Princeton Plasma Physics Laboratory
NSTX Experimental Proposal

Title: Divertor regimes and outer target detachment in NBI-heated plasmas

OP-XP-520	**Revision:**	Effective Date: *(Ref. OP-AD-97)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

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RLM - Run Coordinator:	**J. Menard (S. Sabbagh)**	Date

Responsible Division: Experimental Research Operations

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

1. Overview of planned experiment

The goal of this experiment is to determine conditions of the outer target detachment and in parallel map divertor regimes in the NBI-heated L-mode plasma operational space. Two techniques will be used to achieve the outer target detachment: raising density by means of D_2 injection, and raising edge radiated power by injecting an extrinsic impurity. In the first part of the experiment a density scan will be undertaken in a lower single null (LSN) configuration with the aim of producing a database of divertor conditions and identifying the sheath-limited, high-recycling and detached divertor regimes, commonly observed in tokamaks. Gas injection location is also an important factor, among others, that affects the divertor detachment threshold. Deuterium will be injected from the outer wall and lower dome (bottom) injectors. In the second part of the experiment neon will be injected in increased quantities to yield P_{rad}/P_{in} up to 0.5 to obtain the outer target detachment. Divertor measurements, such as D_α, D_β, D_γ, heat flux, radiated power, divertor Langmuir probe and neutral pressure measurements will be monitored for signs of detachment.

2. Theoretical/ empirical justification

The purpose of a tokamak divertor is to provide particle and power exhaust from the main plasma and to place the plasma – material surface interaction region away from the confined plasma. The divertor also provides main plasma fueling and impurity and working species density control. Divertor target detachment offers an effective power dissipation scenario for long pulse high power density discharges. This experiment is a step toward better understanding of divertor regimes in NSTX and the development of a radiative divertor scenario. Also, neon injections in non-trace amounts would be the first NSTX radiative mantle experience and could lead to the development of improved confinement regimes.

NSTX has an open divertor geometry with the center stack, inner and outer divertor plates and passive stabilizing plates clad in protective graphite tiles. The machine routinely operates in the lower single null or double null configurations with the outer strike point located on the floor (R_{out} = 0.5 – 0.85 m), and the inner strike point located on the inner horizontal divertor plate (R_{in} = 0.3 – 0.48 m) or the vertical target (R_{in} = 0.2775 m). Experimental observations in the LSN (both PF2L and PF1B) and DN configurations suggest that in most cases, in both the L-mode and the H-mode plasmas, the inner divertor target is detached, whereas the outer target is attached. The degree of the inner target detachment is a subject of an on-going discussion. Infra-red camera measurements indicate that the heat flux on the inner target is low: $q_{in} < 1$ MW/m^2, and the peak out-in heat flux asymmetry is 4 – 7, while the LCFS out-in surface ratio is 4.0 – 4.5, and a large Shafranov shift is present in all plasmas. The recycling measurements show that a large in-out asymmetry (up to 15) develops tens of milliseconds after the divertor configuration is formed. Divertor D_γ profile measurements also indicate that the D_γ / D_α ratio sharply increases in the inner target region at the same time, while no D_γ emission is observed in the vicinity of the outer strike point. The D_γ / D_α ratio increase is also correlated with the observation of n<10 Balmer series Stark-broadened spectral lines from the inner leg region. This indicates that the emission originates in a high density (~ 10^{20} m^{-3}) cold (< 5 eV) MARFE-like plasma, where volume recombination is taking place. Finally, 10-15 % of the input power is radiated in the divertor, mostly in the inner target region.

The two point model (2PM) [1] predicts that under the typical NSTX conditions (P_{NBI} = 0.8 – 6 MW, L_c = 30-40 m, q_{in} < 1 MW/m^2 , q_{out} < 1 MW/m^2) the inner target plasma is cold (T_e < 5 eV) and the density in the inner leg is high ($n_e < 10^{20}$ m^{-3}), whereas at the outer target T_e < 20 – 40 eV and $n_e < 5 \times 10^{19}$ m^{-3} (Fig. 1).

The semi-quantitative criterion of detachment is given by the 2PM as

$$\frac{14}{3} c_Z L_Z n_u^2 L > q_u$$

where c_z is the impurity concentration, L_z is the impurity emissivity, L is the connection length and n_u, q_u are the upstream density and heat flux, respectively. The criterion demonstrates the two common ways to induce the detachment: to raise n_u by injecting deuterium, or raise c_z, L_z by injecting impurities. This experiment should clarify the mapping of divertor regimes (sheath-limited, high-recycling, detachment) in the operational (P_{in}-n_e) space, and help understand the ST magnetic geometry effects on the basic parallel transport physics.

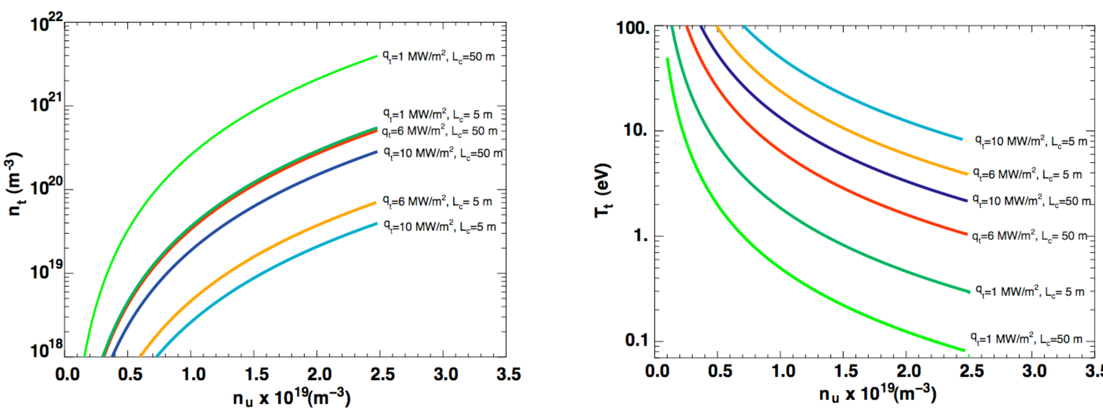


Figure 1. (a) Divertor density and temperature predicted by the two point model

References

[1] P. C. Stangeby, The plasma boundary of Magnetic Fusion Devices, IoP Publishing, Bristol and Philadelphia, 2000.

3. Experimental run plan

1. Setup an LSN (with PF2L coil) LFS-fueled L-mode plasma and perform gas injection rate scan. Obtain several conditions at low, intermediate and high plasma density, with emphasis on the high-density part (15 - 20 shots)
   - Setup an L-mode plasma with 2 NBI sources at full energy, adjust the X-point height so that the inner strike point remains at 1-2 cm from the inner wall throughout discharge. Example shots: 111543, 112833
   - Start with low density (n_e = 2-3 x 10^{19} m^{-3}) (2 shots)
     - Use the prefill of (6 – 6.5)e-5 Torr and Injector 2 at 10-40 Torr l / s for fueling
   - Scan Injector 2 rate from 40 to 100 Torr l / s. (4 shots)
     - Use Injector 2 rates of 40, 60, 80, 100 Torr l / s
     - If disruptive MHD events, sawteeth and/or lock modes develop during heavy gas puffing use Injector 2 at lower rate and add the LDGIS injectors.
   - Attempt to raise density to n_e = (5 –9) x 10^{19} m^{-3} (10-15 shots) by adding LDGIS injectors (50 Torr l / s), Injector 1, and/or CS injector, and the SGI.
     - Add LDGIS injectors in series to obtain one LGDIS gas puff (fill pressure 100 - 200 Torr) s
     - In one high density discharge, turn off NBI at the time when n_e is high (> 6 x 10^{19} m^{-3}) to obtain high density low input power condition for about 50 ms
     - Greenwald density for I_p=0.8 MA is n_G = 5.5 x 10^{19} m^{-3}
     - (Conditional) In one discharge, turn off gas feed at 0.25-0.30 s
     - (Conditional) Run a helium discharge to de-saturate walls if necessary

(Note: if the limit of choking the plasma with gas is reached, proceed to neon injections with configuration as in 1)

2. Perform injections of neon in increasing quantities (0.05 – 0.2 s duration pulses at a rate from 1 to 20 Torr l / s) into intermediate density two NBI source shot from 1. Monitor radiated power (10-15 shots).
   - Use Injector 3 for neon. Neon pulse start time 0.20-0.25 s
   - Start with a neon pulse at the rate of 1 Torr l / s, pulse duration 50 ms
   - Increase neon injection rate to 20 Torr l / s in steps of 1-2 Torr l / s, increase neon pulse duration from 50 ms to 200 ms, in accordance with plasma behavior and the flat-top length obtained (expect shortening due to increased plasma resistivity (Z_{eff}) and higher ohmic flux consumption). Monitor plasma radiated power.
   - The injected quantities are much lower than the quantity of neon used for neon GDC in CHERS calibrations
3. Conditional, time permitting - perform neon injections at established in 2 rates into high density two NBI source shot from 1. Monitor radiated power.

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

Physics Operations Request and Diagnostic Checklist are attached.

Diagnostic capabilities: Tile Langmuir probes, IR cameras, main plasma and divertor bolometers, and the D_α, D_γ cameras should be operational. Lower divertor Langmuir probe locations are (major radii, m): 0.2775, 0.4952, 0.7970, 0.9110, 1.0170.

5. Planned analysis

The following numerical tools will be used for data analysis: EFIT04, UEDGE, ADAS, DEGAS 2, TRANSP, analytic two point divertor model.

6. Planned publication of results

Results will be presented at the upcoming EPS and ITPA meetings, an oral talk at the APS meeting and will be published in a refereed journal if significant.

PHYSICS OPERATIONS REQUEST

Divertor regimes and outer target detachment in NBI-heated plasmas **OP-XP-520**

Machine conditions (specify ranges as appropriate)

I_{TF} (kA): **-52.5** Flattop start/stop (s): **-0.02/1.0**

I_P (MA): **0.8** Flattop start/stop (s): **0.08/0.6**

Configuration: **Lower Single Null**

Outer gap (m): **0.1**, Inner gap (m): **0.05-0.1**

Elongation κ: **1.9-2.0**, Triangularity δ: **0.5**

Z position (m): **0.00**

Gas Species: **D / He / Ne**, Injector: **Midplane / Inner wall / Lower Dome**

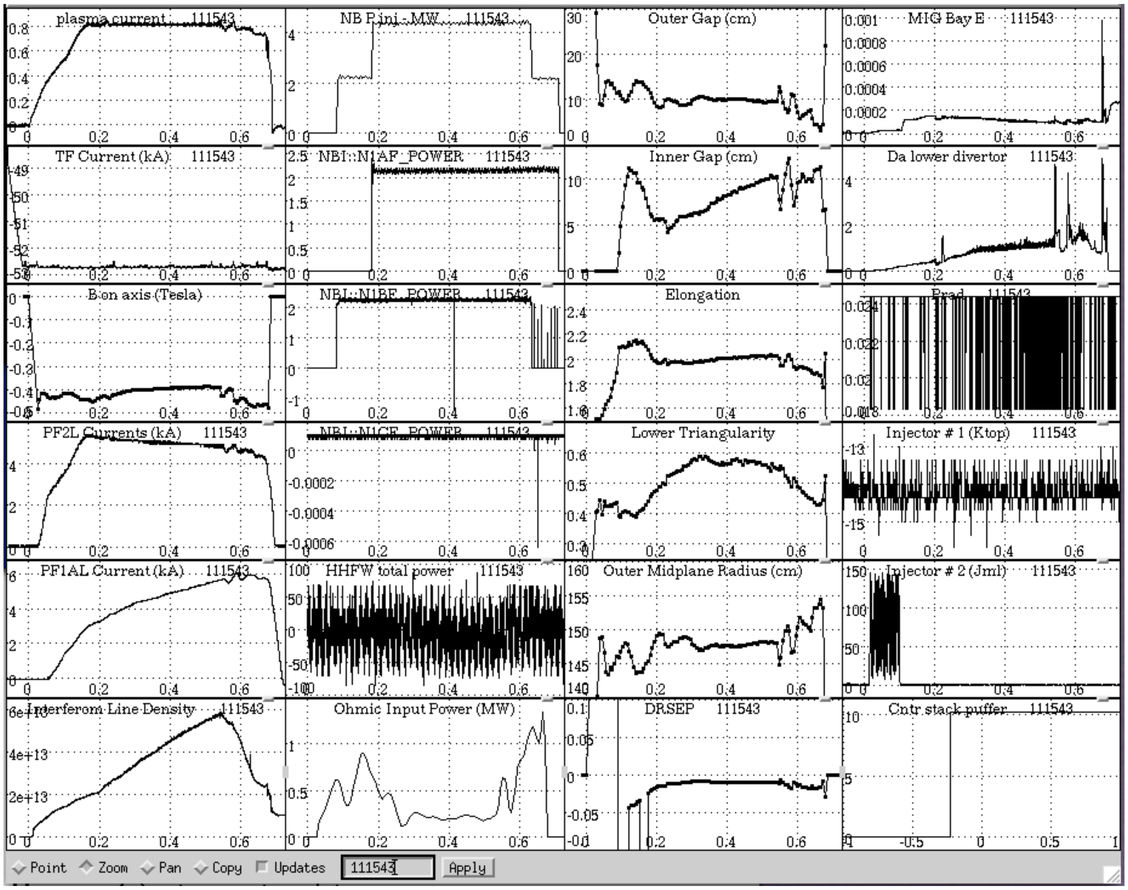
NBI - Species: **D**, Sources: **A/B/C**, Voltage (kV): **80**, Duration (s): **0.6**

ICRF – Power (MW): **0**, Phasing: **Heating / CD**, Duration (s): _____

CHI: **Off**

Either: List previous shot numbers for setup: **111543, 112833**

<u>Gas setup</u>: CS Injector – D_2, LDGIS - D_2, Injector 1 – He, Injector 2 – D_2, Injector 3 - Ne, Injector Bay B High Flow - D_2 or He for GPI


plasma current 111543
NB P inj - MW 111543
Outer Gap (cm)
MIG Bay E 111543
TF Current (kA) 111543
NBI::N1AF_POWER 111543
Inner Gap (cm)
Da lower divertor 111543
B on axis (Tesla)
NBI::N1BF_POWER 111543
Elongation
Prad 111543
PF2L Currents (kA) 111543
NBI::N1CF_POWER 111543
Lower Triangularity
Injector # 1 (Ktop) 111543
PF1AL Current (kA) 111543
HHFW total power 111543
Outer Midplane Radius (cm)
Injector # 2 (Jml) 111543
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Ohmic Input Power (MW)
DRSEP 111543
Cntr stack puffer 111543
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111543
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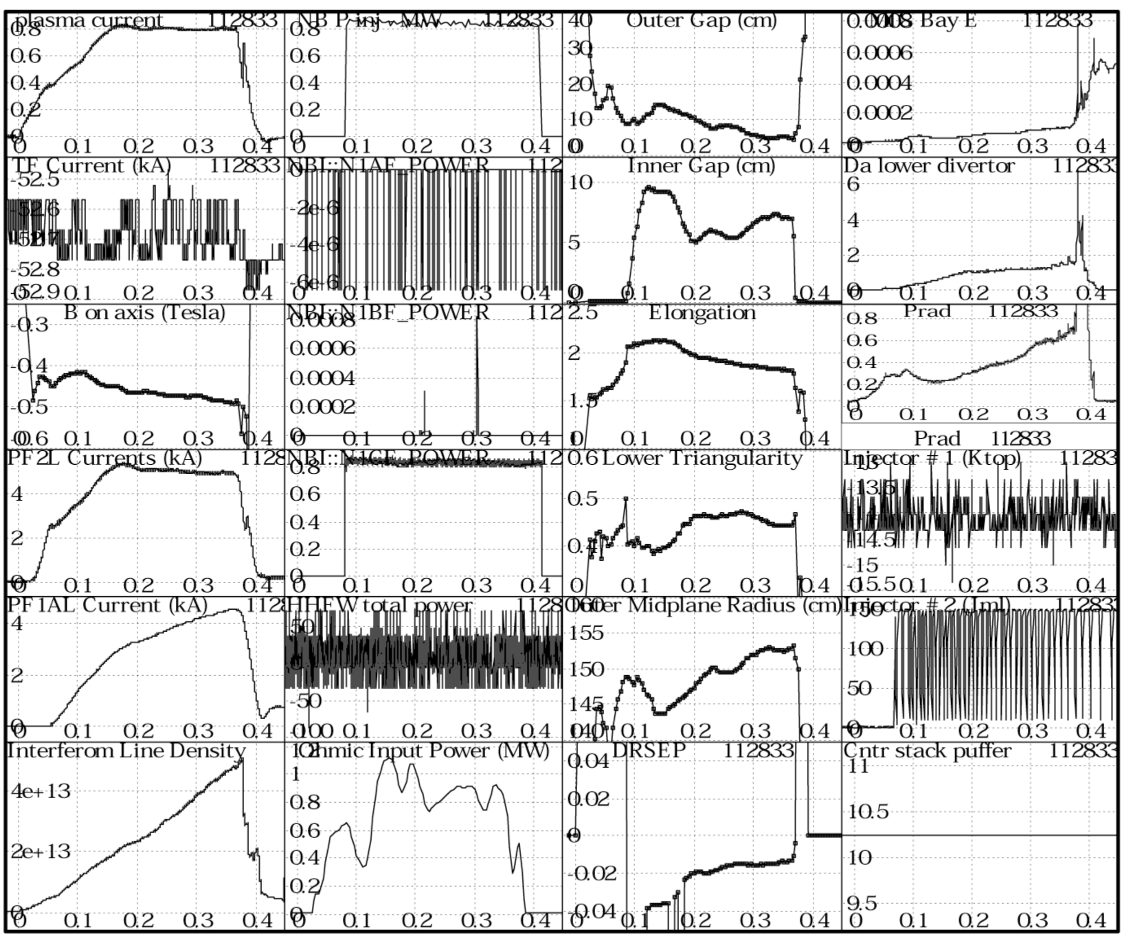
plasma current 112833
NB P inj - MW 112833
Outer Gap (cm)
MIG Bay E 112833
TF Current (kA) 112833
NBI::N1AF_POWER
Inner Gap (cm)
Da lower divertor
B on axis (Tesla)
NBI::N1BF_POWER
Elongation
Prad 112833
PF2L Currents (kA)
NBI::N1CF_POWER
Lower Triangularity
Injector # 1 (Ktop)
PF1AL Current (kA)
HHFW total power
Outer Midplane Radius (cm)
Injector # 2 (Jml)
Interferom Line Density
Ohmic Input Power (MW)
DRSEP 112833
Cntr stack puffer 112833

OP-X

DIAGNOSTIC CHECKLIST

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Diagnostic	Need	Desire	Instructions
Bolometer - tangential array	✓		
Bolometer array - divertor	✓		
CHERS	✓		Need in both deuterium and neon shots
Divertor fast camera	✓		View the X-point region with Dα filter
Dust detector			
EBW radiometers			
Edge deposition monitor			
Edge pressure gauges	✓		
Edge rotation spectroscopy	✓		
Fast lost ion probes – IFLIP			
Fast lost ion probes – SFLIP			
Filtered 1D cameras	✓		CAM1, CAM2: Dα, CAM3: Dβ, CAM4: Dγ
Filterscopes	✓		Use neon filter
FIReTIP	✓		
Gas puff imaging	✓		Measure turbulence in neon shots
High-k scattering			
Infrared cameras	✓		Divertor, lower div shoulder
Interferometer – 1 mm			
Langmuir probes - PFC tiles	✓		
Langmuir probes - RF antenna			
Magnetics – Diamagnetism			
Magnetics – Flux loops	✓		
Magnetics – Locked modes			
Magnetics – Pickup coils	✓		
Magnetics - Rogowski coils	✓		
Magnetics - RWM sensors			
Mirnov coils – high frequency			
Mirnov coils – poloidal array			
Mirnov coils – toroidal array			
MSE			
Neutral particle analyzer			
Neutron Rate (2 fission, 4 scint)			
Neutron collimator			
Plasma TV	✓		Dα filter when requested, no filter otherwise
Reciprocating probe	✓		Operate on several shots when requested
Reflectometer - FM/CW			
Reflectometer - fixed frequency homodyne			
Reflectometer - homodyne correlation			
Reflectometer - HHFW/SOL			
RF antenna camera			
RF antenna probe			
Solid State NPA			
SPRED	✓		
Thomson scattering - 20 channel	✓		
Thomson scattering - 30 channel	✓		
Ultrasoft X-ray arrays	✓		
Ultrasoft X-ray arrays - 2 color		✓	
Visible bremsstrahlung det.	✓		
Visible spectrometers (VIPS)	✓		Chords: inner, outer divertor and CS
X-ray crystal spectrometer - H		✓	
X-ray crystal spectrometer - V		✓	
X-ray PIXCS (GEM) camera			
X-ray pinhole camera			
X-ray TG spectrometer			