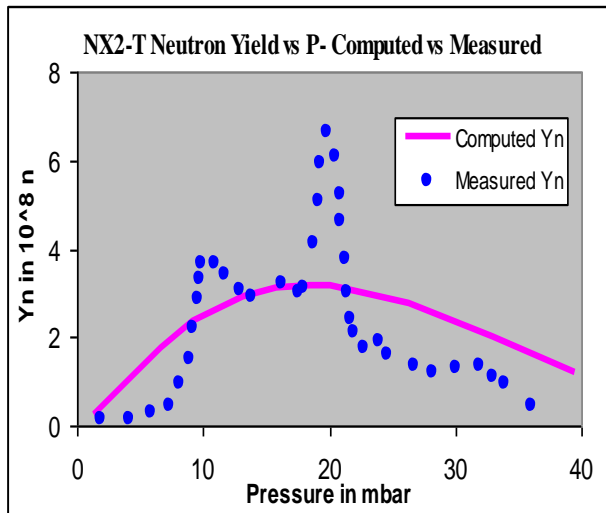


Numerical Experiments Workshop (Research) on Plasma Focus

21 September 2014



A collaborative project of



INTI
International University
LAUREATE INTERNATIONAL UNIVERSITIES*



www.plasmafocus.net



Plasma Focus Numerical Experiments (Research)

(NEWPF Research 2014 Kathmandu)

S Lee & S H Saw in collaboration with Deepak Subedi

www.plasmafocus.net

CONTENT

Introduction: The three machines: FMPF, NX2 and NX3

Exercise 1: To compute: Y_n vs P for FMPF-3 and compare with measured Y_n vs P

Exercise 2: To compute: Y_n vs P for NX2-T and compare with measured Y_n vs P

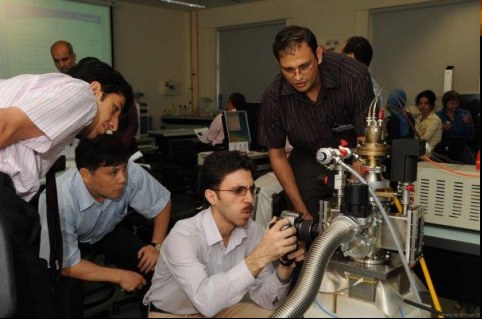
Exercise 3: To compute: Y_n vs P for NX3 and compare with measured Y_n vs P

NEWPF2014 (research) session

As an introduction we compile here images of FMPF, NX2 and NX3 Plasma Focus machines



There are 3 research exercises each based on a machine operated at NTU/NIE Singapore. The machines are: FMPF3, NX2-T and NX3. We thank NTU/NIE Plasma Radiation Laboratory and in particular Assoc Prof Paul Lee, Assoc Prof Rajdeep Singh Rawat and Dr Rishi Verma (Bhabha Atomic Research Centre) for providing some of the data files, images and research papers.

300J portable (25 kg); 10^6 neutrons per shot fusion device



NX2-Plasma SXR Source

- **NX2**
- 11.5kV, 2 kJ
- 16 shots /sec; 400 kA
- 20J SXR/shot (neon)
- 10^9 neutrons/shot (est)



NX3

Exercise 1: To compute: Y_n vs P for FMPF-3 and compare with measured Y_n vs P

As a general facility, you are provided with our code:

A clean copy of *RADPFV5.15de* (Keep this clean copy in a reserve file and take a copy of this clean copy for use each time.)

For this exercise you are provided with:

1. *FMPF3.1 DATA.csv* - A data file taken from one of the shots in experiments reported in the following paper.
2. *FMPF3.2 JoFE32 3-10.pdf*

A look at the data file:

Fig 1 shows 4 graphs plotted from data file *FMPF3.1 DATA.csv* for: **Shot 000 FMPF3 13 kV 4.5 mbar**

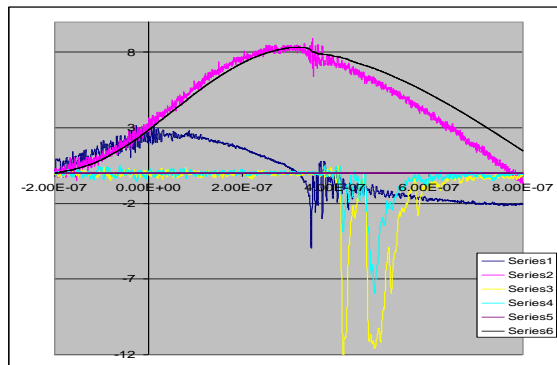


Fig 1: The data of *FMPF3.1 DATA.csv* plotted by EXCEL. The thin black trace is not in original data.

The Pink trace is the measured I- using a current transformer.

The next trace lower down: dark blue; dI/dt (which we call I_{dot}), measured with a Rogowski coil

Light blue: neutron detector 1

Yellow: neutron detector 2.

We have added a 5th trace- of current I numerically integrated from the I_{dot} trace, and placed the I (thin black trace) (suitably scaled in amplitude) against the pink directly measured I.

Note that the directly measured pink I has a droop relative to the integrated I (Note: that this is an often- found defect of directly measured I; it is likely mixed with a dI/dt component)

From experience our opinion is that the I trace obtained from numerically integrating dI/dt is more accurate for numerical experiment purposes. So we use the numerically integrated I trace.

Step 1: Having a preliminary look. (for you to carry out)-

Open the *FMPF3.1 DATA.csv* file. This is a research file obtained during an actual experiment when the plasma focus FMPF1 was fired and current I, dI/dt (which we also call i_{dot}) and neutron measurements (from two detectors) were made.

There are 5 columns of data, the first is time in s, the second is dI/dt (arb units) the third is I (we treat as arb units; they have a calibration constant but we are going to use the code for calibration so we will not use their calibration constant). The 4th and 5th are the neutron detector outputs.

Highlight all 5 columns and use the Excel Chart function (scatter type) to automatically chart the 2nd to 5th columns against the first. You should see the same picture as shown in Fig 1 above (minus the thin black trace) This step is just for you to have a look.

Step 2. Preparing the data – Change to microsec; and numerically integrate the dI/dt to get I. We are going to use only the first 2 columns A and B. So **delete columns C-E**. (so that Columns C and E are cleared of all values).

Save this csv file to the format of EXCEL 2003; **so it becomes 000.xls**

Open this file.

Change time to microsec: In the emptied Column C, place the values of A, changed to microseconds. (Procedure: multiply each value of A by 1,000,000 to convert the time value from seconds to microsec)

Integrating dI/dt to get I: In the emptied Column D, integrate column B.

(Procedure: In Cell D4 type “ $=D3+B4*(C4-C3)$ ” Then copy this to every cell.; Note if you are using the method of copying to each cell of the whole column, the result will be “#REF!” for each of the cells. Explanation: We are integrating by adding the previous value in column D to the product $idot*(time\ interval)$. At Cell D3, the Cell above it contains a non-number; so the method fails.

Resolve this by typing into Cell D3 the value of zero “0”. Then the integration is done from Cell D3 downwards.)

On completing this step, we have the measured data in the following form: in column C the time in microsec; and in Column D, the current in arbitrary units.

Step 3: Providing a time-shift and a multiplication factor for the current.

Time-shift: In switching the capacitor bank, the switching mechanism is non-perfect. There is a transition period when the switch goes from high resistance to negligible value. In the code however the switching is perfect. To account for this difference we provide a time shift between the measured current trace and the computed current trace.

In Column E, in each cell we place the value of the corresponding Column C cell and add to it a value which we may adjust. Procedure: In Cell E3 type “ $C3+\$K\1 ” Copy this to every cell in Column E. Then type into Cell K1 starting value say 0.1; which we are going to adjust later. We call K1 the time shift value.

Multiplication factor: We are going to fit the peak of the measured current to the peak of the computed current. So transfer the values of current in Column D to Column F by the following procedure: in Cell F3 type in “ $=D3*\$L\1 ” and copy to every cell in Column F. Then type in to Cell L1 a starting value say “2” which we are going to adjust in calibrating the measured current. We call L1 the current calibrator value.

Use the EXCEL chart function to chart columns E and F. The measured current waveform appears on the chart.

Go to source data to label this waveform as ‘Measured I’; also label the x-axis as ‘Time in microsec’ and the y-axis as ‘I in kA’. (Note at this stage, the time is accurate as it is measured by the digital

storage oscilloscope DSO. We had also converted the time scale into microsecond. The current is in arbitrary units and needs to be calibrated using the computed current. We have labelled the scale as kA)

This data is for a small plasma focus. We can expect a current of the order of 100 kA. So for the moment, adjust the value of L1 until the peak is about 100. Save this worksheet as 000.xls.

When we have completed this step, column E contains the time in microsec (with a shiftable t=0) and the current in kA (with a built in adjustable calibration factor)

Step 4: Fitting the computed current to the measured current.

(We refer you to NEWPF2013 manual, Module 6; which you have worked with.)

Place the measured 000.xls current waveform on Sheet3 of RADPFV5.15de by the following procedure.

Open a copy of *RADPFV5.15de.xls* (enabling macros; the procedure for enabling macros may vary depending on your version of EXCEL).

Minimize it by clicking on top right hand corner tab with the - sign.

Open *000.xls*

Locate tab Sheet3 on lower left corner of worksheet.

Right click on tab Sheet3.

Select move or copy to book *RADPFV5.15de.xls*

In the dropdown list, Click on (move to end)

Tick Create a copy

Click OK

With this procedure you have copied *000.xls* as Sheet3 in *RADPFV5.15de.xls*. The chart of the measured current is already on Sheet3.

Configure the code for the FMPF-3 using trial model parameters

Toggle to Sheet1.

Type in cell B3: FMPF-3; for identification purposes.

Key in the following configuration; extracted from the paper.

(The anode is is 6mm in radius and is 17 mm long. The last 10 mm is uniformly tapered with an end-radius of 3 mm (See the anode structure in Fig 1 of the paper *FMPF3 JoFE32 3-10.pdf*)

Lo	Co	b	a	zo	ro mOhm	TAPER?	taperstart	endrad
34	2.4	1.5	0.6	1.7	11	Y=1		
massf	currf	massfr	currfr	Model Parameters		N=0	(cm)	(cm)
						1	1	0.37
Vo	Po	MW	A	At-1 mol-2	Operational			
13	3.42	4	1	2	Parameters			

Note: In the configuration we have to configure the Taper section as well.

(note: In 2013, in all the exercises, we have put TAPER? as 0 which selected the non-taper code. In the present exercise we select the taper code and set the taper geometry)

For this exercise we do not know the model parameters. We will use the trial model parameters recommended in the code (See cells T9-V9)

Model: $\text{massf}(f_m)=0.073$, $\text{currf}(f_c)=0.7$, $\text{massfr}(f_{mr})=0.16$, $\text{currfr}(f_{cr})=0.7$; our first try.

Key in accordingly:

A7	B7	C7	D7	
0.073	0.7	0.16	0.7	for first try

Fire a shot: 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 program runs and results are displayed in columns and also in figures.

Place the computed current waveform onto the same chart as the measured current waveform in Sheet3

In the next steps we will place the computed current waveform from Sheet1 into the same chart in Sheet 3, in which the measured current waveform has been placed. Use the following procedure.

Position the cursor on the chart in Sheet3 containing the measured current waveform. Now **right click**. Pop-up appears. Click on “source data”. Click on “series”. Add a series titled “Computed I”.

For Series X values key in “**=Sheet1!\$a\$20:\$a\$6000**”

For Series Y values key in “**=Sheet1!\$b\$20:\$b\$6000**”

Click OK.

The computed current waveform from Sheet1 is now placed in the same chart as the measured current. The Chart should look like Fig 2.

You can now compare the computed current trace with the measured current trace.

You should see a pink trace which has just appeared on the chart. The pink trace (see figure 1 below) is the computed current trace transferred from Sheet1 (where the time data in μs is in column A, from A20-A several thousand; and corresponding computed current data in kA is in column B, from B20 to B several thousands). We are selecting the first 5000 points (if that many points have been calculated) of computed data; which should be adequate and suitable.

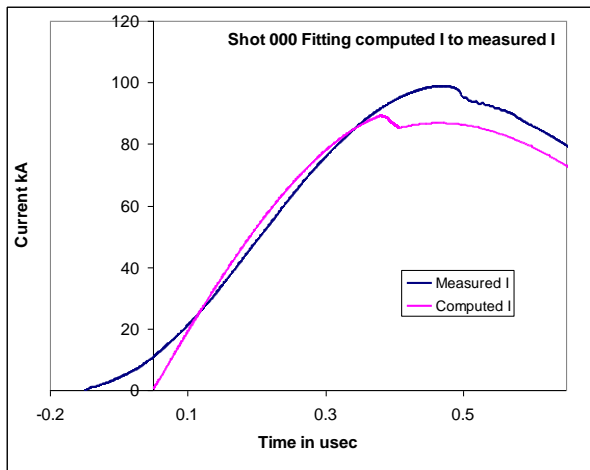


Fig 2. First trial fitting of computed I waveform with measured I; model parameters : $massf(f_m)=0.073$, $curr(f_c)=0.7$, $massfr(f_{mr})=0.16$, $currfr(f_{cr})=0.7$; time shift=0.1 and measured I calibration multiplier=115

Note: A Reminder on the 5 important points of fitting.

(From Module 4 of NEWPF2013 manual)

Fitting of computed I waveform against the measured I waveform.

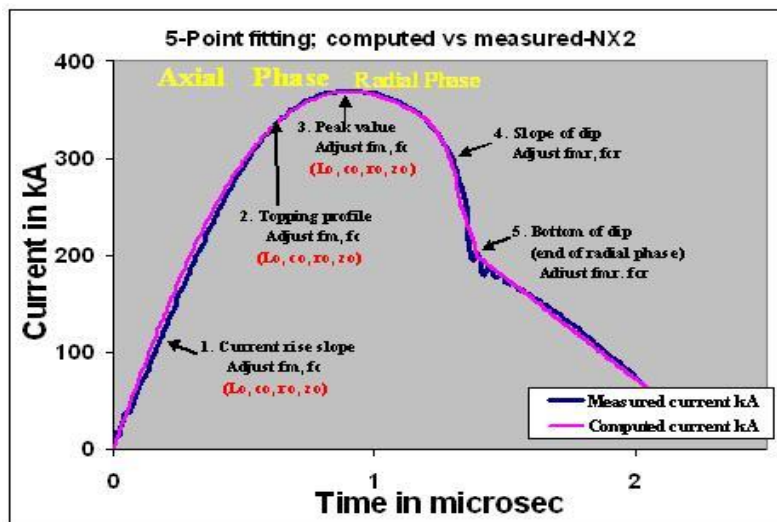


Fig 3. The 5-point fitting of computed current trace to measured (reference) current trace. **Point 1** is the current rise slope. **Point 2** is the topping profile. **Point 3** is the peak value of the current. **Point 4** is the slope of the current dip. **Point 5** is the bottom of the current dip. Fitting is done up to point 5 only. Further agreement or divergence of the computed trace with/from the measured trace is only incidental. The fitting at start of current is also not important.

In our case, Fig 2, we immediately notice that the computed current dip comes too early; so the current sheet is moving too fast. To slow down the current sheet increase f_m in steps (firing at each step) until the current dip comes at about the time of the measured current dip (at about 0.45 microsec).

Then adjust the value of L1 (current calibrator value) until the peak of the computed curve is about the same as the measured peak. Then adjust the value of K1 (time shift) to try to overlay the peak area of the computed with the measured. Then adjust the value of f_m again and repeat the above process until the best agreement is observed for the current rise, and the topping profile up to the **start** of the

current dip. When we have iterated the above steps until we have the best fit up to the start of the current dip, we have completed the fitting of the axial phase.

Next we proceed to fit the radial phase.

We note that the computed slope of dip is too steep compared with the measured slope of dip; and that the computed depth of the dip is more than that of the measured current trace. Both of these indicate that the value of f_{mr} is too small. Increase the value of f_{mr} in steps to try to improve the fit; also making small adjustments to $K1$ and $L1$. It may also be necessary to fine-tune the value of f_m by making very small changes. (for greater sensitivity in fitting you may wish to zoom into the region of the dip by displaying just this region scaling the horizontal axis to 0.3-0.5 usec and the vertical axis to 60-100 kA.)

The final best fit may look something like Fig 4.

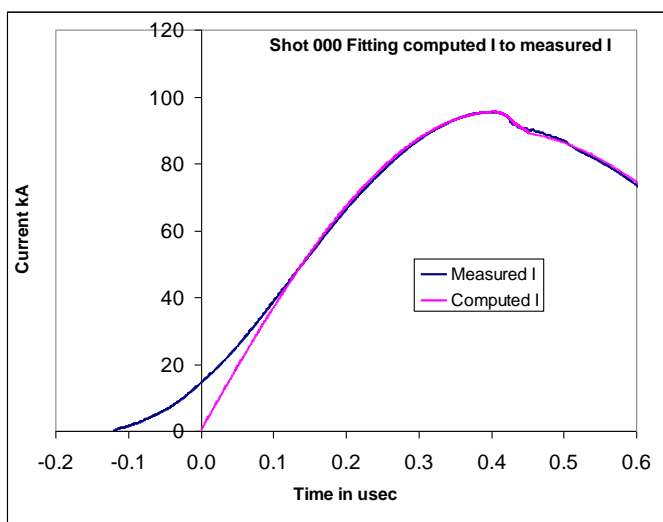


Fig 4. The best fit? This best fit was obtained by keeping $f_c=0.7$ and $f_{cr}=0.7$.

We note that Fig 4 shows quite a bit of difference between the computed and measured current traces in the first 0.12 microsec of time (for the computed current trace). After $t=0.12$ microsec, the agreement of the two traces is reasonable. The difference up to $t=0.12$ microsec is postulated to be due to non-ideal switching action of the switch. We ignore this first part of the measured current trace which we assume to be not important; since we are able to fit the rest of the current traces from $I=40$ kA up to the peak of $I=95$ kA and beyond to the current dip.

Step 5: Record the best fit configuration, including the taper geometry, the time shift and current multiplier in the following format:

Lo	Co	b	a	zo	ro mOhm
34	2.4	1.5	0.6	1.7	11
massf	currf	massfr	curfr	Model Parameters	
	0.7		0.7		
Vo	Po	MW	A	At-1 mol-2	Operational
13	3.42	4	1	2	Parameters

TAPER?	taperstart	endrad
Y=1		
N=0	(cm)	(cm)
1	1	0.37

And $K=0.079$, $L=111$

In the above table, we have left out the values of f_m and f_{mr} which we have determined to be the best fit. **Your job, before we meet, is to get your best fit values of these two model parameters and insert in your own table.**

Step 6: Compute neutron yield Y_n vs operational Pressure to find the optimum pressure with best Y_n per shot. Compare your computed Y_n vs P curve with the published Y_n vs P curve.

For this part we are not fitting current traces any more, since the computed current will change as we vary the pressure. However you may wish to look at the position of the current dip as the pressure is increased. The appearance of the current dip is indicative of whether the focus pinch is severe or weak. The neutron yield will not be optimum when the pinch is weak. We also know that the strongest focus pinch occurs when the pinch is near I peak. So it is worth while studying the appearance of the current dip as we increase P from a low value.

Procedure: Use your best fit configuration. Record the neutron yield Y_n for each shot as we fire our numerical machine FMPF-3, at each of the following pressures: 0.5 Torr, 1, and so on incrementing by 0.5 Torr. When $P = 5$ Torr it is clear that Y_n has peaked and is reducing with P. You may then increase the pressure interval by 1 Torr each time until it is clear that the current dip is occurring too late after the current has peaked. At some point the code may stop running and a warning message may appear:

```
Stop
"Rem WARNING! Total TRANSIT TIME (axial + radial) MAY BE TOO LONG COMPARED TO effective DISCHARGE
Drive TIME
Rem FOLLOWING ACTION RECOMMENDED:
Rem          REDUCE FILL PRESSURE OR
Rem          INCREASE CHARGE VOLTAGE OR
Rem          SHORTEN AXIAL LENGTH"
```

This indicates that the pressure is too high and the radial pinch will be too weak. At this point it is not necessary to increase P anymore.

We recorded our results in an empty area of Sheet3, in the following manner: (The measured data in the published paper *FMPF3.2 JoFE32 3-10.pdf* gives the pressure in mbar so we convert our P from Torr to mbar by dividing by 0.76; so 0.5 Torr=0.66 Torr)

The following computed data of Y_n vs P was obtained using our fitted model parameters. You should produce your own table using your fitted model parameters.

Computed Y_n vs P

P mbar	$Y_n (10^5)$
0.66	1.28
1.32	2.47
1.97	3.23
2.63	3.63
3.29	3.70
3.95	3.5
4.50	3.29
4.74	3.16
5.26	2.82
5.92	2.38
6.58	1.93
7.89	1.15

From Fig 3 of *FMPF3.2 JoFE32 3-10.pdf* we get the following measured data of FMPF-3:

Measured Y_n vs P

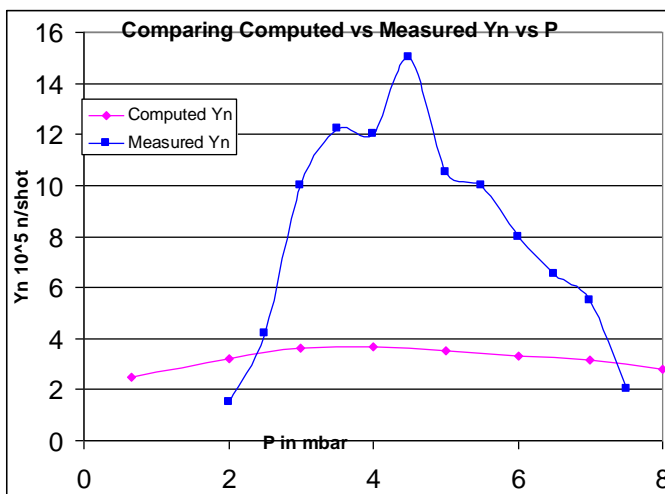
P mbar	$Y_n (10^5)$
2	1.5
2.5	4.2
3	10
3.5	12.2
4	12
4.5	15
5	10.5
5.5	10
6	8
6.5	6.5
7	5.5
7.5	2

The measured Y_n vs P curve is plotted in the following Fig 5.

In the same chart plot your computed Y_n vs P.

As a guide we show the comparative chart which we got.

Now we may compare the computed results with the measured results.



Notes:

We note that the computed optimum Y_n is 3.7×10^5 at 3.3 mbar whilst the measured optimum is 15×10^5 occurring at 4.5 mbar.

Between $P=2.5$ mbar to $P=7$ mb there is a difference of 2-4 times in the measured and computed value, the measured value being higher.

The computed curve is single- peaked. The measured Y_n vs P is has structures near the peak and drops off on both low P and high P side more sharply than the computed curve.

Exercise 2: To compute: Y_n vs P for NX2-T (tapered) and compare with measured Y_n vs P

The data files which are provided:

1. A measured current trace of NX2-T is taken from Koh's FYP project report Fig 3.2. The current waveform is shown below (Fig 2.1). The current waveform is digitized using open source program ENGAUGE. The digitized file is given in File *NX2T.1 measured I digitized fig 3.2.xls*.

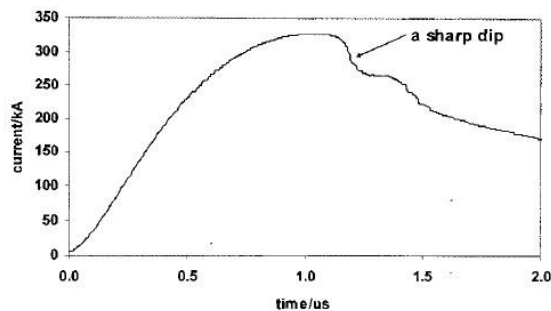


Figure 3.2: A Typical Discharge Signal from the Current Probe

Fig 2.1 A measured current waveform which we use for the fitting of NX2-T

2. Koh et al had published a paper with the Y_n vs P results for NX2-T at various voltages. We select one set of Y_n vs P from the paper for NX2-T operated at 14.5 kV using Fig 4 of the paper. (also given in Koh FYP report as Fig 4.2.) The paper is attached as File *NX2T.2 Koh.pdf*
3. The highest curve of Fig 4 of the paper is digitized and given as File *NX2T.3 koh YnvsP digitized.xls*.

The Y_n vs P measured data is displayed in the following Fig 2.2. We will use the curve with the highest peak.

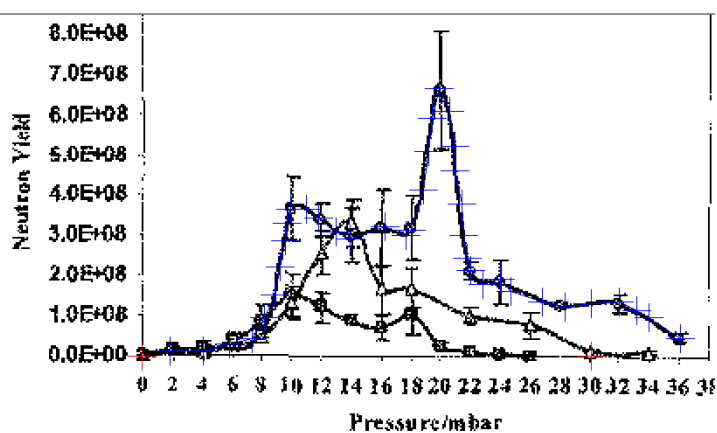


Figure 4.2: Graph of Average Total Neutron Yield against Pressure

Fig 2.2 The Y_n vs P measured data for NX2-T which we will use.

The steps suggested for this exercise are similar to those of exercise 1. The suggested steps are briefly as follows:

Step 1: Prepare the data:

Note the digitised file gives the time in microsecond; and the current in kA. So no conversion of units is necessary. However we will still use the code to calibrate the current. So prepare the data sheet to provide a time-shift and a multiplication factor for the current. (see Ex 1 Step 3)

Step 2: Fitting computed current to the measured current.

Follow the procedure described in Step 4 of Ex 1.

For NX2-T, use the following configuration:

Lo	Co	b	a	zo	ro mOhm
20	28	3.8	1.55	4.5	2.7
massf	currf	massfr	currfr	Model Parameters	
	0.7		0.7		
Vo	Po	MW	A	At-1	Operational
14.5	15.2	4	1	2	Parameters
TAPER?	taperstart	endrad			
Y=1					
N=0	(cm)	(cm)			
1	1	1.15			

Note that the value of L_0 and z_0 are different from those given in the paper. We had to fit these to the present values in order to obtain a good fit. So the measured current trace tells us that the correct effective length of the anode (including the insulated section is 4.5 cm and the inductance is 20 nH).

The values of our fitted f_m and $f_{m,r}$ are not included in the configuration. You have to do the fitting yourself to find these values.

As a guide, our best fitted effort is shown in the following Fig 2.3.

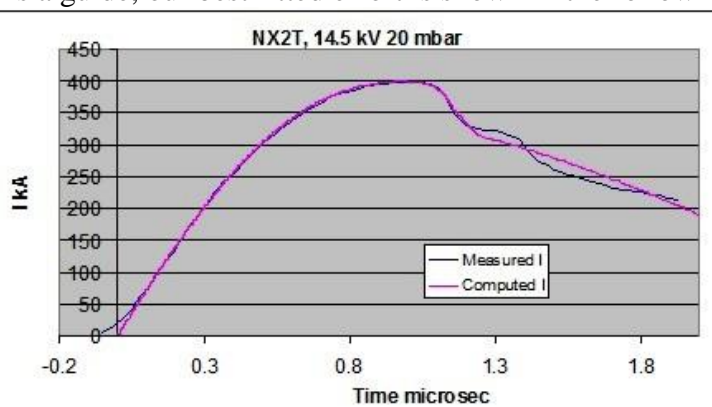


Fig 2.3 Best fit ? for computed current waveform with measured waveform for NX2-T

Step3: Use your fitted model parameters f_m and f_{mr} to run a series of numerical experiments varying P from 2 to 40 mbar so as to get your computed Y_n vs P curve. Compare your computed Y_n vs P curve with that reported by Koh et al.

As a guide the Figure 2.3 below gives our results which we obtained using our fitted model parameters. You should use your computed results to compare with the measured results

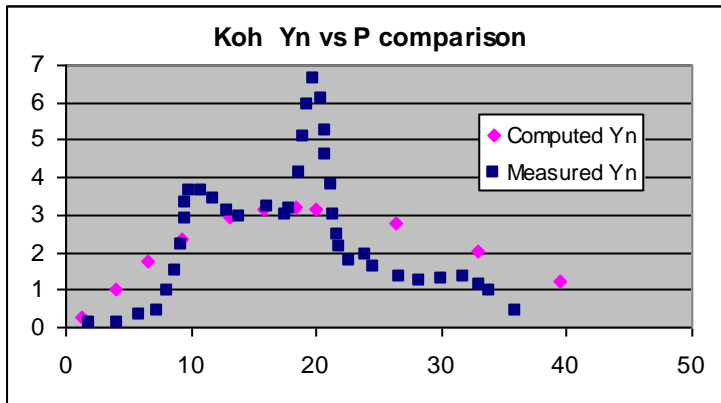


Fig 2.3 Comparison of computed Y_n vs P with measured Y_n vs P for NX2-T

Finally write some notes about the comparison of computed Y_n vs P compared to the measured Y_n vs P.

Exercise 3: Y_n vs P in NX3

You are provided with

1. File NX3.1 DATA A20Z126-14kV15mb.xlsx
2. File NX3.2 M Rasyid.docx
3. File NX3.3 2012 IEEE TPS R Verma.docx

Summary of work:

We use a current trace File *NX3.1 DATA A20Z126-14kV15mb.xlsx* from the research work recorded in Muhammad Rasyid et al File *NX3.2 M Rasyid.docx*

This current waveform is for NX3 with anode configuration of 20 mm radius and nominal length 140 mm (parameters L_0 and z_0 fitted to our corrected values below)

Lo	Co	b	a	zo	ro
49	100	5.6	2	12.6	2.3
massf	currf	massfr	currfr	Model Parameters	
	0.7		0.7		
Vo	Po	MW	A	At-1	Operational
14	11.4	4	1	2	Parameters

Using this configuration we did a fitting and obtained a good fit as shown in Figure 3.1:

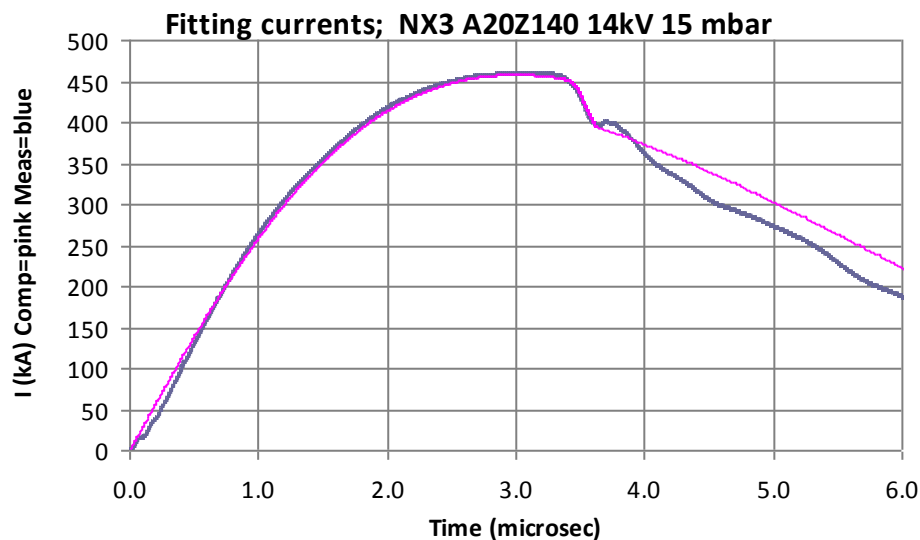


Fig 3.1. Our computed Y_n vs P for NX3 anode A20Z140

We have left out from the configuration table the values of f_m and f_{mr} that we found so that you can find your own values in your own fitting.

When you have recorded your own best fitted values, you will use the completed configuration table to carry out a series of numerical experiments to find Y_n vs P ; for NX3 using anode A20Z140 (with 20 mm radius and nominal length 140 mm).

Comparison of your computed Y_n vs P with the Y_n vs P measured at NIE on NX3 by Rishi Verma and published in a paper a copy of which is given in File *NX3.3 2012 IEEE TPS R Verma.docx* - We use the set of data in Fig 9 (shown in our Fig 3.2 below) of that paper (in brown squares) to compare with our computed Y_n vs P .

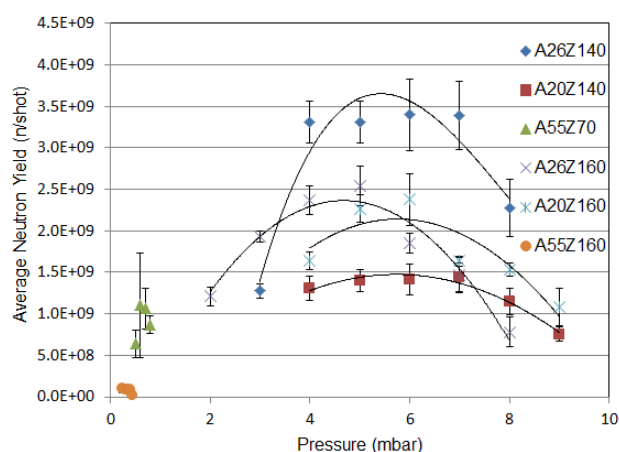


Fig 3.2. Extracted from Fig 9 of RVerma et al; Y_n vs P of NX3 for various anodes

Notes from the two attached papers:

Verma et al did not analyse current waveforms in their paper. They discussed their results using the model parameters which had been fitted for another machine the UNU/ICTP PFF.

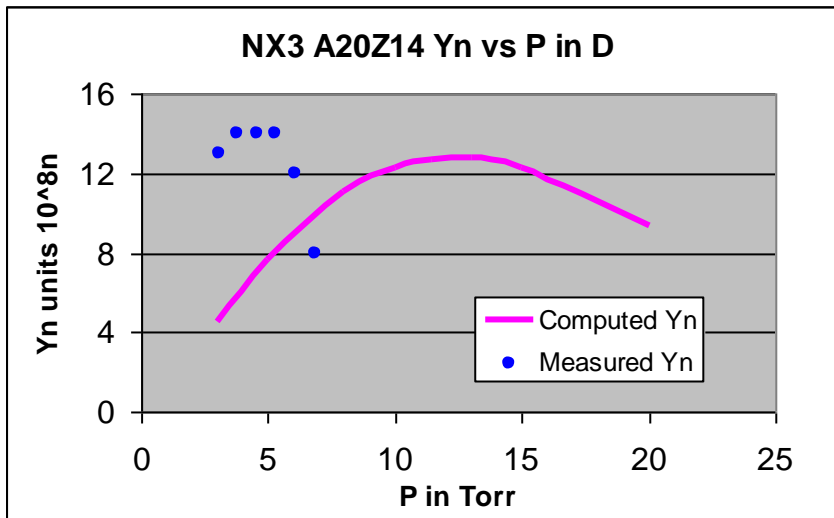
In their later paper Muhammad Rasyid et al (submitted to IEEE TPS) have analysed current traces of NX3 with various anode configuration and thus measured the axial phase model parameters f_m by fitting. They found:

Deuterium has a $f_m = 0.150 \pm 0.040$. For anode design A26Z126,

In this exercise we extend the work of Verma et al and M Rasyid et al. We fit a current trace from M Rasyid's work, obtain f_m and f_{mr} and then proceed to compute Y_n vs P ; so we can compare with the measured Y_n vs P results of Verma et al.

Using your own fitted model parameters you compute your own Y_n vs P for NX3 A20Z140 and compare your computed Y_n vs P with that measured by Verma et al.

As a guide for your work, Fig 3 shows a set of results we obtained.



Notes on the results: