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### X-ray pulse shaping in experiments with planar wire arrays at the 1.6 MA Zebra generator

# V L Kantsyrev<sup>1</sup>, A S Safronova<sup>1</sup>, A A Esaulov<sup>1</sup>, K M Williamson<sup>1</sup>, I Shrestha<sup>1</sup>, G C Osborne<sup>1</sup>, M E Weller<sup>1</sup>, M F Yilmaz<sup>1</sup>, N D Ouart<sup>1</sup>, V V Shlyaptseva<sup>1</sup>, A L Velikovich<sup>2</sup> and L I Rudakov<sup>3</sup>

<sup>1</sup> Physics Department, University of Nevada, Reno NV 89557
<sup>2</sup> Naval Research Laboratory, Washington, DC 20375
<sup>3</sup>Icarus Research Inc., Bethesda, MD 20824

E-mail: victor@physics.unr.edu

**Abstract**. The shaping of the x-ray radiation pulse is very important in both radiation physics research and Inertial Confinement Fusion studies. The novel planar wire array (PWA) was found to be the effective radiator tested at the university-scale 1.6 MA, 100 ns Zebra generator. The single PWA consists of a single row of wires that are parallel to each other, while the double planar wire array (DPWA) and triple planar wire array (TPWA) include two or three parallel plane wire rows, respectively. All multi-planar geometries resulted in a cascade-type array implosion with a complicated multi-step precursor formation before plasma stagnation. The PWAs (without additional core foam target) feature a dynamic precursor evolution that is a powerful tool for x-ray pulse shaping. The shape and timing of the x-ray pulse from different PWAs were theoretically predicted and experimentally analyzed for a variety of planar wire arrays.

#### 1. Introduction.

The shaping of the x-ray radiation pulse from wire array implosions is needed for both radiation physics and Inertial Confinement Fusion (ICF) studies [1]. It is as important as the efficiency magnetic energy conversion to x-ray radiation, x-ray peak power and the source size. Ideal Z-pinch soft x-ray (in sub-keV spectral region) power history for three-step pulse ICF scheme includes the first prepulse 20-25 ns before x-ray peak, the foot prepulse (step) on the front of the main x-ray burst, and the main burst. The energy in prepulses should be 15-20 % from the main burst radiated output [1]. X-ray pulse shaping experiments were performed early with nested cylindrical wire arrays with a load core foam target [2]. Implosions of novel planar wire array (PWA) have been investigated since 2005 [3] with single- or multi-planar wire rows placed in the center of the z-pinch chamber between anode and cathode. It has shown to be a compact x-ray source with appropriate radiation pulse shaping. The PWA's radiation yields exceed that from kinetic energy conversion  $E_K$  ( $E_K < 4-6$  kJ) in 3-5 times, and mechanism of energy coupling is enhanced resistivity of the strongly inhomogeneous plasma (Hall MHD physics) [4]. Double Planar Wire Array (DPWA) with straight wires is currently the best [6] 2010 IOP Publishing Ltd

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radiator at 0.8-1.4 MA current. It is characterized by the combination of highest yield, power, mmscale size, and low opacity effects [5, 6]. At 1 MA current, PWAs show comparable yield and power with another loads, compact cylindrical wire array (CCWA) [7]. However, DPWAs demonstrate substantial advantages over cylindrical wire arrays, for example, they have near quadratic load peak current scaling for yields and powers while CCWA has shown only lower than linear scaling (in 1-5 MA peak current range) [6, 8].

All multi-planar array geometries (without additional core foam target) resulted in a cascade-type wire array implosion with a complicated multi-step precursor formation before stagnation [4, 5]. The sub-keV prepulses generated during precursor formation can be applied for radiation pulse shaping [5, 6]. Another possibility for radiation pulse shaping in multi-planar arrays is based on the fact that plane wire rows imploded independently generating sub-keV prepulses in different times (especially when rows have different initial mass or were made from different materials) [5, 6].

Precursor plasma in multi-planar arrays is formed in multi-steps with some locations not coinciding with the stagnating plasma column position [5]. Typically, primary precursor appeared as early as 40-50 ns before x-ray peak, but at this step emitted radiation is not strong enough to form a prepulse [5]. Secondary precursor formation occurred during the final moments of independent implosion of wire rows and appeared as double plasma columns 10-15 ns before the main x-ray peak is clearly seen even in 1 keV time-gated images [5, 6] (Fig. 1). To observe such images as well as 1 keV precursor images in experiments with different cylindrical wire arrays [3, 9], temperature Te of precursor must be more than 200-250 eV. Recent experiments have proved it: Te > 400 eV and Ne =  $10^{19}$  cm<sup>-3</sup> were found in cylindrical low-wire-number Cu precursor plasmas on Zebra generator [10]. Up to 20 % of L-shell emissions were associated with the precursor. This means that precursor plasma emits strong x-rays to form prepulse and can be applied for radiation pulse shaping from z-pinch plasma.

### 2. Variation of sub-keV prepulse shape with changing PWA geometry and elemental composition

Experiments were performed on the 1.6 MA, 100 ns Zebra generator at UNR. The diagnostic includes filtered PCD (keV region) and XRD (sub-keV region) detectors, x-ray time-gated and time-integrated imaging, and time-integrated spatially-resolved and time-gated spatially-integrated x-ray spectrometers [3, 6].



Figure 1. Experimental results from asymmetric W/Al DPWA with an inter-row gap  $\Delta$ =3 mm: a) the data curves are signals from the current, XRD, and PCD detectors. W<sub>th</sub> is the total radiation yield predicted by WADM and the total experimental yield W<sub>exp</sub>= 18.6 kJ. At the top are positions of frames of time –gated x-ray pinhole camera. b) The time-gated x-ray plasma images obtained with microchannel plate (MCP) detector (1 keV is at the top, 3keV is at the bottom, anode is at the bottom in each row).

The promising results were obtained from asymmetric DPWA with straight wires where plane rows were made from different materials, for example, one row made from Al, and another made from W wires. It was seen that sub-keV prepulse was generated during the secondary precursor formation (double column in frame 1, Fig. 1, b). Experimental results were compared with Wire Ablation Dynamic Model (WADM) simulation [11]. Difference between the predicted  $W_{th}$  and observed  $W_{exp}$  yields can be explained by another energy coupling mechanism that turns on at stagnation stage because WADM takes in account only transformation of kinetic energy into radiation.

DPWA with skewed wires is another load where sub-keV prepulses are generated during precursor formation. Such z-pinch load is a way to mitigate RT instabilities and to provide more control of x-ray generation by creation an axial magnetic field between wire rows [6]. In skewed DPWA the electron temperature Te is higher than in a standard DPWA [6]. Reverse skew angles for opposite wire planes create axial solenoid-type  $B_z$  field (Fig. 2, a).



Figure 2. Implosion characteristics of Al DPWA with skewed wires (inter-row gap  $\Delta$ =6mm and angle between wires is 28°): a) WADM prediction of positions of secondary precursor plasma columns (in white) before stagnation (original wires positions shown as black dotted lines). Direction of observation is under 45° to wire row plane. Azimuthal field  $B_{\parallel} = 25$  T (outside) and axial field  $B_z = 8$ T (inside load) when current reached I = 0.5 MA. b) X-ray time-gated images: at the top >3 keV, at the bottom >1keV. Frame duration is 3ns and interframe interval is 6 ns. Observation is under 45° to wire row plane. The time is in ns before x-ray peak. c) WADM simulation vs experiment. W<sub>th</sub> is the total radiation yield predicted by WADM and W<sub>exp</sub>.> 8 kJ is experimental sub-keV radiation yield.

After appearance of secondary precursor columns (Fig. 2, b) they start to merge firstly from the center of the anode-cathode gap to form an x-ray burst. A central part of the skewed DPWA implodes several ns earlier than the rest of the array, forming the x-ray prepulse. WADM simulation of the x-ray pulse shape vs experiment with skewed DPWA has shown good correlation of prepulse shape and amplitude. Difference between  $P_{pred}$  and  $P_{exp}$  at the x-ray peak can again be explained by another energy coupling mechanism that turns on at stagnation stage.

Another perspective load that provides a possibility of radiation pulse shaping is a triple planar wire array. The prediction of radiation pulse shape for Al triple planar wire array was made with WADM model (see Fig. 3).



Figure 3. Implosion characteristics of Al (5056) TPWA with distributed mass. Number of wires 8 x 8 x 8. Mass distribution: 2:1:2 (wires diameter: 15  $\mu$ m / 10  $\mu$ m / 15  $\mu$ m.) W<sub>th</sub> is the total radiation yield predicted by WADM. W<sub>exp</sub>> 17 kJ is the experimental total radiation yield.

Planar wire rows in triple planar wire arrays are imploded independently generating sub-keV prepulses in different times to form a joint foot prepulse in front of the main x-ray burst. Predicted foot prepulse (step) in front of the main x-ray burst was found in good agreement with simulation.

#### 3. Conclusion.

All multi-planar wire array geometries resulted in a cascade-type implosion with a complicated multistep precursor formation before stagnation. The PWAs feature a dynamic precursor evolution that may be a powerful tool for x-ray pulse shaping. The PWA has demonstrated possibility of radiation pulse shaping. Experiments with multi-planar wire arrays such as double planar array with straight and skewed wires and triple planar array, have shown results that are in qualitative agreement with theoretical simulations.

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