Focusing MeV/c Electron-Positron Pair Beams to Enhance Pair Plasma Instabilities

EPS Plasma Physics Conference, Edinburgh – 03/07/2026

V. Stergiou – University of Oxford / CERN

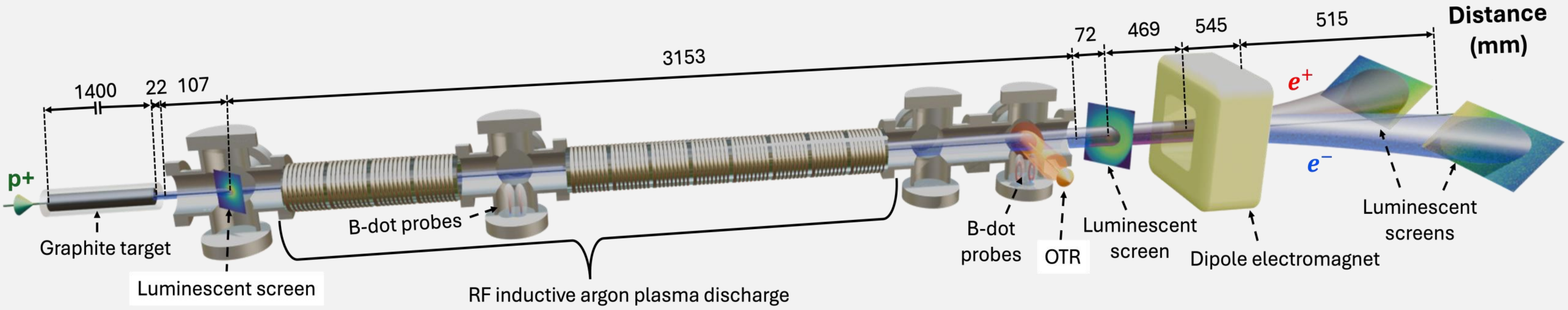
This work is supported in parts by UKRI under grants no. EP/Y035038/1 (converted from ERC Advanced Grant), ST/W000903/1 and MR/W006723/1.

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511 (EURO-LABS)

Collaboration

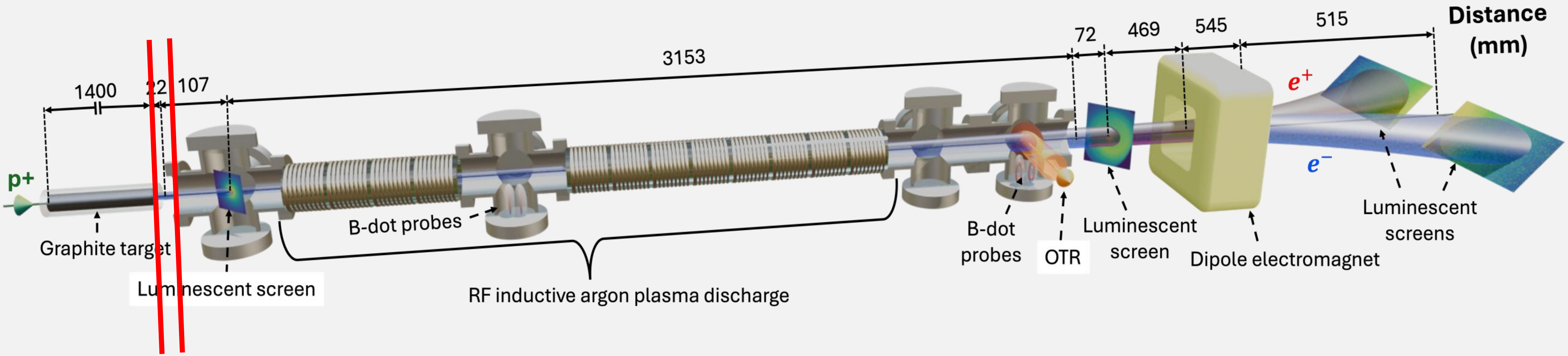
V. Stergiou, P. Alexaki, C. D. Arrowsmith, C. Arran, P. J. Bilbao, R. Bingham, M. Bochmann, A. F. A. Bott, S. Burger, M. Capitani, N. Charitonidis, H. Chen, F. D. Cruz, D. Cusick, T. Davenne, A. Dyson, A. Ebn Rahmoun, I. Efthymiopoulos, D. H. Froula, A. Goillot, G. Gregori, J. T. Gudmundsson, D. Haberberger, J. W. D. Halliday, T. Hodge, B. T. Huffman, S. Iaquinta, B. Lloyd, E. E. Los, G. Marshall, F. Miniati, M. Mudra, S. Parker, H. Ramm, B. Reville, C. P. Ridgers, P. Rousiadou, S. Sarkar, A. A. Schekochihin, K.-G. Schlesinger, P. Simon, R. Simpson, L. O. Silva, T. Silva, E. Soria, S. Steinert, A. G. R. Thomas, R. M. G. M. Trines, V. Tsouknida, T. Vieu, L. Willingdale, S. Zhang

Fireball Platform - Layout



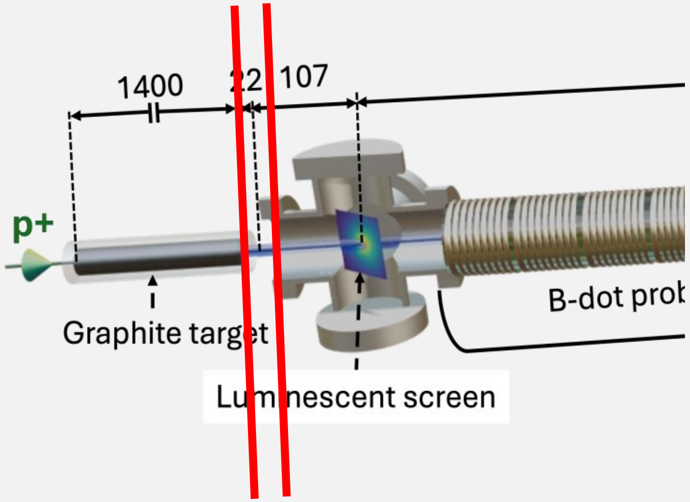
see also E. E. Los' talk – earlier in this session

Fireball Platform - Layout



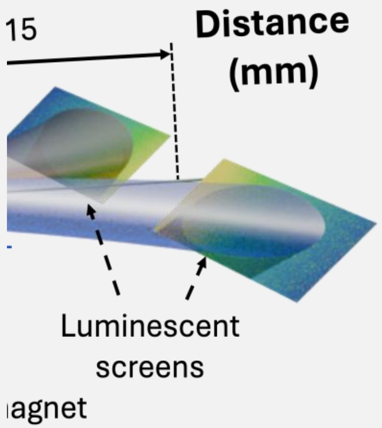
Quadrupoles!

Fireball Platform - Layout



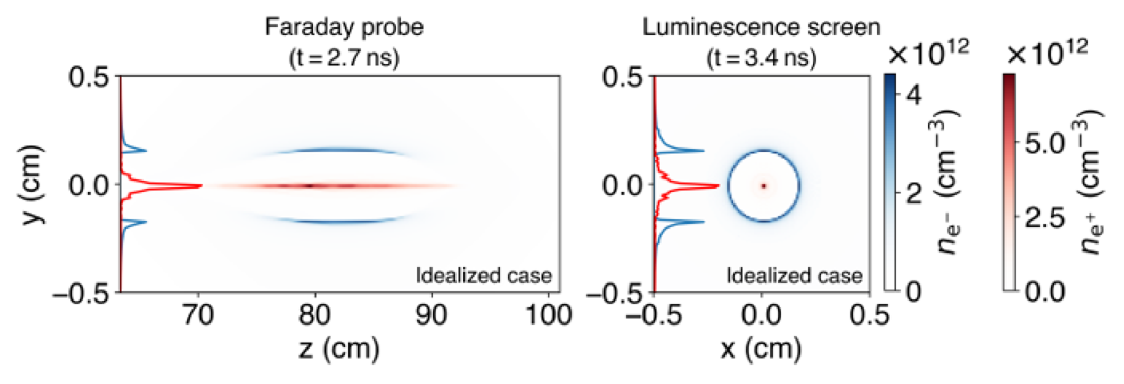
Quadrupoles!

Beam

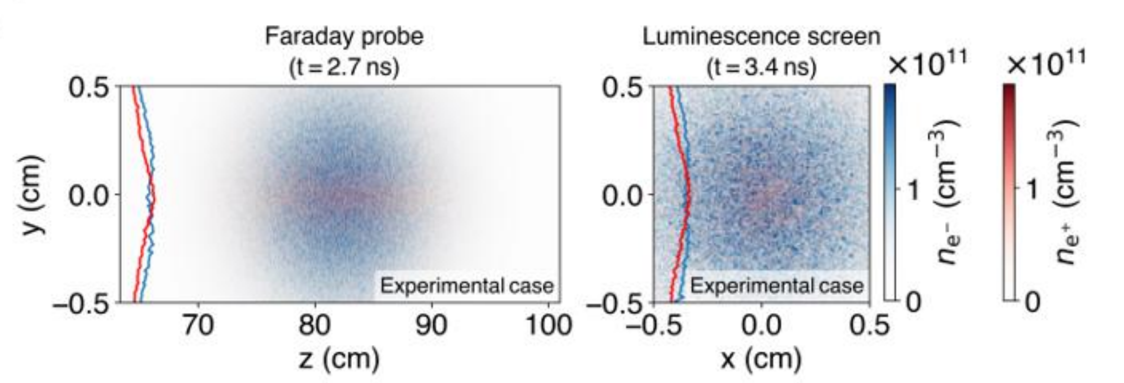


Why divergence matters?

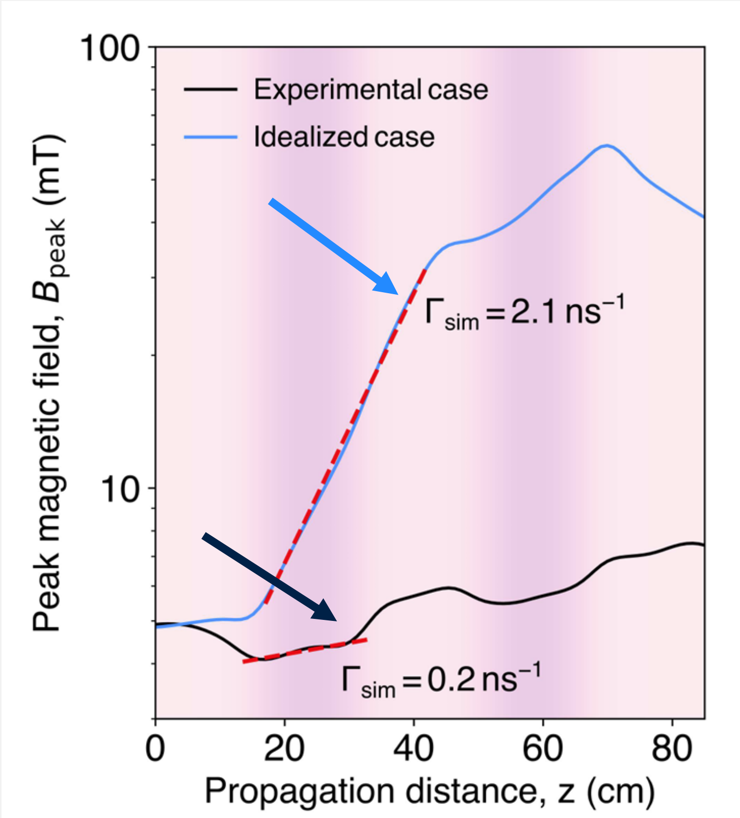
Results from PIC simulations.
Top: Idealized conditions, **collimated and monoenergetic beam**.



Bottom: Realistic experimental conditions.



Stronger charge separation leads to emergence of stronger magnetic fields



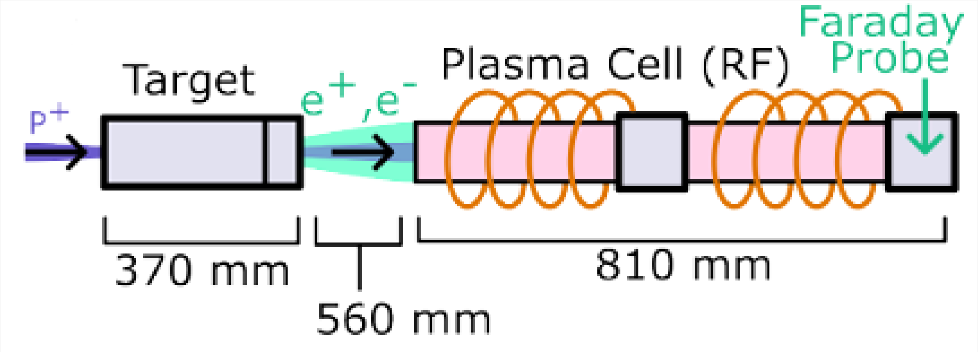
See also P. Bilbao's talk – Tuesday's session

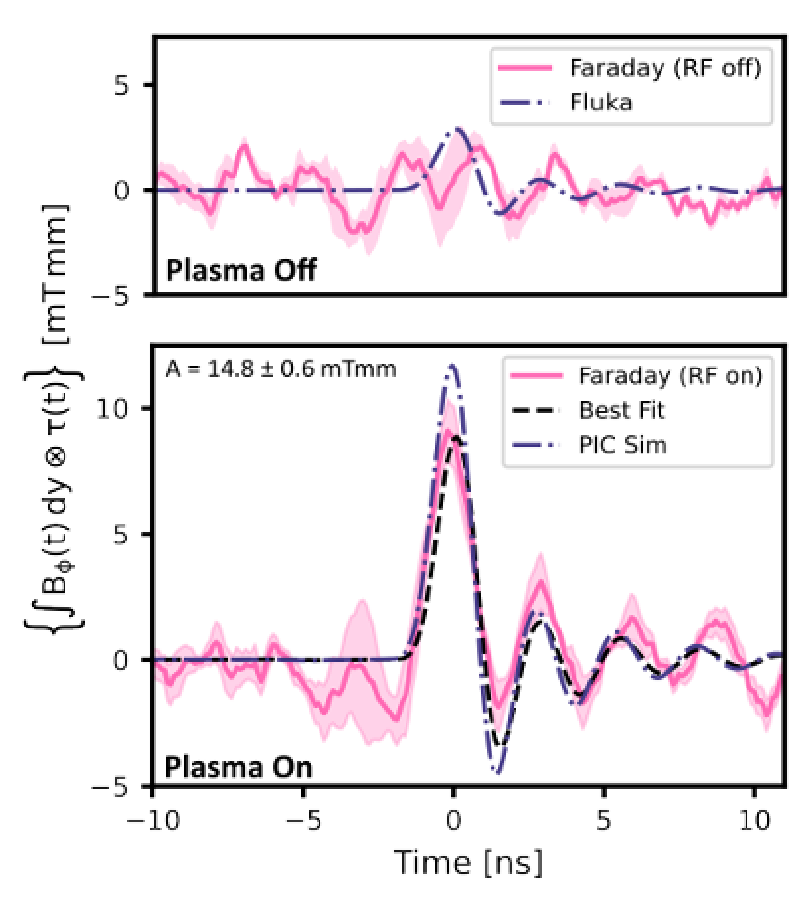
Source: C.D. Arrowsmith, **Suppression of pair beam instabilities in a laboratory analogue of blazar pair cascades**, *Proc. Natl. Acad. Sci.U.S.A.* 122 (45) https://doi.org/10.1073/pnas.2513365122 (2025).

Magnetic field measurements

What did we measure:

- **Beam through gas (*plasma off*)**: no signal above noise level
- **Beam through plasma**: **clear signal peak** is observed, **in agreement with PIC (Particle-In-Cell) simulation results for the actual experimental conditions**





See also J. Halliday's talk – Thursday's session

Source: J. W. D. Halliday, **Laboratory observation of collective beam-plasma instabilities in a relativistic pair jet,** https://doi.org/10.48550/arXiv.2602.16542 (2026).

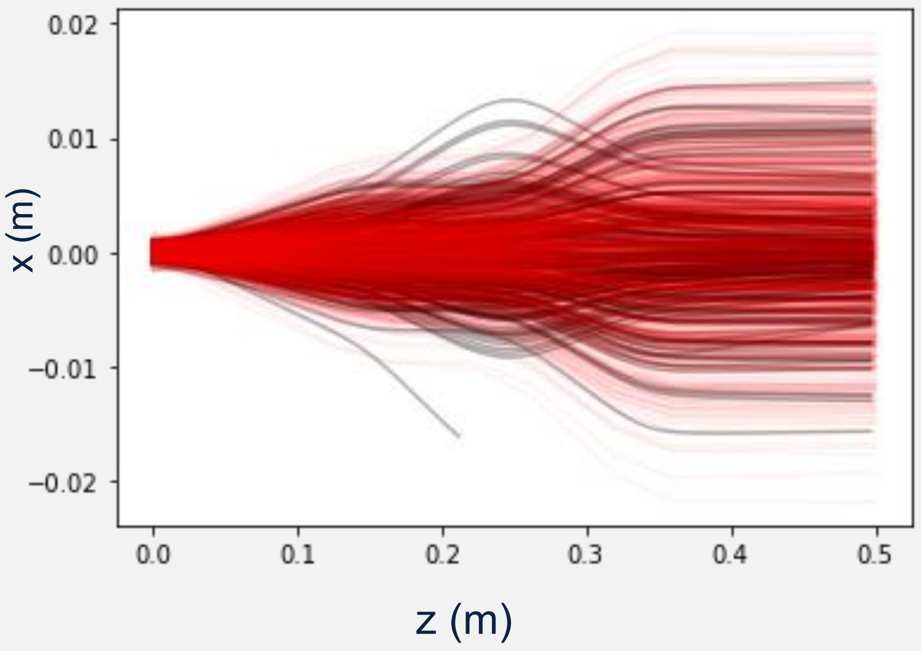
Why quadrupoles ?

- We wanted a simple and layout-effective solution
- Idea: simplified Halbach array quadrupoles*
- Layout optimized using MagPy and COMSOL for a central beam energy
  - Optimisation result for 50 MeV pairs: g ~ 50 T/m, apertures ~ 1 in, L ~ 1-2 in

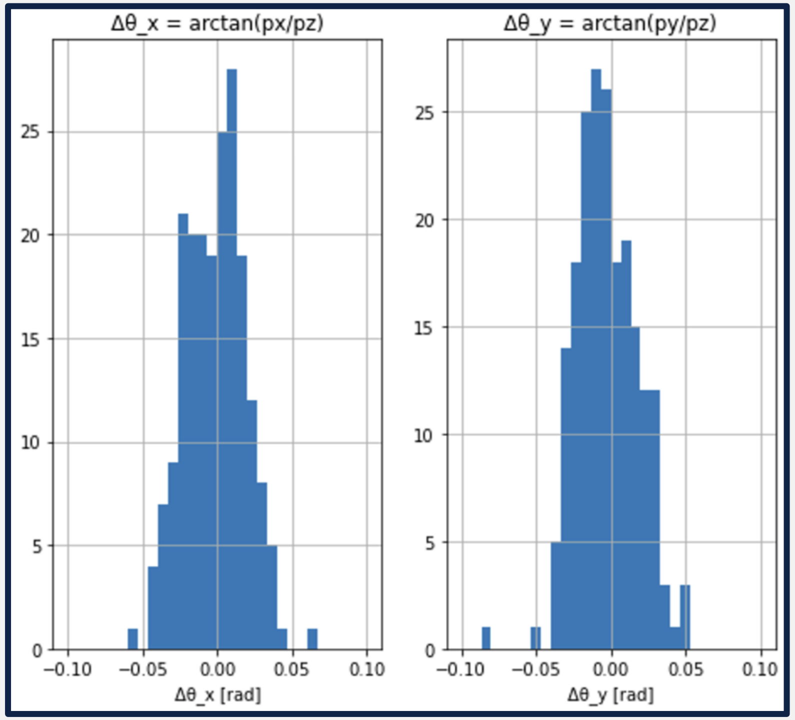
* K. Halbach, https://doi.org/10.1016/0029-554X(80)90094-4

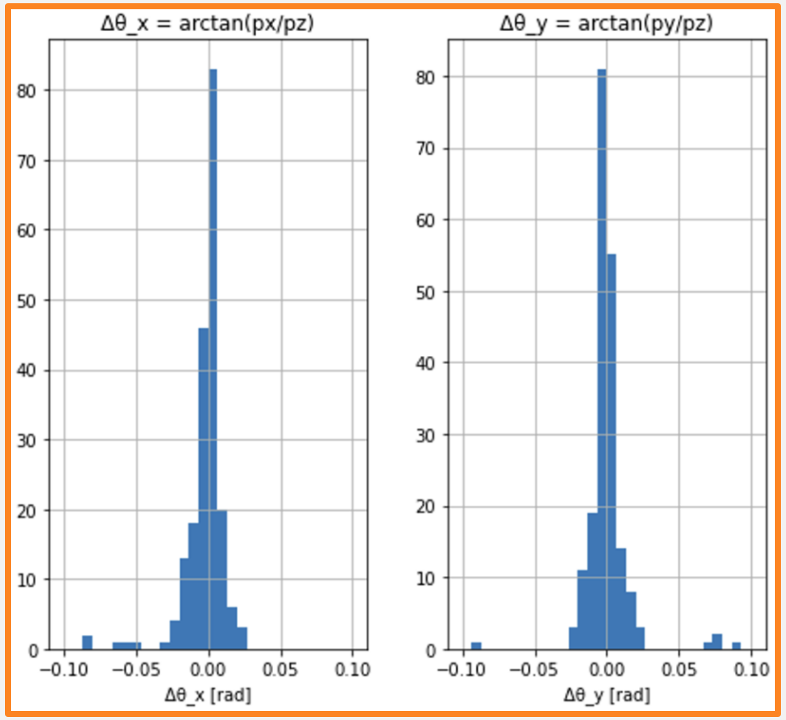
Quadrupole studies – Python/MagPy

Particle trajectories



Angular spread (mrad)

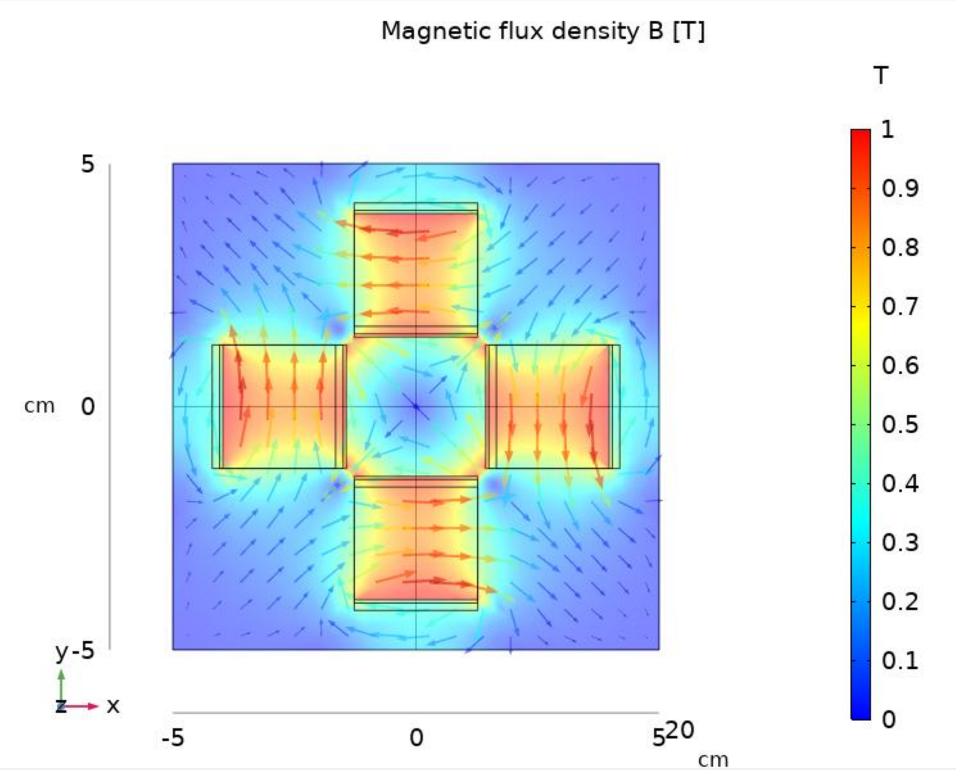


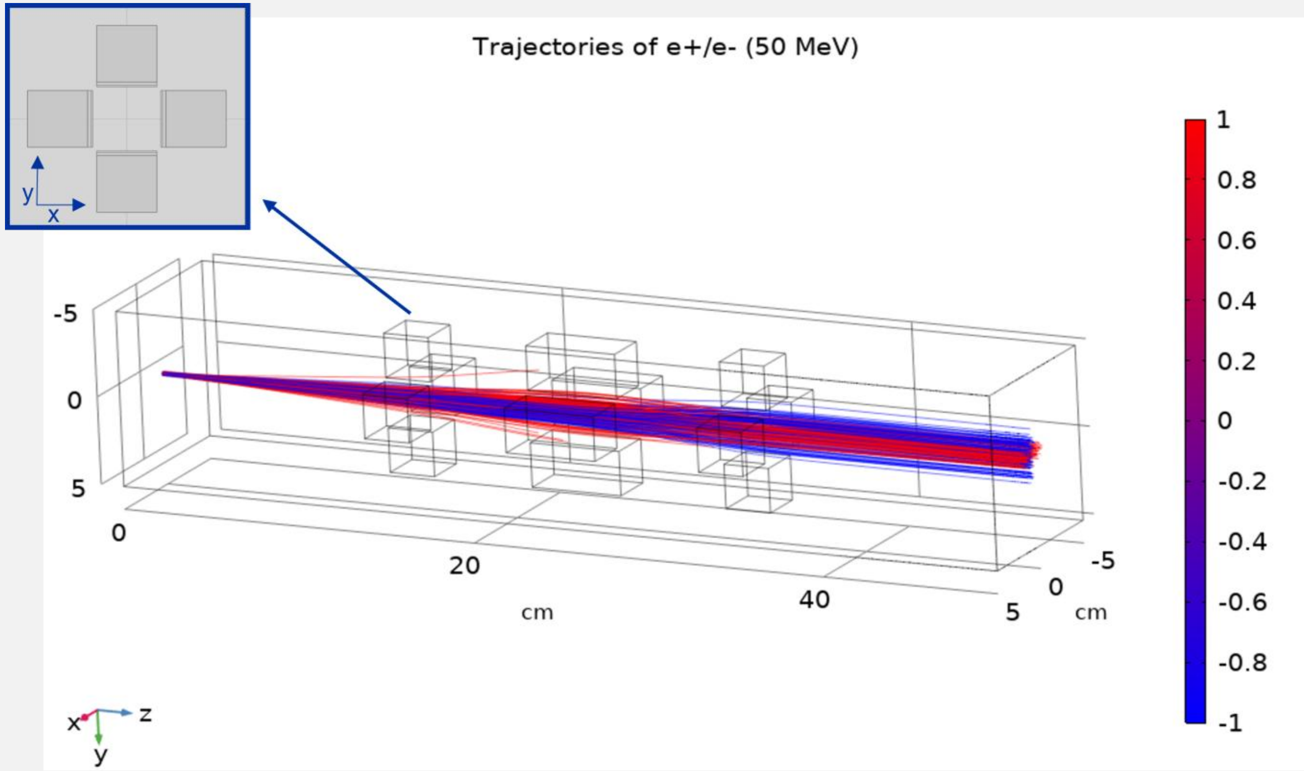


Without quadrupoles

With quadrupoles

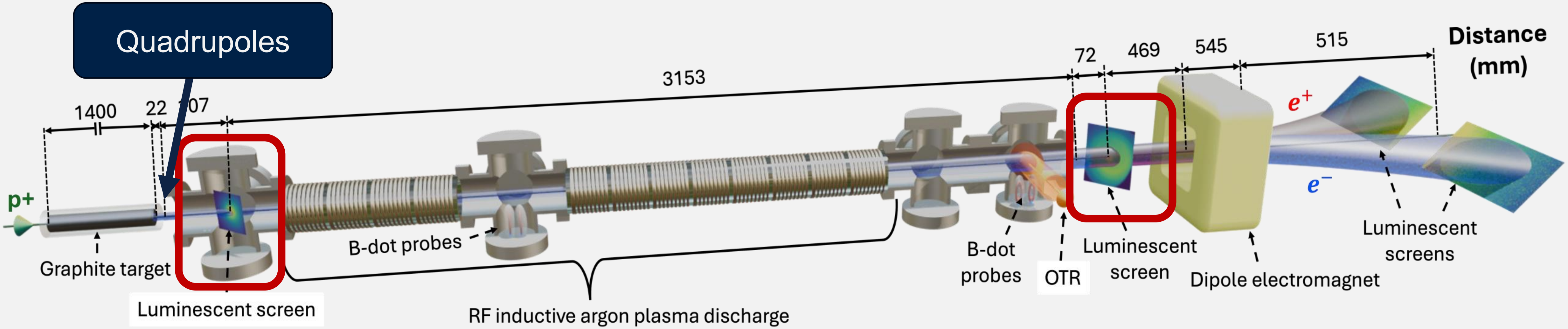
Quadrupole studies – COMSOL





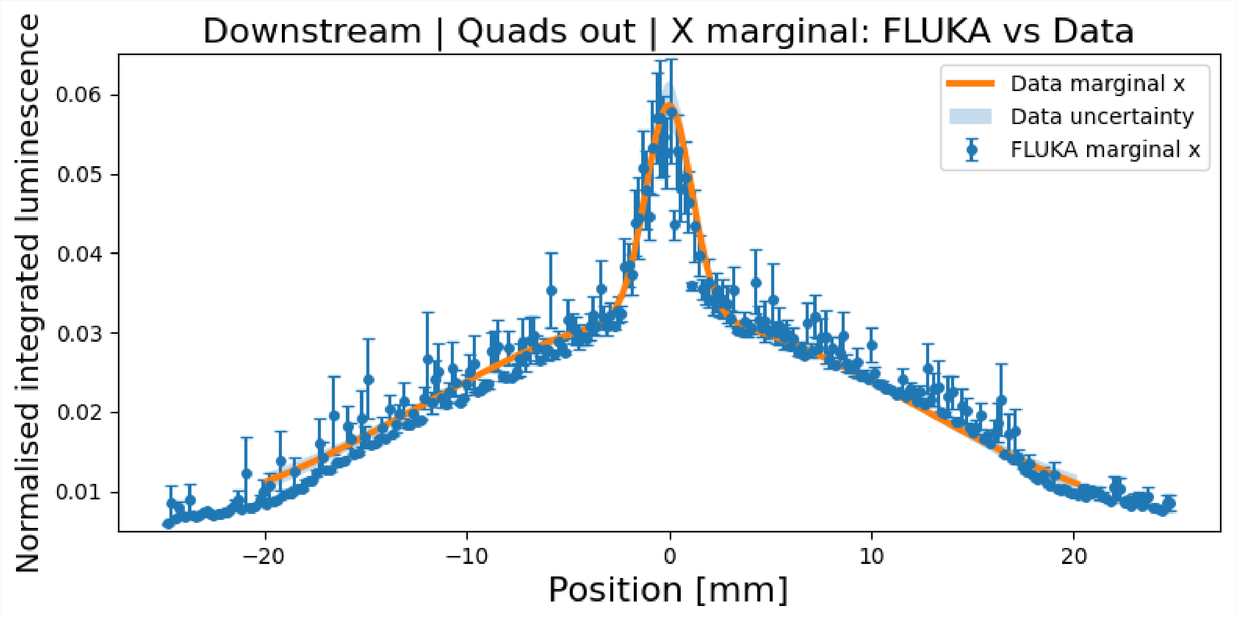
Experimental validation

- We measured the beam shape with and without quadrupoles, upstream and downstream the plasma, using Chromox luminescence screens



Results – FLUKA vs Data

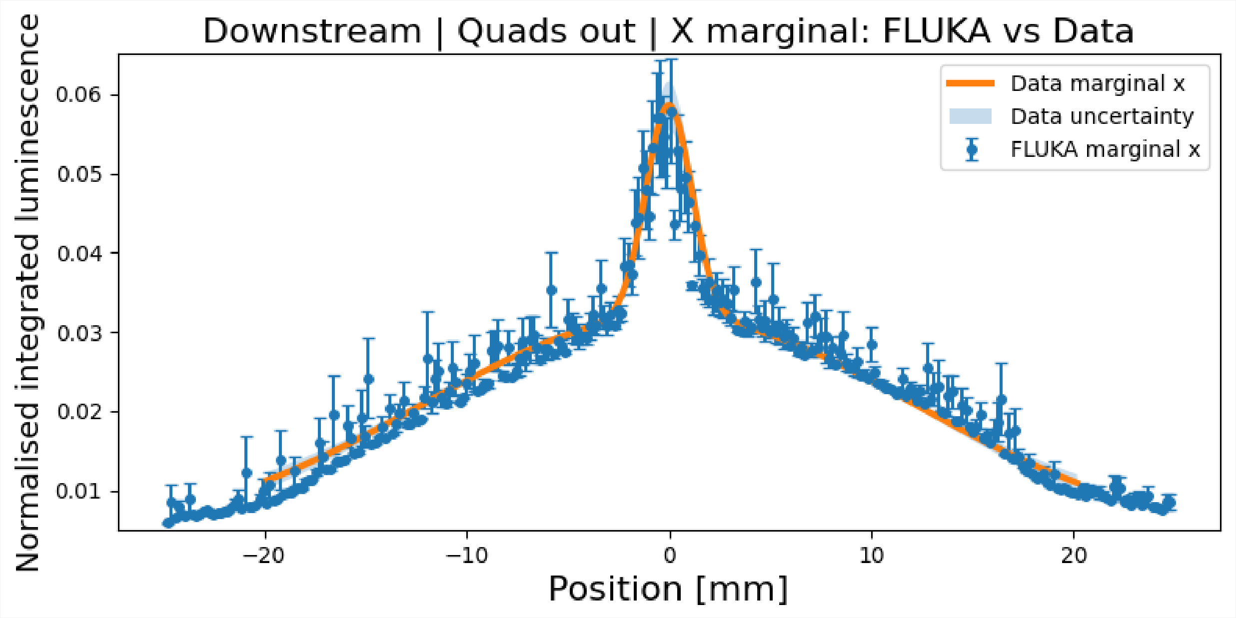
After the plasma cell

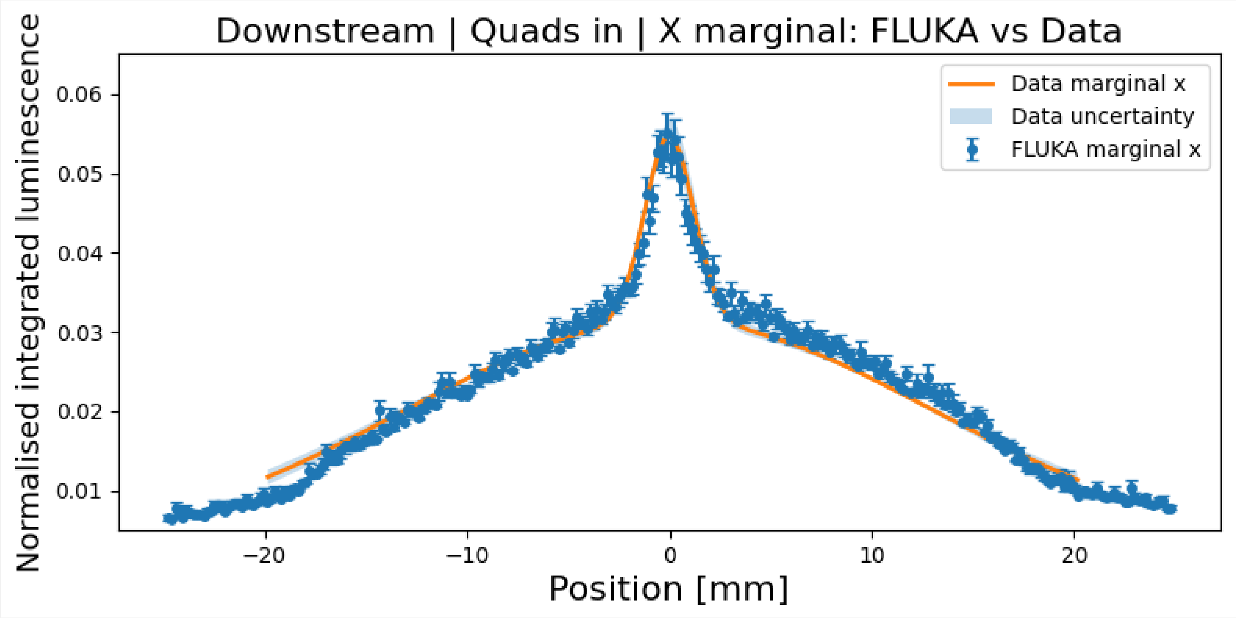


Without quadrupoles

Results – With vs without quadrupoles

After the plasma cell



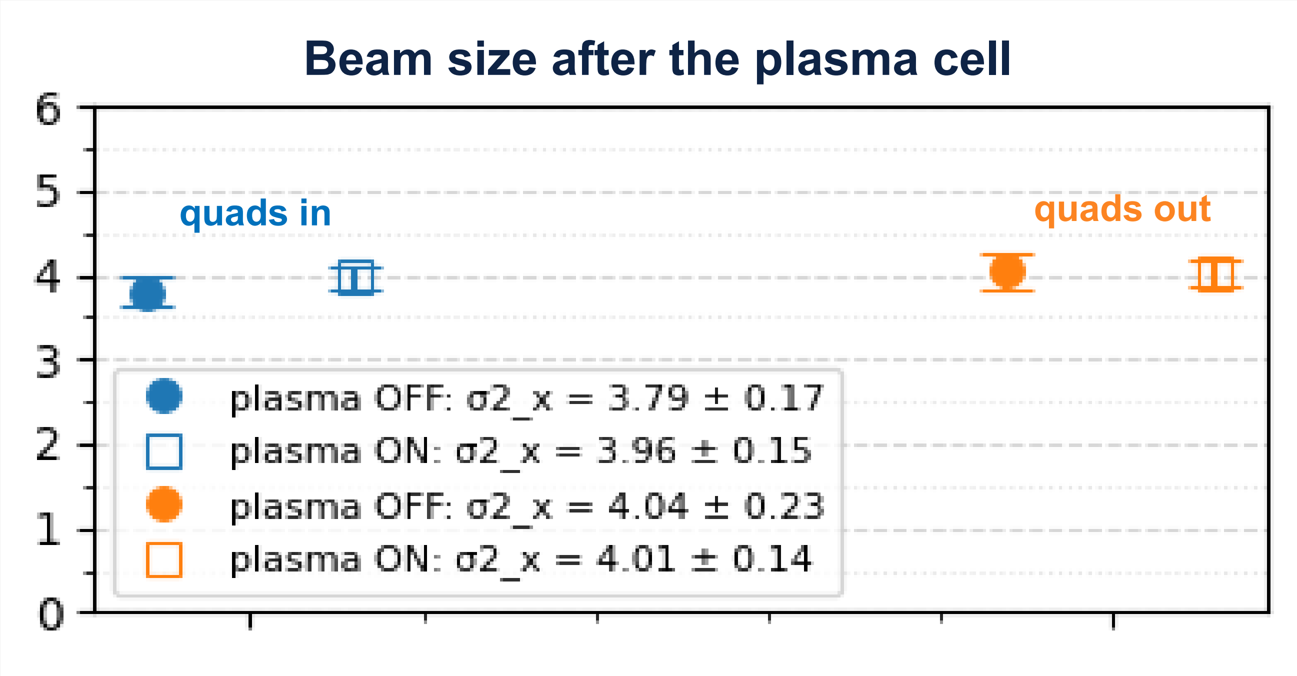


Without quadrupoles

With quadrupoles

Results

Beam spot size (mm)



After analysing many shots and averaging the results, we observe **no strong reduction in the measured beam size or inferred divergence**

What's limiting the focusing effect?

Limitations of the approach

What's limiting the focusing effect?

- Broadband momentum distribution
- Strong multiple scattering through glassy carbon windows
- Magnetic field reduction due to radiation damage
- Material imperfections – known uncertainty in remanent magnetic field of the permanent-magnet blocks

Conclusions

- We implemented a **compact permanent-magnet quadrupole triplet** as a simple first attempt to **control the pair beam phase space**
- **Under realistic experimental conditions, the triplet did not provide robust collimation to enhance the instability growth rate**
- **A reasonable, reliable model & analysis framework has been developed to design & study future setups**
  - An improved design will be optimized for maximum acceptance, including all realistic constraints and properties of the Fireball environment

Thank you for your attention!

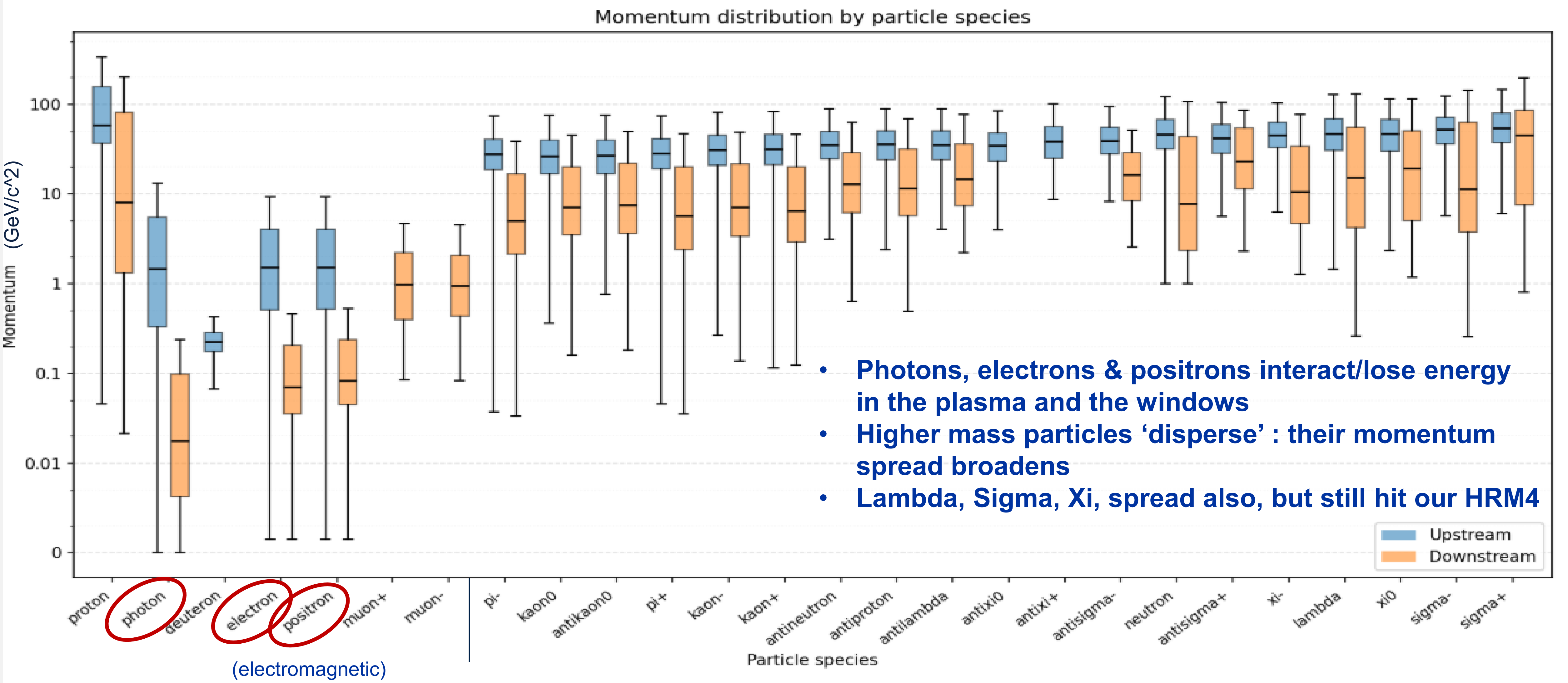
☺

and some back up slides

Outline of this talk

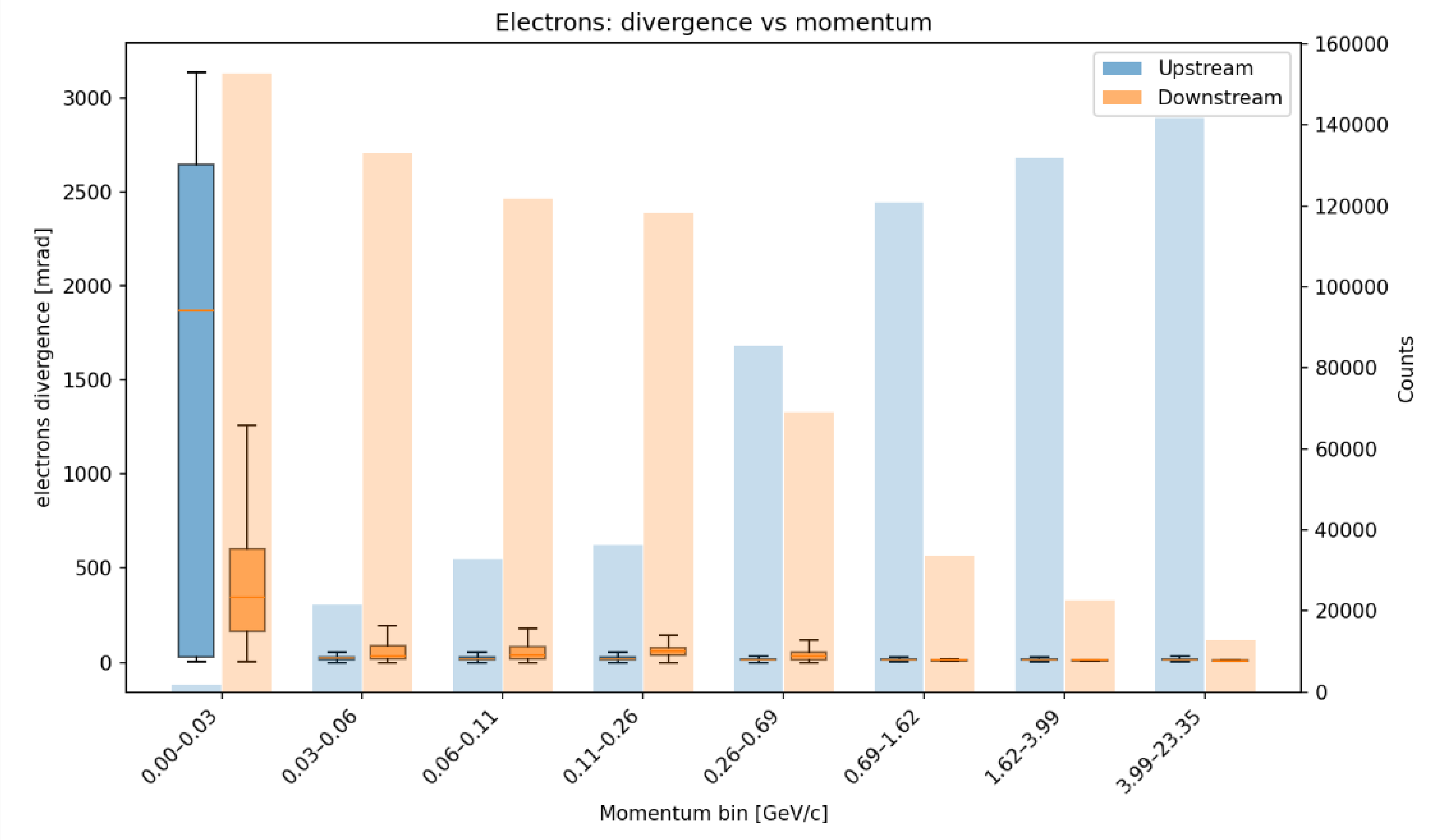
- ➢Plasma instability detection using magnetic fields
- ➢Instability growth rate and the role of divergence
- ➢Permanent-magnet quadrupole triplet
- ➢Experimental implementation and analysis
- ➢Performance limitations & lessons for future experiments

Mass / momentum distribution of particles



- Photons, electrons & positrons interact/lose energy in the plasma and the windows
- Higher mass particles 'disperse' : their momentum spread broadens
- Lambda, Sigma, Xi, spread also, but still hit our HRM4

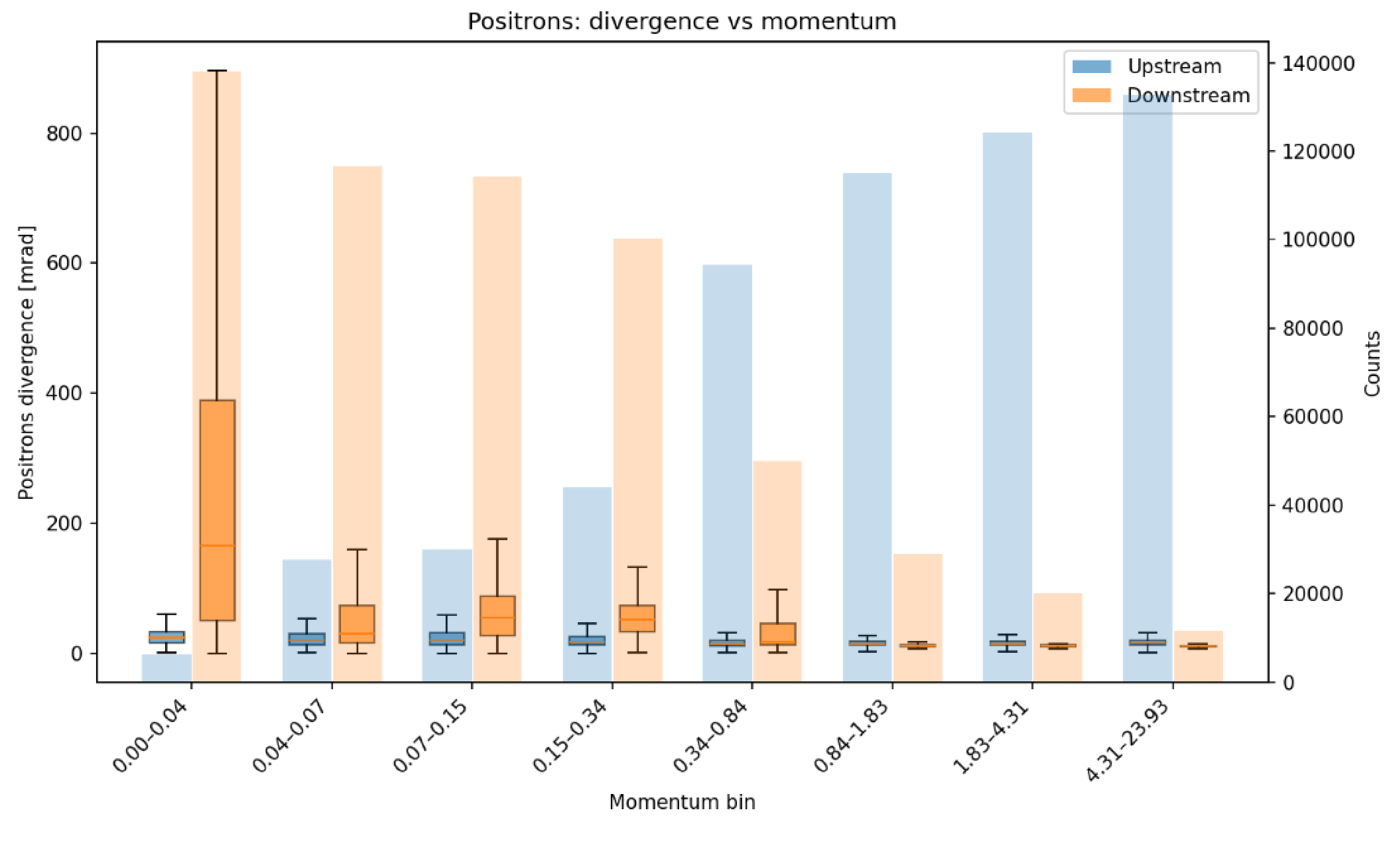
Electrons divergence (FLUKA)



- **Electrons with momenta > 60 MeV/c do not significantly diverge**
- **We still have divergence, so we are naturally losing population as we move downstream**

Momentum bin [GeV/c]	Mean divergence upstream [mrad]	Mean divergence downstream [mrad]
< 30 MeV/c	1397.62	414.42
30 – 60 MeV/c	24.55	71.08
60 – 110 MeV/c	24.03	58.24
110 – 260 MeV/c	23.13	61.48
260 – 690 MeV/c	17.61	39.77
0.690 – 1.62 GeV/c	15.85	19.93

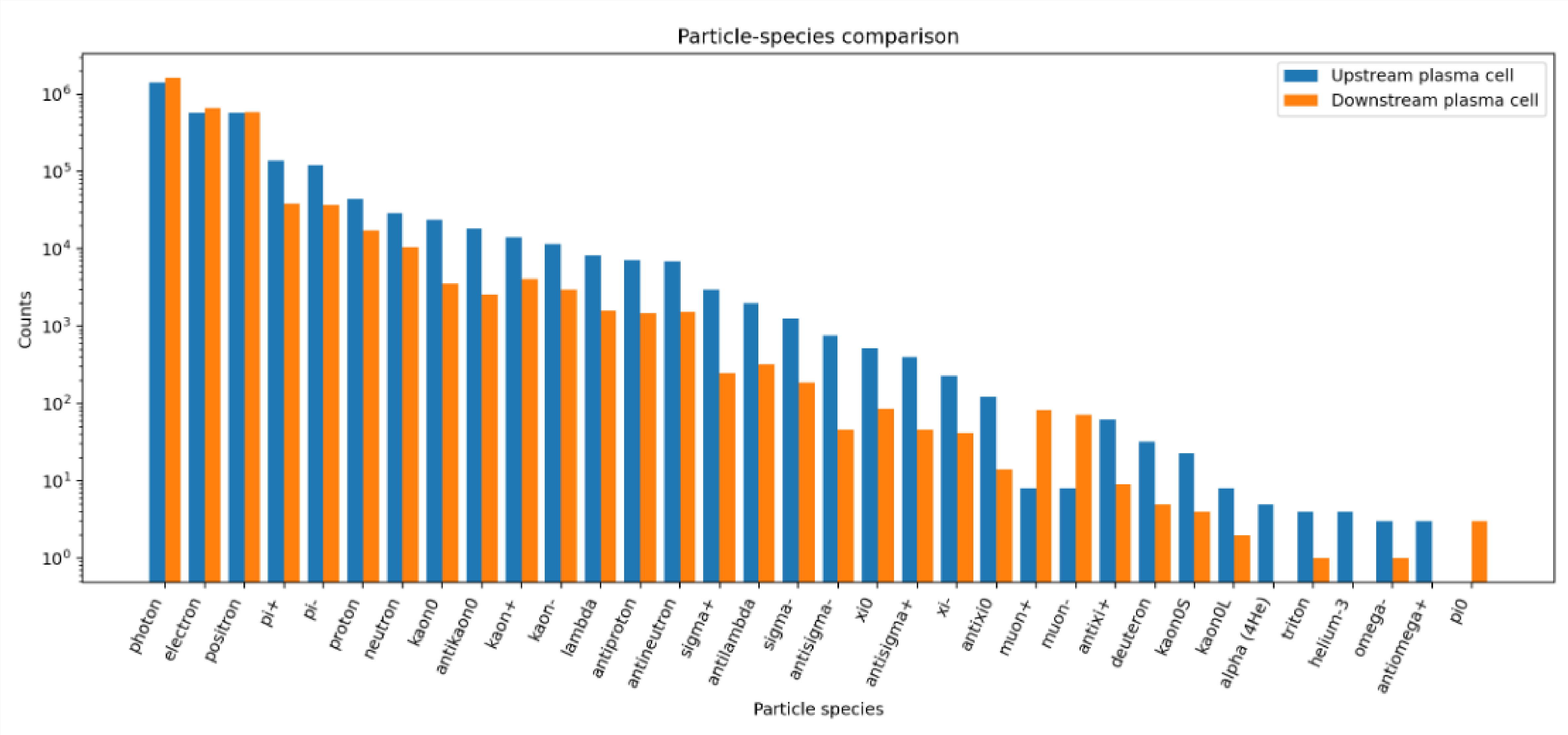
Positrons divergence (FLUKA)



- **Positrons with momenta > 60 MeV/c do not significantly diverge**
- **We still have (some) divergence, also here we are naturally losing population as we move downstream**

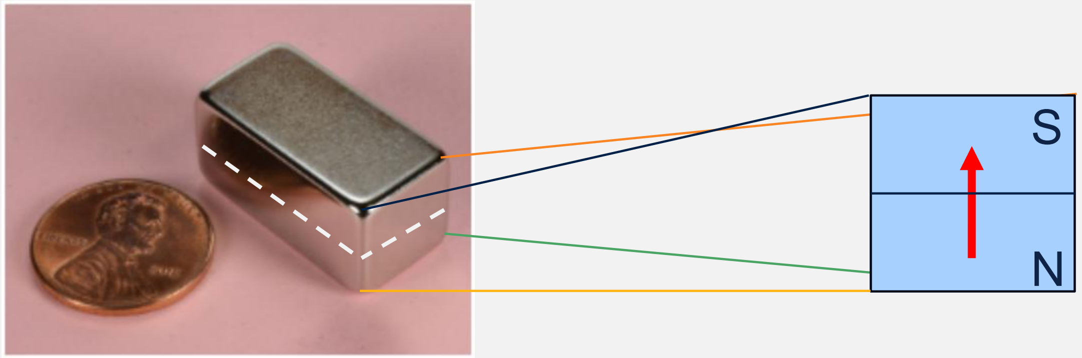
Momentum bin [GeV/c]	Mean divergence upstream [mrad]	Mean divergence downstream [mrad]
< 30 MeV/c	117.36	261.25
30 – 60 MeV/c	23.52	57.00
60 – 110 MeV/c	25.30	63.69
110 – 260 MeV/c	20.93	54.95
260 – 690 MeV/c	16.90	32.40
0.690 – 1.62 GeV/c	15.79	15.40

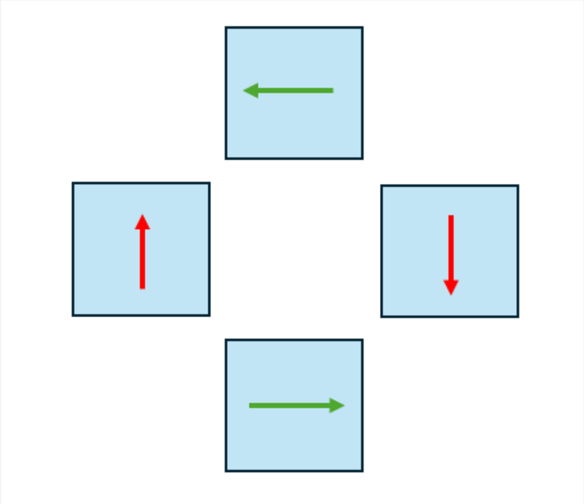
FLUKA – Overall Particle Distribution



Permanent-magnet based focusing system

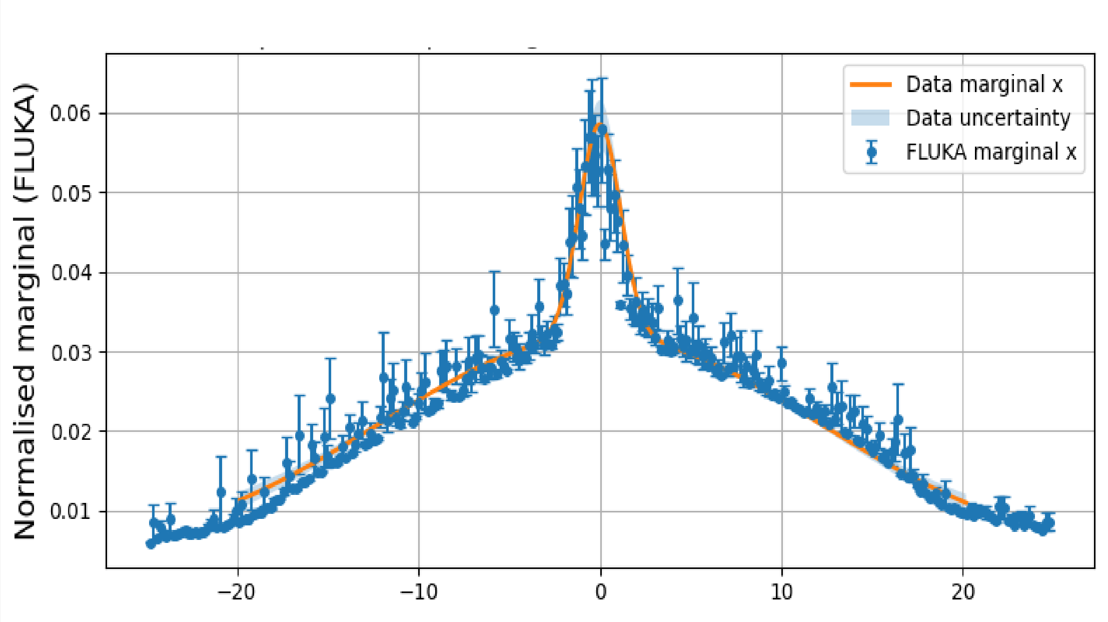
- Custom made quadrupoles based on permanent NdFeB magnets
- Compact, passive, easy-to-procure, compatible with HiRadMat facility constraints
- Triplet geometry: alternating focusing-defocusing planes





Results – FLUKA vs Data

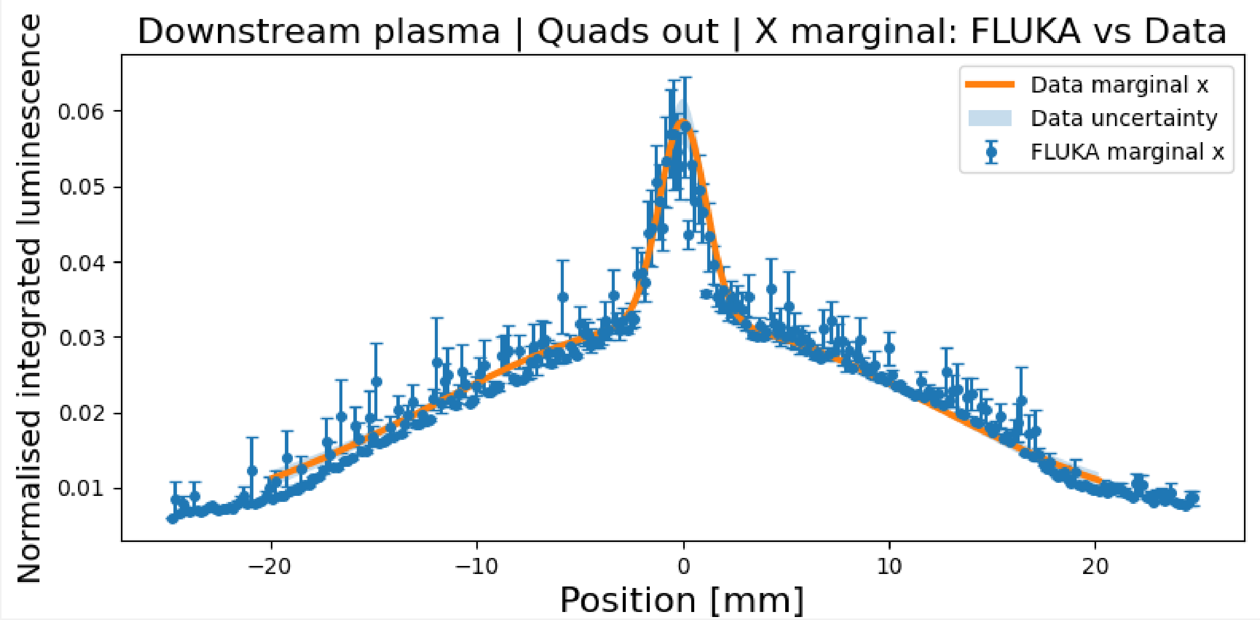
After the plasma cell

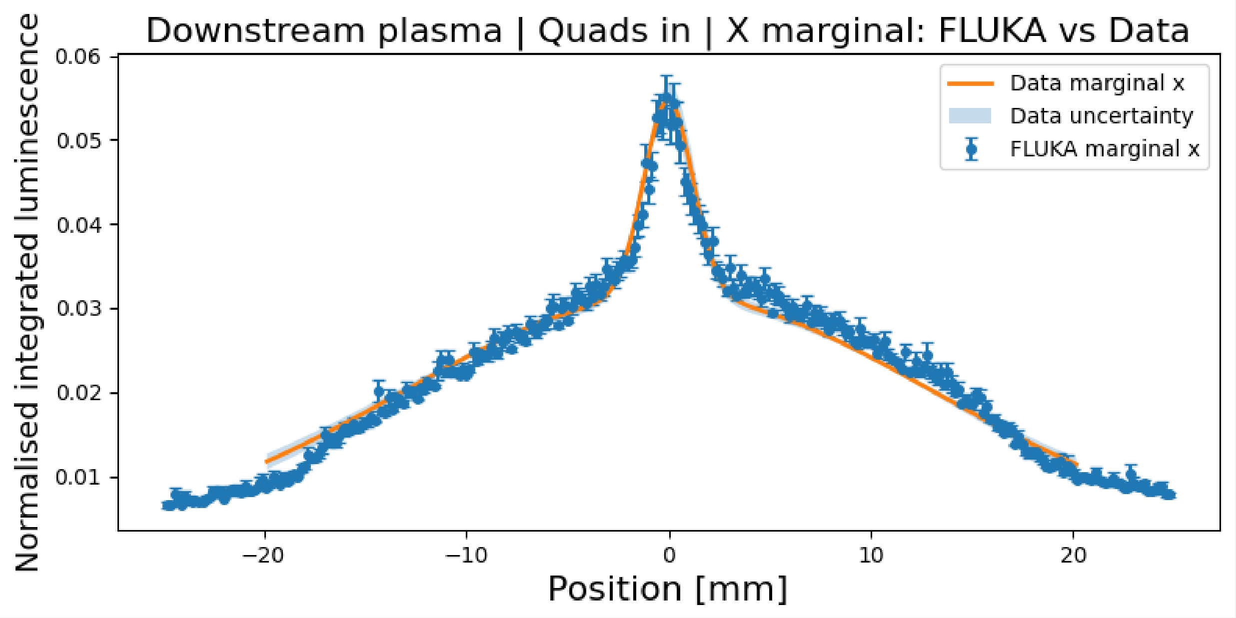


Without quadrupoles

Results – With vs without quadrupoles

After the plasma cell



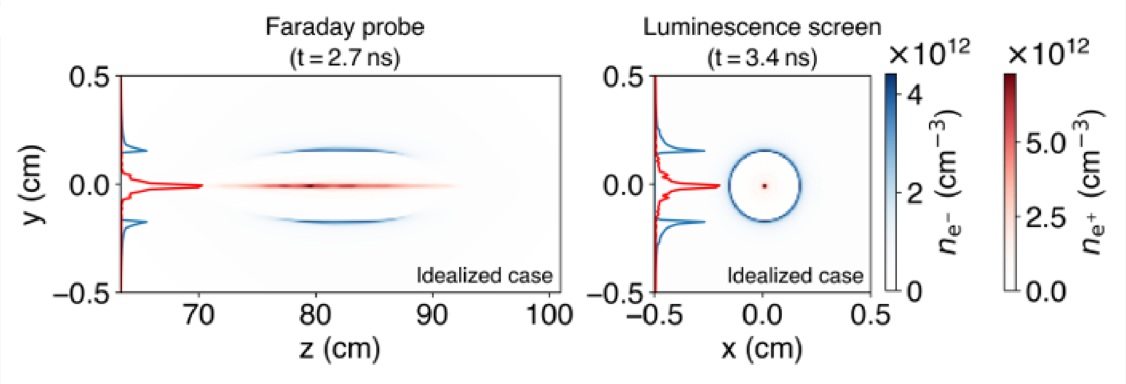


Without quadrupoles

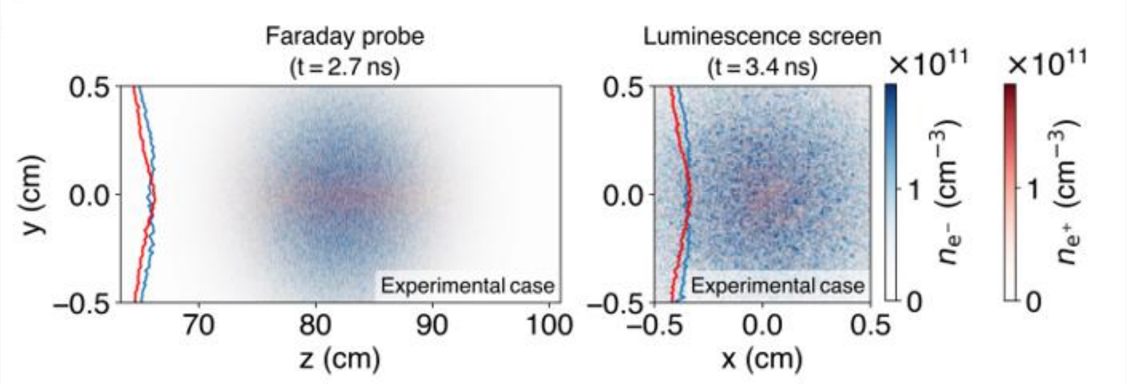
With quadrupoles

Why divergence matters?

Results from PIC simulation.
Top: Idealized conditions, **collimated and monoenergetic beam**.



Bottom: Realistic experimental conditions.



- **Large Δθ (transverse momentum spread) causes suppression of unstable modes before current fluctuations can be amplified**
- Collimating the beam can help by
  - reducing Δθ
  - Increasing on-axis density

➢ **The quadrupole triplet was designed to test this experimentally**