

EXPERIMENTAL CHARACTERIZATION OF ULTRA-FAST ELECTROMAGNETIC TRANSIENTS GENERATED BY A CABLE PULSE GENERATOR FOR FUSION GENERATOR SIMULATION

Alija Jusić^{1,5}, Nenad Kartalović², Uros Kovačević³, Predrag Osmokrović⁴

Abstract: This paper presents the experimental design and analysis of a cable pulse generator used as a simulator of ultra-output electromagnetic waves generated by a fusion generator. The aim of the research was to investigate the possibility of producing rectangular pulses of very short duration (in the nanosecond range) that correspond to the pulses generated by electron guns used in fusion systems. The cable generator consists of a high-voltage transformer, a 50 Ω coaxial water resistor, a 120 m high-voltage cable, and a three-electrode SF₆ spark gap. The generated pulses reached peak values up to 50 kV, with durations of 600 ns and rise times below 2 ns. The generator response was measured using a fast capacitive probe and a Kerr cell, and the quadratic deviations from the theoretical response were determined at 50 equidistant points along the rising, peak, and falling parts of the pulse. The obtained results demonstrate the high accuracy and stability of the cable generator, as well as its applicability for simulating electromagnetic pulses of fusion modulators and testing sensitive electronic equipment under extreme conditions.

Keywords: cable pulse generator, fusion generator, fast capacitive probe, electromagnetic pulse, nanosecond response

INTRODUCTION

The first nuclear properties relevant to nuclei in the natural system were mass and electric charge. The values of mass determined in this way were approximate, since they were based on the fundamentally incorrect assumption of the continuity of matter. The exact value of the nuclear mass could be determined only by solving the complex problem of interactions among multiple hadrons, as they are simultaneously the constituent elements of the nucleus and the carriers of the interactions that bind it. However, even an approximate determination of the nuclear mass can be incorporated into theory due to the semi-empirical nature of the early hypotheses of nuclear physics. As for the nuclear charge, it was determined from the a priori accepted fact of the overall electrical neutrality of the atom, which was indirectly confirmed by astronomical observations [1, 2].

From Figure 1 it is evident that the fusion of light nuclei h, d, and t can lead to the formation of a nucleus with the release of a large amount of energy. This energy is released both in space and on Earth. The use of fusion energy for peaceful purposes has not yet been

achieved, but efforts are ongoing to address this challenge using the most advanced technologies [3, 4].

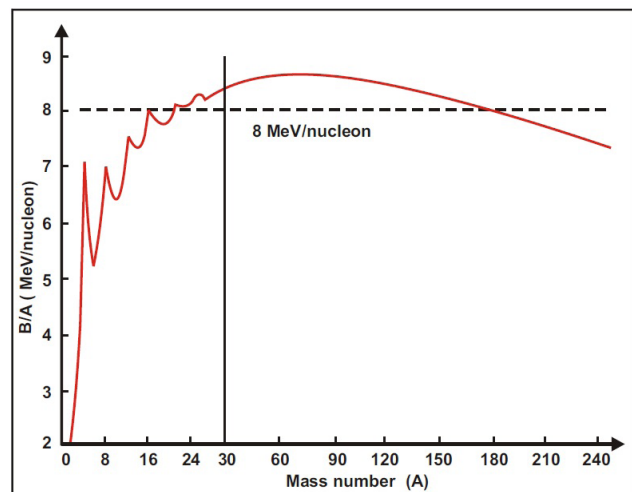


Figure 1: Average binding energy per nucleon as a function of mass number for stable nuclei

The realization of the possibility of using nuclear fusion energy for peaceful purposes would represent a definitive solution to the problem of energy deficit.

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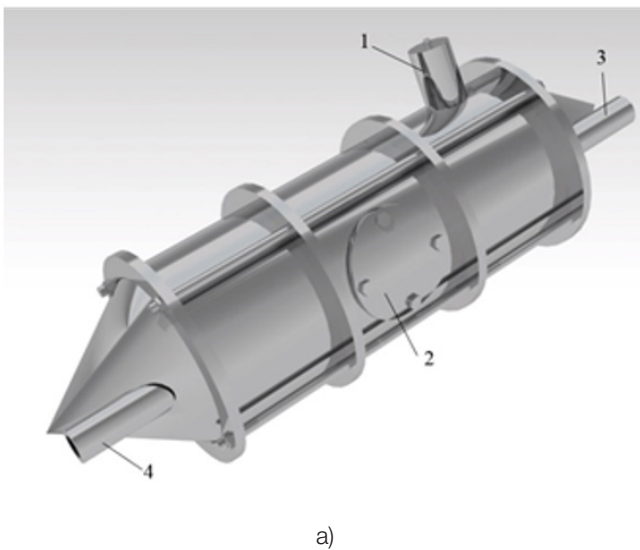
1. FUSION GENERATOR

To achieve controlled fusion, light nuclei must be fused into an α -particle. This nuclear interaction has a very high energy threshold. In early attempts to reach this threshold, energy was first injected into the plasma using electromagnetic radiation. However, it was found that overheated plasma begins to reflect electromagnetic radiation, and energy injection stops before the energy required for fusion is reached [5, 6, 7, 8]. The generation and characterization of such ultra-fast transient electromagnetic phenomena require specially designed transmission systems capable of preserving the waveform of high-voltage pulses. In this context, the geometry and impedance matching of the waveguide structure play a crucial role in minimizing reflections and avoiding pulse deformation. Therefore, the waveguide used in the experimental setup was designed with a characteristic impedance of 50Ω , with conical terminations calculated according to the impedance matching condition given by Equation (1).

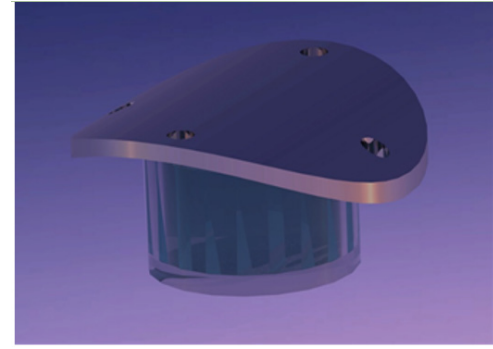
$$Z_c = 50 \Omega = \left(\frac{60}{\sqrt{\epsilon_r}} \right) \ln \left(\frac{\tan \frac{\theta_2}{2}}{\tan \frac{\theta_1}{2}} \right) \quad (1)$$

where θ_1 represents the angle of the output cross-section of the measuring capacitor, θ_2 represents the angle of the conical waveguide housing, ϵ_r is the relative permittivity of the dielectric material, and Z_c represents the characteristic impedance of the transmission line for which impedance matching is performed.

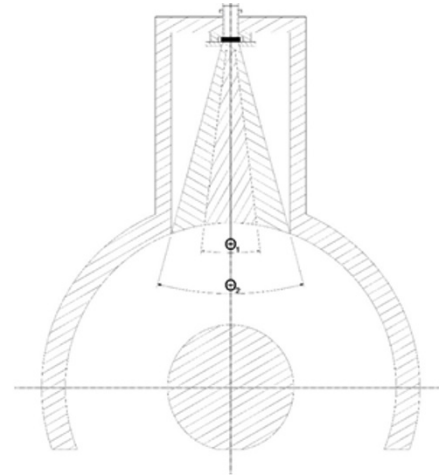
For this reason, particle-based energy injection using electron guns is employed today. Electron guns operate on the principle of a Marx impulse generator with a 1.2/50 ms waveform, which is converted by a system of water capacitors and water resistors into rectangular pulses with a width of 5 ns and a peak power of 10.5 TW. Figure 2 shows such an electron gun.



a)



b)



c)

Figure 2: Electron gun: (a) prototype of the horizontal section of the GES (1 – fast capacitive probe); (c) fast capacitive probe with a conical waveguide resistor of 50Ω ($\theta_1 = 7^\circ 15'$, $\theta_2 = 30^\circ$, Equation 1)

The fusion parameter is conceived as a characteristic arrangement of multiple electron guns, shown in Figure 3, which simultaneously inject energy into the plasma with a duration of 5 ms, as illustrated in Figure 4, thereby reaching the threshold for controlled fusion. Controlled fusion is achieved in magnetic bottles with magnetic induction of several tens of T.

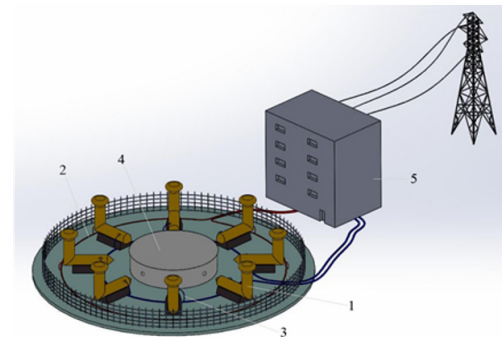


Figure 3: Schematic of the fusion generator: 1 – electron beam generators; 2 – supply and triggering lines for the electron beam generators (shielded with a copper layer and five layers of μ -metal); 3 – measurement lines for the electron beam; 4 – plasma chamber with a magnetic bottle, superconducting magnets, and heat exchangers; 5 – control building for the conversion of thermal energy into electrical energy.

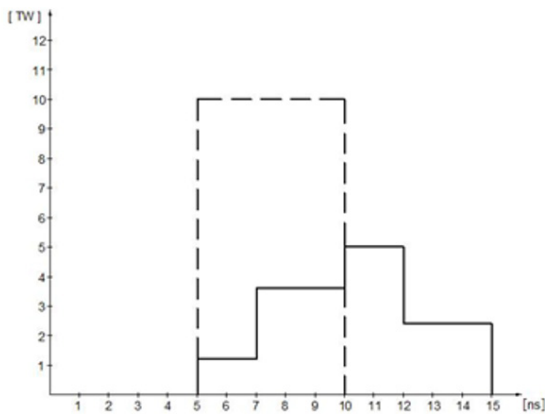


Figure 4: Pulse from eight electron beam generators:
----- without jitter;
_____ with jitter.

2. CABLE PARAMETERS

For the purpose of determining the characteristic parameters of cable systems, a cable pulse generator was used as the voltage source, whose basic schematic is shown in Fig. 5. In addition, a DC generator with a voltage rise rate of 8 V/s and a standard Marx impulse generator were also used in the experimental procedure [9, 10].

The cable pulse generator consisted of the following components:

- a high-voltage transformer,
- a high-voltage AC rectifier,
- a resistor for limiting the cable charging current,
- a coaxial water resistor with a resistance of 50 Ω (corresponding to the characteristic impedance of the generator),
- a coaxial high-voltage cable with a length of 120 m (characteristic impedance of 5 Ω , distributed capacitance of 100 pF/m, and pulse propagation velocity of 200 m/ μ s), and
- a three-electrode spark gap insulated with SF₆ gas, installed at the end of the cable.

The generator produced rectangular pulses with peak values determined by the voltage of the high-voltage transformer, with a duration of 600 ns, and rise and fall times shorter than 2 ns [11, 12]. In the modified configuration (Figure 5), the pulse had a peak value of 50 kV, while the rise time of the leading edge and the fall time of the trailing edge were approximately 5 ns.

The DC voltage was measured using a commercial memory voltmeter and a resistive voltage divider, while the impulse voltages of the Marx generator were measured using a compensating capacitive voltage divider and a GHz digital oscilloscope. The voltages of the cable pulse generator were recorded using a GHz digital oscilloscope and a fast capacitive probe installed inside the experimental chamber.

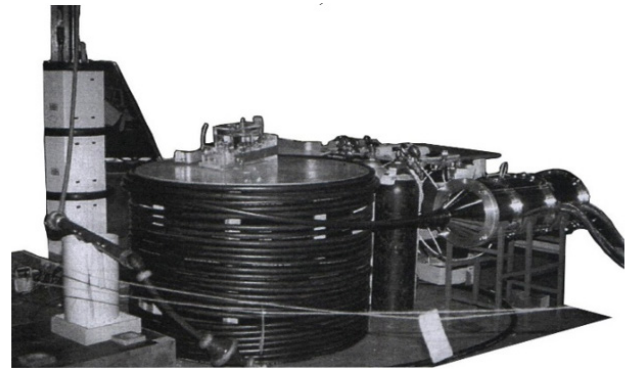
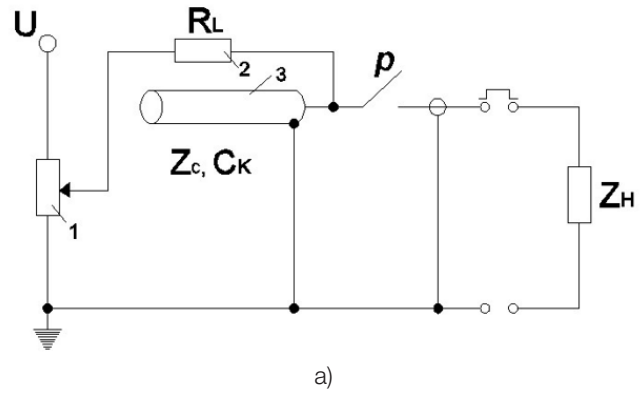


Figure 5: Cable pulse generator: (a) schematic of the cable generator; 1 – potentiometer, 2 – power supply, 3 – resistor, 4 – cable; (b) photograph of the cable generator.

During the measurements, all measuring instruments were placed inside a shielded measurement cabin with electromagnetic shielding greater than 100 dB. Communication between the measurement cabin and the experimental system was established via a non-galvanic connection, ensuring complete electromagnetic isolation and measurement stability.

3. EXPERIMENT AND EXPERIMENTAL RESULTS

The experiment consisted of two hybridized generators—a fusion modulator module (Figure 2) and a cable pulse generator (Figure 5). Pulses from both generators were measured using a fast probe in the nanosecond range (Figure 4). The signals obtained from the super-fast probe were measured in parallel. In addition, a mathematical analysis was performed. Figure 6 shows the obtained probe response results and the corresponding combined uncertainties.

The experimental setup was designed to enable simultaneous acquisition of the transient voltage waveforms generated by both pulse sources under identical operating conditions. The cable pulse generator produced rectangular voltage pulses with a peak value of 50 kV, a pulse duration of 600 ns, and rise and fall times of approximately 5 ns. The fast capacitive probe

was connected through a matched $50\ \Omega$ transmission line in order to minimize signal reflections and waveform distortions during the measurements.

To ensure the repeatability and reliability of the experimental results, the measurements were performed under controlled laboratory conditions while maintaining identical generator charging voltage, triggering conditions, and measurement configuration throughout the entire experimental campaign.

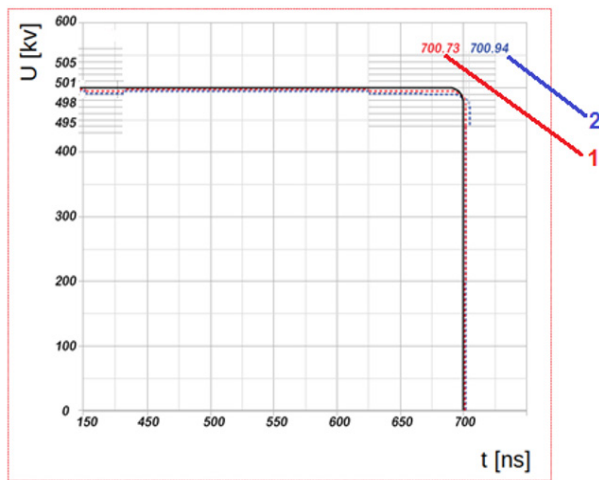


Figure 6: Structure of the pulse response of the cable generator: black line – theoretically calculated response, red (1) – response of the fusion generator, blue (2) – response of the fast capacitive probe.

Table I: Presents the most relevant parameters of the observed experimental procedure

	Measurement Uncertainty	Fast Capacitive Probe
Type A measurement uncertainty	8,1 %	2,9 %
Type B measurement uncertainty	2.2 %	0,64 %
Combined measurement uncertainty	2,23 %	0,83 %
Mean square deviation from the theoretical response at 50 equidistant points of the response peak (top)	2.23 kV	3.48 kV
Mean square deviation from the theoretical response at 50 equidistant points of the rising part of the response	0.64 ns	0.82 ns
Mean square deviation from the theoretical response at 50 equidistant points of the falling part of the response	0.73 ns	0.90 ns

A total of 100 independent generator discharges were recorded. For each discharge, the probe response was measured and subsequently processed using statistical methods. Chauvenet's criterion was applied to remove possible outliers, after which the statistical distribution, central moments, and Type A measurement uncertainty were determined. The overall measurement uncertainty was obtained by combining the Type A uncertainty with the analytically and numerically evaluated Type B uncertainty.

The obtained results demonstrate a stable and highly repeatable probe response for both pulse generators. The measured waveforms showed excellent agreement with the corresponding mathematical analysis, confirming the validity of the proposed experimental methodology. The combined uncertainty analysis further indicates that the developed measurement system provides reliable characterization of nanosecond high-voltage transients and is suitable for the investigation of ultra-fast electromagnetic phenomena generated by fusion modulator systems and cable pulse generators.

4. CONCLUSION

Based on the obtained experimental results, it can be concluded that the nanosecond cable pulse generator exhibits high reliability, stability, and signal repeatability. Its response is characterized by an extremely short pulse rise time, minimal distortion, and good agreement with the theoretical model. These characteristics enable accurate simulation of ultra-high-output electromagnetic waves that occur during the operation of fusion modulators and electron guns.

On the other hand, the hyper-parallelized pulse generator demonstrated the capability of synchronizing multiple output channels, thereby enabling the generation of very high-power pulses—on the order of terawatts (TW)—with a pulse width of approximately 5 ns. This capability for synchronized generation of high-energy pulses represents a key advantage in the design and realization of next-generation fusion generators. By combining the cable pulse generator, which enables precise temporal control and reliable measurements, with the hyper-parallelized generator, which enables high output power, a technological foundation is established for experimental simulations and the development of controlled nuclear fusion systems under laboratory conditions.

The proposed experimental approach provides a reliable methodology for characterization of ultra-fast electromagnetic transients, combining impedance-matched waveguide design, fast capacitive measurements, and uncertainty evaluation in a unified measurement system.

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BIOGRAPHY

Alija Jusić was born in Travnik, Bosnia and Herzegovina, in 1986. He received the master's degree in electrical engineering from the Faculty of Electrical Engineering, University of Sarajevo, Sarajevo, Bosnia and Herzegovina, in 2010, and the Ph.D. degree from the Department of Power Engineering, Faculty of Electrical Engineering, University of Sarajevo, in 2025.

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Predrag Osmokrović was born in Sarajevo in 1949, where he completed primary and secondary school. Obtained his BSc EE degree at the Faculty of Electrical Engineering in Belgrade in 1975, MSc EE in 1978, and PhD EE 1984 godine. From February 1978 to November 1979 he worked as an assistant at Pedagoško-tehnički fakultet in Zrenjanin. Since November 1979 he works at the Faculty of Electrical Engineering in Belgrade. He spent several years working with High Voltage Institute of Karlsruhe University, Germany. He also worked in Energoinvestu, Sarajevo, Bosnia & Herzegovina. At the Faculty of Electrical Engineering in Belgrade he became an assistant, assistant-professor, associate professor and a full professor in 1979, 1985, 1990 i 1995, respectively. Since 1999 he is manager of Institute for Physics of Technical Faculties of Belgrade University.