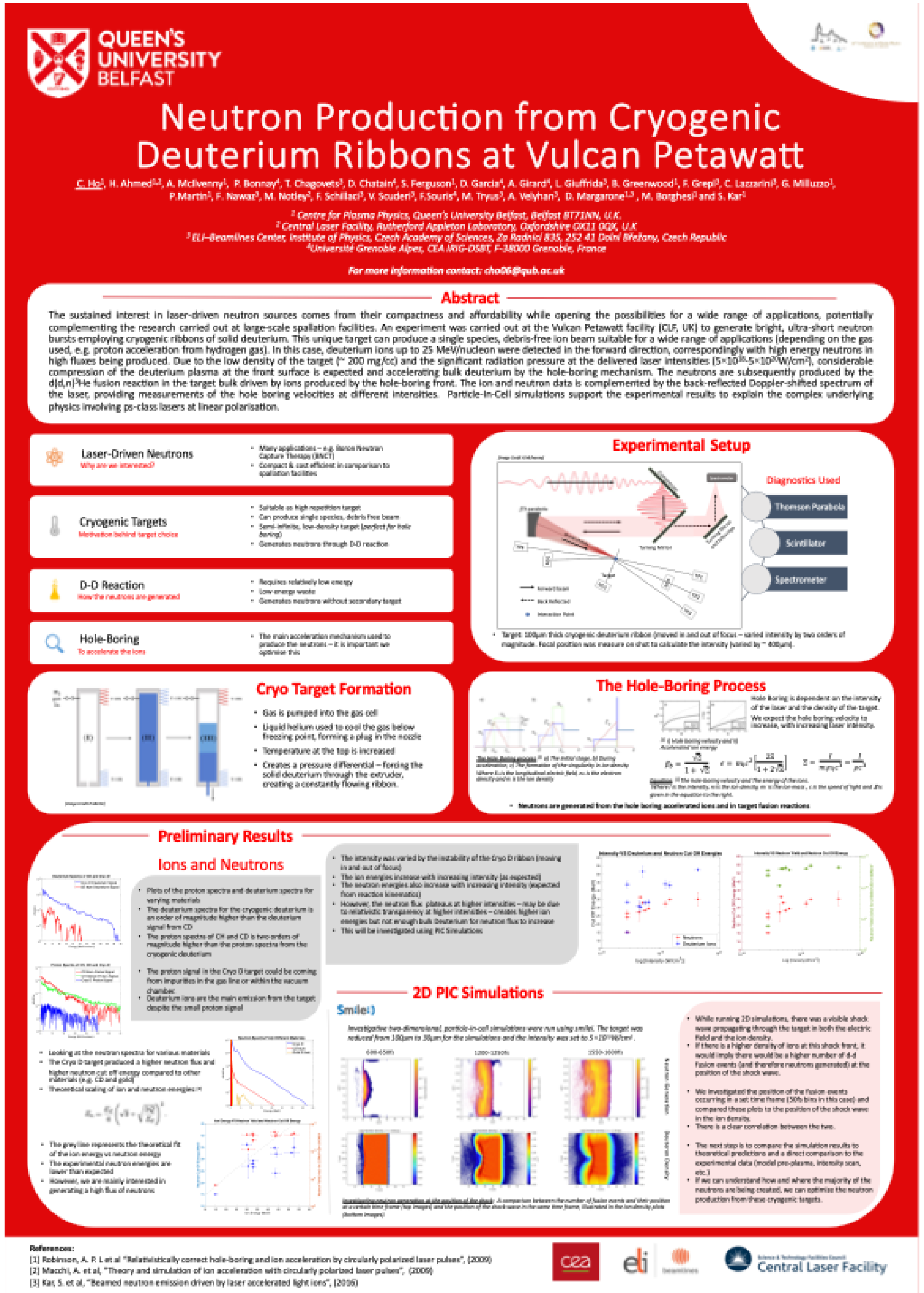
Chloe Ho


QUEEN'S UNIVERSITY BELFAST
Neutron Production from Cryogenic Deuterium Ribbons at Vulcan Petawatt
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Abstract
The sustained interest in laser-driven neutron sources comes from their compactness and affordability while opening the possibilities for a wide range of applications, potentially complementing the research carried out at large-scale spallation facilities. An experiment was carried out at the Vulcan Petawatt facility (CLF, UK) to generate bright, ultra-short neutron bursts employing cryogenic ribbons of solid deuterium. This unique target can produce a single species, debris-free ion beam suitable for a wide range of applications (depending on the gas used, e.g. proton acceleration from hydrogen gas). In this case, deuterium ions up to 25 MeV/nucleon were detected in the forward direction, correspondingly with high energy neutrons in high fluxes being produced. Due to the low density of the target (~ 200 mg/cc) and the significant radiation pressure at the delivered laser intensities (5×10^19-5×10^20 W/cm^2), considerable compression of the deuterium plasma at the front surface is expected and accelerating bulk deuterium by the hole-boring mechanism. The neutrons are subsequently produced by the d(d,n)3He fusion reaction in the target bulk driven by ions produced by the hole-boring front. The ion and neutron data is complemented by the back-reflected Doppler-shifted spectrum of the laser, providing measurements of the hole boring velocities at different intensities. Particle-In-Cell simulations support the experimental results to explain the complex underlying physics involving ps-class lasers at linear polarisation.
Laser-Driven Neutrons
Cryogenic Targets
D-D Reaction
Hole-Boring
Experimental Setup
Diagnostics Used
Thomson Parabola
Scintillator
Spectrometer
Cryo Target Formation
Gas is pumped into the gas cell
Liquid helium used to cool the gas below freezing point, forming a plug in the nozzle
Temperature at the top is increased
Creates a pressure differential – forcing the solid deuterium through the extruder, creating a constantly flowing ribbon.
The Hole-Boring Process
Preliminary Results
Ions and Neutrons
2D PIC Simulations
Smilei
References:
Central Laser Facility

Noel Kehoe

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Coherent Ion Acceleration: a Novel Acceleration Mechanism

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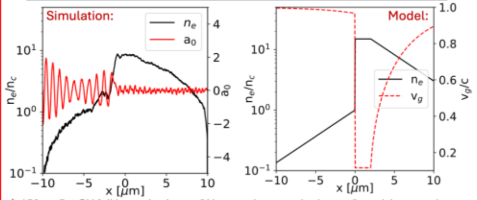
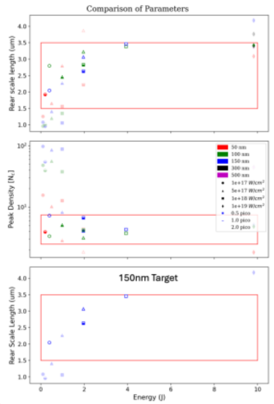
- Leading high-power laser facilities can provide extreme laser intensities of $10^{21}\ W/cm^2$, corresponding to pressures of >600 Gbar. These enormous pressures can be exploited to produce high-energy ions through the Radiation Pressure Acceleration (RPA) mechanism. Previous work have achieved ~30 MeV proton ions[1] and 30 MeV/u carbon ions[2].
- The two regimes of RPA (Light Sail (LS) and Hole Boring (HB)) have several issues that result in a reduction of their acceleration efficiency:
  - The development of transverse instabilities[1]; Induced transparency[2]; The fastest, 'reflected' ions travel at $2v_{HB}$.[3]
- Optically tailored plasma profiles can be used to alter the laser front velocity of a propagating laser pulse to coincide with the ion front of the highest energy ions.
- Utilising electrostatic fields produced in a near-critical plasma by a propagating laser pulse[4], the co-moving ions can undergo acceleration over an extended distance.
- The acceleration scheme can be split into two phases: (i) the Heating Phase using a foil and (ii) the Acceleration Phase.

(i) Heating Phase



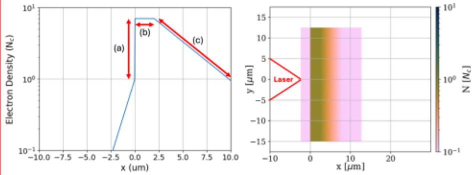
- 150nm flat CH foil heated using an 8J laser pulse stretched up to 2ps, giving a peak intensity of $2\times10^{19} W/cm^2$.
- Radiation pressure is sufficient to overcome target's thermal pressure to maintain sharp front surface.
- The group velocity of the accelerator pulse is reduced during the HB phase to match the ~0.1c velocity of the protons and trap them within the produced electrostatic field.
- The group velocity then gradually increases as it propagates through the rear surface plasma as the protons are accelerated.



- The density profile shown above can be produced using a range of laser and target parameters.

- Red box indicates optimal parameters.
- Opaque points create all optimal parameters simultaneously.
- Initial flat foils of thickness 50, 100, 150, 300 and 500 nm.
- Laser intensities of 1×10^{17}, 5×10^{17}, 1×10^{18} and $1\times10^{19}\ W/cm^2$.
- Pulse durations of 0.5, 1.0 and 2.0 ps.

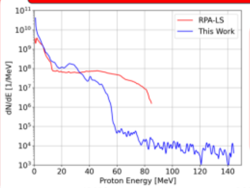
(ii) Acceleration Phase



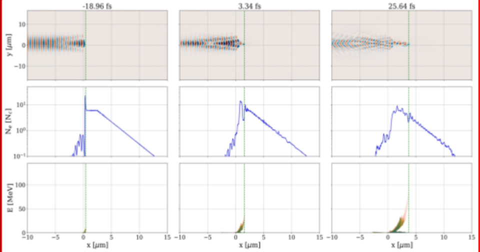
Parameter scan of optimal density profile using 2D SMILEI PIC code:
- (a): Peak density;
- (b): Bulk thickness;
- (c): Rear scale length

- Simulation box of $40\times35\ \mu m$ with a resolution of $10\times20\ nm$.
- C6+ and H+ with neutralising e- species with 50 PPC each.

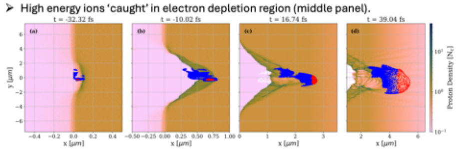
0.3PW Pulse



- Optimum parameters found to be (a) 6N$_c$, (b) 2.5μm, (c) 2.5μm
- Proton energies up to 146 MeV.
- Close to twice the max energy of RPA-LS with a flat foil and identical laser parameters.
- Small number of protons are getting accelerated to these high energies.

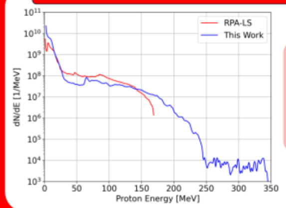


- Laser field (top panel) co-moves with ion front (green dashed line).
- High energy ions 'caught' in electron depletion region (middle panel).



- Red proton group correspond to energies $58\ MeV \le E < 146\ MeV$.
- Electrostatic field created is only trapping a small region of protons, due to small channel created by the pulse in the bulk target and few protons accelerated to $2v_{HB}$ during the initial HB phase.

1.0PW Pulse



- Optimum parameters found to be (a) 8N$_c$, (b) 3.5μm, (c) 1.5μm
- Proton energies of up to 350 MeV.
- Energies twice of RPA-LS case with same laser pulse.

Conclusion

- Optically tailoring a plasma can enhance ion energies;
- Can be further tuned to optimise the charge for a given energy (for radiobiology applications);
- Further work includes improving ion particle number trapped by the laser pulse and input energy selection and acceleration.

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Hannah Maguire

Laser-Driven, Ultra-Short, High Dose-Rate Electron Beams for Radiotherapeutic Applications

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NPL National Physical Laboratory

Introduction

The main goal of radiotherapy is to minimise the exposure of normal tissue to radiation, while delivering the required dose to cancerous cells. Although radiotherapy is an effective method to treat cancer, it can:

- induce significant side effects- e.g. damage to normal tissue, formation of secondary cancers
- be unsuccessful- tumour cells have a higher radioresistance than normal cells [1].

Laser-driven particle accelerators can deliver ultra-short, high dose-rate, pulsed irradiation sources with timescales in the picosecond (ps) to femtosecond (fs) range. Preliminary findings, delivering laser-wakefield accelerated (LWFA), very high energy electron (VHEE) beams onto in-vitro cell samples, have revealed significantly different cellular responses compared to conventional radiotherapy. Notably, this work demonstrated a significant reduction in the relative radioresistance of tumour cells [2].

Recent and future experiments are focussed on extending these preliminary studies and to further establish the radiobiological effects of laser-driven, ultra-short electron beams. Comparisons with irradiations at the picosecond level [3] suggest that this novel cellular response may be linked to the ultra-high density of ionising tracks and very high energies of femtosecond-scale radiation pulses.

LWFA Electron Beams

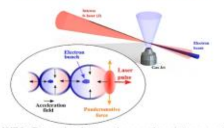


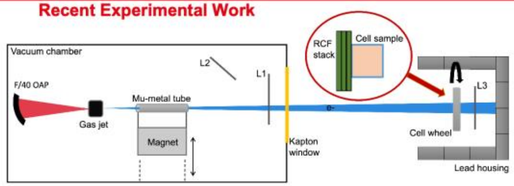
Figure 1. LWFA. Focussing intense laser pulses into a gas target and creating plasma waves, which act like a wake to accelerate electrons over very short distances [4].

- Production of VHEEs (e^- energy spectra >100MeV)
- High-charge (~1-2nC)
- Gy-scale dose deposition over cm^2 areas achieved with a single fs pulse
- Reaching unprecedented average dose rates >10 Gy/s

Recent Experimental Work

An experiment at the Gemini Laser Facility, UK, was completed this year completed to extend on the preliminary data:

- **Irradiation of a wider range of cells**- two normal, healthy cell lines (AGO1522D, RPE-1) and five cancerous cell lines (E2, MCF7, DU145, H460, HeLa)
- Dose values **up to 3Gy** achieved for each cell line



E_L = 10 J
τ_{FWHM} = 45 fs
$I_0 = (4.1 \pm 0.5) \times 10^{18}\ Wcm^{-2}$
$n_e \sim 3 \times 10^{18}\ cm^{-3}$
τ_b = 25fs
$E_e \sim$ 250-700MeV
$\bar{Q}$ = 1.8 ±0.4nC

Figure 2. Sketch (top view) of the experimental set-up. L1, L2 and L3 are Lanex scintillator screens. The cell wheel holds up to 10 cell samples each with stacks of Radiochromic Film (RCF) for dose measurements. Laser and electron beam parameters are listed on the right.

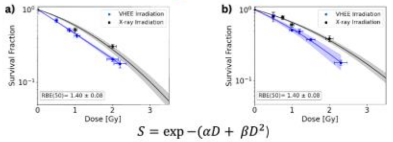
This work will be repeated at different facilities to allow comparisons between different beam characteristics:

TARANIS Laser, QUB, UK
- ps pulses of irradiation (10^{10}-10^{11} Gy/s)
- 1-10MeV electrons

SPARC accelerator, Laboratori Nazionali di Frascati, Italy
- tuneable sub-ps irradiation
- 100-170MeV electrons

PGJ Centre for Cancer Research, QUB, UK
- conventional x-ray irradiation (0.49 Gy/min)
- conventional electron source (6-20MeV)

Biological Analysis



$$S = \exp -(\alpha D + \beta D^2)$$

Figure 3. Clongenic Assays. Modelled by the above cell survival equation, clonogenic assay results are shown for [a] AGO1522D and [b] E2 cell lines following irradiation with ultra-short pulses of electrons [2].

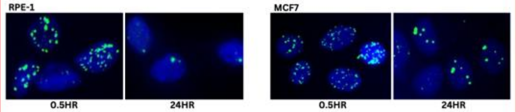


Figure 4. 53BP1 Foci Formation. Foci distributions as functions of time (0.5hr, 24hr after irradiation) for RPE-1 and MCF7 cell lines. Shown are merged channel images of 53BP1 DNA DSB marker (green) and DAPI nuclear stain (blue).

Modelling LWFA Electron Beam Profiles -TOPAS

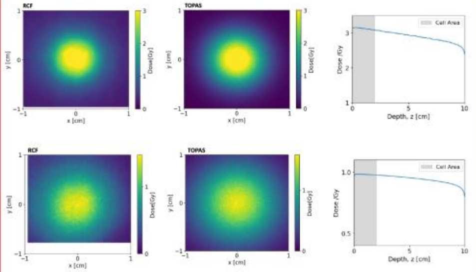


Figure 5. Examples of Measured (RCF), simulated (Monte Carlo scattering code TOPAS) and corresponding depth-dose profiles. Top row: dose profiles for Clonogenic Assay analysis. Bottom row: dose profiles for Foci Induction analysis.

Limitations

- **Spatial uncertainties** due to shot-to-shot electron beam pointing instability in the plasma bubble can cause cell samples to only be partially irradiated or missed entirely

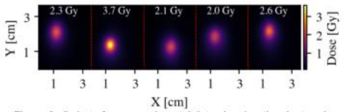


Figure 6. 5 shots from experimental data showing the electron beam shot-to-shot pointing instability and the peak dose values [2].

- **Dosimetry** of this beam modality is not trivial:
  - Plane-parallel ionisation chambers (recommended secondary standard systems for clinical reference dosimetry of electrons), experience high levels of charge collection inefficiency at high dose-rates [5]
  - RCFs are dose-rate independant, have high resolution and are suitable for VHEE dosimetry but fail to provide dose measurements in real-time (require post-irradiation processing and data analysis) [6]

Conclusions

- Ongoing analysis from a recent experiment to extend from preliminary studies and to further establish the radiobiological effects of this beam modality
- Detailed research into accurate dosimetric techniques for LWFA electron beams planned- mandatory to establish the effects of ultra-short irradiation on cells [6]
- Final aim is to create a new scheme for radiotherapeutic cancer treatment

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Temour Foster

Laser-driven positron sources for Positron Annihilation Lifetime Spectroscopy (PALS)

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EuPRAXIA

Introduction

- Material characterisation exploiting, for instance, laser-driven Positron Annihilation Lifetime Spectroscopy (PALS) benefits from a high repetition rate source of keV to MeV positrons with a high flux of particles, over a region with mm to cm transverse size. PALS works with virtually any material, is non-destructive and can identify sub-nanometre defects

Positrons have usually been generated via a radioactive source; however, they have their issues:

1. The positrons energy generated is in the keV range, reducing the penetration depth of positrons so it would only be useful for surface studies
2. The positrons generated also have a long duration, matching the typical annihilation of a positron in material at around 200ps [1]

- Laser-driven positrons solve both issues, providing MeV scale positrons with a duration of 60ps[2], with a proof-of-principle experiment currently paused at Queens

Theory

- Laser pulse generates hot electrons via JxB heating
- Hot electrons generate high energy photons via Bremmsstrahlung
- High energy photons produce positron-electron pairs via Bethe-Heitler pair production
- Defects in material cause local potential for positron to be temporarily trapped
- Delay measurable via recorded gamma intensity, giving information about defect

$$a_0 = 8.53 * 10^{-10} * (I\lambda_{\mu m}^2)^{\frac{1}{2}}$$

Equation 1: Quiver velocity of electrons in electric field

$$W_{osc} = (\sqrt{1+\frac{a_0^2}{2}} - 1)m_e c^2$$

Equation 2: Cycle-averaged kinetic energy of electrons via laser electric field

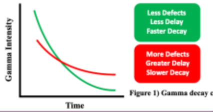

Figure 1) Gamma decay curve

Experiment

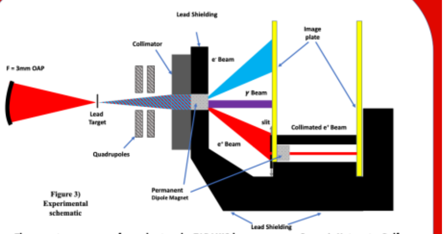

Figure 3) Experimental schematic

- The experiment was performed using the TARANIS laser system at Queen's University Belfast
- 11.5J laser shot with a pulse duration of 800fs and focused onto a FWHM of 5.9µm x 6.2µm
- 3.00x10 [19] Wcm [-2] peak intensity
- Equation 1) predicts max electron temperature of around 1MeV

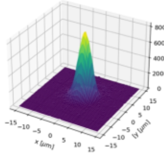

Figure 4) Focal spot of TARANIS

Simulations

- Modelling was done using the Monte Carlo code FLUKA[3].
- 0.9MeV input with 2mm tantalum target
- Simulations show 10^6 positrons can be acquired with tunable energies

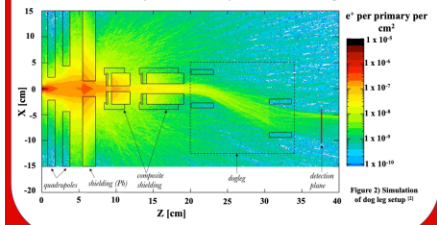

Figure 2) Simulation of dog leg setup [2]

Results

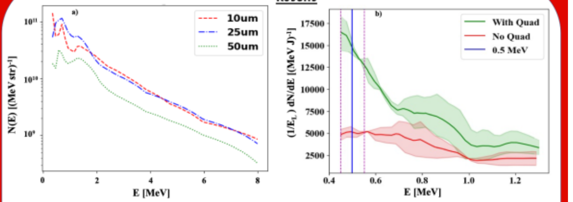

Figure 5a) Electron spectra to characterize JxB electrons using thin gold foil b) Positron spectra; 0.5mm

- 10^5 positrons generated between 0.45-1.3MeV entering 2nd dipole
- 4.5x improved collection with new quadrupoles
- Electron spectra gives initial electron temp of 0.87MeV, used as input for future simulations
- Positron-to-electron ratio of 0.0487

Quadrupole Design

- Old quadrupoles were too weak, added too much noise and increased the distance between foil and Target
- New quadrupoles designed, simulated and used
- Improved positron collection by 5x compared to without quadrupoles

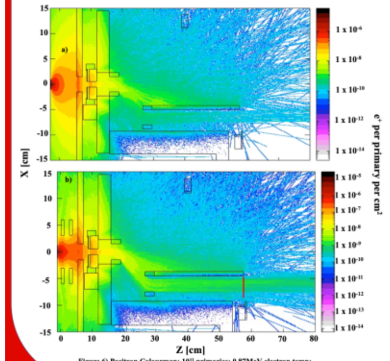

Figure 6) Positron Colourmap; 10^{11} primaries; 0.87MeV electron temp; 1mm Lead a) No Quad b) New Quad

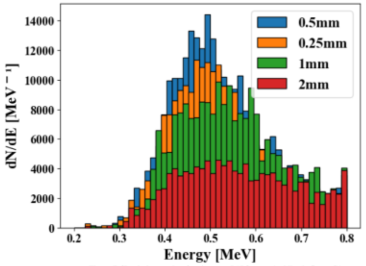

Figure 7) Simulation results of positrons at PALS target (red line in figure 6b)

Thickness [mm]	0.2-0.8MeV positrons	0.4-0.6MeV positrons
0.25	2648	1741
0.5	3317	2170
1	2612	1608
2	1510	784

Table 1: Positrons at PALS target

Future work

- An experiment is set to be done in June at ELI-Beamlines, using the high repetition rate ALFA Laser system
- Preliminary simulations show that the ALFA system us capable of delivering 10^3 positrons to a PALS target per shot
- With a repetition rate of 1kHz, it would equate to 10^6 positrons, similar to current facilities output
- This would represent the first experimental demonstration of a positron source with high average flux, short duration (20-30ps) and MeV-scale energy

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