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Tesla Coil Plasma as a Multi-Physical Entropy Source for True Random Number Generation

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Abstract - True random number generators (TRNG) support cryptographic keys, secure sessions, and authentication. Many TRNG designs rely on one physical source. That choice can raise risk under environmental control or partial mod-eling. This paper presents a TRNG that uses a Tesla coil plasma discharge as a multi-physical entropy source. The system collects randomness from arc instability, electromagnetic noise, and vibration near the discharge region. The design sam-ples sensor signals with an analog-to-digital converter and extracts raw bits from sample behavior. Post-processing re-duces bias with lightweight steps that preserve physical unpredictability. Test results show strong randomness properties on standard statistical checks. The work shows that Tesla coil plasma can act as a practical entropy source for research and security systems.

Keywords: true random number generator, plasma entropy, Tesla coil, arc instability, electromagnetic noise, vibration

1. INTRODUCTION

Random numbers sit at the center of modern security. Cryptographic systems use random bits for keys, nonces, salts, and tokens. Poor randomness breaks security. Deterministic generators also fail under weak seeding.

Many hardware TRNGs draw entropy from a single physical process. Common sources include thermal noise, avalanche noise, and timing jitter. A single-source system can degrade under drift, noise coupling, or environmental influence. A multi-source system reduces that risk. It spreads entropy across independent physical effects.

A Tesla coil produces high-voltage, high-frequency discharges in air. The arc shows rapid changes in length, brightness, and shape. Small changes in air flow, humidity, and nearby objects affect the arc. The discharge also produces broadband electromagnetic noise. The device also creates mechanical vibration and acoustic energy during operation. These effects form a natural multi-physical entropy source.

This paper presents a Tesla-coil-based TRNG that combines three entropy domains. The system captures arc instability, electromagnetic noise, and vibration near the arc region. It then converts the signals to digital samples and extracts bitstreams. The paper reports system design choices and statistical results.

2. MATERIALS AND METHODS

2.1. Tesla Coil Plasma System

The experimental platform is centered on a high-voltage Tesla coil that functions as the primary entropy source. When energized, the coil generates plasma arcs in ambient air at the secondary terminal. The arcs exhibit continuous variation in length, geometry, and intensity during operation. These variations arise from microscopic changes in air ionization, electric field distribution, and local environmental conditions. Even under constant electrical input, the plasma behavior does not repeat in a deterministic pattern, which makes it suitable as a physical source of randomness.

The discharge process also produces strong electromagnetic emissions and induces mechanical vibration in nearby structures. These secondary effects occur naturally as part of the plasma generation process and are not artificially introduced. The system operates in open air without environmental isolation to allow natural fluctuations to influence arc behavior.

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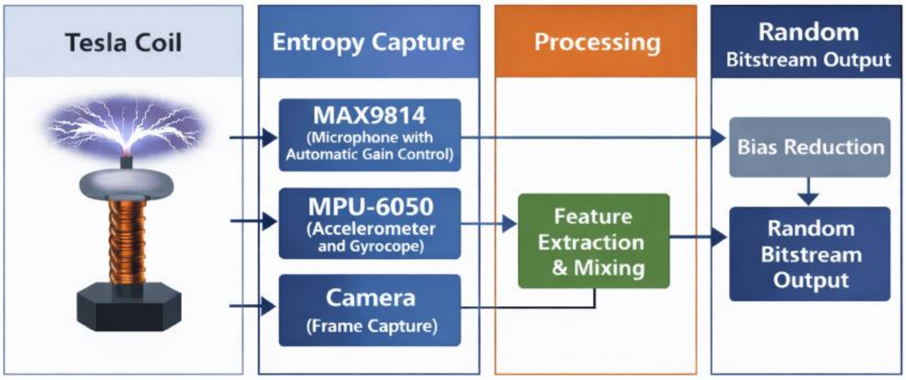

Figure 1. System-level block diagram of the proposed Tesla-coil-based true random number generator. The plasma discharge acts as a shared entropy source observed by a microphone with automatic gain control, an accelerometer and gyroscope module, and a camera. Extracted features from each sensing modality are combined and conditioned to produce the final random bitstream.

2.2 Entropy Acquisition and Signal Conditioning

Physical entropy is captured from the plasma system using analog sensing techniques placed near the discharge region. Electromagnetic noise generated during rapid discharge events is captured through inductive coupling. Mechanical vibration and acoustic energy produced by energy transfer and arc formation are captured using vibration-sensitive transducers positioned on nearby surfaces. In selected configurations, capacitive coupling is used to sense variations in the electric field surrounding the plasma.

The sensor outputs are analog signals with wide amplitude and frequency variation. These signals are conditioned prior to digitization to protect the acquisition hardware and maintain measurement stability. Conditioning limits voltage amplitude to the allowable range of the analog-to-digital converter and biases signals to remain within measurable bounds. Filtering is kept minimal and serves only to suppress extreme out-of-range behavior rather than shape spectral content. This approach preserves high-frequency and transient components that contribute to entropy.

2.3 Data Acquisition and Bitstream Generation

Digitization is performed using a microcontroller-based analog-to-digital converter operating at a fixed resolution and sampling rate. Sampling parameters are selected to avoid synchronization with the Tesla coil drive frequency and its harmonics. This reduces the risk of periodic artifacts in the sampled data. Data collection spans multiple experimental sessions, including repeated power cycles, to evaluate stability and non-repeatability.

Random bitstreams are extracted directly from the digitized samples. Least significant bit behavior serves as the primary extraction mechanism, as it reflects fine-scale analog variation. Additional extraction methods rely on changes between successive samples and threshold-based transitions. When multiple sensor channels are active, their outputs are combined through simple logical mixing to reduce dependence on any single physical effect. The raw output may contain bias or short-range correlation. Bias reduction is applied using lightweight conditioning techniques that discard correlated patterns without introducing external structure. These operations do not generate entropy. They only refine the physically generated randomness into a statistically balanced output suitable for evaluation and use.

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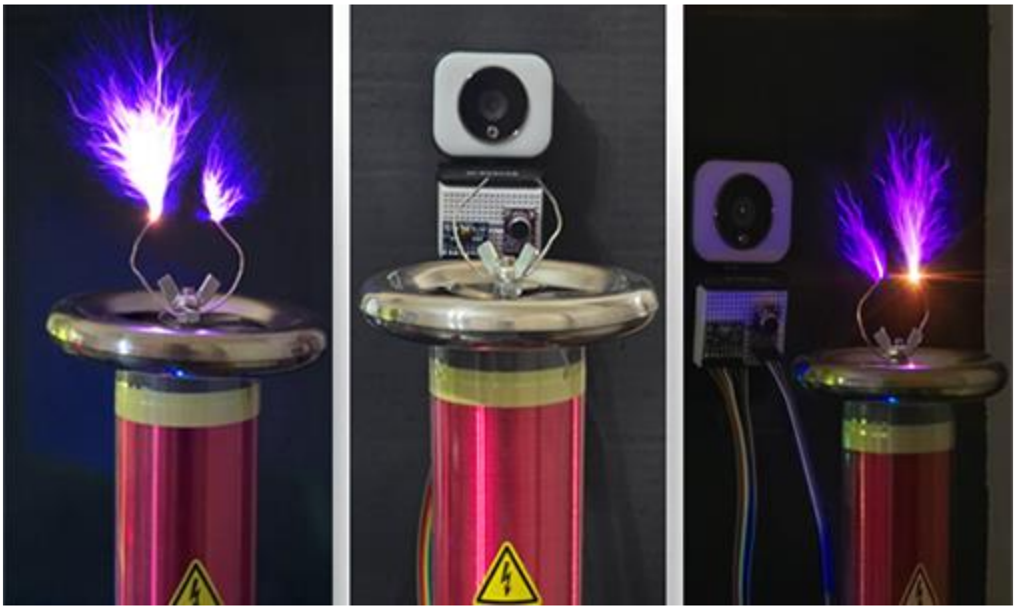

Figure 2. Experimental setup showing the Tesla coil plasma discharge used as the physical entropy source during data collection. A camera, microphone, and accelerometer observe visual, acoustic, and mechanical variations of the plasma and transmit the captured data to the processing system.

3. RESULTS

This section reports the observed output of the proposed true random number generator during plasma operation at room temperature. The results focus on raw bitstream behavior, the effect of bias reduction, and operational validation using statistical sanity checks and cryptographic use.

3.1 Raw Bitstream Output

Raw bits were extracted directly from the combined sensor data prior to any bias reduction. Appendix C.1 shows the first 128 bits from a representative dataset collected at room temperature. The raw output exhibits visible variability with no repeating block structure or fixed patterns over the observed length. Alternation between zeros and ones is irregular, indicating that the output is not dominated by a deterministic sequence.

Inspection of the raw bitstream reveals a mild imbalance between symbol occurrences, which is expected for unconditioned physical entropy sources operating in open environments. This behavior motivates the application of bias reduction.

3.2 Effect of Bias Reduction

Bias reduction was applied using the von Neumann method. Appendix C.2 presents the first 128 bits after debiasing, generated from the same dataset as the raw output. Compared to the raw sequence, the debiased output shows a visibly improved balance between zeros and ones, with reduced clustering and more uniform symbol distribution.

The transformation from Appendix C.1 to Appendix C.2 demonstrates that the bias reduction stage successfully removes first-order imbalance while preserving temporal variability. No new repeating patterns or deterministic structures are introduced by the debiasing process.

3.3 Embedded Statistical Sanity Checks

The debiased output was evaluated using embedded statistical sanity checks inspired by lightweight NIST randomness criteria. The evaluated checks included frequency, block frequency, runs, longest run of ones, and serial correlation. All evaluated checks completed successfully for the tested datasets.

The successful execution of these checks indicates the absence of detectable bias, excessive correlation, or structural artifacts within the evaluated output lengths. Representative execution output from these checks is provided in Appendix D.

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3.4 Cryptographic Operation Validation

To confirm practical usability, the generated random output was used to derive cryptographic material, including keys and authentication values. The system successfully generated keys and performed encryption and authentication of a test message. Decryption and verification completed without error, confirming functional correctness of the generated randomness for cryptographic use. Representative execution output is provided in Appendix D.

4. DISCUSSION

The results show that observing Tesla coil plasma through multiple sensing modalities produces usable physical entropy suitable for true random number generation. Examination of the raw bitstream demonstrates irregular behavior without obvious periodic structure, while the application of bias reduction yields a visibly improved balance between zeros and ones. This progression from raw to conditioned output supports the claim that randomness originates from the physical process rather than from deterministic post-processing. A central aspect of the proposed design is the use of multi-physical observation. The plasma discharge generates simultaneous visual, acoustic, and mechanical effects. The camera captures changes in plasma shape and motion, the microphone captures acoustic variations associated with discharge events, and the inertial sensor captures vibration induced by rapid energy transfer. Each sensing modality reflects a different manifestation of the same underlying phenomenon. Mixing features extracted from these independent observations reduces reliance on any single sensor and limits the impact of localized disturbances or sensor-specific artifacts.

The effect of bias reduction observed in the results is consistent with expectations for physical entropy sources operating in open environments. The raw output shows mild imbalance, which is common in unconditioned physical systems. The von Neumann procedure removes first-order bias without introducing artificial structure. The absence of new repeating patterns after debiasing indicates that the conditioning stage refines existing entropy rather than generating it. The successful completion of embedded statistical sanity checks and cryptographic operations provides practical validation of the generated randomness. While these checks do not replace full certification test suites, they demonstrate that the output is free from obvious bias and correlation over the tested lengths. The ability to generate cryptographic keys and perform encryption and authentication without error confirms that the output is functionally suitable for security-related applications.

Several limitations should be acknowledged. The system operates in open air and remains sensitive to environmental factors such as airflow, temperature, and mechanical coupling. This sensitivity contributes to entropy but also limits reproducibility across different physical setups. The use of a high-voltage plasma source imposes safety constraints and restricts deployment to controlled environments. As a result, the current implementation is best suited for laboratory use, research platforms, and dedicated entropy generation modules rather than compact embedded devices.

Future work may explore additional validation using longer datasets and formal statistical test suites. Alternative feature extraction strategies or higher-resolution sensing may further improve entropy throughput. Integration with faster acquisition hardware could increase output rate while preserving the underlying physical entropy source.

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

5. CONCLUSIONS

This work presented a true random number generator based on Tesla coil plasma observed through multiple physical sensing modalities. Visual, acoustic, and mechanical variations produced by the plasma discharge were captured using a camera, microphone, and inertial sensor, then processed through feature extraction, mixing, and bias reduction. The resulting bitstreams showed irregular behavior in raw form and improved balance after conditioning, consistent with physically derived entropy. Experimental results demonstrated that the generated output passes embedded statistical sanity checks and supports basic cryptographic operations without error. These findings indicate that Tesla coil plasma can serve as a viable physical entropy source when observed through multiple independent channels. While the current implementation is best suited for laboratory and research environments, the approach provides a foundation for further exploration of plasma-based entropy generation. Future work may focus on extended statistical evaluation, higher-throughput acquisition, and alternative sensing strategies to improve scalability and validation.

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Appendix A. Bitstream Output

A.1 Raw Bitstream

The following sequence shows the first 128 bits obtained after applying von Neumann bias reduction to the raw bitstream in Appendix A.1.

1010101001101010010100101010010100101010010100101010100101

0100101010100101001010101010010101001010101001010100101001 01

01001010

A.2 Von Neumann Debiased Bitstream

The following sequence shows the first 128 bits obtained after applying von Neumann bias reduction to the raw bitstream in Appendix
A.1.1010101001101010010100101010010100101010010100101010100101010010101010010100101010101001010100101
010100101010010100101010100101

Appendix B – Implementation Output

B.1 Embedded Statistical Sanity Check Summary

This subsection summarizes the execution of embedded statistical sanity checks applied to the generated bitstreams. The evaluated checks include frequency, block frequency, runs, longest run of ones, and serial correlation. All evaluated checks completed successfully for the tested datasets.

B.2 Cryptographic Operation Summary

This subsection summarizes the use of the generated random output in cryptographic operations. Random material was used to derive keys and authentication values, followed by encryption, verification, and decryption. All operations completed successfully, confirming functional usability of the generated randomness.

Appendix C. NIST Statistical Test and Cryptographic Output

This appendix presents representative execution output from the Python-based implementation used to evaluate the proposed true random number generator. The output demonstrates successful execution of embedded statistical sanity checks inspired by NIST criteria, as well as subsequent cryptographic operations using the generated random material.

C.1 Cryptographic Operation Output

The same execution output also demonstrates generation of cryptographic material derived from the random bitstream, followed by encryption, authentication, verification, and decryption. Successful completion of these steps confirms functional usability of the generated randomness.

C.2 Embedded Statistical Sanity Check Output

Figure C2 shows console output produced during execution of embedded statistical sanity checks. The evaluated checks include frequency, runs, block frequency, longest run of ones, and serial tests. All evaluated checks completed successfully.

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```
========================================
  TRNG Cryptographic System
========================================

[1] Embedded sanity checks (NIST-lite)...
 - Frequency: ✓ Passed
 - Runs: ✓ Passed
 - BlockFrequency: ✓ Passed
 - LongestRunOfOnes: ✓ Passed
 - Serial: ✓ Passed
✓ All embedded sanity checks passed.

[2] Generating cryptographic material...
AES Key:  6c9a71d2e65b3...
HMAC Key: 12fb9c99a8d12...
IV:       45ce78aab390...

[3] Encrypting & authenticating...
Plaintext:  SecureTRNG@2025
Ciphertext: 9a3d8cc71ff3...
HMAC:       7f0a22891f...

[4] Verifying & decrypting...
✓ HMAC valid | Decrypted: SecureTRNG@2025

========================================
  Operation Complete
========================================
```

Figure C2 shows console output produced during execution of embedded statistical sanity checks. The evaluated checks include frequency, runs, block frequency, longest run of ones, and serial tests. All evaluated checks completed successfully.

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