# Pinch current limitation effect in plasma focus

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The Lee model couples the electrical circuit with plasma focus dynamics, thermodynamics, and radiation. It is used to design and simulate experiments. A beam-target mechanism is incorporated, resulting in realistic neutron yield scaling with pinch current and increasing its versatility for investigating all Mather-type machines. Recent runs indicate a previously unsuspected "pinch current limitation" effect. The pinch current does not increase beyond a certain value however low the static inductance is reduced to. The results indicate that decreasing the present static inductance of the PF1000 machine will neither increase the pinch current nor the neutron yield, contrary to expectations. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2827579]

This model in its two-phase form was described in 1984.[1] It was used to assist in the design and interpretation of several experiments.[2–4] An improved five-phase model and code incorporating finite small disturbance speed,[5] radiation and radiation coupling with dynamics assisted several projects,[6–8] and was web published[9] in 2000 and in 2005.[10] Plasma self-absorption was included[9] in 2007. It has been used extensively as a complementary facility in several machines, for example, UNU/ICTP PFF,[2,6] the NX2,[7,8] NX1,[7] and DENA.[11] It has also been used[12] in other machines for design and interpretation including Soto's subkilojoule plasma focus machines,[13] FNII,[14] and the UBA hard x-ray source.[15] Information obtained from the model includes axial and radial velocities and dynamics,[1,7,12,11] soft x-ray (SXR) emission characteristics and yield,[5,7,8,16] design of machines,[13,16] optimization of machines, and adaptation to other machine types such as the Filippov-type DENA.[11] A study of speed-enhanced neutron yield[4,13] was also assisted by the model code.

A detailed description of the model is already available on the internet.[9,10] A recent development in the code is the inclusion of neutron yield using a phenomenological beam-target neutron generating mechanism,[17] incorporated in the present RADPFV5.13. A beam of fast deuteron ions is produced by diode action in a thin layer close to the anode, with plasma disruptions generating the necessary high voltages. The beam interacts with the hot dense plasma of the focus pinch column to produce the fusion neutrons. In this modeling, each factor contributing to the yield is estimated as a proportional quantity and the yield is obtained as an expression with proportionality constant. The yield is then calibrated against a known experimental point.

The beam-target yield is written in the form $Y_{b-t} \sim n_b n_i (r_p^2 z_p)(\sigma v_b)\tau$ where $n_b$ is the number of beam ions per unit plasma volume, $n_i$ is the ion density, $r_p$ is the radius of the plasma pinch with length $z_p$, $\sigma$ is the cross section of the D–D fusion reaction, $n$ branch,[18] $v_b$ is the beam ion speed, and $\tau$ is the beam-target interaction time assumed proportional to the confinement time of the plasma column.

Total beam energy is estimated[17] as proportional to $L_p I_{\text{pinch}}$,[2] a measure of the pinch inductance energy, $L_p$ being the focus pinch inductance. Thus, the number of beam ions is $N_b \sim L_p I_{\text{pinch}}^2 / v_b^2$ and $n_b$ is $N_i$ divided by the focus pinch volume. Note that $L_p \sim \ln(b/r_p) z_p$, that[4] $\tau \sim r_p \sim z_p$, and that $v_b \sim U^{1/2}$ where $U$ is the disruption-caused diode voltage.[17] Here, $b$ is the cathode radius. We also assume reasonably that $U$ is proportional to $V_{\max}$, the maximum voltage induced by the current sheet collapsing radially toward the axis.

Hence, we derive $$Y_{b-t} = C_n I_{\text{pinch}}^2 z_p^2 [(\ln b/r_p)] \sigma / V_{\max}^{1/2}, \quad (1)$$

where $I_{\text{pinch}}$ is the current flowing through the pinch at start of the slow compression phase; $r_p$ and $z_p$ are the pinch dimensions at end of that phase. Here, $C_n$ is a constant which, in practice, we will calibrate with an experimental point.

The D–D cross section is highly sensitive to the beam energy so it is necessary to use the appropriate range of beam energy to compute $\sigma$. The code computes $V_{\max}$ of the order of 20–50 kV. However, it is known[17] from experiments that the ion energy responsible for the beam-target neutrons is in the range of 50–150 keV,[17] and for smaller lower-voltage machines the relevant energy[19] could be lower at 30–60 keV. Thus, to align with experimental observations the D–D cross section $\sigma$ is reasonably obtained by using beam energy equal to three times $V_{\max}$.

A plot of experimentally measured neutron yield $Y_n$ vs $I_{\text{pinch}}$ was made combining all available experimental data.[2,4,11,13,17,19–22] This gave a fit of $Y_n = 9 \times 10^{10} I_{\text{pinch}}^{3.8}$ for $I_{\text{pinch}}$ in the range 0.1–1 MA. From this plot, a calibration point was chosen at 0.5 MA, $Y_n = 7 \times 10^9$ neutrons. The model code[23] RADPFV5.13 was thus calibrated to compute $Y_{b-t}$ which in our model is the same as $Y_n$.

From experience, it is known that the current trace of the focus is one of the best indicators of gross performance. The axial and radial phase dynamics and the crucial energy transfer into the focus pinch are among the important information that is quickly apparent from the current trace. Numerical experiments were carried out for machines for which reliable current traces and neutron yields are available. Figure 1 shows a comparison of the computed total current trace

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