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New Paradigm: Controlling Initiation Phase is Necessary for Optimization of Wire-Array Z-Pinch Performance

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ABSTRACT

The initiation phase of a wire-array is of paramount importance for achieving an axially homogeneous z-pinch and reproducible, high x-ray power. The significance of wire-array initiation during current prepulse for z-pinch performance has not been widely acknowledged. To achieve new levels of progress in wire-array z-pinch physics it is necessary to accept the importance of initiation physics, and to implement diagnostics of array initiation. This communication provides a brief review pointing out the need to control the initiation phase of a wire array for optimum z-pinch performance, and suggesting why multi-MA wire-array z-pinch experiments fail to meet MHD expectations.

CONTENTS

FIGURES

I. INTRODUCTION

The most powerful laboratory source of x-ray radiation is based on the wire array z-pinch [1]. An axial plasma column is formed from the individual ablating metal wires comprising the array. The degree of magnetic compression of the axial plasma cylinder depends on both its azimuthal and axial symmetries, with improved symmetry resulting in increased x-ray power. The azimuthal symmetry of a z-pinch depends essentially on the number of wires comprising the array: a larger number of wires leads to better azimuthal symmetry [2,3]. A z-pinch's axial symmetry primarily depends on the wire-array initiation. We do not consider in this brief communication the issue of small-scale axial inhomogeneity that should also be controlled to get good compression and high x-ray power. Recent investigations [4,5] show two main wire-initiation effects during the current prepulse that impact the axial symmetry of ablation of the wire array: the polarity effect [6,7,8] and the current rate effect [9,10,11].

II. POLARITY EFFECT

Effective Joule heating of a wire core occurs up to the moment of plasma generation (breakdown). After breakdown the current switches from the wire core to a low-resistance plasma surrounding the wire. Before breakdown, a strong radial electric field can enhance or prevent electronic emission from the hot wire surface. Enhanced electronic emission contributes to earlier breakdown of surrounding vapor. The moment of breakdown varies along the wire length due to axial variation of the radial electric field. Later breakdown enables higher temperature of the wire core by prolonged Joule heating. Hence, an axial variation of the radial electric field maps to an axial variation of the wire temperature at breakdown- the so-called polarity effect [6,12].

III. CURRENT-RATE EFFECT

Faster energy deposition into a metal wire leads to more energy absorption before breakdown. This behavior constitutes the current rate effect [9], and it is related to the inertia of metal/impurities vaporization. Joule heating by a faster current brings the wire to a higher temperature before a breakdown-level vapor density has time to develop around the wire. Higher temperature of the wire core also reduces the polarity-effect induced inhomogeneity [13].

IV. ABLATION SYMMETRY VS. CORE CONDITION

After breakdown a wire core remains in either a solid, melt, liquid, or a vaporized state [13]. Breakdown that occurs during melting produces the greatest disturbance to axial ablation symmetry. A melting wire is axially phase-inhomogeneous [13]. Liquid metal expands in the form of submicron drops surrounded by vapor [14]. The melted parts of the wire expand and ablate faster than its solid parts, because the ablation rate is proportional to the ablating surface [15]. In contrast, an axially uniform homogeneous ablation has been observed from wire cores that were totally in a hot liquid state at breakdown [5]. Breakdown during a hot liquid state can be achieved by applying an appropriately fast–rising prepulse current. The optimal current rate per wire must be appropriate for transforming wire cores to a *hot liquid state,* and depends on metal type [9]: it is relatively fast (dI/dt~100-150 A/ns/wire) for refractory metals like W; and slower (dI/dt~20-50 A/ns/wire) for non-refractory metals like Al, with a wire diameter ~10-20 μm for either metal. An applied current rate high enough to rapidly transform the wire cores into a gas-plasma state will eliminate the uniformity of the ablation phase [5], leading to an axially non-uniform implosion and weak x-ray power.

V. COLD CORE VS. HOT CORE

Recent results from 1-μs/6-MA Sphinx [16] show increased X-ray radiation by controlling the initiation phase of an Al array explosion. A homogeneous condition of the wire cores was achieved in [16] using 8 specially designed prepulse generators which support ultra slow heating (dI/dt~0.002 A/ns/wire, heating time ~4 μs) with resulting low-voltage (~100 V/cm) breakdown of hydrocarbon impurities before Al melting. After breakdown the Al wires were in a homogeneous solid state (T~ 600 K), leading to axially symmetric ablation and enhanced X-ray yield. A liquid wire core ablates for a shorter time than a solid core owing to its larger expansion velocity. This means a liquid core (short-time ablation) is more appropriate for ~100-ns current accelerators, while a solid core (long-time ablation) can be an effective ablator for ~1-μs accelerators. Moreover, increasing the initial liquid wire core temperature (increasing the expansion velocity and therefore the ablation rate), allows one to effectively regulate the ablation time to match it to the time of implosion for obtaining the highest peak X-ray power [17,18].

V. CONCLUSION

For the same prepulse current, one cannot increase indefinitely the wire number to achieve better azimuthal symmetry without degradation of the axial symmetry, due to decreasing of the current rate per wire [3,5,19]. Also, smaller-diameter wires, typically employed in larger-wire-number arrays, produce stronger radial electric fields that would require higher current rates per wire to minimize polarity-effect induced axial inhomogeneity. So, an appropriate current-rate-per-wire prepulse (for axial symmetry), combined with the largest possible wire number (for azimuthal symmetry) that allows the necessary current rate per wire, results in the creation of the most symmetrical plasma cylinder possible, critical for final magnetic compression and X-ray power. Symmetrical ablation must be maintained for any parameter-scan experiments in order to best observe expected scaling relationships [18]. Experiments designed to maximize x-ray power by varying load parameters as suggested by MHD simulations have failed to demonstrate the predicted behavior [19] probably because the symmetry conditions assumed in the simulations were violated when the optimum wire-initiation requirements were no longer met.

The symmetrical geometry of a wire-array does not automatically guarantee symmetrical ablation. To obtain symmetrical ablation the initiation phase of the wire array must be appropriately controlled.

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VIII. APPENDIX

Monitoring and improvement of ablation symmetry of wire arrays on the ZR-accelerator

Simple diagnostics of ablation symmetry and tools for optimization of wire array initiation can be proposed for wire-array experiments on the upcoming ZR accelerator. Figure 1 presents a schematic of the typical cathode-anode plate with a wire array. Main B-dots allow measurement of the large 28-MA current, while a prepulse B-dot, mounted in the wall of the current return can, has greater sensitivity to measure the small prepulse current. A plastic insert on the high-voltage cathode would operate as a flashover switch with internal breakdown [4,5]. This switch can be used to change the prepulse current rate. The external surface has a longer flashing length than the internal. This should lead to surface breakdown across the internal surface rather than over the external. This important design feature avoids early plasma generation in the narrow ~5 mm MITL gap and thereby prevents a short circuit upstream of the wire array load.

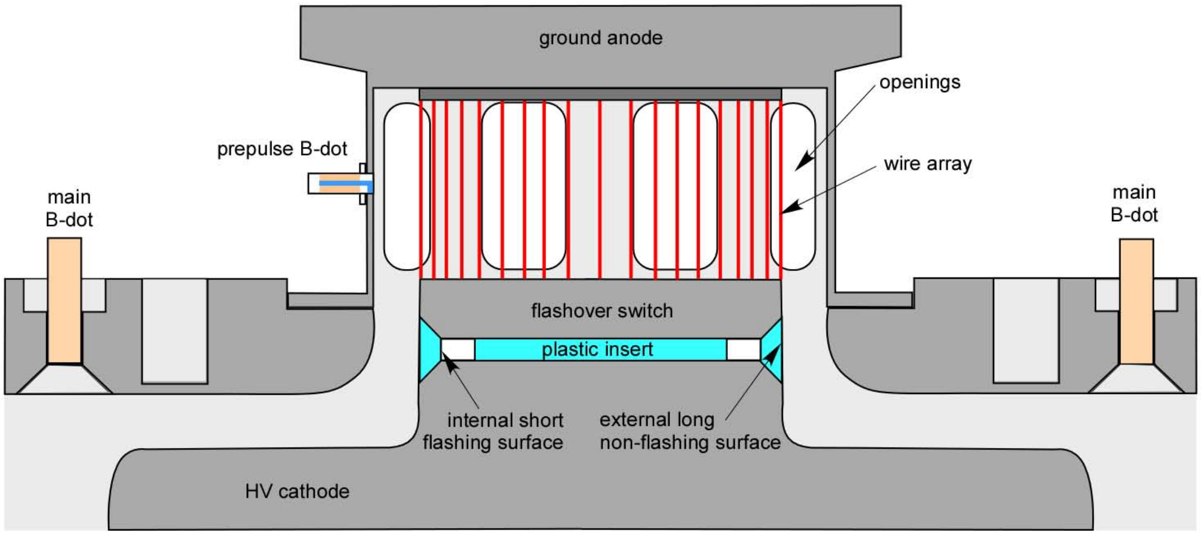

Figure 1. Experimental setup with flashover switch and prepulse B-dot for ZR.

Figure 2(a) shows the setup for a 6-directional observation of the axial symmetry of the wire-array-breakdown light and later ablation plasma-light emission. Because of the 4-5 order of magnitude difference between breakdown and plasma light emission, the registration of the light at the end of the optical fiber must be done using two fast photo-diodes with different attenuation filters. For a double array load, the number of channels

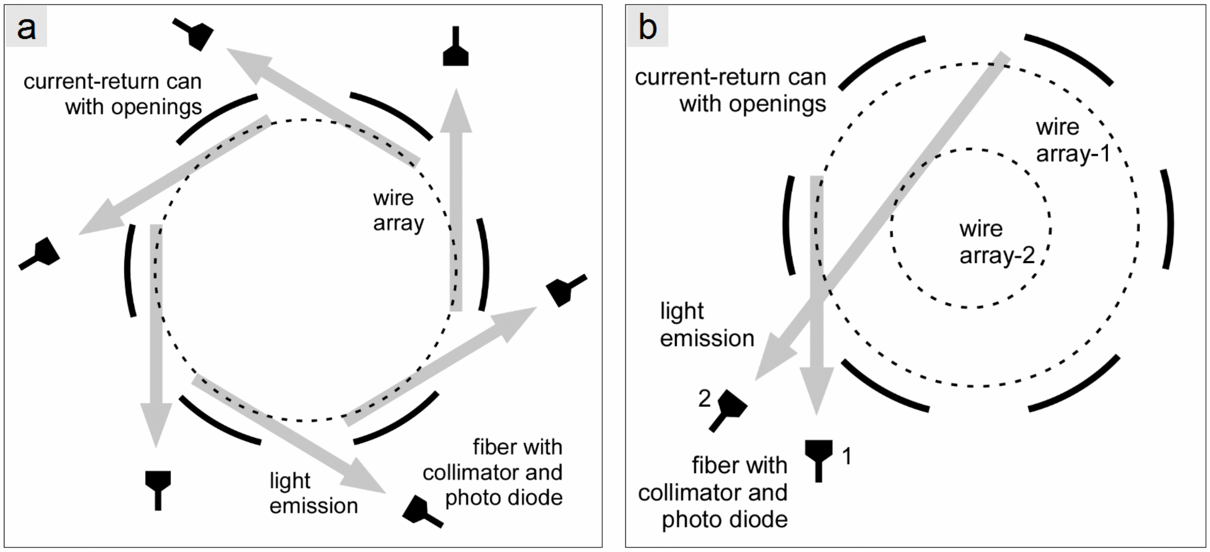

Figure 2. Experimental setup for monitoring of the light emission symmetry at ZR.

should be twice what is needed for a single array as shown in Fig. 2(b). This diagnostic setup allows estimating the axial homogeneity of initial energy deposition into a wire array before plasma generation as well as axial homogeneity of the array ablation. The state of the wire cores (solid, liquid, or gas-plasma) at the moment of breakdown can be estimated using the current prepulse waveform and the time and amplitude of the breakdown light emission spike.

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