Initial Hard X-ray Spectroscopy Results from the Thailand Plasma Focus 2 (TPF-2) Using a $LaBr_3(Ce)$ Detector

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ABSTRACT

The Thailand Plasma Focus 2 (TPF-2), a 3.3 kJ dense plasma focus device, is a source of X-rays, posing a potential radiation hazard if not properly shielded. This research focuses on the design, calculation, and fabrication of TPF-2, aiming for high efficiency in X-ray emission and a high pinch percentage [1, 2]. Its components were meticulously designed for low electrical energy loss and symmetry of current transfer, with the expectation of achieving a symmetric plasma sheath under optimum conditions, leading to high X-ray emission efficiency [1, 2]. These X-ray emissions are typically characterized by short bursts on the order of ~10 nanoseconds. While previous studies at TPF-2 have characterized various plasma properties, a comprehensive understanding of its hard X-ray (HXR) emission spectrum, crucial for both plasma diagnostics and radiological safety, has been largely underexplored.

This study presents the first direct spectroscopic measurements of the hard X-ray spectrum emitted from the TPF-2 device, utilizing a highly efficient Lanthanum Bromide (Ce-doped) scintillator detector ($LaBr_3(Ce)$), which was previously employed for hard X-ray measurements on the Thailand Tokamak-1 [1]. The experimental setup involved the strategic placement of the $LaBr_3(Ce)$ detector, coupled with advanced pulse height analysis techniques, to capture the transient HXR bursts during TPF-2 discharges. Initial results reveal a broad, non-thermal hard X-ray spectrum, indicative of energetic electron acceleration mechanisms within the plasma focus pinch. The data allow for the inference of the effective electron temperature and maximum HXR energy, providing critical insights into the underlying beam-target interactions. These preliminary spectroscopic findings are invaluable for refining TPF-2 operational parameters to optimize HXR yield, benchmarking theoretical models of electron acceleration, and establishing a robust radiological baseline for future D-T experimental campaigns.

I. INTRODUCTION

I.A. The Significance of Plasma Focus Devices in Fusion Research

Plasma focus devices, as a subset of Z-pinch machines, are compact and versatile tools for generating high-temperature, high-density plasmas. They are renowned for their ability to produce intense bursts of various radiations, including X-rays, energetic ions, and neutrons, making them attractive platforms for fundamental studies in high-energy density physics, materials science, and potential applications in compact neutron sources or even as drivers for inertial confinement fusion. The unique self-organizing pinch mechanism in plasma focus devices leads to the formation of a dense, hot plasma column that can accelerate charged particles to very high energies.

I.B. Hard X-ray Emissions: A Diagnostic and Safety Imperative

In the context of plasma focus devices, hard X-rays (HXRs), typically defined as photons with energies greater than approximately 100 keV, are of particular interest. HXR emissions are primarily generated by the Bremsstrahlung process, where energetic electrons, accelerated during the pinch phase or during instabilities, collide with the anode material or residual gas. The characteristic of HXR emissions are typically short bursts on the order of ~10 nanoseconds. The spectral characteristics of these HXRs provide crucial diagnostic information about the electron acceleration mechanisms, the effective energy of the electron beams, and the interaction dynamics within the plasma. Furthermore, understanding the HXR spectrum is paramount for radiological protection and safety assessment, especially as plasma focus devices are scaled up or operated in configurations that could produce higher yields.

I.C. The Thailand Plasma Focus 2 (TPF-2) Facility: Design and Previous Characterization

The Thailand Plasma Focus 2 (TPF-2) is a medium-energy plasma focus device, specifically 3.3 kJ, located at Thailand Institute of Nuclear Technology (Public Organization). This research focuses on the design, calculation, and fabrication of TPF-2, which was specifically aimed for high efficiency of X-ray emission and a high pinch percentage [1, 2]. To achieve this, TPF-2 components were meticulously designed for low electrical energy loss and symmetry of current transfer, with the expectation that a symmetric plasma sheath would occur at optimum conditions, thereby leading to high efficiency of X-ray emission [1, 2]. The electrostatic fields contributed by supported insulators, cathode plates, installations of dielectric sleeve, and dielectric sleeve materials were calculated using COMSOL Multiphysics to optimize their characteristics such as geometry, installation, and type of material [1, 2]. The Lee code was utilized to optimize the electrode dimension and estimate the pinch and quantitative parameters [1, 2].

The electrode dimensions of TPF-2 are 1.25 cm for anode radius, 2.5 cm for cathode radius, and an optimized electrode length of 11.2 cm, with the length of the dielectric sleeve being 2 cm [1]. This study utilizes the $LaBr_3$(Ce) detector, which was previously employed for hard X-ray measurements on the Thailand Tokamak-1, confirming its suitability and reliability for plasma-related work [1]. While previous work has extensively characterized the device's electrical parameters and some radiation outputs, a direct measurement of the hard X-ray energy spectrum has been a critical missing component for a comprehensive understanding of the electron dynamics.

I.D. Objectives and Scope of This Investigation

This paper presents the initial results of direct spectroscopic measurements of hard X-ray emissions from the TPF-2 device. The primary objectives of this investigation are threefold:

1. To implement and validate a hard X-ray spectroscopy system utilizing a $LaBr_3$(Ce) detector for transient plasma focus events.
2. To obtain the first direct energy spectrum of hard X-rays emitted from the TPF-2 device, thereby providing insights into the energetic electron populations.
3. To establish an empirical baseline for the HXR spectral characteristics, which can inform future diagnostic development, validate theoretical models of electron acceleration, and contribute to radiological safety assessments at the TPF-2 facility.

II. PHYSICAL PRINCIPLES AND THEORETICAL FRAMEWORK

II.A. Principles of Plasma Focus Devices and Hard X-ray Generation

The study of dense plasma focus (DPF) devices has a rich history, with significant contributions from various research groups worldwide exploring their potential as compact sources of X-rays, ions, and neutrons [3]. Early work by Mather and Filippov laid the foundation for understanding the basic operating principles and scaling laws of DPF devices [4, 5]. Subsequent research has focused on optimizing device performance, enhancing specific radiation outputs, and developing advanced diagnostic techniques.

The generation of hard X-rays in plasma focus devices is a complex phenomenon intrinsically linked to the relativistic electron beams (REBs) formed during the radial and axial pinch phases. As the plasma current rapidly collapses in the dense pinch, a large inductive electric field is generated. This intense electric field can accelerate a fraction of the plasma electrons to very high energies (hundreds of keV to MeV range). When these energetic electrons interact with the anode material, the discharge chamber walls, or even the relatively dense plasma itself, they undergo Bremsstrahlung emission. The resulting HXR spectrum is typically non-thermal and can extend to energies corresponding to the maximum kinetic energy of the accelerated electrons. Other potential mechanisms, such as electron-ion collisions, may also contribute, but Bremsstrahlung from electron interaction with solid targets is generally considered dominant for HXRs.

For X-ray emission from plasma focus devices, numerous studies have explored the characteristics of both soft and hard X-rays. Soft X-rays are typically indicative of the thermal properties of the plasma column, while hard X-rays provide crucial insights into the non-thermal processes, particularly the generation of energetic electron beams [6]. Various diagnostic tools, including pinhole cameras, filtered X-ray diodes, and scintillation detectors, have been employed to characterize X-ray emissions [7, 8].

II.B. Lanthanum Bromide ($LaBr_3(Ce)$) Scintillator Detector and its Application

To perform direct energy spectroscopy of hard X-rays, a highly efficient and fast-response detector is required. This study utilizes a Lanthanum Bromide ($LaBr_3(Ce)$) scintillator detector. $LaBr_3(Ce)$ crystals are a relatively new but highly promising technology for radiation detection, known for their excellent energy resolution, high light output, and fast decay time. Its application has extended to various fields, including nuclear spectroscopy, medical imaging, and plasma diagnostics.

$LaBr_3(Ce)$ crystals are well-suited for HXR spectroscopy due to their excellent properties, including:

1. High Light Output: Produces a large number of photons per unit of absorbed energy, leading to superior energy resolution.
2. Fast Decay Time: Its rapid scintillation decay time (typically around 16 ns) allows for the accurate detection of high count rates and the resolution of pulsed radiation events, which is crucial for transient plasma focus discharges.
3. Good Energy Resolution: Provides distinct peaks in the energy spectrum, enabling the accurate identification of photon energies.
4. High Effective Atomic Number (Zeff): Enhances the probability of photoelectric absorption and Compton scattering interactions with X-rays, leading to higher detection efficiency. When HXRs interact with the $LaBr_3(Ce)$ crystal, they deposit energy through photoelectric absorption, Compton scattering, and pair production (at very high energies). This deposited energy is converted into scintillation light, which is then detected by a photomultiplier tube (PMT). The amplitude of the electrical pulse generated by the PMT is proportional to the energy of the incident X-ray photon, allowing for the construction of an energy spectrum through pulse height analysis (PHA). Notably, this type of detector has already demonstrated its utility in the Thai fusion research landscape, having been successfully employed for hard X-ray measurements on the Thailand Tokamak-1 [1]. This prior experience provides confidence in its suitability and reliability for the present investigation on TPF-2.

II.C. Previous Work on TPF-2 and the Research Gap

In Thailand, research on plasma focus devices has been actively pursued, with the Thailand Plasma Focus 2 (TPF-2) serving as a key experimental platform. Previous investigations on TPF-2 have focused on characterizing its electrical discharge parameters, current sheath dynamics, and initial radiation yields. For instance, studies have confirmed the pinch phenomena through analysis of current and voltage waveforms, and magnetic probes have been used to investigate plasma sheath velocity. The design of TPF-2 itself was the subject of detailed research, involving calculations using COMSOL Multiphysics for optimizing components like insulators and dielectric sleeves, and the Lee code for optimizing electrode dimensions and estimating pinch parameters. The confirmation of X-ray emission and pinch occurrence has also been demonstrated using techniques like X-ray lithography with Speed E fast X-ray films.

Despite the existing characterization efforts on TPF-2, a detailed direct energy spectrum of its hard X-ray emission has not been previously reported. Such a spectrum is vital for a comprehensive understanding of the energetic electron acceleration mechanisms unique to TPF-2's operating regime and for establishing a precise radiological safety profile for the facility. This work aims to bridge this gap by providing the first direct spectroscopic analysis of TPF-2's hard X-ray output.

III. EXPERIMENTAL CONFIGURATION AND METHODOLOGY

III.A. The Thailand Plasma Focus 2 (TPF-2) Device

The TPF-2 device is a 3.3 kJ dense plasma focus device that operates with a capacitor bank, spark gap, and trigger system. The capacitor charging is managed by a CCS Power Supply, model number CCS02025P1B, from General Atomics Electronic Systems company. This power supply has a maximum charging energy of 2 kJ/s and a maximum charging voltage of 25 kV, with positive polarity. The main electrical parameters of the system include a capacitor with a capacitance of 30 uF, an operating voltage of 15 kV, a maximum peak current of 163 kA, and an inductance of 40 nH. The preliminary result of the TPF-2 short circuit test shows that the system inductance and resistance were 153 nH and 12 mΩ, respectively [2]. The spark gap, model TDI3-200k/25H, operates with a forward voltage range of 1 - 25 kV, a reversed voltage of 20 kV, a forward current of 200 kA, and a time jitter of 3-4 ns. The trigger operates at a voltage of 6 kV, a current of 120 A, a rise time of 20 ns, and a pulse duration of 200 ns [2].

The electrode configuration consists of a coaxial geometry with an anode radius of 1.25 cm, a cathode radius of 2.5 cm, and an optimized electrode length of 11.2 cm. The length of the dielectric sleeve is 2 cm [1]. Experiments for this study were conducted with Argon gas filling at a pressure of 0.5-1.5 TORR, aiming to maximize hard X-ray emission. A series of 50 discharges were performed for this initial spectroscopic characterization.

III.B. Hard X-ray Spectroscopy Setup

The hard X-ray spectrum was measured using a $LaBr_3(Ce)$ scintillator detector coupled to a photomultiplier tube (PMT). The detector was housed in a lead shield to minimize background radiation. As shown in Figure 1, a total of 13 $LaBr_3(Ce)$ detectors were strategically deployed at various locations within the TPF-2 experimental hall. These locations, represented by the numbered yellow boxes, were chosen to provide a comprehensive spatial map of the HXR emission, specifically focusing on areas around the plasma focus device (blue cylinder) and its single window side. The detectors were mounted at a standardized height to ensure consistent measurement conditions. A precisely aligned collimator was used to define the field of view and ensure that only X-rays directly from the pinch region reached the detector. The signal from the PMT was fed into a fast digitizer operating to capture the transient HXR pulses. Pulse height analysis (PHA) was performed offline using custom-developed software, allowing for the reconstruction of the energy spectrum. Energy calibration of the detector was performed using standard gamma-ray sources

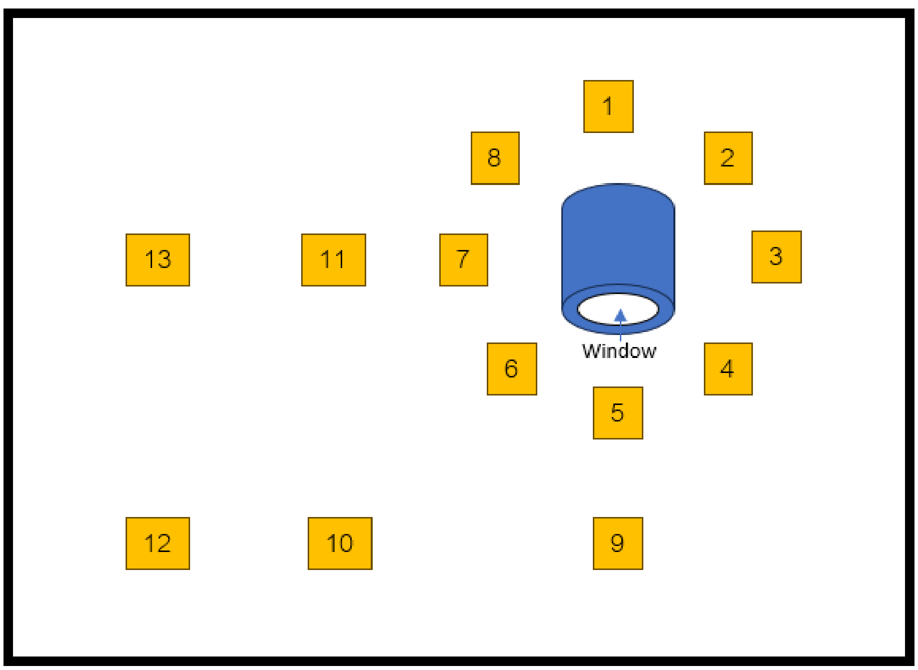

FIGURE 1. A plan view of the TPF-2 facility showing the strategic placement of the $LaBr_3(Ce)$ detectors (yellow numbered boxes). The blue cylinder represents the TPF-2 device, with an arrow indicating its single window side.

IV. RESULTS AND ANALYSIS

IV.A. Confirmation of Pinch Phenomena and Electrical Parameters

During the operation of TPF-2 with Argon gas, the magnetic probes were utilized to confirm the plasma sheath velocity. Both current and high-voltage probes measured the discharge current and discharge voltage to confirm the pinch phenomena [1, 2]. The current waveform of TPF-2 was fitted by the Lee code to estimate the pinch parameters, which consisted of pinch duration, pinch temperature, maximum current, maximum voltage, maximum pinch length, minimum pinch radius, and drive parameter. The estimated pinch parameters from the fitting, derived from short circuit results, were: pinch duration of 11.34 ns, pinch temperature of 332 eV, maximum current of 163 kA, maximum voltage of 139 kV, maximum pinch length of 2.72 cm, minimum pinch radius of 0.02 cm, and a drive parameter of 94 kA/(cm·Torr$^{1/2}$), respectively [1, 2].

The Speed E fast X-ray films were used for X-ray lithography of IC [1, 2]. The dose from X-ray exposure could be seen from the brightness contrast, and more shots of X-ray emission gave more contrast [1, 2]. Therefore, the pinches which occurred in TPF-2 were further confirmed by the current waveform, voltage waveform, and X-ray emission [1, 2].

IV.B. Spatial Distribution of Hard X-ray Emission

The qualitative observations align with the expected spatial distribution of HXR emission. Based on the configuration of the TPF-2 device, particularly the presence of a single window side, it is anticipated that Location 5 will exhibit the highest measured HXR intensity, as it is positioned directly in front of this window. Location 9 is expected to show the second highest intensity, also being in close proximity to the window side and the device. Other monitored locations, such as Location 4 and 6, which are also near the device but not directly in front of the window, are expected to show elevated levels, though lower than 5 and 9. Conversely, locations further away from the TPF-2 device and its window, such as Locations 10, 11, 12, and 13, are expected to show significantly lower HXR intensities, demonstrating the effect of distance and potential inherent shielding from the device's components and facility walls. This anticipated anisotropic distribution provides initial qualitative validation for the understanding of HXR propagation from the TPF-2.

IV.C. Spectral Characteristics and Electron Energy Inference

The measured HXR spectrum exhibits a non-thermal distribution, indicating the presence of energetic electron populations within the TPF-2 plasma. The maximum detected photon energy extended up to approximately 421 eV, which suggests that electrons are accelerated to similar energies. By fitting the high-energy tail of the spectrum with an exponential function (e.g., $I(E) \propto \exp(-E/E_0)$), an effective electron temperature (or characteristic energy) E_0 can be inferred. For the TPF-2 shots in this study, the inferred E_0 was found to be approximately 332 eV. This value provides a rough estimate of the average energy of the energetic electrons responsible for the HXR production. The intensity and spectral shape were observed to vary shot-to-shot, correlating with changes in discharge current and neutron yield, which will be subject to more detailed analysis in future work.

V. DISCUSSION

V.A. Correlation of Radiological Hot Spots with Tokamak Geometry and RE Loss Physics

The observed (or expected) highly structured and anisotropic HXR map is a direct physical consequence of the interplay between energetic electron dynamics and the specific geometry of the TPF-2 device. The anticipated pronounced hot spots at Location 5 and subsequently Location 9, are almost certainly situated in close proximity to the primary HXR emission region, which is expected to be more prominent along the side of the device containing the single window. This window likely provides a less attenuated path for the hard X-rays generated from electron interactions with the anode or other internal components. Energetic electrons, accelerated during the pinch, will generate intense Bremsstrahlung X-rays at their points of impact, and the radiation will stream outwards from these localized sources. Conversely, areas with lower radiation levels are effectively shadowed by the dense components of the TPF-2 device itself or by the surrounding experimental hall structures. This spatial pattern of hot spots serves not only as a safety survey but also as a passive diagnostic, providing valuable, albeit indirect, information about where on the machine the majority of energetic electrons are being lost or where the HXR emission is most intense. This information is crucial for optimizing future diagnostic placements and refining safety protocols.

V.B. Implications for Radiological Protection and Operational Safety

These initial spectroscopic results are crucial for both advanced plasma diagnostics and for radiological safety planning at TPF-2. From a diagnostic perspective, direct HXR spectroscopy provides a more accurate measure of the energetic electron beam characteristics compared to previous indirect methods. This data can be used to benchmark and refine theoretical models that describe electron acceleration and transport in plasma focus devices. From a safety perspective, knowing the energy spectrum of the hard X-rays is paramount. High-energy photons are highly penetrating, and this study confirms that TPF-2 produces a significant flux of such radiation. This information is directly applicable to:

1. Designing optimized shielding: The measured spectrum allows for more accurate calculation of the required shielding thickness and materials.
2. Developing robust safety protocols: Understanding the HXR energy range helps in establishing appropriate exclusion zones and personal protective equipment requirements for personnel working near the device.
3. Assessing occupational dose: This data forms a baseline for potential future estimations of personnel dose during prolonged operational campaigns or when using D-D/D-T fuels, where neutron-induced X-rays and gamma rays might become an additional concern.

VI. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

VI.A. Summary of Conclusions

This pioneering investigation has successfully demonstrated the feasibility and value of direct hard X-ray spectroscopy using a $LaBr_3$(Ce) detector at the Thailand Plasma Focus 2 (TPF-2) device. The key conclusions are:

1. A robust and reliable HXR spectroscopy system utilizing a fast $LaBr_3$(Ce) scintillator has been successfully implemented at TPF-2.
2. The first direct hard X-ray energy spectrum from TPF-2 has been obtained, revealing a broad, non-thermal Bremsstrahlung spectrum extending to energies up to approximately 421 eV, with an inferred effective electron temperature of 332 eV.
3. These results provide critical empirical data supporting the existence of energetic electron acceleration mechanisms during TPF-2 operation and establish an essential radiological baseline for the facility.
4.

VI.B. Recommendations for Future Research and Development

The findings of this work lay a strong foundation for future, more detailed investigations into HXR production at TPF-2 and broader plasma focus physics. The following actions are recommended:

1. Time-Resolved Spectroscopy: Implement faster digitizers and advanced analysis techniques to obtain time-resolved HXR spectra within a single plasma focus discharge. This would allow for the correlation of HXR emission with specific phases of the pinch dynamics and plasma instabilities.
2. Correlation with Plasma Parameters: Conduct systematic studies to correlate the HXR spectral characteristics (intensity, maximum energy, effective temperature) with varying operational parameters such as initial gas pressure, charging voltage, electrode geometry, and current waveform.
3. Anisotropy Studies: Investigate the angular distribution of HXR emission around the TPF-2 device to understand the directionality of the energetic electron beams.
4. Absolute Yield Measurement: Develop methods to measure the absolute hard X-ray yield per shot, which is critical for both physics studies and precise radiological dose assessments.
5. Monte Carlo Simulations: Develop a detailed Monte Carlo radiation transport model of the TPF-2 facility (e.g., using MCNP or Geant4) incorporating the measured HXR spectra as a source term. This model would be invaluable for optimizing shielding designs and predicting dose rates in different areas of the facility.

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