Target Normal Sheath Acceleration as an improved ion source for a novel Laser-hybrid Accelerator for Radiobiological Applications

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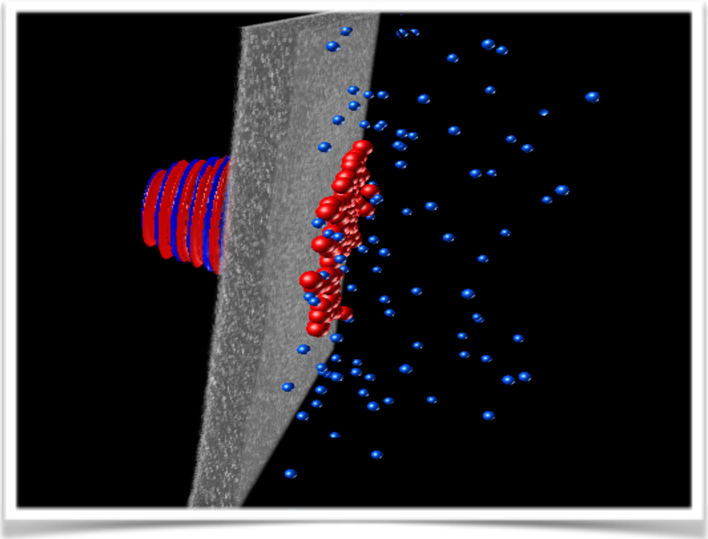

Lancaster University

The Cockcroft Institute of Accelerator Science and Technology

Acknowledgments

Work in collaboration with

L. A. Gizzi, L. Labate and **G. Cristoferetti** (Consiglio Nazionale delle Ricerche, Italy)

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C. Baker (Swansea University, UK)

C. Whyte (University of Strathclyde, UK)

B. Bingham (Rutherford Appleton Laboratory, UK)

LhARA working group

Simulation results obtained on
Galileo (CINECA, Italy), ARCHER2 (EPCC, UK), Tesseract (EPCC, UK) and Marenostrum (BSC, Spain)

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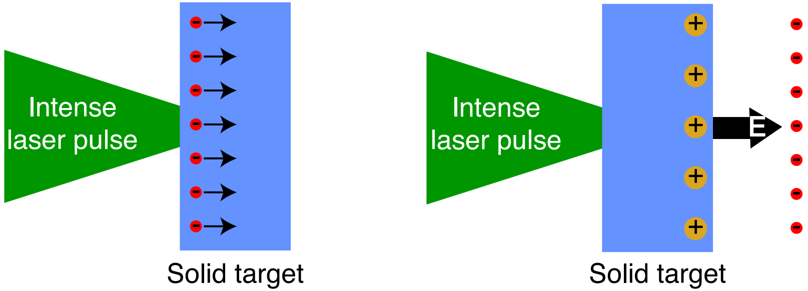
*now at Instituto Superior Tecnico

Target Normal Sheath Acceleration: the most consolidated laser-driven ion acceleration scheme



Features of TNSA accelerated ions

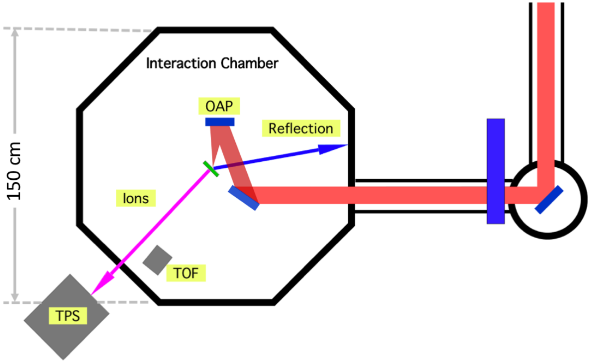
Short particle bunches (~ps)
High currents (~kA)
Low transverse emittance ($<10^{-2}$ mm-mrad)
Broad energy spectrum (~100% energy spread)

Challenges

Enhancing ion cut-off energy
Improving beam quality
Boosting conversion efficiency
Increasing stability

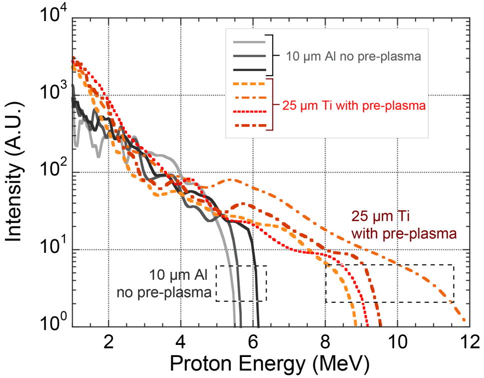
Proton energy is enhanced
in the presence of a controlled pre-plasma generated by a fs pre-pulse

Experimental setup*

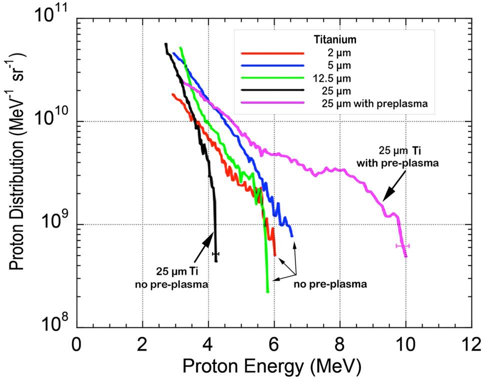


ILIL, INO-CNR (Italy)

Thomson Parabola Spectrometer diagnostic



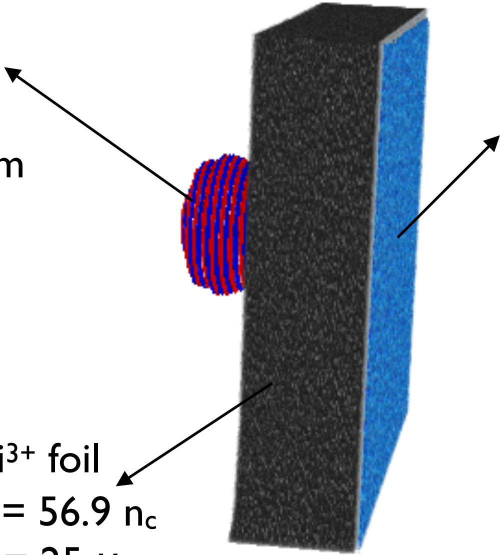
Time Of Flight diagnostic



*L. A. Gizzi et al., Nucl. Instruments Methods Phys. Res. 909, 160 (2018)

Multidimensional PIC simulations:
exploring the role of different pre-plasma scale lengths

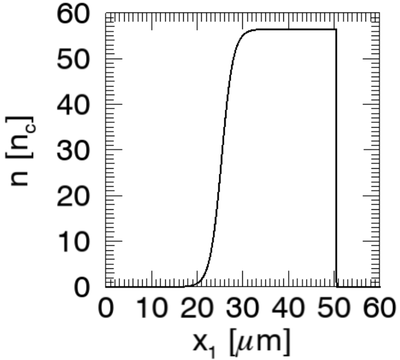
$I = 2.4 * 10^{20}$ W/cm^2
$\lambda_0 = 795$ nm
$a_0 = 10.6$
$\tau_{FWHM} = 27$ fs
$w_0 = 2.2$ μm
focal point = 25.3 μm
p - polarised



H$^+$ layer
$n_{H+} = 1.14\ n_c$
$L_{H+} = 128$ nm

Ti^{3+} foil
$n_{Ti3+} = 56.9\ n_c$
$L_{Ti3+} = 25$ μm

Initial density profile detail



$$n_{Ti^{3+}} = 56.9\frac{n_c}{2}\left[\tanh\left(\frac{x_1 - x_{1,0}}{L_g}\right) + 1\right]$$

$x_{1,0} = 25.3$ μm
$L_g = 0.13 - 5.07$ μm

In the case of a long pre-plasma gradient, the laser undergoes self-focusing and steepening

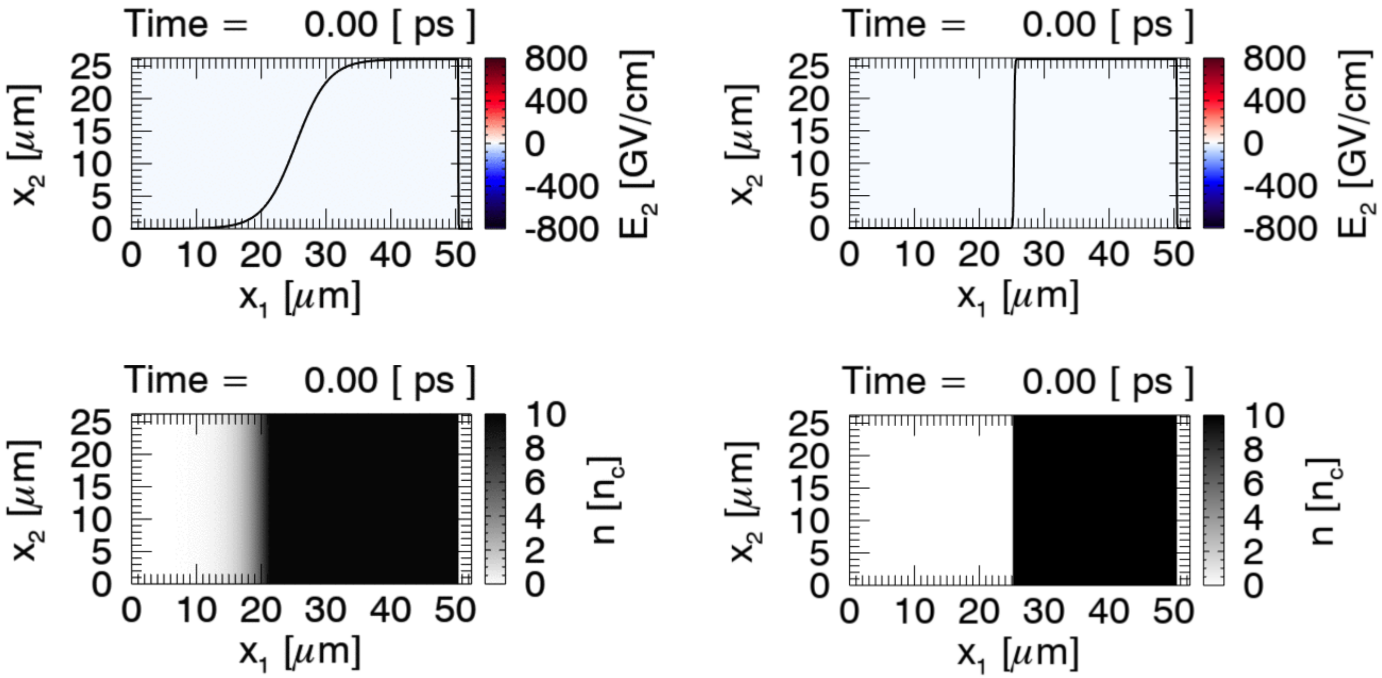
Laser electric field

Longitudinal electron density

Electron density

L_g = 5.07 µm

L_g = 0.13 µm



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Laser electric field

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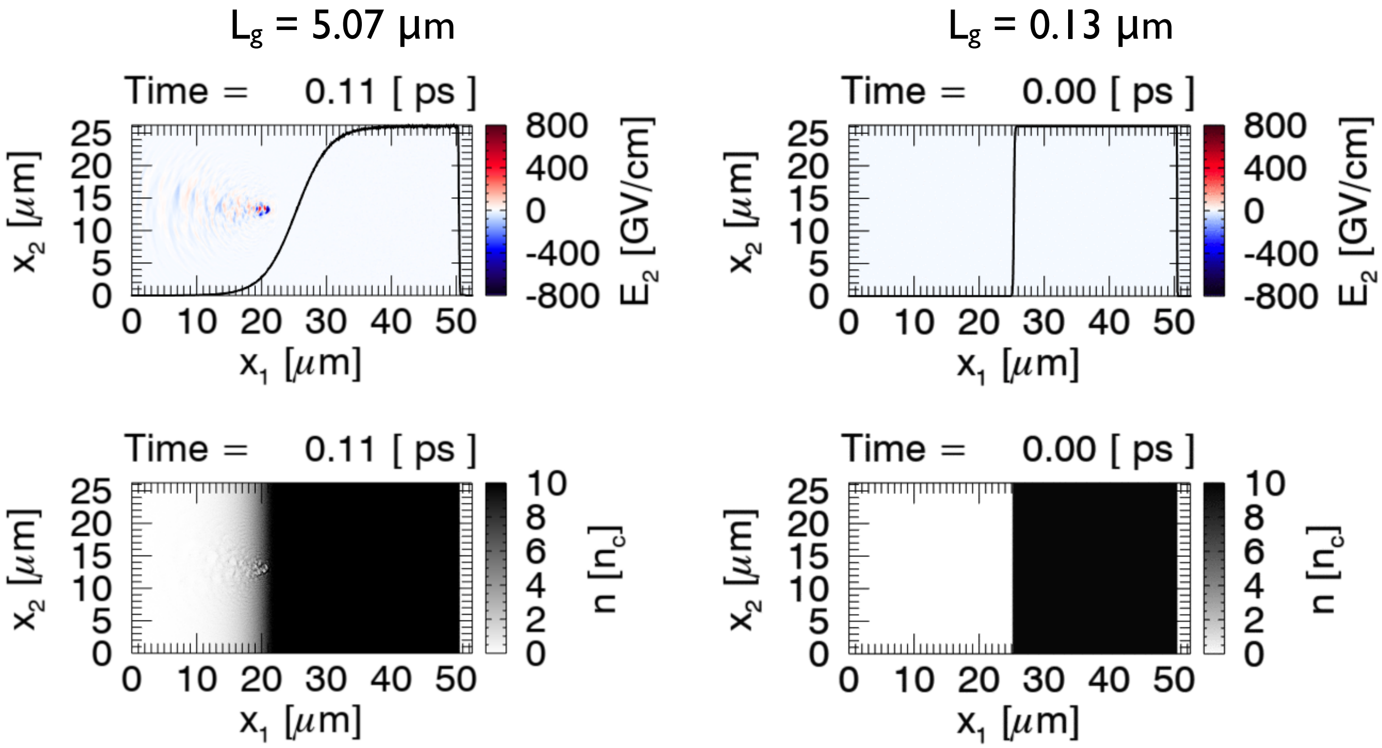


L_g = 5.07 µm

L_g = 0.13 µm

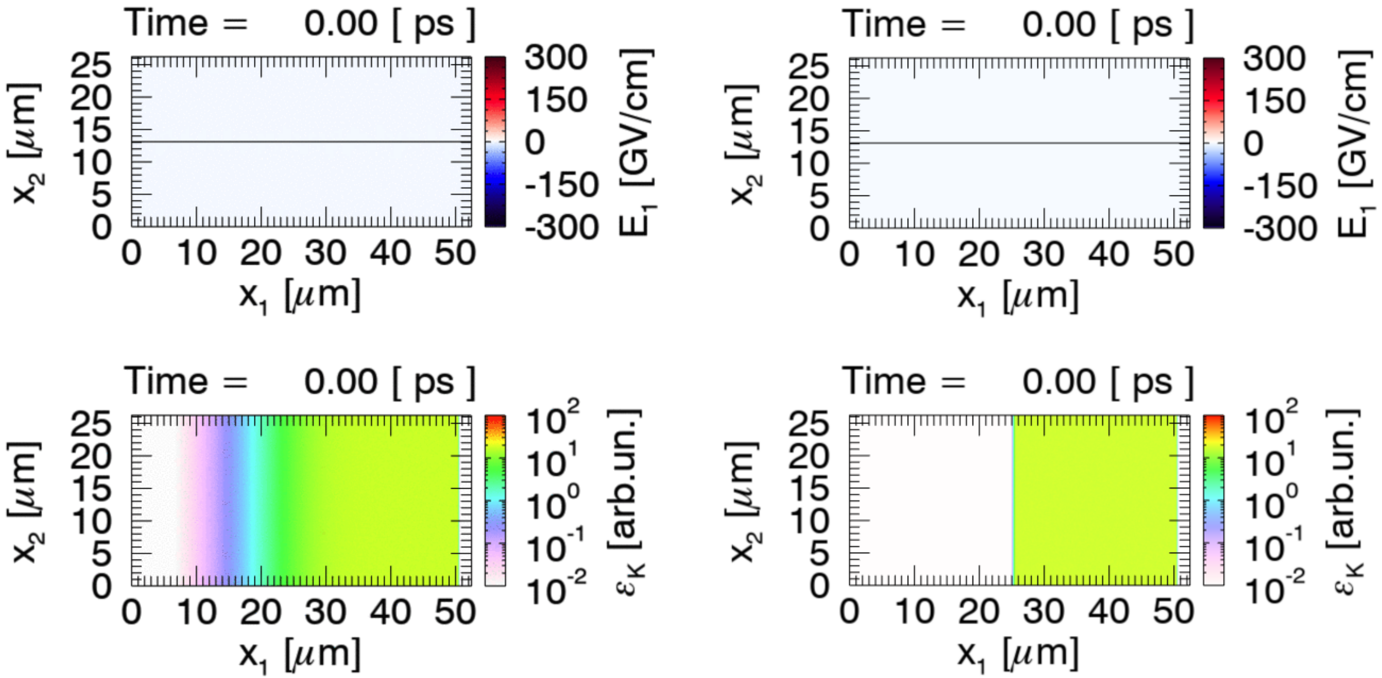
A standing wave in the underdense plasma improves the laser-to-electron energy conversion efficiency

L_g = 5.07 μm

L_g = 0.13 μm

Longitudinal electric field

Electron kinetic energy



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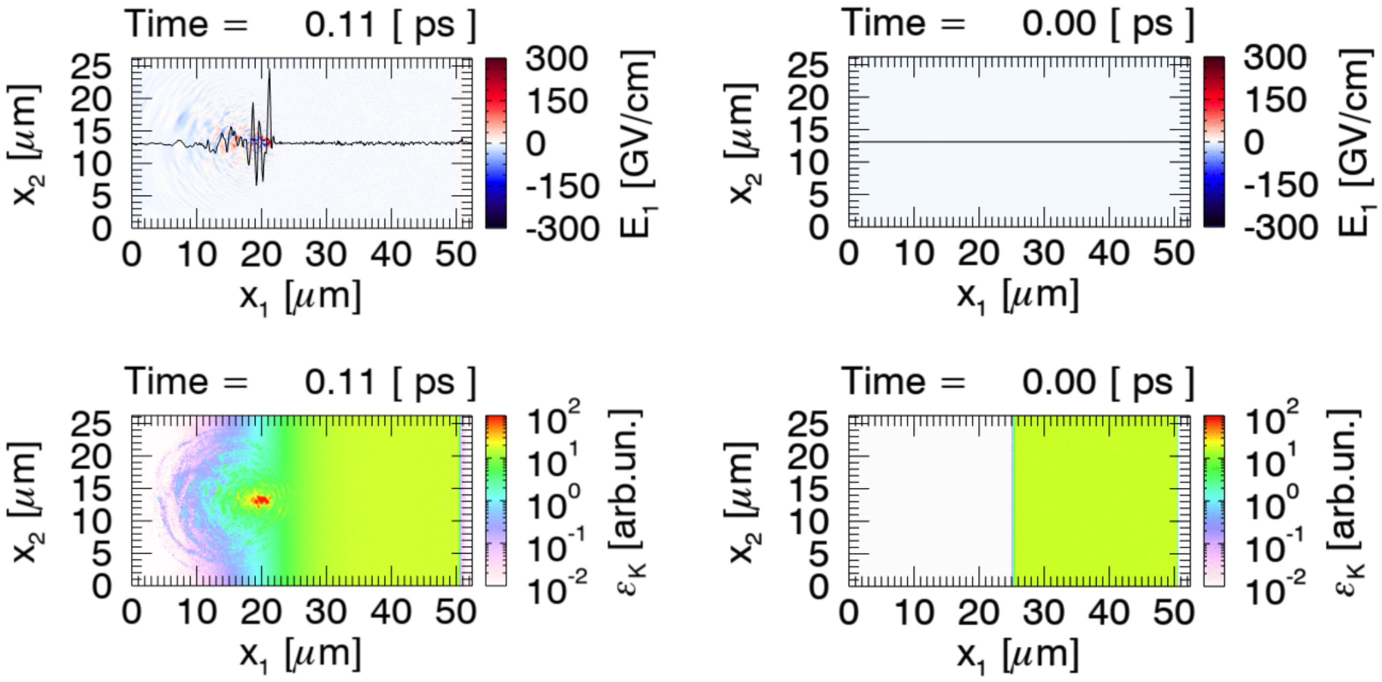
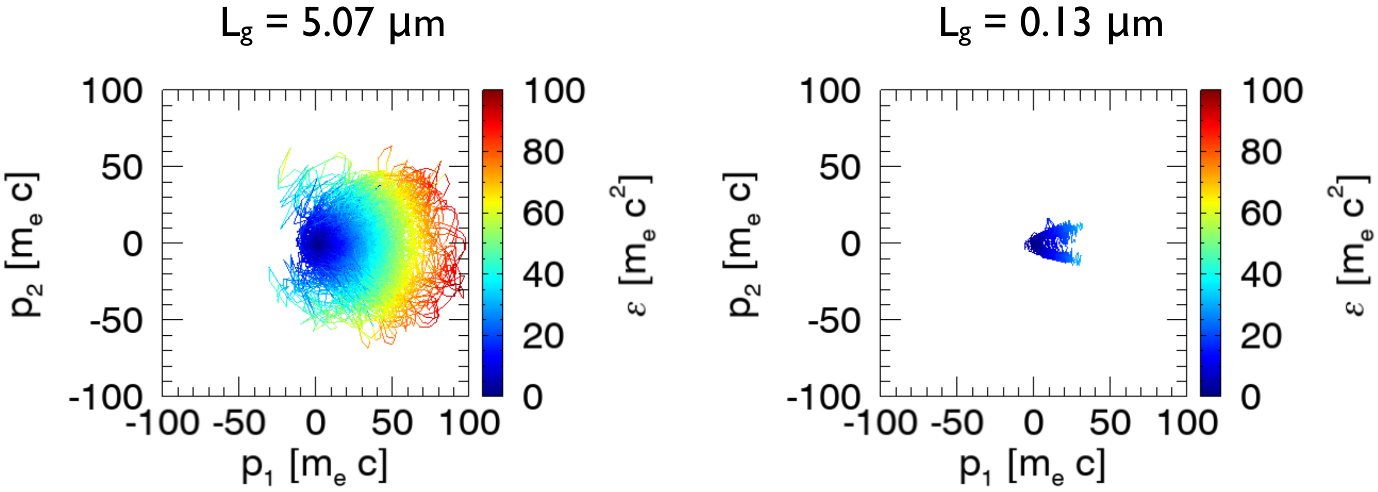


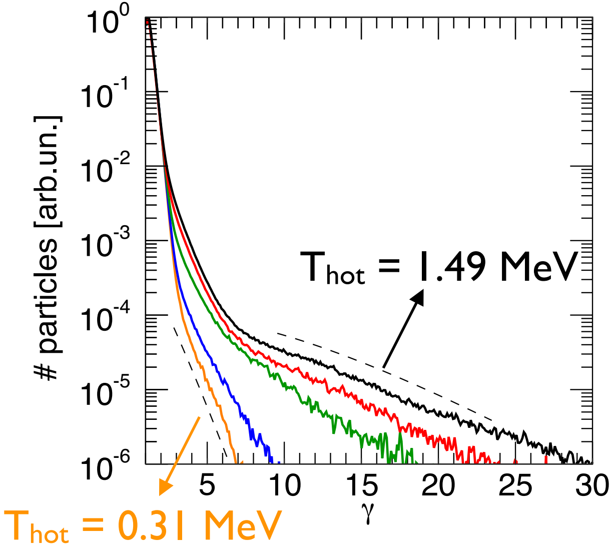
Electrons undergo stochastic motion in the standing wave favouring a more efficient heating mechanism

Electron trajectories in phase space

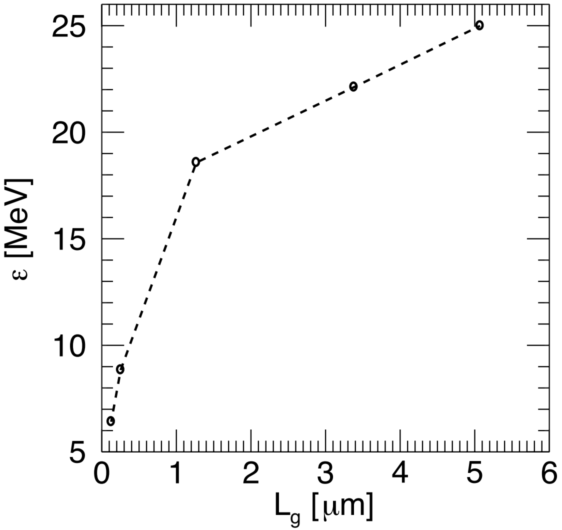


Simulation results confirm that a controlled pre-plasma enhances the cutoff energy

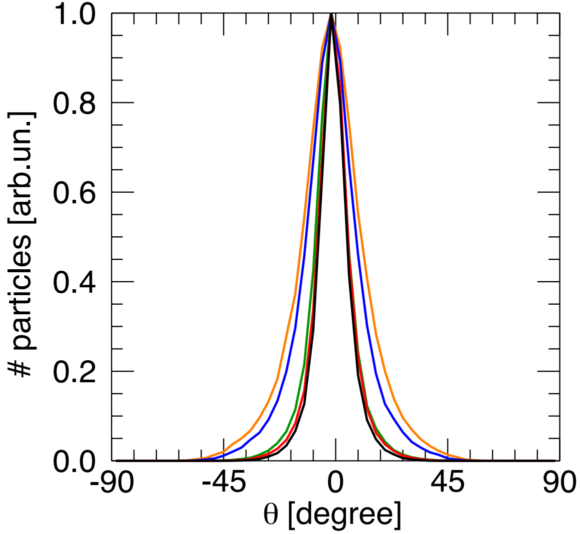
Electron distribution



Proton cut-off energy vs pre-plasma scale length



Proton angular distribution



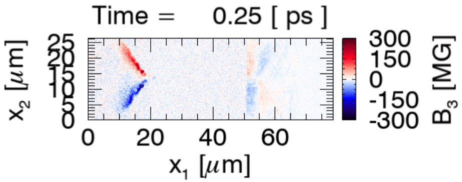
— L_g = 0.13 μm, — L_g = 0.25 μm, — L_g = 1.27 μm, — L_g = 3.38 μm, — L_g = 5.07 μm

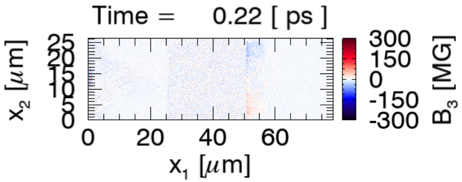
A strong magnetic field at the back of the target reduces the proton divergence in the case of long pre-plasma gradients

L_g = 5.07 µm

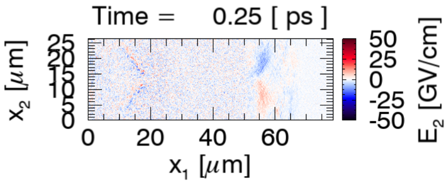
L_g = 0.13 µm

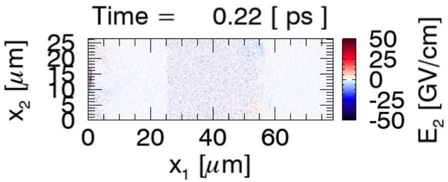
Out-of-plane magnetic field



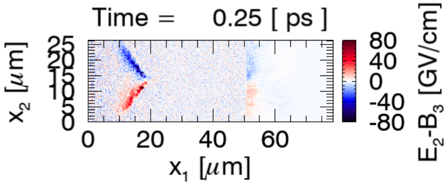


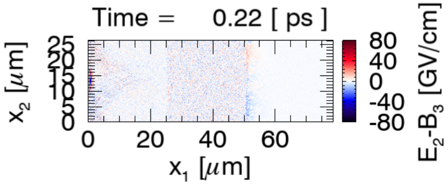
Transverse electric field





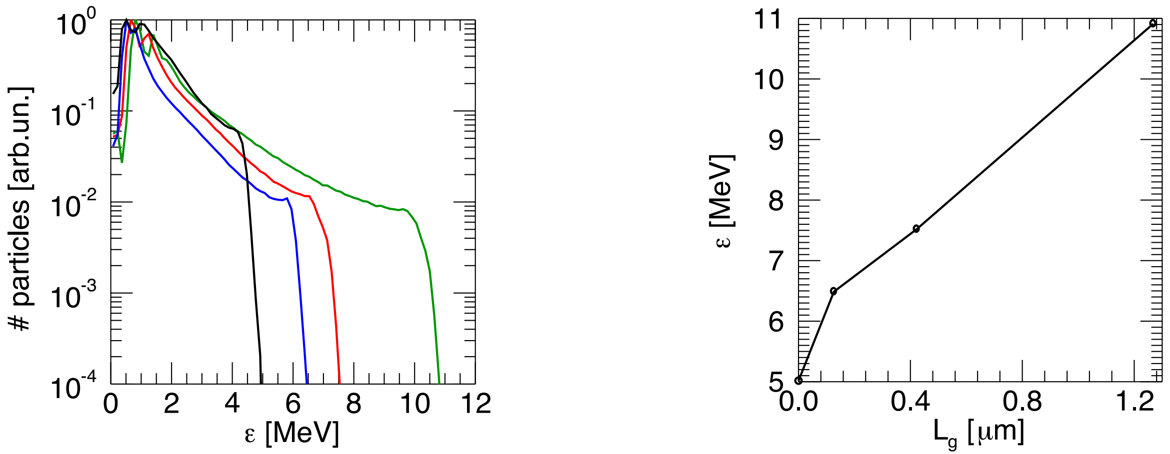
Focusing force





Three-dimensional PIC simulations show quantitative agreement with experimental results

3D PIC simulations modelling the interaction between the main pulse and a 10 µm Al target

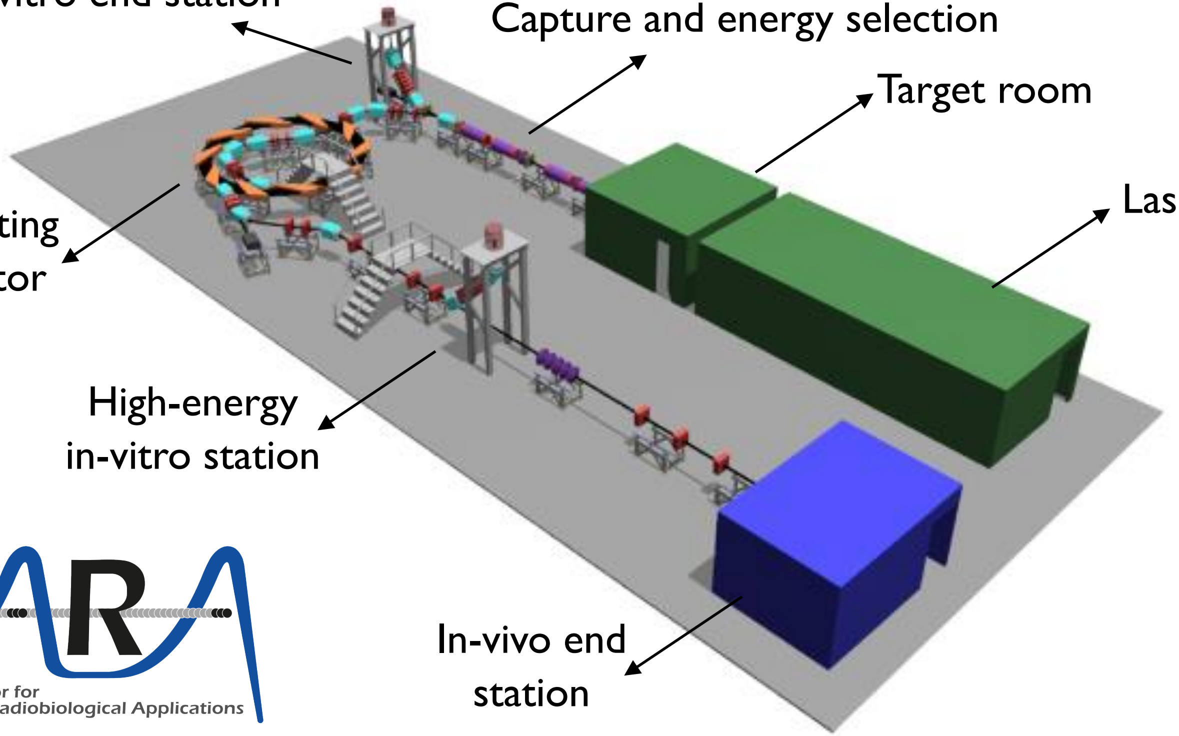


— sharp plasma-vacuum transition, — L_g = 0.13 µm, — L_g = 0.42 µm, — L_g = 1.27 µm

Simulations indicate that in the absence of pre-pulse
a very short scale length pre-plasma (L_g ~ 0.1 µm) is generated by the ps pedestal of the laser pulse.

L. A. Gizzi, E. Boella et al., Scientific Reports 11, 13728 (2021).

TNSA as a reliable ion source for a novel Laser-hybrid Accelerator for Radiobiological Applications



In-vitro end station

Capture and energy selection

Target room

Laser room

Fixed-field alternating gradient accelerator

High-energy in-vitro station

In-vivo end station

LhARA
Laser-hybrid Accelerator for
Radiobiological Applications

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

An international multidisciplinary collaboration for a ground-breaking project

Imperial College London

ICR The Institute of Cancer Research

Medical Research Council
UKRI
Oxford Institute for Radiation Oncology

University of Oxford

JAI John Adams Institute for Accelerator Science

CCAP Centre for the Clinical Application of Particles

Imperial College Academic Health Science Centre

Cancer Research UK | Imperial Centre

NHS Imperial College Healthcare NHS Trust

LhARA Laser-hybrid Accelerator for Radiobiological Applications

Manchester 1824 The University of Manchester

University of Birmingham

University of Liverpool

NHS University Hospitals Birmingham NHS Foundation Trust

NHS The Clatterbridge Cancer Centre NHS Foundation Trust

NHS The Christie NHS Foundation Trust

institut Curie

Queen's University Belfast

Swansea University Prifysgol Abertawe

UCL Medical Physics & Biomedical Engineering

University · Clinical · Laboratory · Industry · Accelerator

Partners

Netherlands Cancer Institute Antoni van Leeuwenhoek

Hampton University Proton Therapy Institute Fighting Cancer, Saving Lives

University of Strathclyde Glasgow Department of Physics

Royal Holloway University of London

Lancaster University

UKRI Science and Technology Facilities Council
ASTeC
Daresbury Laboratory
Particle Physics Department
ISIS Neutron and Muon Source

CLF central laser facility

University of Birmingham | Cyclotron Facility | Positron Imaging Centre

INFN Catania

The Cockcroft Institute of Accelerator Science and Technology

CERN

Corerain 鲲云科技

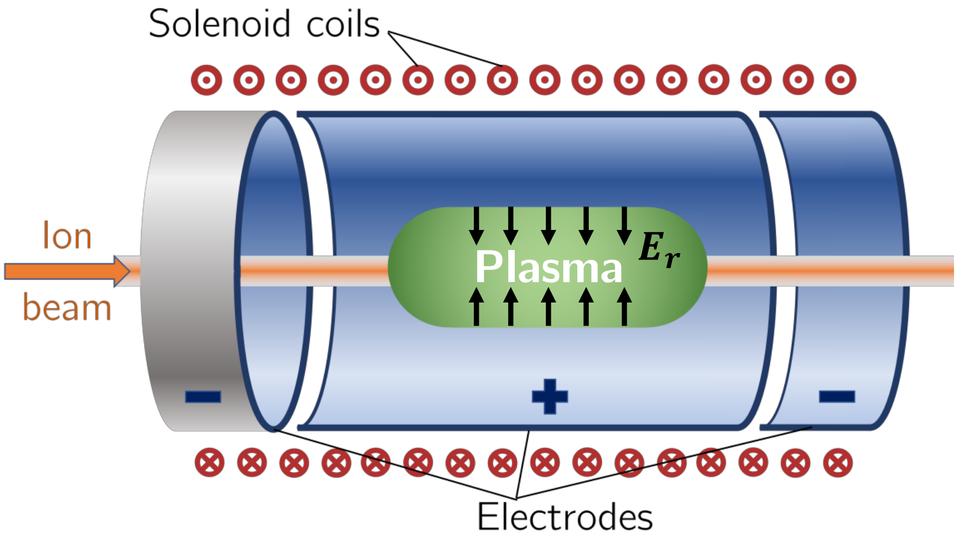
LEO Cancer Care

Maxeler Technologies Maximum Performance Computing

The Rosalind Franklin Institute

NPL National Physical Laboratory

Ion focussing is obtained using innovative Gabor lenses



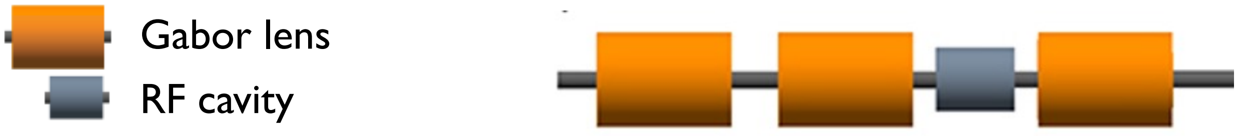
Advantages

Provides focusing in both planes simultaneously
Operates continuously
Cost effective solution
Highly tunable

Alternative

DC solenoids

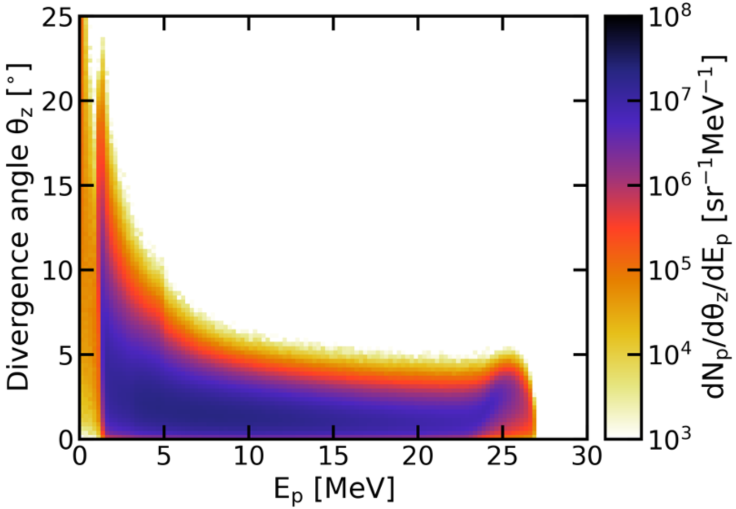
Nearly all 15 MeV protons are transmitted through the first three Gabor lenses

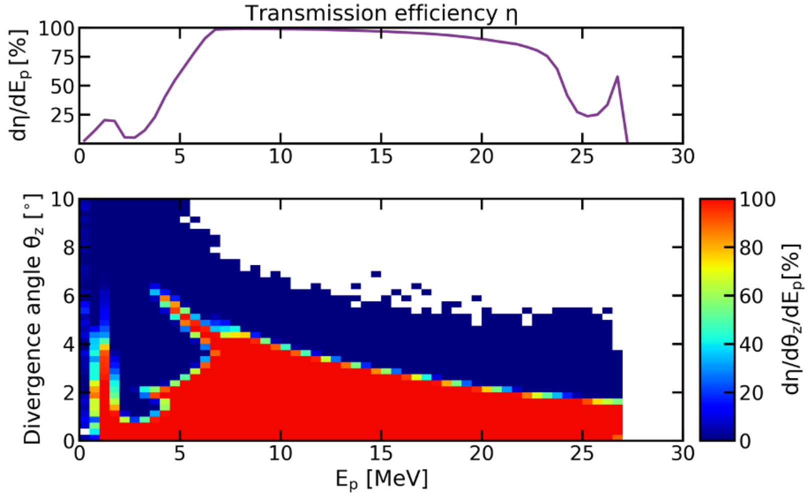


Gabor lens

RF cavity

Proton spectrum from 3D PIC simulations

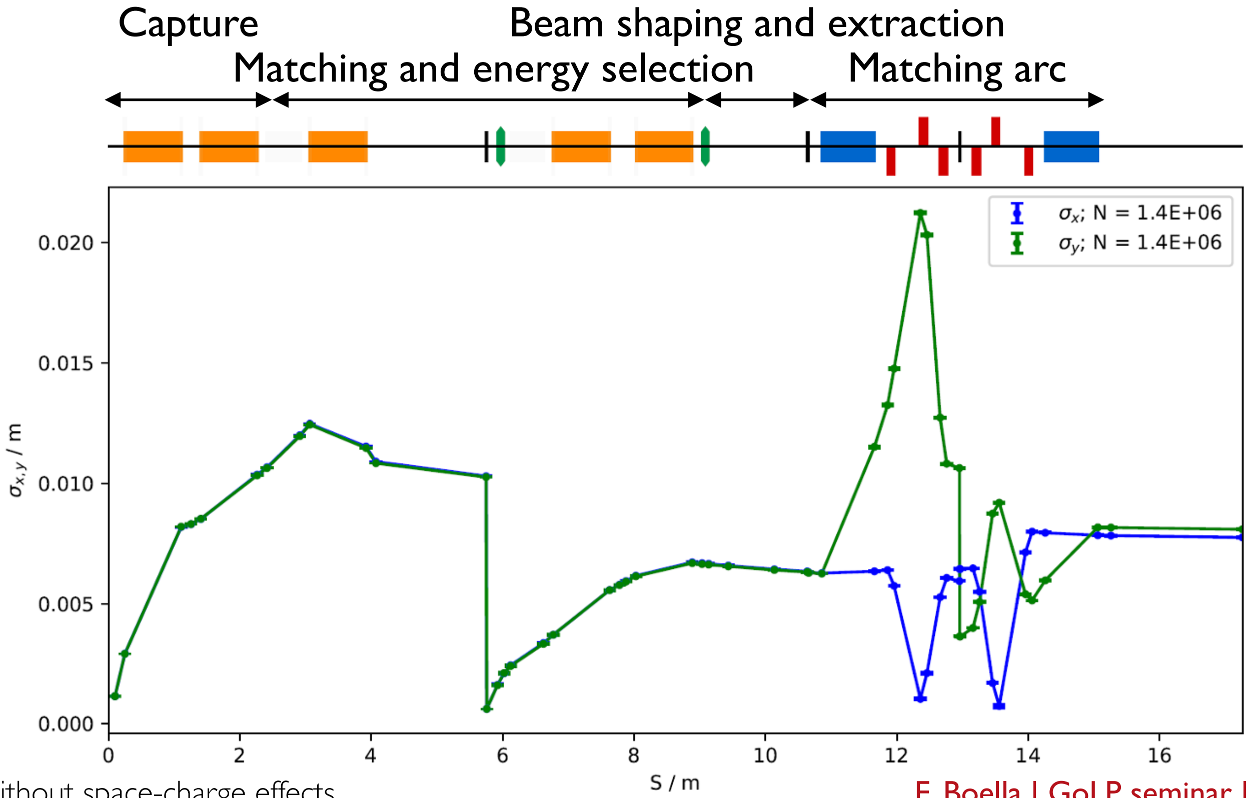




Simulations performed with GPT including space-charge effects

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

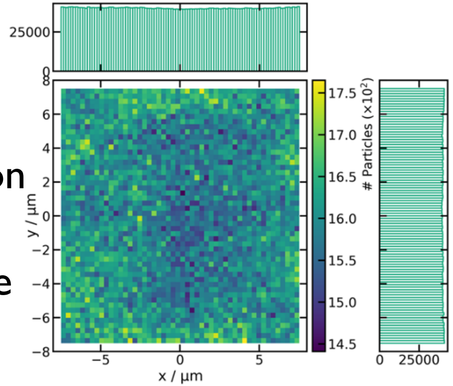
- Gabor lens
- RF cavity
- Octupole
- Collimator
- Dipole
- Quadrupole

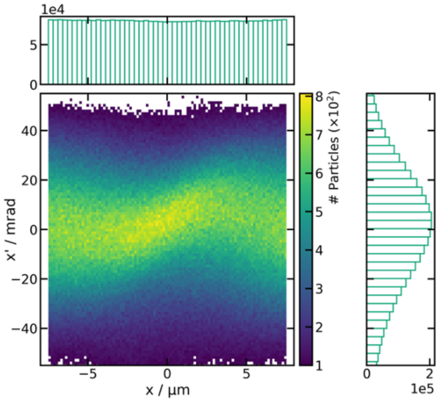


Simulations performed with BDSIM without space-charge effects

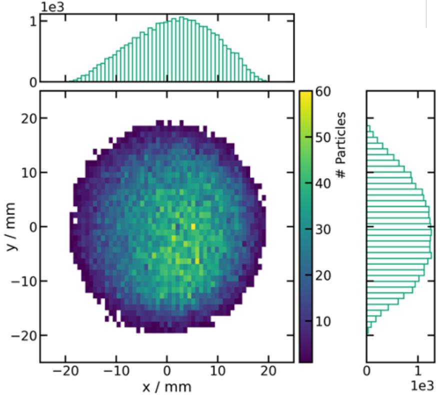
At the end of the line, proton beam is circular and very collimated

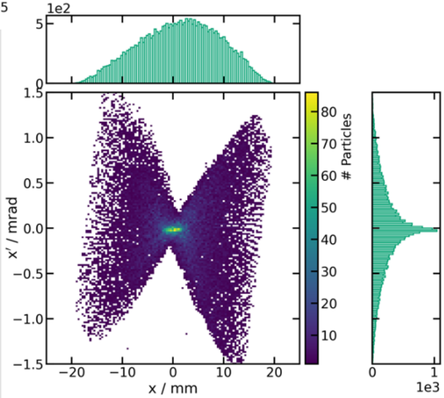
Ion beam spatial distribution and divergence @source



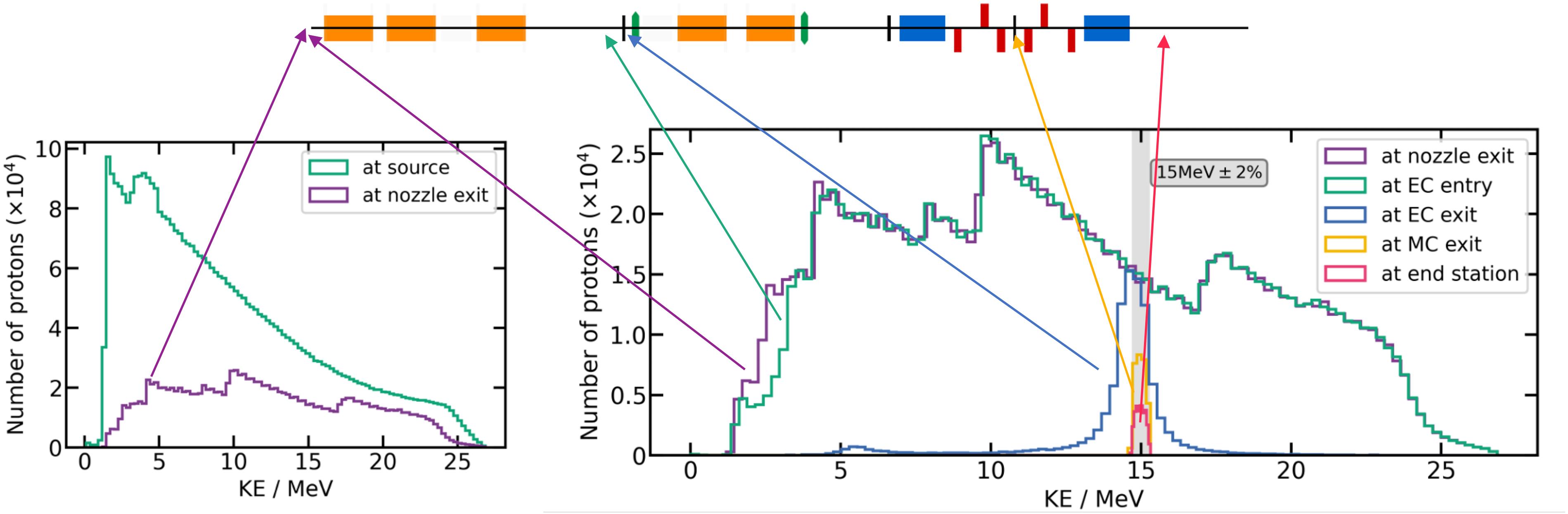


Ion beam spatial distribution and divergence @end station





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



LhARA will allow for exploring ion therapy in the FLASH regime and ion therapy with mini beams

	12 MeV protons	15 MeV protons	127 MeV protons	33.4 MeV/u carbon
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	1.0 x 10^9 Gy/s	1.8 x 10^9 Gy/s	3.8 x 10^8 Gy/s	9.7 x 10^8 Gy/s
Average dose rate	71 Gy/s	128 Gy/s	156 Gy/s	730 Gy/s

Conventional therapy: ~ 2 Gy/min
Flash regime: > 40 Gy/s

Conventional therapy: > 1 cm diameter
Mini beams: < 1 mm diameter

Summary

Experimental data show that the proton cutoff energy can be highly enhanced by a micrometer-size scale-length pre-plasma, provided that the pre-plasma is generated in a controllable way.

Simulations indicate that the proton energy enhancement is due to a better laser-to-hot electron conversion efficiency, which is enabled by the complex laser dynamics in the long plasma gradient.

3D PIC simulations results are in excellent agreement with experimental data.

LhARA will provide a flexible facility that will overcome the dose-rate limitations of present proton and ion beam therapy sources, thus enabling radiobiological studies in new regimes.

Laser contrast is higher than 10^{-6}