Princeton Plasma Physics Laboratory

NSTX Experimental Proposal

Title: NPA Measurement of the Anisotropic NB Energetic Ion Distribution and Beam Ion Profile in NSTX		
OP-XP-417	**Revision: 1**	Effective Date: 01/12/04 *(Ref. OP-AD-97)* Expiration Date: 01/12/06 *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Author:	**S. S. Medley**	Date
ATI – ET Group Leader:	**R. Maingi**	Date
RLM - Run Coordinator:	**S. M. Kaye**	Date

Responsible Division: Experimental Research Operations

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

Revision 1: Setup shot 111522 developed during initial run of XP417 was inserted in Physics Operations Request. SSM

NSTX EXPERIMENTAL PROPOSAL

Title: NPA Measurement of the Anisotropic NB Energetic Ion Distribution and Beam Ion Profile in NSTX **No.: OP-XP-417**

1. Overview of planned experiment

The Neutral Particle Analyzer (NPA) on NSTX can be remotely scanned both horizontally and vertically on a shot-to-shot basis. As shown in Fig. 1, the NPA sightline intersects the neutral beam injection paths and can be scanned from a tangency radius of R_{tan} = 135 cm (viewing co-going ions) to R_{tan} = - 65 cm (viewing counter-going ions). At any midplane tangency radius, the NPA can also be scanned vertically from the midplane downwards through an angular range of 26 degrees. The vertical 'minor' radius depends on the choice of midplane tangency radius. However, for any value of midplane tangency the vertical scan range extends well beyond the vertical extent of the neutral beam profiles.

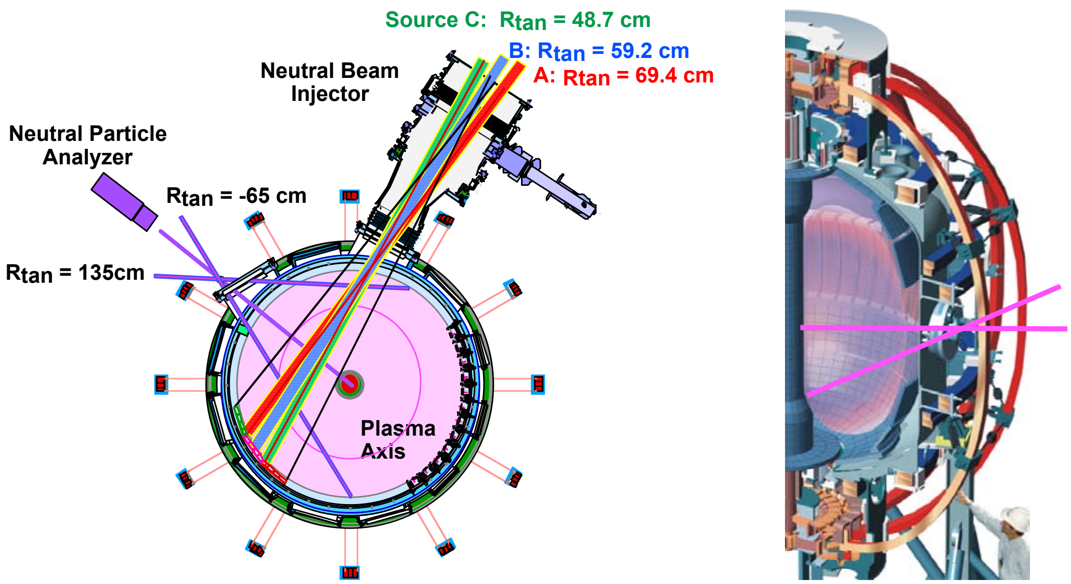


Figure 1. Layout of the neutral particle analyzer on NSTX illustrating the horizontal (left panel) and vertical (right panel) scanning ranges.

The experimental plan is to sequentially inject Sources A, B and C into a highly reproducible L-mode plasma with minimal MHD activity and scan the NPA in the horizontal midplane to obtain the anisotropic energy distribution for each of the sources. At a selected tangency radius, a vertical scan will then be performed to measure the vertical beam profile from the midplane downward for all of the sources. Approximately 15 shots will be required for each of the horizontal and vertical scans.

A potential interference between the Li pellet injector (if installed at Bay K) and the vertical scanning of the NPA will need to be addressed prior to scheduling and execution of this experimental proposal.

2. Theoretical/ empirical justification

2.1 Horizontal NPA Scan

The energy distribution and profile of injected beams in NSTX are valuable quantities to experimentally measure, since they are important for such issues as energetic ion driven instabilities, MHD-induced redistribution and/or loss of energetic ions, beam driven current and so forth [1]. Initial measurements were performed in earlier runs, as shown in Fig 2, to develop the basic analytical tools and initial benchmarking of TRANSP (shot range SN108831-SN108847). However, the shot-to-shot reproducibility of the discharges was minimally acceptable and not all of the NB sources were injected.

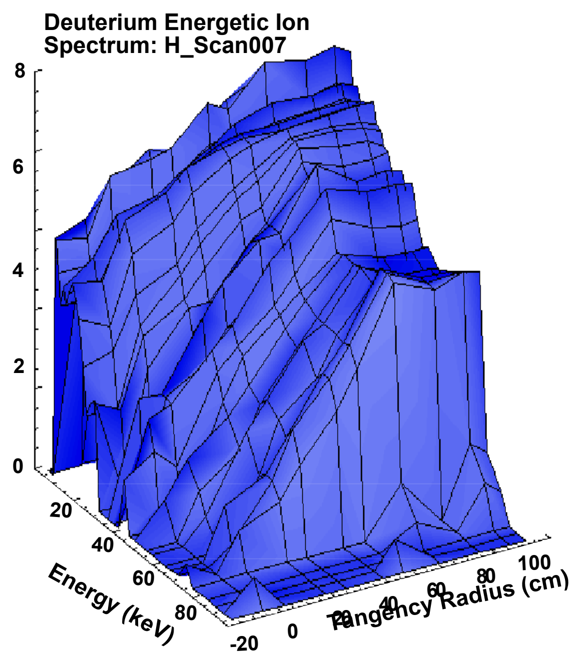


Figure 2. Illustration of initial NPA measurement of the neutral beam anisotropic energy distribution in NSTX (Source B @ 80 keV).

While the Monte Carlo simulation of the beam energetic ion distribution in TRANSP is regarded as reliable for MHD-quiescent discharges, it is useful to perform the NPA experimental measurements for at least two reasons. One is to benchmark measurements against simulation under MHD-quiescent conditions. Recall that TRANSP does not use full Larmor orbits that are appropriate in the low field NSTX device, so validation of the orbit approximation is merited. The other is to provide a baseline measurement against which the effects of various MHD activity (which TRANSP does not model) on the energetic ion distributions can be assessed.

TRANSP simulation shows that the energetic ion distribution is highly anisotropic and the flux exhibits a peak around the injection tangency radius, as illustrated in Fig. 3. The higher energy region depletes with decreasing tangency radii which corresponds to decreasing pitch angle. This is simply because with tangential injection, few ions a born with small pitch angles and the passing ions slow down before pitch angle scattering is able to populate this region of the energetic ion distribution. For typical NSTX conditions, the pitch angle scattering time is approximately double the slowing down time. For increasing tangency radii, the spectrum initially decays but afterwards grows because of increased charge exchange on the edge neutrals. Up to the initial NPA scan limit denoted by the red line, these features are in qualitative agreement with the NPA measurements shown in Fig. 2. The proposed NPA scan will cover the entire range of tangency radii shown in Fig. 3 and will offer the potential information on characteristics of NSTX edge neutral density.

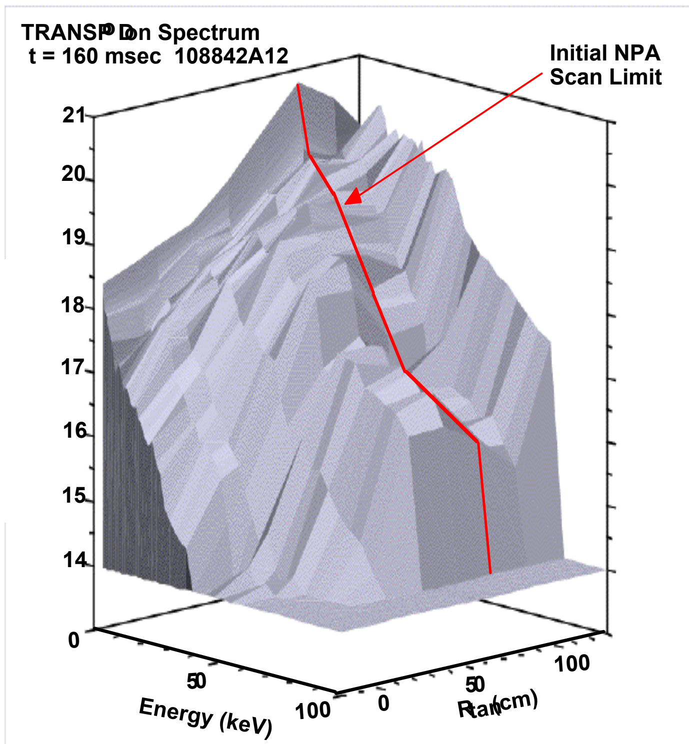


Figure 3. TRANSP simulation of the NPA energetic ion distribution measurements presented in Fig. 2.

In order to measure the equilibrated energy spectra, the duration of the injected beam pulses needs to be selected based on the characteristic slowing down and 90^o pitch angle scattering times. For $T_e \sim 1$ keV < $W_c \sim 15$ keV << $E_{b0} \sim 80$ keV, the beam ion slowing down time, τ_{slow}, is given by

$$\tau_{slow} = (\tau_{ei}/3)\ln[\ 1 + (E_{b0}/\ W_c)^{3/2}]\ \text{sec.} \qquad (1)$$

Here $W_c \sim 14.8\ T_e(keV)$ is the critical energy at which background ions and electrons receive an equal energy transfer from the beam ions, E_{b0} is the beam full energy and the electron-ion collision time, τ_{ei}, is

$$\tau_{ei} \sim 2.6\text{x}10^{12}\ kT_e(keV)^{3/2}/n_e(0)(cm^{-3})\ sec. \qquad (2)$$

Thus for 80 keV deuterium beam ions and $n_e(0) \sim 5\text{x}10^{13}\ cm^{-3}$, the slowing down time is $\tau_{slow} \sim 46$ ms. On the other hand, the 90° pitch angle scattering time, τ_{scat}, for full energy deuterium ions under these conditions is

$$\tau_{scat} \sim 7.3\text{x}10^{9}\ E_{b0}(keV)^{3/2}/n_e(0)(cm^{-3})\ sec \qquad (3)$$

or $\tau_{scat} \sim 104$ ms, about twice the slowing down time. Thus NB pulse lengths of order ~ 100 ms are desired with beam-off gaps between pulses of order ~ 40 ms to avoid co-mingling of ions from adjacent pulses. The XP remains viable, however, with up to 50% reduction in these numbers.

2.2 Vertical NPA Scan

The NPA vertical scanning capability will be utilized for the first time in the FY2004 run

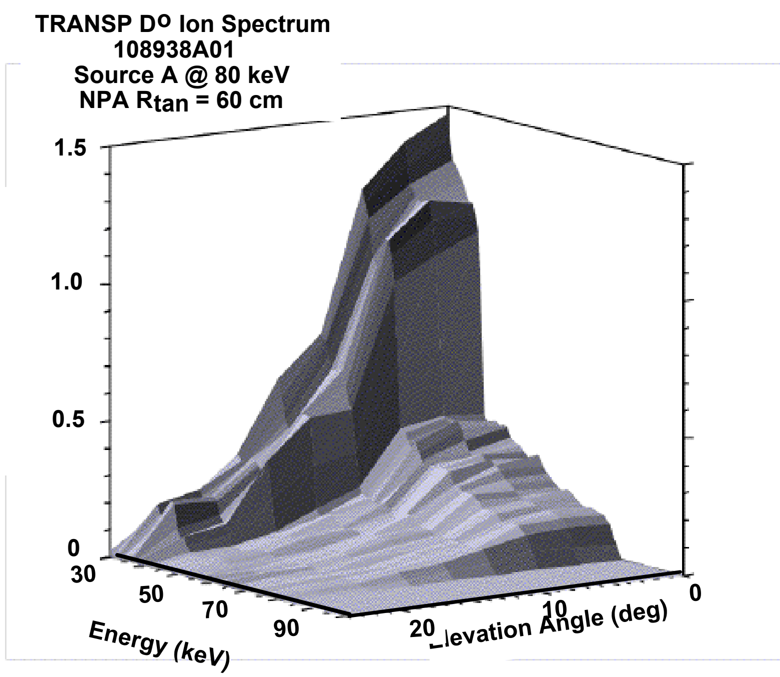


Figure 4. TRANSP simulation of the NPA beam profile measurement

period. TRANSP simulation of a vertical scan, shown in Fig. 4, indicates the feasibility of measuring the beam profile using either the full or half energy region of the beam energy distribution. From the known beam parameters, the vertical half-height of the beam at the intersection of the NPA sightline is ~ 25 cm. The spatial resolution of the NPA diagnostic is ~ 2.5 cm. Hence a 10 point scan of the main profile plus a more widely spaced 5 point scan of the wing region should be adequate to produce a quality profile measurement.

From TRANSP simulations, the optimal horizontal tangency radius is ~ 60 cm ± 10 cm at which position the profiles for all three sources can be obtained simultaneously.

References:

[1] W. W. Heidbrink, *et al.*, 2003 Rev. Sci. Instrum. **74** 1743

3. Experimental run plan

The experimental plan is to sequentially inject Sources A, B and C into a highly reproducible plasma and scan the NPA in the horizontal midplane to obtain the anisotropic energy distribution for each of the sources. At a selected tangency radius, a vertical scan will then be performed to measure the vertical beam profile from the midplane downward for all of the sources. Approximately 15 shots will be required for each of the horizontal and vertical scans.

The desired target plasma conditions are as follows. An L-mode discharge is required with machine parameters that do not tax the production of highly reproducible plasmas yet is representative of 'standard' plasmas of interest to a broader range of experiments on NSTX. The L-mode is chosen to avoid the irreproducibility of the L-H transitions, avoid modification of the beam deposition arising from broad, high electron density profiles and minimization of plasma attenuation effects on the emerging neutral flux. The most important characteristic of the target discharge is the length of the current flattop. This provides another reason for L-mode operation, since ELM activity characteristic of DN operation consumes volt-sec that would reduce the achievable I_p flattop. The neutral beam pulses should be in the range of 70 – 100 ms in duration with 30 – 50 ms off time between pulses. This scenario allows the initial slowing down time, pitch angle scattering time, equilibrated energy spectrum and turn-off decay time to be measured for each of the sources. The range of acceptable flattop times is therefore 270 ms – 400 ms, the longer the better. The target plasma should be somewhere in the middle of the NSTX operating range: e.g 0.8 ± 0.1 MA, B_T = 4.5 kG, $n_e(0) \sim 3 - 5\times10^{13}$ cm^{-3}. Other features of the target plasma are: stable outer gap in the 5 - 10 cm range, minimal low-n MHD activity in the frequency range f ~ 0 – 50 kHz and no IRE activity. Lower dome fueling should be used to minimize tearing modes that can slow down and lock resulting in a plasma current glich and to avoid H-mode generation. With the LSN there are no particular requirements for elongation or triangularity beyond what may be helpful in maximizing the current flattop. GDC between shots will be required in order to maintain discharge reproducibility.

3.1 Horizontal Scan

Once the target plasma is available, the horizontal scan will be performed. rThe scan will go from the maximum tangency radius of ~ 130 cm to near the minimum tangency radius of ~ - 50 cm in 12 cm steps for a total of 15 shots. The 3D energy spectra will be accumulated and plotted between shots for each of the sources.

3.2 Vertical Scan

The horizontal scan results will be used to validate the optimum horizontal tangency radius, estimated from TRANSP as 60 cm ± 10 cm, at which the vertical scan will be performed. The vertical scan will use 10 shots taken at 2.5 cm steps followed by 5 shots at 5.0 cm steps for a total of 15 shots. A grand total of 30 shots is required to complete both scans.

3.3 Run Plan Details

Specifics of the shot sequence and certain decision points are presented here. To begin with, if the I_p flattop time available in the target discharge setup is insufficient (e. g. < 200 ms), then source B will be omitted and the XP performed with sources A and C in that order. The horizontal and vertical scan sequence will be as follows.

- **Horizontal Scan**

Shot Number	Horizontal Position(cm)	
1	125	❒
□	˜ı	❒
3	75	❒
4	50	❒
5	25	❒
6	0	❒
7	-25	❒
8	-50	❒
9	-75	❒
10	-12.5	❒
11	12.5	❒
12	37.5	❒
13	62.5	❒
14	87.5	❒
15	112.5	❒
16	125	❒

If the spectra for shots 7 – 9 show little variation, shot 10 can be omitted. If the measured spectra show signal enhancement due to edge neutral density effects as noted in Figure 3, shot 16 will be run with increased gas feed (x2 if possible). This should provide an indication of whether cold or warm edge neutrals are responsible for the signal enhancement.

- **Vertical Scan**

Shot Number	Vertical Angle (degrees)	
17	0	❐
18	3.0	❐
19	6.0	❐
20	9.0	❐
[illegible]	[illegible]	❐
22	15.0	❐
23	21.0	❐
24	24.0	❐
25	18.0	❐
26	13.5	❐
27	10.5	❐
28	7.5	❐
29	4.5	❐
30	1.5	❐

If the profile wing shows little variability, shots 23 and/or 24 could be eliminated if need be.

If time permits, a check will be made of the effect of the beam sequencing used. With the NPA sightline in the horizontal plane at a tangency radius of 62.5 cm, then if the sequence used above was A,B,C the sequences B,C,A and C,A,B will be run for an additional 2 shots. If the sequence used was A,C then only C,A is required. Timing for the sources (start, duration and off time) will be adjusted to preserve the generic timing as illustrated in the physics operations request. This beam sequencing check is placed at the end of the XP run since a possibility exists that the target discharge might be adversely affected.

4. Required machine, NBI, RF, CHI and diagnostic capabilities

Machine:	4.5 kG, 0.8 ± 0.1 MA, $n_e(0) \sim 3 - 5\times10^{13}$ cm^{-3}, GDC between shots
Beams:	Sources A, B, and C @ 80-90 keV deuterium
ICRF:	None
Diagnostics:	Magnetics for EFIT equilibria and full kinetic profiles of electrons, ions and impurities are essential.

5. Planned analysis

TRANSP simulation of the NPA beam energy distributions and profiles will be performed both to validate the code as well as to extract information on the passive neutral density distribution. MPTS, CHERS, magnetics data and EFIT magnetic equilibria are essential for this analysis.

6. Planned publication of results

Measurements of the beam spectra in MHD-quiescent plasmas and their utilization to benchmark TRANSP may in themselves not provide sufficiently novel results to warrant publication, unless the analysis also yields information on the passive neutral density distribution. However, supplementing these results with measurements showing modification of the spectra due to effects such as H-mode operation, low-n MHD-induced and/or wave driven energetic ion loss would be novel. The beam profiles in themselves would contribute sufficiently new material to warrant publication. The goal is to publish the results of this XP, supplemented as deemed appropriate by additional measurements, in Nuclear Fusion within a year after the XP is performed.

PHYSICS OPERATIONS REQUEST

Title: NPA Measurement of the Anisotropic NB Energetic Ion Distribution and Beam Ion Profile in NSTX **No.: OP-XP-417**

Machine conditions (specify ranges as appropriate)

I_{TF} (kA): **53 (4.5 kG)** Flattop start/stop (s): **0/0.6**

I_P (MA): **0.8** Flattop start/stop (s): **0.1/0.5**

Configuration: **Center Stack Limited**

Outer gap (m): **0.05 - 0.10** Inner gap (m): **0.01 – 0.05**

Elongation κ: **1.5 – 1.7** Triangularity δ: **0.4 – 0.5**

Z position (m): **0.00**

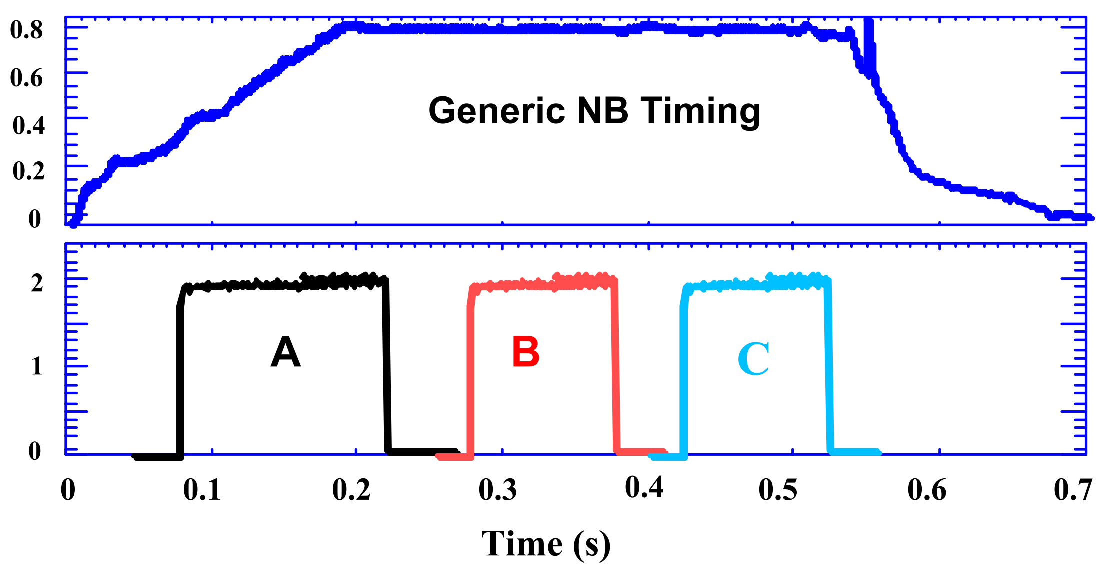
Gas Species:**D** Injector: **Outer Midplane**

NBI - Species: **D** Sources: **A/B/C** Voltage (kV): **80-90** Duration (s): **0.1**

ICRF – Power (MW): **0** Phasing: **NA** Duration (s): **0**

CHI: **Off**

Either: List previous shot numbers for setup: **111522**
Or: Sketch the desired time profiles. The time profiles shown below are for illustrative purposes only. The duration of Source B can be modified as needed to facilitate production of the desired discharge described in Section 3.



DIAGNOSTIC CHECKLIST

Title: NPA Measurement of the Anisotropic NB Energetic Ion Distribution and Beam Ion Profile in NSTX **No.: OP-XP-417**

Diagnostic system	Need	Desire	Instructions
Bolometer – tangential array		✔	
Bolometer array - divertor		✔	
CHERS	✔		
Divertor fast camera		✔	
Dust detector			
EBW radiometer			
Edge deposition monitor			
Edge pressure gauges	✔		
Edge rotation spectroscopy		✔	
Fast lost ion probes - IFLIP		✔	
Fast lost ion probes - SFLIP		✔	
Filtered 1D cameras		✔	
Filterscopes		✔	
FIReTIP	✔		
Gas puff imaging			
Infrared cameras		✔	
Interferometer – 1 mm			
Langmuir probe array			
Magnetics - Diamagnetism	✔		
Magnetics - Flux loops	✔		
Magnetics - Locked modes	✔		
Magnetics - Pickup coils	✔		
Magnetics - Rogowski coils	✔		
Magnetics - RWM sensors		✔	
Mirnov coils – high freqency	✔		
Mirnov coils – poloidal array	✔		
Mirnov coils – toroidal array	✔		
MSE			
Neutral Particle Analyzer	✔		
Neutron measurements	✔		
Plasma TV	✔		
Reciprocating probe			
Reflectometer - core			
Reflectometer - SOL			

RF antenna camera			
RF antenna probe			
SPRED		✔	
Thomson scattering	✔		
Ultrasoft X-ray arrays	✔		
Visible bremsstrahlung det.		✔	
Visible spectrometers (VIPS)		✔	
X-ray crystal spectrometer - H		✔	
X-ray crystal spectrometer - V		✔	
X-ray PIXCS (GEM) camera			
X-ray pinhole camera			
X-ray TG spectrometer			