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Developing a plasma focus research training system for the fusion energy age

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The 3 kJ UNU/ICTP Plasma Focus Facility is the most significant device associated with the AAAPT (Asian African Association for Plasma Training). In original and modified/upgraded form it has trained generations of plasma focus (PF) researchers internationally, producing many PhD theses and peer-reviewed papers. The Lee Model code was developed for the design of this PF. This code has evolved to cover all PF machines for design, interpretation and optimization, for derivation of radiation scaling laws; and to provide insights into yield scaling limitations, radiative collapse, speed-enhanced and current-stepped PF variants. As example of fresh perspectives derivable from this code, this paper presents new results on energy transfers of the axial and radial phases of generalized PF devices. As the world moves inexorably towards the Fusion Energy Age it becomes ever more important to train plasma fusion researchers. A recent workshop in Nepal shows that demand for such training continues. Even commercial project development consultants are showing interest. We propose that the AAAPT-proven research package be upgraded, by modernizing the small PF for extreme modes of operation, switchable from the typical strong-focus mode to a slow-mode which barely pinches, thus producing a larger, more uniform plasma stream with superior deposition properties. Such a small device would be cost-effective and easily duplicated, and have the versatility of a range of experiments from intense multi-radiation generation and target damage studies to superior advanced-materials deposition. The complementary code is used to reference experiments up to the largest existing machine. This is ideal for studying machine limitations and scaling laws and to suggest new experiments. Such a modernized versatile PF machine complemented by the universally versatile code would extend the utility of the PF experience; so that AAAPT continues to provide leadership in pulsed plasma research training in preparation for the Fusion Energy Age.

Keywords: Plasma focus; plasma focus modelling; fusion training.

1. Introduction — UNU/ICTP PFF

From 1985 to the mid-Nineties and on to this Millennium the AAAPT (Asian African Association for Plasma Training) assisted in the starting and strengthening of several laboratories on plasma focus studies[1], using a 3 kJ plasma focus the UNU/ICTP PFF[2]

(United Nations University/International Centre for Theoretical Physics Plasma Fusion Facility) specially designed for that purpose. More than 20 fellows were trained to build, use and maintain this plasma focus through intensive hands-on training programs sponsored by UNU, ICTP, UNESCO (United Nations Educational, Scientific and Cultural Organization) and TWAS (Third World Academy of Sciences) and the AAAPT. This plasma focus, though low-cost, has proven very useful in the education of plasma focus scientists. It is now actively operated in 7 countries and research on it has produced more than 22 PhD theses, 50 Masters theses and 200 peer reviewed research papers[3]. It has developed into several modern variants notably the Kansas State University KSU PF (USA)[4], and the University of Sofia PF (Bulgaria)[5]; and many devices have been/are being built based on its design and general design principles formulated in the original paper[2]. The sub-systems are shown in Fig. 1.

The impact of this device is felt even beyond the plasma focus world. Towards the end of 2010 an approach was made by EXECO Consulting, a Luxemburg-based project development company to develop a plasma research centre in Asia or the Middle East based on devices such as the UNU ICTP PFF. Discussions were held resulting in an invitations-only 2012 Conference[6] in Bangkok at which a small group of plasma focus experts met for 3 days of intensive discussions with a team of financial, legal and engineering consultants on the theme "The Plasma Focus-Enhancing Knowledge and Applications". The experience convinces that commercial and scientific interests may converge sufficiently to benefit new generations of plasma focus scientists in developing groups.

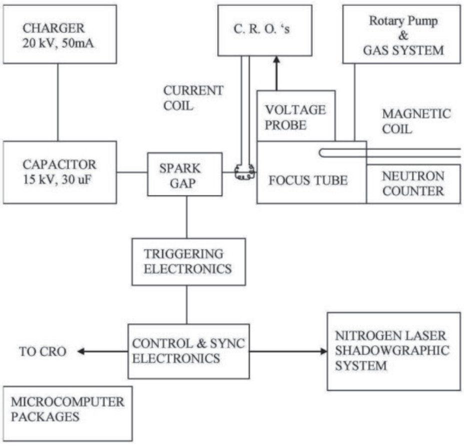

Fig. 1. Sub-systems of the UNU/ICTPPFF.

2. The Code

From the very beginning of that program it was realized that the laboratory work should be complemented by computer simulation. A 2-phase model was developed in 1984[7,8]. Over the years we have developed the model until its present still evolving form[9-12]. It now includes thermodynamics data so the code can be operated in H_2, D_2, N_2, O_2, He, Ne, Ar, Kr, Xe. We have used it to simulate a wide range of plasma focus devices from the sub-kJ PF400 J (Chile)[13] through the small 3kJ UNU/ICTP PFF (Network countries)[14], the NX2 3kJ Hi Rep lithographic focus (Singapore)[15], medium size tens of kJ DPF78[16] and Poseidon (Germany) to the MJ PF1000[17,18]. An Iranian Group has modified the model, giving it the name of Lee model, to simulate Filippov type plasma focus[11].

We are now confident that the Lee model code in its latest version the RADPFV6.1[19], realistically simulates all Mather plasma focus, small to large, high and low static inductance; and produce reliable results including axial and radial trajectories, speeds, pinch dimensions and lifetimes[20], circuit and plasma currents and energy distributions; and also gives a good representation of temperatures and densities, radiation and neutron yields[10]; ion beam number and energy fluences, post-pinch plasma and sputtered anode jet energetics[21,22]. The numerical experiments have resulted in important insights: current and yield limitations as bank inductance becomes too small, current and neutron (as well as soft x-ray SXR) yield ‘saturation’ at multi-MJ bank energy due to dynamic resistance; neutron, SXR and ion yield scaling laws, radiative cooling and collapse and current-stepped devices[23-33]. Although we can simulate any machine without any experimental input, our standard practice requires a measured circuit current waveform from the specific machine together with bank parameters (capacitance, static inductance), tube parameters (cathode/anode radii, anode length) and operating parameters (voltage, pressure and gas). We configure the code with these parameters. We use 4 model parameters[34,35] (a mass swept-up factor and a plasma current factor for each of axial and radial phases) to fit the computed to the measured current trace. The process, carried out sequentially for axial and radial phases, usually ends with an excellent fit for both shape and absolute magnitudes of the total current waveform.

The discharge current, particularly the fraction of it flowing in the plasma, drives all the electrodynamic processes in the axial and radial phases; even the plasma heating and radiation are coupled into the equation of motion. Conversely all these processes are reflected back in the profile of the plasma and circuit current. The circuit current carries

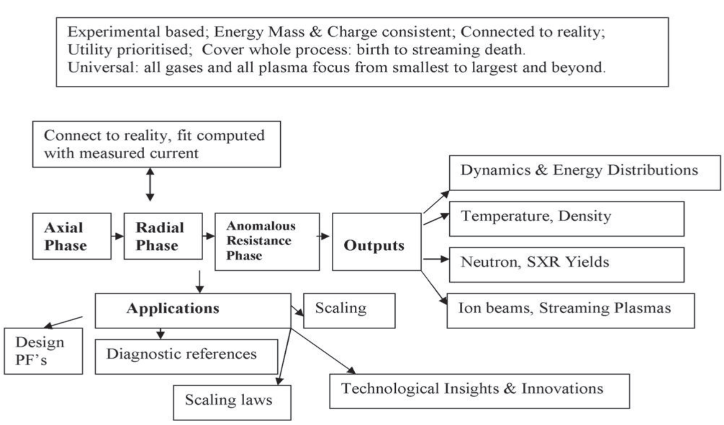

Fig. 2. The philosophy, the phases, the outputs and applications of the Lee model code.

in its profile and magnitudes the information of all processes that go on in the focus. Thus having fitted the computed with the measured I_{total} trace, we are confident that all processes are realistically simulated; and the numerical results are realistic representation of the actual properties of that particular plasma focus.

The philosphy, the computation phases, the outputs and applications of the code are shown in Fig. 2. The strength of the code is its rigorous basis in being energy-, mass- and charge-consistent, and its flexibility in encompassing all machine effects including known effects and even unsuspected effects by adjusting (fitting) two factors, the mass swept-up factor and the current drive factor, in each phase so that the computed circuit current waveform agrees with the measured circuit current waveform in 5 critical features. When the computed waveform is properly fitted to the measured waveform, the code outputs the gross behaviour and properties of the plasma focus from its electric birth through all its phases. The axial phase dynamics are presented. The lifetime and dimensions of the focus pinch are obtained and even the data of its streaming death in terms of the ion beam number and energy fluences and the energetics of the plasma stream and anode sputtered copper jet are presented; these latter data being of particular interest to materials applications. For a mid-distance view the model presents the complete life history and properties of any plasma focus operating with a choice of many gases. The versatility of the model is unmatched.

At this point we demonstrate that the code continues to deliver fresh research perspectives.

3. Energy Transfers of the Axial and Radial Phases of the Plasma Focus

In continuing discussions[36,37] about plasma focus optimisation there is a tendency to over-emphasize ‘matching’ in the Maximum Power Transfer Theorem sense[38,39]. There are at least 3 separate effects/mechanisms which are best differentiated, from fundamental considerations. These are: (a) maximum power (energy) transfer; (b) current and yield limitations as static bank inductance L_0 is reduced and (c) neutron and yield scaling deterioration with increase of bank energy E_0. In addition there are (d) real (non-scaled) effects such as speed, temperature, temperature-window requirements.

Note that conditions to maximise power or energy transfer may not be the same conditions to maximise circuit peak current or pinch current. Effects (b), (c) and (d) have been submitted to rigorous testing using numerical experiments[23,24,26,28]. An optimum inductance for maximising pinch conditions in Stuttgart machines has also been discussed in some detail by Trunk[40]. In this new work we examine the concept of impedance matching for maximising power (or energy) transfer.

The Maximum Power Transfer (MPT) Theorem is applicable to a generator with a fixed resistance R_{gen}. With the generator at a given voltage, maximum power is delivered when $R_{load} = R_{gen}$. This is said to be the matched condition for Maximum Power Transfer.

The situation of the plasma focus is the converse. The question here is: with a fixed (though time-varying; averaged if you like) load, how do you arrange the generator to give maximum power transfer (MPT)? For the plasma focus we are not at liberty to specify the load resistance or impedance. At an axial speed of 10 cm/μs the typical PF has a 'dynamic resistance' of some 5 mΩ, with little variation among plasma focus, large and small. A small capacitor bank like the UNU ICTP PFF has, during the axial phase, a surge impedance ($Z_0=(L_0/C_0)^{1/2}$) some 10 times that whilst a large bank like the PF1000 has a surge impedance about the size of the dynamic resistance. A capacitor bank 10 times larger than the PF1000 will have its dynamic resistance overwhelming its surge impedance.

In this situation because we have little control over the 'fixed' resistance and impedance of the load, the question about maximum power transfer is about variation in the generator impedance. In such a case MPT theorem does not apply. The energy transfer to the load (taking the plasma focus as a whole) will keep increasing towards (approaching but not reaching) 100% when the generator impedance is reduced towards zero.

To show this, we did a test with a 28 μF capacitor reducing L_0 in steps from 20 nH down to 1 nH, adjusting 'a' and z_0 to optimise energy transfers at each step, also adjusting pressure so that the axial speed is around 10 cm/μs [we put $f_c = f_{cr} = 1$ to allow full effect of the circuit current]. With reducing L_0 there is a progressive increase in total energy dissipated in the plasma focus system. For example at L_0=1.5 nH, (we found tube inductance L_a=1.2 nH, pinch inductance L_p~25.0 nH), the energy dissipated in piston work is 11% into the axial phase and 60% into the radial phase and pinch; total energy transferred dissipated into the plasma being 71% of initial stored energy.

These results may be contrasted to the maximum transfer into the pinch estimated by Krishnan et al[38] (using hypothesised matching condition $L_0= L_p$) of 25% of stored energy; and the maximum transfer estimated by Bernard et al[39] (using hypothesised matching condition Z_0=0.7dL/dt) of 43% of stored energy.

4. Energy Transfer for the Generalised Case

In the above test we used one specific plasma focus configuration. We broaden the test by considering all plasma focus devices using non-dimensionalised (ND) technique.

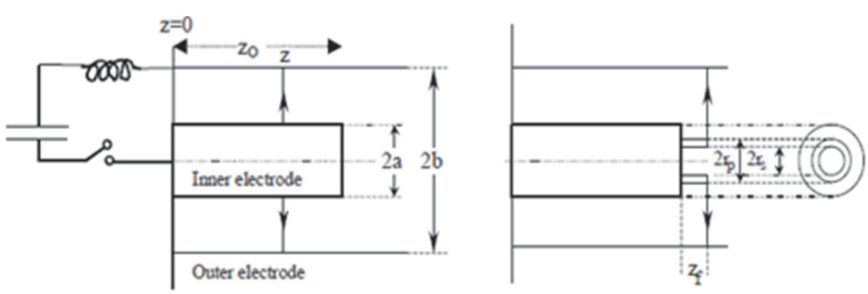

Fig. 3. Schematic of the axial and radial phases. The left section depicts the axial phase, the right section the radial phase. In the left section, *z* is the effective position of the current sheath-shock front structure. In the right section r_s is the position of the inward moving shock front driven by the piston at position r_p. Between r_s and r_p is the radially imploding slug, elongating with a length z_f. The capacitor, static inductance and switch are shown for the axial phase schematic only.

4.1 *Axial phase (or electromagnetic shock tube)*

We start with the axial phase; the results of which are also applicable to the electromagnetic shock tube. We write the equations of motion and circuit as follows[10]:

Equating rate of change of momentum at current sheath, position z, to the driving magnetic force (a function of current I) we get the acceleration as:

$$\frac{d^2 z}{dt^2} = \left[\frac{f_c^{\,2}}{f_m} \frac{\mu(\ln c)}{4\pi^2 \rho_o (c^2 - 1)} \left(\frac{I}{a}\right)^2 - \left(\frac{dz}{dt}\right)^2 \right] / z \tag{1}$$

where f_m = fraction of mass swept down the tube in the axial direction; f_c = fraction of current flowing in piston layer; c=b/a being the ratio of outer cathode radius and inner anode radius.

Ignore r(t), plasma resistance (the electromagnetic drive approximation valid for such extreme supersonic situations) we write the circuit equation as:

$$\frac{dI}{dt} = \left[V_o - \frac{\int I dt}{C_o} - r_o I - I f_c \frac{\mu}{2\pi} (\ln c) \frac{dz}{dt} \right] / \left[L_o + \frac{f_c \mu}{2\pi} (\ln c) z \right] \tag{2}$$

Eqs (1) and (2) are the coupled generating-equations of the model.The equations may be normalised to obtain scaling parameters by replacing variables t, z, I by non-dimensionalised quantities as follows:

$$\tau = t/t_o, \quad \varsigma = z / z_o, \quad \iota = I/I_o$$

where the normalising quantities t_0, z_0 and I_0 are: $t_0 = (L_0 C_0)^{1/2}$, z_0 = length of the anode, and $I_0 = V_0/(L_0/C_0)^{1/2}$ is the undamped current amplitude of the L_0-C_0 discharge circuit with capacitor C_0 charged initially to V_0.). We have:

$$\frac{d^2\zeta}{d\tau^2} = \frac{\left[\alpha^2 \iota^2 - \left(\frac{d\zeta}{d\tau}\right)^2 \right]}{\zeta} \tag{3}$$

and

$$\frac{d\iota}{d\tau} = \left(1 - \int \iota d\tau - \beta \iota \frac{d\zeta}{d\tau} - \delta \iota\right) / (1 + \beta\zeta) \tag{4}$$

Scaling parameters:

$\alpha = (t_0/t_a)$ - scaling parameter; ratio of characteristic electrical discharge time to characteristic axial transit time where

$$t_a = \left[\frac{4\pi^2 (c^2 - 1)}{\mu \ln c} \right]^{1/2} \frac{\sqrt{f_m}}{f_c} \frac{z_o}{(I_o / a)/\sqrt{\rho}}$$

is characteristic axial transit time of the current sheet to the end of the anode.

$\beta=L_a/L_0$ -scaling parameter; where $L_a=(f_c\mu/2\pi)$ (lnc)z_0 is the inductance of the axial phase when current sheet reaches the end z = zo. The third scaling parameter $\delta=r_0/(L_0/C_0)^{1/2}$ is the ratio of circuit stray resistance to surge impedance. This exerts a damping effect on the current.

Numerical experiments were carried out and quickly establish that the best transfers are achieved when δ=0 and when α is in the region of 1.5. Putting α=1.5, δ=0 we vary β to get the energy transfer as a function of β.

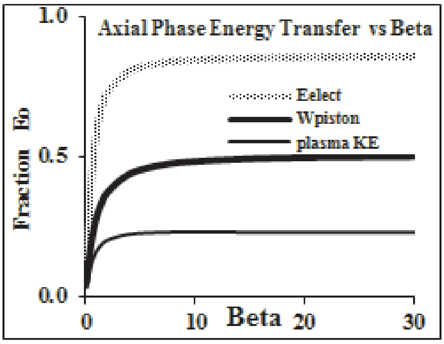

Fig. 4. Energy Transfer of axial phase (α=1.5, δ=0) as functions of β. Eelec=electrical energy that has flowed into the PF tube cumulated throughout the discharge. Wpiston=energy imparted by the piston to the plasma during the axial phase. Plasma KE=Kinetic energy stored in the plasma sheath layer. Vertical axis is in fraction of E_0. Displayed fractional E_0 is peak value recorded during the axial phase. These results are also applicable to the electromagnetic shock tube.

The results (Fig. 4) show that the conversion of capacitor energy into the tube electrical energy exceeds 80% when β exceeds 4 and approaches 90% for larger values of β. The piston work done on the plasma sheath is 44% at β=4 and exceeds 50% for large β values. The sheath kinetic energy exceeds 22% for β=4 and reaches a maximum value of of 23% at β=10. Thus these numerical experiments show us that the larger β, the better; though practically it hardly makes any difference to make β any bigger than 4. Thus for the axial phase of a plasma focus there is no matching L_0. The smaller L_0 the better, although in practice there is no advantage to be gained in making L_0 smaller than ¼ L_a. These results apply also to electromagnetic shock tubes. We note that in actual situations δ=0 is not feasible. We repeated the above with δ=0.05 and note that there is a small reduction in each of the energy transferred; without affecting our main conclusion that the smaller L_0 the better the energy transferred.

4.2 *The radial inward shock phase*

In the same way we look at the radial phase non-dimensionalised in the same way as the axial phase for time and current; with radial distances normalised to the anode radius ‘a’. The four coupled equations modelling this phase are respectively the radial shock speed

$d\kappa_s/d\tau$, the axial column elongation speed $d\zeta_f/d\tau$, the radial piston speed $d\kappa_p/d\tau$ and the circuit equation $d\iota/d\tau$ written in normalised dimensionless form as follows:

$$\frac{d\kappa_s}{d\tau} = -\alpha\alpha_1 \iota / \kappa_p$$

$$\frac{d\zeta_{\mathrm{f}}}{\mathrm{d}\tau} = -\frac{2}{\gamma+1}\frac{d\kappa_s}{d\tau}$$

$$\frac{d\kappa_p}{d\tau} = \frac{\frac{2}{\gamma+1}\frac{\kappa_s}{\kappa_p}\frac{d\kappa_s}{d\tau} - \frac{\kappa_p}{\gamma\iota}\left(1-\frac{\kappa_s^2}{\kappa_p{}^2}\right)\frac{d\iota}{d\tau} - \frac{1}{\gamma+1}\frac{\kappa_p}{\zeta_{\mathrm{f}}}\left(1-\frac{\kappa_s^2}{\kappa_p^2}\right)\frac{d\zeta_{\mathrm{f}}}{\mathrm{d}\tau}}{(\gamma-1)/\gamma + (1/\gamma)(\kappa_s^2/\kappa_p^2)}$$

and

$$\frac{d\iota}{d\tau} = \frac{1-\int \iota d\tau + \beta_1\left[\ln(\kappa_p/c)\right]\iota\frac{d\zeta_{\mathrm{f}}}{\mathrm{d}\tau} + \beta_1\frac{\zeta_{\mathrm{f}}\iota}{k_p}\frac{d\kappa_p}{d\tau} - \delta\iota}{\left\{1+\beta-(\beta_1)\left[\ln\left(\kappa_p/c\right)\right]\zeta_{\mathrm{f}}\right\}} \quad (5)$$

where the scaling parameters are
$\beta_1=\beta/(F\ln c)$, and

$$\alpha_1 = \left[(\gamma+1)\left(c^2-1\right)/(4\ln c)\right]^{1/2} F\left[\mathrm{f}_m/\mathrm{f}_{\mathrm{mr}}\right]^{1/2}$$

with the ratio $F=z_o/a$.

Note that we may interpret $\alpha_1 = t_a/t_r$ where t_r is a characteristic radial transit time and the scaling parameter $\alpha\alpha_1=t_0/t_r$.

$$t_r = \frac{4\pi}{\left[\mu(\gamma+1)\right]^{1/2}}\frac{\sqrt{f_{mr}}}{f_c}\frac{a}{(I_0/a/\sqrt{\rho}}$$

It is important to note that the radial phase scaling parameters α_1 and β_1 are fixed once F is specified (since the specific ratio γ is fixed by the thermodynamics of the plasma; and c, f_m and f_{mr} have narrow ranges of variation). Thus F is the ratio controlling the values of α_1 and β_1. When we have specified a value of α_1, we should not independantly specify a value for β_1. We should rather just specify a value of F which then fixes the pair of values of α_1 and β_1.

Using the example we discussed at the end of Section 3 above as a starting point, we carried out numerical experiments and found the following set of scaling parameters with good energy transfer for radial phase: (α=3.4, β=0.8, δ=0.06 [fixed as a typical unavoidable value]). We use a typical value of c=2, and γ=1.667 for deuterium plasma. Additionally we may show that the ratio L_p/L_a~3/F.

We carried out numerical experiments to fine-tune the variation of energy transfers as a function of F. The results (Fig. 5) show that for this set of parameters at F=0.2, radial W_{piston} peaks at 61%; and E_{elec} is at near peak value of 93% . For these parameters L_a~L_0 and L_{pinch}~15 L_0.

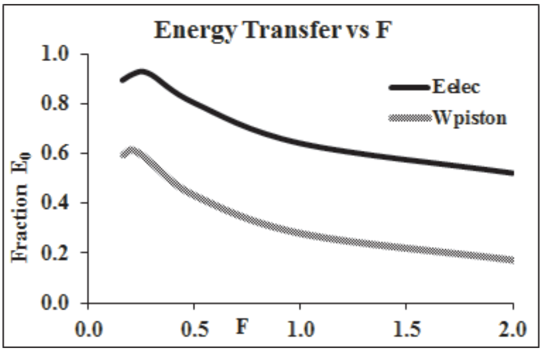

Fig. 5. Energy transfer of radial phase (α=3.4, β=0.8, δ=0.06, c=2, γ=1.667) as funcions of aspect ratio F=z_0/a. Values of radial scaling parameters α_1 and β_1 vary as F is varied. F=0.2 is optimum energy dissipated into the plasma. F=2 is typical of a machine such as the NX2.

Matching of capacitor bank characteristic time with both axial and radial characteristic times is important. For a given value of C_0, small values of L_0 increases discharge currents and reduces t_0. In reducing L_0, matching the axial phase times requires reducing the length z_0. To increase energy transfer into the radial phase requires adjusting the ratio $\alpha_1=t_a/t_r$. For this set of parameters we note that F is optimised at 0.2, with an anode radius 5 times the anode length. As a result the value of α_1 is 0.22 with t_r almost 4.6 times t_a. Thus t_0 needs to be considerably smaller than t_a, to allow t_r to end whilst there is still considerable current. This explains the large value of α.

4.3 *Discussion*

Our generalised results show that in the axial phase the key to optimise energy transfer is matching t_0 to t_a. The lower L_0 is the greater the energy transfer (though ¼ L_a is typically good enough).

For the radial phase the key to optimise energy transfer is also time matching involving t_a, t_o and t_r. Consequential to time matching there arises the requirement that L_0 is close to the value of L_a and both these need to be much smaller than the pinch inductance L_p. More numerical experiments should be run to map out the whole matrix of parameters.

These results are for maximising energy transfers. For optimising plasma focus performance these results should be considered together with optimising pinch current together with a consideration of pinch current scaling deterioration at large storage energies. Moreover real effects are important.

For applications involving neutron yield: for beam-gas target yields, speed considerations are important; for thermonuclear yield, temperatures are important.

For soft x-rays: there is a temperature window for each group of characteristic soft x-rays.

For materials deposition: uniform large area fast plasma streams FPS may be important; the consideration of good energy transfer with large anode radius (i.e. small values of $F=z_0/a$) considered in the non-dimensionalised analysis above may provide invaluable design guidelines. Thus ND numerical experiments may be most relevant for the study of FPS and deposition of advanced materials such as nano-surfaces.

Thus, incorporating complementary non-dimensionalisation to our numerical experiments adds new understanding for research, training and applications.

5. The Best Training and Applications Package in the World — Training Scientific Manpower for the Dawning of the Fusion Age

From the successful experience of the research results produced by the 3.3 kJ UNU ICTP PFF, there is a case to be made for an updated version. A 1 kJ system consisting of a 10 kV fast capacitor, 20 μF in capacity switched by a pseudo-spark gap along the lines of the KSU plasma focus[4] is envisaged with the diagnostic subsystems[41-43] as shown in Fig. 1 so that all basic measurements of electrical parameters, dynamics and neutron yield may be measured. In addition SXR spectrometry could be introduced together with simple experiments for thin film fabrication and nano-particle sythesis.

We will operate this plasma focus in both the typical strong-focus phase (or fast focus mode FFM) as well as a slow-focus mode (SFM) illustrated in the following Fig. 6. The SFM is operated at typically 2 to 4 times the initial pressure of the FFM and may be expected to produce a much more uniform and bigger deposition footprint[43].

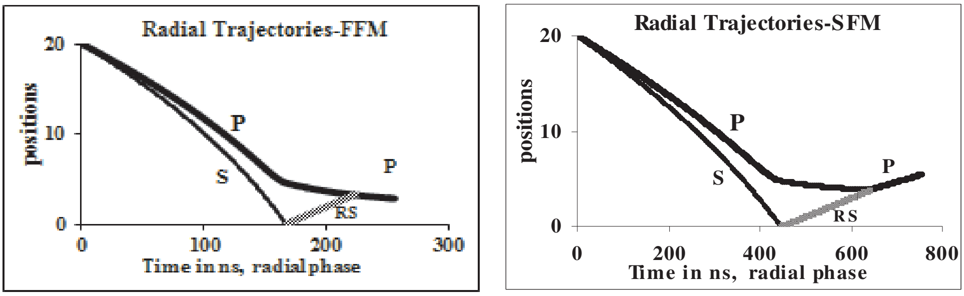

Fig. 6. The FFM (left) produces a much tighter pinch (pinch radius ratio of 0.15a) than the SFM (right) with a pinch radius ratio more than twice that of the FFM.

6. Conclusion

The upgraded 1 kJ training hardware package is complemented by our model code[10] which will allow the detailed mechanisms of the 1 kJ focus to be fully explored. This package will have unprecedented range by extending the typical strong focus regime

(FFM) to a slow SFM mode which will have superior characteristics of a larger and more uniform beam footprint for materials deposition. The code also allows the research to be extended for comparative studies with other machines since the code handles all machines and all gases. Whilst fixed firmly in laboratory measurements with the experiments provided by the 1 kJ machine, the research may explore technology-leading systems including the latest frontiers involving radiative cooling[30] and circuit manipulation[31] in the quest for compression enhancement. Such an integrated package will provide excellent and cost-effective training, research and applications in the coming age of nuclear fusion energy[45-48]. There is continuing demand for such a training package. This is shown by the recent very enthusiastic and effective response to the intensive hands-on Numerical Experiments Workshop on Plasma Focus 26 September to 8 October 2013 at Kathmandu University, Dhulikhel, Nepal (NEW PF Kathmandu 2013)[49].

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