**Princeton Plasma Physics Laboratory**

# NSTX Experimental Proposal

## Title: Divertor regimes and divertor detachment in NSTX

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| **OP-XP-438** | **Revision: 29 June 2004** | Effective Date:<br>*(Ref. OP-AD-97)*<br>Expiration Date:<br>*(2 yrs. unless otherwise stipulated)* |

## PROPOSAL APPROVALS

| | |
|---|---|
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| **ATI – ET Group Leader: H. W. Kugel, R. Kaita** | Date |
| **RLM - Run Coordinator: S. Kaye** | 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 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 detachment offers an effective power dissipation scenario for long pulse high power density discharges. The goal of this experiment is to conduct a dedicated study of the NSTX divertor conditions and to develop means to attain a detached divertor state. Two methods have been used in tokamaks to achieve divertor detachment: raising density by means of gas injection, or 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 induce the detachment. Divertor measurements, namely $D_\alpha$, $D_\beta$, $D_\gamma$, heat flux, radiated power profiles and divertor Langmuir probe and neutral pressure measurements will be monitored for the signs of detachment.

## 2. Theoretical/ empirical justification

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 configuration with the outer strike point located on the outer divertor plate ($R_{out} = 0.72 – 0.85$ 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 and DN configurations suggest that in most NSTX plasmas the inner divertor is detached, whereas the outer divertor is attached. Infra-red camera measurements indicate that the heat flux density in the inner divertor is low: $q_{in} < 1$ MW/m$^2$, and the peak out-in heat flux asymmetry is 4 – 6. The recycling measurements show that a large in-out asymmetry (up to 15) develops tens of milliseconds after the divertor configuration is formed. Recent divertor $D_\gamma$ measurements also indicate that the $D_\gamma / D_\alpha$ ratio sharply increases as the discharge progresses, and the presence of the $D_\gamma$ emission is correlated with a high $D_\alpha$ asymmetry. The two point model (2PM) [1] predicts that under the typical NSTX conditions ($P_{NBI} = 0.8 – 6$ MW, $L_c = 1 – 30$ m, $q_{in} < 1$ MW/m$^2$, $q_{out} < 1$ MW/m$^2$) the inner divertor is cold ($T_e < 5 – 7$ eV) and the density in the inner divertor is high ($n_e < 10^{20}$ m$^{-3}$), whereas in the outer divertor $T_e < 20 – 40$ eV and $n_e < 5 \times 10^{19}$ m$^{-3}$ (Fig. 1). This suggests that the inner divertor is detached. The 2D multi-fluid code UEDGE predictions are presented in Fig. 2. This figure shows the inner and outer divertor state as a function of input power and electron density at the 90 % flux surface. It indicates that for the considered range of upstream parameters the inner divertor temperature is sufficiently low for the volumetric processes to take place. The calculated plasma flux to the plates also saturates at similar upstream parameters, further supporting the notion of inner divertor detachment. A corresponding plot of the NSTX experimental data is shown in Fig. 3. Each point plotted in the ($P_{in} - n_e$) space (density at the 90 % flux surface) corresponds to the divertor $D_\alpha$ asymmetry greater than 2, an empirical criterion suggesting conditions leading to the inner divertor detachment. Many points lie outside of the range predicted by UEDGE, especially in the lower density region.

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. In order to map the divertor detachment space, and better understand the boundaries of the sheath-limited and high-recycling regimes, a dedicated experiment will be carried out.

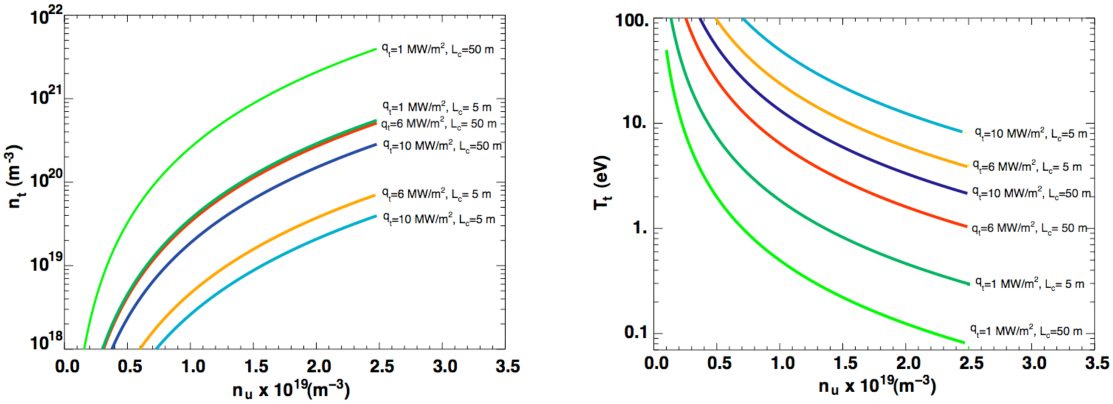


**Figure 1.** (a) Divertor density and temperature predicted by the two point model

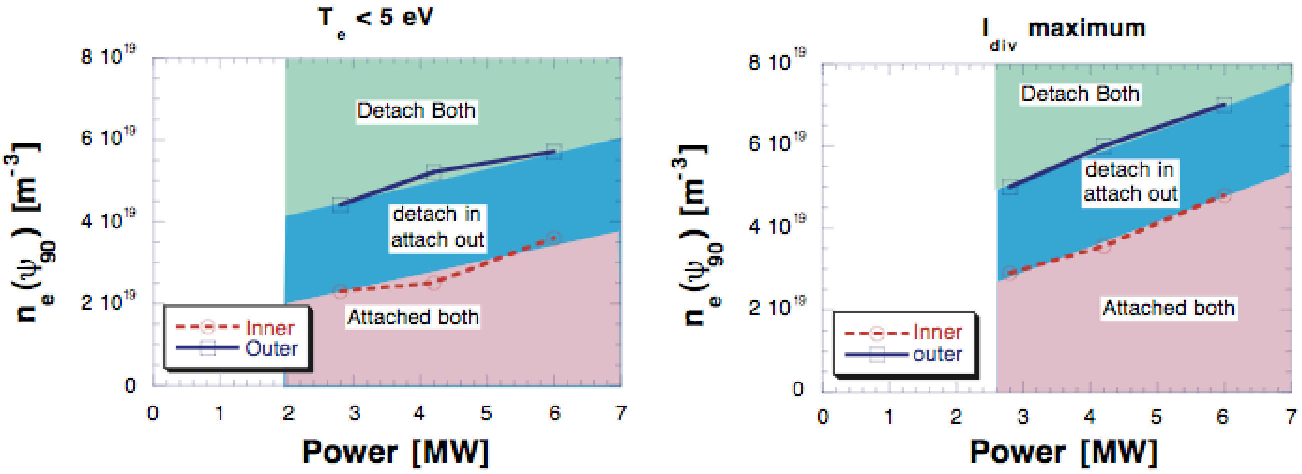


**Figure 2.** UEDGE predictions of divertor temperature (top) and plasma flux to the plate (bottom) in the input power – density space

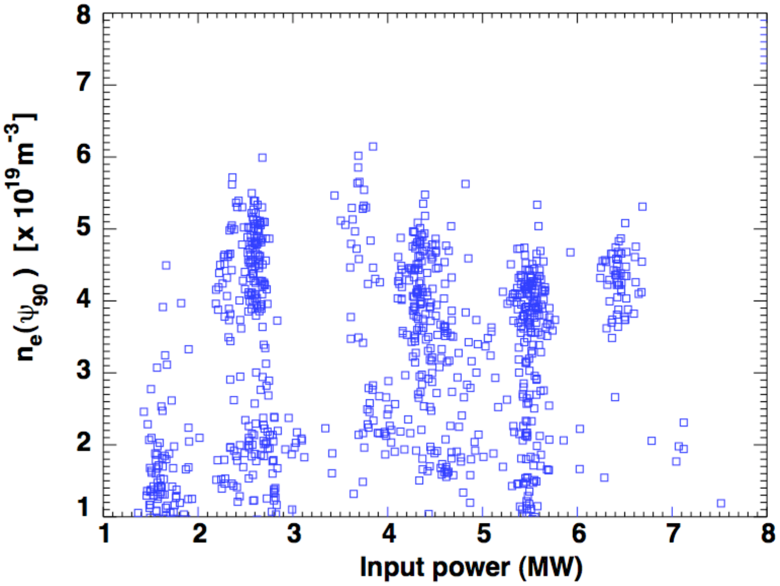


**Figure 3.** NSTX operating space in input power – edge density space. Each point represents a LSN configuration plasma with the divertor $D_\alpha$ asymmetry A > 2, thought to be indicative of the inner divertor detachment (compare to Fig. 2).

## References

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

# 3. Experimental run plan

1. Develop an LSN LFS-fueled L-mode plasma and perform gas injection scan to obtain low, intermediate and high density conditions (15 - 20 shots)
   - Re-establish L-mode shot 112829 (NBI at full energy, lower X-point)
     - 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 Torr l / s for fueling
   - Scan Injector 2 rate from 40 to 140 Torr l / s. (5 shots)
     - Use Injector 2 rates of 40, 80, 120, 140 Torr l / s
   - Raise density to $n_e$ = (6 –9) x $10^{19}$ $m^{-3}$ (10 shots) by adding LDGIS injector (50 Torr l / s), Injector 1 and/or CS injector
     - Add LDGIS injector (fill pressure 100 - 200 Torr) s
     - (Conditional) Add Injector 1 at 50 – 100 Torr l /s at 0.22 s for 0.2 s
     - In one high density discharge, turn off NBI at 0.3 s to obtain high density low input power condition
     - In one discharge, turn off gas feed at 0.25 s
     - (Conditional) Run a helium discharge to de-saturate walls if necessary
     - Include NBI blips for CHERS 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 neon injections in increasing quantities (0.05 – 0.2 s duration pulses at a rate from 2 to 30 Torr l / s ) into intermediate density one NBI source shot from 1. Monitor radiated power. Introduce 2nd NBI source blip for CHERS if needed. (15 shots)
    - Use Bay B Hi-Flo Injector for neon – start at 0.25 s
    - Start with 2 Torr l / s for 50 ms
    - Increase neon injection rate to 30 Torr l / s in steps of 5 Torr l / s, Increase neon pulse from 50 ms to 200 ms, monitor plasma radiated power
    - The injected quantities are much lower that the quantity of neon used for neon GDC for CHERS calibration
3. Time permitting - perform neon injections at established in 2 rates into intermediate and high density two NBI source shot from 2. Monitor radiated power.

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

Physics Operations Request and Diagnostic Checklist are attached.

Diagnostic capabilities: Must have the Langmuir probes, IR cameras, main plasma and divertor bolometers, and the $D_\alpha$, $D_\gamma$ cameras 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 in an oral talk at the APS meeting and will be published in a referee journal if significant.

# PHYSICS OPERATIONS REQUEST

**Divertor** regimes and divertor detachment in NSTX **OP-XP-438**

Machine conditions (specify ranges as appropriate)

$I_{TF}$ (kA): **52.6** Flattop start/stop (s): _____/_____

$I_P$ (MA): **0.8** Flattop start/stop (s): _____/_____

Configuration: **Lower Single Null**

Outer gap (m): **0.10+/- 0.03** Inner gap (m): **0.06 +/- 0.02**

Elongation $\kappa$: **1.9 +/- 0.1**, Triangularity $\delta$: **0.45 +/- 0.05**

Z position (m): **0.00**

Gas Species: **D / Ne**, Injector: **Midplane (1, 2, 3) / Inner wall**

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:

**112828 – 112830, but use 80 kV NBI**

*Or:* Sketch the desired time profiles, including inner and outer gaps, $\kappa$, $\delta$, heating, fuelling, etc. as appropriate. Accurately label the sketch with times and values.

NBI setup: src C 80 – 600 s, src B a 20 ms blips at 220, 300 ms. Use 80 kV beams

Gas setup:

CS Injector – $D_2$, plenum pressure 1000 - 1200 Torr (30 – 40 Torr l / s)

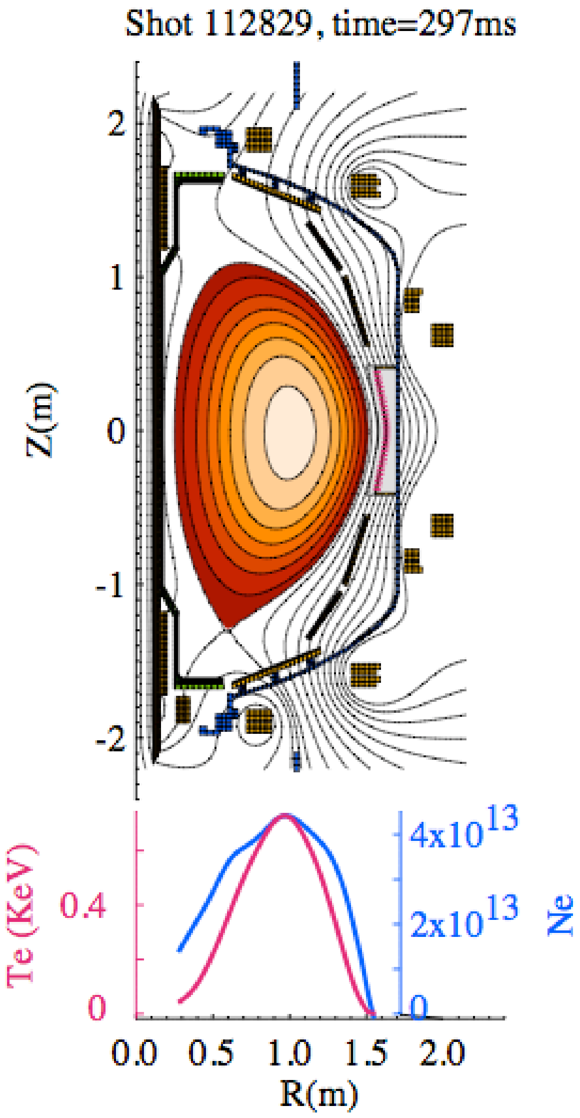
LDGIS - $D_2$, fill pressure 100 – 200 Torr

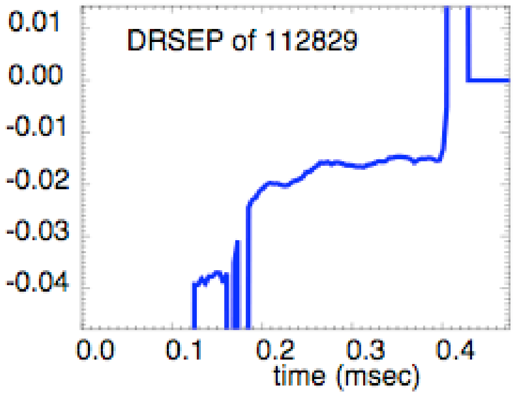
Injector 1 – $D_2$

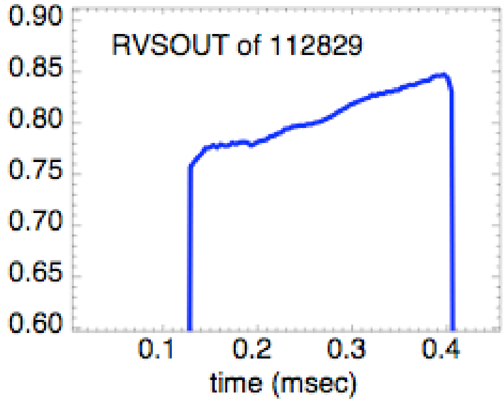
Injector 2 – $D_2$, scan rate from 0 to 120 Torr l / s

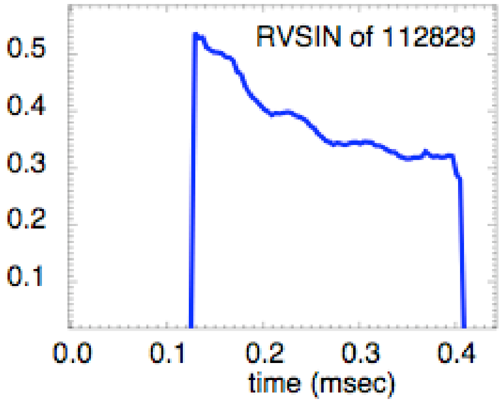
Injector 3 - He

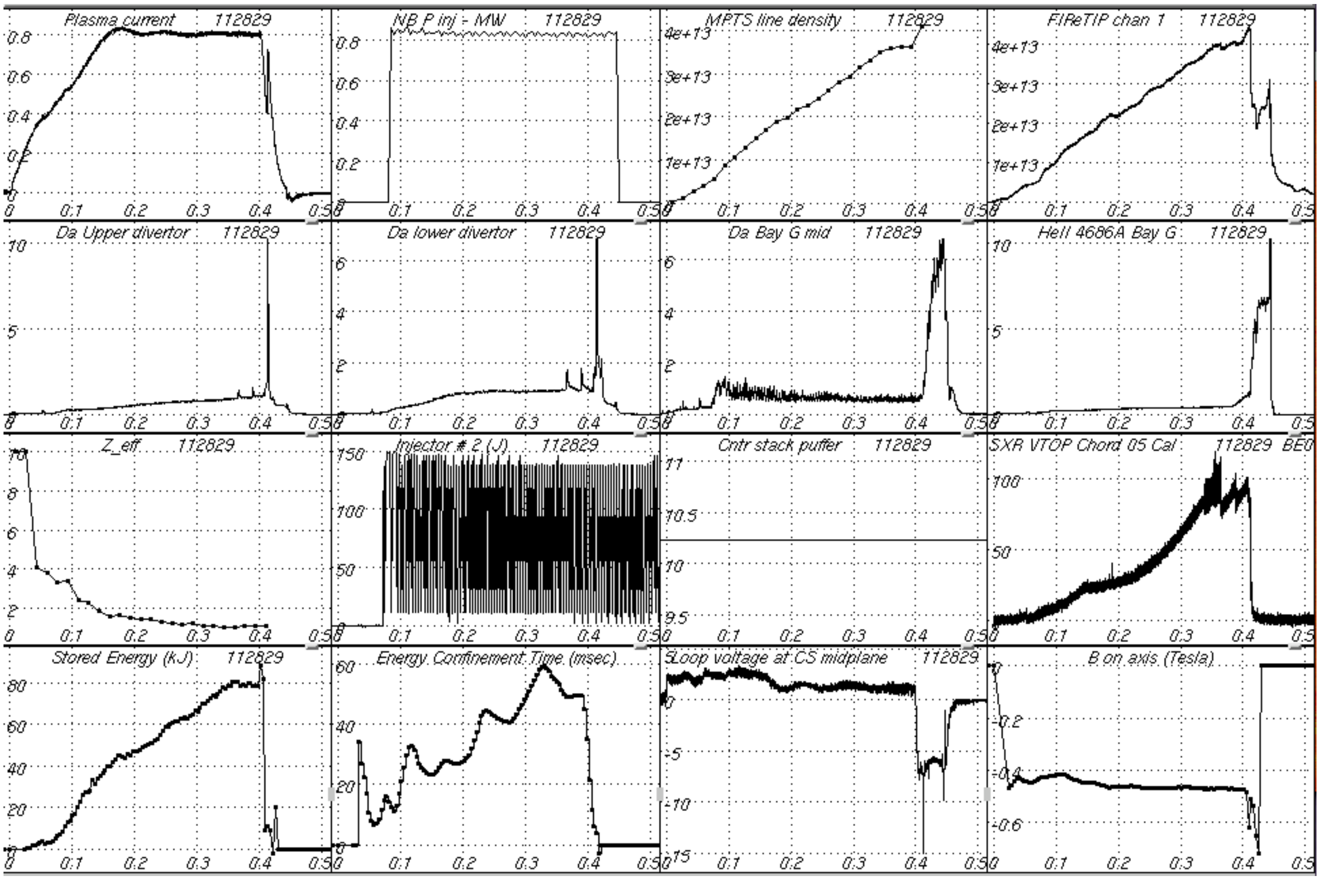
Injector Bay B Hi Flo - Ne, scan rate from 2 to 30 Torr l / s


Shot 112829, time=297ms
Z(m)
2
1
0
-1
-2
Te (KeV)
0.4
0
4x10^13
2x10^13
0
Ne
0.0
0.5
1.0
1.5
2.0
R(m)


DRSEP of 112829
0.01
0.00
-0.01
-0.02
-0.03
-0.04
0.0
0.1
0.2
0.3
0.4
time (msec)


RVSOUT of 112829
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.1
0.2
0.3
0.4
time (msec)


RVSIN of 112829
0.5
0.4
0.3
0.2
0.1
0.0
0.1
0.2
0.3
0.4
time (msec)


Plasma current 112829
NB P inj - MW 112829
MPTS line density 112829
FIReTIP chan 1 112829
Da Upper divertor 112829
Da lower divertor 112829
Da Bay G mid 112829
HeII 4686A Bay G 112829
Z_eff 112829
Injector # 2 (J) 112829
Cntr stack puffer 112829
SXR VTOP Chord 05 Cal 112829 BE0
Stored Energy (kJ) 112829
Energy Confinement Time (msec)
Loop voltage at CS midplane 112829
B on axis (Tesla)
0 0.1 0.2 0.3 0.4 0.5
0.8 0.6 0.4 0.2 0
4e+13 3e+13 2e+13 1e+13
10 5 6 4 2
10 8 6 4 2
150 100 50
11 10.5 10 9.5
100 50
80 60 40 20
60 40 20
5 0 -5 -10 -15
0 -0.2 -0.4 -0.6

# DIAGNOSTIC CHECKLIST

**Divertor** regimes and divertor detachment in NSTX **OP-XP-438**

| **Diagnostic** | **Need** | **Desire** | **Instructions** |
|---|---|---|---|
| Bolometer – tangential array | ✓ | | |
| Bolometer array - divertor | ✓ | | |
| CHERS | ✓ | | |
| Divertor fast camera | ✓ | | Load $D_\alpha$, C II, C III filters in filter wheel |
| Dust detector | | ✓ | |
| EBW radiometers | | | |
| Edge deposition monitor | | | |
| Edge pressure gauges | ✓ | | Enable all midplane and divertor gauges |
| Edge rotation spectroscopy | ✓ | | |
| Fast lost ion probes - IFLIP | | | |
| Fast lost ion probes - SFLIP | | | |
| Filtered 1D cameras | ✓ | | Cam1 – $D_\alpha$, Cam2 – $D_\alpha$, Cam3 – $D_\gamma$, Cam4 - $D_\beta$ |
| Filterscopes | ✓ | | Use Bay G filterscope with Ne filter |
| FIReTIP | ✓ | | |
| Gas puff imaging | | | |
| Infrared cameras | ✓ | | Enable midplane and divertor camera |
| 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 frequency | | | |
| 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 | | ✓ | Run top array with Ti filter |
| 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 | | | |