Princeton Plasma Physics Laboratory

NSTX Experimental Proposal

Title: Transient CHI Startup

OP-XP-606	**Revision: 0**	Effective Date: **2/24/06** *(Ref. OP-AD-97)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

Responsible author: R. Raman	Date
ATI – ET Group Leader: D. Mueller	Date
RLM – Run Coordinator: R. Raman	Date

Responsible Division: Experimental Research Operations

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

NSTX EXPERIMENTAL PROPOSAL

Title: **Transient CHI Startup** **OP-XP-606**

Authors: **R. Raman, M. Bell, T.R. Jarboe, B.A. Nelson, D. Mueller**

1. Overview of planned experiment

We will apply the "Transient CHI" scheme developed in HIT-II to demonstrate persistent toroidal current following a pulse of coaxial helicity injection (CHI) applied with the newly upgraded CHI capacitor bank. This XP has three parts: 1) Demonstrating the persistence of CHI-induced toroidal current; 2) handing off the CHI-induced plasma to inductive sustainment and ramp-up, and 3) measuring the benefits of CHI in saving inductive flux.

2. Theoretical/ empirical justification

Using a new CHI-specific capacitor bank, the method of Transient CHI was tested on NSTX during 2004. The capacitor bank produced reliable discharge initiation and operation over a wide range of gas pressure and injector flux conditions. However, analysis of the results pointed to four areas for improvement:

a) The need for improved pre-ionization so that the amount of injected gas can be reduced by a factor of at least four to provide more energy per particle from the fixed capacitor bank energy. The required capacitor bank energy per particle should preferably be about 100eV so that, after losses, the resulting plasma could burn through radiation barriers and reach temperatures of about 30eV or higher.

b) Increasing the capacitor bank voltage above the 1kV operational limit applied in 2004 should enable breakdown at lower gas pressures and increase the available energy by a factor of four over what was available in 2004.

c) Reducing the injector flux footprints is required to produce a sufficiently narrow flux foot print for inducing reconnection near the injector throat region.

d) Improved equilibrium control.

During the 2005 run these improvements were implemented and resulted, for the first time in NSTX, the observation of current persistence after the injector current was reduced to zero. This XP has minor modifications to the XP run in 2005 (No. 531).

3. Experimental run plan

3.1 Reproduce current persistence and diagnose to obtain missing data

Configure the CHI capacitor bank initially with three capacitors in parallel (C = 15mF). The capacitor bank will be triggered at t = 5ms throughout this experiment.

Open line and ground switches in the OH circuit to prevent current from flowing in it.

Use 5min HeGDC between shots to maintain constant wall conditions. Use the Movable glow probe if it is found to reduce the time needed for glow discharge cleaning.

Start with the gas timing and plenum pressure developed in shot 118340. Reload this shot. (Note: all PF coil currents are specified in the physics convention, *i.e.* positive current is counter-clockwise from above.). Extend the current flat-top duration in the following coils to +500ms (TF, PF5, PF3U, PF3L, PF1AU, PF1AL and PF2U).

Program the CHI capacitor bank crowbar ignitron to fire at t = +8ms to rapidly reduce the CHI injector current.

Start with a capacitor bank charging voltage of 1.0kV, and increase in steps of 100V up to 1.5kV, while monitoring the fast injector voltage signals for noise spike excursions.

After current persistence is observed, readjust the PF3U coil current so as to position the plasma at z=0. Reduce the vertical field if the plasma moves inboard.

If possible apply 40-50kV NBI (one to three sources, 20ms pulse, starting from the time of peak in the plasma current) to increase the plasma temperature (as in 2005).

Now diagnose using (1) soft x-ray array, (b) bolometer array, (c) fast camera, (d) Thomson scattering and (e) spectroscopy.

3.1b Test use of PF4 to provide a pre-charged vertical field

If possible, starting from the previous shot, add current in PF4 (in steps of 0.2kA, starting from -50ms) to see if this provides vertical field with reduced incidence of the negative current spike during discharge initiation time.

Optimize currents in PF4 and PF5 to improve horizontal position control.

3.1c Increase the magnitude of closed flux current by increasing the injector flux and the toroidal flux.

Starting from the previous shot (TF=48kA), change the current in the TF coils to 41.5kA, 46, 44, 40, 50 kA to observe the effect on current multiplication at constant injector flux (if experimental condition allow, expand the range). Scan in TF only if you see a change from 48 to 41.5kA.

Starting from the best case above (PF1B=4.67kA), change the current in the injector flux coils proportionally in steps of 10% (to increase and decrease the injector flux), as follows: PF1B = 4.2, 3.8, 3.4, 5.2 kA (if experimental conditions permit, further increase the injector flux).

For the case with the highest injector flux, readjust the current in the TF coil to maximize the closed flux fraction. To do this it may be necessary to go to higher voltage, so this part may need to be delayed until higher voltage capability is available. Use Table 1 in the appendix as a guide.

Repeat the above optimization for the lowest possible value of injector flux.

Use 4 or 5 capacitors if the discharge indicates lack of capacitor bank energy.

3.1d Use Lithium wall conditioning capability to improve closed flux generation

Based on the work conducted in XP 601(Li deposition) and the methods developed there, select a suitable amount of Li to apply either between shots or once per several shots (for example like Ti gettering in HIT-II). Repeat the best discharges with Li wall conditioning to asses the impact of Li on these discharges. Note that it may not be necessary to do between shot HeGDC for several shots in a row (as on HIT-II) because unlike inductive operation there is no gas puffing during the shot.

In conducting this experiment it may be necessary to increase the amount of gas injected in the region below the lower divertor plates to avoid the negative current spike, however, depending on how effective Li is, CHI discharges may now require higher amounts of gas to be injected into the lower dome.

3.1e Operate at higher voltage (up to 2kV)

Starting from step 3.1c, for discharges with the higher values of injector flux, increase the capacitor bank voltage in steps of 100V, as required to maximize the amount of closed flux current.

Use the information gained from step 3.1b to use both PF4 and PF5 to provide the needed vertical field based on EFIT reconstructions and fast camera observation.

If MSE capability is available, use to measure the current profile of one or two of the highest current discharges.

If the HHFW system is operational and the antennas are well conditioned apply short pulses at low power, in the heating phase, to further heat the CHI produced plasmas (as in 2005).

<u>3.2 Hand-off to inductive operation using the central solenoid</u>

a) Close the OH circuit line switches and enable the OH power supply. Starting from the time of peak toroidal current, ramp the OH from zero to -10kA in progressively shorter periods to determine the response of the plasma to induction, as follows:

   2V/turn: t_1 to t_1+62ms, t_1 = time of peak CHI-induced current when OH ramp is initiated;

   4V/turn: t_1 to t_1+41ms;

b) Apply the OH induction for the time needed to ramp the plasma current by about 100% of the minimum of the plasma current during hand-off or by 100kA, whichever is higher.

Using the ratios $I_{PF3}/I_p = -2.4kA/100kA$ and $I_{PF2}/I_p = +1.2kA/100kA$. Program the current in PF5 approximately in the ratio $I_{PF5}/I_p = -0.3kA/100kA$, to provide radial equilibrium.

c) If induction is not able to sustain the CHI-induced current, either:

- Apply a 40ms, 1 – 2 MW pulse of HHFW power phased for plasma heating (0-π), or
- If the CHI-induced plasma current is above 100kA and the edge neutral pressure is below 5E-5 Torr (\ENGINEERING::GS_IG_TORR) during the current decay, apply a 20 ms pulse of NBI at 50-60 keV, initially from one source and adding sources if needed.

d) After the initial inductive ramp to I_{OH} = -10kA, continue to ramp the OH current, if necessary at a lower rate, until the OH coil current reaches the maximum of -24kA, to maximize the plasma current. Use EFIT reconstructions to adjust the currents in PF3 and PF2 coils.

e) Attempt to introduce normal feedback control of the equilibrium and plasma current using the PCS after I_p reaches 100kA and after imposing a time delay of at least 25ms from start time of current in the OH coil.

3.3 Assessment of Inductive Flux Saving

a) After reliable, reproducible discharges are obtained, repeat 5 shots using CHI start-up assist. If necessary, use feedback controlled current ramp after an initial phase of pre-programmed current ramp. Based on the observed current evolution, the value for the current setting at which feedback controlled operation commences may need to be revised in the plasma control system software.

b) Develop an inductive startup discharge which reaches the same current and configuration in the same time as the CHI-assisted discharges in a). This will require bipolar operation of the OH, reprogramming the initial PF waveforms and switching to the standard LFS gas injector. Note that since the OH power supply voltage will be limited to 4kV for CHI experiments, some discharge development will be needed. Run 5 shots with inductive-only start-up to measure the poloidal flux consumption under identical current ramp-up conditions. Determine differences in density profile, current profile and temperature profile evolution.

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 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.

NOTE: The trained personnel identified in the procedure for changing the capacitor bank configuration should be available during the initial phase of CHI operations when the capacitor bank size is being changed.

Configuration

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

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

4.3 Configure PF1B for 2kV operation to drive current in the anti-clockwise direction as seen from above (normal for CHI). Change PF1B RIS and software limits to provide 10kA capability (from the present 5kA).

4.4 Configure PF2L for 2kV operation.

4.5 Configure PF4 to have the same polarity as PF5

4.6 Enable the EC-PI klystron #2 to provide the divertor chamber preionization and disable klystron #1 connected to the midplane EC-PI launcher. Apply the EC-PI power from t = -3 to +8ms.

4.7 Configure HHFW for 0-π phasing during heating, if required.

4.8 Increase the gain on the Mirnov coils by connecting the appropriate cables and changing the attenuation factor. For Step 3.2 on, return the Mirnov coil gains to the standard values used for inductive discharges.

4.9 Operate the NB sources at 40-60kV acceleration voltage if NBI is needed.

LDGIS system checks

4.10 Ensure LDGIS is in the "Puff" mode and has been tested prior to the experiment.

4.11 Ensure LDGIS gas pressure interlocks (PE107, PE104) are functional.

4.12 Set LDGIS operating line pressure to 100Psig helium.

4.13 Ensure 2000 Torr D_2 filling gas pressure in LDGIS system

Pre-operational checklist

4.14 Ensure MIG and Penning gauges are selected for operation.

4.15 Remove CHI jumpers.

4.16 Check TF interlock is set to 10kA.

4.17 Check for the appearance of ionization light on the fast camera during the EC-PI pulse to ensure correct triggering.

5. Planned analysis

The magnetic analysis codes MFIT, EFIT and ESC will be used to analyze the plasma equilibrium. It is hoped to be able to use data from the MPTS and other kinetic diagnostics to supplement the magnetic data for the assessment of flux closure.

6. Planned publication of results

These results will be published at meetings and in journal articles.

Appendix: Useful coil current table for increasing values of plasma current:

Based on the evolution of the discharge, adjust PF currents to obtain an equilibrium of the evolving discharge and maximize the toroidal plasma current. Use the values listed in Table 1 as a guide. Program PF3U and PF1AU to zero at t = 0 and the value listed at t = 2ms. Program PF5 to have the value specified for t ≥ 0. Adjust the timing of the PF ramps to match the discharge evolution. Note that the values **(in bold)** in Table 1 for PF5, PF3U and PF1AU are upper limits calculated using the iSolver code (J. Menard) for hypothetical steady-state, closed-flux equilibria located at R=0.85m, a=0.6m. Calculations of CHI discharge evolution using the TSC code with the most up-to-date NSTX vessel geometry and open-field-line currents always show lower current requirements for the PF3U and PF5 coils than the steady-state calculation. Therefore, initially use a value about 25% of that listed in the table and make further adjustments based on experimental observations.

Table 1: Reference coil currents (kA) for steady-state equilibrium at specified plasma current

I_p(kA)	PF1B	PF1AL	PF2L	PF5	PF3U	PF1AU
50	4.0	-1.5	-2.0	**-0.21**	**-0.38**	**-0.03**
75	4.0	-1.5	-2.0	**-0.33**	**-0.44**	**-0.10**
100	4.0	-1.5	-2.0	**-0.49**	**-0.46**	**-0.05**
150	4.0	-1.5	-2.0	**-0.79**	**-0.53**	**-0.07**
150	4.0	-2.0	-2.0	**-0.77**	**-0.55**	**-0.12**
150	4.0	-2.0	-2.5	**-0.57**	**-0.75**	**-0.60**
150	4.0	-2.0	-3.0	**-0.51**	**-0.90**	**-0.54**
50	4.0	-2.0	-3.0	**-0.19**	**-0.64**	**+0.53**
100	4.0	-3.0	-2.0	**-0.38**	**-0.82**	**+0.14**
200	6.0	-3.0	-4.5	**-0.67**	**-1.32**	**-0.19**
150	6.0	-3.0	-4.5	**-0.51**	**-1.22**	**+0.22**
250	6.0	-3.0	-4.5	**-0.79**	**-1.39**	**-0.90**
200	6.0	-2.5	-3.75	**-0.67**	**-1.06**	**-0.66**
150	6.0	-2.5	-3.75	**-0.48**	**-0.96**	**-0.45**

PHYSICS OPERATIONS REQUEST

Title**: Transient CHI Startup** **OP-XP-606**

Machine conditions (specify ranges as appropriate)

I_{TF} (kA): **-41 to -52** Flattop start/stop (s): **-0.02 / 0.7**

I_P (MA): **0.5** Flattop start/stop (s): **n/a**

Configuration: **CHI transitioning to CS limited**

Outer gap (m): **N/A**, Inner gap (m): **N/A**

Elongation κ: **N/A**, Triangularity δ: **N/A**

Z position (m): **0**

Gas Species: **D**, Injector: **LDGIS + LFS midplane**

NBI- **40kV to 60kV D^0 injection, 20ms pulse**

ICRF- **Up to 2MW in the heating phasing (0-π).**

CHI- **Capacitor bank operation, 2 – 10 capacitors active**

Shot numbers for setup: **118340, Other useful shot numbers: 118346, 118257**

DIAGNOSTIC CHECKLIST

Transient CHI Startup **OP-XP-606**

Diagnostic	**Need**	**Desire**	**Instructions**
Bolometer – tangential array	X		* Use when reproducible conditions are achieved
Bolometer array - divertor		X	
CHERS			
Divertor fast camera		X	
Dust detector			
EBW radiometers			
Edge pressure gauges	X		
Edge rotation spectroscopy		X	*
Fast lost ion probes - IFLIP			
Fast lost ion probes - SFLIP			
Filterscopes		X	
FIReTIP		X	*
Gas puff imaging			
H□ camera - 1D		X	*
Infrared cameras		X	
Interferometer - 1 mm			
Langmuir probe array		X	
Magnetics – Diamagnetism	X		
Magnetics - Flux loops	X		
Magnetics - Locked modes			
Magnetics - Pickup coils	X		
Magnetics - Rogowski coils	X		
Magnetics - RWM sensors			
Mirnov coils – high frequency	X		
Mirnov coils – poloidal array	X		
Mirnov coils – toroidal array	X		
MSE		X	
Neutral particle analyzer			
Neutron measurements			
Plasma TV	X		
Reciprocating probe		X	
Reflectometer – core			
Reflectometer - SOL			
RF antenna camera			
RF antenna probe			
SPRED		X	
Thomson scattering		X	*
Ultrasoft X-ray arrays		X	*
Ultrasoft X-ray arrays – bicolor		X	*
Visible bremsstrahlung det.		X	*
Visible spectrometer (VIPS)		X	
X-ray crystal spectrometer - H			
X-ray crystal spectrometer - V			
X-ray fast pinhole camera		X	*