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Review

A review of new wire arrays with open and closed magnetic configurations at the 1.6 MA Zebra generator for radiative properties and opacity effects

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The studies emphasize investigation of plasma formation, implosion, and radiation features as a function of two load configurations: compact multi-planar and cylindrical wire arrays. Experiments with different Z-pinch loads were performed on 1.6 MA, 100 ns, Zebra generator at University of Nevada, Reno. The multi-planar wire arrays (PWAs) were studied in open and closed configurations with Al, Cu, brass, Mo and W wires. In the open magnetic configurations (single, double, triple PWAs) magnetic fields are present inside the arrays from the beginning of discharge, while in closed configurations (prism-like PWA) the global magnetic field is excluded inside before plasma flow occurs. The new prism-like PWA allows high flexibility in control of implosion dynamics and precursor formation. The spectral modeling, magneto-hydrodynamic (MHD) and wire ablation dynamic model (WADM) codes were used to describe the plasma evolution and plasma parameters. Experimentally observed electron temperature and density in multiple bright spots reached 1.4 keV and 5×10^{21} cm^{-3}, respectively. Two types of bright spots were observed. With peak currents up to 1.3 MA opacity effects became more pronounced and led to a limiting of the X-ray yields from compact cylindrical arrays. Despite different magnetic energy to plasma coupling mechanisms early in the implosion a comparison of compact double PWA and cylindrical WA results indicates that during the stagnation stage the same plasma heating mechanism may occur. The double PWA was found to be the best radiator tested at University scale 1 MA generator. It is characterized by a combination of larger yield and power, mm-scale size, and provides the possibility of radiation pulse shaping. Further, the newer configuration, the double PWA with skewed wires, was tested and showed the possibility of a more effective X-ray generation.

1. Introduction

The Z-pinch based radiation physics and Z-pinch [1] driven Inertial Confinement Fusion (ICF) [1–3] research require an understanding of several scientific aspects of the pulsed power and load coupling. These aspects include the effective conversion of magnetic energy to soft X-ray radiation, reducing the source size while maintaining the total output energy yield, E_T, shaping of the radiation pulse, and understanding the magnetic energy to Z-pinch plasma coupling.

The change Z-pinch inductance leads to plasma shell acceleration and plasma heating due to thermalization of kinetic energy, E_k, at on-axis stagnation through outgoing strong shock and pdV work [4]. However, this is not the only channel of conversion of magnetic energy to soft X-ray radiation, as the resistivity of a strongly inhomogeneous wire-array plasma leads to magnetic field penetration, its decay and Joule heating [5].

In general, the main method used to optimize X-ray generation from a wire-array plasma is to mitigate the magneto-Rayleigh–Taylor (MRT) instabilities [6]. However, as there is still uncertainty about the role of instabilities in Z-pinches, particularly for wire-array implosions [7]. Since the goal is a compact, efficiently radiating pinch, instabilities may help its formation. For example, MRT instability-driven MHD turbulence can dissipate through ion viscosity, causing substantial energy release by the change of

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inductance [8]. Recently, compact planar wire array and cylindrical wire array experiments demonstrated significant radiation from bright spots that are a signature of different types of plasma instabilities, i.e., magnetic field dissipation through annihilation (reconnection). In particular, recent experiments with compact multi-planar arrays [8–13] and fast imploded compact cylindrical arrays [10,14,15], which are loads with a high level of instabilities, as well as new research with conventional nested arrays [16,17], and a modified multilayered – star-like – nested array [18], demonstrated interesting results.

We focus here on compact multi-planar and cylindrical wire arrays. In particular we study the single planar wire array (SPWA), with cascade-type implosion as multilayered nested array [8], and double planar wire arrays (DPWAs) in the center of the Z-pinch chamber between anode and cathode, were found to provide a possible path toward the production of compact, efficient X-ray sources. The SPWA consists of a single plane row of wires that are parallel to each other [8–10], while the DPWA includes two parallel plane wire rows [8,11]. Experiments were performed on the UNR 1 MA, 100 ns generator "Zebra" [10]. Scaling of the E_T (up to 23 kJ, or 11.5 kJ/cm) and peak power P_{subk} (up to 0.9 TW, or 0.45 TW/cm) from array dimensions and elemental composition shows that SPWA and DPWA can be as small as 3–5 mm $\times$ 1.5–3 mm, which is very compact but with modest decreases in yield and power [10,11]. A significant part of SPWA and DPWA radiation was found to be associated with bright spots. Further, in principle the possibility of X-ray pulse shaping was demonstrated [10,11]. The DPWA yield and power were found to be larger than that from the SPWA and low-wire-number CWA, during ns-scale rise time bursts. In all experiments the E_T exceeded the E_K, which is $<$4–6 kJ, by a factor of 3–5 times, and it was found that the energy coupling mechanism was enhanced resistivity of the strongly inhomogeneous plasma [5,9–11].

The specific feature of the DPWA implosion, which is a complicated two-step precursor formation with the independent implosion of wire rows made from different materials [11], may open new paths for controlling the shapes and spectra of radiation pulses. Along this path we note that the first experiments with SPWA were performed at 3–5 MA on SNL generator "Saturn" [12,13].

Another wire load, the fast imploded compact cylindrical wire arrays (CCWAs), tested for the first time at 4 MA [14] were studied on 1 MA Zebra [10] where a CCWA with a smaller diameter ($\Phi < 4$–6 mm), than traditionally used in 1 MA experiments low-wire-number CWAs ($\Phi > 8$–16 mm), was employed. In the CCWA the gap, d, between wires is $d \leq 1$ mm, which is closer to d in experiments on multi-MA generators. The size and mass of the SPWA and CCWA were chosen to ensure that the array implosion times were similar and coincided with the current maximum. In Al CCWA experiments on 1 MA Zebra the performance was close to that of the SPWA and better than those of the lower wire-number CWA [10]. However, tungsten CCWAs showed much lower power than tungsten SPWAs, i.e., 7 TW compared to 15 TW, in experiments on Sandia National Laboratories (SNL) Saturn at 5 MA peak current [13]. These experiments with a 5 MA generator showed that there is a limit on the minimal size of CCWA, which may be due to large internal energy and opacity for the big Z-pinch mass needed to match the implosion time and current rise time on multi-MA current generators [13].

The next steps with multi-planar wire arrays were studies of loads that consist of several parallel planar wire rows, a triple planar wire array (TPWA) and an array where at least two single planar arrays cross each other under 90° (CPWA). Experiments with TPWA and CPWA provided additional data on increasing of radiated powers and yields and radiation pulse shaping.

2. Z-pinch generator and diagnostics

The experiments to be discussed were performed at the University of Nevada, Reno Nevada Terawatt Facility (NTF). The NTF Zebra generator has a 1 MA peak current in conventional mode [19] with 100 ns rise time, 1.5 TW electrical power, and 1.9 Ω pulse-forming line impedance. To obtain data on the scaling of radiated energies and powers with peak Z-pinch load current a novel technology based on Load Current Multiplier (LCM) [20] was applied. The Zebra current range was extended from 0.8–0.9 MA up to 1.4 MA for experiments with plasma-generated loads and up to 1.6 MA with short circuit loads. The initial energy stored in the Marx generator capacitors was about 150 kJ. X-ray/EUV diagnostics covered the spectral range from 10 eV up to more than 10 keV. These included X-ray imaging (time-integrated and time-gated) systems, fast X-ray detectors, two time-integrated X-ray spectrometers with KAP and LiF convex crystals, a time-gated X-ray spectrometer with a KAP convex crystal, and a time-integrated extreme ultraviolet (EUV) grazing incident spectrometer. The total radiation yield in the spectral range from 10 eV to 4–5 keV was measured by a Ni bolometer. Measurements of the X-ray radiation with sub-nanosecond time resolution were performed with absolutely calibrated X-ray diodes (XRD) and photoconducting detectors (PCD) in the same assembly as the Ni bolometer. The XRD was filtered by a 5 μm kimfoil and registered radiation in two photon energy ranges, $0.18\ \text{keV} < h\nu < 0.28\ \text{keV}$ and $h\nu > 0.7$ keV, the "sub-keV" spectral range. Several filters were fielded on the PCD, but most results were obtained with an 8 μm beryllium filter that recorded radiation with the photon energy $>$0.75 keV, the "keV" spectral range. A second beamline with the similar XRD and PCD were installed on Zebra to provide the capability to measure X-ray radiation from the plasma at 90° to direction of the first Ni bolometer/XRD/PCD beamline. Different silicon X-ray diodes, filtered with cut off energies $>$0.017 keV, $>$9 kev, $>$25 kev, and $>$30 kev, were installed in a third beamline to investigate the characteristics of EUV and hard X-ray radiation. Time-integrated and time-gated X-ray and EUV spectra from four spectrometers were used to study the values and evaluation of the plasma electron temperature and density. Further, optical diagnostics included a streak camera, a one-frame ICCD camera with a temporal resolution of 2 ns, and laser shadowgraphy performed at a wavelength of $\lambda = 532$ nm in four time-shifted frames of 0.2 ns duration each. The synchronization accuracy for all diagnostics was within 1–2 ns.

3. Radiative properties of compact multi-planar and cylindrical wire arrays

We focus here on investigation of Z-pinch plasma implosion and stagnation stages for different wire-array configurations. The spectral modeling has been used for plasma stagnation stages' parameters simulation [21].

The new classification of multi-planar wire arrays studied in past and present articles is shown in Fig. 1. It includes previously tested SPWA, DPWA (with straight wires), new TPWA and CPWA, novel prism-like triangle planar wire array (PPWA), and a new modification of DPWA with skewed wires, which will be described below. Most of multi-planar arrays belong to an open magnetic configuration, while PPWA represents a closed magnetic configuration. Specifically, in an open magnetic configuration (single, double, or triple PWAs), wire rows are parallel to each other and a magnetic field may exist inside the array from the initiation of the discharge. A closed magnetic configuration (PPWA), eliminates the global magnetic field inside the array before the plasma flow starts.