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Runaway electrons as a source of impurity and reduced fusion yield in the dense plasma focus

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Impurities produced by the vaporization of metals in the electrodes may be a major cause of reduced fusion yields in high-current dense plasma focus devices. We propose here that a major, but hitherto-overlooked, cause of such impurities is vaporization by runaway electrons during the breakdown process at the beginning of the current pulse. This process is sufficient to account for the large amount of erosion observed in many dense plasma focus devices on the anode very near to the insulator. The erosion is expected to become worse with lower pressures, typical of machines with large electrode radii, and would explain the plateauing of fusion yield observed in such machines at higher peak currents. Such runaway electron vaporization can be eliminated by the proper choice of electrode material, by reducing electrode radii and thus increasing fill gas pressure, or by using pre-ionization to eliminate the large fields that create runaway electrons. If these steps are combined with monolithic electrodes to eliminate arcing erosion, large reductions in impurities and large increases in fusion yield may be obtained, as the I^4 scaling is extended to higher currents. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4898733>]

I. INTRODUCTION

In the first decade and a half after the invention of the dense plasma focus (DPF) device in the early 1960s, multiple experiments demonstrated¹ a favorable scaling of fusion yield with peak current of at least I^4 . However, this scaling leveled off above 1 MA and reached a plateau, for pure D fill gas, of about 1 J or 10^{12} neutrons. While the reason for this plateauing has been debated since the early 1980s, some researchers thought that impurities, possibly originating in the insulator, may be responsible.² Based on these hypotheses, researchers attempted to reduce the current density and thus the production of impurities by increasing the radii of the electrodes. This failed to produce better results.

We observed the same plateauing of fusion yield in our own FF-1 device and have explored the hypothesis that this is indeed due to impurities.³ The FF-1 device is energized by a 113 μF , 12-capacitor bank. In the experiments we are discussing, the cathode, consisting of copper rods screwed into in a tungsten base plate, had a radius of 5 cm, and the copper anode had a radius of 2.8 cm, both had a length of 14 cm, with a 2.8-cm-long alumina insulator between them. Both the copper rods and copper anode were plated with 25 μm of silver. The capacitor bank in these experiments was charged to either 35 kV or 40 kV, with a rise time of 2 μs and peak current of 1.0–1.2 MA. Fill pressure was 16–20 Torr of deuterium at 35 kV and 24–30 Torr D at 40 kV.

Our observations indicate that these impurities are due to the vaporization of the electrode metals. For some time, we have observed that vaporization occurred in FF-1 due to arcing where two parts of the electrodes were joined. For example, there is visible arcing damage to the silver plating around the base of the cathode rods, where they screw into the tungsten plate.

However, there is also a clear line of erosion around the anode close to the insulator, where no arcing can occur as

there is a solid anode there (Figure 1). We made measurements of the amount of metal vaporized. The depth of material removed was approximately 100 μm and the width of the band 0.08 cm, so 8×10^{-3} cc or 70 mg of material was vaporized in 125 shots, giving an average of 0.6 mg per shot.

Since we estimate that the total mass of deuterium in the current sheath is about 3 mg, this source of impurity is very significant, amounting to about 20% of the sheath mass. We have elsewhere³ been able to determine that the total amount of impurities in the current sheath averages around 1.5 mg, so the anode ring erosion amounts to about 40% of total impurities.

II. THE RUNAWAY ELECTRON MECHANISM FOR VAPORIZATION OF THE ANODE

The question remains, what is the mechanism to produce the erosion near the insulator? Since the sheath moves away from the insulator, this erosion has to be produced early in the current pulse, when the current is weakest. While the erosion around the insulator is almost universally observed in DPF, as far as we know no explanation has been put forward for it.

We here propose that an explanation can be based on runaway electrons generated during the breakdown of the neutral gas at the start of the pulse. As described by Tarasenko and Yakovlenko,⁴ runaway electrons can be produced in the breakdown of a neutral gas and accelerated to an energy, V_{re} , that is a function of the field strength E divided by the pressure p . For helium, for example, they show that the experimental data can be well fit by

$$V_{\text{re}} = 5.5e^{(E/40p)^{1/2}} \text{ eV}, \quad (1)$$

where E is the field in V/cm and p is the pressure in Torr. Since the authors point out that the relationship mainly

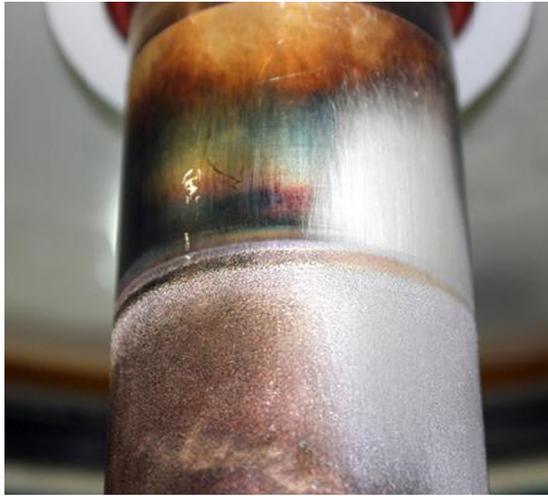


FIG. 1. The FF-1 copper anode, which is plated with 25 μm of silver, shows a ring of erosion near the end of the insulator (which has been removed along with the cathode). On the right side, where deposits have been cleaned away, the copper color shows clearly where a ring of silver has been vaporized. On the left side, not cleaned, the copper is deposited from the plasma lower on the anode, covering up silver below.

depends on the molecular mass of the gas, this can be used to a first approximation for deuterium as well.

We can determine under what conditions runaway electrons can lead to vaporization. At any given instant, the heat generated at the contact is IV , where V is the average electron energy. The length of the contact is L and its width is w . The total thermal flux is therefore

$$F = IV/Lw \text{ W/m}^2. \quad (2)$$

If vaporization is to be avoided, the thermal conduction, C , at the boiling point of the conductor, T , has to be sufficient to carry away the heat generated. So the distance d over which the temperature falls to ambient must be less than

$$d_c = CTLw/IV \text{ m}. \quad (3)$$

Then, $d > d_c$ when a volume d_cLw has been heated to an average temperature of $T/2$. This requires an energy of

$$E = \rho E_T CT^2 L^2 w^2 / 2IVJ, \quad (4)$$

where ρ is density and E_T is specific thermal capacity.

The energy available is approximately $IVt/3$ considering average power over a rise time. So the condition for vaporization is

$$IVt/3 > \rho E_T CT^2 L^2 w^2 / 2IV \quad (5)$$

or

$$I^2 V^2 > 1.5 \rho E_T CT^2 L^2 w^2 / t. \quad (6)$$

Thus,

$$V > 1.22 LwT (\rho E_T C/t)^{1/2} / I. \quad (7)$$

Combining with Eq. (1) we have the condition for vaporization

$$e^{(E/40p)^{1/2}} eV > 0.22LwT(\rho E_T C/t)^{1/2} / I. \quad (8)$$

We can compare the prediction of this theory with the observed erosion in FF-1. With silver-plated 2.8-cm-radius anodes, 2.7-cm-length insulator, and typical operating conditions of 35 kV charging and 16 Torr deuterium fill pressure we can calculate inequality (8) if we know the width of the eroded region w , the time of the break down t , and the peak current during the break down I . From our measurements, we find $w = 0.08$ cm. The initial rise of the current from the main Rogowski coil lasts 32 ns and the peak current during breakdown is 70 kA. We find that the electron energy is 460 eV and the critical energy is 922 eV, so apparently not enough for vaporization. However, this calculation assumes that there is no local enhancement of the E field near the anode, while in fact there should be. If we assume a 40% enhancement in the field, then we get electron energy of 1.13 keV, above the threshold for vaporization.

We can then check that this would have sufficient energy to vaporize the observed loss of metal. We find that 1.9 J of energy would be released, just enough to vaporize the observed 0.6 mg of silver.

Since the critical energy varies with the material of the anode, we can also check our theory against Shyam and Rout's results⁵ with different anode materials. Here, the anode is 1.05 cm in radius, the charging voltage is 25 kV, and the insulator length is 4.5 cm. For silver and copper, the fill pressure of deuterium was 3.4 Torr, while for tungsten it was 6.2 Torr. We do not have the current during breakdown or the duration of breakdown, but we can assume that the breakdown current scales as the peak current (in this case 180 kA) and the breakdown time is approximately independent of the device. In this case, again assuming a 40% enhancement of field, we have for silver and copper a predicted runaway electron energy of 10.6 keV and for tungsten 1.5 keV. The critical energy for silver is 1.9 keV, for copper 2.6 keV, and for tungsten 4.5 keV. Thus, the copper and silver should vaporize but the tungsten should not. Shyam and Rout⁵ observed in fact that the mass of impurities for copper and silver was about the same but that copper lost almost 10 times as much mass as tungsten, in agreement with the predictions of inequality (8).

III. EFFECTS OF RUNAWAY-ELECTRON-GENERATED IMPURITIES

To see how the effects of runaway electron erosion varies with I and the fill pressure, we have, from Eq. (9), that for deuterium

$$I/L > 0.22wT(rE_T C/t)^{1/2} / e^{(E/28.6p)^{1/2}}, \quad (9)$$

if we take into account a 40% enhancement in the E field. In addition, based on conservation of energy, the runaway electron potential cannot exceed the charging voltage of the device, so for low pressure that limit must be substituted in the denominator of Eq. (9). The pressure in the exponential term is approximately proportional to B^2 so the dependence on I and the radius of the anode is non-linear.

We can most easily see the result of Eq. (9) graphically. In Figure 2, we have plotted the ratio R of the two sides of

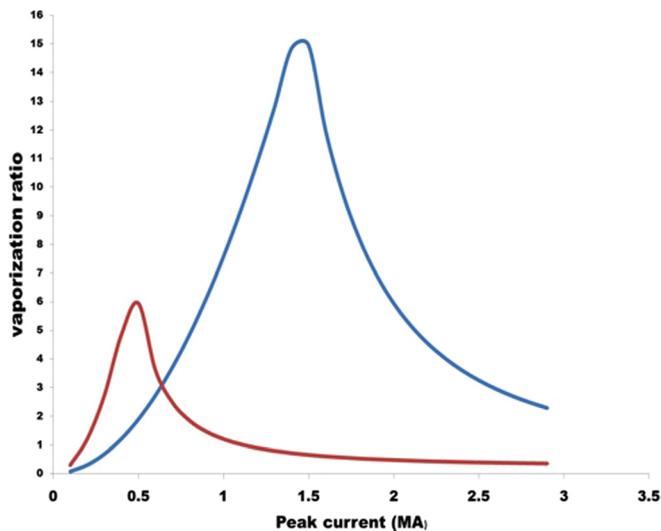


FIG. 2. The vaporization ratio R (defined by the ratio of the two sides of Eq. (9)) plotted against peak current for a 20 cm radius copper cathode and 10 cm radius copper anode DPF (blue) and a 5 cm radius cathode and 2.5 cm radius copper anode DPF (red). For ratios >1 , vaporization by runaway electrons is expected. For both electrode sets, low-current machines escape vaporization, but for high currents, only the small-radius electrodes do.

Eq. (9), so that a value $R > 1$ means that vaporization will occur. The red, lower line is for a device with an anode radius of 2.5 cm and the blue, upper line is for one with anode radius 10 cm, with both anodes made of copper. We assume a constant “drive factor” or peak velocity for the sheath. As can be seen, at very low current, less than 200 kA for the smaller anode and 400 kA for the larger one, the power of the runaway current is insufficient to vaporize the metals. However, due to the lower pressure in the larger machine, vaporization will occur at all values of I above 400 kA up to 3 MA. For the smaller anode, pressure raises sufficiently to suppress the runaway electron energy above 1 MA.

Thus, for high current machines, the runaway electron erosion becomes more severe for large-radius machines than for small ones. This, we believe, is the basic reason that the effort to reduce arcing impurities by increasing the radius of the electrodes and thus decreasing the current density did not lead to greater yields.

IV. ELIMINATION OF RUNAWAY ELECTRON EROSION

Elimination of runaway electron erosion can be achieved in two ways. First, the electrodes can be designed with sufficiently small radii so that the pressure of the gas fill is high enough to prevent erosion. The design criterion is thus to ensure that inequality (9) is not fulfilled.

Criterion (9) also shows that choice of material can help to eliminate runaway vaporization. Thus, tungsten should be resistant to runaways at I that are $\sim 10\%$ less than for copper.

A second approach is to eliminate high electric fields by pre-ionization. Pre-ionization has been studied experimentally in the DPF since at least 1986,⁶ although not especially with the intent of alleviating impurities or erosion. More recently, Ahmad *et al.*^{7,8} showed that in small, 200 kA DPF, x-ray output was increased by 65% and neutron output by 54% with pre-ionization, either with a shunt resistor or with

alpha emission from uranium. In both cases, the shot-to-shot variability was greatly decreased as well, to about 10% RMS, quite unusual for a DPF. Based on time-integrated x-ray pinhole images, the radius of the x-ray emitting region also decreased, implying an increase in plasma density.

There is some indirect evidence that pre-ionization is accompanied by a decrease in impurities. In 2013, working with the same device, Khan *et al.*⁹ reported that pre-ionization led to a striking 60% increase in rundown velocity of the current sheath. If it is assumed that the magnetic energy driving the sheath is unchanged, the mass of the sheath would be decreased by a factor of 2.5, as would be expected if a large mass of impurities present without pre-ionization were eliminated with pre-ionization. The team did observe an increase in peak current with pre-ionization, but only of 17%. This would still imply a decrease in sheath mass by a factor of 1.9.

While these results are consistent with the hypothesis that pre-ionization decreases impurities and increases plasma density and fusion yield, one can ask why the increase is not much more dramatic, as we expect for MA devices. The probable explanation of this relatively modest change is the increased robustness of the current filaments with lower peak current I and lower peak B field. As we have shown,³ the destruction of the current filaments is a major reason for the decrease in fusion yield.

The magnetization of the filaments depends on the ratio of B/n , since gyrofrequency is proportional to B and collision frequency to n . However, for a given set of electrodes and a given rise time, the Alfvén velocity must remain close to a constant so that the sheath arrives at the pinch simultaneously with the peak current time. Since Alfvén velocity is proportional to $B/n^{1/2}$, as I and therefore B increases, B/n must fall, making magnetization more difficult and the disruption of that magnetization by impurity easier. Conversely at lower B , the filament ions would still be magnetized and thus the filaments would still be expected to survive up to the pinch. With a peak current of 145 kA and anode radius of 0.9 cm, the device in these tests has a B field 2.2 times less than, for example, our own FF-1 device at 1 MA. The large decreases in density that accompanied the destruction of the filaments are therefore not expected to occur.

Reinforcing this conclusion, we find the pre-ionization yield of 4×10^8 neutrons reported by Ahmad *et al.*⁸ at a peak current of 170 kA compares very favorably with the anticipated scaling law for pure D.

We have obtained some preliminary experimental evidence with FF-1 that pre-ionization does eliminate the conditions for runaway electron erosion. We used a 100 M Ω shunt resistor to connect the input contact on one capacitor to the anode plate. During charging to 20 kV at 16 Torr pressure, the anode plate repeatedly charged to 1.3 kV and then discharged through the chamber. Maximum current was calculated to be 50 A on the basis of the rate of fall of the potential and the capacitance of the transmission plates, calculated to be 20 nF. We estimate that the resulting ionization ratio is about 10^{-5} . By comparison, at an ionization ratio of 10^{-3} we estimate that runaway vaporization will be eliminated for the full discharge. Since simulations¹⁰ indicate that

in these conditions an increase in ionization by a factor of 100 takes only a few ns, this gives us some confidence that pre-ionization will be effective in eliminating this source of vaporization. To ensure the maximum chances of success, however, we intend to use higher pressure, and small tungsten electrodes as well as pre-ionization.

V. CONCLUSIONS

Runaway electrons during the breakdown process are a major source of electrode vaporization and thus of impurities in the dense plasma focus device. These impurities significantly reduce fusion yield. Since the runaway electron problem becomes worse for lower fill pressures and large electrode radius, it is a major cause of the failure of large-radius, high current DPFs to attain high fusion yields. Conversely, the problem does not exist for low current DPFs. Vaporization by runaway electrons can be eliminated by using sufficiently small-radius electrodes for high currents, by the correct choice of materials for the electrodes, and by pre-ionization to eliminate the high fields that allow runaway electron generation. Since arcing erosion can be eliminated by monolithic electrodes,³ both major sources of impurities can be eliminated, with resultant increases in fusion yield. If these impurities are indeed the reason for the

leveling off of fusion yields above 1 MA, elimination of such impurities and the continuation of the I^4 scaling laws could lead to increases of fusion yields of more than a factor of ten.

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