Multi-scaling of the dense plasma focus

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Abstract. The dense plasma focus is a copious source of multi-radiations with many potential new applications of special interest such as in advanced SXR lithography, materials synthesizing and testing, medical isotopes and imaging. This paper reviews the series of numerical experiments conducted using the Lee model code to obtain the scaling laws of the multi-radiations.

1. Introduction

Plasma focus machines of various energies are increasingly being studied as sources of neutrons, soft x-rays and 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] 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. A comparison was made for the case of the NX2 machine [4], showing good agreement between computed and measured $Y_{sxr}$ [8-10]. This gives confidence that the Lee model code gives realistic results in the computation of $Y_n$ and $Y_{sxr}$.

In recent years, 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, signatures 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.

In this review, we show the comprehensive range of numerical experiments conducted to derive scaling laws on neutron yield $Y_n$ [11, 12] and neon $Y_{sxr}$ [8, 10], in terms of storage energy $E_0$, peak discharge current $I_{peak}$ and peak focus pinch current $I_{pinch}$ obtained from studies [13-15] 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 some beam ion defining properties.

2. 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 [16] was successfully used to assist several projects [17-19]. Radiation-coupled dynamics was included in the five-phase code leading to numerical experiments on radiation cooling [20]. The vital role of a finite small disturbance speed discussed by Potter in a Z-pinch situation [21] was incorporated together with real gas thermodynamics and radiation-yield terms. Before this ‘communication delay effect’ was incorporated, the model consistently over-estimated the radial speeds. This is serious from the point of view of neutron yields. A factor of two in shock speeds gives a factor of four in temperatures leading to a difference in fusion cross-sections of ~1000 at the range...
of temperatures we are dealing with. This version of the code assisted other research projects [22-27] and was web-published in 2000 [28] and 2005 [29]. Plasma self-absorption was included in 2007 [27] improving SXR yield simulation. The code has been used extensively in several machines including UNU/ICTP PFF [1, 17, 22, 23, 25-27, 30, 31], NX2 [24, 27, 32], NX1 [3, 32] and adapted for the Filippov-type plasma focus DENA [33]. Neutron yield $Y_n$ using a beam-target mechanism [11, 12, 14, 15, 34], is incorporated the code [9] (versions later than RADPFV5.13), resulting in realistic $Y_n$ scaling with $I_{pinch}$[11, 12]. The versatility and utility of the model are demonstrated in its clear distinction of $I_{pinch}$ from $I_{peak}$[13] and insights of current and neutron yield limitations [14, 15], neutron saturation [12, 35], radiative collapse [36] and current-stepped PF [37-39] and extraction of diagnostic data [13, 40-45] and anomalous resistance data [46, 47] from current signals. The description theory, code and a broad range of results of this ‘Universal Plasma Focus Laboratory Facility’ are available for download from [9]. We summarise the five phases used in the model code.

i) Axial Phase: Described by a snowplow model with an equation of motion coupled to a circuit equation. The equation of motion incorporates the axial phase model parameters: mass and current factors $f_m$ and $f_c$ [9, 45, 48-50] respectively; $f_m$ accounting for the porosity of the current sheet, the inclination of the moving current sheet-shock front structure and all other unspecified effects which have effects equivalent to increasing or reducing mass in the moving structure; $f_c$ accounting for the fraction of current effectively flowing in the moving structure (due to all effects including current shedding at or near the back-wall and current sheet inclination).

ii) Radial Inward Shock Phase: Described by four coupled equations using an elongating slug model. The first equation computes the radial inward shock speed from the driving magnetic pressure; the second the axial elongation speed of the column; the third the speed of the current sheath (aka the magnetic piston), allowing the current sheath to separate from the shock front by an adiabatic approximation. The fourth is the circuit equation. Thermodynamic effects due to ionization and excitation are incorporated, being important for gases other than hydrogen and deuterium. A communication delay between shock front and current sheath due to the finite small disturbance speed is crucially implemented. The model parameters, radial phase mass swept-up and current factors $f_{mr}$ and $f_{cr}$ respectively are incorporated in all three radial phases.

iii) Radial Reflected Shock (RS) Phase: When the shock front hits the axis, because the focus plasma is collisional, a RS develops which moves radially outwards, whilst the radial current sheath piston continues to move inwards. Four coupled equations are used, these being for the RS moving radially outwards, the piston moving radially inwards, the elongation of the annular column and the circuit. The plasma temperature behind the RS undergoes a jump by a factor of approximately two.

iv) Slow Compression (Quiescent) or Pinch Phase: When the out-going RS hits the in-coming piston the compression enters a radiative phase, with inclusion of energy loss/gain terms from Joule heating and radiation losses into the piston equation of motion; so that for gases such as krypton, radiation emission may enhance the compression. Three coupled equations describe this phase; the piston radial motion, the pinch column elongation and the circuit equations.

v) Expanded Column Phase: To simulate the current trace beyond this point, we allow the column to suddenly attain the radius of the anode. Two coupled equations are used; similar to the axial phase above.

2.1 Computation of Neutron Yield
The neutron yield is computed using a phenomenological beam-target neutron generating mechanism described recently by Gribkov et al [34]. 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 [11, 12, 14, 28] as:
\[ Y_{bt} = C_b n_i I_{\text{pinch}}^{2}\frac{\sigma}{\sigma_{TP}^2} \left( \ln(b/r_p) \right) / U^0.5 \]
where \( n_i \) = ion density, \( b \) = cathode radius, \( r_p \) = radius of the plasma pinch with length \( z_p \), \( \sigma \) = cross-section of the D-D fusion reaction, \( n \)-branch [51] and \( U \) = beam energy. \( C_b \) is treated as a calibration constant combining various constants in the derivation process.

The D-D cross-section is sensitive to the beam energy in the range 15-150 kV. The code computes induced voltages (due to current motion inductive effects) \( V_{\text{max}} \) of the order of only 15-50 kV. However it is known, from experiments that the ion energy responsible for the beam-target neutrons is near MJ, the D-D cross section \( \sigma \) is of the order of 50-150 keV [34], and for smaller lower-voltage machines the relevant energy could be lower at 30-60 keV [31]. Fitting with extensive experimental observations of machines from sub-kJ to near MJ, the D-D cross section \( \sigma \) is reasonably obtained by using \( U=3V_{\text{max}} \). A value of \( C_b=2.7\times10^7 \) was obtained by calibrating the yield [9], [13]-[14] at an experimental point of 0.5 MA.

The thermonuclear component is also computed in every case and it is found that this component is negligible when compared with the beam-target component.

2.2 Computation of Neon SXR Yield
In the code [9, 32, 52], neon line radiation \( Q_L \) is calculated as follows:
\[ \frac{dQ_L}{dt} = -4.6 \times 10^{-31} n_i^2 Z Z_n^4 (\pi r_p^2) z_p^2 / T \]
where for the temperatures of interest in our experiments we take the SXR yield \( Y_{\text{sxr}} = Q_L \). \( Z_n \) is the atomic number.

This generated energy is then reduced by the plasma self-absorption which is included by computing volumetric plasma self-absorption factor \( A \) derived from the photonic excitation number \( M \) which is a function of \( Z_n, n_i, Z \) and \( T \). For SXR scaling there is an optimum small range of temperatures (around 200-500 eV \( T \)-window necessary to produce the He-like, H-like neon ions) [23, 24] to operate.

2.3 Computation of Beam ion properties
In the latest (2013 version) 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 is given below:
\[ \text{Flux} = J_b = 2.75 \times 10^{15} (f_e[MZ_{\text{eff}}]^{1/2}) \left( \frac{z_p}{r_p} \right) (I_{\text{pinch}}^2 / U^{1/2}) \text{ ions m}^{-2} \text{s}^{-1} \]
The beam is produced uniformly across the whole cross-section of the pinch,

The beam speed is characterized by an average value $v_b$,

The beam energy is a fraction $f_e$ of the pinch inductive energy, taken as 0.14 in the first instance; to be adjusted as numerical experiments indicate,

The beam ion energy is derived from the diode voltage $U$,

The diode voltage $U$ is $U = 3V_{\text{max}}$; a relationship obtained from data fitting in extensive earlier numerical experiments [11, 14].

The value of the ion flux is deduced in each situation by computing $Z_{\text{eff}}, r_p, I_{\text{pinch}}$ and $U$.

### 3. Numerical Experiments and Results

The Lee code is configured to work as any plasma focus by inputting the bank parameters, $L_0$, $C_0$ and stray circuit resistance $r_0$; the tube parameters $b$, $a$ and $z_0$ and operational parameters $V_0$ and $P_0$ and the fill gas. The computed total current waveform is fitted to an experimentally measured total current waveform [11, 13-15, 28-29] using the four model parameters $f_m, f_c$ for the axial phase and $f_{mr}$ and $f_{cr}$ for the radial phases.

#### 3.1 Scaling laws for neutrons from numerical experiments over a range of energies from 10kJ to 25 MJ

We apply the Lee model code to the MJ machine PF1000 over a range of $C_0$ to study the neutrons emitted by PF1000-like bank energies from 10kJ to 25 MJ.

First, we fitted a measured current trace to obtain the model parameters. A measured current trace of the PF1000 with $C_0 = 1332 \ \mu \text{F}$, operated at 27 kV, 3.5 torr deuterium, has been published [34], with cathode/anode radii $b=16 \ \text{cm}$, $a=11.55 \ \text{cm}$ and anode length $z_0=60 \ \text{cm}$. In the numerical experiments we fitted external (or static) inductance $L_0=33.5 \ \text{nH}$ and stray resistance $r_0 = 6.1 \ \text{mΩ}$ (damping factor $\text{RESF} = r_0/(L_0/C_0)^0.5 = 1.22$). The fitted model parameters are: $f_m=0.13, f_c=0.7, f_{mr}=0.35$ and $f_{cr}=0.65$. The computed current trace [11, 15] agrees very well with the measured trace through all the phases; axial and radial, right down to the bottom of the current dip indicating the end of the pinch phase as shown in figure 1.

This agreement confirms the model parameters for PF1000. Once the model parameters have been fitted to a machine for a given gas, these model parameters may be used with some degree of confidence when operating parameters such as the voltage are varied [9].

![Figure 1. Current fitting of computed current to measured current traces to obtain fitted parameters $f_m=0.13, f_c=0.7, f_{mr}=0.35$ and $f_{cr}=0.65$.](image)
This series is carried out at 35 kV, 10 Torr D, $L_0=33.5$ nH, $r_0=6.1$ mΩ (damping factor $RESF=r_0/(L_0/C_0)^{0.5} =1.22$). The ratio $c=b/a$ is kept at 1.39; $C_0$ ranges from 14 µF to 39960 µF corresponding $E_0$ of 8.5 kJ to 24 MJ [12]. For each $C_0$, anode length $z_0$ is varied to find the optimum. For each $z_0$, $a$ is varied so that end axial speed is 10 cm/µs.

We find that the $Y_n$ scaling changes from $Y_n \sim E_0^{2.0}$ at tens of kJ to $Y_n \sim E_0^{0.84}$ at the highest energies (up to 25MJ) investigated (figure 2).

![Figure 2](image)

**Figure 2.** $Y_n$ plotted as a function of $E_0$ in log-log scale, showing $Y_n$ scaling changes from $Y_n \sim E_0^{2.0}$ at tens of kJ to $Y_n \sim E_0^{0.84}$ at the highest energies (up to 25MJ). The scaling deterioration observed in this figure is discussed in the Conclusion section.

The scaling of $Y_n$ with $I_{\text{peak}}$ and $I_{\text{pinch}}$ over the energy range up to 25 MJ (figure 3) is: $Y_n = 3.2 \times 10^{11} I_{\text{pinch}}^{4.5}$ and $Y_n = 1.8 \times 10^{10} I_{\text{peak}}^{3.8}$ where $I_{\text{peak}}$ ranges from 0.3 to 5.7 MA and $I_{\text{pinch}}$ ranges from 0.2 to 2.4 MA.

![Figure 3](image)

**Figure 3.** Log($Y_n$) scaling with log($I_{\text{peak}}$) and log($I_{\text{pinch}}$) for the range of energies up to 25 MJ.
This scaling result confirms an earlier study carried out on several machines with published current traces with $Y_{sxr}$ yield measurements, operating conditions and machine parameters including the PF400, UNU/ICTP PFF, the NX2 and Poseidon [11].

4. Scaling laws for neon SXR from numerical experiments over a range of energies from 0.2 kJ to 1 MJ

We next use the code to carry out numerical experiments for bank energies from 0.2 kJ to 1 MJ [52] using a fast PF machine with optimised values for $c$ and typical low $L_0$. The following parameters are kept constant: (i) $c=b/a$ (kept at 1.5, which is practically optimum; (ii) the operating voltage $V_0$ (kept at 20 kV); (iii) static inductance $L_0$ (kept at 30 nH, which is low enough to reach the $I_{pinch}$ limitation regime [13,14] and (iv) ratio of stray resistance to surge impedance $RESF$ (kept at 0.1). The model parameters $f_m, f_c, f_{mr}, f_{cr}$ are also kept at fixed values 0.06, 0.7, 0.16 and 0.7 representing average values of large range of machines we have studied. A typical current waveform is shown in figure 4.

![Figure 4. Computed total current versus time for $L_0=30nH$ and $V_0=20kV$, $C_0=30uF$, $RESF=0.1$, $c=1.5$ and model parameters $f_m, f_c, f_{mr}, f_{cr}$ are fixed at 0.06, 0.7, 0.16 and 0.7 for optimised $a=2.285\, \text{cm}$ and $z_0=5.2\, \text{cm}$.](image)

The storage energy $E_0$ is varied by changing the capacitance $C_0$. Parameters that are varied are operating pressure $P_0$, anode length $z_0$ and anode radius $a$. Parametric variation at each $E_0$ follows the order; $P_0, z_0$ and $a$ until all realistic combinations of $P_0, z_0$ and $a$ are investigated; the number of runs totalling some 2000. A plot of $Y_{sxr}$ against $E_0$ is shown in figure 5.

We then plot $Y_{sxr}$ against $I_{peak}$ and $I_{pinch}$ and obtain SXR yield scales as $Y_{sxr} \sim I_{pinch}^{3.6}$ and $Y_{sxr} \sim I_{peak}^{3.2}$. The $I_{pinch}$ scaling has less scatter than the $I_{peak}$ scaling. We next subject the scaling to further test when the fixed parameters $RESF, c, L_0$ and $V_0$ and model parameters $f_m, f_c, f_{mr}, f_{cr}$ are varied. We add in the results of some numerical experiments using the parameters of several existing plasma focus devices including the UNU/ICTP PFF [17, 26] ($RESF=0.2, c=3.4, L_0=110\, \text{nH}$ and $V_0=14\, \text{kV}$ with fitted model parameters $f_m=0.05, f_c=0.7, f_{mr}=0.2, f_{cr}=0.8$) [7-9, 23], the NX [10, 24, 27] ($RESF=0.1, c=2.2, L_0=20nH$ and $V_0=11\, \text{kV}$ with fitted model parameters $f_m=0.06, f_c=0.7, f_{mr}=0.16, f_{cr}=0.7$) [7-10, 24] and PF1000 ($RESF=0.1, c=1.39, L_0=33\, \text{nH}$ and $V_0=27\, \text{kV}$ with fitted model parameters $f_m=0.1, f_c=0.7$, $RESF=0.1, c=1.39, L_0=33\, \text{nH}$ and $V_0=27\, \text{kV}$ with fitted model parameters $f_m=0.1, f_c=0.7$,}
These new data points (un-blackened data points in figure 6) contain wide ranges of $c$, $V_0$, $L_0$ and model parameters. The resulting $Y_{sxr}$ versus $I_{\text{pinch}}$ log-log curve remains a straight line, with scaling index 3.6 unchanged and with no increased scatter. However the resulting $Y_{sxr}$ versus $I_{\text{peak}}$ curve now exhibits larger scatter and the scaling index has changed.

![Graph of $Y_{sxr}$ vs $E_0$. The parameters kept constants are: RESF=0.1, $c=1.5$, $L_0=30\text{nH}$ and $V_0=20\text{kV}$ and model parameters $f_m, f_c, f_m, f_{cr}$ at 0.06, 0.7, 0.16 and 0.7 respectively. The scaling deterioration observed in this figure is discussed in the Conclusion section.](image)

We highlight that the consistent behaviour of $I_{\text{pinch}}$ in maintaining the scaling of $Y_{sxr} \sim I_{\text{pinch}}^{3.6}$ with less scatter than the $Y_{sxr} \sim I_{\text{peak}}^{3.2}$ scaling particularly when mixed-parameters cases are included, strongly support the conclusion that $I_{\text{pinch}}$ scaling is the more universal and robust one. Similarly conclusions on the importance of $I_{\text{pinch}}$ in plasma focus performance and scaling laws have been reported [11-15].

It is remarkable that our $I_{\text{pinch}}$ scaling index of 3.6, obtained through a set of comprehensive numerical experiments over a range of energies 0.2 kJ to 1 MJ, on Mather-type devices is within the range of 3.5 to 4 postulated on the basis of sparse experimental data, (basically just two machines one at 5 kJ and the other at 0.9 MJ), by Filippov [6], for Filippov configurations in the range of energies 5 kJ to 1 MJ.

We point out that the results represent scaling for comparison with baseline PF devices that have been optimized in terms of electrode dimensions. It must also be emphasized that the scaling with $I_{\text{pinch}}$ works well even when there are variations in device from $L_0=30\text{nH}$, $V_0=20\text{kV}$ and $c=1.5$. However there may be many other parameters which can change and could lead to a further enhancement of x-ray yield.
Figure 6. $\gamma_{\text{spr}}$ is plotted as a function of $I_{\text{pinch}}$ and $I_{\text{peak}}$. The parameters kept constant for the black data points are: $\text{RESF} = 0.1$, $c = 1.5$, $L_0 = 30\,\text{nH}$ and $V_0 = 20\,\text{kV}$ and model parameters $f_{\text{mr}}$, $f_{\text{cr}}$, $f_{\text{sc}}$, $f_{\text{cc}}$ at 0.06, 0.7, 0.16 and 0.7 respectively. The unblackened data points are for specific machines which have different values for the parameters $c$, $L_0$, $V_0$ and $\text{RESF}$.

5. Scaling Laws for Beam Ions

Another set of series of numerical experiments on machines from sub-kJ to 1 MJ [50,51] were carried out to obtain relevant scaling laws for ions beam emitted from the pinch plasma. The results for PF deuteron beams (beam energy versus $E_0$) is presented in figure 7.
The beam ions (in J) at exit of a deuterium plasma pinch dependent of the currents (in kA) have the following scaling:

\[ Y_{\text{beamions}} = 2.8 \times 10^{-7} I_{\text{pinch}}^{3.7}, \ Y_{\text{beamions}} = 8.4 \times 10^{-7} I_{\text{peak}}^{3.16}, \ Y_{\text{beamions}} = 18.2 E_0^{1.23} \]

where \( Y_{\text{beamions}} \) is in J and \( E_0 \) is in kJ ranging from 1 kJ to 1MJ.

We note the considerable scatter with square of residual ‘\( R^2 \)’ of 0.89, deviating considerably from the perfect value of 1.00 in this initial attempt to present quantitative ideas of ion beams to provide reference data for laboratory measurements. More numerical experiments and laboratory measurements are needed to put the scaling laws on a firmer footing.

The PF operating in any gas and over a wide range of pressure emits ion beams and plasma streams. These ion beams are being studied to synthesize nano-materials and damage candidate materials of reactor walls. The Lee model code computes the ion beam yields emitted from the pinch column.

6. Conclusion

Numerical experiments carried out using the universal plasma focus laboratory facility based on the Lee model code gives reliable scaling laws for neutrons production and neon SXR yields for plasma focus machines. The scaling laws obtained:

For neutron yield: (yield in number of neutrons per shot)

\[ Y_n = 3.2 \times 10^{11} I_{\text{pinch}}^{4.5}, \ Y_n = 1.8 \times 10^{10} I_{\text{peak}}^{3.8}, \ I_{\text{peak}}(0.3 \text{ to } 5.7) \text{ and } I_{\text{pinch}}(0.2 \text{ to } 2.4) \text{ in MA.} \]

\[ Y_n \sim E_0^{2.0} \text{ at tens of kJ to } Y_n \sim E_0^{0.84} \text{ at MJ level (up to 25MJ).} \]

For neon soft x-rays: (yield in J per shot)

\[ Y_{\text{sxr}} = 8.3 \times 10^3 I_{\text{pinch}}^{3.6}, \ Y_{\text{sxr}} = 6 \times 10^2 I_{\text{peak}}^{3.2}, \ I_{\text{peak}}(0.1 \text{ to } 2.4) \text{ and } I_{\text{pinch}}(0.07 \text{ to } 1.3) \text{ in MA.} \]

\[ Y_{\text{sxr}} \sim E_0^{1.6} \text{ (kJ range) to } Y_{\text{sxr}} \sim E_0^{0.8} \text{ (towards MJ).} \]

For beam ions at exit of a deuterium plasma pinch: (yield in J per shot)

\[ Y_{\text{beamions}} = 2.8 \times 10^{-7} I_{\text{pinch}}^{3.7}, \ Y_{\text{beamions}} = 8.4 \times 10^{-7} I_{\text{peak}}^{3.16}, \text{ and currents in kA.} \]

\[ Y_{\text{beamions}} = 18.2 E_0^{1.23}, \text{ where } E_0 \text{ is in kJ; averaged over } 1 \text{ kJ to } 1 \text{ MJ} \]

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 or neon SXR sources. More recently, the scaling of \( Y_n \) versus \( E_0 \) as shown above has been placed in the context of a global scaling law [38] with the inclusion of available experimental data. From that analysis, the cause of scaling deterioration for neutron yield versus energy as shown in figure 2 (which has also been given the misnomer ‘neutron saturation’) has been uncovered as due to a current scaling deterioration caused by an almost constant axial phase ‘dynamic resistance’ interacting with a reducing bank impedance as energy storage is increased at essentially constant voltage. The deterioration of soft x-ray yield with storage energy as shown in figure 5 could also be ascribed to the same axial phase ‘dynamic resistance’ effect as described in reference [38]. This deterioration of scaling will also appear in the scaling trends (with stored energy) of beam ions.

We emphasis here that the scaling laws with \( I_{\text{pinch}} \) is the more fundamental and robust one compared to \( I_{\text{peak}} \). This is because although the PF is reasonably consistent in its operations, there will be occasions when even the best optimized machines may not focus or poorly focused although having a high \( I_{\text{peak}} \) with no neutrons. However, \( I_{\text{pinch}} \) being the current actually flowing in the pinch is more consistent in all situations.

The numerical experiments gives robust scaling laws for PFs covering a wide range of energies from sub kJ to tens of MJ. It supplements the limited (non-existent in the case of beam ions) scaling laws available to predict PF radiations yields. Now, we have on stronger footing the useful scaling laws for neutron, SXR and ion yields from PF machines.
7. References

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

[2] Kato Y and Be S H 1986 Appl. Phys. Lett. 48 686

[3] Bogolyubov E P et al 1998 Phys. Scripta. 57 488-494

[4] Lee S et al 1998 IEEE Trans. Plasma Sci. 26 1119

[5] Filippov N V et al 1996 IEEE Trans Plasma Sci. 24 1215-1223

[6] Filippov N V et al 1996 Phys Lett A 211(3) 168-171

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

[8] Lee S Internet Workshop on Plasma Focus Numerical Experiments(IPFS-IBC1)14April-19May 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, Rawat R S, Lee P and Saw S H 2009 J. Appl. Phys. 106 023309

[11] Lee S and Saw S H 2008 J Fusion Energy 27 292-295

[12] Lee S 2008 Plasma Phys. Control. Fusion 50 105005

[13] Lee S, Saw S H, Lee P C K, Rawat R S and Schmidt H 2008 Appl. Phys. Lett. 92 111501

[14] Lee S and Saw S H 2008 Appl. Phys. Lett. 92 021503

[15] Lee S, Lee P, Saw S H and Rawat R S 2008 Plasma Phys. Control. Fusion 50 065012

[16] Lee S, 1984 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 978–987

[17] Lee S et al 1988 Am. J. Phys. 56 62-68

[18] Tou T Y, Lee S and Kwek K H 1989 IEEE Trans. Plasma Sci. 17 311-315

[19] Lee S 1991 IEEE Trans. Plasma Sci. 19 912-919

[20] Jalil bin Ali 1990 Development and Studies of a small Plasma Focus PhD thesis, Universiti Teknologi Malaysia, Malaysia

[21] Potter D E 1978 Nucl. Fis. 18 813-823

[22] Lee S and Serban A 1996 IEEE Trans. Plasma Sci. 24(3) 1101-1105.

[23] Liu Mahe 2006 Soft X-rays from compact plasma focus PhD thesis, NIE, Nanyang Technological University, Singapore. ICTP Open Access Archive: http://eprints.ictp.it/327/.

[24] Bing S 2000 Plasma dynamics and x-ray emission of the plasma focus PhD Thesis, NIE, Nanyang Technological University, Singapore. ICTP Open Access Archive: http://eprints.ictp.it/99/.

[25] Serban A and Lee S 1998 J Plasma Physics 60(1) 3-15.

[26] Liu M H, Feng X P, Springham S V and Lee S 1998 IEEE Trans. Plasma Sci. 26 135–140

[27] Wong D, Lee P, Zhang T, Patran A, Tan T L, Rawat R S and Lee S 2007 Plasma Sources Sci. Technol. 16 116-123

[28] Lee S 2000–2007 http://ckplee.myplace.nie.edu.sg/plasmaphysics/

[29] Lee S 2005 ICTP Open Access Archive: http://eprints.ictp.it/85/

[30] Mohammed M A, Sobhanian S, Wong C S, Lee S, Lee P and Rawat R S 2009 J. Phys. D: Appl.Phys. 42 045203

[31] Springham S V, Lee S and Rafique M S 2000 Plasma Phys. Control. Fusion 42 1023-1032

[32] Lee S, Lee P, Zhang G, Feng X, Gribkov V A, Liu M, Serban A and Wong T 1998 IEEE Trans. Plasma Sci. 26, no. 4 1119-1126

[33] Siahpoush V, Tafreshi M A, Sobhanian S and Khorram S 2005 Plasma Phys. Control. Fusion 47 1065-1072

[34] Gribkov V A, Banaszak A, Bienkowska B, Dubrovsky A V, Ivanova-Stanik I, Jakubowski L, Karpinski L, Miklaszewski R A, Paduch M, Sadowski M J, M Scholz M, A Szydlowski and Tomaszewski K 2007 J. Phys. D: Appl. Phys. 40 3592-3607.
[35] Lee S 2009 Appl. Phys. Lett. 95 151503
[36] Lee S, Saw S H and Jalil Ali 2013 J Fusion Energy 32 42-49
[37] Lee S and S H Saw 2012, J Fusion Energy 31 603-610
[38] Saw S H 1991 Experimental studies of a current-stepped pinch PhD Thesis Universiti Malaya, Malaysia
[39] Lee S 1984 J Phys D: Appl Phys 17 733-739
[40] Lee S et al 2011 IEEE Trans Plasma Sci 39 3196-3202
[41] Saw S H et al 2010 Rev Sci Instruments, 81 053505
[42] Lee S et al 2012 J Fusion Energy 31 198–204
[43] Lee S, Saw S H, Soto L, Springfield S V, Moo S P 2009 Plasma Phys Contr Fusion 51 075006
[44] Saw S H, Rawat R S, Lee P, Talebitaher Alireza, Abdou A E, Chong P L, Roy F Jr, Ali J and Lee S 2013 IEEE Trans Plasma Sci 41 (11) 3166-3172
[45] Lee S, Saw S H, Hegazy H, Ali J, Damideh V, Fatis N, Kariri H, Khubrani A, Mahasi A J Fusion Energy published online 5 January 2014
[46] Lee S, Saw S H, Abdou A E and Torreblanca H 2011 J Fusion Energy 30, 277-282
[47] Aghamir F M and Behbahani R A 2012 J. Plasma Physics 78(5) 585-588
[48] M. Akel, Sh Al-Hawat, S H Saw and S Lee 2010 J Fusion Energy 29(3) 223-231
[49] Sh. Al-Hawat, M. Akel, S H Saw, S Lee 2012 J Fusion Energy 31 13-20
[50] Akel M, Lee S, Saw S H, IEEE Trans Plasma Sci 40 3290-3297
[51] Huba J D 2006 Plasma Formulary 44
[52] Lee S, Saw S H, Lee P and Rawat R S 2009 Plasma Phys and Controlled Fusion 51 105013
[53] Lee S and Saw S H 2012 Phys. Plasmas 19 112703
[54] Lee S and Saw S H 2013 Phys. Plasmas 20 062702

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