Queen's University Belfast

Laboratory studies of the dynamics of neutral electron-positron beams

Gianluca Sarri
School of Mathematics and Physics, Queen's University Belfast, UK
g.sarri@qub.ac.uk

Main Collaborators

M. Zepf, D. J. Corvan, D. Doria, G. Samarin, J. Warwick, T. Dzelzainis

J. Cole, S. P. D. Mangles, K. Poder, Z. Najmudin,

D. Symes and ASTRA-GEMINI technical staff

A.G.R. Thomas, W. Schumaker, K. Krushelnick

S. Kuschel

L. Romagnani

L. Gizzi, G. Grittani

A. Di Piazza, Ch. Keitel

J. Vieira, N. Shukla, L. Silva

Talk Outline

- **INTRODUCTION**
  - Electron-positron beams in astrophysics
  - Positron beams in conventional accelerators
  - Alternative schemes towards neutral electron-positron plasmas

- **NEUTRAL ELECTRON-POSITRON BEAMS**
  - Optical set-up
  - Electron-positron beam characteristics

- **ELECTRON-POSITRON BEAM DYNAMICS**
  - Beam filamentation
  - Magnetic field generation
  - Expected beam profile
  - Experimental evidence

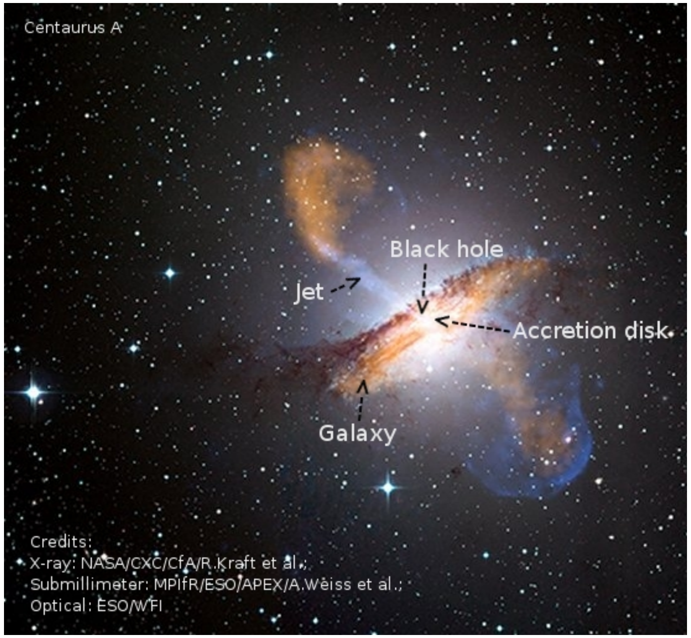
- **CONCLUSIONS AND OUTLOOK**
  - Ongoing experiments

Queen's University Belfast

Introduction

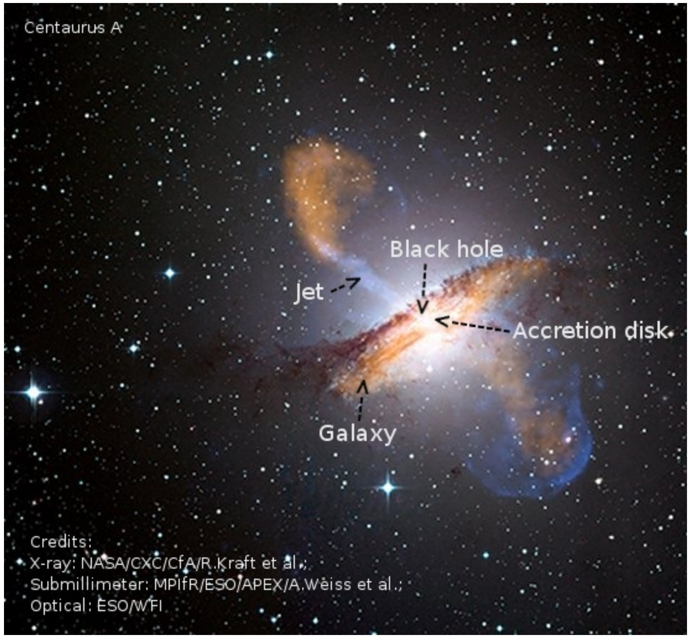
Astrophysical jets

- Highly-collimated electron-positron jets are observed being emitted by massive and powerful objects, such as quasars, pulsars, and active galactic nuclei



Astrophysical jets

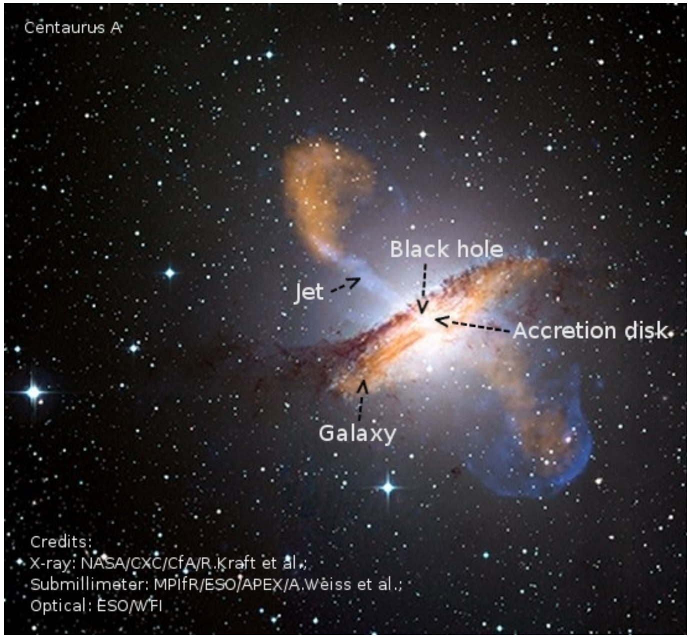
- Highly-collimated electron-positron jets are observed being emitted by massive and powerful objects, such as quasars, pulsars, and active galactic nuclei



- Associated with strong emission of gamma-rays
- Optically thin
- Power-law spectrum: $n(\gamma) \propto \gamma^{-(2\alpha+1)}$, $\alpha \approx 0.5$
- Some predominantly leptonic
- Relativistic
- Strong interaction with the intergalactic medium
- Largest single events observed in the Universe
- Equipartition: $10^{-1} - 10^{-5}$

Astrophysical jets

- Highly-collimated electron-positron jets are observed being emitted by massive and powerful objects, such as quasars, pulsars, and active galactic nuclei

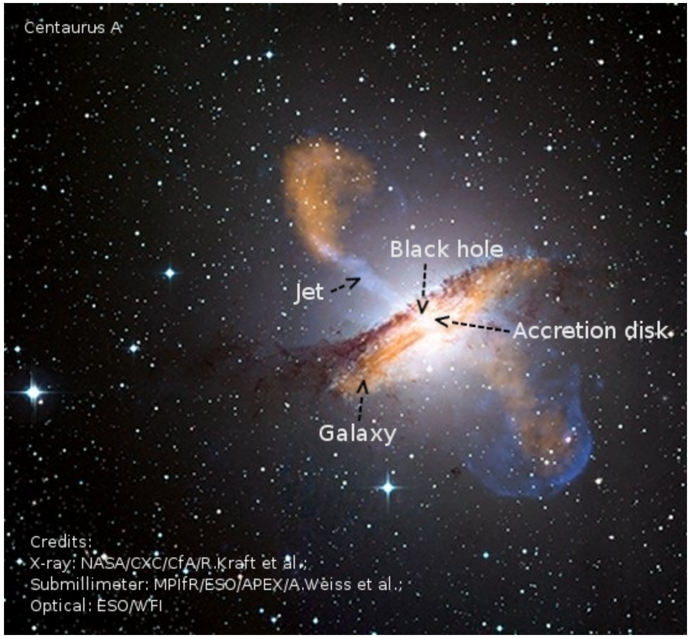


- Associated with strong emission of gamma-rays
- Optically thin
- Power-law spectrum: $n(\gamma) \propto \gamma^{-(2\alpha+1)}$, $\alpha \approx 0.5$
- Some predominantly leptonic
- Relativistic
- Strong interaction with the intergalactic medium
- Largest single events observed in the Universe
- Equipartition: $10^{-1} - 10^{-5}$

The generation of gamma rays requires strong and long-lived magnetic fields:

Astrophysical jets

- Highly-collimated electron-positron jets are observed being emitted by massive and powerful objects, such as quasars, pulsars, and active galactic nuclei



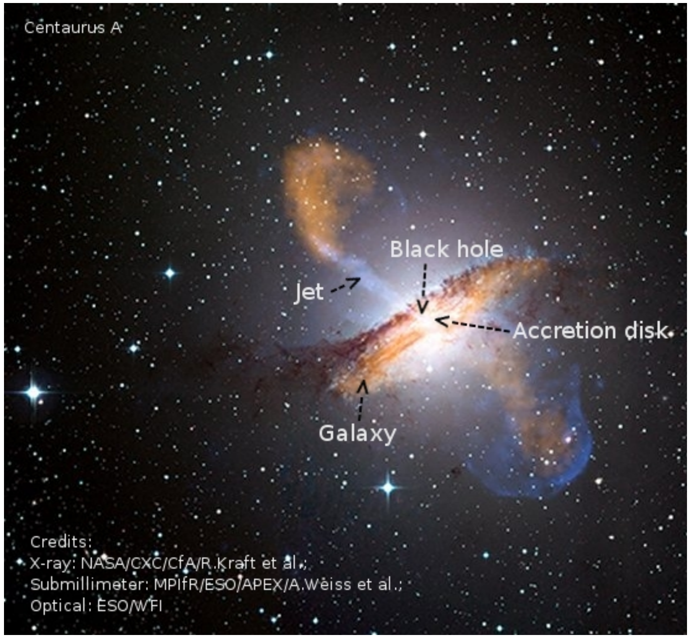
- Associated with strong emission of gamma-rays
- Optically thin
- Power-law spectrum: $n(\gamma) \propto \gamma^{-(2\alpha+1)}$, $\alpha \approx 0.5$
- Some predominantly leptonic
- Relativistic
- Strong interaction with the intergalactic medium
- Largest single events observed in the Universe
- Equipartition: $10^{-1} - 10^{-5}$

The generation of gamma rays requires strong and long-lived magnetic fields:

- **Intergalactic magnetic field (~ nT) too small**
- **MHD shock-compression, equipartion of 10^{-11}**
- **Fields from the central engine, equipartition of 10^{-7}**
- **Weibel-generated fields, too short-lived**

Astrophysical jets

- Highly-collimated electron-positron jets are observed being emitted by massive and powerful objects, such as quasars, pulsars, and active galactic nuclei



- Associated with strong emission of gamma-rays
- Optically thin
- Power-law spectrum: $n(\gamma) \propto \gamma^{-(2\alpha+1)}$, $\alpha \approx 0.5$
- Some predominantly leptonic
- Relativistic
- Strong interaction with the intergalactic medium
- Largest single events observed in the Universe
- Equipartition: $10^{-1} - 10^{-5}$

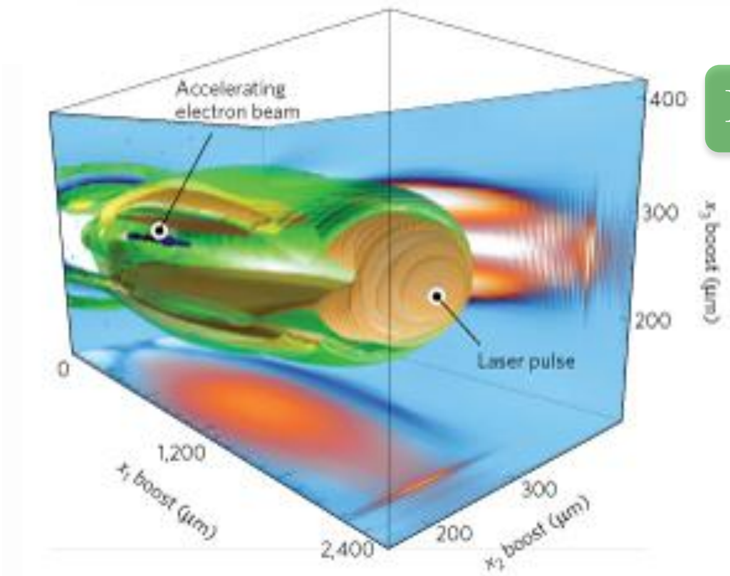
The generation of gamma rays requires strong and long-lived magnetic fields:

- **Intergalactic magnetic field (~ nT) too small**
- **MHD shock-compression, equipartion of 10^{-11}**
- **Fields from the central engine, equipartition of 10^{-7}**
- **Weibel-generated fields, too short-lived**

Electron-positron beam filamentation?

Wake-field based positron generator

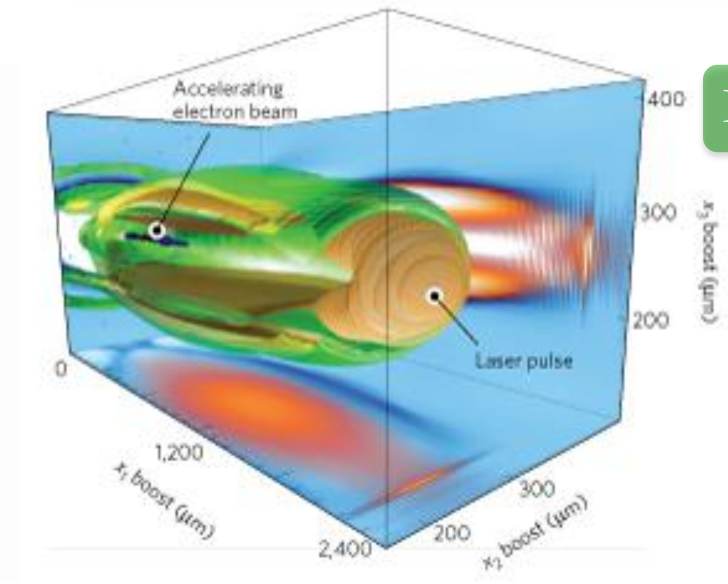
General setup



Laser-wakefield electrons to trigger the cascade in a solid

G. Sarri *et al.*, Phys. Rev. Lett. 110, 255002 (2013)

General setup

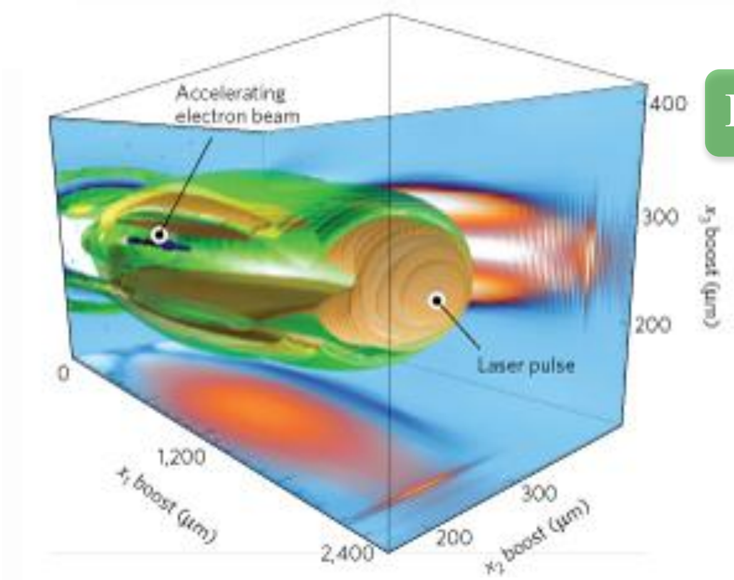


Laser-wakefield electrons to trigger the cascade in a solid

- ✓ Divergence: 1-5 mrad (from solid: ~ 20 degrees)
- ✓ Duration: ~ 10 fs (from solid: 1 – 10 ps)
- ✓ Energy: 100s of MeV (from solid: 10s of MeV)
- ✓ Laser energy: ~1-10J (from solid: ~kJ)
- ✓ Possibility of generating neutral e^-/e^+ beams in situ!

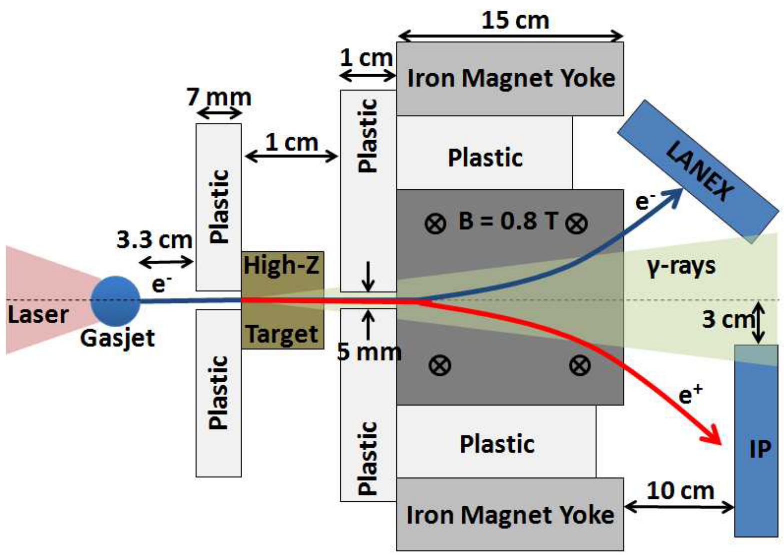
G. Sarri *et al.*, Phys. Rev. Lett. 110, 255002 (2013)

General setup



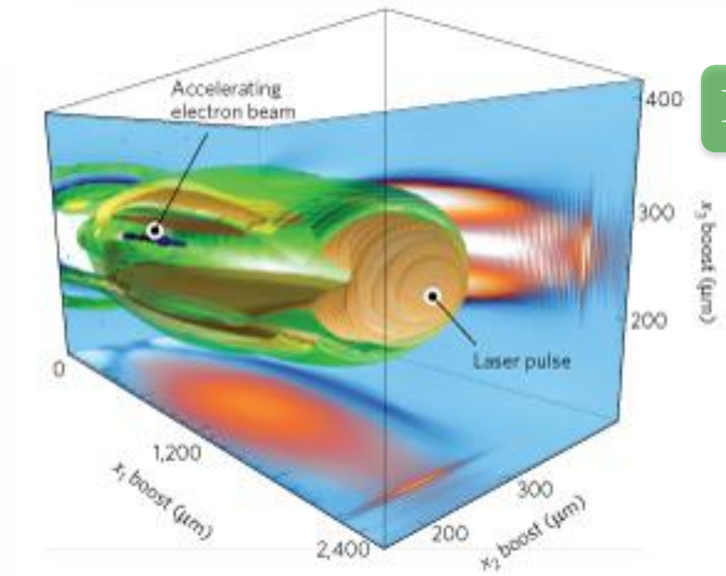
Laser-wakefield electrons to trigger the cascade in a solid

- ✓ Divergence: 1-5 mrad (from solid: ~ 20 degrees)
- ✓ Duration: ~ 10 fs (from solid: 1 – 10 ps)
- ✓ Energy: 100s of MeV (from solid: 10s of MeV)
- ✓ Laser energy: ~1-10J (from solid: ~kJ)
- ✓ Possibility of generating neutral e^-/e^+ beams in situ!



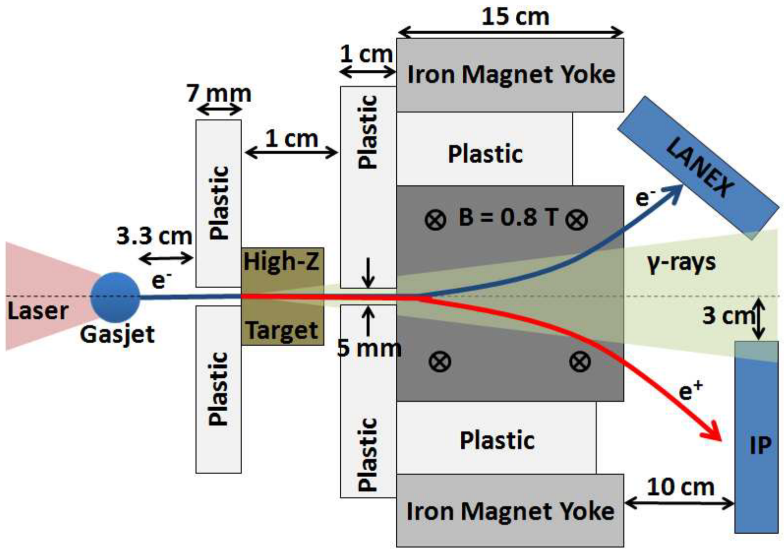
G. Sarri *et al.*, Phys. Rev. Lett. 110, 255002 (2013)

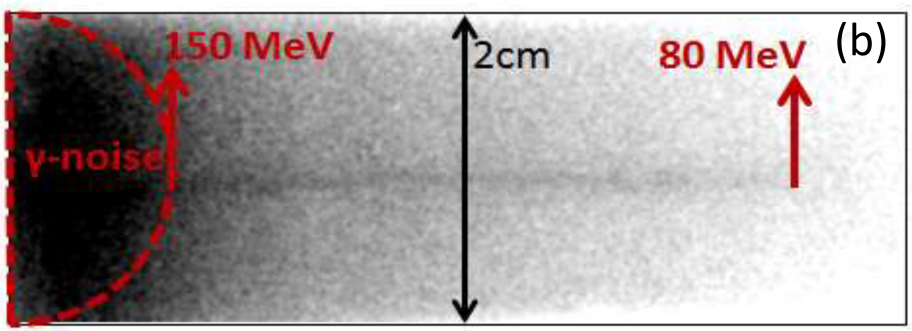
General setup



Laser-wakefield electrons to trigger the cascade in a solid

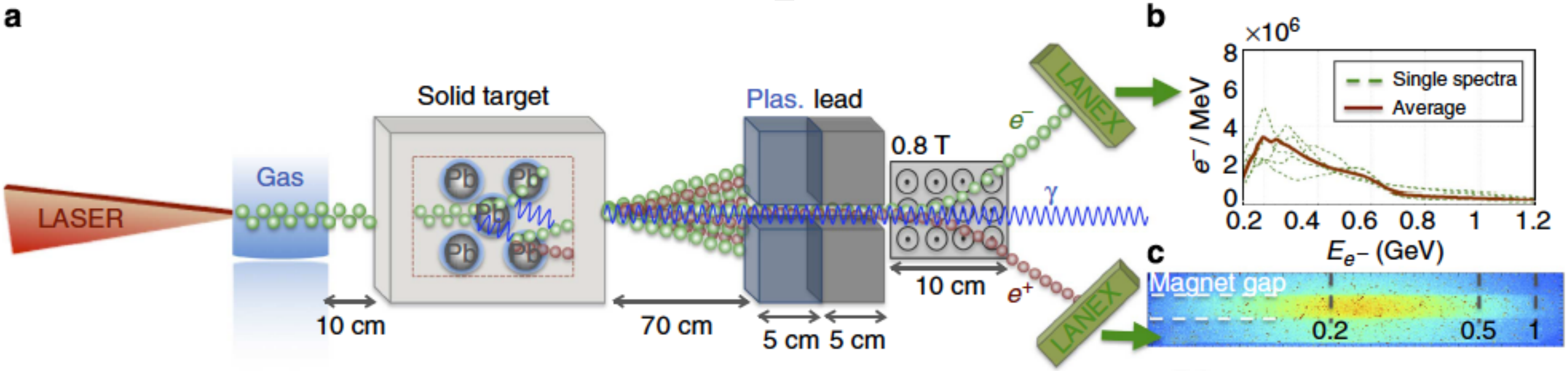
- ✓ Divergence: 1-5 mrad (from solid: ~ 20 degrees)
- ✓ Duration: ~ 10 fs (from solid: 1 – 10 ps)
- ✓ Energy: 100s of MeV (from solid: 10s of MeV)
- ✓ Laser energy: ~1-10J (from solid: ~kJ)
- ✓ Possibility of generating neutral e^-/e^+ beams in situ!





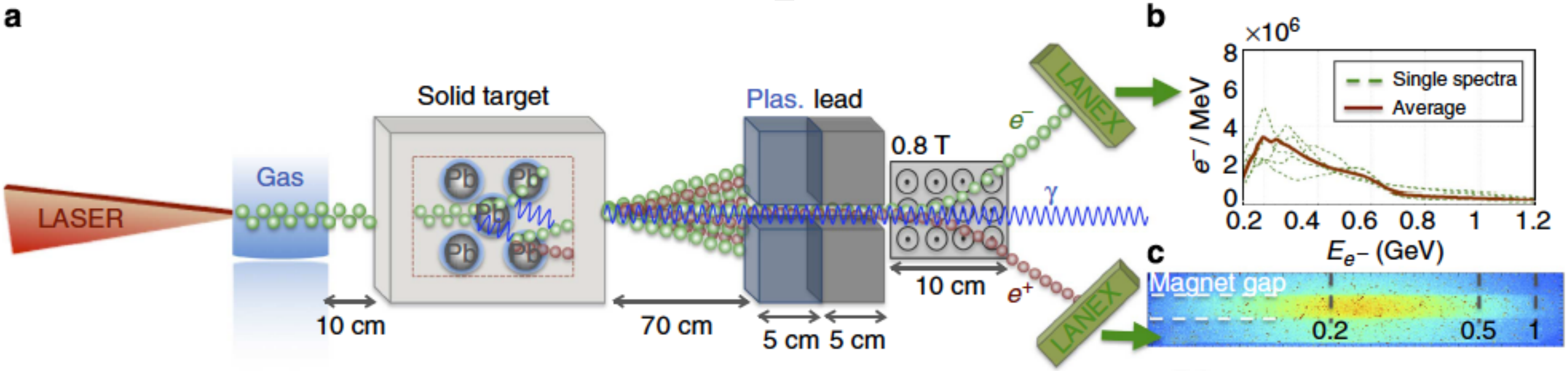
G. Sarri *et al.*, Phys. Rev. Lett. 110, 255002 (2013)

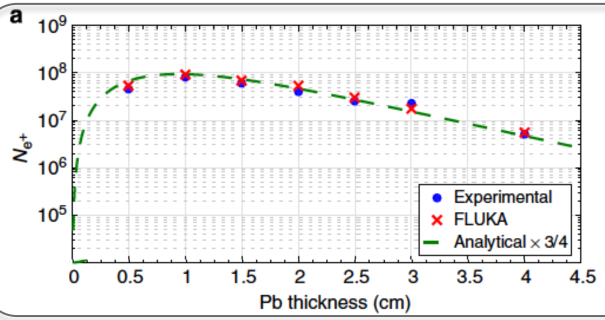
A neutral pair beam



G. Sarri *et al.*, Nature Communications 6, 6747 (2015)

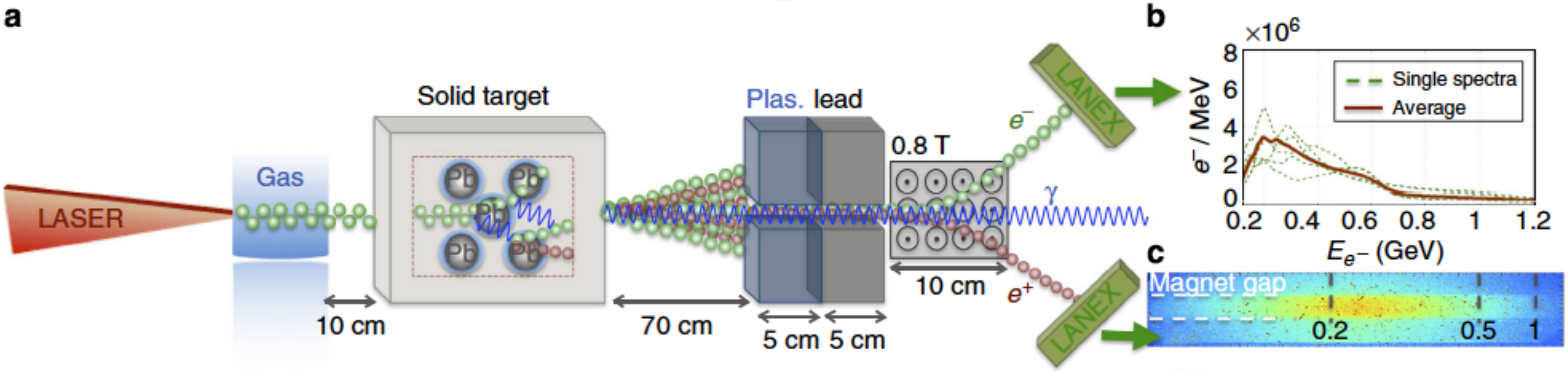
A neutral pair beam

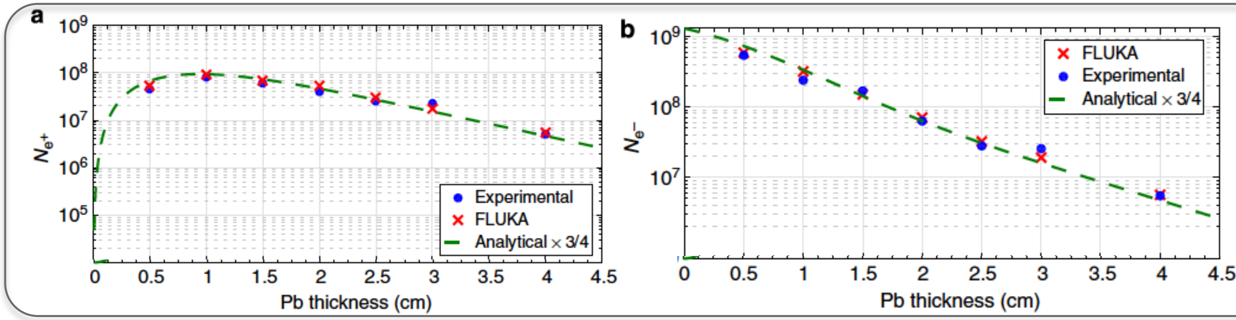




G. Sarri *et al.*,
Nature Communications
6, 6747 (2015)

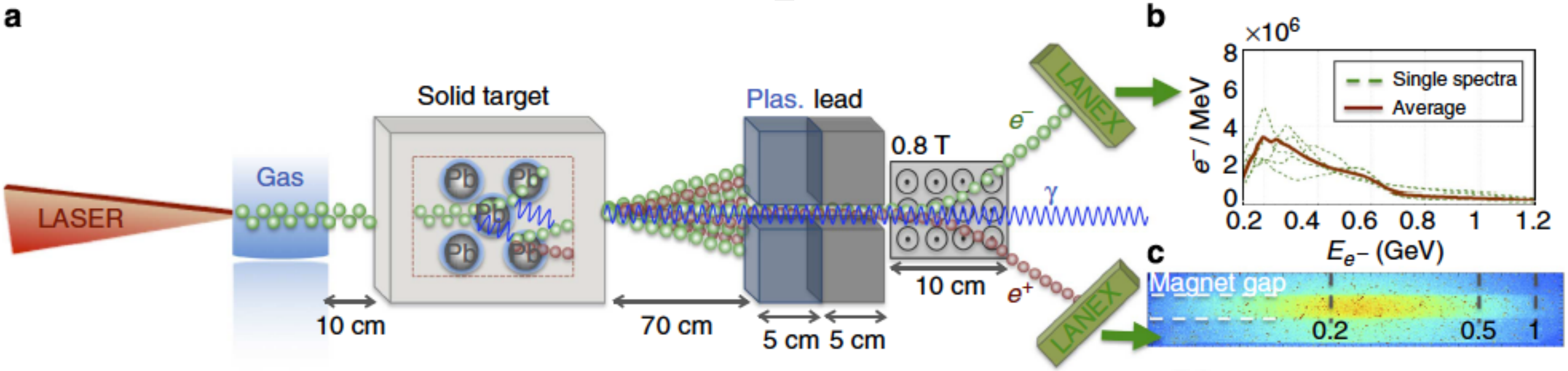
A neutral pair beam

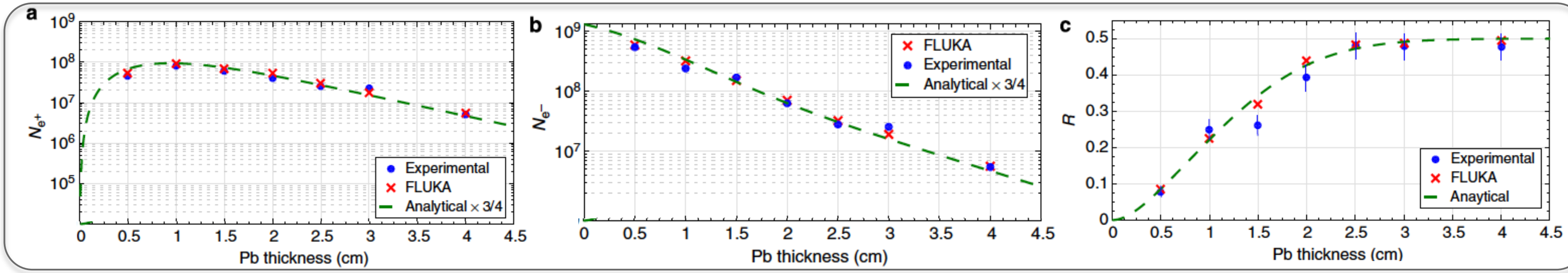




G. Sarri *et al.*,
Nature Communications
6, 6747 (2015)

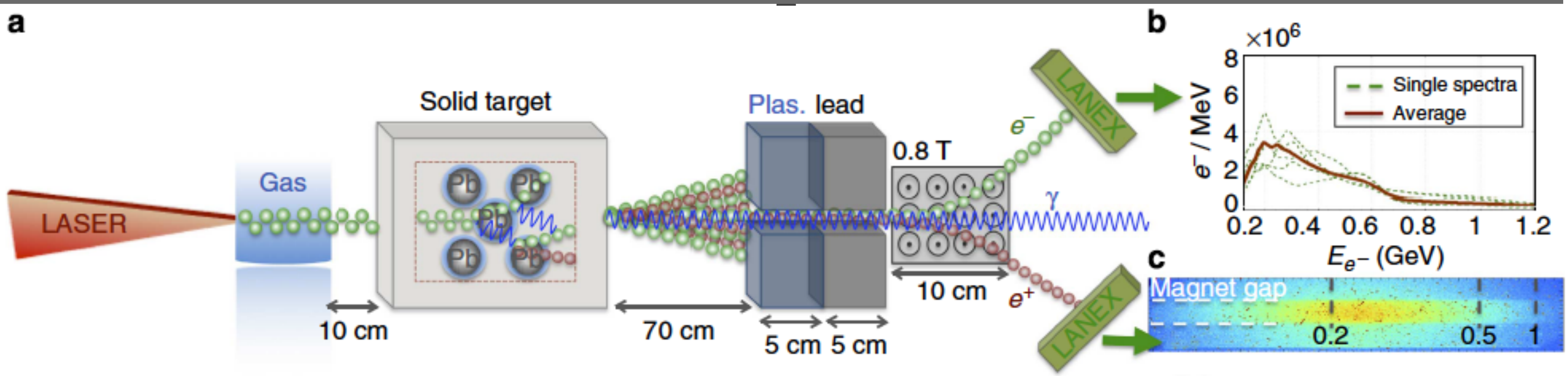
A neutral pair beam

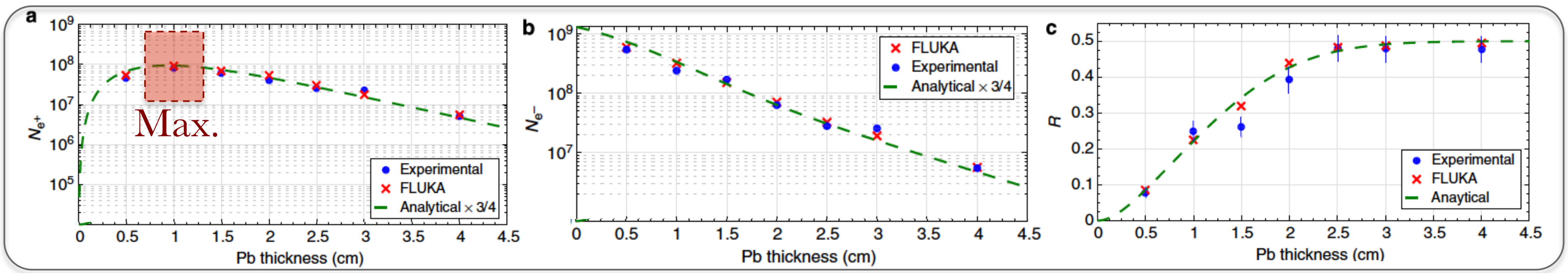




G. Sarri *et al.*,
Nature Communications
6, 6747 (2015)

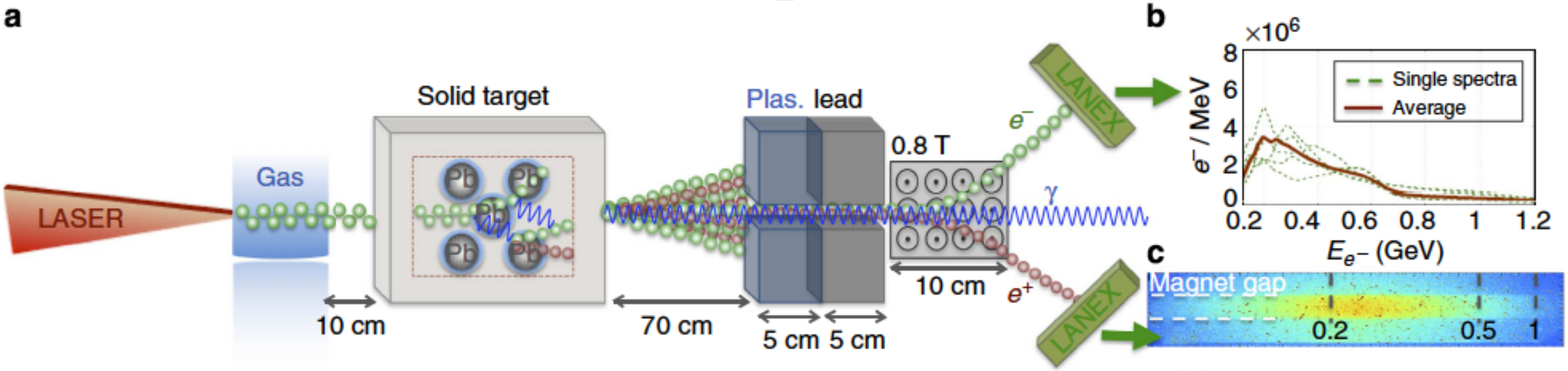
A neutral pair beam

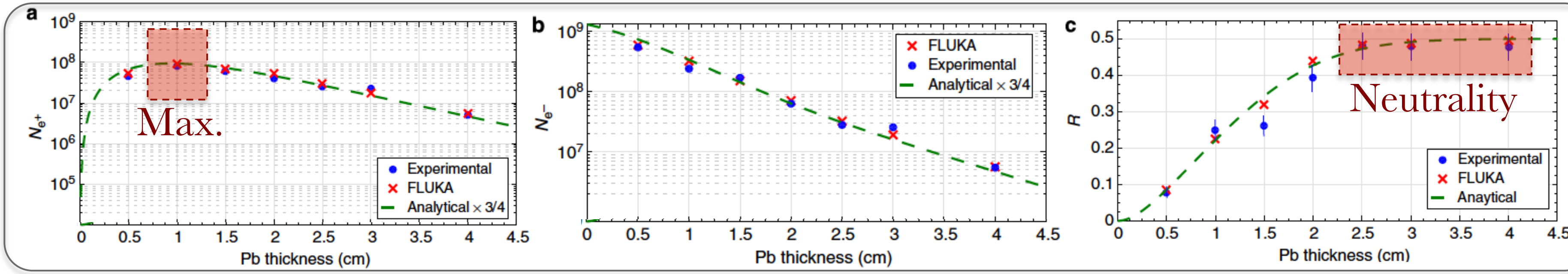




G. Sarri *et al.*,
Nature Communications
6, 6747 (2015)

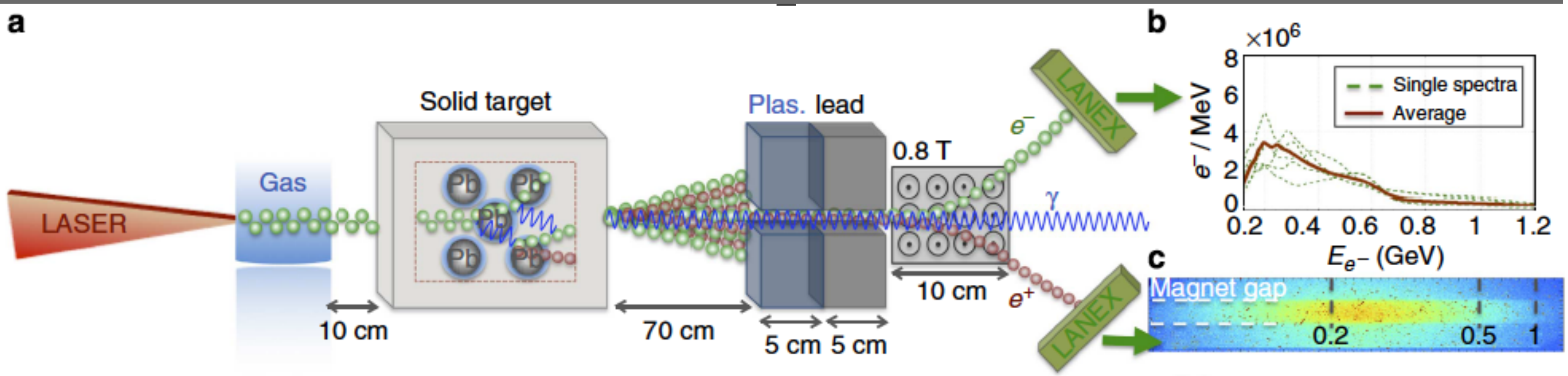
A neutral pair beam

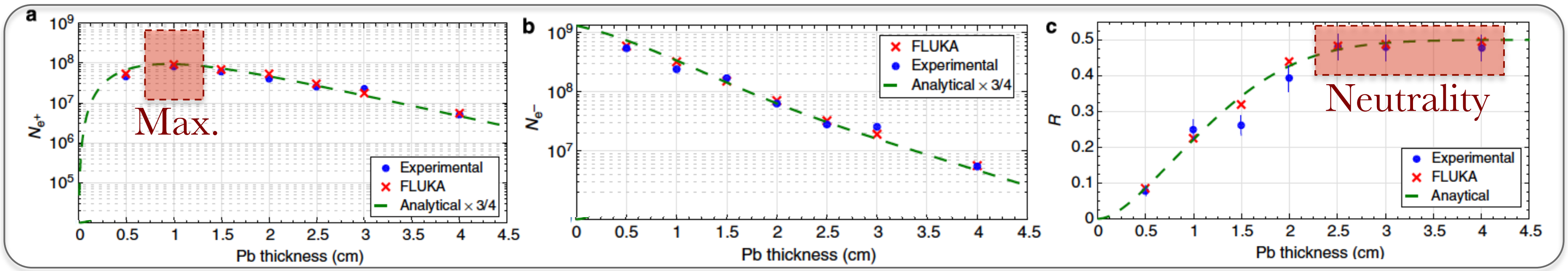




G. Sarri *et al.*, Nature Communications 6, 6747 (2015)

A neutral pair beam

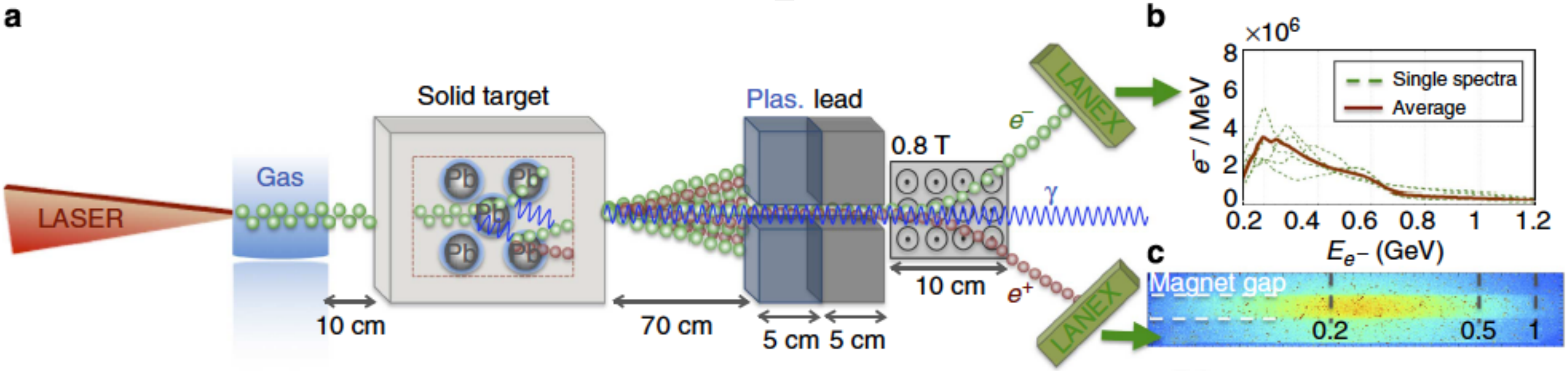


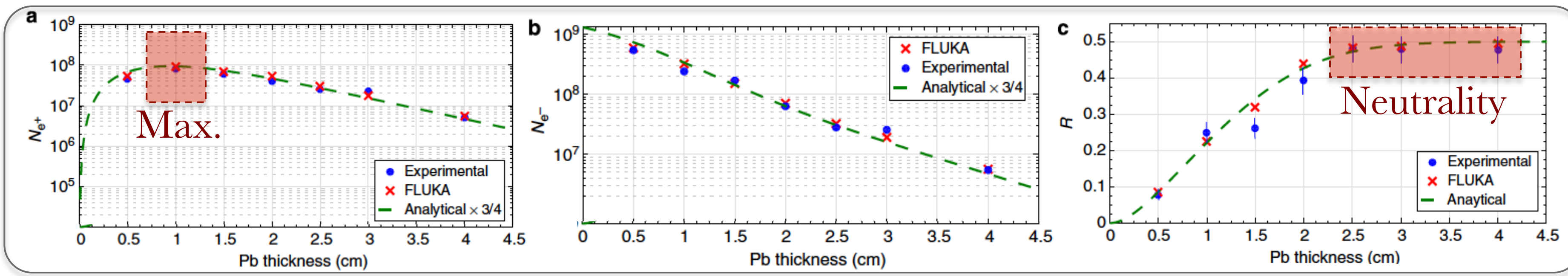


- ✓ Maximum positron yield at ~2 L_{RAD}
- ✓ ~48% of positrons at ~ 5 L_{RAD}
- ✓ Beam duration: ~ tens of fs
- ✓ Beam diameter: > c/w_p
- ✓ Beam divergence: ~ tens of mrad

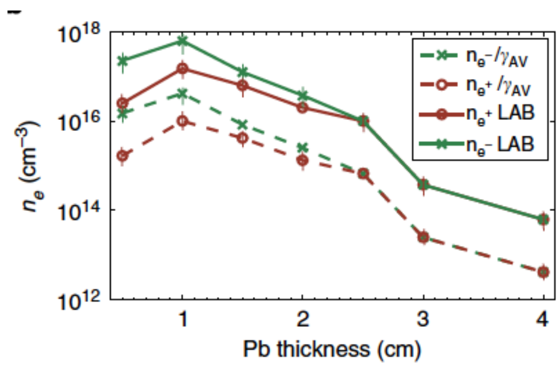
G. Sarri *et al.*, Nature Communications 6, 6747 (2015)

A neutral pair beam



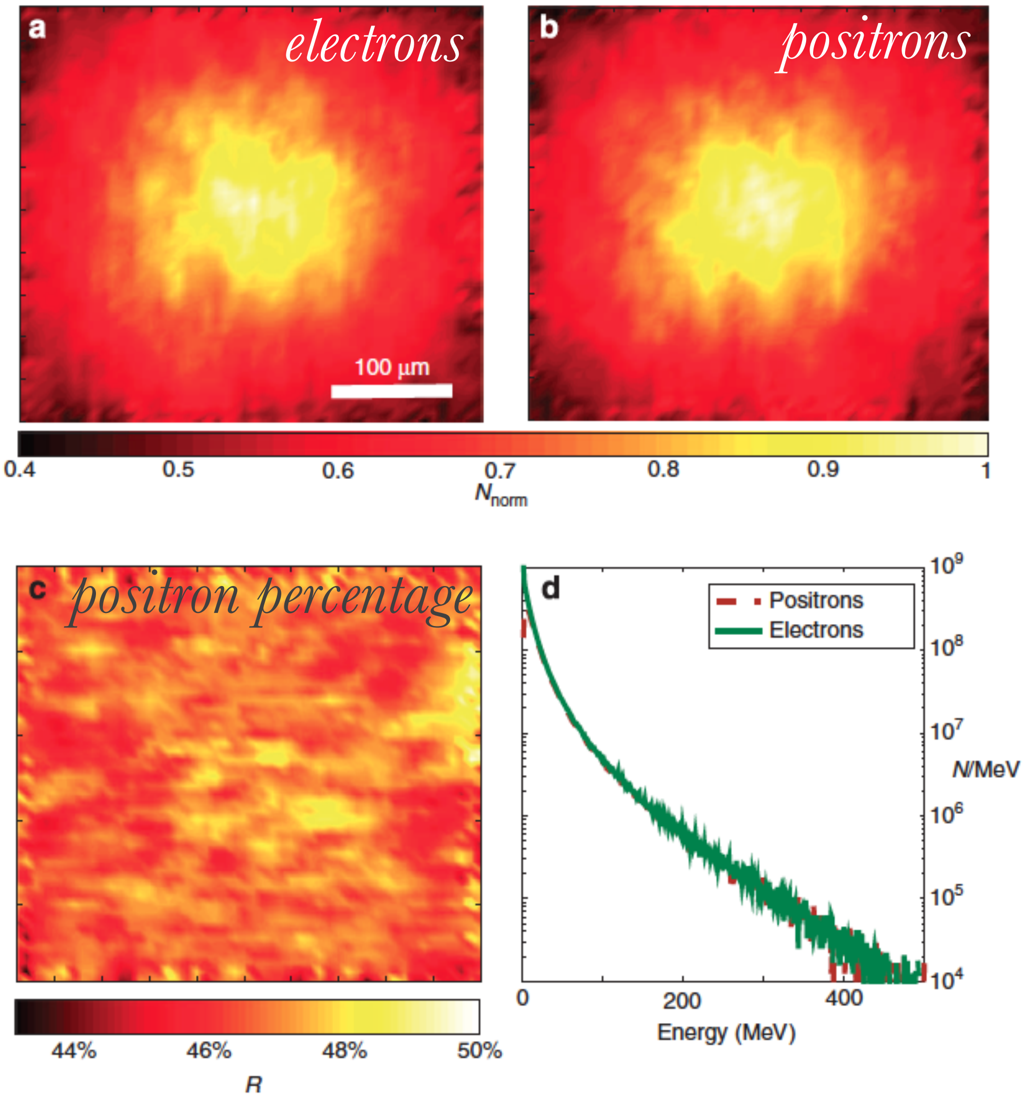


- ✓ Maximum positron yield at ~2 L_{RAD}
- ✓ ~48% of positrons at ~ 5 L_{RAD}
- ✓ Beam duration: ~ tens of fs
- ✓ Beam diameter: > c/w_p
- ✓ Beam divergence: ~ tens of mrad



G. Sarri *et al.*,
Nature Communications
6, 6747 (2015)

A neutral pair beam



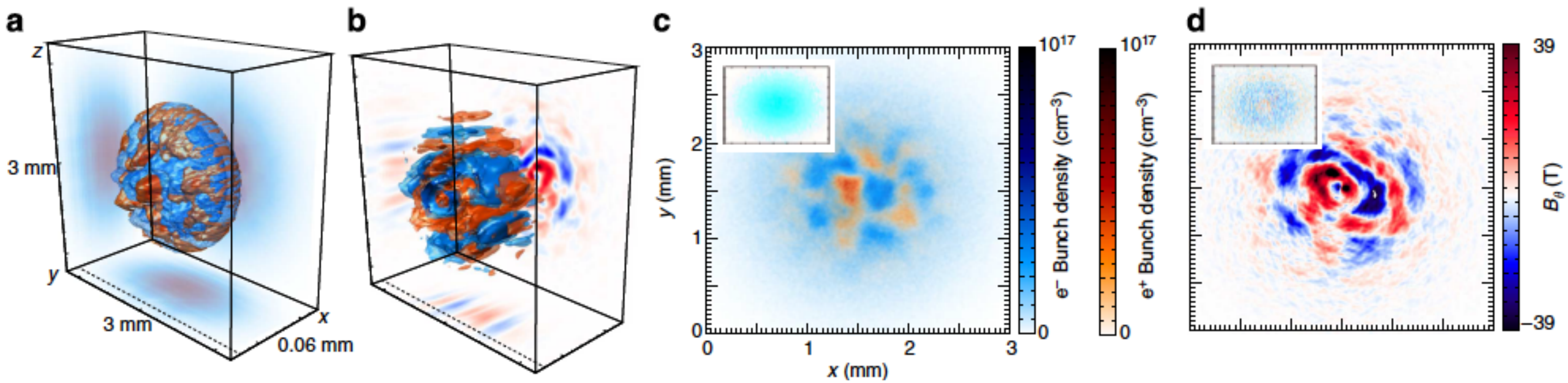
FLUKA simulations

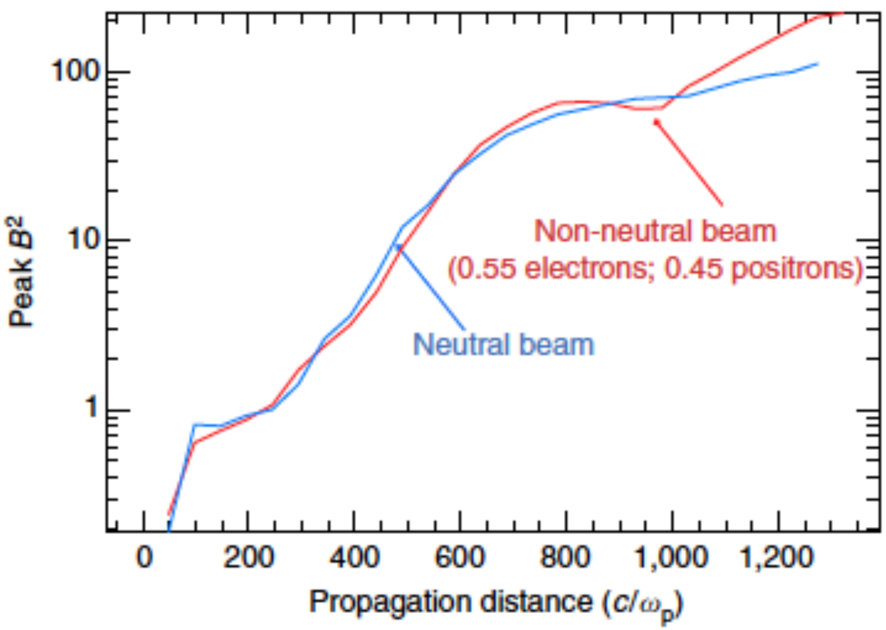
- similar spatial distribution
- beam radius: ~ 150 microns
- positron percentage 46 – 50 %
- spectral symmetry
- departure from neutrality only at low energies (< 5 MeV)

G. Sarri *et al.*, Nature Communications 6, 6747 (2015)

Beam filamentation PIC simulations

Beam filamentation: ideal



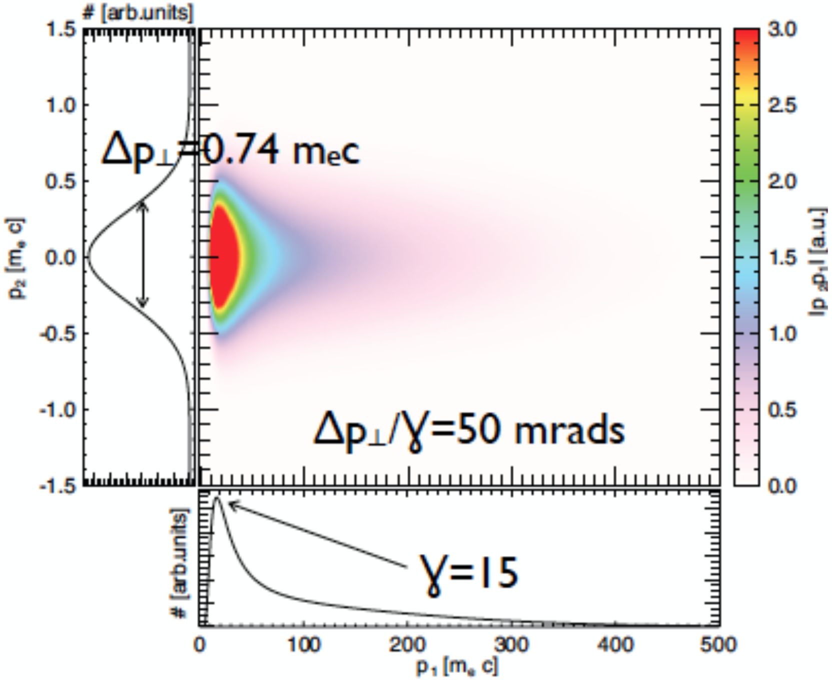


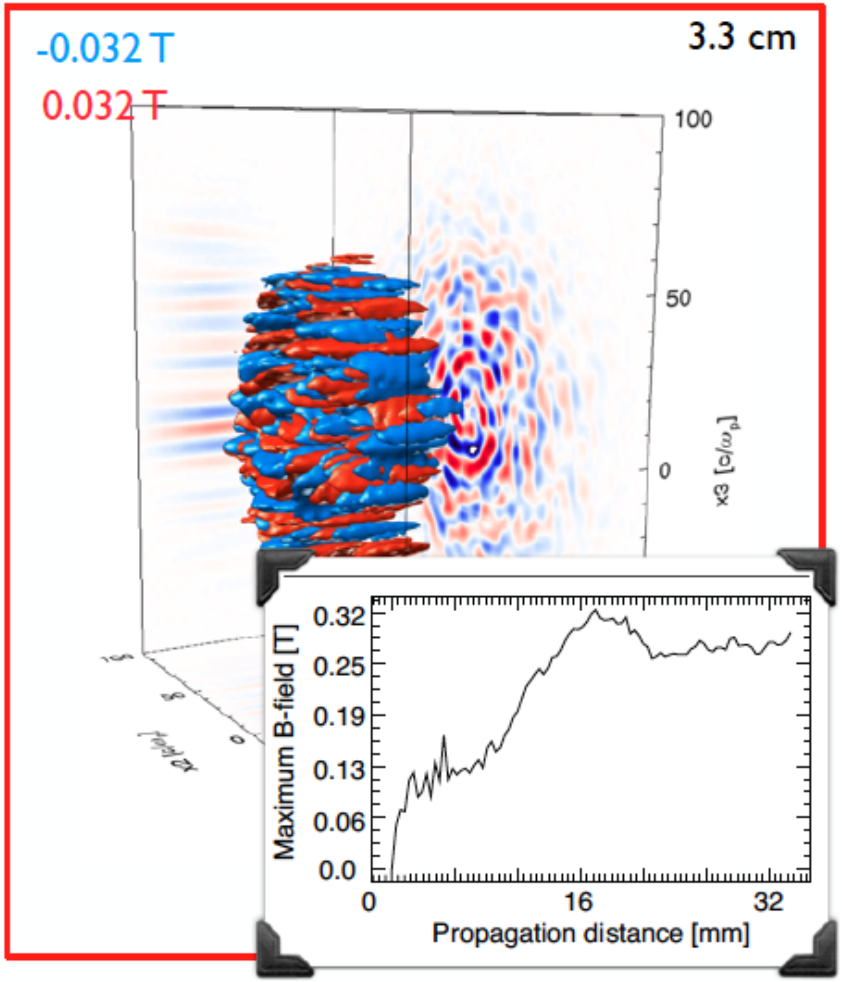
- ✓ Strong filamentation only for neutral beam (>40%)
- ✓ Saturation reached at ~800 c/w_p
- ✓ Generation of strong B fields
- ✓ Equipartition of the order of $10^{-2} - 10^{-4}$
- ✓ Long-lived fields

G. Sarri *et al.*, Nature Communications 6, 6747 (2015)

Beam filamentation: real

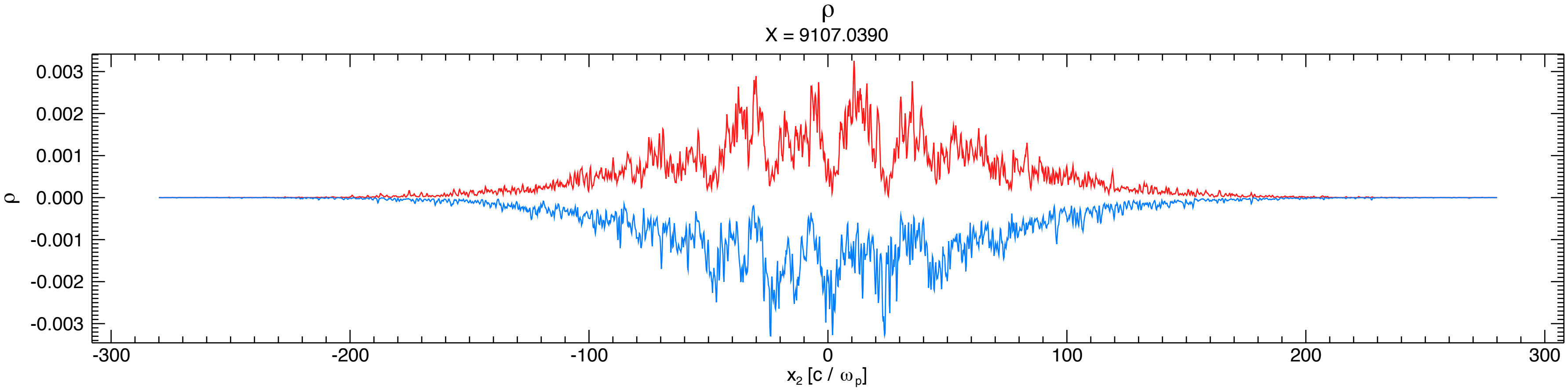
Laser-driven electron-positron beams have, however, a broad spectrum (Maxwell-Juttner distribution and a wide divergence





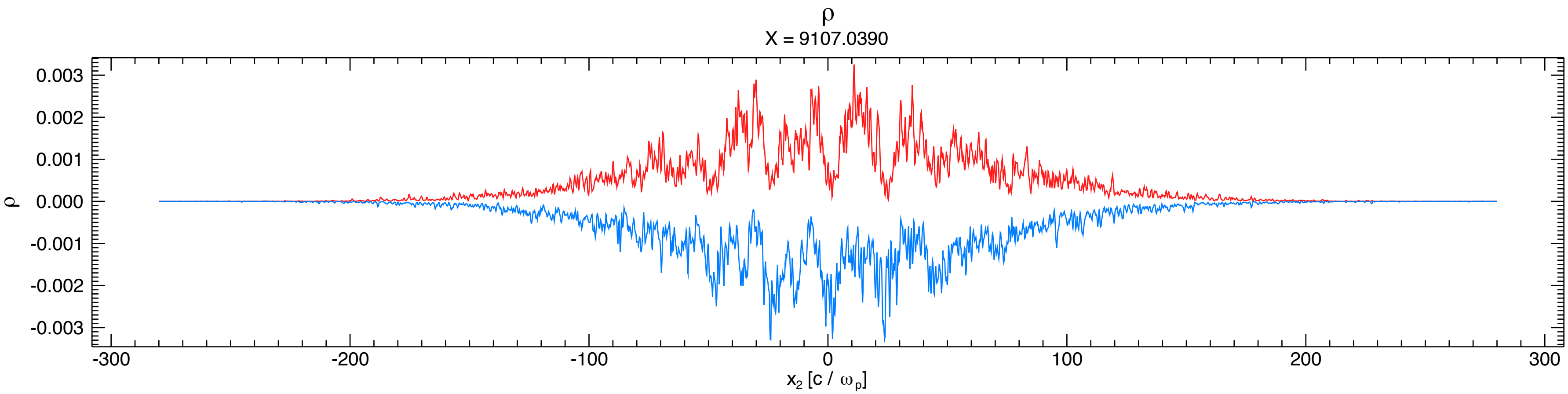
- ✓ Filamentation still a strong process
- ✓ Generation of strong fields on a scale of the order of the beam collisionless skin depth

Beam profile

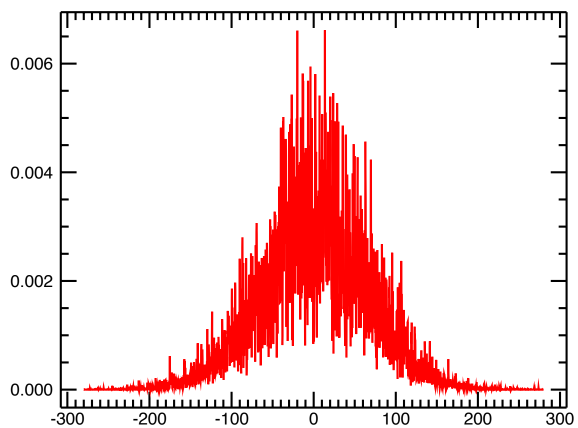


- ✓ Electrons (blue) and positrons (red) produce beam-lets with a characteristic diameter of the order of the relativistic skin depth of the beam
- ✓ The beam-lets tend to distribute by filling each others density gaps

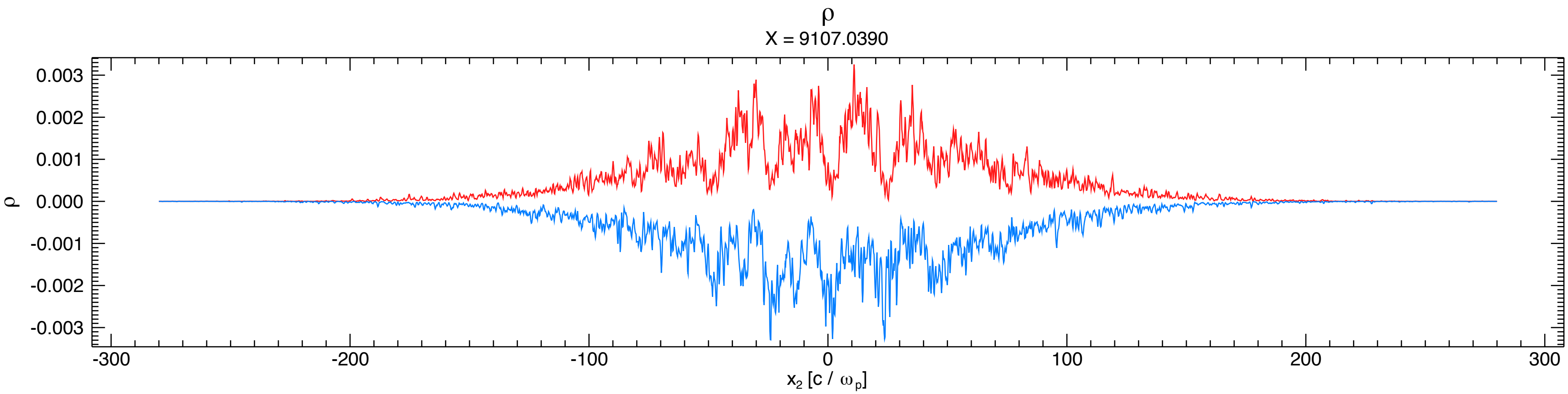
Beam profile



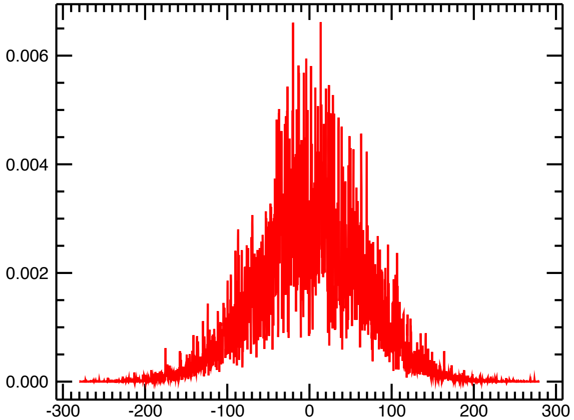
- ✓ Electrons (blue) and positrons (red) produce beam-lets with a characteristic diameter of the order of the relativistic skin depth of the beam
- ✓ The beam-lets tend to distribute by filling each others density gaps



Beam profile

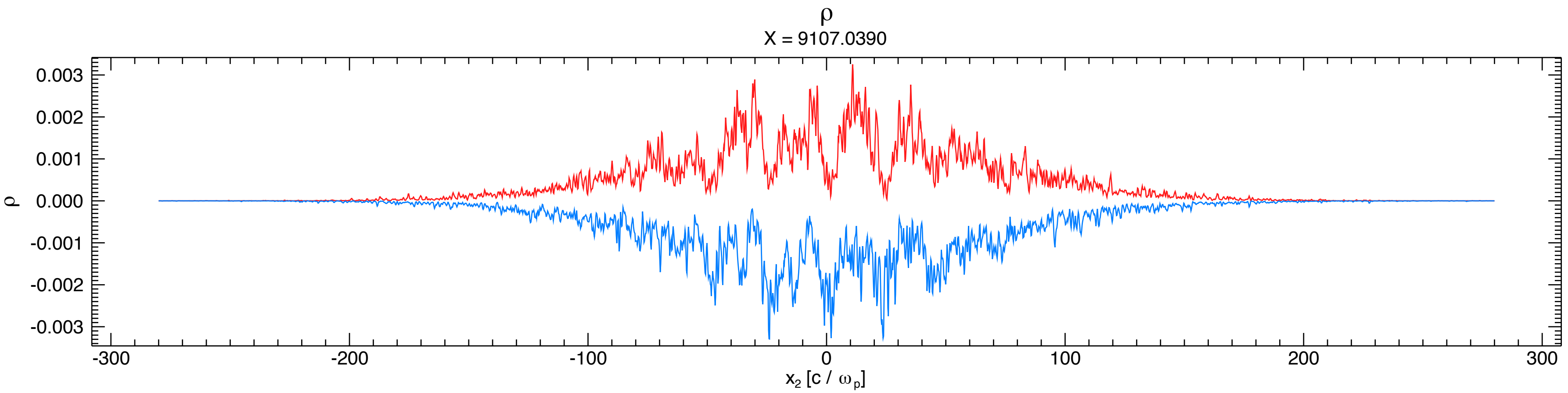


- ✓ Electrons (blue) and positrons (red) produce beam-lets with a characteristic diameter of the order of the relativistic skin depth of the beam
- ✓ The beam-lets tend to distribute by filling each others density gaps

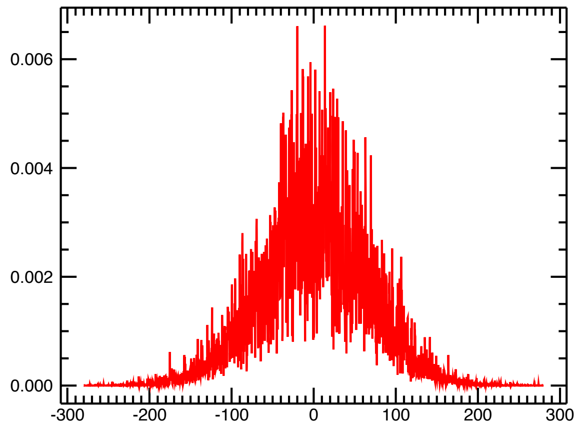


- ✓ The beam preserves a smooth density distribution
- ✓ Total particle symmetry

Beam profile



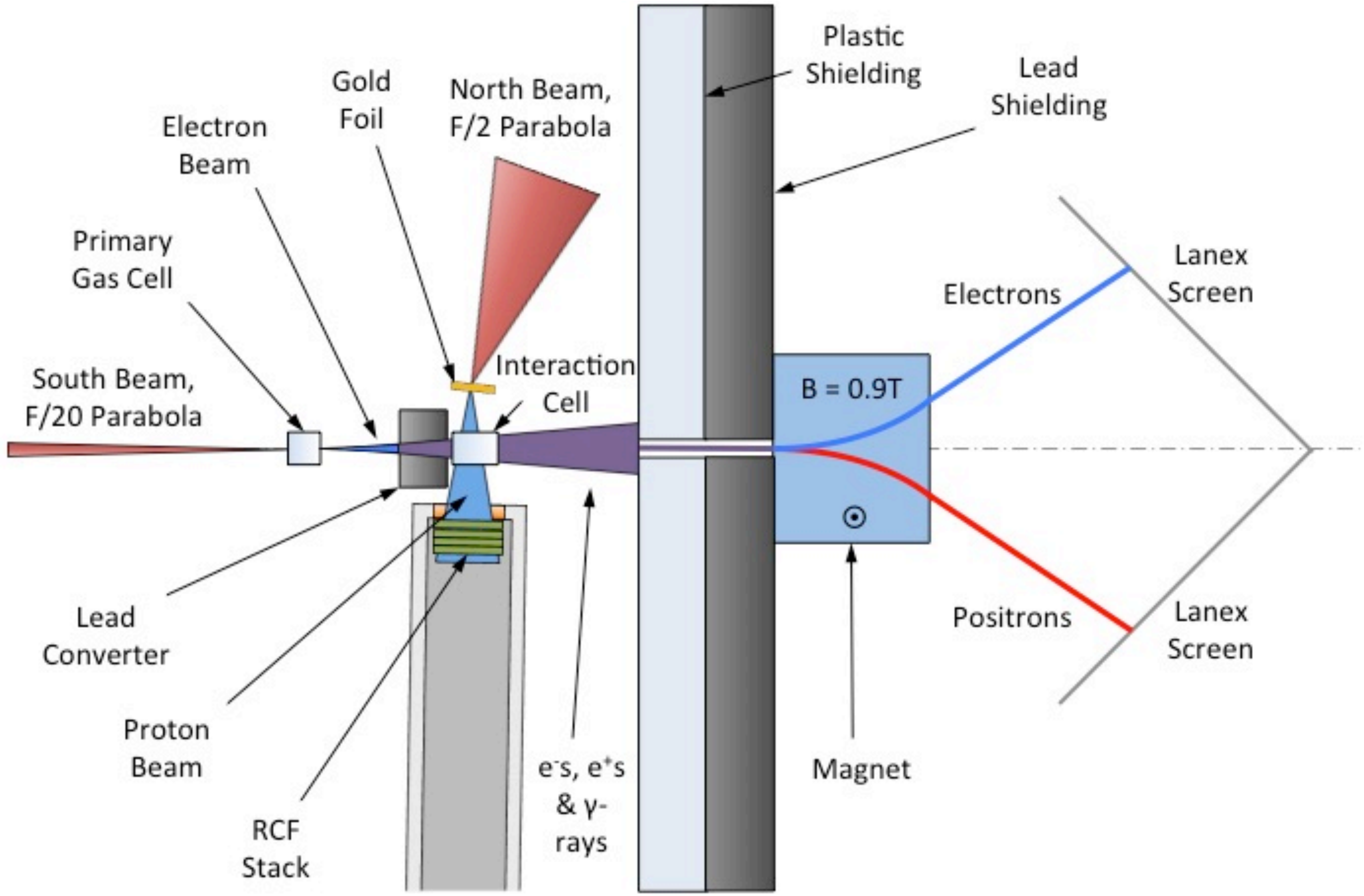
- ✓ Electrons (blue) and positrons (red) produce beam-lets with a characteristic diameter of the order of the relativistic skin depth of the beam
- ✓ The beam-lets tend to distribute by filling each others density gaps



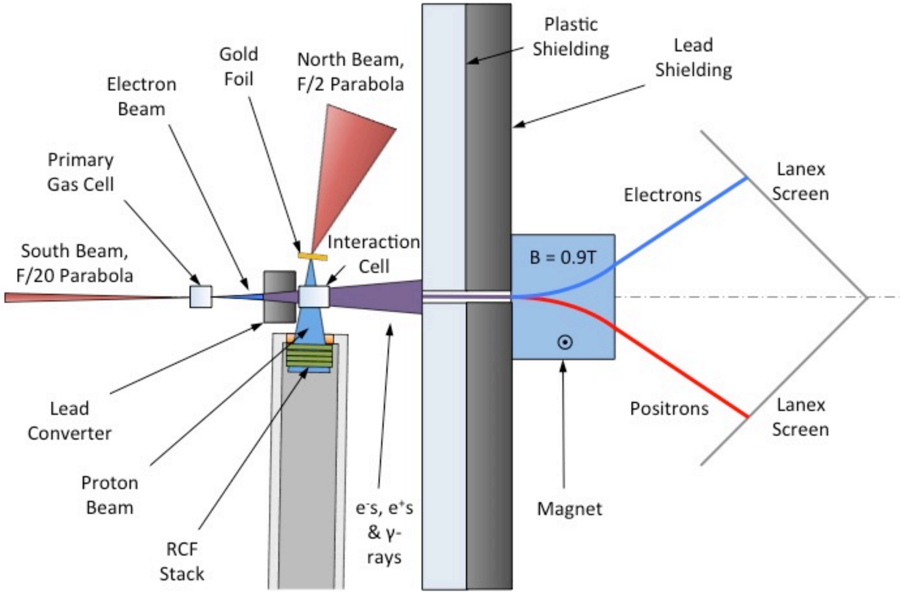
- ✓ The beam preserves a smooth density distribution
- ✓ Total particle symmetry
- X Undistinguishable by scintillator screen or any other charge-independent detector

Beam filamentation experimental evidence

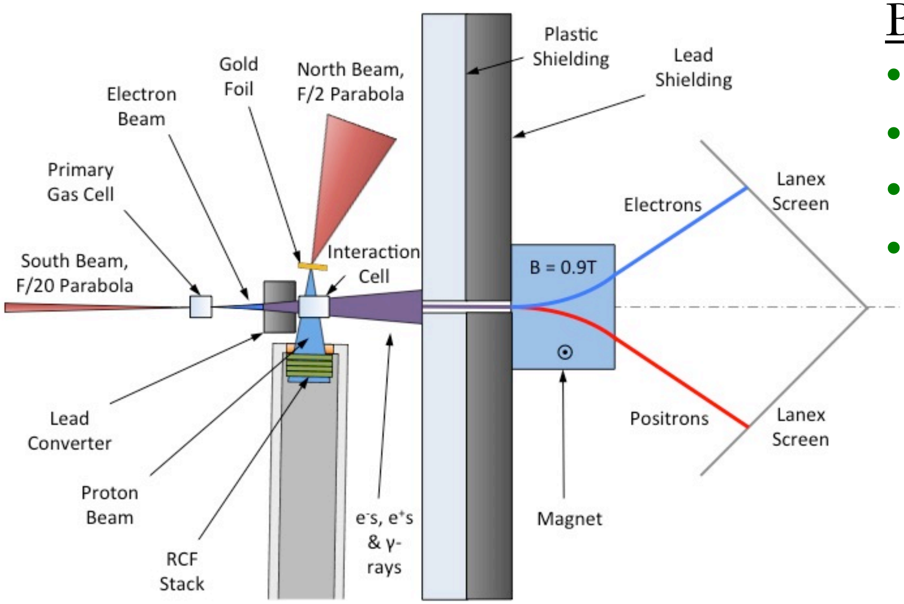
Filamentation: experiment



Filamentation: theory



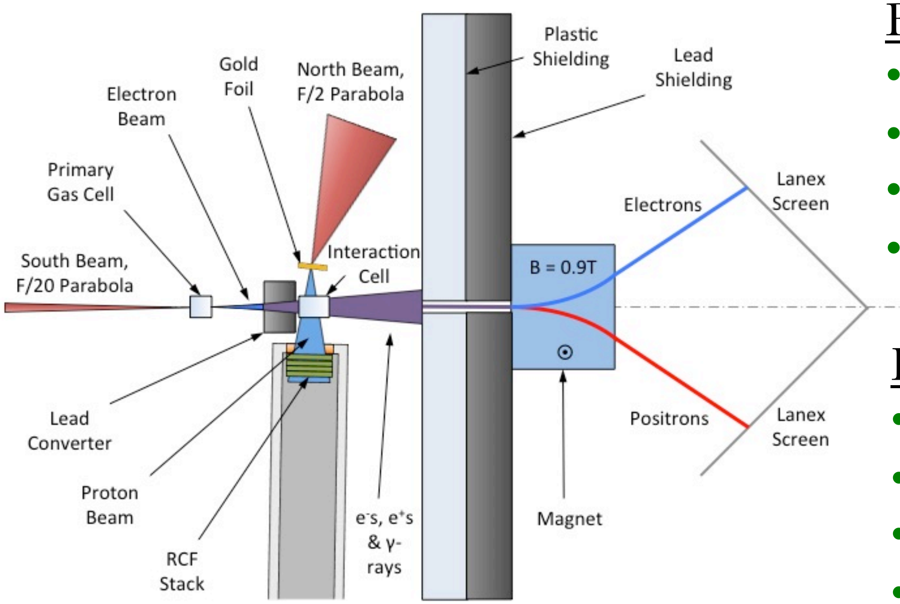
Filamentation: theory



Background plasma

- $n_P = 10^{18}\ cm^{-3}$
- $T_P \sim 100$ eV (from Hydro simulations)
- $w_P = 5.6x10^{13}$ Hz ➔ $t_P \sim 100$ fs
- $v_{th} \sim 7x10^6$ m/s ➔ $r_P \sim 40\ \mu m$

Filamentation: theory



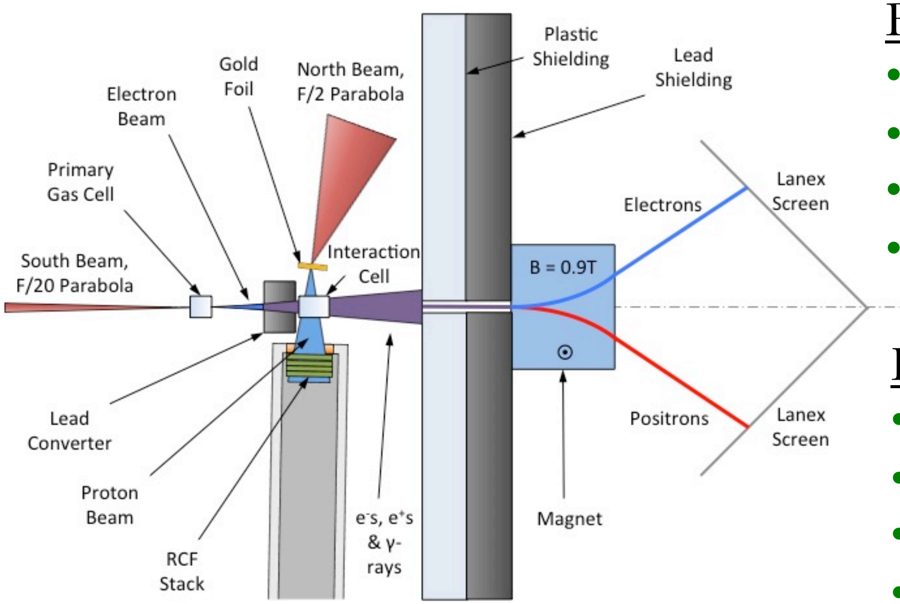
Background plasma

- $n_P = 10^{18}$ cm^{-3}
- $T_P \sim 100$ eV (from Hydro simulations)
- $w_P = 5.6\text{x}10^{13}$ Hz ➔ $t_P \sim 100$ fs
- $v_{th} \sim 7\text{x}10^6$ m/s ➔ $r_P \sim 40$ µm

Electron-positron beam

- $n_B = 4\text{x}10^{15}$ cm^{-3}
- $\gamma_{AV} \sim 15$
- $w_B = 3.6\text{x}10^{12}$ Hz ➔ $t_P \sim 1.7$ ps
- $c/w_B \sim 80$µm ➔ (relativistic) $c/w_B \sim 320$µm

Filamentation: theory



Background plasma

- $n_P = 10^{18}$ cm^{-3}
- $T_P \sim 100$ eV (from Hydro simulations)
- $w_P = 5.6\text{x}10^{13}$ Hz ➔ $t_P \sim 100$ fs
- $v_{th} \sim 7\text{x}10^6$ m/s ➔ $r_P \sim 40$ μm

Electron-positron beam

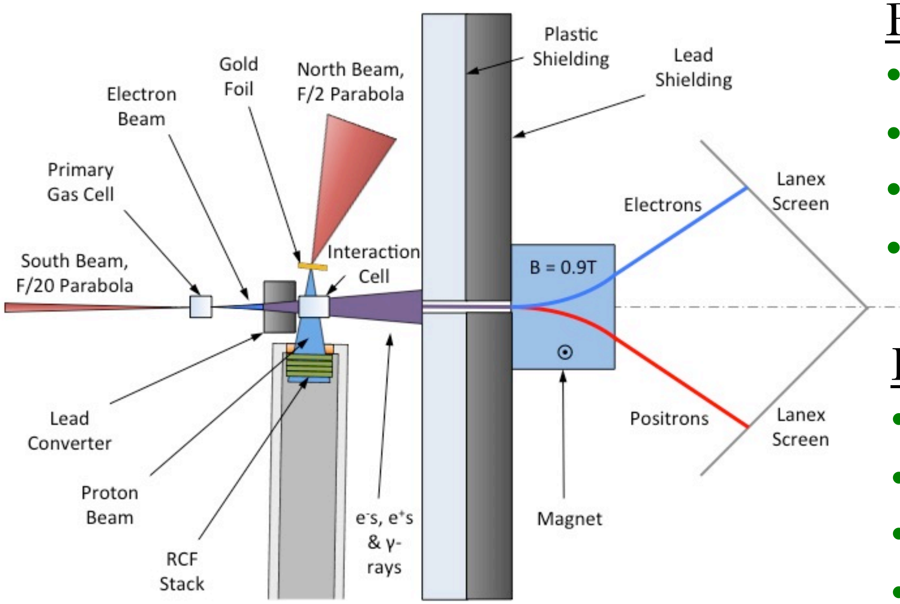
- $n_B = 4\text{x}10^{15}$ cm^{-3}
- $\gamma_{AV} \sim 15$
- $w_B = 3.6\text{x}10^{12}$ Hz ➔ $t_P \sim 1.7$ ps
- $c/w_B \sim 80\mu m$ ➔ (relativistic) $c/w_B \sim 320\mu m$

✓ Beam-plasma linear instability theory predicts a growth rate and a wavelength:

$$\Gamma \sim \sqrt{\omega_B \omega_P} \sim 10^{13}\ Hz\,,\ \ \lambda \sim 2\pi c / \Gamma \sim 150\ \mu m$$

M. V. Medvedev *et al.*, APJ 526, 697 (1999)

Filamentation: theory



Background plasma

- $n_P = 10^{18}\ cm^{-3}$
- $T_P \sim 100$ eV (from Hydro simulations)
- $w_P = 5.6\text{x}10^{13}$ Hz ➔ $t_P \sim 100$ fs
- $v_{th} \sim 7\text{x}10^6$ m/s ➔ $r_P \sim 40\ \mu m$

Electron-positron beam

- $n_B = 4\text{x}10^{15}\ cm^{-3}$
- $\gamma_{AV} \sim 15$
- $w_B = 3.6\text{x}10^{12}$ Hz ➔ $t_P \sim 1.7$ ps
- $c/w_B \sim 80\mu m$ ➔ (relativistic) $c/w_B \sim 320\mu m$

✓ Beam-plasma linear instability theory predicts a growth rate and a wavelength:

$$\Gamma \sim \sqrt{\omega_B \omega_P} \sim 10^{13}\ Hz\,,\ \ \lambda \sim 2\pi c / \Gamma \sim 150\ \mu m$$

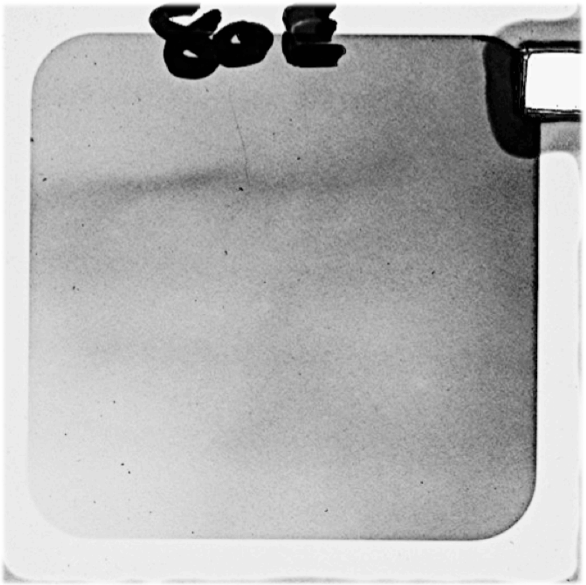
M. V. Medvedev *et al.*, APJ 526, 697 (1999)

✓ The instability should then grow within tens of microns, producing **1-2 filaments!**

✓ The background plasma gyroradius is smaller than the filament wavelength, suggesting that the **plasma can get magnetised**

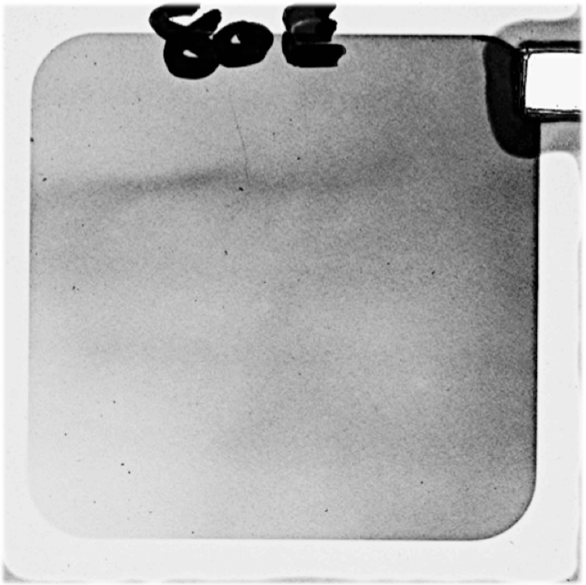
Proton radiography

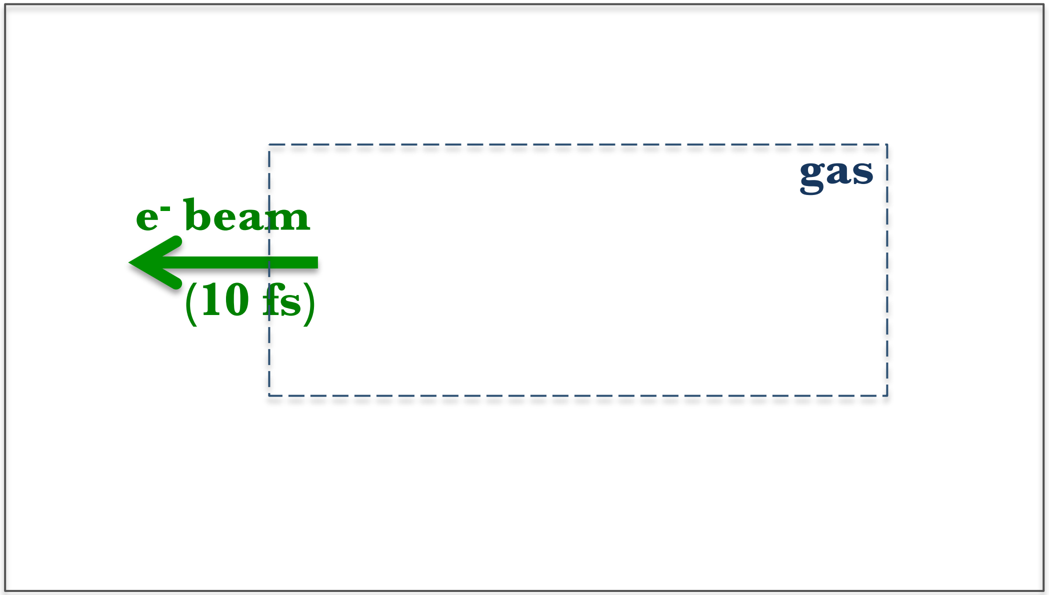
Can proton radiography see these fields?



Proton radiography

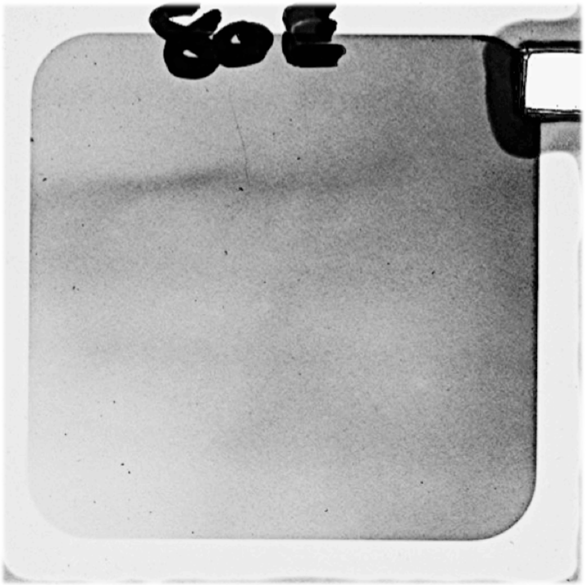
Can proton radiography see these fields?

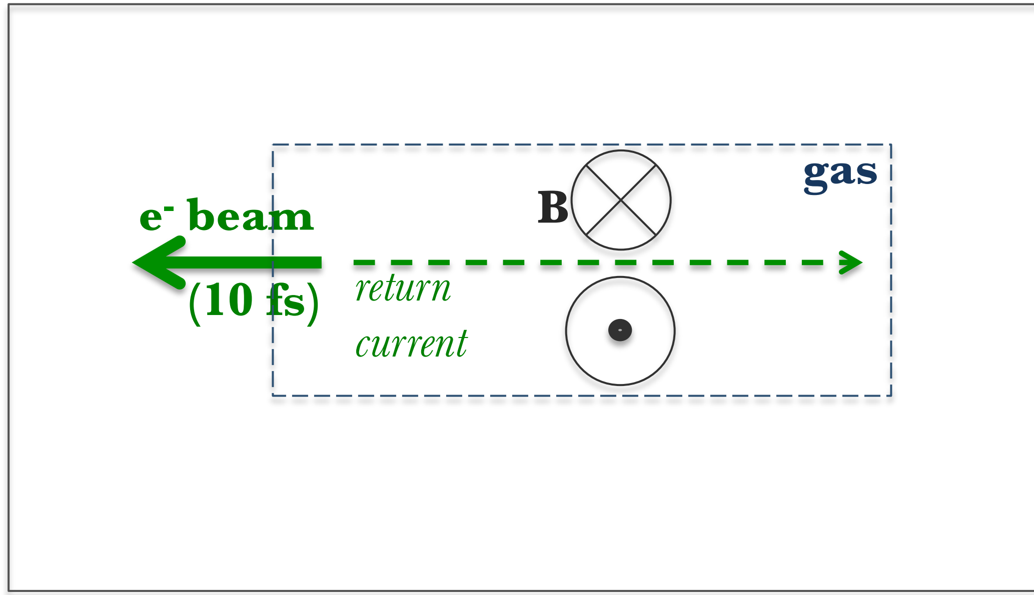




Proton radiography

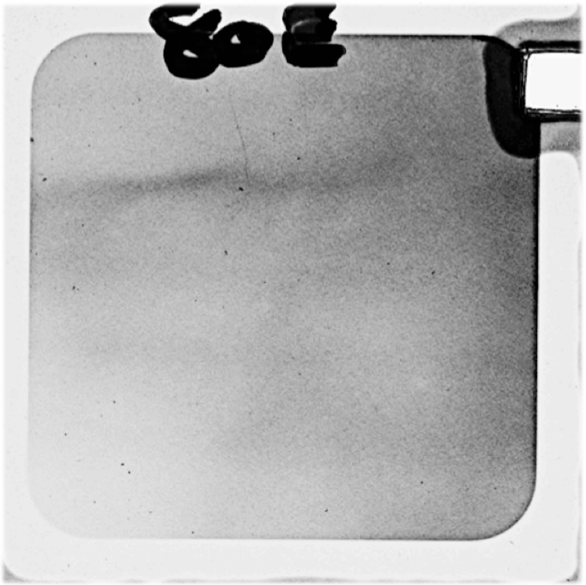
Can proton radiography see these fields?

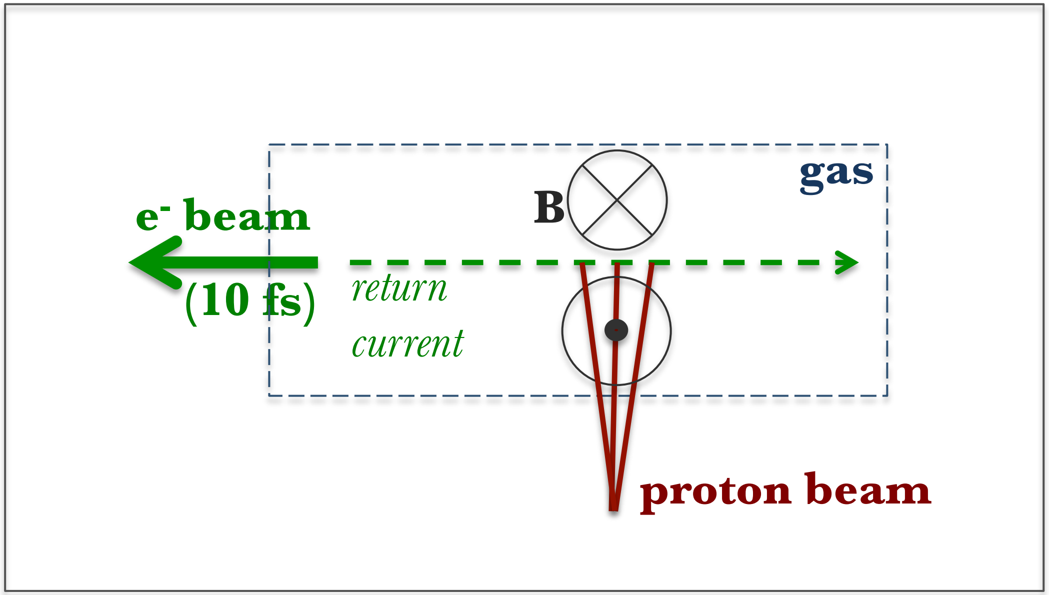




Proton radiography

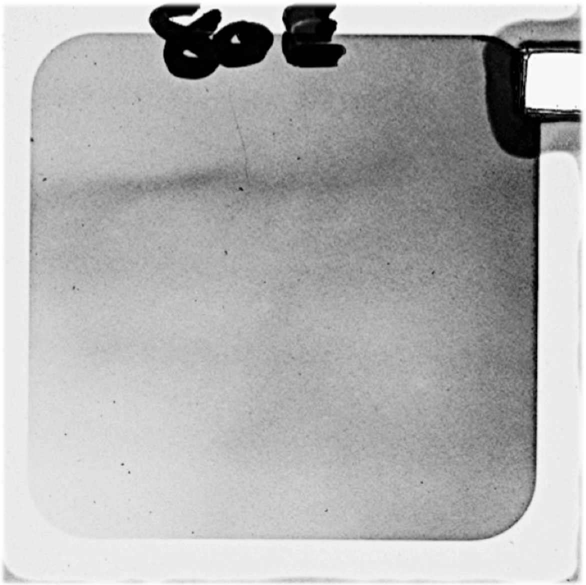
Can proton radiography see these fields?

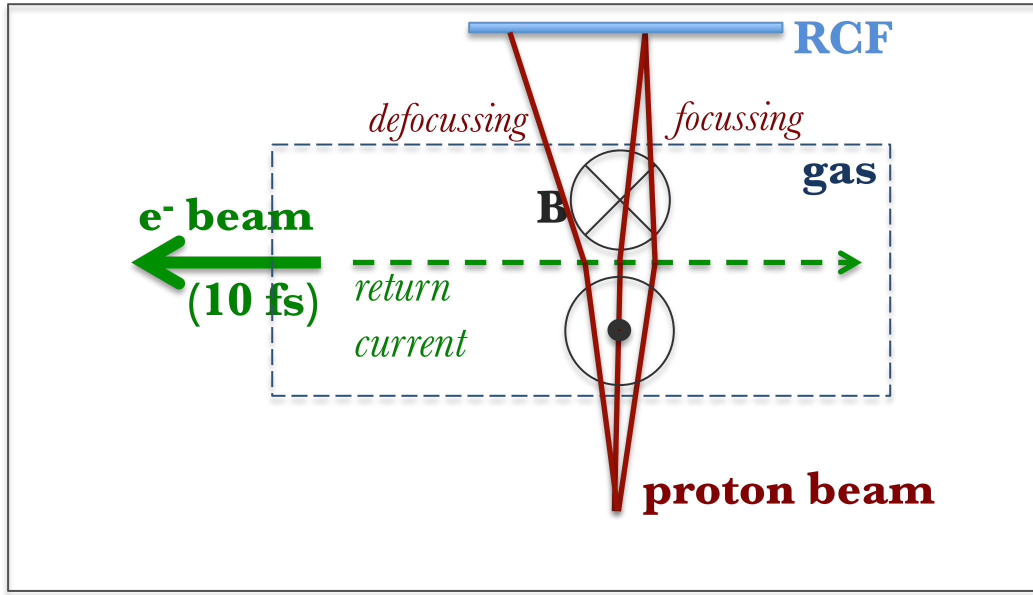




Proton radiography

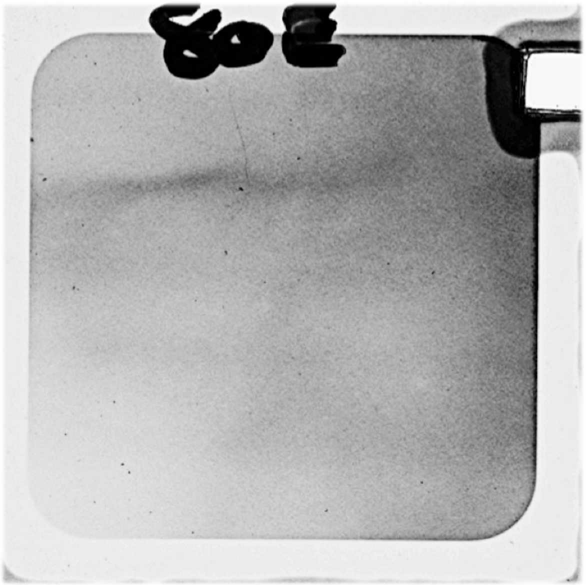
Can proton radiography see these fields?

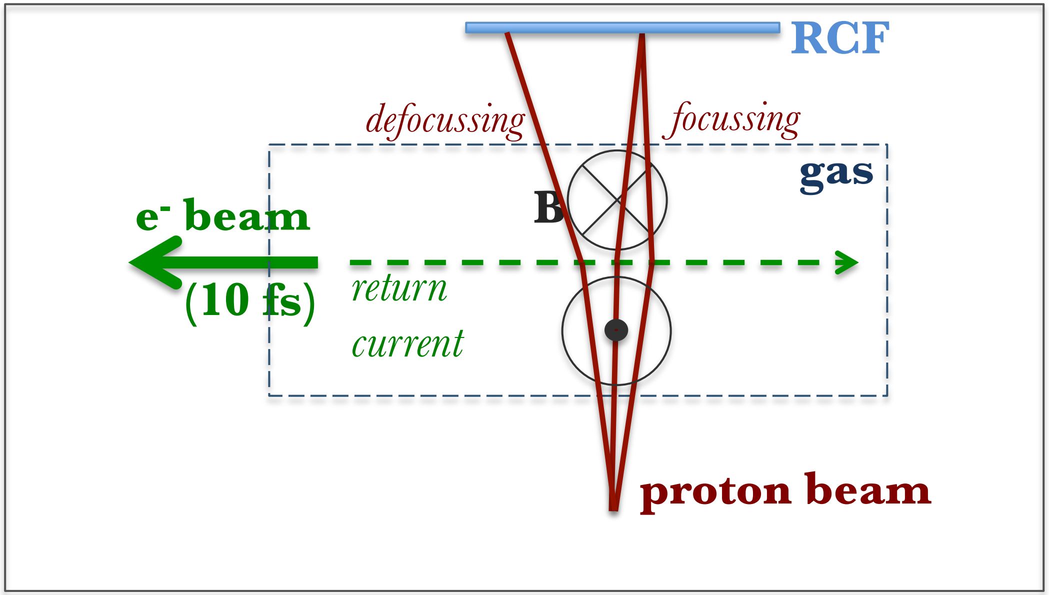




Proton radiography

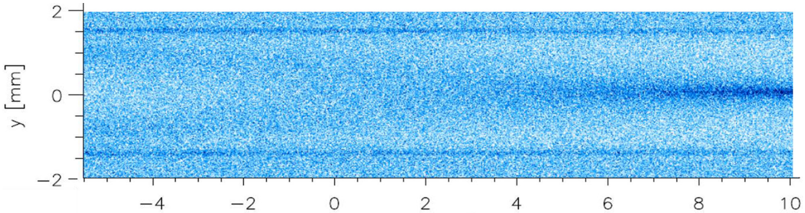
Can proton radiography see these fields?





- ✓ Azimuthal magnetic fields left in the background plasma persist for longer than the duration of the beam (proton radiography resolution ~ ps)

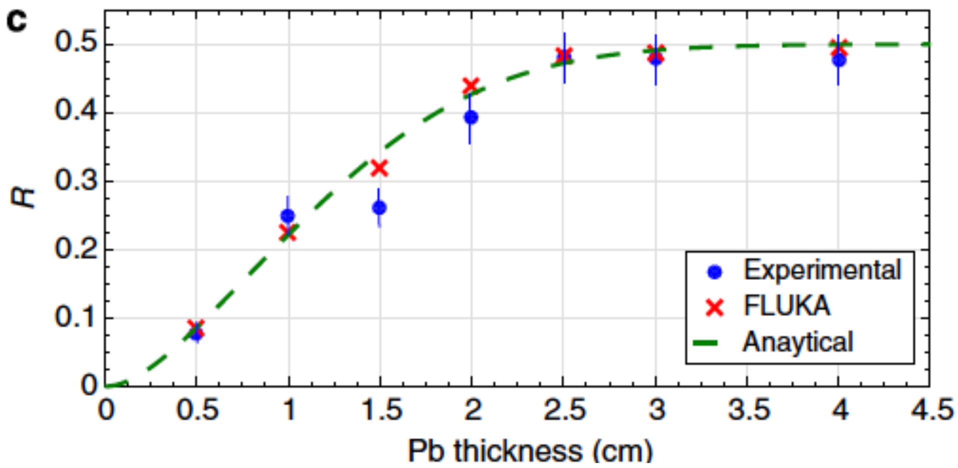
- ✓ The divergent nature of the proton beam implies that azimuthal magnetic fields induce focussing/defocussing of the protons



A. Smyth et al. Phys. Plasmas 23, 063121 (2016)

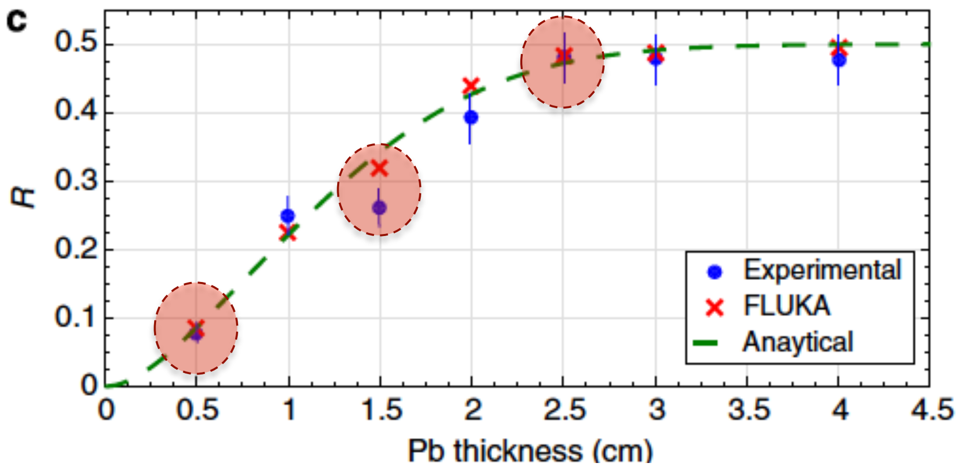
Proton radiography

✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:

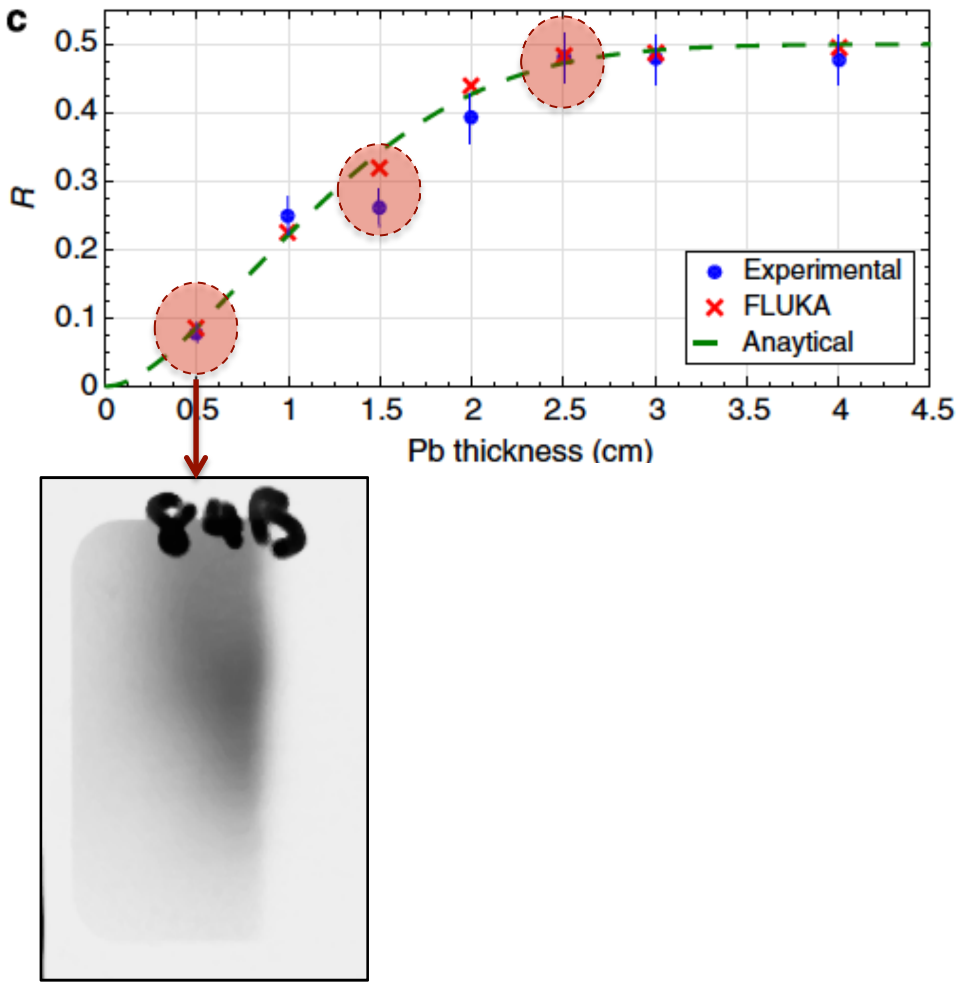


Proton radiography

✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:

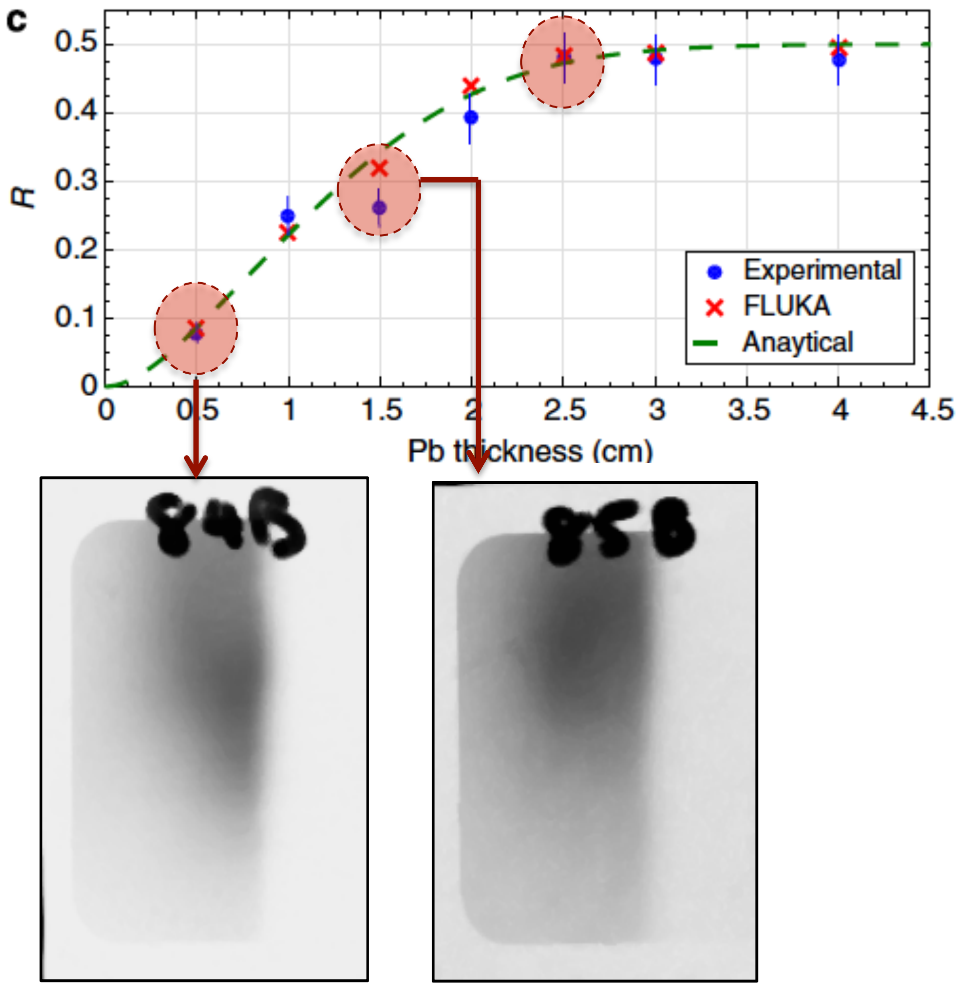


✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:



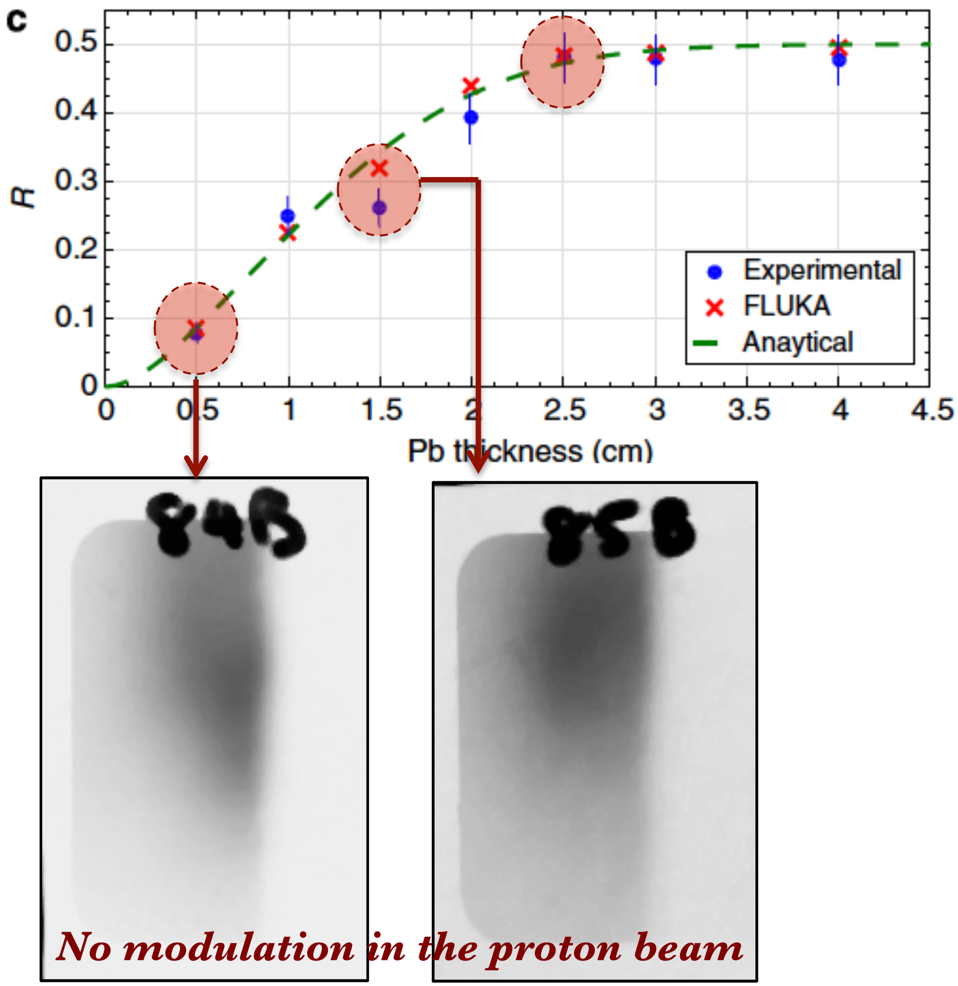
Proton radiography

✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:



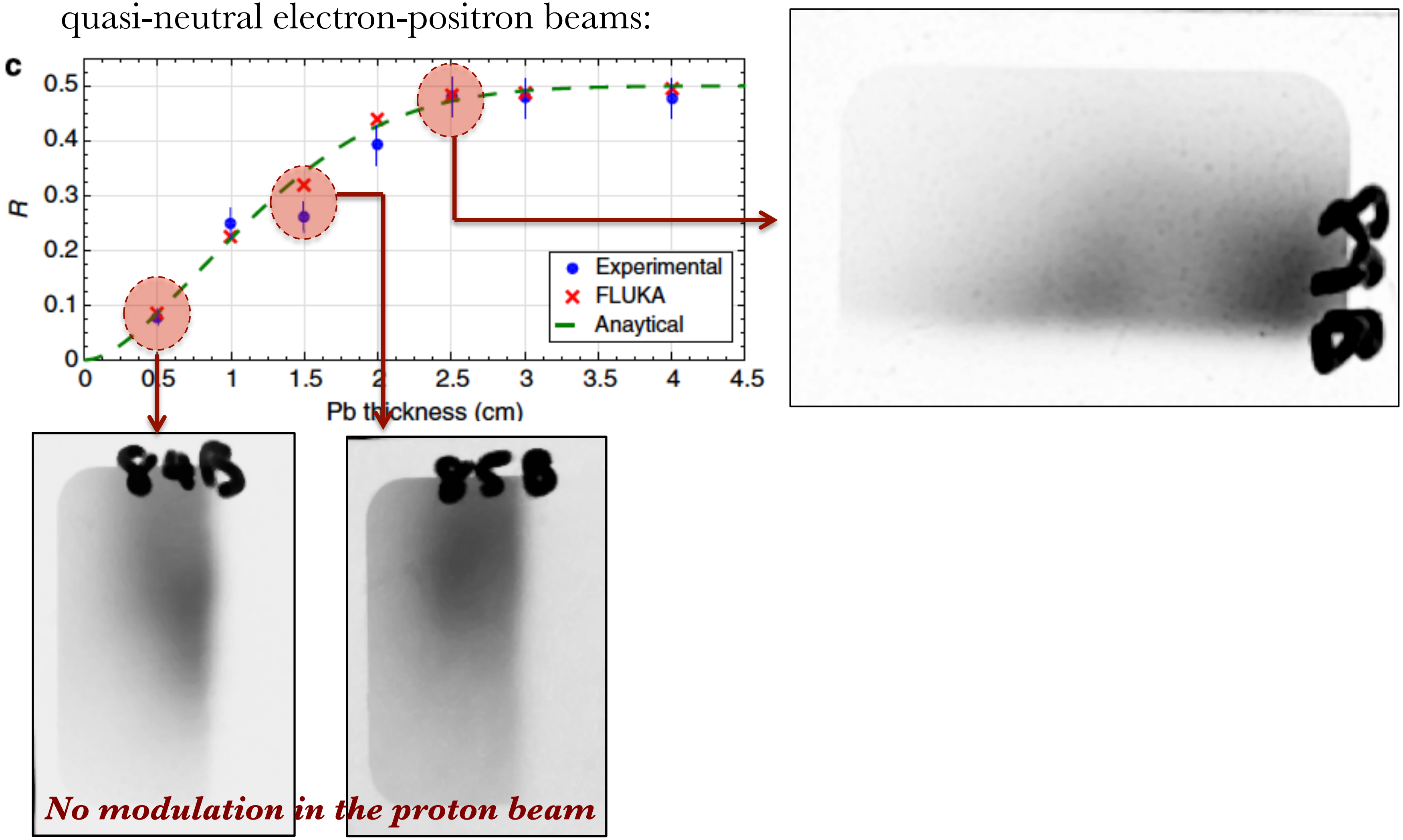
Proton radiography

✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:



Proton radiography

- ✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:

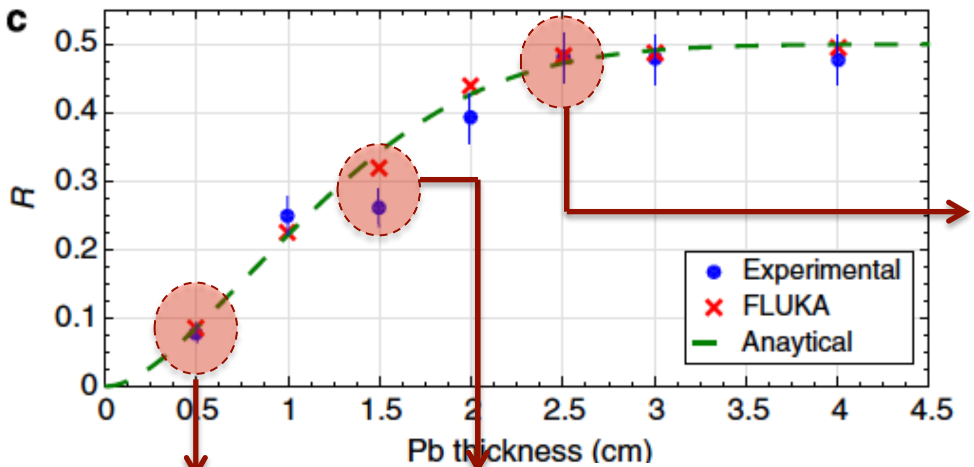


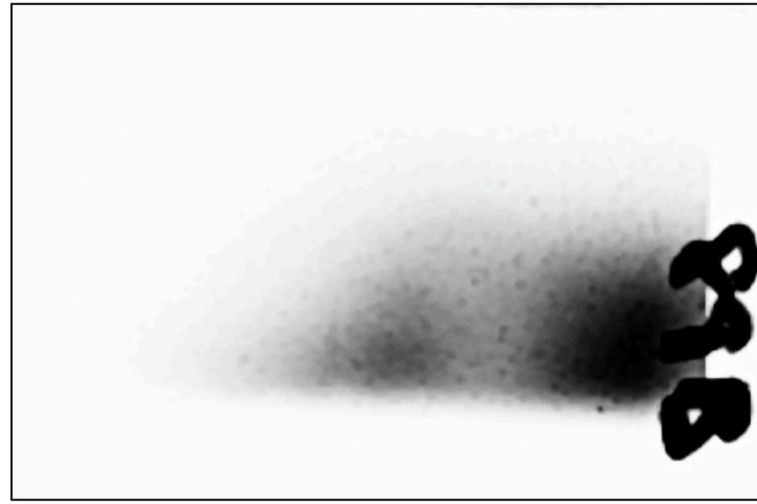
Queen's University Belfast

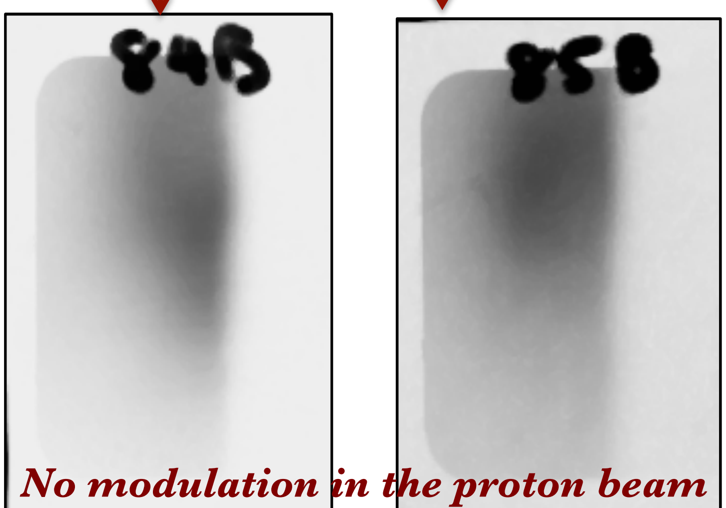
Proton radiography

EPSRC

✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:



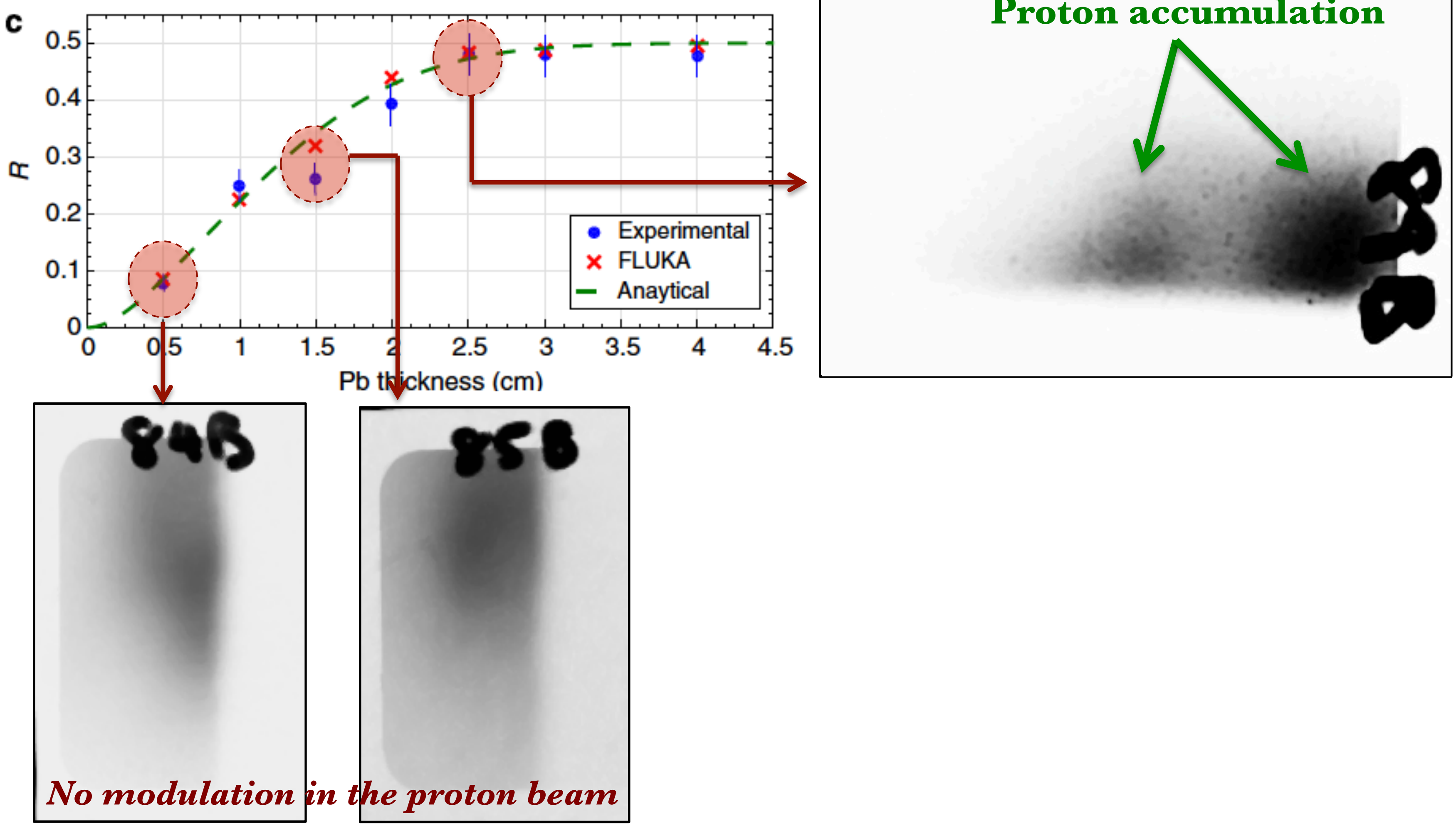




No modulation in the proton beam

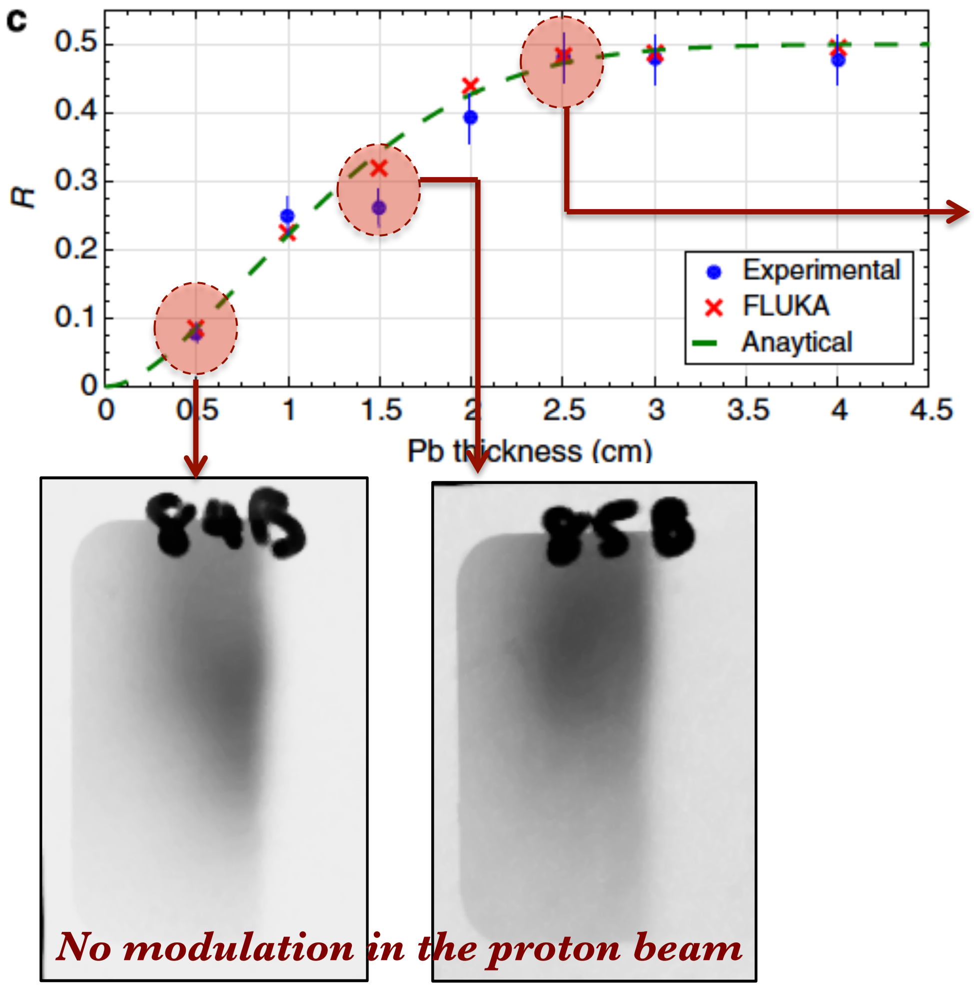
Proton radiography

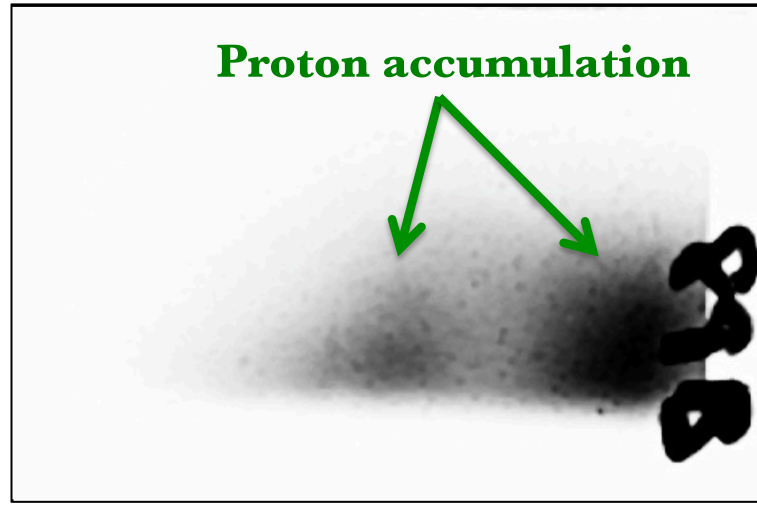
✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:

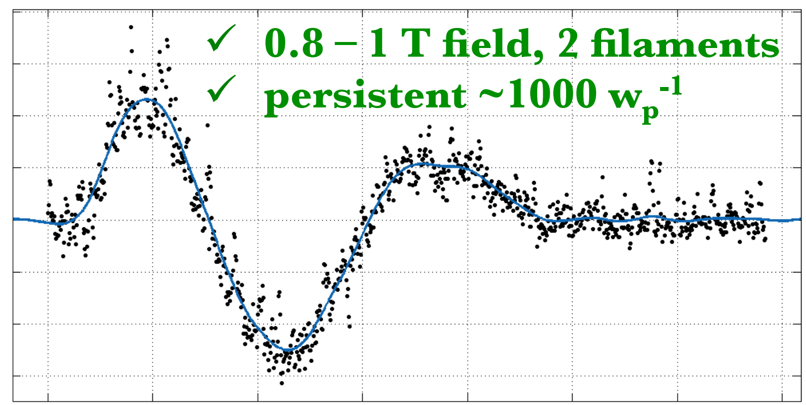


Proton radiography

- ✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:

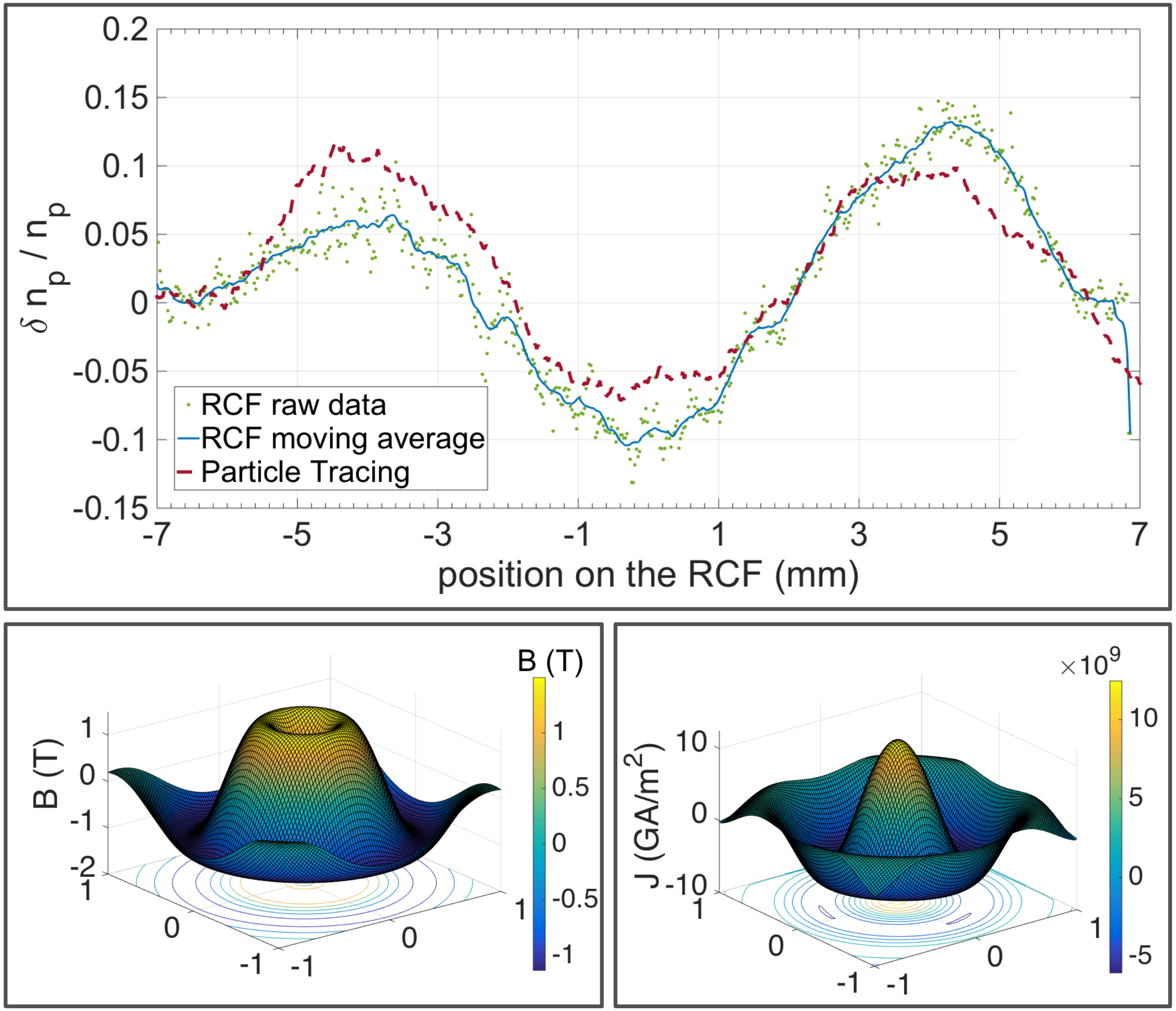






G. Sarri et al., in preparation (2016).

Proton radiography



Peak magnetic field
(1.0 ± 0.3) T

Spatial extent
(1.5 ± 0.2) mm

Current density
$\sim 10^{10}$ A/m^2

Equipartition
10^{-3}

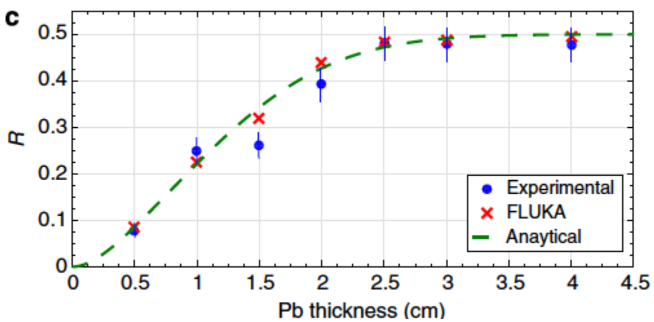
G. Sarri et al., in preparation (2016).

Queen's University Belfast

Conclusions and Outlook

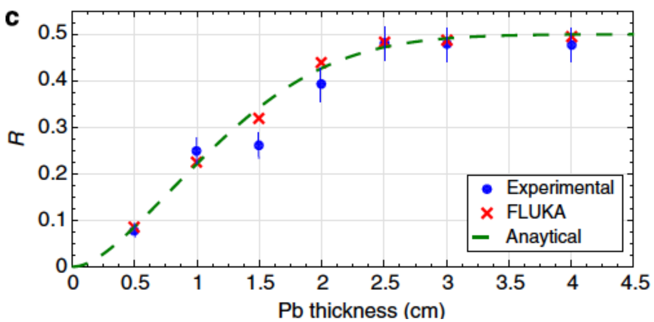
Conclusions and Outlook

- First generation of **neutral electron positron beams**

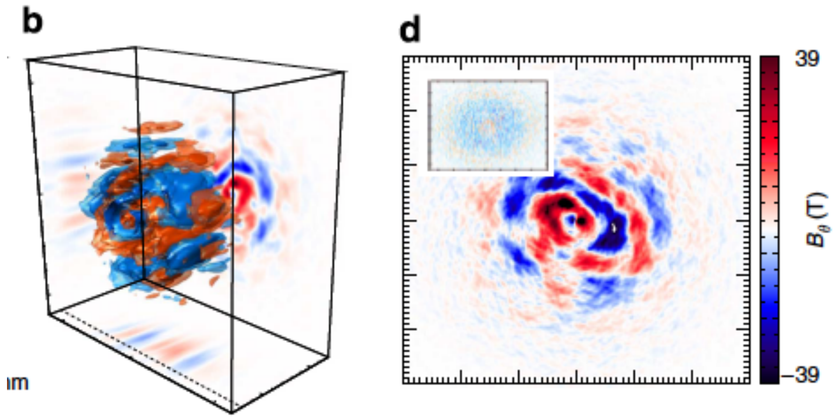


Conclusions and Outlook

- First generation of
  neutral electron positron beams

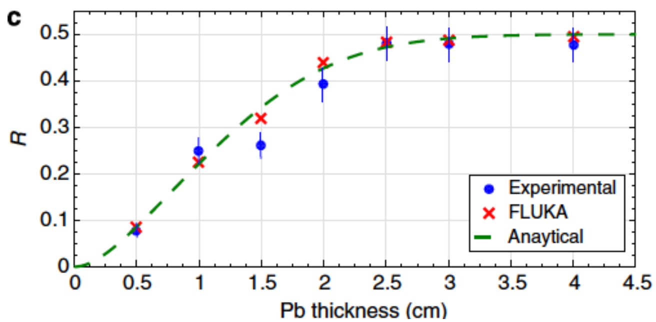


- These beams can be used to investigate fundamental **pair beam dynamics** to test models used to study astrophysical jets.

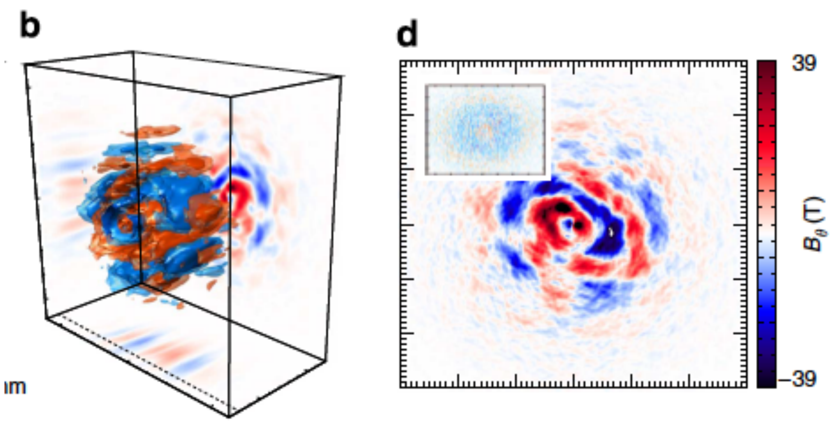


Conclusions and Outlook

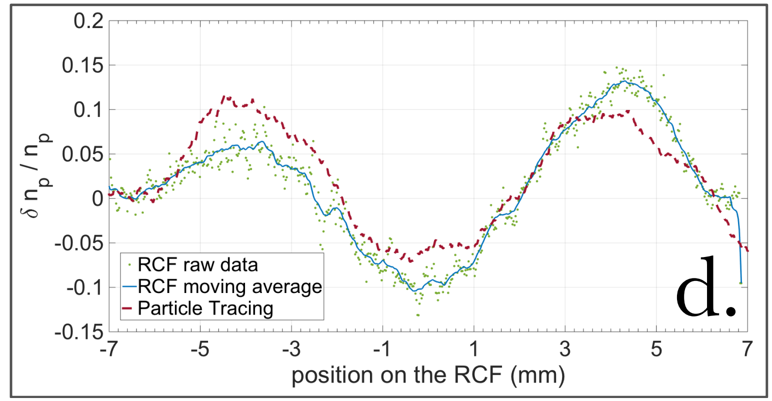
- First generation of **neutral electron positron beams**



- These beams can be used to investigate fundamental **pair beam dynamics** to test models used to study astrophysical jets.

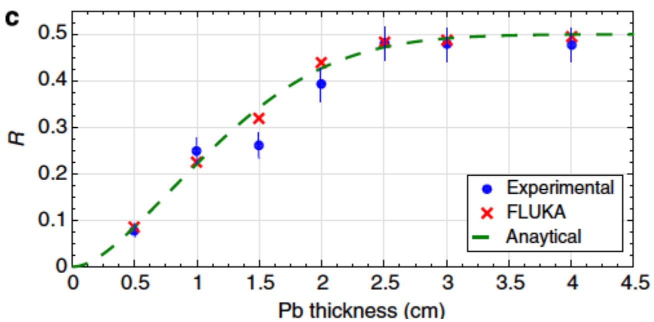


- Proton radiography gives first evidence of **magnetic field generation**

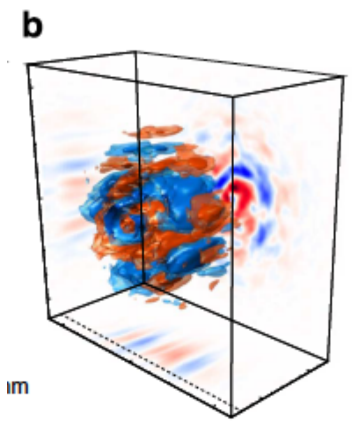


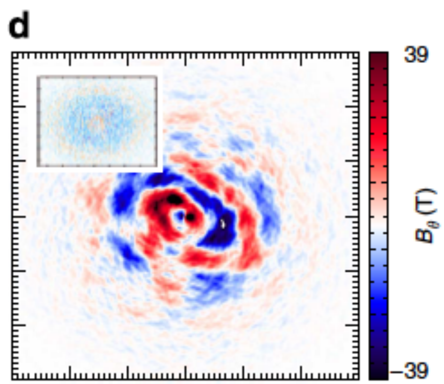
Conclusions and Outlook

- First generation of **neutral electron positron beams**

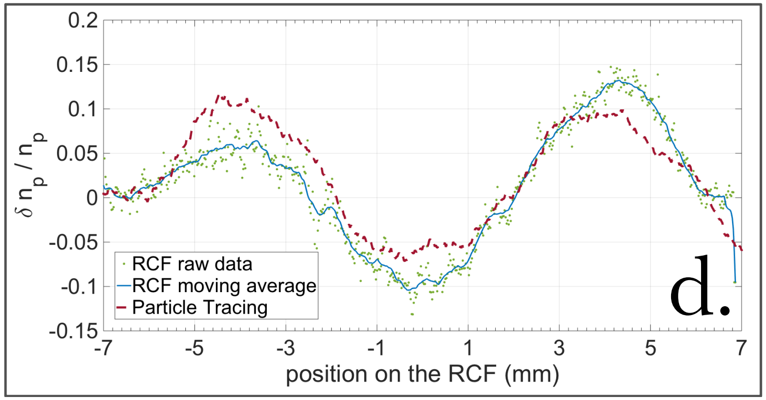


- These beams can be used to investigate fundamental **pair beam dynamics** to test models used to study astrophysical jets.

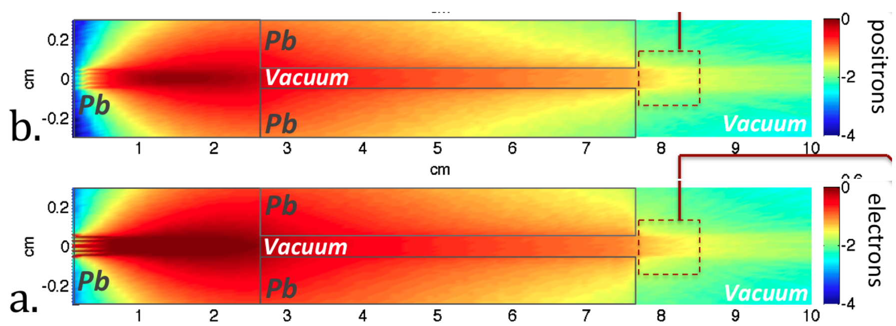




- Proton radiography gives first evidence of **magnetic field generation**



- Current work devoted to generating **collimated** pair jets and characterize their dynamics in detail



Thanks for your attention!

Gianluca Sarri
g.sarri@qub.ac.uk