Neutron yield saturation in plasma focus: A fundamental cause

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Plasma focus research in the direction of fusion energy faces the limitation of observed neutron saturation; the neutron yield Y_n falls away from $Y_n \sim E_0^2$, the scaling deteriorating as storage energy E_0 increases toward 1 MJ. Numerical experiments confirm that $Y_n \sim E_0^2$ applies at low energies and drops to $Y_n \sim E_0^{0.8}$ toward 25 MJ; deteriorating already at several hundred kilojoules. We point out that the cause is the dynamic resistance of the axial phase that is constant for all plasma foci. This dynamic resistance dominates the circuit as capacitor bank surge impedance becomes insignificant at large E_0, causing current, hence neutron "saturation." © *2009 American Institute of Physics*. [doi:10.1063/1.3246159]

It was observed early in plasma focus research[1] that neutron yield $Y_n \sim E_0^2$ where E_0 is the capacitor storage energy. Such scaling gave hopes of possible development as a fusion energy source. Devices were scaled up to higher E_0. It was then observed that the scaling deteriorated, with Y_n not increasing as much as suggested by the E_0^2 scaling. In fact some experiments were interpreted as evidence of a neutron saturation effect[2,3] as E_0 approached several hundreds of kilojoules. As recently as 2006, Kraus[4] and Scholz[5] (November 2007) have questioned whether the neutron saturation was due to a fundamental cause or to avoidable machine effects such as incorrect formation of plasma current sheath arising from impurities or sheath instabilities.[3] We should note here that the region of discussion (several hundreds of kilojoules approaching the megajoules region) is in contrast to the much higher energy region discussed by Schmidt[6] at which there might be expected to be a decrease in the role of beam target fusion processes.[3]

Recent extensive numerical experiments[7,8] also showed that whereas at energies up to tens of kilojoules the $Y_n \sim E_0^2$ scaling held, deterioration of this scaling became apparent above the low hundreds of kilojoules. This deteriorating trend worsened and tended toward $Y_n \sim E_0^{0.8}$ at tens of megajoules. The results of these numerical experiments are summarized in Fig. 1 with the solid line representing results from numerical experiments. Experimental results from 0.4 kJ to megajoules, compiled from several available published sources[3,9–14] are also included as squares in the same figure. The combined experimental and numerical experimental results[15] appear to have general agreement particularly with regards to the $Y_n \sim E_0^2$ at energies up to 100 kJ, and the deterioration of the scaling from low hundreds of kilojoules to the 1 MJ level. It is proposed here that the global data of Fig. 1 suggest that the apparently observed neutron saturation effect is overall not in significant variance with the deterioration of the scaling shown by the numerical experiments.

We wish now to provide a simple yet compelling analysis of the cause of this neutron saturation. In Fig. 2 is shown a schematic of the plasma dynamics in the axial phase of the Mather-type plasma focus.

We consider the simplest representation in which the current sheet is shown to go from the anode to the cathode perpendicularly. Observation shows that there is actually a canting of the current sheet[16] and also that only a fraction (typically 0.7) of the total current participates in driving the current sheet. These points are accounted for in the modeling[17–22] by model parameters f_m and f_c. For the moment we do not consider these two effects. The outer cathode radius is shown as b, inner anode radius as a and the moving current sheet is shown at position z in the axial phase.

By surveying published results of all Mather-type experiments we find that all deuterium plasma focus devices operate at practically the same speeds[23] and are characterized by a constancy of energy density (per unit mass) over the whole range of devices from the smallest subkilojoule to the largest megajoule devices. The time varying tube inductance is $L=(\mu/2\pi)\ln(c)z$, where $c=b/a$ and μ is the permeability of free space. The rate of change in inductance is $dL/dt=2\times10^{-7}(\ln c)\,dz/dt$ in SI units. Typically on switching, as the capacitor discharges, the current rises toward its peak value, the current sheet is accelerated, quickly reaching nearly its peak speed, and continues accelerating slightly toward its peak speed at the end of the axial phase. Thus for most of its

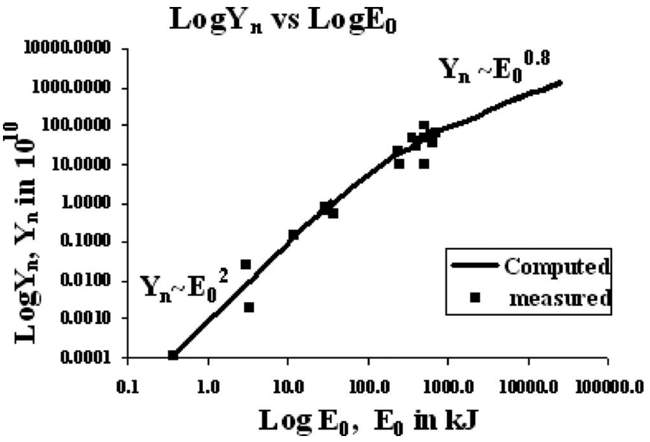

FIG. 1. Illustrating Y_n scaling deterioration observed in numerical experiments from 0.4 kJ to 25 MJ (solid line) using the Lee model code, compared to measurements compiled from publications (squares) of various machines from 0.4 kJ to 1 MJ.

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