Laboratory realization of relativistic pair-plasma beams: an experimental platform at HiRadMat - CERN

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Motivation

Relativistic outflows enriched with electron-positron pair plasma can be found in various highly energetic astrophysical environments, e.g. around active galactic nuclei, black holes or in the jets of gamma ray bursts. Plasma instabilities associated with such pair-dominated outflows play an important role in explaining their energy dissipation and the radiative signatures we observe from these objects on Earth. In our last experiment, HRMT62 [1], inaugurating a newly developed experimental platform for such studies at the HiRadMat facility of CERN [2,3], **high intensity, high density, ultra-relativistic, quasi-neutral electron-positron pair beam production was achieved**, opening up the possibility to study the microphysics of such pair plasmas via experimental means. In the follow-up experiment, HRMT64, modifications including a secondary target and a magnetic collimating setup will be introduced in order to study the emergence of magnetic fields associated with the growth of filamentation instabilities as collimated relativistic pair-plasma beams propagate through ambient plasma; an analogue for the propagation of astrophysical pair jets through intergalactic medium.

An experimental platform at HiRadMat of CERN

- Extracts beam from the CERN-SPS (Super Proton Synchrotron).
- Material samples and accelerator components are tested under LHC-type, high-intensity pulsed beam [2].
- Protons: up to 6x10^{13} protons/pulse, 1-288 bunches/pulse, 440 GeV/c momentum, 0.5-2 mm^2 spot size.
- The extracted beam gets transported into the HiRadMat experimental area where various test setups can be installed.

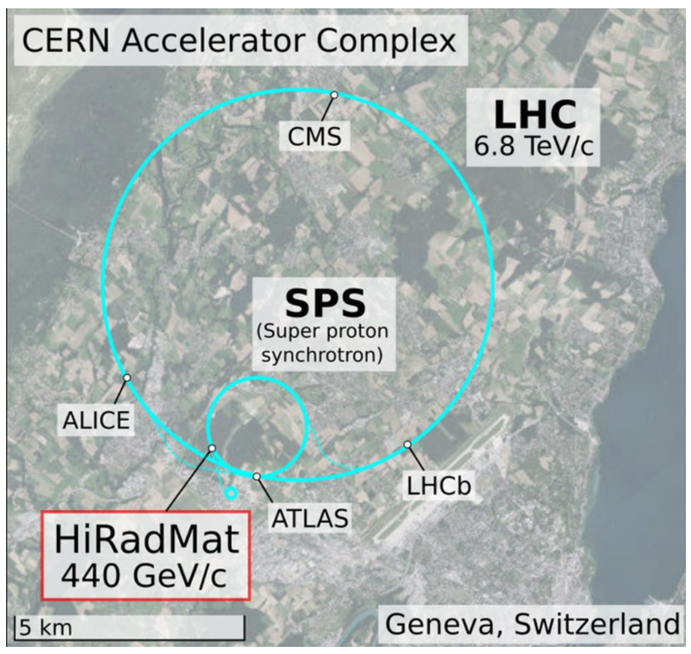


Figure 1: CERN accelerator complex.

HRMT62 - Experimental Setup

- Primary beam of 440 GeV/c protons impinge on a 360 mm graphite target followed by a 10 mm Ta converter.
- Hadronic and EM cascades: π^0 -> 2 γ, subsequent e^-e^+ pair production and Bremsstrahlung - result in an e^-e^+ enriched secondary beam (other species negligible).
- The secondary beam propagates through 1m long Ar plasma.
- An electromagnet used as an e^-e^+ spectrometer separates charges downstream.

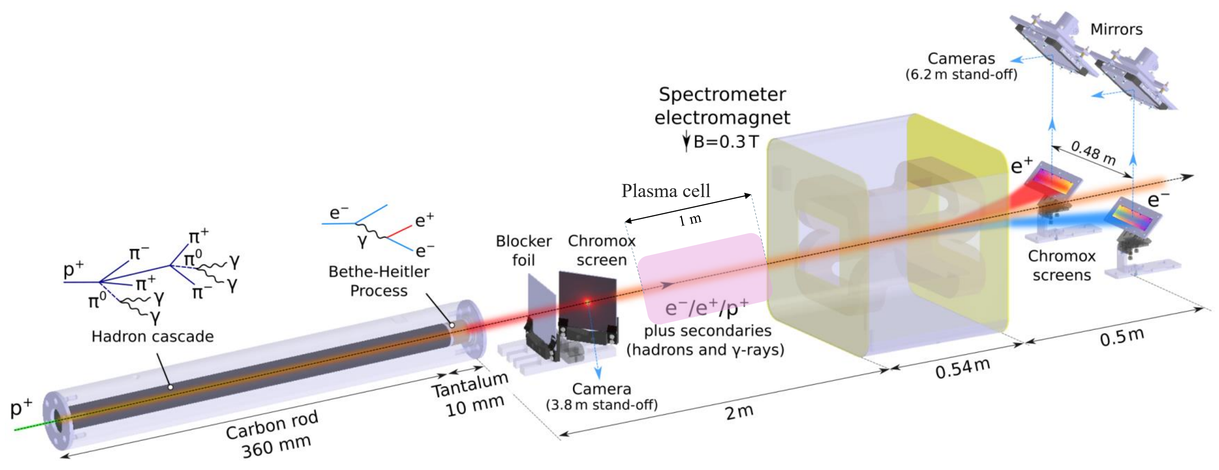
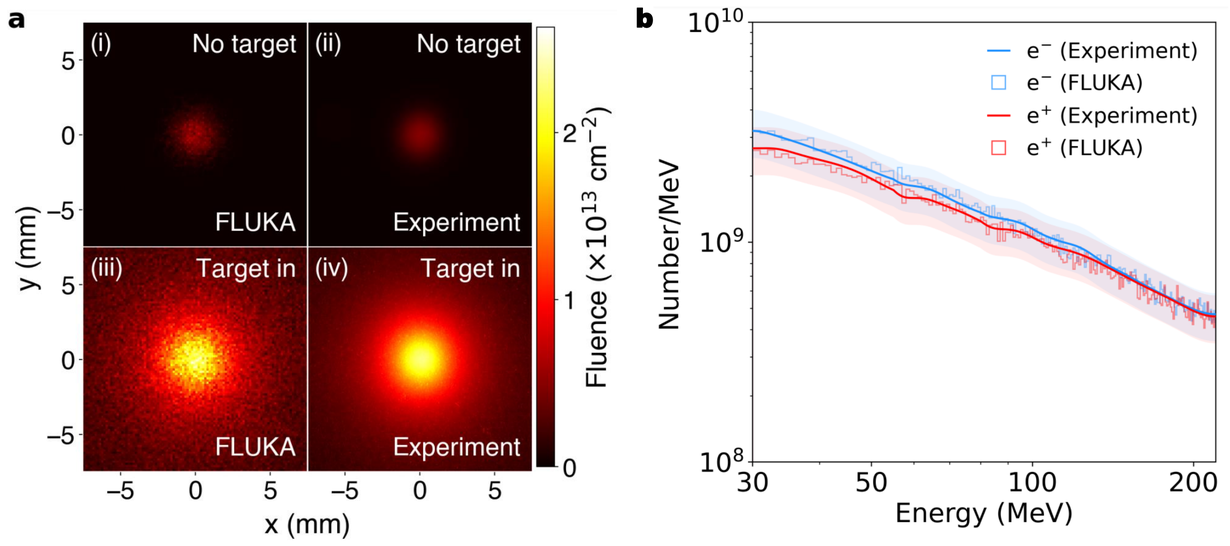


Figure 2: Schematic of the HRMT62 experimental setup. Chromox luminescence screens are positioned before and after the plasma cell, and after the spectrometer, allowing for validation of the beam profile and the energy spectrum.

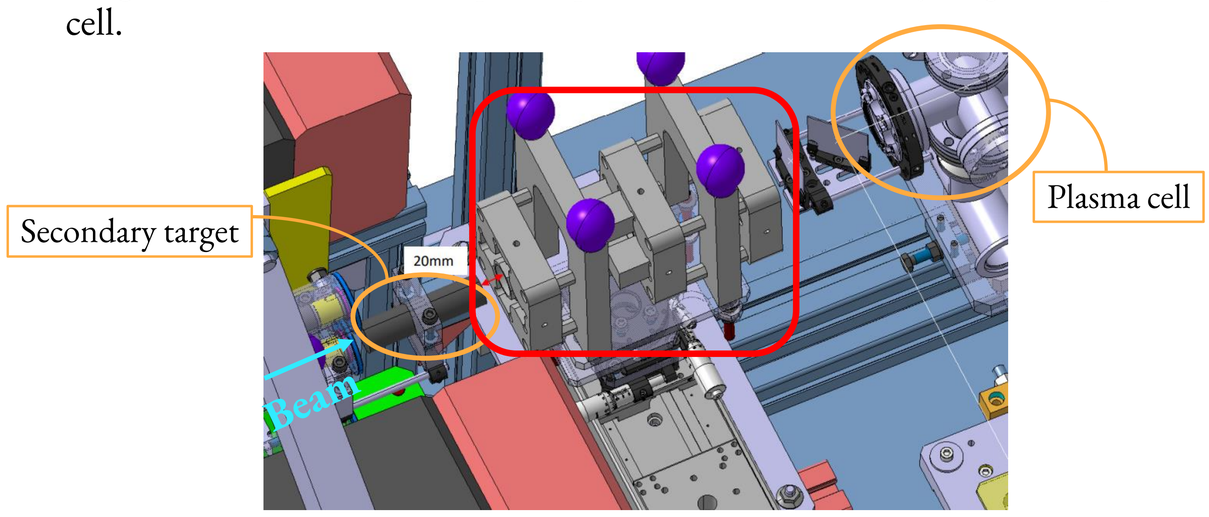
HRMT62 - Results



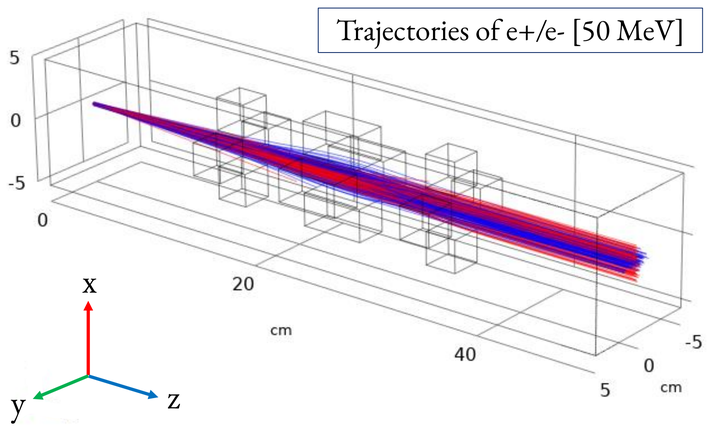
- **Excellent agreement between simulations and experimental data**: **(a)** transverse beam profile post-target, **(b)** deflected e^- and e^+ energy spectra after the spectrometer.
- **Beam quasi-neutrality, high e^-e^+ yields and densities:** unique beam parameters achieved at HiRadMat, access to study astrophysics processes. **(c)**: Comparison of laboratory-produced high density pair beams.

HRMT64 in Apr 2024 – Improved setup

- **Magnetic collimation** - 3 quadrupoles between secondary target and plasma cell.



- Results from PIC simulations: **reduced beam divergence can drive growth of filamentation instabilities** as the pair beam propagates through ambient plasma.
- Setup **optimised for specific particle energy range**, around 50 MeV.



References

[1] C. D. Arrowsmith et al., https://arxiv.org/abs/2312.05244.
[2] I. Efthymiopoulos et al. (2011) Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11) TUPS085.
[3] C. D. Arrowsmith et al., Phys. Rev. Res. 3, 023103, (2021).

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