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**Review of First Light Fusion Ltd's experimental report 'validate production of neutrons from gas-gun driven targets'**

Summary: UKAEA have conducted a review of First Light Fusion Ltd's recent (485 series) experimental campaign. The UKAEA technical team involved have had the opportunity to interact with the FLF experimental team as part of the review. The review included assessments of the experimental planning, scientific equipment used and associated diagnostics, processes to extract and analyse the data obtained from the diagnostics and analysis included within the associated experimental report.

The experimental campaign comprised 21 high velocity impact experiments ('shots') overall. 12 of these were reported to have used deuterium-fuelled (base-case) targets, one was a deuterium design variant shot, four were hydrogen null shots and a further four were test shots. UKAEA staff witnessed a sub-set of these which were two deuterium-fuelled target shots; the first took place on the 22nd February 2022 and yielded no detection events (reportedly due to projectile failure); the second (successful) shot on the 4th March 2022 yielded three scintillator events and a single $^{3}$He detection event within the defined time windows.

In assessing the experimental campaign as a whole, the diagnostic data obtained and analyses performed from the experiments in aggregate, and with detailed consideration of terrestrial background or other potential sources of spurious signals, we support FLF's finding that high energy particles have been detected. In the context of fusion experiments the number of events detected is small. However, the events detected and the associated temporal analysis are sufficient to indicate a link to the impact experiments using deuterium-loaded targets. The aggregated time-of-flight data comprising 29 detection events obtained using the scintillator array (each event corresponds to the detection of a single particle), together with the basic analysis performed to estimate a neutron energy range provides some evidence that neutrons have been produced which would be consistent with the energy of those produced in D–D fusion processes. The supporting $^{3}$He detection events within an expected time window following the expected fusion time are fewer, though in aggregate do provide some complementary evidence through a separate detection system to the scintillator array that neutrons are present.

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# 1 Introduction

UKAEA have conducted a review of First Light Fusion Ltd's (FLF) recent nuclear experiments which have been detailed in the associated report '0485: Validate Production of Neutrons from Gas Gun Driven Targets' [1]. The campaign involved conducting a series of individual impact experiments where a projectile with a mass of around 100 g is fired at high velocity (nominally at around 6.5 km/s) at a target embedded inside a plastic block that contains either deuterium fuel or hydrogen. The projectile is launched using a 38 mm bore, two-stage light gas-gun, primed with around 3 kg gunpowder on each occasion it is fired. The kinetic energy of the projectile is able to produce impact pressures of the order of 100 GPa[1]. The pressure amplification process derived from the proprietary target design used by FLF is claimed to induce the conditions for thermonuclear fusion to occur when the target has been loaded with deuterium fuel. Simulations of the target temperatures were reported to reach of the order of 100's eV for short periods of time. Nuclear diagnostics were used which surround the experiment blast vessel, with the aim to determine the presence of characteristic neutrons emitted from thermonuclear fusion reactions taking place within the target. These included large area arrays of nuclear detectors: 16 large area EJ-200 plastic scintillator detectors and 12 five tube $^3$He gas-filled neutron detector assemblies in polyethylene moderators. The detectors were placed on a framework at various locations surrounding the target chamber enclosure, for the purpose of detecting particles generated within a short time window following a time referred to as the 'fusion event', measured using timing diagnostics (also referred to as timing fiducials).

In relation to FLF's experiments, the basic questions that needed to be assessed were whether neutrons have been produced due to the shock-driven process and, if so, whether the neutrons were generated due to fusion reactions taking place relating to dynamics occurring within the D–D fuel target[2]. To provide evidence in answering these questions, measurements were needed to determine whether neutrons were produced that can be associated with the impact experiment, born with energies associated with D–D fusion reactions taking place. A secondary, and more challenging aspect to determine would be to establish whether fusion neutrons were generated entirely due to thermal plasma (so-called thermonuclear) processes. Neutrons produced in a thermal deuteron plasma via the D–D fusion reaction would have an energy distribution centered around 2.45 MeV with an expected width related to the Maxwell–Boltzmann distribution of fuel ions at the measured plasma temperature, and exhibit an isotropic distribution of emissions. Neutrons produced by non-thermal processes—for example in Z-pinch and dense plasma focus devices are known to potentially generate neutrons through ion-beam–target mechanisms as well as through thermal plasma generation

[1] See, for example, pressures generated in various materials from high velocity impact experimental data in [2].

[2] Whilst distinct from FLF's gas-gun approach, for context some relevant historical experiments reported in the literature relating to the production of fusion through chemical explosive-driven or electromagnetic-driven approaches include [3], [4], [5], [6], [7].

(see e.g. [8])—could be misinterpreted as thermal in origin, if not properly diagnosed[3]. Suitable diagnostics enabling accurate measurement of the isotropy (and spatial generation) of neutron emissions, the width of the neutron energy distribution and measurements of the plasma temperature would therefore be needed to provide definitive evidence.

To be able to review the experimental configuration and the evidence derived from the data collected from these experiments, a number of work packages were agreed between UKAEA and FLF to form the scope of the review. UKAEA have extensive experience in the development, calibration and operation of fusion diagnostics and nuclear instrumentation in general gained through several decades of research in the operation of experimental fusion devices, such as JET and MAST. UKAEA's primary role in this phase of work has been to assess whether FLF's experimental campaign produced neutrons that are associated with D–D fusion reactions taking place. It should be noted that UKAEA have not seen, nor assessed any aspect of the target technology itself (due to the proprietary nature of its design), the fuel loading, nor any underlying target hydrodynamic physics associated with the experiment in this review, though are aware that these aspects together with the experimental results themselves have been reviewed recently by their scientific advisory board. It should be noted that no assessment of whether fusion reactions originate from a thermal plasma processes, or via other processes, has been possible in UKAEA's present review[4]. The main activities that were agreed were to:

1. develop a radiation transport model of the gas-gun experimental configuration including the associated neutron detector systems; perform simulations to determine absolute and temporal detector responses to characteristic D–D fusion neutrons;
2. conduct a review of the instrumentation, detection processes and experimental measurements of instrument response to 2.45 MeV neutrons[5];
3. provide on-site verification of the experimental set-up and witness experiment(s);
4. conduct a review of the output data and FLF conclusions.

The work conducted in the first of these activities have been included in a separate UKAEA report [9] that was provided to FLF. Some of the simulation results and analysis from synthetic data have been included in [1] by FLF to support the interpretation of results. The three activities that follow constitute the main review and verification aspects of the work

[3]In the FLF approach the target is driven in a purely hydrodynamic fashion and no external magnetic field is applied; any ion-beam–target fusion mechanisms would need to be generated in the target through a self-generated magnetic field.

[4]Further experiments integrating suitable plasma and nuclear diagnostics would be needed.

[5]Conducted at the National Physical Laboratory's (NPL) low-scatter neutron irradiation facility, based in Teddington.

which are summarised in this report. The subheadings below include brief details and comments relating to the review of the experimental setup, diagnostics and data collection techniques; a discussion of the main results obtained and supporting analysis; main conclusions on FLF's findings and some recommendations for future work. In the appendix to this report we have included supplementary details relating to the two site visits by UKAEA staff to witness experimental shots. FLF's main report '0485: Validate Production of Neutrons from Gas Gun Driven Targets' [1], was issued to UKAEA in March 2022 and forms the main input to UKAEA's review under the fourth of these work areas.

## 1.1 Experimental setup, diagnostics and data collection

UKAEA have reviewed FLF's experimental processes specified within [1]. This was performed using information from FLF's experimental report and data included within it, combined with in-person inspection of the equipment, diagnostics, data collection and analyses processes, which were facilitated and supported by FLF's scientific staff during site visits. Some specific remarks on different aspects of the review are included in the subsections below.

### 1.1.1 Experimental setup

The experimental setup is well described in [1]. UKAEA were able to verify the presence of the equipment and consistency with the described arrangement for deuterium-fuelled shots during visits when witnessing shots 92 and 104.

### 1.1.2 Timing fiducials

The timing fiducials provide an essential role in the experiments in determining $t_0$, the so-called 'fusion event' time. The fusion events themselves are reported by FLF to take place on timescales $< 1$ ns (based on modeling predictions not seen by UKAEA) and thus the associated uncertainty in the evolution of the fusion reaction rate presents a relatively small contribution to the overall uncertainty in time. From knowing $t_0$ a time window is defined to bound the expected arrival time-of-flight (TOF) for a neutron at a given scintillator detector; a 2.45 MeV neutron takes 46.2 ns to traverse 1 m[6]. Additionally the timing window is used to discriminate signals from terrestrial background radiation, mechanical vibrations, optical or other processes. $t_0$ is determined from an ionisation pin signal (generated when the shock wave reaches the pin, the 'shock time') used together with an applied modeling correction in time to establish the fusion event time. The ionisation pin is accurately positioned very close to the target, metrologised to 1 $\mu$m and is shocked nominally within 20 ns of $t_0$. A

[6] Since the scintillator detectors used in the experiments are flat and have a large area, the neutron flight path varies to different sensitive regions of the detector; the TOF distribution is spread out as a result. See, for example, UKAEA's neutronics simulations in Figure 5 of [1] which predicts the spread.

time correction based on the shock wave speed to the ionisation pin location is applied to the shock time to determine $t_0$. The overall temporal uncertainty in the probe shock time is dominated by the exact probe position and has been estimated by FLF based on limiting cases (bounding cases on the exact probe position with consideration of the Kapton insulation layer thickness). From this assumption and modelling it was estimated by FLF to be -8 / +5 ns[7]. Signal transfer times through cables and equipment used with all diagnostics were reported to have been measured and stored in a .csv file that is later used to synchronise all signals for post-shot comparison and analyses (diagnostic cable delay data and oscilloscope channel linkages are detailed in Appendix E of [1]). There are some unusual features in the raw signal data from the scintillators (see Appendix B of [1]); they are variable between events on a single detector and between detectors—each event does not generate a characteristically shaped signal i.e. similar on all detectors. This could be, in part, due to issues with the cabling and electronics for very fast (nanosecond timescale) signals. This may mean that the determination of the delay times has additional uncertainty, but it is probably reasonable to take the first peak in the signal as the event time, which is what FLF have done in their analyses using a peak finding algorithm. The uncertainty along with the expected time-of-flight to each detector for D–D neutrons provide a basic time band (or 'window') to evaluate detected events within.

### 1.1.3 Scintillator and $^3$He detector characterisation, data acquisition and analysis methodology

The nuclear detector systems used in the campaign were:

1. 16 large area EJ-200 scintillator detectors each coupled to a photomultiplier tube. The detectors were arranged in three groups outside of the vessel: 'core' located at a nominal distance of 1 m from the target, 'perimeter' at 1.5 m and 'roof' at 2 m;

2. 1 small area EJ-200 scintillator detector coupled to a photomultiplier tube (used sacrificially for some shots, placed in the blast vessel);

3. 60 $^3$He gas proportional counters in 12 groups of five tubes, each group embedded within a polyethylene moderator and positioned immediately behind the large area scintillator detectors.

The systems are well described in [1], along with the specific usage in individual shots[8]. The scintillator detectors used are sensitive to the detection of high energy neutrons and photons, wheras the $^3$He detectors' sensitivity to gamma rays is very small. UKAEA saw the positions

[7]For an unscattered 2.45 MeV neutron this uncertainty translates to positional uncertainty of -17 cm / + 11 cm.

[8]For example shots 86–88 used fewer $^3$He detector systems compared to later shots, and some shots did not field the small area EJ-200 scintillator detector.

of the detection systems prior to shot 92 (noting that the small area EJ-200 scintillator was not fielded in this particular shot) and the outputs linked to arrays of oscilloscopes. Steps to experimentally characterise one of the scintillator detectors combined with a 5 tube $^3$He detector array have been taken, and estimates of the intrinsic efficiency have been made when exposed to a well characterised source of 2.45 MeV neutrons using NPL's low scatter neutron irradiation facility. The neutrons at the National Physical Laboratory are produced using a proton beam, accelerated using a Van de Graaf generator, and a target utilising the (p,t) reaction. A representative large area scintillator detector with $^3$He tube array positioned directly behind the scintillator i.e. as located in the FLF experiments has been irradiated to a known neutron fluence. Following those tests and analysis, the scintillator detector was experimentally determined to have an intrinsic efficiency of 30.7 $\pm$ 6 % and the $^3$He tube array, 11.9 $\pm$ 0.5 %.

Functional testing of scintillators has been performed on individual detectors using sources e.g. a $^{137}$Cs gamma source with some additional testing of instruments in-situ, based on observing background events. UKAEA would recommend that additional testing of the instruments in-situ is done in the future using of calibrated sources. Some that might be considered include e.g. use of a $^{252}$Cf or a $^{241}$Am–Be neutron source and/or coincident emission gamma sources such as $^{60}$Co or $^{22}$Na. Such sources would be useful to further test the instrument performance, particularly uniformity of response to particles originating from the target location, but also to test coincidence timing performance between detection units and to underpin neutron yield calculations.

#### 1.1.4 Potential sources of spurious signals on neutron detectors and terrestrial background analysis

The FLF experimental team have taken a number of steps to identify and eliminate potentially spurious signals that might originate from the following: optical light, mechanical vibration, EM noise, target ionising radiation or high energy particles from nuclear interactions.

Due to the very short time windows used for both the scintillator diagnostics (400 ns following $t_0$) and the $^3$He tubes (300 $\mu$s following $t_0$), the probability of receiving a single event due to terrestrial background within the time window is very small. Since the total background count rate has been measured to be 40 kHz for the full array of scintillator systems the probability is $1.6 \times 10^{-2}$ per shot. The background rate for the full set of $^3$He tubes was measured to be 16.6 Hz and so the probability of a single background event is $5 \times 10^{-3}$ per shot. In consideration of the coincident background event rates in different detectors, FLF have adopted a 'worst case' conservative approach, making the assumption that the probability background coincident event rate is the same as the singles rate. This assumption, whilst conservative, could be revised through direct measurement in the future to provide an improved estimate.

Optical emission above the ambient level within the experimental chamber were reported to take place during shots. Stray light has the potential to cause spurious signals in the scintillator photomultiplier tube, if the instrument is not completely light tight. FLF reported having tested the integrity of the scintillator optical shielding prior to installation using a bright illumination source whilst monitoring the PMT output with a rate counter. During experiments, the temporal profile of the ambient light level in the laboratory was monitored using an avalanche photodiode positioned close to a viewport on the chamber checks for any correlation between ambient light levels and 'hits' on the neutron detector array; the lack of correlation indicates that the scintillators are light-tight.

Mechanical noise; the detection rig is decoupled from the main vessel. The impact of mechanical noise from the impact would in any case take place on a 'speed of sound' timescale rather than the very short timescales used for the scintillator time windows.

Electromagnetic noise was not reviewed by UKAEA, but this is unlikely to be present or and issue as the gas-gun is driven by gunpowder explosive.

X-rays produced within the target, given the reported simulation temperature of the order of 100's eV, would not escape the chamber.

The four hydrogen null shots (as well as the failed deuterium shots) that were performed serve as tests for the observation of signals due to any of these potential effects. None of the null shots yielded any detection events within the relevant detector time windows.

## 1.2 Discussion of main results

A hierarchy of evidence for the detection and discrimination of fusion neutrons has been used to guide FLF's experimental plan (Section C of [1]). Each point in the hierarchy is discussed below.

### 1.2.1 Coincident detection in scintillators within the expected event window

There is clear evidence of coincident events on scintillators occurring within the expected event window (400 ns); 7 out of 9 deuterium fuelled shots exhibited coincidences of 2 or more. Shot 102 in particular produced a multiplicity event of 9 detection events on separate detectors. There was one shot which produced a coincident event within the $^3$He detector arrays (300 $\mu$s time window).

The solid angle analysis of detection events in figure 14 in [1] and the distribution of events across different detectors shown in figure 15 provide some data indicating the isotropy of emissions from the aggregated events; the events are distributed across most of scintillator detectors. However, the statistics are poor and a reliable assessment of the isotropy cannot be made. A more accurate neutron isotropy measurement might be sufficient to indicate that D–D fusion reactions are non-inconsistent with thermal plasma origins. However, careful consideration of additional diagnostic techniques probing the target and plasma itself will be needed to fully assess whether fusion neutrons are generated entirely and definitively through thermal plasmas or other ion-beam–target type mechanisms.

### 1.2.2 Repeatability of deuterium-fuelled shots

The main parameters that UKAEA were able to review were the projectile velocity itself and FLF's own assessment of whether the projectile failed or not during transit (judged from the Shimadzu HPV-X2 high speed camera image data). There was limited other data to judge this, however an example examination of the Shimadzu HPV-X2 fast framing camera and the associated optical emissions during shot 103 shows an example of a successful shot with a clearly defined boundary of the projectile tip on impact. FLF reported that the angle of impact is also important, though UKAEA have not seen data relating to the angle of impact per shot. There are also no diagnostics included which show that plasma is generated.

Shots 102, 103 and 104 were performed with high velocity projectiles at 6.7 km/s; these three shots appear to be a consistent and repeatable set of data and used by FLF for the neutron yield analysis that was performed. Consistent projectile velocities were not seen across all of the shots, which ranged (in successful shots) from 6.2–6.7 km/s. This variation in projectile velocity has allowed some basic velocity–event correlation analysis to be performed (see figure 16 of [1]), showing for the 1 m distance scintillator group that a greater number of events are detected with higher projectile velocities (and only weak correlation at greater distanced detector groups, since the statistics were poorer). The lower velocity end of the range at 6.2 km/s did not produce detection events. FLF reported that the variability is typical for these types of gun and that the likely main variables causing spread in projectile velocity are room temperature variation, gun barrel wear and variations in smokeless powder burn consistency.

There were also some different detector configuration used in the earliest shots (fewer $^3$He arrays in shots 86–88 for example). Small sacrificial scintillator detectors were only fielded in 3 shots (90, 91, 104).

### 1.2.3 Neutron time-of-flight results

The aggregated data used within the time-of-flight plot, figure 14 in [1], show all D–D experiment scintillator events per shot and nominal detector position plotted as a function of time after the expected 'fusion event' (data in the time window extending until 400 ns after this time). The data set comprises 29 detection events, and in the context of fusion experiments, the number of events detected is small. Whilst the number of events is low, the aggregated data constitutes evidence pointing to neutrons being a likely explanation. In extracting the data, FLF reported that a discrimination threshold was set at 30 mV above the noise and a peak finding algorithm has been applied to obtain the time of event. The nominal distance of the detectors (to the centre of the detector volume) has been used to offset the events into the y (distance) axis, such that an expected time-of-flight line can be drawn from the expected fusion time origin for an unscattered 2.45 MeV neutron. The error band associated with this captures the timing uncertainty of neutrons travelling to the shortest and furthest points on the scintillator detector from the target position.

One aspect of the data which requires more detailed analysis to fully explain is that some of the TOF events at the closest large scintillator detectors occur at shorter times than expected (i.e. from the D–D neutron arrival time) e.g. shot 87 has an event around 30–35 ns, shot 87 has an event around 25 ns, as well as other examples. Some events are later than expected. One basic interpretation could be that the events are appearing to come from significantly faster or slower neutrons. To take the shot 87 event, at around 25 ns for a scintillator detector located at approximately 1 m from the target; this time would correspond to a neutron energy greater than 8 MeV and, if this energy were correct, the number of deuterons in this range in a thermal plasma would be very small indeed. However, these events could also be from: (a) photons generated from neutrons interacting with intermediate material i.e. between the target and detector, or (b) neutrons scattering into the detectors thus taking longer paths with lower energies following scattering. While the UKAEA neutronics modelling predicts a significant number in group (b), the proportion seen in group (a) seems to be higher than expected. Since these effects are not accounted for fully, the timing uncertainty bands may have been underestimated slightly. Further work with detailed neutronics simulations would be recommended to substantiate and explain such events in more detail. UKAEA's supporting neutronics analysis work detailed in [9] has generated temporal response distributions for each detector based on 2.45 MeV neutrons, along with some synthetic TOF data which illustrates expected variations across all of the detectors with low yield experiments and such data could be useful to include to improve the uncertainty estimation. Further analysis of the rates of detection in the three groups of scintillators, and consistency with the expectation of rates from the equivalent neutronics simulations should be performed, but presently since the experimental statistics are poor it is difficult to make a detailed assessment. The analysis of the average velocity and derivation of a neutron energy from the analysis performed by FLF (2.46 $\pm$ 0.3 MeV) is consistent with the characteristic D–D neutron energy of 2.45 MeV. However, the uncertainty appears small from this analysis. Following the earlier discussion on the outlying events we observe that FLF have rejected a fraction of the later events (we understand that the faded points in Figure 18a of [1] were reportedly rejected to minimise the influence of down-scatter) to have arrived at this small uncertainty, but we have not seen the detailed reasons for the rejections. We recognise that the analysis is simplified and does neglect some physical correction factors, which would account for neutron scattering effects that result in the later-than-expected detected events, but also the earlier-than-expected detected events that may be due to neutron production of photons via interactions with materials around the target and vessel.

### 1.2.4 $^3$He detector results

The number of events is low, with only 5 events being detected in total over the campaign, though this is expected given the measurement of detection efficiency together with the assessment of neutron yield performed by FLF. The assessed average yield per shot, based on data from the three most recent high velocity shots (at 6.7 km/s) shots 102, 103 and 104, were reported analysed using Bayesian inference analysis. The 95% confidence assessment of the neutron yield range was 12–124 for the $^3$He-based detector with the most likely value being 47. This is consistent with the range of 24–68 derived from the scintillator detection system with the most likely value being 42. The averaged neutron yield per shot is low, though despite this there is no inconsistency in the evaluation of neutron yield from the two independent detection systems.

Some noise in the $^3$He detection systems were observed at later times. FLF, in their preliminary investigations, suggest that this could be due to some grounding issues with the signal, potentially a transient voltage on the earth of the local power supply. The timescale for the onset of this does not appear to invalidate the reliability of the $^3$He data. However, further investigation is recommended to provide a definitive explanation for this.

### 1.2.5 Comparison of deuterium-fuelled and null shots

Four hydrogen-loaded target nulls shots were performed in total. Two of the earlier hydrogen null shots in the campaign (88 and 89) were reported to have projectile velocities of 6.2 and 6.3 km/s. These velocities are lower than some of the shot velocities exhibited in later D–D fuel shots (6 of these), which were with velocities around 6.7 km/s. Notably the projectile velocity of D–D shot number 95 was 6.2 km/s and this resulted in no detection events being observed; events were only seen with projectile velocities of 6.3 km/s or above. FLF have reported on the correlation of this (see figure 16 of their experimental report, and discussed earlier in this report) and state that this is expected because the impact pressure is a strong function of the impact velocity and the targets work by amplifying the initial impact pressure to reach conditions in the fuel that are required for D–D fusion reactions taking place. In March 2022 FLF conducted two further hydrogen-loaded target null shots, 115 and 116 which were reported to have projectile velocities of 6.6 and 6.5 km/s respectively. These, together with shot 89, were conducted within the velocity range where detection events were seen when using deuterium-loaded targets. None of the null shots yielded detection events within the associated time windows and provide further evidence that the background events are negligible. Whilst the four hydrogen loaded target nulls shots indeed produce no signals, there is no evidence provided that these produced relevant plasmas.

# 2 Conclusions and recommendations

UKAEA have conducted a review of First Light Fusion Ltd's recent (485 series) experimental campaign. The UKAEA technical team involved have had the opportunity to interact with the FLF experimental team as part of the review. The review included assessments of the experimental planning, scientific equipment used and associated diagnostics, processes to extract and analyse the data obtained from the diagnostics and analysis included within the associated experimental report.

The experimental campaign comprised 21 high velocity impact experiments ('shots') overall. 12 of these were reported to have used deuterium-fuelled (base-case) targets, one was a deuterium design variant shot, four were hydrogen null shots and a further four were test shots. UKAEA staff witnessed a sub-set of these which were two deuterium-fuelled target shots; the first took place on the 22nd February 2022 which yielded no detection events (reportedly due to projectile failure); the second (successful) shot on the 4th March 2022 yielded three scintillator events and a single $^3$He detection event within the defined time windows.

In assessing the experimental campaign as a whole, the diagnostic data obtained and analyses performed from the experiments in aggregate, and with detailed consideration of terrestrial background or other potential sources of spurious signals, we support FLF's finding that high energy particles have been detected. In the context of fusion experiments the number of events detected is small. However, the events detected and the associated temporal analysis are sufficient to indicate a link to the impact experiments using deuterium-loaded targets. The aggregated time-of-flight data comprising 29 detection events obtained using the scintillator array (each event corresponds to the detection of a single particle), together with the basic analysis performed to estimate a neutron energy range provides some evidence that neutrons have been produced which would be consistent with the energy of those produced in D–D fusion processes. The supporting $^3$He detection events within an expected time window following the expected fusion time are fewer, though in aggregate do provide some complementary evidence through a separate detection system to the scintillator array that neutrons are present.

A number of recommendations have been made below.

## Recommendations

Recommendations to strengthen the evidence case further as part of future work include:

1. Conducting more experimental high velocity shots to provide additional data to improve statistics;
2. Include diagnostics to establishing the presence of plasma (and conditions) in both hydrogen null and fuelled shots;
3. Future testing of the detection system in-situ using traceably calibrated gamma sources and neutron sources for characterisation purposes, to enable more accurate determination of neutron yield;
4. Performing detailed radiation transport analyses of neutron scattering and photon production impacts on timing to quantify the proportion of time-of-flight events outside of the expected uncertainty bands . This would usefully include particle event tracking analyses for insight. Such analysis would be required to derive analysis correction factors to enable the neutron energy and uncertainty to be determined more accurately in an aggregated data analysis approach;
5. Perform detailed statistical analysis recognising variation in projectile velocity and other parameters impacting the success of shots;
6. Explore whether the fast scintillator signals can be cleaned up further;
7. Incorporate diagnostics to measure plasma conditions to provide sufficient evidence that neutrons are produced from thermal deuteron plasma.

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# A Appendices

## A.1 UKAEA visits to FLF premises

Two technical staff from UKAEA's Applied Radiation Technology group visited the FLF premises at Yarnton to audit the experimental set up on-site, to verify consistency with the agreed experimental plan and to witness gas-gun experiments. Visits took place on the 22nd February 2022 and the 4th March 2022. An experimental 'shot' was witnessed on each occasion.

The visit on the 22nd February included a tour and technical discussions on the following aspects of the experiment prior to the shot:

### 'BFG' 2-stage gas-gun

- First stage polyethylene projectile which is shot through the gun impacting on a metal bursting disk to initiate the second stage projectile. Following firing, the polyethylene slug is significantly extruded and UKAEA staff saw evidence of a number of extruded slugs from previous shots during the campaign.
- The slowest burn non-military grade gunpowder available is used – approximately 3.3 kg was reported to have been used in the shot that was witnessed on the 22nd February ('shot 92').
- The second-stage of the gas-gun used a much smaller 38 mm plastic projectile. The end is very slightly flanged to ensure a tight fit in the gun tube, the tip is flat with an embedded disc made from copper (used for testing), tantalum (for most runs) or occasionally, tungsten. The overall mass does not exceed 100 g, with the plastic projectile mass adjusted to account for varying tip mass for different materials.
- The projectile flight can be impacted by the petal valve thickness, hydrogen gas pressure and gunpowder mass and generally. The hydrogen fill pressure is used for fine adjustments to the flight performance. The final projectile velocity is typically 6.7 km/s with 0.2 km/s uncertainty. The velocity is recorded using a spatial high speed camera.
- Hydrogen is sealed in the gun by a piston at the far end and steel plate at the projectile end.

### Target Chamber and timing diagnostics

- The target design was reported to inherently increase the pressure following impact (amplification); this is reported to be the key IP of FLF. Temperatures of the deuterium fuel ions were reported by FLF as being expected to reach a few hundred eV.
- Three optical fibre electrodes are used to form the two main timing fiducials: impact and fusion time (ionisation pin). For the latter, as the target shock front reaches the

tip of the ionisation pin, the pin shorts and the bias voltage drops.

- Metrology of the positioning of the timing diagnostics (the ion pin in particular) needs to be very accurately performed.
- Cable lengths are all known and are accounted for in the data post-processing.
- Timing fiducials fibre optic cables feed an avalanche photodiode, after which data is fed to scopes by 30 metre cable run.
- Projectile angle can deviate by around 0.5 degrees.
- The piston velocity is measured at the far end of the gun.
- An aluminium block is added around the target itself.
- Behind the target are multiple capture plates spaced out to absorb the energy from the impact post event.

## Nuclear detection systems

- Detection systems based on EJ-200 plastic scintillators (1000 × 500 × 50 mm) coupled to a 51mm diameter 9266 PMT from ET-Enterprises) and assembled by Scionix. Detectors are generally positioned at a tangent normal to the target location. 9 detectors are at 1 m, three at 1.5 m, 4 at 1.95 m (1 intended to be placed inside the chamber and was included in the second shot UKAEA witnessed; A relatively small EJ-200 plastic scintillator 200 × 100 × 40 mm coupled to a 28mm diameter Hamamatsu R9420 PMT.
- 60 $^3$He tubes, in banks of 5 tubes per module (12 modules) each with a PE moderator (loaned from a UK nuclear organisation, manufacturer: Precision Data Technology inc, pulse width 50 micro seconds).
- 1 small sacrificial scintillator can be placed inside the blast vessel for additional timing information.

## Electronics and data processing

- Piston velocity is measured at the far end of the gun.
- Aluminium block is added around the target itself.
- 3 optical fibre electrodes are used to form two timing fiducials: impact and fusion time (ionisation pin). For the latter, as the target shock front reaches the tip of the ionisation pin, the pin shorts and the bias voltage drops.
- Metrology of the positioning of the timing diagnostics (the ion pin in particular) needs to be very accurately performed.

Further details of UKAEA staff witnessing of experimental shots are below.

## Witness of shot 92

UKAEA staff arrived at the premises approximately 9:30 and had a detailed tour (covering the aspects detailed in the earlier subsections of this appendix). The FLF team led UKAEA staff around relevant aspects of the experiment including the two-stage gas gun, the target chamber arrangement, the detector configuration, the oscilloscopes, data collection and processing aspects.

Experimental shot 92 took place at approximately 14:23. A python script was run in the control room which applied a set of pre-measured delay factors for the various diagnostic cables and delays in oscilloscope etc for the purposes of synchronising the multiple scope traces. Following the shot and subsequent data processing which took a few minutes to complete, no scope traces were evident in any of the scintillator signals, nor from any of the $^3$He detector signals. FLF staff showed the UKAEA team the 'shim' high speed camera images had indicated at the time that there was some debris in advance of the projectile and the shot was suspected to have failed. This was compared to footage captured from a previous 'successful' shot to illustrate their point. The following day the team reported a defect on the inside of the gun launch tube, explaining the projectile break-up. This led to the team having to change the barrel over, conducting test shots before returning to fusion shots.

## Witness of shot 104

UKAEA staff arrived at the premises at approximately 12:30. A brief tour of the gas-gun area, target chamber area. A photograph of the target in position and timing fiducials was shown to UKAEA. Prior to the shot, pre-shot scope function tests and set up were demonstrated, as before in shot 92.

The experimental shot took place at approximately 13:16.

After the post processing analysis in the control room UKAEA team saw three 'hits' on the scintillator systems and one on the $^3$He tube arrays. One of the scintillator events was from the sacrificial small detector inside the blast chamber, demonstrating the event at short time. The shot was described as successful by FLF based on the high speed shim camera images. Post-shot the UKAEA team re-visited the oscilloscopes and saw the raw data - a basic spot check confirmed the same data set as was seen in the control room following the application of python post-processing routines.