge field map as it is much faster to generate (few minutes vs. several hours)