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Institute for Plasma Focus Studies

Internet Workshop on Numerical Plasma Focus Experiments

(Supplementary Notes for Module 2 & 3)

Are the results any good?

Are there any indications that our computed results are anywhere near the actual results that may be measured on the device in actual operation?

NOT if we just guess the model parameters f_m, f_c, f_{mr}, f_{cr};. Then the results are just hypothetical; although with experience we may assign some reasonable values of the model parameters for the particular machine in its particular operating conditions. And the results may be useful for planning or designing purposes.

How do we make the results realistic?

The standard practice is to **fit the computed total current waveform to an experimentally measured total current waveform.**

From experience it is known that the current trace of the focus is one of the best indicators of gross performance. 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** namely capacitance C_o, external, or static inductance L_o and circuit resistance r_o, by the focus **tube geometry** namely electrode radii, outer 'b' and inner anode 'a', and the anode length 'z_o'; and on the **operational parameters** which are the charging voltage V_o and the fill pressure P_o and the fill gas. It also depends on the fraction of 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 will also reflect the joule heating and radiative yields. At the end of the pinch phase the total current profile will also reflect the sudden transition of the current flow from a constricted pinch to a large column flow. Thus the discharge current powers all the 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 occurs in the various phases of the plasma focus**.

Our standard practice for any existing plasma focus is to obtain a measured current trace. Then we fit the computed current trace to the measured current trace. The fitting process involves adjusting the model parameters f_m, f_c, f_{mr}, f_{cr} one by one, or in combination until the computed current waveform fits the measured current waveform.

Once this fitting is done our experience is that the other computed properties including dynamics, energy distributions and radiation are all realistic.

Fitting computed current trace to experimental current trace of existing machine:

The main model parameters are the tube current flow factor CURRF (known to be 0.7 for most machines) and the mass swept-up factor (MASSF, for axial & MASSFR, for radial). First try model parameters are suggested in a table towards the right of the worksheet. These could be tried, but may be adjusted so that the time of focus, and the radial inward shock transit time, fit the experimentally observed times for each machine. The computed current trace is compared with the experimental current trace.

Features for comparison include current risetime and rising shape, peak current, current 'roll off' and dip, both shape and amplitude. Absolute values should be compared. Our experience with a number of machines shows that the fit is usually very good, occasionally almost exact..
The machine parameters and operating conditions should already have been determined and inputted into the active sheet. The model parameters are then adjusted, one by one, or in combination until best fit is obtained between the computed current trace and the experimental current trace.

First step is fitting the axial phase. This involves variation of f_m and f_c whilst observing the changes that appear on the resulting computed I_{total} trace in respect to the **risetime, rising shape and I_{peak};** and how these features compare with the corresponding features of the measured I_{total} trace. During this fitting an increase in f_c increases axial speed which increases dynamic resistance, thus lowering current magnitude on the rising slope. The greater rate of increase of tube inductance flattens out the rising slope. A decrease in f_m has almost the same effect. However a change in f_c has an additional subtle effect of changing the relative effect of the tube inductance. This means that increasing the speed by a certain amount by increasing f_c, then reducing it by exactly the same amount by a corresponding increase in f_m will not bring the I_{total} shape and magnitude back to the shape and value before either change is made. Thus one has to get each of f_m and f_c separately correct to get both the current shape and magnitude correct in the rising current profile.

Second step is fitting of the radial phases. We need particularly to understand the transition from the axial to the radial phase. For a plasma focus to work well, it is usually operated with a speed such that its axial run-down time is about equal to the risetime of the circuit with the device short-circuited across its back-wall. With the focus tube connected, the current risetime will be larger. At the same time the current trace is flattened out. In most cases this increased risetime will be cut short by the start of the radial phase. As this phase starts the current trace starts to roll over, at first imperceptibly, then clearly dipping and then dips sharply as the focus dynamics enters the severe pinch phase which absorbs a significant portion of the energy from the driving magnetic field. Thus, the second step in the fitting consists of adjusting f_{mr} and f_{cr} so that the computed current roll-over and the dip agree in shape, slope and extent of dip with the measured waveform.

[The rest of the notes may be left to be read in conjunction with the work of Part 3.]

Besides the model parameters, sometimes (when all else fails in the fitting process) the inductance (as published or given by the experimenters) needs to be adjusted. Very commonly the inductance L_o may be given as the short circuit bank inductance whereas it should be the 'static' inductance of the plasma focus; ie the inductance of the PF before the current sheet moves.

Adjustment to L_o is indicated when the computed current rise slope differs significantly from the measured slope. (adjustment to C_o will also

affect the current slope, but the value of C_o is usually more reliably given than that of L_o).

Usually also the value of stray resistance r_o needs to be guessed at as few experimenters determine this carefully if at all. We usually start with the value of r_o as 0.1 of $(L_o/C_o)^{0.5}$; and make small adjustment as necessary; noting that capacitor banks are such that the ratio of RESF= r_o / $(L_o/C_o)^{0.5}$ seldom goes below 0.05.

Sometimes, especially for PF's using very low values of C_o, it may also be necessary (when all else fails) to adjust the value of C_o (for sub-uF capacitor banks, the closely spaced connecting parallel plates and parallel connecting cables may actually significantly change the value of $C_{o)}$.

In cases where there is very good fit in current profiles but the absolute values of currents don't match, it has been reasonable to suspect that the calibration constant for the current profile has been given wrongly by the experimenter. Calibration errors can be ascertained by checking the quantity of charge that has flowed out of the capacitor when the voltage across it has dropped to zero. If this quantity differs significantly from $(1/2)C_oV_o^2$; then the suspicion of calibration error is confirmed. Actually this checking is already implicit in the model.

In adjusting r_o we note that an increase of r_o lowers the current trace at all points proportionately. In adjusting L_o we note that increasing L_o lowers the slope of the rising current. When all values are properly adjusted and when f_m and f_c are correctly fitted, the measured rising profile of the computed I_{total}, usually up to the peak value I_{peak}, is found to fit the measured rising profile well in both shape and magnitude.

Two other points need to be noted[6,7]. The measured I_{total} profile usually has a starting portion which seems to rise more slowly than the computed trace. This is due to the switching process during which, until fully switched, the spark gap presents additional resistance. It could also be compounded by the lift-off delay[22]. Practically this effect is compensated by shifting the whole computed trace forward in time, usually by a small amount around 50ns. A related note is that z_o may need to be reduced to account for the shape of the back-wall insulator.

A final remark in response to the general observation that the measured slope of the current dip towards the end of the radial phases is almost always steeper than can be reasonably fitted. This is indeed the case. All adjustments e.g. to L_o, C_o and r_o do not have the necessary short-time influence on this feature of the current trace. To steepen the dip slope the best we could do is to either decrease f_{mr} or increase f_{cr}; however either of these adjustments also tend to increase the computed depth of the dip; which often is already excessive. Moreover there are usually small but significant ‘bouncing’ features towards and beyond the bottom of the measured current dip. These features are not modeled. So the fitting has to accept the best compromise to achieve the ‘best’ fit. I tend to attribute this as a limitation of the model at this stage of its development.

Moreover this method of fitting the computed current to the measured current obviously depends on the actual plasma focus machine performing in accordance to the main features of the model. The plasma focus operated in the so-called ‘neutron optimised’ mode appears to be most suited for this model. For gases other than Deuterium, perhaps we can also identify range/modes of operations suitable for simulation with this model; e.g. a plasma focus in Neon operated to optimize SXR yield with a temperature around 100-400eV appears also to be very suited to this model code.

On the other hand, unoptimised machines, for example, may have axial phase current sheet so much fragmented that the axial phase model parameters just cannot be stretched for the model to fit the experiment. Or as another example, a plasma focus may be operated to optimize ion or electron beams; in which case conditions are manipulated for the instabilities to be so much enhanced that the radial model parameters cannot be stretched to simulate these effects. Such situations and range of operation may be outside the scope of this mode.

Despite these limitations, our experience show that the model may be used to compute plasma conditions and neutron and SXR yields with reasonable agreement over an unprecedented range of experiments, from sub-kJ PF400 (Chile) to low kJ NX2 (Singapore) and UNU/ICTP PFF (Network countries) all the way to the MJ PF1000.