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Understanding Plasma Dynamics of Argentina Nano Focus Machine Using the Lee Code

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Argentina Nano Focus Machine is a small plasma focus machine used as an intense neutron source. To understand the working of its plasma dynamics, the Lee model code is used. The results obtained from the Lee code agree reasonably well with the experimental data in terms of the peak current, radial start time and the pinch duration. Additionally, this code also produces information such as the optimum neutron yield ($6.2\text{x}10^4$), maximum ion beam energy (1.2 J) and the dependence of these yields and various speeds on operating pressure. The resultant data is reliable and all the input that is required is just one experimental current waveform together with the actual machine and operating parameters.

Keywords: Plasma focus machine; Plasma dynamics; Lee code; ion beam energy; neutron yield

I. INTRODUCTION

Our world has a limited amount of fossil fuel but has an ever increasing appetite for electrical power, thus the need to find an environmentally friendly and practically inexhaustible source of power is of extreme importance. Many alternatives sources of energy (renewable sources) are currently being explored and developed and one of them is controlled nuclear fusion. To improve the data-base of nuclear fusion devices, dense plasma focus (DPF) machines have been constructed in many countries including the United States, Russia, Britain, India, Pakistan, China, Argentina, Singapore, Malaysia etc. A Dense Plasma Focus (DPF) machine is a device that produces a transient, dense and high temperature plasma that releases radiation and experiences nuclear fusion when it operates in deuterium gas or Deuterium Tritium (D-T) mixture.

To help in the designing, building and operating of the DPF machines for the optimum radiations, the need for numerical experiments is of importance. Lee code has been successfully developed to fulfil this need, in particular for “Mather type” DPF devices (Mather, 1960). The code has been widely used in designing several machines including the “United Nations University/International Centre for Theoretical Physics Plasma Fusion Facility (UNU/ICTP PFF), KSU PF, NX2 and NX3 and have been adapted for the Filippov-type plasma focus DENA” (Lee, 2014).

According to a research article by Lee and Saw (2010), “the current waveform should be investigated in detail as it reveals all the information about the plasma properties which includes its speed and trajectories, electrical and magnetic fields, and compression and radiative properties that occur in the axial and radial phases and sub-phases of the device”.

The objective of this paper is to show that using only one experimental current waveform together with the actual machine and operating parameters, the Argentina Nano focus machine could be numerically modelled to enable the study of its plasma dynamics. This demonstrates that the code is a useful tool to complement the actual experiment by revealing the dynamics of the axial and radial trajectories through the measured current waveform. The code is also used to study

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the variation of ion beam energy and neutron yield as functions of pressure. The resultant data is reliable and all the input that is required is just a measured current waveform.

To appreciate the value of the ability of the code to study ion beam characteristics and neutron yield in plasma focus devices, it is useful to note that a summary has been made of what has been achieved in similar simulation work (Lim *et al.,* 2016), and another particularly on the use of computations to add to the database of plasma focus in respect to thermonuclear and beam-target fusion (Saw *et al.,* 2015). Those summaries reviewed the work starting from Potter's (Potter, 1971) ground-breaking magnetohydrodynamics (MHD) studies demonstrating qualitative agreement with experimentally measured deuterium-deuterium (D-D) neutron yield although his thermonuclear mechanism was at odds with the "neutron yield anisotropy measured in plasma focus discharges". Moreno (Moreno *et al.,* 2000) and Gonzalez (González *et al.,* 2009a) achieved agreement between their computed neutron yield and measured neutron yield by fine-tuning their axial and radial mass swept-up factors. Such an approach has no predictive value. They over-estimated the radial shock speed, temperature and thermalised fusion cross-sections by a factors of 2, 4 and 1000, respectively (Lee *et al.,* 2009). Gonzalez (González *et al.,* 2009b) also used Von Karman approximations to fit the measured neutron yield versus pressure curve of the seven machines they examined using a thermonuclear mechanism. None of these work mention testing any other results of modelling against measured experiment results. Schmidt (Schmidt *et al.,* 2014) used a fully kinetic self-consistent simulation to obtain detail distributions of dynamics, electric fields, and plasma properties to estimate the ion beam and neutron yield. The kinetic code requires massive computing power and they managed only 26 ns, so they had to stitch their results onto 6.6 μs of two dimensional (2-D) fluid simulation. Out of this work they obtained a range of neutron yields $1.4 – 2.2 \times 10^{11}$ which agrees with the measured yield of a 1.5×10^{11} for the 2 MA Gemini DPF at 3.6 Torr deuterium. Although the measured yields span a range of pressures from 2.4 – 5.4 Torr, they were able to compare only at one pressure point. Together with neutron yield they also obtained characteristics of the ion beam showing that the main mechanism for neutron yield is beam-plasma target. However, the fully kinetic simulation method is not readily available to use for any plasma focus because of the immense computing power required to follow the plasma evolution for even a few nanoseconds. We are not able to find any other reliable computations of neutron yield or ion beams in the literature. Hence our method, requiring only laptop computing power offers a unique tool to complement any plasma focus laboratory.

II. MATERIALS AND METHOD

In this paper, the Lee model code is used. This code couples the "electrical circuit with plasma focus dynamics, thermodynamics, and radiation. It is energy- charge and mass-consistent" (Lee & Saw, 2010). The current waveform of the Lee code is computed through 5 phases. The axial phase uses a snow-plow model with two coupled equations, one for motion and the other for the electrical circuit. The radial inward shock phase uses a slug-model with 4 coupled equations for the: 1) shock front position; 2) piston position; 3) slug elongation; and 4) circuit. The radially outward moving reflected shock phase also uses similar 4 coupled equations whilst in the pinch phase the boundary of the pinch is defined by the magnetic piston whose motion is Joule heat and radiation-coupled and the piston motion is coupled to the circuit equation. Pinch elongation is continued and radiation and Joule heat dissipated in the plasma resistance are appropriately computed with the help of Bennett balance to compute the plasma temperature. Plasma self-absorption of radiation is included in this phase. The pinch phase requires 3 coupled equations and another 7 auxiliary equations. The details of this code including its "physics is explained in the article entitled Plasma Focus Radiative Model: Review of the Lee Model code" (Lee, 2014).

It is observed that over any series of shots with all controllable parameters kept the same, there is considerable variation from shot to shot in radiation yields for example 10% variation in neutron yield is quite typical. This variation may be attributed to the variation of the mass swept-up and drive current factors in axial and radial phases. After all it is unlikely that all the complex mechanisms responsible for these four factors remain constant for all the shots. By fitting the mass factors and current factors for each shot we are able to account for the net effect of all variations in each and thus model each shot with reasonable accuracy. Thus from just a measured current waveform, the dynamics, energetics and radiation yields are predicted. Numerous comparisons of the predicted dynamics and neutron and soft x-ray yields based on just the measured current waveforms have been made with satisfactory agreement (Lee & Saw, 2017).

Moreover, in the case where no measured currents are available, typical values of the mass swept-up and current factors may be used for any given machine over a wide range of gases. Thus for any plasma focus machine, the code may give reasonable indicative picture of the dynamics, energetics and radiation yield (Hawat *et al.,* 2012).

To use this code, the general fitting technique is explained in the paper "Numerical Experimentation to obtain the Scaling Laws of Mather type Dense Plasma Focus machines working in Argon gas" (Singh *et al.,* 2020). This technique can either use a measured current (or current derivative) signal which could either by published or measured signal (without data file) or a measured signal using digital oscilloscope where data file is available. For published (measured) signals without data files, the signal is digitised using open source digital software called "Engauge" (Engauge Digitizer, 2017).

For this research paper, we use the current derivative waveform published in the article about neutron yield from the Argentinian sub-kJ Nano focus" (Milanese *et al.,* 2013). This Nano focus device uses a brass Mather type anode of length 18 mm long, 7.5 mm in radius. The cathode was arranged with an inner radius of 2.1cm. This device has a static inductance of 74 nH (Pouzo *et al.,* 2003). It was powered via a spark gap switch by a 1.1 µF capacitor which was charged to 16 kV. The current derivative waveform for this machine was obtained from the research paper when it was operated at 2 mbar (1.5 Torr) deuterium gas to measure its neutron yield.

The current derivative dI/dt waveform from the published article (Milanese *et al.,* 2013) was digitised. To derive the measured current waveform, the obtained digital data of dI/dt was numerically integrated relative to time, thus giving the measured current. The 5 phase code (RADPF5.15, 2020) was then configured as the Argentina Nano focus by entering into the control panel the values of the parameters of bank, tube and operation. The current waveform flowing in the discharge circuit calculated from the code was than fitted to the measured waveform by adjusting the model parameters, these being the mass factor of the axial phase fm, the corresponding current factor fc, and the appropriate factors for the radial phases fmr and fcr. This fitting procedure was performed systematically, one phase at a time until the waveform produced in the computation matches the measured waveform.

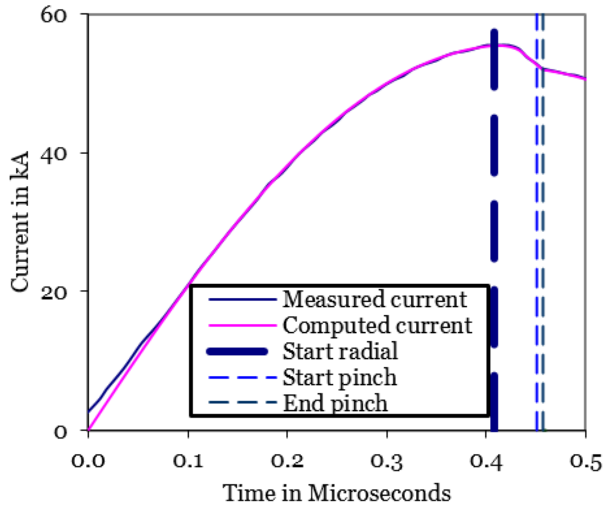

Figure 1. The computed current versus the measured current illustrated at 5 fitting points. This fit is for the Argentina Nano focus at 16kV, 1.5 Torr in deuterium gas.

Figure 1 shows the fitting between the measured current curve and the current curve computed from the Lee 5 phase code. The good fitting assures that the Lee codes has been configured to simulate the actual Argentina Nano focus including known mechanisms such as inclination, geometry and porosity of the current sheet and speculated even unknown effects including unspecifiable edge effects. All these effects are accounted for in the code in one sweep by the resultant mass sweeping (fm and fmr) and effective current fractions (fc and fcr).

III. RESULT AND DISCUSSION

The maximum computed current is found to be 55 kA (compared to 62 kA as reported (Milanese *et al.,* 2003). It reveals that this particular shot (shot #572) has a radial start time at 0.408 µs with a pinch duration of 0.049 µs. It has a speed factor (Lee & Serban, 1996) of 60 (kA/cm) /Torr$^{0.5}$ and neutron yield of 5.73 × 10^4 n/shot. The Lee model code computed the neutron yield using a phenomenological beam-target neutron generating mechanism as described in an article by Gribkov *et al.* (2007).

M Milanese (Milanese *et al.,* 2003) article stated that at 1.5 Torr (2 mbar) pressure, a thin and very sharp dip lasting around 50 ns occurs when the current derivative curve goes to zero (around 400 ns). The Lee code computed current waveform shows that this matches to the radial start time (occurring at 0.41 µs) until the end of the pinch duration (50 ns). Figure 1 shows this occurrence when the two waveforms are plotted together.

Using the machine parameters together with the fitted mass and current factors, the Argentina Nano Focus is now numerically modelled in the range of pressures from 0.5 Torr to 2.0 Torr to study the relationship between operation pressure, pinch length and the peak speeds in the axial and radial phases. This range was chosen because the maximum neutron yield occurs in this duration as will be shown in Figure 8. The results obtained from this study are shown in Figures 2-6. It should be noted, that the numerical experimental data (represented by the blue dots) is compared with the best fit line obtained from the excel trend line (represented by the black dots). R^2 shows the relationship between the axis as well as the statistical measure of how close the data is to the fitted regression line.

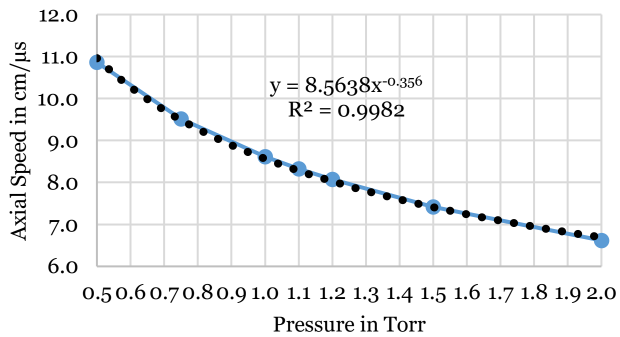

Figure 2. The computed peak axial speed versus pressure at capacitor charge of 16 kV for the Argentina Nano Focus operated in deuterium

From the results, it is noted that the axial speed *Va* shows a pressure dependence of $P_0^{-0.36}$ (Figure 2).

The peak radial shock speed *Vs* (Figure 3) and the peak piston speed *Vp* (Figure 4) are also observed to reduce with pressure with a rate of $P_0^{-0.44}$. As these two radial speeds decrease with pressure, the time required for the radial reflected shock to start and the pinch duration increase (Lee & Serban, 1996). Figure 5 shows pinch duration versus pressure with dependence of $P_0^{0.46}$.

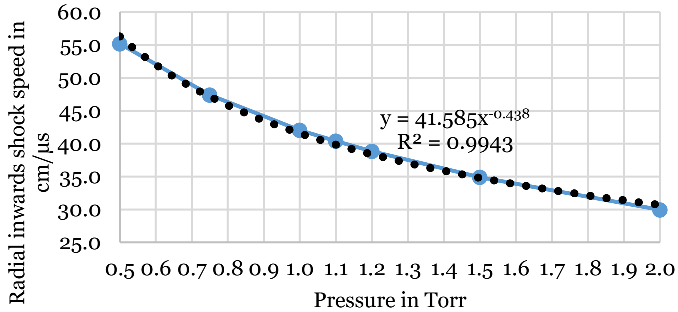

Figure 3. The computed radial inward shock speed versus pressure operating at 16 kV in deuterium for the Argentina Nano Focus machine

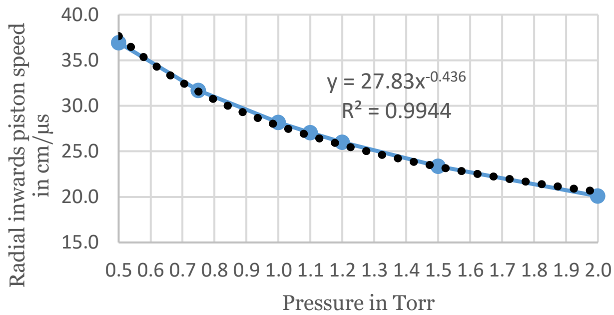

Figure 4. The computed radial inward piston speed versus pressure operating at 16 kV in deuterium for the Argentina Nano Focus machine

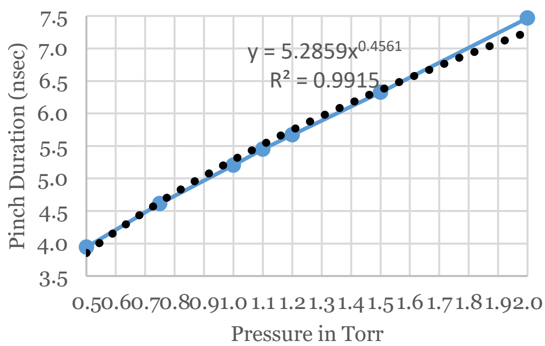

Figure 5. The pinch duration versus pressure operating at 16 kV in deuterium for the Argentina Nano Focus machine

An analysis of ion beam (simulated from a range of 0.5 to 4.5 Torr is shown in Figure 6). It reveals that the ion number per shot increases with the pressure P_o at the rate of $P_0^{0.74}$. It should be noted, that the ion beam leaves the pinch along its axis. It is assumed to be a narrow beam. This beam starts with the same radius as the pinch and is assumed to have only a small divergence. The small divergence is maintained until the beam reaches the slower axially moving post-pinch shock wave (Akel *et al.*, 2014). The plot of number of beam ions versus pressure is shown in Figure 7.

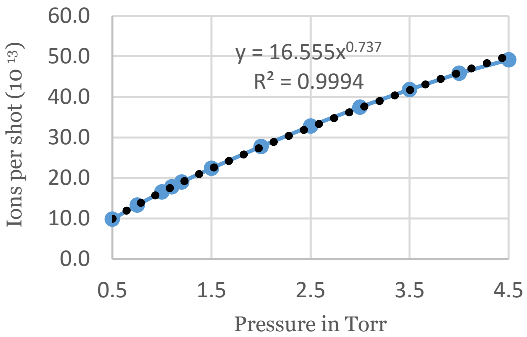

Figure 6. The yield of ions per shot versus pressure operating at 16 kV in deuterium for the Argentina Nano Focus machine. The ion number is the number of deuterium ions in the beam

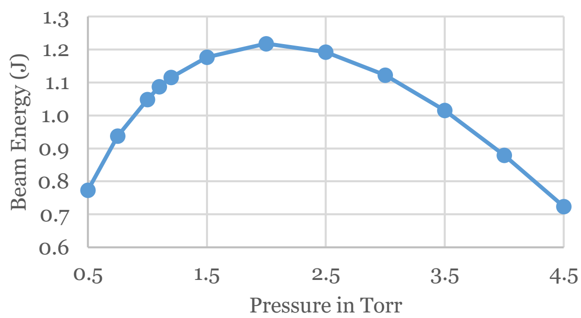

Figure 7. The ion beam energy versus pressure operating at 16 kV in deuterium for the Argentina Nano Focus machine

Ion beam energy (in J) is equal to the ion energy times the number of ions. The variation of ion beam energy with pressure is shown in Figure 8, where the maximum ion beam energy occurs at 2 Torr with the beam energy of 1.22 J.

Since the Argentina Nano Focus machine is working in deuterium, the maximum neutron yield is important. From the numerical experiment as shown in Figure 8, the optimum neutron yield obtained is 6.2 × 10^4 n/shot at 1.1 Torr with the energy input into plasma at 7.0 %. The published paper (Milanese *et al.*, 2003) does not give a neutron yield.

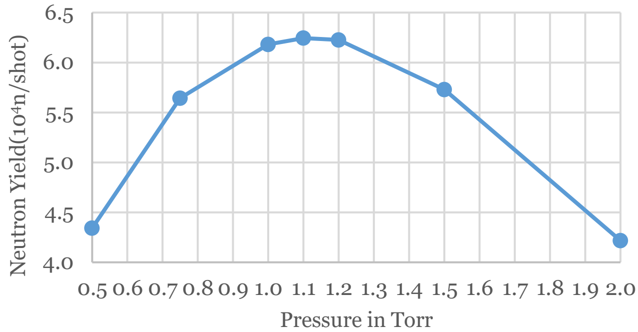

Figure 8. The neutron yield versus pressure operating at 16 kV in deuterium for the Argentina Nano Focus machine

From Figure 7, the ion beam energy is optimum at 2 Torr whereas from Figure 8 the optimum neutron yield is at 1.1 Torr. From Figure 7, the number of beam ions keeps increasing with pressure. Thus, although the yield should depend on the number of beam ions as well as the plasma density, there is also a dependence on fusion cross-section which increases more strongly with beam ion energy (energy of the ion) than ion beam energy (energy of the beam) in the range of ion energy of 10 to 100 keV which is the range of relevance in these plasma focus experiments. The computed optimum pressure of 1.1 Torr is the result of the interplay of mainly these two factors on the fusion yield. These factors are the number of beam ions and target ions (generally the higher the pressure the more these numbers) and the ion energy (generally the lower the pressure the higher the ion energy). The ion energy in particular has a great effect on the D-D fusion cross-section.

IV. CONCLUSION

It is shown that using only one experimental current waveform together with the actual machine and operating parameters, the Argentina Nano focus machine could be numerically modelled using Lee code to enable the study of its plasma dynamics which includes the axial, radial, piston speeds as well the pinch duration, pinch temperature, the number of ions produced and its beam energy. The computed results agree reasonably with the measured in terms of the peak current, the radial phase start time and the duration of the pinch phase. The code is a useful tool to complement the actual experiment by revealing the dynamics of the axial and radial trajectories through the measured current waveform.

The code is also used to study the variation of ion beam energy and neutron yield as functions of pressure. The optimum pressures obtained from the numerical experiments for ion beam energy is at 2 Torr with a yield of 1.22 J and for neutron is at 1.1 Torr with a yield of 6.2×10^4 n/shot.

V. REFERENCES

Akel, M, Salo, SA, Saw, SH & Lee, S 2014, 'Ion beam features produced by two plasma focus machines operated with different gases', IEEE Transactions on Plasma Science, vol. 42, no. 9, pp. 2202-2206.

Engauge Digitizer,2017, Download Engauge Digitizer 12.1 – Softpedia, viewed 24 December 2021, <https://www.softpedia.com/dyn-postdownload.php/8c19b2ec1106fbd12bcc322dec7179da/61c5492b/132f0/0/1>.

González, JH, Barbaglia, M, Casanova, F & Clausse, A 2009, 'A lumped parameter model of free expanding plasma focus', Brazilian Journal of Physics, vol. 39, no. 4, pp. 633-637.

González, JH, Brollo, FR & Clausse, A 2009, 'Modeling of the dynamic plasma pinch in plasma focus discharges based in Von Karman approximations', IEEE Transactions on Plasma Science, vol. 37, no. 11, pp. 2178–2185.

Gribkov, VA, Banaszak, A, Bienkowska, B, Dubrovsky, A V, Ivanova-Stanik, I, Jakubowski, L, Karpinski, L, Miklaszewski, R A, Paduch, M, Sadowski, M J, Scholz, M, Szydlowski, A & Tomaszewski, K 2007, 'Plasma dynamics in the PF-1000 device under full-scale energy storage: II. Fast electron and ion characteristics versus neutron emission parameters and gun optimization perspectives', Journal of Physics D: Applied Physics, vol. 40, no. 12, pp. 3592–3607.

Hawat, Al Sh, Akel, M, Lee, S & Saw, SH 2012, 'Model parameters vs gas pressure in two different plasma focus devices operated in Argon and Neon', Journal of Fusion Energy, vol. 31, no. 1, pp. 13–20.

Lee, S 2014, 'Plasma focus radiative model-review of the Lee Model code', Journal of Fusion Energy, vol. 33, no. 4, pp. 319–335.

Lee, S & Serban, A 1996, 'Dimensions and lifetime of the plasma focus pinch', IEEE Transactions on Plasma Science, vol. 23, no. 3, pp. 1101-1105.

Lee, S & Saw, SH 2010, 'The plasma focus- scaling properties to Scaling Laws', Joint ICTP-IAEA Workshop on Dense Magnetized Plasma and Plasma Diagnostics, 15-26 November 2010.

Lee, S & Saw, SH 2017, 'The plasma focus—numerical experiments, insights and applications', Plasma Science and Technology for Emerging Economies, Chapter 3, pp. 113–232.

Lee, S, Saw, SH, Soto, L, Springham, SV & Moo, SP 2009, 'Numerical experiments on plasma focus neutron yield versus pressure compared with laboratory experiments', Plasma Physics and Controlled Fusion, vol. 51, no. 7, pp.1-11.

Lim, LK, Yap, SL, Lim, LH, Neoh, Y S, Khan, MZ, Ngoi, SK, Yap SS & Lee, S 2016, 'Parametric optimisation of plasma focus devices for neutron production', Journal of Fusion Energy. vol. 35, no. 2, pp. 274-280.

Mather, JW 1965, 'Formation of a high-density deuterium plasma focus', Physics of Fluids, vol. 38, no. 2, pp. 366-377.

Milanese, M, Moroso R & Pouzo, J 2003, 'D-D neutron yield in the 125 J dense plasma focus Nanofocus', The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics, vol. 27, no. 1, pp.77–81.

Moreno, C, Bruzzone, H, Martinez, J & Clausse A 2000, 'Conceptual engineering of plasma-focus thermonuclear pulsors', IEEE Transactions on Plasma Science, vol. 28, no. 5, pp. 1735-1741.

Potter, DE 1971, 'Numerical studies of the plasma focus', The Physics of Fluids, vol. 14, no. 9, pp. 1911-1924.

Pouzo, J, Milanese, M & Moroso, R 2003, 'Portable neutron probe for soil humidity measurements', Plasma Physics, vol. 669, pp. 277-280.

RADPF5.15, 2020, Institute for Plasma Focus Studies, 2020, The Universal Plasma Focus Laboratory RADPF5.15b, viewed 24 December 2021, <http://www.plasmafocus.net/IPFS/modelpackage/UPF.htm>.

Saw, SH, Lee, P, Rawat, RS, Verma, R, Subedi, D, Khanal, R, Gautam, P, Shrestha, R, Singh, A & Lee S 2015, 'Comparison of measured neutron yield versus pressure curves for FMPF-3, NX2 and NX3 plasma focus machines against computed results using the Lee Model code', Journal of Fusion Energy, vol. 34, no. 3, pp. 474-479.

Schmidt, A, Link, A, Welch, D, Meehan, BT, Tang, V, Halvorson, C, May, M & Hagen, EC 2014, 'Fully kinetic simulations of megajoule-scale dense plasma focus', Physics of Plasmas, vol. 21, no. 10, pp. 102703.

Singh, A, Saw, SH & Lee, S 2020, 'Numerical experimentation to obtain the Scaling Laws of Mather type Dense Plasma Focus machines working in Argon gas', INTI Journal, vol. 2020, no. 2, pp. 1-6.