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S.S. Medley, D.S. Darrow,
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S. S. Medley, D. S. Darrow, and A. L. Roquemore

Princeton Plasma Physics Laboratory, Princeton, New Jersey, 08543, USA

Email: ***medley@pppl.gov***

Abstract

A change in the response of the neutron detectors on the National Spherical Torus Experiment occurred between the 2002-2003 and 2004 experimental run periods. An analysis of this behavior by investigating the neutron diagnostic operating conditions and comparing measured and TRANSP-calculated neutron rates is presented. Also a revised procedure for cross calibration of the neutron scintillator detectors with the fission chamber detectors was implemented that delivers good agreement amongst the measured neutron rates for all neutron detectors and all run periods. For L-mode discharges, the measured and TRANSP-calulated neutron rates now match closely for all run years. For H-mode discharges over the entire 2002-2004 period, the 2FG scintillator and fission chamber measurements match each other but imply a neutron deficit of 11.5% relative to the TRANSP-calulated neutron. The results of this report impose a modification on all of the previously used calibration factors for the entire neutron detector suite over the 2002 – 2004 period. A tabular summary of the new calibration factors is provided including certified calibration factors for the 2005 run.

1. Introduction

The neutron emission measurements on the National Spherical Torus Experiment (NSTX) utilize an array of neutron detectors and electronics from the TFTR era [1 - 3]. As indicated in the layout of the neutron diagnostics on NSTX shown in Fig. 1, the neutron detector suite consists of one 1.0 gram moderated ^{235}U fission chamber (designated FC1), one 0.01 gram moderated ^{235}U fission chamber (designated FC2), and four plastic scintillator detectors (including one NE 451 ZnS detector). The FC1 fission chamber is ~ 27x more sensitive than the FC2 fission chamber. The fission chambers can be operated in either pulse-counting mode or current mode while the scintillator detectors are all operated in the current mode. In principle, the fission chambers can also be operated in the mean-square voltage (Campbell) mode to provide a bridge between the pulse-counting and current modes, but this feature not used on NSTX. The count rate mode is linear up to ~ $4x10^{x13}$ n/s where it is limited by pulse pileup. The range of the current mode is limited to ~ 10^{13} – 10^{15} n/s. In the current mode, the lower limit is set by the need for sufficient signal for the current mode to be operative and the upper limit is set by saturation of the signal electronics. In fission chambers, these ranges increase as the quantity of ^{235}U is decreased.

Cross calibration of the pulse-counting and current modes is performed in the operating overlap region of ~ 1 - $4x10^{x13}$ n/s where the FC2 fission chamber remains in the pulse-counting mode while the FC1 fission chamber in the current mode (because of the larger quantity of ^{235}U). Obtaining conditions with sufficiently low yields for overlap operation of the fission chambers typically requires using NSTX discharges with one source operated at ~ 65 keV. Fission chambers are highly stable, with the detection efficiency varying typically less than 5% over extended periods of time [1]. "Detection efficiency" refers to the ratio of the time-dependent global fusion neutron rate, S_n (n/s), to the detector signal (volts).

Only FC1 operating in the current mode is used for the fission chamber neutron measurements presented in this report and this detector is simply designated FC.

The detection efficiency of the plastic scintillators can be more prone to variation but these detectors have the advantage of a faster time response compared with the fission chambers. From the TFTR experience, neither fission chambers nor plastic scintillators showed any susceptibility to radiation damage [2]. (Radiation damage was found to produce a continuous decline in the detection efficiency of silicon surface barrier detectors, but these are not used on NSTX.)

Absolute calibration of the neutron diagnostics begins with using a ^{252}Cf radio-isotope source for simulation of the 2.5 MeV d-d neutrons. The source is inserted into the NSTX vacuum vessel and both fission chambers are operated in the pulse-counting mode to measure the neutron response. The source is moved to numerous toroidal and poloidal locations to map the detector response function througout the NSTX vacuum vesel. An example of the reslults from this calibration procedure is shown in Fig. 2. Analysis of the calibration data is performed using the Monte-Carlo N-Particle (MCNP) transport code [4] that models the effect of the material composition of internal and surrounding structures to simulate the calibration results. Spatial integration of the calibration data yields the global neutron sensitivity factor. The scintillator detectors are cross calibrated using discharges having suitable neutron emission rates that allow operational overlap of the fission chamber detectors operatingin the pulse-counting mode. Typical uncertainties using the ^{252}Cf radio-isotope source are in the range of ± 10% though statistical variations under plasma measurement conditions can increase the total absolute calibration uncertainty of the fission chamber detectors to ~ ± 20%.

2. Comparison of Measured and TRANSP-calculated Neutron Emission in NSTX

The various complex physical processes in fusion plasmas require sophisticated computer simulation tools to bring together theoretical models with measured data. One of the most comprehensive of such tools is the 1 1/2-D time dependent transport code TRANSP [5] that is routinely employed worldwide for analysis of tokamak experiments [6 - 8] including the MAST [9,10] and NSTX [11] spherical tokamaks. TRANSP analysis of fast ion transport in MHD-quiescent TFTR plasmas heated with different fractions and powers of deuterium and tritium neutral beams established that the spatially constant diffusion coefficient for energetic ions is low: $D_f \leq 0.2 \pm 0.2$ m^2/s [6]. Deuterium-tritium beam blip experiments gave an even lower limit: $D_f < 0.05$ m^2/s [7]. On TFTR, however, evidence was also found for spatially variable energetic ion diffusion [8] where neutron flux measurements indicated a small diffusion coefficient in the plasma core that increased toward the plasma periphery. For plasmas with strong MHD activity (fishbones, TAE modes) the inferred energetic ion diffusion coefficient was significantly larger: $D_f > 1$ m^2/s. With the exception of such cases, TRANSP calculations of the neutron emission agreed very well with the neutron measurements within the uncertainties imposed by the input data measurements required by TRANSP [6].

In low aspect ratio spherical tokamaks, the magnetic field topology can cause energetic ion behavior to differ in several aspects compared with conventional aspect ratio tokamaks. Spherical tokamaks operate at significantly lower toroidal magnetic field than most tokamaks; e.g. B_T = 0.3 – 0.6 T in NSTX compared to 2 – 5 T in conventional tokamaks and this leads to a large energetic ion gyroradius. For example, the gyroradius of 80 keV D co-injected neutral beam ions in NSTX can be ~ 0.3 m at the outboard midplane of the plasma. This is a sizeable fraction of the 0.68 m minor radius for typical plasmas. One consequence of this is that the guiding center model used in TRANSP for ion orbit tracking had to be modified. Implementing a full Monte-Carlo orbit following model was not computationally viable, so a simpler modification was invoked. In layman terms, this modification basically consisted of displacing ions from their guiding center orbit and re-calculating the gyro orbit size at random times during the evolution of a gyro transit. TRANSP analysis using this approach compares favorably with full Monte-Carlo orbit tracking codes such as LOCUST [9]. On MAST, good agreement is observed between measured and TRANSP-calculated neutron rates [10].

In the 2002 period for H-mode discharges with low-n, low-f MHD activity, the charge exchange Neutral Particle Analyzer (NPA) diagnostic evidenced sizeable energetic ion loss and consistent with this observation the standard TRANSP-calculated neutron emission significantly exceeded measurements obtained with the 2FG scintillator neutron detector. Reconciliation of this situation required invoking anomalous energetic ion diffusion [11] with spatially constant but time and energy dependent diffusion coefficients up to $D_f \sim 5\ m^2/s$. In the 2004 NSTX run, however, a conundrum arose wherein the NPA measurements continued to indicate energetic ion loss but there was no longer a deficit between the 2FG-measured and TRANSP-calculated neutron emission leaving no headroom for invoking anomalous energetic ion loss. Resolution of this situation, along with other anomalies regarding calibration of the neutron detector suite, is the focus of this report.

With this preamble, attention is now directed toward the main topic of this section; namely comparison of measured and TRANSP-calculated neutron emission on NSTX. An analysis was performed based primarily on a LOCUS database provided by S. Kaye. The H-mode entries in this database were filtered to retain only H-mode discharges for which the NPA was tuned to detect energetic ion loss and that did not use TRANSP analyses invoking anomalous energetic ion loss. The L-mode entries were not filtered. This database, augmented by other discharges including an L-move database provided by E. Fredrickson, consisted of 50 entries for 2002 spanning a shot range of 107540 – 109070, 18 entries for 2003 spanning a shot range of 109794 – 110184 and 75 entries for 2004 spanning a shot range of 112063 –114150. TRANSP analysis was performed for all entries except those for 2003. Some entries included multiple time points during a given shot.

In Fig. 3, the measured and calculated neutron rates are compared for L-mode discharges for 2004 (upper panel) and pre-2004 (lower panel). The 2FG scintillator data is shown by the red squares and the fission chamber data by the green circles. We introduce the terms “neutron deficit” to refer to measured neutron rates falling below TRANSP-calculated rates and “neutron excess” to refer to measured neutron rates exceeding the TRANSP-calculated rates. The fission chamber measurements showed a modest neutron excess of 8% for 2004 and 9% for pre-2004 discharges. The 2FG scintillator measurements, however, changed drastically between 2004 and pre-2004. The 2FG scintillator measurements showed a neutron excess of 13% for 2004 but a neutron deficit of 28% for pre-2004 discharges. Hence the first conundrum: what caused the drastic change in the 2FG scintillator response between 2004 and pre-2004? The second conundrum is: why do the highly reliable fission chamber measurements not match the TRANSP-calculated neutron rates more closely? The L-mode data set was extracted from modest density discharges at MHD-quiescent time points. Under these conditions, measured and TRANSP-calculated neutron rates have traditionally been in virtually perfect agreement, since such discharges have only classical ion loss effects (i.e. no anomalous energetic ion losses) that TRANSP handles well.

In Fig. 4, the measured and calculated neutron rates are compared for H-mode discharges for 2004 (upper panel) and pre-2004 (lower panel). Again, the 2FG scintillator data is shown by the red squares and the fission chamber data by the green circles. The fission chamber measurements showed a neutron deficit of 4% for 2004 and neutron excess 2% for pre-2004 discharges. Again, the 2FG scintillator measurements, however, changed drastically between 2004 and pre-2004. The 2FG scintillator measurements showed a neutron excess of 14% for 2004 but a neutron deficit of 33% for pre-2004 discharges.

The total spread over the 2002 – 2004 period in the fission chamber measurements compared with TRANSP calculations for both L-mode and H-mode discharges ranges from + 9% to – 4%. These variations could likely be within the statistics of the data sets so it is reasonable to regard the fission chamber response to be stable over the 2002 – 2004 period, unlike the 2FG scintillator detector.

These results present a third conundrum: the NPA diagnostic observes an MHD-induced loss of energetic ions for H-mode discharges but not for L-mode discharges [11] that can be supported only by the pre-2004 2FG scintillator measurements in Fig. 4. For the moment, we ignore the discrepancy between measured and calculated rates and focus on the discrepancy amongst the diagnostic measurements themselves obtained with the fission chamber and the 2FG sc;intillator as well as the other scintillator detectors.

3. Analysis of Neutron Diagnostic Operational History on NSTX

In Fig. 5, the relative response of the 2FG scintillator to the fission chamber is compared for pre-2004 L-mode and H-mode discharges and the equivalent comparison for 2004 is given in Fig. 6. From the linear fits in Fig. 5 it can be seen that the relative response of the 2FG scintillator and fission chamber is independent of L-mode or H-mode operation. The same is true for the 2004 data in Fig. 6. The minimal data scatter in these figures demonstrates the excellent stability of the two detectors within a given operational period. However, a drastic change in the slope on the linear fits to the pre-2004 and 2004 data is observed. The relative response of the 2FG scintillator to the fission chamber for

2004 is ~ 78% higher than for pre-2004. Again, this suggests that a major change in the 2FG scintillator operational conditions occurred between pre-2004 and 2004.

An insight into this situation is afforded by comparing the raw voltage signal ratios of the scintillator detectors to the fission chamber as shown in Fig. 7a and Fig. 7b. The NSTX raw signal ratio for the "control room standard" 2FG scintillator to the current-mode fission chamber (FC) detector are shown by open red squares for pre-2004 and by solid red squares for 2004 in Fig. 7a. The ratios of other scintillators to the fission chamber are similarly displayed. Of particular note is an approximately 61±17% increase in the 2FG/FC ratio between the 2004 and pre-2004 periods. Since the fission chamber detector is believed to be the most stable, the primary message here is that there appears to be a significant increase in the detection efficiency of the 2FG detector from pre-2004 to 2004. The 3DE and 4AB ratios also varied with time, with the 3DE detector showing the least change. However, these detectors are seldom used for calibrated neutron measurements and should be regarded as "indictor only" devices. It is also noteworthy that the 2FG/FC and 4AB/FC ratios appear to decrease with time during a run period, at least in 2003 and 2004. In Fig. 7b, similar data is shown for the 1DE(ZnS) scintillator. The response of this detector showed a marked change following the 2002 run but remained constant to within ~ ± 10% thereafter (note the suppressed zero in the plot abscissa).

Another view of this data is provided in Fig. 8 where detector signal ratios are plotted against the TRANSP-calculated neutron emission rates. This plot reflects the same conclusions as for Fig. 7a, but also indicates that the neutron diagnostic measurements are independent of neutron rate: i.e. no saturation effects are observed with increasing neutron emission.

The most obvious approach to address the discrepancy between the measured versus calculated neutron emission is to investigate the operational conditions for the neutron diagnostics over time. The detector bias voltages for the scintillation detectors have been monitored since 2002 using an H320 digitizer and recorded in the MDSPlus tree. In Fig. 9, the monitored detector bias voltages for the 2FG and 1DE(ZnS) scintillator detectors are plotted against NSTX shot number. While small changes were recorded for the 1DE(ZnS) detector over time, a large drop in the 2FG bias from ~ 1010 volts to ~ 950 volts occurred early in the 2002 run and persisted through the 2003 run. The bias decrease in early 2002 was unintentional and is attributed to a malfunction of the TFTR-legacy high voltage power supply. The 2FG bias was restored to the early 2002 value for the 2004 run. Knowing that the scintillator signal outputs vary as the photomultipier bias voltage to around the 7th power, this implies that the apparent neutron emission measurement for the 2FG detector increased by ~ 52% between pre-2004 and 2004. This resolves the first conundrum noted in the previous section.

Unlike the scintillator detectors, the fission chamber bias is contained in a sealed unit along with the signal conditioning electronics and is therefore not subject to external changes. Although the fission chambers are the most stable of the detectors in the neutron suite, variations of the detection efficiency in the range of ± 5% have been observed over the 2002 – 2004 period. Fig. 10 shows the neutron rate measured by the fission chamber (FC) versus the TRANSP-calculated rate for H-mode discharges with the data points separated for 2004 and pre-2004. The solid line fit to the solid-circle data points suggests that the 2004 measurements are ~ 9% lower than the pre-2004 values (dashed line fit to open-circle data points). The same result is obtained from Fig. 4 which has a slightly different data set.

4. Renormalization of the Neutron Detector Calibration Factors

The procedure for absolute calibration of the NSTX fission chamber neutron detectors was outlined in Sec. 1. The resulting fission chamber calibration factor, $9x10^{13}$ n/s/volt, has an absolute accuracy of ± 20% and has been stable over the 2002 – 2005 time period. The scintillation detectors are cross calibrated against the fission chambers. Historically, this procedure used NSTX discharges with a *sufficiently low neutron yield* that the fission chambers remained in the pulse-counting mode but simultaneously a sufficiently high yield so that the scintillators were solidly in the current mode. Recently, however, it was discovered that this cross-calibration procedure was faulty. The problem was that the manufacturer of the fission chambers claimed that the pulse-counting mode was linear up to $5x10^5$ cps where the scintillators had adequate signal for cross calibration in the current mode. But in fact the fission chambers were linear only up to about one-half this count rate. Thus non-linear saturation of the pulse-counting mode led to the erroneously low scintillator cross-calibration factors.

In this report, the procedure for cross calibration of the scintillators was modified wherein NSTX discharges with *sufficiently high neutron yield* (~ $0.5\text{-}2x10^{14}$ n/s) were used so that the fission chambers and scintillator detectors were all in the current mode. This procedure is illustrated in Fig. 11. The upper panel shows the fission chamber (FC) neutron rate using the calibration factor 9×10^{13} n/s/volt. By way of example, the center panel shows the ratio of the 2FG scintillator detector raw voltage signal to the fission chamber raw voltage signal. Of note here is that this ratio does not stabilize until the neutron yield has "flat topped". This is because the slower time response of the fission chamber causes it to lag the scintillator during periods when the neutron rate is changing rapidly. The cross calibration of the scintillator to the fission chamber was performed during the stabilized phase of the ratio. The calibration factors for the scintillators were then adjusted to make the neutron rates match those of the fission chamber. The result is shown in the overlay of the neutron rates for the fission chamber and the 2FG ad 1DE(ZnS) scintillators shown in the bottom panel.

However, before applying this new calibration procedure a further step was taken. It was noted in Sec. 2 that a second conundrum arose in the analysis of the neutron behavior: namely, for L-mode discharges why do the fission chamber measurements not match the TRANSP-calculated neutron rates more closely since such discharges have only classical ion loss effects (i.e. no anomalous energetic ion losses) that TRANSP handles well? To reconcile this conundrum, the decision was made to normalize the neutron rate measured by the fission chamber to the TRANSP-calculated rates for L-mode discharges. Using the L-mode data sets for 2004 and pre-2004 shown in Fig. 3 along with the combined sets augmented by other L-mode data, a multiplicative factor of 0.91 ± 0.01 was derived leading to a renormalized calibration factor for the fission chamber (FC) of

$8.2 \pm 0.1 \times 10^{13}$ n/s/volt. This value remains well within the error bars for the absolute calibration of the fission chambers and resolves the second conundrum noted earlier.

The first step in renormalization of the neutron detector suite was to apply the above renormalization of the fission chamber. Then the procedure in Fig. 11 for the scintillator detectors was applied to ~ 120 discharges covering the 2002, 2003, 2004 and 2005 experimental run periods by laboriously displaying the scintillator waveforms on a scope page (available at USER1:[SSM.NSTX] neutron_analysis.scope) and manually adjusting the scintillator calibration factors to match the fission chamber waveforms and the averaged calibration factors in each year were obtained. In the data set for each year, discharges were chosen over a range of peak neutron rates of ~ $0.5–3.5 \times 10^{14}$ n/s. No systematic dependence of the calibration factors on neutron rate was observed. The resulting renormalized calibration factors for each year from 2002 – 2005 are given in Table 1. In Table 1, calibration factors used prior to the current renormalization are bracketed. The explanatory notes appended to the table should be consulted for other information. In particular, the procedure for applying the voltage offset and new calibration factors to the neutron waveforms has been revised wherein a correction for the offset voltage is subtracted from the raw signal before multiplying by the appropriate calibration factor.

This recalibration procedure is illustrated in more detail for the 2FG scintillator in Fig. 12. The upper panel shows 2FG/FC recalibration ratio versus shot number. Stepwise changes can be seen between 2002 (red squares), 2003 (green circles) and 2004 (blue diamonds). On average, the earlier calibration factor for the 2FG scintillator (8.8×10^{13}

n/s/volt) needed to be revised upward by factors of 1.35 in 2002 and 1.10 in 2003 but downward by a factor of 0.85 in 2004. The post-2002 variations were due to changes in the bias voltage applied to the 2FG scintillator detector. In the lower panel, the recalibrated neutron emission rates for the 2FG scintillator are plotted against the fission chamber measurements for combined L-mode and H-mode data sets over the entire 2002–2004 operational period. As can be seen, the 2FG scintillator and the fission chamber measurements are in good agreement for all discharge conditions and all years. The minimal data scatter also indicates that both detectors exhibit good stability over time.

Fig. 13 shows the neutron rates measured with the renormalized 2FG scintillator and fission chamber plotted against the TRANSP-calculated rate for the combined L-mode (upper panel) and H-mode (lower panel) data sets over the entire 2002-2004 time period. The 2FG scintillator and fission chamber measurements are in close agreement under all conditions. For the L-mode data set, the measured neutron rates lie within ± 1% of the TRANSP-calculated rates. The measurements for the H-mode data set, however, indicate a neutron deficit of 11.5% relative to the TRANSP-calculated rates under all conditions, albeit with considerable scatter in the data points. If in fact MHD-induced energetic ion loss is operative, this scatter can be attributed to variations the MHD activity such as the mode number, mode amplitude and spatial location of the mode (i.e. q profile). Note that the 11.5% neutron deficit is approximately one-third of that ascribed (erroneously) to the 2FG scinillator measurements for pre-2004 shown in Fig. 4. This resolves the third conundrum noted earlier.

5. Conclusions

The reason that the neutron rates measured with the 2FG scintillator increased in 2004 relative to pre-2004 was traced to an increase in the detector bias voltage in 2004 that was not properly accounted for by appropriately modifying the calibration factor. Furthermore, a long-standing discrepancy between the neutron rates measured with the fission chamber and the scintillator detectors was traced to a flaw in the cross calibration procedure. This was resolved and new calibration factors were derived for each of the years 2002, 2003, 2004 and 2005 so that the neutron rates measured by all detectors under all discharge conditions over the entire 2002-2005 are now in close agreement. With the new neutron calibration factors, the measured neutron rates for L-mode discharges lie within ± 1% of the TRANSP-calculated rates under all studied conditions. The measurements for the H-mode data set, however, indicate a neutron deficit of 11.5% relative to the TRANSP-calculated rates under all studied conditions.

Notwithstanding the analysis presented in Sec. 4, in the interest of simplicity and maintaining continuity with extant TRANSP analyses and associated databases omitting the L-mode normalization step and using the legacy fission chamber calibration factor, 9.0×10^{13} n/s/volt, is deemed acceptable. Further refinements will be made pending the outcome of calculated/measured comparisons during the 2005 run.

Acknowledgements

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Table I Overview of NSTX Neutron Detector Operation

and Revised Calibration Factors

Parameter	Year (Shot Range)	FC1 - Fission Chamber	2FG Scintillator	1DE (ZnS) Scintillator
Detector Bias (V)	Early 2002 (107213-107670)	NA	(1008-960)	(1016)
	2002 (107671-109077)	NA	(945 ± 10)	(1017 ±1)
	2003 (109772-110186)	NA	(954 ± 4)	(1016 ± 2)
	2004 (111060-114475)	NA	(1013 ± 2)	(1005 ± 2)
	2005 (115674 -)	NA	1060 (1008)	850 (804)
Calibration Factor (n/s/Volt)	Early 2002 (107213-107670)	(7.6×10^{13})	($5.4 \pm 1.4 \times 10^{13}$)	
	2002 (107671-109077)	(9.0×10^{13}) $8.2 \pm 0.1 \times 10^{13}$ Offset=0.040v	($8.8 \pm 0.5 \times 10^{13}$) $12.2 \pm 0.70 \times 10^{13}$ Offset=0.082v	($1.2 \pm 0.2 \times 10^{13}$) $1.78 \pm 0.09 \times 10^{13}$ Offset=0.147v
	2003 (109772-110186)	$8.2 \pm 0.1 \times 10^{13}$ Offset=0.040v	$10.2 \pm 0.90 \times 10^{13}$ Offset=0.087v	$1.24 \pm 0.14 \times 10^{13}$ Offset=0.180v
	2004 (111060-114475)	$8.2 \pm 0.1 \times 10^{13}$ Offset=0.040v	$6.95 \pm 0.72 \times 10^{13}$ Offset=0.069v	$1.18 \pm 0.72 \times 10^{13}$ Offset=0.063v
	2005 (115674 -)	$8.2 \pm 0.1 \times 10^{13}$ Offset=0.040v	$7.23 \pm 0.36 \times 10^{13}$ Offset=0.063v	$7.61 \pm 0.07 \times 10^{13}$ Offset=0.095v

Explanatory notes for Table 1 are given on the following page.

1. Bracketed detector biases are monitored values that are ~ 50 volts less than the set value.
2. Bracketed calibration factors are values used prior to new cross calibration and renormalization presented in this report.
3. Shots prior to 115674 in 2005 had various bias voltage settings and special analysis is required if neutron data is needed.
4. Correction for a baseline offset is necessary for the 2FG and 1DE(znS) scintillator detectors. The proper procedure to do this is to correct the raw signal voltage for the voltage offset and then multiply by the calibration factor to get the calibrated neutron rate. For example, on the scope page the tag for 2FG scintillator for 2006 would be: (\NEUT_FLUCT_SLW_2FG-0.063)*7.23e13. This offset should be carefully checked for individual discharges where the measured neutron rate is of special importance.
5. Calibration errors are maximum variations in the data set. RMS error is ~ 1/3 of these values.
6. Within the data statistics, the 2FG and 1DE detector responses did not drift in 2002.
7. With increasing time during the 2003 run, the 2FG/FC raw signal ratio decreased approximately linearly by 25% and the 1DE/FC by 15%. The offset was constant. Since the fission chamber is stable, this means that the observed decrease is in the 2FG and 1DE responses. Correspondingly, the 2FG and 1DE calibration factors increased during the run by the quoted percentages. The calibration factors given in Table 1 are the mean values over the 2003 run.
8. With increasing time during the 2003 run, the 2FG/FC raw signal ratio decreased approximately linearly by 55% and the 1DE/FC by 11%. The offset was constant. Since the fission chamber is stable, this means that the observed decrease is in the 2FG and 1DE responses. Correspondingly, the 2FG and 1DE calibration factors increased during the run by the quoted percentages. The calibration factors given in Table 1 are the mean values over the 2003 run.

Neutron Detector Locations

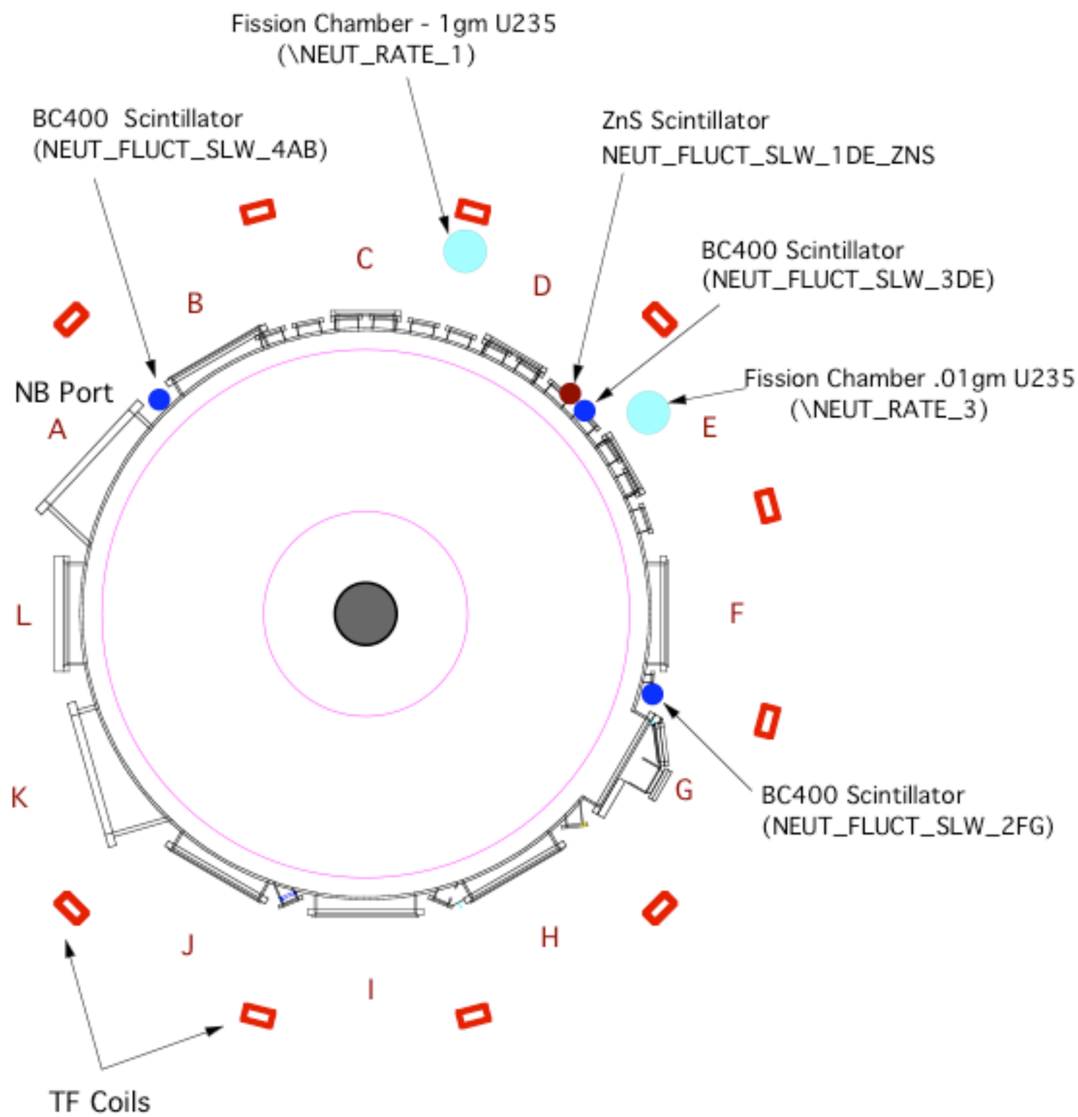


Fig. 1. The layout of the neutron diagnostics on NSTX is shown. The neutron detector suite consists of two absolutely calibrated fission chambers that can operate in the pulse-counting or current modes and four plastic scintillator detectors (including one ZnS detector) all operated in the current mode.

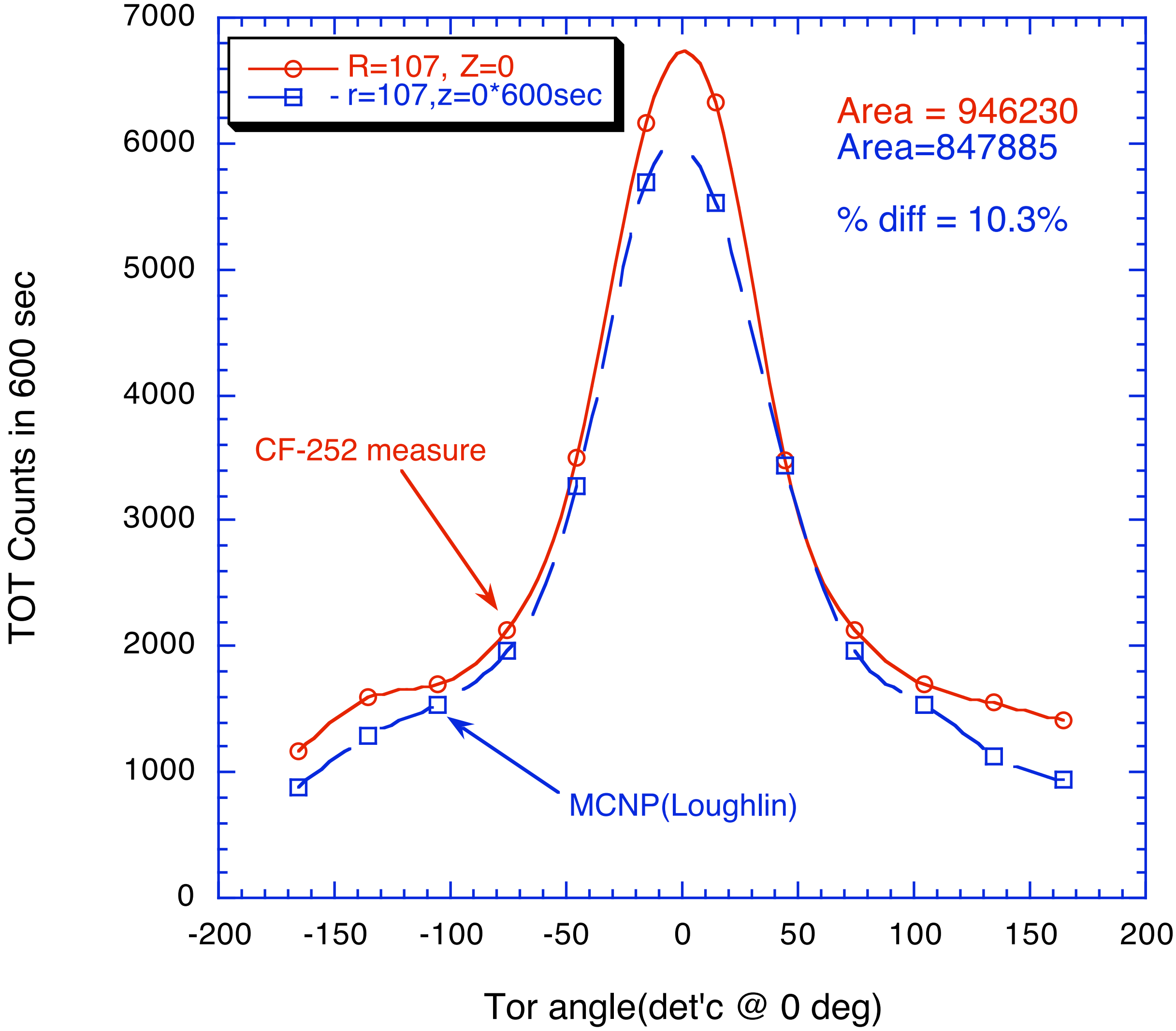


Fig. 2. A ^{252} Cf radio isotope source was placed at R = 107 cm for 10 accessible bays and the neutron rate was measured with the fission chambers in the pulse-counting mode. The neutron code, MCNP, reproduced the calibration results to within 10%.

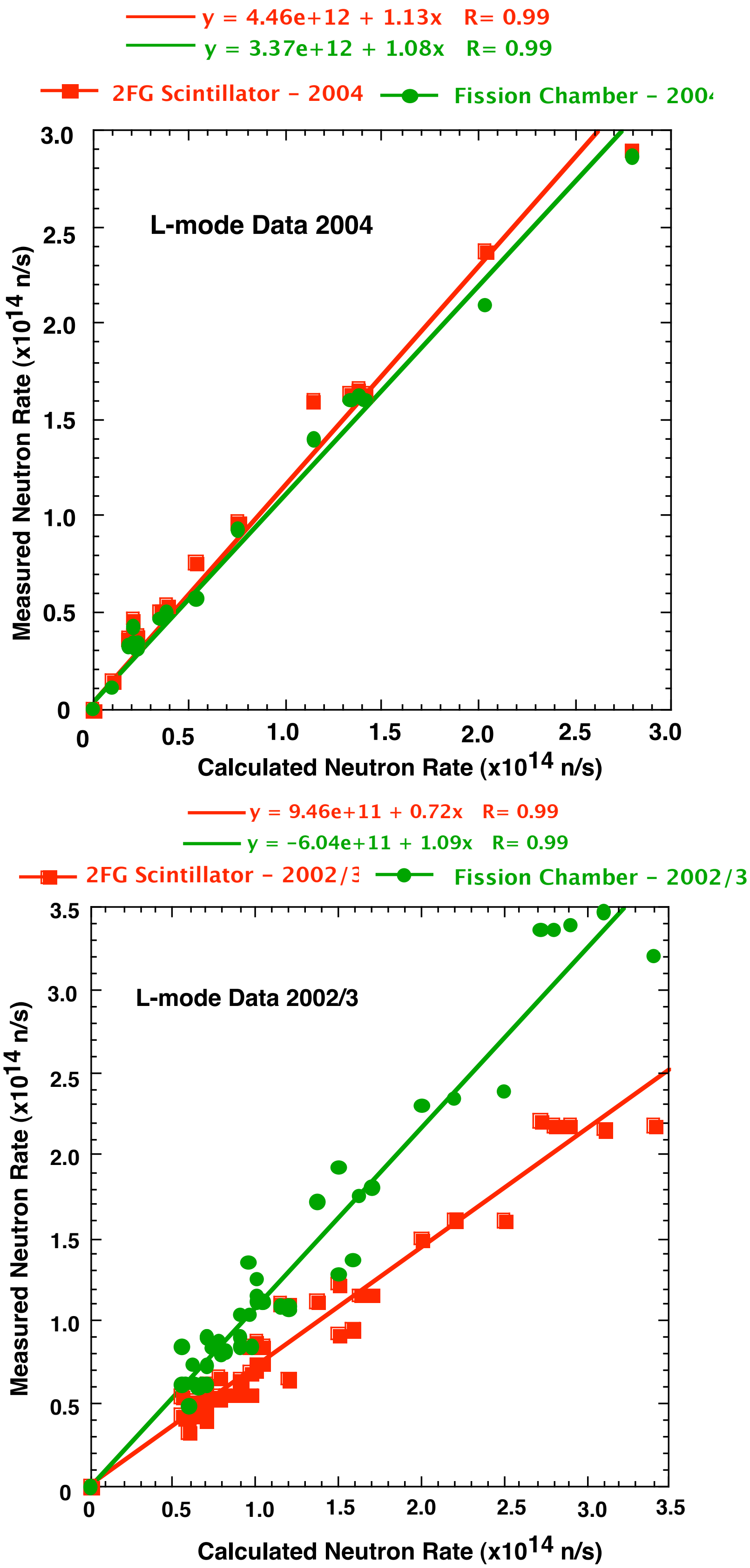


Fig. 3. L-mode discharges are compared for 2004 and pre-2004.

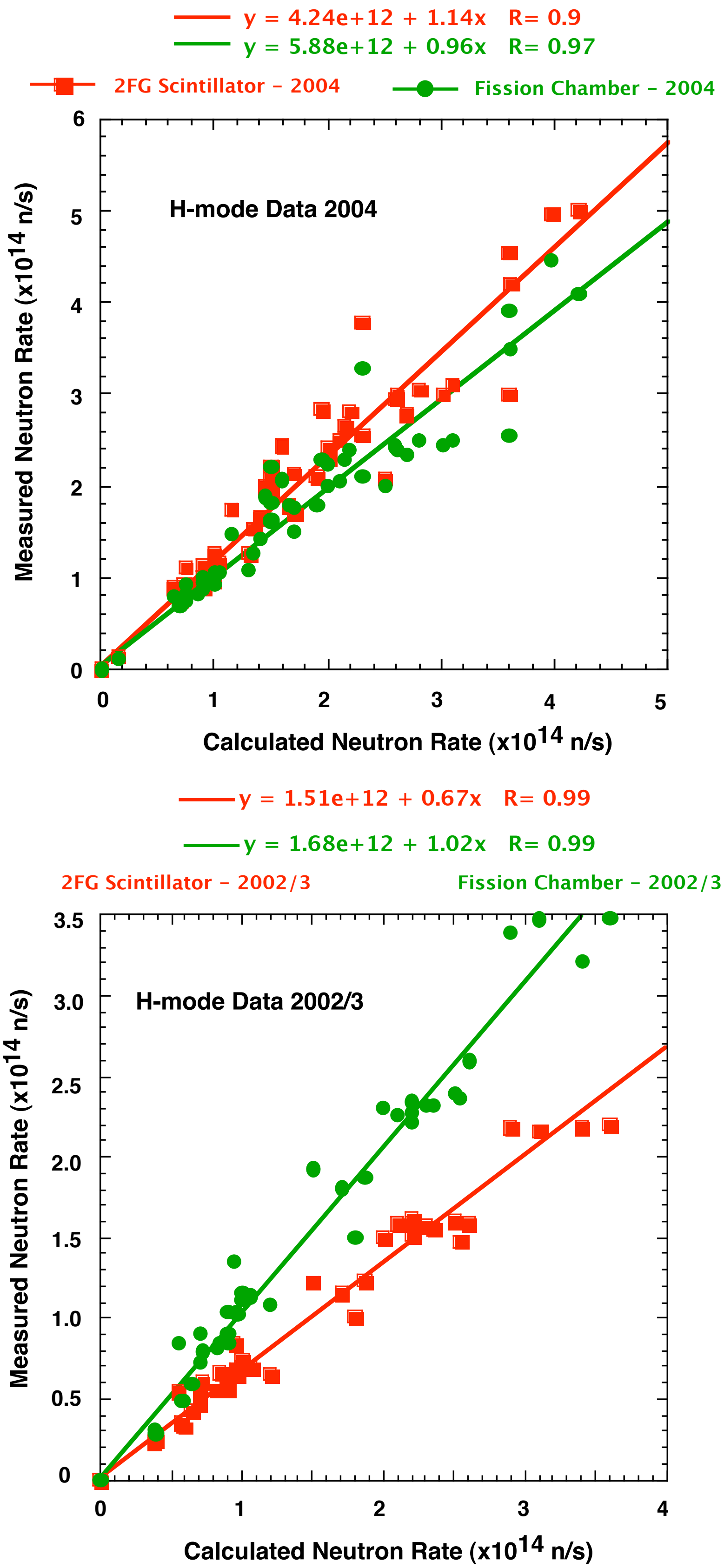


Fig. 4. H-mode discharges are compared for 2004 and pre-2004.

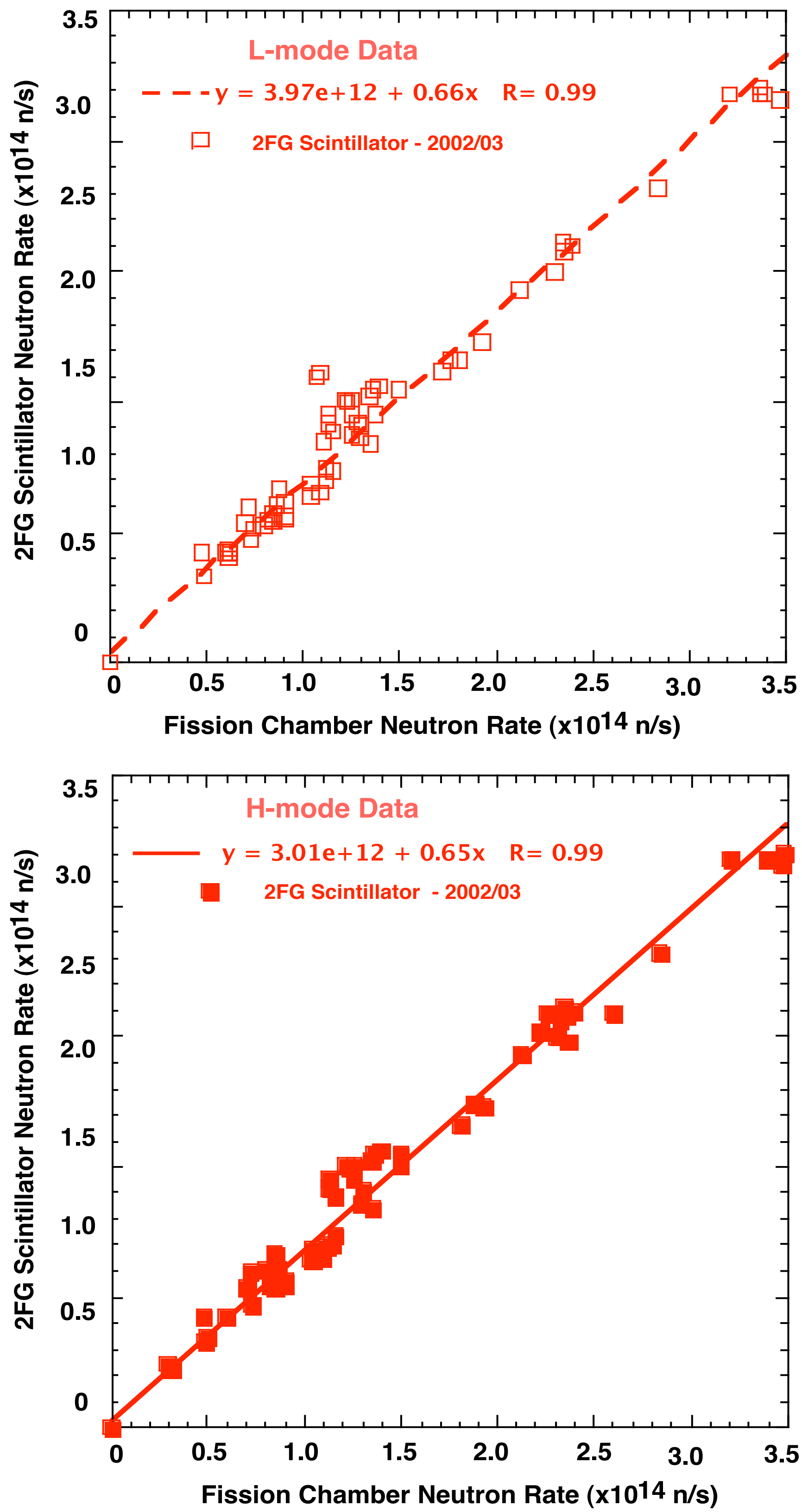
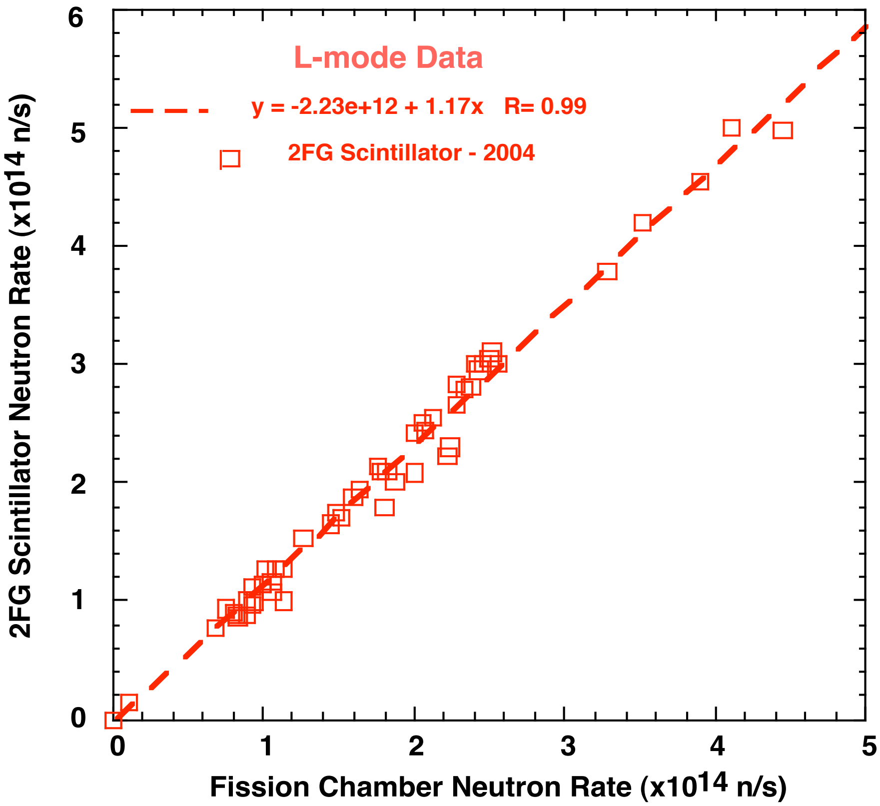


Fig. 5. The relative response of the 2FG scintillator to the fission chamber is independent of L-mode or H-mode discharges for pre-2004 operation.



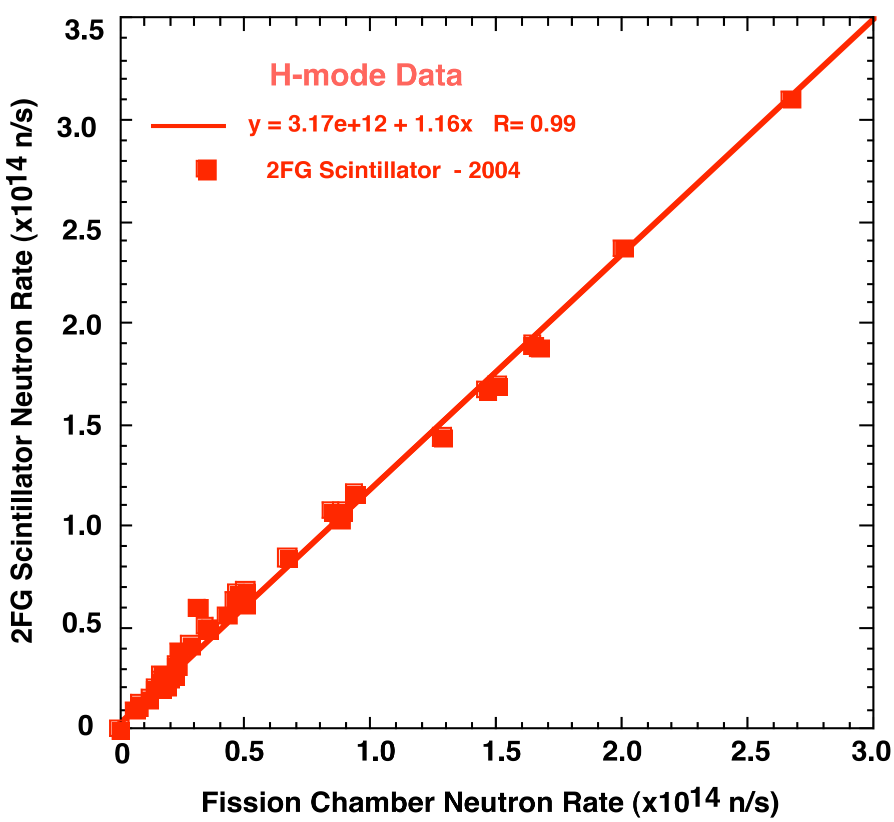


Fig. 6. The relative response of the 2FG scintillator to the fission chamber is independent of L-Mode or H-mode discharges for 2004 operation.

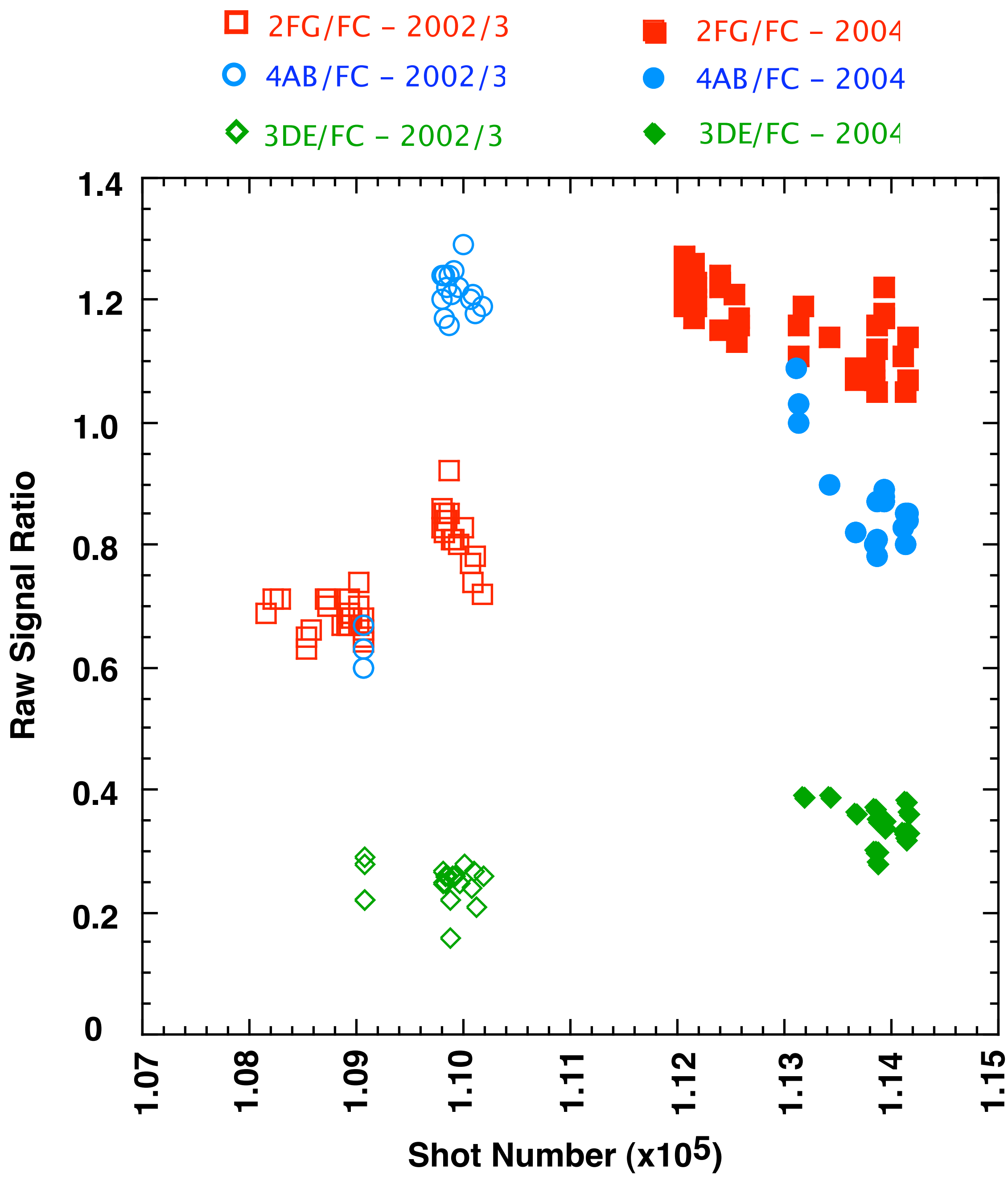


Fig. 7a. The 2FG/FC raw signal ratio changed dramatically between the pre-2004 and 2004 runs. Note also that the ratio of 2FG/FC drooped during the run.

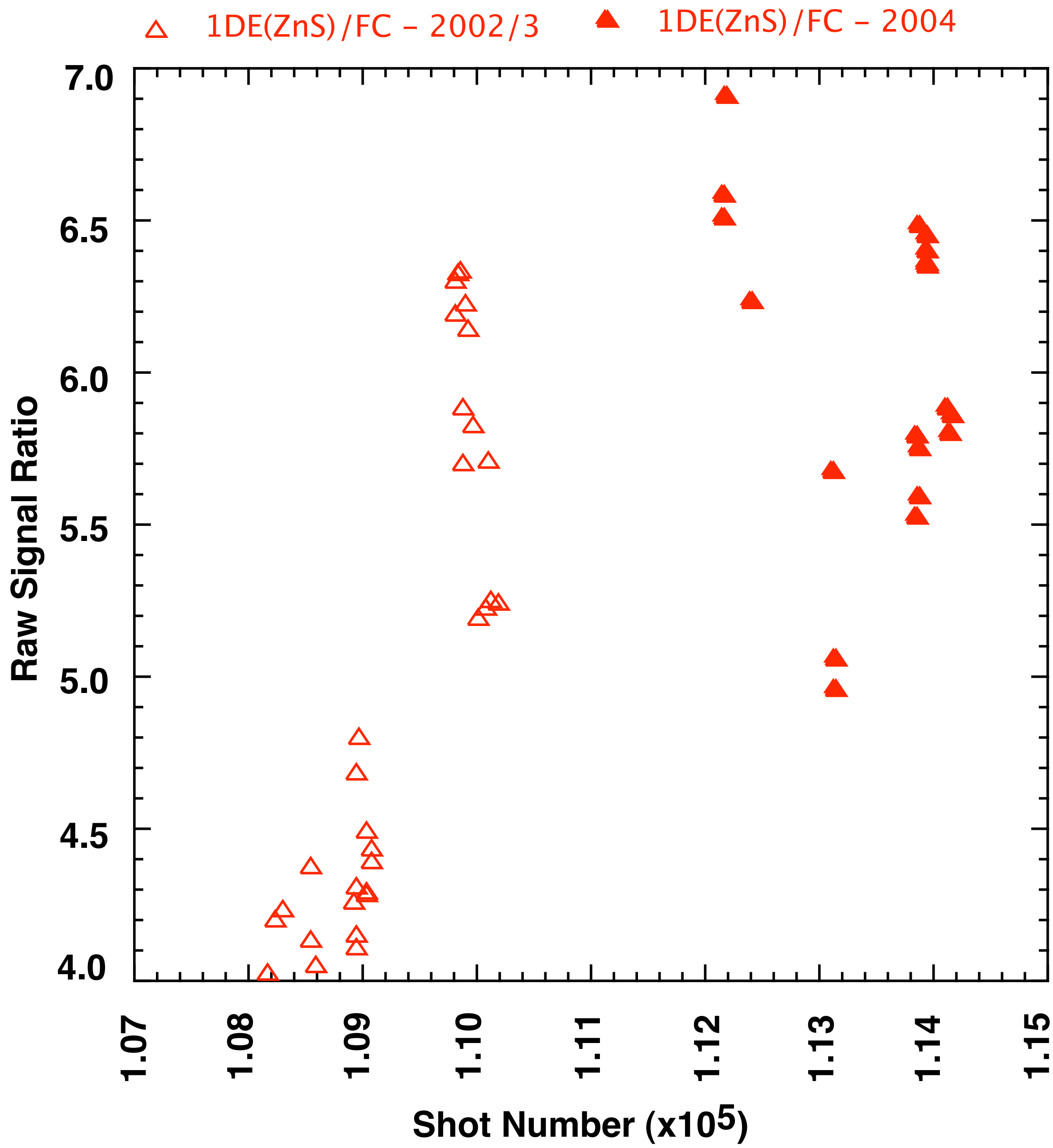


Fig. 7b. The 1DE(ZnS)/FC raw signal ratio increased by ~ 50% following the 2002 run and exhibited a data scatter of ~ 10%. Note the suppressed zero.

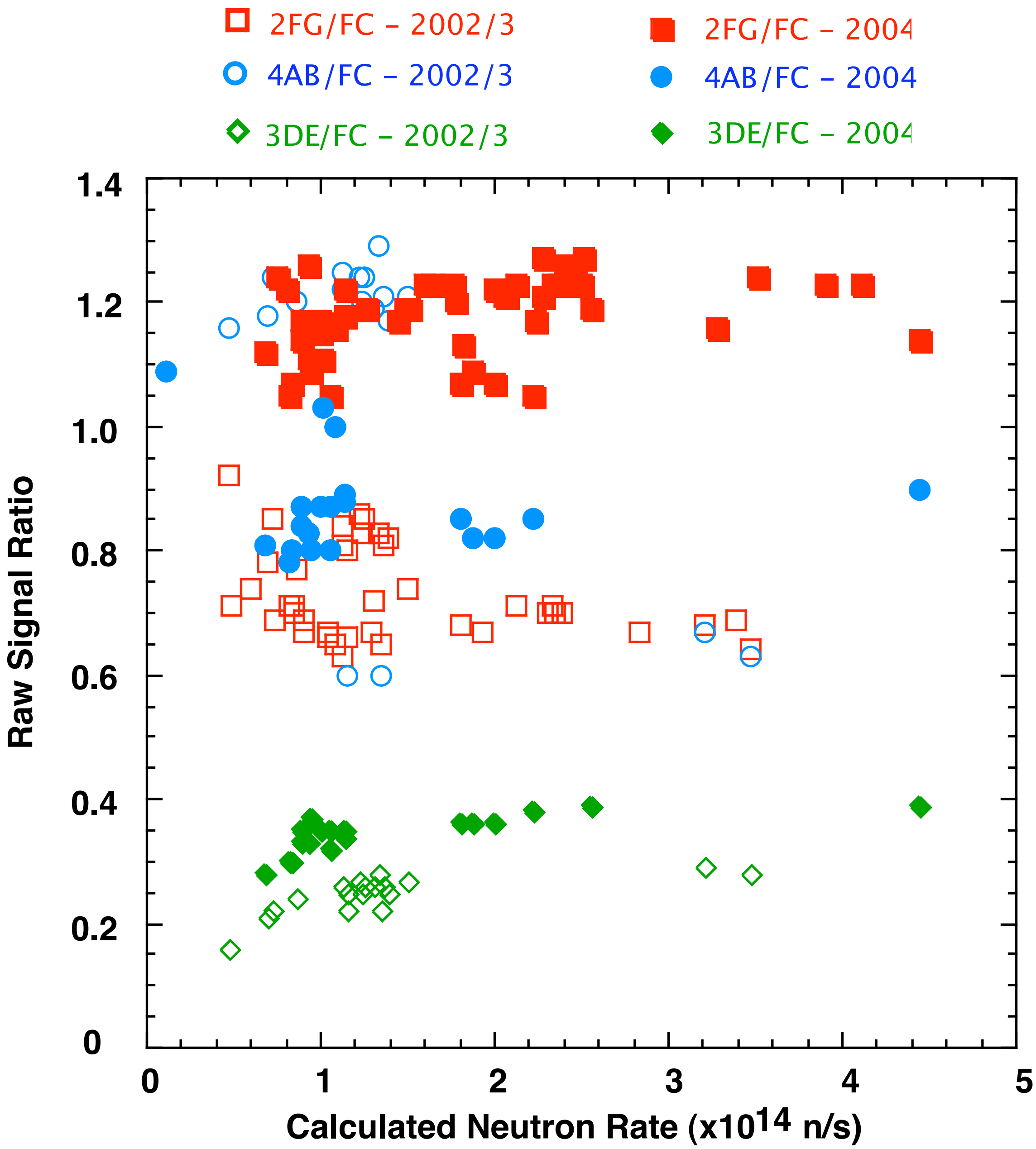


Fig. 8. The ratios of the scintillator raw signals to the fission chamber raw signal are plotted against the TRANSP-calculated neutron rate, sorted into 2004 and pre-2004 data. There is no evidence of detector saturation with increasing neutron yield. In 2004, the 2FG/FC ratio is significantly larger compared with pre-2004.

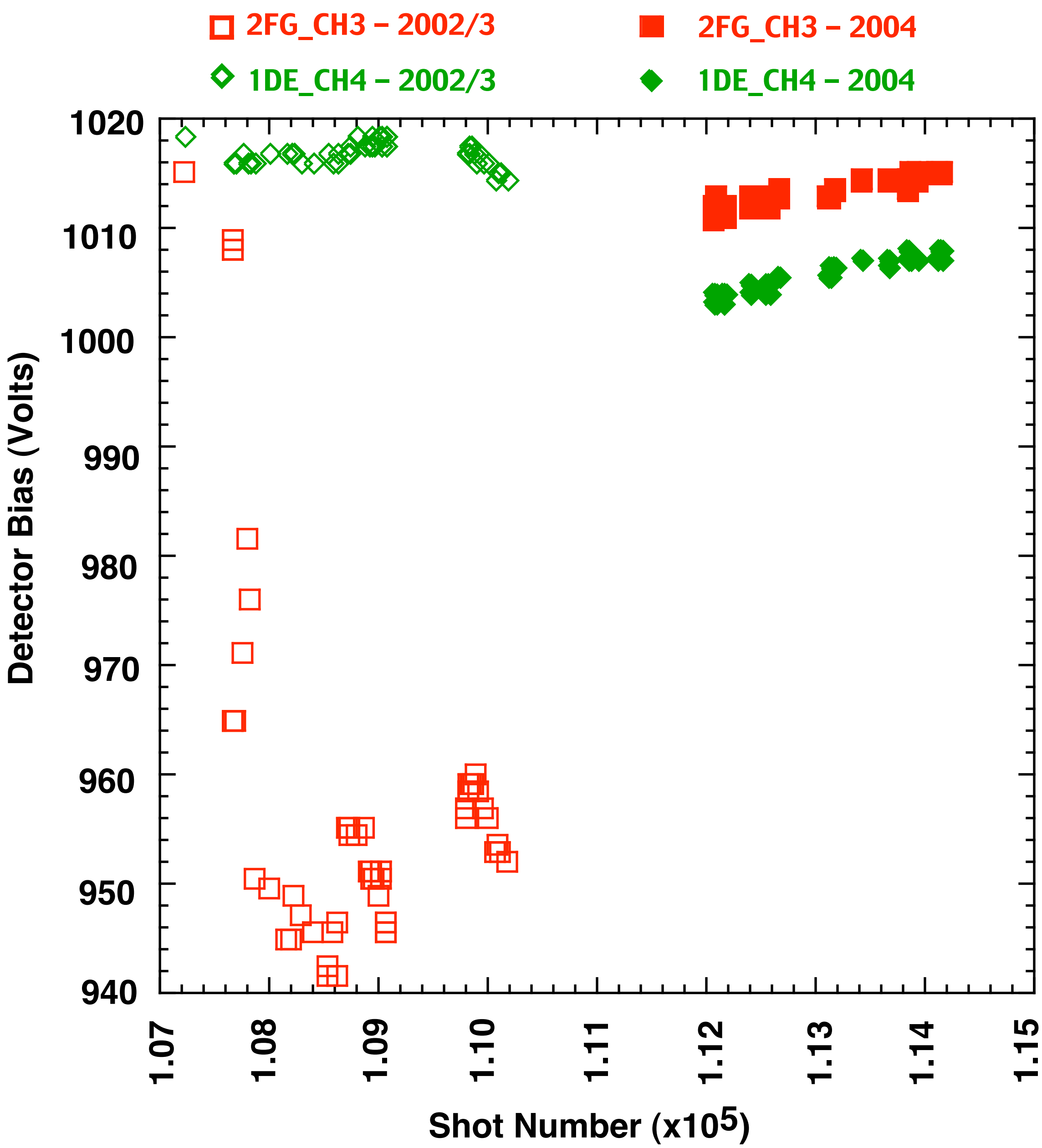


Fig. 9. Evident is a large change in the 2FG scintillator bias from ~ 960 volts in 2003 to ~ 1012 volts in 2004. Since the photomultiplier output varies as $(1012/960)^7 \sim 1.52$, this implies that the 2FG measurement increased by 52% from 2003 to 2004.

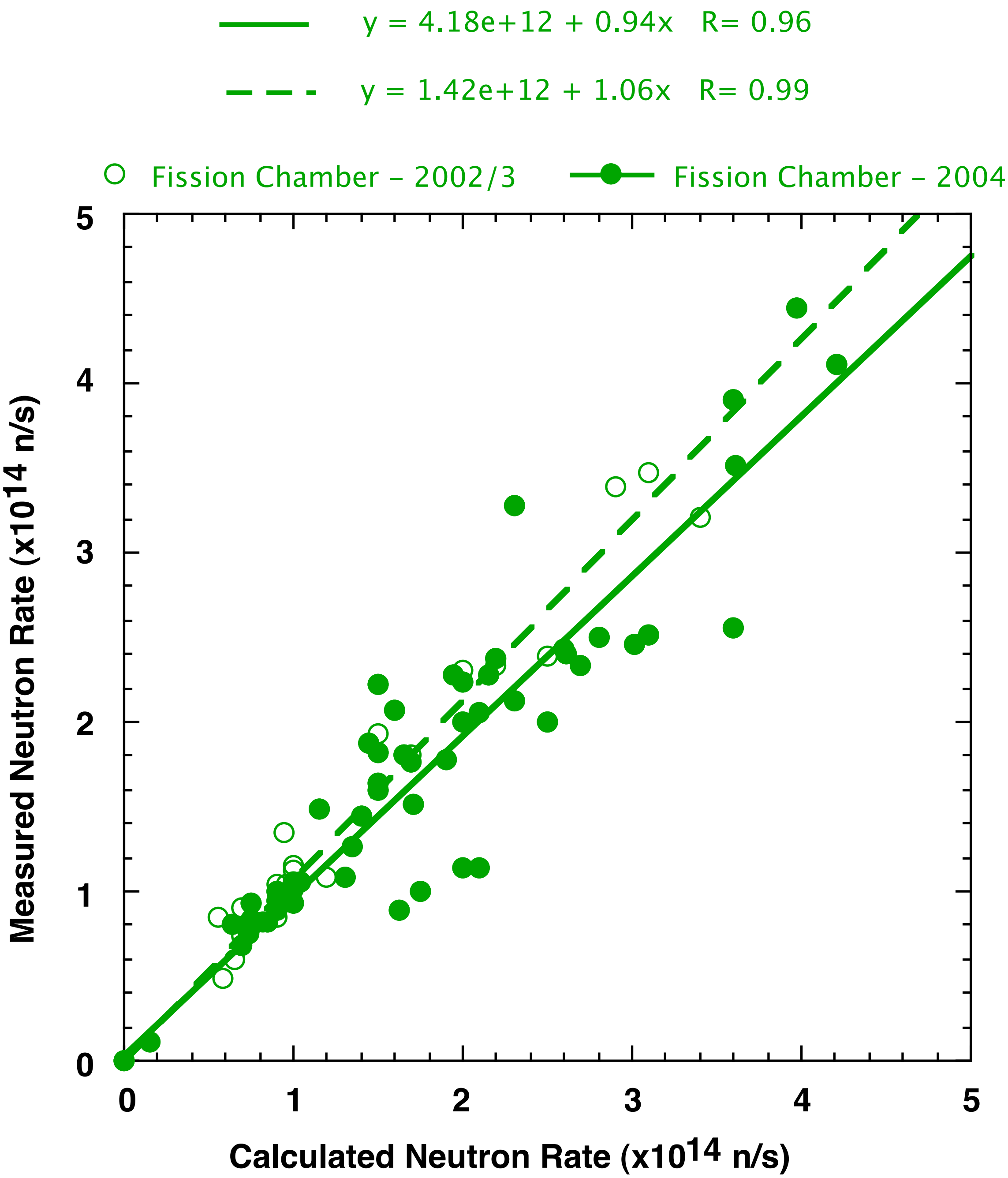


Fig. 10. The fission chamber neutron measurements versus TRANSP calculations vary only by ± 6% around unity for the 2002 – 2004 period.

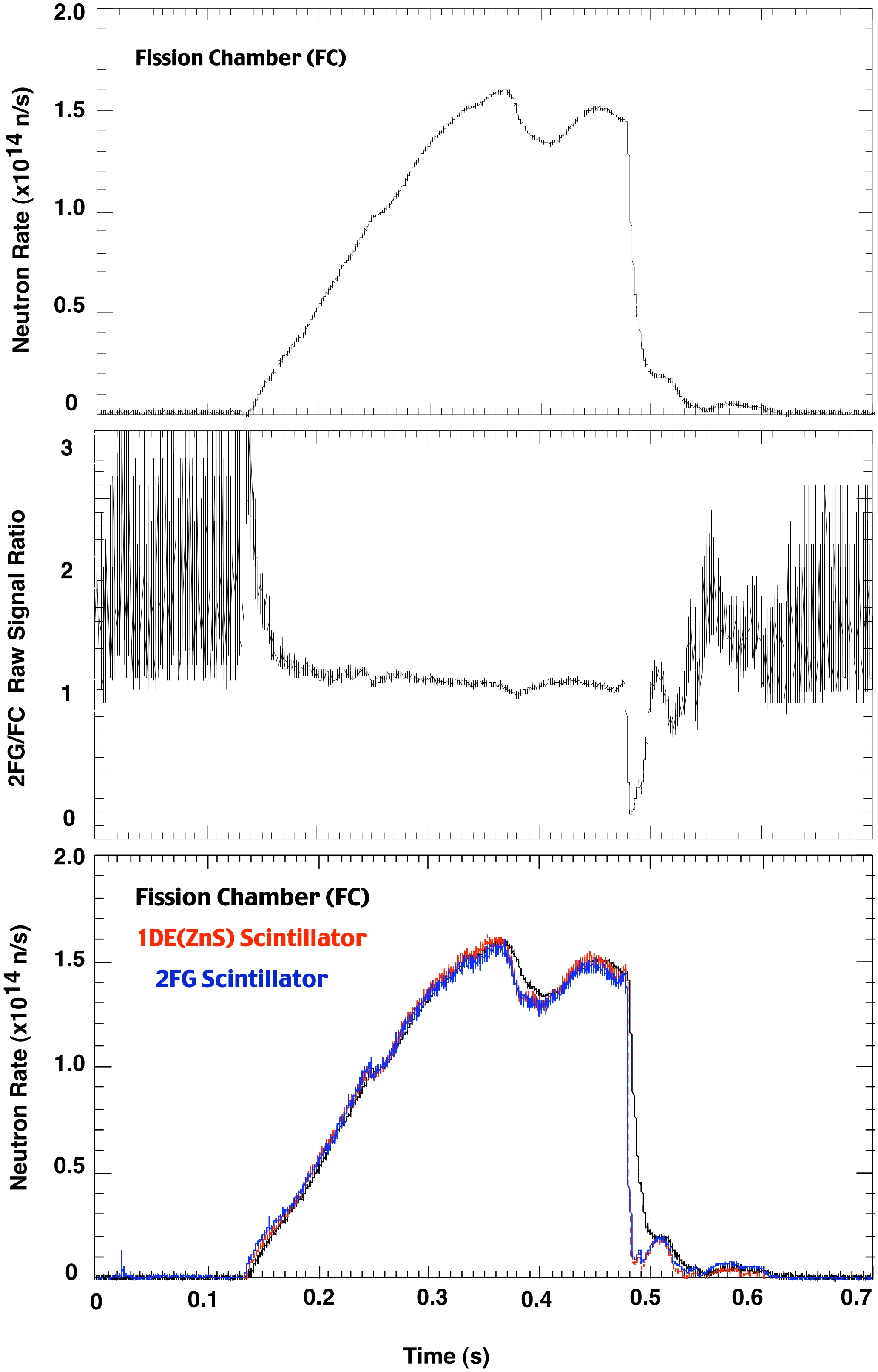


Fig. 11. Illustration of the revised neutron cross calibration procedure.

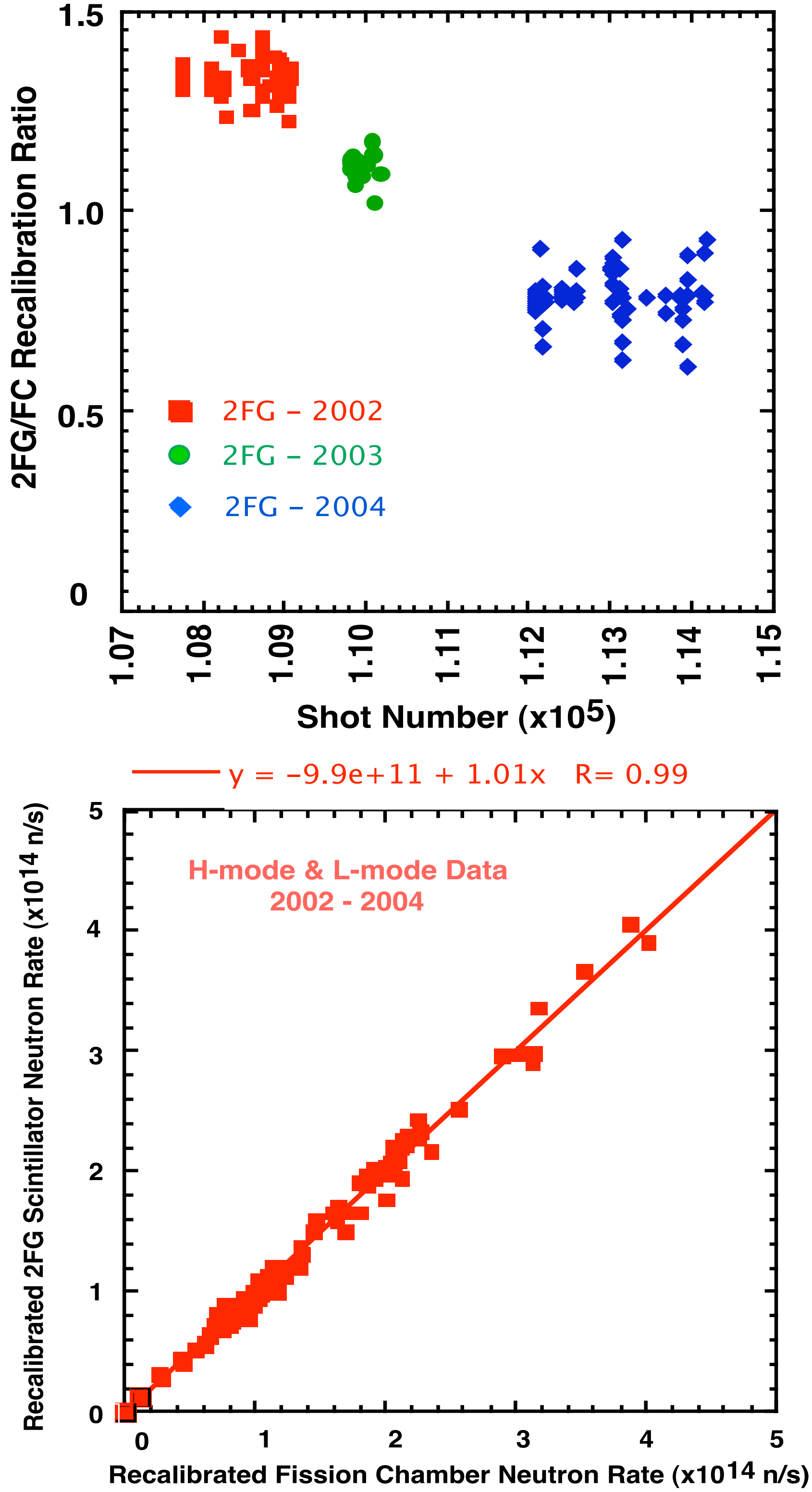


Fig. 12. The coefficients for renormalization of the 2FG scintilltor to the fission chamber (upper panel) varied over time due to changes in the bias voltage. Neutron measurements for the 2FG scintillator and the fission chambers are in good agreement over the entire 2002-2004 period after being renormalized.

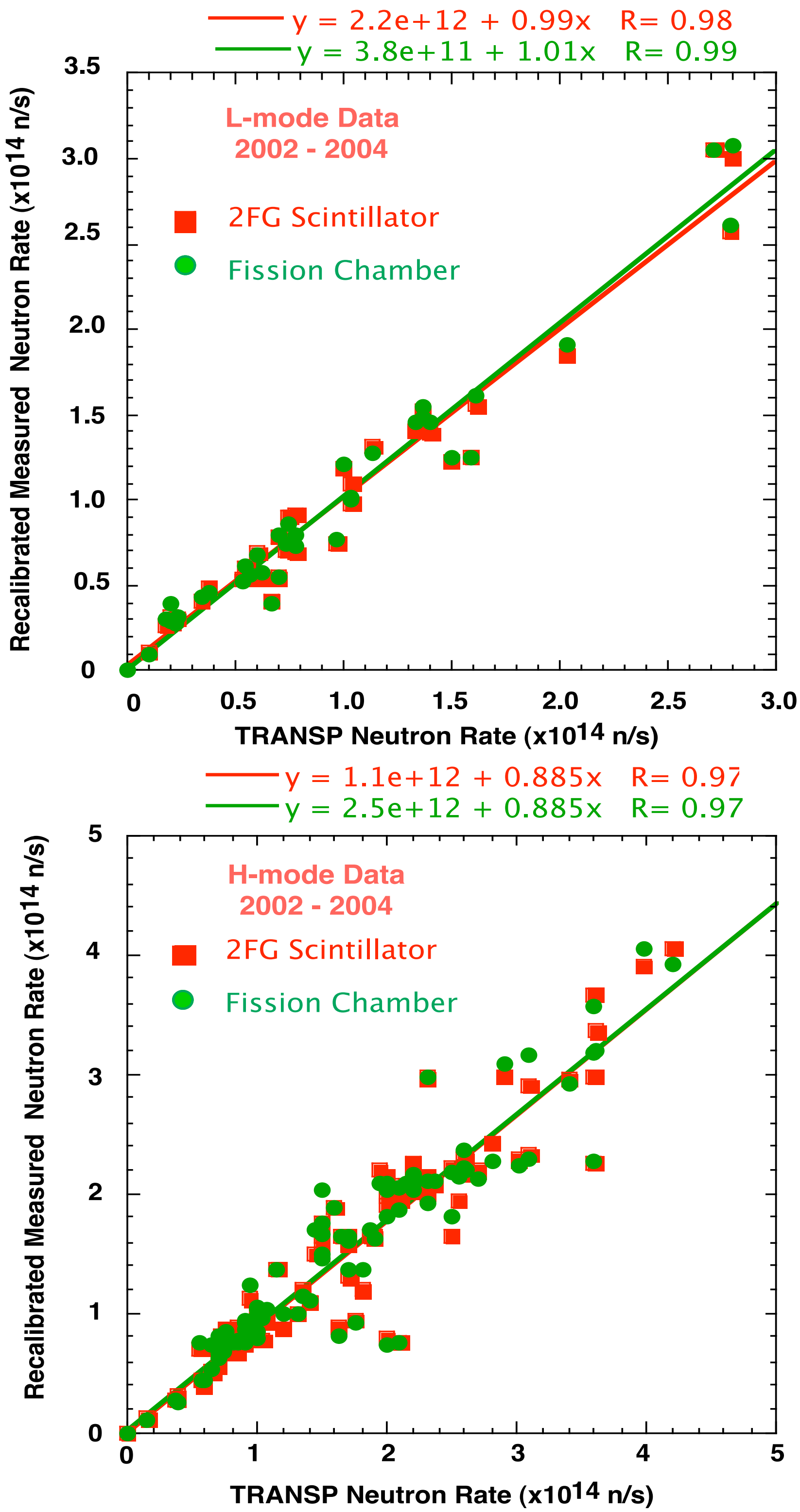


Fig. 13. After renormalization, the 2FG scintillator and fission chamber measurements agree with TRANSP calculations to within ±1% over the entire 2002-2004 period for L-mode data (upper panel). For H-mode data over the same period, the two neutron measurements are also in good agreement and show a neutron deficit of 11.5% relative to TRANSP calculations (lower panel).

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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov