The Abdus Salam
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2370-6

School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, their Diagnostics and Applications

8 - 12 October 2012

Plasma Focus Numerical Experiments and BORA

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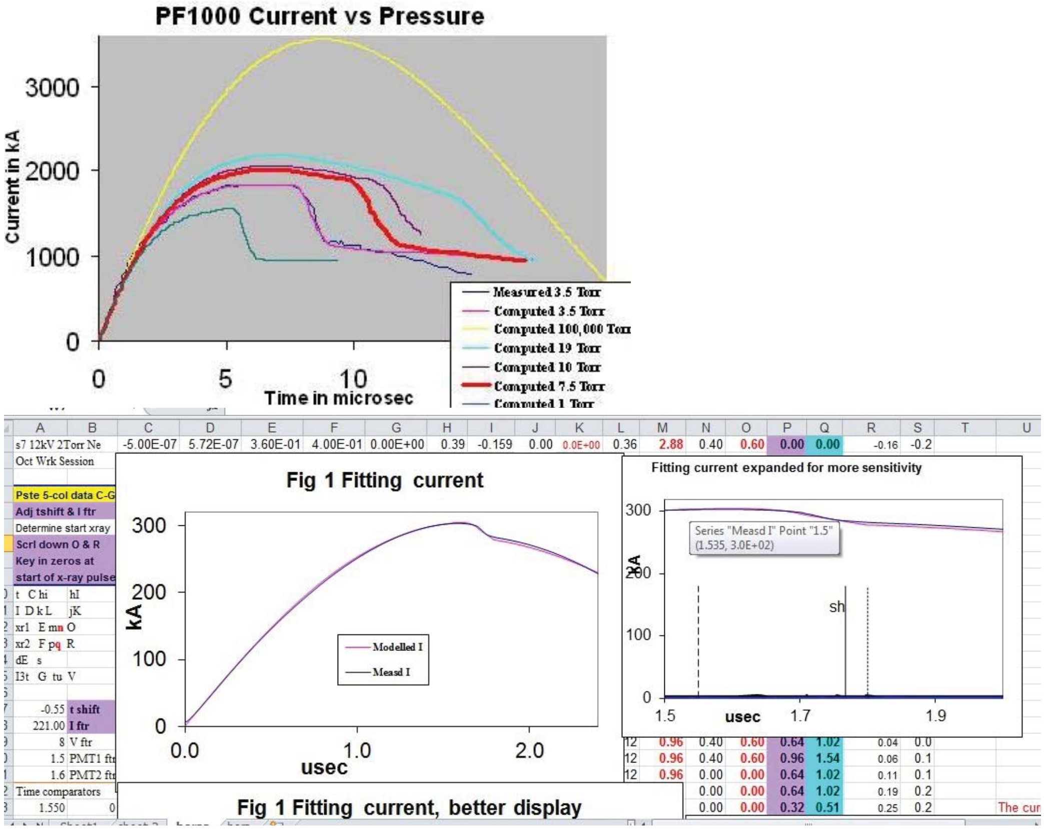
School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, Their Diagnostics and Applications
8-12 October 2012, ICTP, Trieste

Plasma Focus Numerical Experiments and BORA

S H Saw and S Lee

Fitting BORA: Computed Current fitted to Measured Current



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IPFS Institute For Plasma Focus Studies
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Reference to the Lee model code should be given as follows:

Lee S. Radiative Dense Plasma Focus Computation Package (2012): RADPF
www.plasmafocus.net **http://www.intimal.edu.my/school/fas/UFLF/**

3-hour Plasma Focus Numerical Experiment and Bora

Presented by S H Saw & S Lee

At the School and Training Course on Dense Magnetized Plasma as a Source of Ionizing Radiations, Their Diagnostics and Applications, 8-12 October 2012, ICTP, Trieste

Course materials

An e-manual (this document)
An e-folder (**RADPFV5.15df.xls (or 5.15de)**)

3-hour Plasma Focus Numerical Experiment and Bora

Part 1: Universal Plasma Focus Laboratory-The Lee model code

Follow the instructions (adapted to EXCEL 2003) in the following notes. You may also wish to refer to the supplementary notes **SP1.doc.** Instructions are given in some details in order to accommodate participants who may not be familiar with EXCEL. Those who find the instructions unnecessarily detailed may wish to skip the unnecessary lines. Excel 2003 or 2010 are preferred. Avoid EXCEL 2007 (which can be very slow working with this code).

Summary

1.1 Introduction to the Worksheet
1.2 Configuring the Universal Plasma Focus Laboratory (UPFL)
1.3 Firing a shot in NX2
1.4 Studying the results
1.5 Conclusion

The material
You should have **RADPFV5.15df.xls (or 5.15de)** on your Desktop for the next step. Please also ensure you have kept an identical original copy in a RESERVE folder. You are going to work with the desktop copy; and may be altering it. Each time you need an unaltered copy; you may copy from the reserve folder and paste it onto the desktop.

1.1 Introduction to the Worksheet

1.1.1 Opening the worksheet (and enabling Macro)

Double click on **RADPFV5.15df.xls**
Work sheet appears and should look like Figure 1.1 [shown only as an example]; for the following please refer not to Figure 1.1 but to your worksheet.

Security pop-up screen appears.
Click on **enable macros** [or enable content for 2010]

[2007 Security Warning "Macros have been disabled" appears at top left hand corner of Worksheet with side box "options". **Click** on "options"- select the button "Enable this content"- click OK]

After this procedure, the worksheet is macro-enabled and is ready to run.

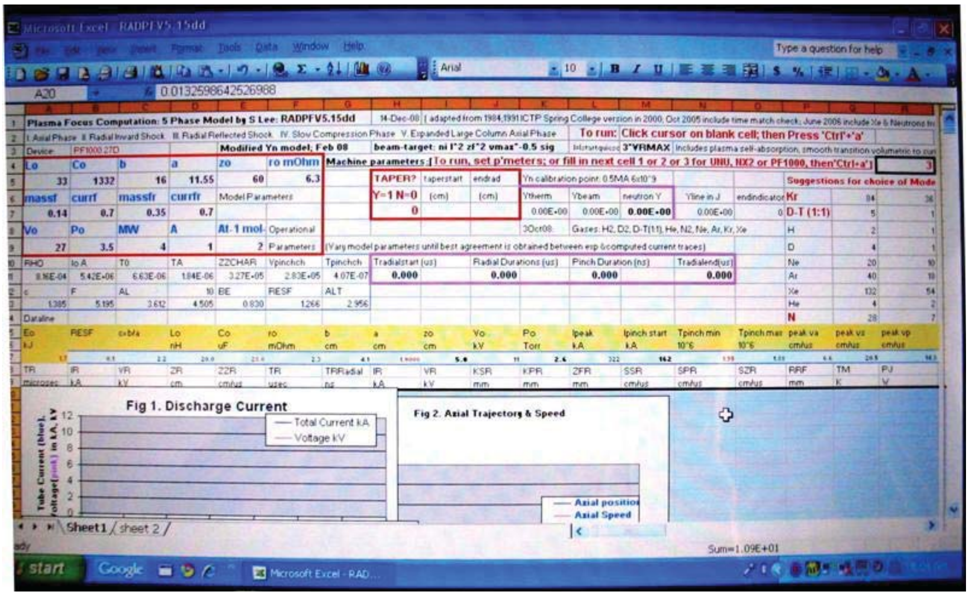


Figure 1.1 Appearance of worksheet-EXCEL 2003 version; EXCEL 2010 version should not look too different.

1.1.2 Preliminary orientation for setting controls

(For the following instructions, use your Excel Sheet; not the above image)

Device configuration:
(*Note: Each Cell of the Excel Worksheet is defined by a Column alphabet A, B, or C….. and a Row number 1, 2 or 3 etc. The Column alphabets are shown along the top border of the worksheet. The Row numbers are shown along the left border of the Worksheet. For example, Cell A4 is located at column A row 4. Another example: A4-F9 refers to the block of cells within the rectangle bordered by row A4-F4, column A4-A9, row A9-F9 and column F4-F9; the larger orange-red bordered rectangle, containing 6x6 cells, near the top left of figure1.*)

Locate Cells A4 to F9. These cells are for setting bank parameters, tube parameters, operating parameters and model parameters.

Taper: Control Cells for anode taper are normally inactivated by typing 0 (number zero) in Cell H7. **Ensure that H7 is filled with 0** (number zero); unless anode taper feature is needed.
One Click Device: This control cell R4 allows choice of a specific plasma focus using numbers; currently 3 machines are available chosen with numbers 1, 2 or 3. **Ensure that R4 is filled with the number 0. (**Otherwise the code will keep defaulting to the selected machine ‘1’ or ‘2’ or ‘3’.)

1.1.3 Preliminary orientation for computed results

Cells A10-G13: computed characteristic quantities of the configured plasma focus.
Cells K6-M7: computed neutron yield, component & total; if operated in deuterium
Cell N6-N7: computed SXR line radiation

Cells H10-N11: computed durations of axial phase, radial phase and pinch phase and end time of radial phase.

Cells A15-AI17: dataline: contains data on row 17 with corresponding labels (and units) in rows 15 and 16. Data: E_0, RESF, $c=b/a$, L_0, C_0, r_0, b, a, z_0, V_0, P_0, I_{peak}, $I_{pinchstart}$, $T_{pinchmin}$, $T_{pinchmax}$, peak v_a, peak v_s, peak v_p, a_{min} (which is r_{min}), z_{max}, pinch duration, V_{max}, $n_{ipinchmax}$, Y_n, $Qsxr$, $Qsxr$%, f_m, f_c, f_{mr}, f_{cr}, *EINP*, *taxialend*, *SF*, *ID* and Q_{line}; others may be added from time to time.

This is a recently introduced very useful feature; enables computed data for each shot to be copied and pasted onto another sheet; so different shots may be placed in sequence, and comparative charts may be made.

Columns A20 to AP20: computed point by point results (data are correspondingly labeled in row A18 with units in row 19) for the following quantities respectively:

Time in μs, total current, tube voltage, axial position, axial speed, time of radial phase in μs measured from the start of axial phase, time of radial phase in *ns* from the start of the radial phase, corresponding quantities of current, voltage, radial shock position, radial piston position, radial pinch length, radial shock, piston and pinch elongation speeds, reflected shock position, plasma temperature, Joule power, Bremsstrahlung, recombination, line emission powers, total radiation power, total power, Joule, Bremsstrahlung, recombintion, line emission energies, total radiation energy, total energy, plasma self-absorption correction factor, black-body power, specific heat ratio and effective charge number, number thermonuclear neutrons, number beam target neutrons, number total neutrons, ion density, volume radiation power, surface radiation power, plasma self-absorption correction factor , radial phase piston work in % of E_0, neon SXR energy emission.

Each computed quantity as a function of time (displayed in the relevant column) is displayed in a column. After a run each of these columns is typically filled to several thousand cells.

Computed results are also summarized in 8 figures:

Fig 1: (Top left) total discharge current and tube voltage
Fig 2: (Top right) axial trajectory and speed
Fig 3: radial trajectories
Fig 4: total tube voltage during radial phase
Fig 5: radial speeds
Fig 6: plasma temperature
Fig 7: Joule heat and radiation energies
Fig 8: Joule power and radiation powers

An additional Fig 8a on the right displays the specific heat ratio and effective charge number during the radial phase.

1.2 Configuring the Universal Plasma Focus Laboratory (UPFL)

1.2.1 Configuring the worksheet for a specific machine

As a first exercise we configure the UPFL so it operates as the NX2, the High-repetition rate neon focus developed for SXR lithography in Singapore.

The parameters are:

Bank: L_0=20 nH, C_0=28 μF, r_0=2.3 mΩ
Tube: b=4.1 cm, a=1.9 cm, z_0=5 cm
Operation: V_0=11 kV, P_0=2.63 Torr, *MW*=20, *A*=10, *At-Mol*=1 (these last 3 defines neon for the code i.e. molecular (atomic) weight, atomic number and whether atomic or molecular)

Model: massf (f_m)=0.0635, currf (f_c)=0.7, massfr (f_{mr}) =0.16, currfr (f_{cr})=0.7; these are the mass and current factors for the axial and radial phases.
(Note: 1. *These model parameters had been fitted earlier by us so that the computed total current best fits a measured total current trace from the NX2.*
Note:2. *We will carry out exercises in fitting model parameters in Module 3 in an exercise with Bora*)

Configuring: Key in the following: (e.g. in Cell A5 key in 20 [for 20 nH], Cell B5 key in 28 [for 28 μF] etc.

	A5	B5	C5	D5	E5	F5
	20	28	4.1	1.9	5	2.3
Then	A9	B9	C9	D9	E9	
	11	2.63	20	10	1	
Then	A7	B7	C7	D7		
	0.0635	0.7	0.16	0.7		

You may of course find it easier to follow the labels in A4-F4, to key in A5-F5 for the relevant parameters; i.e. A4 states L_0 nH; so fill in below it in A5 20 ; and so on.
For identification purposes key in at B3 'NX2'

1.3 Firing a shot in NX2

Place the cursor in any blank non-active space, e.g. G8. (point the cursor at G8 and **click** the mouse). Press 'Ctrl' and 'A' (equivalent to firing a shot).

The programme runs and in less than a minute [provided you are running on EXCEL 2003, For some reason for EXCEL 2007, the process may take longer, sometimes much longer] the run has completed and your worksheet will look something like Figure 1.2 below:

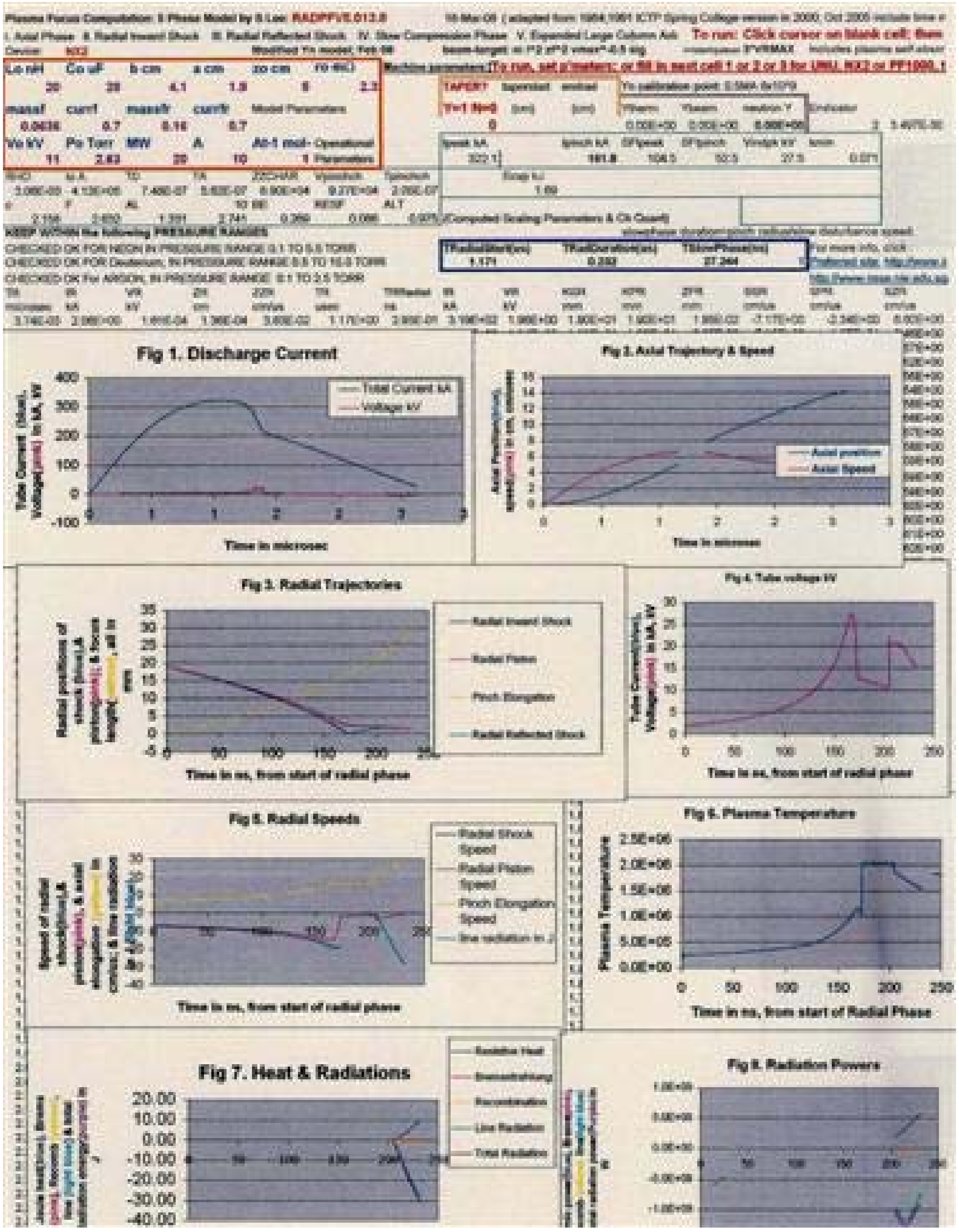


Figure 1.2 Appearance of Worksheet after a shot.

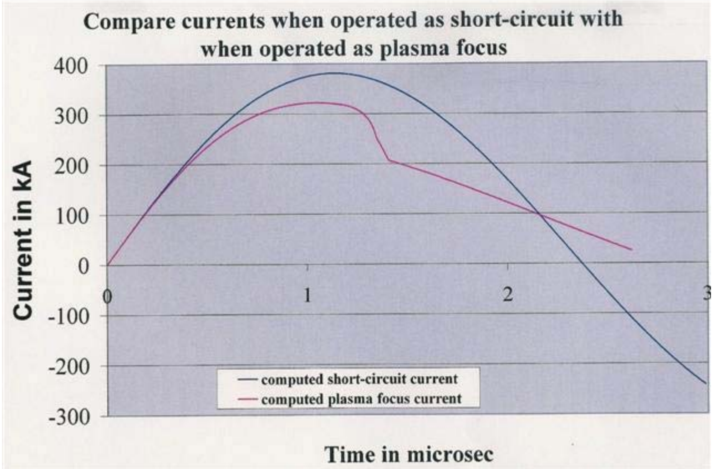


Figure 1.3 Plasma focus current is distorted from unloaded current wave form.

In Figure 1.3 is superimposed a current waveform (in blue) of the plasma focus short-circuited across its input end insulator; with the current waveform (pink) you have just computed

Notes:

The first important point to note is that the plasma focus current waveform is very much distorted from the damped sinusoid of the *L*-*C*-*R* discharge without the plasma focus load (figure 3). The 'distortions' are due to the electrodynamical effects of the plasma motion, including the axial and radial dynamics and the emission of SXR from the Neon plasma. The features of these 'distortions' contain the information of the plasma electrodynamics.

The plasma focus loads the electrical circuit in the same manner as an electric motor loads its driving circuit. The loading may be expressed as a resistance. The dynamic resistance due to the motion in the axial phase is more than the stray resistance of the capacitor bank in the case of the NX2. The dynamic resistance due to the plasma motion in the radial phase is so large as to completely dominate the situation. This causes the large current dip as shown in figure 3.

1.4 Studying the results

(The results are obtained from your **Excel Sheet**; not from the above images in figure 2)
Remember we are operating a neon plasma focus.

Here are some important quantities obtained from the data line in row 17.

Computed	I_{peak}:	L17	322 *kA*
	I_{pinch}:	M17	162 *kA* (pinch current at start of pinch phase)
	Peak tube voltage:	V17	26.1 *kV*
	k_{min}:	S17	0.075 (r_{min} or a_{min}/a) [you may also check this against figure 3 of the worksheet.]

Durations: H11-N11

Axial phase ends at 1.172 μ*s*

Radial phase ends at 1.407 μ*s* (add 1.172 to 0.235 μ*s*) of which the last 26.2 *ns* is the pinch phase.

Now we study the **various figures displayed on the worksheet**, Sheet1 (also shown in figure 2).

Fig 1

Computed current trace; One point of interest is to locate the ends of axial and radial phases on this trace; as well as the start and end of the pinch phase. To do this, select Fig 1 (by pointing cursor on figure 1 and clicking). Then point cursor arrow at trace near peak and move until point 1.17 μ*s* appears; that is the end of axial phase which is also the start of the radial phase.

Note: This point occurs not at the apparent start of current dip, but a little before that. There is no distinct indication on the trace that precisely marks this point. The term rollover may be a better term suggesting a smooth merging of the axial and radial phase. The apparent current dip occurs a little after the end of the axial phase.

Next locate point 1.41 μ*s* which is the end of the radial phase. Also locate the point 1.38 μ*s* which is the start of the pinch phase. There is no clear indication on the trace to mark this point either.

Fig 2

Select Fig 2 (with cursor) and read off the pink curve that the peak axial speed reached is 6.6 *cm*/μ*s*. Confirm this on the data line; Cell P17. How many *km* per hour is this? And what is the Mach Number? 1 *cm*/μ*s*=36,000 *km*/*hr*; so 6.6 *cm*/μ*s*=237,600 *km*/*hr*

Expressing this speed in *km*/*hr* is to give an idea of how fast the speeds are in the plasma focus; it should give the idea also of temperature, since for strong shock waves (high Mach number motion) there is efficient conversion of energy from directed to thermal, i.e. from high kinetic energy to high temperature.

Fig 3

Select Fig 3. Read from dark blue curve that piston hits axis (radius=0) at 177*ns* after start of radial phase; and outgoing reflected shock (light blue) hits incoming piston (pink curve) at 209*ns* at radius of 2.03*mm*. The pinch phase starts at this 209*ns* and ends at 235 *ns* at a further compressed radius of 1.42*mm*.

Note the square of the ratio of pinching a/r_{min} *is a measure of the how much the ambient density has been increased by the pinching effect.*

Fig 4

Computed waveform of tube voltage during radial phase. Note the peak value of the tube voltage induced by the rapid plasma motion.

Fig 5
Select Fig 5. Note from the dark blue curve that peak radial shock speed is 20.4 *cm*/µ*s* just before the radial shock hits the axis at 178 *ns* after start of radial phase. Also read from the pink curve that peak piston speed is 14.2 *cm*/µ*s* reached just before the radial shock reaches its peak speed. Yellow curve shows column elongation speed. Note that these peak speeds are also recorded in the data line.

Other figures:
Select **Fig 6**: and read the peak temperature reached.
Select **Fig 7**: and read the various energies.
Select **Fig 8**: and read the various powers

Note that more charts are plotted on Sheet2 of **RADPFV5.15df.xls** These charts form a more complete picture of the plasma focus pinch, and may be used as starting guides for laboratory measurements of the various plasma properties.

1.5 Conclusion

We had an introduction to the Worksheet of **RADPFV5.15df.xls**
We configured the UPFL as the NX2 at 11 *kV* 2.6 *Torr* neon.
We used properly fitted model parameters. (*Note: Fitting model parameters will be covered in a future session*).
We noted that the current waveform is distorted from damped sinusoid-like waveform (damped sinusoid-like waveform is the current waveform when the plasma focus is short-circuited).
We studied the computed results, including total current, tube voltage, pinch current, radial and axial trajectories, radial and axial speeds, plasma temperature and plasma Joule heating and radiation energies.
We also located various points on the current trace including: end of axial phase/start of radial phase; end of radial phase; start and end of pinch phase.

Note: This particular numerical 'shot' used properly fitted model parameters. The results of dynamics, electrodynamics and radiation as seen above are, in our experience, comparable with the actual experiments conducted at NTU/NIE.

End of Part 1

Reference to the Lee model code should be given as follows:

Lee S. Radiative Dense Plasma Focus Computation Package (2012): RADPF
www.plasmafocus.net **http://www.intimal.edu.my/school/fas/UFLF/**

Part 2: Exercise with BORA

Summary

For this module we fit BORA computed current waveform to match a BORA measured current waveform.
From fitting the rising slope (and the risetime) of the current we obtain the static inductance L_0. From the fit of rising profile and the topping profile (including the peak values) we obtain the bank stray resistance r_0. From fitting the axial mass factor f_m and radial mass factor f_{mr} (where necessary also fitting current factors f_c and f_{cr}) we obtain a good overall fit. The final fitting produces from the code realistic results of I_{peak}, I_{pinch}, axial and radial dynamics and pinch properties.

Data for BORA is taken from the following paper:

Dense Plasma Focus "Bora" operational at The Abdus Salam International Centre for Theoretical Physics and experiments provided with the device
V.A. Gribkov, M.V. Chernyshova, A. Cicuttin, M.L. Crespo,
R.A. Miklaszewski, M. Scholz, A.E. Shapiro, K. Tomaszewski, C. Tuniz

2.1 Data

1. Capacitance C_0=**24.4 µF** (from pg 15 Table 1)
2. Chamber: cathode radius b=**2.5 cm**; anode radius a=**1.5** cm (pg 65 Fig 62)
   'axial' length z_0=3.5 cm (nominal) curved; will be fitted as an equivalent straight axial length
3. Current derivative trace; (from pg 84 Fig 89) - bottom most trace is used; as this is the trace with effectively the whole trace visible and distinguishable.

2.1.1 Current derivative trace: (from pg 84 Fig 89)

The final conditioning of the device has resulted in its proper operation at 17-18 kV with deuterium pressure of about 10 mbar. Corresponding oscilloscope traces obtained by miniature magnetic probes installed near each of our 4 PSSs are presented in Fig. 89.

From this picture one may see that the rise-time of current of our main discharge is equal to about 1.5 µs with the "peculiarity" of the current positioned in a proper place at the moment of 1.8 microsecond from the start of the discharge. By means of Rogowski coil we have measured the amplitude of our discharge current. With 3 capacitors and maximal achievable voltage (19.5 kV) supplied by our charger we obtained the current magnitude equal to 234 kA.

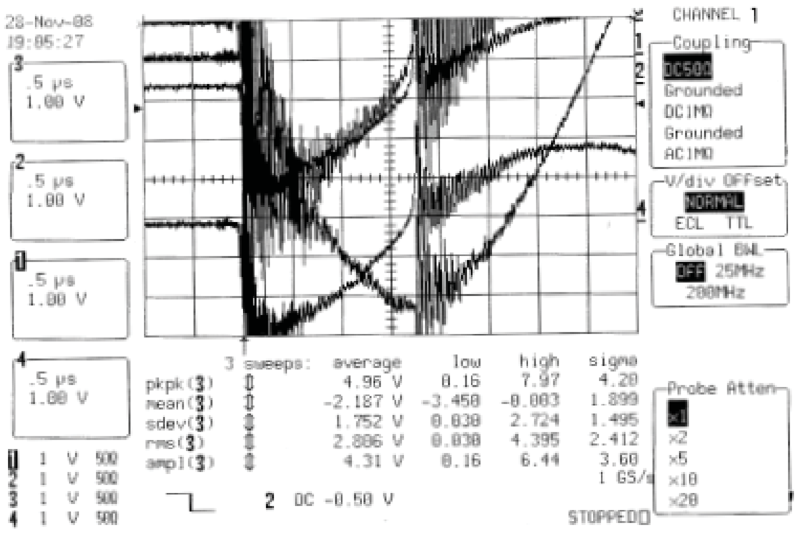


Fig. 89 Oscilloscope traces of the discharge current derivatives in a property-sheet mode of the DPF operation obtained at all 4 PSSs

Maximal current amplitude was detected with 4 capacitors (with the whole bank) at 18 kV of charging voltage and with initial deuterium pressure of 11 mbar. It was equal to about I_{tot} = 300 kA. With this current, according to a well-known experimental scaling law for neutron production by DPF with deuterium as a working gas, we may expect neutron yield in a single shot on the level of:

$$Y_n \approx 10^{10} \times I_{tot}^4 \approx 10^{10} \times (0.3)^4 \approx 10^8 \text{ neutrons/pulse} \qquad (12)$$

Notes:

1. The current derivative trace is dI/dt taken at one of the 4 PSSs.

2. Inductance (static) of bank L_0 is not given; we will fit it unambiguously from the slope of the computed current trace fitted to the measured current.

3. Stray resistance of bank is not given; we will use 0.1 of surge impedance of bank and check that this is consistent during the fitting.

4. We only have the waveform; ie the shape of the current trace taken at one of the 4 PSSs. However the model code we are using is charge-‘consistent. Hence once we have the current waveform correctly fitted, the computed current amplitudes are correct and may be used to calibrate the system current; we assume the shape of the current trace at the PSS that we are using is consistent with the overall current waveform.

2.2 Data treatment

2.2.1 Tracing the dI/dt, filtering out the high frequency ‘noise’ oscillations

Since we have no digital file, we trace out the dI/dt **<u>Current derivative trace; (from pg 84 Fig 89 bottom-most trace)</u>** as best we could (filtering out the high frequency ‘noise’ oscillations by drawing a line through the middle of the high frequency ‘noise’ oscillations as judged visually. We obtained the following as shown in Figure 2.1 after an inversion to obtain the starting dI/dt positive.

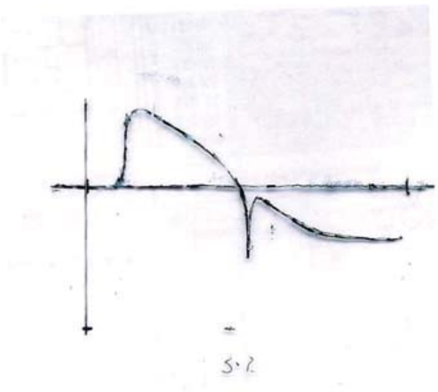


Figure 2.1 Current derivative trace (from pg 84 Fig 89 bottom-most trace) after filtering out the high frequency ‘noise oscillations

2.2.2 Digitizing the ‘noise’-reduced dI/dt curve and integrating it to obtain the ‘measured’ current trace

Then we digitized this trace using a digitizer called “Engauge” obtaining the digitized trace & its integration is shown in Figure 2.2 (a screen capture).

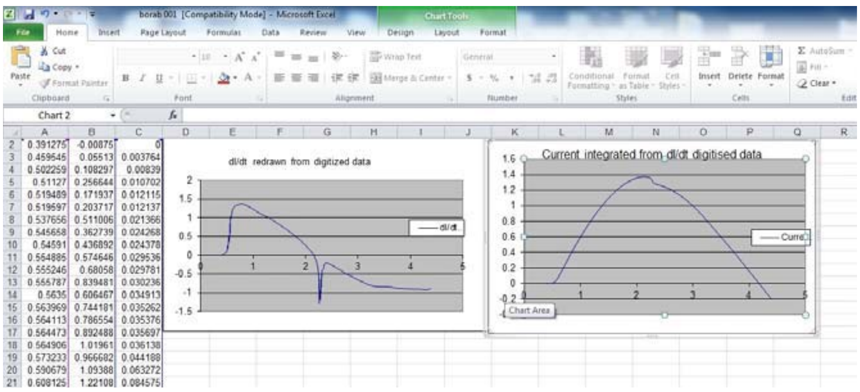


Figure 2.2 Digitized dI/dt trace and the integrated measured current waveform

2.2.3 Using the measured current trace for fittings of the computed current trace to 'calibrate' the model code to the Bora Plasma Focus

We configure the UPFL (**RADPFV5.15df.xls**) for Bora using the following trial configuration.

Values in black: given; **Values in red: trial**

Lo nH	Co uF	b cm	a cm	zo cm	ro mΩ
30	24.4	2.5	1.5	4	2.3
massf	currf	massfr	currfr	Model Parameters	
0.07	0.7	0.16	0.7		
Vo kV	Po Torr	MW	A	At=1 mol=2	Operational Parameters
17	7.6	4	1	2	

We fire a shot. We place the computed current trace on the same chart as the measured current data (sheet bora001).

In order to make the comparison meaningful we note:

1. The computed curve and the measured curve may need to be shifted in time one relative to the other. To do that we add an amount of time (time shift) specified in Cell K1 which is varied until the start of the computed and measured traces coincide.
2. The measured current has unknown (hence treated as arbitrary) amplitude. To make meaningful fit it is necessary to adjust the measured current amplitude to that of the computed amplitude. To do this we place a multiplying factor (multiplier) in Cell L1 which is varied until the measured amplitude is equal to the computed. Then we start the profile (shape) fitting.

2.3 Fitting the static inductance L_0.

Having completed adjusting the time shift (-0.5) and amplitude multiplication (220) as explained in (1) and (2) above; the overlay of the two traces are shown in the Figure 2.3 below:

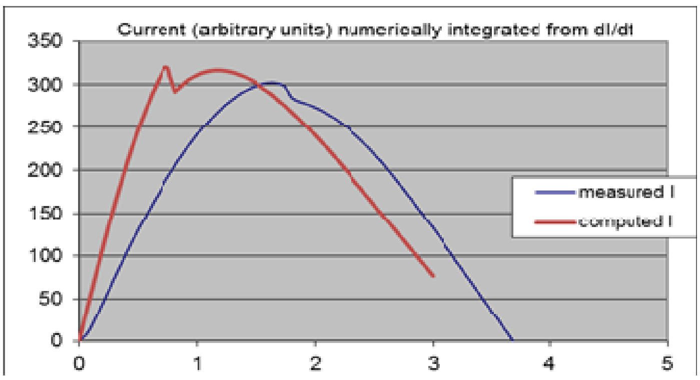


Figure 2.3 Overlay of computed current to measured current traces to facilitate fitting

We note that the computed trace has a much steeper slope (hence shorter risetime) when compared to the measured current trace. Since the periodic time of an L-C circuit is dtermined by $(L_0C_0)^{0.5}$, we need to increase L_0 in the computed circuit.

We increase the configured value of L_0 step be step. When L_0=55 nH, with the configuration as follows:

Lo	**Co**	**b**	**a**	**Zo**	**ro mOhm**	
55	**24.4**	**2.5**	**1.5**	**4**	**4**	
massf	**currf**	**massfr**	**currfr**	Model Parameters		
0.07	**0.7**	**0.16**	**0.7**			
Vo	**Po**	**MW**	**A**	**At-1 Mol-2**		Operational
17	**7.6**	**4**	**1**	**2**		Parameters

The overlay looks much better as far as the comparison of the current rise profile is concerned (with further adjustments to time shift (-0.55) and multiplier (218) as shown in Figure 2.4.

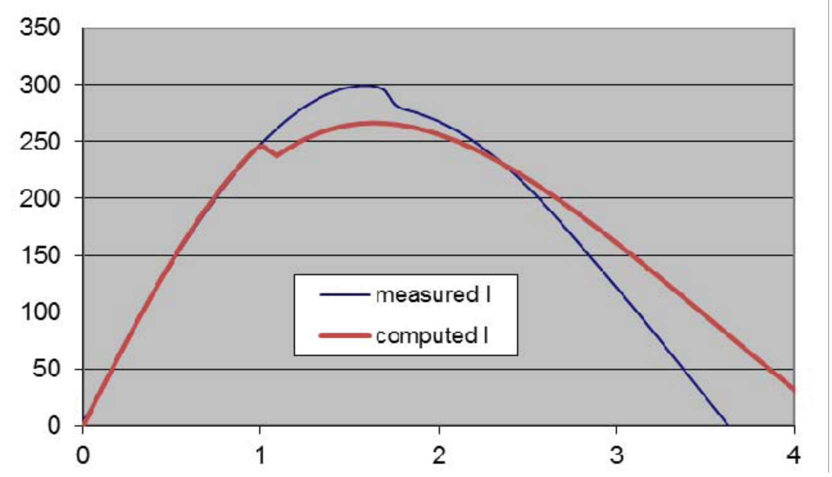


Figure 2.4 Fitting of computed current to measured current waveform by adjusting L_0

So we know the value of $\mathbf{L_0}$ is close to **55 nH** and $\mathbf{r_0}$**~4 mΩ**. We may need to fine tune a little later.

2.4 Fitting f_m and where necessary f_c

From the latest fit above it is clear that the computed (brown trace) trace has the radial phase starting far too early; ie the axial speed is too fast.
We need to slow down the axial speed. This can be done by increasing fm.
We try increasing f_m to 0.1, then 0.15, then 0.2. With each increase the computed current dip comes later and later making the fit better. At f_m=0.2, the following is the overlay in Figure 2.5.

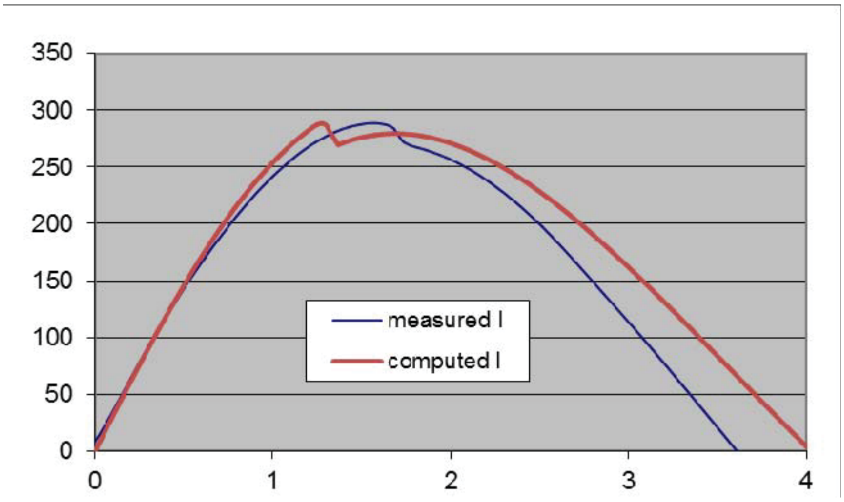


Figure 2.5 Improved fitting of computed current to measured current by adjusting f_m

2.5 Fitting effective 'straight-length' channel z_0

We note that although the computed current dip is approaching the measured current dip and the current amplitudes are about the same, yet the computed current dip does not have the flattening behaviour of the measured. This suggests that we should increase either the value of L_0 or the length z_0 (which also in effect increases the contribution to risetime. We try increasing L_0 to 60 and then to 65 nH, (each time adjusting the multiplier as well) but we are not able to get the rounding behaviour of the current dip such as is seen on the measured topping and dipping profile. Neither can we get the correct shape by an increase of L_0 and fm. (although at L_0=70 nH and f_m=0.3 we get the computed current dip up close to the measured; but the shape is just too angular for the computed when compared to the measured profile. Moreover we know that the 4-capacitor configuration of Bora would not possibly have such a large L_0. Even L_0=55 nH is already (to us) surprisingly high.

So we go back to L_0=55nH and fm=0.2 and try increasing z_0, which will also move the current dip later in time towards the measured current dip. When we reach z_0= 6 cm the configuration looks like this:

Lo	Co	b	a	zo	ro mOhm
55	24.4	2.5	1.5	6	6
massf	currf	massfr	currfr	Model Parameters	
0.2	0.7	0.16	0.7		
Vo	Po	MW	A	At-1 mol-2	Operational
17	7.6	4	1	2	Parameters

And the overlay in Figure 2.6 shows the computed curve is now close to the measured; with time shift of -0.55µs and multiplier=218
(Note: we do not look at the fit beyond the bottom of the dip as that is outside the region of interest.)

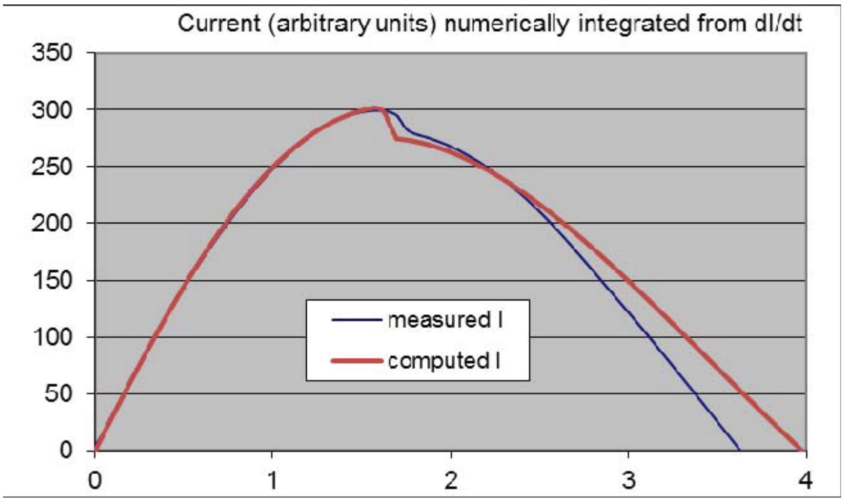


Figure 2.5 Improved fitting of computed current to measured current by adjusting for effective 'straight length' channel z_0

2.6 Fitting the radial phase.

We note that for Bora the f_m (at 0.2) is higher than most other machines which typically have f_m=0.1. Hence we expect that fmr should also be bigger, likely bigger than 0.2. (since our experience is that f_{mr} is generally bigger than f_m, typically about twice f_m. Increasing fmr by such a large amount will also move the current dip significantly to a later time, since a close examination (Sheet 1 H11) shows that the radial phase starts a little (about 0.1 μs in this case) before the plunging start of the current dip. This small amount of time leading up to the plunging dip is sometimes referred to as the 'roll-off' region which is the turning of the flat-top into the dip. Because the radial phase starts before the dip, increasing the mass factor of the radial phase will make the roll-off more pronounced thus delaying the current dip.

Thus, at this point of the fitting we move to the radial phase fitting; by increasing f_{mr}. We increase f_{mr} in small steps from 0.16 to 0.25 then to 0.3, noting the improvement in the fit as f_{mr} is increased. When we get to 0.4 the configuration is:

Lo	Co	b	a	zo	ro mOhm	
55	24.4	2.5	1.5	6	6	
massf	currf	massfr	currfr	Model Parameters		
0.2	0.7	0.4	0.7			
Vo	Po	MW	A	At-1 mol-2		Operatio
17	7.6	4	1	2		Paramet

And the overlay looks good as shown in Figure 2.7.

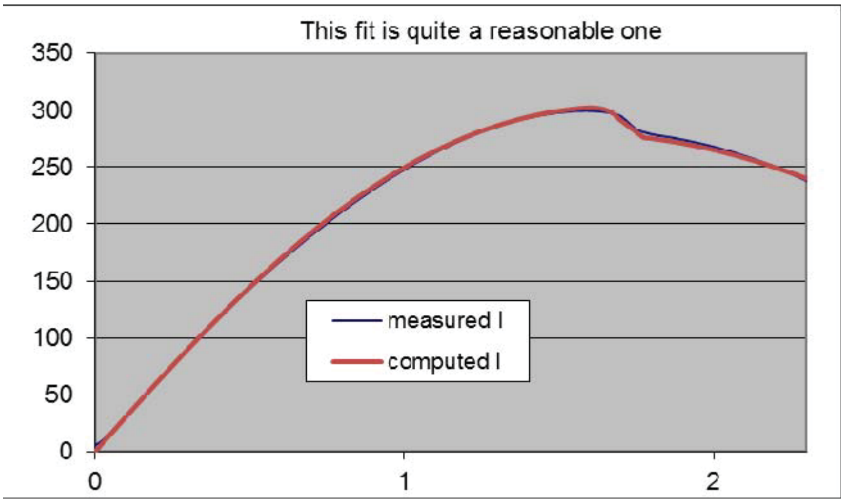


Figure 2.7 Ftting of the radial phase completes the fitting of the computed to measured current

We could make the fit marginally better by making small iterative adjustments again to L_0, r_0, f_m and f_{mr}. But the end result would not make much difference to either the the value of I_{peak} or Y_n, the neutron yield or to any of the key dynamics such as axial and radial speeds or the properties of the focus pinch such as dimensions or pinch duration. So for discussions we accept this fit.

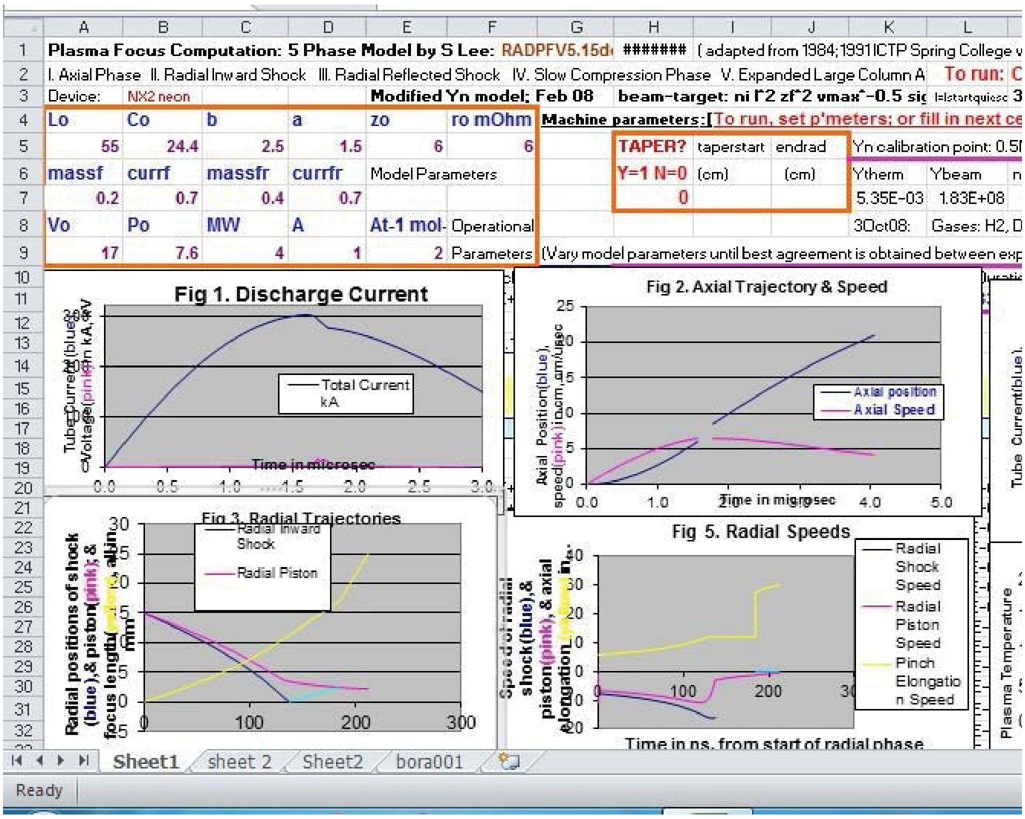
2.7 Concluding Notes

1. The inductance (55 nH fitted) is surprisingly high when compared with the predecessors PF-5M (33 nH) or NX1 (30 nH). The Designer of BORA will be able to confirm this aspect of the design in comparing with PF-5M and NX1.

2. The mass factor f_m and radial mass factor f_{mr} are unusually high indicating (a) that the solid channel of the Bora is conducive to a more efficient mass swept-up (b) and the possibility that the pressure that was actually in the chamber could be higher than “about” 10 mbar as stated against Fig 89;

3. Peak circuit current Ipeak=304 kA and the neutron yield Yn= $1.9\text{x}10^8$.

4. The dynamics and some Pinch Properties are presented in the following screen capturein the next page.



End of Part 2

Reference to the Lee model code should be given as follows:
Lee S. Radiative Dense Plasma Focus Computation Package (2012): RADPF
www.plasmafocus.net http://www.intimal.edu.my/school/fas/UFLF/