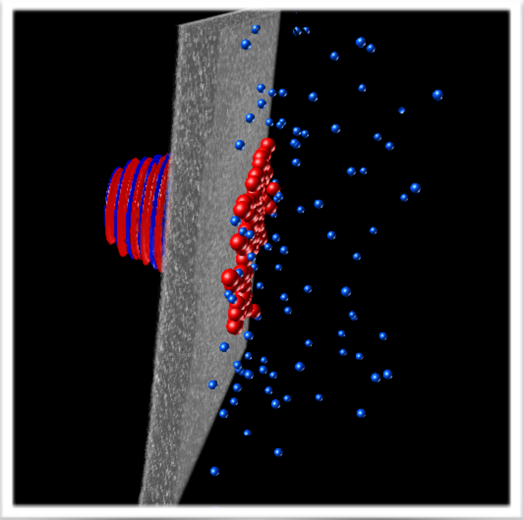
One-to-one simulations of the LhARA proton source

Elisabetta Boella

Physics Department, Lancaster University
and
Cockcroft Institute, Daresbury Laboratory

e.boella@lancaster.ac.uk

https://www.lancaster.ac.uk/staff/boella/



Lancaster University

The Cockcroft Institute of Accelerator Science and Technology

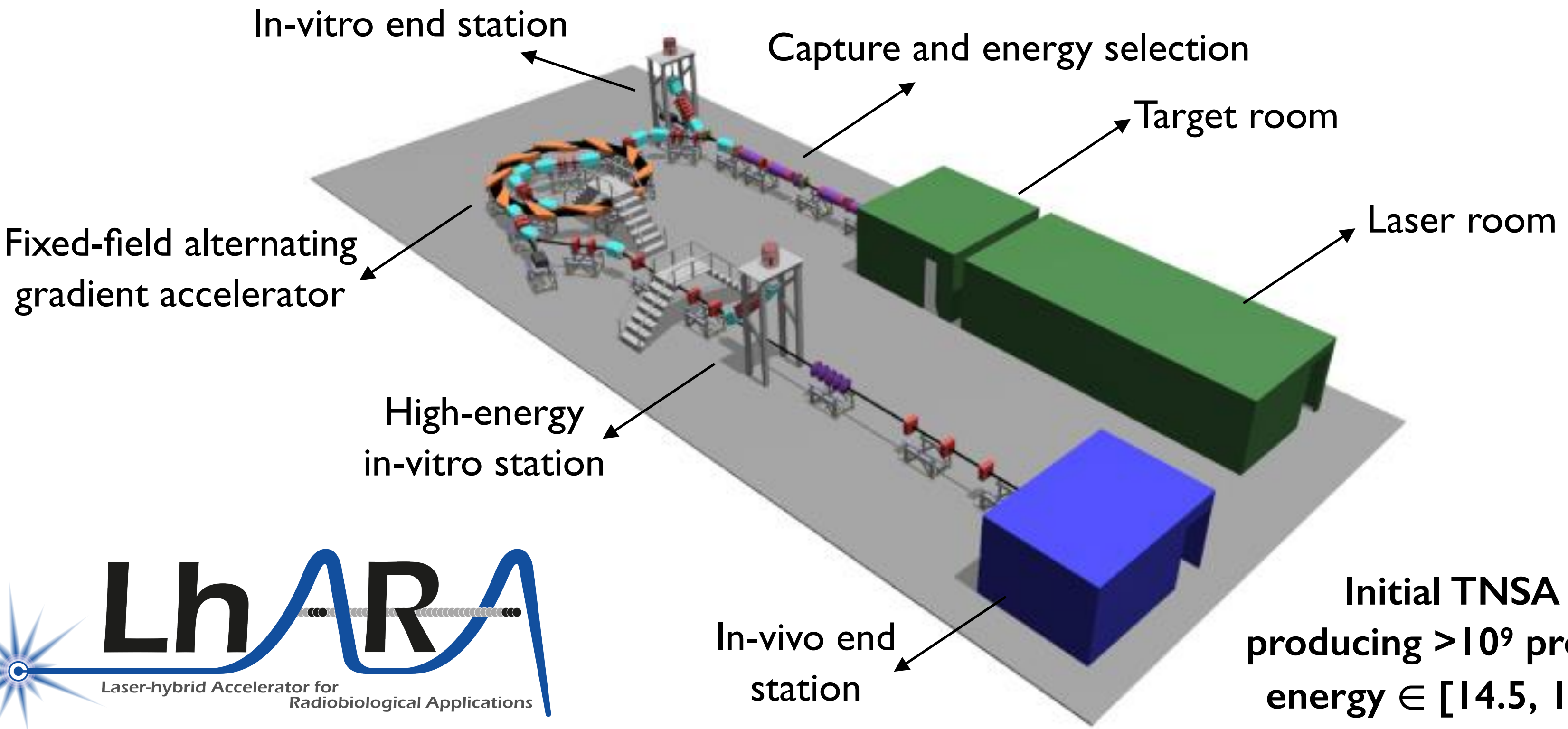
Acknowledgements

Nicholas Dover and Titus Dascalu (Imperial College London)

Ross Gray and Paul McKenna (University of Strathclyde)

Simulations performed on Marenostrum (BSC, Spain) under PRACE allocation
and DiRAC (EPCC, UK) under STFC allocation

In LhARA, we would like to produce a large flux of protons via Target Normal Sheath Acceleration

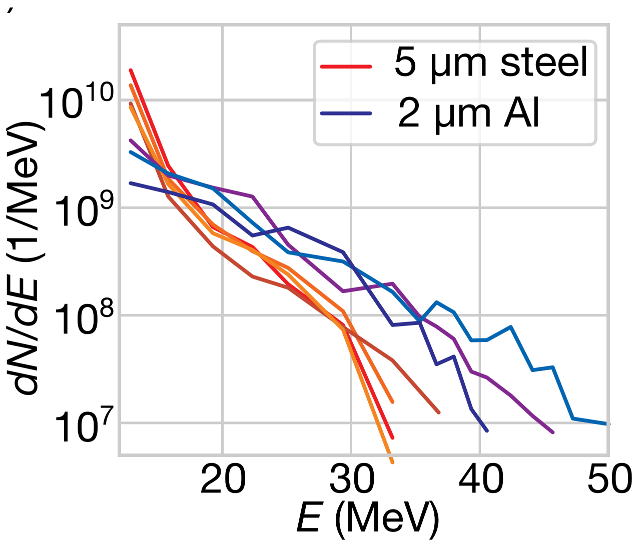


LhARA
Laser-hybrid Accelerator for Radiobiological Applications

G. Aymar et al., Frontiers in Physics 8, 567738 (2020)

Initial TNSA goal: producing >10^9 protons with energy ∈ [14.5, 15.5] MeV

Previous experiments show that LhARA goal could be achieved



	> 12 MeV	15 MeV, $\Delta E = 1\% E$, 1 msr
N_p	$\sim 2 \times 10^{10}$	$\sim 3 \times 10^{6}$
Q_p	$\sim$ 3 nC	$\sim$ 0.5 pC
E_{beam}	$\sim$ 50 mJ	$\sim$ 7 μJ
I_{peak}	$\sim$ 30 kA	$\sim$ 5 A
I_{avg} (0.1 Hz)	$\sim$ 0.3 nA	$\sim$ 50 fA
I_{avg} (10 Hz)	$\sim$ 30 nA	$\sim$ 5 pA

Considering ~13% energy spread and 15 msr acceptance, this would lead to a proton beam with Q ~ 100 pC and ε = 15 MeV ± 0.5 MeV

However, these results were obtained @J-KAREN-P

ε_L = 10 J and I = 5 x 10^{21} W/cm^2

N. Dover et al., High Energy Density Physics 37, 100847 (2020)

Provided initial laser specs are quite different. What can we achieve with them?

Initial laser parameters*

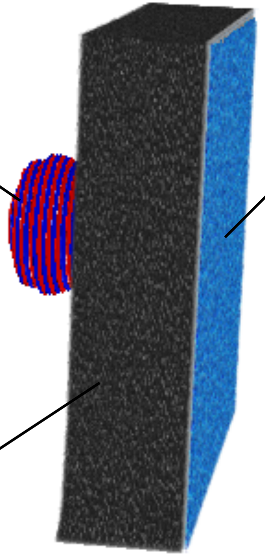
P	[TW]	100
τ	[fs]	25
rep. rate	[Hz]	10
contrast		10^{10}

- 100 TW → For higher flexibility "off-shelf" alternatives: 250 or 500 TW
- 10 Hz → Need high-rep. rate target
- 10^{10} → To be evaluated

*To be better defined after R&D

SCAPA specs are similar to LhARA specs. What can we expect?

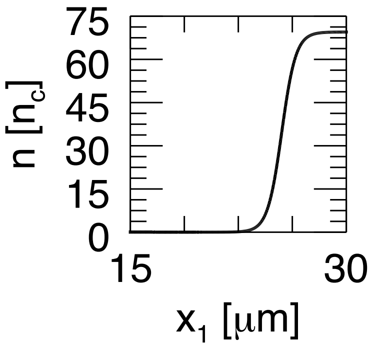
$I = [8 — 10] \times 10^{20}$ W/cm^2
$\lambda_0 = 800$ nm
$a_0 = [19.32 — 21.60]$
$\tau_{FWHM} = 25$ fs
$w_0 = 1.5$ μm
p - polarised



H^+ layer
$n_{H+} = 1.15\ n_c$
$L_{H+} = 31.83$ nm

Al^{3+} foil
$n_{Al3+} = 70\ n_c$
$L_{Al3+} = [2 — 6]$ μm

Initial density profile detail



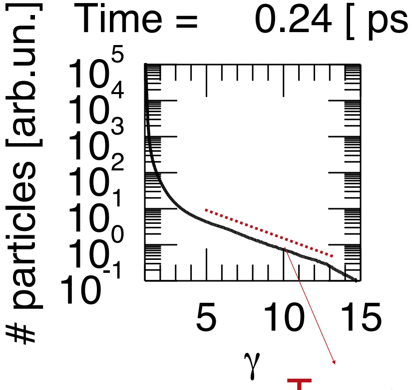
$$n_{Al^{3+}} = 70\frac{n_c}{2}\left[\tanh\left(\frac{x_1 - x_{1,0}}{L_g}\right) + 1\right]$$

$x_{1,0} = 25.5$ μm
$L_g = [0.08 — 1]$ μm

A short scale-length pre-plasma leads to proton energies higher than 15 MeV using thicker targets

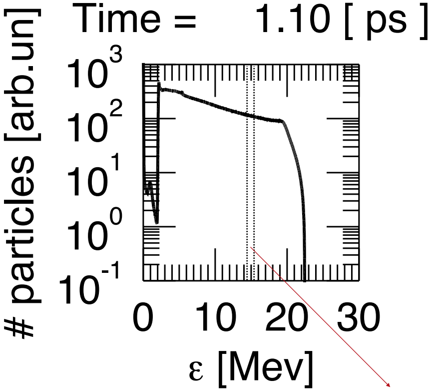
6 μm thick target, L_g = 1 μm

Electron distribution function



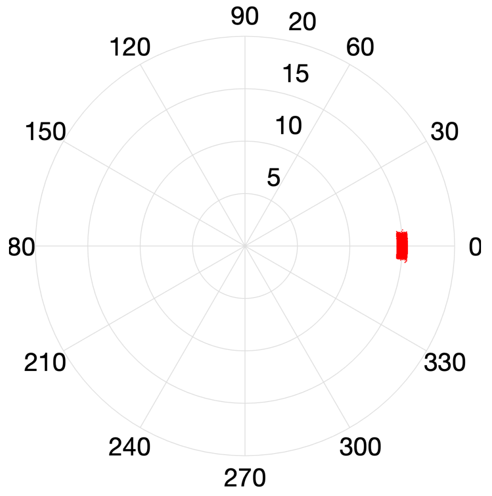
$T_{e,hot}$ ~ 1.85 MeV

Proton spectrum



78 pC

Divergence of proton with $14.5 \text{ MeV} \leq \varepsilon \leq 15.5 \text{ MeV}$

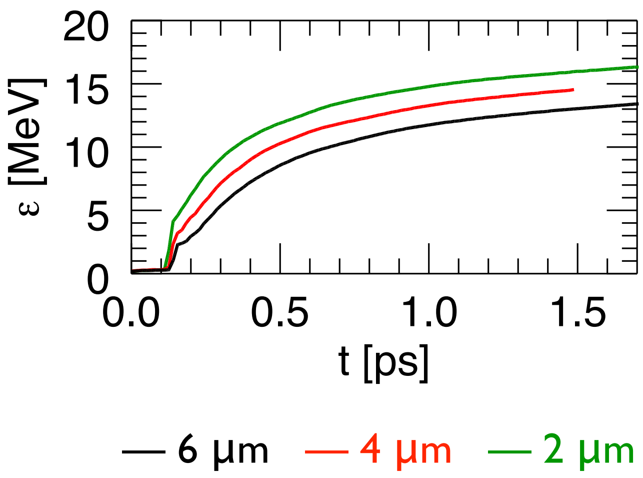


θ_{rms} ~ 1.14°

In the case of almost abrupt plasma-to-vacuum transition, only the 2 µm Aluminium target allows for achieving LhARA target goals

$I = 9 \times 10^{20}$ W/cm^2, $L_g = 0.08$ µm

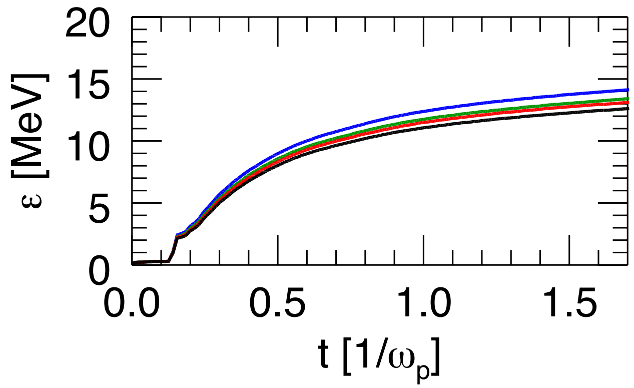
Proton cutoff energy vs time



A laser intensity ~ 10^{21} W/cm^2 would be required to achieve a proton cutoff energy of 15 MeV with 6 μm targets

6 μm thick target, L_g = 0.08 μm

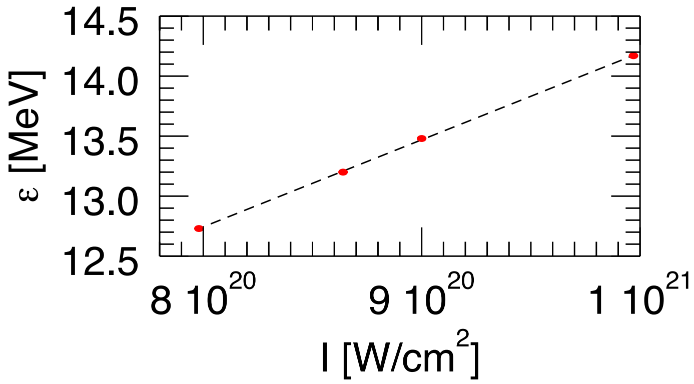
Proton cutoff energy vs time



— 8.0 x10^{20} W/cm^2 — 8.6 x10^{20} W/cm^2

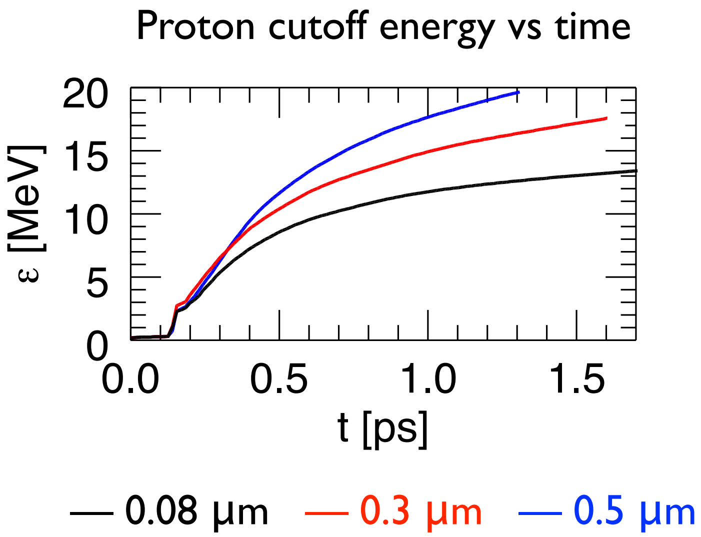
— 9.0 x 10^{20} W/cm^2 — 10.0 x 10^{20} W/cm^2

Proton cutoff energy vs laser intensity



A short pre-plasma allows for boosting the proton cutoff energy to ε > 15 MeV using 6 μm targets

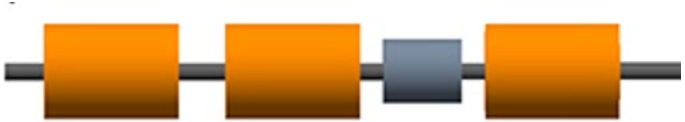
$I = 10 \times 10^{20}$ W/cm^2, 6 μm thick target



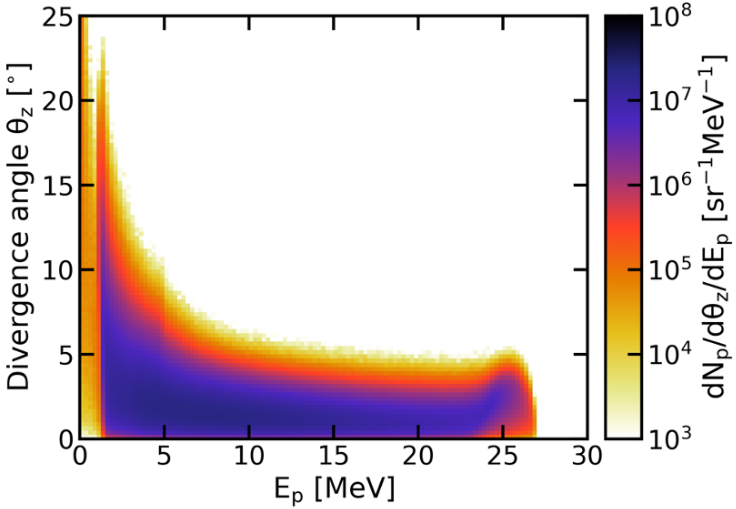
Nearly all 15 MeV protons are transmitted through the first three Gabor lenses

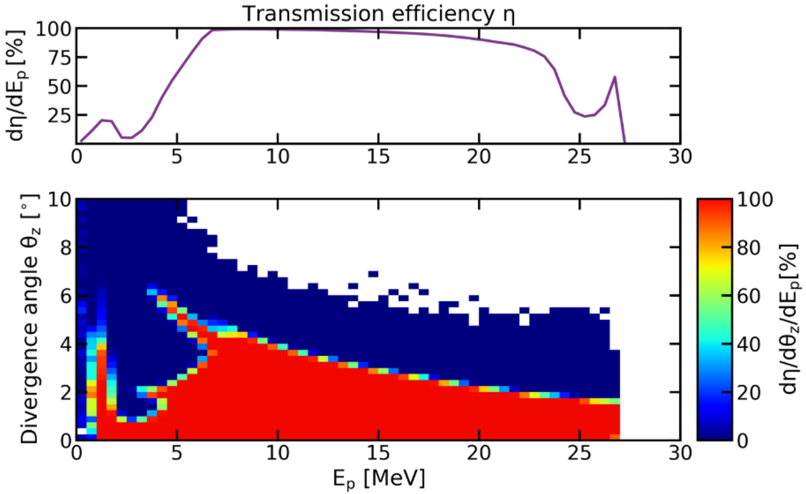
Gabor lens

RF cavity



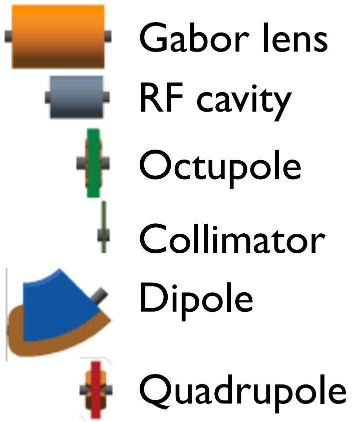
Proton spectrum from most promising simulation

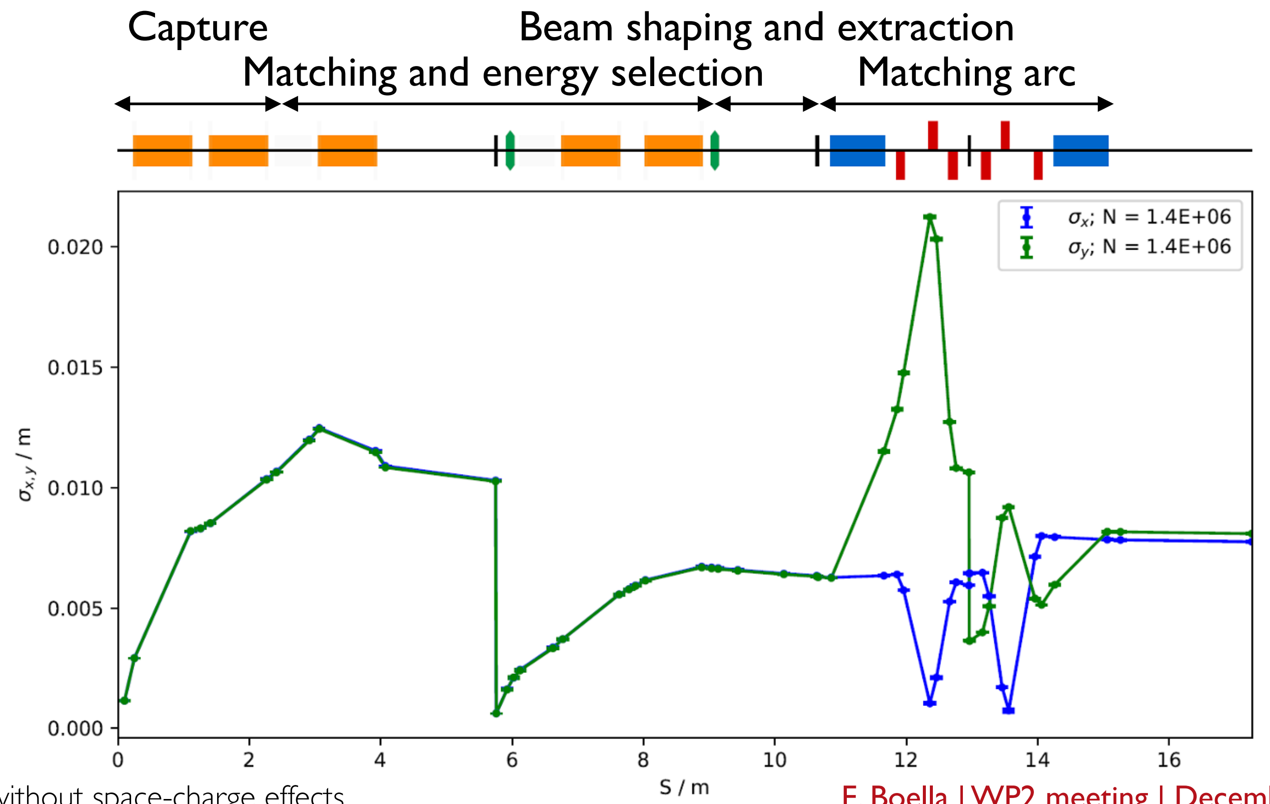




Simulations performed with GPT including space-charge effects

At the end of the line, proton beam is circular and very collimated

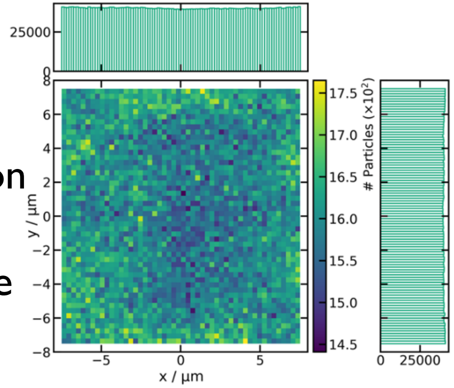


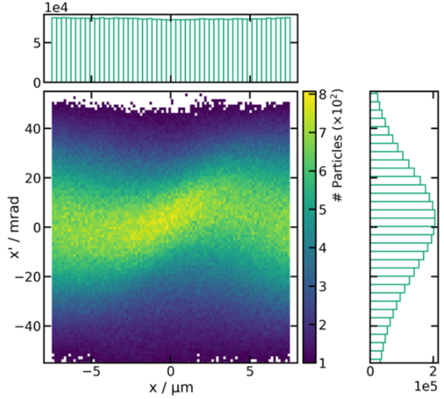


Simulations performed with BDSIM without space-charge effects

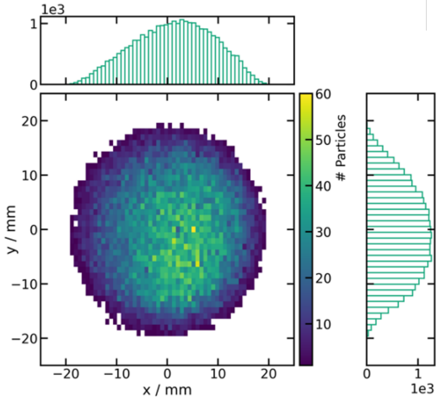
At the end of the line, proton beam is circular and very collimated

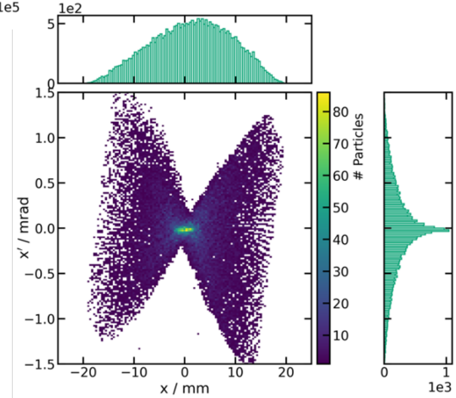
Ion beam spatial distribution and divergence @source



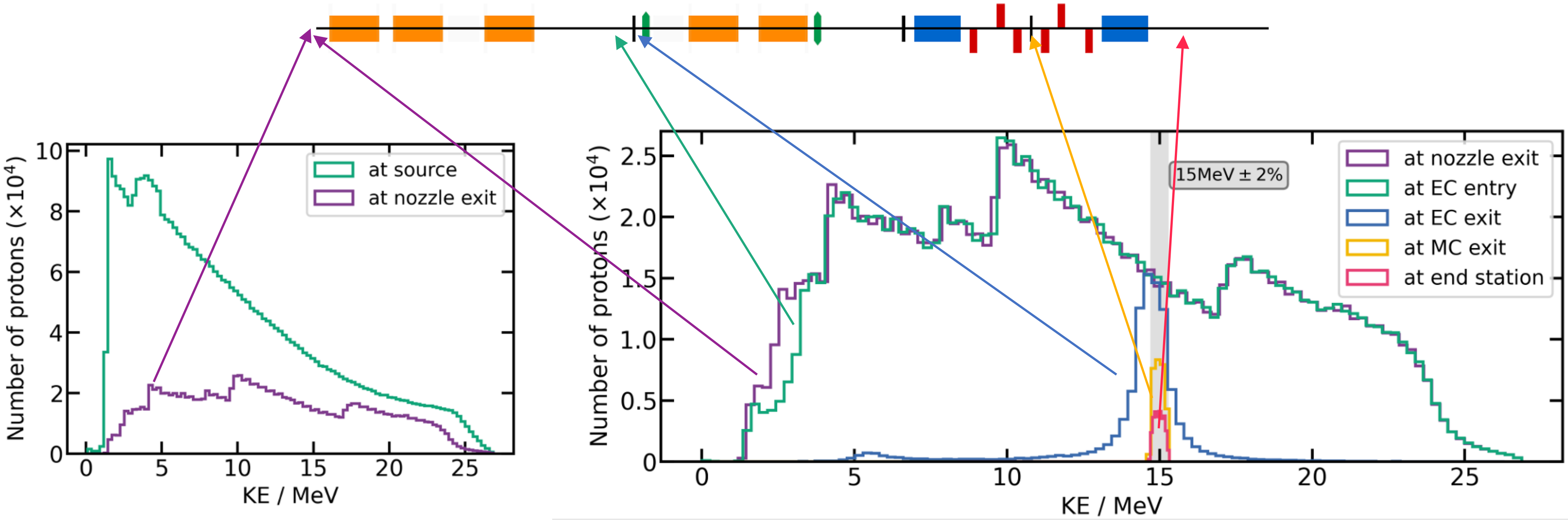


Ion beam spatial distribution and divergence @end station





At the end station, protons have an energy of 15 MeV and an energy spread of 2% suitable for radiological applications



Summary

- We explored via 3D Particle-In-Cell simulations the interaction of the SCAPA laser with Aluminium foils.
- We investigated the effect of target thickness, laser intensity and pre-plasma scale-length.
- In the case of almost abrupt plasma-vacuum transition, very thin Aluminium targets (~2 μm) will be necessary to exceed proton energies of 15 MeV.
- For thicker targets (~ 6 μm), higher laser intensities will be necessary to exceed proton energies of 15 MeV.
- The presence of a pre-plasma allows for accelerating protons to energies >> 15 MeV with thicker targets.
- Protons obtained from a realistic PIC simulation were propagated through the beamline, showing that TNSA protons can be shaped into a beam suitable for radiobiological applications.

Future works (open to suggestions)

- Include more points to the performed scans.
- Explore role of laser angle of incidence.
- Combine hydro simulations with PIC to get more realistic information on the pre-plasma.
- Increase density of the contaminant layer

Actions:

- Share SCAPA measurements of laser contrast and laser intensity in focal spot
- Check possibilities for hydro simulations and plan further discussion