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Ultra-intense lasers: an ideal tool for the study of matter under extreme conditions

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Talk Outline

- **INTRODUCTION**
  - High-power and high-energy lasers: state of the art
  - Laser-driven particle accelerators

- **NEUTRAL ELECTRON-POSITRON BEAMS**
  - A pair-plasma in the laboratory
  - Instabilities and magnetic field generation

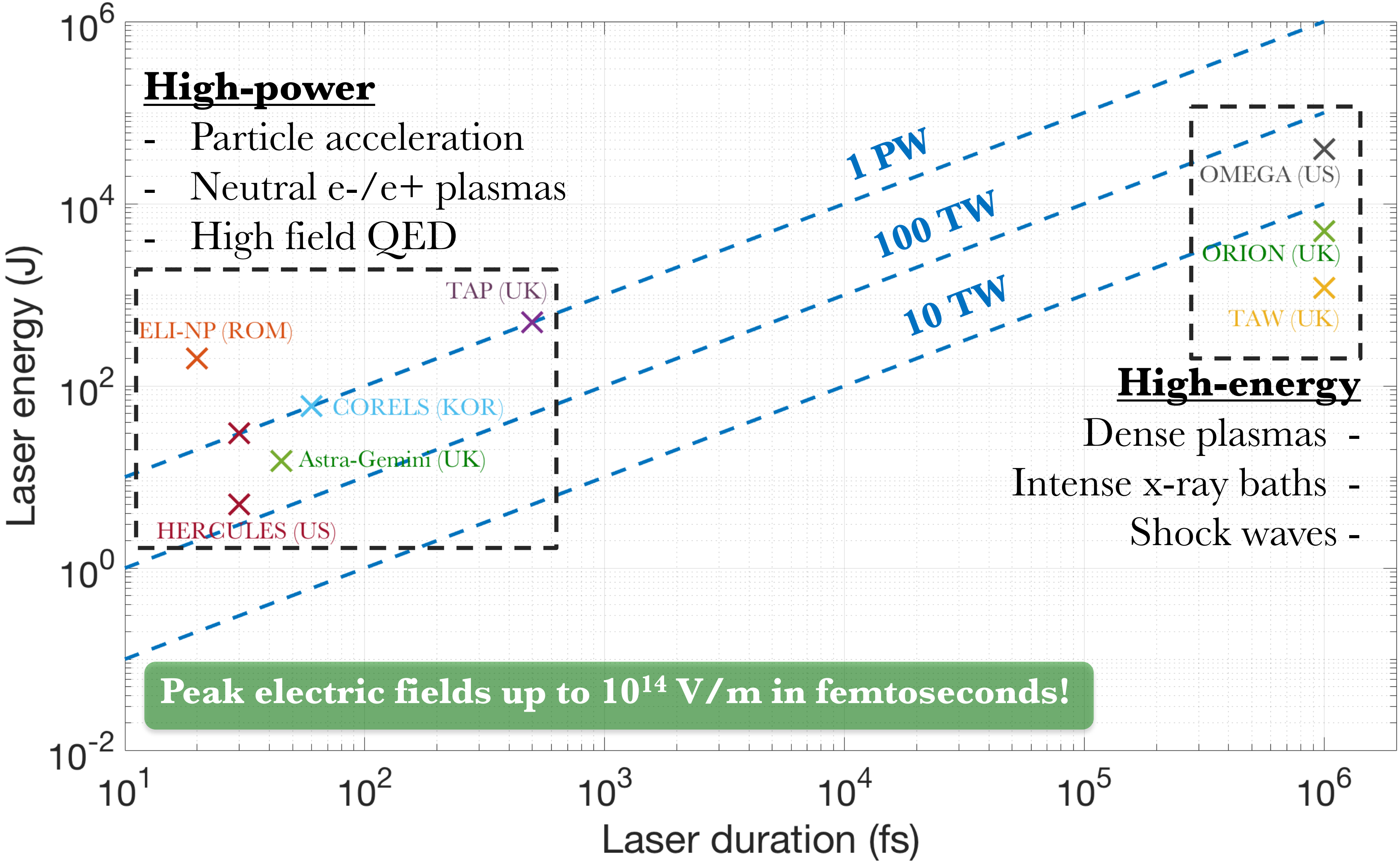
- **QED AND PHOTON-PHOTON SCATTERING**
  - Radiation Reaction
  - Pair production in a laser field

- **COLLISION-LESS SHOCK WAVES**
  - The birth of a collision-less shock
  - Instabilities in the shock front
  - Magnetised shock waves

- **CONCLUSIONS AND OUTLOOK**

Introduction

High-power lasers



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High-energy lasers

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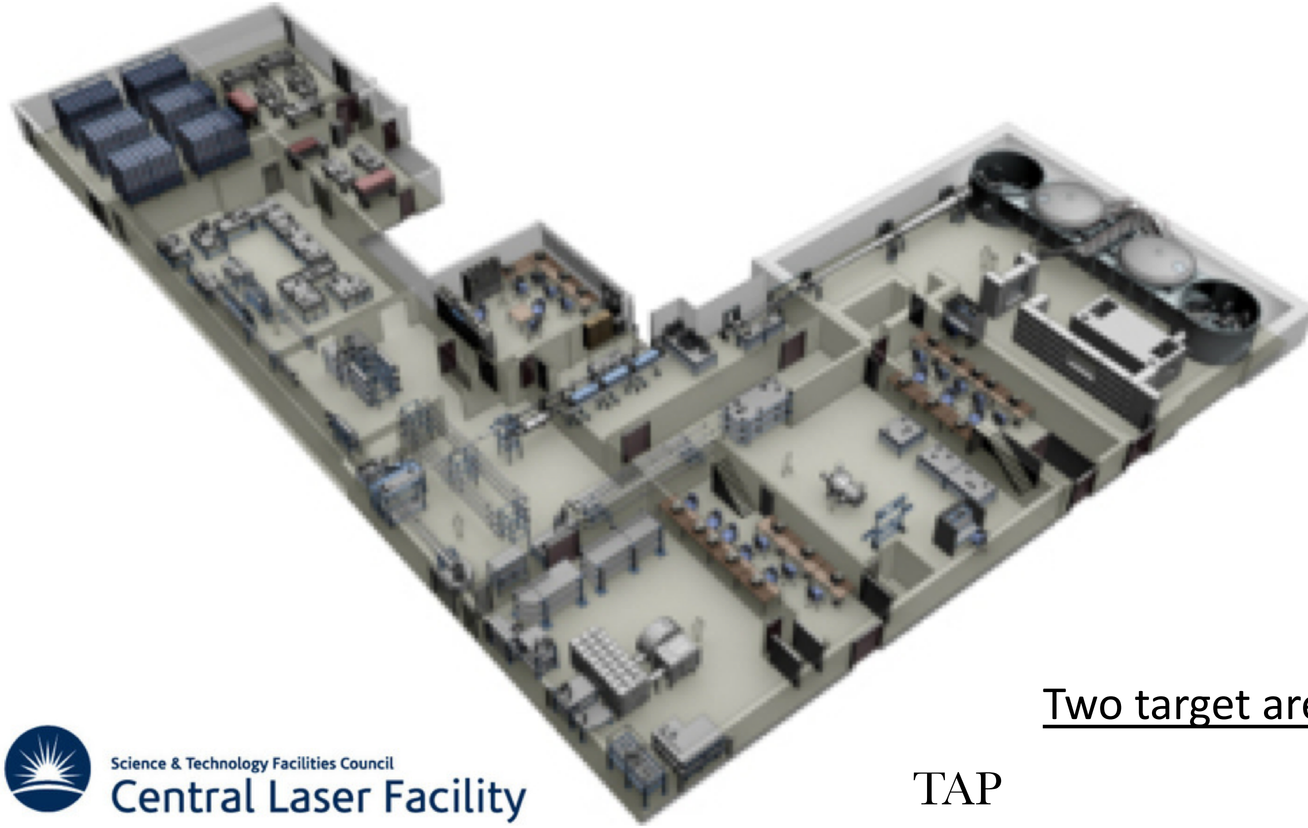


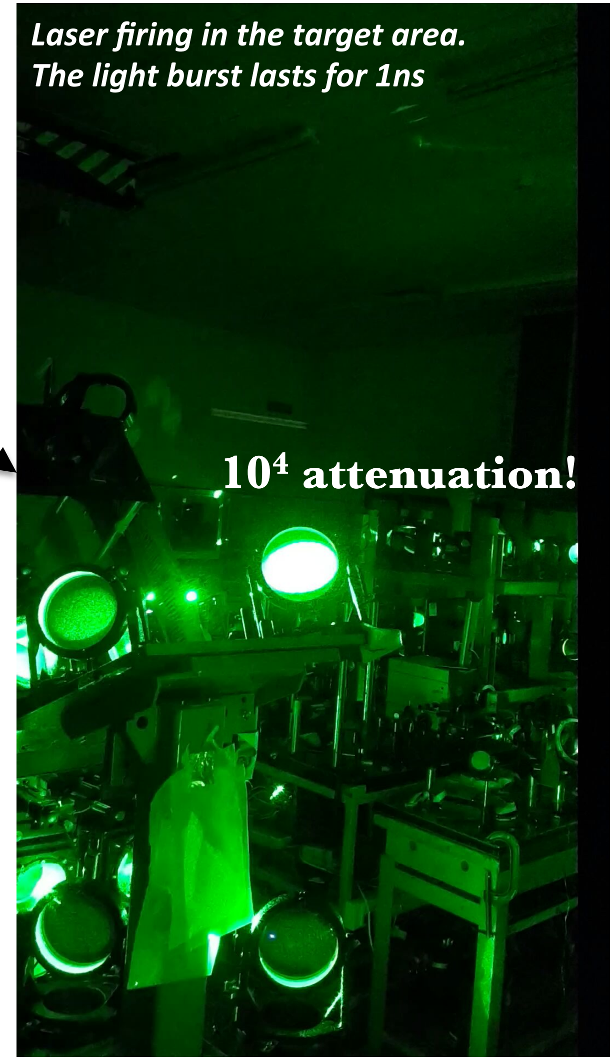
Science & Technology Facilities Council Central Laser Facility

Two target areas

TAP	TAW
τ = 0.5ps - 1ns	τ = 1ps - 1ns
E = 700 J	E = 0.1 - 1 kJ
P ~ 1 PW	P ~ 100 TW
I_{max}= 5x10^{20} Wcm^{-2}	I_{max}= 8x10^{19} Wcm^{-2}

High-energy lasers

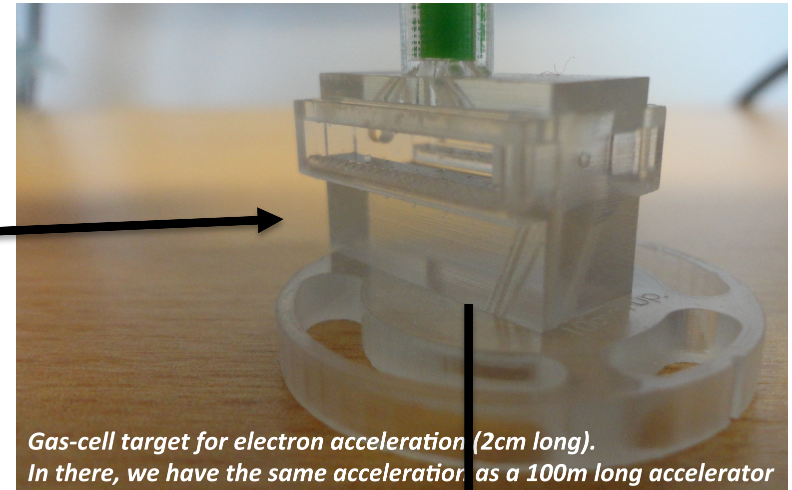
- Target Area West, Vulcan Laser, Rutherford Appleton Laboratory (UK)

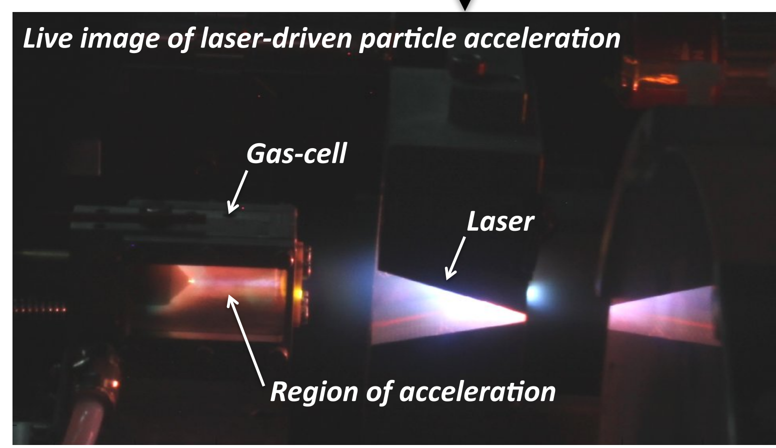


- ns-scale heating of materials up to multi-keV temperatures
- Dense plasmas and warm dense matter
- Ion-acoustic and collision-less shock waves

High-power lasers

- Astra-Gemini Laser, Rutherford Appleton Laboratory (UK)





- GeV-scale acceleration in a few cm!
- Relativistic plasmas (>MeV temperatutres)
- Ultra-intense fields, close to the Schwinger field
- Pair plasmas

High-power lasers: ELI-NP

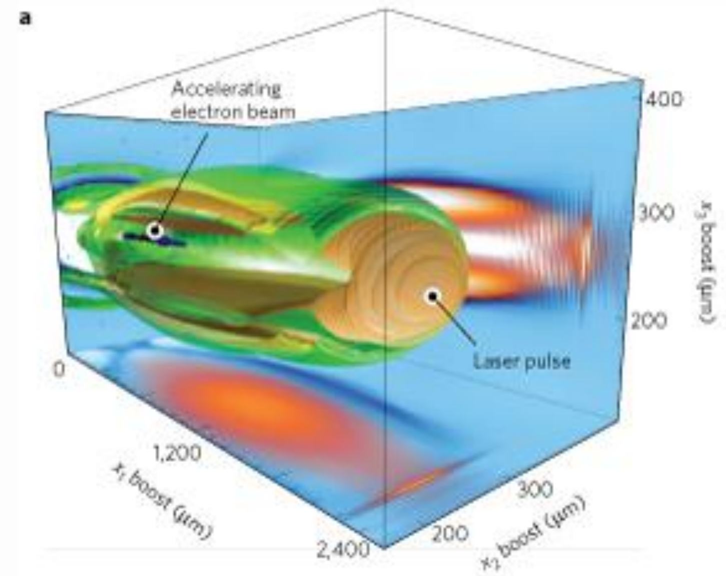
Goal Specs (2019)

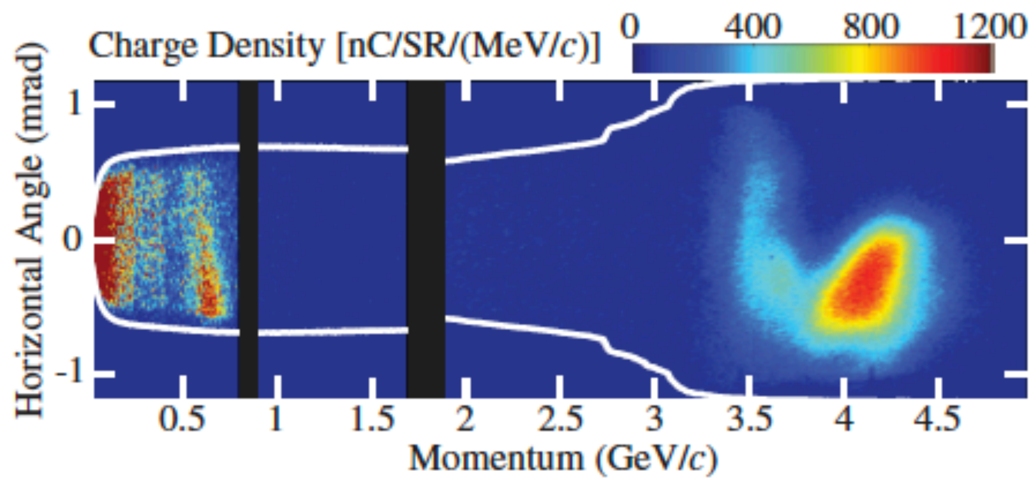
- E = 200 J
- d = 45 cm
- τ = 20 fs
- P = 10 PW
- F/80 focusing (36 m)

Generation of 10+ GeV electron beams within one acceleration stage

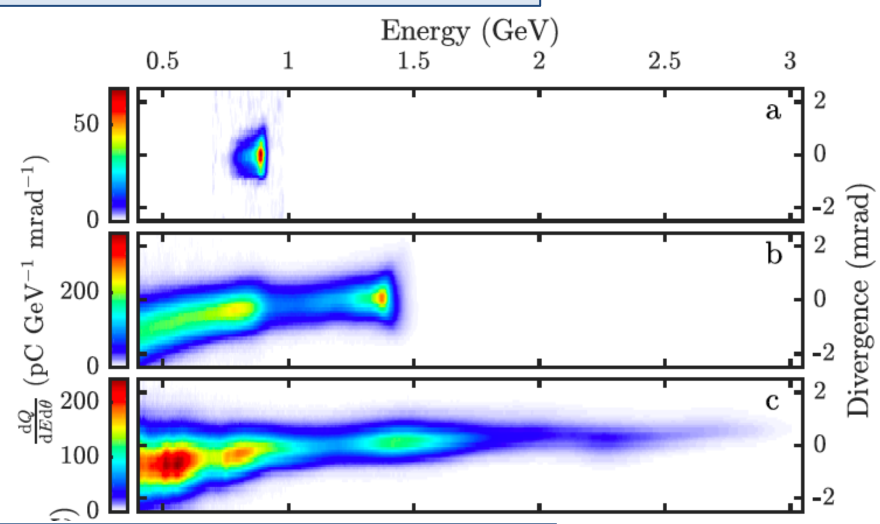
Laser-driven electron acceleration

Electron acceleration





W. P. Leemans et al., Phys. Rev. Lett. 2014

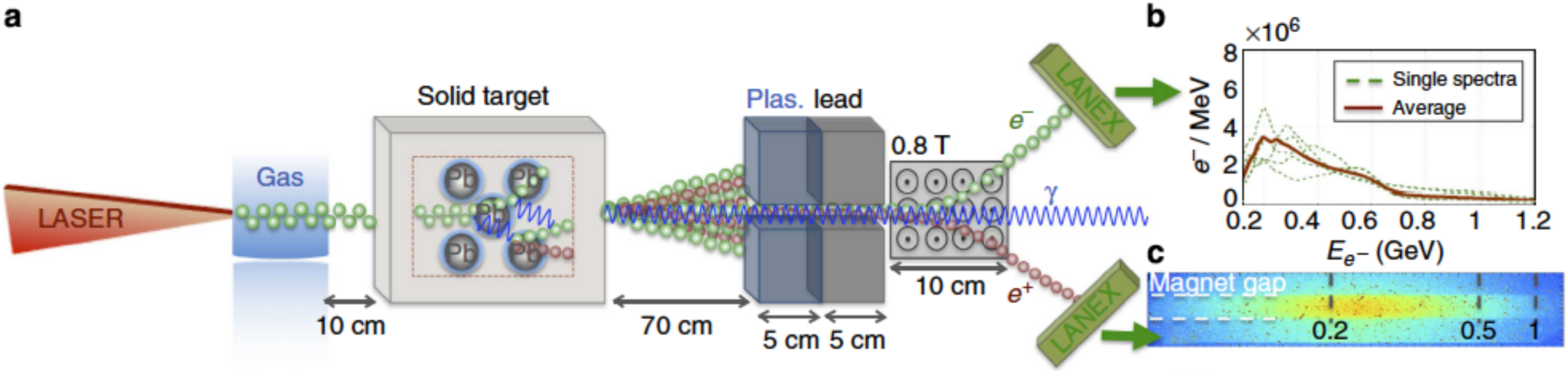


K. Poder et al., Nat. Phys. (submitted) 2018

- Energy GeV
- Divergence <mrad
- Duration ~fs
- Source size < micron
- Charge ~ 100 pC (10^9 e^-)
- Repetition rate ~ Hz
- Total energy ~ 0.2 J
- norm. emittance ~ mm mrad

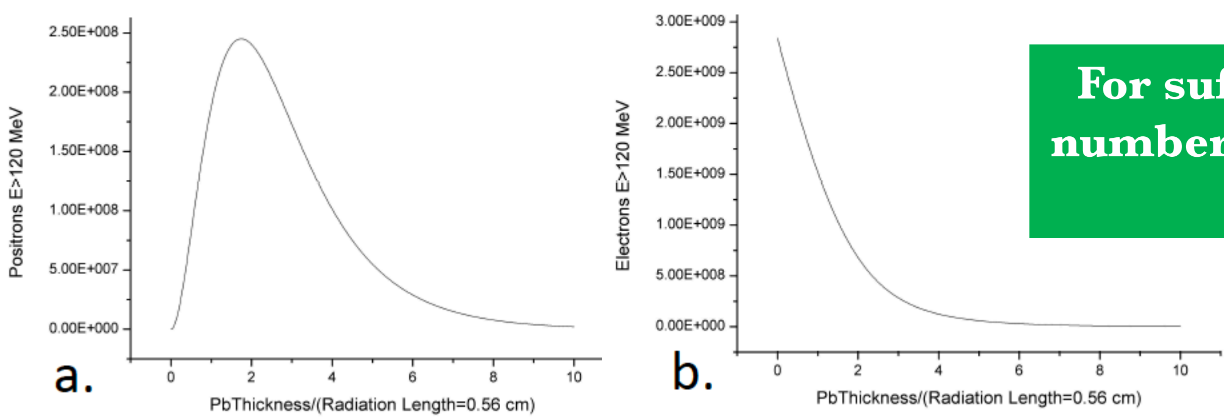
A neutral pair-plasma in the laboratory

A neutral pair beam



The laser-driven electrons initiate a quantum cascade, whose main steps are:

1. Generation of a high-energy photon during bremsstrahlung in the field of a nucleus
2. Creation of an electron-positron pair during the photon propagation in the field of the nucleus

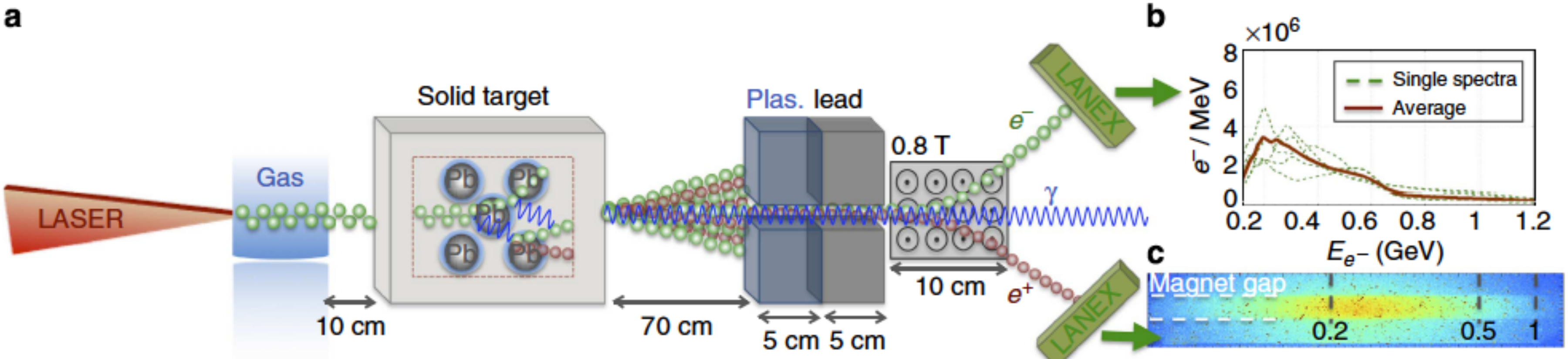


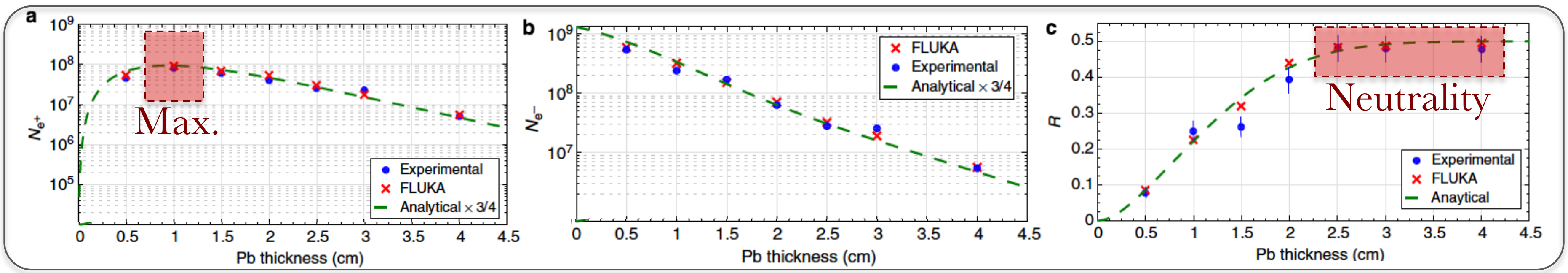
For sufficient thicknesses, the number of electrons equals that of the positrons

G. Sarri et al., Nat. Comm. 2015

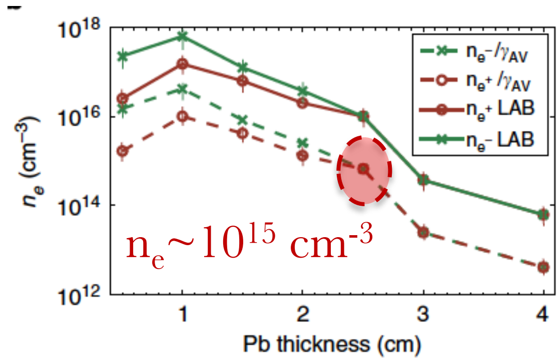
G. Sarri et al., PPCF 2013

A neutral pair beam





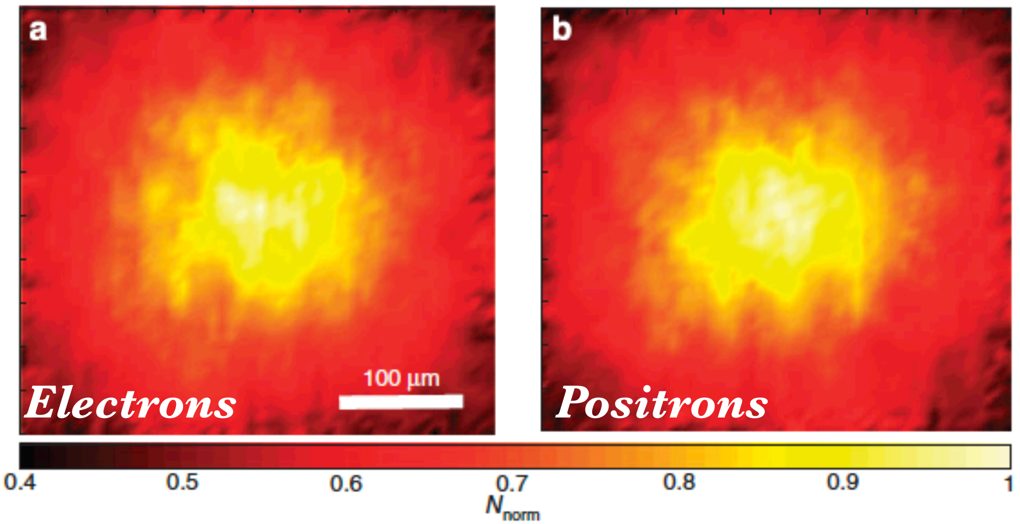
- ✓ Maximum positron yield at ~2 L_{RAD}
- ✓ ~48% of positrons at ~ 5 L_{RAD}
- ✓ Beam duration: ~ tens of fs
- ✓ Beam diameter: ~ 1.2 c/ω_p
- ✓ Beam divergence: ~ tens of mrad

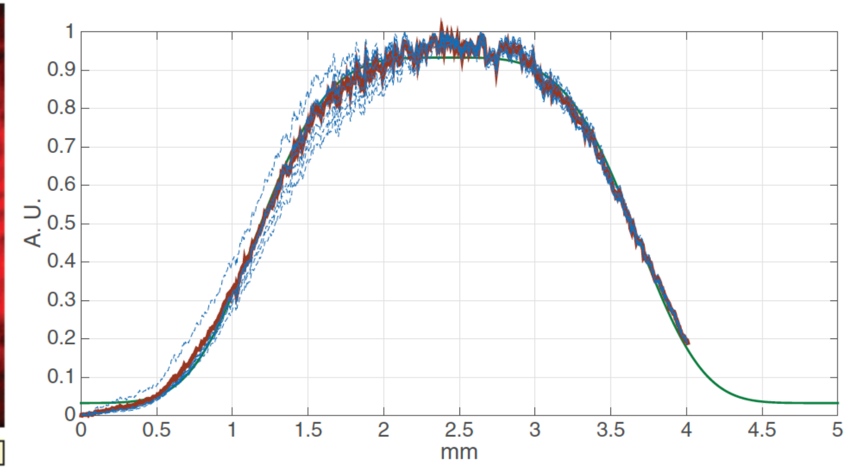


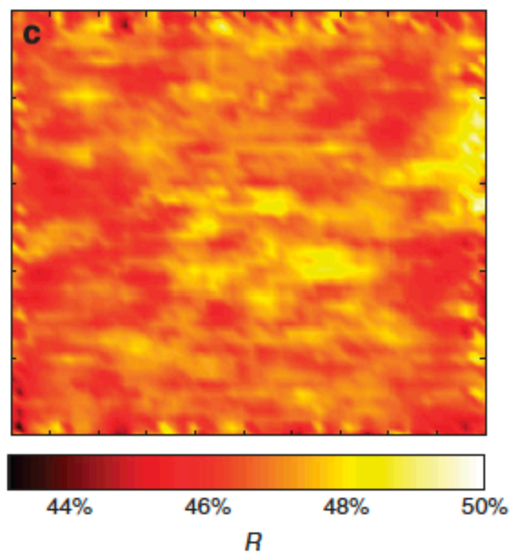
G. Sarri et al., PRL 2013

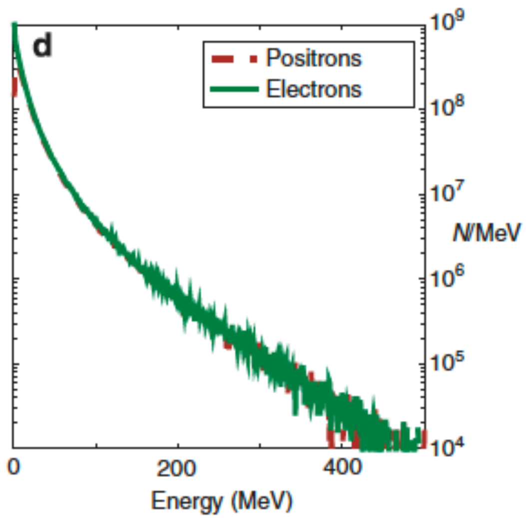
G. Sarri et al., Nat. Comm. 2015

A neutral pair beam









- ✓ Super-Gaussian smooth spatial distribution
- ✓ fs-scale durations
- ✓ Pair density up to 10^{16} cm^{-3}

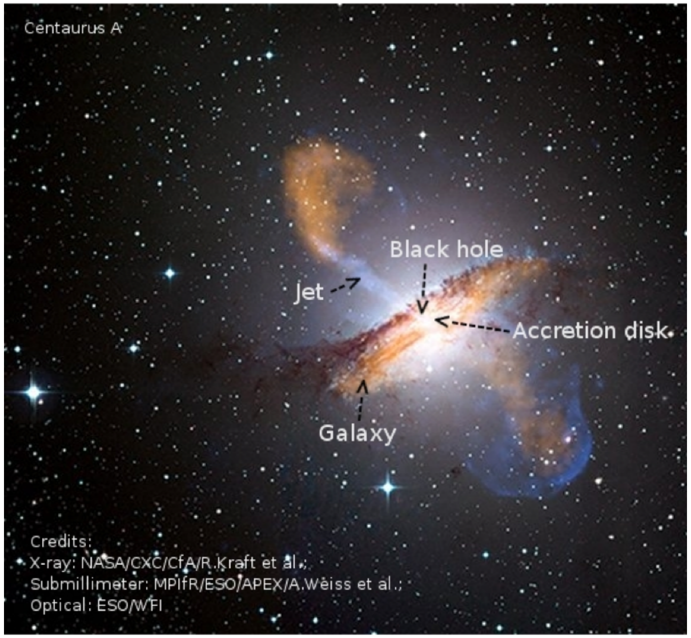
G. Sarri et al., Nat. Comm. 2015

G. Sarri et al., PPCF 2017

Pair-plasma dynamics in the laboratory

Astrophysical jets

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



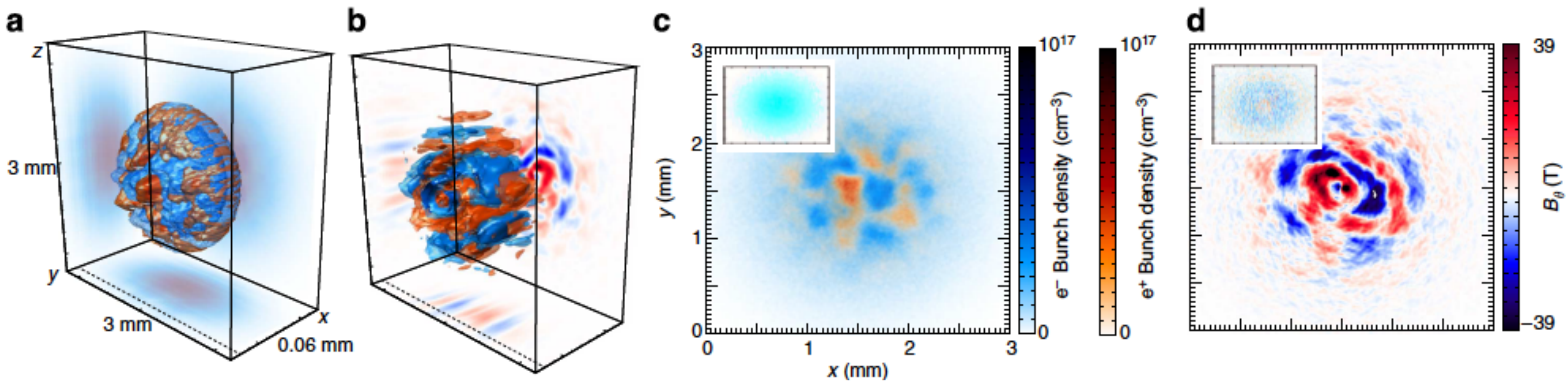
- Associated with strong emission of gamma-rays
- Optically thin
- Power-law spectrum: $n(\gamma) \propto \gamma^{-(2\alpha+1)}$, $\alpha \approx 0.5$
- Some predominantly leptonic
- Relativistic
- Strong interaction with the intergalactic medium
- Largest single events observed in the Universe
- Equipartition: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

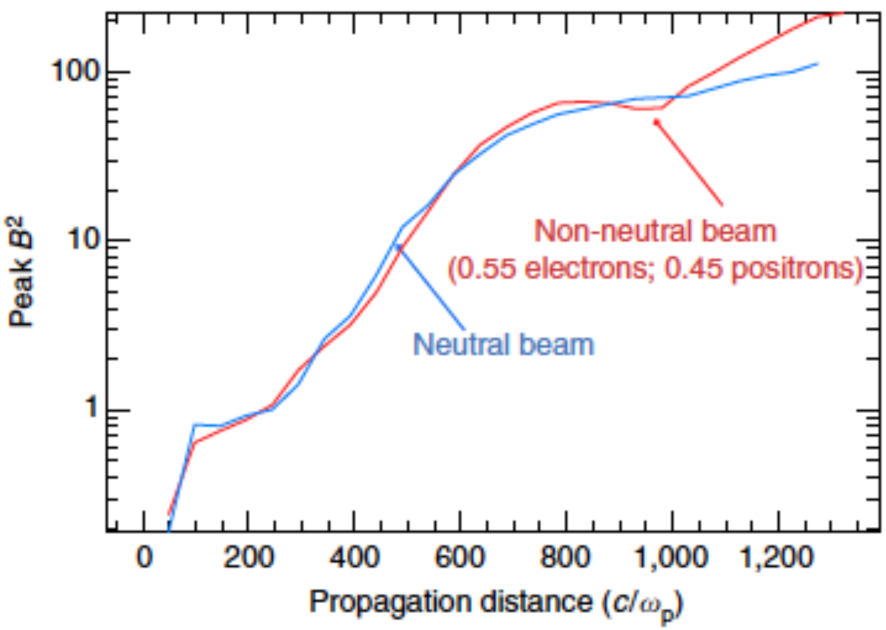
The generation of gamma rays requires strong and long-lived magnetic fields:

- **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?**

Beam filamentation: ideal



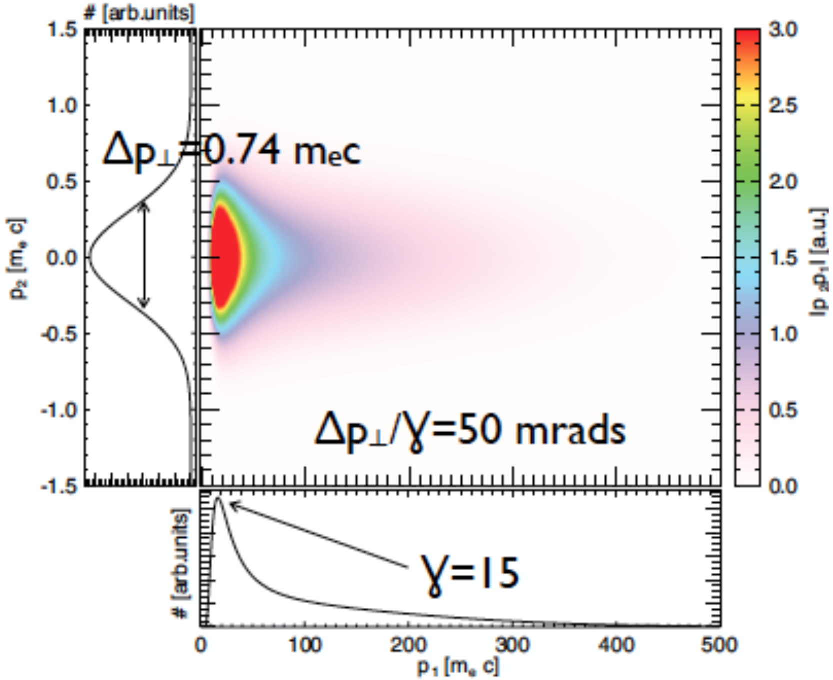


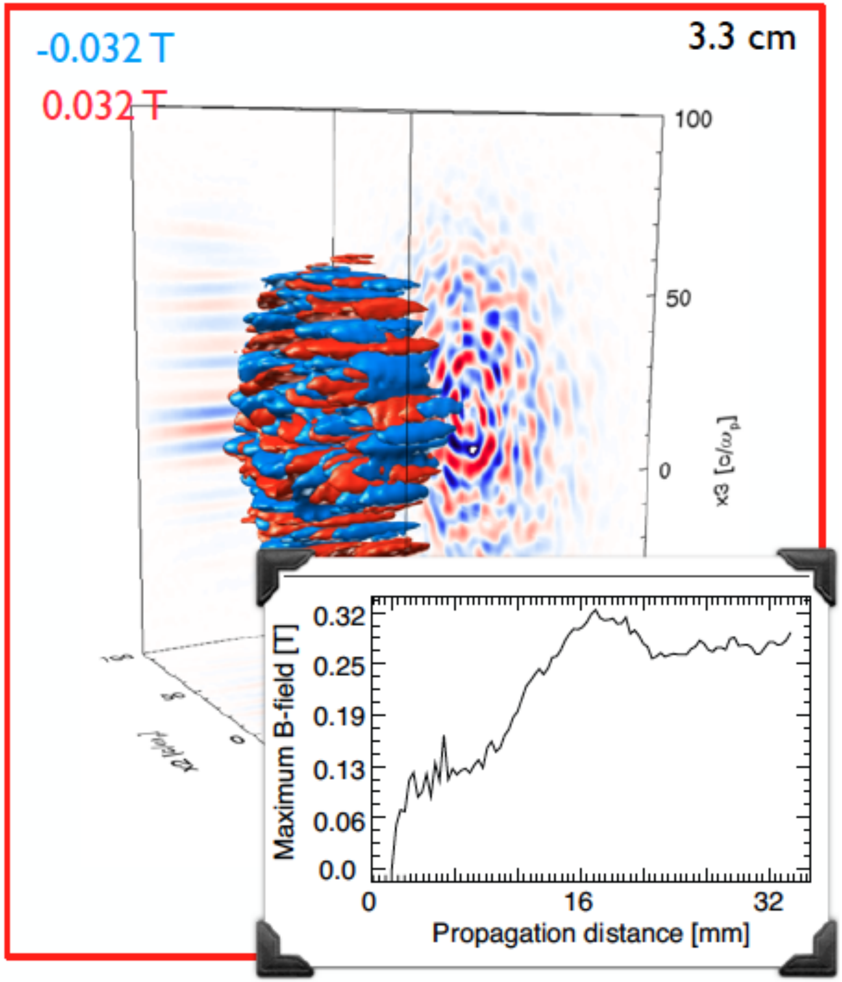
- ✓ Strong filamentation only for neutral beam (>40%)
- ✓ Saturation reached at ~800 c/w_p
- ✓ Generation of strong B fields
- ✓ Equipartition of the order of $10^{-2} - 10^{-4}$
- ✓ Long-lived fields

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

Beam filamentation: real

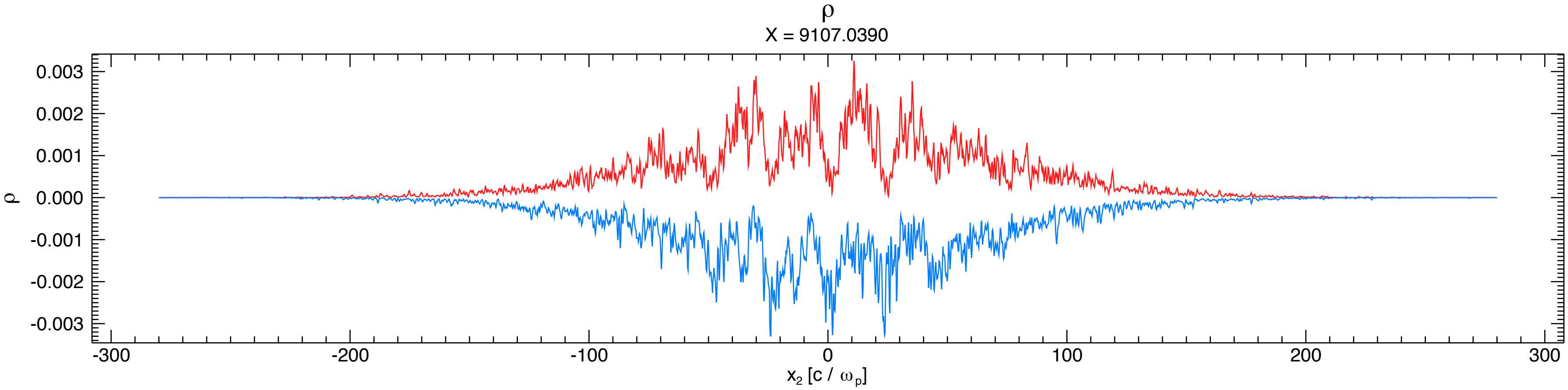
Laser-driven electron-positron beams have, however, a broad spectrum (Maxwell-Juttner) and a wide divergence



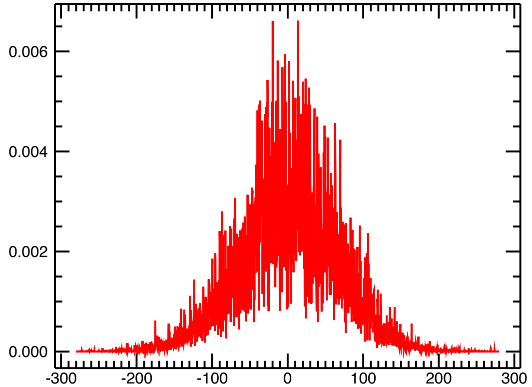


- ✓ Filamentation still a strong process
- ✓ Generation of strong fields on a scale of the order of the beam collisionless skin depth

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

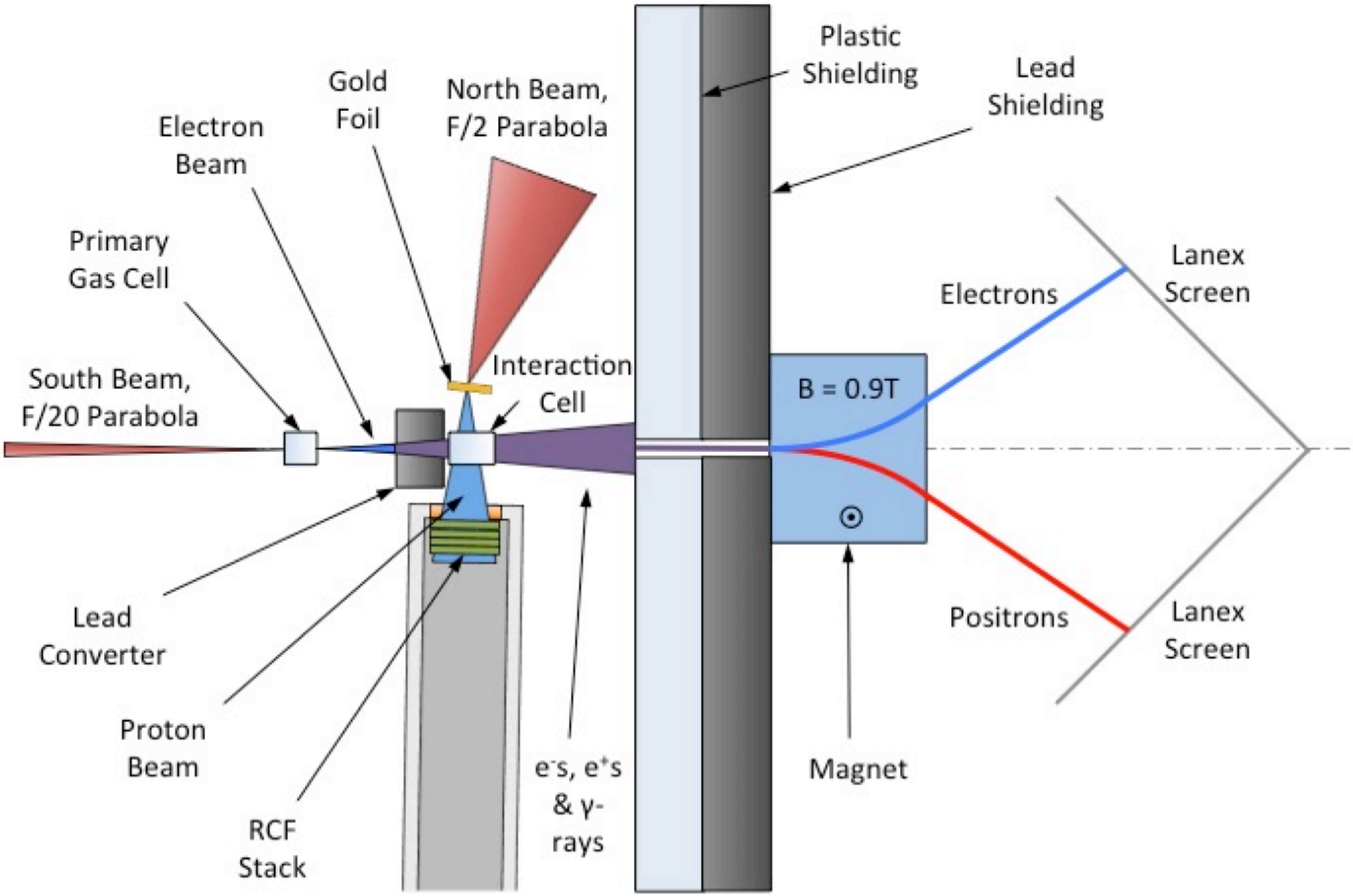


- ✓ The beam preserves a smooth density distribution
- ✓ Total particle symmetry

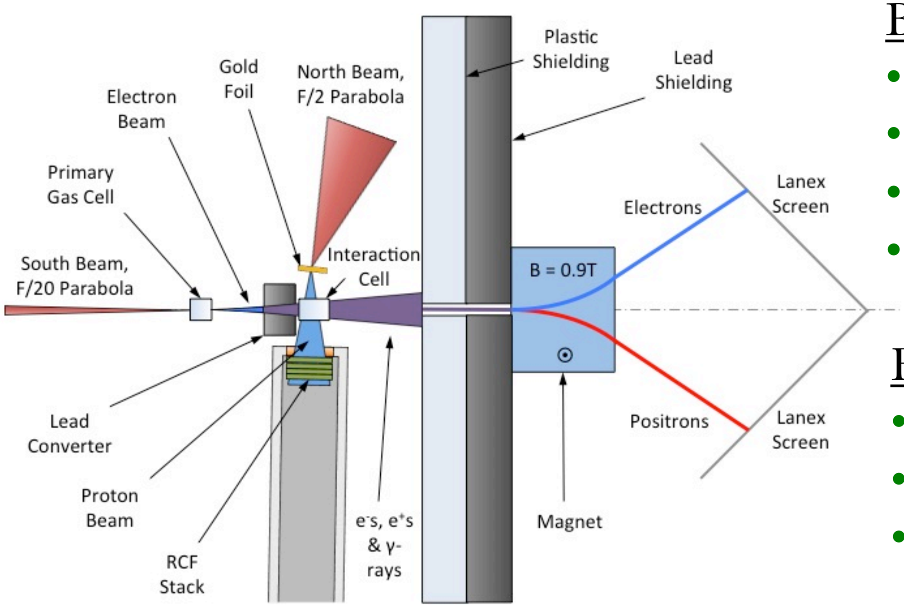
X Undistinguishable by scintillator screen or any other charge-independent detector

Beam filamentation experimental evidence

Filamentation: experiment



Filamentation: theory



<u>Background plasma</u>

- $n_P = 10^{17}$ cm^{-3}
- $T_P \sim$ 10-20 eV (from Hydro simulations)
- $w_P = 1.8 \times 10^{13}$ Hz ➔ $t_P \sim 100$ fs
- $v_{th} \sim 2 \times 10^6$ m/s ➔ $r_P \sim 30$ µm

<u>Electron-positron beam</u>

- $n_B = 3 \times 10^{14}$ cm^{-3}
- $\gamma_{AV} \sim 15$
- $w_B = 2 \times 10^{11}$ Hz ➔ $t_P \sim 5$ ps

✓ The instability grows within 5 ps (1.5mm) producing **1-2 filaments!**

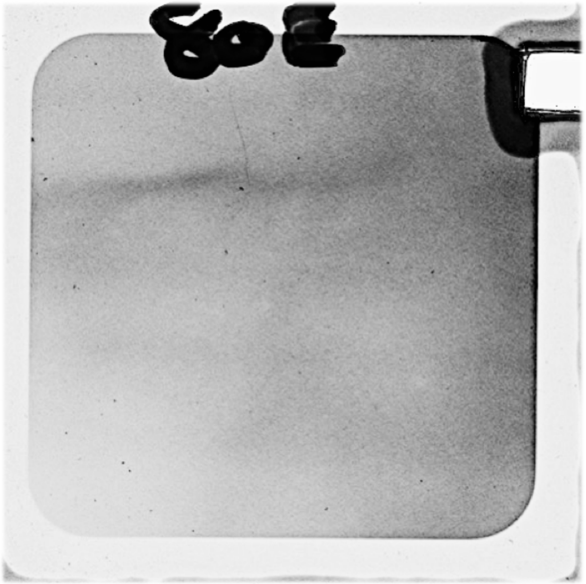
✓ Expected magnetic field of ~ 1 T (equipartition parameter of ~10^{-3})

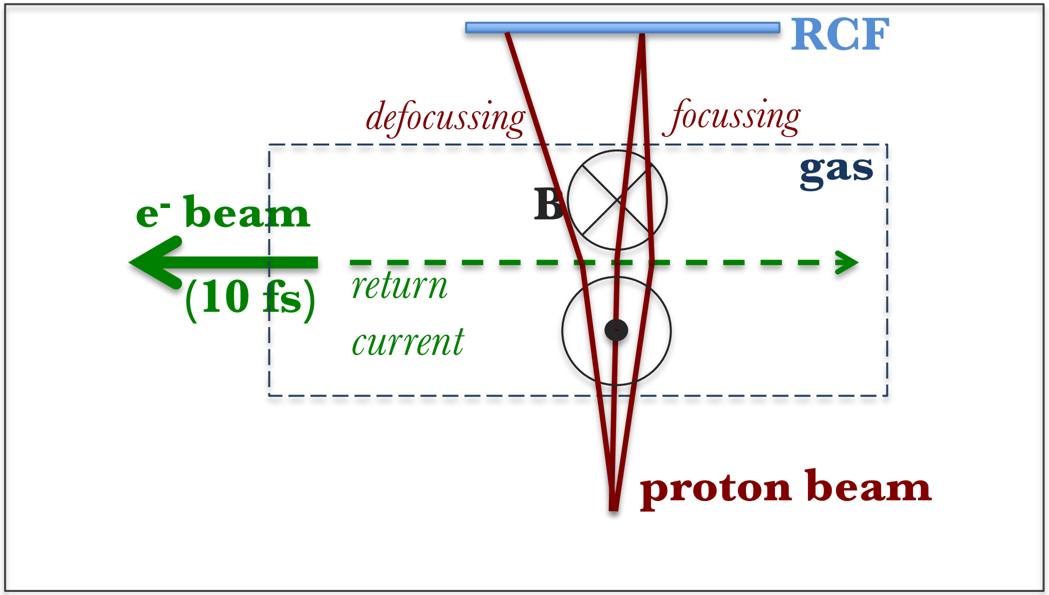
✓ The background plasma gyroradius is smaller than the filament wavelength, suggesting that the **plasma can get magnetised**

J. Warwick et al., Phys. Rev. Lett. (2017)

Proton radiography

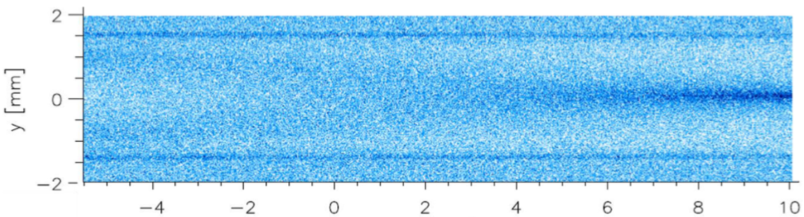
Can proton radiography see these fields?





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

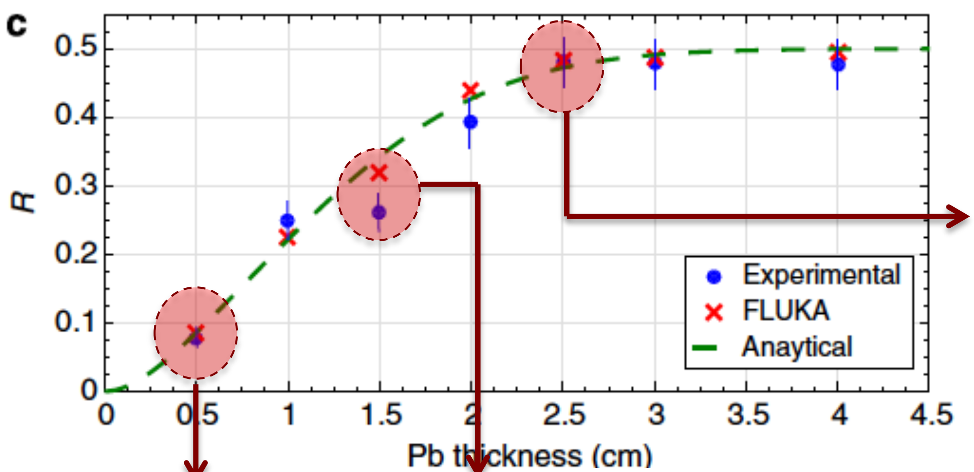
- ✓ The divergent nature of the proton beam implies that azimuthal magnetic fields induce focussing/defocussing of the protons

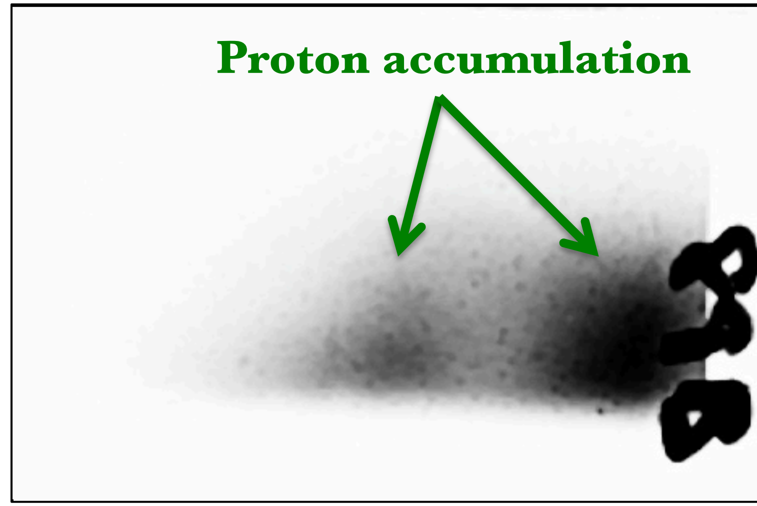


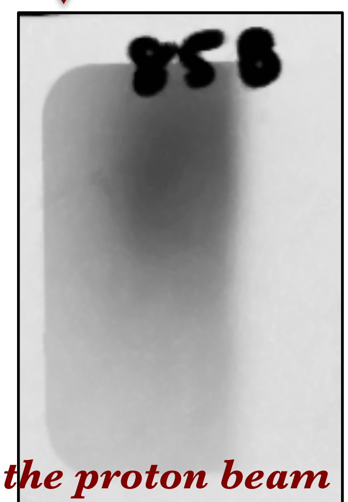
A. Smyth et al. Phys. Plasmas 23, 063121 (2016)

Proton radiography: results

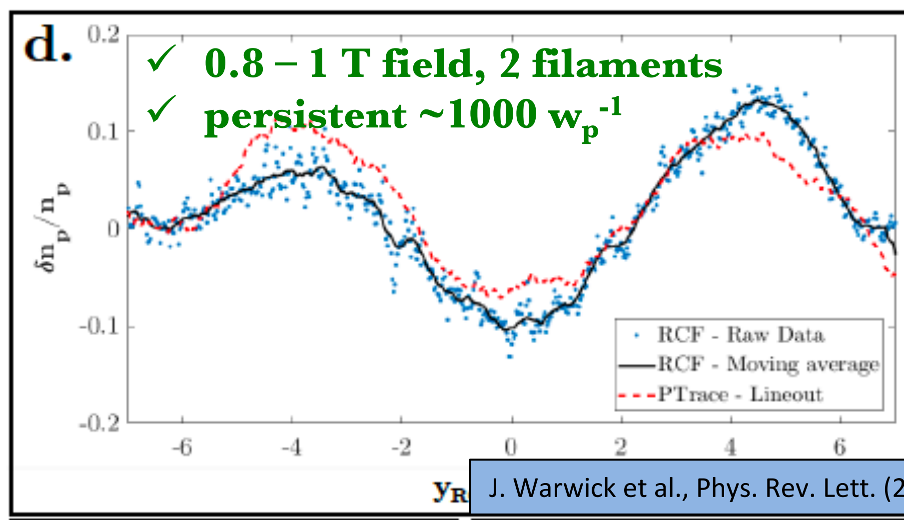
✓ Proton radiographs of the background gas, show clear proton modulation only for quasi-neutral electron-positron beams:





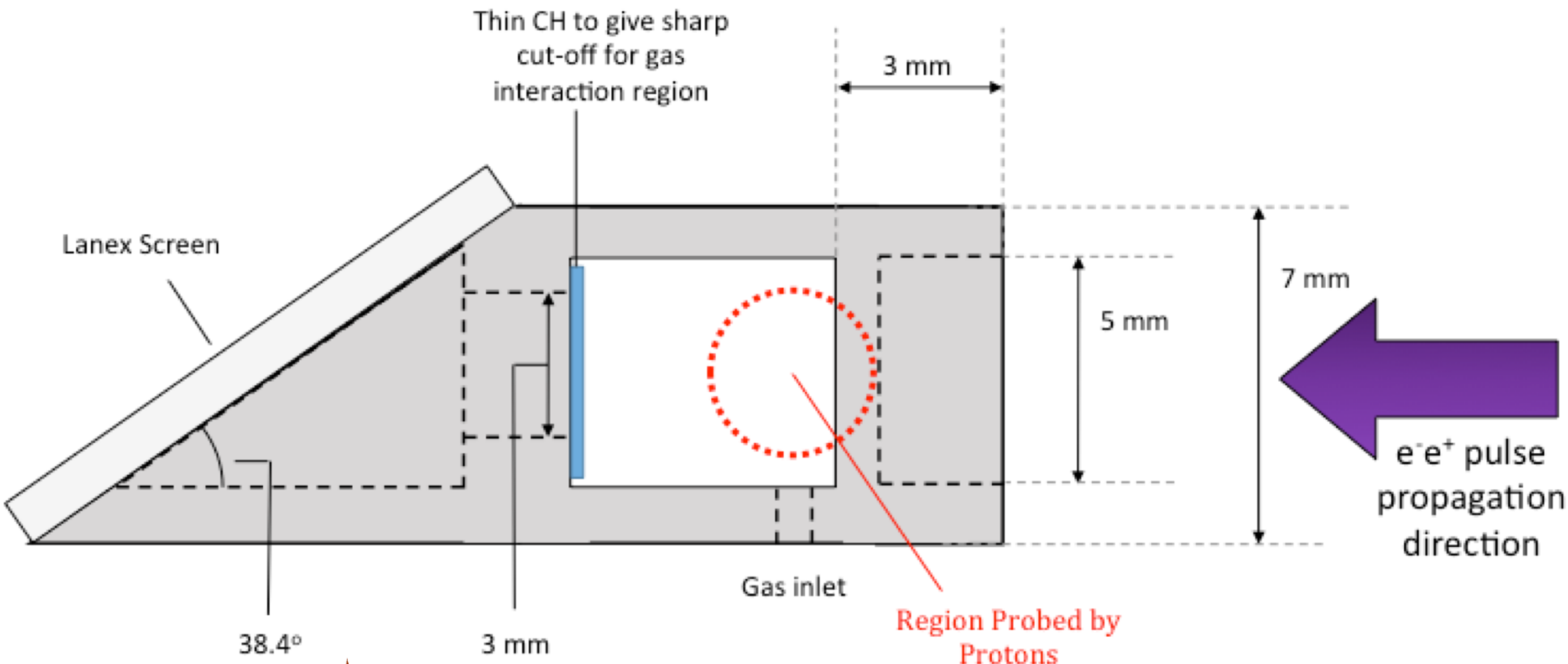


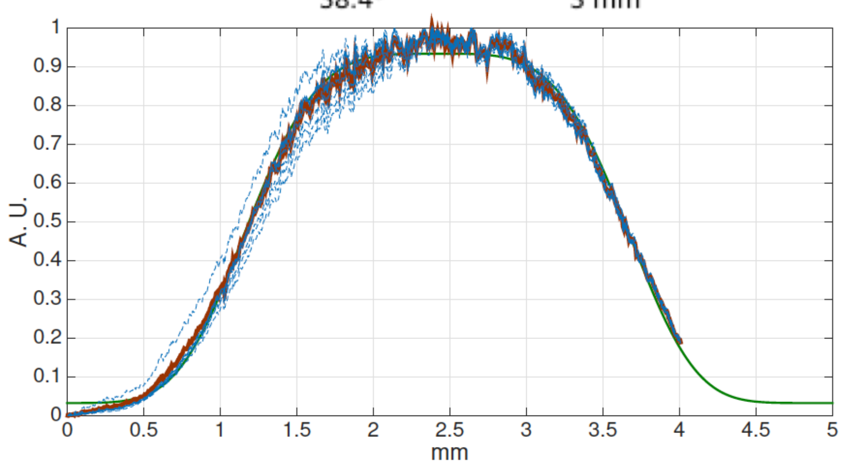
No modulation in the proton beam



J. Warwick et al., Phys. Rev. Lett. (2017)

Beam profile



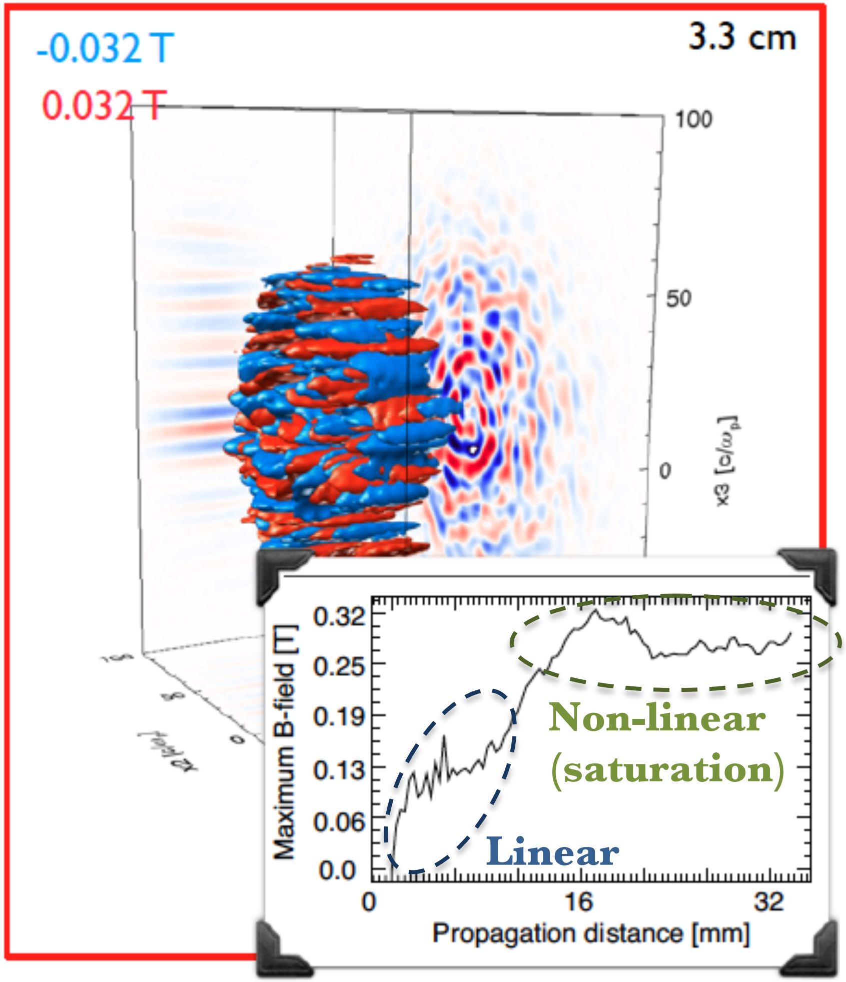


- ✓ Smooth profile after subtraction of γ-ray signal.
- ✓ No high-frequencies in Fourier Transform
- ✓ Consistent with pair-beam instability
- ✓ Current – driven phenomenon

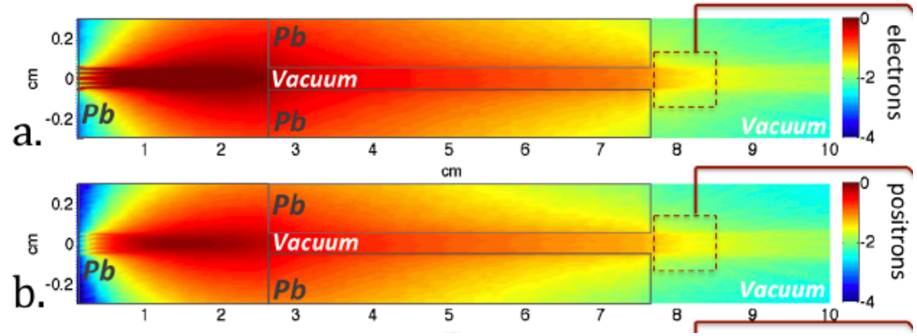
J. Warwick et al., Phys. Rev. Lett. (2017)

Next steps

The divergence and low-density of the pair beam only allows for the **linear stage of the instability** to be detected



Collimating the electron-positron beam



Increase the density

- Use of a 10+ GeV beam will increase the pair-plasma density 40-fold!
- Possibility of longitudinal dynamics (shocks?)

High-field QED in the laboratory

Radiation Reaction

Radiation Reaction

⇒ Radiation Reaction is one of the oldest and most fundamental problems in electromagnetism: How do we correctly model the electron dynamics if we include radiative losses?

0. Classical Lorentz force

$$m\frac{du^u}{ds} = eF^{uv}u_v$$

X No energy loss

1. LAD Equation

$$m\frac{du^u}{ds} = eF^{uv}u_v + \frac{2}{3}e^2\left(\frac{d^2u^u}{ds^2} + \frac{du^v}{ds}\frac{du^v}{ds}u^u\right)$$

✓ Damping force (radiation reaction term)

X Classical renormalisation (point-like electron)

X Runaway solutions! Diverging acceleration even without external field: $a(t) = a_0\, e^{-t/\tau}$, $\tau \sim 10^{-23}$ s

2. LL Equation

$$m\frac{du^u}{ds} = eF^{uv}u_v + \frac{2}{3}e^2\left(\frac{e}{m}(\partial_\alpha F^{uv})u^\alpha u_v - \frac{e^2}{m^2}F^{uv}F_{\alpha v}u^\alpha + \frac{e^2}{m^2}(F^{\alpha v}u_v)(F_{\alpha\lambda}u^\lambda)u^u\right)$$

✓ No runaway solutions

✓ Valid in classical relativity

X Not experimentally tested yet!

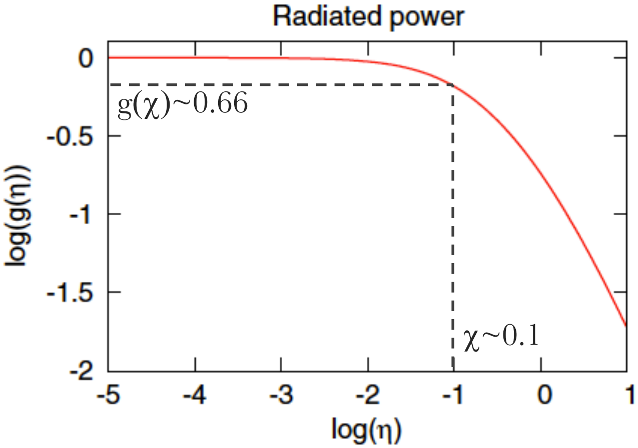
$\lambda >> \alpha\lambda_C$ (localised wavefunction)

$F << F_{cr}/\alpha$ (classical critical field)

Quantum Radiation Reaction

⇒ The classical treatment of radiation reaction neglects three main additional phenomena:

1. The energy of a single emitted photon can not exceed that of the electron



Generally speaking, this leads to a classical overestimate of the total energy loss experienced by the electron $(\chi = \gamma F_L / F_S)$

$$g(\chi) \sim \left(3.7\chi^3 + 31\chi^2 + 12\chi + 1\right)^{-4/9}$$

J. G. Kirk et al., PPCF 2013

A. G. R. Thomas et al., PRX 2012

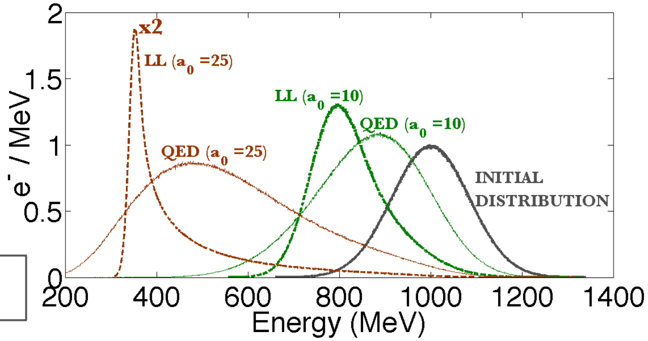
2. Photon emission is probabilistic

2.a $a_0 >> 1$

2.b constant cross-field approximation (instantaneous photon emission))

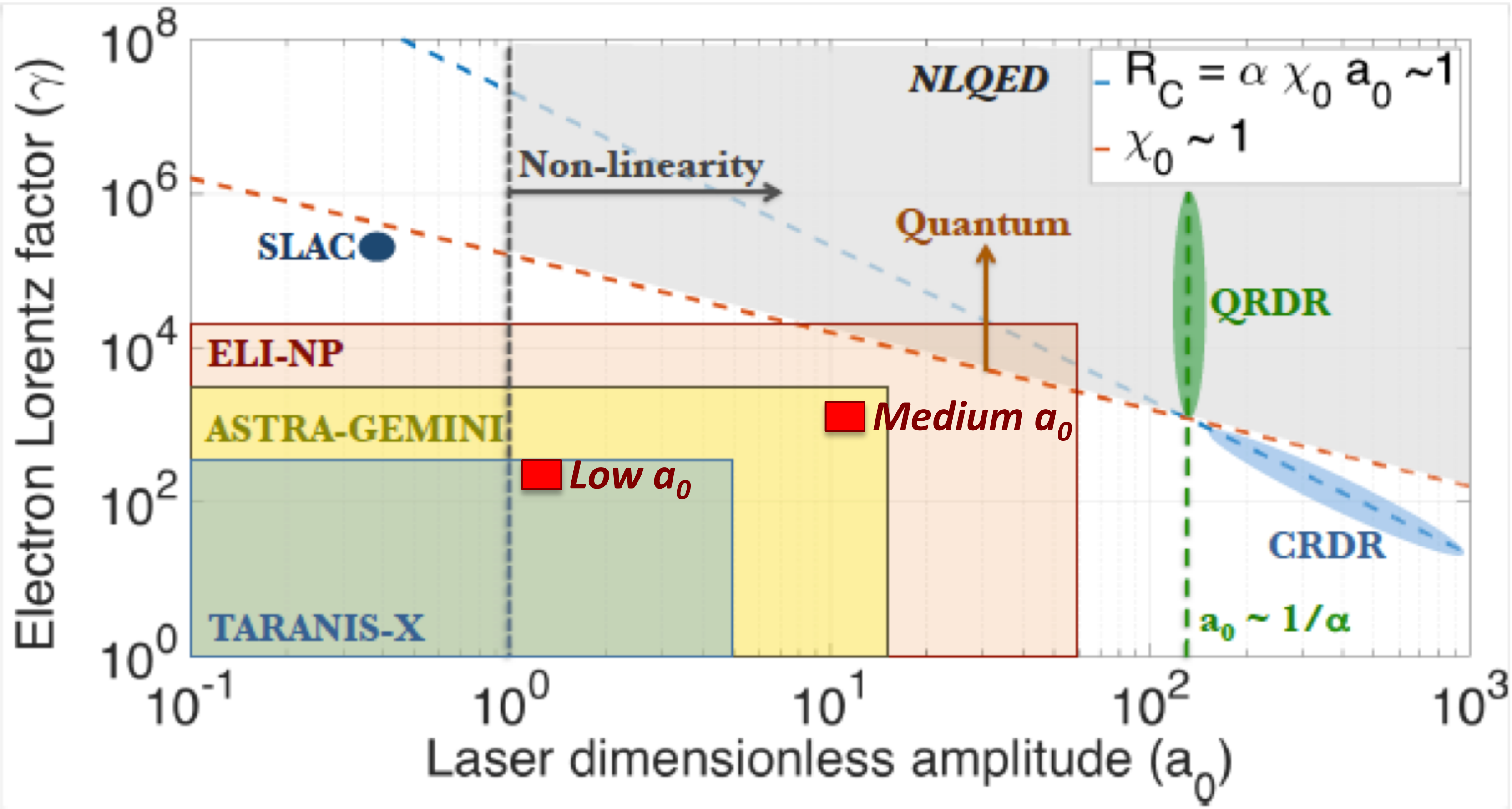
V. I. Ritus, J. Sov. Laser Res. 1985

N. Neitz and A. Di Piazza, PRL 2013



3. Production of electron-positron pairs (important only for $\chi \geq 1$)

Radiation Reaction

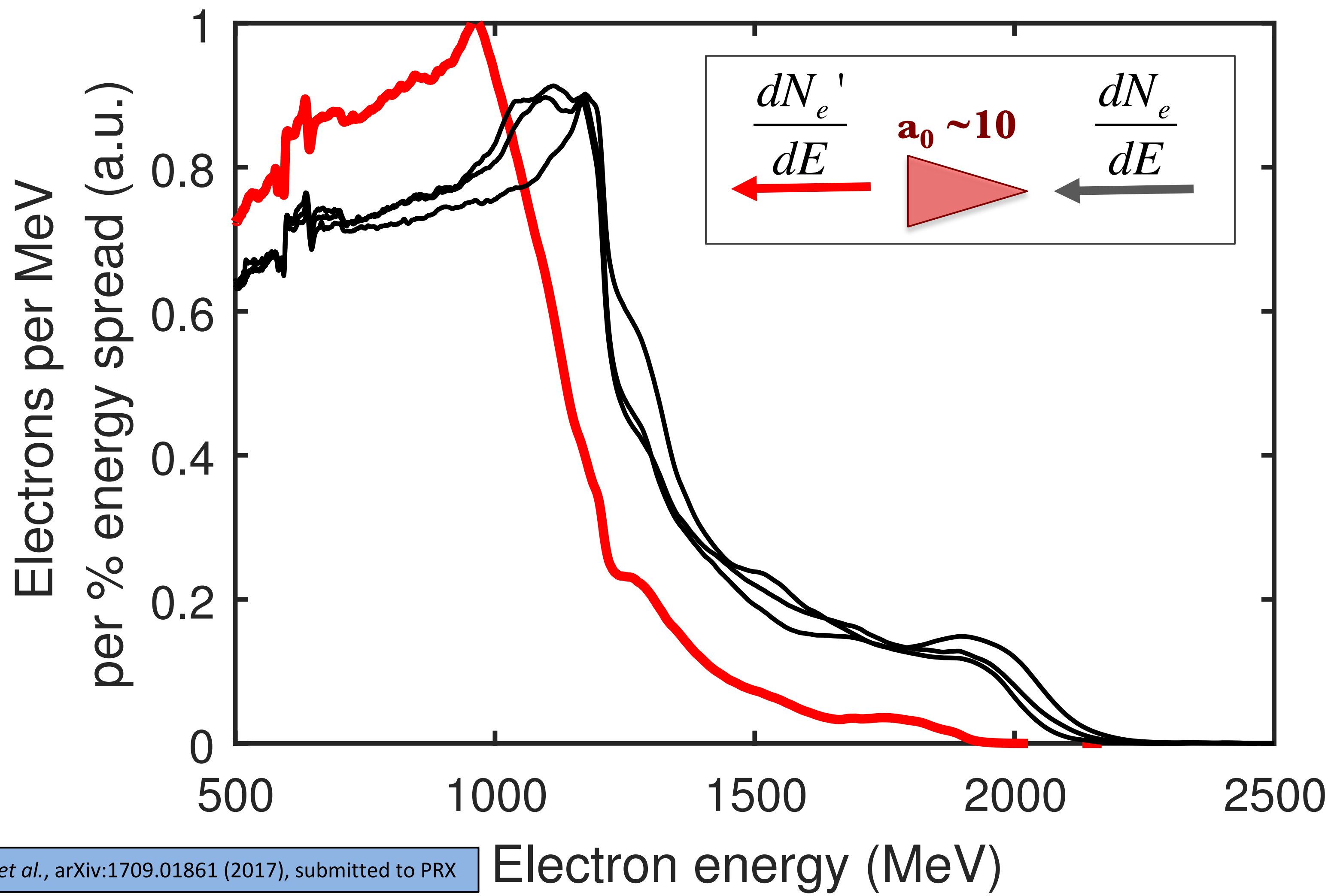


$$a_0 \sim 6\lambda_L[\mu m]\sqrt{I_L[10^{20}\,\mathrm{W/cm^2}]}$$

$$\chi \sim 6.1\times10^{-6}\gamma_e a_0$$

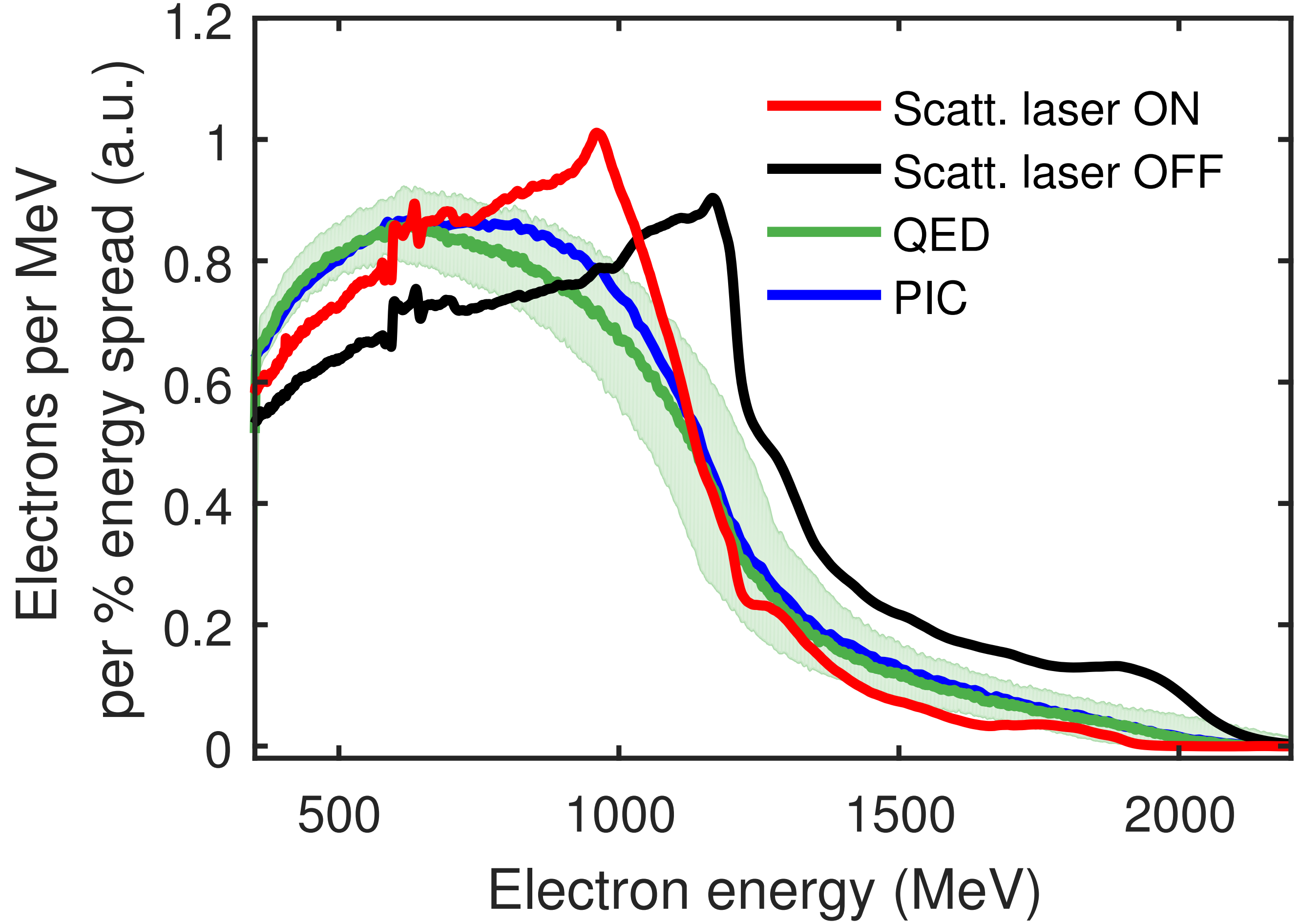
Radiation Reaction: The first experiment

What do we see?



K. Poder *et al.*, arXiv:1709.01861 (2017), submitted to PRX

Comparison with theory



Perturbative
(No RR)

LL
(Classical RR)

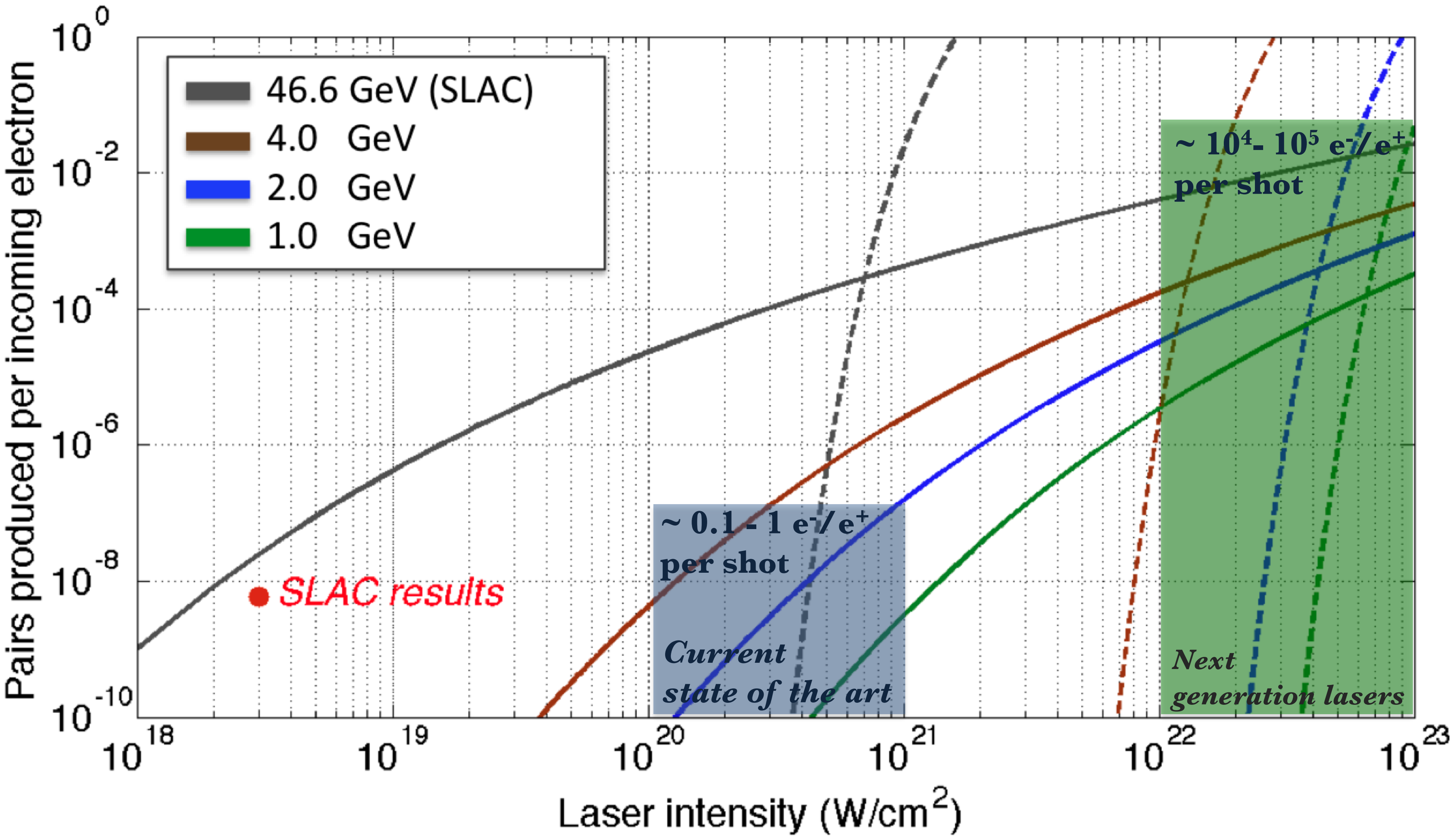
SC
(hard cut-off)

QED
(probabilistic)

K. Poder *et al.*, arXiv:1709.01861 (2017) submitted to PRX

Pair production in the Laser field

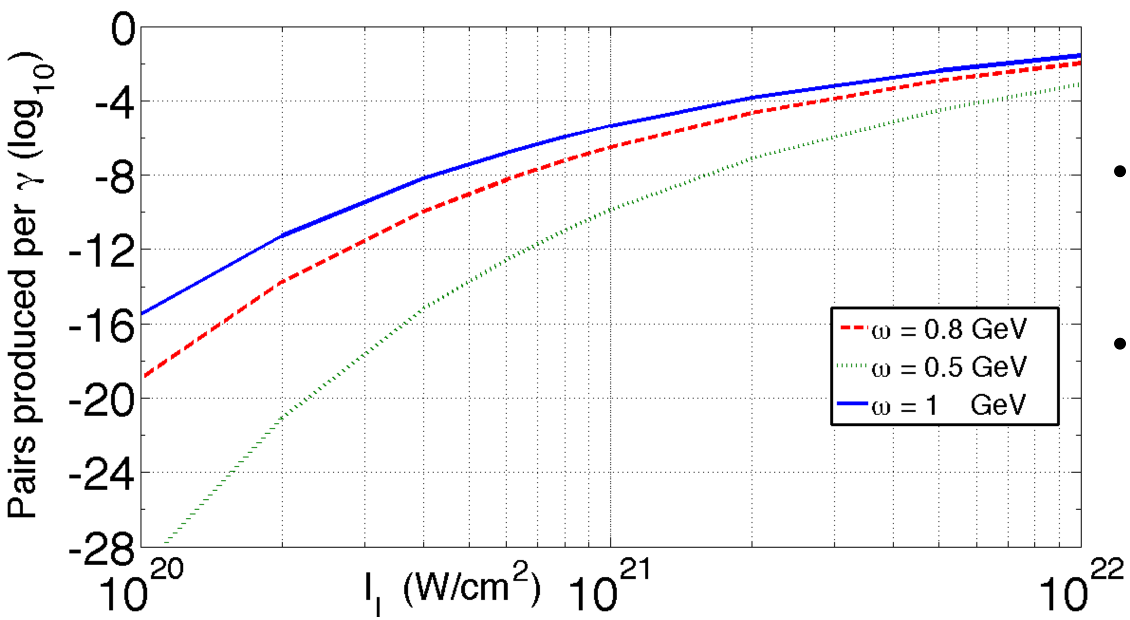
Pair production: electron-laser



Pair production: photon-laser

$$\frac{dP_{\perp/\parallel}}{d\phi} = \sqrt{\frac{3}{2}}\frac{(3\pm1)\alpha}{16}\xi_0|f(\phi)|\exp\left[-\frac{8}{3k_0|f(\phi)|}\right], \quad P_{\perp/\parallel} = \int_0^{2\pi N_0} d\phi \frac{dP_{\perp/\parallel}}{d\phi}$$

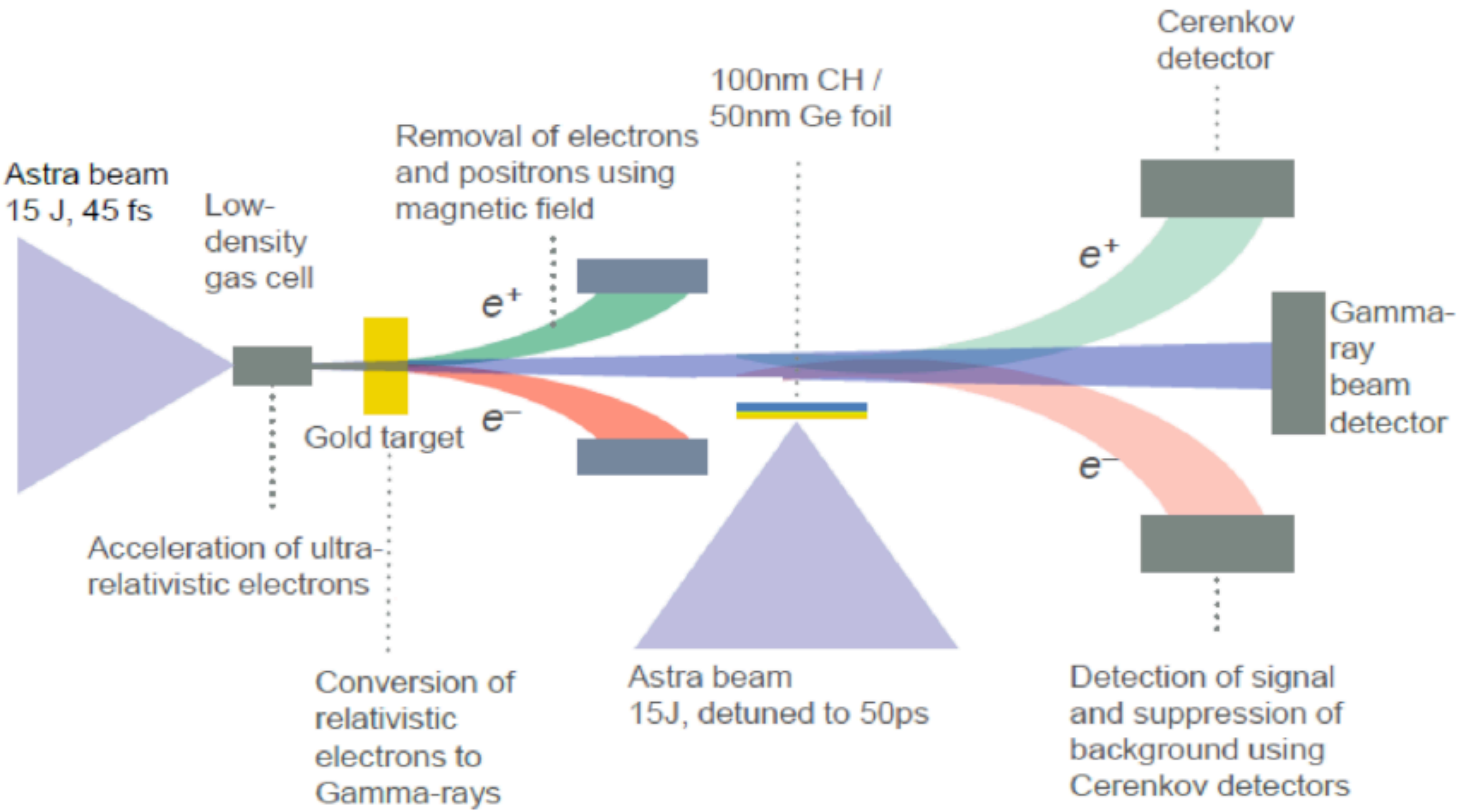
Where:
$$\begin{cases} \xi_0 \approx \frac{10.66\sqrt{I_0[10^{20}\,\mathrm{W/cm^2}]}}{\omega_0[\mathrm{eV}]} \\ k_0 \approx 8.16\times10^{-5}\omega[\mathrm{MeV}]\sqrt{I_0[10^{20}\,\mathrm{W/cm^2}]} \end{cases}, \quad E(\phi) = E_0 f(\phi) = E_0\sin^2\left(\frac{\phi}{2\pi N_0}\right)\sin(\phi)$$



V. I. Ritus, J. Sov. Laser Res. **6**,497 (1985).

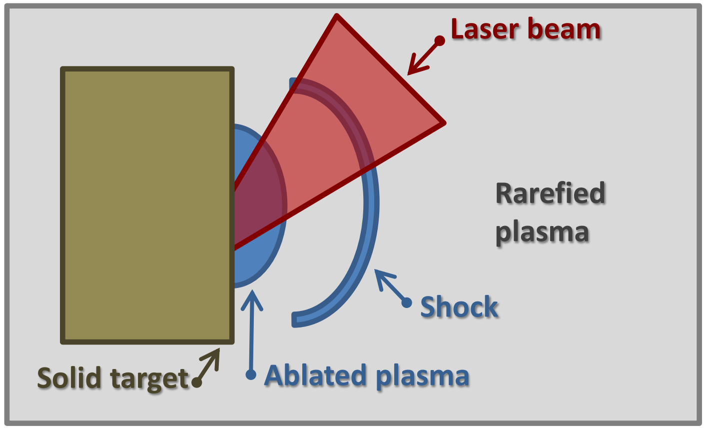
- Rate exponentially suppressed by k_0 (function of ω_γ and I_L).
- For I_L in the 10^{22} W/cm^2 regime, detectable pair production occurs only for γ energies in the GeV regime.

Pair production: photon-laser



Collisionless shocks in the laboratory

Collision-less shock generation



Laser beam: $E = 10s\ J$

$\tau = ns$

Rarefied plasma: $n_e = 1 - 10 \times 10^{15}\ cm^{-3}$

$\omega_p = 1.5 – 5 \times 10^{12}\ Hz$

$T_e = keV = 10^7\ K$

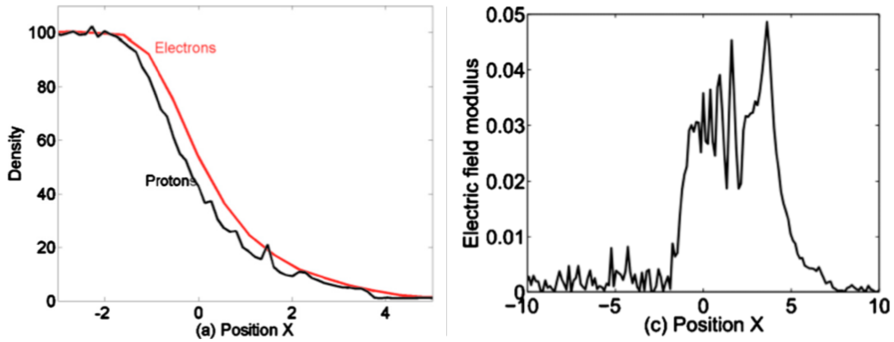
$\lambda_D = 2 – 7$ microns

Dense plasma: $n_e = 1 - 10 \times 10^{19}\ cm^{-3}$

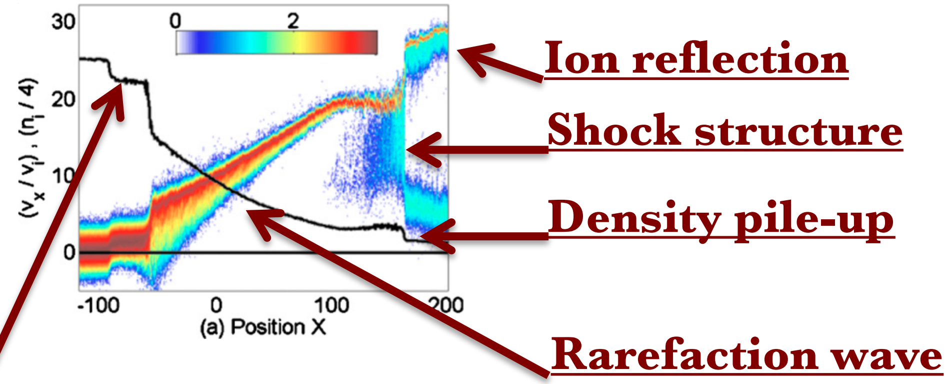
$T_e = 1 – 10\ keV$

G. Sarri *et al.* Phys. Plasmas **17**, 082305 (2010)

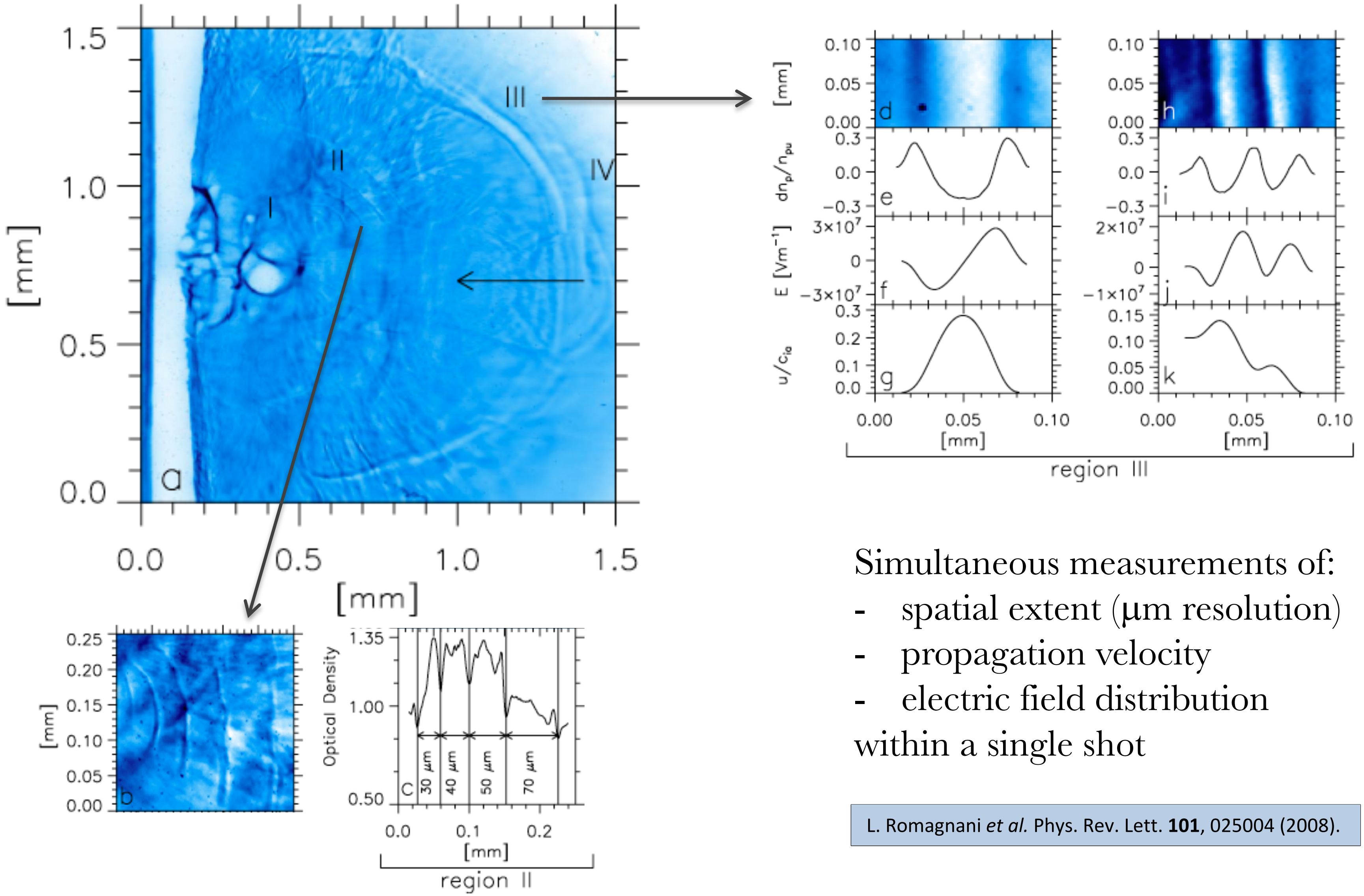
- The background gas gets photo-ionised by x-rays generated in the laser-matter interaction
- The ablated plasma forms a rarefaction wave streaming in the low-density background plasma



- As time progresses, the plasma clouds interpenetration induces an ion pile-up



Collision-less shock: first experiment



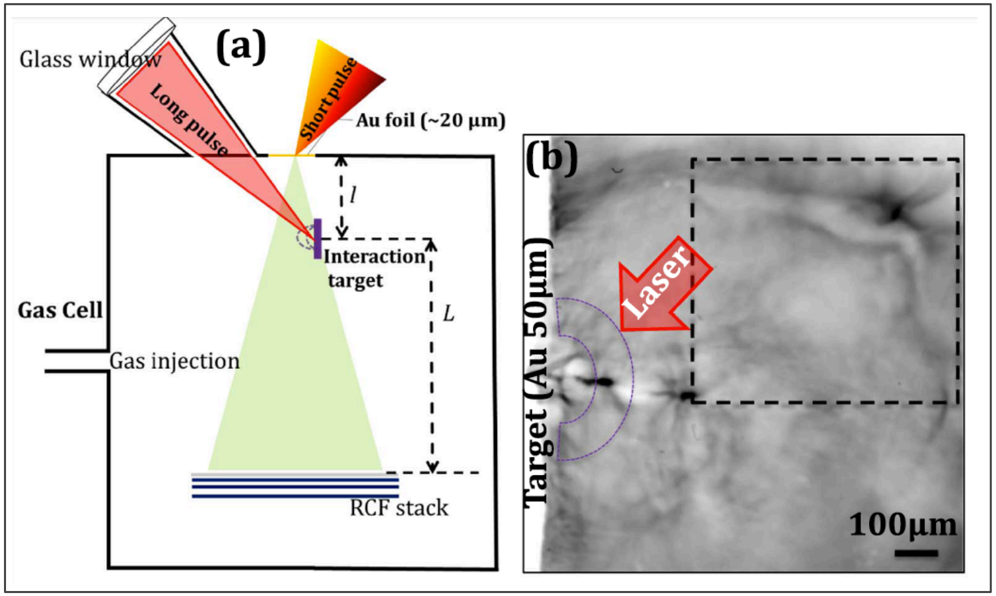
Simultaneous measurements of:

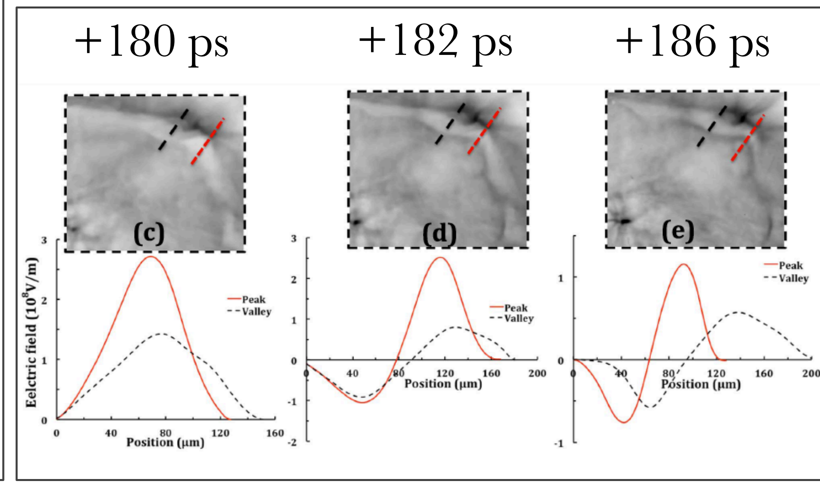
- spatial extent (μm resolution)
- propagation velocity
- electric field distribution

within a single shot

L. Romagnani *et al.* Phys. Rev. Lett. **101**, 025004 (2008).

Instabilities on the shock front





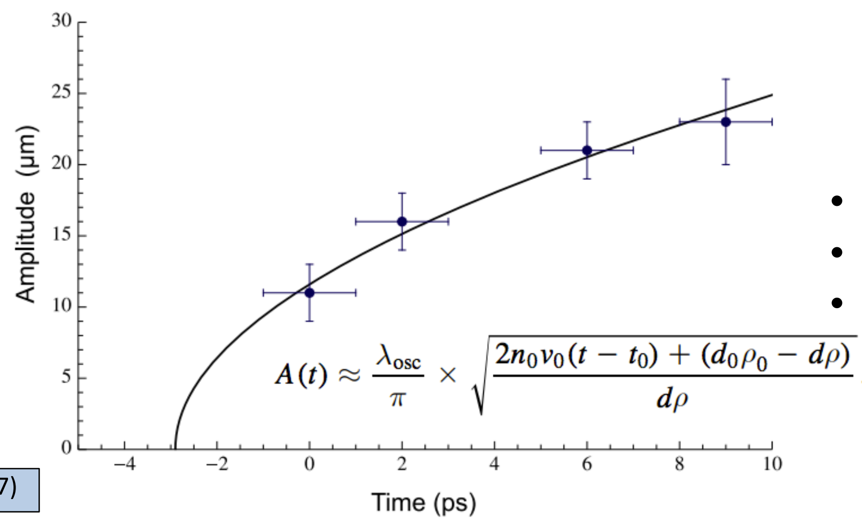
$n_e = 10^{17}$ cm^{-3}

$T_e = 1.3$ keV

$\omega_p = 1.7 \times 10^{13}$ Hz

$\lambda_D = 0.6$ μm

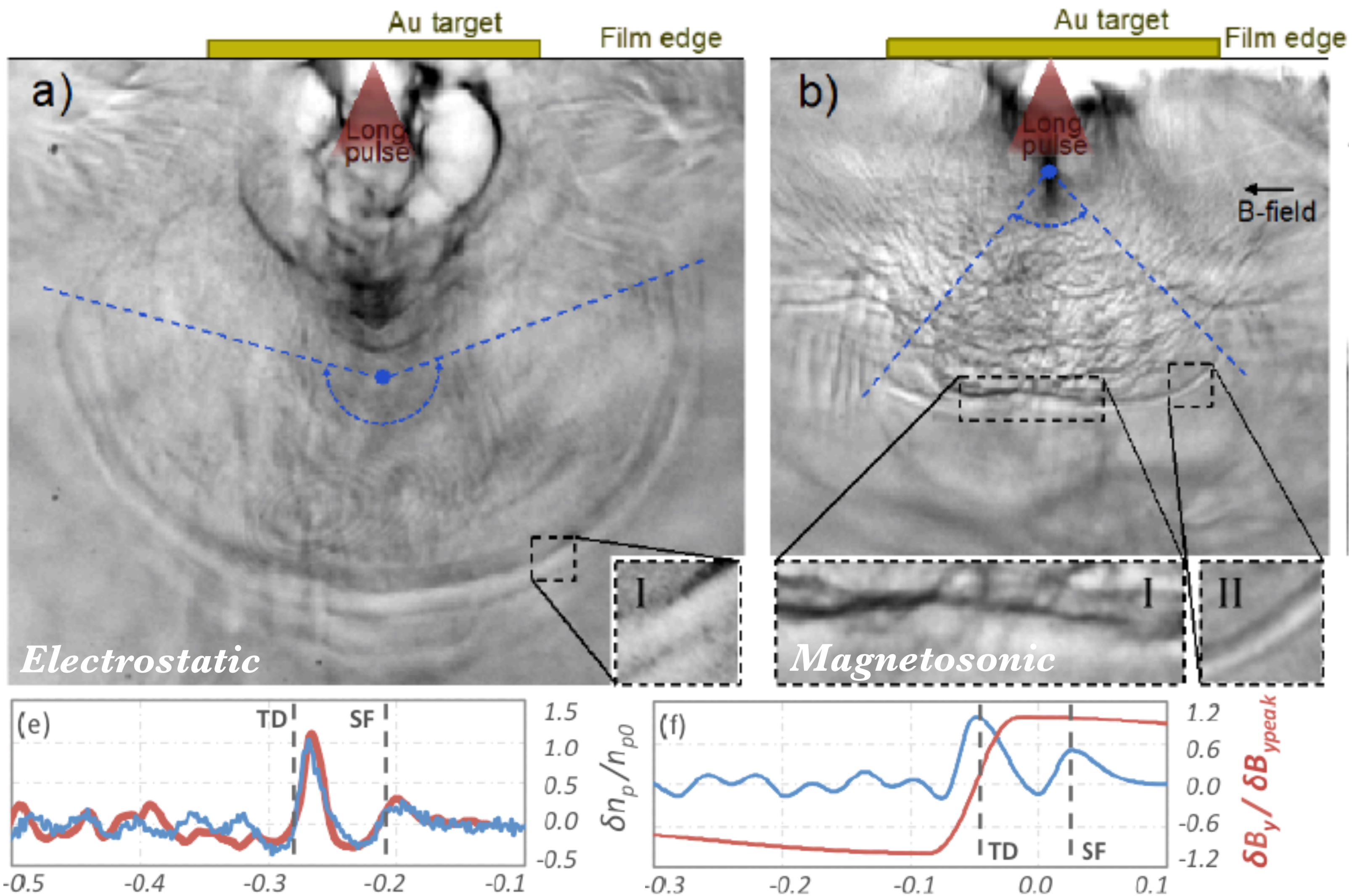
$c_s = 2.5 \times 10^5$ m/s



- modulation: 200 λ_D
- collision-less evolution
- modulation in propagation velocity

H. Ahmed *et al.* Astrophys. J. Lett. 834, L21 (2017)

Magnetised collision-less shock

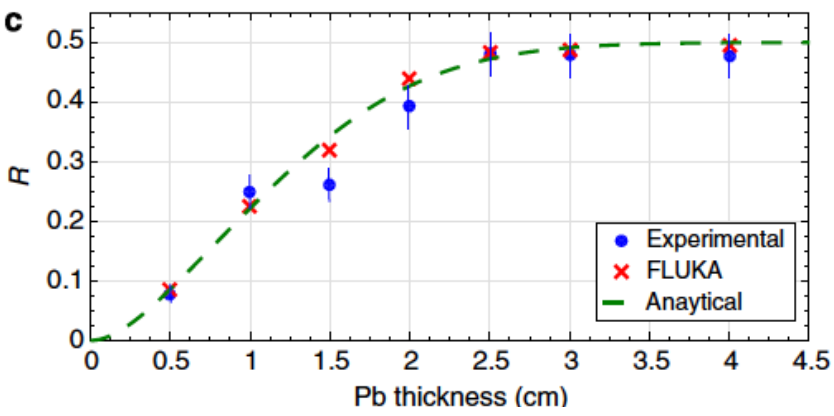


D. Doria et al., Nat. Phys. Submitted (2018)

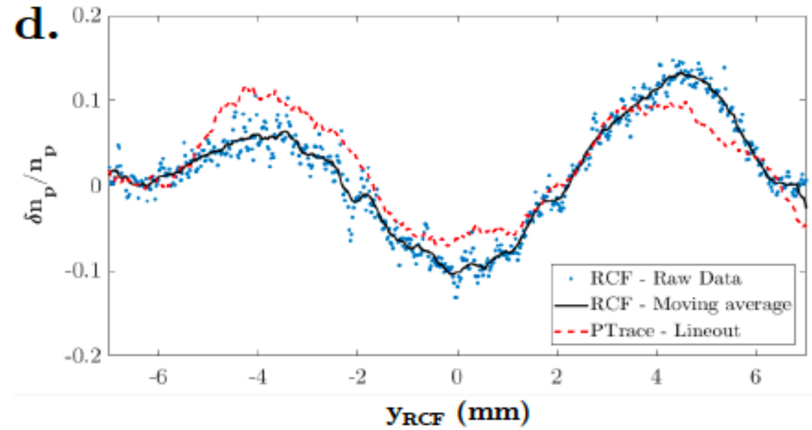
Conclusions and Outlook

Pair plasmas

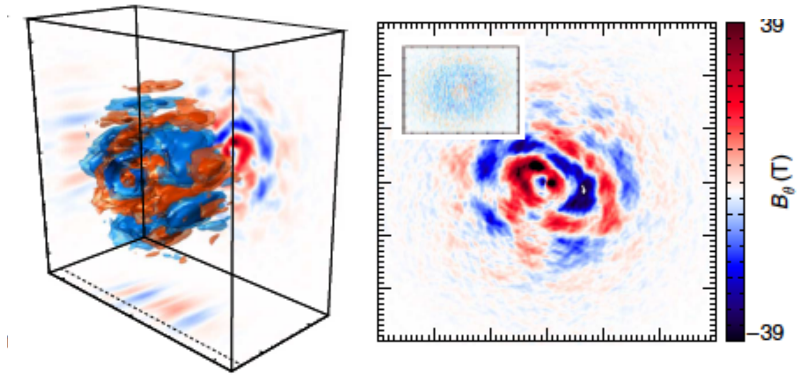
First generation of a neutral electron-positron plasma



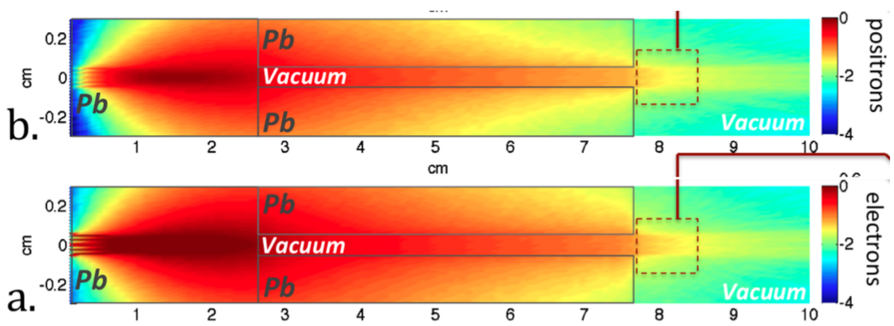
First demonstration of collective behavior: instabilities



Investigating fundamental pair beam dynamics to test models used to study astrophysical jets.

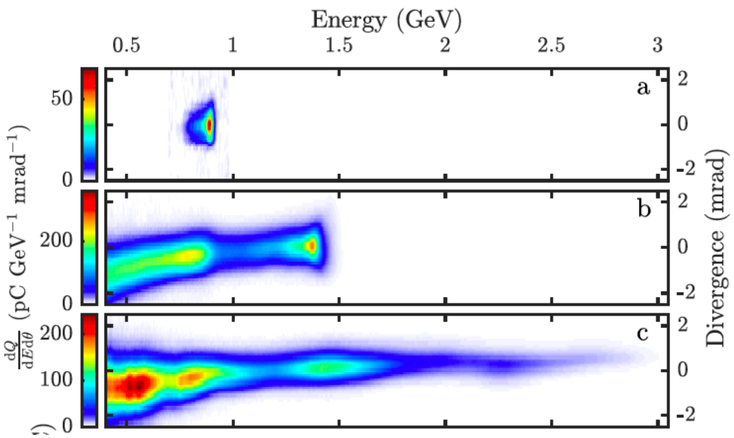


Current work devoted to generating collimated and denser pair jets

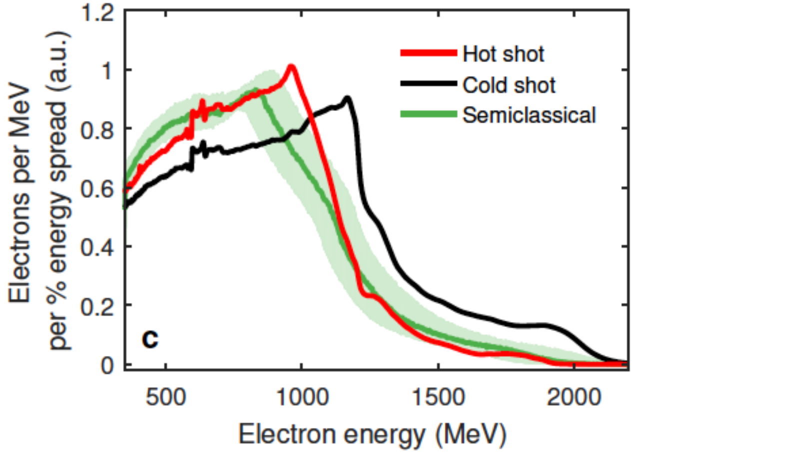


High field QED

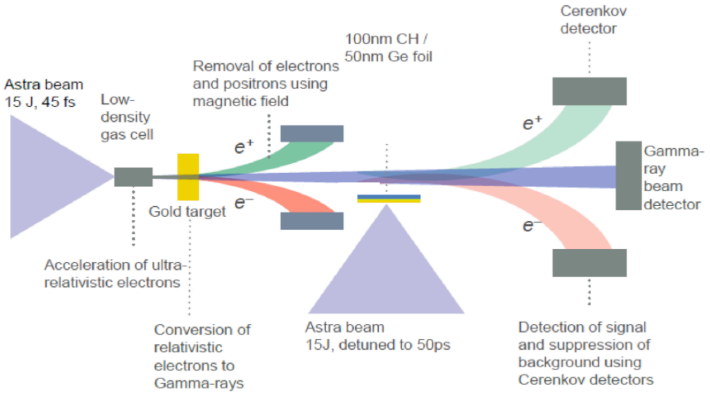
Multi-GeV electron beams in cm-scale accelerators



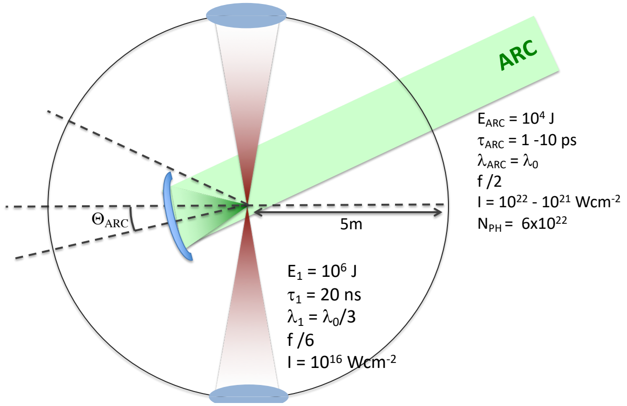
Direct demonstration of quantum effects in radiation reaction



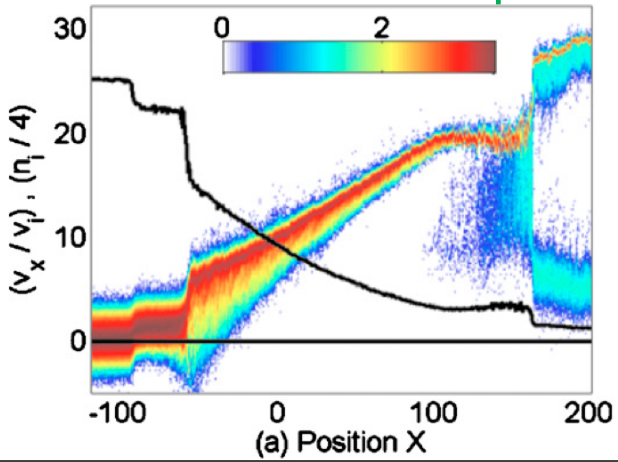
Direct pair production in photon-photon collisions



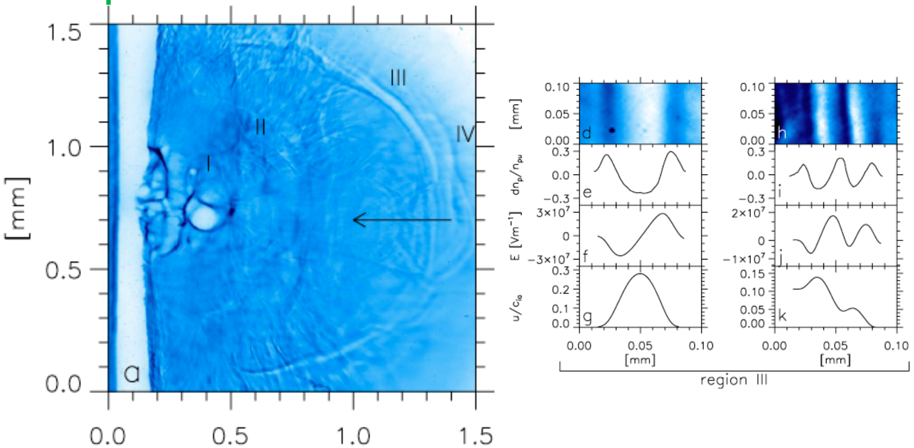
Vacuum polarization and birifrengence



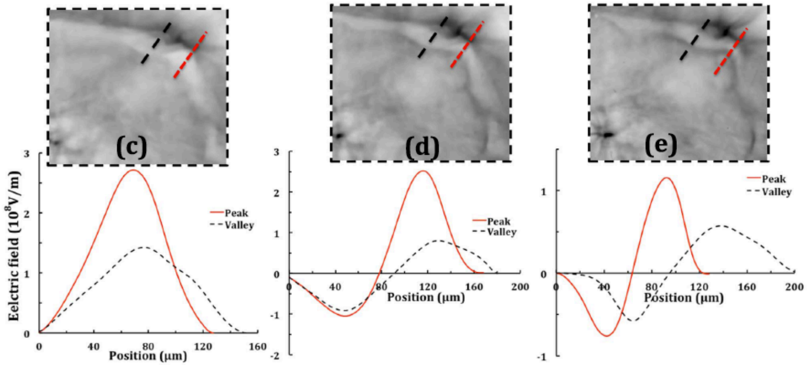
Collision-less shock-waves in laser-plasma exps.



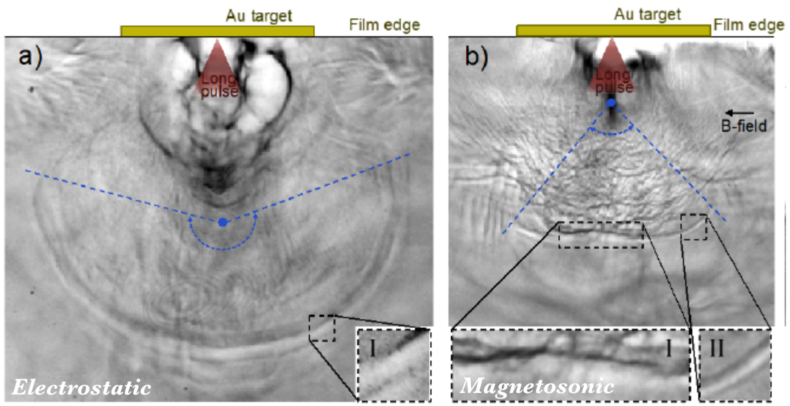
First experimental evidence



Kinetic instabilities at the shock front



Magnetised shock waves



Thanks for your attention!

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g.sarri@qub.ac.uk

Further reading:

Pair plasmas:
[1] G. Sarri et al., Phys. Rev. Lett. 110, 255002 (2013)
[2] G. Sarri et al., Plasma Phys. Contr. F. 55, 124017 (2013)
[3] G. Sarri et al., Nat. Comm. 6, 6747 (2015)
[4] G. Sarri et al., Plasma Phys. Contr. F. 59, 014015 (2017)
[5] J. Warwick et al., Phys. Rev. Lett. 119, 185002 (2017)

QED:
[6] G. Sarri et al., Phys. Rev. Lett. 113, 224801 (2014)
[7] J. Cole et al., Phys. Rev. X 8, 011020 (2018)
[8] K. Poder et al., *submitted to PRX* available on ArXiv (2018)

Shocks:
[9] G. Sarri et al., Phys. Rev. Lett. 107, 025003 (2011)
[10] H. Ahmed et al., Phys. Rev. Lett. 110, 205001 (2013)
[11] H. Ahmed et al., Astrophys. J. Letters 834, L21 (2017)