Data Analysis of Quiescent Plasma Shot 22907

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1 Data Analysis Procedure

The Mega Amp Spherical Tokamak located at the Culham Centre for Fusion Energy creates plasma discharges for the study of nuclear fusion. There are many ways to measure the different properties of a plasma to then make hypotheses about eliminating instabilities to where the fusion reactions can perpetuate subsequent reactions and thusly create a partially self sustaining reactor. Charged fusion products such as protons, tritons, and helium-3 measured by the FIU Experimental Plasma Physics group are emitted from the fusion between Deuterium nuclei. However, the concept of measuring these protons is a complicated maneuver since there are so many aspects of a charged fusion product to measure as well as the process of detecting them.

Detecting and measuring charged fusion products can offer insights about the plasma, in the case of FEPP, emission profiles. Emission profiles are the region of area within the plasma that shows a distribution of nuclear fusion emissivity. FEPP used 4 solid state surface barrier detectors (SSBD) to detect these fusion products. These SSBDs are held in a stainless steel housing shielded with a Boron Nitride shell, this diagnostic is aptly named the Charged Fusion Product Diagnostic (CFPD). Detection of charged fusion products on the SSBD result in a time dependent voltage signal. Charged fusion products show up as peaks within the voltage signal and can be distinguished according to their characteristic peak heights.

Some valuable parameters to be discovered are individual rates as a function of time per charged fusion product, the total rate of all charged fusion products, and the individual particle energy spectra for multiple time slices of a plasma discharge. Constructing the charged fusion product rates allows a view into the stability of fusion reactions within the plasma discharge. To build these rate plots, the amount of peaks corresponding to a plasma discharge must be counted and divided by the width of time where the peaks were found in.

$$rates = \frac{no.\ of\ voltage\ peaks}{time\ slice\ width} \tag{1}$$

Typical plasma discharges occur for approximately 500 ms. These 500 ms can be divided into time slices of small lengths (∼1 ms) to generate rate plots of higher resolution. In this method, it is easier to see any fast changes in the rates as a function of time. Increasing this time slice width to larger values (∼100 ms) will not decrease resolution in rate plots but can generate energy spectra of fusion products for each time slice. These results provide different information about the activity during a single plasma discharge .

Ideally these plots and histograms would demonstrate plasma activity from the specific volumes from where these fusion products are emitted. An aluminum foil was placed in front of each detector to reduce any possible electrical noise from x-rays, and photons. However due to the electrical noise interference from elsewhere, the noise signal was overlaid with fusion product signals, making it difficult to distinguish proton signals, more so for tritons, and most of all for the elusive helium-3 if any at all were detected. This report will only investigate protons within the plasma discharge #29907.

To mitigate this electrical noise interference and salvage data, a peak finding algorithm was created by Dr. Werner U. Boeglin, the principle investigator. This peak finding algorithm uses 12 peaks selected from each channel signal for that plasma discharge, to create a normalized average peak shape. This normalized average peak shape is then used to find other peaks within the same voltage signal channel. The peak finding algorithm then sorts peaks according to their heights to either: protons (∼0.6 V, post foil interaction) and tritons (∼0.4 V, post foil interaction). The clear line between peaks and noise has yet to be found. Different fitting parameters are implemented to count more occurrences of both noise and peaks or less occurrences of both noise and peaks.

$$\frac{\sigma_A}{A} \tag{2}$$

σ_A is the error in the normalized average peak amplitude and A the amplitude of the peak. This parameter can be set to allow for a more strict or loose peak finding method.

$$p\_min,\ p\_mean,\ p\_max \tag{3}$$

These parameters define the maximum, mean, and minimum voltage values for the proton. This filters any other peaks from being counted into the rate for that specific time slice. The analysis this report will delve into is that of a single plasma discharge, 29907, a reported quiescent scenario. Quiescence refers to when a plasma discharge is "quiet" or when little or no activity is occurring.

2 Rates and Energy Spectra of 29907

2.1 Channel 0

Using the peak finding algorithm to find the rate plot of Channel 0 of 29907 shows rates that are inconsistent with expected rates. This rate plot was generated at 2.0 $\frac{\sigma_A}{A}$,1 ms intervals with a p_min, p_mean, and p_max of 0.51 V, 0.63 V, and 0.76 V respectively. To see the fitted peaks with their constituent normalized average peak, see Appendix A.

Viewing the histograms at 100 ms time slices illustrates the domination of noise in the plasma shot and shows that there is a severe lack of protons in Channel 0 of this plasma discharge.

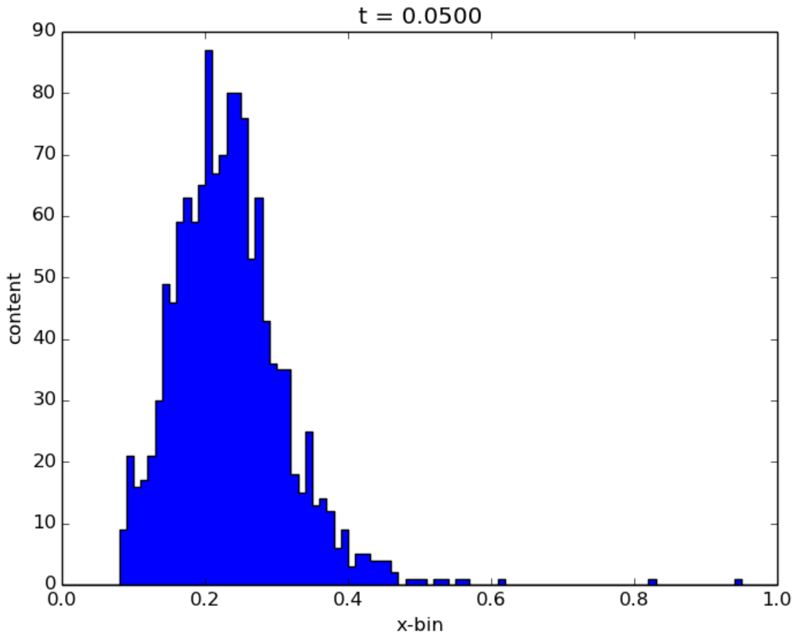

Figure 1: Energy Spectrum Ch 0, 0 ms - 100 ms

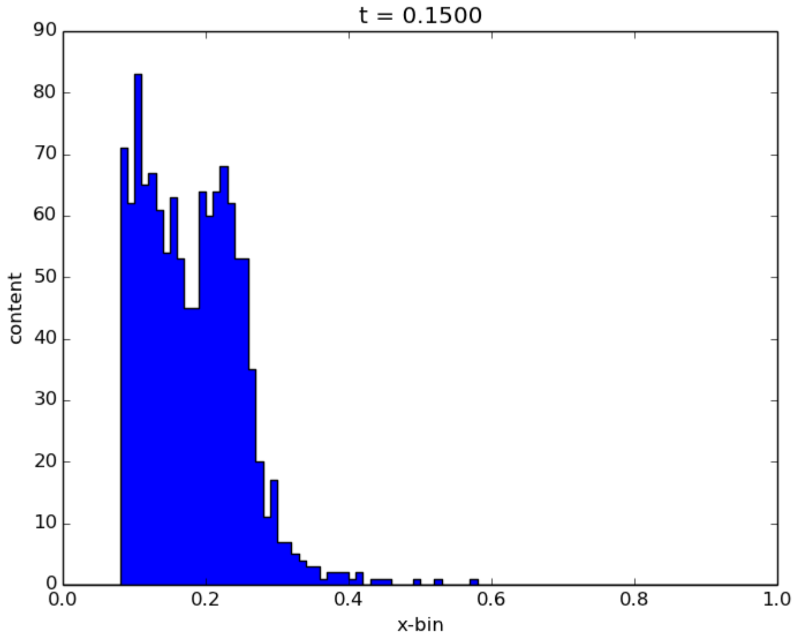

Figure 2: Energy Spectrum Ch 0, 100 ms - 200 ms

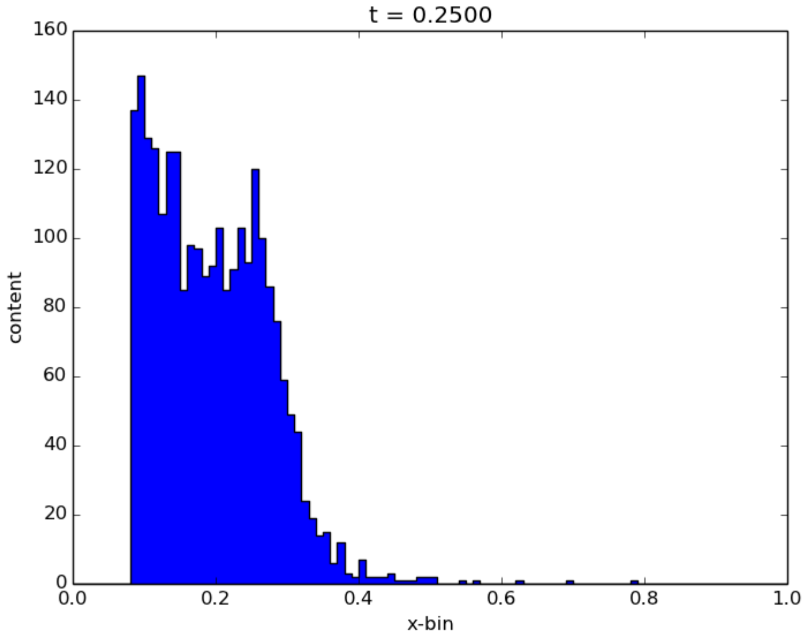

Figure 3: Energy Spectrum Ch 0, 200 ms - 300 ms

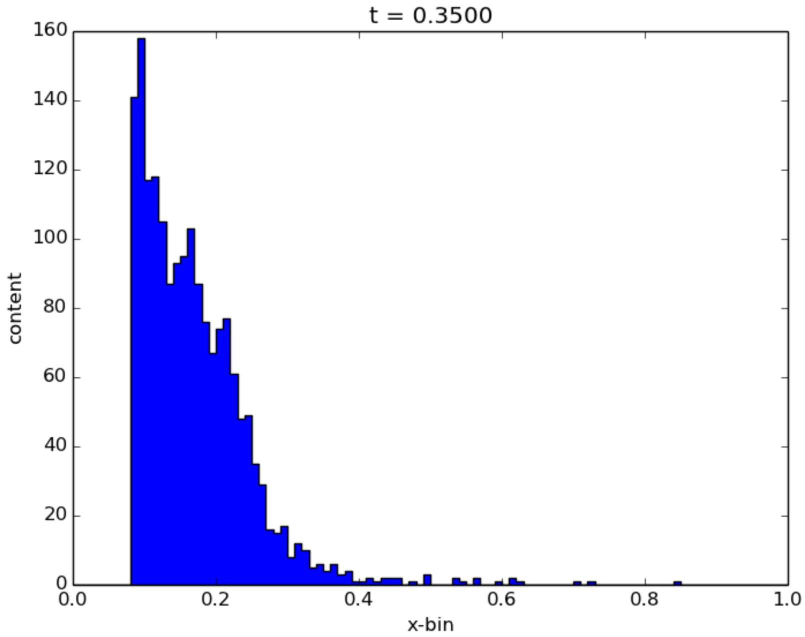

Figure 4: Energy Spectrum Ch 0, 300 ms - 400 ms

To validate this assumption about the lack of protons within Channel 0 of plasma discharge 29907, the actual voltage signal should be investigated.

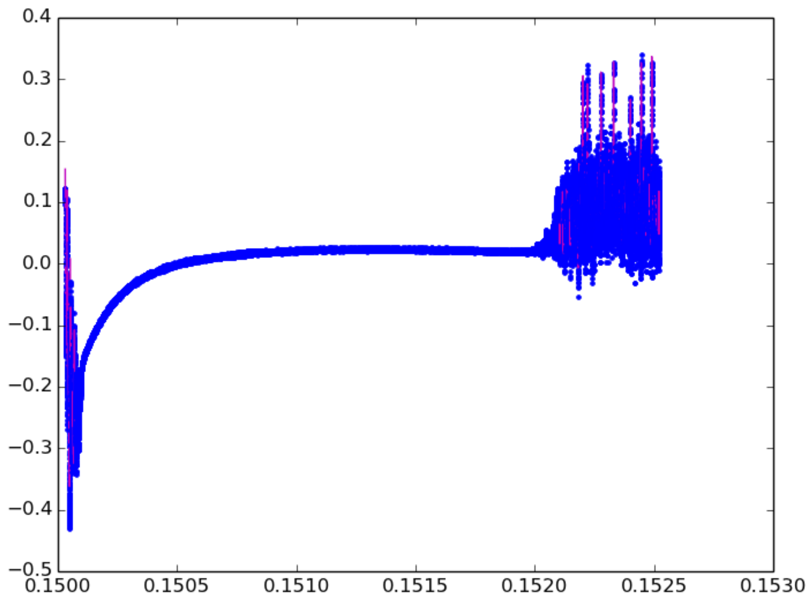

Figure 5: Ch 0 Voltage Signal

Within this voltage signal it can be seen how the presence of electrical noise such as in the plot above can interfere with the peak finding algorithm and severely reduce down the amount of protons counted.

2.2 Channel 1

In channel 1, the peak finding algorithm fits peaks at 2.0 $\frac{\sigma_A}{A}$,1 ms intervals with a p_min, p_mean, and p_max of 0.44 V, 0.64 V, and 0.80 V respectively.

An initial rate plot of channel 1 shows various fast changes in rates. An initial spike in proton rates before a series of fast oscillations would dictate that this shot is not quiescent. Regardless of the rate plot's appearance as of right now, corrections must be made as well as a comparison to the neutrons detected and other properties of the plasma discharge. Likewise, another misgiving is the drop in rates from ∼80 particles per second to almost 0 implies there is an issue with this signal.

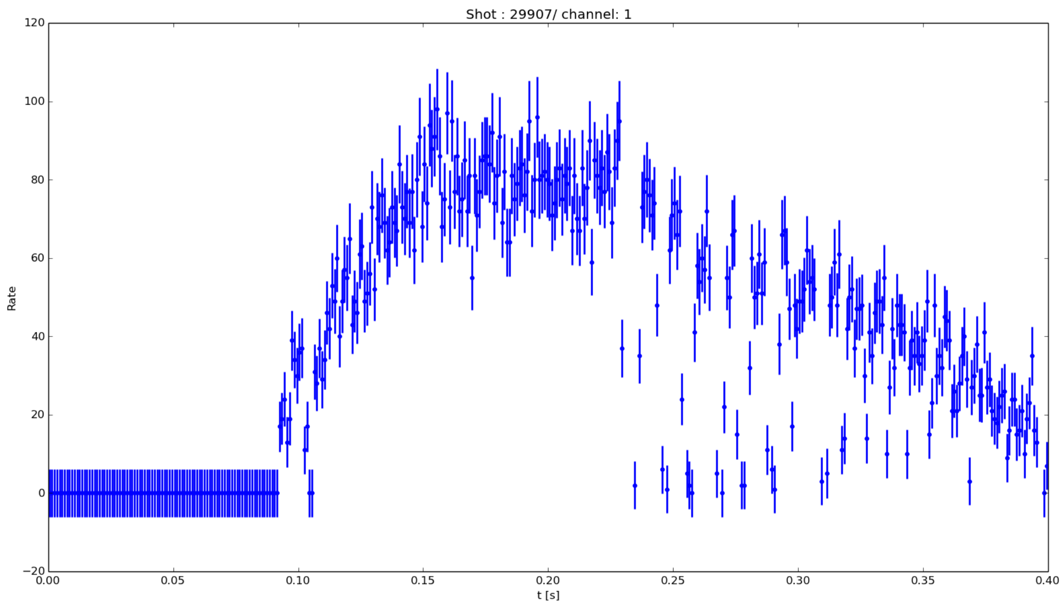

Figure 6: Ch 1 Proton Rates

Examining the histograms generated from 100 ms time slices show the protons obey a Gaussian distribution for each time slice. The range of protons stays within the predefined minimums, maximums, and means crediting the rate plot but fails to explain the sudden drops in rate.

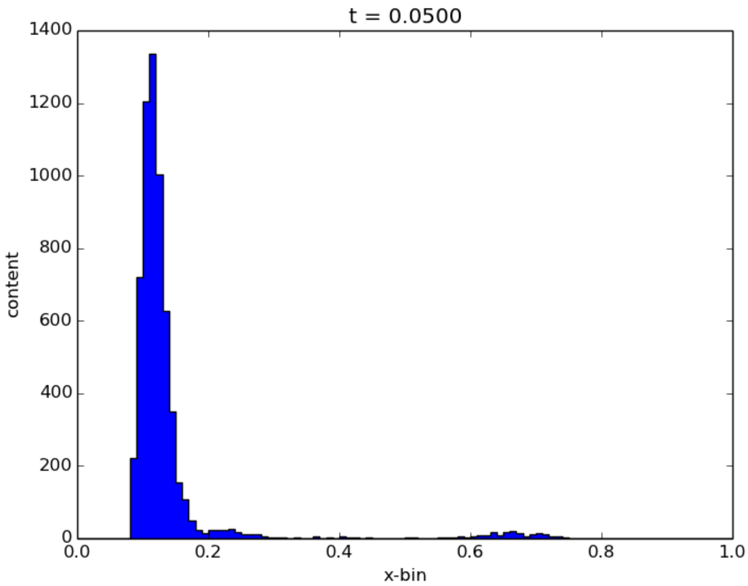

Figure 7: Energy Spectrum Ch 1, 0 ms - 100 ms

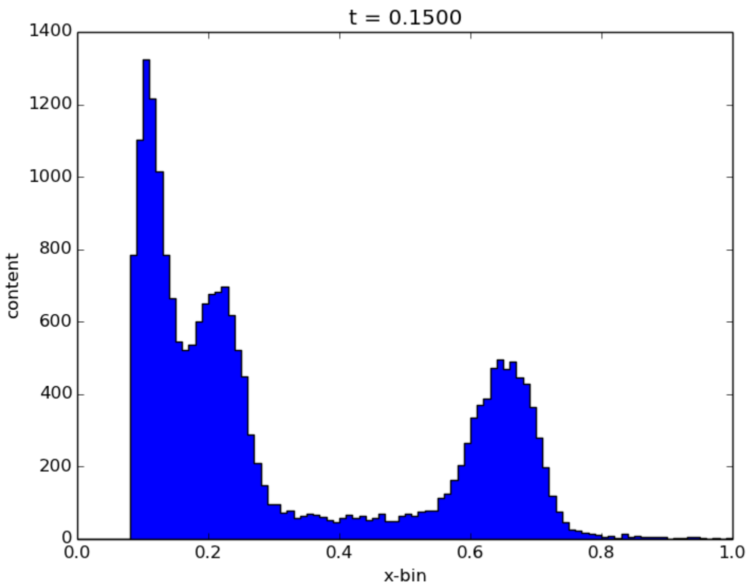

Figure 8: Energy Spectrum Ch 1, 100 ms - 200 ms

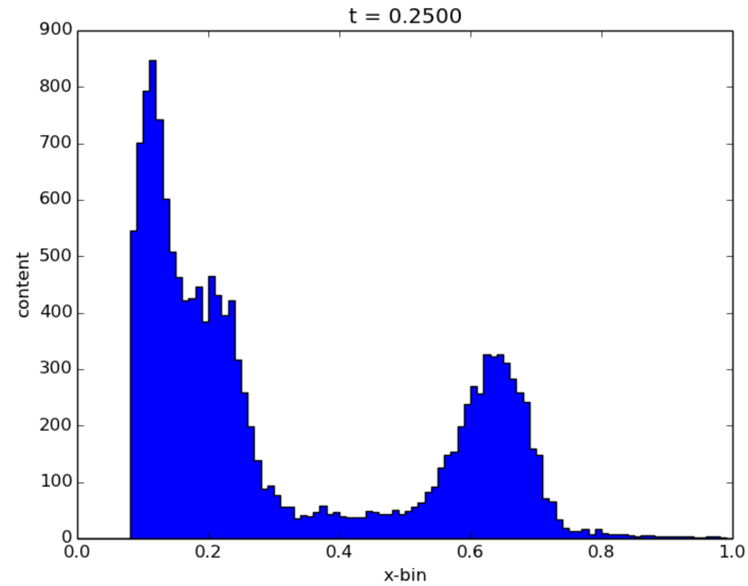

Figure 9: Energy Spectrum Ch 1, 200 ms - 300 ms

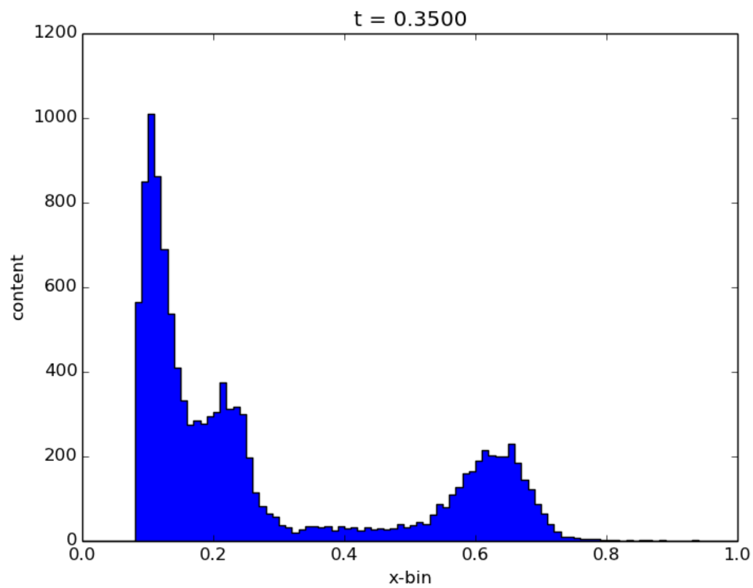

Figure 10: Energy Spectrum Ch 1, 300 ms - 400 ms

2.3 Channel 2

In channel 2, an initial rate plot of 2.0 $\frac{\sigma_A}{A}$,1 ms intervals with a p_min, p_mean, and p_max of 0.51 V, 0.63 V, and 0.76 V respectively shows the same fast changes in rates seen in channel 1 without the extreme drops in rates.

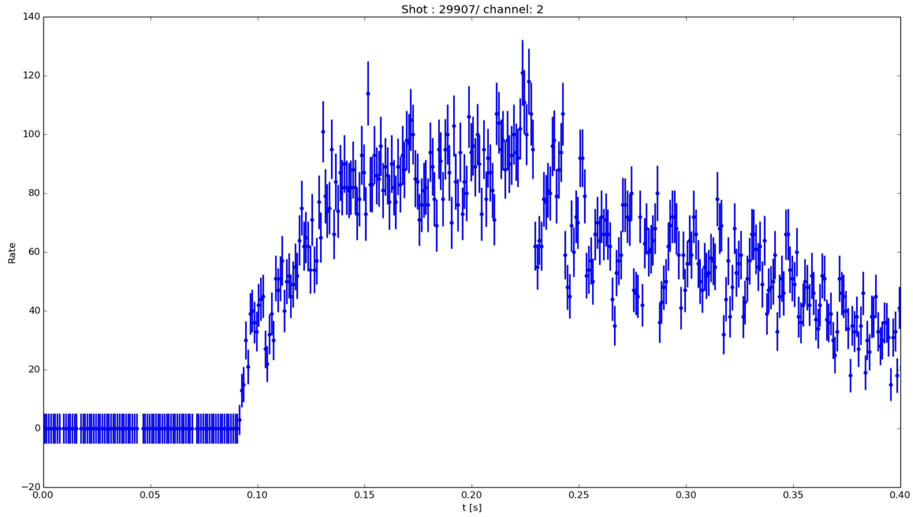

Figure 11: Ch 2 Proton Rates, Pre-Proton Range Correction

The corresponding histograms of this channel at 100 ms time slices show another Gaussian distribution of protons for each time slice with a range of 0.40 V to 0.80 V and a mean of 0.61 V. Corrections to these values in the peak finding algorithm were made and the algorithm was ran again at 2.0 $\frac{\sigma_A}{A}$, 1 ms time slices. The energy spectrum from 0 ms to 100 ms is omitted because it shows the low counts for all voltages since it is early in the shot.

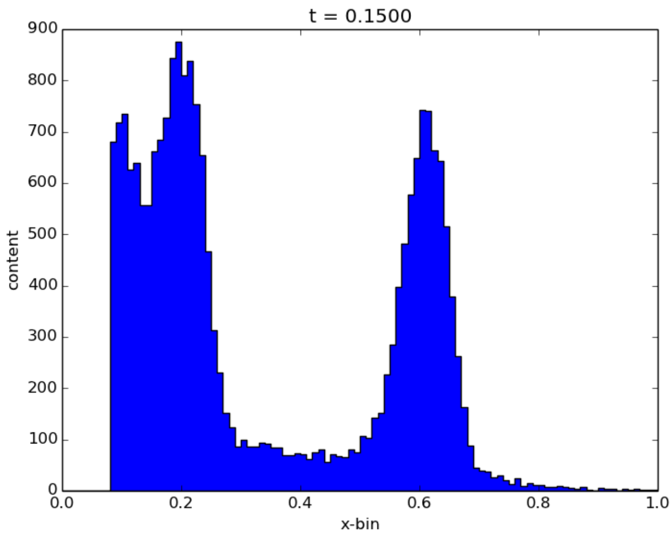

Figure 12: Energy Spectrum Ch 2, 100 ms - 200 ms

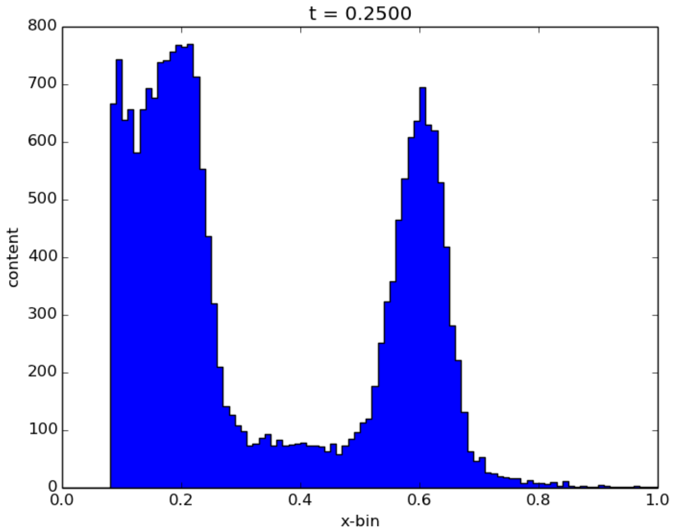

Figure 13: Energy Spectrum Ch 2, 200 ms - 300 ms

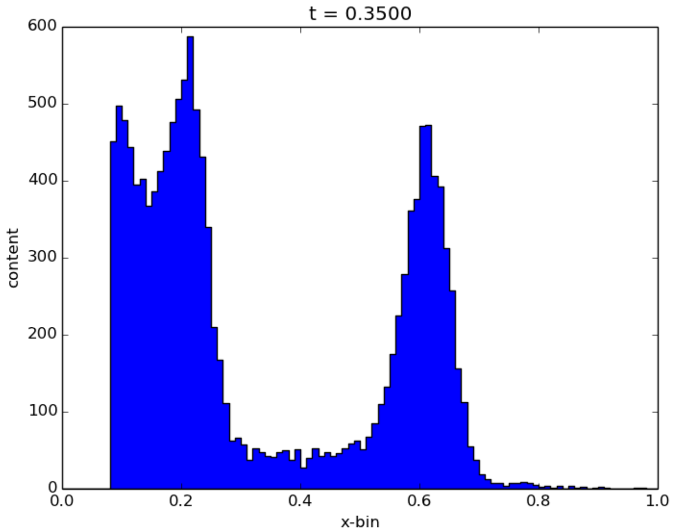

Figure 14: Energy Spectrum Ch 2, 300 ms - 400 ms

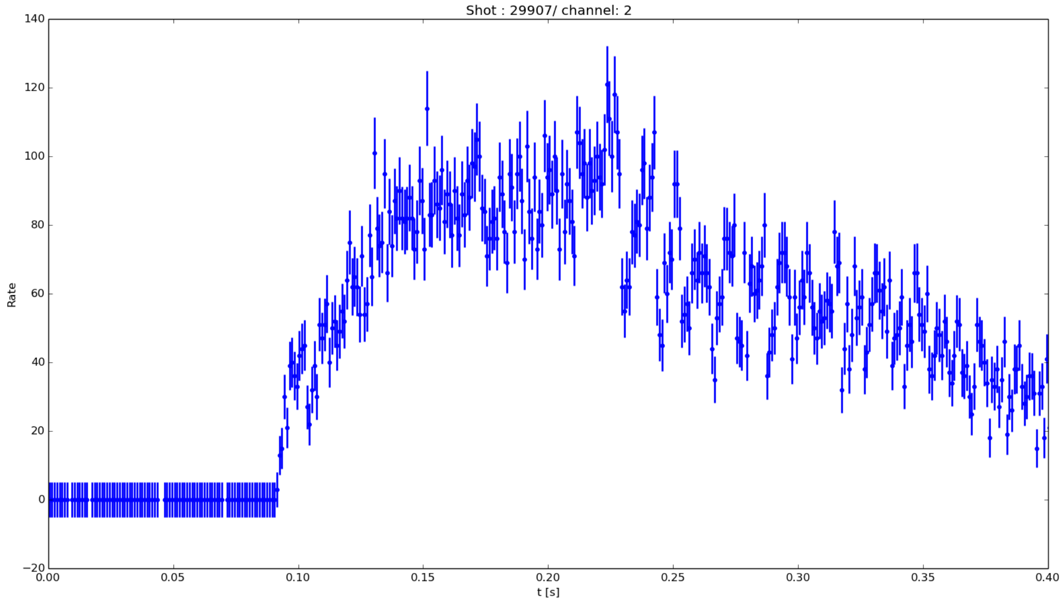

Figure 15: Ch 2 Proton Rates, Post-Proton Range Correction

Note the decrease in rates overall in the rate plot. The appropriate question is whether the decrease is due a filtering of mostly noise or peaks. The solution is not covered in this report but it is a future endeavor that will be addressed.

2.4 Channel 3

In channel 3, an attempted rate plot was made at 2.0 $\frac{\sigma_A}{A}$,1 ms intervals with a p_min, p_mean, and p_max of 0.51 V, 0.63 V, and 0.76 V respectively.

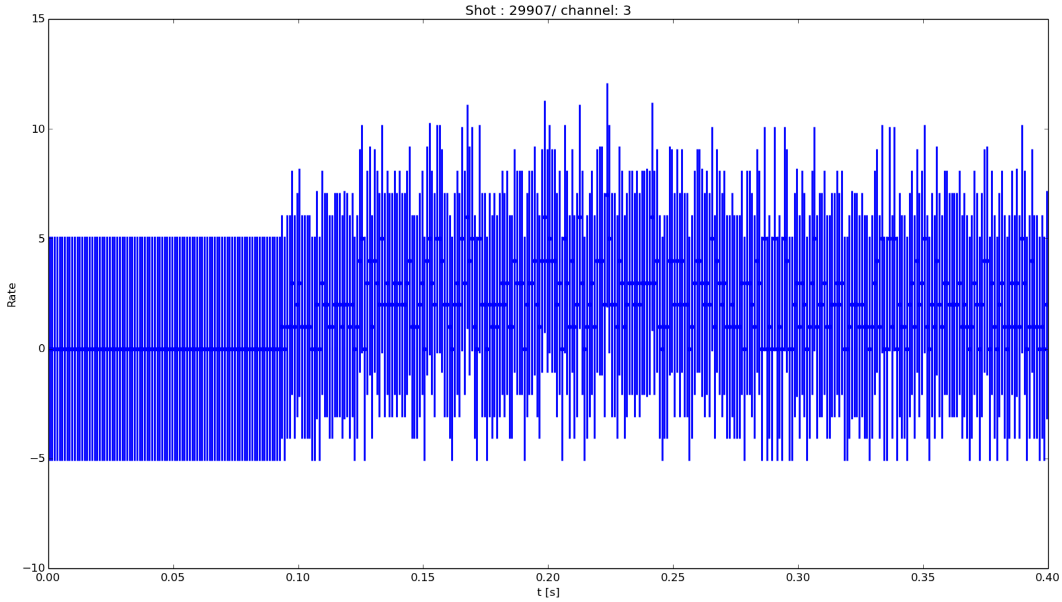

Figure 16: Ch 3 Proton Rates

It is clear that something is amiss within the fitting or the voltage signal itself. A closer inspection of the histograms reveal that very few peaks are registered as protons.

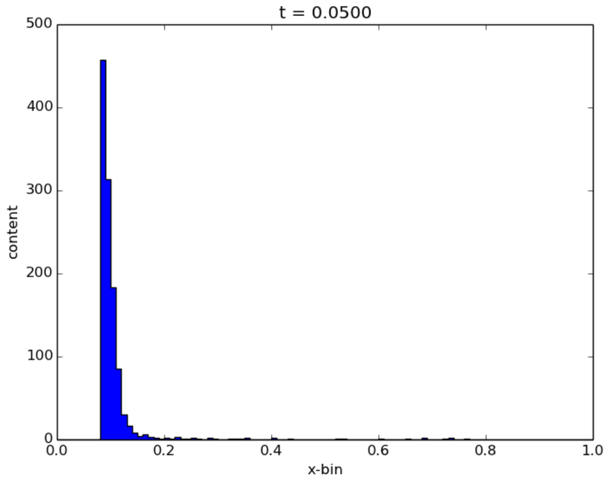

Figure 17: Energy Spectrum Ch 3, 0 ms- 100 ms

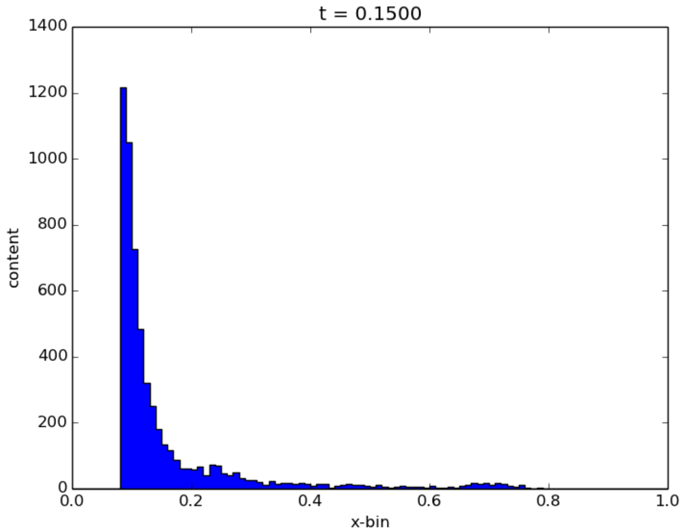

Figure 18: Energy Spectrum Ch 3, 100 ms- 200 ms

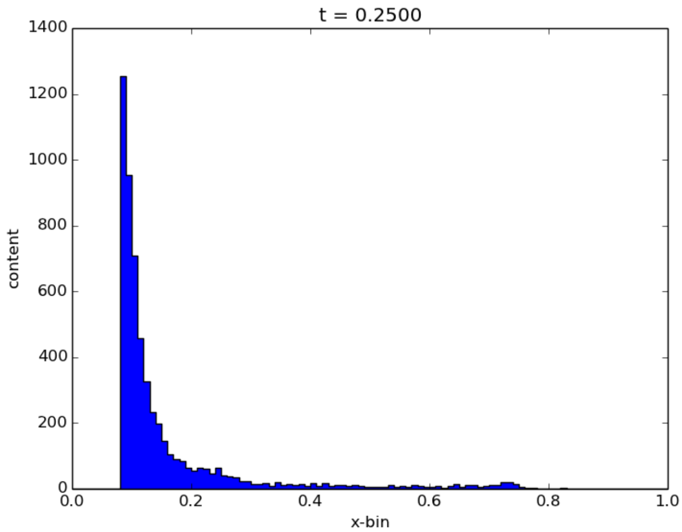

Figure 19: Energy Spectrum Ch 3, 200 ms- 300 ms

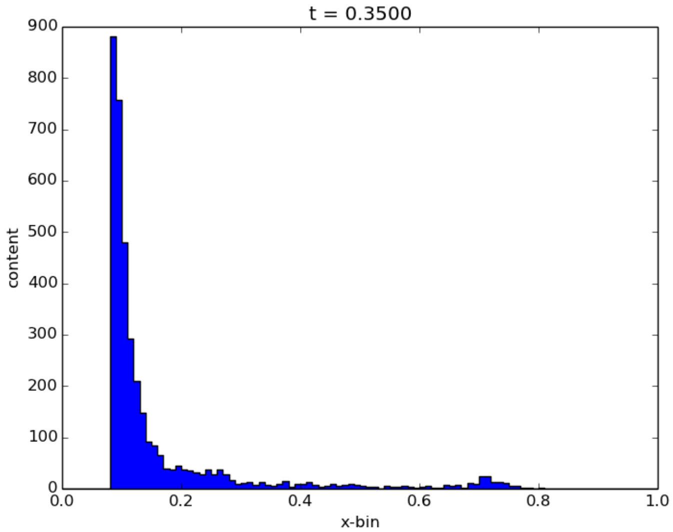

Figure 20: Energy Spectrum Ch 3, 300 ms- 400 ms

Increases in $\frac{\sigma_A}{A}$ only increased the amount of noise and few hits in the range of proton voltages. Looking at the voltage signal reveals what seems to be normal peaks and the typical noise but not more than usual. At the current moment it is unknown as to why channel 3's rate plot becomes nonsensical but will also be investigated in the future.

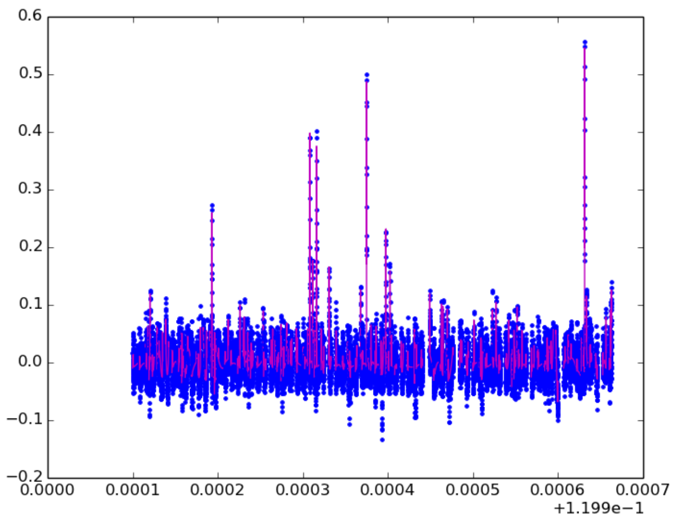

Figure 21: Ch 3 Voltage Signal

3 External Plasma Data

To validate any claims made in this report, additional data must be obtained from external plasma data. In this report, external plasma data refers to any data about the plasma discharge that is not charged product fusion data.

3.1 Neutral Beam Injection

The neutral beam injection is a device used to inject deuterium atoms to induce nuclear fusion reactions within the confined plasma. The beam power for the plasma discharge 22907 averages around 1.6 MW with oscillations in amplitude of around 0.1 MW. At first it may seem that these fluctuations could potentially cause the oscillations in rates. However, these changes do not occur at similar times to any of the fast oscillations in the proton rates and are disregarded.

3.2 Mirnov Coils

The Mirnov coils measure the emf of the magnetic field of the plasma and can be used to accurately determine the scenario of the plasma discharge in question. The large spikes in voltage within the plot below conclude that this plasma discharge is indeed not quiescent. Furthermore, the voltage spike at 280 ms not only occurs at the same time as the largest spike in proton rates but neutron rates as well. Subsequent spikes in Mirnov Coil Voltage align with the later neutron rate oscillations verifying the existence of such activity in the plasma discharge. This disproves erroneous charged fusion product data.

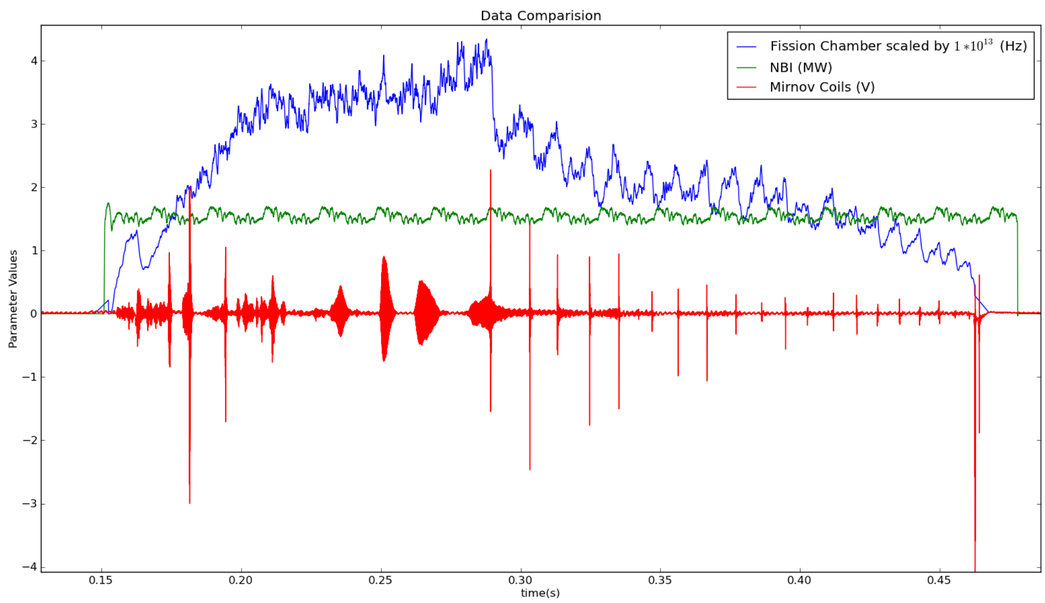

Figure 22: Mirnov Coil, Fission Chamber Data, and Neutral Beam Power

4 Neutron Rates

4.1 Fission Chamber

The fission chamber is a device used to measure the global rate of neutrons from the plasma. As shown before, even at a global rate scale (10^{13}) the spike in rates and fast oscillations can still be seen even at this order of magnitude. This only furthers the idea of plasma discharge 29907 as a non-quiescent discharge.

4.2 Neutron Camera

The Neutron Camera is similar to the fission chamber in counting neutron rates but it does so from specific target volumes from within the plasma. Four channels sample different heights and radii to provide an insight into nuclear fusion reaction rates within and around the core of the plasma. Comparing proton and neutrons rates seem to be the most direct manner to complement the rates of the CFPD. In Card 1, channels 0 and 1 sampled neutron rates from the longitudinal plane (z = 0 m) of the plasma. In these particular plots, the rate oscillations are very pronounced and similar to those as seen in channel 1 and 2 of the CFPD.

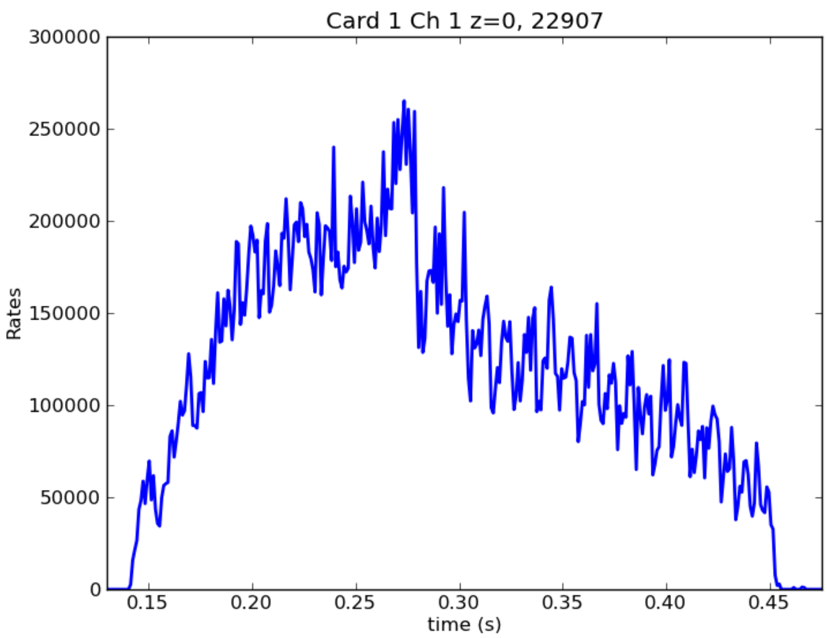

Figure 23: Card 1, Ch 1 Neutron Camera Data, z = 0 m, R = 0.62 m

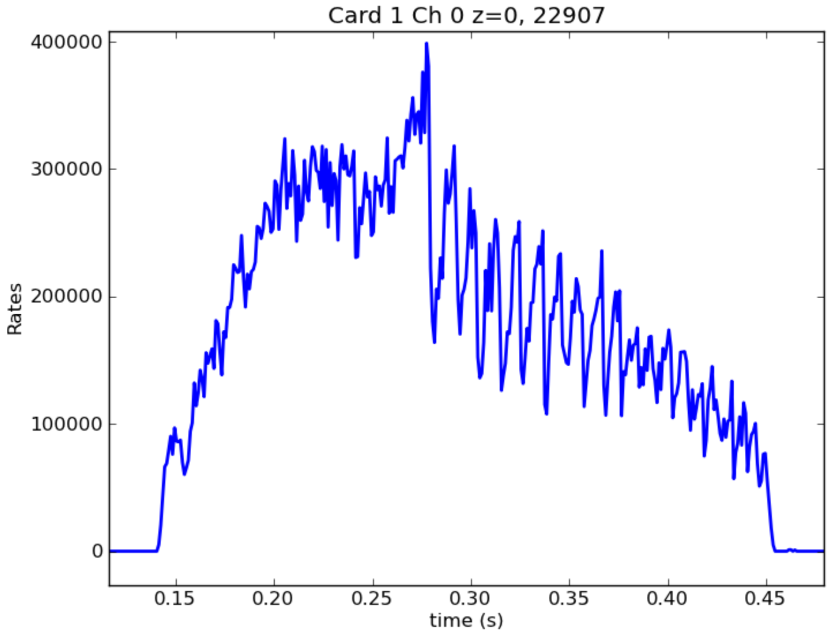

Figure 24: Card 1, Ch 0 Neutron Camera Data, z = 0 m, R = 0.82 m

However in Card 0, channel 1 the same neutron rates are seen fluctuating but are less pronounced than in the previously mentioned channels. Card 1 channel 0 is omitted because the detector has failed to function.

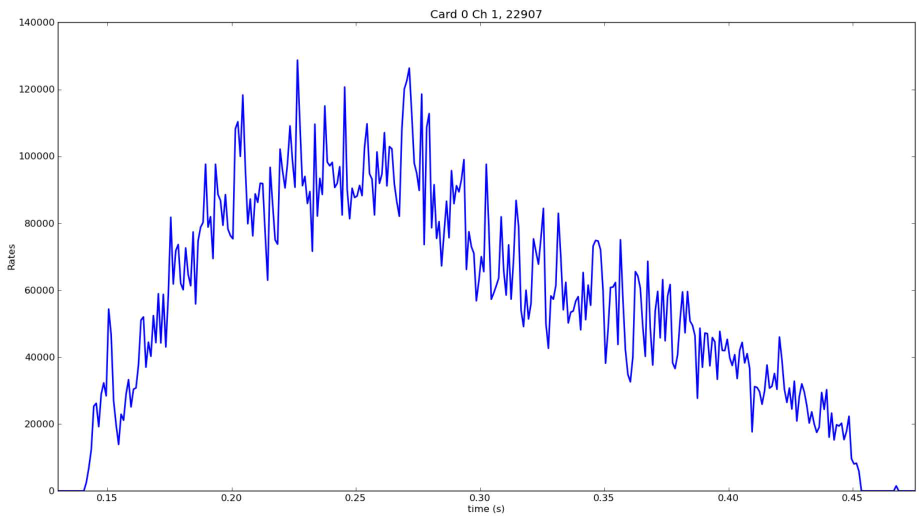

Figure 25: Card 0, Ch 1 Neutron Camera Data, z = -0.22 m

Neutron Camera data as mentioned before is valuable to supporting any claims made in this report as the nuclear fusion reactions of deuterium nuclei emits roughly about the same amount of neutrons and protons. With Card 1, both channels sample neutron rates from the longitudinal plane of the tokamak (z=0 m). Channel 1 observes rates at a radial distance of 0.62 m while channel 0 looks at 0.82 m. These positions were obtained from the Neutron Camera's reference pages on the MAST wiki page, see Appendix C. The proximity to the plasma core supports the proton rate trends observed by the CFPD and can verify the activity seen with the voltage signal.

5 Efit Data and Trajectories

An efit file is a data storage format used by MAST to share external plasma and tokamak data specifically for simulations to rebuild tokamak structure, magnetic fields, current, etc. for the purposes of simulation. The orbit code is such a simulation that provides FEPP with charged fusion product trajectories. Using this data, FEPP was able to predict the angles at which the CFPD may see charged fusion products from the core of the plasma. Likewise, efit data and the orbit code provide a means to correlate data and theoretical predictions. The orbit code used is the one as of January 29, 2013.

In the efit data for plasma discharge 29907, trajectories were plotted in 10 ms intervals. For all trajectories see Appendix B. In the orbit code trajectories, it is noted the orbit of channel 0 (Red trajectory) commonly misses the red core of the plasma which may explain the low amounts of peaks occurring in channel 0. Channel 1 (Yellow trajectory) and channel 2 (Green trajectory) are often crossing the core of the plasma. This is the expected area of high emissivity and it follows from here that as shown in the rate data, the detectors are seeing comparable proton rates. Channel 3 (Blue trajectory) despite sharing the same consequences has trajectories passing through the plasma core several times. This necessitates a closer look into the low rates of channel 3 (Blue trajectory) as it seems that the corresponding voltage signal should see sufficient amounts of protons. It is also possible since the modeled emissivity function of the plasma is incorrect that there may be an area within the core that is low in fusion rates. However, that is very grand speculation and will require many more consistent examples to be conclude that. At 280 ms there is a sharp increase in both proton and neutron rates. The Mirnov Coil data shows a spike in magnetic field magnitude at 280 ms as well. Thereby as expected, the efit trajectory at this time also shows a strange orbit with channel 0 (Red trajectory). It is unknown whether this orbit has any contribution to channel 0 noise or over saturation.

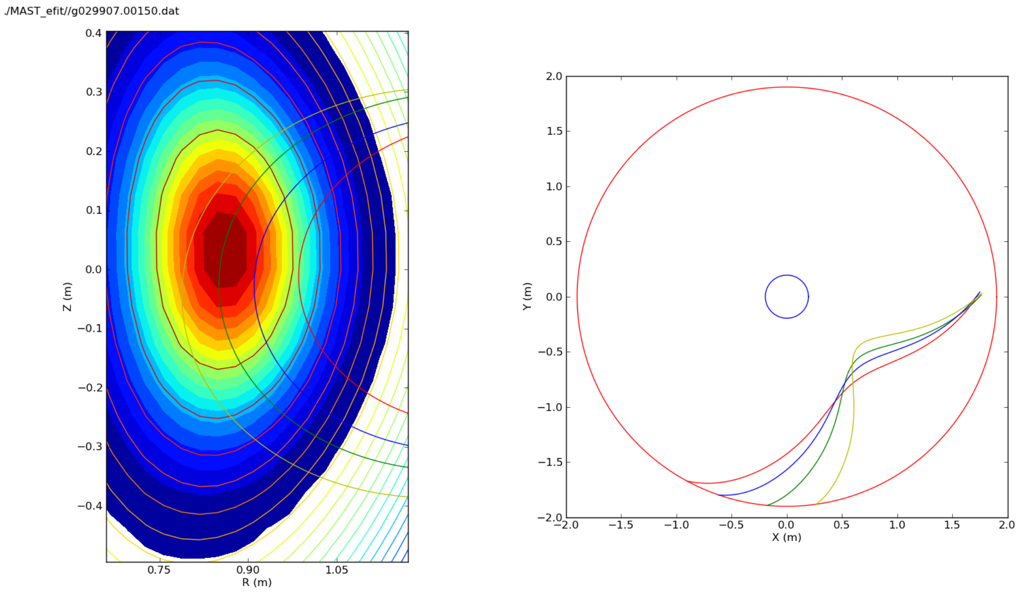

Figure 26: Zoomed efit Trajectory data at 150 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

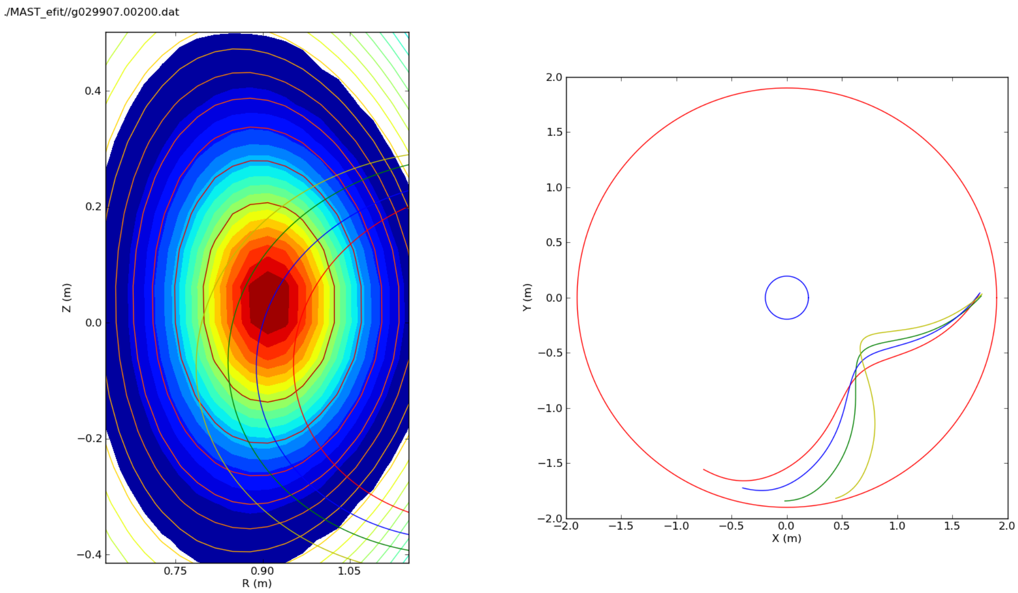

Figure 27: Zoomed efit Trajectory data at 200 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

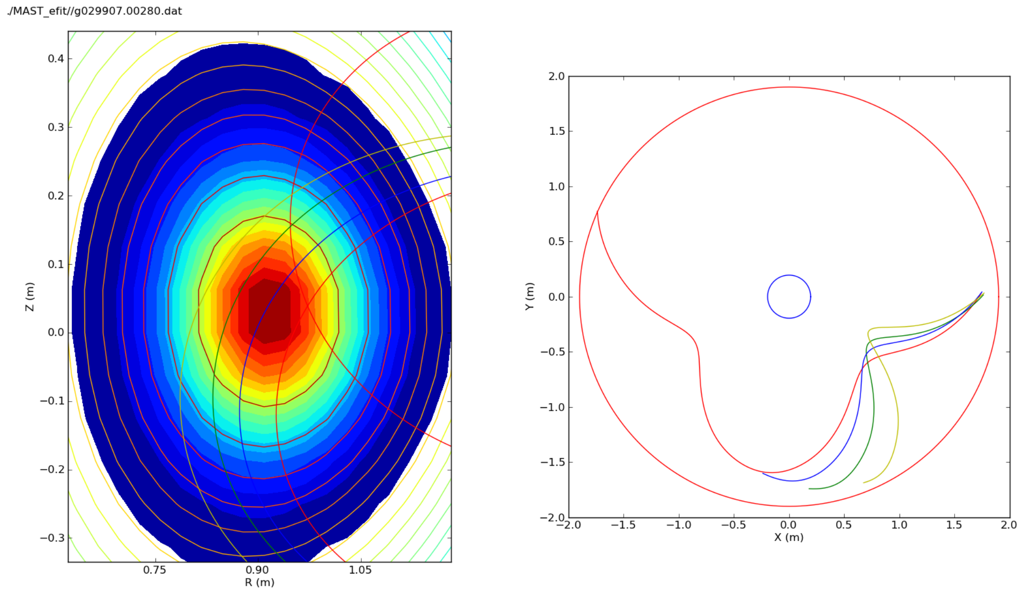

Figure 28: Zoomed efit Trajectory data at 280 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue , the rate spike occurs at this time

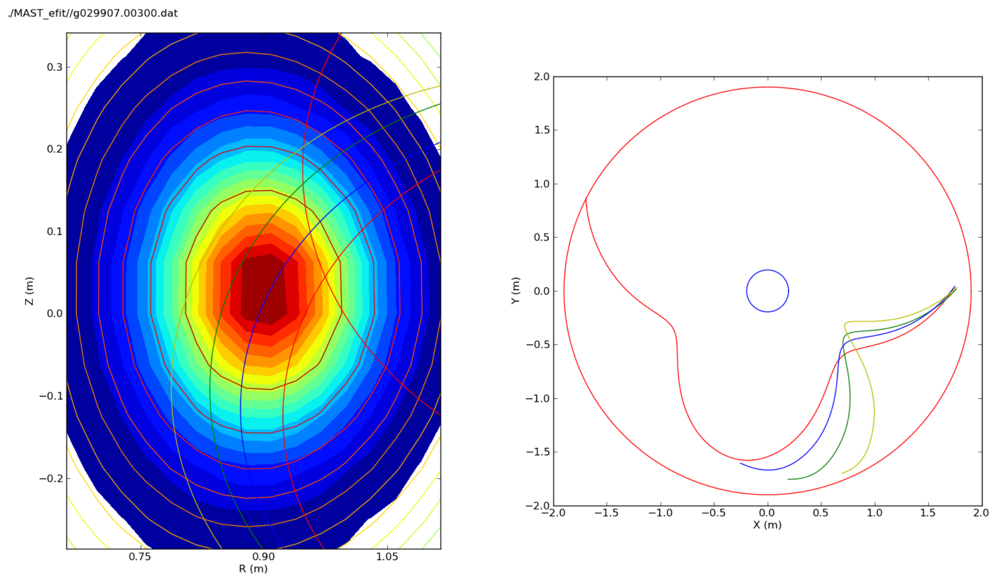

Figure 29: Zoomed efit Trajectory data at 300 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

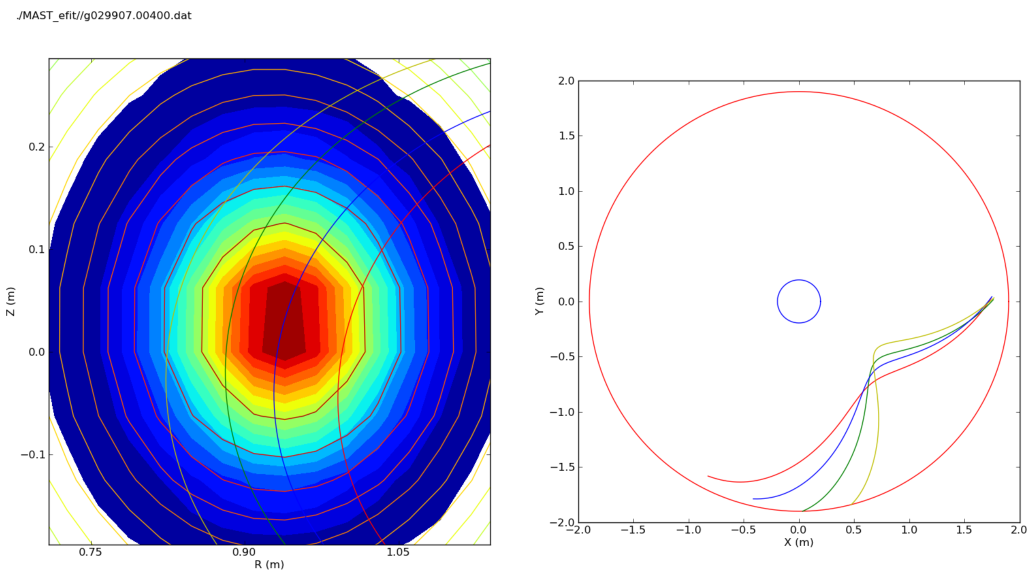

Figure 30: efit Trajectory data at 400 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

6 Conclusion

From the external plasma data and proton rates, it is indeed true that plasma discharge 29907 is not quiescent. However this does not deprive the usefulness of the discharge for purposes of speculation. For example, the fast and large drop of rates in the CFPD channel 1 is an interesting avenue to explore. This may lead to better peak finding algorithms or an indication of potential unstable activity in that volume of the plasma. As mentioned before, the decrease in proton rates after expanding voltage ranges for channel 2 is a future topic to investigate. Is this an appropriate filtration of noise? If not, what must be done in order to differentiate proton peaks from electrical noise more accurately? Channel 0 experiences a depreciation of data, is it due to electrical noise or is the detector experiencing an over-saturation of charges? Channel 3 seems to not register many proton peaks, is this really due to a low-fusion area within the plasma core? In addition, neutron rates and proton rates at the longitudinal plane share similar trends, is this pattern consistent across all plasma discharges and scenarios? These are the questions raised by this report which require further investigation to better understand plasma discharges and emission profiles.

7 Appendix A: Peak Fits and Peak Times

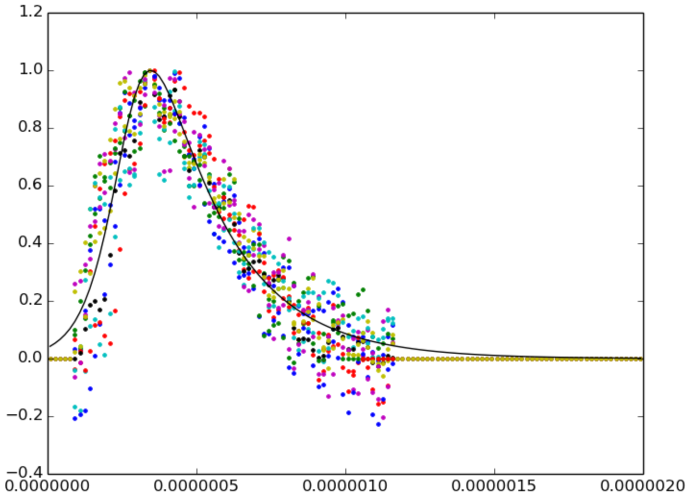

Figure 31: Channel 0 fitted peaks

Channel 0 Peak Times

0.25929689155916785	0.25929885886976656
0.25972209276304659	0.2597249246373734
0.25989012390465016	0.25989120964743534
0.26146047067915879	0.26146181330400764
0.26203533098982923	0.26203695614382616
0.2630181723129672	0.26302069957894819
0.26410643109478055	0.26410764152026001
0.26469343483094032	0.26469454802152659
0.26727185125689251	0.26727281507386763
0.2697587956854739	0.26975983312735685
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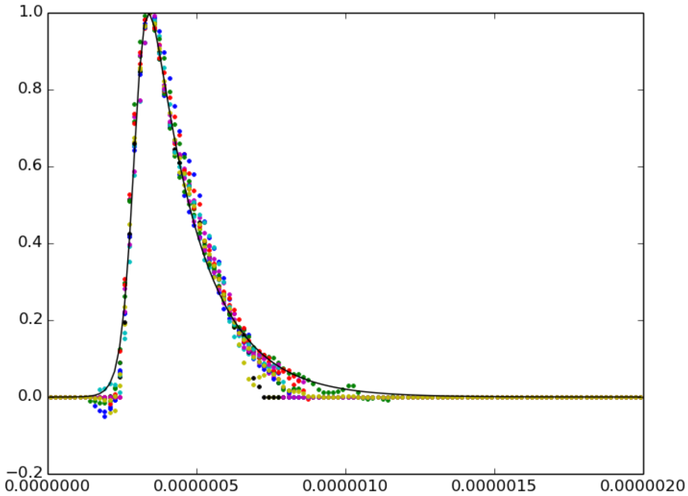

Figure 32: Channel 1 fitted peaks

Channel 1 Peak Times

0.1128693	0.1128699
0.1129542	0.1129555
0.1131835	0.1131841
0.1132271	0.1132276
0.1135454	0.1135460
0.1138372	0.1138377
0.1139009	0.1139014
0.1143918	0.1143924
0.1145371	0.1145377
0.1146095	0.1146101
0.1146265	0.1146271
0.1149932	0.1149937

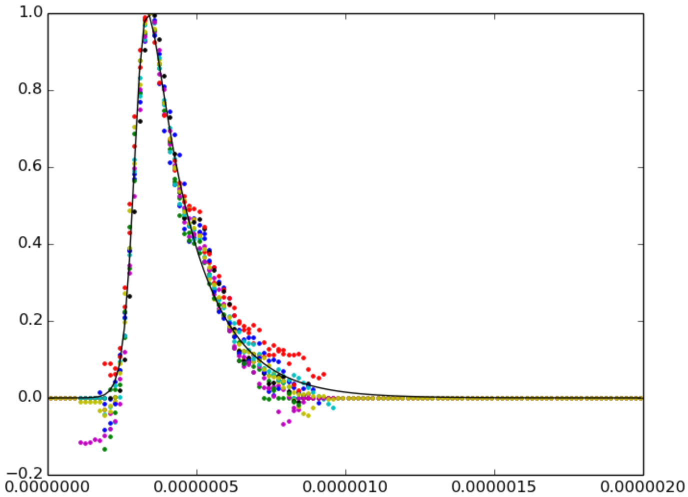

Figure 33: Sample Voltage Signal

Channel 2 Peak Times

0.11890880112824485	0.11890944351939649
0.11952753238921911	0.11952808812448103
0.12044433153857456	0.12044505422862016
0.12071845840094422	0.12071908009282542
0.12120286130028284	0.12120354080736767
0.1212774172173417	0.1212781238476085
0.12136039175534659	0.12136104820743897
0.12137454176309342	0.1213752726614704
0.12154651843960176	0.12154714798293037
0.12158848264158238	0.12158913359794937
0.1217527591894864	0.12175350150815051
0.12179884040498108	0.12179952990481717

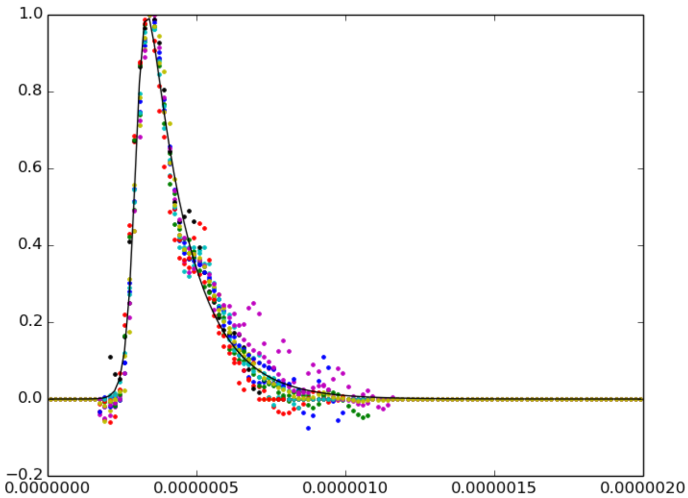

Figure 34: Sample Voltage Signal

Channel 3 Peak Times

0.19356468865496979	0.19356529535772413
0.19426066049257087	0.19426136527893717
0.19466617467904507	0.19466698159370832
0.19531188698526009	0.19531251492261081
0.19557718485664388	0.19557814344699573
0.23680699986175849	0.23680752350282602
0.237134554976386	0.23713508931100133
0.23768086881751635	0.23768167323399178
0.23892812541602707	0.23892901143997103
0.35506665715359331	0.35506716735696792
0.36986982234345217	0.36987039251356757
0.3794467041248541	0.37944757016329556

8 Appendix B: efit Trajectories

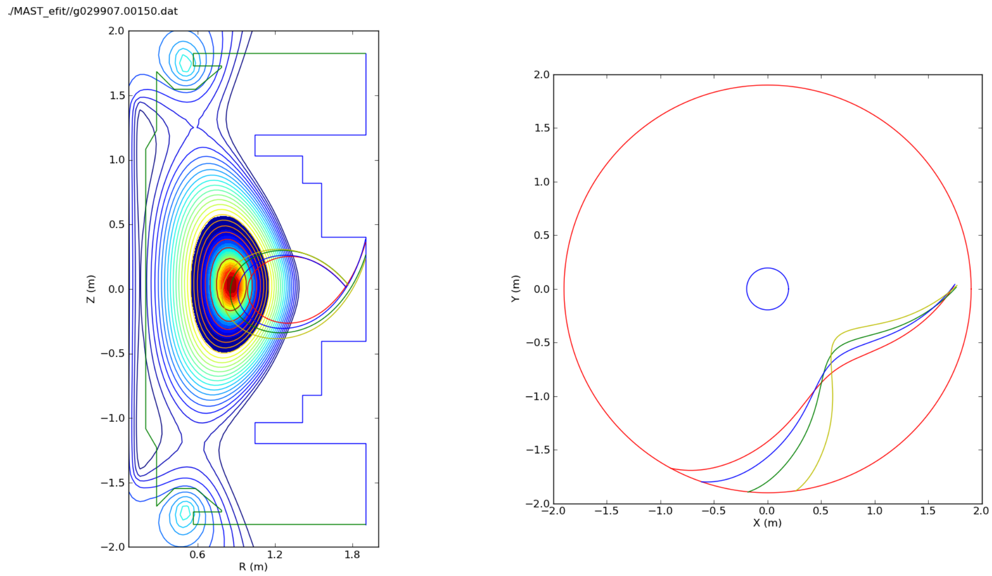

Figure 35: efit Trajectory data at 150 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

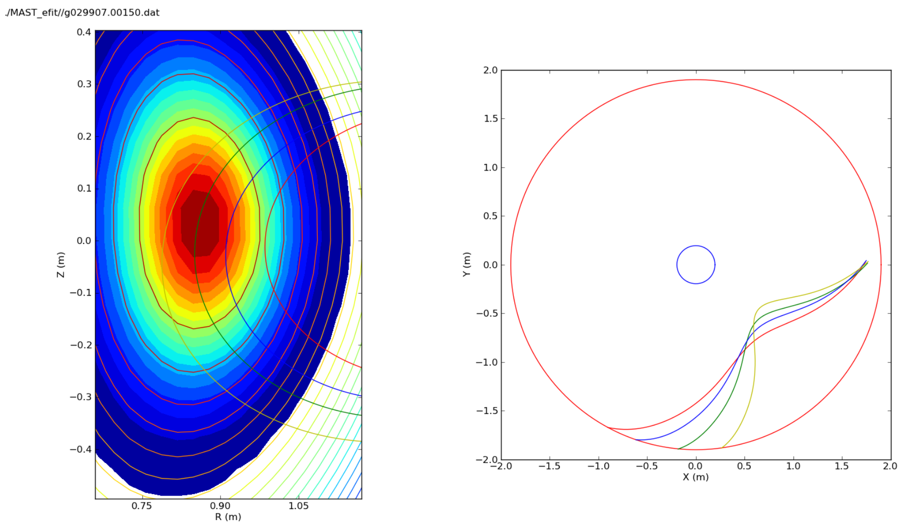

Figure 36: Zoomed efit Trajectory data at 150 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

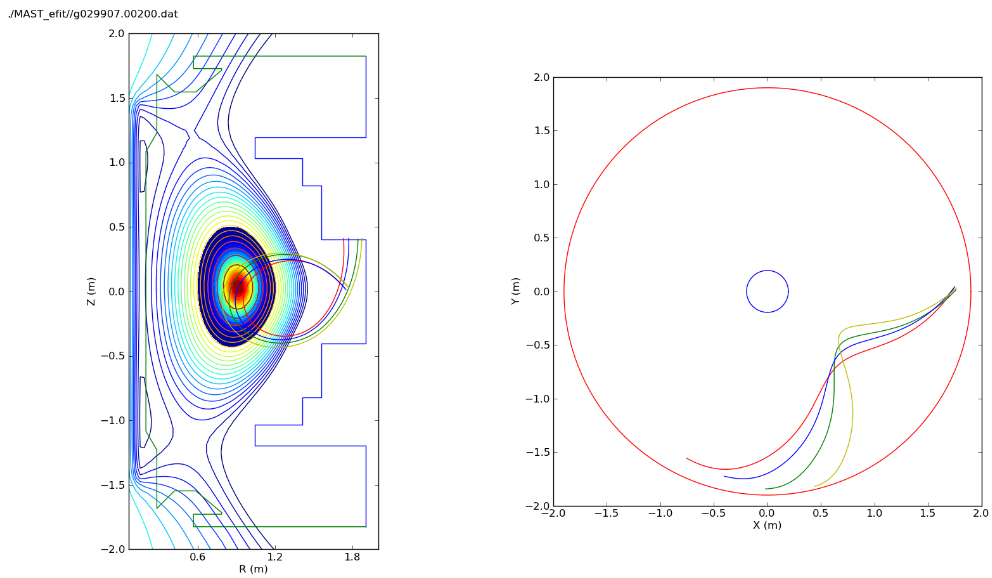

Figure 37: efit Trajectory data at 200 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

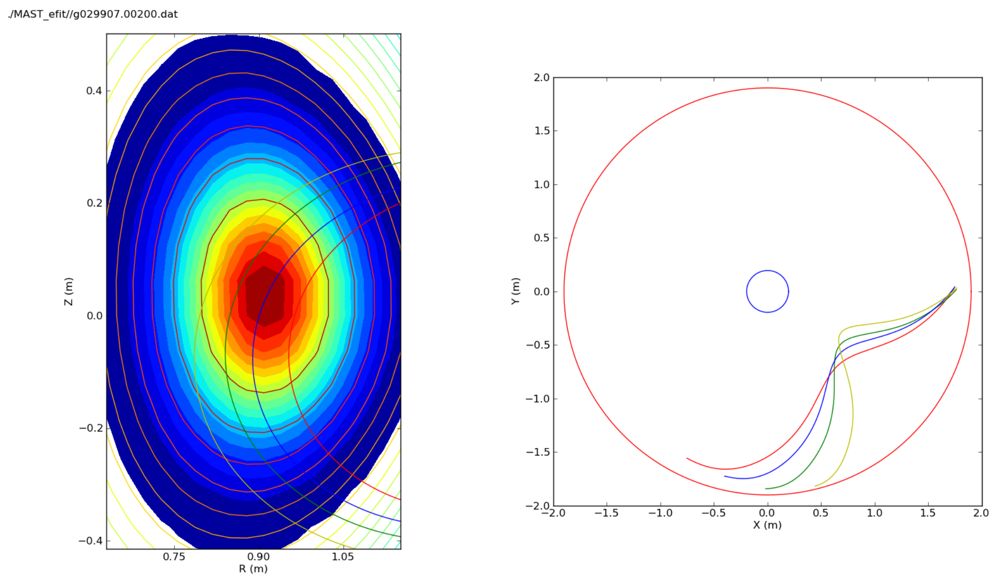

Figure 38: Zoomed efit Trajectory data at 200 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

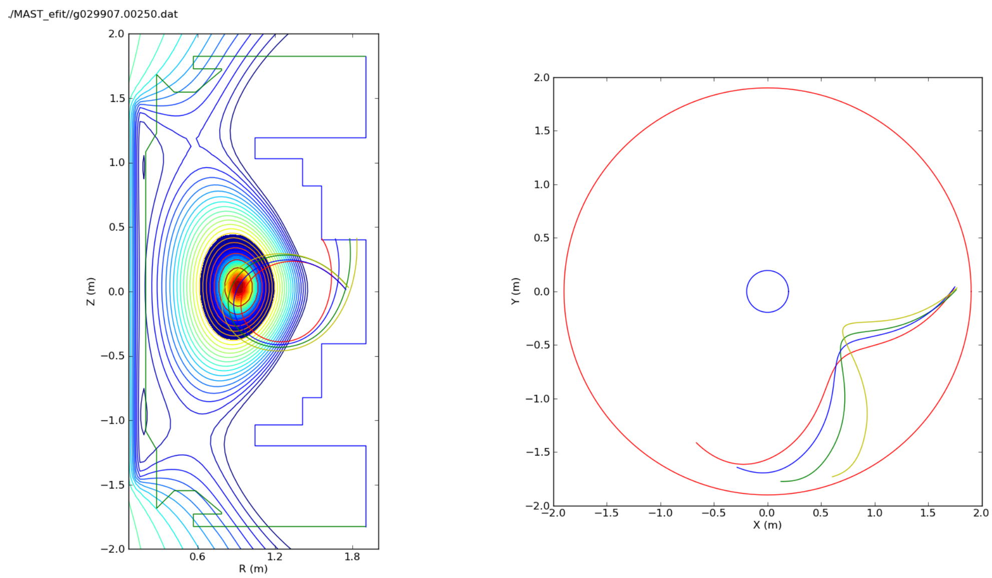

Figure 39: efit Trajectory data at 250 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

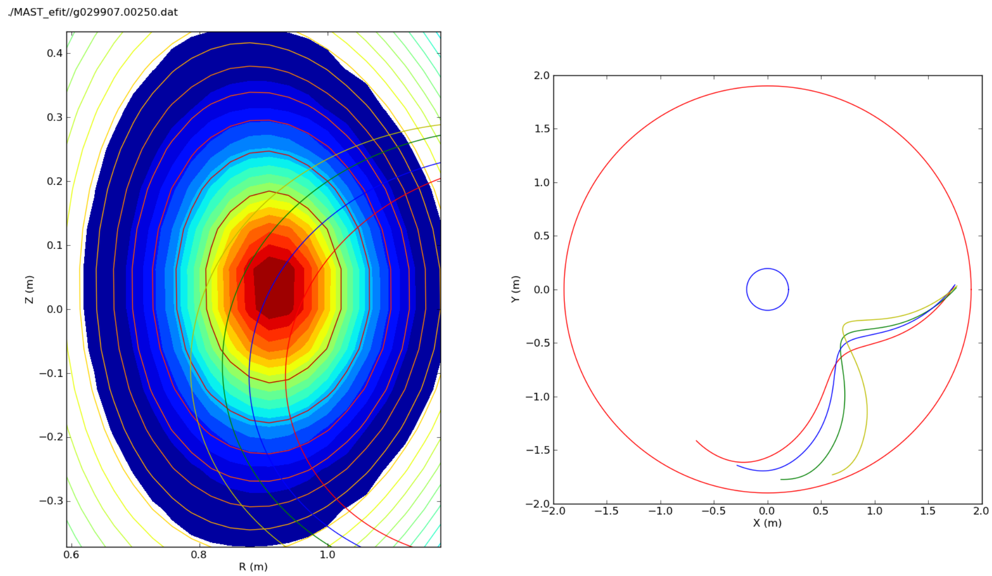

Figure 40: Zoomed efit Trajectory data at 250 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

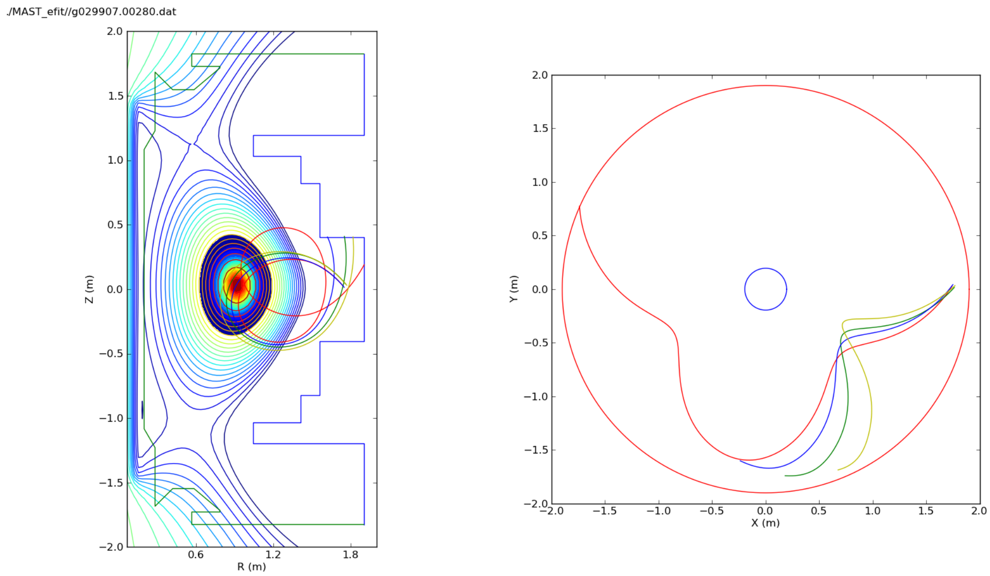

Figure 41: efit Trajectory data at 280 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue , the rate spike occurs at this time

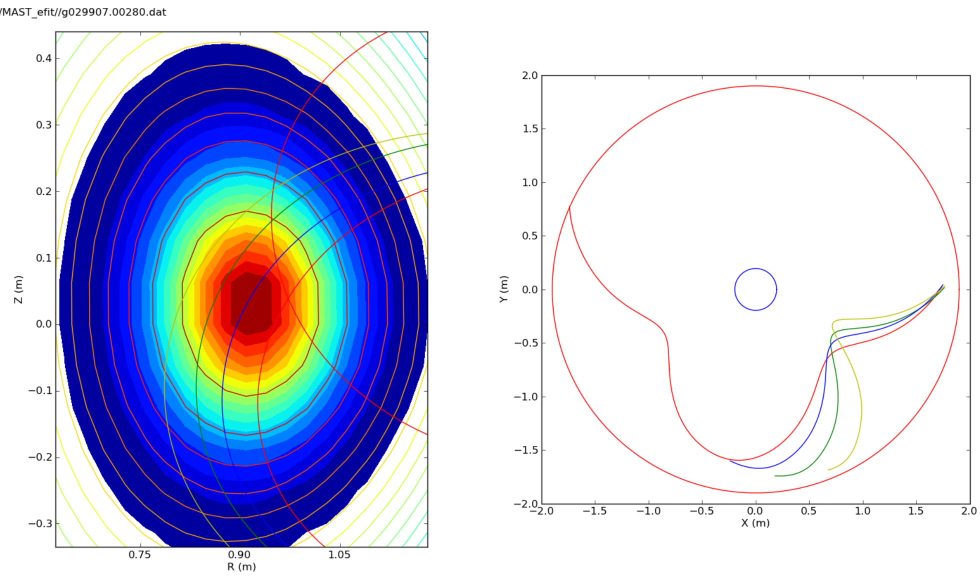

Figure 42: Zoomed efit Trajectory data at 280 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue , the rate spike occurs at this time

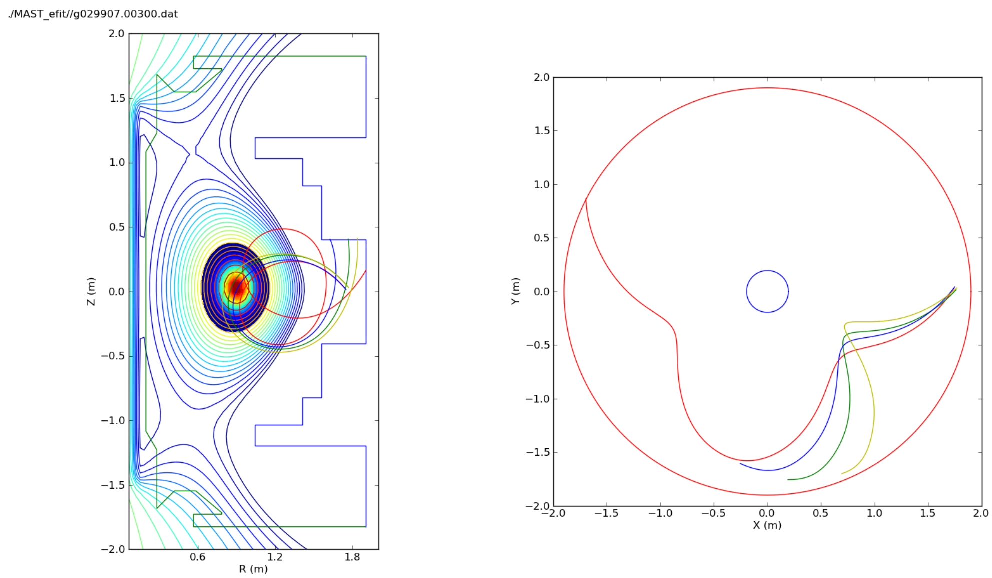

Figure 43: efit Trajectory data at 300 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

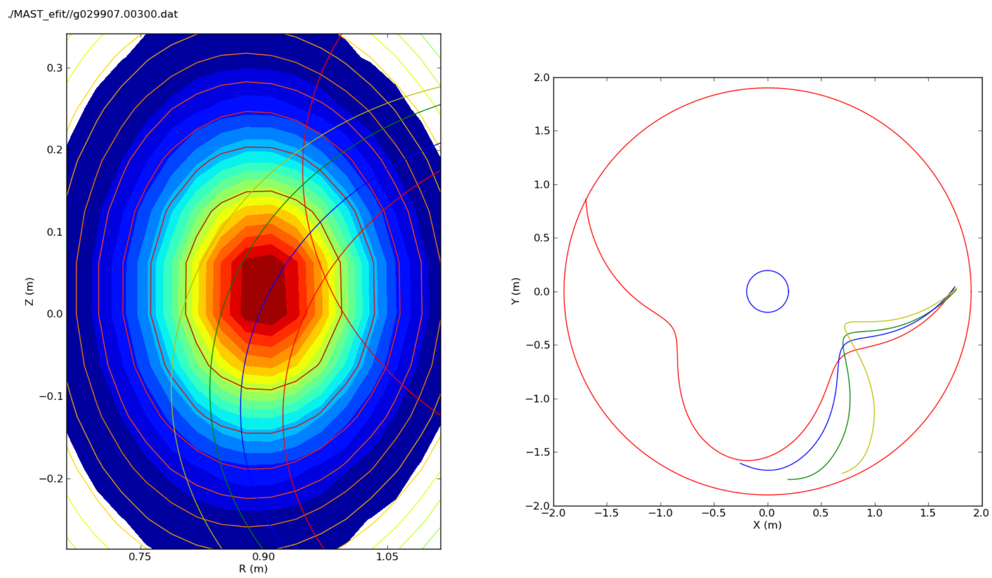

Figure 44: Zoomed efit Trajectory data at 300 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

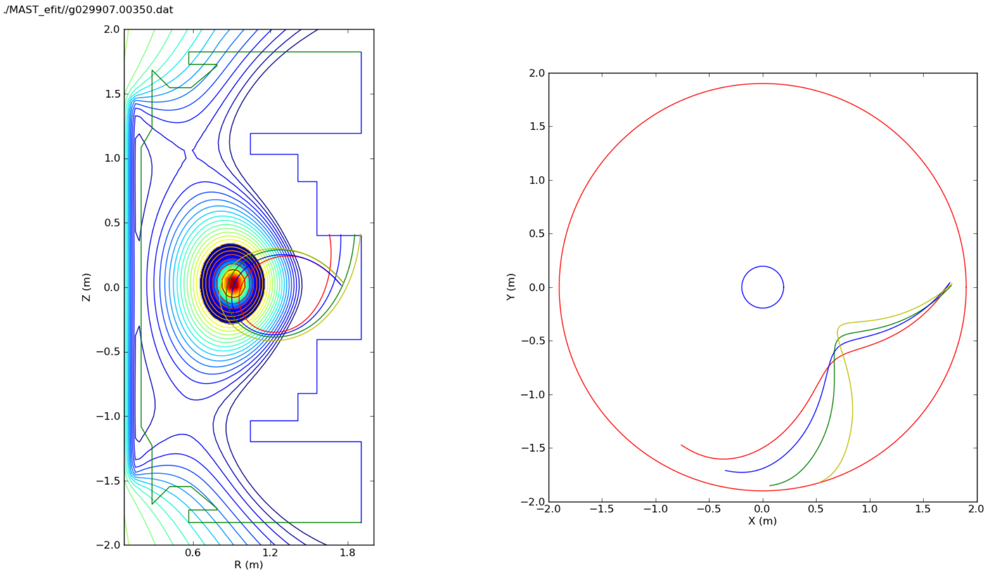

Figure 45: efit Trajectory data at 350 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

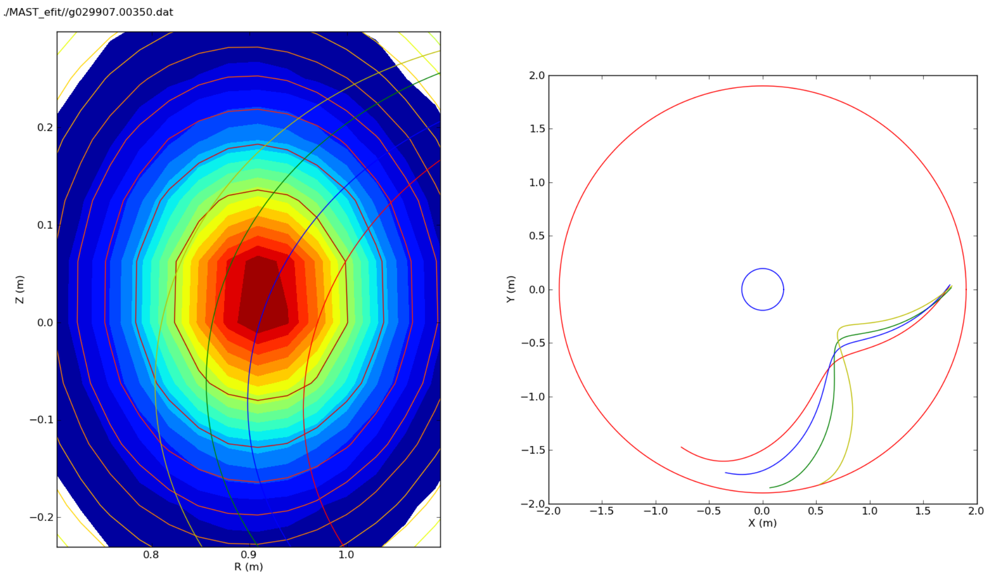

Figure 46: Zoomed efit Trajectory data at 350 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

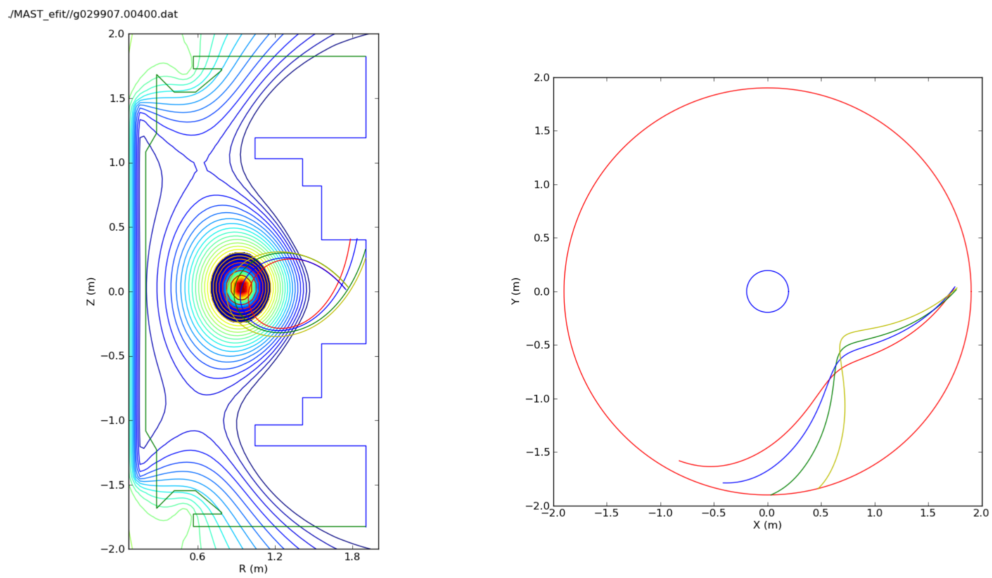

Figure 47: efit Trajectory data at 400 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

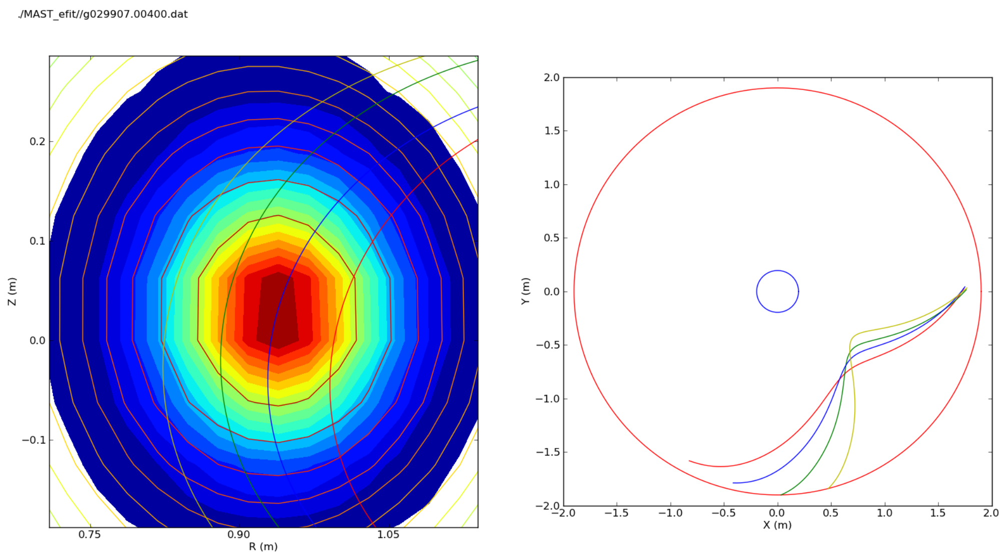

Figure 48: Zoomed efit Trajectory data at 400 ms, Ch 0 - red, Ch 1 - yellow, Ch 2 - green, Ch 3 - blue

Appendix C: Neutron Camera References

Specialised Diagnostic Requirements

Lost Proton Detector

For the proton detector field-of-view check, a B field scan is needed. This test will be carried out together with FPP-005 in the second part of the experiments

Scanning neutron camera

Two possible sets of camera positions are listed below based on the latest rail calibration (Jun 2013).

SET 1

10 points (5 pulses) with 6.5 - 10 cm resolution with p in the range 48 to 119 cm.

M(mm)	L(cm)	R(cm)
150	1.13	0.93
80	1.19	1.00
220	1.06	0.86
490	0.79	0.58
590	0.69	0.48

Figure 49: Neutron Camera Reference 1

Session of 20 August 2013 - Experiment 3A and 3B - FPP-001 and IPS-002 Quiescent MHD for FID reconstruction with LPD

Pulse	MAST Pulse	Ref. Pulse	NBI Power Time	B_T(T) I_{TF} (kA)	NC position (mm)	Impact par. (m)	LPD Radial Position (m)/(deg)	Notes
NA	29902	29195	SS 2 MW @ 0.150 - 0.600 s	0.585 -85	70	1.20, 1.01	Rec. Probe 1.83 m	Good match to the reference pulse but for the NBI power which is 2 instead of 1.5 MW. Next pulse will be at 1.5 MW. Keeping the NC at the same position. OMAHA set at 1 MHz. Hih. LPD channel radial position: 0.85, 0.91, 0.96, 1.04m.
Position 1	29904	29195	SS 1.5 MW @ 0.150 - 0.600 s	0.585 -85	70	1.20, 1.01	Rec. Probe 1.74 m	Ok, good match to the reference and quiet MHD activity for this pulse. LPD channel radial position: 0.8, 0.86, 0.9, 0.96m.
Position 2	29905	29195	SS 1.5 MW @ 0.150 - 0.600 s	0.585 -85	134	1.14, 0.95	Rec. Probe 1.74 m	Ok, good repeat. Moving the camera to the next position. LPD channel radial position: 0.8, 0.86, 0.9, 0.96m.
Position 3	29906	29195	SS 1.5 MW @ 0.150 - 0.600 s	0.585 -85	204	1.08, 0.88	Rec. Probe 1.83 m	Ok, good repeat. LPD channel radial position: 0.85, 0.91, 0.96, 1.04m.
NA	29907	29195	SS 1.5 MW @ 0.150 - 0.600 s	0.585 -85	460	0.82, 0.62	Rec. Probe 1.74 m	Not a good pulse, unclear why. So we repeat the pulse in the same position. LPD channel radial position: 0.8, 0.86, 0.9, 0.96m.
Position 4	29908	29195	SS 1.5 MW @ 0.150 - 0.600 s	0.585 -85	460	0.82, 0.62	Rec. Probe 1.65 m	Ok, good repeat: note however that the MHD activity at the beginning is slightly different. Continue the series. MSE data available. LPD channel radial position: 0.76, 0.81, 0.85, 0.9m.
Position 5	29909	29195	SS 1.5 MW @ 0.150 - 0.600 s	0.585 -85	524	0.76, 0.55	Rec. Probe 1.785 m	Ok, good pulse. MSE data available. LPD channel radial position: 0.83, 0.89, 0.93, 0.99m.

Figure 50: Neutron Camera Reference 2

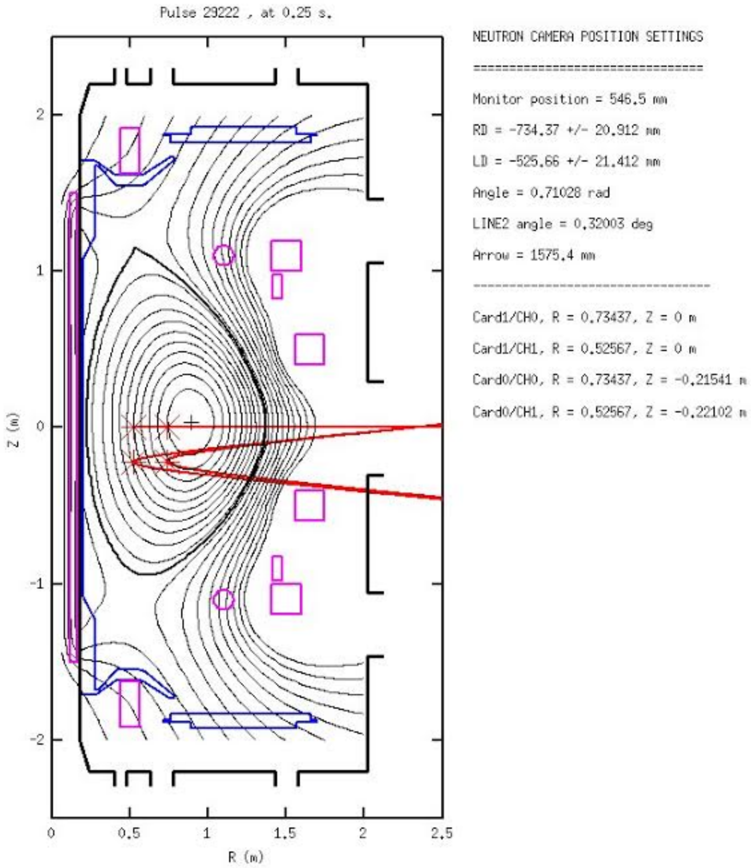

Figure 51: Neutron Camera Reference 3, used to correspond detector Channels and Cards