A measurement of a relativistic pair-plasma beam instability at the HiRadMat Facility (CERN)

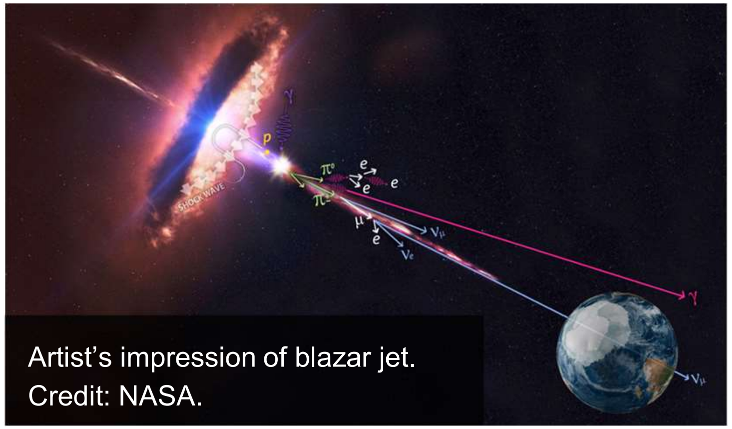
Jack Halliday[1,7]*, Charlie Arrowsmith[1], F. Miniati[1], P. J. Bilbao[2], P. Simon[3,4], E. Andersen[5], A. F. A. Bott[1], S. Burger[3], H. Chen[6], F. D. Cruz[2], T. Davenne[7], A. Dyson[1], I. Efthymiopoulos[3], D. H. Froula[8], A. Goillot[3], J. T. Gudmundsson[9,10], D. Haberberger[8], T. Hodge[1,11], B. T. Huffman[1], S. Iaquinta[1], E. E. Los[1], G. Marshall[11], B. Reville[12], P. Rousiadou[13], S. Sarkar[1], A. A. Schekochihin[1], L. O. Silva[2], R. Simpson[6], V. Stergiou[1,3,14], R. M. G. M. Trines[7], T. Vieu[12], S. Zhang[1], N. Charitonidis[3], R. Bingham[7,15], G. Gregori[1]

APS Division of Plasma Physics Meeting 2024, 9th October 2024

*jack.halliday@stfc.ac.uk – jackhalliday.github.io/

[1]University of Oxford, [2]Instituto Superior Técnico, Lisboa, [3]European Organization for Nuclear Research (CERN), [4]GSI Helmholtzzentrum für Schwerionenforschung GmbH, [5]University of Bergen, [6]Lawrence Livermore National Laboratory, [7]STFC Rutherford Appleton Laboratory, [8]University of Rochester Laboratory for Laser Energetics, [9]University of Iceland, [10]KTH Royal Institute of Technology, Stockholm, [11]AWE, [12]Max-Planck-Institut für Kernphysik, Heidelberg, [13]University of Ioannina, [14]National Technical University of Athens, [15]University of Strathclyde.

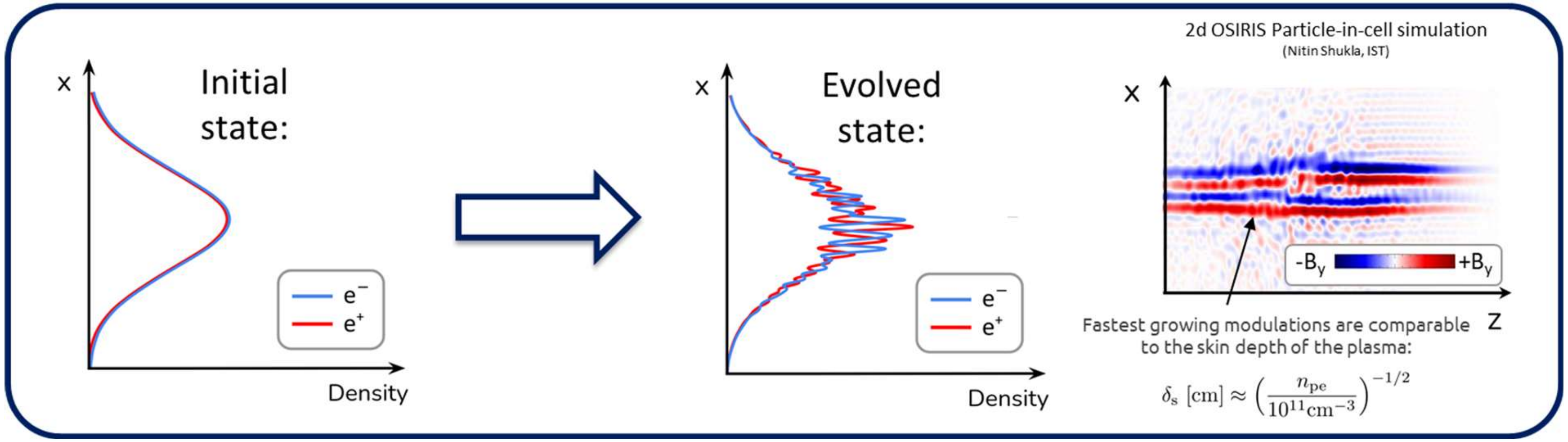
Mass symmetry in pair plasmas leads to different plasma behaviour to traditional plasmas, and they can enrich outflows from extreme astrophysical objects



Artist's impression of blazar jet.
Credit: NASA.

Pair plasma processes play a fundamental role in energy dissipation and radiative emission...

…but models have never been tested in the laboratory.

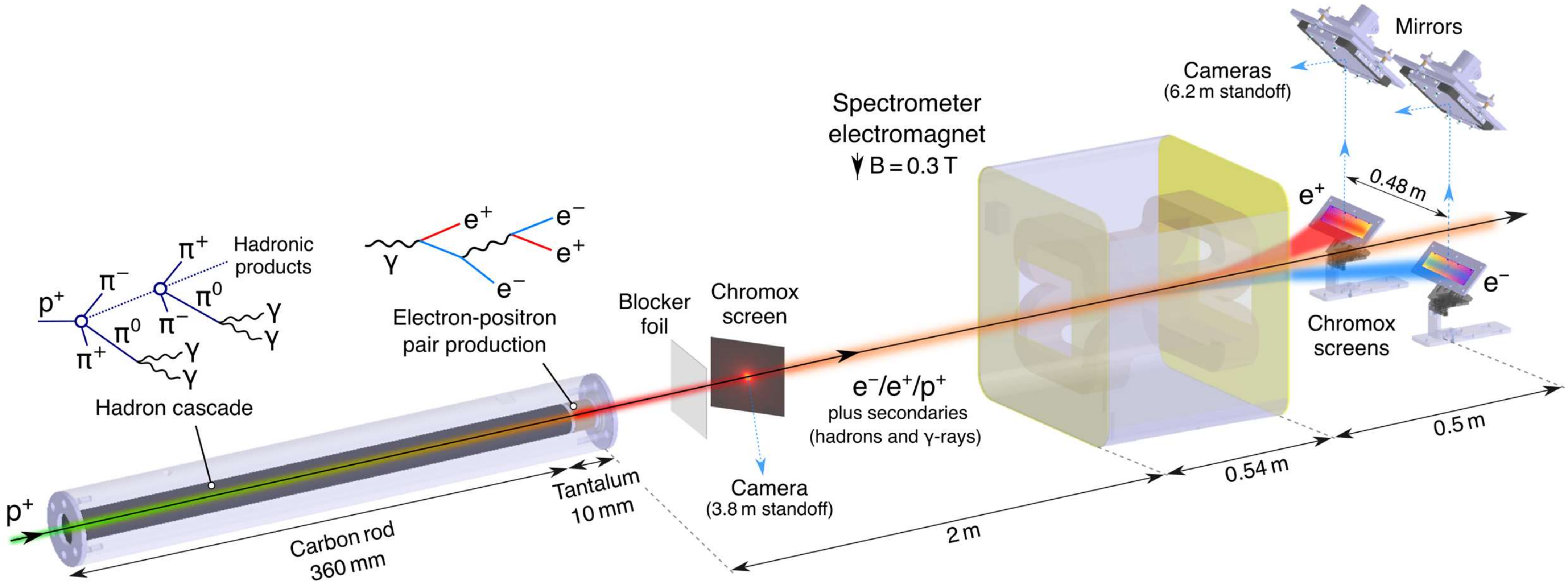


2d OSIRIS Particle-in-cell simulation
(Nitin Shukla, IST)

Fastest growing modulations are comparable to the skin depth of the plasma:

$$\delta_s\ [\mathrm{cm}] \approx \left(\frac{n_{\mathrm{pe}}}{10^{11}\mathrm{cm}^{-3}}\right)^{-1/2}$$

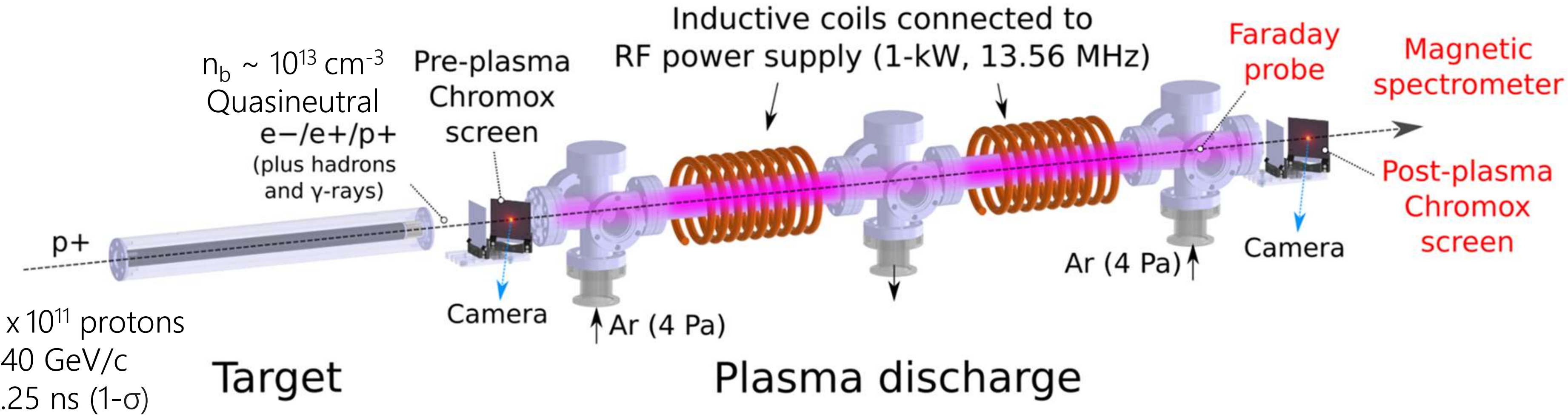
High-yield pair beams can be produced using ultra-relativistic protons accelerated by the Super Proton Synchrotron at CERN.



3×10^{11} protons
440 GeV/c
0.25 ns (1-σ)

C. D. Arrowsmith, et al., *"Laboratory realization of relativistic pair-plasma beams"*, Nature Communications **15**, 5029 (2024).

A laboratory testbed for relativistic electron positron plasma studies has been developed at the HiRadMat facility, driven using the Super Proton Synchrotron at CERN



$n_b \sim 10^{13}$ cm^{-3}
Quasineutral
e−/e+/p+

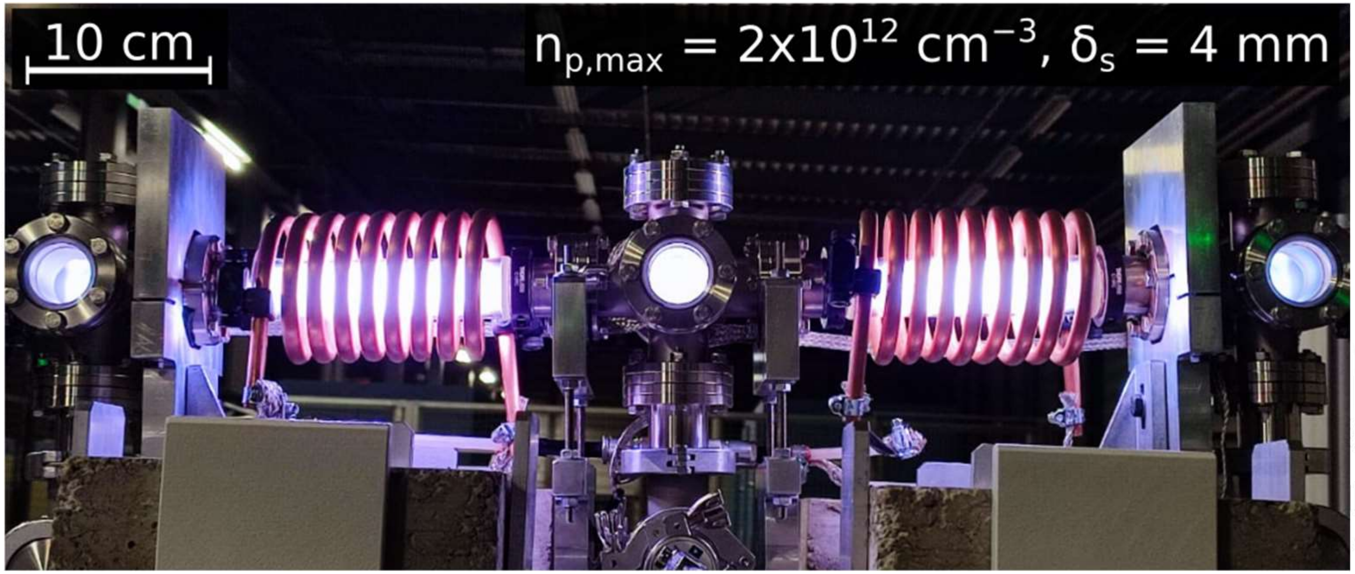
3 x 10^{11} protons
440 GeV/c
0.25 ns (1-σ)

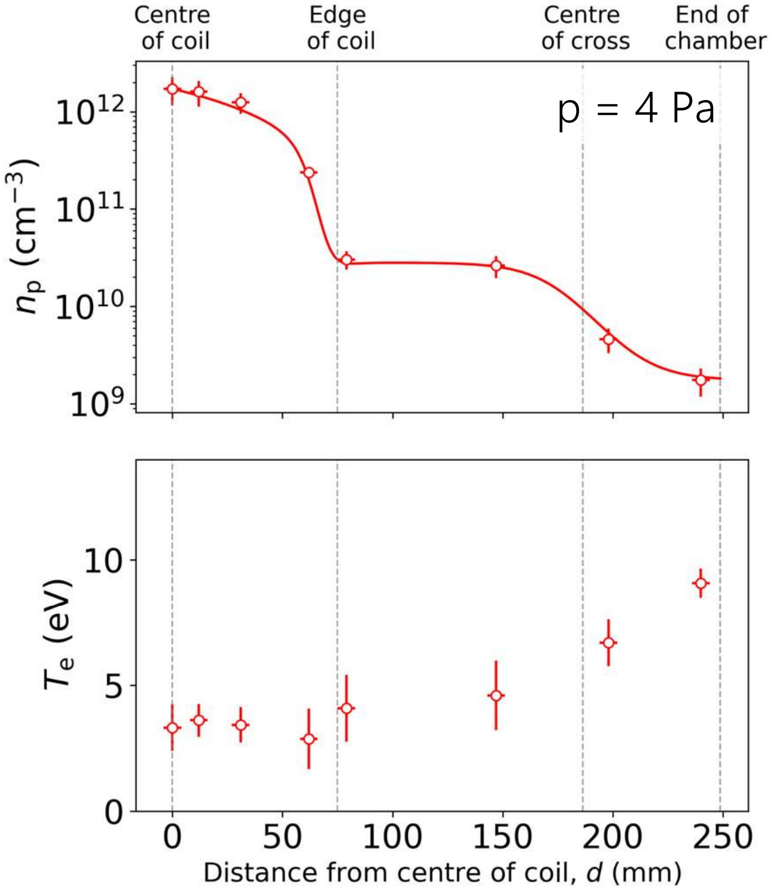
C. D . Arrowsmith et al., JINST 18(04), P04008 (2023)

For an ambient plasma, a meter-scale inductively coupled argon plasma discharge was constructed, and the plasma parameters characterized using a Langmuir probe.

Design criteria:

1. Beam dimensions exceed skin depth ($n_p > 10^{11}$ cm^{-3}).
2. Long enough for instabilities to develop (L ~ 10's of cm).
3. Diverging beam is contained over 1 m (d > 2.5 cm).





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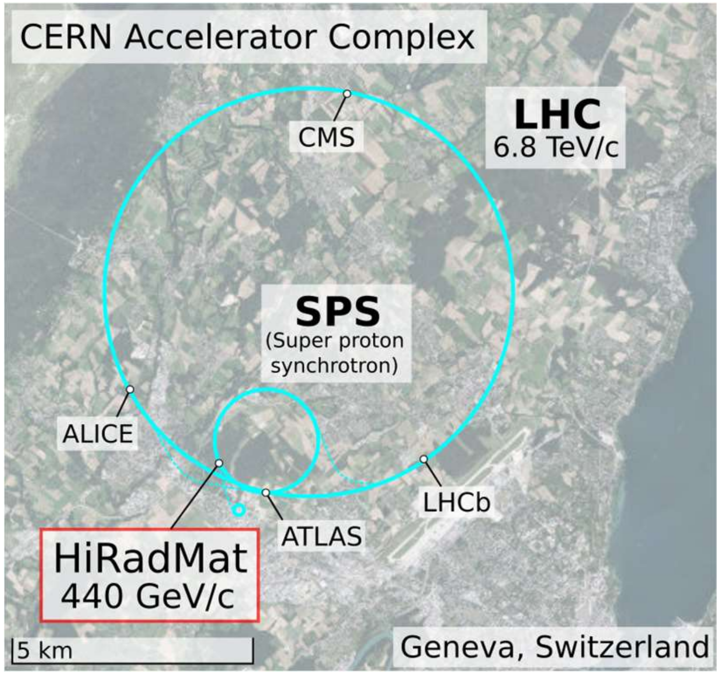

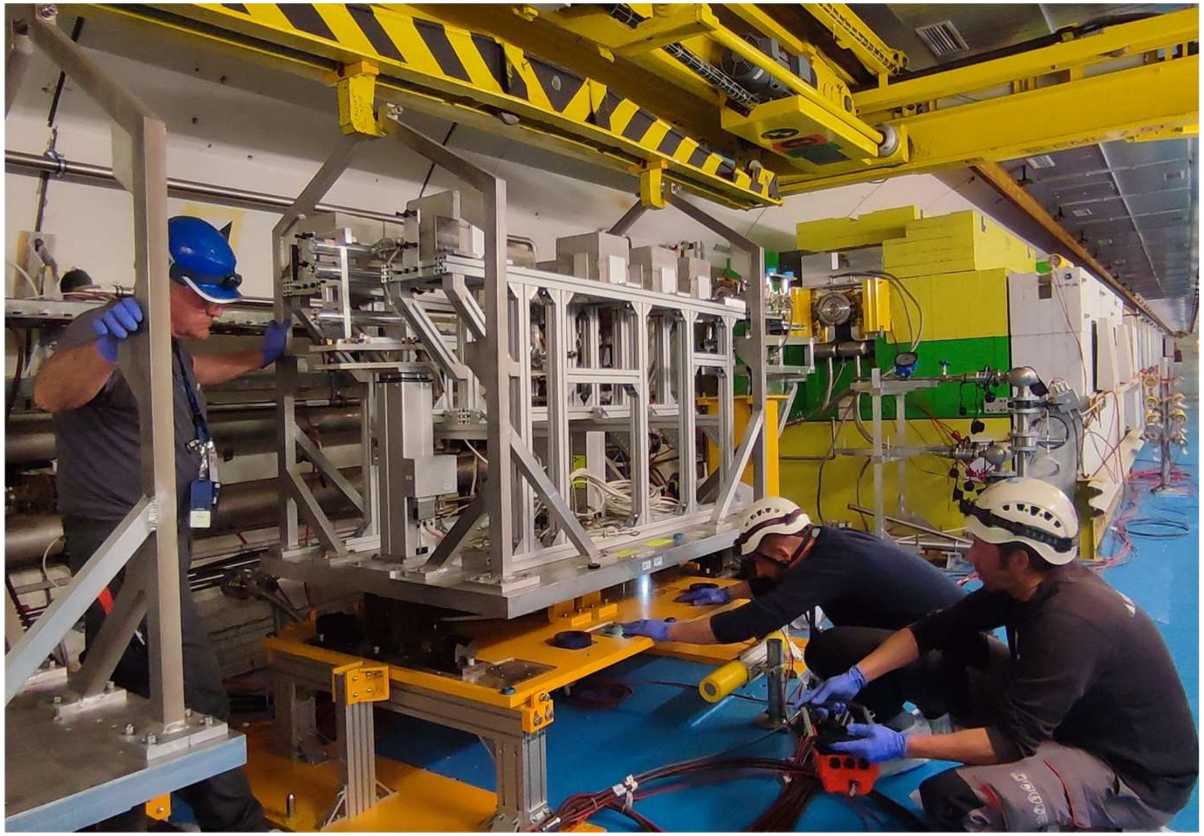

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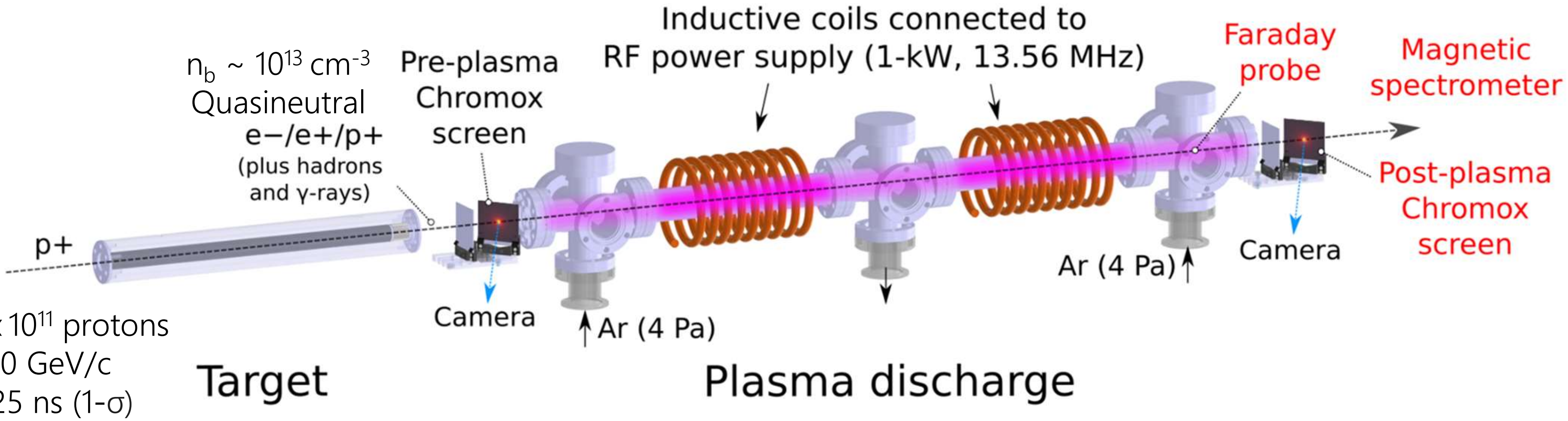

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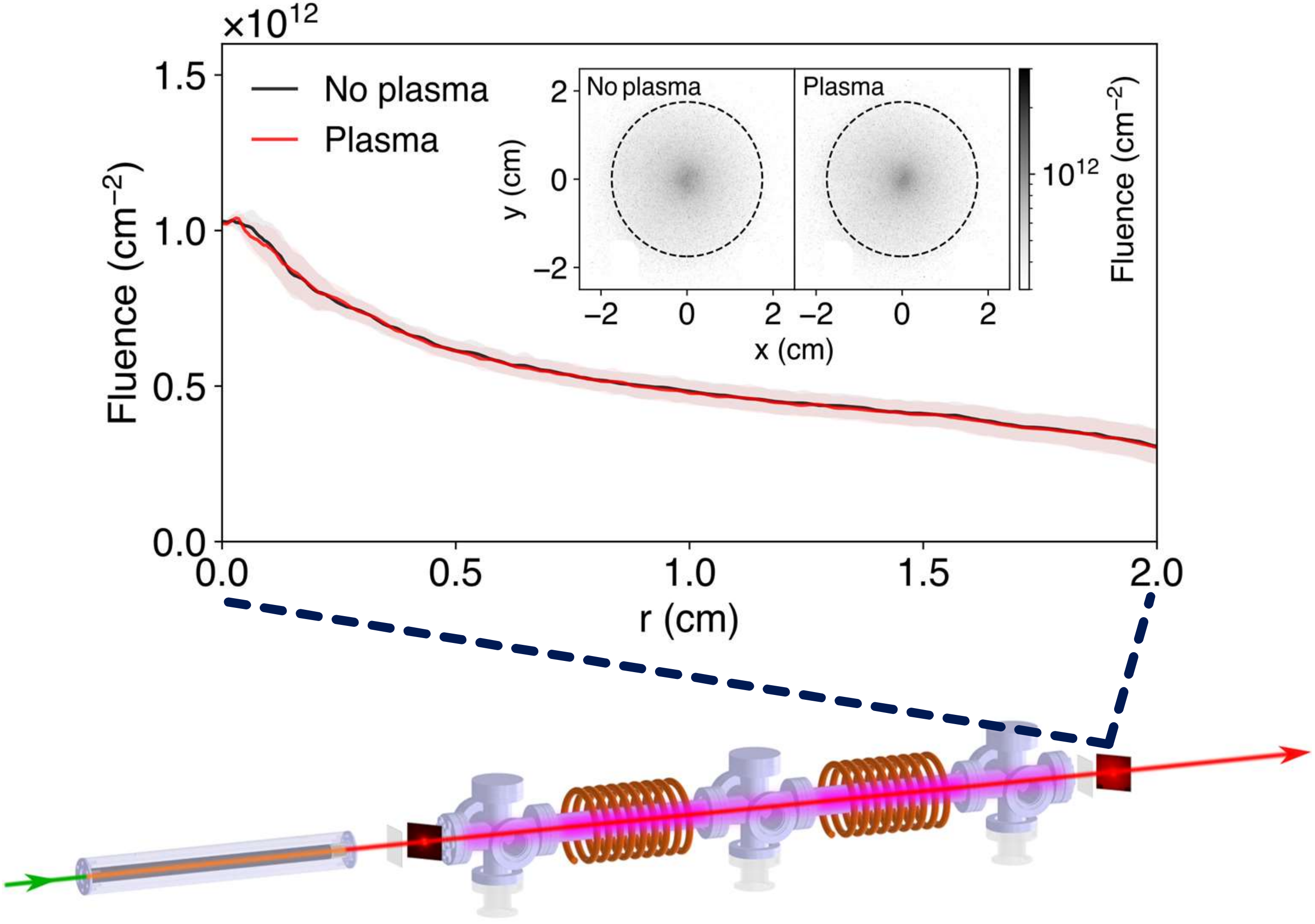
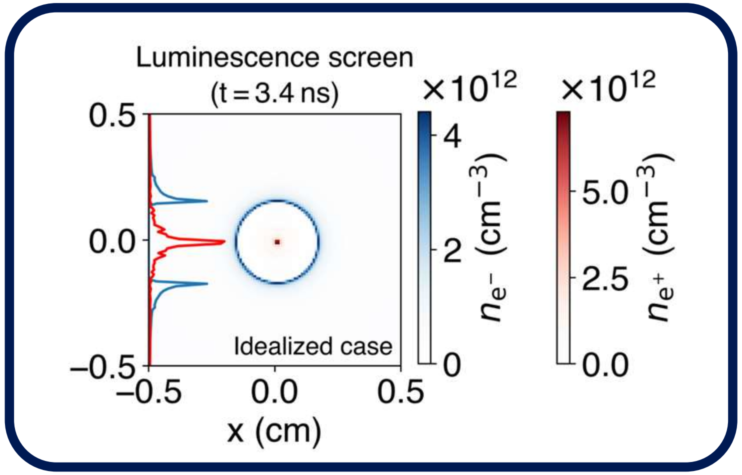
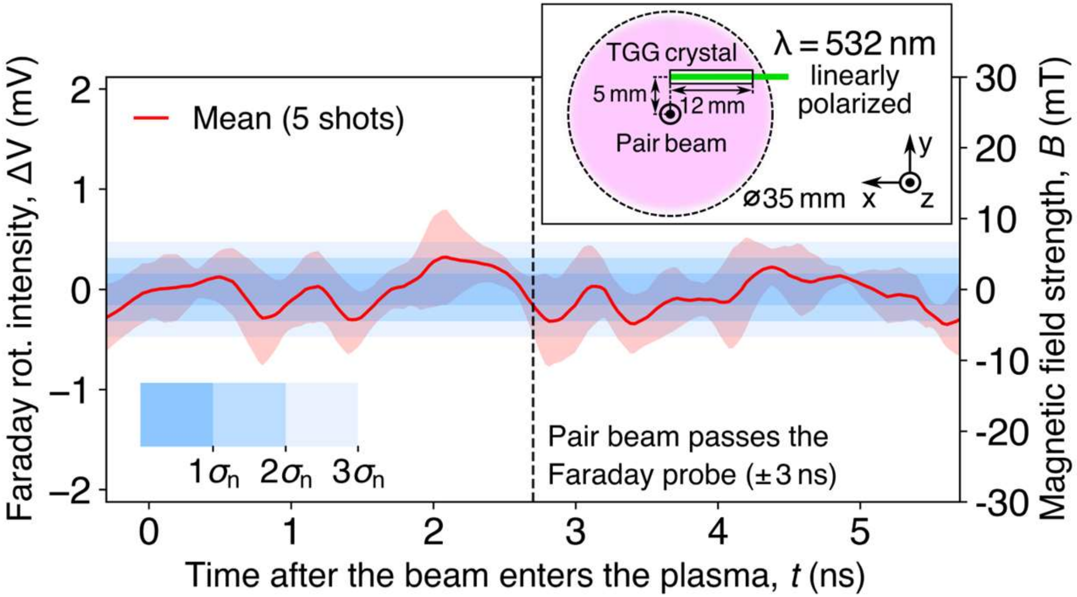
No evidence of filamentation is observed in the transverse beam profile, imaged using luminescence screens.

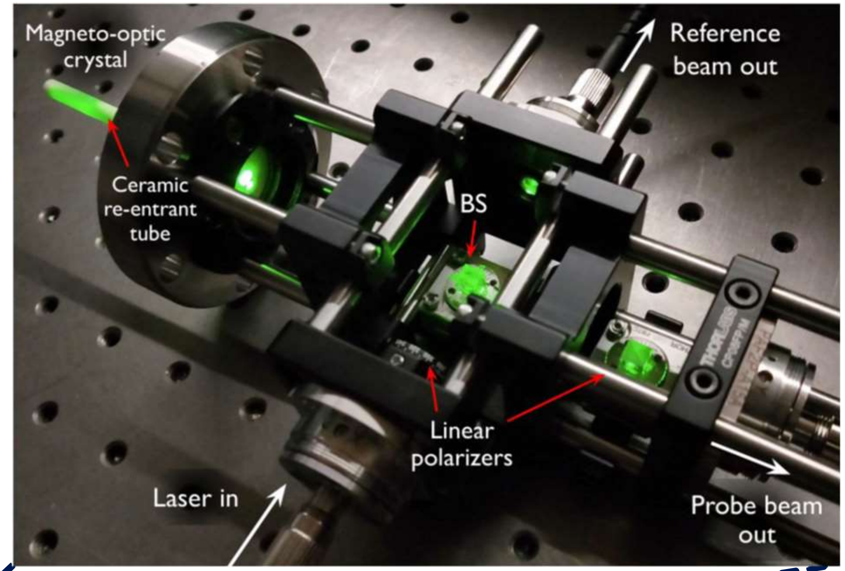


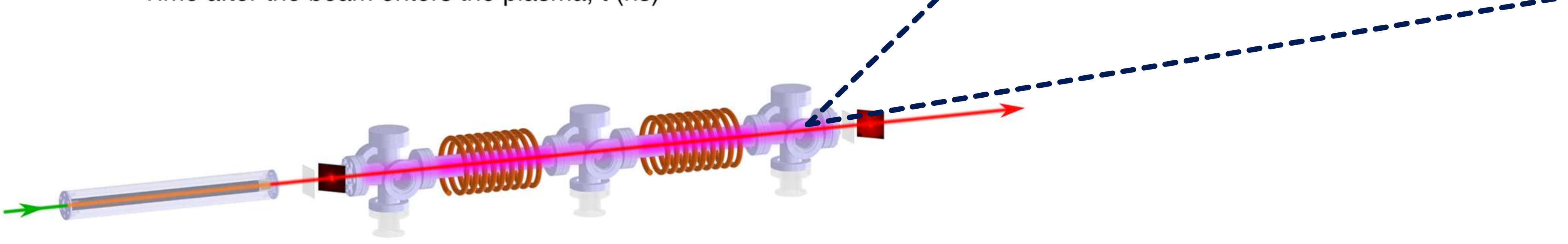
PIC (OSIRIS) simulation



Faraday rotation using a magneto-optic crystal achieves a magnetic field sensitivity of B~5 mT, but no significant fields are observed.

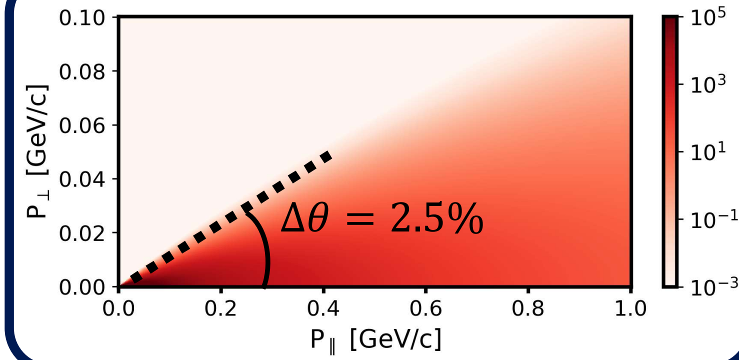


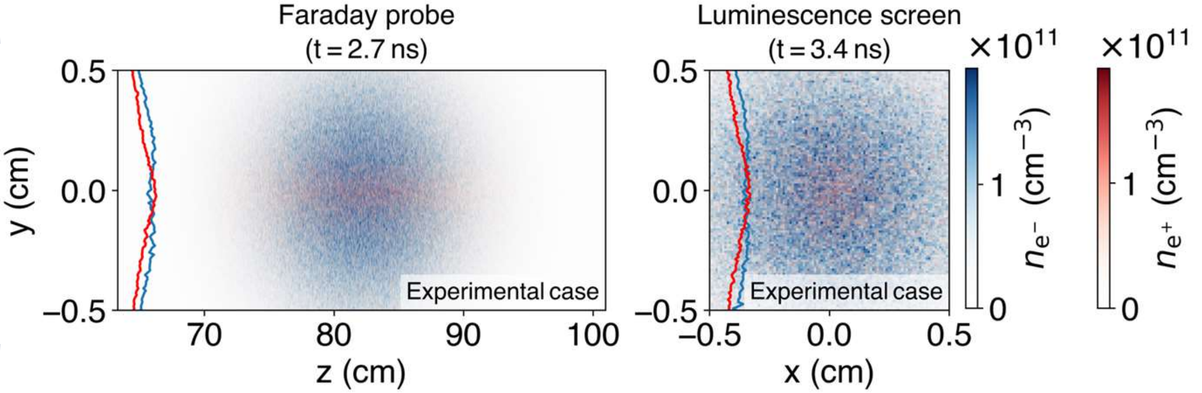




Suppressed beam instability due to the finite thermal spread of the beam is the most plausible explanation, which is confirmed by 3D particle-in-cell simulations.

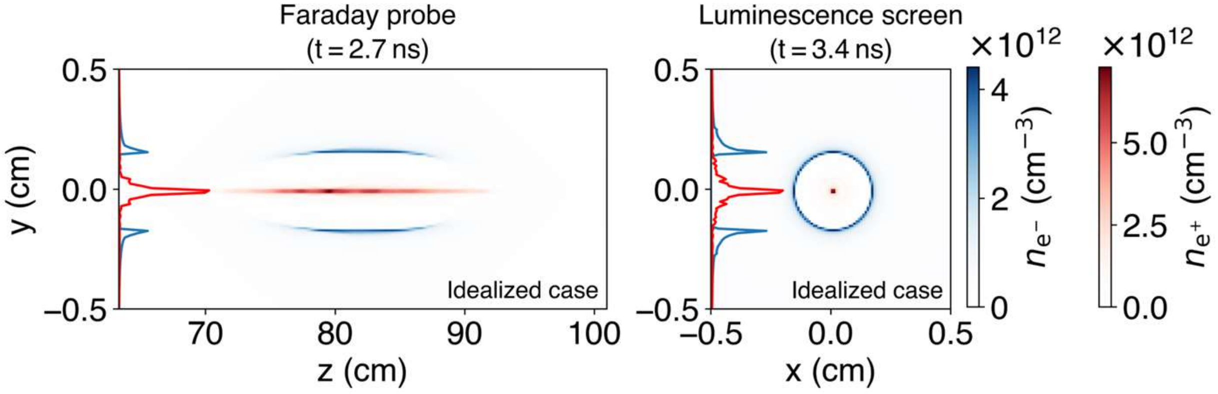
Experimental Conditions





Idealised Conditions

(cold beam, $\Delta\theta$=0)



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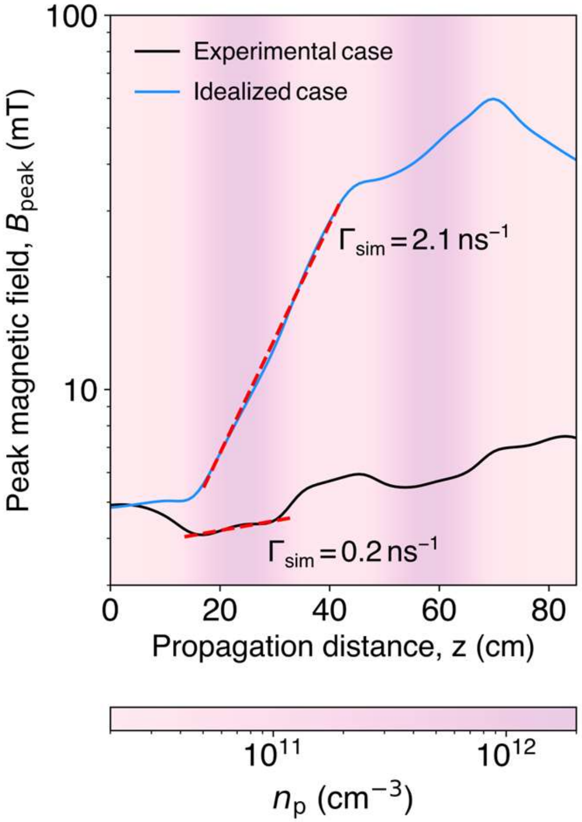
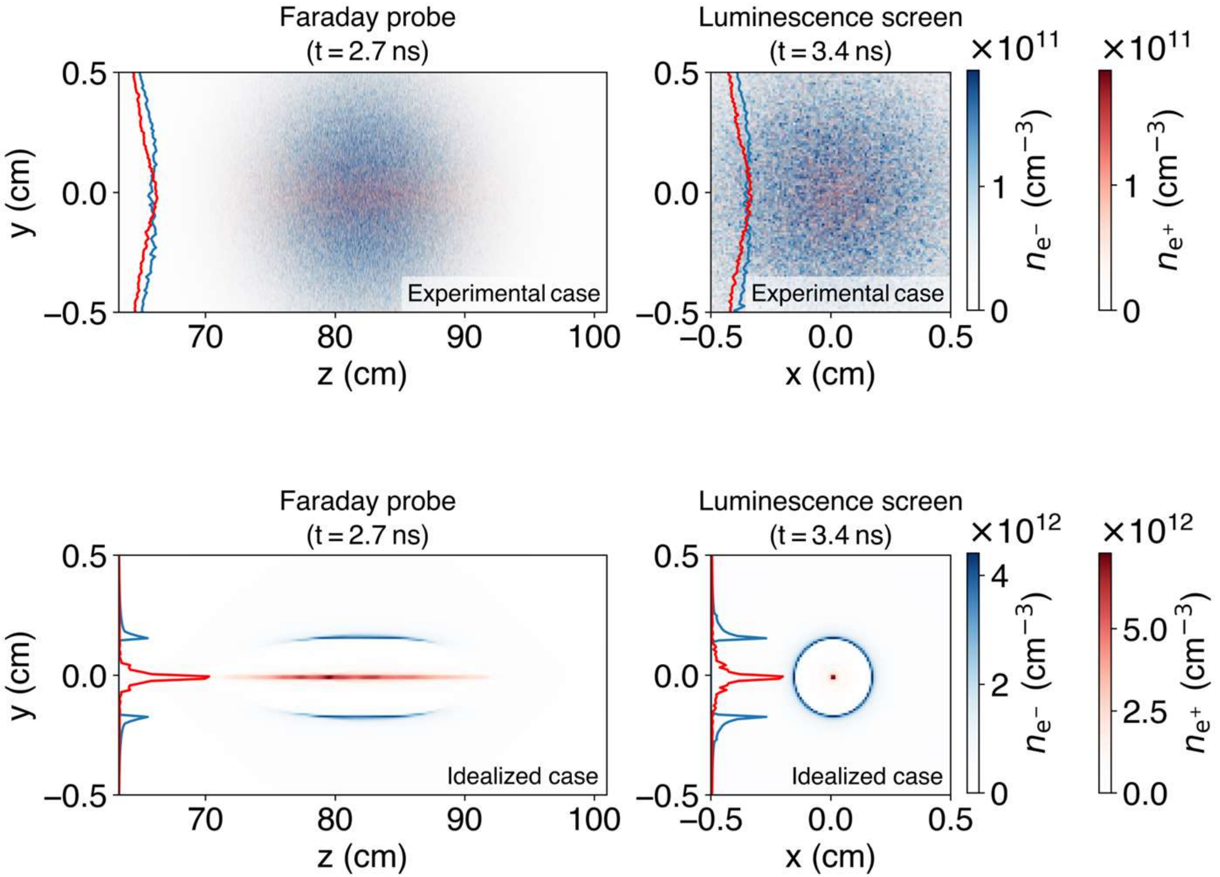
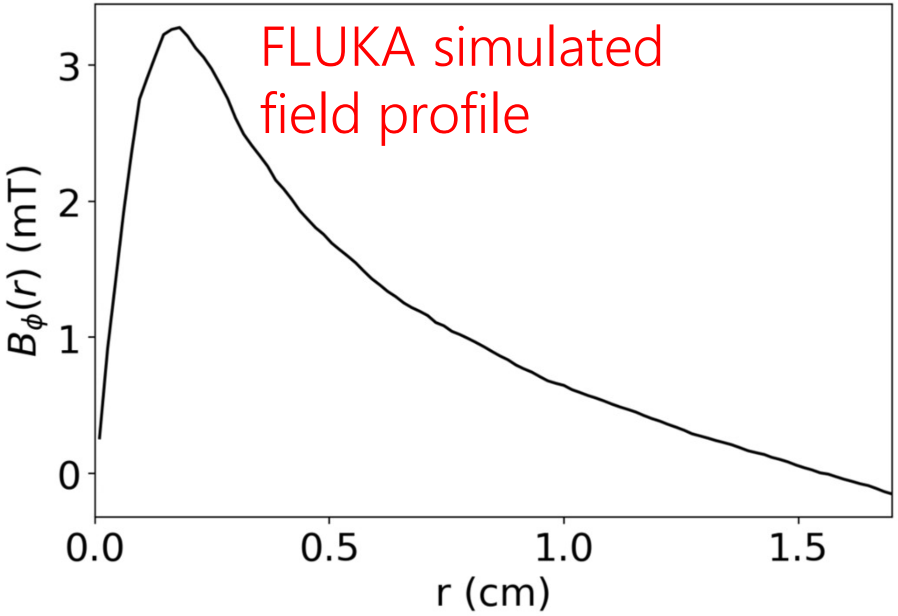




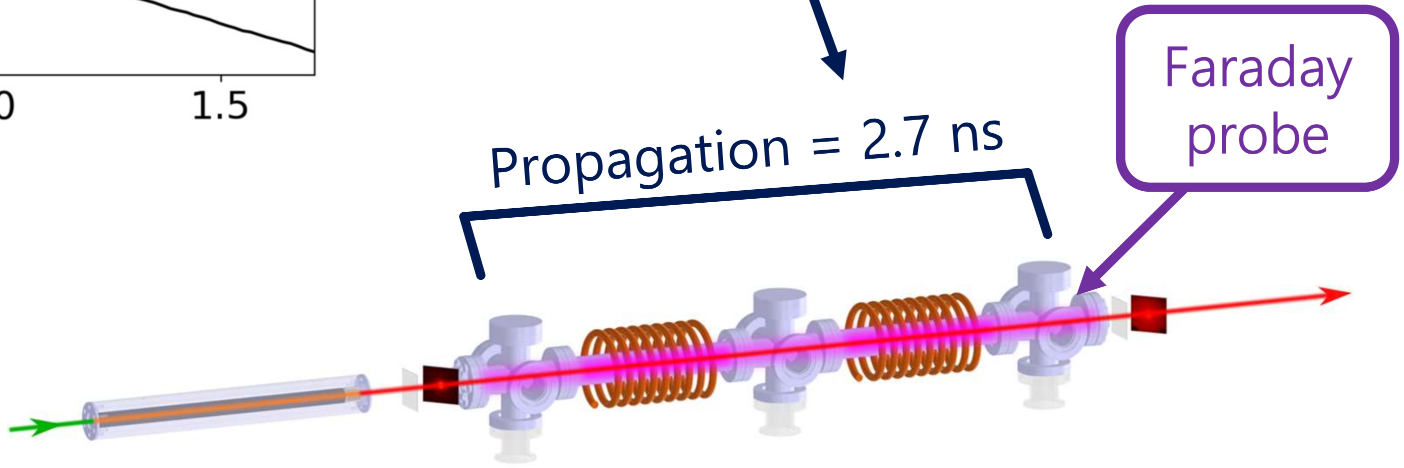
Assuming the instrument sensitivity as the upper bound, we estimate an upper bound for the growth rate of the magnetic field



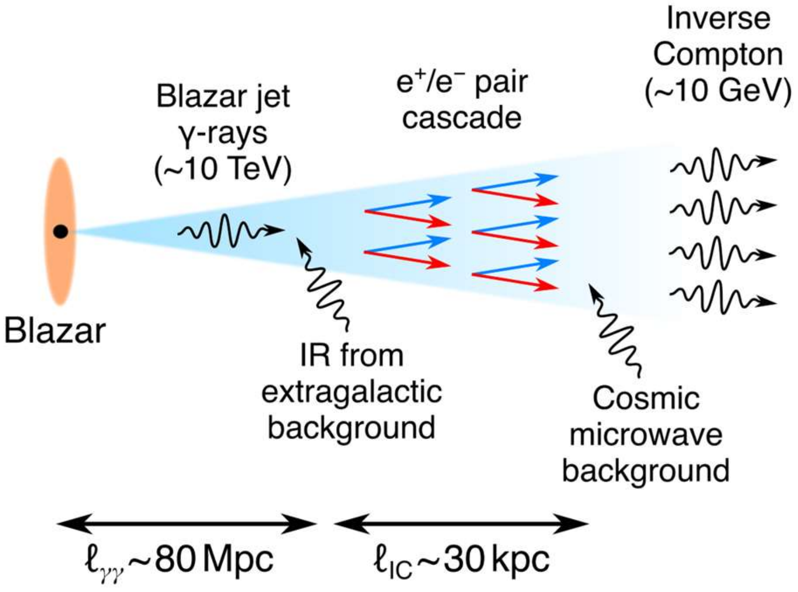
FLUKA + Ampere's Law ⇒ $B_0 = 0.78\ \mathrm{mT}$

Faraday sensitivity ⇒ $B_{\mathrm{exp}} \lesssim 5\ \mathrm{mT}$

$$\langle \Gamma_{\mathrm{exp}} \rangle \lesssim t_{\mathrm{prop}}^{-1} \ln\left(\frac{\langle B_{\mathrm{exp}} \rangle}{B_0}\right) \approx 0.7\ \mathrm{ns}^{-1}$$



Scaling the growth rate and saturated magnetic field amplitude



Theoretical growth rate:

$$\Gamma_{\text{fastest}} = \sqrt{2/3}\,\frac{\omega_p}{\Delta\theta}\left(\frac{n_\pm}{2n_p\gamma_\pm}\right)^{\frac{2}{3}} \qquad \left\{\Delta\theta \gg \left(\frac{n_{pm}}{2n_p\gamma_\pm}\right)^{1/3}\right\}$$

Scaling relation:

$$\Gamma_{\text{blz,sc}}[\text{s}^{-1}] \leq 3\times 10^{-11}\left(\frac{\Gamma_{\text{exp}}}{0.7\ \text{ns}^{-1}}\right)$$

	Pair beam			Plasma	
Parameter	$n_\pm$ (cm^{-3})	$\langle\gamma_\pm\rangle$	$\Delta\theta$	n_p (cm^{-3})	$\nu_\text{e}/\omega_\text{p}$
Experiment	5×10^{10}	10^3	0.025	10^{12}	10^{-3}
Typical blazar jet	10^{-23}	10^5	10^{-4}	2×10^{-7}	10^{-13}

Pair density, mean Lorentz factor and transverse momentum spread of beam, and electron density and collisionality of plasma.

Implications for blazar pair cascades – here include B scaling.