Kathmandu University
Journal of Science, Engineering and Technology
KUSET

Proceedings of the International Conference on Plasma Science and Applications (ICPSA-2014)

Saw & Lee *et al.*, Vol.10, No.II, December, 2014, pp 42- 49

ORIGINAL RESEARCH ARTICLE OPEN ACCESS

THE PLASMA FOCUS SCALED FOR NEUTRONS, SOFT X-RAYS, FAST ION BEAMS AND FAST PLASMA STREAMS

[1,2]S. H. Saw*, [1,2,3]S. Lee
[1]INTI International University, Nilai, Malaysia
[2]Institute of Plasma Focus Studies, Chadstone 3148, Australia
[3]University Malaya, Kuala Lumpur Malaysia

*Corresponding author's email: sorheoh.saw@newinti.edu.my

ABSTRACT

Being an intense source of neutrons, soft x-rays, ion beams and fast plasma streams, the plasma focus promises applications such as fusion energy, advanced microlithography, materials synthesizing and testing, radiation diagnostics, medical isotopes and imaging. This paper reviews the scaling laws of neutrons, soft x-rays, ion beams and fast plasma streams derived from extensive numerical experiments conducted over the past 7 years.

Keywords: dense plasma focus scaling laws, ion beams and fast plasma stream, Lee model code

INTRODUCTION

Plasma focus machines of various energies have been extensively studied as sources of neutrons, soft x-rays and energetic beam ions. An exciting prospect is for scaling the plasma focus up to regimes relevant for fusion energy studies. However, even a simple machine such as the UNU/ICTP PFF 3 kJ machine consistently produces 10^8 neutrons in deuterium [1]. Plasma focus machines operated in neon have also been studied as intense sources of soft x-rays [2-4]. Whilst many recent experiments have concentrated efforts on low energy repetitive devices [2-4], other experiments have looked at larger plasma focus devices [5,6] extending to MJ regime. Numerical experiments are also gaining interest [7,8] with the Lee model code [9,10] demonstrating that it computes realistic focus pinch parameters and absolute values of neutron yield Y_n and soft x-ray yield Y_{sxr} which are consistent with those measured experimentally [8,11-13]. A comparison was made for the case of the NX2 machine [4], showing good agreement between computed and measured Y_{sxr} [11]. This gives confidence that the Lee model code gives realistic results in the computation of Y_n and Y_{sxr}.

More recently, we see increasing investigations on the ion beams and plasma streams emission from PF devices. The motivation for these studies is the potential applications for materials synthesis, and damage studies of candidate wall materials of fusion reactors. Hence we have extended our model code to enable numerical experiments to be carried out on defining properties of beam ions in various gases [14-16]. In this review, we show the comprehensive range of numerical experiments conducted to derive scaling laws on neutron yield Y_n [17,18] and neon Y_{sxr} [12,19-21], in terms of storage energy E_0, peak discharge current I_{peak} and peak focus pinch current I_{pinch} obtained from studies carried out over E_0 varying from 0.2 kJ to 25 MJ for optimised machine parameters and operating parameters. We also present as yet unpublished results of the scaling of fast ion beam and fast plasma streams.

THE LEE MODEL CODE

The Lee model code couples the electrical circuit with plasma focus dynamics, thermodynamics and radiation, enabling realistic simulation of all gross focus properties. The basic model, described in 1984 [22] was successfully used to assist several projects [23-26]. Radiation-coupled dynamics was included leading to radiation cooling [27]. The vital role of a finite small disturbance speed [28] was incorporated. This version of the code assisted other research projects [29-34]. Plasma self-absorption was included in 2007 [35] improving SXR yield simulation. The code has been used extensively in several machines [1, 4, 11-21, 23-26, 30-34]. Neutron yield Y_n using a beam–target mechanism [9,10,17,18] is incorporated. Insights include current and yield limitations with reduced (very low) static inductance [36,37], neutron saturation [38], radiative collapse [39], current-stepped PF [40-42], extraction of diagnostic data [43-51] and anomalous resistance data [52,53].

a. Computation of Neutron Yield

The neutron yield is computed using a phenomenological beam-target neutron generating mechanism described recently by Gribkov et al [54]. 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. The beam-target yield is derived [9,10,17,18] as:

$$Y_{b\text{-}t} = C_n\, n_i\, I_{pinch}{}^2 z_p{}^2 (\ln (b/r_p)\, \sigma / U^{0.5} \qquad (1)$$

where n_i=ion density, b=cathode radius, r_p= radius of the plasma pinch with length z_p, σ=cross-section of the D-D fusion reaction, n- branch [55] and U=beam energy. C_n is treated as a calibration constant combining various constants in the derivation process.

b. Computation of Neon SXR Yield

In the code [9,10], neon line radiation Q_L is calculated as follows:

$$\frac{dQ_L}{dt} = -4.6x10^{-31} n_i^2 Z Z_n^4 \left(\pi r_p^2\right) z_f / T \qquad (2)$$

where in our experiments we take the SXR yield $Y_{sxr} = Q_L$ within an appropriate temperature window [9,10,21]. Z_n is the atomic number.

c. Computation of Beam ion and fast plasma stream properties.

In the latest (RADPF.FIB) the Lee code computes the flux of the ion beams $J_b=n_b v_b$ where n_b=number of beam ions N_b divided by volume of plasma traversed is derived from pinch inductive energy considerations; and v_b=effective speed of the beam ions is derived from the accelerating voltage taken as diode voltage U. All quantities are expressed in SI units, except where otherwise stated. The resulting equation [14,15] is given below:

$$\text{Flux} = J_b = 2.75x10^{15}\ (f_e/[MZ_{eff}]^{1/2})\{(\ln[b/r_p])/(r_p^2)\}(I_{pinch}^2)/U^{1/2} \quad \text{ions m}^{-2}\text{s}^{-1} \qquad (3)$$

where M=ion mass, Z_{eff}= effective charge, b=cathode radius, r_p=pinch radius and I_{pinch}=pinch current. The parameter f_e= fraction converted into beam energy from the inductive energy of the pinch. The extended code computes FIB fluence and flux and energy fluence and flux, power flow, FIB damage factor and FIB energy. It also computed FPS energy. Techniques used in the code includes a self-consistent check of the energy distribution amongst the various energy components of the system including electromechanical energy input into the plasma, FIB energy, electron beam energy, radiation losses and FPS energy.

NUMERICAL EXPERIMENTS

Series of numerical experiments were carried out on machines with storage energies ranging from sub-kJ to half MJ searching for optimum neutron yield, neon soft x-ray yield and more recently beam and FPS yields by variation of pressure. Some results (as yet unpublished) are summarized in the following graphs indicating the scaling of FIB energy and FPS energy with current and PF storage energy.

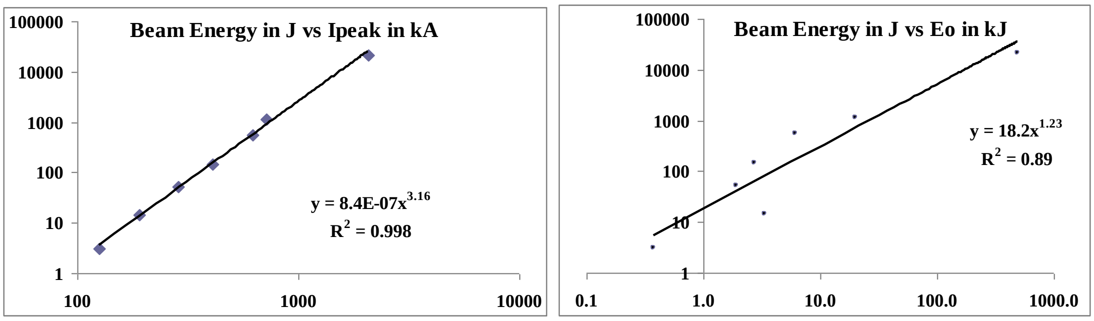

Fig 1 Scaling laws for FIB ion beam energy as functions of I_{peak} and storage energy E_0.

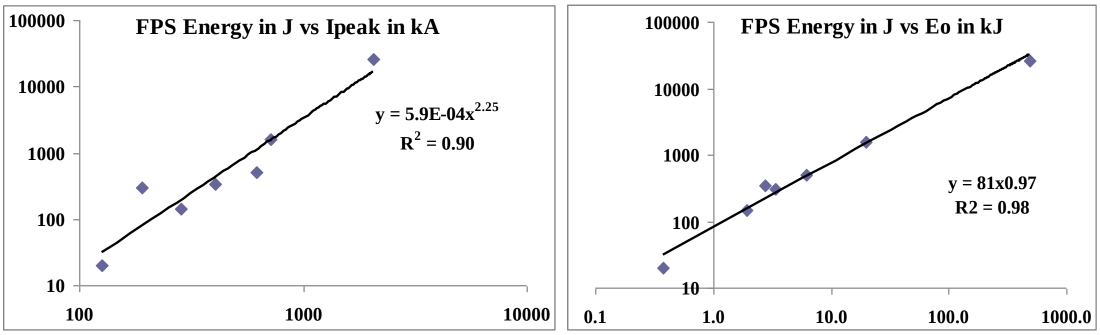

Fig 2 Scaling laws for FPS Fast Plasma Stream energy as functions of I_{peak} and storage energy E_0.

These results could be useful as reference data for design or interpretation of target interaction experiments for materials fabrication/modification/deposition or for target damage studies. They have already been used in the scaling of radiation for consideration of target irradiation for production of SLR (short-lived radioisotopes) [55].

CONCLUSION

Numerical experiments carried out using the universal plasma focus laboratory facility based on the Lee model code give reliable scaling laws for neutrons production and neon SXR yields for plasma focus machines. These have been extended to scaling laws for fast ion beams and post-pinch fast plasma streams. The scaling laws obtained are:

For neutron yield: (yield in number of neutrons per shot)
$Y_n = 3.2\text{x}10^{11}\, I_{pinch}^{4.5}$; $Y_n = 1.8\text{x}10^{10}\, I_{peak}^{3.8}$; I_{peak} (0.3 to 5.7), I_{pinch} (0.2 to 2.4) in MA.
$Y_n{\sim}E_0^{2.0}$ at tens of kJ to $Y_n{\sim}E_0^{0.84}$ at MJ level (up to 25MJ).

For neon soft x-rays: (yield in J per shot)
$Y_{sxr} = 8.3\text{x}10^3\, I_{pinch}^{3.6;}$ $Y_{sxr} = 6\text{x}10^2\, I_{peak}^{3.2}$; I_{peak} (0.1 to 2.4), I_{pinch} (0.07 to1.3) in MA.
$Y_{sxr}{\sim}E_0^{1.6}$ (kJ range) to $Y_{sxr}{\sim}E_0^{0.8\,(}$towards MJ).

For energy of beam ions at exit of a deuterium plasma pinch: (yield in J per shot)
$Y_{beam}{=}2.8\text{x}10^{-7} I_{pinch}^{3.7}$ $Y_{beam}{=}\ 8.4\text{x}10^{-7} I_{peak}^{3.16}$ and currents in kA.
$Y_{beam}{=}\ 18.2E_0^{1.23}$; where Y_{beam} is in J and E_0 is in kJ; over 1 kJ to 1MJ

For energy of FPS at exit of a deuterium plasma pinch: (yield in J per shot.)
$Y_{FPS}{=}2.9\text{x}10^{-4} I_{pinch}^{2.63}$ $Y_{FPS}{=}5.9\text{x}10^{-4} I_{peak}^{2.25}$ where currents are in kA
And $Y_{FPS}{=}81E_0^{0.97}$ where storage energy E_0 is in kJ.

These laws provide useful references and facilitate the understanding of present plasma focus machines. More importantly, these scaling laws are also useful for design considerations of new plasma focus machines particularly if they are intended to operate as optimized neutron, neon SXR, FIB ion or FPS plasma sources.

ACKNOWLEDGMENTS

This work is partially supported within IAEA Research Contract: 16934 of CRP F1.30.13 (Investigations of Materials under High Repetition and Intense Fusion-relevant Pulses). The author also acknowledges research grants INT-CPR-01-02-2012 and FRGS/2/2013/SG02/INTI/01/1.

REFERENCES

[1] Lee S, “Twelve Years of UNU/ICTP PFF—A Review,” IC/ 98/ 231 Abdus Salam ICTP, Miramare, Trieste; pp.5-34, 1998, ICTP Open Access Archive http://eprints.ictp.it/31/.

[2] Kato Y & Be S H, “Generation of soft x rays using a rare gas-hydrogen plasma focus and its application to x-ray lithography”, *Appl. Phys. Lett.* 48, 686, 1986, DOI: 10.1063/1.96743

[3] Bogolyubov E P, Bochkov V D, Veretennikov V A, Vekhoreva L T, Gribkov V A, Dubrovskii A V, Ivanov Yu P, Isakov A I, Krokhin O N, Lee P, Lee S, Nikulin V Ya, Serban A, Silin P V, Feng X & Zhang G X, “A powerful soft x-ray source for x-ray lithography based on plasma focusing”, *Phys. Scripta.*, vol. 57, pp. 488-494,1998, DOI:10.1088/0031-8949/57/4/003

[4] Lee S, Lee P, Zhang G, Feng X,Gribkov V, Liu M, Serban A & Wong T K S , “High rep rate high performance plasma focus as a powerful radiation source” , *IEEE Trans. Plasma Sci*, 26, pp. 1119-1126,1998, DOI: 10.1109/27.725141

[5] Filippov N V Filippova T I, Karakin M A, Krauz V I, Tykshaev V P, Vinogradov V P, Bakulin Y P, Timofeev V , Zinchenko V F, Brzosko J R, Brzosko J S,"Filippov type plasma focus as intense source of hard X-rays (E_x≃50 keV)",*IEEE Trans Plasma Sci.*,Vol 24,Issue 4, pp. 1215 – 1223, 1996, DOI: 10.1109/27.536568

[6] Filippov N V, Filippova T I, Khutoretskaia I V, Mialton V V, Vinogradov V P, "Megajoule scale plasma focus as efficient X-ray source", Phys Lett A , Vol 211, Issue 3, pp. 168-171, 1996, DOI: 10.1016/0375-9601(95)00960-4

[7] Institute for Plasma Focus Studies http://www.plasmafocus.net

[8] Internet Workshop on Plasma Focus Numerical Experiments (IPFS-IBC1) 14 April-19 May 2008 http://www.plasmafocus.net/IPFS/Papers/IWPCAkeynote2ResultsofInternet-basedWorkshop.doc

[9] Lee S Radiative Dense Plasma Focus Computation Package: RADPF http://www.intimal.edu.my/school/fas/UFLF/File1RADPF.htm http://www.plasmafocus.net/IPFS/modelpackage/File1RADPF.htm

[10] Lee S , "Plasma Focus Radiative Model: Review of the Lee Model Code"J Fusion Energy 33, 4, pp. 319-335, 2014, DOI:10.1007/s10894-014-9683-8

[11] Lee S, Rawat R S, Lee P, & Saw S H, "Soft x-ray yield from NX2 plasma focus" J. Appl. Phys. 106, 023309(6 pages), 2009, http://dx.doi.org/10.1063/1.3176489

[12] Lee S, Saw S H, Lee P, Rawat R S, "Numerical experiments on plasma focus neon soft x-ray scaling", Plasma Phys Controlled Fusion 51 (10), 105013(8 pages), 2009, DOI: 10.1088/0741-3335/51/10/105013

[13] Akel M, Al-Hawat S, Saw S H, Lee S, "Numerical Experiments on Oxygen Soft X-Ray Emissions from Low Energy Plasma Focus Using Lee Model",J Fusion Energy 29,3, pp. 223-231,2010, DOI: 10.1007/s10894-009-9262-

[14] Lee S & Saw S H, "Plasma focus ion beam fluence & flux—Scaling with stored energy", Phys. Plasmas ", Phys. Plasmas 19, 112703, 2012, DOI:10.1063/1.4766744

[15] Lee S & Saw S H, "Plasma focus ion beam fluence and flux—For various gases", Phys. Plasmas 20, 062702, 2013, DOI: 10.1063/1.4811650

[16] Akel M, Alsheikh Salo S, Saw S H & Lee S, "Properties of Ion Beams Generated by Nitrogen Plasma Focus", J Fusion Energy,33, pp. 189-197, 2014, DOI 10.1007/s10894-013-9660-7

[17] Lee S & Saw S H, "Neutron scaling laws from numerical experiments", *J Fusion Energy*, 27, 4, pp. 292-295, 2008, DOI: 10.1007/s10894-008-9132-7

[18] Lee S, "Current and neutron scaling for megajoule plasma focus machine", *Plasma Phys. Control Fusion*, 50, 10, 2008, DOI: 10.1088/0741-3335/50/10/105005

[19]Saw S H & Lee S, "Scaling Laws for Plasma Focus Machines from Numerical Experiments", *Energy and Power Engineering*, 2, 01, pp.65-72, 2010 DOI:10.4236/epe.2010.21010

[20] Saw S H & Lee S, "Scaling the plasma focus for fusion energy considerations", International Journal of Energy Research 35, 2, pp. 81-88, 2011, DOI: 10.1002/er.1758

[21] Akel M, Lee S, Saw S H, "Numerical experiments in plasma focus operated in various gases", *IEEE Transactions on Plasma Science*, 40, 12, pp. 3290 - 3297 , 2012 DOI:10.1109/tps.2012.2220863

[22] Lee S, “Plasma focus model yielding trajectory and structure” in *Radiations in Plasmas*, ed B McNamara (Singapore: World Sci Pub Co, ISBN 9971-966-37-9) vol. II, pp.978–987, 1984

[23] Lee S, Tou T Y, Eissa M A, Gholap A V, Kwek K H, Mulyodrono S,Smitj A J, Suryadi,Usada W & Zakaullah M, “A simple facility for teaching of plasma dynamics and plasma nuclear fusion”, *Am. J. Phys*, 56, pp.62-68, 1988 http://dx.doi.org/10.1119/1.15433

[24] Tou T Y, Lee S & Kwek K H, “Non perturbing plasma focus measurements in the run-down phase”, *IEEE Trans. Plasma Sci.* 17,2, pp.311-315,1989, DOI: 10.1109/27.24641

[25] Favre M, Lee S, Moo S P & Wong C S, “X-ray emission in a small plasma focus operating with H_2-Ar mixture”, *Plasma Sources Science and Technology*,1,2, 122, 1992, DOI:10.1088/0963-0252/1/2/008

[26] Lee S, “A sequential plasma focus”,*IEEE Trans. Plasma Sci.*, vol. 19, no. 12, pp 912-919,1991 DOI:10.1109/27.108433

[27] Jalil bin Ali, “*Development and Studies of a small Plasma Focus*,” PhD thesis, UTM Malaysia, 1990.

[28] Potter D E, *“The formation of high density z-pinches”, Nucl. Fus.,* vol. 18,6, pp. 813-823, 1978,DOI: 10.1088/0029-5515/18/6/008

[29] Lee S & Serban A “Dimensions & lifetime of the PF pinch,” *IEEE Trans. Plasma Sci.*, 24,3, pp1101- 1105,1996,DOI: 10.1109/27.533118

[30] Liu M, “*Soft X-rays from compact plasma focus*,” PhD thesis, NIE, NTU Singapore, 2006.

[31] Bing S, “*Plasma dynamics and x-ray emission of the PF*,” PhD Thesis, NIE, NTU Singapore, 2000.

[32] Serban A & Lee S, “Experiments on speed-enhanced neutron yield from a small plasma focus”,*J Plasma Physics*, vol. 60 part 1, pp. 3-15,1998

[33] Liu M H, Feng X P, Springham S V & Lee S, “Soft x-ray measurement in a small plasma focus operated in neon”, *IEEE Trans. Plasma Sci*. 26, pp. 135-140,1998 DOI: 10.1109/27.669614

[34] Wong D, Lee P, Zhang T, Patran A, Tan T L, Rawat R S, Lee S, “An improved radiative plasma focus model calibrated for neon-filled NX2 using a tapered anode”, Plasma Sources Sci. Technol. 16,1, pp. 116-123, 2007, DOI: 10.1088/0963-0252/16/1/016

[35] Lee S http://ckplee.myplace.nie.edu.sg/plasmaphysics/

[36] Lee S & Saw S H, “Pinch current limitation effect in plasma focus” *Appl. Phys. Lett*. 92, 021503, 2008, DOI: 10.1063/1.2827579

[37] Lee S, Lee P, Saw S H & Rawat R S, “Numerical experiments on plasma focus pinch current limitation” ,*Plasma Phys. Control. Fusion*, 50, 6, 065012(8pages), 2008, DOI: 10.1088/0741-3335/50/6/065012

[38] Lee S, “Neutron Yield Saturation in PF: A Fundamental Cause”, *Appl. Phys. Lett*. 95 151503, 2009, DOI: 10.1063/1.3246159

[39]Lee S, Saw SH & Jalil Ali, “Numerical Experiments on Radiative Cooling and Collapse in Plasma Focus Operated in Krypton”, J Fusion Energy, 32, 1, pp 42–49, 2013, DOI: 10.1007/s10894-012-9522-8

[40]Lee S & Saw S H, "Current-Step Technique to Enhance Plasma Focus Compression and Neutron Yield",*J Fusion Energy* 31,6, pp 603-610, 2012 DOI: 10.1007/s10894-012-9506-8

[41]Saw S H, "*Experimental studies of a current-stepped pinch*", PhD Thesis Universiti Malaya, 1991.

[42]Lee S, "A current-stepping technique to enhance compression", *J Phys D: Appl Phys* 17, 4, pp 733-739, 1984, DOI: 10.1088/0022-3727/17/4/012

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

[44] Lee S, Saw S H, Rawat R S , Lee P, Talebitaher A, Chong P L, Roy F, Singh A, Wong D & Devi K, "Correlation of measured soft X-ray pulses with modeled dynamics of the plasma focus",*IEEE Trans Plasma Sci* 39, 11, 3, pp 3196-3202, 2011, DOI: 10.1109/TPS.2011.2166812

[45] 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, 2010, DOI: 10.1063/1.3429207

[46]Lee S, Saw S H , Rawat R S , Lee P, Verma R, Talebitaher A, Hassan S M, Abdou A E, Mohamed Ismail, Amgad Mohamed, Torreblanca H, Hawat Sh Al, Akel M, Chong P L, Roy F, Singh A, Wong D, Devi K , *J Fusion Energy* 31, 2, pp 198–204, 2012, DOI :10.1007/s10894-011-9456-6

[47] Lee S, Saw S H, Soto L, Springham S V & Moo S P, "Numerical experiments on plasma focus neutron yield versus pressure compared with laboratory experiments *"Plasma Phys Control Fusion*, 51(11 pages), 075006, 2009 DOI: 10.1088/0741-3335/51/7/075006

[48] Saw S H, Rawat R S, Lee P, Talebitaher A, Abdou A E, Chong P L, Roy Jr F., Ali J, Lee S, "SXR measurements in INTI PF operated in neon to identify typical (Normal N) profile for shots with good yield", IEEE Trans. Plasma Sci, 41,11,pp 3166–3172, 2013, DOI:10.1109/TPS.2013.2281333

[49] Lee S, Saw S H, Hegazy H, Ali Jalil, Damideh V, Fatis N, Kariri H, Khubrani A, Mahasi A, "Some generalised characteristics of the electro-dynamics of the plasma focus in its axial phase- illustrated by an application to independantly determine the drive current fraction and the mass swept-up fraction, J Fusion Energy 33, 3 pp 235-241, 2014, DOI:10.1007/s10894-013-9658-1

[50] Sh. Al-Hawat, Akel M, Lee s & Saw S H, "Model Parameters Versus Gas Pressure in Two Different Plasma Focus Devices Operated in Argon and Neon"'*J Fusion Energy*, 31, pp13 – 20, 2012, DOI 10.1007/s10894-011-9414-3-3

[51] Lee S, Saw S H, Abdou A E & Torreblanca H, "Characterizing Plasma Focus Devices—Role of the Static Inductance—Instability Phase Fitted by Anomalous Resistances", *J Fusion Energy* 30, pp 277-282, 2011, DOI:10.1007/s10894-010-9372-1

[52]Aghamir F M & Behbahani R A, J. "Role of static inductance on ion beam emission in plasma focus devices", *Plasma Physics,* 78, 5, pp 585-588, 2012, DOI: 10.1017/S0022377812000438

[53] 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, "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," J. Phys. D: Appl. Phys. 40, pp. 3592-3607, 2007, DOI:10.1088/0022-3727/40/12/008

[54] Huba J D, "NRL *Plasma Formulary",* page 44,2006.Avaliable on line: http://www.dtic.mil/dtic/tr/fulltext/u2/a447173.pdf

[55] Akel M, Alsheikh Salo S, Ismael Sh, Saw S H & Lee S, "Interaction of the high energy deuterons with the graphite target in the plasma focus devices based on Lee model", Physics of Plasmas (1994-present), 21 (6 pages), 072507, 2014, DOI: 10.1063/1.4890222