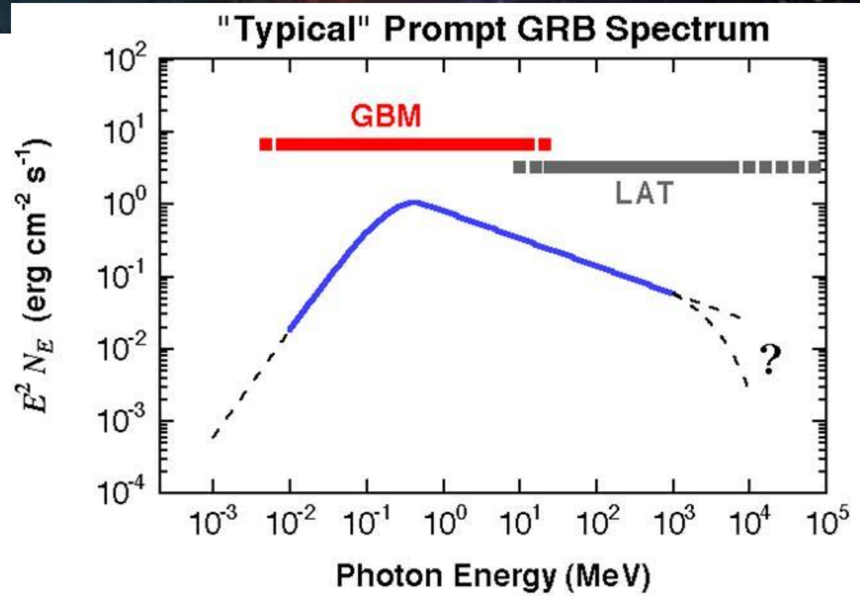
PHANTASY: PHotonuclear-hAdroN physics for parTicle AStrophYsics

Town Meeting, Hadron Physics in Horizon Europe, Nantes 1-3 July 2025

Principle Investigators: C. Curceanu (INFN-LNF), **G. Gregori (University of Oxford)**, B. Reville (Max Planck Institute for Nuclear Physics)

Motivation: Unlocking extreme Astrophysics

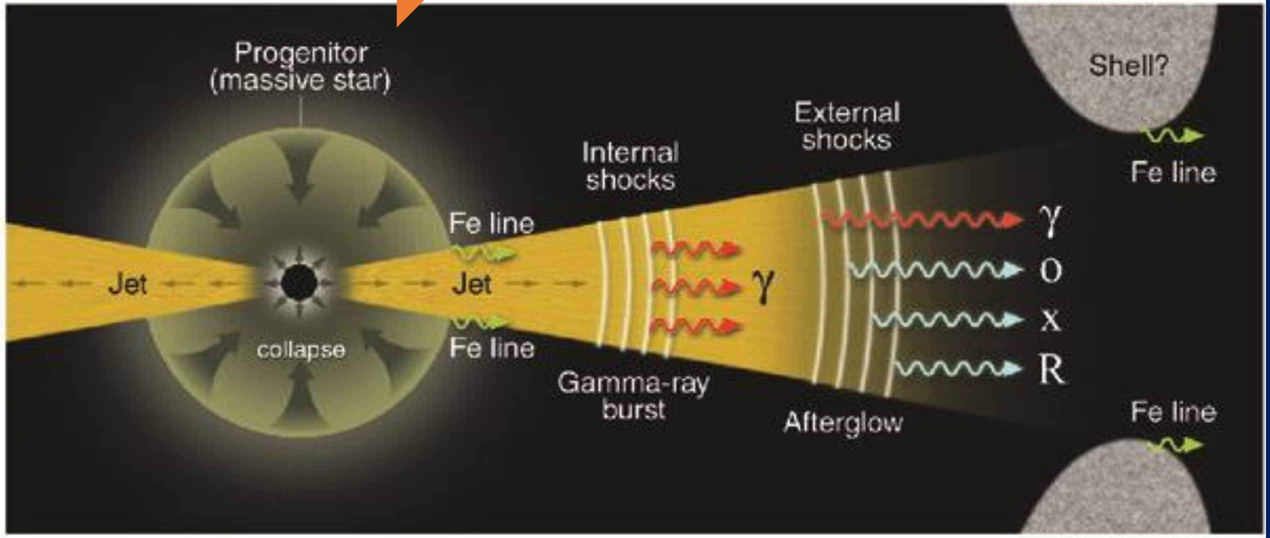
- **GRBs**: most luminous radiation source in the universe, gamma & X-rays.
- GRBs consist of ultra-relativistic beams of electron and positrons.
- High-energy photons are produced via Synchrotron and Inverse Compton Scattering (ICS) from the background stellar light.
- **These gamma rays interacts with intergalactic and interstellar medium. <u>The importance and relevance of involved processes, including hadronic interactions, are not well understood.</u>**



The astrophysical Gamma-ray Burst model

Fireball: relativistic e-e+ jets ejected by black holes, pulsars & quasars (BW process)

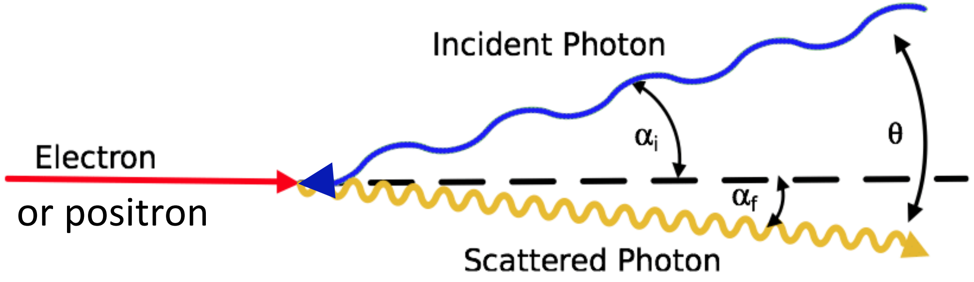
Pairs → Plasma instabilities → B field → Synchrotron emission



P. Mészáros, Science (2001)

ICS from pairs is a source of collimated high-energy photons

Pairs → ICS from ambient photons and from self-generated synchrotron



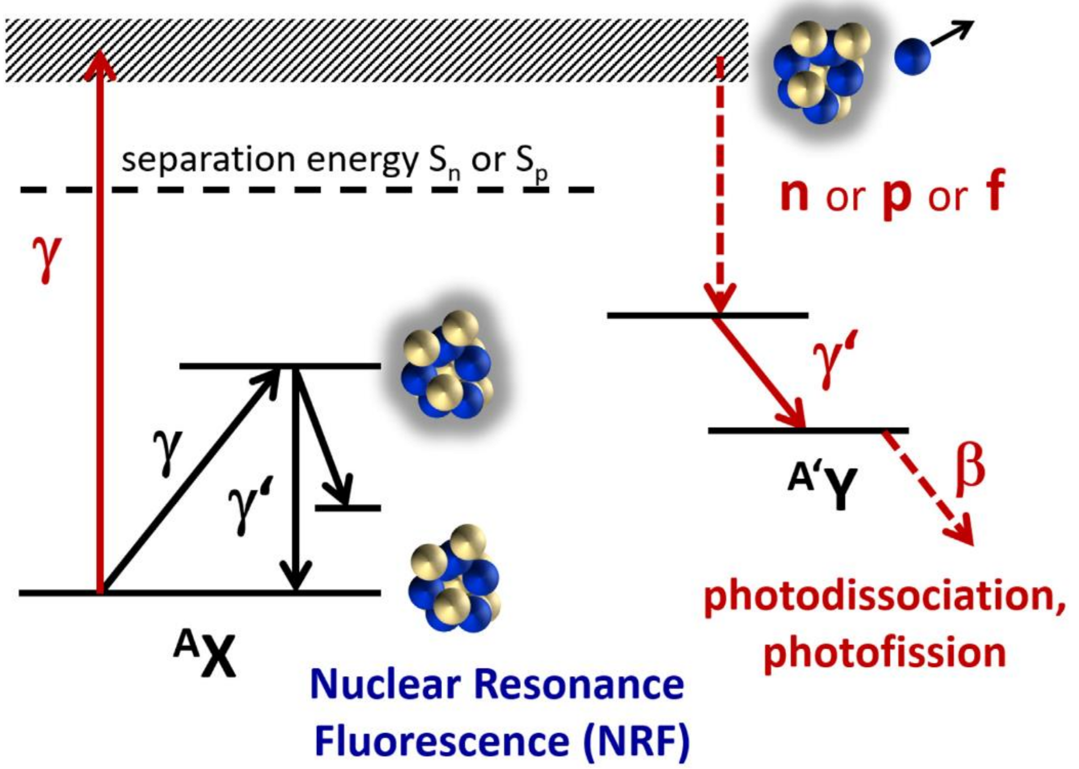
$$E_s = \frac{4}{3}\gamma^2\hbar\omega$$

$$N_s = 2\rho_p\sigma c t_{int}$$

$$\frac{N_s}{N_i N_e} = \frac{3r_e^2}{\pi r^2\gamma\hbar\omega}$$

Motivation: scientific background (2)

- MeV photons can break apart atomic nuclei — sensitive to the hadronic interaction models and nuclear structure inputs that define (γ,n), (γ,p), and (γ,α) cross sections.
    - **Important for the understanding of photo-induced processes by GRBs and SN explosions**
- Photonuclear reactions act as analogues for neutrino-induced processes:
    - **The interaction between neutrinos and nuclei is still one of the uncertain inputs for theoretical models of high-energy astrophysics**



A. Zilges et al. (2022)

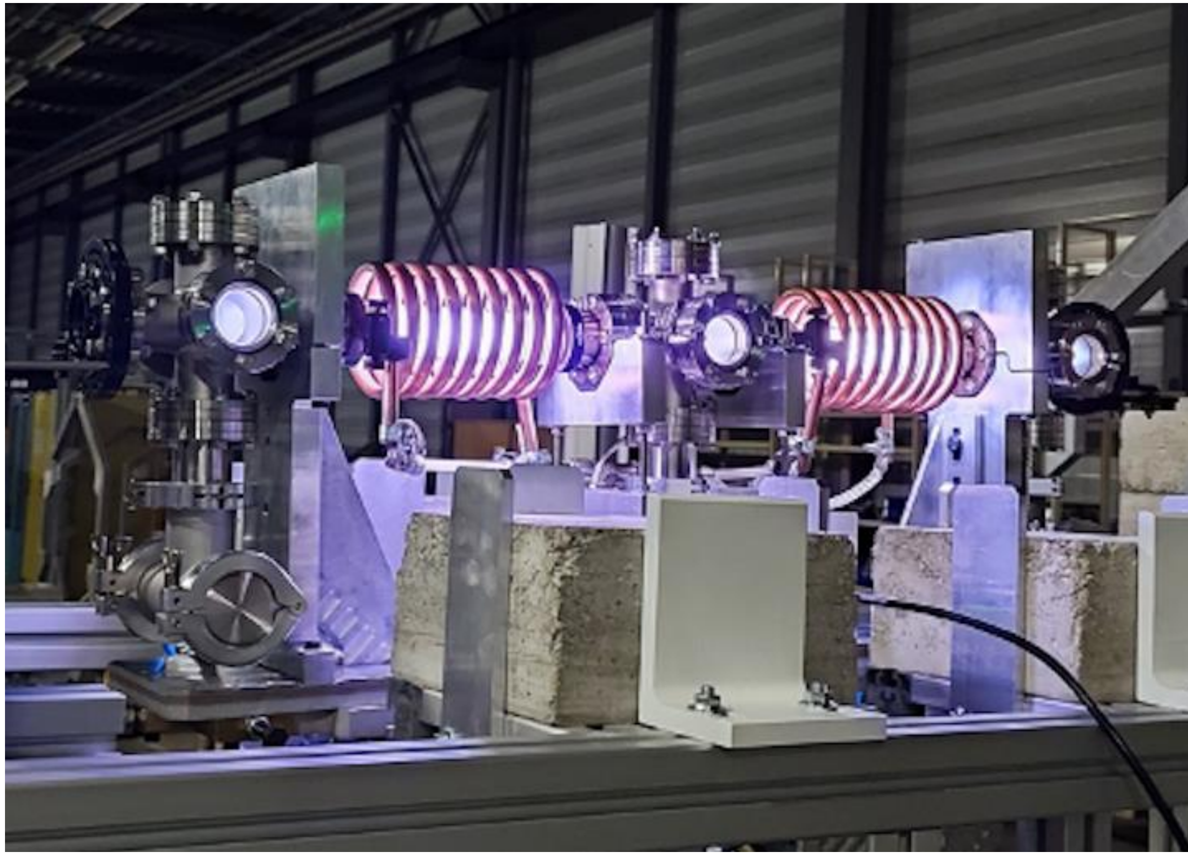
Motivation: PHANTASY aims to develop an experimental platform for Extreme Astroparticle Physics

Aim: validate astrophysical models of photonuclear interactions in Gamma-ray Bursts (GRBs) and Supernova (SN) explosions.

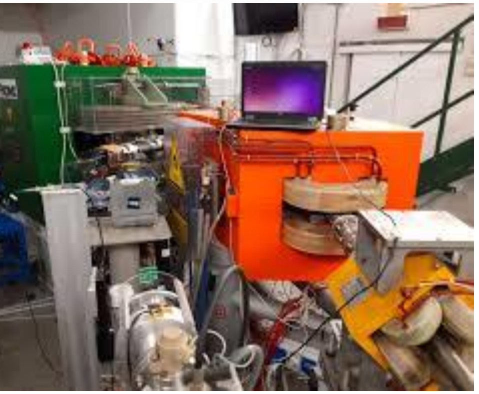
- Observations: limited resolution.
- Simulations: computationally expensive to resolve length scales orders of magnitude apart.

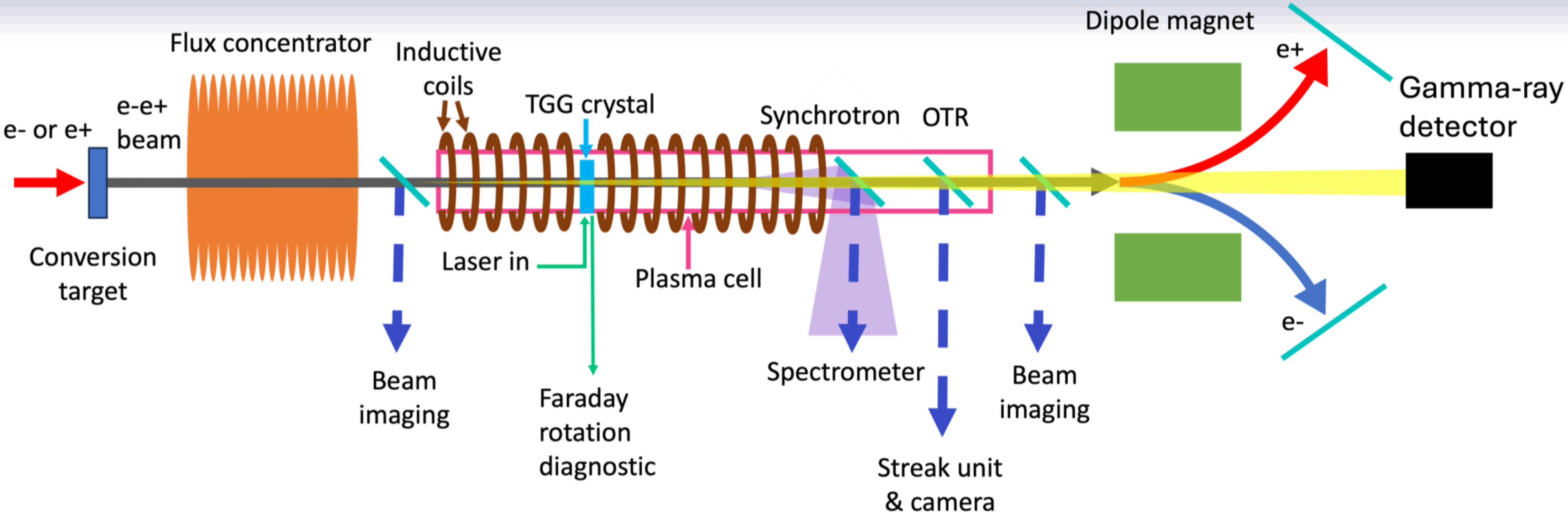
Laboratory experiments offer complementary access to key aspects involving hadron physics d.o.f. in extreme astrophysical environments.

Fireball at CERN



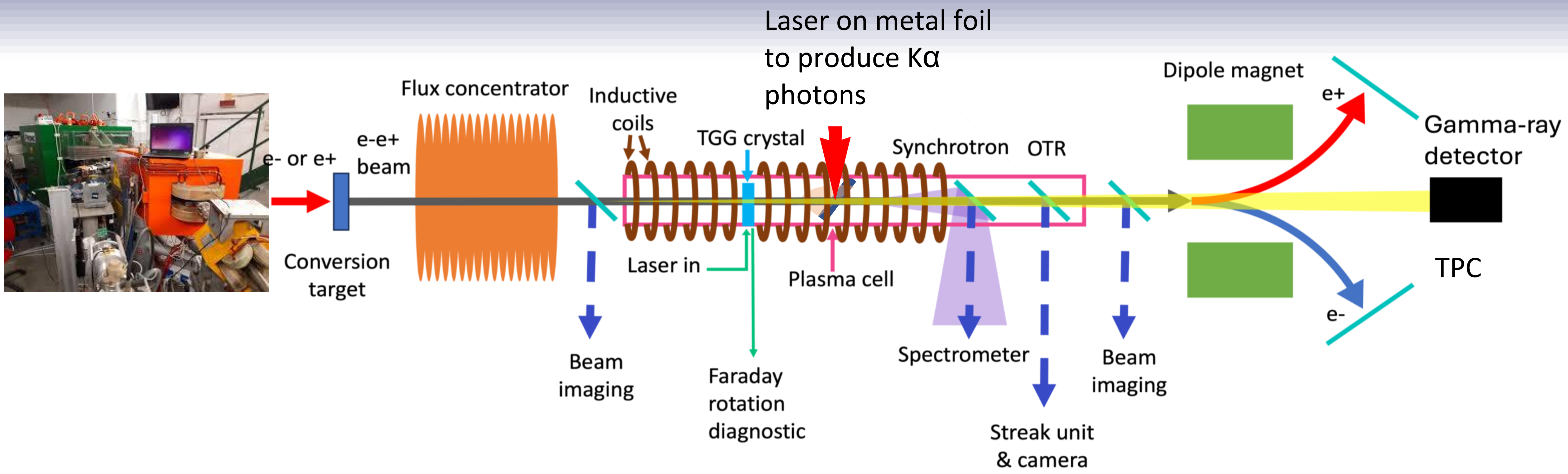
PHANTASY: a laboratory GRB to produce MeV photons





- **Use electron beam from BTF at LNF (or CERN or GSI…) to produce a shower of electron-positrons.**
- ICS produced from scattering off background plasma light and synchrotron radiation.
- Expect γ-ray spectrum to have power-law distribution energies up to a few MeV.
- Characterization X-ray/gamma led by developing dedicated detector (DRESS).

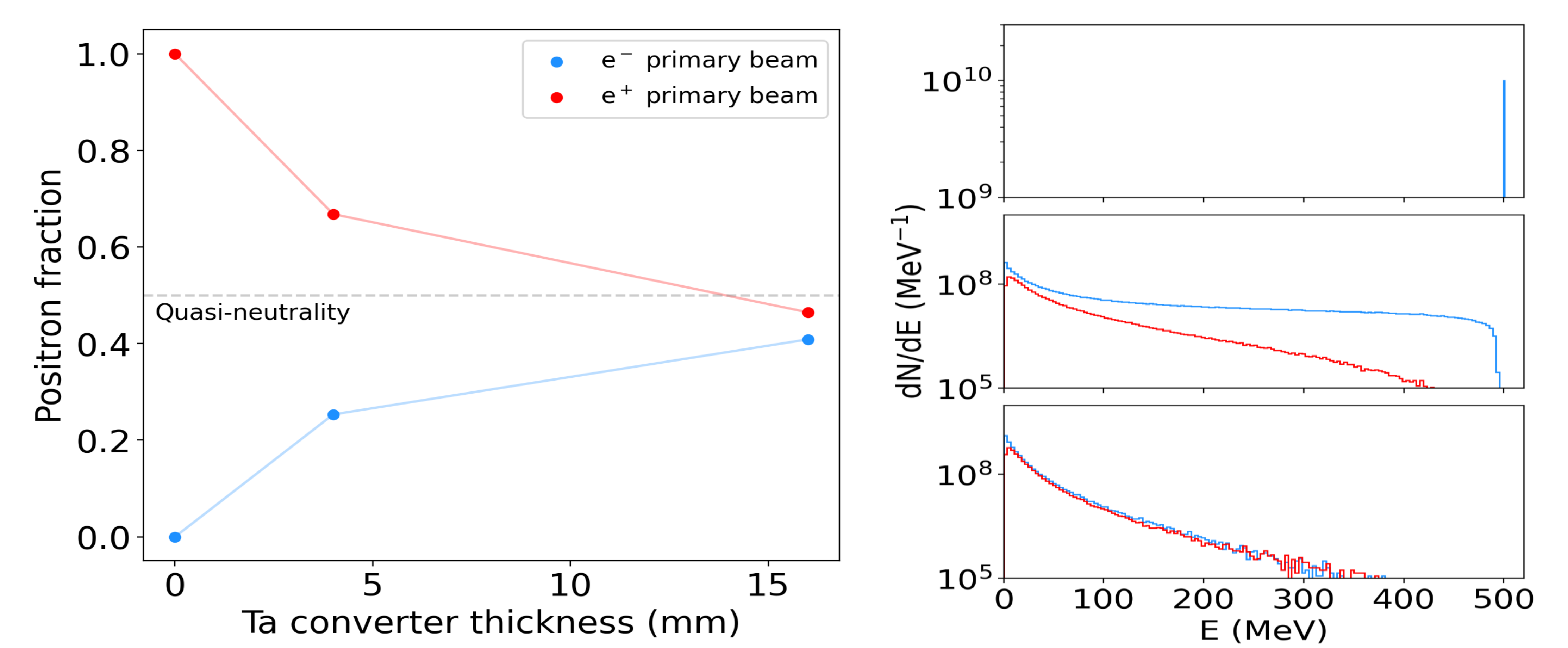
Multi-MeV gamma rays can be also generated



- Use secondary laser source on metal foil to generate Kα/Heα radiation in the ablated plasma plume
- Expect ICS to reach the Klein-Nishina limit and generate up to 100s MeV gamma rays
- Photoproduction reactions

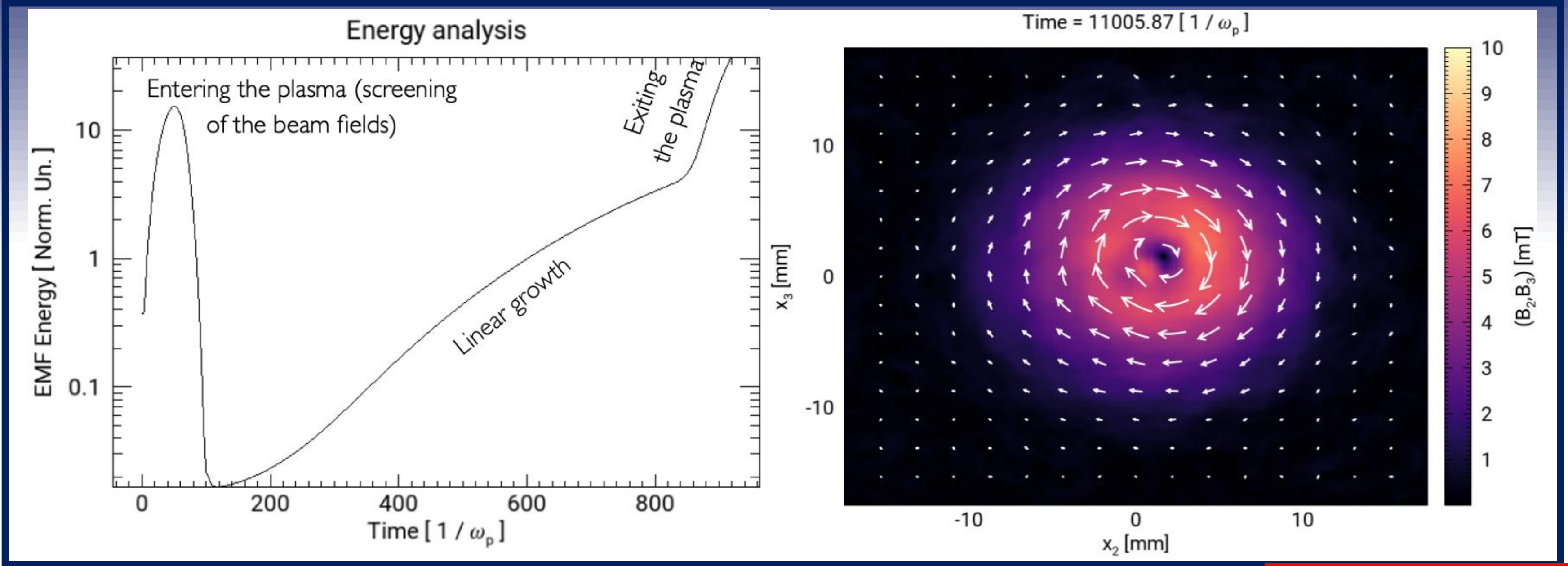
Pair beam showers: FLUKA simulations

Simulated incident electron beam: 10^{10} particles, 0.1-0.6 GeV energy, 1.5 ns duration.



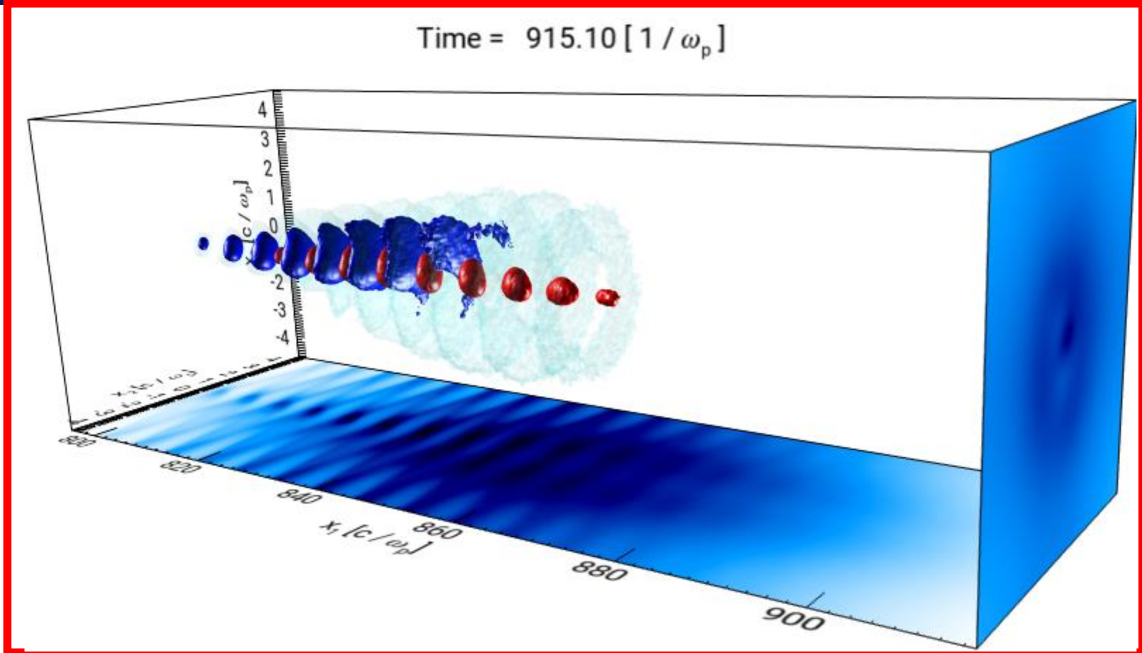
Approximate beam densities = 10^8–10^9 cm^{-3} (assuming 1 cm^2 beam size and 1.5 ns pulse).

Simulations of the self-generation of magnetic fields



Magnetic field

Beam density profile



- 3m plasma cell, uniform plasma, density 2×10^{12} cm^{-3}
- Pair beam 8×10^{12} cm^{-3} density, 2% divergence, 275 ps duration.
- 10 mT self-generated magnetic fields
- Primarily linear growth regime
- Plasma density modulations ~skin depth (10 ps)

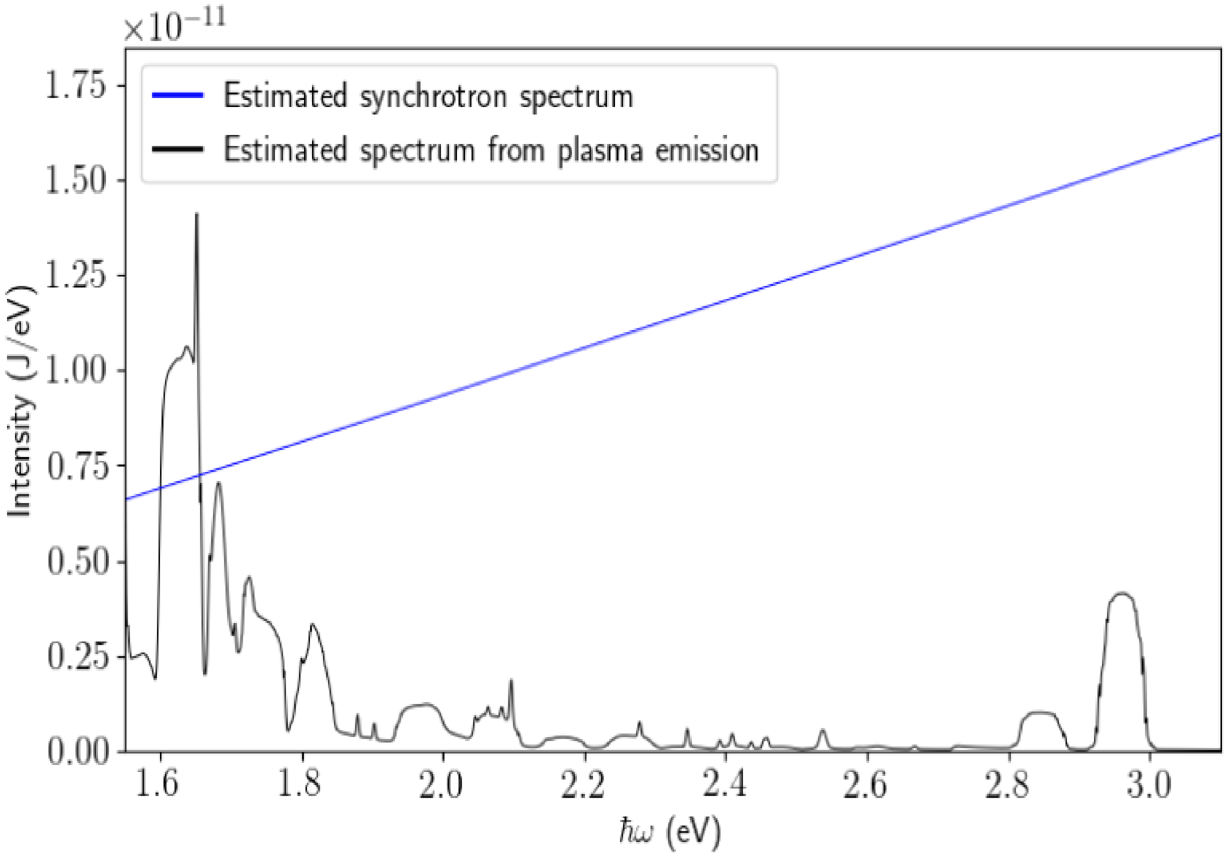
R. A. Fonseca et al., LNCS 2331, 342-351 (2002)

Predictions for synchrotron emission & ICS

Inverse Compton scattering

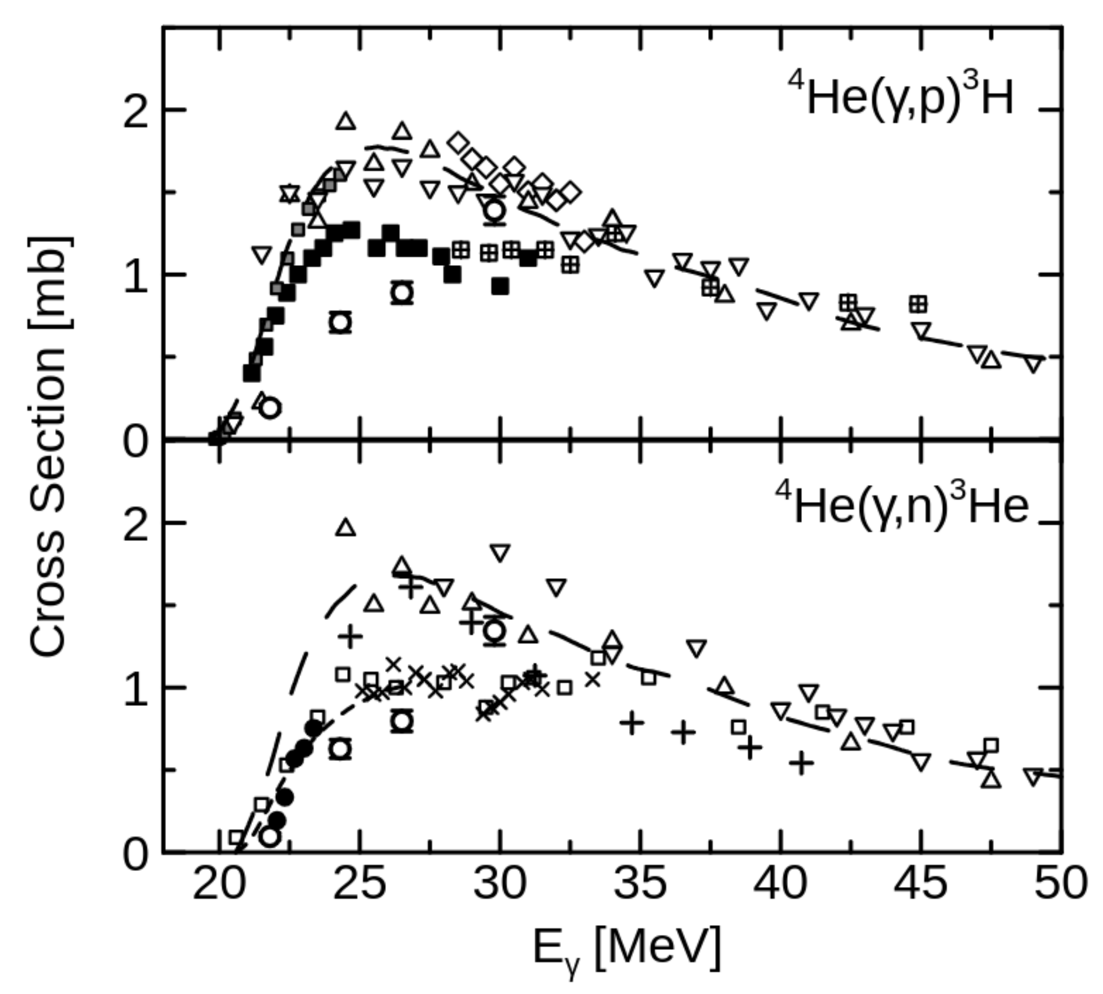
- Expect scattered photons to have 100 keV's to MeV's + high harmonics
- $\frac{N_s}{N_i N_e} = 10^8$

Synchrotron emission



R. A. Fonseca et al., LNCS 2331, 342-351 (2002)

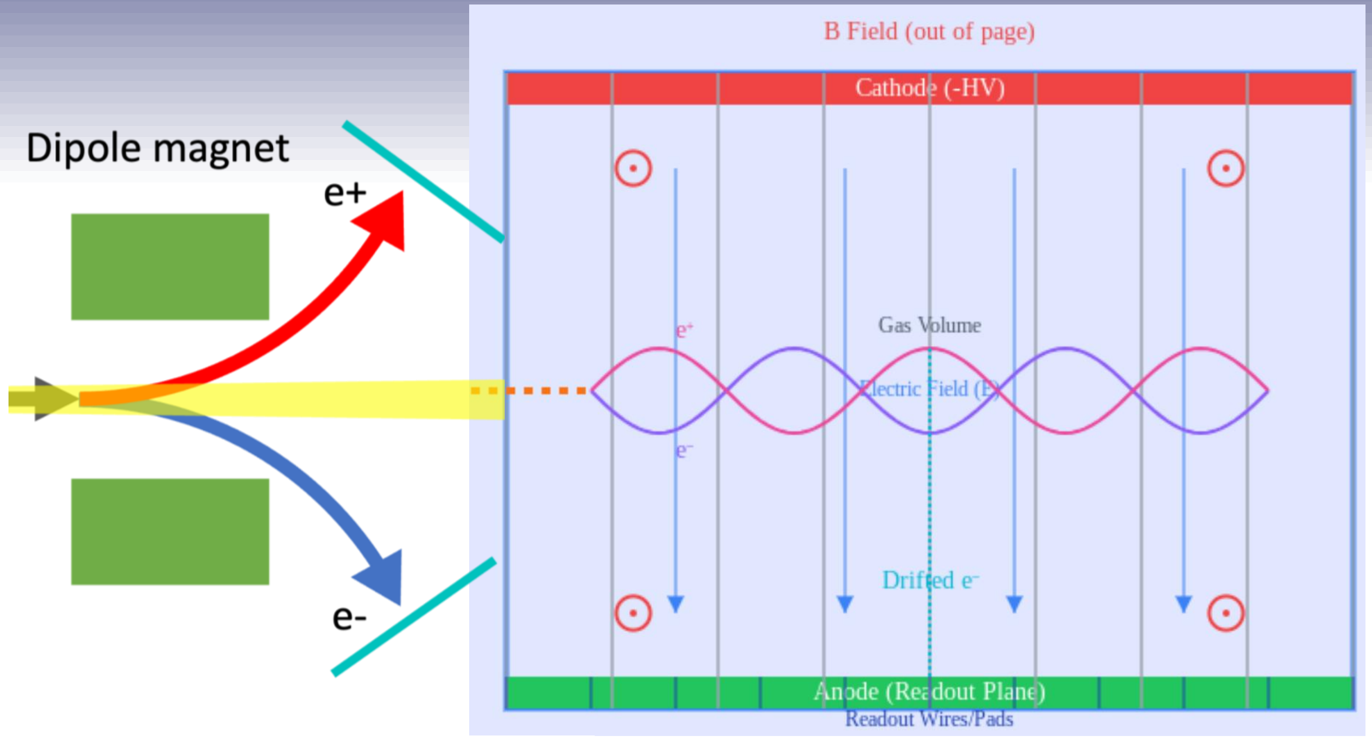
Photonuclear physics with a TPC



T. Shima (2006)

- Time Projection Chamber (TPC) will be used to study photo-nuclear processes.
- Focus on light elements: H, Li, B, O, C, and N.
- Currently, many uncertainties in the actual cross sections.
- Experiments will help solve develop a more realistic model which is applicable to extreme astrophysical systems.

Photonuclear physics with a TPC (conceptual)



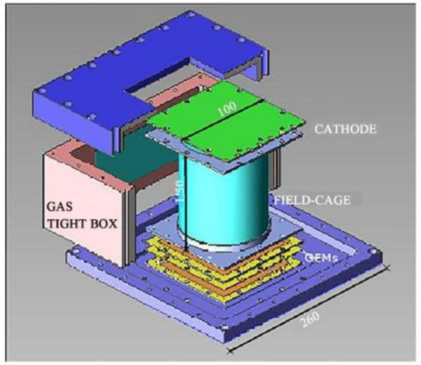


Figure 4. Exploded view of the GEM-TPC prototype.

Modern Instrumentation, 2015, 4, 32-41
Published Online July 2015 in SciRes. http://www.scirp.org/journal/mi
http://dx.doi.org/10.4236/mi.2015.43004
Scientific Research Publishing

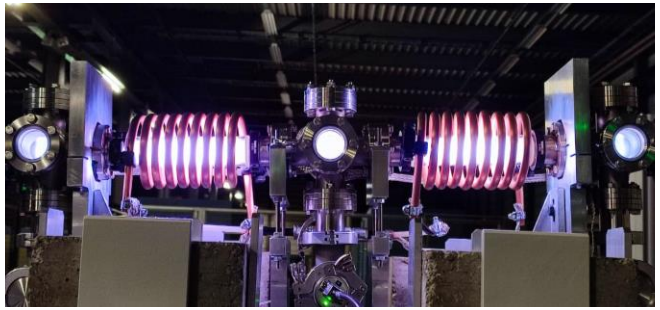
Performances of an Active Target GEM-Based TPC for the AMADEUS Experiment

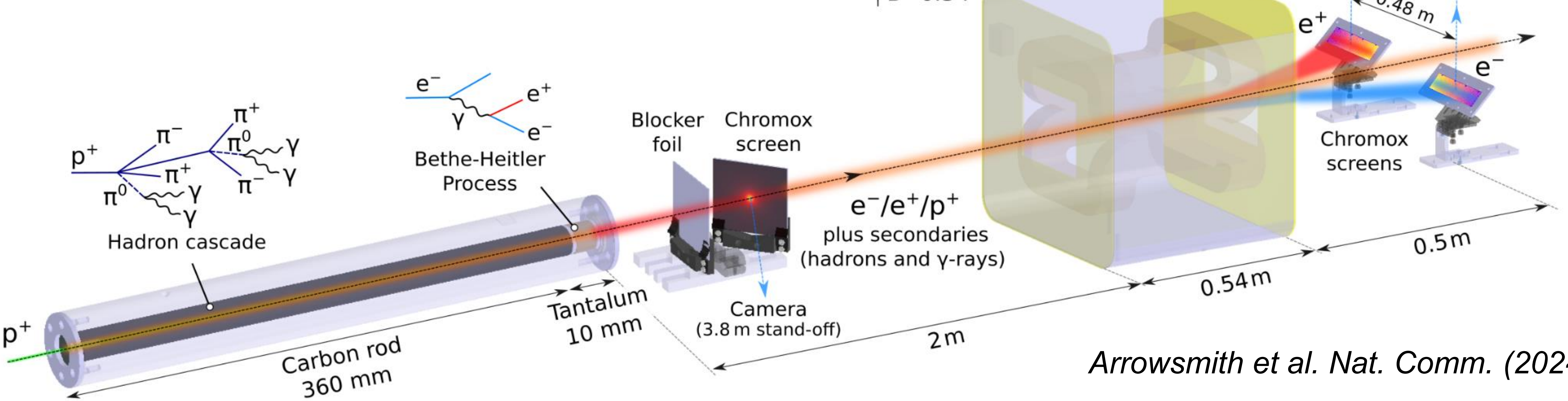
Marco Poli Lener[1], Giovanni Corradi[1], Catalina Curceanu[1], Diego Tagnani[1], Antonio Romero Vidal[2], Johann Zmeskal[3]

- Time Projection Chamber (TPC) will be used to study photo-nuclear processes.
- Focus on light elements: H, Li, B, O, C, and N.
- Positively charged fragments drift to the cathode.
- Electrons, produced by the interaction of charged fragments with the background target gas, drift towards the anode.

We have already exercised the GRB laboratory platform at CERN (HiRadMat)

Experiments performed in 2023, 2024 and 2025



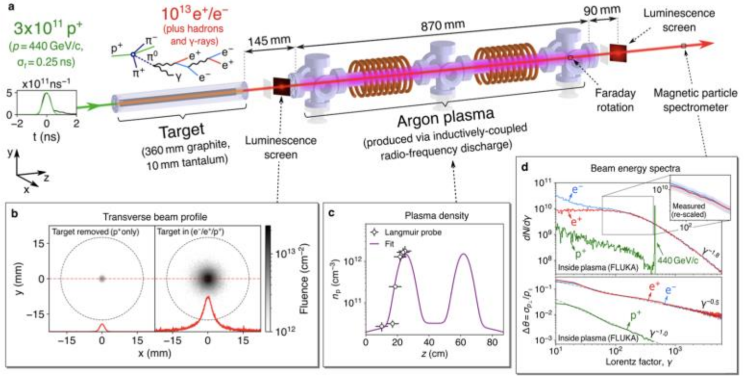


Arrowsmith et al. Nat. Comm. (2024)

We are planning to extend the GRB laboratory platform to LNF and (possibly) CERN and GSI

CERN campaign

- Using primary protons.
- Measured pair spectrum, and B-field, but no γ-ray (overlaps with primary protons).



LNF campaign

- Use similar setup as CERN, but with primary electron.
- γ-ray beam without proton contamination.
- Design phase.

GSI campaign

- Use similar setup as CERN.
- Primary ions (increase pair and γ-ray yield)
- Discussion phase.

PHANTASY: participants

Experimental Gamma Ray Burst Fireball: Design and implementation

Lead: University of Oxford

Numerical simulations: Monte Carlo and Particle-in-Cell

Lead: Max Planck Institute for Nuclear Physics

Detector development: Measurement of gamma rays and charged particles

Lead: Laboratori Nazionali di Frascati

Work Package	Year 1 (M1–M12)	Year 2 (M13–M24)	Year 3 (M25–M36)	Year 4 (M37–M48)	Deliverables & Milestones
WP1 – Design of GRB Analogue	🟦🟦🟦🟦🟦🟦🟦🟦🟦🟦 Design Phase				**D1.1:** GRB Design Report (M12) **M1:** Design Complete (M12)
WP2 – Experiments at BTF		🟩🟩🟩🟩🟩🟩 Preparation	🟩🟩🟩🟩🟩🟩 Data Taking	🟩🟩🟩 Data Analysis	**D2.1:** Experimental Setup Installed (M24) **D2.2:** Raw Data Package (M36) **M4:** Experiments Complete (M42)
WP3 – Theory & Simulations	🟧🟧🟧🟧🟧🟧 Simulations Start	🟧🟧🟧🟧🟧 Modeling & Prediction	🟧🟧🟧🟧🟧 Comparison to Data	🟧🟧 Final Validation	**D3.1:** Simulation Benchmark Report (M18) **D3.2:** Model Validation Report (M46)
WP4 – Mechanical Design	🟪🟪🟪🟪🟪🟪🟪 Drawings & Plans	🟪🟪🟪 Mechanical Development			**D4.1:** Mechanical Drawings Package (M12) **M2:** Mechanical Design Complete (M18)
WP5 – Mechanical Integration		🟫🟫 Preparation	🟫🟫🟫 Assembly	🟫🟫🟫 Integration & Reporting	**D5.1:** Integrated System (M36) **D5.2:** Final Report & Dissemination Package (M48) **M5:** Project Closure (M48)

Budget

INFN-LNF:	Personnel:	€60,000
	Consumables:	€60,000
	Travel:	€7,000
University of Oxford:	PhD student:	€132,000
	Consumables:	€55,000
	Travel	€15,000
MPIK:	Personnel:	€20,000
	Compute access:	€15,000
	Travel:	€8,000
Indirect costs:		€92,750
Total:		**€463,750**

PHANTASY: advancing Hadron Physics frontiers

Laboratory validation of photonuclear processes in **extreme astrophysical conditions.**

Enabling **precise cross-section measurements essential for modeling GRBs and supernovae**.

Connection with EU TA : INFN-LNF, CERN, GSI (and maybe more, including VA)

Delivering **innovation in detectors and simulations with impact beyond astrophysics.**