Kathmandu University
Journal of Science, Engineering and Technology
KUSET

Proceedings of the International Conference on Plasma Science and Applications (ICPSA-2014)
Singh *et al.*, Vol.10, No.II, December, 2014, pp 34- 41

ORIGINAL RESEARCH ARTICLE OPEN ACCESS

NUMERICAL EXPERIMENTS TO OBTAIN THE SCALING LAWS FOR NEUTRON YIELD ON MATHER-TYPE PLASMA FOCUS MACHINES BELOW 500 JOULES

[1]A. Singh*, [1,2,3]S Lee, [1,2]S. H. Saw

[1]INTI International University, 71800 Nilai, Malaysia
[2] Institute for Plasma Focus Studies, 32 Oakpark Drive, Chadstone, VIC3148, Australia
[3] University of Malaya, Kuala Lumpur, Malaysia

*Corresponding author's email: arwinders.jigiris@newinti.edu.my

ABSTRACT

In this paper, we explain how we have fitted Lee's 5-phase and 6-phase model code to analyze the current waveforms of 6 small plasma focus machines (below 500Joules) working in deuterium gas medium. Using the information from the codefitted to these current waveforms, the scaling laws for these small- energy machines were obtained as follows

$$Y_n \approx E_0^{2.1}; \qquad Y_n \approx I_{peak}^{3.9}; \qquad Y_n \approx I_{pinch}^{5.0}$$

Key words: Lee's model code, neutron yield, scaling law, plasma focus neutron scaling laws

INTRODUCTION

According to S Lee and SH Saw [1] the current trace of the plasma focus is one of the best indicators of gross performance of the plasma focus machine. The axial and radial phase dynamics and the crucial energy transfer into the focus pinch are among the most important information that is quickly apparent from the current trace. The exact time profile of the total current trace is governed by the bank parameters, by the focus tube geometry and the operational parameters. The current trace is also dependent on the fraction of mass swept-up and the fraction of sheath current and the variation of these fractions through the axial and radial phases. These parameters determine the axial and radial dynamics, specifically the axial and radial speeds which in turn affect the profile and magnitudes of the discharge current. The discharge current waveform contains information on all the dynamic, electrodynamic, thermodynamic and radiation processes that occur in the various phases of the plasma focus.This explains the importance attached to matching the computed total current trace to the measured total current trace in the procedure adopted by the Lee model code [2-16]. Once matched, the fitted model parameters assure that the computation proceeds with all physical mechanisms accounted for, at least in the gross energy and mass balance sense. One of the most important procedures therefore is to connect the numerical experiment to the reality of the actual machine by fitting the computed current trace to a measured current trace. Using this information, we look into the existing scaling laws such as those assembled by H. Krompholz et al in their paper "A Scaling

Law for Plasma Focus Devices" [17]and by S Lee and S H Saw in their papers"The Plasma Focus- Scaling Properties to Scaling Laws"[1]and "Neutron Scaling Laws from Numerical Experiments" [5] in which are proposed general scaling laws. The papers by Lee and Saw are based on large (up to MJ) and small machines and cover the whole range of energy from 400 J to MJ, using data derived from both measured results and numerical experiments. We now examine machines below 400 J.

MATERIALS AND METHODS

Using the Lee model code, the computed total current waveform was fitted to the measured waveform (obtained from the published articles [18, 19, 20, 21, 22, 23] current or current derivativewaveformswhich were digitalized with Engauge [24]) by changing model factors f_m, f_c, $f_{mr}$and f_{cr}one by one, till the computed waveform agrees with the measured waveform. First, $f_m$and$f_c$are tuned sequentially until the features of the computed rising slope of the total current trace and the rounding off of the peak current as well as the peak current itself are in reasonable fit with the measured total current trace. We then continue to fit the radial $f_{mr}$and f_{cr}until features of the computed slope and the depth of the dip agree with the measured current waveform.Using theLee Model 5-phase code the fitting ends here. If there is an extended part of the measured current dip which cannot be fitted by the computed current dip no matter how the model parameters are varied, then Lee Model 6-phase code is used. The 6-phase code has an additional phase between the end of pinch and the expanded column phase. This additional phase is fitted by adding anomalous resistance terms into the circuit equation (typically 3 sequential anomalous resistance terms)[16].

RESULTS AND DISCUSSION

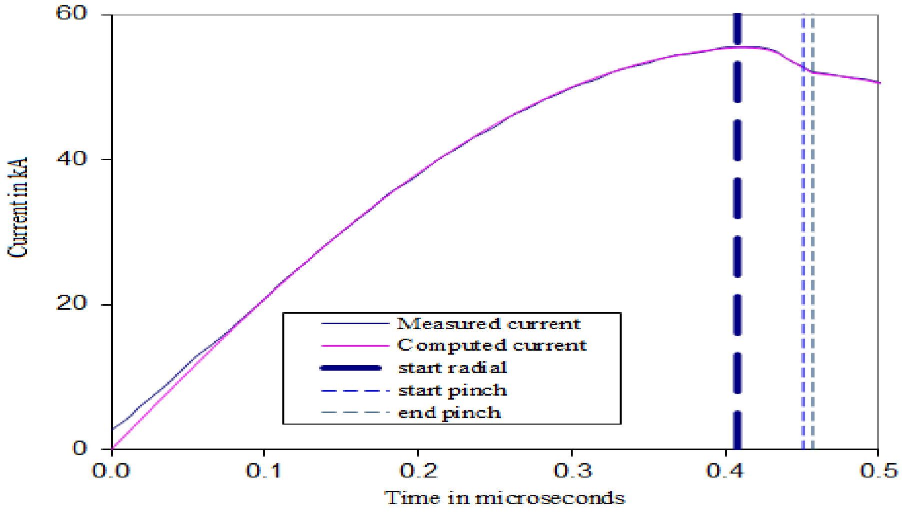

Figure 1: The fitting of the computed current trace to the measured current trace obtained from Argentina Nanofocus operating at 16kV, 1.5 Torr deuterium gas. The measured current waveform was extracted from shot number 572, Figure 7 in the paper entitled "D-D neutron yield in the 125 J dense plasma focus Nanofocus" [19]. Figure 1 shows a typical fitting of

computed current waveform to measured current waveform for the case of the Argentinian Nanofocus ANF. Once the current waveform is fitted, the model parameters are obtained. This process was repeated for all 6 machines. Four machines were fitted with Lee's 5-phase code whereas the other 2 machines (AASC and *India PF) have extended dips and required the extension of the 6-phase code. Using the fitted model parameters, the Lee code was configured for each machine at different pressures to find the optimum neutron yield for each machine.The machine configurations are recorded in Table 1.The informationobtained at optimum yield for each machine is recorded in Table 4.Additionally Tables 2 and 3 record the anomalous resistance data required to fit the two machines with extended dips ED that could not be fitted completely with the 5-phase code.

Table 1: Machine and operating parametersand fitted model parameters of each of the machines.

	PF50	ANF	AASC	FMPF-1	*India PF	PF400
Capacitance C_0 (μF)	0.2	1.1	10.88(ES)	2.4	4	0.95
Static inductance L_0 (nH)	38	74	15.8(ES)	32.9	46	40
Circuit resistance r_0 (mΩ)	20	25	3.9	60	10	10
Outer radii, 'b'(cm)	1.35	2.1	2	1.5	1.6	1.55
Inner anode 'a'(cm)	0.3	0.75	0.75	0.6	0.5	0.6
Anode length 'z_0'(cm)	0.48	1.8	3	1.7	2	1.7
Charging voltage V_0 (kV)	25,29	16	4.5(ES)	12	10	28
Fill pressure P_0 (Torr)	6.8	1.5	2.9	2.25	6	6.6
Fill gas(molecular weight)	4	4	4	4	4	4
Fill gas(atomic number)	1	1	1	1	1	1
Fill gas(molecule(2))	2	2	2	2	2	2
Axial phase mass factor, f_m	0.13	0.055	0.065	0.155	0.135	0.08
Axial phase current factor, f_c	0.7	0.7	0.7	0.7	0.7	0.7
Radial phase mass factor, f_{mr}	0.1	0.1	0.1	0.165	0.1	0.11
Radial phase current factor, f_{cr}	0.75	0.95	0.75	0.75	0.8	0.71
Taper type machine						
Taper starts at (cm)				1.0		
Final tapered radius (cm)				0.3		

Note: (i) PF 50 was charged at 25kV and 29kV [18];so we have two set of results for PF50 in Table 4 (ii) ES is equivalent secondary; (iii)*India PFis India smallest sealed type machine; (iv)ANF is Argentina Nanofocus

Table 2: The fitted anomalous resistance terms for AASC Plasma Focus machine.

	R_0(Ω)	Characteristic of fall time, τ_2 (ns)	Characteristic of rise time, τ_1 (ns)	End fraction time
Dip 1	0.8	24	10	1
Dip 2	0.03	100	10	1
Dip 3	0.01	100	10	1

Table 3: The fitted anomalous resistance terms for India smallest sealed type machine.

	$R_0(\Omega)$	Characteristic of fall time, τ_2 (ns)	Characteristic of rise time, τ_1 (ns)	End fraction time
Dip 1	0.5	22	10	1
Dip 2	0.02	80	10	1
Dip 3	0.03	100	10	1

Table 4: Some of the information obtained from the Lee Model code configured when optimum yield was obtained.

	PF 50	PF 50	ANF	AASC	FMPF-1	India PF	PF 400
Energy(J)	62.5	84.1	140.8	110.2	172.8	200	372.4
Peak current (kA)	54	63	54	87	69	82	125
Pinch start current (kA)	39	45	50	57	48	62	84
Pinch minimum temperature(10^6 K)	16.2	15.5	9.5	5.8	18.3	7.4	8.5
Pinch maximum temperature(10^6 K)	16.5	15.9	9.7	6.2	18.9	7.6	8.7
Peak axial speed (cm/µs)	6.5	6.4	8.6	9.1	7.3	5.3	10
Peak radial shock speed (cm/µs)	54.7	53.8	42.1	35.4	36.9	37.4	40.3
Peak radial piston speed (cm/µs)	36.7	36.0	28.2	24.9	25	25.7	26.9
Final pinch radius r_{min} (cm)	0.04	0.04	0.10	0.11	0.06	0.07	0.08
Pinch length z_{max} (cm)	0.4	0.4	1.1	1.1	0.6	0.7	0.8
Pinch duration (ns)	1.6	1.6	5.2	6.7	3.5	3.9	4.4
Peak induced voltage (kV)	15.1	17.2	13.2	10.2	17.3	14.6	20.6
Neutron yield ($x10^4$n)	2.2	5.2	6.2	7	8.8	25.3	125

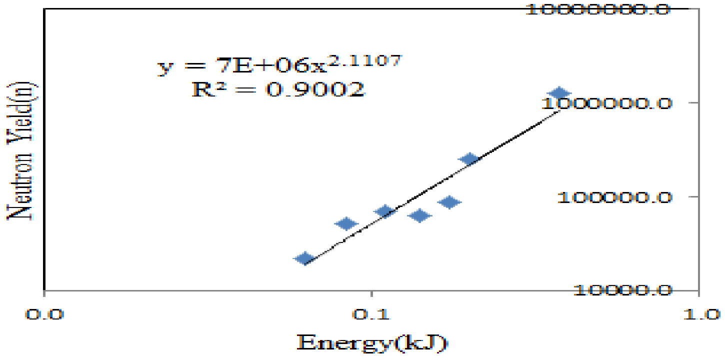

Figure 2: Neutron yield versus stored energy for the 6 machines studied.

Next, we use some of the information obtained from Table 4 and plot the graphs as shown in Figure 2, 3 and 4. Figure 2 shows the plot of neutron yield versus the energy input into the plasma focus machine in log-log scale. From Figure 2, we have: $Y_n = 7x10^6 E^{2.1}$ where E is in kJ, which is close to the generally accepted neutron yield versus energy scaling law of $Y_n \approx E^2$ [1, 5, 7, 17].

Figure 3 shows the plot of neutron yield versus the peak current in the plasma focus machine in log-log scale. From Figure 3, we obtain: $Y_n = 0.0058 I_{peak}^{3.9}$ where I_{peak} is in kA, which is close to $Y_n \approx I_{peak}^{3.9}$ which was obtained by S Lee and SH Saw in their paper "Neutron Scaling Laws from Numerical Experiments" [5].

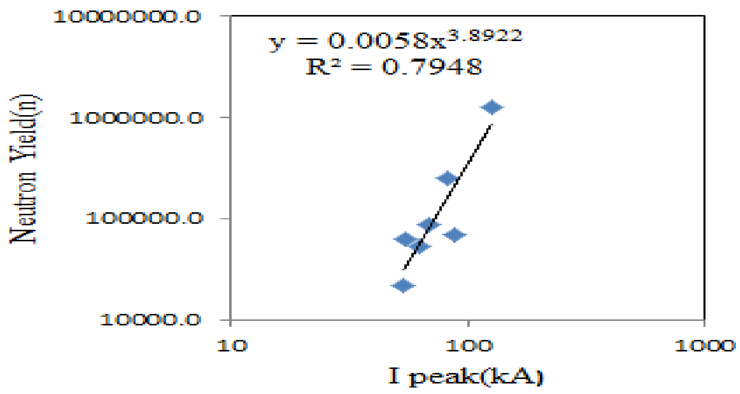

Figure 3: Neutron yield versus peak current for the 6 machines studied.

Figure 4 shows the plot of neutron yield versus the pinch current in the plasma focus machine. Figure 4 gives us the relationship of $Y_n = 0.0002 I_{pinch}^{5.0}$ where I_{pinch} is in kA, which is close to $Y_n \approx I_{pinch}^{4.7}$ which was obtained by S Lee and SH Saw in their paper "Neutron Scaling Laws from Numerical Experiments"[5].

.

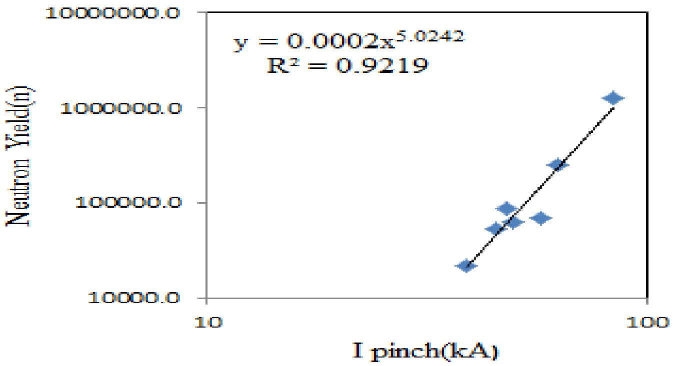

Figure 4: Neutron yield versus pinch current for the 6 machines studied.

CONCLUSION

Combining the computed data of the 6 plasma focus machines studied, we obtain the following scaling laws. Neutron yield Y_n in deuterium as functions of stored energy E_0, peak circuit current I_{peak} and pinch current I_{pinch}:

$$Y_n \approx E_0^{2.1}; \qquad Y_n \approx I_{peak}^{3.9}; \qquad Y_n \approx I_{pinch}^{5.0}$$

Thus we can conclude that the scaling laws from the two papers [1, 17] are still valid for plasma focus machines below 500 joules.

REFERENCES

[1] Lee S & Saw S H, "The Plasma Focus- Scaling Properties to Scaling Laws", *Joint ICTP-IAEA Workshop on Dense Magnetized Plasma and Plasma Diagnostics* ,15 - 26 November 2010—ICTP 2168-1

[2] Lee S, Tan B C, Wong A C & Chew C S, "Laser and Plasma Technology: *Proceedings of the First Tropical College on Applied Physics*, 26th December, 1983 to 14th January, 1984 Kuala Lumpur. Pub. World Scientific, Singapore (1985).

[3] Lee S, "Plasma Focus Model Yielding Trajectory and Structure", *Radiation in Plasmas, Volume II. Proceedings of the 1983 College on Plasma Physics International Centre for Theoretical Physics, Trieste, Italy. Edited by B. McNamara. Published by World Scientific*, pp.978, (1984)

[4] Website: http://www.plasmafocus.net/

[5] Lee S & Saw S H, "Neutron scaling laws from numerical experiments*", J Fusion Energy*, 27, pp 292–295, DOI: 10.1007/s 10894-008-9132-7, (2008)

[6] Lee S & Saw S H, "Pinch Current Limitation Effect in Plasma Focus", *Applied Physics Letters*, 92, 021503, DOI:10.1063/1.2827579, (2008)

[7] Saw S H & Lee S, “Scaling Laws for Plasma Focus Machines from Numerical Experiments”, *Energy and Power Engineering,* pp 65-72, DOI:10.4236/epe.2010.21010, (2010)

[8] Saw S H & Lee S, “Scaling the plasma focus for fusion energy considerations”, *International Journal of Energy Research*, 35, pp 81-88, DOI:10.1002/er.1758, (2011)

[9] Lee S, Saw S H, Soto L, Moo S P, Springham S V, “Numerical experiments on plasma focus neutron yield versus pressure compared with laboratory experiments”, *Plasma Phys Control Fusion*, 51, 075006, DOI:10.1088/0741-3335/51/7/075006, (2009)

[10] Lee S & Saw S H, “The Plasma Focus- Trending into the Future” , *Int J of Energy Research*, DOI: 10.1002/er.1918, (2011)

[11] Lee S, Saw S H, Lee P C K, Rawat R S & Schmidt H, “Computing plasma focus pinch current from total current measurement”, *Appl. Phys. Lett*, 92, 11, pp 111501, DOI:10.1063/1.2899632, (2008)

[12] Lee S, Saw S H, Lee P & Rawat R S, “Numerical Experiments on Neon plasma focus soft x-rays scaling”, *Plasma Physics and Controlled Fusion*, 51, 105013, DOI:10.1088/0741-3335/51/10/105013, (2009).

[13] Saw S H, Lee S, Roy F, Chong P L, Vengadeswaran V, Sidik A S M, Leong Y W & Singh A, “In-situ determination of the static inductance and resistance of a plasma focus capacitor bank” , *Rev Sci Instruments*, 81, 053505, DOI:10.1063/1.3429207, (2010)

[14] Lee S, “Neutron Yield saturation in Plasma focus:A fundamental cause” *Applied Physics Letters* 95 (15), 151503,(2009)

[15] Lee S, Rawat R S, Lee P & Saw S H, “Soft x-ray yield from NX2 plasma focus”, *Journal of Applied Physics*, 106, 023309, DOI: 10.1063/1.3176489, (2009)

[16] Lee S, Saw S H, Abdou A E & Torreblanca, H “Characterizing Plasma Focus Devices- Role of Static Inductance- Instability Phase Fitted by Anomalous Resistances”, *J Fusion Energy*, 30, pp 277-282, DOI: 10.1007/s10894-010-9372-1, (2010)

[17] Krompholz H, Rühl F, Schneider W, Schönbach K., Herziger G, A Scaling Law for Plasma Focus Devices, *Phys Lett* A, Volume 82, Issue 2, 9 March 1981, Pages 82–84

[18] Leopoldo Soto, Patricio Silva, José Moreno, Marcelo Zambra, Walter Kies, Roberto E Mayer, Alejandro Clausse, Luis Altamirano, Cristian Pavez & Luis Huerta,, “Demonstration of neutron production in a table-top pinch plasma focus device operating at only tens of joules”, *Journal of Physics D:Applied Physics*, 41, 205215, pp 1-7, DOI: 10.1088/0022-3727/41/20/205215, (2008)

[19] Milanese M, “D-D neutron yield in the 125 J dense plasma focus Nanofocus*”, Eur. Phys. J. D*, 27, pp 77–81, DOI: 10.1140/epjd/e2003-00247-9, (2003)

[20] Bures B L, “Application of an impedance matching transformer to a plasma focus*”, Rev. Sci. Instrum*. 82, 103506, DOI: 10.1063/1.3648117, (2011)

[21] Rishi Verma, M V Roshan, F Malik, P Lee, S Lee, S V Springham, T L Tan, M Krishnan & R S Rawat,, “Compact sub-kilojoule range fast miniature plasma focus as portable neutron source”, *Plasma Sources Science and Technology*, 17, 045020, pp 1-11, DOI:10.1088/0963-0252/17/4/045020, (2008)

[22] Ram Niranjan, R. K. Rout, Prabhat Mishra, Rohit Srivastava, A. M. Rawool, T. C. Kaushik & Satish C. Gupta, “Note: A portable pulsed neutron source based on the

smallest sealed-type plasma focus device*", Rev. Sci. Instrum*, 82, 026104, pp 1-3, DOI:10.1063/1.3534827,(2011)

[23] Patricio Silva, José Moreno, Leopoldo Soto, Lipo Birstein, Roberto E. Mayer & Walter Kies, "Neutron emission from a fast plasma focus of 400 joules", *Applied Physics letters*, Volume 83, 16, pp 3269-3271,DOI:10.1063/1.1621460, (2003)

[24] Website: http://sourceforge.net/project/showfiles.php?groupid=67696&package id=130007&release id=500277,(2009)