Focus Fusion Eco Safe * Green * Clean * Virtually Unlimited * Cheap

Lawrenceville Plasma Physics, Inc

High technology research, development and consulting in plasma physics, X-ray sources, and Focus Fusion

LPP Focus Fusion Report
October 28, 2016

Summary:

- **Experiments, Conference Discussion Yield New Understanding of Impurities**
- **New Insights Help to Plan Next Experiments**
- **Beryllium Anodes Arrive, Cathode Due in February**
- **Collaboration Begins with Krakow Effort for Hydrogen-Boron Fusion**
- **Summer Intern(s) Needed**

Experiments, Conference Discussions Yield New Understanding of Impurities, Ways to Reduce Them

The recently-completed set of experiments with LPPFusion's FF-1 device, combined with discussions with colleagues at the International Center for Dense Magnetized Plasma (ICDMP) conference in Warsaw, have produced a greater understanding of the ways impurities are produced in our device and how to reduce them. LPPFusion's research team has long identified heavy-metal impurities, produced by the erosion and vaporization of the metal electrodes, as the key obstacle to obtaining higher plasma densities and thus higher fusion energy yield. Experiments with tungsten electrodes have led to some reductions in impurities, but not enough. The new understanding of how the impurities are produced has helped to plan the next steps in getting rid of them.

First, experiments in early September with the preionization system showed that erosion of the anode near to the insulator, a major source of impurities, was still continuing. The preionization system applies a tiny current between the electrodes prior to the main current. The idea is to get into motion lots of electrons, which the small current strips off atoms in the gas, producing ions, and thus "pre-ionization." Having more electrons means that the electrons move slower, carry less energy and thus do less damage to the anode—a kind of deliberately-induced electron traffic jam (without advice from Gov. Christie!).

But measurements between shots of these small, several-microamp currents showed changes in the relation between the amount of current (controlled by the power supply) and the resulting voltage on the anode (up to 1500 kV). We were able to greatly change this voltage vs current curve between shots just by purging the chamber with high-pressure nitrogen. (Fig.1) The only thing that could change with just gas blowing around was tiny tungsten dust particles. These tiny particles could act as lightning rods, providing an easier path for the current and making preionization asymmetrical. But if dust was continuously being produced (and it was, even after many purges) then vaporization of the tungsten to produce the dust was also occurring. Indeed, the dust particles, by concentrating the main, million-ampere current, made vaporization of the anode far easier. So, "dust breeds dust" and erosion was not going to stop until we had a fresh, smooth anode.

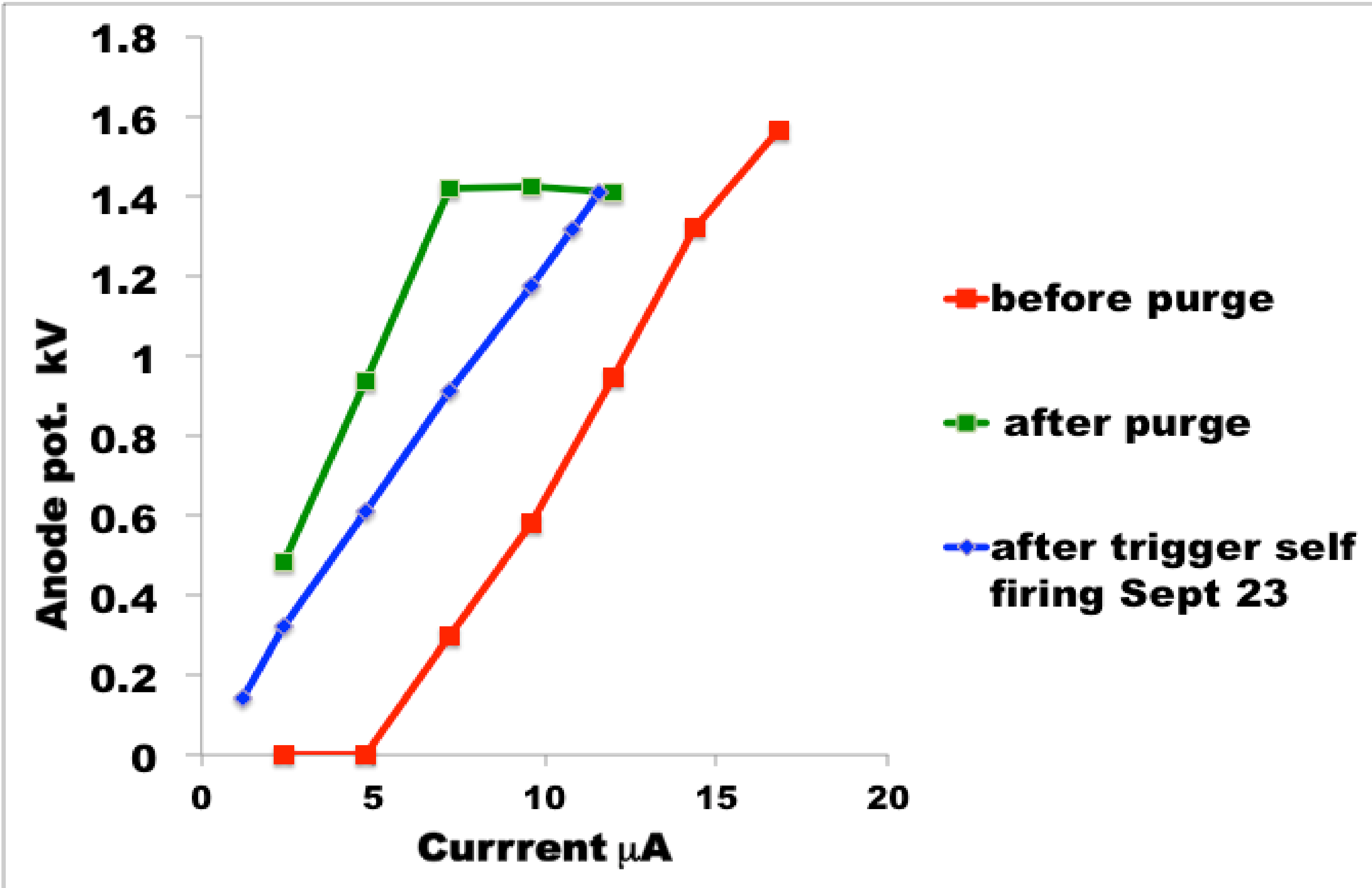

Figure 1. When the measured voltage on the anode is plotted against the current supplied by the preionization power supply, even blowing nitrogen through the chamber (purging) can greatly change the plot. So can the very small current supplied by the trigger circuit. This indicates that dust particles are moving around, making it easier for currents to move from one electrode to the other.

Next, when we disassembled the vacuum chamber at the end of September, we confirmed that oxidation contributed to the erosion of tungsten. The deposits on the tungsten were clearly a different material, not pure tungsten. (From the dark gray color, it is probably a compound of tungsten, oxygen and the fill gases, deuterium and nitrogen.) Tungsten oxide is about 200 times easier to vaporize than pure tungsten, and we found from a literature search that tungsten nitride is not that much better than the oxide. We could measure the optical absorption of the deposits on our windows and from this determine that the total mass of impurity metal in the plasma had indeed declined by about 60% from our previous experiments with copper electrodes. This was progress, but not enough.

More insight came when LPPFusion's Chief Scientist participated in the ICDMP conference in Warsaw in mid-October. This is a small conference of those working with the plasma focus device. One presentation by Czech researcher Monika Vilemova showed that when tungsten melts, tiny pores of gas burst open as bubbles, sending droplets of metal into the plasma to be vaporized. (All manufactured tungsten is porous and our electrodes are about 5% porous by volume.) This indicated that even for pure tungsten, erosion only requires heating to the melting point, not to the boiling point.

Other discussions pointed to a likely source of the electrodes' second main region of erosion—the end of the anode. Previously, Lerner had blamed the anode's heavy erosion on the electron beam that comes from the plasmoid. But when the anode was carefully measured during this disassembly, there was no evidence of the increase in erosion in the center of the anode that is expected from a beam. Perhaps, Lerner hypothesized, the erosion instead comes from high-energy particles leaking out of the plasmoid. But in Warsaw, Lerner saw anodes from the large PF-1000 plasma focus device that showed clear signs of erosion by the current filaments (dense vortices of current) prior to the formation of the plasmoid (Fig.2).

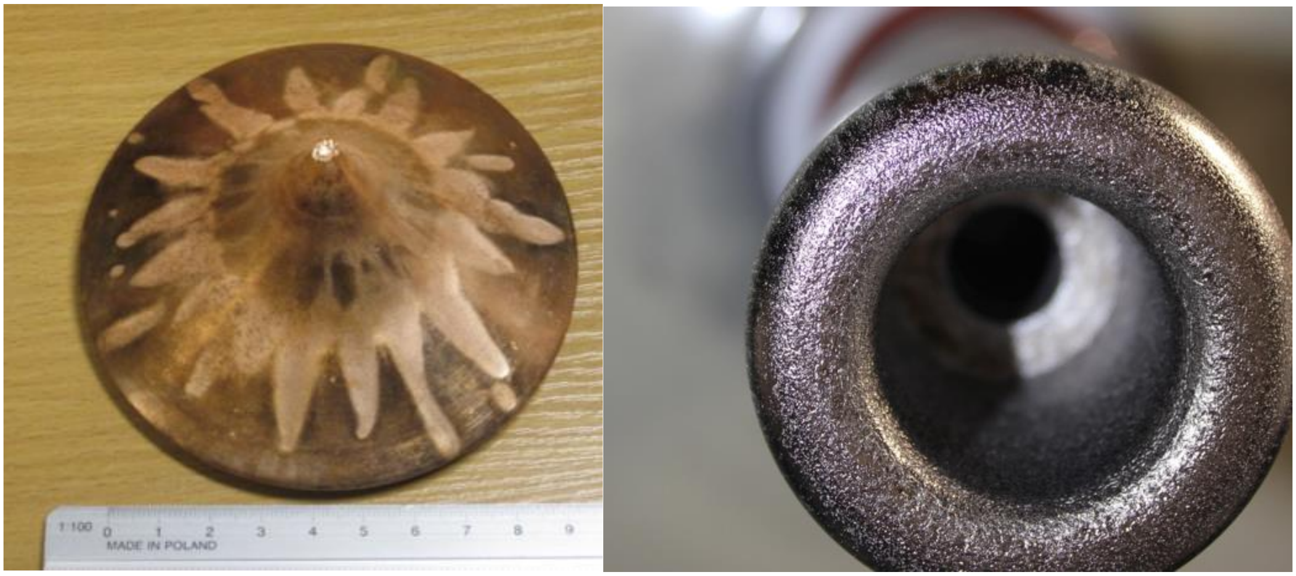

Figure 2. Erosion on anode tip of PF-1000 plasma focus device in Warsaw (left) shows evidence that it was generated by current filaments. Recombination radiation X-rays from tungsten impurities may have also caused erosion on FF-1 tungsten anode (right.)

A leading expert in plasma spectroscopy at the conference, Dr. Hans Kunze, suggested that with heavy metal impurities like tungsten, recombination and line radiation might be very important because they increase proportionally to z^4, where z is the number of charges on the ion. In the case of tungsten, z can be as high as 74, depending on how many electrons the ion has lost. Recombination radiation occurs when electrons that have been stripped from an ion get back together with it, emitting UV or x-ray photons in the process. Line radiation occurs when the electrons that are still bound to an ion drop down to lower energy levels (like lower stair-steps) after being excited to higher ones.

For deuterium, which has only one electron, such radiation is unimportant once the plasma in the device heats up and all the electrons are moving freely. But Lerner calculated that with even a bit of tungsten impurity, the recombination and line radiation can be enough to melt tungsten and cause the heavy erosion seen at the anode tips. Thus impurity breeds more impurity. The erosion occurs only at the tips, since the intensity of the radiation also depends strongly on plasma density, which increases at the anode tip as the plasma is compressed inwards toward the anode axis. Since the plasma filaments touch the whole top surface of the anode, this radiation hypothesis explains why there was no central concentration of the erosion damage. Finally, this hypothesis would directly explain how impurities limit plasma density, as the energy loss from the radiation would prevent the plasma sheet from reaching high density.

New Insights Help Plan Next Experiments

In all scientific research, experiments and observations give rise to new theoretical concepts, which in turn lead to the design of more advanced experiments. LPPFusion has gone through such a cycle in the past few months, with new insights revising our plans for the next experiments. In August, the expected availability of beryllium anodes in September (see next section) led Lerner to propose that the next experiments use a combination of beryllium anode and tungsten cathode. The idea was to test the expected great reduction in impurities from beryllium without waiting for the beryllium cathode, not expected until February. However, cogent reasons led to the rejection of this plan.

First, LPPFusion Chief Information Officer Ivy Karamitsos raised the concern that the vaporization from the tungsten cathode might contaminate the beryllium anode, making it difficult to use for pure beryllium experiments later on. This seemed a strong objection, especially as cleaning the beryllium anode is made difficult by the toxicity of beryllium dust. In addition, literature searches by LPPFusion volunteer Charles Loney turned up experiments that showed that contamination of tungsten by beryllium produced an alloy that had a lower melting point than either pure material—another strong reason to avoid mixing the two metals in one experiment. This is a major concern for existing and planned tokamaks which do use both metals.

Instead, the next experiments, now planned for late November, will use the tungsten cathode with a new shorter tungsten anode—which had been the original plan prior to the proposed, and now rejected, August shift. A shorter anode (10 cm instead of the present 14 cm) will be a first step towards increasing the current produced by FF-1, as it reduces the energy stored in the magnetic field. While a shorter electrode will also reduce the angular momentum—spin—that is needed for the tiny spinning plasmoid. We expect our axial field coil (AFC) to compensate for this. Its magnetic field will give the electrons moving toward the anode additional angular momentum.

To reduce impurities from tungsten compounds, we will take a number of steps, based on our previous experiments. We will bake the moisture out of the chamber at only 60 C, preventing the formation of oxides during bake-out, and carefully purge all valves of trapped water. After bake-out, we'll use flowing hydrogen heated by microwaves to react away remaining oxides. (We could not use the microwaves during the previous experiment, as our windows were already so coated with metal that they reflected the microwaves.) Since nitrides may be another problem, as LPPFusion Research Physicist Syed Hassan suggested, in this experiment we'll run only with pure deuterium. We had used a mix mainly to reduce damage from the electron beam, and our new insights indicate that the beam is not the main cause of anode tip erosion.

In addition, we will use our ultra-low current, corona-discharge preionization from the start. This should avoid the kind of electrical breakdowns that initially generated a rough anode surface and the dust problem. Finally, the shorter anodes will allow the use of somewhat more deuterium gas. Shorter electrodes need a slower speed for the current sheet to get to the end of the anode. For the same energy input, more gas can be pushed to this slower speed. In turn, more deuterium will dilute whatever tungsten impurities still exist. Overall, we hope to reduce the fraction of impurities in the plasma by about 5-10 times. This should lead to comparable increases in plasma density and fusion yield.

Discussions at the Warsaw conference have also led to ways to improve the performance of our instruments. We intend to put the ICCD camera, which has worked only intermittently, on battery power to completely isolate it from electromagnetic noise sources. We will move our photomultiplier tubes outside of the experimental room, connecting them via optical fiber to plastic scintillators inside the room. As well, we will improve our photographic monitoring of the symmetry of the breakdown process at the beginning of the pulse.

Beryllium Anodes Arrive, Cathode Due in February

Right on schedule, Rev Manufacturing delivered from California two new beryllium anodes to LPPFusion at the beginning of September. The anodes are carefully sealed (see Fig.3) and will remain so until we are ready to use them. Beryllium is vulnerable to reactions with humid air, so we will minimize both humidity and the time the anodes are exposed. Once we receive the beryllium cathode from Hardric Lab in February, we will use the 10-cm beryllium anode to assemble our first electrodes with **no** heavy metals, and thus no heavy metal impurities. With only four electric charges each, the beryllium ions will have almost no impact on the plasma, so these electrodes will allow a complete test of the basic hypothesis that impurities have limited fusion yield in the plasma focus device.

Figure 3. The 10-cm (left) and 7-cm (right) beryllium anodes in their sealed bags at LPPFusion's Middlesex laboratory await the arrival of the beryllium cathode in February.

We expect that we will probably be able to do the nitrogen-mix experiments using the beryllium electrodes. From experiments in tokamaks, it appears that beryllium nitride, which is a high-temperature material, does not increase beryllium erosion, but we will be looking into this more thoroughly over the coming months. Mixes of nitrogen and deuterium will allow us to study mixed ions before our crucial experiments with hydrogen-boron fuel later next year.

The second, 7-cm anode will be used in later experiments to further increase peak current and plasma density. With these electrodes in place we also expect to upgrade the connections between the switches and the electrodes for additional increases in current. Thanks to volunteer Sergey Sukhotskiy in Kazakhstan and contractor Lalit Marepalli in nearby New York City we expect to have the COMSOL simulations we need soon. To validate the simulations we will be using a spare capacitor to set up a mini-plasma-focus test bed early next year.

Collaboration Begins with Krakow Effort for Hydrogen-Boron Fusion

In the same trip to Poland in October, Lerner also visited the Institute of Nuclear Physics of the Polish Academy of Sciences in Krakow. There he discussed with Dr. Marek Scholz and other researchers the Institute's plans to initiate their own research into hydrogen-boron fusion using a plasma focus device. This is only the second such effort, after LPPFusion's own work. Dr. Scholz explained that they currently plan such experiments to begin as early as 2018, perhaps six months after the planned initiation of hydrogen-boron experiments at LPPFusion's FF-1 facility. The Krakow experiments will use the PF-24 device, which is very similar in many ways to FF-1, having a similarly-sized capacitor bank and similarly small electrodes. While PF-24 is at the moment running with only about half of the current now produced by FF-1, it is capable at full power of producing mega-ampere currents.

Figure 4. Institute of Nuclear Physics PF-24 plasma focus device in Krakow. The blue boxes are 24 capacitors, providing current to the electrodes inside the steel vacuum chamber (center).

Given the common goals of hydrogen-boron fusion with a plasma focus device and the similarity in the devices, Lerner and Dr. Scholz agreed to remain in close contact. Already the collaboration has provided benefits to both efforts. From the Krakow team, LPPFusion learned of better methods of shielding our instruments from electromagnetic noise, while Lerner was able to point to ways that PF-24 could improve the functioning of their switching system. "We expect both teams will be able to learn a lot more from each other in the coming months," said Lerner. "We look forward to a growing collaboration with this and other labs in achieving aneutronic fusion."

Summer Intern(s) Needed

As in many past summers, next summer LPPFusion will be hiring one or two interns for 2017. We invite undergraduate and graduate students in physics, chemistry or any engineering field to apply for these paid, full time summer positions. Interns will be helping out as needed in the lab, but will also work on special projects. Please send resumes to fusionfan@lppfusion.com by Nov. 20. We expect to make decisions by mid-December.