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by

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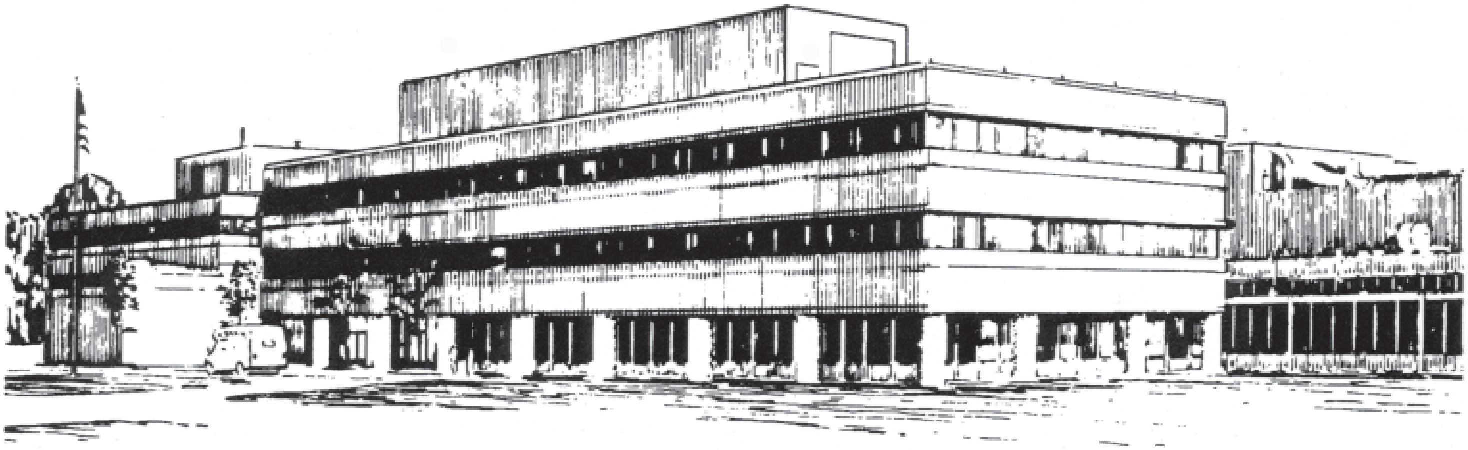

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Application of Natural Diamond Detector to Energetic Neutral Particle Measurements on NSTX

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Two natural diamond detectors have been installed on the National Spherical Torus Experiment to look at escaping neutrals at or near the Neutral beam injection energy. Time resolved measurements have been obtained from these detectors at various tangency radii. The close proximity of the detector to the vessel required the development of a very fast low-noise preamplifier, which has been shown to be superior to similar commercial units. With this amplifier arrangement, electromagnetic pick-up noise was reduced to acceptable levels. However, radiation shielding was required to reduce the background levels from neutron-induced pulses in the detector. Calibration data along with the measured energy resolution is presented in the useful energy range of NSTX. Example data from plasma

discharges will also be presented.

I. Introduction.

Neutral particle analyzers (NPA) are well known as diagnostic tools used to measure the energy distribution of plasma ions. However, their large size and high cost make it difficult to apply multi-channel systems in space-limiting environments. Compact semiconductor detectors can be used as fast neutral-particle analyzers (FNA) and provide a promising alternative for measuring the energy of fast escaping neutrals when the high-energy ion component produced by NBI and/or ICRF heating are to be investigated. Recently two types of semiconductors were successfully applied to the plasma devices for this purpose: the natural diamond detectors (NDD)[1-3] and the silicon diodes[4,5].

Diamond detectors are known to be "blind" to the photons with energy below 5.5 eV, have high radiation hardness[6,7], and operate at the temperatures up to 200°C [8]. By utilizing ultra thin front-end contacts, the low energy cut-off value of NDD's may be reduced to as low as 10-15 keV for deuterium atoms, with an energy resolution ~15 keV FWHM with room-temperature preamplifier. Hence, the NDD provides reliable spectra measurements in the energy region $E_d > 25$-30 keV depending on the fast neutral count rate.

Thin "dead" layer silicon diodes have much lower cut-off energy and better resolution, but they are more sensitive to near-infrared and visible light ($E_{ph} > 1$ eV). If the amplitude of fast variations of light intensity is too high, it could require installing a front-end filter, thus negating the advantages. It was found, however, that visible light does not affect the detector performance at plasma devices, if the relative intensity of the fast neutral flux is high, and the required detector field-of-view (FOV) is small enough to suppress the light[4]. It should be noted also, that the sensitive volume of Si detectors can be chosen to be reasonably small (0.1 mm^3 and lower) in order to reduce the sensitivity to X-rays, gamma and neutron radiation, if needed. However, the stability of Si detectors performance under bombardment by energetic particles still remains questionable, though there have been promising technology improvements[9].

In this paper, the development of NDD-based FNA for application on the NSTX tokamak is reported. The major goals are to study the dynamics of escaping neutrals at or near the neutral beam injection energy, measure the slowing down of confined fast ions, and determine the correlation of ion loss-rate at different pitch-angles.

II Detector Characteristics

The detectors were fabricated in TRINITI (Russia) with the use of extremely pure natural type IIa diamond samples (nitrogen content < 10^{17} cm^{-3}). Common diamond plates have irregular shape of 10-20 mm^2 area and 0.2-0.3 mm thickness. Ultra-thin (40-100 nm) pyrographite contacts were deposited on the both plate sides, forming a conventional sandwich structure having a low energy cut-off of E^D_{co} = 10-20 keV for deuterium ions. The nature of this lower ion energy limit will be discussed below.

Two NDDs were selected which fulfilled the following requirements: each detector operated at a reasonable bias voltage of ~150 volts, displayed a low leakage current, provided a stable and uniform spectral response over its 3-5 mm^2 sensitive area and had low energy cut-off value E^D_{co} < 15 keV with an acceptable energy resolution ~15 keV FWHM.

A. Detector Unit Design

Since NDDs are intended to be installed in close proximity to the NSTX and maintained at the primary vacuum of the vessel, the detector unit design has to meet a number of strong requirements including compact size, good vacuum and compatibility at high temperatures, good Faraday shielding and the shortest length between the detector and preamplifier. A schematic drawing of the detector housing is shown in Fig.1. An NDD is mounted on a Ceramaseal^{TM} glass-ceramic SMA vacuum feed-through connector that is welded on the axis of 2.75” Conflat flange. A copper cylinder surrounding the detector provides EMI shielding and reduces the detector FOV. The preamplifier is mounted inside of a 22 mm diameter copper cylinder fixed on the outer flange surface. The design provides the shortest (~2.5cm) coupling between NDD and preamplifier input eliminating intermediate connectors which reduces the stray capacitance and provides better EMI noise suppression. A circular aperture located in the flight tube 25-50 cm in front of the detector defined the actual FOV. The diameter of the aperture was varied between 0.2-0.5mm to accommodate the plasma conditions. A remotely controlled variable-aperture is presently being fabricated to allow adjustment of the FOV between discharges if necessary.

B. NDD Calibration

The precise calibration of NDD spectral response to D^+ ions in the 25-350 keV energy range was performed at the ion accelerator of the Lebedev Institute of Physics, Moscow. An output ion beam was focused onto a 1 mm circular aperture for reducing the contribution of residual H_2^+, secondary D_2^+ and lower energy D^+ ions down to the negligible level. In order to reduce the beam intensity, the detectors were irradiated by ions, which were backscattered from 10 nm thick Au target deposited on a polished diamond plate. Large differences between the energys of ions backscattered from a gold layer and from a carbon substrate provides good separation between the calibration peak and the background spectrum (Fig.2). According to the measurements performed with a reference Si detector, the broadening of the incident ion spectra due to the straggling and non-uniformity of the Au layer does not exceed 5 keV FWHM for 60 keV D^+ test beam. The results of NDD2 calibration are shown in Fig. 3a. The response in 30…100 keV energy range is almost linear with low-energy cut-off value $E^{D}_{co} \approx$ 14 keV. The energy resolution varies in the range 13…16 keV FWHM (Fig. 3b).

The value of low-energy cut-off is approximately expressed as:

$$E_{co} \approx E_{dead} + E_i \tag{1}$$

Where E_{dead} is an amount of ion energy deposited in the surface "dead" layer, which does not contribute to the motion of the charge carriers. This includes the contact layer and the surface low-electric field region and effective surface recombination layer. E_i is an intrinsic lower ion energy limit. An ion with energy below this value cannot transfer enough momentum and energy to an electron in valence band to overcome the semiconductor bandgap E_g (5.5 eV for diamond). For the simplest indirect parabolic energy band model:

$$E_{min} = E_g \cdot M_i/m^{*}_{e}(1+ \_/E_g(1-\surd 1+E_g/\_)) \approx E_g \cdot M_i/2m^{*}_{e} \tag{2}$$

where M_i is the ion mass, m^{*}_{e} is the effective electron mass in diamond lattice, and $\_ = p_m^2/2m^{*}_{e}$ where p_m is the electron quasi-momentum at the bottom of diamond conductive band valley. More complicated analysis taking into account the detailed energy band structure is required for better accuracy, but the lowest achieved up to now experimental energy cut-off E^D_{co} = 9.6 keV agrees well with an approximate value of E^D_{min} ~10 keV derived from equation (2).

Final calibration of the total system was made by special NBI shots into the neutral gas in the vacuum vessel with no plasma, similar to the procedure described ealier[5]. Additional data is obtained in some plasma shots, when the NBI was still injecting during the current ramp-down phase.

C. Preamplifier and Electronic Setup

A fast low-noise charge-sensitive amplifier (CSA) was designed so that the required detector bias (up to V_{bias}=200V) and decoupled signal transmission could be provided by a single 50-Ohm coaxial cable. This design results in the reduction of EMI noise pick-up by eliminating ground loops. The preamplifier has 20 ns risetime with the detector capacitance < 10 pF, and the quiescent current < 6 mA at V_{bias} = 150 V. The detector current along with the 2 mA supply current required by the DC shifter circuit is < I_{max} = 10 mA which is easily supplied by an ORTEC-556 HV bias module.

The block diagram of a typical NDD electronic setup is shown in Fig.4. A fast ORTEC-579 amplifier with 100 ns shaping time and octal low-level discriminators were used to obtain 2 MHz upper count rate as required for 1 ms temporal resolution.

D. Shielding and Radiation Hardness

With up to 6 MW NBI power, the maximum DD-neutron yield from NSTX exceeds 10^{14} n/sec. The NDD installed 1.5 m from the plasma axis, will receive $\sim 2 \cdot 10^8$ n/cm$^2 \cdot$sec DD neutrons, not taking into account the additional scattered component. Measured background counts from neutrons as well as n-γ's are of the order of 10^4 n/sec in a detector 1.5m from the plasma axis. Hence a radiation shield to suppress neutron and gamma signals is required. Due to the space limitations at currently available ports on NSTX, an inner layer of lead ~5 cm thick and an outer wall of boronated-polyethylene 5-10 cm thick were installed but resulted in less than 10-fold attenuation in the radiation induced noise. For future measurements additional options are to be considered, for instance, moving the NDD back further, increasing the shield thickness and collimator design, decreasing the sensitive volume of the NDD and extending the upper level of the counting electronics.

Very fast MCA devices with ultra-high throughput in pulse-height analysis (PHA) mode of up to $4 \cdot 10^6$ events/sec and higher, are commercially available now[10]. A promising new approach based on fast digital signal processing (DSP) is potentially able to reach the ultimate detector count rate level of $\sim 10^7$ cps for the NDD. With this equipment, the dynamic range of NDD-FNA would be acceptable even at ~10^4 cps background. However, the increase of input neutral flux intensity results in more rapid degradation of detector front-end surface.

The studies of NDD radiation hardness with respect to 80 keV D^+ ions up to the deuteron fluence ~$6\cdot10^{12}$ cm^{-2}, were performed at the same ion accelerator facility. The relative variations of NDD count rate (defined by detector actual sensitive area), charge carrier collection efficiency and spectral resolution of 80 keV D^+ test beam ions are shown in Fig. 5. A large degradation of the NDD sensitivity was observed above ~10^{12} cm^{-2} of deuteron fluence. This implies that for a NDD with 3-5 mm^2 sensitive area it can withstand ~1hour of continuous operation at the ultimate count rate of 10^7 cps.

The NDD neutron radiation hardness is known to be >10^{14} n/cm^2, which is sufficient to withstand the total NSTX neutron yield over the estimated life of the project[6,7].

III. Experimental

The NDD's were placed in three locations. In the first location the detector viewed the plasma radially between a 5 cm gap between two HHFW antennas. The radial view produce little signal from the fast neutral beam ions, which were injected parallel to the plasma axis. This did however provide a good test for a special battery-powered preamplifier, which exhibited excellent noise immunity to the high-powered (up to 3.5 MW) radio-frequency currents in the immediate vicinity of the NDD location.

A second location viewed the co-going particles at a fixed tangency radius of ~90 cm. Calibration results obtained by injecting a single NB source into a neutral gas inside the vessel successfully verified the location of the full, half, and third energy neutral beam components obtained during initial calibration in Russia. Because of a problem with the data acquisition electronics, no useful plasma data was obtained at this location.

The third location was mounted on the straight-through port behind the scanning NPA. Extensive data was taken in this location as the NPA sightline was scanned through a range of tangency angles. This data is to be presented in a future paper. However, it can be noted that for energies greater than 30 keV, qualitative agreement was found between the NDD and NPA. This initial data were taken with only eight discriminator settings spanning the full range from 30-100 keV so quantitative data is difficult. Fig. 6 is a good example of the data taken with source B (tangency radius of 60 cm) injecting at 100keV with 2 MW of beam energy. The NPA, and thus the NDD, was set to view at 82 cm tangency radius for this discharge. The neutral beam is initially injected into the current ramp-up phase where the density and current are low and the features of the full, half, and third energy beam components are readily observed. As the plasma current increases the ions are better confined and the beam features are less pronounced. At the end of this discharge the beam continues to inject during the current-ramp down and the beam components again start to appear.

IV. Summary and Future Work

Two NDD-FNA modules were developed and installed on the National Spherical Torus Experiment facility to provide time resolved measurements of the fast neutral spectra. Reliable data in the energy range E_D > 30 keV with ~1 ms temporal resolution had been obtained. For the detector locations in the close proximity to NSTX, the proper neutron shielding and application of EMI noise suppression techniques were found to be of great importance. Two fixed tangential views with tangency radii of ~70 cm (same as NB source A) and 90 cm are presently being developed. They should give information on the evolution of fast ion confinement especially during MHD. Further developments are underway for the reduction of the background count rate, improvement of the device reliability and noise immunity, and to extend the dynamic range of the fast neutral flux. The number of discriminator channels will also be doubled and a full function multi-channel analyzer will provide time dependant spectra.

Acknowledgments

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Figures Captions:

Fig.1 Detector and preamplifier schematic provides maximum EMI shielding and reduces stray capacitance between the detector and pre-amplifier.

Fig.2 NDD measured spectra obtained at selected D^+ energies.

Fig.3a. Linear fit of the peak MCA channel number from FIG.2 versus deuterium beam energy.

Fig.3b Full-Width-Half-Max of spectra from FIG.2 as a funtion of deuterium beam energy.

Fig.4 Typical schematic of NDD signal processing electronics.

Fig.5 Changes occur in the detector sensitivity, charge collection time, and FWHM of NDD detector with total accumulated fluence.

Fig.6 Evolution of fast neutral spectrum obtained during 100 keV, 2MW injection of Source B. The full, half and third energy components are evident during the current ramp-up and ramp-down phases of the discharge. Confinement is seen to improve during the current flattop.

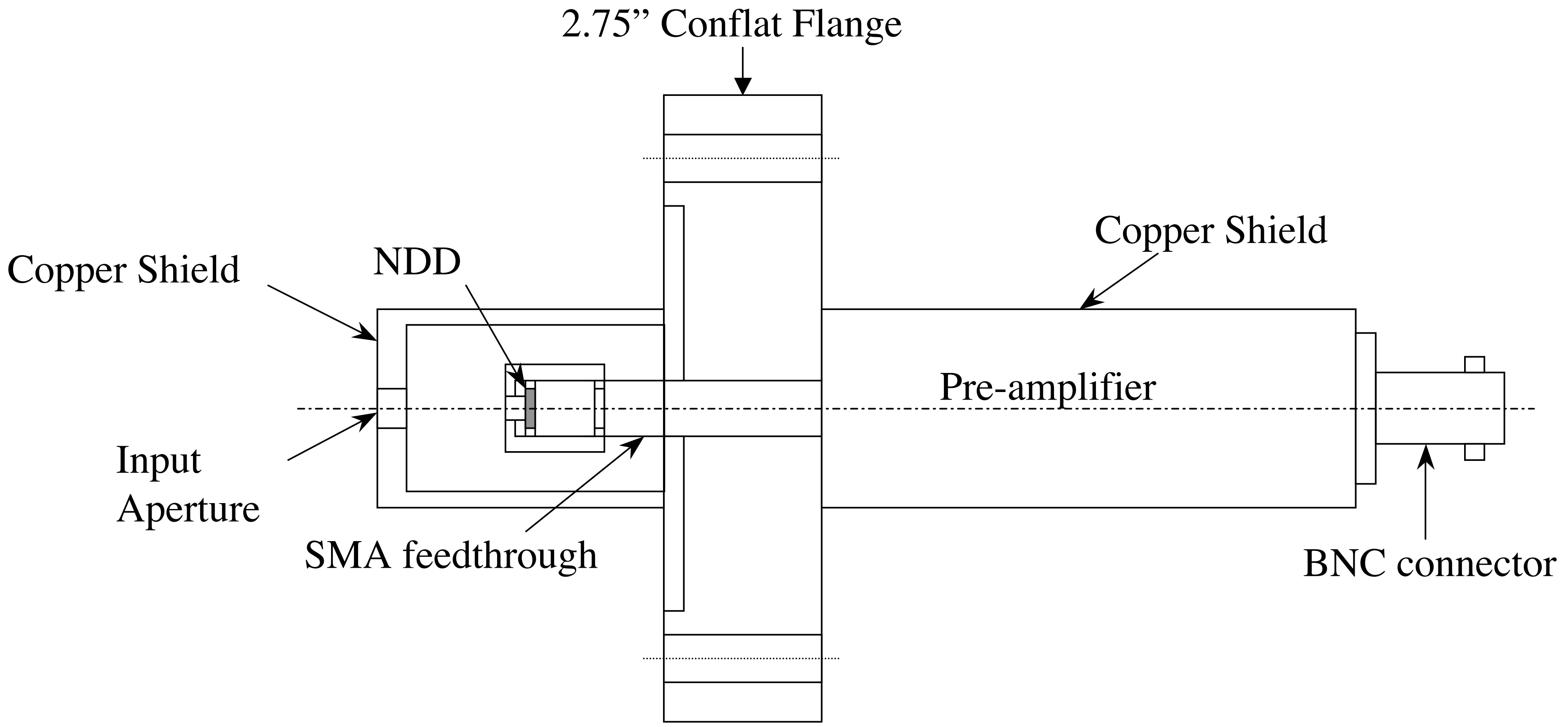

2.75” Conflat Flange
Copper Shield
NDD
Copper Shield
Pre-amplifier
Input
Aperture
SMA feedthrough
BNC connector

FIG 1.

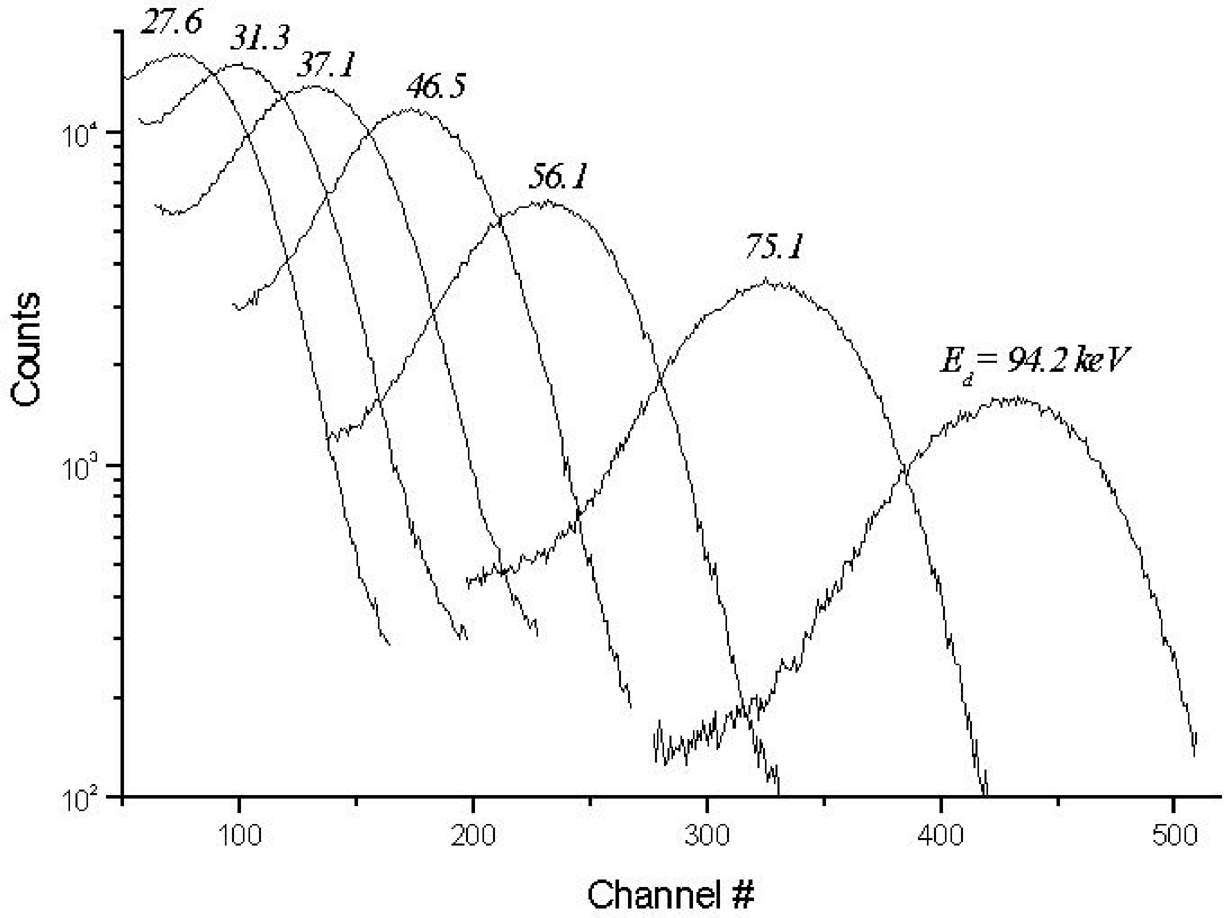

27.6
31.3
37.1
46.5
56.1
75.1
E_d = 94.2 keV
Counts
10^4
10^3
10^2
100
200
300
400
500
Channel #

FIG. 2.

Fig3a..

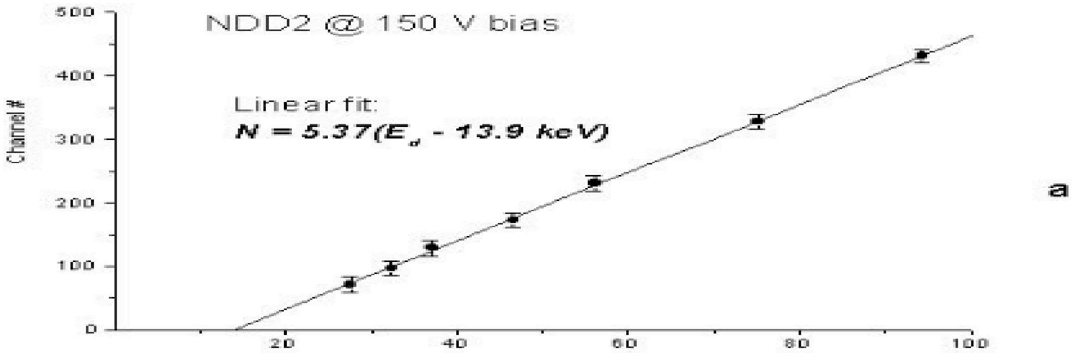
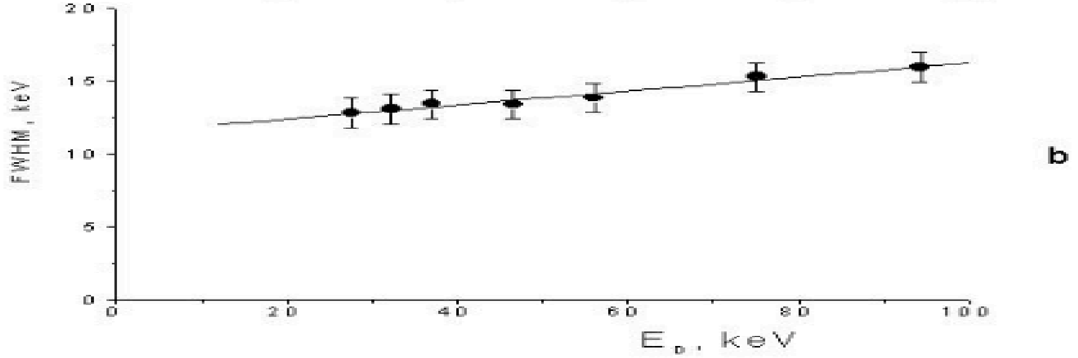

NDD2 @ 150 V bias
Linear fit:
$N = 5.37(E_d - 13.9\ keV)$
Channel #
500
400
300
200
100
0
20
40
60
80
100
a

Fig. 3b.


FWHM, keV
20
15
10
5
0
0
20
40
60
80
100
E_D, keV
b

NDD Schematic

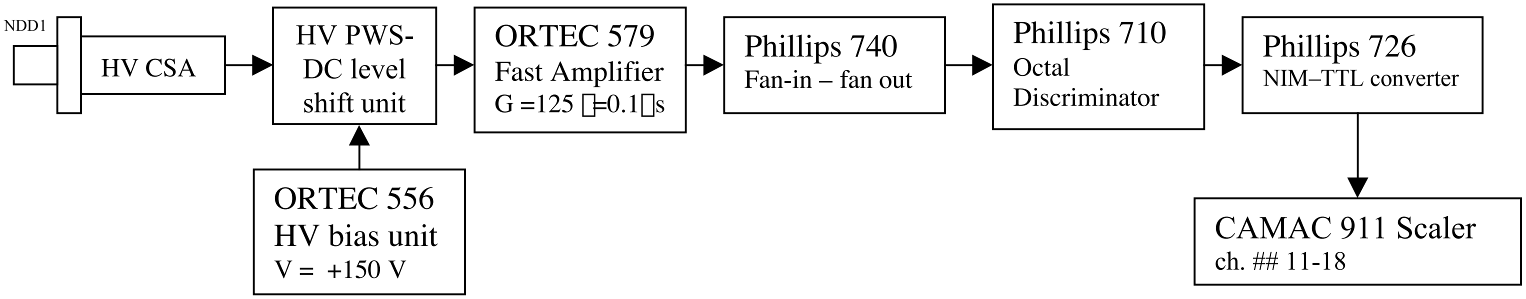


Fig. 4.

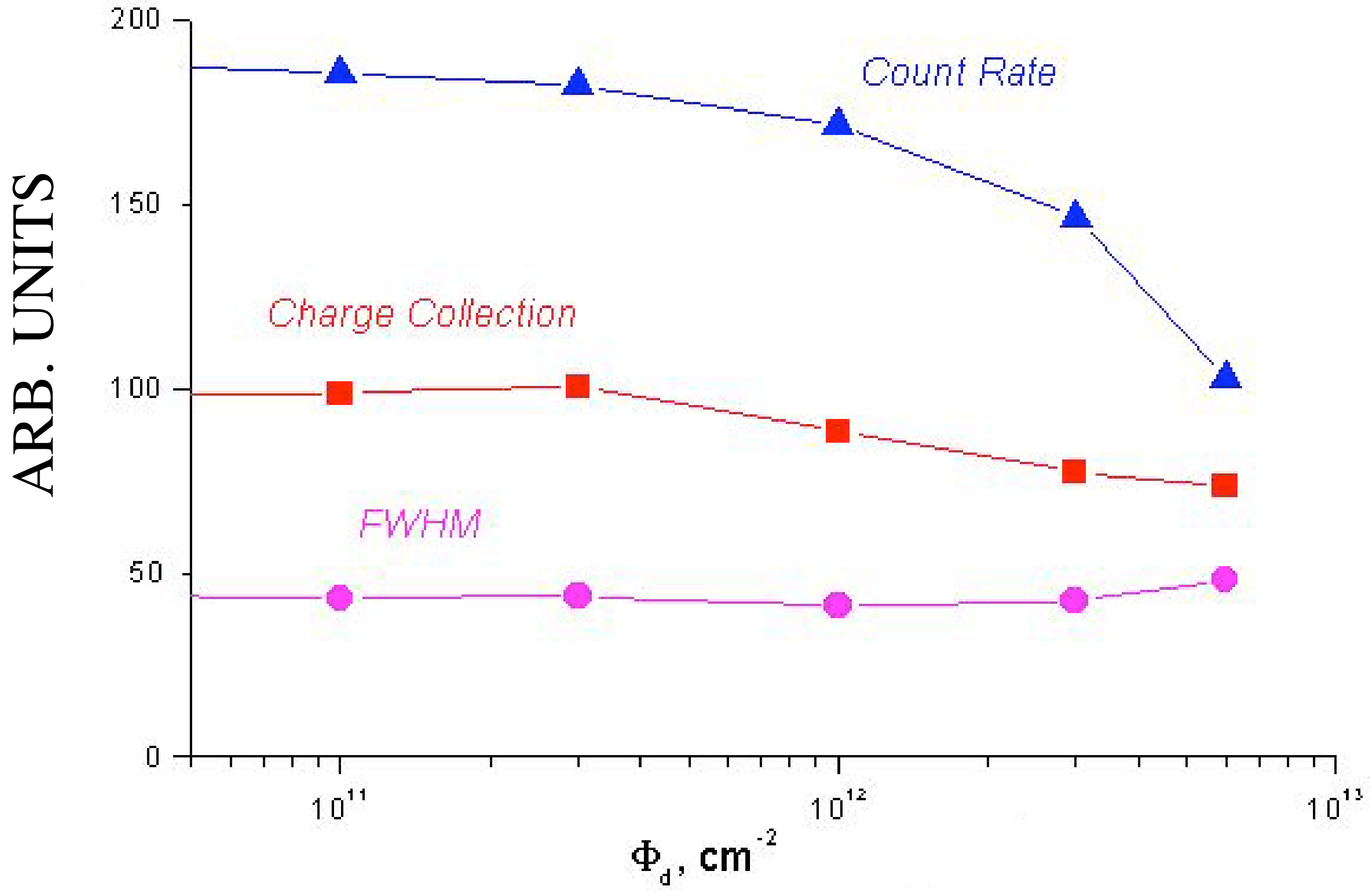

ARB. UNITS
200
150
100
50
0
Count Rate
Charge Collection
FWHM
10^{11}
10^{12}
10^{13}
Φ_d, cm^{-2}

Fig 5

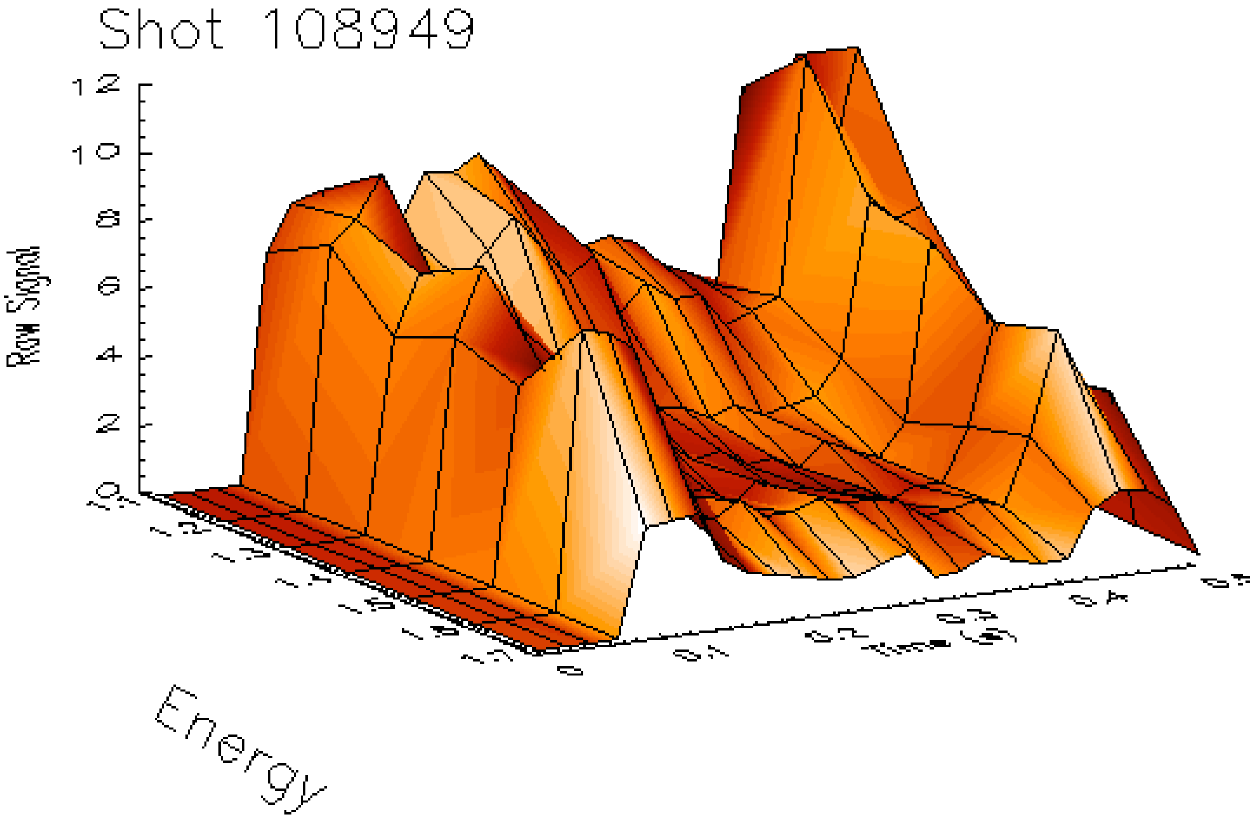

Shot 108949
Raw Signal
0
2
4
6
8
10
12
Energy
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Time (s)
0
0.1
0.2
0.3
0.4
0.5

Fig. 6

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