HRMT-64
Extreme Astrophysics with laboratory electron-positron jets

Gianluca Gregori (University of Oxford)

CERN
2nd December 2024

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)

The FIREBALL Collaboration

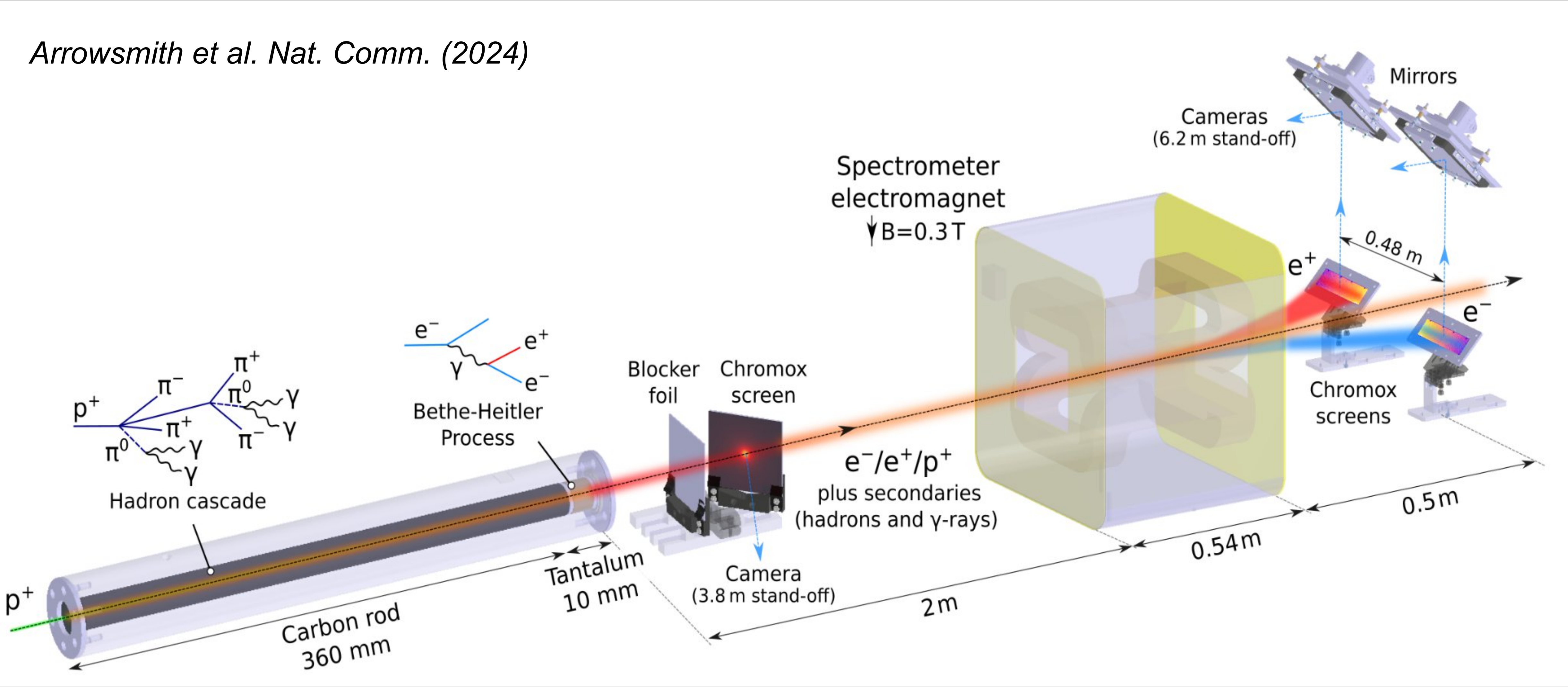
E. E. Los, G. Gregori, A. Dyson, B. T. Huffman, H. Ramm, S. Sarkar, S. Zhang, V. Stergiou, P. Alexaki, N. Charitonidis, A. Goillot, C. D. Arrowsmith, D. H. Froula, R. Bingham, J. W. D. Halliday, P. J. Bilbao, F. D. Cruz, L. O. Silva, J. T. Gudmundsson, B. Reville, T. Vieu, C. P. Ridgers, P. Simon, A. G. R. Thomas, L. Willingdale, M. Bochmann, K.-G. Schlesinger

Laboratory astrophysics *vs* conventional astrophysics

- Laboratory experiments can be complementary to observations (we can measure the property of the plasma in details) and offer a means to directly validate numerical simulations as well as reach spatial and temporal scales not accessible by state-of-art calculations.
- *Syntactic isomorphism*: **two systems are described by the same mathematical equations through a mapping that assigns different physical interpretations to the same mathematical objects.**

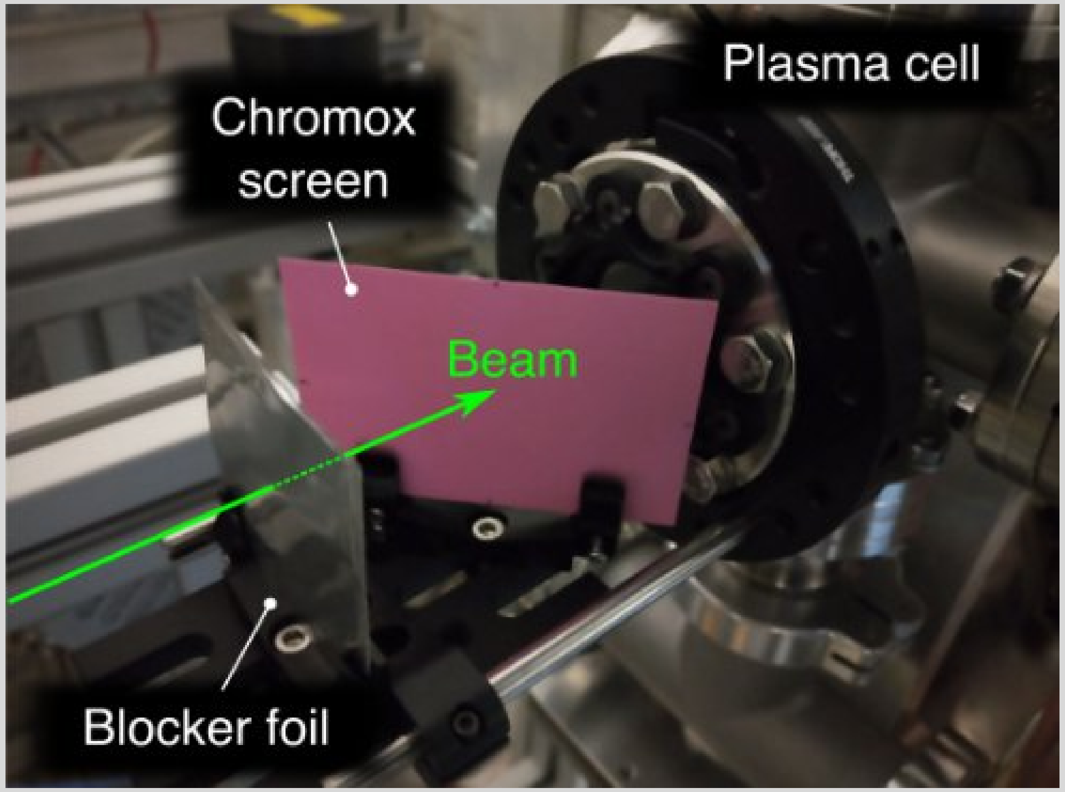
Instability	Growth rate, Γ
Current filamentation (CFI)	$\frac{\sqrt{3}}{2^{4/3}}\left(\frac{\alpha}{\gamma_b}\right)^{1/3}\omega_{pe}$
Oblique instability (OBI)	$\frac{v_b}{c}\sqrt{\frac{\alpha}{\gamma_b}}\,\omega_{pe}$
Two-stream (TS)	$\frac{\sqrt{3}}{2^{4/3}}\frac{\alpha^{1/3}}{\gamma_b}\,\omega_{pe}$

The first objective of HRMT-62 was to demonstrate we can get high density pair jets



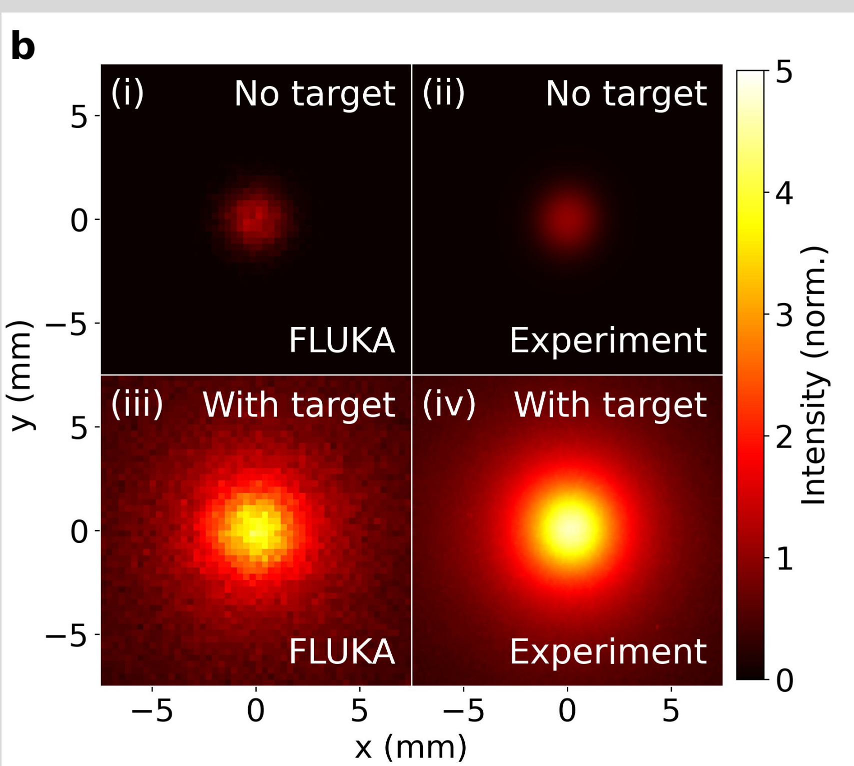
- ➜ Large number of pairs and large densities are needed in order for the jet to behave as a plasma.
- ➜ Experimental platform to provide test and validation of Monte Carlo simulations.

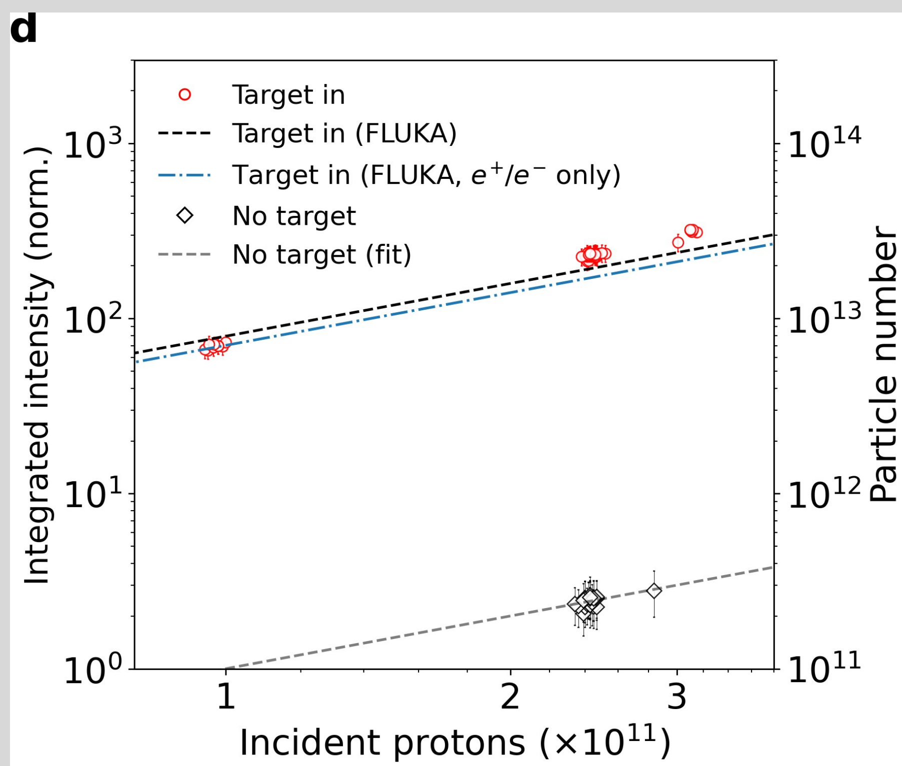
Evidence of high-yield pair plasma (as predicted from simulations)

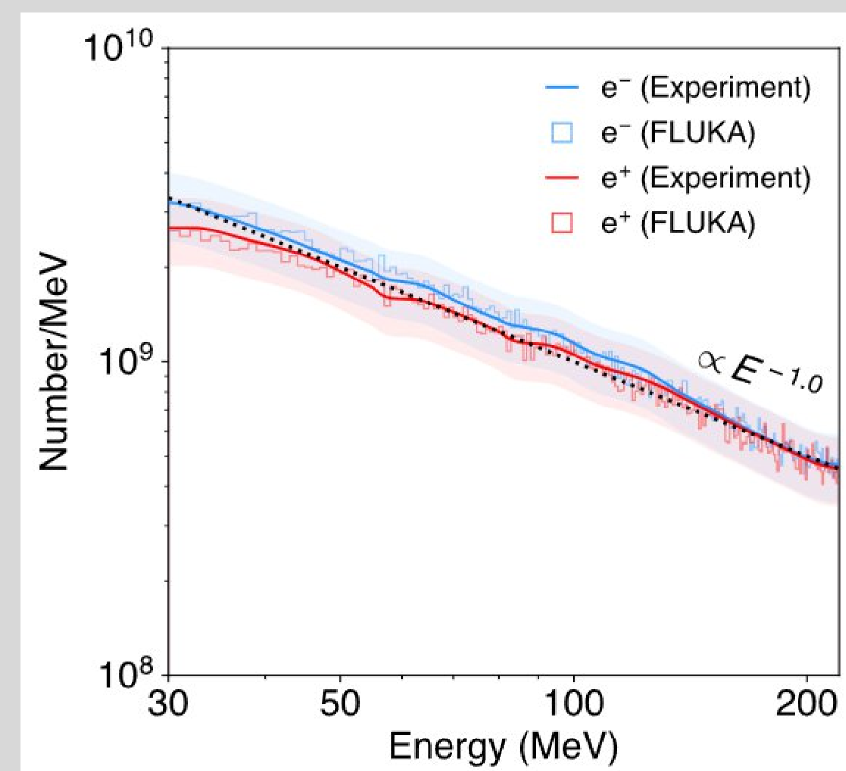


- Pair beams have extended power-law energy distributions and divergences of a few % (not unlike astrophysical jets).
- Pair beams are quasi-neutral except at lower energies <10 MeV, where positrons annihilate before they can escape the high-Z material
- **Estimated pair number is >10^{13}**.

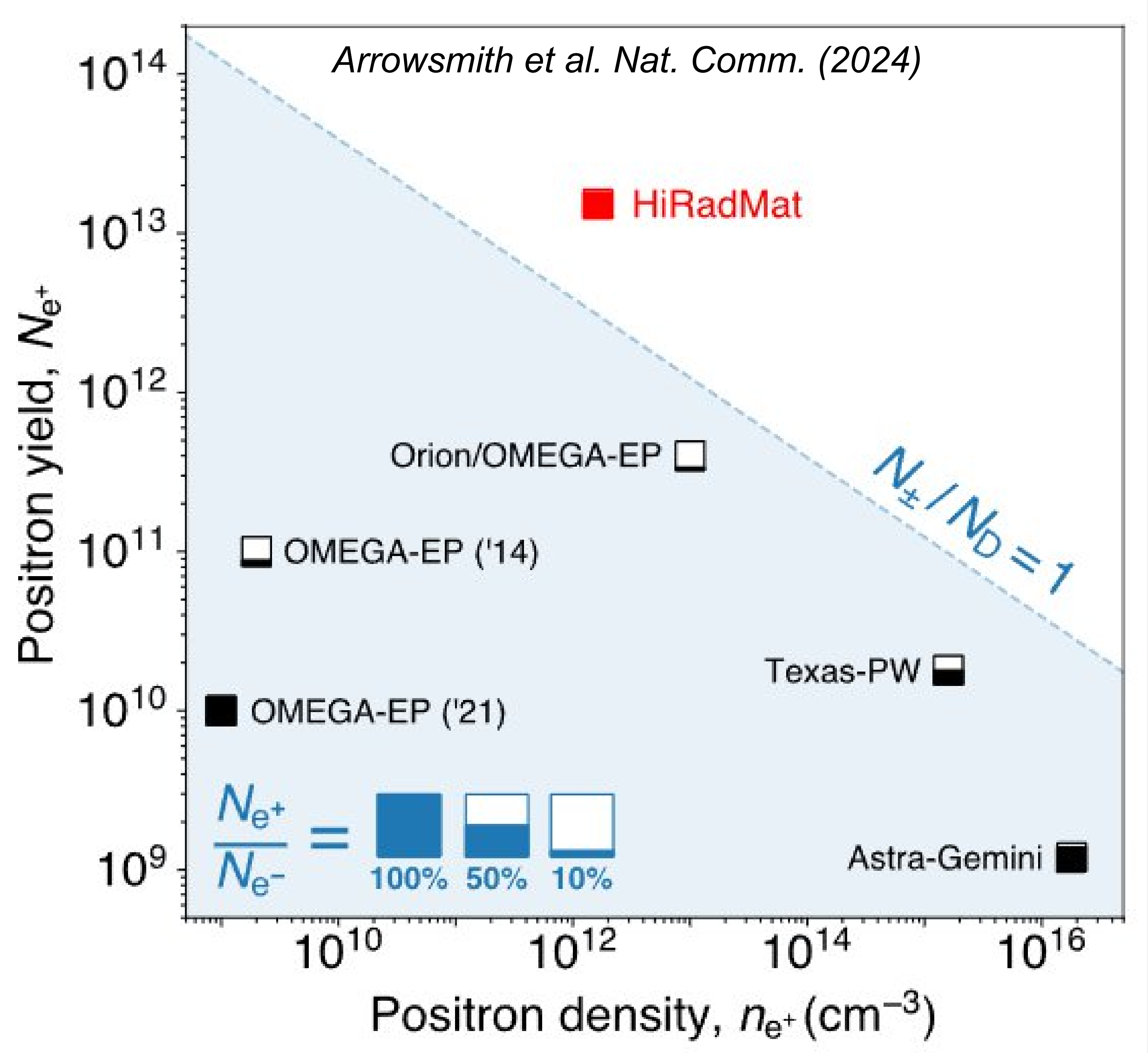
Arrowsmith et al. Nat. Comm. (2024)



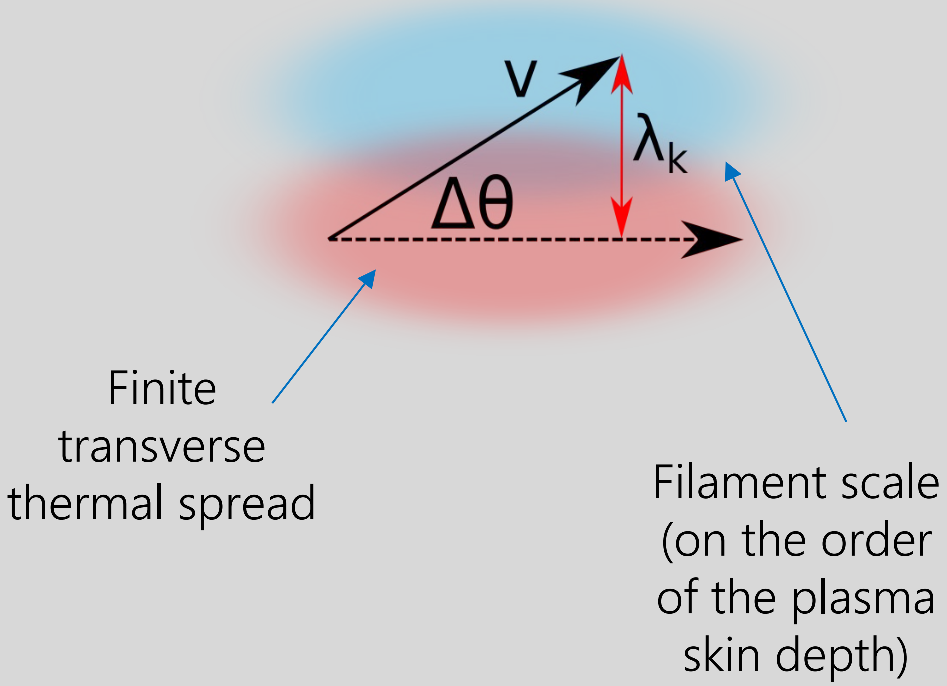




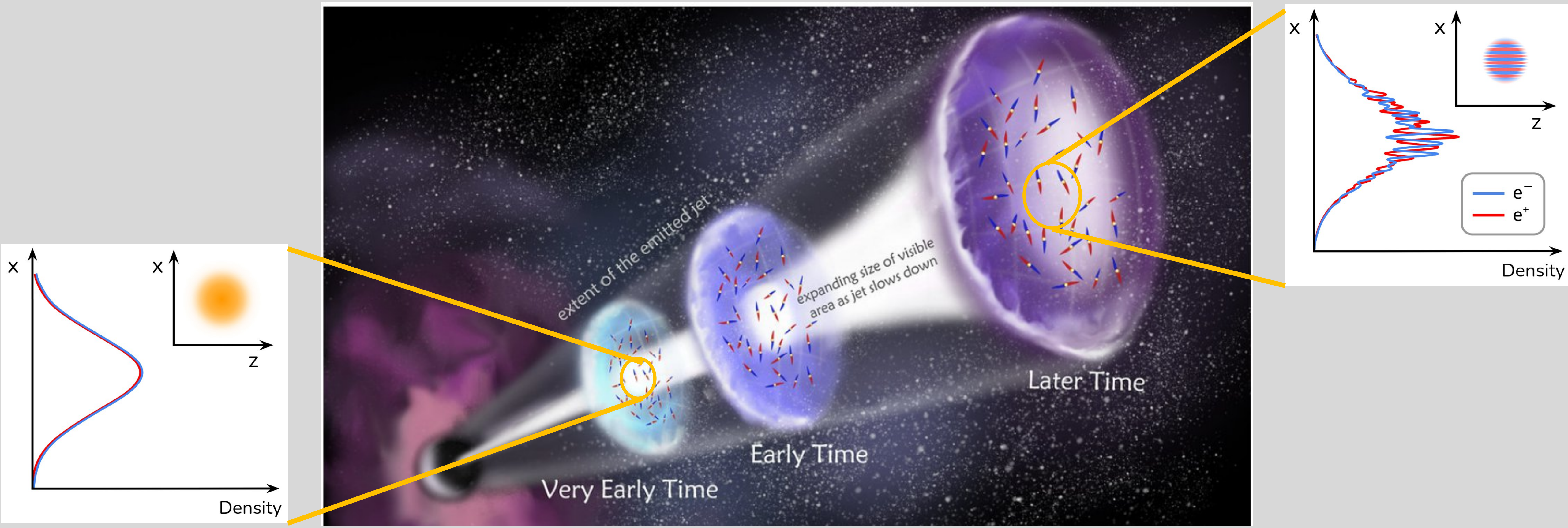
HRTM-62 showed we can achieve conditions for studying kinetic instabilities in pair jets



Instability	Growth rate, Γ
Kinetic OBI	$\frac{1}{\Delta\theta^2}\left(\frac{n_b}{\gamma_b n_p}\right)\omega_p$



Propagation of pair beams through plasmas is relevant to many astrophysical processes

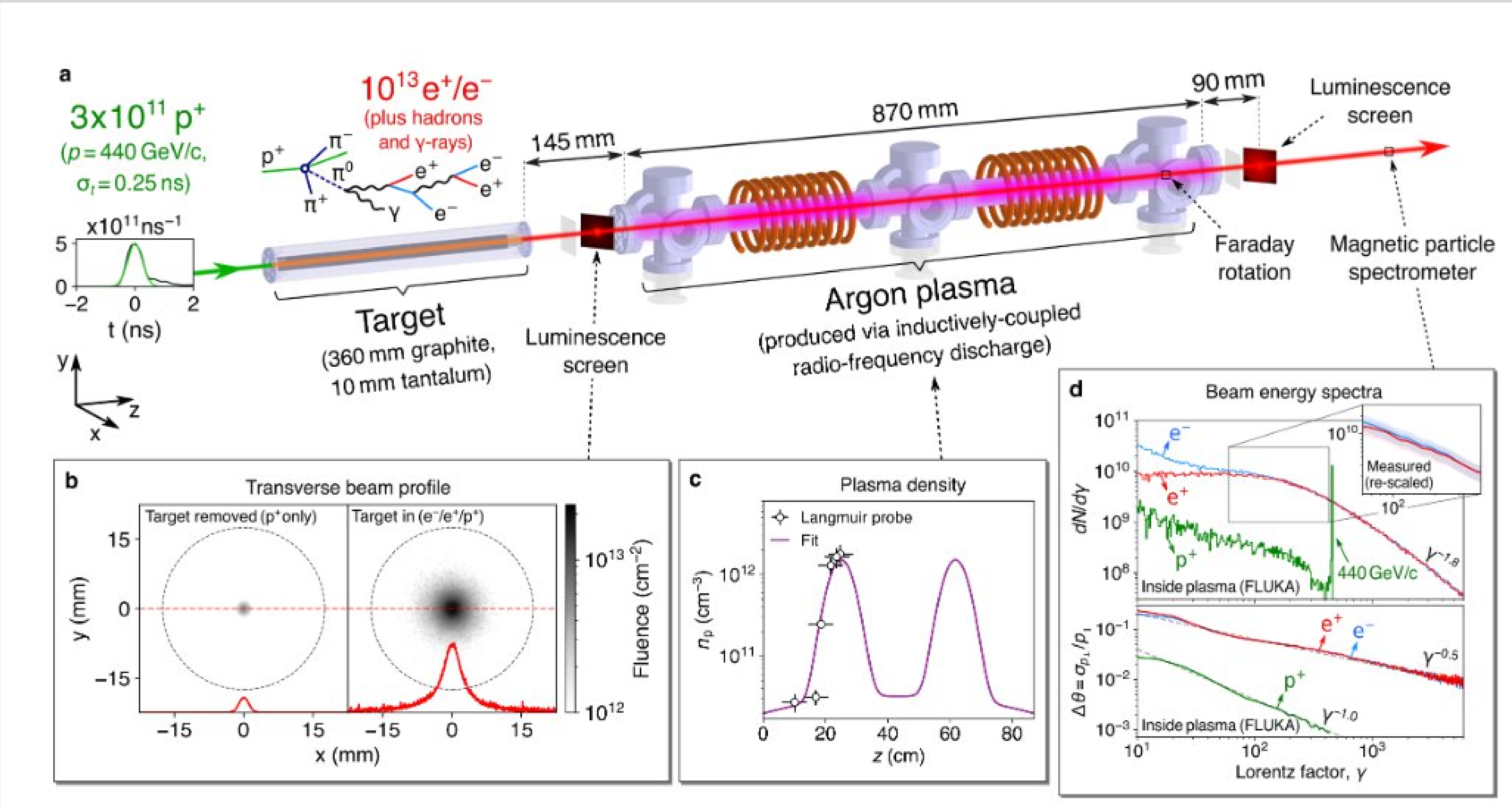


Electromagnetic field generation associated to filamentation instabilities is expected to play a role in:

- Blazar jets
- Gamma-ray bursts

Understanding the microphysics of these instabilities is challenging.

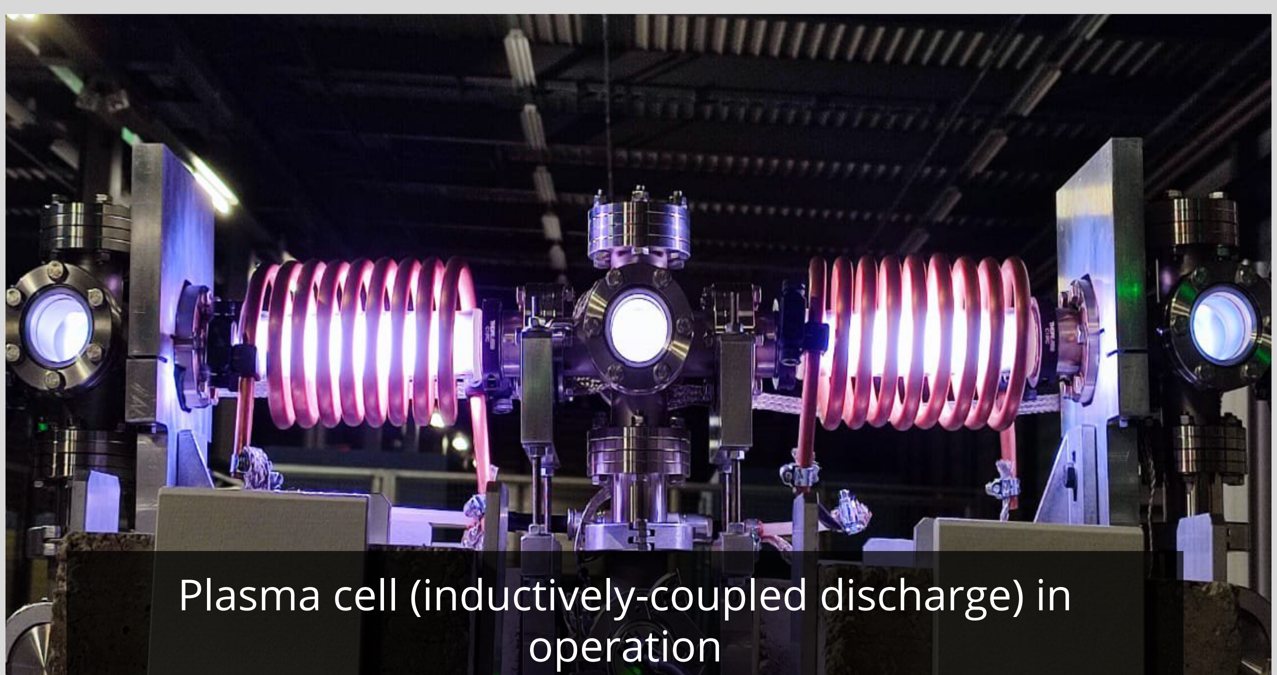
HRMT-64: we combine the pair-beam generation to a preformed ambient plasma



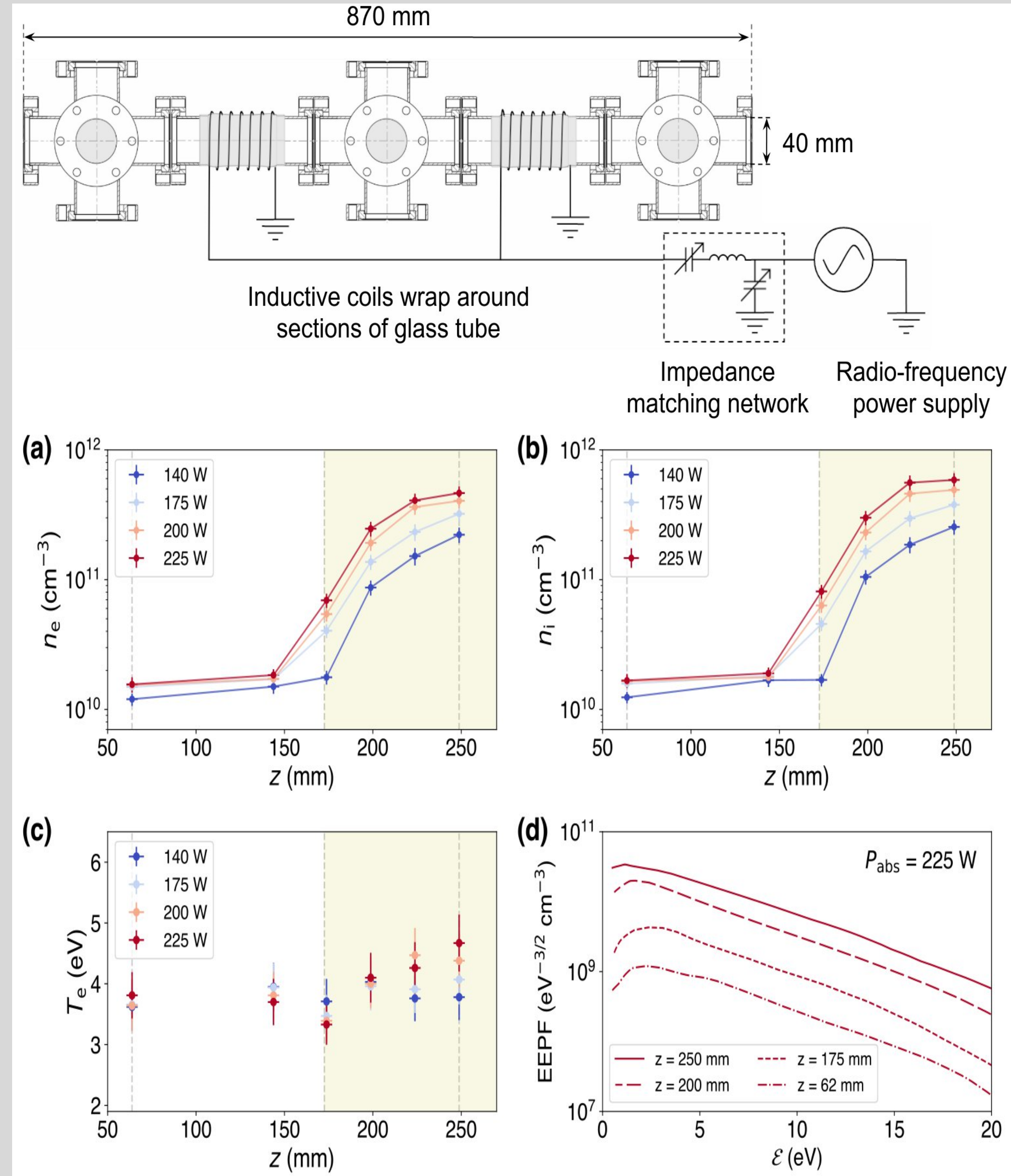
Arrowsmith et al., submitted (2024)

The ambient plasma is produced using a radio-frequency discharge

- ➜ Argon plasma produced using an ICP source.
- ➜ Plasma is long and large enough to contain pair beam over 100 cm.
- ➜ Ambient plasma is fully characterized using a Langmuir probe.

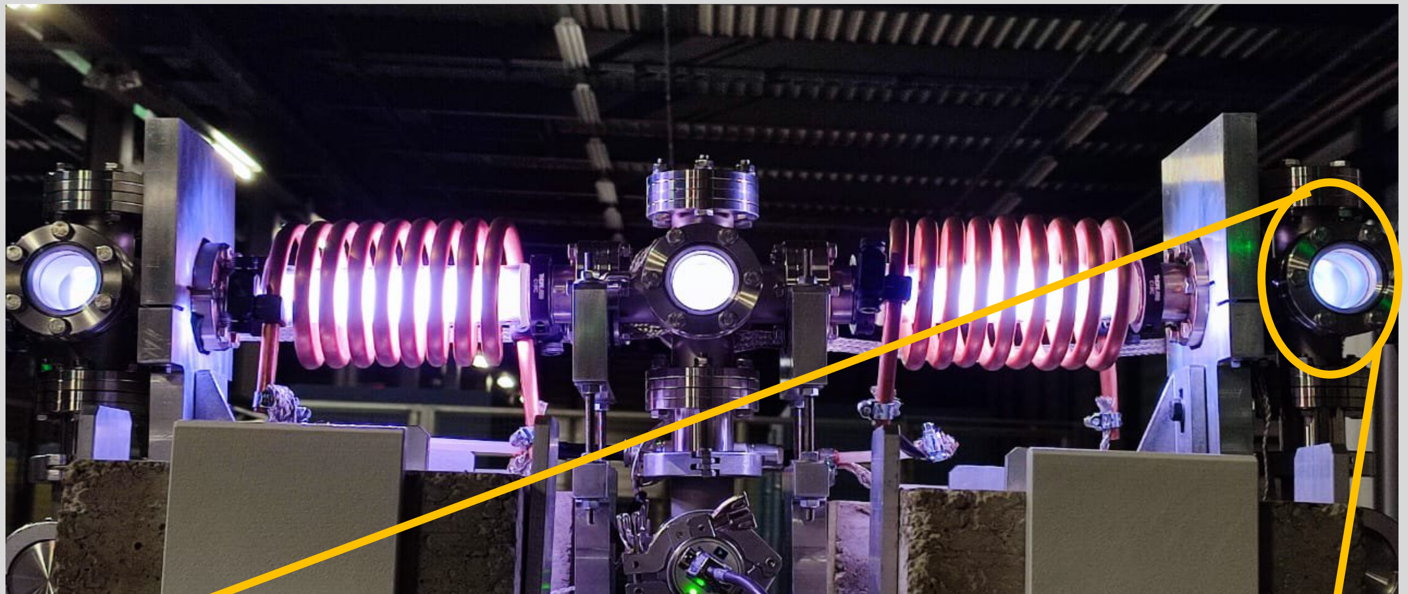


Plasma cell (inductively-coupled discharge) in operation

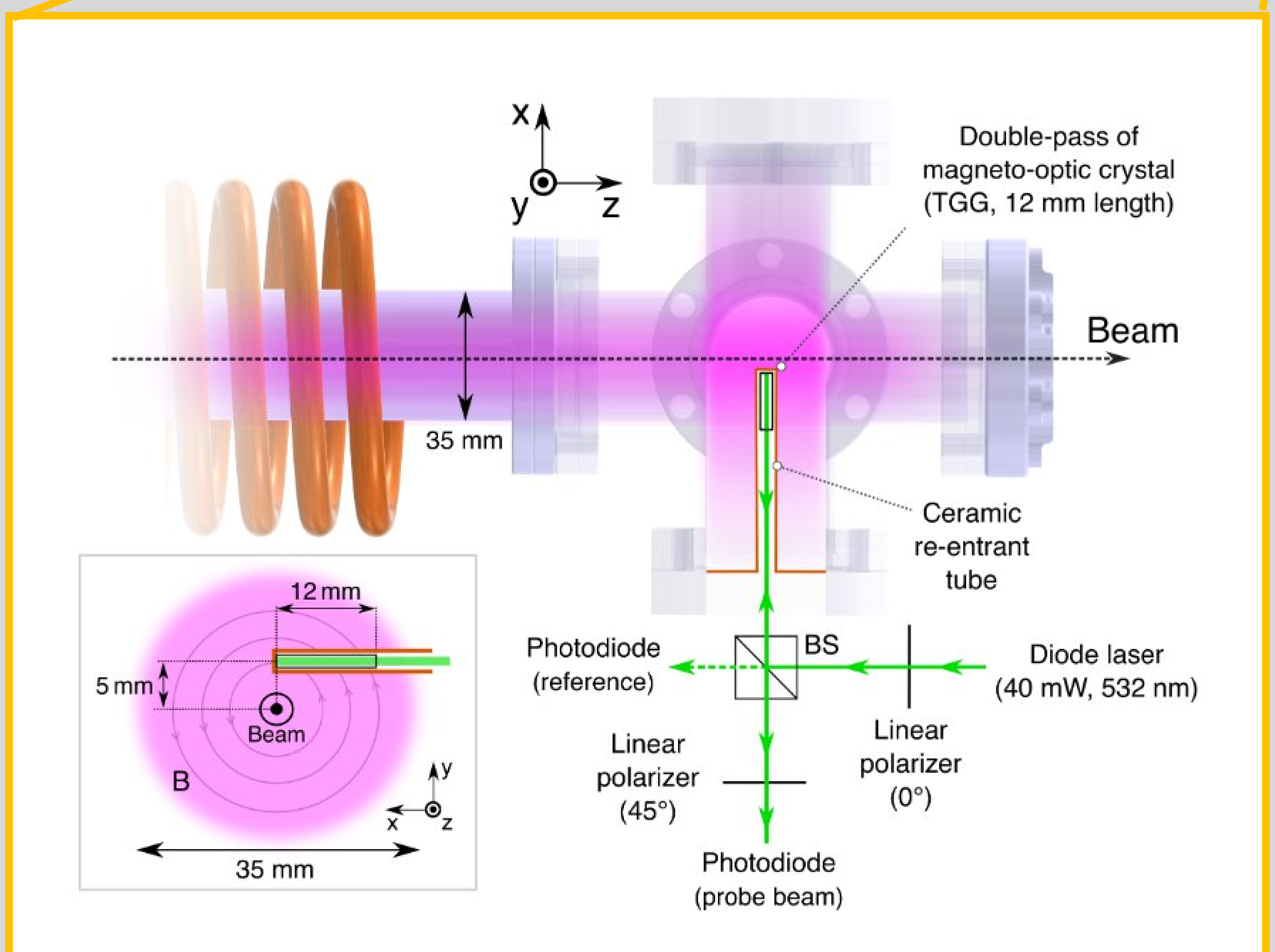


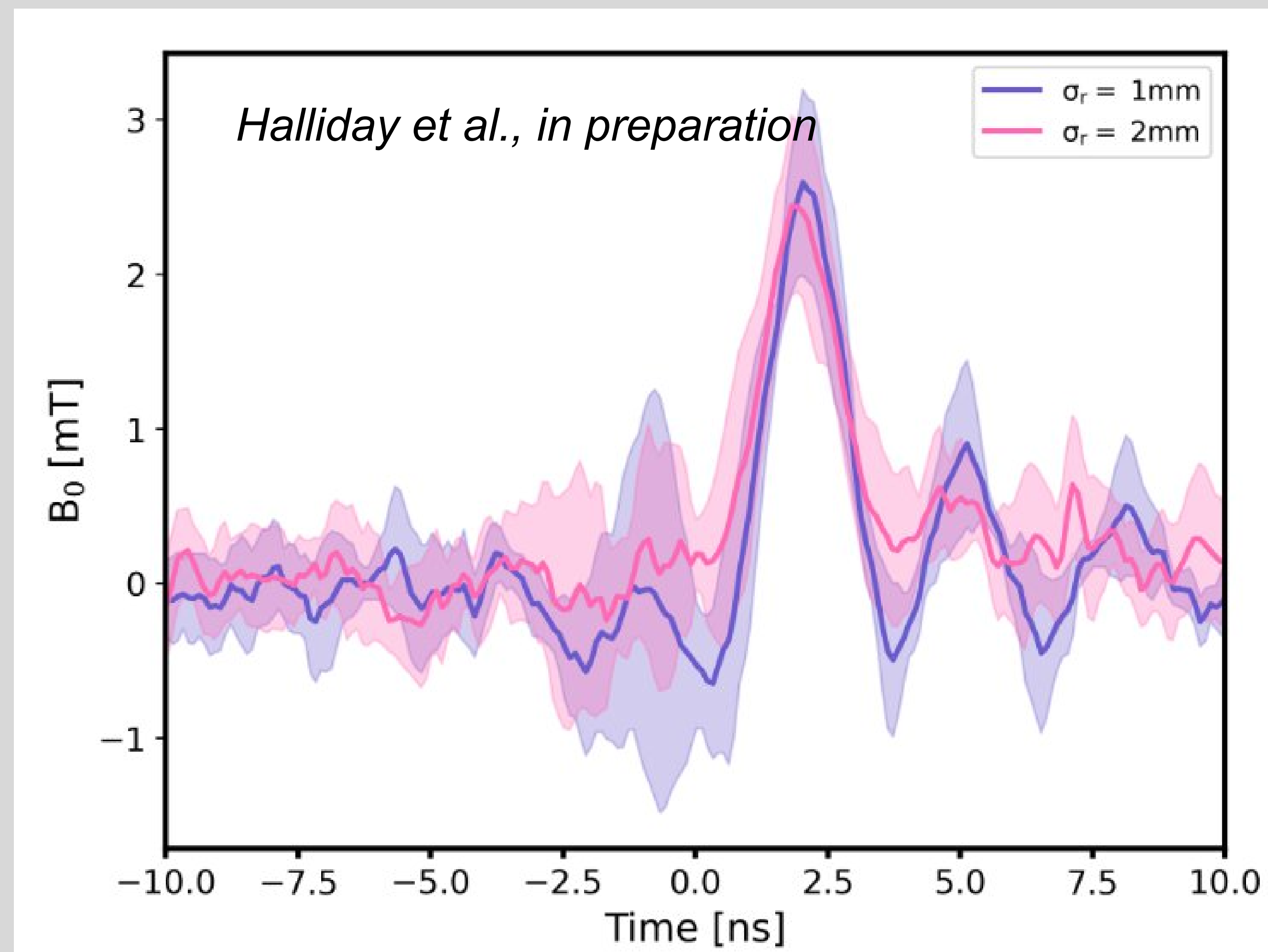
Arrowsmith et al. (2023)

Magnetic fields produced by plasma instabilities are measured using Faraday rotation



- Faraday rotation signal is amplified by using a magneto-optic crystal (Terbium-Gallium Garnet).
- Diagnostics sensitivity is limited by the intrinsic electrical noise in the setup.





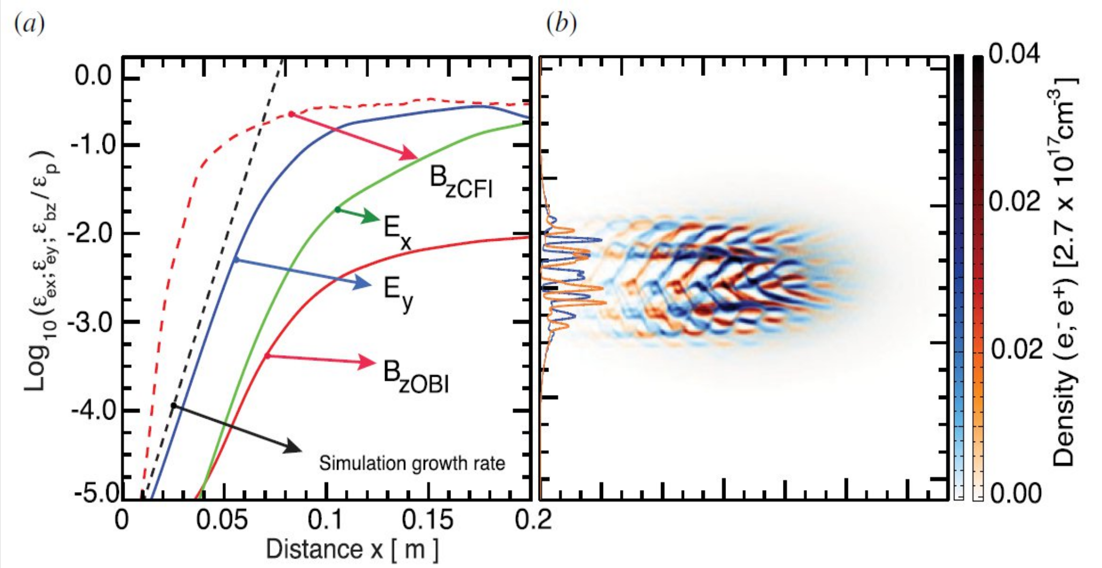
Full experimental implementation at the HiRadMat facility at CERN

Installation completed

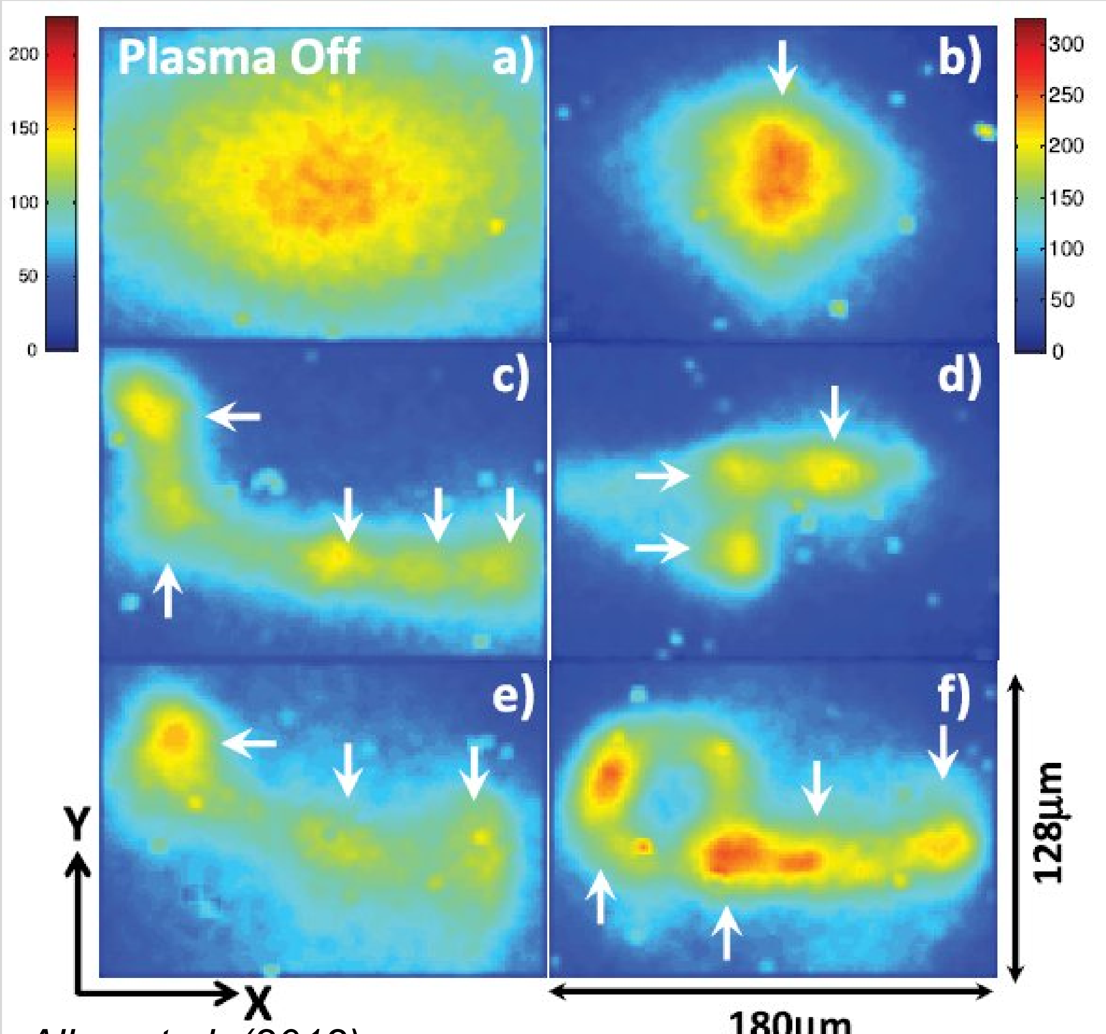
Remote operations from CERN Control Center (CCC)

The presence of magnetic fields is an indication that plasma instabilities are active

Shukla et al. (2019)



- Small fluctuations of magnetic field lead to separation of currents in e^+/e^- beam.
- These currents further amplify magnetic field.
- The growth time is proportional to the inverse plasma frequency of the ambient plasma.

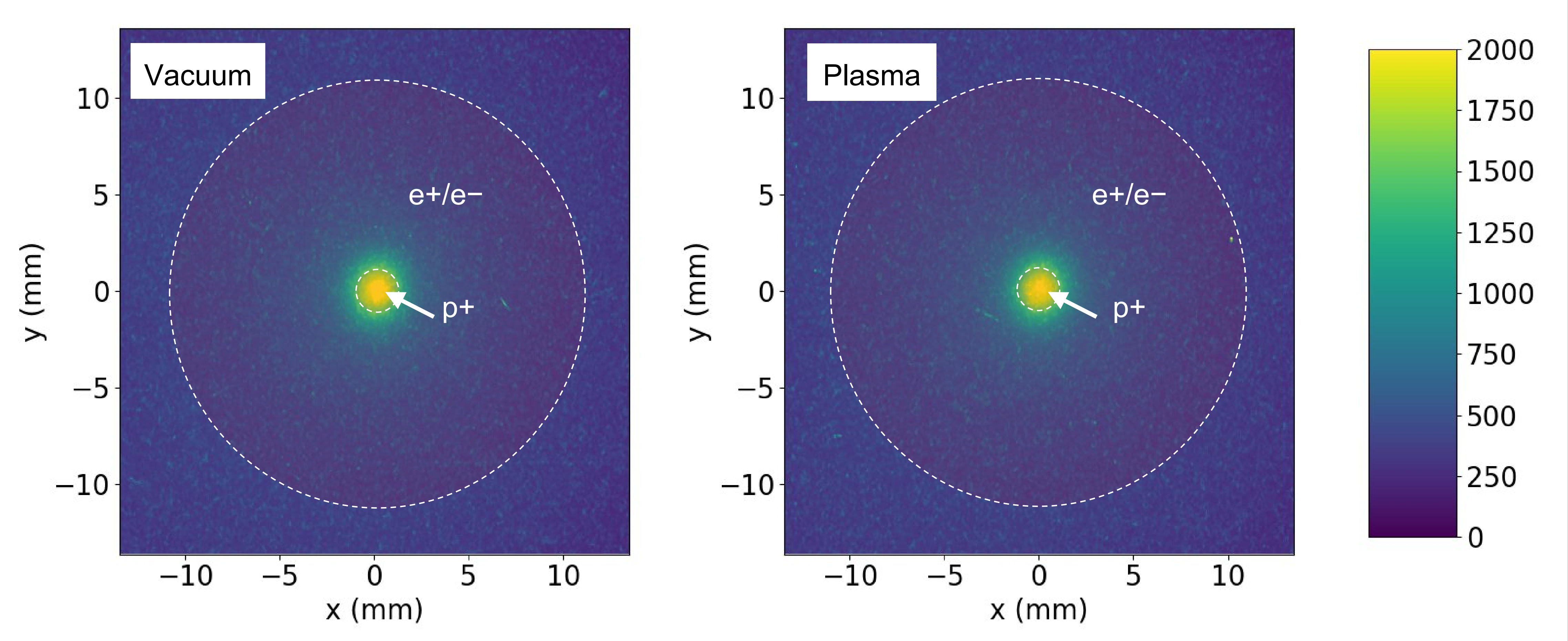


Allen et al. (2012)

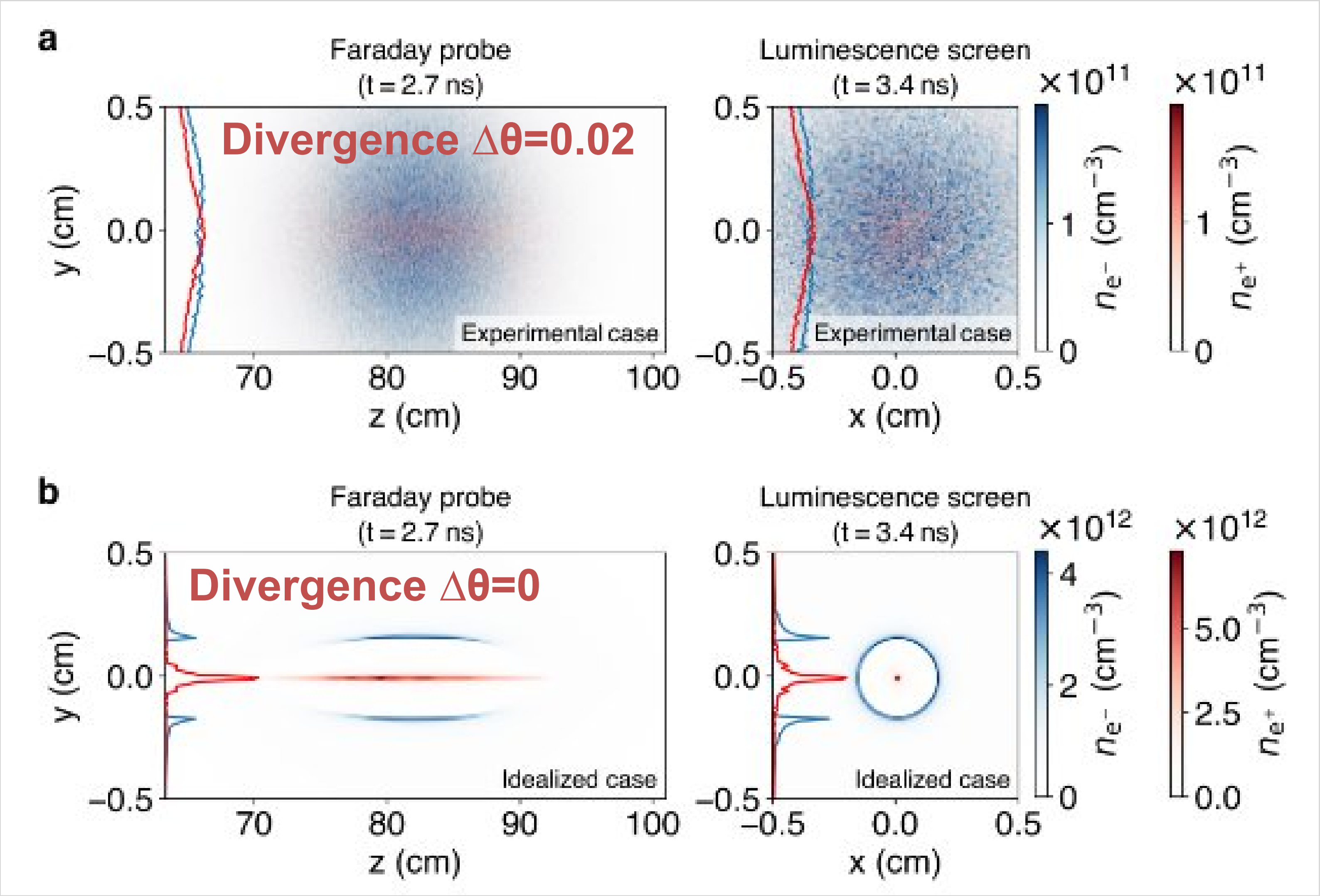
- Previous Brookhaven data with 60 MeV / 5 ps / $6x10^9$ e^- beam only (about 1.5^o divergence) shows formation of filaments.
- **This is different from a realistic blazar's jet (not quasi-neutral).**

In HRTM-64 there is no evidence of plasma filamentation at discharge exit

- ➜ Post plasma luminescence screen show the time-integrated transverse beam profile (all species combined).
- ➜ Very little difference between the images when the plasma is turned on - but filaments may be overlapped.



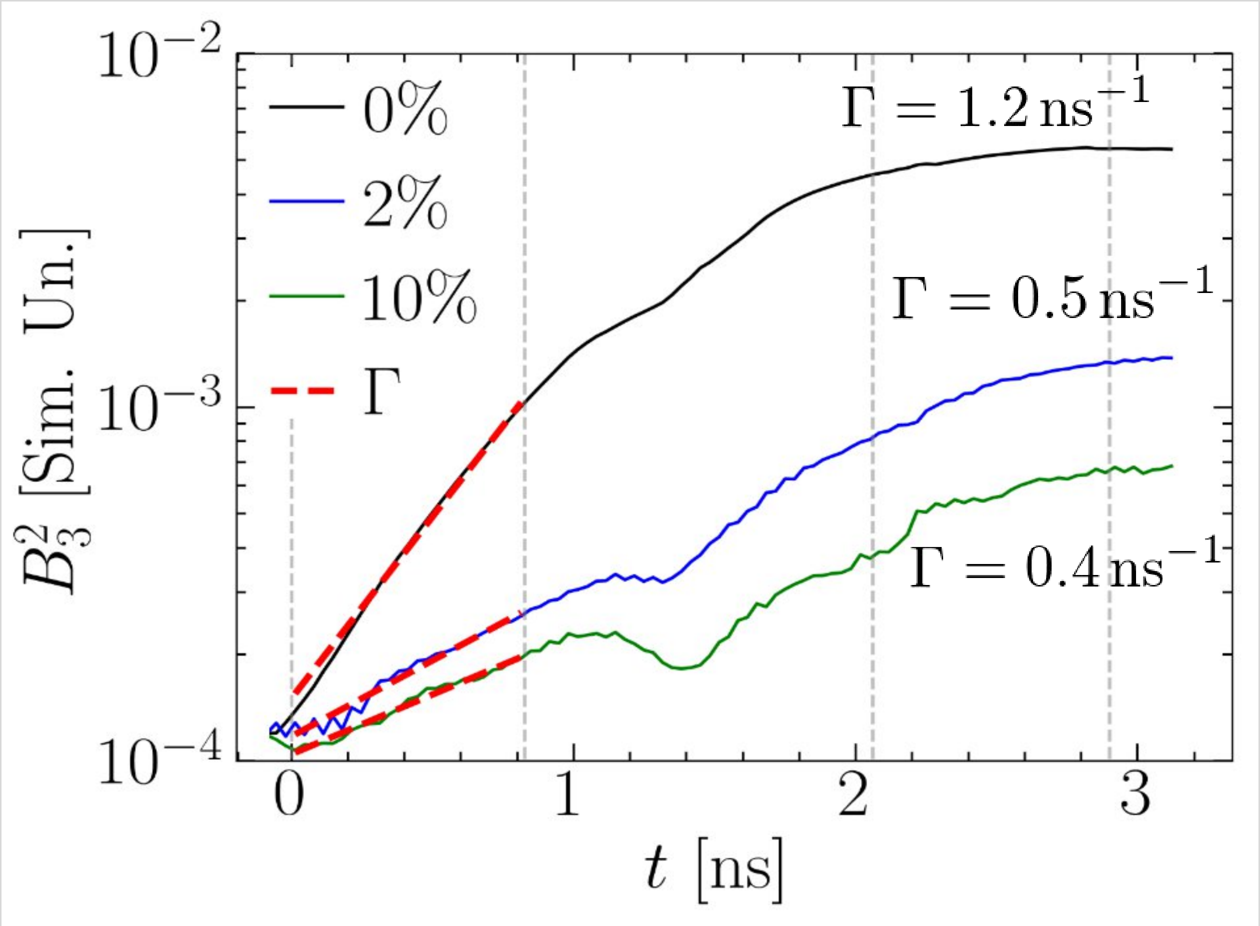
Numerical simulations shows filaments forming for collimated pair beams



Arrowsmith et al., submitted (2024)

- ➜ With no transverse divergence, PIC simulations predict the formation of filaments at the plasma exit.
- ➜ With transverse divergence, PIC simulations **does not** predict the formation of filaments at the plasma exit.

Growth rate of instabilities is suppressed for collimated beams

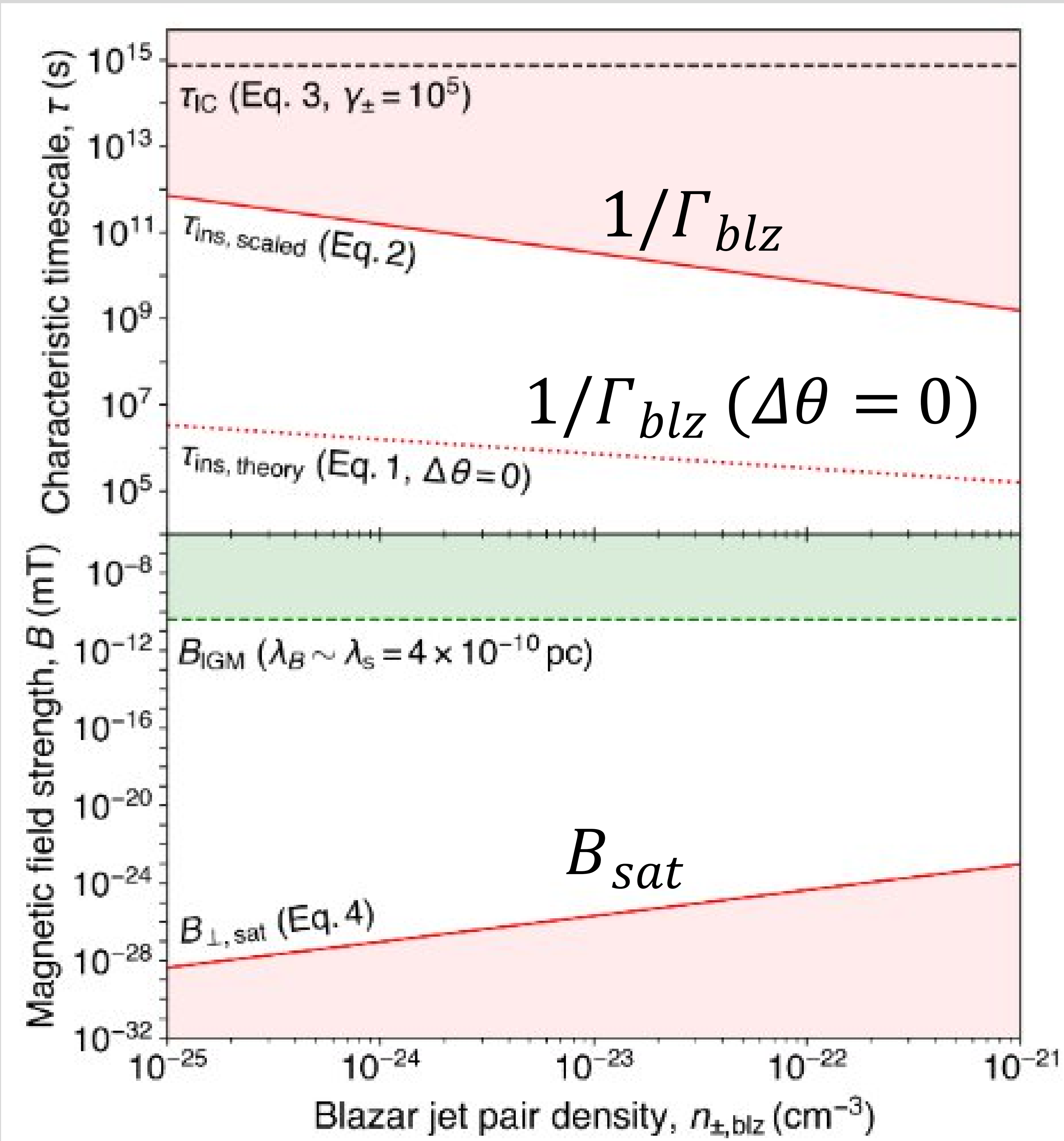


$$\Gamma_{exp} = \frac{1}{t_{prop}} ln\left(\frac{B_{exp}}{B_0}\right) \sim 0.5\ ns^{-1}$$

➜ PIC simulations using realistic beam conditions predict that the growth rates are strongly suppressed compared to idealized linear theory, and saturated magnetic field strengths are much smaller.

➜ Filamentation instability growth rate estimates from PIC simulations agree with experimental constraint if beam is divergent $\Delta\theta \geq 0.02$.

Growth rate of instabilities is compared to other processes in the blazar's case



Arrowsmith et al., submitted (2024)

The instability grows very fast and it reaches the saturated state well before the Inverse Compton scattering becomes important.

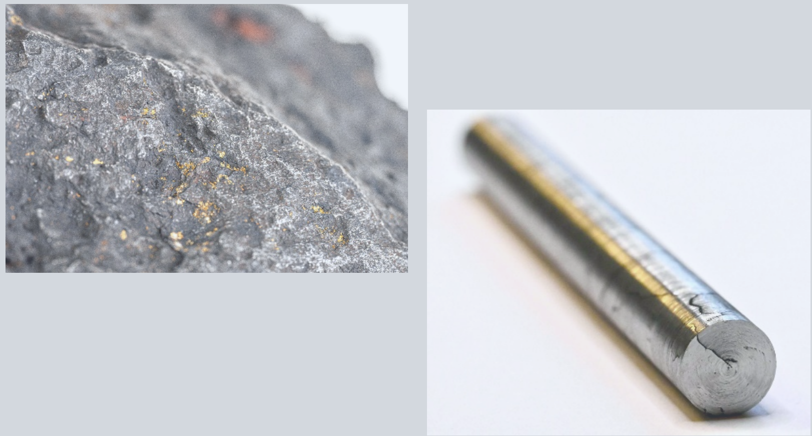
The saturated field is very small.

HRMT-64 has also been used to study properties of meteorite materials

Background	• Material properties of asteroid samples exhibit a dynamic response under high-energy/ high-intensity irradiation
Relevant research fields	• Asteroid deflection concepts – Accurate modeling of deflection orbits – Predicting transfer of kinetic energy • Study of the planetary core of the Earth • Super-Earth exoplanets], exemplified by NASA's mission 16 Psyche • Advanced material science
Recent discussion	Moore, Nathan W., et al. "Simulation of asteroid deflection with a megajoule-class X-ray pulse." *Nature Physics* (2024). • Breakthrough measurement since for the first time total momentum transfer onto a scaled mock asteroid was achieved • No experiments are known that cover direct form of material response
MOTIVATION	Measure dynamical response of momentum transferred onto the meteorite sample in real-time

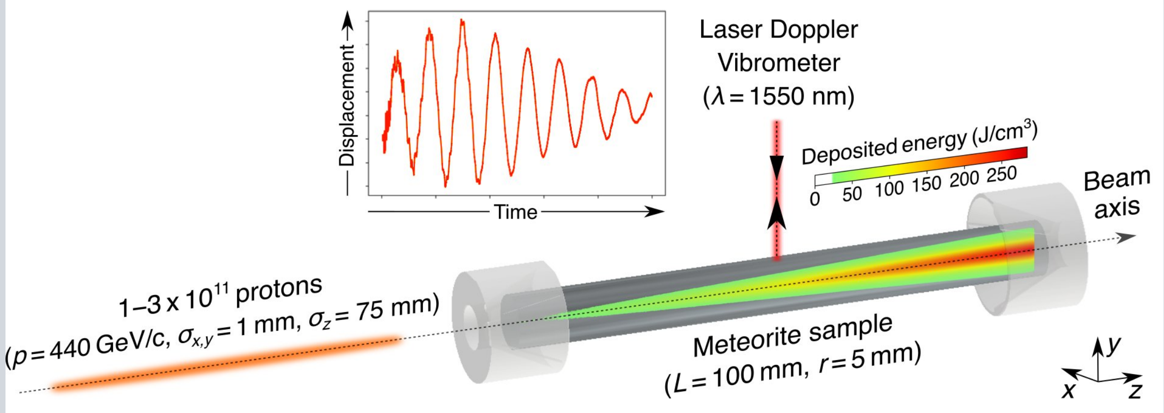
Meteorite experiment took place as a parasitic proof-of-principle test

CAMPO DEL CIELO IRON METEORITE



- *Campo del Cielo* iron meteorite was cut into a cylindrical shape
  - 100 mm in length
  - 5 mm in radius
- Phase boundary was placed under LDV

EXPERIMENTAL SETUP IN FIREBALL II

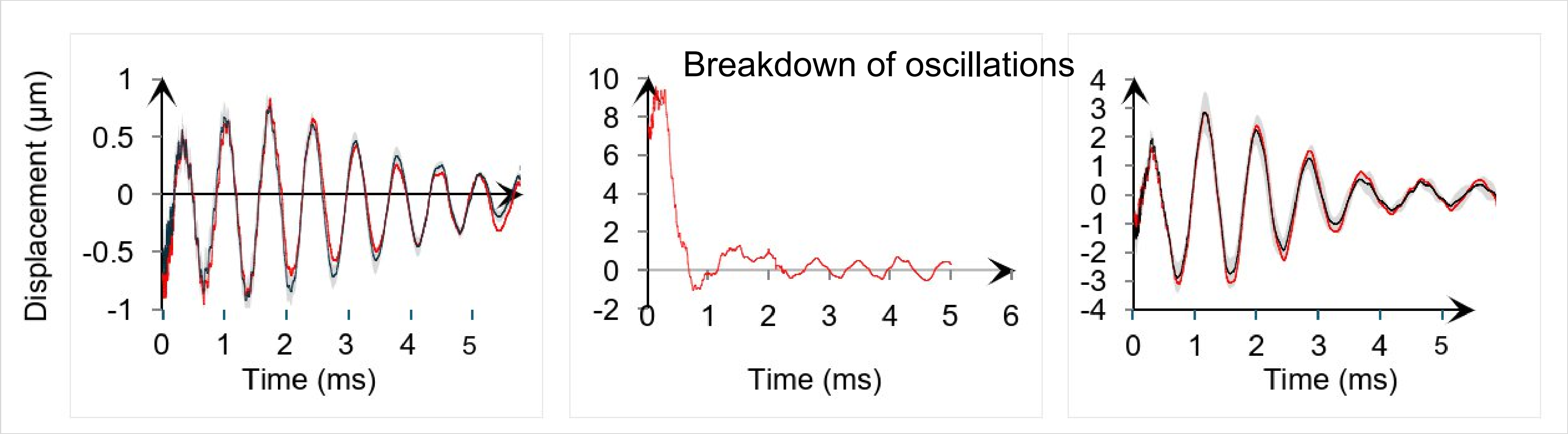


- 27 beam shots with 440 GeV/c protons
  - 14 shots at 1 x 10^{11} protons
  - 13 shots at 3 x 10^{11} protons
- Same setup as Fireball, with meteorite target
- Measurement of radial vibrations and deformation of the sample using Laser Doppler vibrometry (LDV)

Results from proton irradiation show significant hardening of meteorite material

LDV DISPLACEMENT DATA OVER TIME

Oscillating profile ▸ „Plastic“ profile ▸ Oscillating profile



Start | Experimental beam shots | End

- 8 shots @ 10^{11} protons
- σ_{VM} = 40 MPa

- 10 shots @ 10^{11} - 3 x 10^{11} protons
- σ_{VM} =120 MPa

- 4 shots @ 3 x 10^{11} protons
- σ_{VM} =120 MPa

DISCUSSION

- Dynamic change of material properties observed
- Fast and homogeneous hardening of meteorite material
- Critical advance on Moore paper: non-destructive probing & energy deposition from X-rays

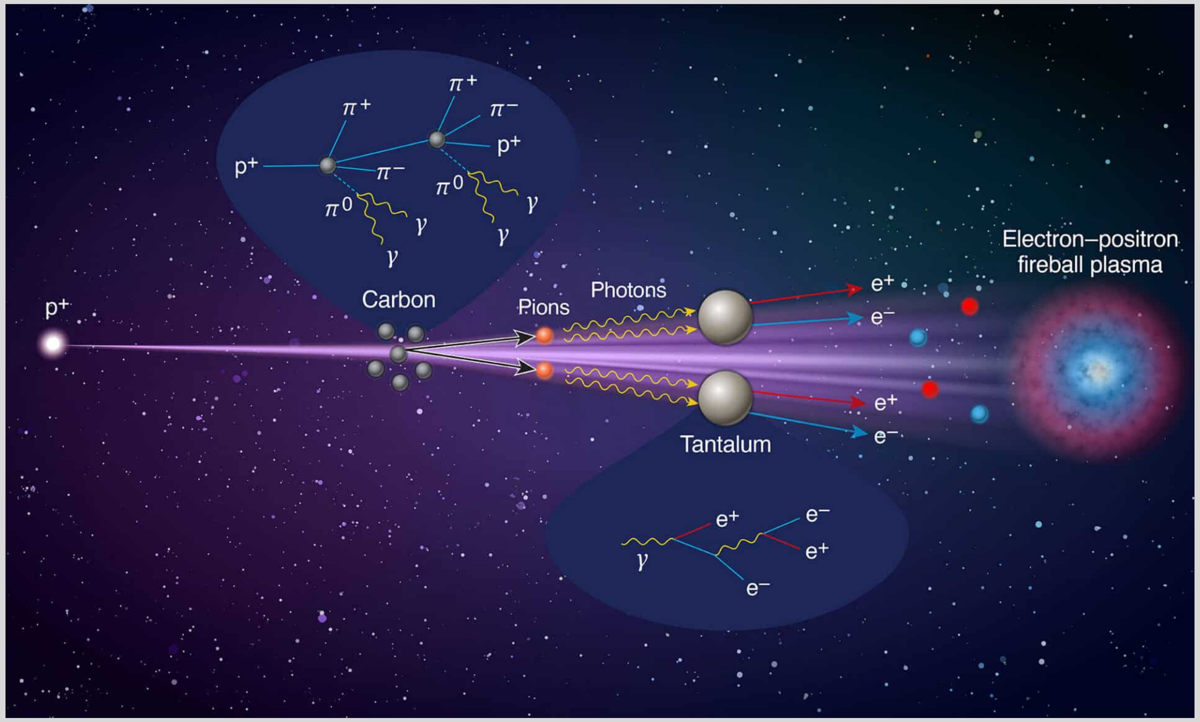
Impact from FIREBALL Collaboration

High impact research:

- 5 articles, 3 published in or submitted to Nature
- 14 press releases, including 2 from CERN
- Attention score of 260: 99th percentile of the 329,972 tracked articles of a similar age in all journals.

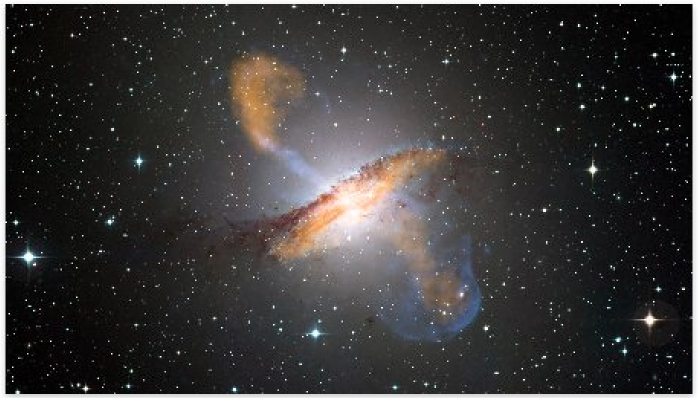
- **Novelty, impact and scope of research necessitates its continuation**

physicsworld



Publications

1. C.D. Arrowsmith et al. under review Nat. Phys.
2. C.D. Arrowsmith et al. Nature Communications, 15(1):5029, 2024
3. C.D. Arrowsmith et al. *JINST* **18** P04008, 2023
4. C.D. Arrowsmith et al. Phys. Rev. Res., 3:023103, 2021
5. M. Bochmann et al. submitted to Nature Communications



Bringing black hole jets down to Earth

The Fireball collaboration has used CERN's HiRadMat facility to produce an analogue of the jets of matter and antimatter that stream out of some black holes and neutron stars

News | Physics | 13 June, 2024

CERN

The whole team in the CCC at the end of the experiment