Experimental and Theoretical Studies of High-Field QED Effects in Laser-Plasma Interactions

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Apollon FIRE Meeting
12th February 2016

Current Collaborators

UNIVERSITY of York

Imperial College London

UNIVERSITY OF MICHIGAN

AVANCEZ 1829

University of Strathclyde Glasgow

STFC Central Laser Facility

- University of York
  - Chris Murphy, Chris Ridgers, Chris Baird
- Imperial College London
  - Stuart Mangles, Jason Cole, Jonathan Wood, Elias Gerstmayr, Kristian Poder
- University of Strathclyde
  - Paul McKenna, Ross Gray, Matthew Duff, Robbie Wilson
- University of Michigan
  - Alec Thomas, Keegan Behm
- Central Laser Facility
  - Dan Symes, James Green, Nicola Booth, Dean Rusby
- Chalmers University of Technology, Gothenburg
  - Tom Blackburn, Anton Ilderton, Mattias Marklund, Chris Harvey

Continuing and Future Collaborators

UNIVERSITY of York

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Apollon

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eli Nuclear Physics

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- Chalmers University of Technology, Gothenburg
  - Tom Blackburn, Anton Ilderton, Mattias Marklund
- ELI-NP and STFC – Rutherford Appleton Laboratory
  - Edmond Turcu

Queens University Belfast
  - Gianluca Sarri, Matt Zepf, Guillermo Marrero Samarin

Helmholtz Institute Jena

University of Warwick
  - Tony Arbor, Chris Brady

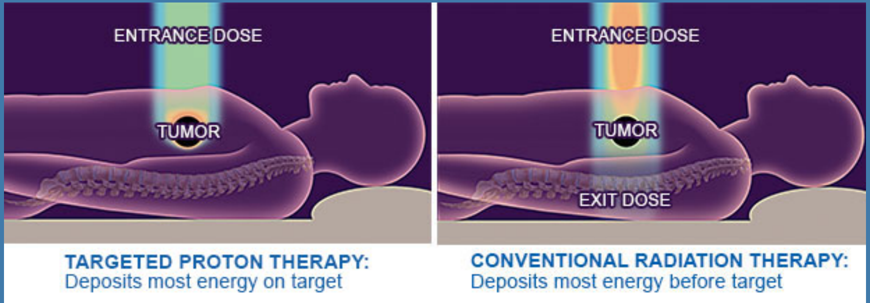
MPK
  - John Kirk

- Apollon?
- LULI?
- LOA?
- **Anyone else interested?**

Ultimate Goals

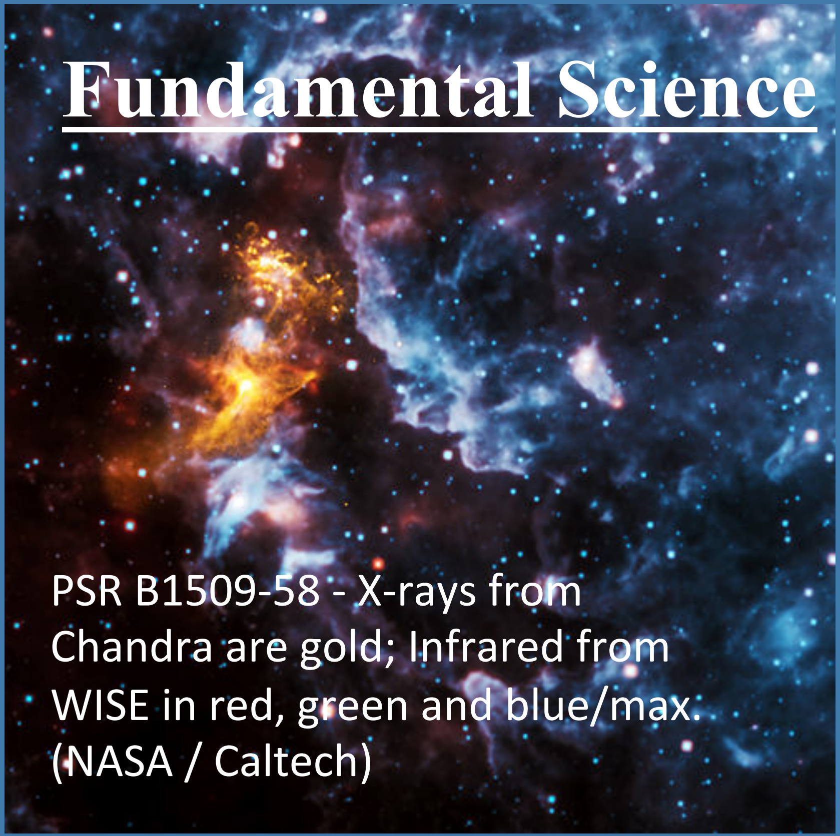
Applications

- Oncology, radioisotope production, perhaps nuclear physics and smart scanners
- Many improve with increasing laser intensity



http://www.floridaproton.org/what-is-proton-therapy/benefits

Fundamental Science



PSR B1509-58 - X-rays from Chandra are gold; Infrared from WISE in red, green and blue/max. (NASA / Caltech)

- The *ultimate* intensity for study would be 10^{29} Wcm^{-2}
  - Equivalent of 1.3 x 10^{18} Vm^{-2}
    - The critical field in QED
- At E_{crit} the laser field is strong enough to break down the vacuum into pairs
- Studying quantum effects may be possible at lower laser intensity

Laser-Plasma Interactions

The Quantum Regime

- For a pure electromagnetic wave:

$$\eta = \frac{|\mathbf{E} + \mathbf{v} \times \mathbf{B}|}{E_{crit}}$$

- In the electron's inertial frame, the threshold is reduced by gamma:

$$\eta = \gamma \frac{|\mathbf{E} + \mathbf{v} \times \mathbf{B}|}{E_{crit}}$$

- So we can say:

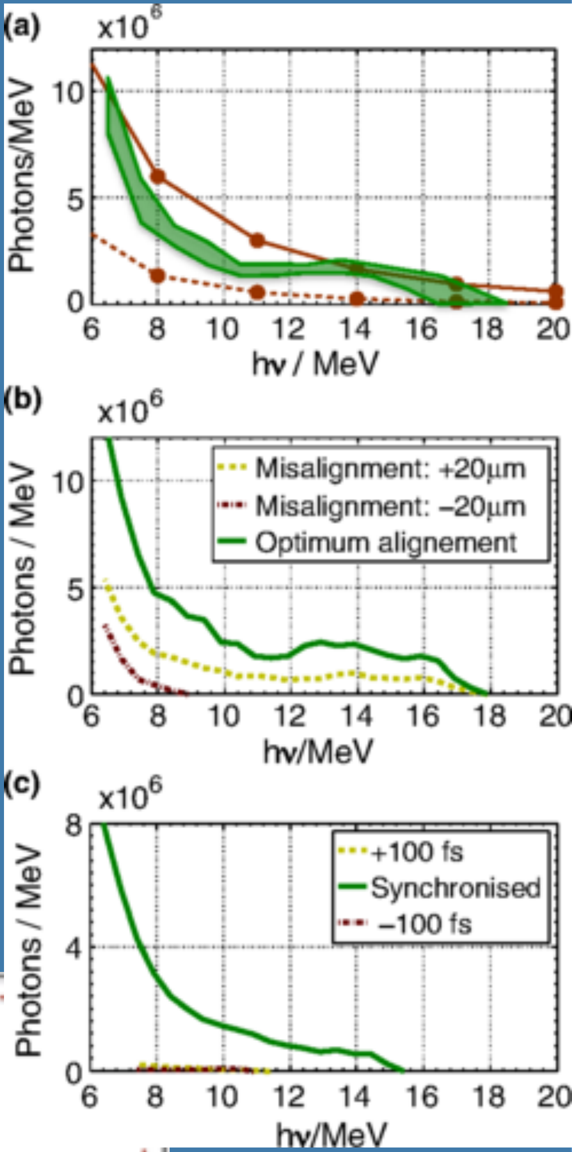
$$\eta \approx 0.1 \frac{\gamma}{1000} \left(\frac{I}{10^{21} W cm^{-2}} \right)^{1/2}$$

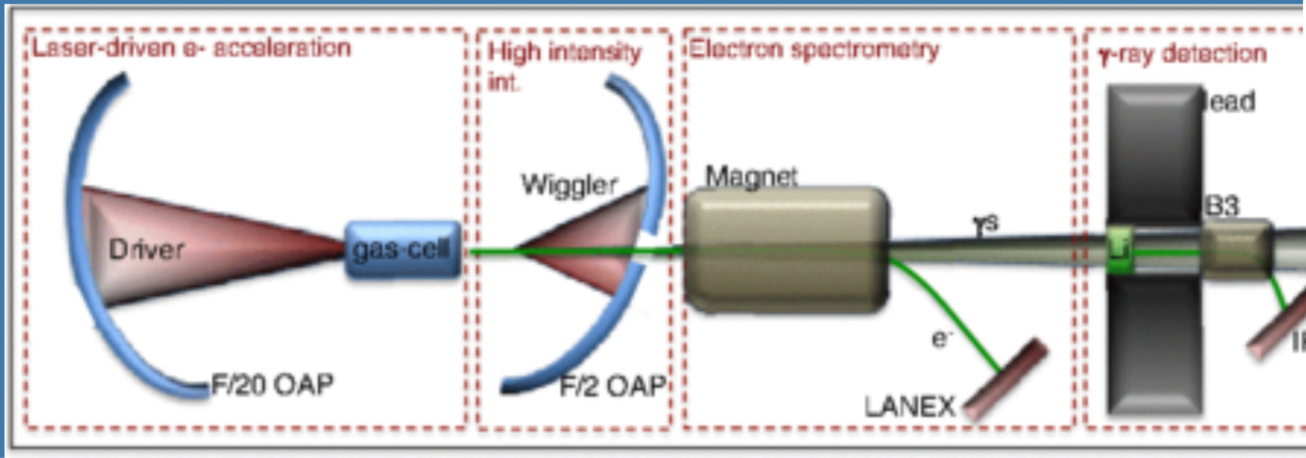
- Effects of radiation reaction become important at 10^{21} Wcm^{-2} if the 'target' is at 500 MeV
  - INVERSE COMPTON SCATTERING
- Ideal experiment for a dual beam laser system

Laser-Plasma Interactions

Nonlinear Inverse Compton Scattering

- First observation of nonlinear ICT by Sarri et al.
- Much was learned about measuring the gamma rays and the experimental difficulties associated with this setup





Recent Experiment: Astra Gemini

- Astra Gemini Laser
  - Dual Beam PW-class Ti:Sapphire laser
  - Common front end (oscillator and three amplifiers)
  - Independently controlled fourth amplification stage and compressor

- On our run:
  - pulse energy = 15 J per beam
  - pulse duration = 44 fs
  - F/20 focusing – 20 micron spot
  - F/2 focusing – 2 micron spot
  - Shot on demand (up to 1 every 20 seconds)

Similar to Apollon, but 10x less energy

Overview of Gemini Experiment

- In certain regimes, the electron beam may be elongated along the polarisation direction
- Plan was to hit the electrons as they left the gas jet to try to increase the fraction of electrons which interact
- EPOCH was used to optimise the ‘drift’ between the gas jet and the interaction
- Then all we needed was a nice electron bunch and good overlap…

- ‘Murphy’s Law’ kicked in.
- We saw gamma rays on a CsI scintillator stack but not at tightest focus
  - Preliminary ‘estimate’ $a_0 \sim 5$

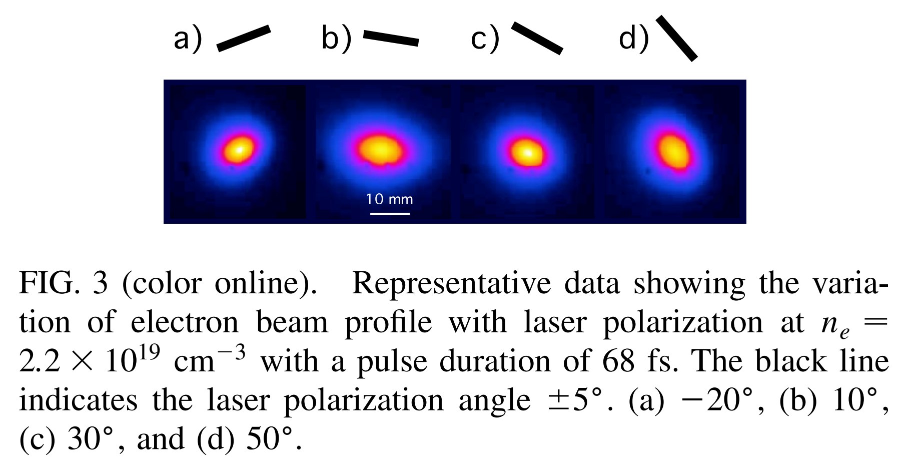
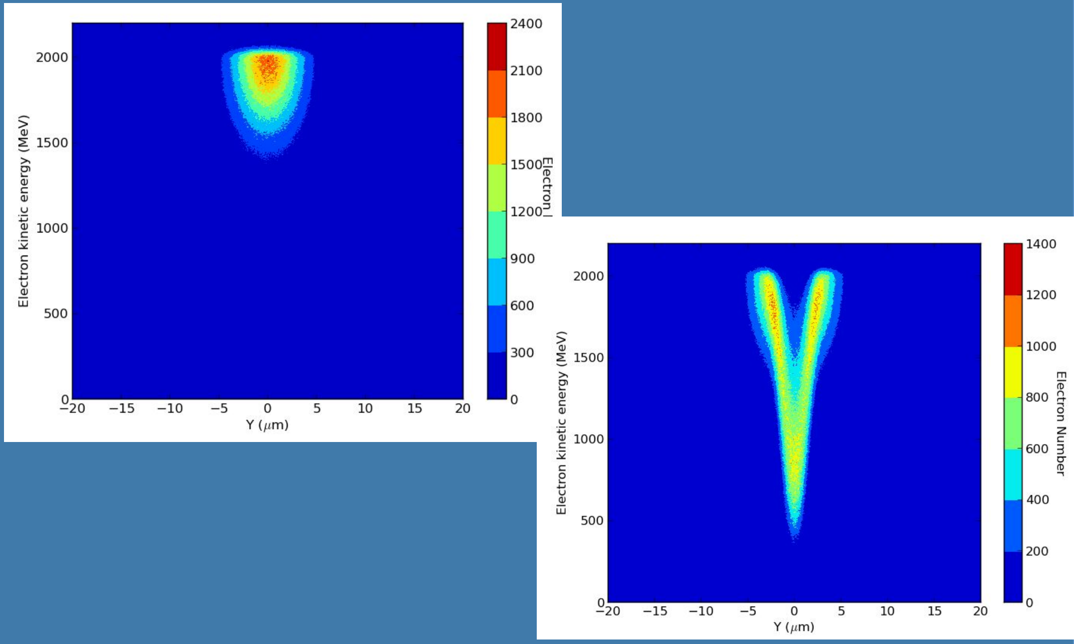


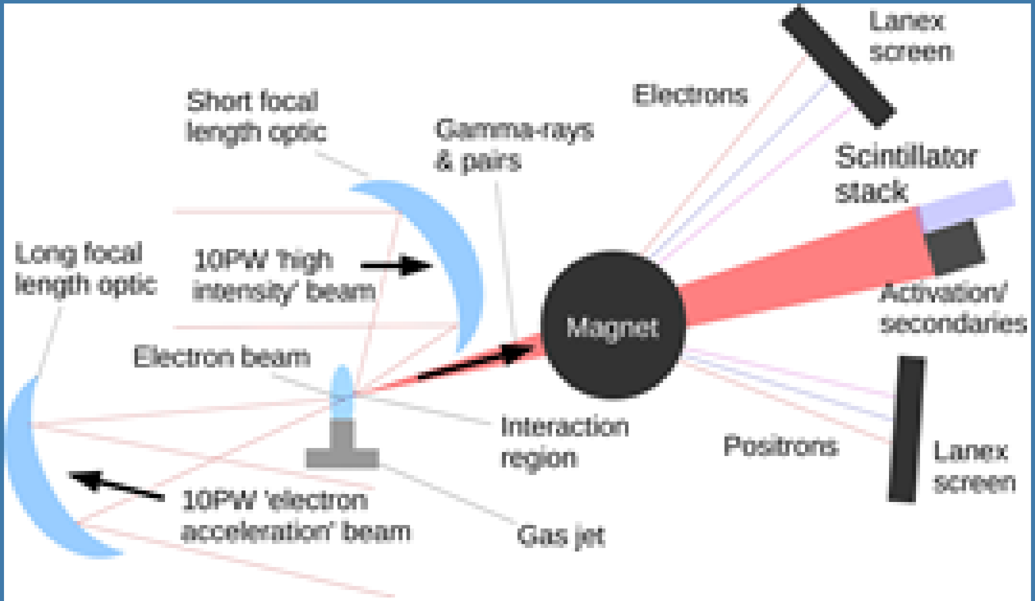
FIG. 3 (color online). Representative data showing the variation of electron beam profile with laser polarization at $n_e = 2.2 \times 10^{19}$ cm^{-3} with a pulse duration of 68 fs. The black line indicates the laser polarization angle ±5°. (a) −20°, (b) 10°, (c) 30°, and (d) 50°.



S P D Mangles et al. PRL **96** 215001 (2006)

Example Apollon Experiment 1: Collisions

- In either LFA or SFA:
- We can generate electrons with F2
  - 2 GeV should be achievable
- We can interact with the electron beam with F1
  - 10^{22} Wcm^{-2} should be accessible in early experiments
- Beam stability of one focal spot width would allow interaction at the highest intensity
- Even with the Phase 1 parameters exciting regimes will be accessible
- Possibly the first observation of positrons in the strongly nonlinear Breit-Wheeler regime



$$\eta \approx 0.1 \frac{\gamma}{1000} \left(\frac{I}{10^{21} W cm^{-2}} \right)^{1/2}$$

For example:

E_e = 2 GeV (g = 4000)

I = 10^{22} Wcm^{-2}

η = 1.2

However, what about a solid target?

$$\eta = \gamma \frac{|\mathbf{E} + \mathbf{v} \times \mathbf{B}|}{E_{crit}}$$

- In an accelerated electron's inertial frame: $\eta \approx 0.1 \frac{\gamma}{1000} \left(\frac{I}{10^{21} W cm^{-2}} \right)^{1/2}$

- But in laser solid interactions, gamma is simply the a_0 of the laser:

$$a_0 = \frac{p_{\mathrm{osc}}}{m_e c} \propto (I \lambda^2)^{\frac{1}{2}}$$

$$\eta \propto a_0 I^{1/2}$$

- So we can say:

$$\eta \approx 0.2 \frac{I}{10^{23} W cm^2}$$

The QED+Plasma Regime

$$\eta \sim 0.1 \frac{I}{5 \times 10^{22} Wcm^{-2}}$$

FEEDBACK

QED processes

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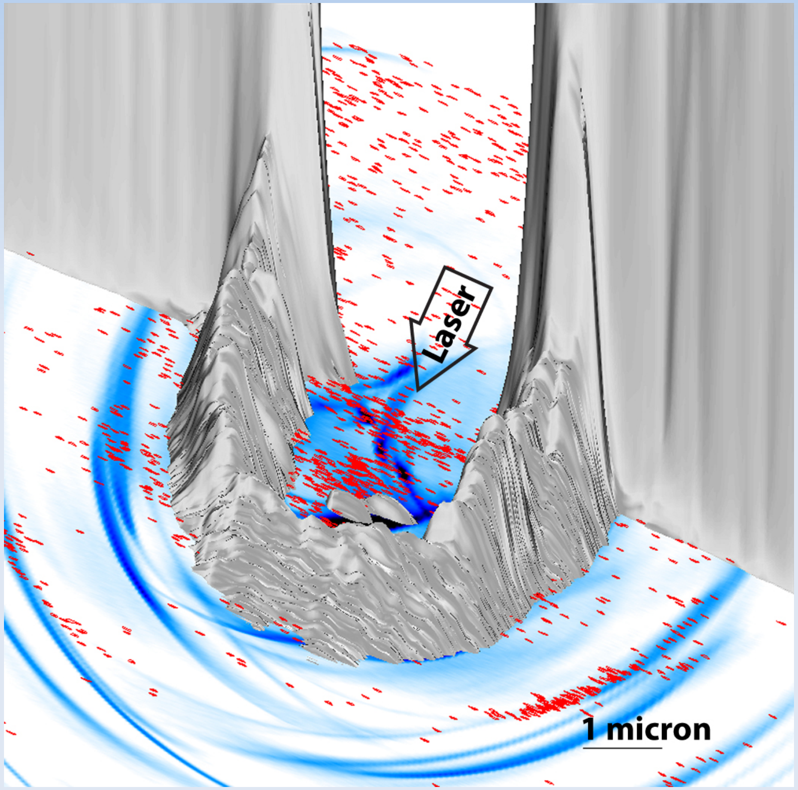
Classical Plasma Physics

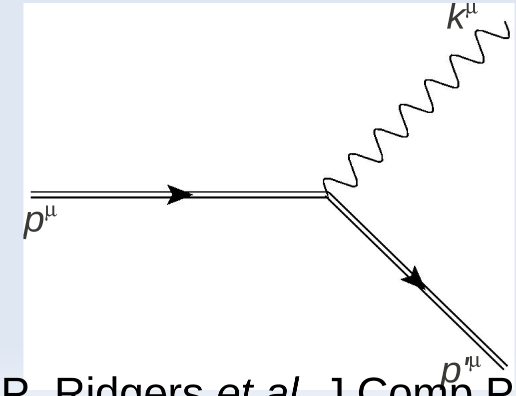


C.P. Ridgers, *et al*, PRL, 108, 165006 (2012)

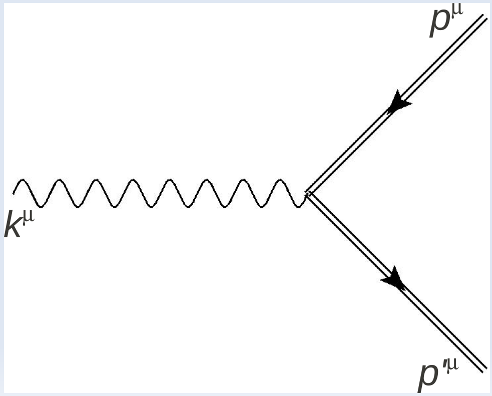
Quasi-classical model

1. Split EM field into 'low frequency' (laser-fields) & 'high frequency' (gamma-rays) components
2. 'Low frequency' fields are treated classically
3. Use strong-field QED – basis states dressed by fields
4. Keep lowest order interactions between electrons, positrons, gamma-rays with classical low frequency fields

Photon emission

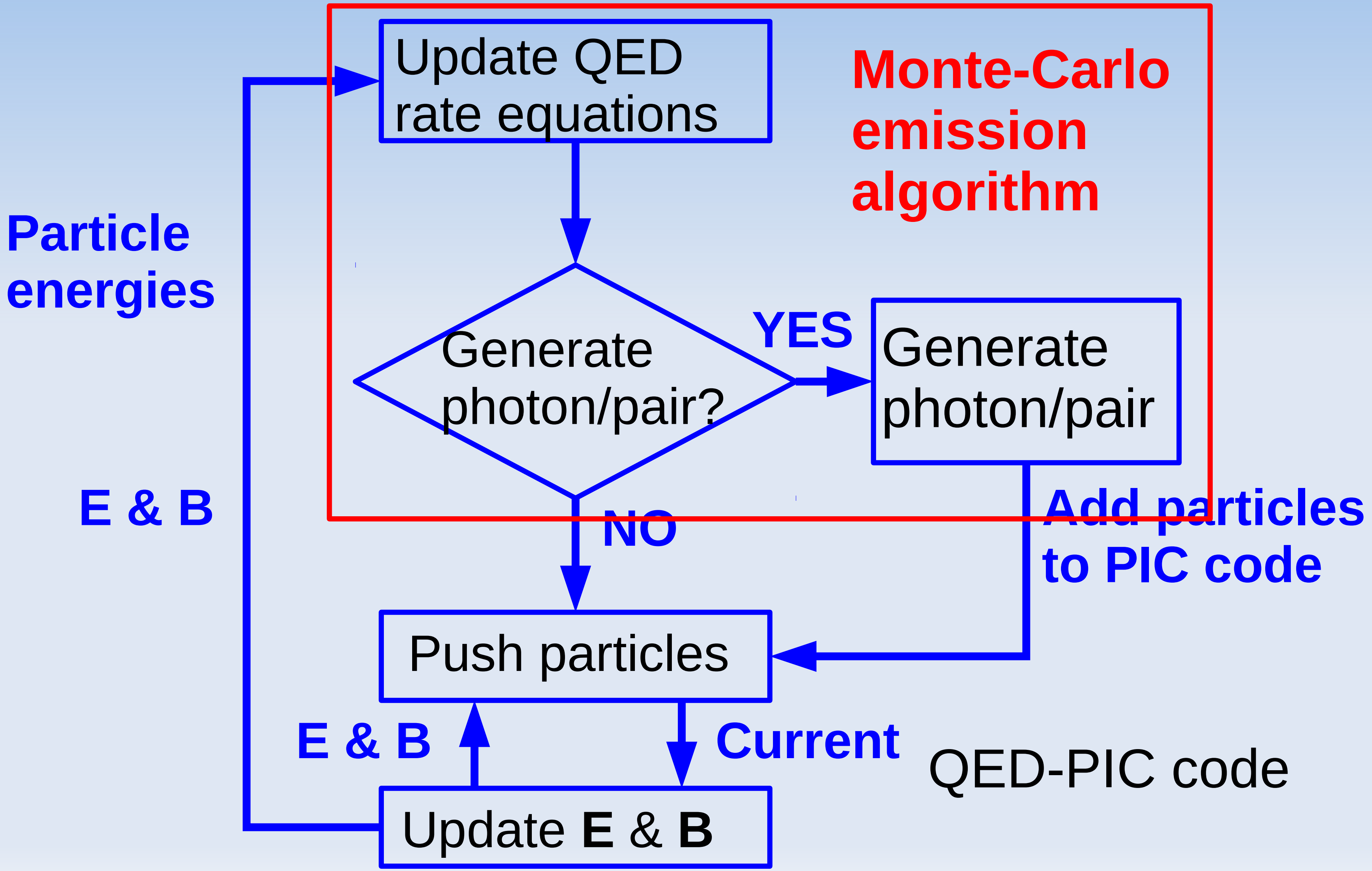


Pair production



C.P. Ridgers *et al*, J Comp Phys, 260, 273 (2014)

QED-PIC Codes



QED-PIC code

Ultra-relativistic plasma processes

1. QED effects: $\eta \sim 0.1 \frac{I}{5 \times 10^{22} Wcm^{-2}}$

2. Relativistic transparency

$$n_c^{rel} \sim n_s \sqrt{\frac{I}{10^{23} Wcm^{-2}}}$$

Relativistic correction to critical density

$$n_c = \frac{\boxed{\gamma} m_e \epsilon_0 \omega_L}{e^2}$$

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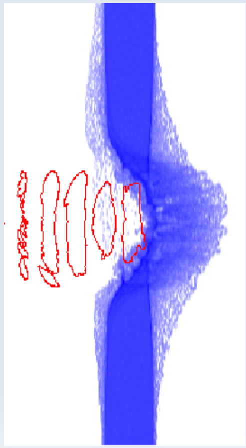
$$\Xi \sim \frac{I}{10^{23} Wcm^{-2}}$$



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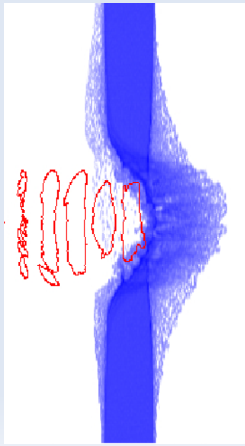
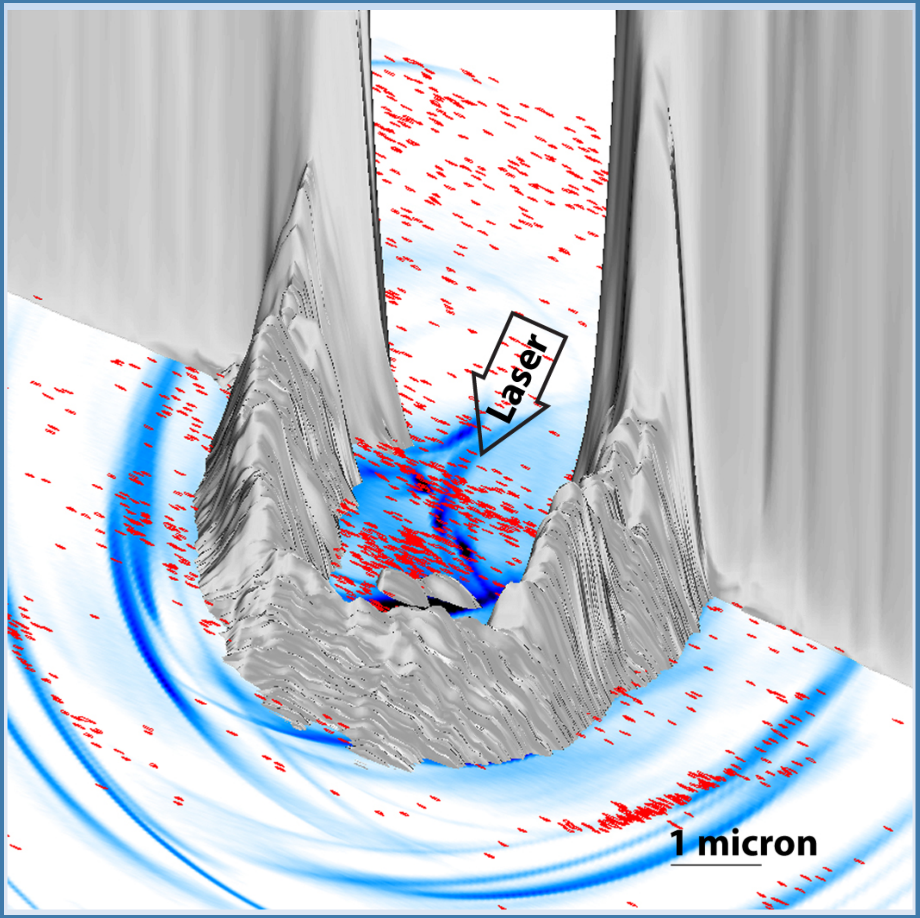


All 'switch-on' at ~10^{23}Wcm^{-2}

Example Apollon Experiment 2:

Solid Target Study

- Just shoot it.
- May potentially need advanced focusing to reach the required intensity
  - Rick?
- The important / difficult aspects here are:
  - Positioning the target
    - THE Ohio State University
    - Central Laser Facility
  - Measuring the gamma rays generated
    - Demonstrates a need for spectral measurement of gamma rays at ultra-high flux



‘Conclusions’

- Experiments on current facilities are succeeding to make measurements but the experiments are very challenging and the results are often difficult to interpret
  - Increased involvement from other groups is essential
- Challenges and opportunities:
  - Electron Stability
    - Should be improved by lower plasma density and improved laser pointing stability at Apollon
  - Hitting the electrons with the laser
    - Currently experiments have yielded many ideas and expertise in this is growing
  - How will we obtain a gamma spectrum
    - Current work in conjunction with the University of York Nuclear Physics group at developing detector ideas
    - Queens University Belfast are also working on detector development