

Exceeding 10^{12} D–D Flash Neutrons in the 4.5-MA 1-MJ Dense Plasma Focus FAETON-X

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Abstract

In this paper, experimental results of the world’s most energy-efficient and highest-current Mega-Joule-class dense plasma focus (DPF) facility, FAETON-X (FX), are presented. FX was designed as the direct MJ-class scale-up of FAETON-I (F-I), which demonstrated the correlation between dynamics-induced pinch voltage and neutron yield. Building on those results, Fuse Energy Technologies designed, constructed, and commissioned FX as a single-pulse flash neutron source purpose-built as a pulsed power fusion R&D and radiation effects testing

platform with both D-D and D-T fusion fuels. Its 500 μF capacitor bank comprises 20 capacitors, each rated at 25 μF and 100 kV, storing 1 MJ at a 65 kV charge voltage, with a peak discharge current exceeding 4.5 MA and a static inductance of 55 nH. FX achieves a figure of merit of 4.5 MA/MJ, the highest reported for any MJ-class DPF and significantly above all contemporaneous MJ-class peers, which range from 2.35 to 3.25 MA/MJ. Since neutron yield scales as $Y_n \propto I^4$, this step-change in energy efficiency directly translates to superior neutron output per joule of stored energy in optimized conditions. FX, not yet fully conditioned, produces consistent $\sim 5 \times 10^{11}$ D-D neutrons/shot, with a peak recorded yield of $(1.27 \pm 0.27) \times 10^{12}$ neutrons/shot at 10 Torr deuterium. Continued conditioning is expected to further increase neutron production.

Keywords: Z-pinch, Dense Plasma Focus, Neutron yield, Pulsed power fusion, Dynamics-induced pinch voltage, Plasma dynamics

1 Introduction

The dense plasma focus (DPF) is a pulsed power device first independently conceived in the early 1960s by J.W. Mather in the United States and N.V. Filippov in the Soviet Union [1–4]. The device operates by electromagnetically accelerating and compressing an ionized deuterium or a mixture of deuterium–tritium column via the Lorentz force into an intense, transient z -pinch, producing simultaneous bursts of multi-MeV X-rays, energetic ion and electron beams, and fusion neutrons on nanosecond timescales [5–8]. This unique combination of extreme instantaneous flux, compact form factor, and single-shot simplicity has made the DPF one of the most compelling pulsed neutron sources in existence, with direct relevance to a wide range of fusion research, materials science, and national security and defense applications, including fusion diagnostics, neutron source development, radiation effects studies, materials qualification, nuclear survivability testing, radiation effects qualification of electronics, and nuclear hardness assessments of strategic subsystems [1, 2, 4, 5].

The neutron yield of a DPF scales empirically as $Y_n = 3.2 \times 10^{11} I_{\text{pinch}}^{4.5}$ with peak pinch current I_{pinch} and $Y_n = 1.8 \times 10^{10} I_{\text{peak}}^{3.8}$ with peak circuit current I_{peak} over a broad range of device sizes and stored energies [8–11]. For scaling purposes, we generally use $Y_n \propto I^4$. This strong dependence makes peak current the primary lever for maximizing neutron yield, and motivates a key figure of merit for energy efficiency: the peak discharge current per unit of stored capacitor bank energy, expressed in MA/MJ. Maximizing MA/MJ requires simultaneously minimizing circuit static inductance, optimizing electrode and transmission line geometry, and ensuring efficient energy transfer from the bank into the pinch dynamics. Notable past MA-class DPFs include SPEED 2 [12], Poseidon [13], the Frascati DPF [14], and the Los Alamos DPF 6.5. MA-class DPFs operational today include PF-1000 [15], Gemini [16, 17] and Sodium (ZEUS) [18] at the Nevada National Security Site (NNSS) and a DPF operated by the private company Verus Research [19]. In the published literature, these facilities report D-D neutron yields ranging from 1.2×10^{11} to 4.8×10^{11} neutrons per pulse, with MA/MJ figures ranging from approximately 2.35 to 3.25.

More recently, the MegaJOuLe Neutron Imaging Radiography (MJOLNIR) DPF at Lawrence Livermore National Laboratory (LLNL) was commissioned specifically for flash neutron radiography and high-yield operations, achieving 3.8×10^{11} neutrons/shot at 2.5 MA peak current with 1 MJ of stored energy in its original pulsed power configuration [20]. A new upgraded design reported in October 2024 produced a record neutron yield of 1.2×10^{12} with 3.8 MA peak current and 1.3 MJ of stored energy [21], representing the highest published D-D yield for a DPF operating in deuterium gas which demonstrates a 30-fold increase from its first shots in 2018 with a stated goal of reaching 10^{13} neutrons/shot to meet radiography requirements. The original MJOLNIR team goal was to commission the device to its full stored energy and current of 2 MJ/4.5 MA, which unfortunately was never realized due to limitations in their triggering system [21].

Fuse Energy Technologies recently designed and constructed FAETON-X (FX), a single-pulse flash neutron source built as a pulsed power fusion R&D and radiation effects testing platform with both D-D and D-T fusion fuels. FX employs a 500 μF , 1 MJ capacitor bank composed of 20 capacitors, each rated at 25 μF and 100 kV, and achieves a peak discharge current exceeding 4.5 MA at a 65 kV charge voltage, with a static inductance of only 55 nH yielding a figure of merit of 4.5 MA/MJ, the highest reported for any MJ-class DPF. This current level surpasses all previously published MA-class DPF facilities, while the energy-to-current ratio represents a step-change in energy efficiency for the MJ class. FX produces $\sim 5 \times 10^{11}$ D-D neutrons/shot, with a peak recorded yield of $(1.27 \pm 0.27) \times 10^{12}$ neutrons/shot at 10 Torr deuterium, placing it among the highest-yielding D-D DPF facilities.

The predecessor to FX, FAETON-I (F-I) was developed by Fuse Energy Technologies as the world's highest direct-charged-voltage DPF, operating at 100 kV and achieving 1 MA peak current from 125 kJ of stored energy [4]. The F-I experimental campaign established a clear correlation between the dynamics-induced pinch voltage and neutron yield, confirming that the high-voltage design philosophy [4, 5, 10, 22] delivers both energetic efficiency and high neutron production. Building on this, the FX platform is efficient for D-D operation, extending to D-T and D- ^7Li operation as well. The D- ^7Li reaction is especially valuable because it produces fast neutrons extending up to ~ 14 MeV, depending on the deuteron beam energy. The resulting fast-neutron output is well suited to fusion research and radiation-effects, enabling laboratory-scale evaluation of electronics, materials, and components against displacement damage, single-event effects, and dose-rate phenomena that would otherwise require reactor irradiation or underground nuclear testing. This positions the FX platform as a compact, controllable fast-neutron source for survivability qualification and radiation-hardness assurance [23–28].

With its much-reduced inductance compared to F-I, FX has peak dynamics-induced voltages approaching 114 kV, with expected D-D yields of greater than 2×10^{12} neutrons at 12 Torr operation when fully conditioned. Whilst FX has one of the highest D-D yields among PF facilities, its signature strength may be its D-T yield. With fast beam ion energies around 115 keV, FX is designed to operate near the peak of the D–T fusion cross section, enabling the potential production of $\sim 5 \times 10^{13}$ D–T neutrons per shot. To increase its scope as a pulsed power fusion R&D platform, FX

could be operated with lower pressures to produce substantial deuteron beams of sufficient energies to be of interest for D-⁷Li fusion reaction. These design features are discussed further in this paper.

This paper presents the experimental design, pulsed power architecture, and first experimental results of FX. Section II describes the capacitor bank, electrode geometry, and overall experimental setup. Section III reports the correlation between experimental data and simulation results from the Lee code. Section IV presents the measured results of its current and voltage waveforms, plasma and radiation diagnostics including neutron yield measurements. Section V provides conclusions and outlook for future operations including D-T upgrade.

2 Experimental set-up

This section describes the design and key operational parameters of FX and the diagnostic suite employed to characterize its plasma dynamics and radiation output. The diagnostics were selected to provide complementary and cross-validated measurements of the discharge current, electrode voltage, pinch dynamics, X-ray emission, and neutron yield across a range of operating conditions.

2.1 FAETON-X design

FX is a 65 kV, 1 MJ dense plasma focus with two coaxial, concentric electrodes made of oxygen-free copper. The electrodes are isolated at the launching end by a 9 cm long, 15 mm thick quartz insulator, and separated by an A-K (anode-cathode) gap of 5 cm. The hollow anode is 41.2 cm long with a 15 cm radius and has a taper that starts at 38.7 cm with a final radius of 10 cm. The cathode is made of 36 copper bars, 20 mm in diameter and 61.5 cm long, that encircle the anode with a radius of 21 cm.

The aluminum vacuum chamber is filled with deuterium at pressures ranging from 1 to 20 Torr. The capacitor bank comprises twenty 25 μ F, 100 kV capacitors storing 1 MJ at a 65 kV charge voltage. Each capacitor is discharged through a 120 kV, 750 kA self-mounted rail gap switch filled with SF₆ at 1 atm, designed and fabricated in-house. The switches are individually triggered by two ten-channel BFMGs, which deliver -90 kV pulses with a 10-90% rise time of approximately 18 ns to the knife-edge of each switch [4, 28]. Inter-switch triggering jitter is less than 2 ns, ensuring synchronized multi-module discharge. Energy from the capacitor bank is delivered to FX through 180 parallel RG-220/U coaxial transmission lines. The system static inductance is approximately 55 nH, and a full discharge generates a peak current exceeding 4.5 MA with a rise time of approximately 8 μ s. The principal design and operational parameters of FX were modeled using the Lee Model Code [9]. Table 1 summarizes the design and operational characteristics of the FX DPF system. Thus, FX will serve as a broad platform for D-D, D-T and D-⁷Li operation for testing and development of various aspects of diagnostics, trigger synchronization, radiation effects and shielding testing, tritium handling, target design, and optimization. Figure 1 shows renderings of the current FX system (Fig. 1(a)) and the tritium chamber (Fig. 1(b)), which incorporates double confinement and a reduced internal volume for safe D-T operation.

Table 1 Design and operational characteristics of FAETON-X

Parameters	Values
Anode radius	15 cm
Cathode radius	21 cm
Cathode length	61.5 cm
Effective anode length	41.2 cm
Insulator sleeve length	9 cm
Insulator sleeve thickness	1.5 cm
System capacitance	500 μ F
Capacitor bank energy	1 MJ
Operating voltage	65 kV
Static inductance	$\sim$ 55 nH
Operating gas	D ₂ , D ₂ +Kr, D ₂ +T ₂
Operating gas pressure	1-20 Torr
Peak current	5 MA

2.2 Diagnostics

Three Rogowski-coil systems measure discharge current: a total-current coil encircling the anode; four segmented coils at 90° azimuthal spacing, whose summed output agrees with the total-current trace to within 1%, confirming symmetric current delivery; and 20 individual coils (one per capacitor bank cable) used primarily to verify a few ns inter-bank triggering jitter. Anode–cathode voltage is recorded with a high-voltage resistive-divider probe (North Star High Voltage model number PVM-7; 1000:1, 140 MHz, 2.5 ns risetime) and cross-checked with a CVR (585 Ω custom resistor, 5% tolerance, 80 kV DC withstand; Pearson Electronics Inc. model number 6585, 1 V/A, 1.5 ns risetime).

Diamond-based photo-conducting detectors (PCDs) record plasma radiation during the implosion and pinch phases with nanosecond resolution (CV Technologies model number DRD3010xx-SMA-HBFF). They capture the soft and hard X-ray pulse during the $m = 0$ disruption window, provide the prompt X-ray reference for nToF measurements, and offer an independent indicator of pinch onset complementing the voltage-probe pinch voltage spike. Visible-light emission is measured with two photodiode systems (ThorLabs models FDS010 and FDS100). A 6-photodiode array was mounted (see sectional sketch of FX in Fig. 1) to measure the speed of the current sheath. Another array was mounted to detect backwall flashovers. The detector outputs were normalized.

Activation on indium foils (5 cm $\times$ 5 cm $\times$ 0.05 cm) with the $^{115}\text{In}(n,n')^{115m}\text{In}$ reaction, which has a threshold of 0.336 MeV, were used to determine the fluence of the fast (2.45 MeV) neutron component from the reaction. The $^{115}\text{In}(n,\gamma)^{116m}\text{In}$ reaction was used to determine the thermal component of the reaction. ^{115m}In releases a gamma at 336.24 keV and ^{116m}In releases gammas at 138.33 keV, 416.86 keV, 818.7 keV, 1097.3 keV, 1293.54 keV, and 1507.4 keV. Simulations in Geant4 with the full chamber were performed to determine the energy spectrum at the foil location to obtain flux-weighted cross sections of 276 mb for $^{115}\text{In}(n,n')^{115m}\text{In}$ and 53 b for $^{115}\text{In}(n,\gamma)^{116m}\text{In}$. These peaks were counted with an ORTEC IDM-200-V high purity

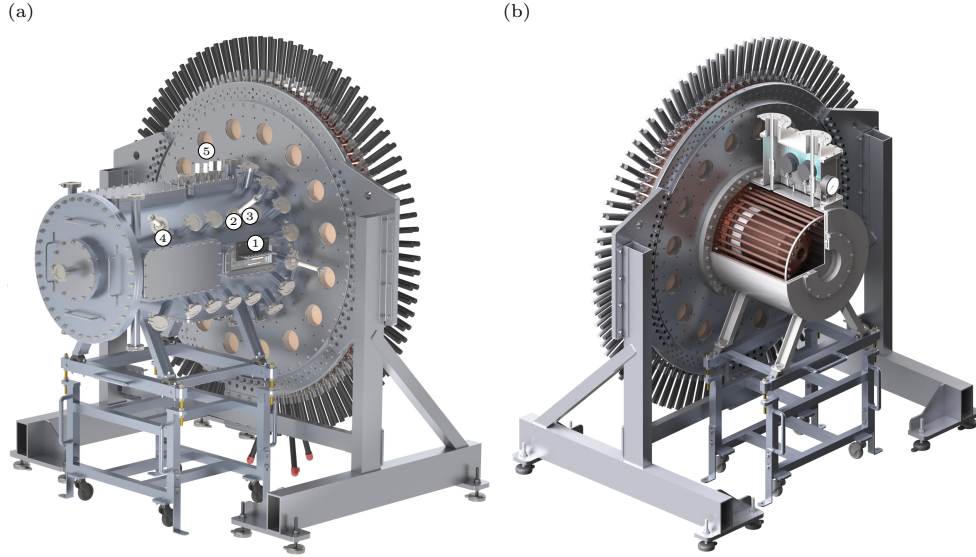


Fig. 1 (a) Rendered view of FX showing the relative diagnostic layout: 1) photodiode array, 2) photodiode 1, 3) PCD 1, 4) PCD 2, and 5) B-Dot probes; and (b) cross-sectional view of the D-T chamber design for FX.

germanium (HPGe) detector system after each shot. During operation, the foils were placed behind the anode base to determine neutron fluence 30.9 cm from the pinch through 3.45 cm of copper [29, 30].

The photon energy spectrum from emitted X-rays and gammas were determined with a sampling calorimeter consisting of alternating absorber and image plate layers. The calorimeter consists of 24 Carestream Industrex Imaging Plates (20 cm $\times$ 20 cm) interleaved with PMMA, aluminum, brass, and steel absorbers (30 cm $\times$ 30 cm) of varying thicknesses (2–16 mm), as seen in Fig. 2. The plates store the incident X-ray and gamma signal and are read out using a 650 nm phosphor laser with a Typhoon FLA 7000 scanner. A gray value is outputted for each layer, and the energy spectrum was reconstructed using a Bayesian unfolding algorithm based on the detector response matrix computed with Geant4. Contributions from neutron-induced high energy photon signals were simulated with Geant4 and subtracted from the measured response. The calorimeter was placed 50 cm from the chamber of FX. Soft X-rays below approximately 45 keV are largely attenuated by the chamber and do not reach the calorimeter [31].

Neutron time-of-flight (nToF) measurements were performed using two lead-shielded PMT-scintillators (Model M540-20x20-6 with EJ-204 scintillator) and a microchannel plate PMT (Hamamatsu R3809U-52) aligned with lasers and positioned at 5 and 8 m from the pinch. The nToF system measured the temporal delay between prompt X-rays and neutron signals at varying distances, enabling the determination of neutron energies based on their velocities [4, 32]. Neutron dose measurements were performed using BTI bubble detectors with sensitivities ranging from 0.16 b/ μ Sv to 2.0 b/ μ Sv [33]. These detectors were positioned at two locations: one positioned 3.64 m

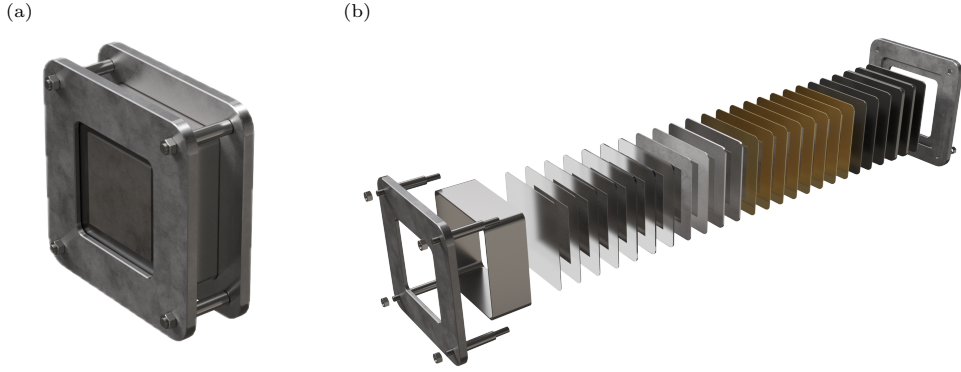


Fig. 2 (a) Assembled calorimeter and (b) Exploded view of calorimeter design

axial to the pinch in the z -direction and the other positioned 7.95 m from the pinch, enabling spatially resolved neutron dose quantification.

All plasma and nuclear diagnostics combined with the current measurement and $V(t)$ yields the plasma inductance $L(t)$ and the dynamics-induced pinch voltage.

3 Simulation

The plasma focus is an electromechanical device with gross dynamics and energetics described by a suitable choice of equations of motion applied to a current-plasma sheath coupled to circuit equations. However, experimental observations of sheath inclinations, filamentation, mass and magnetic field leakages, sheath rotation leading to complex magnetic structures demand more detailed theoretical treatment leading to MHD and kinetic modeling [8–10, 34–38]. These have resulted in providing detailed pictures of some of the structures although in the process, the correlation with simple yet essential experimental measurements such as current waveforms appear to be lost. It was found to be useful to maintain the description of the plasma focus in terms of coupled equations of motion and circuit and to put into these equations a pair of parameters, one representing mass fraction operating on the mass and the other representing current fraction incorporated into the current. The choice of these representative, so-called model parameters is based on the assumption that every mechanism such as sheath inclination or filamentation affects either the mass fraction or the current fraction or both. Then the sum of all the effects of all known mechanisms such as those listed above and even others not yet observed are incorporated into the model by the mass fraction f_m and the current fraction f_c . How then do we know what values of the mass fraction and the current fraction are to be used in the model? The Lee code generates for each shot of each machine a current waveform. This generated waveform is compared with the measured current waveform. The two parameters f_m and f_c are then varied until the waveforms are identical, which then fixes the values of this pair of model parameters. The Lee code computes the plasma focus through its axial phase and various radial phases. Each phase and sub-phase are then fixed by its fitted pair of model fractions. Once the model parameters for the machine are

fixed, the dynamics and energetics of the machine as well as its radiation yields such as soft X-rays, hard X-rays, fast ion beams, neutron yields are also computed [39–42]. The Lee code has been tested by several groups in a whole range of machines from sub-kJ to MJ. The computed results in dynamics and radiation yields are found to be consistent with the measured values. The Lee code is a current-based code, with the core tenet that the current waveform contains the information on all the significant time-varying electrodynamical, thermodynamical, and radiative processes that occur in the plasma focus. Therefore, once the code-generated current waveform is fitted to the measured current waveform, the fitted pairs of f_m and f_c represent the sum of all the unaccounted mechanisms acting on the system.

The Lee code has been extensively developed, used and tested in a whole range of machines from sub-kJ to multi-MJ, in gases ranging from hydrogen to xenon. The computed dynamics and radiation yields (neutron, SXR, fast ions and fast plasma streams) have been favorably compared with available published measurements. Thus, the Lee code is a proven and verified current-based code which is most useful for designing plasma focus machines, in guiding and optimizing experiments and in describing the dynamics and energetics of experiments.

The Lee code was tailored for the F-I experiments with the radial phase found to require the incorporation of a current restrike phase. The Lee code was used to design FX incorporating the experience gained from F-I, with an expected neutron yield of at least 2×10^{12} D-D neutrons from 4.5 MA of current. The measured diagnostics of current, tube voltage, photodiodes, magnetic probes, and PMT-scintillators are planned to be superimposed onto the code trajectories for time correlation studies besides comparison of measured radiation values. The results of these measurements on FX are included in the following section.

4 Results and discussion

The design of FX was guided by a single governing principle: maximizing peak discharge current per unit of stored energy, expressed as the MA/MJ figure of merit. This metric is physically motivated by the $Y_n \propto I^4$ neutron yield scaling law, whereby small gains in peak current yield disproportionately large improvements in neutron output. The architecture of FX was scaled directly from FAETON-I, which demonstrated that high direct-charged voltage (100 kV), fast synchronized multi-module triggering, and low inductance are the three key requirements for record-breaking current efficiency [4]. Translating these principles to the 1 MJ class while targeting a figure of merit of 4.5 MA/MJ, the highest achieved by any MJ-class DPF, drove every major design decision in FX such as the 100 kV capacitor rating, the 55 nH static inductance target, the in-house rail gap switch development, the 180-line coaxial transmission architecture, and the sub-2 ns inter-switch jitter requirement. The diagnostics for FX are used to provide specific important information. However, we put together results from various diagnostics correlated with results from the code in one picture and thereby obtain a better understanding of the interaction of the electromagnetics with the dynamics which guide us in the design of future machines for example for D-T operation.

Figure 3 presents neutron yield as a function of shot number across the full commissioning campaign of FX with 229 total shots. Operations began at 81 kJ stored energy and were incrementally scaled to the full 1 MJ design point as machine conditioning progressed and confidence in system performance was established. Throughout this commissioning phase, several electrode configurations were evaluated, including both hollow and solid anode tip geometries, anode-cathode (AK) gaps of 5 cm and 10 cm, and quartz insulator lengths ranging from 6 cm to 9 cm, with the objective of optimizing pinch formation and neutron output. The electrode geometry and insulator dimensions described in Section II represent the configuration to which the machine ultimately converged in the latter stages of commissioning. A clear upward trend in peak neutron yield is evident across the 1 MJ shot series, consistent with the well-established phenomenon of machine conditioning in dense plasma focus devices, wherein repeated high-current discharges progressively clean and condition electrode surfaces, improving current sheath formation and pinch dynamics. As commissioning continues, neutron yield is expected to further improve toward the machine’s design performance.

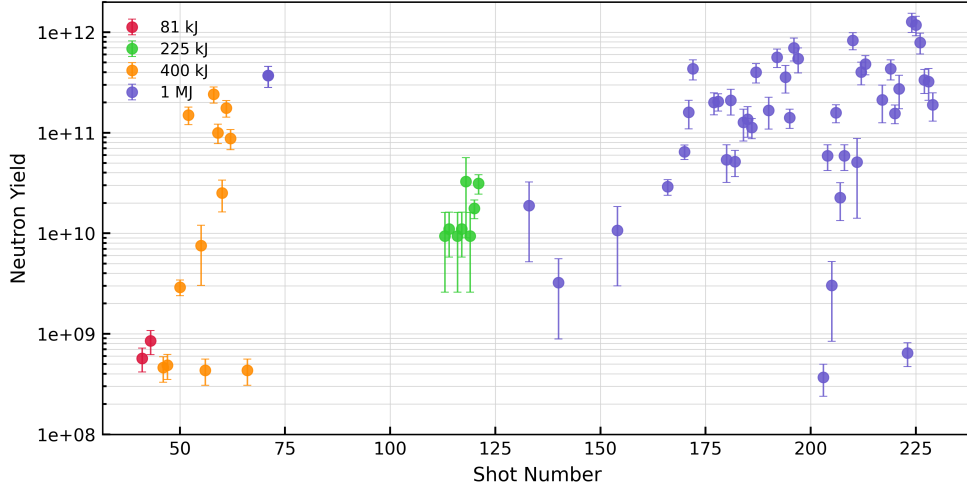


Fig. 3 Neutron yield vs. shot number during the FX commissioning campaign (12/15/25–08/04/26), color-coded by stored energy. Only valid pinch shots are shown; excluded shots include pre-fires, asynchronous or partial discharges, and initial conditioning after electrode or insulator replacement. Error bars represent ± 1 standard deviation from neutron diagnostic calibration uncertainty.

Next, we present a set of results from the array of photodiodes (PDs) in Fig. 4(a). From this figure, the development of a moving structure which we identify as a current sheath is clearly shown. In Fig. 4(b), PDs are used to indicate the end of the axial phase; and filtered PCDs are used to measure XUV and X-rays.

For each shot, the trajectory of the axial phase is measured and typically shows reasonable agreement with the trajectory computed from the code. An example from

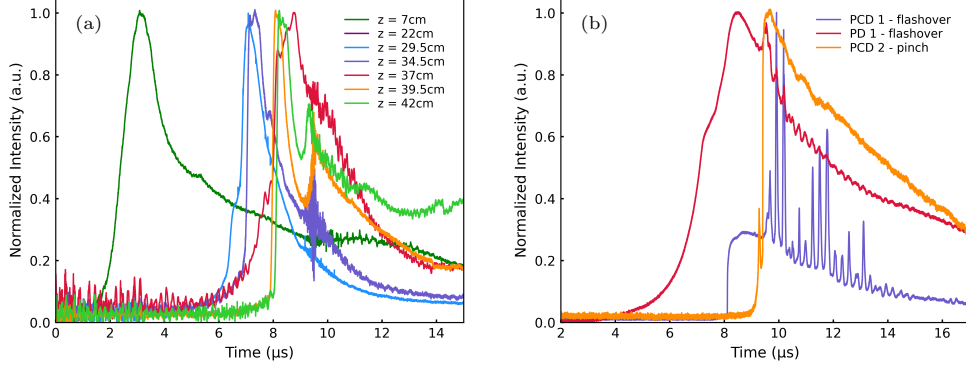


Fig. 4 (a) Normalized signals from the photoarray from 6 photodiodes at various distances along the z -axis, and (b) PD and PCD signals; the red trace shows current sheath arrival at the end of the axial phase and the purple and orange PCD traces show XUV and X-ray emission peaking at $9 \mu\text{s}$.

shot #114 is shown in Fig. 5, with good agreement between the measured trajectory and that computed from the code. The first measured point at 6 cm deviates from the computed trajectory indicating that the current sheath structure has not properly formed so early in the axial run-down.

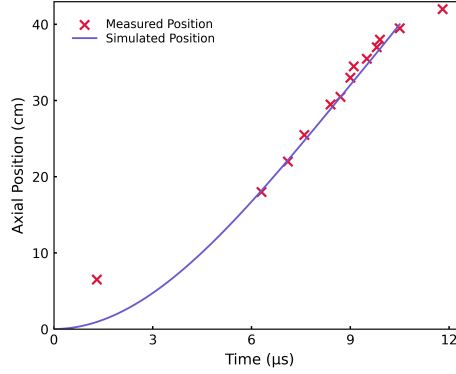


Fig. 5 Comparison of measured and simulated trajectories

A calorimeter was developed to characterize the photon spectrum of the FX discharge. The photon energy spectrum was reconstructed via Bayesian unfolding at iteration 1000 using a uniform initial guess. Two datasets are compared in Fig. 6(a): the blue waveform corresponds to calorimeter results averaged over 4 pinches with a mean yield of 4.4×10^{11} neutrons per shot, and the red waveform corresponds to 3 pinches averaging 3×10^{11} neutrons per shot, recorded shortly after replacing the quartz insulator. The result shows photons predominantly of 250 to 750 keV for the FX discharge. Additionally, the neutron energy was computed from nToF using a PMT-scintillator at 5 m distance from the pinch column, shielded with 1 in of lead. A set of results is presented in Fig. 6(b).

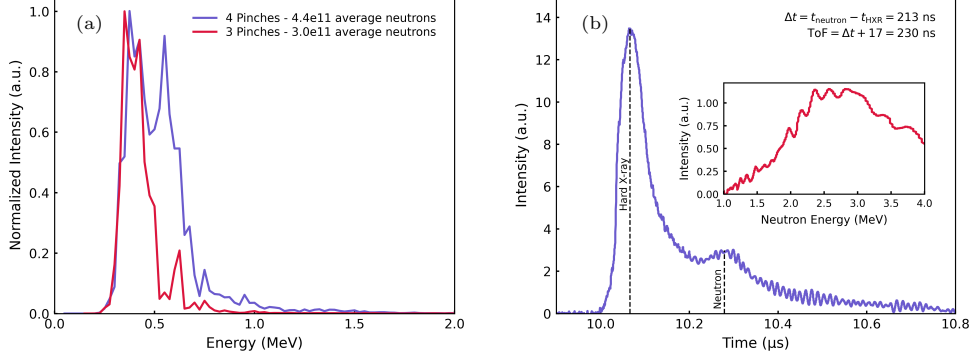


Fig. 6 (a) Bayesian-unfolded calorimeter photon spectra before (blue) and after (red) quartz replacement, averaged over 4 (4.4×10^{11}) and 3 (3×10^{11}) pinches, respectively; and (b) lead-shielded PMT-scintillator signal with a time-of-flight of 230 ns and flight length of 5 m, which corresponds to a neutron energy of 2.48 ± 0.45 MeV.

Next, we put together (for shot #224 yielding $(1.27 \pm 0.27) \times 10^{12}$ neutrons) the fitted and measured current profiles together with the resultant computed and measured induced voltage profiles and also the corresponding radial dynamics (see Fig. 7).

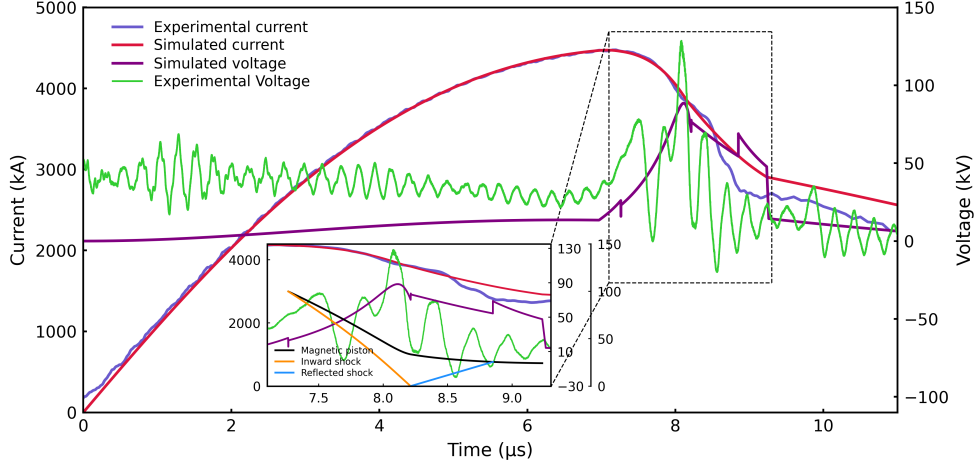


Fig. 7 Experimental data fitted with Lee Code simulation data for shot #224. The radial phase expanded to reveal the correlation of the current and voltage waveforms with the trajectories of the plasma structure.

The code produced a current trace fitted to the measured current trace (left axis values). Also added to the figure are the measured and code produced voltage (right axis in kV) pulses, and the code produced trajectories (right axis, in mm) of the radially inward moving shock front, followed by the reflected shock and also the piston driving the plasma layer. We note that the axial phase is fitted well. The reasonable

fit continues in the radial phase following the rollover of the current, to about half way down the dip at time $8.45 \mu\text{s}$. The fitted value of the radial current fraction f_{cr} was 0.35. Then the measured current dip steepened. It was found that the use of the two-part fit does not work for this shot because the time of $8.45 \mu\text{s}$ was after the radial shock had already reached the axis, beyond the limit of that method of fitting. In any case we increase the value of f_{cr} to f_{cr2} of 0.7. When properly formulated, this increase should steepen the computed slope somewhat to match the steepness of the measured current trace. It appears that the current sheath is more diffuse or spread out in space in both the axial and first part of the radial phase which reflects in f_c and f_{cr} being significantly less than the typical 0.7. Then, during the second part of the radial phase, the dynamics was such that the rearward part of the current sheath caught up with the frontal part, in effect increasing the participation of more current in the radial compression. To reflect the ebb and flow of compression forces in this situation likely requires the code to adopt a continuously varying combination of current and mass fractions over all the radial sub-phases. This has not yet been implemented. In the subfigure in Fig. 7 we look at the correlation of the voltage and current pulses with the dynamics of the plasma slug.

The radial phase for the slug starts at the end of the anode taper at a radius of 100 mm. The shock front moves with increasing speed inward. When the radial shock front coalesces on axis, the reflected shock (light blue trace) starts moving radially outwards indicating the start of stagnation. The driving magnetic piston is at a distance of 33 mm at this time and reaches 25.4 mm when the reflected shock front hits the piston forming the stagnated column at the start of the pinch. The measured tube voltage rises during the radial shock wave phase, reaching a peak with a value of 127 kV. The computed voltage pulse has a similar but broader shape and a peak of 88 kV. We assume that these pre-stagnation dynamically induced voltages drive ion beams responsible for the D-D beam-target fusion. Then the measured value of 127 keV is associated with the measured neutron yield of $(1.27 \pm 0.27) \times 10^{12}$ compared to that of the code computed as 1.4×10^{12} .

The code also details the energetics of the system. At the start of the radial phase the inductive energy in the system was 62.7% of the initial stored capacitor energy and at the end of the pinch phase this had dropped to 35.9%, the difference of 26.8% amounting to some 270 kJ is an indication of the energy that was expended on the plasma by the magnetic field in the overall dynamic processes. An image of the FAETON-X facility is shown in Fig. 8.

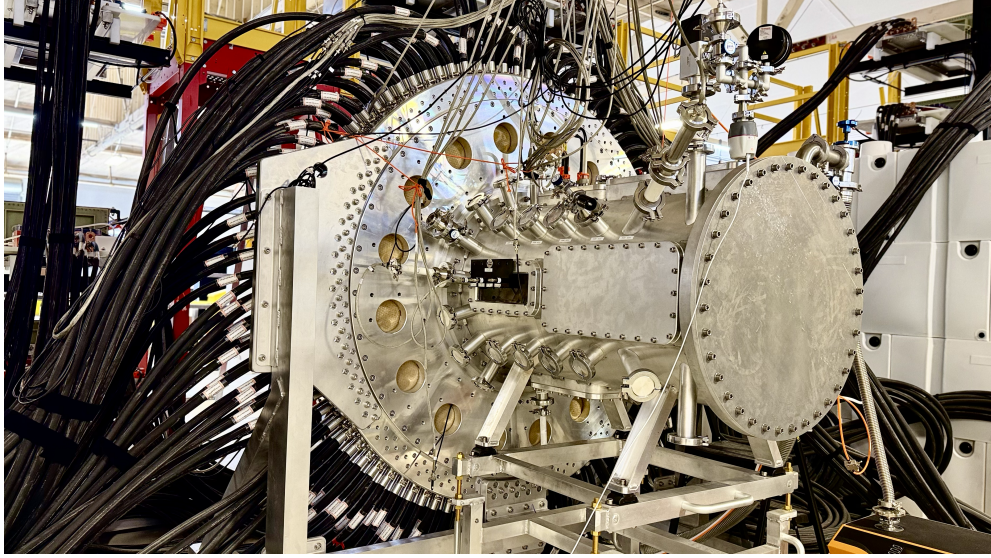


Fig. 8 The FAETON-X (FX) dense plasma focus facility at Fuse

5 Conclusion

Experimental results of the world's most energy-efficient and highest-current Mega-Joule-class dense plasma focus (DPF) facility, FAETON-X (FX), were presented. FX was designed as the direct MJ-class scale-up of FAETON-I (F-I), which demonstrated the correlation between dynamics-induced pinch voltage and neutron yield [4]. Our results confirm that for FX, a high direct-charged voltage of 65 kV, fast synchronized multi-module triggering and reduced inductance are the three enabling conditions for exceptional current efficiency of 4.5 MA/MJ. Our diagnostics reveal that FX has well-defined plasma structures and dynamics validating the correlation of measured and simulated results. The dynamically-induced voltage pulse occurs just before the start of the stagnation process. The voltage pulse is a good indicator of plasma focus performance and state of conditioning. Although not yet fully conditioned, FX surpassed its design goal of $\sim 5 \times 10^{11}$ neutrons per shot, achieving a best measured yield of $(1.27 \pm 0.27) \times 10^{12}$ neutrons per shot. Continued conditioning is expected to further increase neutron production.

The parameters of FX are optimized for D-T operation, with a design value of $\sim 5 \times 10^{13}$ D-T neutrons per pulse. Thus, FX will serve as a broad platform for D-D, D-T and D- ^7Li operation for testing and development of various aspects of diagnostics, trigger synchronization, radiation effects and shielding testing, tritium handling, target design, and optimization.

All results reported here correspond to the hollow anode configuration of FX enduring conditioning phase. Alternative electrode configurations are already available for

the platform, and future campaigns will systematically vary electrode geometry and length to raise the figure of merit toward 5 MA/MJ.

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Declarations

Data Availability. Data sets generated during the current study are available from the corresponding authors on reasonable request.

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