Commissioning of a Rotated Wire Array Configuration for Improved Diagnostic Access (October 2014)

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***Abstract*—A new rotated wire array z-pinch configuration has been developed for use in experiments on the Magpie generator at Imperial College London. The wire array is rotated onto its side such that the array axis lies perpendicular to the axis of the pulsed power electrodes. This arrangement provides greatly improved end-on diagnostic access to the array and has a number of potential experimental applications; the design has recently been used to make novel Thomson scattering measurements of ablation flow interactions in tungsten wire arrays. Turning the wire array on its side leads to an uneven distribution of current through the wires, due to the variation in the inductance of the current path through each wire. The forces acting on each wire will therefore be imbalanced, leading to uneven ablation of the wire cores. An experimental campaign was carried out in order to inductively re-tune the current distribution in the wire array. The results of these experiments are presented, along with discussion of potential future experimental applications.**

***Index Terms*—Laser Imaging, Plasma Devices, Thomson Scattering, Wire Array, Z-Pinch.**

I. INTRODUCTION

Wire array z-pinch implosions are employed routinely as powerful and energetic sources of both soft x-ray [1] and k-shell radiation [2]. Peak radiative powers of up to 280 TW and yields of up to 1.8 MJ [3] have been achieved in experiments on the 20 MA Z-machine [4] at Sandia National Laboratories Albuquerque, NM. Applications of these radiation sources include experiments in fields such as inertial confinement fusion [5], laboratory astrophysics[6] and radiation science [7].

One of the main barriers to fully understanding the dynamics of wire-array implosions has historically been a lack of diagnostic access to the experiment; inductance considerations meant load designs used on high current generators such as the Z-machine required closely coupled current-return cans and views of the wire array in these experiments were restricted to thin slots cut in this can. Diagnostics were largely limited to measurements of the x-ray power and energy, and to imaging of the emission structure of the stagnated pinch. A great deal of progress in advancing the understanding of the plasma dynamics of wire array implosions was made on lower current, higher impedance generators such as Magpie[8] (1.4 MA, 240 ns) at Imperial College London, Cobra[9] (1 MA, 100 ns) at Cornell University, Zebra[10] (1.7 MA, 100 ns) at the University of Nevada, Reno, NV and Angara-5-1[11] (4 MA, 100 ns) at the Kurchatov Institute. The higher output impedance of these

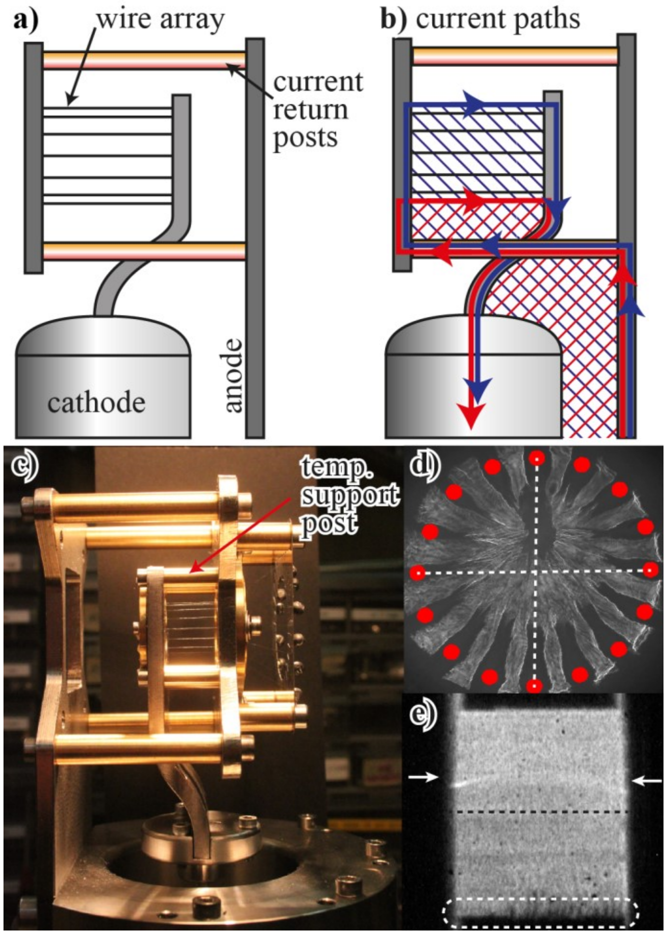

Fig. 1. Initial horizontal array hardware design. a) hardware schematic. b) examples of current paths through top (blue) and bottom (red wires). Areas enclosed by these current paths are hatched in respective colours. c) Photograph of horizontal array ready for installation into MAGPIE. Temporary support posts are still in place to support the weight of the cathode during installation. d) End-on shadowgram (red dots mark initial wire positions) and e) side-on gated XUV emission. In this image the position of the array axis is indicated by a black dashed line.

devices allowed experimenters to move the return current out to larger radii, and to channel it through discrete return posts, providing clear lines of sight to the entire array for the duration of the experiment. Among other things, the work on these machines led to a deeper understanding of the importance of the wire ablation in the early phase of wire array evolution[1], [12], [13].

One of the major remaining diagnostic access limitations in wire array experiments is access to so called “end-on” views of the array; these are the views that lie parallel to the array axis, providing an axially integrated view of the radial-azimuthal plane of the array. End-on views have a number of advantages over side-on views; the plasma is unobscured by the dense, strongly emitting wire cores, and interpretation is often much easier, as methods such as Abel inversion are not required in order to properly analyse the data. In a typical experimental configuration the cathode end of the wire array is blocked by the presence of the generator. Whilst a hollow anode may be employed to provide access for diagnostics sensitive to plasma self-emission, such as optical emission imaging, optical streak imaging, gated and time integrated x-ray imaging etc., fielding diagnostics which require active backlighting, such as laser interferometry, x-ray absorption imaging etc. is more difficult. Previous experiments have overcome these limitations to some extent. Mirrors placed in the cathode have been used to make laser probing measurements of the axially integrated electron density in the pinch during the ablation phase [12], [14], [15] and end-on x-pinch-driven point projection x-ray backlighting measurements of mass density in wire arrays [16] has been carried out by connecting an x-pinch and z-pinch in series, and positioning one above the other.

In this paper we present a new rotated wire array configuration, which allows an unprecedented degree of diagnostic access to the end-on line of sight through wire arrays. A schematic of the hardware design is shown in Fig. 1. a). This configuration has recently been used to make detailed Thomson scattering measurements of the flow velocity vectors in tungsten wire arrays[17], [18] and has many other potential diagnostic applications. While the experiments carried out using this configuration so far have been designed primarily to study the interactions of plasma streams during the “ablation phase” (the phase where the wire cores remain stationary), this configuration also has potential applications in the study of implosion and stagnation phase physics. In particular, it may be used to make quantitative measurements of the density and structure of the trailing mass left behind by the implosion. The increased inductance of the load hardware in this configuration means that the peak current through the wire array, and therefore radiative yields and powers, will be reduced (this effect should be small on Magpie thanks to its large 1.25Ω output impedance). It should be noted that the point of this apparatus is not to optimise these parameters but rather to gain a better understanding of the underlying dynamics.

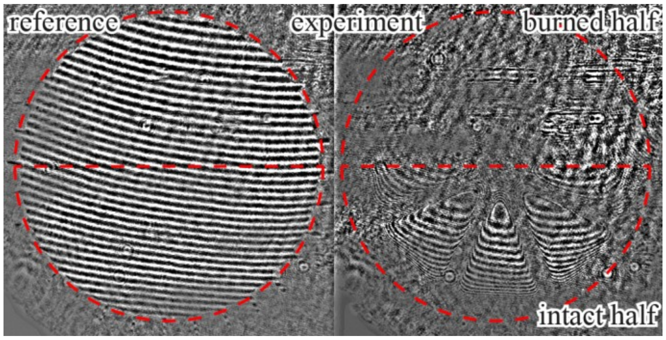

Fig. 2. Example of the effects of mirror burn-through. Left reference interferogram, right, experimental interferogram. The top half of the experimental interferogram is obscured due to burn-through of the top half of the mirror.

II. HORIZONTAL ARRAY HARDWARE DESIGN & INDUCTIVE CURRENT BALANCING

The design of a new wire array hardware configuration was initially driven by the need to improve diagnostic access to the end-on view of the wire array interior. In previous experiments on the Magpie generator end-on laser interferometry measurements of ablation stream interactions were made possible by placing a mirror inside the cathode, either horizontally to produce a double pass Michelson-Morley interferometer [12] or at 45° and to produce a Mach-Zehnder configuration [14], [15]. This technique was successful at early times in the ablation phase, however the lifetime of the cathode mounted mirror was limited to times before the collapse of the precursor column[19], which typically occurs in Magpie experiments at around ~160ns. At this time an intense pulse of radiation is released which “burns-through” the mirror surface, destroying its reflectivity. The effect is illustrated in Fig. 2., which shows an interferogram captured 160ns into the 240ns Magpie current rise-time, approximately the time of precursor collapse. This image was captured half way through the process of mirror burn-through. The mirror was mounted at 45° in the cathode in this experiment, such that the distance from the mirror to the pinch varied continuously across it. At this point only the half of the mirror closest to the pinch has burned-through, and so only the portion of the interferogram that should have reflected off this half has been lost. Turning the entire array on its side obviates the need for a mirror by providing a straight through, end-on view of the array and so solves this problem.

A schematic of the initial design for the rotated array hardware is depicted in Fig. 1. a), and a photograph of the hardware ready for installation is shown in c). The short rise-time of the Magpie current pulse (~240 ns) means that inductive rather than resistive division dominates the distribution of current between the wires and return posts. In normal wire array experiments using conventional hardware designs the intrinsic cylindrical symmetry of the anode, wires and cathode ensures that current is more or less evenly distributed between the wires (assuming all the wires are of the same diameter and made of the same material). Fig. 1. b) shows examples of the current paths that might be expected in the rotated array. These paths represent the lowest inductance paths for current flowing though both the top (blue line) and bottom (red line) wires. This diagram is a gross simplification of the true situation, as it ignores the current paths through the upper pair of return posts, however it is still useful for illustrating the problem. All else being equal, the difference in the inductance of the two current paths may be thought of roughly in terms of the areas enclosed by each of the current loops. The area marked by blue hatchings thus corresponds roughly to the inductance of the current path through the top wire, while the area marked with red hatchings corresponds to the inductance of the current path through the bottom wire. The inductance required to drive the bottom wire is clearly smaller, and as a result it should be expected that a greater fraction of the drive current will flow through it than through the top wires.

An experiment, diagnosed using a combination of end-on laser shadowgraphy and side on gated extreme ultra-violet (XUV) self-emission imaging[20], was carried out using a 20mm long, 16mm diameter cylindrical wire array consisting of 16 evenly distributed 13 µm Ø tungsten wires. The data recorded in this experiment are shown in Fig. 1. d) and e). These images were captured ~180ns into the 240ns Magpie current pulse. The initial wire positions in the end-on shadowgraph are marked by red dots, and the position of the collapsed precursor column is indicated in the side-on XUV emission image by a pair of white arrows. Both images indicate that the collapsed precursor column has formed significantly above the array axis, which is consistent with a greater fraction of the drive current flowing in the lower wires. Assuming that the ablation velocity remains constant, the increased current and corresponding locally enhanced magnetic field should increase the mass ablation rate of the bottom wires with respect to the top wires, which in turn should increase the dynamic pressure these flows impart on the central precursor plasma. The increased dynamic pressure from the bottom wires should result in a shift in the centre of mass of the prefill plasma, which should in turn result in a displaced collapsed precursor column; the effect is discussed in greater detail in [21]. Further evidence of enhanced current in the bottom wires is seen in the XUV emission image in Fig. 1 e); at the bottom edge of the array, in the region highlighted by the white dashed box, breaks in the wires appear to have formed, whilst the wires along the top edge appear to remain intact. This is again consistent with a greater mass ablation rate in the bottom wires, as these wires have clearly ablated a larger fraction of their mass at this time.

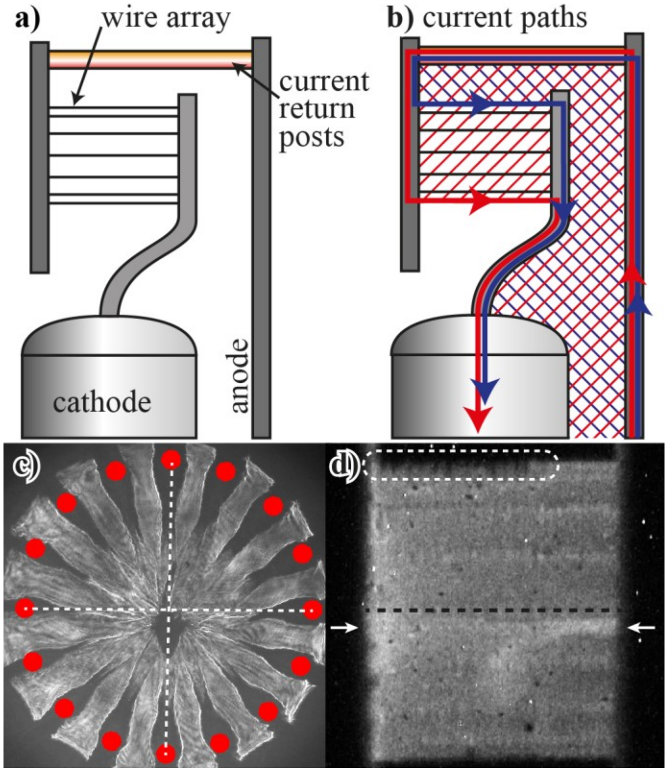

Fig. 4. Modified horizontal array hardware a) hardware schematic with lower return posts removed. b) modified current paths through top (blue) and bottom (red wires). Areas enclosed by these current paths are hatched in respective colours. c) End-on shadowgram (red dots mark initial wire positions) and d) Side-on gated XUV emission. In this image the position of the array axis is indicated by a black dashed line.

The first step to correct this problem was to prove that the current distribution in the array could be controlled. The most straight-forward method of achieving this was to remove the two lower current return posts from the array hardware, as illustrated in Fig. 4. a). This change in the configuration of the current return path should have the effect of reversing the imbalance in the array inductance seen in the previous experiment. Fig. 4. b) shows the new current paths; as before the inductance of the path through each wire is roughly related to the area enclosed by that path. In this configuration the red hatched area is larger than the blue hatched area and therefore the inductance of the top wires should now be smaller than that of the bottom wires. Assuming that our previous arguments hold, this change in the relative inductance of the wires should cause the collapsed precursor to form below the array axis. An experiment was carried out using this modified

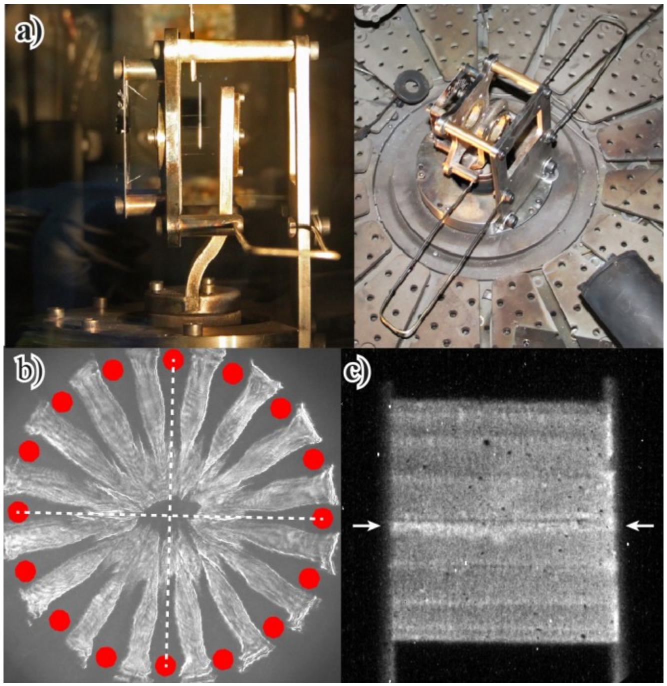

Fig. 3. Horizontal hardware with inductive correction “wings”. a) Photographs of the hardware with “wings” installed b) End-on shadowgram (red dots mark initial wire positions) and c) side-on gated XUV emission.

return post configuration, with no other changes to the wire array load or the diagnostic probing time; the results are shown in Fig. 4. c) and d). As expected the collapsed precursor column is now displaced below the array axis, albeit not as far below the axis as it was above the axis in the previous experiment. Inspection of the XUV emission image in d) reveals that breaks are now forming earlier in the wires at the top of the array (highlighted by a white dashed box); again this is consistent with a greater mass-ablation rate in the top wires than in the bottom wires, and by extension with a greater current fraction flowing in the top wires than in the bottom wires. The results of this experiment indicated that it should be possible to control and correct the current distribution by tuning the inductance of the lower return posts.

The final experiment employed a pair of modified lower current-return posts; instead of simple posts, these consisted of a pair of high inductance “wings” constructed from 1.8 mm Ø brass rod. These “wings” should allow a small amount of current to flow through to the bottom return posts; control of the size and therefore the inductance of these “wings” should allow the experiment to be tuned in order to produce a symmetrical current drive. Photographs of the experimental

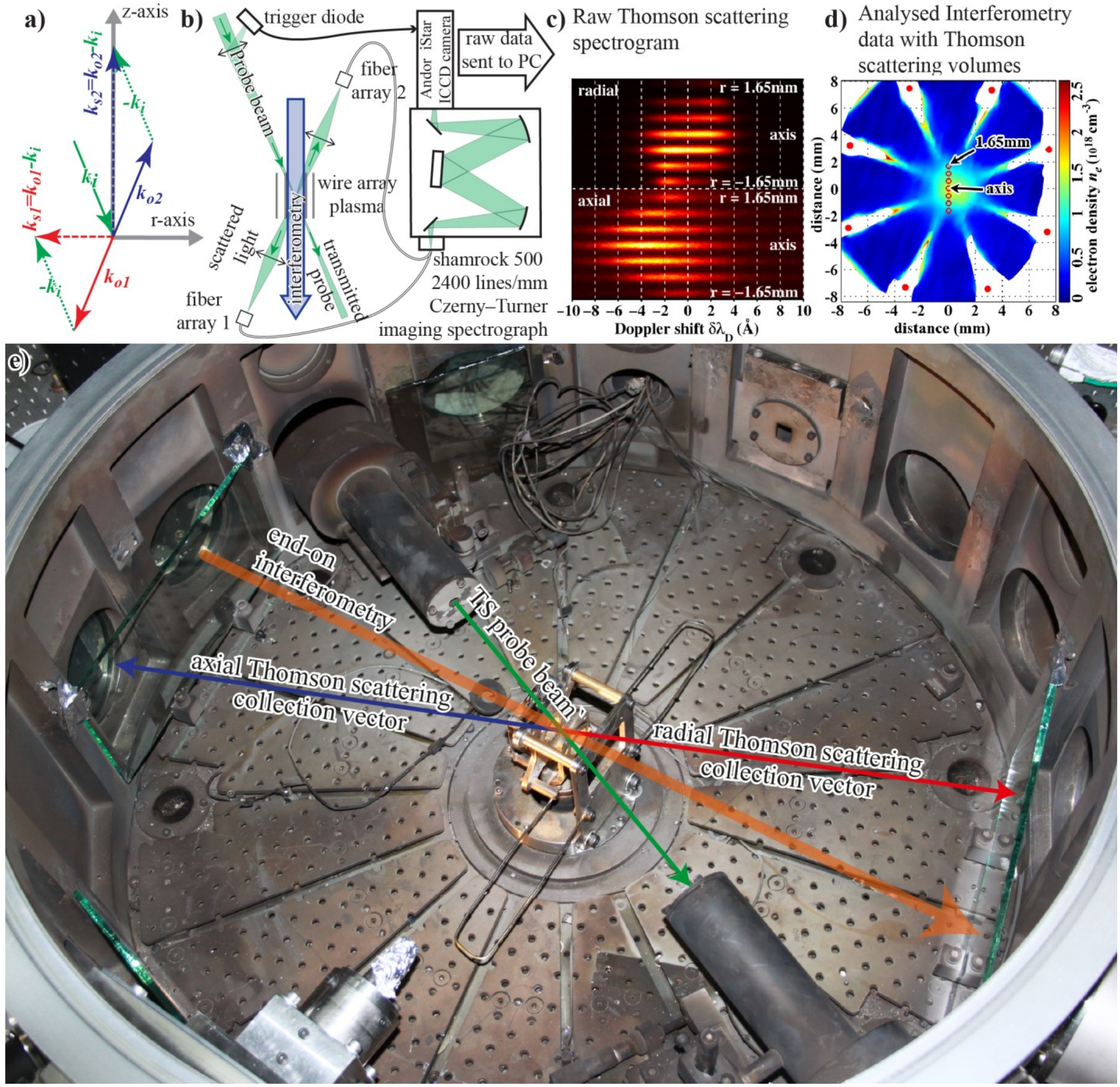

Fig. 5. a) Thomson scattering geometry. Probe enters with wave vector k_i, scattering collected along wave vectors k_{o1}, k_{o2}, resulting in scattering vectors k_{s1} in the radial direction and k_{s2}, in the axial direction. b) schematic diagram of the experimental setup. c) Raw Thomson spectra. d) electron density distribution extracted from end-on interferometry. Scattering volumes indicated by red circles, initial wire positions by red dots. e) Photograph showing experimental setup employing horizontal array hardware. Parts a), b) reproduced with permission from Swadling *et al.* Rev. Sci. Instrum., 85,11E502 (2014) and parts c), d) reproduced with permission from Swadling *et al* . Phys. Rev. Lett. 113, 035003 (2014).

hardware with these "wings" installed are shown in Fig. 3. a) and experimental data is shown in b) and c). Again no changes were made to the wire array load or diagnostic probing times. These data clearly indicate that we have succeeded in moving the collapsed precursor column back to the array axis. Looking carefully at the XUV emission data in c) we can see that the self-emission from the precursor column is now back-lighting the wire core in front of it. This wire was aligned to obscure the axis and may therefore be used as a diagnostic to confirm that the collapsed precursor has indeed returned to the axis.

III. APPLICATION TO THOMSON SCATTERING EXPERIMENTS

The first experimental application for the horizontal wire array was a campaign designed to study the dynamics of ablation stream interactions in the precursor region of tungsten wire arrays [17], [18]. The main aim of these experiments was to use a novel scattering geometry which would allow simultaneous measurements of the radial and axial (with respect to the wire array) velocity components of the ion velocity distributions. These measurements required scattered radiation to be collected at acute angles both above and below the wire array; this would be technically very difficult to achieve using a conventional wire array configuration.

The Thomson scattering geometry used in these experiments is shown in Fig. 5 a), and a schematic of the overall experimental setup is shown in b), the raw Thomson scattering spectra measured in the experiment are shown in c) and an electron density map extracted from simultaneous end-on interferometry is shown in d). The red rings superimposed over the electron density data indicate the positions of the volumes from which the Thomson spectra were collected. Analysis of these Thomson spectra not only revealed long scale plasma flow interpenetration in the axial interaction region, but also revealed a previously unobserved axial deflection of the ablation streams as they approached the array axis[17]. Fig. 5 e) contains a photograph of the actual experimental layout used in these experiments; the arrows overlaid on this photograph indicate the various diagnostic lines of sight. The horizontal configuration of the wire array vastly simplified alignment of the Thomson scattering diagnostic, while also allowing simultaneous interferometry of the wire array interior, even at late times.

IV. CONCLUSION AND NOTES ON APPLICATIONS

A novel rotated wire array configuration has been developed. This configuration provides improved diagnostic access to the end-on view of the array, allowing a straight-through line of sight which facilitates the use of backlight-driven diagnostics. Control of the distribution of current through the wires in the array has been demonstrated via inductive tuning of the lower current return posts and symmetric current drive has been achieved using this method.

The new configuration was used in a recent experimental campaign to study the interactions of ablation streams in tungsten wire arrays. The double-sided end-on access to the array plasma afforded by the rotated array allowed simultaneous measurements to be made of the axial and radial components of the ion velocity distribution, greatly increasing the value of these measurements. In particular this has led to the discovery of an axial deflection of the ablation streams as they approached the array axis[17].

The horizontal array configuration will be of great value in future experiments. It will extend the range of experimental times over which laser interferometry may be used to study ablation flow interactions, and opens up the possibility of using interferometry to study trailing mass dynamics during array stagnation. It also provides an ideal platform for x-ray backlighting experiments. In particular this configuration may be used in conjunction with a new mono-chromatic x-ray backlighting diagnostic currently under development [22] in order to make quantitative measurements of the ablation mass density. Combining mass density measurements with electron density measurements made via interferometry would lead to a direct measurement of the plasma average ionisation state ($\bar{Z}$). This parameter is notoriously difficult to measure in high atomic mass plasmas (e.g. tungsten), where spectroscopic techniques may be unsuitable due to the high density of atomic lines. These measurements could be particularly useful as a validation test for the atomic models used in many simulations.

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