Numerical study of proton beam transport through space-charge lens

Titus-Stefan Dascalu

Department of Physics, Imperial College London

1. Introduction

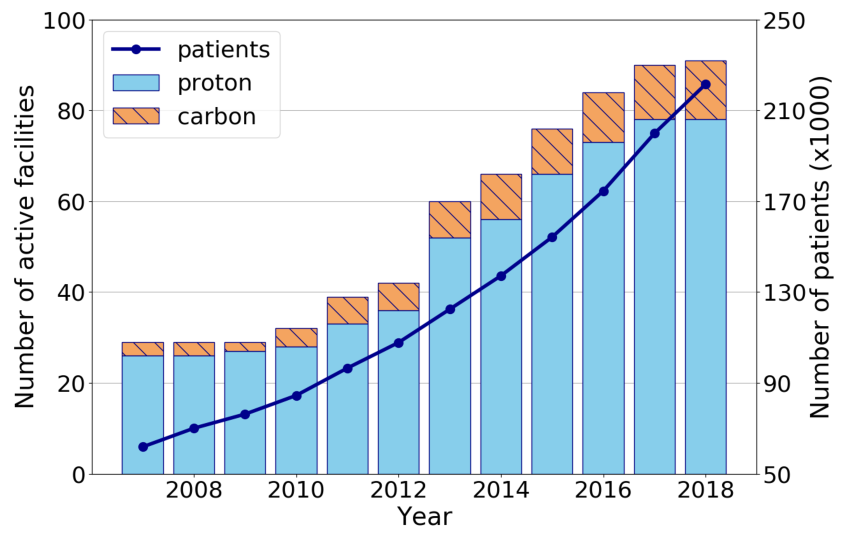

Fig. 1: Patients treated in particle therapy facilities worldwide [4].

- More than 50% of cancer patients receive **radiation therapy (RT)** at some stage of their treatment.
- Proton-beam therapy (PBT) facilities in operation worldwide are located predominantly in **high-income countries**.
- Nearly 70% of cancer patients globally do not have **access to RT** [2].
- The challenge is to develop PBT machines that are **smaller, cheaper and more flexible** in their use.
- Need for **systematic studies of the interaction** between ion beams and cancer cells to **develop better treatments.**

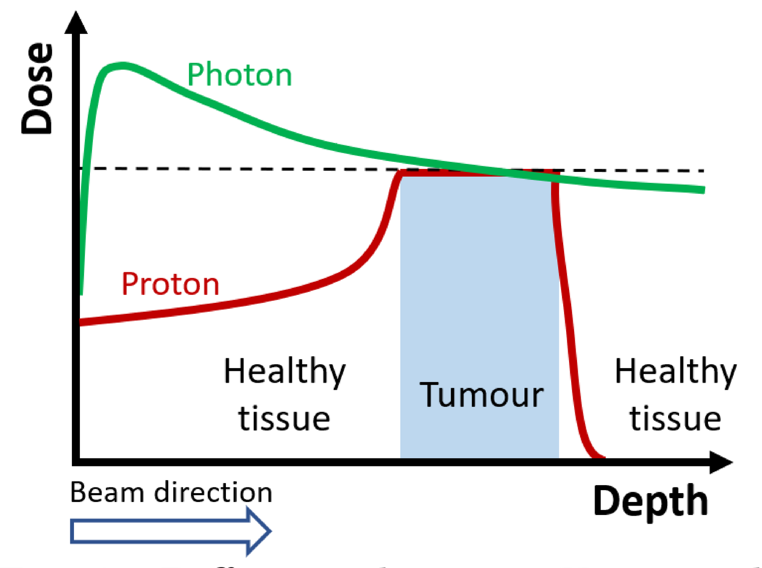

Fig. 2: Difference between X-ray and proton beam therapy (PBT).

2. LhARA

- LhARA aims to develop and demonstrate the technologies required to deliver PBT in a new regimen:
  - **multiple ion species** in a single treatment fraction
  - **ultra-high dose rates**
  - a variety of time structures, spectral distributions, and spatial configuration

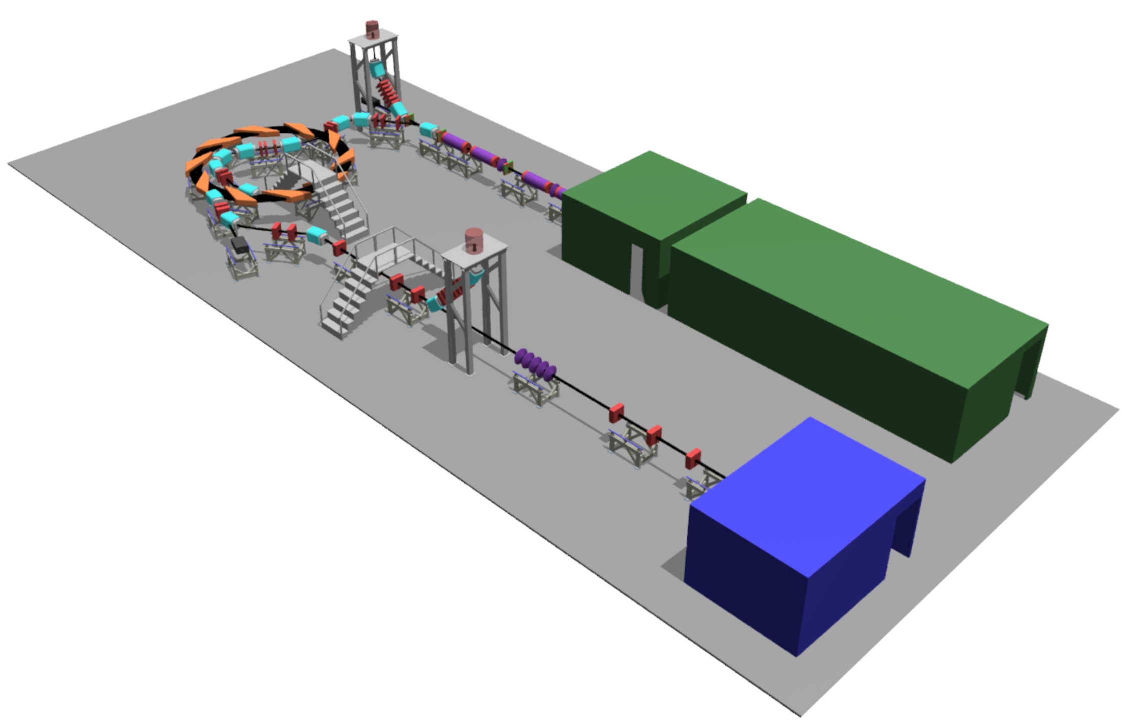

Fig. 3: The LhARA facility concept [1] - a novel, flexible facility dedicated to the study of radiobiology.

- Strong-focusing Gabor lenses **capture** the protons and ions.
- Particles captured at energies significantly above those that pertain in conventional facilities.
- Evade the limits on the instantaneous dose rates.

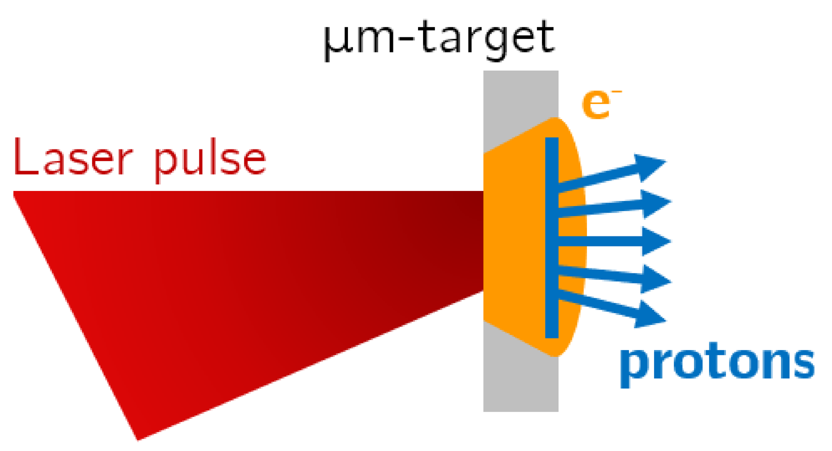

Fig. 4: A high-power pulsed laser drives the creation of a large flux of protons or light ions.

3. Gabor lens

- Proton beams can be focused by an electron cloud.
- Higher focusing strength for higher plasma density.
- Compared to the more expensive alternative of a solenoid, a Gabor lens uses a greatly reduced magnetic field.

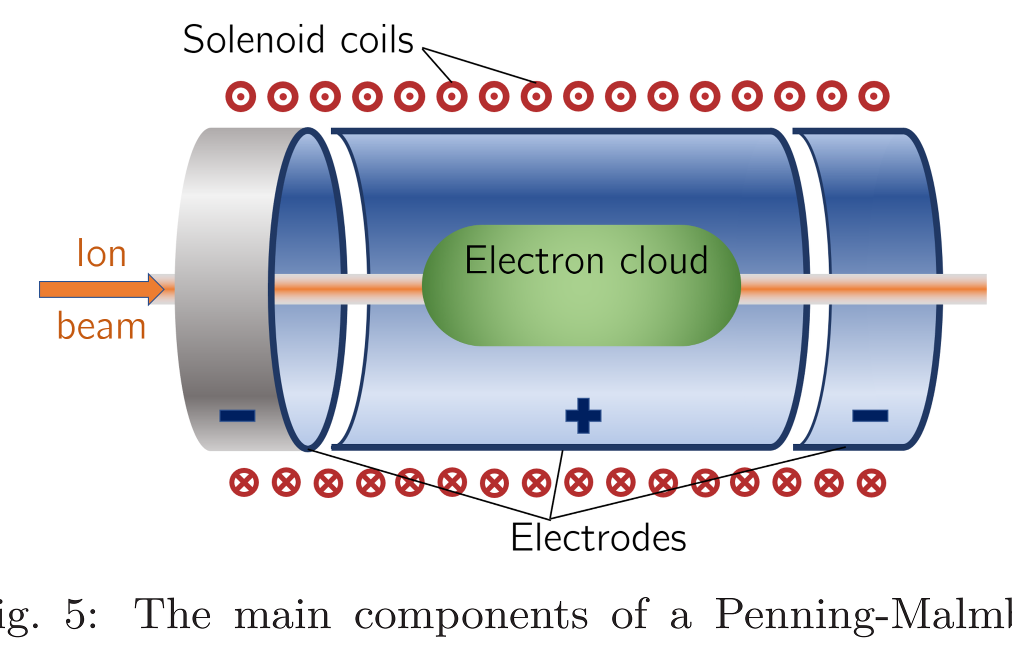

Fig. 5: The main components of a Penning-Malmberg trap proposed for use in the Gabor lens for LhARA.

4. Numerical studies

The Gabor lens must be filled with an electron cloud of constant density to **avoid instabilities**.

- In practice, plasma instabilities disrupt the ion beams that travels through the lens.
- The plasma, and 6 beamlets affected by instabilities were modelled in a 3D particle-in-cell code [5].

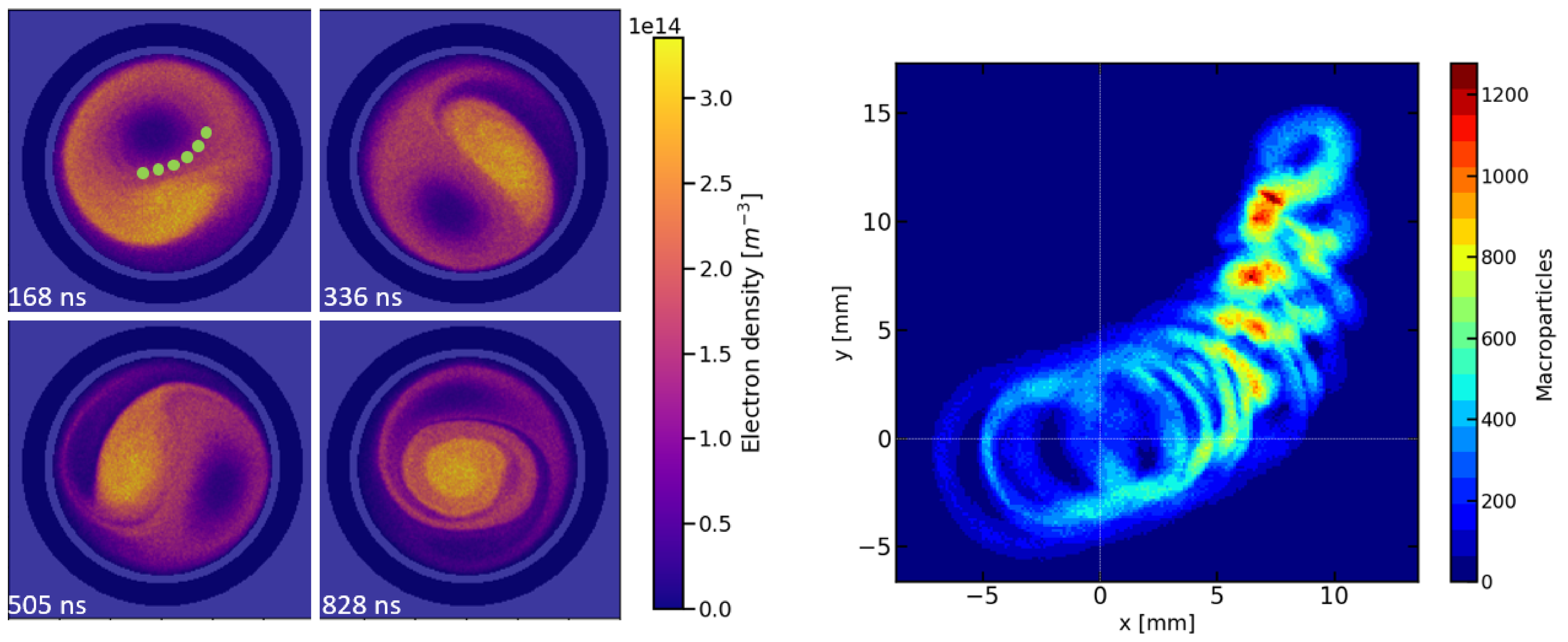

Fig. 6: (Left) Time evolution of a plasma instability with dipole structure as simulated with VSim [5]. The green spots show the entry position of six beamlets that travel through the instability. (Right) The corresponding intensity distribution of the six beamlets at the exit plane of the lens.

- Instability driven by two regions of high and low electron density.
- Instability diminishes gradually on a time scale of 1 μs.
- Possible driving mechanism: electrons streaming out of the end electrodes.
- Dipole structure rotates around beam-axis.
- Narrow beam focused in a ring-like pattern that has also been **observed experimentally**.

5. Data vs. simulation

Alternative method: electron cloud modelled as simplified time-dependent charge distribution.

- **Ring spots** produced by instabilities with:
  - **rotation of the plasma** column
  - electron density with **negative radial gradient**
  - **non-zero offset** between the centroid of the plasma column and the beam axis.
- **High similarity** to images from experiment of proton beam transport through a prototype of the Gabor lens.

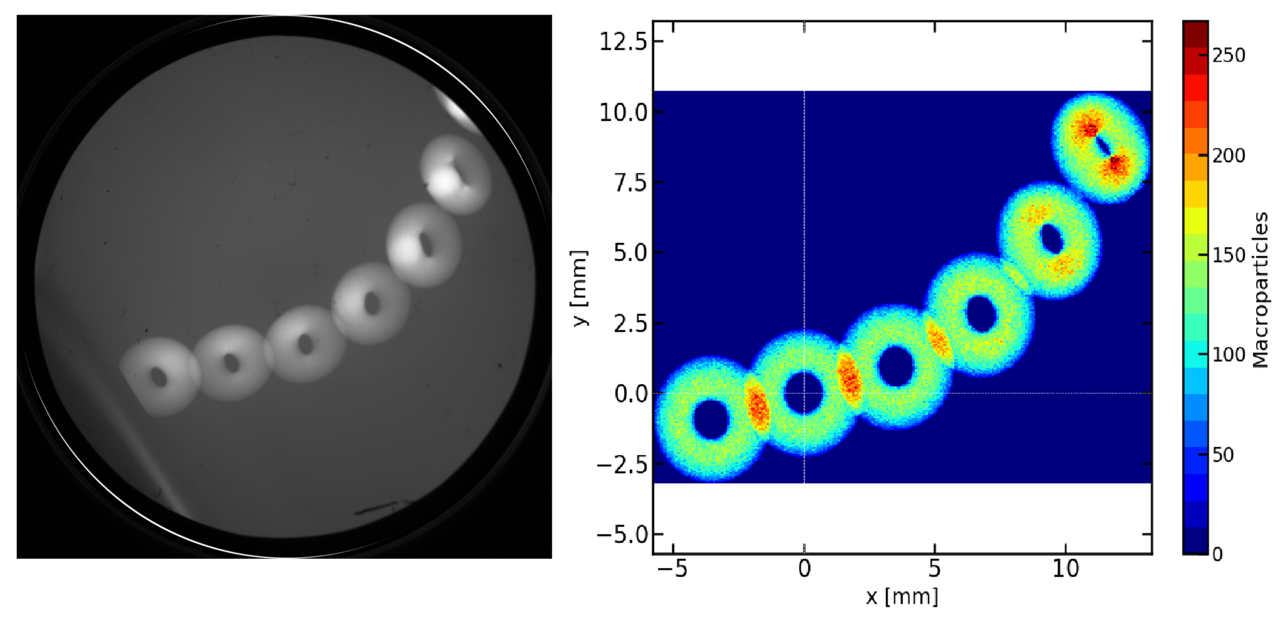

Fig. 7: (Left) Camera image of the six beam spots on a screen downstream of the lens. (Right) Number of macroparticles hitting the screen for an idealised rotating electron plasma as simulated using BDSIM [3].

6. Conclusions

- The stability of the Gabor lens is being studied with a particle-in-cell (PIC) code.
- Several instabilities occurred in the simulations, all being driven by the initial electron cloud distribution.
- The effect of the instabilities on an ion beam is being studied with both a PIC and a particle tracking code.
- Qualitative agreement between simulation and experiment allows for an estimation of the plasma density and a characterisation of the corresponding instability.

7. References

[1] G. Aymar et al. LhARA: The Laser-hybrid Accelerator for Radiobiological Applications. *Frontiers in Physics*, 8:432, 2020.
[2] N. R. Datta et al. Challenges and Opportunities to Realize "The 2030 Agenda for Sustainable Development" by the United Nations. *Int. J. Radiat. Oncol., Biology, Physics*, (5):918–933, dec.
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[4] PTCOG. Particle Therapy Co-Operative Group, 2020.
[5] TECH-X. Vsim for plasma, 2020. https://www.txcorp.com/vsim.