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Responses to questions from *Wire Journal International* editor
Questions forwarded from Neal Singer
Answers supplied by Brent Jones
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About *Wire Journal International:* WJI is the monthly trade publication published by Wire Association International, a non-profit association now in its 76th year of serving international wire and cable professionals. *WJI* has circulation of about 13,000 to readers in 99 countries. WAI, which has some 2,500 members and chapters in the U.S. as well as Poland and India, each year organizes an international technical event, most recently in The Czech Republic (2005), Mexico (2004), Italy (2003), Canada (2002) and the U.K. (2001), as well as the Interwire and Wire Expo trade shows that are held in alternating years in the U.S.

Questions:

Q: I would be very interested in knowing more about the types of wire involved. Specifically, what kind of tungsten wire? What size was it? Was it alloyed?

A: Several types of wire have been used in experiments on the Z machine. The most common is tungsten wire--tungsten is high atomic number and so it radiates well in the soft x ray range, and it is strong and well suited to making small diameter wire. The size of tungsten used varies, but 5-10 micron diameter is common. This is not alloyed (it would be interesting to include a lower atomic number spectroscopic dopant in tungsten wire, but I'm not aware that such wire is available). Other types of wire used in z-pinch experiments at Sandia range in atomic number from aluminum to copper.

Q: Why was it used in the first place? Who came up with the idea to try steel wire?

A: High atomic number (tungsten) wire is the best choice for generating large amounts of x rays in the 100-1000 eV photon energy range. This is useful, for example, for inertial confinement fusion studies in which radiation from the z pinch drives the implosion of a capsule containing deuterium fusion fuel. Other applications of z pinches involve production of higher photon energies, i.e. 1000-10,000 eV. For these tests, it is best to choose a wire made of an element that will radiate these higher energy photons when the nuclei are stripped of all but one or two electrons in the hot, collisional plasma pinch. Aluminum wire arrays generate copious x rays at about 1.7 keV on the Z machine, and significant x-ray yields are produced even at about 8 keV using copper wires. Work on these types of radiation sources has a long history, and the use of stainless steel (~6.7 keV photons) is an extension of that work. The stainless steel radiation studies on Z were carried out by Christine Coverdale, Chris Deeney (now at DOE), and Brent Jones.

Q: What kind of steel wire was used (high-low- or medium-carbon)? What diameter? How long a length? What company supplied the wire?

A: The alloy used on Z was stainless steel 304L. This is used instead of pure iron as stainless steel is ductile and makes strong small diameter wires. Diameters from 8-18 microns have been used, with 10 microns being typical. Wire of all types used in arrays on Z is ordered from California Fine Wire, produced by extrusion through a series of dies, and delivered in lengths of a few hundred feet on spools about the size of a spool of thread. Technicians at Sandia have developed technology to string this wire into arrays for Z experiments with up to 600 wires (300 is typical for tungsten, ~150 is typical for stainless steel) and wire spacing as close as 100 microns. It is cut into lengths of a few feet and weighted on each end for assembly, during which the wires are hung by hand in a manner such that the weights keep tension on the wire in the z-pinch region (arrays are 10-20 mm tall, with wires spaced on 20-80 mm diameter).

Q: What exactly happened to the steel wire (versus the tungsten) when it was exposed to the 20 million amps? How long does it take to go from ambient temps to such high temps?

A: Both types of wires exhibit similar behaviors: the rising current creates sheaths of plasma around the dense wire cores which continue to ablate. The magnetic force on this ablated plasma drives it toward the axis of the wire array. At some point, the wires start to run out of mass; the cores break up and the entire array begins to implode, exhibiting characteristic instabilities. The plasma then accumulates into a dense column on the axis of what was the wire array, and generates immense x-ray radiated power as its kinetic energy (along with energy deposited through compressonal and Ohmic heating) is thermalized and then radiated away. This basic behavior is essentially the same for tungsten and stainless steel loads [See D. B. Sinars et al., Physics of Plasmas 12, 056303 (2005) for x-ray radiographs of the ablation and implosion of tungsten, stainless, and copper wire arrays on Z]. In all cases, the entire sequence of ablation, implosion, and stagnation takes about 100 ns, which is the rise time of the Z 20 MA current pulse. The radiation comes out in a main pulse lasting only a few nanoseconds (the time for the energy input into the plasma during the compression to be deposited on axis, thermalized and radiated away), with a tail at lower power due to residual heating that may last a few tens of nanoseconds. In the early phase of the current pulse, when the wires first turn to plasma, the temperatures are probably ~300,000 degrees C in the plasma that surrounds the wires. These plasma are created on nanosecond time scales, but last about half the length of the current pulse. When the pinch starts to implode, temperatures begin to rise to probably in the range of ~1 million degrees C. The thermalization of the kinetic energy (and other heating) at stagnation is what takes the plasma temperature up to the ~3 billion degrees C temperatures that were reported, and this happens on sub-nanosecond time scales. Note also that the ions get this hot, but the electrons are cooler (~40 million degrees C). This is because the heavier ions carry the kinetic energy and thus are heated directly when that kinetic motion turns into thermal motion; the electrons are heated indirectly by colliding with the ions. Other points to note are that the stainless steel arrays are larger diameter than the typical tungsten arrays (55 mm vs. 20 mm) which gives them a higher implosion velocity (they are accelerated over a larger distance). Thus the kinetic energy per ion is greater, and the resulting plasma temperature at stagnation is greater--this is required to generate the higher energy photon radiation from the stainless steel plasma. Tungsten arrays likely are not as hot as stainless steel pinches, though this hasn't been measured.

Q: Is there any update for this story as to what may or may not come from this discovery? Are other types of wire being considered for tests as well?

A: The report of high ion temperatures in a stainless steel z pinch on the Z machine really broke new ground in this regard. It would certainly be interesting to apply this measurement to other types of z pinches. The lower atomic number pinches (Al through Cu) are best suited for this, as the plasma conditions can be diagnosted by x-ray spectroscopic techniques that would be difficult to apply to tungsten. The issues associated with energy coupling in the z pinch and relationships between heating, radiation, and plasma conditions are topics of continuing and significant research interest. The Z machine is currently being refurbished, and it will be extremely exciting to continue these studies when the 26 MA ZR machine comes back online in 2007.

Q: Is there any chance of getting a photo for this story?

A: I'll attach some pictures of nested stainless steel wire arrays from the Z machine (55 mm diameter outer array, 20 mm tall, 10 micron diameter wire). Some of these show the halo structure that holds the wire weights above the array so that the wires remain under tension and straight. These photos were taken by Andy Shay during wire array assembly of Z shot 1086. The tungsten arrays have even more wires and are smaller diameter.