J Fusion Energ (2010) 29:94–99
DOI 10.1007/s10894-009-9238-6

ORIGINAL PAPER

Pinch Current and Soft X-Ray Yield Limitations by Numerical Experiments on Nitrogen Plasma Focus

M. Akel · Sh. Al-Hawat · S. Lee

Published online: 21 August 2009

Abstract The modified version of the Lee model code RADPF5-15a is used to run numerical experiments with nitrogen gas, for optimizing the nitrogen soft X-ray yield on PF-SY1. The static inductance L_0 of the capacitor bank is progressively reduced to assess the effect on pinch current I_{pinch}. The experiments confirm the I_{pinch}, limitation effect in plasma focus, where there is an optimum L_0 below which although the peak total current, I_{peak}, continues to increase progressively with progressively reduced inductance L_0, the I_{pinch} and consequently the soft X-ray yield, Ysxr, of that plasma focus would not increase, but instead decreases. For the PF-SY1 with capacitance of 25 µF, the optimum $L_0 = 5$ nH, at which $I_{pinch} = 254$ kA, Ysxr = 5 J; reducing L_0 further increases neither I_{pinch} nor nitrogen Ysxr. The obtained results indicate that reducing the present L_0 of the PF-SY1 device will increase the nitrogen soft X-ray yield.

Keywords Plasma focus SY1 · Pinch current limitation · Soft X-ray · Nitrogen gas · Lee model RADPF5.15a

M. Akel (✉) · Sh. Al-Hawat
Department of Physics, Atomic Energy Commission, P.O. Box 6091, Damascus, Syria
e-mail: scientific@aec.org.sy

S. Lee
Institute for Plasma Focus Studies, 32 Oakpark Drive, Chadstone, VIC 3148, Australia

S. Lee
Nanyang Technological University, National Institute of Education, Singapore 637616, Singapore

S. Lee
INTI University College, 71800 Nilai, Malaysia

Introduction

The plasma focus is well known as a source of fusion neutrons and X-rays. Besides being a ready source of hot dense plasma and fusion neutrons, the focus also emits plentiful amounts of soft X-rays, especially when operated with high Z gases rather than deuterium. Because of its simple construction, cost-effectiveness and easy maintenance, the plasma focus appears to be a promising device for X-ray generation, with enhanced efficiency. The nitrogen plasma focus is used as an emitter of the X-ray radiation [1–3].

The total current I_{total} waveform, which is a "fingerprint" of the plasma focus discharge, is easily measured using a Rogowski coil, and from experience, it is known that the current trace of the focus is one of the best indicators of gross performance [4–9]. The focus pinch current I_{pinch}, which is defined as the value of the plasma sheath current at the start of pinch, is difficult to measure and this is the reason that the total current I_{peak} is experimentally used instead of I_{pinch}, despite the fact that yields should more consistently be scaled to the focus pinch current I_{pinch}, since it is I_{pinch} which directly powers the emission processes. The numerical method to consistently deduce I_{pinch} from any measured trace of I_{total} was developed in numerical experiments using the Lee Model [4–9].

For enhancing of the neutron and X-ray yields from plasma focus devices, many experiments have been investigated by some modifications on the bank, tube and operating parameters of the devices; for example, the two plasma focus devices UNU/ICTP PFF and the NX2 both have capacitance of about 30 µF and maximum operating voltage V_0 of 15 kV. The UNU/ICTP PFF has L_0 of 110 nH whilst the NX2 was designed for much higher performance with $L_0 = 20$ nH. As a result of the much lower L_0 for NX2, I_{peak} became more than doubled, compared with that of the UNU/ICTP PFF; and more importantly, though less than doubled, the pinch current I_{pinch} increased from 120 to 220 kA, and consequently the neutron yields increased three to five times [5], as well soft X-ray yields.

However, contrary to the general expectation that performance of a plasma focus would progressively improve with progressive reduction of its static inductance L_0, there is, in fact, an optimum L_0 below which although the peak total current increases progressively the pinch current and consequently the neutron yield of that plasma focus would not increase, but instead decreases [5, 6]. For example, it was expected that the plasma focus PF1000 in Warsaw could increase its discharge current, and its pinch current, and consequently neutron yield by a reduction of L_0 [10]; but numerical experiments [5] showed that reducing L_0 of PF1000 from its present 20–30 nH will increase neither the observed I_{pinch}, nor the neutron yield. This previously unsuspected pinch current limitation effect observed by Lee et al. is not the same as the maximum current related mechanism proposed by Nukulin et al. [11] to explain an observed neutron saturation effect [6].

In this paper we investigate some numerical experiments for studying of the effect of reduction of L_0 on the soft X-ray yield and the pinch current in the 2.8 kJ low energy plasma focus PF-SY1 operated with nitrogen, using the Lee model code RADPF5.15a [7] which we have modified to include operation in nitrogen [12].

The Model Code Used for the Numerical Experiments

The dynamics of plasma focus discharges is complicated; for this purpose, to investigate the plasma focus phenomena, the Lee model couples the electrical circuit with plasma focus dynamics, thermodynamics and radiation, enabling realistic simulation of all gross focus properties. In the radial phases, axial acceleration and ejection of mass are caused by necking curvatures of the pinching current sheath result in time-dependent strongly center-peaked density distributions. Moreover laboratory measurements show that rapid plasma/current disruptions result in localized regions of high densities and temperatures particularly in the heavy gases like xenon. We need to point out that these center-peaking density effects and localized regions are not modeled in the code, which consequently computes only an average uniform density and an average uniform temperature which are considerably lower than measured peak density and temperature. However, because the 4-model parameters are obtained by fitting the computed total current waveform to the measured total current waveform, the model incorporates the energy and mass balances equivalent, at least in the gross sense, to all the processes which are not even specifically modeled. Hence the computed gross features such as speeds and trajectories and integrated soft X-ray yields have been extensively tested in numerical experiments for several machines and are found to be comparable with measured values.

Thus the code provides a useful tool to conduct scoping studies, as it is not purely a theoretical code, but offers means to conduct phenomenological scaling studies for any plasma focus device from low energy to high energy machines.

The model in its two-phase form was described in 1984 [13]. It was successfully used to assist in the design and interpretation of several experiments [14–18]. Radiation-coupled dynamics was included in the five-phase code leading to numerical experiments on radiation cooling [19]. The signal-delay slug [20], so crucial to radial simulation, was incorporated together with real gas thermodynamics and radiation-yield terms and assisted other research projects [21–23] and was web-published in 2000 [24] and 2005 [25]. All subsequent versions of the Lee model code [7] incorporate the ‘signal-delay slug’ as a must-have feature. Plasma self-absorption was included in 2007 [24] improving soft X-ray yield simulation in neon, argon and xenon among other gases. It has been used extensively as a complementary facility in several machines, for example, UNU/ICTP PFF [14, 17, 21, 22, 26–28], NX1 [22], NX2, [22, 23] and DENA [29]. It has also been used in other machines for design and interpretation including sub-kJ plasma focus machines [30]. Information obtained from the model includes axial and radial velocities and dynamics [29], dimensions and duration of the focus pinch, gross information of temperatures and densities within the pinch, soft X-ray emission characteristics and yield [22, 23, 31], design and optimization of machines [30, 31], and adaptation to other machine types such as the Filippov-type DENA [29].

The versatility and utility of the improved model is demonstrated in its clear distinction of pinch current from peak current [5] and the recent uncovering of a plasma focus pinch current limitation effect [6, 7].

The modified version of the Lee model code RADPF5-15a enables to run numerical experiments with the following gases: hydrogen, deuterium, deuterium–tritium, helium, neon, argon, xenon, krypton and nitrogen [7]. The detailed description, theory, code and a broad range of results of this ‘Universal Plasma Focus Laboratory Facility’ are available for download from [7].

Procedures for the Numerical Experiments

The Lee code is configured to work as any plasma focus by inputting the bank parameters, the tube parameters, operational parameters and the fill gas. The standard practice is to fit the computed total current waveform to an experimentally measured total current waveform using four model parameters representing the mass swept-up factor f_m, the plasma current factor f_c for the axial phase and factors f_{mr} and f_{cr} for the radial phases.

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. The exact time profile of the total current trace is governed by the bank parameters, by the focus tube geometry and the operational parameters. It also depends on the fraction of the 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 detailed profile of the discharge current during the pinch phase also reflects the Joule heating and radiative yields. At the end of the pinch phase the total current profile also reflects the sudden transition of the current flow from a constricted pinch to a large column flow. Thus, the discharge current powers all dynamic, electrodynamic, thermodynamic and radiation processes in the various phases of the plasma focus. Conversely all the dynamic, electrodynamic, thermodynamic and radiation processes in the various phases of the plasma focus affect the discharge current. It is then no exaggeration to say that 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 current trace to the measured current trace in the procedure adopted by the Lee model code [4–6, 8, 9, 24, 25].

The numerical experiments were investigated on the low energy plasma focus PF-SY1, which was constructed and operated locally at the Atomic Energy Commission, Damascus, Syria and is described elsewhere [32] in detail. An ohmic voltage divider 1:100 and a Rogowskii coil were used to determine the voltage and current traces during the plasma focus process, using a TDS storage oscilloscope with 1:10 attenuator. The bank parameters were $L_0 = 1{,}430$ nH, $C_0 = 25$ μF and $r_0 = 50$ mΩ. The tube parameters were the outer radius $b = 3.2$ cm, the inner radius 'a' = 0.95 cm, and the anode length $z_0 = 16$ cm. The operating parameters were $V_0 = 15$ kV, and $p_0 = 0.38$ Torr, filling nitrogen gas. The above mentioned parameters were put into the code RADPF5.15a. The best fit for the computed total current with the measured total current waveform was obtained with the following parameters: $L_0 = 1{,}600$ nH, $r_0 = 70$ mΩ; and model parameters $f_m = 0.1$, $f_c = 0.7$, $f_{mr} = 0.15$, and $f_{cr} = 0.7$. With these parameters, the computed total current trace agrees very well with the experimental trace (Fig. 1) for the time period of the axial and radial phases.

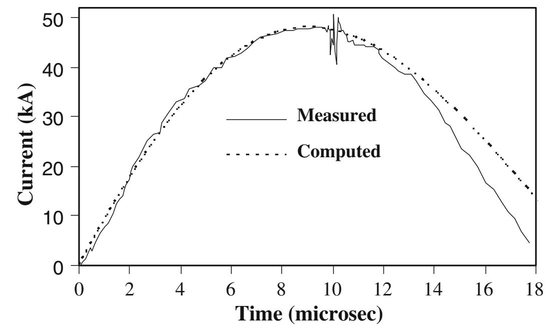

Fig. 1 Measured (*solid line*) vs. computed (*dotted line*) current traces PF-SY1 at 15 kV and 0.38 Torr N_2

The numerical experiments with the above model parameters may be used with some degree of confidence when operating parameters such as the pressure are varied.

In this work we kept the model parameters constant and ran numerical experiments for PF-SY1 with $C_0 = 25$ μF, operating at 15 kV and 10 Torr of nitrogen gas. The numerical experiments were conducted using a constant value of a factor RESF = 0.277 (RESF = stray resistance/surge impedance), where at each L_0 the corresponding resistance value was found. Also at each L_0 the ratio ($c = b/a$) was kept constant at value $c = 3.368$.

To optimize the soft X-ray yield from PF-SY1 with nitrogen gas, varying L_0, z_0 and 'a' keeping 'c' and RESF constant. The external inductance L_0 was varied from 1,600 to 1 nH.

The following procedures were used:

At each L_0, the pressure was fixed at constant value (in our case $p_0 = 10$ Torr) and also the anode length was fixed at a certain value:

> Then the inner radius 'a' was varied, whilst keeping $c = 3.368$, until the maximum X-ray yield was obtained for this certain value of z_0.
> After that we chose another value of z_0, varying 'a' until maximum X-ray yield and so on, until we have obtained the combination of z_0 and 'a' for the best maximum X-ray yield at a fixed L_0 (Ysxr vs. z_0 and 'a' at fixed L_0 and p_0).
> We repeated the above procedure for progressively smaller L_0 until $L_0 = 1$ nH.

Results and Discussions

The influence of L_0 reduction on the total current traces using RADPF5.15a was investigated. For example it was found that reducing L_0 changes the current rise time as well as effective drive time as shown in Fig. 2, which shows

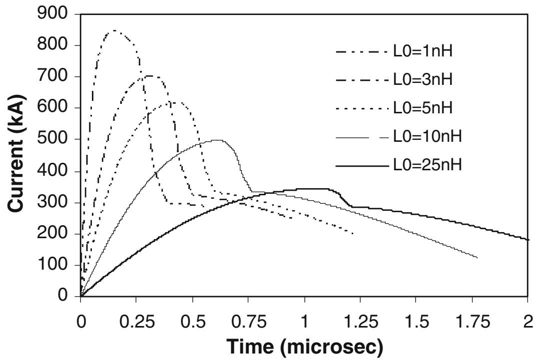

Fig. 2 Current traces (computed) PF-SY1 at 15 kV, 10 Torr of N_2 for a range of L_0 (25–1 nH)

five current traces corresponding to $L_0 = 25$ nH (I_{peak} at 345 kA), $L_0 = 10$ nH (I_{peak} at 494 kA), $L_0 = 5$ nH (I_{peak} at 616 kA) and $L_0 = 1$ nH (I_{peak} at 844 kA). As L_0 was reduced, I_{peak} increased; 'a' is necessarily increased leading to longer pinch length (Z_{max}), hence a bigger pinch inductance L_p. At the same time because of the reducing current drive time, z_0 needed to be reduced. The geometry moved from a long thin Mather-type to a shorter fatter one (see Table 1). Thus whilst L_0 and axial section inductance L_a reduced, the pinch inductance L_p increased due to increased pinch length [5, 18]. It can be noticed from (Fig. 2) that the rising current profile at $L_0 = 25$ nH is flattened and peak current occurs around 1.07 µs whereas at $L_0 = 5$ nH the rising current profile is shorter; and as soon as the peak is reached, the current trace droops significantly. At small values of L_0, the I_{peak} value is much bigger than that calculated using the full tube inductance. This is because with such a small L_0, there is a very short rise time [6].

At each L_0, after z_0 was varied, the inner radius 'a' was adjusted to obtain the optimum X-ray yield, which corresponds closely to the largest I_{pinch}.

The soft X-ray optimization for each value of L_0, varying z_0 and 'a' is shown in Table 1. The table shows that as L_0 is reduced, I_{peak} increases with each reduction in L_0 with no sign of any limitation as function of L_0. However, I_{pinch} reaches a maximum of 254 kA at $L_0 = 5$ nH, then it decreases with each reduction in L_0, but the ratio I_{pinch}/I_{peak} drops progressively as L_0 decreases. Figure 3 shows the effect of the reduction L_0 on currents and the ratio I_{pinch}/I_{peak}. Thus I_{peak} does not show any limitation as L_0 is progressively reduced. However, I_{pinch} has a maximum value. This pinch current limitation effect is not a simple, but it is a combination of the two complex effects: the interplay of the various inductances involved in the plasma focus processes abetted by the increasing coupling of C_0 to the inductive energetic processes, L_0 is reduced [5]. From Fig. 3 it is clearly shown the difference between I_{pinch} and I_{peak}.

From Table 1 it can be seen, that as L_0 decreased, the soft X-ray yield increases until it reaches a maximum value of 5 J at $L_0 = 5$ nH (where I_{pinch} also has maximum); beyond which the soft X-ray yield does not increase with reducing L_0. Thus with decreasing L_0 the pinch current I_{pinch} and the soft X-ray yield show limitation. The obtained results confirm the pinch current limitation effect in Nitrogen plasma focus, and consequently the soft X-ray yield. Figure 4 represent I_{pinch} and X-ray limitation effects

Table 1 For each L_0 the optimization combination of z_0 and 'a' were found and are listed here

L_0 (nH)	z_0 (cm)	a (cm)	b (cm)	I_{peak} (kA)	I_{pinch} (kA)	I_{pinch}/I_{peak}	a_{min} (cm)	Z_{max} (cm)	Ysxr (J)
1,600	13.5	0.200	0.67	48	34	0.708	0.02	0.3	0.004
500	8.0	0.320	1.08	85	59	0.698	0.03	0.4	0.03
200	5.0	0.470	1.58	132	92	0.696	0.048	0.65	0.14
150	4.8	0.500	1.68	152	105	0.69	0.05	0.7	0.20
100	4.0	0.620	2.09	184	125	0.679	0.06	0.9	0.40
75	3.3	0.700	2.36	211	142	0.672	0.07	1.0	0.60
50	2.7	0.800	2.69	253	167	0.66	0.08	1.1	1.05
40	2.6	0.850	2.86	280	180	0.643	0.09	1.2	1.40
25	2.35	0.970	3.27	345	208	0.603	0.11	1.4	2.30
15	1.7	1.100	3.70	423	234	0.553	0.13	1.6	3.57
10	1.55	1.180	3.97	494	247	0.5	0.16	1.7	4.42
8	1.51	1.210	4.08	534	251	0.47	0.17	1.77	4.75
5	**1.5**	**1.240**	**4.18**	**616**	**254**	**0.412**	**0.19**	**1.83**	**5.00**
3	1.39	1.255	4.23	700	252	0.36	0.21	1.86	4.92
1	1.35	1.260	4.24	844	235	0.278	0.24	1.9	3.99

Bank parameters: $L_0 = 1{,}600$ nH, $C_0 = 25$ µF, $r_0 = 70$ mΩ; tube parameter: $c = b/a = 3.368$; model parameters: $f_m = 0.1$, $f_c = 0.7$, $f_{mr} = 0.15$, $f_{cr} = 0.7$; operating at 10 Torr nitrogen gas, $V_0 = 15$ kV

Bold values indicate the pinch current limitation effect in plasma focus

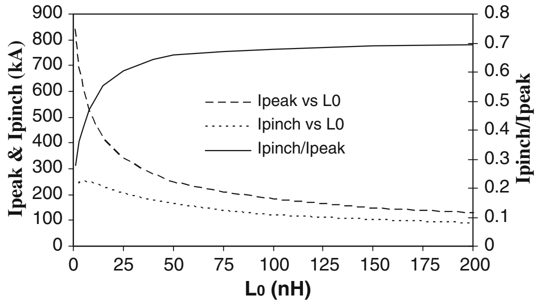

Fig. 3 Effect of L_0 reduction on currents and current ratio (computed) PF-SY1 at 15 kV, 10 Torr of N_2

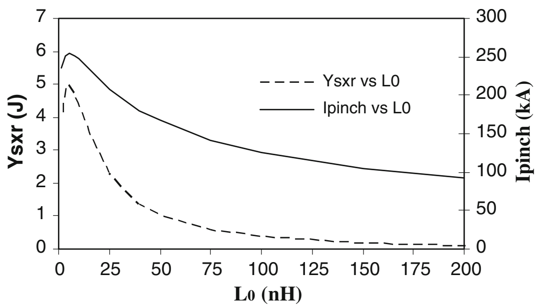

Fig. 4 The X-ray yield and I_{pinch} (computed) vs. L_0 (200–1 nH)

in nitrogen plasma focus at 10 Torr as L_0 is reduced from 200 to 1 nH.

Looking at Table 1, it is noticed that as L_0 was progressively reduced, to optimize 'a' had to be progressively increased and z_0 progressively decreased. Also the plasma pinch dimensions (pinch radius a_{min} and pinch length Z_{max}) increased as L_0 was reduced. Figure 5 show a variation of plasma focus dimensions as L_0 was reduced in PF-SY1 of 15 kV and 10 Torr nitrogen.

As the external inductance L_0 is lowered from 1,600 to 1 nH, the tube inductance ($L_a = 2 \times 10^{-7} \ln(b/a)z_0$) is decreased from 32.78 to 3.28 nH and the focus pinch inductance ($L_p \sim \ln(b/a_{min})Z_{max}$) is increased from 1 to 5.46 nH [5, 8]. In addition, the percentage of energy put into the plasma in the radial phase has increased from 0.04 to 23.3%.

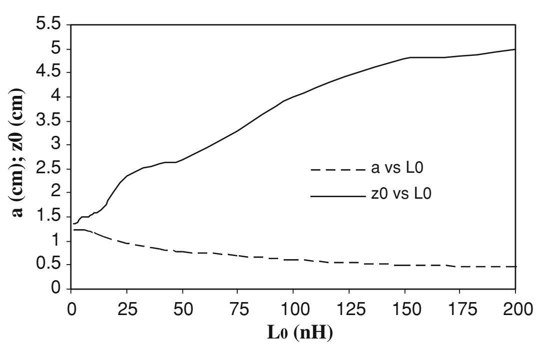

Fig. 5 Effect on the anode length and inner radius (computed) as L_0 is reduced

We carried out several sets of experiments on the PF-SY1 at the same model parameters and over wide range of pressures (2–15 Torr). In every set, an optimum inductance was found around 5–10 nH. For example, at $p_0 =$ 7 Torr, the pinch current limitation is clearly seen; at $L_0 = 5$ nH with $I_{pinch} = 239$ kA, and a corresponding Ysxr maximum of 5.9 J. The optimum soft X-ray yield reduced with increasing pressure.

Based on the obtained results of these sets of numerical experiments on PF-SY1 with nitrogen gas, we can say that to improve the soft X-ray yield, L_0 should be reduced to a value around 10–15 nH (which is an achievable range incorporating low inductance technology [22]), below which the pinch current I_{pinch} and the soft X-ray yield Ysxr would not be improved much, if at all. These experiments confirm the pinch current limitation effect, and consequently the soft X-ray yield for the nitrogen plasma focus. Finally, we would like to emphasize that we, practically, have no intention (or ambition) to go below 10–15 nH (which is an achievable range), but in our numerical experiments using RADPF5.15a we go down to a low values of L_0 (8–1 nH) just to find the pinch current limitation effect.

Conclusions

The Lee model code RADPF5-15a was used to run numerical experiments on PF-SY1 with nitrogen gas for optimizing soft X-ray yield with reducing L_0, varying z_0 and 'a'.

Contrary to the general expectation that performance of a plasma focus would progressively improve with progressive reduction of its external inductance L_0, the pinch current limitation effect in plasma focus was confirmed with reducing L_0 (maximum I_{pinch} is about 254 kA at $L_0 = 5$ nH), and consequently the maximum soft X-ray yield was computed as 5 J at $L_0 = 5$ nH; operating the inductance-reduced PF-SY1 at 15 kV, 10 Torr nitrogen pressure.

From these numerical experiments we expect to increase the nitrogen Ysxr of PF-SY1 with reducing L_0, from the present 4 mJ at $L_0 = 1{,}600$ nH to maximum value of near 5 J at an achievable $L_0 = 10$ nH. Because of the current limitation effect, there is little to gain to try to reduce L_0 to 5 nH (which is technically very difficult); and even a loss to reduce L_0 below 5 nH.

Acknowledgments The authors would like to thank Director General of AECS, for encouragement and permanent support. One of authors (Dr. Mohamad Akel) would also like to express thanks to

Mrs. Sheren Isamael, who collaborated with me going through with all the numerical experiments using Lee Model.

References

1. M. Shafiq et al., Mod. Phys. Lett. B. **16**(9), 309–318 (2002)
2. M. Shafiq et al., J. Fusion Energ. **20**(3), 113–115 (2001). (q 2002)
3. N.K. Neog et al., J. Appl. Phys. **99**, 013302 (2006)
4. S. Lee et al., Appl. Phys. Lett. **92**, 111501 (2008)
5. S. Lee et al., Appl. Phys. Lett. **92**, 021503 (2008)
6. S. Lee et al., Plasma Phys. Control Fusion **50**, 065012 (2008)
7. S. Lee, Radiative Dense Plasma Focus Computation Package: RADPF (2009), http://www.intimal.edu.my/school/fas/UFLF/. http://www.plasmafocus.net/IPFS/modelpackage/File1RADPF.htm
8. S. Lee, Plasma Phys. Control Fusion **50**, 105005 (2008)
9. S. Lee et al., J. Fusion Energ. **27**(4), 292–295 (2008)
10. V.A. Gribkov et al., J. Phys. D Appl. Phys. **40**, 3592–3607 (2007)
11. V.Ya. Nukulin, S.N. Polukhin, Plasma Phys. Rep. **33**, 271–277 (2007)
12. M. Akel, S. Al-Hawat, S. Lee, J. Fusion Energ. (2009). doi: 10.1007/s10894-009-9203-4, published online 19 May
13. S. Lee, in *Radiations in Plasmas*, ed. by B. McNamara (World Scientific, Singapore, 1984), pp. 978–987
14. S. Lee et al., Am. J. Phys. **56**, 62–68 (1988)
15. T.Y. Tou, S. Lee, K.H. Kwek, IEEE Trans. Plasma Sci. **17**, 311–315 (1989)
16. S. Lee, IEEE Trans. Plasma Sci. **19**, 912–919 (1991)
17. A. Serban, S. Lee, J. Plasma Phys. **60**, 3–15 (1998)
18. S. Lee, A. Serban, IEEE Trans. Plasma Sci. **24**, 1101–1105 (1996)
19. J.B. Ali, Development and Studies of a small Plasma Focus. PhD thesis, University Technology Malaysia, Kuala Lumpur, Malaysia, 1990
20. D.E. Potter, Nucl. Fusion. **18**(6), 813–823 (1978)
21. M.H. Liu et al., IEEE Trans. Plasma Sci. **26**, 135–140 (1998)
22. S. Lee et al., IEEE Trans. Plasma Sci. **26**, 1119–1126 (1998)
23. S. Bing, Plasma dynamics and X-ray emission of the plasma focus. PhD Thesis, NIE ICTP Open Access Archive: http://eprints.ictp.it/99/, 2000
24. S. Lee (2000–2009), http://ckplee.myplace.nie.edu.sg/plasmaphysics/
25. S. Lee (2005), ICTP Open Access Archive: http://eprints.ictp.it/85/13
26. S. Lee, Twelve Years of UNU/ICTP PFF—A Review IC, 98, (231) ICTP, Miramare, Trieste, (1998), ICTP OAA: http://eprints.ictp.it/31/
27. S.V. Springham et al., Plasma Phys. Control Fusion **42**, 1023–1032 (2000)
28. A. Patran et al., Plasma Sources Sci. Technol. **14**(3), 549–560 (2005)
29. V. Siahpoush et al., Plasma Phys. Control Fusion **47**, 1065–1075 (2005)
30. L. Soto et al., Braz. J. Phys. **34**, 1814–1821 (2004)
31. D. Wong et al., Plasma Sources Sci. Technol. **16**, 116–123 (2007)
32. S. Al-Hawat, IEEE Trans. Plasma Sci. **32**(2), 764–769 (2004)