**Princeton Plasma Physics Laboratory**

# NSTX Experimental Proposal

Title: **Exploration of Fast Discharge Shutdown Using Coaxial Helicity Injection**

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|---|---|---|
| **OP-XP-901** | Revision: **0** | Effective Date: **5/18/09**<br>*(Approval date unless otherwise stipulated)*<br>Expiration Date:<br>*(2 yrs. unless otherwise stipulated)* |

## PROPOSAL APPROVALS

| | |
|---|---|
| **Responsible Author**: **S.P. Gerhardt** | Date: 5/12/09 |
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| **Responsible Division: Experimental Research Operations** | |

**Chit Review Board** (designated by Run Coordinator)

**MINOR MODIFICATIONS** (Approved by Experimental Research Operations)

# NSTX EXPERIMENTAL PROPOSAL

TITLE: Fast Shutdown with CHI No. **OP-XP-901**

AUTHORS: S.P. Gerhardt, R. Raman, W. Choe, R. Maingi, J-W. Ahn, N. Eidietis, S.A. Sabbagh, T.R. Jarboe, D. Mueller, B. A. Nelson.

DATE: **5/12/09**

## 1. Overview of planned experiment

The purpose of this is experiment is to use the existing CHI hardware to initiate fast plasma-shutdowns in NSTX. A standard inductive plasma with NBI will be formed. CHI will then be "fired" into the plasma, with the goal of rapidly shutting-down the discharge without generating large changes in the plasma vertical position or large halo currents.

## 2. Theoretical/ empirical justification

Disruptions pose a major challenge to any tokamak reactor: i) the eddy currents driven by the current quench cause large overturning moments on in-vessel components, ii) halo currents, due to the plasma coming in contact with the vessel after a VDE (Vertical Displacement Event), can cause additional serious electromagnetic loading, iii) impulsive heat loading during the thermal quench can cause melting/vaporization of the walls and divertor, and iv) runaway electrons can cause localized but severe damage to the vessel and internal components. It is necessary to devise methods to both predict disruptions, and to rapidly shut-down the plasma when such a prediction is made. This XP is designed to study a possible fast shut-down technique that is unique to NSTX (or any device with CHI capability).

The discussion above implies certain characteristics than any disruption mitigator should possess; a CHI mitigation system may be optimal for many of these.

1: Rapid Response: In order to mitigate a disruption, the disruption must first be detected. If the mitigation scheme is extremely rapid, then the "look-ahead" time required for detection can be made smaller, and thus possibly easier. CHI is in principle extremely rapid; the CHI gas and plasma are brought to the main tokamak plasma electromagnetically, which is much faster than the propagation of a neutral gas front.

2: Halo Currents: Disrupting plasma are often vertically unstable. When the plasma comes in contact with the top or bottom of the device, currents flow between the cold outer "halo" region of the plasma and the PFCs. Hence, halo currents can be eliminated by never allowing the plasma to become vertically unstable. This can be achieved by quenching the discharge more quickly than the VDE can develop. By injecting a large amount of neutral gas and plasma with CHI, such a rapid shut-down may be achieved. Indeed, ***achieving a rapid & vertically centered shutdown with CHI is the major goal of this XP***.

3: Thermal Quench Loading: The complete thermal energy of the plasma is lost during the thermal quench of a disruption. If this full thermal energy is deposited in the divertor, the impulsive heat fluxes can easily exceed the melting/ablation thresholds of solid materials (35-40 $MJ/m^2s^{1/2}$). However, if the power is radiated uniformly over the inner surface of the wall/vessel, then the thermal consequences are less severe. With the CHI mitigation technique (and in contrast to MGI), a radiating impurity gas can be introduced nearly axisymmetrically, ensuring a uniform radiation loading.

4: Runaway Electron Formation: Disruption runaway electrons can be formed by three mechanisms: the textbook Dreicer mechanism, the “Hot-tail” mechanism, and the “Rosenbluth Knock-On” mechanism. The last is of particular concern for ITER or a reactor, as the avalanche gain scales as $e^{Ip}$. A large runaway tail growth rate, however, can be mitigated if the loss rate is sufficiently large. Results from DIII-D and ALCATOR C-MOD, as well as theoretical studies, have indicated that if the field is sufficiently stochastic, the runaway loss-rate can be increased sufficiently. It is quite possible that the additional currents drive by CHI will lead to further field stochastization, and thus enhance runaway loss.

# 3. Experimental run plan

The goal of this XP will be to assess points 1,2, and possibly 3 described in section 2. The experimental plan will be divided into sections below. Note the “Upper X-point Optimization” set of tasks in case absorber arcs occur, and a “Neon Contingency” in case mitigation with He is clearly unsuccessful.

***3.0 Gas valve timing.***

The purpose of these shots is to determine the timing between when the command to puff gas and the gas actually entering the vessel. These shots to be done at least one day before the XP runs. The information is then used to come up with most plausible timings. These are then optimized in step 3.3.

| **Shot(s)** | **Gas** | **Plenum** | **Pressure** |
|---|---|---|---|
| | He | Small | 2400 |
| | He | 4 Large | 2400 |
| | Ne | Small | 2400 |
| | He | 4 Large | 2400 |

***3.1 Develop Target Discharge.*** ***(3 shots)***

Note: for a 4kV OH, the OH rampup waveform must be modified. See shot 120403 from 2005 for an example.

____ Reload and recreate target shot 132124

____ Increase PF2L current (0.005 kA/kA->0.0078 kA/kA), to increase flux linkage.

***3.2 Low energy CHI (safety check).*** ***(5-10 shots)***

____ Add CHI to target, 2400 Torr He in Branch 5, $t_{CHI}$~250 msec, 2 Capacitors charged to 0.9 kV

____ Add CHI to target, 2400 Torr He in Branch 5, $t_{CHI}$~250 msec, 2 Capacitors charged to 1.8 kV

In both cases, $t_{LDGIS}=t_{CHI}-t_D$, where $t_D$ is the delay time (~13msec) measured in step 3.0.

_____Skip to and execute the "Upper X-point Location Optimization" step described below.

____ Add CHI to target, *no gas injection*, $t_{CHI}$~250 msec, 2 Capacitors charged to 0.9 kV

____ Add CHI to target, *no gas injection*, $t_{CHI}$~250 msec, 2 Capacitors charged to 1.8 kV

***3.3 Shutdown Experiment, CHI Timing Scan*** ***(4 shots)***

____ Switch to 4-Plenum system, 2400 Torr He,

____ Add CHI to target, $t_{CHI}$~250 msec, Bank 3 (5 capacitors) charged to 1.8 kV

Test different timings of the CHI voltage application with respect to the gas injection: $t_{LDGIS}=t_{CHI}-t_D$.

| Shot | $t_D$ |
|---|---|
| | 0.01 |
| | 0.02 |
| | 0.03 |

____ Test case with gas injection, but no CHI voltage. This tests the role of CHI, as opposed to simply over-fueling the plasma.

***3.4 Shutdown Experiment, CHI Energy Scan*** ***(4 shots)***

____ Use 4-Plenum system, 2400 Torr He, with observed "optimal" gas timing, 1800 V on the capacitor banks.

____ Test various combination of capacitor banks, providing a range of CHI energies

| Shot | Banks Fired | # of Capacitors | Capacitance (mF) | CHI Energy (kJ) |
|---|---|---|---|---|
| | 1,2 | 5 | 25 | 40 |
| | 1,2,3 | 10 | 50 | 81 |
| | 1,3 | 7 | 35 | 57 |

____ Test case with gas injection, but no CHI voltage. This tests the role of CHI, as opposed to simply over-fueling the plasma.

*If no centered shutdown has yet been observed and there are >2 hours left in the run-day, consider switching to the section labeled "Neon Contingency"*

### *3.5 Shutdown Experiment, Plasma Energy Scan* *(5 shots)*

____ Take optimal configuration from steps 4 & 5, repeat the scan as a function of plasma stored energy, utilizing various levels of NBI power.

| Shot | Sources | Power (MW) |
|---|---|---|
| | None | 0 |
| | A+B | 3 |
| | A+B+C | 4 |
| | B | 1 |

### *3.6 Documentation of an Interesting Case* *(4 shots)*

____ Choose the most interesting case from steps 3.3, 3.4, & 3.5.

____ Repeat twice with various timing of the MPTS lasers

____ Modify the USXR filters between shots.

| Shot | MPTS Timing Relative to Refernce |
|---|---|
| | |
| | |
| | |

### ***Upper X-point Location Optimization*** *(4 shots)*

The reference shot is strongly LSN, with the upper X-point located between the plasma and the PF1AU upper coil. In order to avoid absorber arcs, it may be necessary to place the upper X-point in the vicinity of the upper CHI gap. To accomplish this, do the following in multiple shots:

_______ Reduce the PF1AU coil current to zero. This will allow the upper X-point to drift up and out.

_______ Increase the elongation, in order to move the upper X-point into the gap between the inner and outer divertors. It is likely that the upper elongation will needed to be increased by about 0.4, corresponding to an increase of the upper outer squareness of about 0.08. A smaller initial step (~0.03 or 0.04) is recommended, however.

***<u>Neon Contingency</u>***

### *3.7 Neon Contingency Shutdown Experiment, CHI Timing Scan*

____ Switch to 4-Plenum system, 2400 Torr Ne

____ Add CHI to target, $t_{CHI}$~250 msec,  bank 3 (5 capacitors) charged to 1.8 kV

Test different timings of the CHI voltage application with respect to the gas injection: $t_{LDGIS}=t_{CHI}-t_D$

| Shot | $t_D$ |
|---|---|
| | 0.01 |
| | 0.02 |
| | 0.03 |

____ Test case with gas injection, but no CHI voltage.  This tests the role of CHI, as opposed to simply over-fueling the plasma.

### *3.8 Neon Contingency Shutdown Experiment, CHI Energy Scan*

____ Use 4-Plenum system, 2400 Torr Ne, with observed "optimal" timing, 1800 V on the capacitor bank(s).

____ Test various combination of capacitor banks, giving a range of CHI energies

| Shot | Banks Fired | # of Capacitors | Capacitance (mF) | CHI Energy (kJ) |
|---|---|---|---|---|
| | 1,2 | 5 | 25 | 40 |
| | 1,2,3 | 10 | 50 | 81 |
| | 2 | 7 | 35 | 57 |

____ Test case with gas injection, but no CHI voltage.  This tests the role of CHI, as opposed to simply over-fueling the plasma.

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

**NOTE:** Do NOT conduct “hi-pot” tests of any of the NSTX vacuum vessel components above 2kV with either the CHI supply capacitors or the CHI snubber capacitors or the MOVs connected to NSTX, as these capacitors have a rating of only 2kV.

**NOTE**: Ensure LDGIS interlocks are in the “green” state prior to conducting any “hi-pot” tests.

**NSTX Configuration**

4.1 All MOVs to be connected during this operation

4.2 Bank-1: 2 capacitors, Bank 2: 3 capacitors, Bank3: 5 capacitors

4.3 Connect the CHI capacitor to the CHI bus at the machine and connect the snubber capacitor and the MOV protection devices.

4.4 Reduce the maximum voltage capability on the OH circuit to 4kV (from the normal 6kV).

# 5. Planned analysis

EFIT analysis between shots, possibly with very high time resolution. Will likely use the USXR emission to reconstruct the plasma motion and timing of its thermal collapse.

# 6. Planned publication of results

If this process is indeed successful in shutting down the plasma, the results will be appropriate for publication in a journal such as Nuclear Fusion.

# PHYSICS OPERATIONS REQUEST

TITLE: Fast Shutdown with CHI | No. **OP-XP-901**
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**Describe briefly the most important plasma conditions required for the XP:**

LSN similar to 132124, with minimal flux connecting the upper divertor.

**List any pre-existing shots:**

**Equilibrium Control:** Gap Control / rtEFIT(isoflux control):

Machine conditions *(specify ranges as appropriate, use more than one sheet if necessary)*

$I_{TF}$ (kA): -0.44 T, -53 kA    Flattop start/stop (s):

$I_P$ (MA): 600kA    Flattop start/stop (s): t = 0 to 0.4s

Configuration: **LSN** *Reference shot is 132124*

Outer gap (cm): **7-8**    Inner gap (cm): **4-6**    Z position (cm): ~-2

Elongation κ: **1.9**    Upper/lower triangularity δ: 0.25/0.34

Gas Species: **D2 in injector 2, He in LDGIS**    Injector(s):

**NBI** Species: **D** Voltages (kV or off) **A: 90** **B: 70** **C:** 70    Duration (s): ~0.4

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

**CHI**: **On**    Bank capacitance (mF): **Banks [1,2,3] with [2,3,5] capacitors**

**LITERs: Standby**    Total deposition rate (mg/min): ~5mg/min, if at all

**EFC coils: Off**

# DIAGNOSTIC CHECKLIST

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*Note special diagnostic requirements in Sec. 4*

| **Diagnostic** | **Need** | **Want** |
|---|---|---|
| Bolometer – tangential array | x | |
| Bolometer – divertor | | x |
| CHERS – toroidal | x | |
| CHERS – poloidal | x | |
| Divertor fast camera | x | |
| Dust detector | | |
| EBW radiometers | | |
| Edge deposition monitors | | |
| Edge neutral density diag. | | |
| Edge pressure gauges | x | |
| Edge rotation diagnostic | | |
| Fast ion D_alpha - FIDA | | |
| Fast lost ion probes - IFLIP | | |
| Fast lost ion probes - SFLIP | | |
| Filterscopes | x | |
| FIReTIP | | |
| Gas puff imaging | | |
| H$\alpha$ camera - 1D | x | |
| High-k scattering | | |
| Infrared cameras | x | |
| Interferometer - 1 mm | | |
| Langmuir probes – divertor | | |
| Langmuir probes – BEaP | | |
| Langmuir probes – RF ant. | | |
| Magnetics – Diamagnetism | | |
| Magnetics – Flux loops | x | |
| Magnetics – Locked modes | x | |
| Magnetics – Pickup coils | x | |
| Magnetics – Rogowski coils | x | |
| Magnetics – Halo currents | x | |
| Magnetics – RWM sensors | x | |
| Mirnov coils – high f. | x | |
| Mirnov coils – poloidal array | x | |
| Mirnov coils – toroidal array | x | |
| Mirnov coils – 3-axis proto. | | |

*Note special diagnostic requirements in Sec. 4*

| **Diagnostic** | **Need** | **Want** |
|---|---|---|
| MSE | x | |
| NPA – ExB scanning | | |
| NPA – solid state | | |
| Neutron measurements | x | |
| Plasma TV | x | |
| Reciprocating probe | | |
| Reflectometer – 65GHz | | |
| Reflectometer – correlation | | |
| Reflectometer – FM/CW | | |
| Reflectometer – fixed f | | |
| Reflectometer – SOL | | |
| RF edge probes | | |
| Spectrometer – SPRED | | |
| Spectrometer – VIPS | | |
| SWIFT – 2D flow | | |
| Thomson scattering | x | |
| Ultrasoft X-ray arrays | x | |
| Ultrasoft X-rays – bicolor | x | |
| Ultrasoft X-rays – TG spectr. | | |
| Visible bremsstrahlung det. | | |
| X-ray crystal spectrom. - H | | |
| X-ray crystal spectrom. - V | | |
| X-ray fast pinhole camera | | |
| X-ray spectrometer - XEUS | | |