Research Results of Plasma Focus Numerical Experiments

Presented by

SH Saw
INTI International University College

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- **Pinch current limitation effect in plasma focus**
  S. Lee and S. H. Saw, Appl. Phys. Lett. 92, 021503 (2008), DOI:10.1063/1.2827579

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Pinch current limitation effect in plasma focus

(S. Lee and S. H. Saw, Appl. Phys. Lett. 92, 021503 (2008), DOI:10.1063/1.2827579)

- Pinch current limitation effect-

  I_{pinch} does not increase beyond a certain value however low L_o, the static inductance is reduced to.

- Decreasing the present L_o of the PF1000 machine will neither increase the pinch current nor the neutron yield, contrary to expectations.

Lee Model Code – (1/3)

- Radiative Plasma Focus Computational Code – Five-phase Model

1. Axial Phase
2. Radial Inward Shock Phase
3. Radial Reflected Shock Phase
4. Slow Compression Radiative Phase
5. Expanded Column Axial Phase

Note: Detailed description of the model is available at http://www.intimal.edu.my/school/fas/UFLF/

Lee Model Code – (2/3)

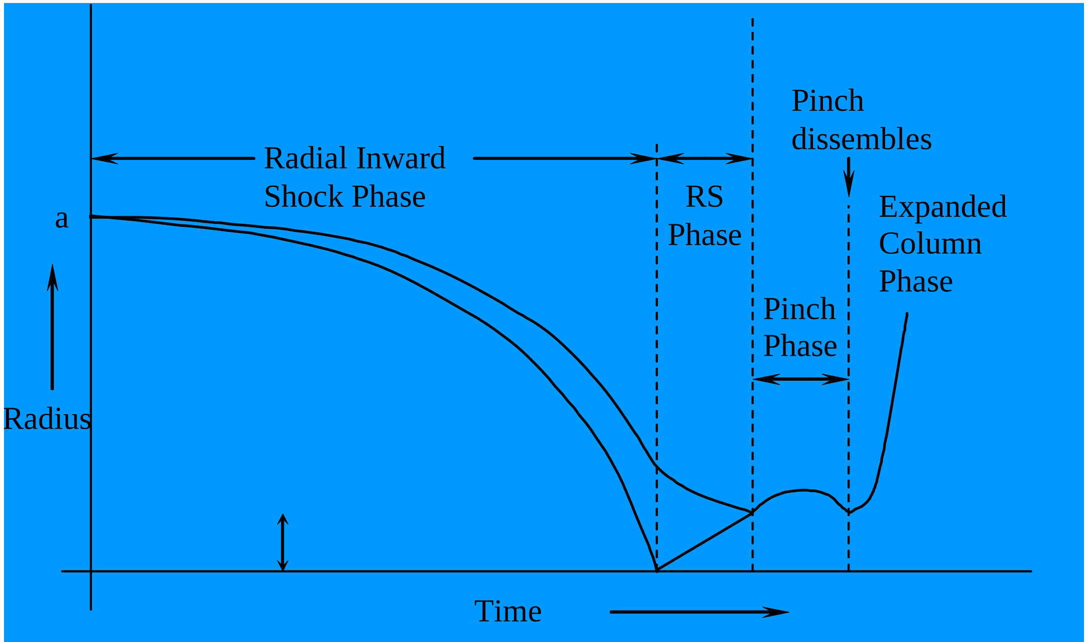


Fig 1. Schematic of radial phases

Lee Model Code – (3/3)

- Information provided
  - Axial and radial velocities and dynamics
  - Soft X-ray emission characteristics and yield
  - Speed-enhanced neutron yield

Lee Model Code – (4/4)

- **Neutron Yield**

- $Y_{b-t} = C_n n_i I_{pinch}^{2} z_p^{2} (\ln(b/r_p)) \sigma / V_{\max}^{1/2}$

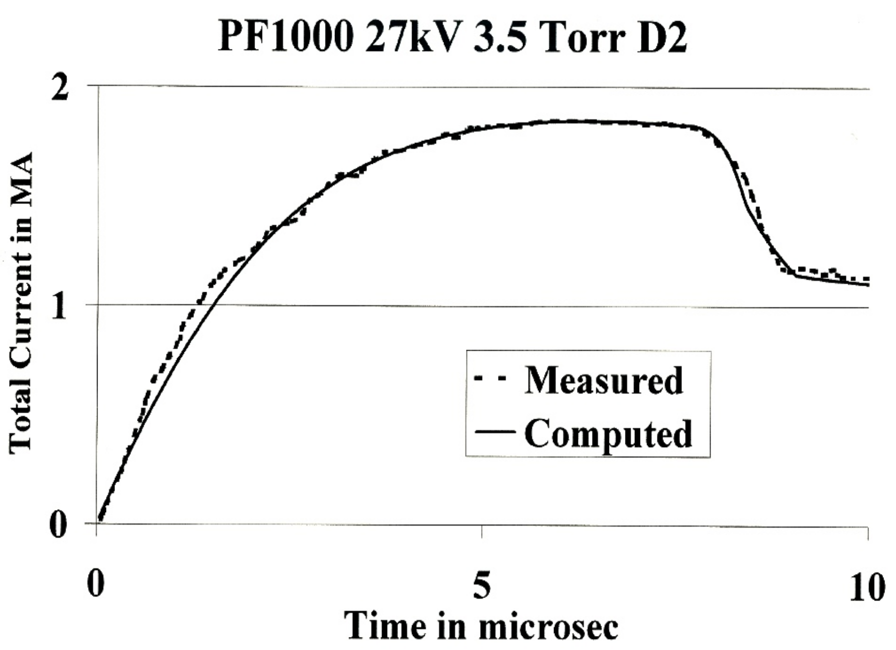
Where
$I_{\mathbf{pinch}}$ is the current flowing through the pinch at start of the slow compression phase;

$r_{\mathbf{p}}$ and $z_{\mathbf{p}}$ are the pinch dimensions at end of that phase and

$C_{\mathbf{n}}$ is a constant calibrated with an experimental point
(**S Lee and S H Saw, J of Fusion Energy, DOI: 10.1007/s10894-008-9132-7)**

Determination of Pinch Current

- by fitting a measured current trace with reliable neutron yield to the computed current trace.



Results from Numerical Experiments with PF1000

- For decreasing L_o - from 100 nH to 5 nH

- As L_o was reduced from 100 to 35 nH - As expected
  - I_{peak} increased from 1.66 to 3.5 MA
  - I_{pinch} also increased, from 0.96 to 1.05 MA
- Further reduction from 35 to 5 nH
  - I_{peak} continue to increase from 3.5 to 4.4 MA
  - I_{pinch} decreasing slightly to - Unexpected
    → 1.03 MA at 20 nH,
    → 1.0 MA at10 nH, and
    → 0.97 MA at 5 nH.
- Y_n also had a maximum value of 3.2×10^{11} at 35 nH.

Energy distribution in the system at the end of the axial phase and at the end of the pinch-(1/2)

- The energy equation describing this current drop is written as follows:

  - $0.5I_{peak}{}^2(L_o + L_a f_c{}^2) = 0.5I_{pinch}{}^2(L_o/f_c{}^2 + L_a + L_p) + \delta_{cap} + \delta_{plasma}$

Where L_a = inductance of the tube at full axial length z_o.

δ_{plasma} = energy imparted to the plasma as the current sheet moves to the pinch position
= integral of $0.5(dL/dt)I^2$
~ $0.5L_pI_{pinch}{}^2$ (an underestimate for this case)

δ_{cap} =energy flow into or out of the capacitor during this period of current drop.
= 0 (capacitor is effectively decoupled-duration of the radial phase is short compared to the capacitor time constant)

- $I_{pinch}{}^2 = I_{peak}{}^2(L_o + 0.5L_a)/(2L_o + L_a + 2L_p)$ (Note : f_c=0.7, $f_c{}^2$~0.5)

Energy distribution in the system at the end of the axial phase and at the end of the pinch-(2/2)

- $I_{pinch}/I_{peak} = ((L_o + 0.5L_a)/(2L_o + L_a + 2L_p))^{0.5}$

  Example : PF1000 at 35kV

  - **Where L_a~0.65 nH/cm of z_o & L_p~3.8 nH/cm of z_p~a**

- ***For L_o=100nH, L_a=52nH, L_p=29nH, I_{pinch}/I_{peak}=0.63***
- ***For L_o=5nH, L_a=13nH, L_p=77nH, I_{pinch}/I_{peak}=0.25***

- ***At first, increase in I_{peak} more than compensates drop in I_{pinch}/I_{peak}***

  → I_{pinch} increases from L_o=100-40 nH
- ***Below 40 nH, drop in I_{pinch}/I_{peak} catches up with increase in Ipeak***

  → numerically observed flat maximum of Ipinch

- ***Yn → flat maximum at 40-30 nH***

Pinch Current Limitation Effect - (1/3)

- L_o decreases→ higher I_{peak} →bigger a →z_p longer →bigger L_p
- L_o decreases →shorter rise time→ shorter z_o→ smaller L_a

L_o decreases, I_{pinch}/I_{peak} decreases

Pinch Current Limitation Effect - (2/3)

- L_o decreases, L-C interaction time of capacitor decreases
- L_o decreases, duration of current drop increases due to bigger a

→Capacitor bank is more and more coupled to the inductive energy transfer

→ $\delta_{cap} > 0$

Effect is more pronounced at lower Lo

Pinch Current Limitation Effect - (3/3)

- A combination of two complex effects
  - Interplay of various inductances
  - Increasing coupling of C_o to the inductive energetic processes as L_o is reduced

Conclusions – (1/2)

- Several sets of Numerical results For PF1000 with different damping factors indicate
  - Optimum inductances are around 30-60 nH with I_{pinch} decreasing for L_o below optimum value
  - Reducing L_o from its present 20-30 nH will increase neither I_{pinch} nor Y_n

Conclusions – (2/2)

- For a fixed C_o powering a plasma focus, there exist an optimum L_o for maximum I_{pinch}
- Reducing L_o will increase neither I_{pinch} nor Y_n

- Because of the Pinch Current Limitation Effect

Numerical Experiments on Plasma Focus Pinch Current Limitation

S Lee, P Lee, S H Saw and R S Rawat, Plasma Phy. Control Fusion 50 (2008) 65012

- Contrary to the general expectation that performance of a plasma focus would progressively improve with progressive reduction of its static inductance L_o, a recent paper suggests that there is in fact an optimum L_o 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
- This paper describes the numerical experiments and results that led to this conclusion.

Numerical Experiments Using Lee Model

- The I_{total} trace is computed and fitted to a measured I_{total} trace from the particular focus.
- Model parameters used for fitting:
  - **axial mass swept-up factor f_m, current factor f_c, radial mass factor f_{mr} and radial current factor, f_{cr}.**
- When correctly fitted
  - **the computed I_{total} trace agrees with the measured I_{total} trace in peak amplitude, rising slope profile and topping profile (see Figure 1) which characterize the axial phase electro-dynamics.**
  - **The radial phase characteristics are reflected in the roll-over of the current trace from the flattened top region, and the subsequent current drop or dip.**
  - **Any machine effects, such as re-strikes, current sheath leakage and consequential incomplete mass swept up, not included in the simulation physics is taken care of by the final choice of the model parameters, which are fine-tuned in the feature-by-feature comparison of the computed I_{total} trace with the measured I_{total} trace.**
- The computed gross dynamics, temperature, density, radiation, plasma sheath currents, pinch current and neutron yield can be confidently compared with experimental values.

The numerical experiments and discussions - 1/4

- At each L_o, after 'a' was adjusted for optimum S, the computed shape of the current waveform was used as a guide to fine-tune z_o for optimum performance, which was finally indicated by the largest I_{pinch} which corresponds closely to the largest Y_n.

- The optimized situation for each value of L_o is shown in Table 1.

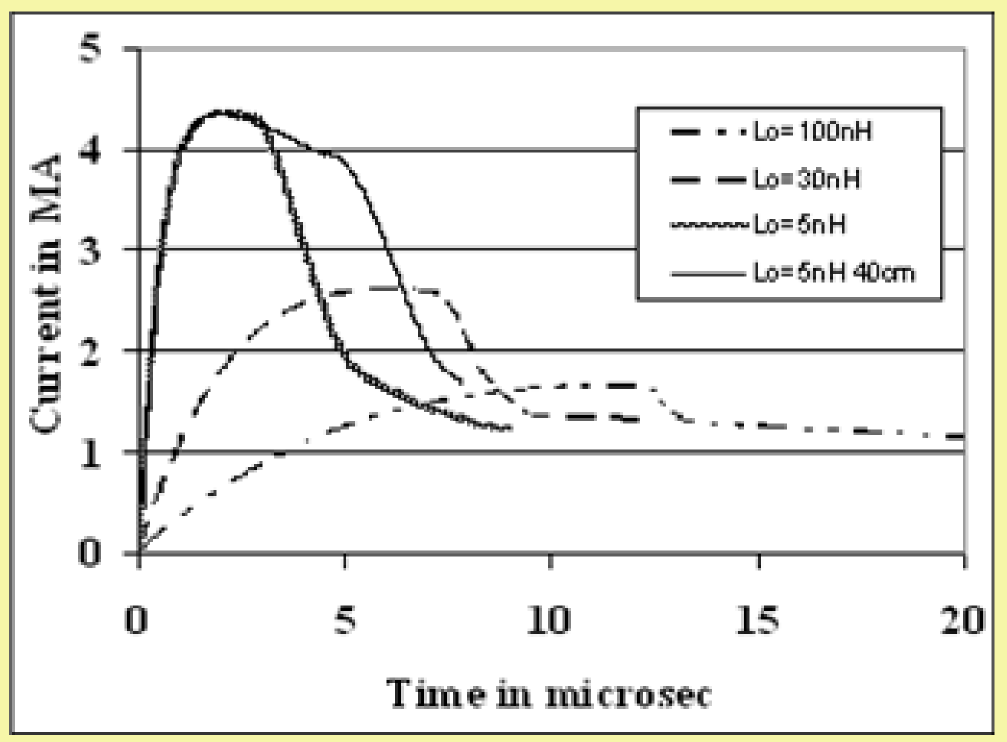
- Table 1 shows that as L_o is reduced,
  - I_{peak} rises with each reduction in L_o with no sign of any limitation.
  - However, I_{pinch} reaches a broad maximum of 1.05MA around 40–30 nH
  - Neutron yield Y_n also shows a similar broad maximum peaking at 3.2
  - $\times 10^{11}$ neutrons

The numerical experiments and discussions – 2/4

Table 1. Effect on currents and ratio of currents I_{pinch}/I_{peak} (computed) as L_o is reduced-PF1000at 35 kV, 3.5 Torr D_2.

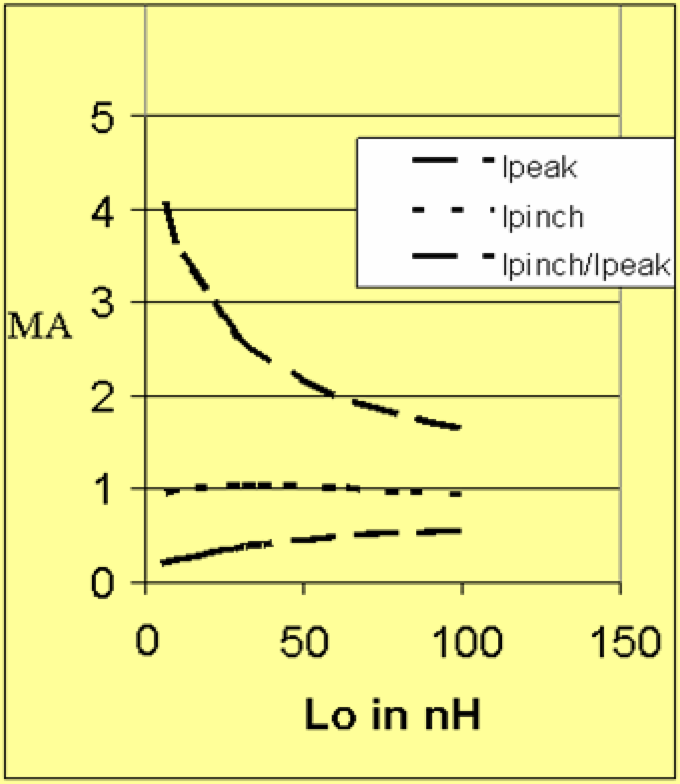
L_o (nH)	b (cm)	a (cm)	z_o (cm)	I_{peak} (MA)	I_{pinch} (MA)	Y_n (10^{11})	I_{pinch}/I_{peak}
100	15.0	10.8	80	1.66	0.96	2.44	0.58
80	16.0	11.6	80	1.81	1.00	2.71	0.55
60	18.0	13.0	70	2.02	1.03	3.01	0.51
40	21.5	15.5	55	2.36	1.05	3.20	0.44
35	22.5	16.3	53	2.47	1.05	3.20	0.43
30	23.8	17.2	50	2.61	1.05	3.10	0.40
20	28.0	21.1	32	3.13	1.03	3.00	0.33
10	33.0	23.8	28	3.65	1.00	2.45	0.27
5	40.0	28.8	20	4.37	0.97	2.00	0.22

The numerical experiments and discussions – 3/4



- Figure 2. PF1000 current waveforms (computed) at 35 kV, 3.5 Torr D_2 for a range of L_o.

The numerical experiments and discussions – 4/4



- **Figure 3. Effect on currents and current ratio (computed) as L_o is reduced-PF1000, 35 kV,3.5 Torr D_2.**

Neutron Scaling Laws from Numerical Experiments

S Lee and S H Saw, J of Fusion Energy, DOI:10.1007/s10894-008-9132-7

published first online 20 February 2008 at http://dx.doi.org/10.1007/s10894-008-9132-7

- **Experimental data of neutron yield Y_n against pinch current I_{pinch} is assembled to produce a more global scaling law than available.**

$$Y_n = 2\text{x}10^{11} I_{pinch}^{4.7} \quad \text{and}$$

$$Y_n = 9\text{x}10^{9} I_{peak}^{3.9}$$

Compilation of Experimental Results – 1/2

- Use recent results from some smaller machines e.g. Soto's PF400 and the large PF1000 as well as a high performance repetitive device, the NX2.
- This gives a good fit of $Y_n=9\times10^{10} I_{pinch}^{3.8}$.
- This compilation of experimental results is to provide a calibration point for setting the neutron yield mechanism of the Lee Model code.
- A calibration point is chosen at around the middle of the current range at $I_{pinch}=0.5$MA, $Y_n=6\times10^9$ neutrons. This point is close to the PF1000's machine parameters with properly adjusted dimensions if it could be fired at 13.5kV.
- The results of the compilation are shown in Fig 1

Compilation of Experimental Results – 2/2

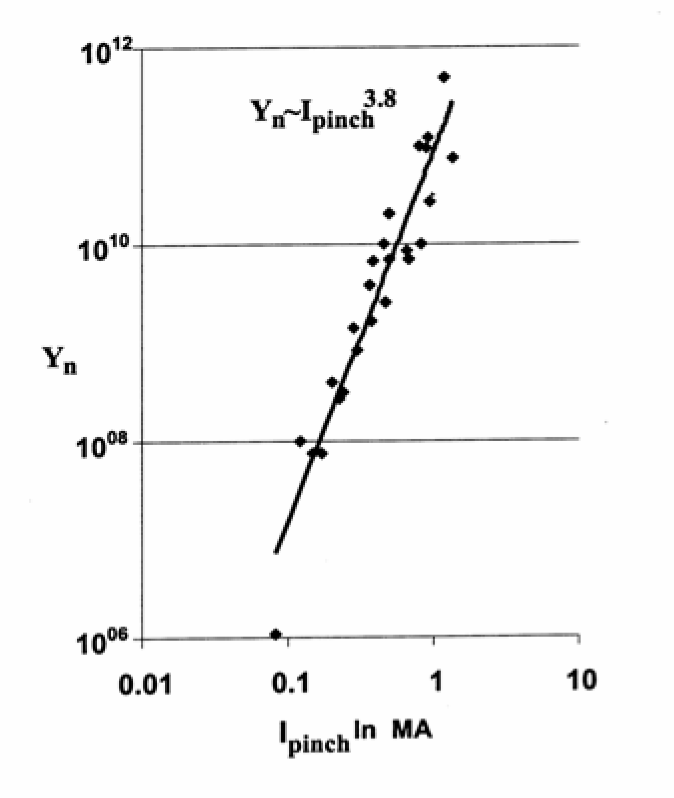


Fig 1. Y_n scaling with I_{pinch} from laboratory data

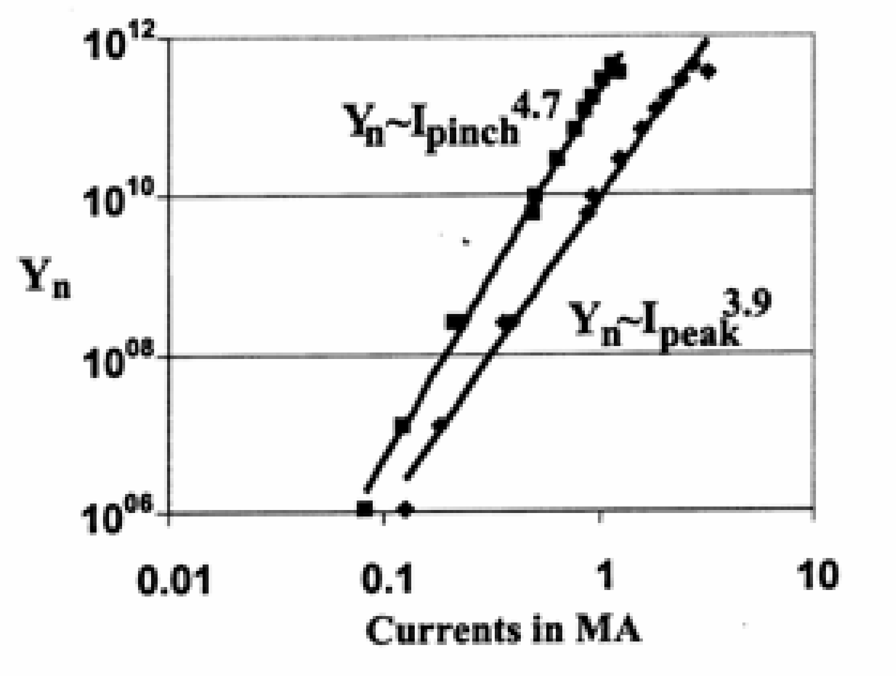
Scaling Laws derived from the numerical experiments -1/3

- Lee Model code is applied to several machines including the PF400, UNU/ICTP PFF, the NX2 and Poseidon.
- The PF1000 which has a current curve published at 27kV and Y_n published at 35kV provided an important point.
- Moreover using parameters for the PF1000 established at 27 kV and 35 kV, additional points were taken at different voltages ranging from 13.5kV upwards to 40kV.
- These machines were chosen because each has a published current trace.

Scaling Laws derived from the numerical experiments -2/3

- The current curve computed by the model code is fitted to the measured current trace.
- Once this fitting is done our experience is that the other computed properties including dynamics, energy distributions and radiation are all realistic.
- This gives confidence that the computed Y_n for each case is also realistic.
- Moreover since each chosen machine also has measured Y_n corresponding to the current trace, the computed Y_n could also be compared with the measured to ensure that the computed results are not incompatible with the measured values.
- The results are shown in Fig 2.

Scaling Laws derived from the numerical experiments -3/3



- Fig 2. Yn scaling with I_{pinch} and I_{peak} from numerical experiments

Computing Plasma Focus Pinch Current from Total Current Measurement

S. Lee, S. H. Saw, P. C. K. Lee, R. S. Rawat and H. Schmidt, Appl Phys Letters 92, 111501 (2008)

- The total current I_{total} waveform in a plasma focus discharge is the most commonly measured quantity, contrasting with the difficult measurement of I_{pinch}.
- However, yield laws should be scaled to focus pinch current I_{pinch} rather than the peak I_{total}.
- This paper describes how I_{pinch} may be computed from the I_{total} trace by fitting a computed current trace to the measured current trace using the Lee model.
- The method is applied to an experiment in which both the I_{total} trace and the plasma sheath current trace were measured.
- The result shows good agreement between the values of computed and measured I_{pinch}.

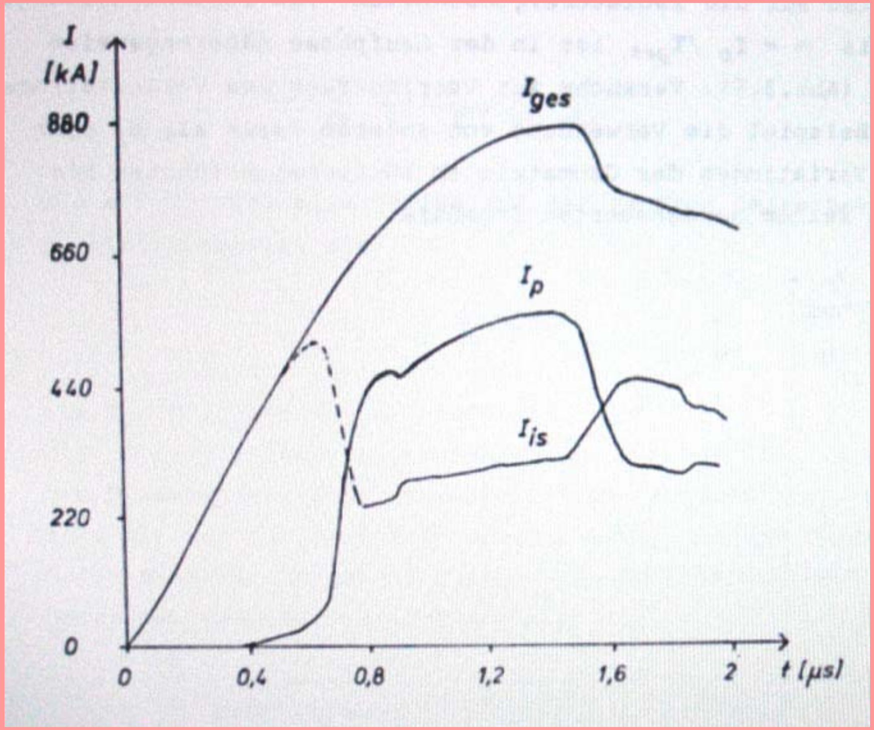
The method

- The method requires a measured I_{total} waveform from a discharge in which the bank parameters, the tube geometry, and operating parameters are known.
- The Lee Model code is used to simulate this discharge using the model parameters for fitting.
- The model parameters are varied until the simulated I_{total} trace agrees with the measured I_{total} trace.
- The start of the quiescent or pinch phase is pinpointed from the computation and the computed value of I_{p} at this time is obtained as I_{pinch}.

The Experiment -1/2

- In an experiment in Stuttgart using the DPF78, current traces were measured using Rogowski coil for the total current (I_{ges} in Fig 2) and an array of magnetic probes for the plasma sheath current (I_p in Fig 2).
- The bank parameters were given as: C_o=15.6μF (nominal), L_o=45 nH (nominal)
- The tube parameters were given as: b= 50 mm, c=25 mm and z_o=150 mm
- Operating parameters were given as: V_o=60 kV, P_o=7.6 Torr in deuterium.

The Experiment -2/2

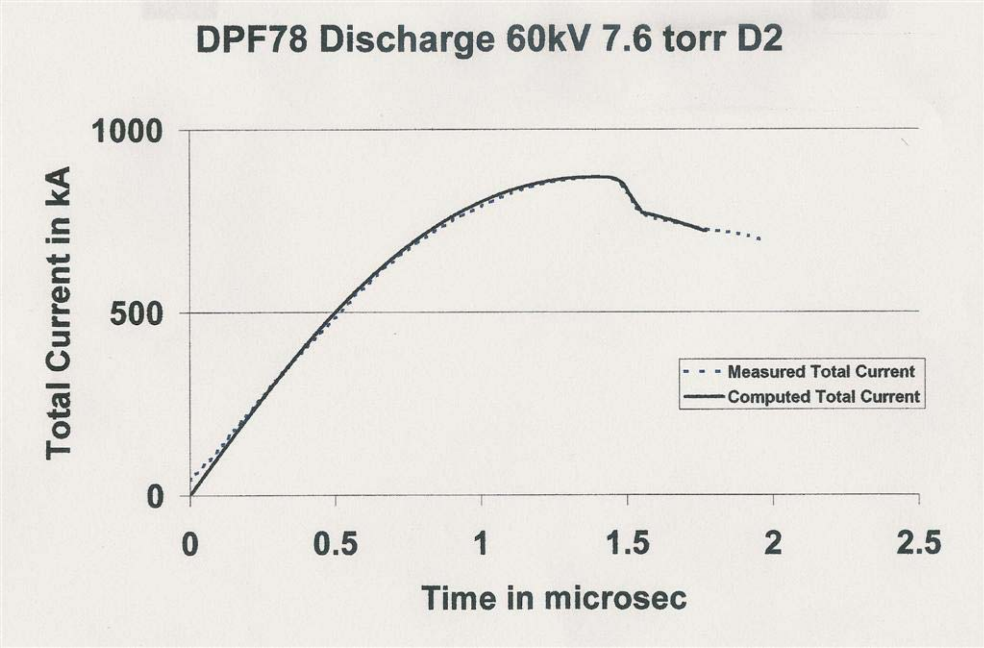


- Fig 2. DPF78 Measured Total Current I_{total}(labelled as I_{ges}) and Measured Plasma Sheath Current (I_p). The third trace I_{is} is the difference of I_{total} and I_p

Numerical Experiment

- These parameters were input into the code.
- The best fit was obtained with the following parameters:
- Bank Parameters: C_o=17.2 μF, L_o=55 nH, and r_o=3.5 m Ω
- Tube parameters: b=50 mm, a=25 mm and z_o=137 mm
- Operating parameters: V_o=60 kV, Po=7.6 torr deuterium
- Model parameters: f_m=0.06, f_c=0.57, f_{mr}=0.08 and f_{cr}=0.51.
- With these parameters the computed total current trace compares with the measured total current trace as shown in Fig 3.

Results -1/4



- Fig 2. Comparison of computed and measured I $_{total}$ waveforms

Results – 2/4

- From the computation results the start of the pinch phase was obtained as 1.551 s. At this time $I_{\mathbf{pinch}}$ was computed as 0.51778=396.8 kA.

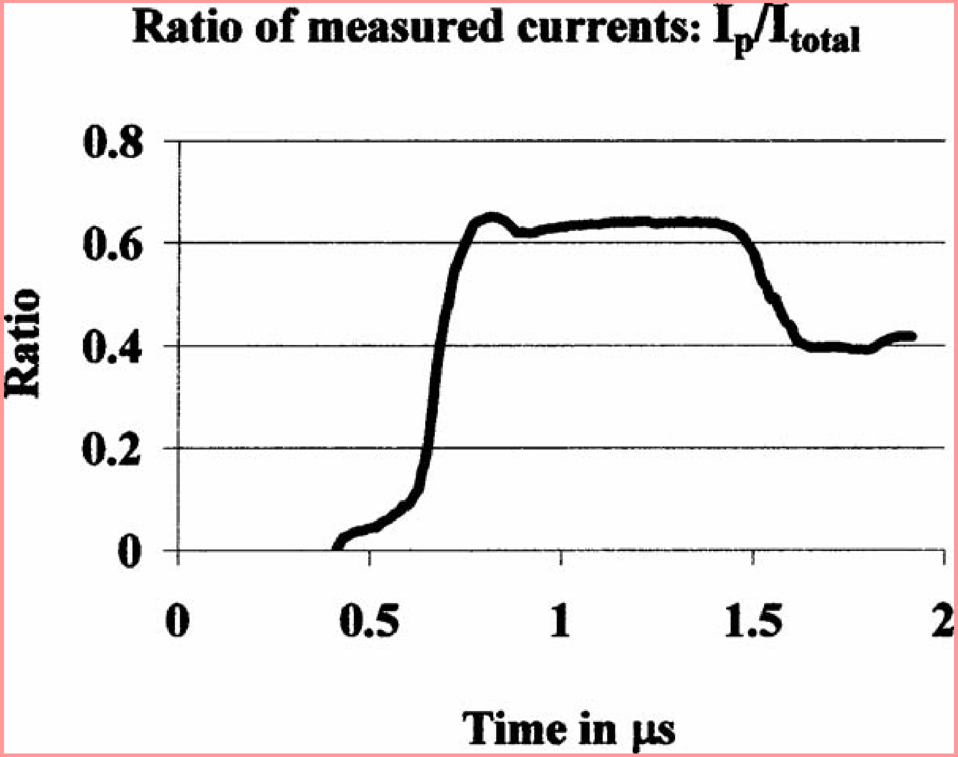
- The value of $I_{\mathbf{pinch}}$ from the measured $I_{\mathbf{p}}$ trace was not immediately obvious since there was no striking feature that marked this moment on the measured $I_{\mathbf{p}}$ trace.

- We used the following procedure to obtain it, at the same time to get further insight into $f_{\mathbf{c}}$ and f_{cr}.

Results - 3/4

- **The ratio I_p / I_{total} digitized from Fig. 1 was plotted as a function of time and shown in Fig. 3.**
- **At time=1.551 μs, the ratio was found to be 0.49, and I_{total} was measured to be 778 kA. Hence, I_{pinch}=381.2 kA was measured in the Stuttgart DPF78 experiment.**
- **The computed I_{pinch} was 4% larger than the measured I_{pinch}.**
- **This difference was to be expected considering that the modeled f_{cr} was an average value of 0.51; while the laboratory measurement showed Fig. 3 that in the radial phase I_p / I_{total} varied from 0.63 to 0.4, and at the start of the pinch phase this ratio was 0.49 and rapidly dropping.**
- **Thus, one would expect the computed value of I_{pinch} to be somewhat higher than the measured, which turned out to be the case.**
- **Nevertheless, the difference of 4% is better than the typical error of 20% estimated for I_{pinch} measurements using magnetic probes.**

Results -4/4



- Fig. 3 Ratio of measured I_p to I_{total} as a function of time.

Conclusion

- The numerical method to determine I_{pinch} is
  - a good alternative
  - more accurate and convenient
  - needing only a commonly measured I_{total} waveform

Comments from a Reviewer

- **Reviewer #1 (Comments to the Author):**
- **This is a very clearly written paper that offers an important addition to the DPF (and z-pinch) literature,** as regards scaling of radiation output (be it x-rays ro neutrons) with current. For four decades, the community has glibly claimed I^4 and other scaling laws for pinches, which have been "verified" by plotting output vs. a current that is almost always measured far away from the pinch.
- **This paper breaks new ground by showing how one can deduce the "pinch" current from the measured loop current, using the Lee Model.** The central question in use of such a model with fitting parameters is: do the parameters stay rigid or must one choose different parameters for each set of conditions? It is clearly shown by the authors that once they have fixed the key fractions (f_c, f_m, etc. for a given machine, those fractions remain fixed for different operating conditions. hence these "fitting parameters" are useful and robust.
- **This Letter should spark a flurry of new papers in which others revisit their old data and show how the neutron or soft x-ray output scales with pinch current rather than discharge current.** This Letter is stimulating and worthy of rapid publication. **The Lee Model upon which the paper is based is itself an unsung hero of the DPF community.**
- Perhaps this Letter will stimulate more widespread use of that model in DPF research worldwide.

Thank You