Numerical study of proton beam transport through space-charge lens

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1. Introduction

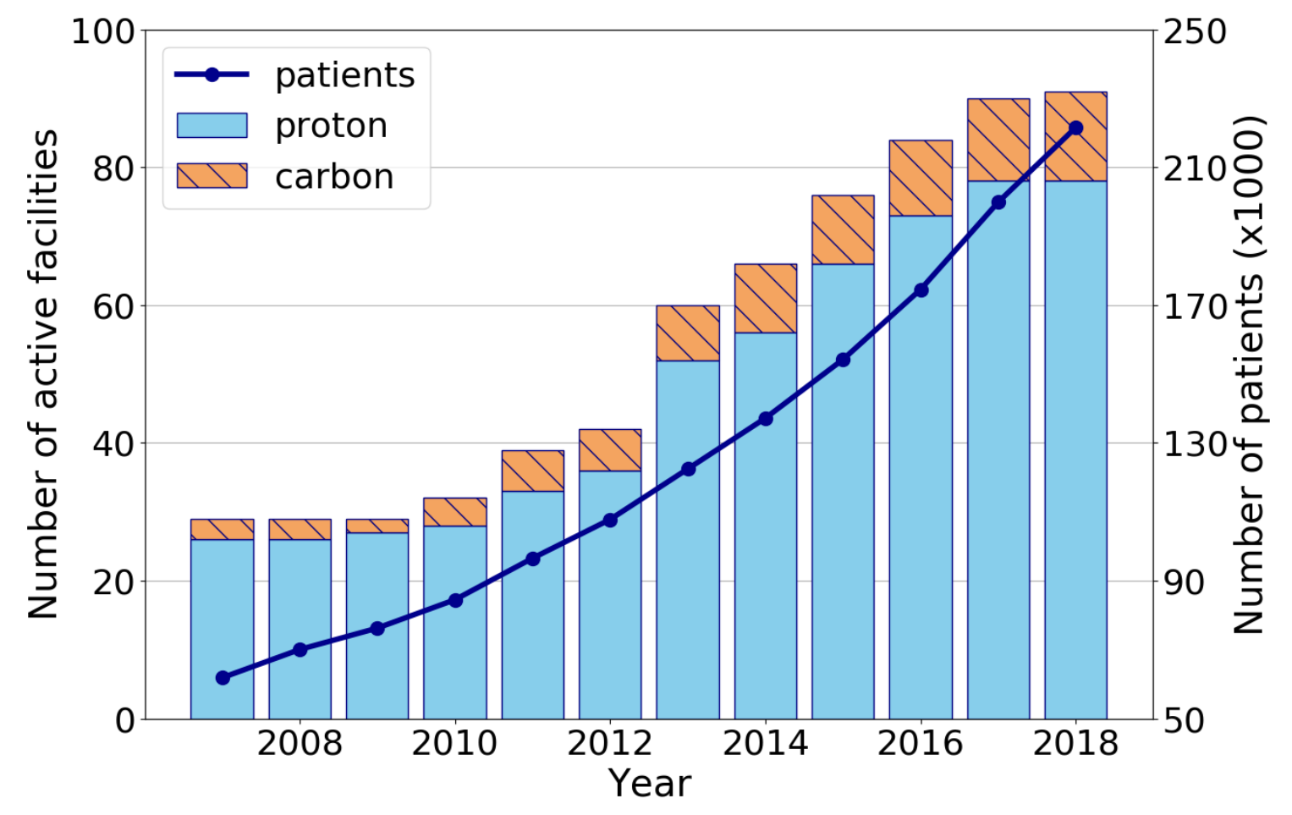

Fig. 1: Statistics of patients treated in particle therapy facilities worldwide - data adapted from [4].

More than 50% of cancer patients receive radiation therapy (RT) during one stage of their treatment. While, most frequently, the patients are treated today using photon or electron beams, proton and ion-beam therapy (PBT) offers substantial advantages due to the ability of heavier particles to spare the healthy tissue around tumours. Even though the number of PBT facilities in operation worldwide has increased in the last 20 years, these are located predominantly in high-income countries. Thus, 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.

Scientifically, there is also a need for systematic studies of the radiobiological interaction between ion beams and cancer cells to develop better treatments. Some therapeutic benefit may come from the delivery of RT at very high dose rates ("FLASH" regime) and spatially dividing the dose as a group of micro-beams.

2. LhARA

The "Laser-hybrid Accelerator for Radiobiological Studies" is conceived as a novel, flexible facility dedicated to the study of radiobiology. LhARA aims to develop and demonstrate the technologies required to deliver PBT in a new regimen by combining multiple ion species in a single treatment fraction with ultra-high dose rates and under a variety of time structures, spectral distributions, and spatial configurations.

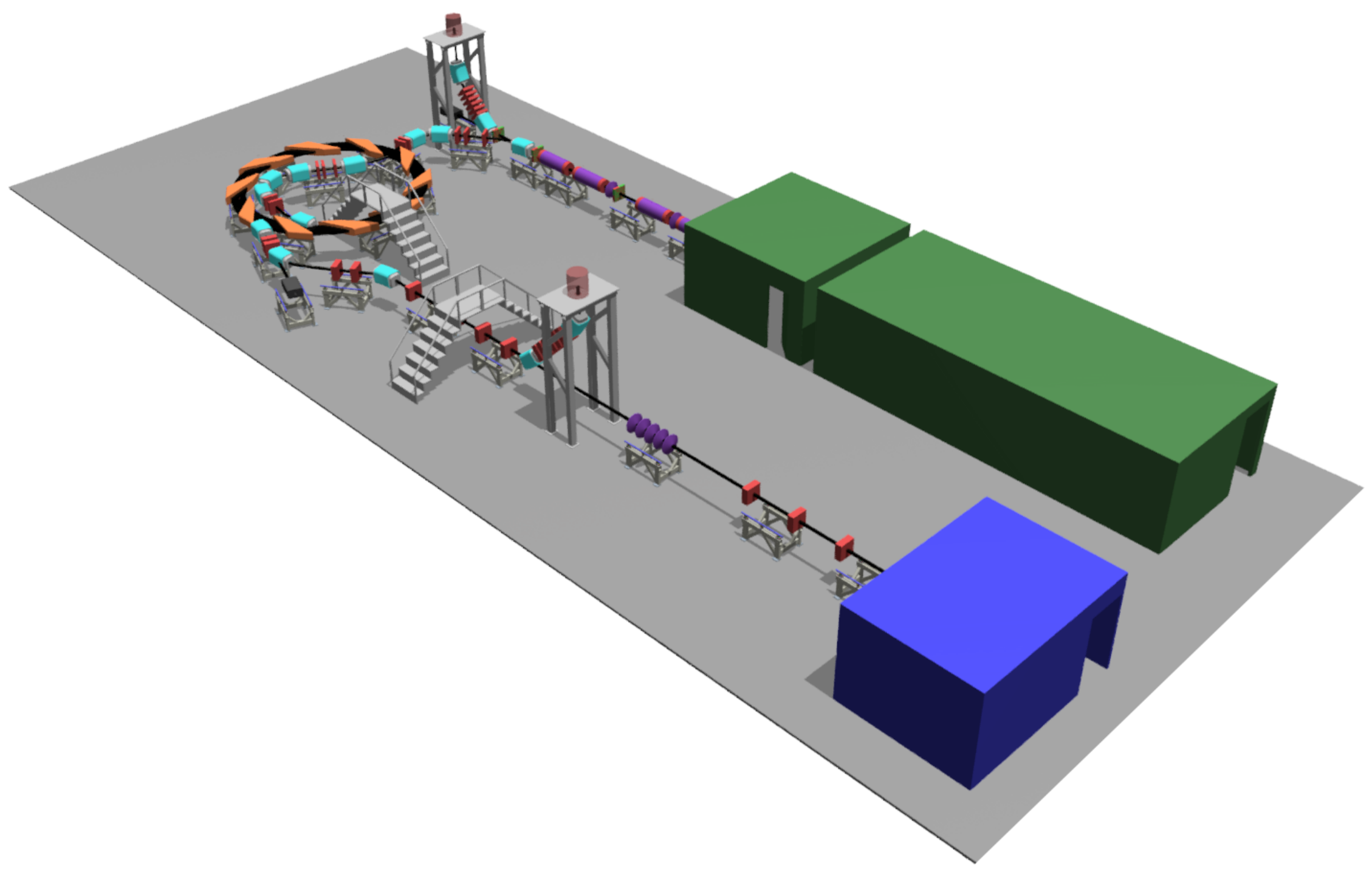

Fig. 2: The LhARA facility [1].

- The hybrid approach is based on a high-power pulsed laser to drive the creation of a large flux of protons and light ions that are captured and focused by electron-plasma (Gabor) lenses. The laser-driven source together with the strong-focusing lenses allow protons and ions to be captured at energies significantly above those prevalent in conventional facilities, thus evading the limits on the instantaneous dose rates that can be delivered.
- Further acceleration is provided by a fixed-field alternating-gradient accelerator (FFA) which preserves the unique time and energy flexibility of the beam as enabled by the source.

3. Gabor lens

- Charged-particle beams can be focused with the use of an electron cloud. The electrons are confined longitudinally by a system of electrodes and radially by an uniform magnetic field.
- The focusing strength of the lens depends on the density of the confined plasma. Compared to the more expensive alternative of a solenoid, equivalent focusing can be obtained with a Gabor lens for a magnetic field greatly reduced.

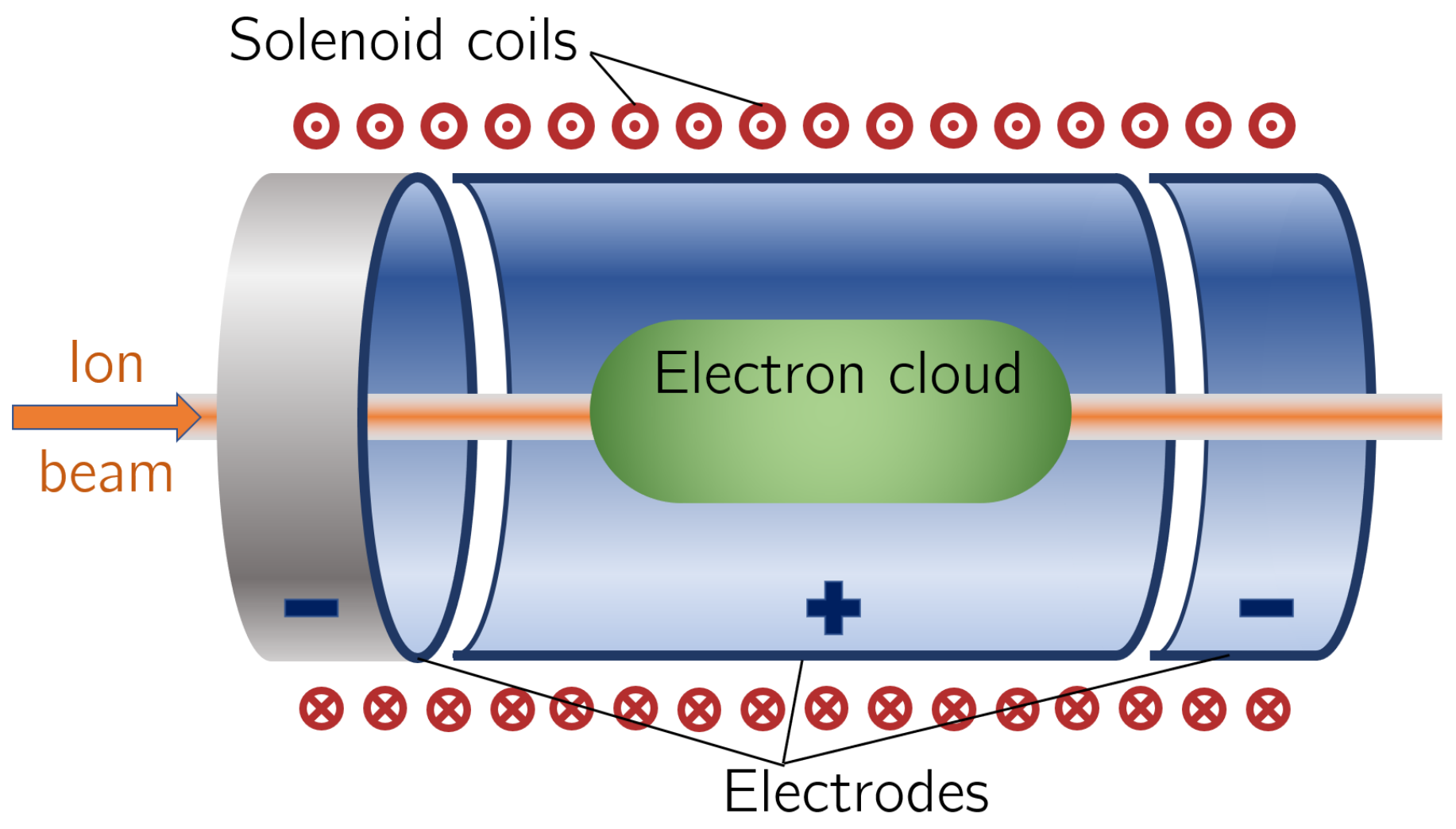

Fig. 3: The main components of a Penning-Malmberg trap proposed for use in the Gabor lens for LhARA. The longitudinal magnetic field is produced by the solenoid coils. A central cylindrical anode and two cylindrical negative end electrodes produce the confining electrostatic potential.

4. Numerical studies

The main challenge in the experimental operation of a Gabor lens is to find a regime free from plasma instabilities. In the ideal operation regime, the lens needs to be filled with an electron cloud of constant density. However, in practice, various plasma instabilities have been observed to significantly disrupt the ion beam which travels through the lens. To investigate the stability of the lens, a 3D particle-in-cell code [5] was used to model the dynamics of the plasma under various electrode configurations and magnetic fields, as well as initial electron distributions. The same code also allowed the study of six beamlets which travel through the lens during various instabilities.

One example of a disruptive plasma instability involves the rotation of the plasma column around the central axis of the lens. This instability was observed in simulations to be driven by a dipolar electron distribution: two regions of high and low electron density respectively. While the instability was seen to gradually diminish on a time scale of $1\,\mu s$, in practice, it can be driven by electrons streaming out of the surface of the end electrodes. Such an instability is of particular interest due to the effect it has on a proton beam passing through the lens. The dipole symmetry and the rotation of the plasma causes a narrow beam to be focused on a ring-like pattern that has also been observed experimentally.

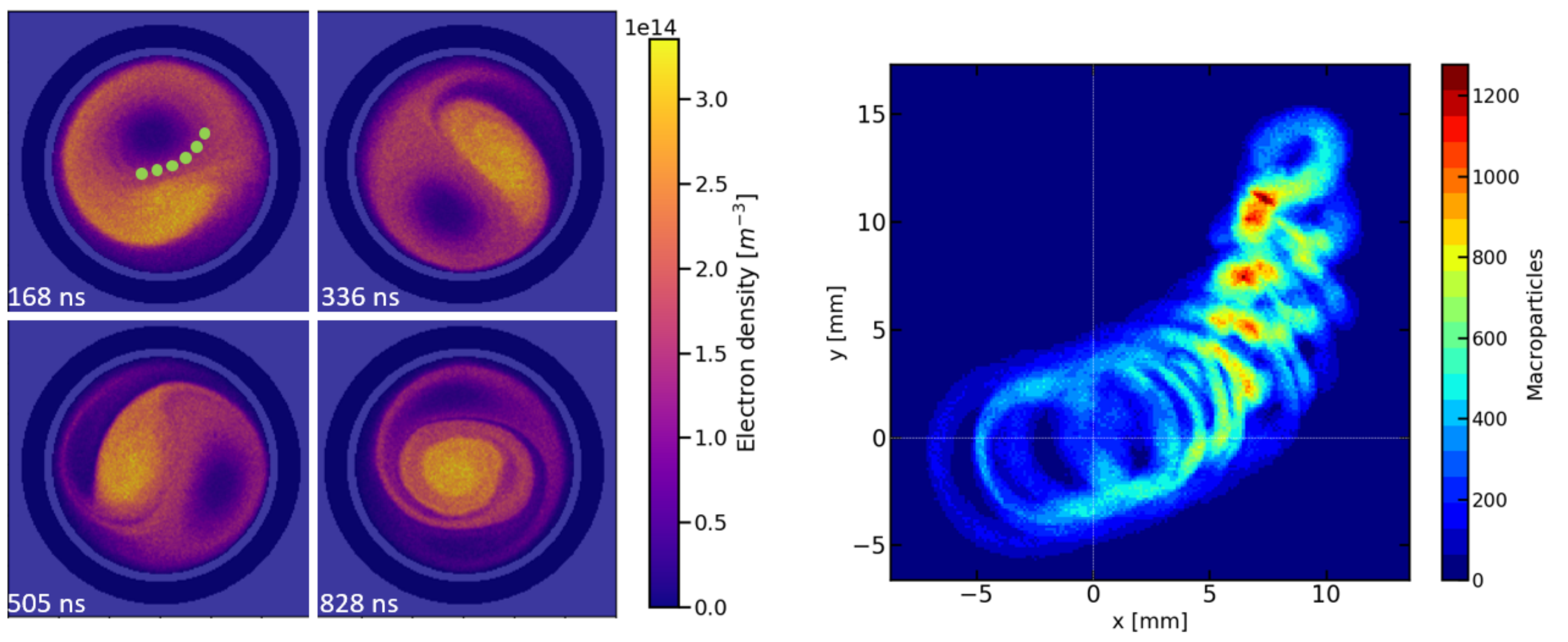

Fig. 4: (Left) Time evolution of the plasma for an instability with dipole structure as simulated with VSim [5]. The averaged electron density is shown in transverse cross-section inside the central anode of the Gabor lens at four time-stamps. The green spots show the entry position of six beamlets that travel through the lens during the instability. (Right) The corresponding intensity distribution of the six beamlets at the exit plane of the lens shown as the number of macroparticles that hit a screen as simulated with VSim [5].

5. Data vs. simulation

An alternative method to study the dynamics of the plasma inside the Gabor lens was to model the electron cloud using simplified time-dependent charge distributions. Then, a particle tracking code [3] was used to simulate the effect of the instabilities on a proton beam.

- Ring-like patterns were seen to be produced by instabilities with the following common characteristics: rotation of the plasma around the central axis of the lens, negative radial gradient of the electron density, non-zero offset between the centroid of the plasma column and the beam axis.
- By tuning the parameters of the plasma, simulations yielded ring-like beam distributions. The patterns are highly similar to images obtained during experiments of proton beam transport through a prototype of the Gabor lens.

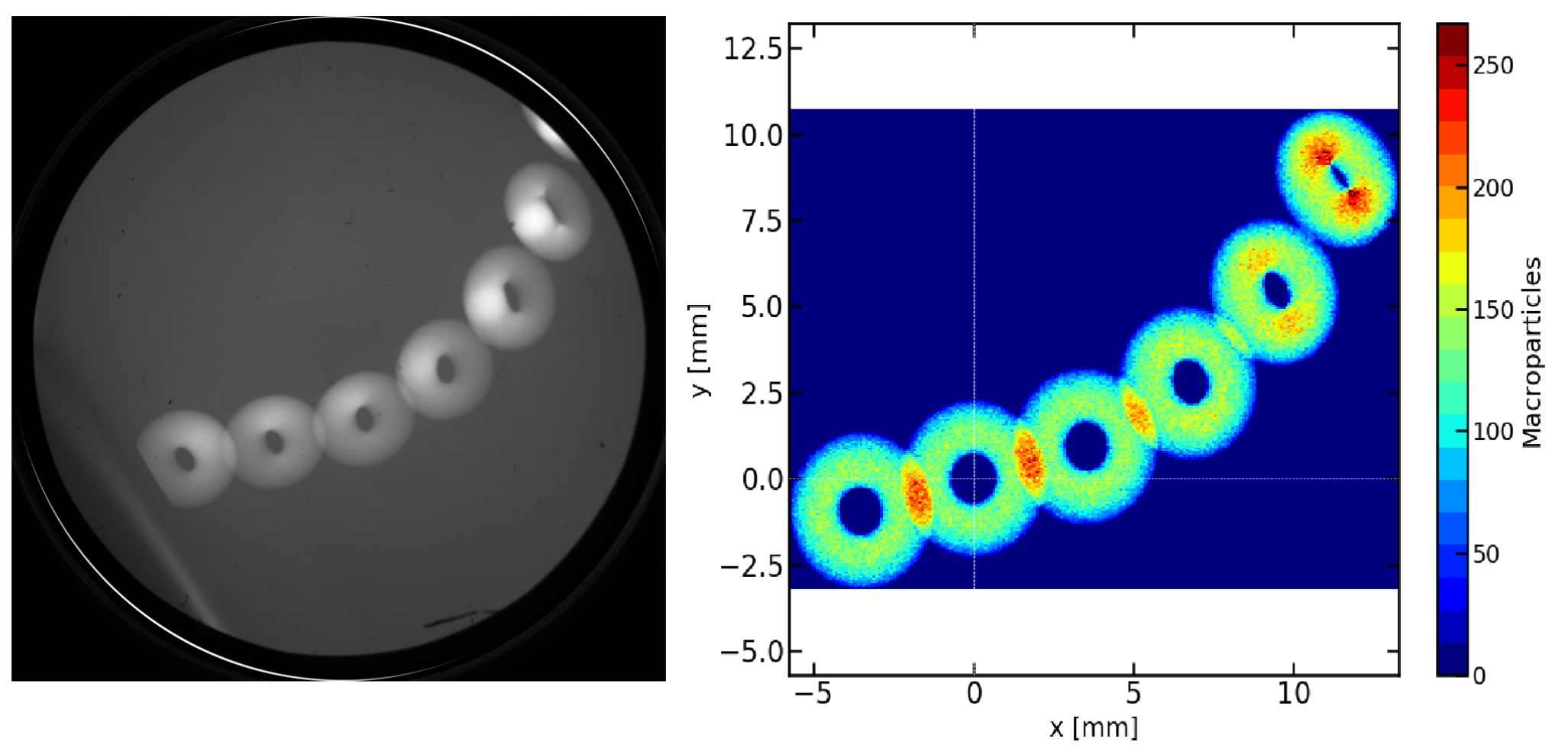

Fig. 5: (Left) Camera image of the six beam spots on a phosphor screen at 67cm downstream of the Gabor lens. (Right) Number of macroparticles hitting the phosphor screen for an idealised rotating electron plasma inside the lens. The particles were tracked using BDSIM [3].

6. Conclusions

- The stability of the Gabor lens is being studied with a particle-in-cell (PIC) code
- Simulations have shown several types of instabilities to appear in the lens, 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
- Comparison between simulation and experiment shows qualitative agreement that allows for an estimation of the electron density and a characterisation of the corresponding plasma instability

7. References

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