NSTX Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Minimization of Solenoid Flux Usage Using Transient CHI Start-up

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R. Raman, T.R. Jarboe, B.A. Nelson, D. Mueller et al.
University of Washington/PPPL

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NSTX Research Forum for FY2011-12 Research
March 15-18, 2011
PPPL, Princeton, NJ

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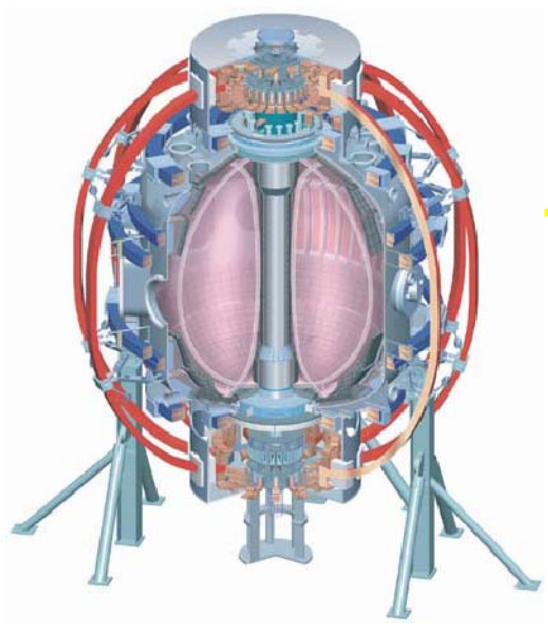
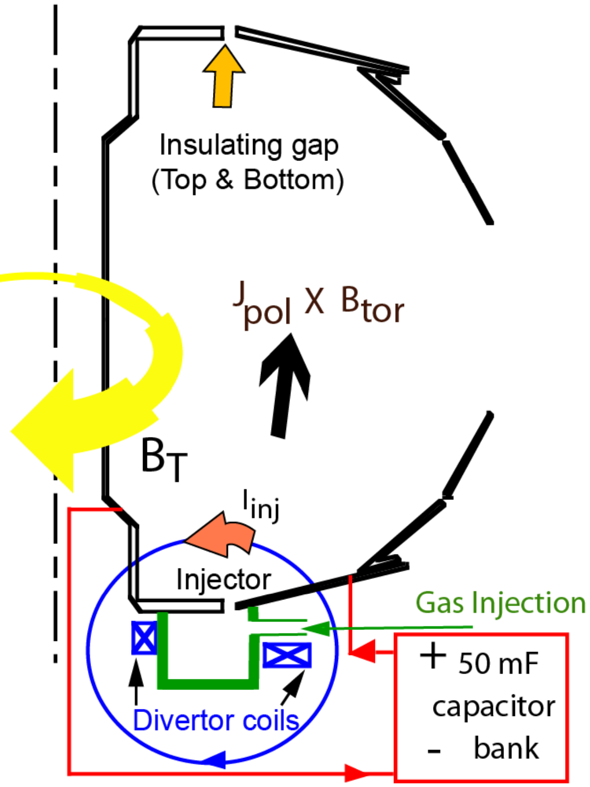
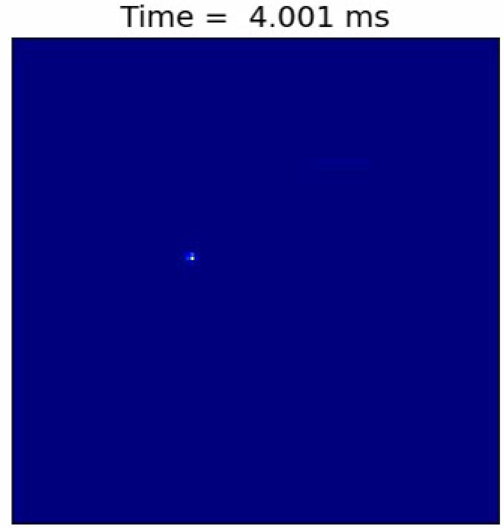
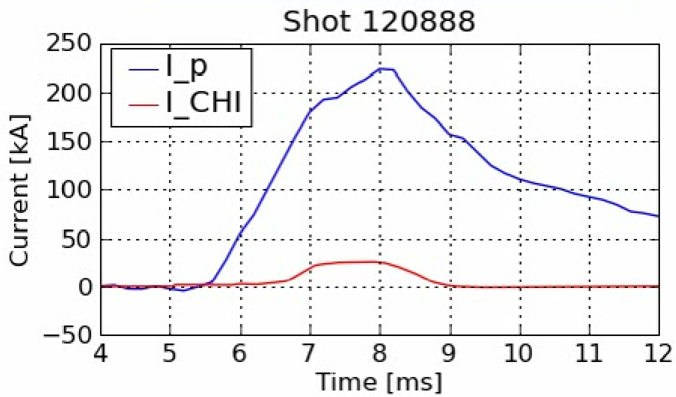
Transient CHI: Axisymmetric Reconnection Leads to Formation of Closed Flux Surfaces







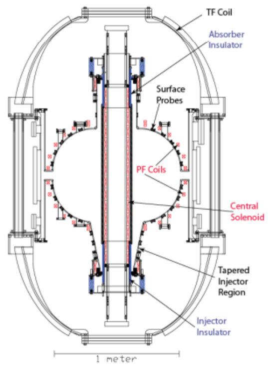


- Parameters to consider
  - Current multiplication factor
  - Effect of toroidal field
  - Magnitude of generated plasma current
  - New desirable features?

Fast camera: **F. Scotti, L. Roquemore, R. Maqueda**

CHI for an ST: **T.R. Jarboe, Fusion Technology, 15 (1989) 7**
Transient CHI: **R. Raman, T.R. Jarboe, B.A. Nelson, et al., PRL 90, (2003) 075005-1**

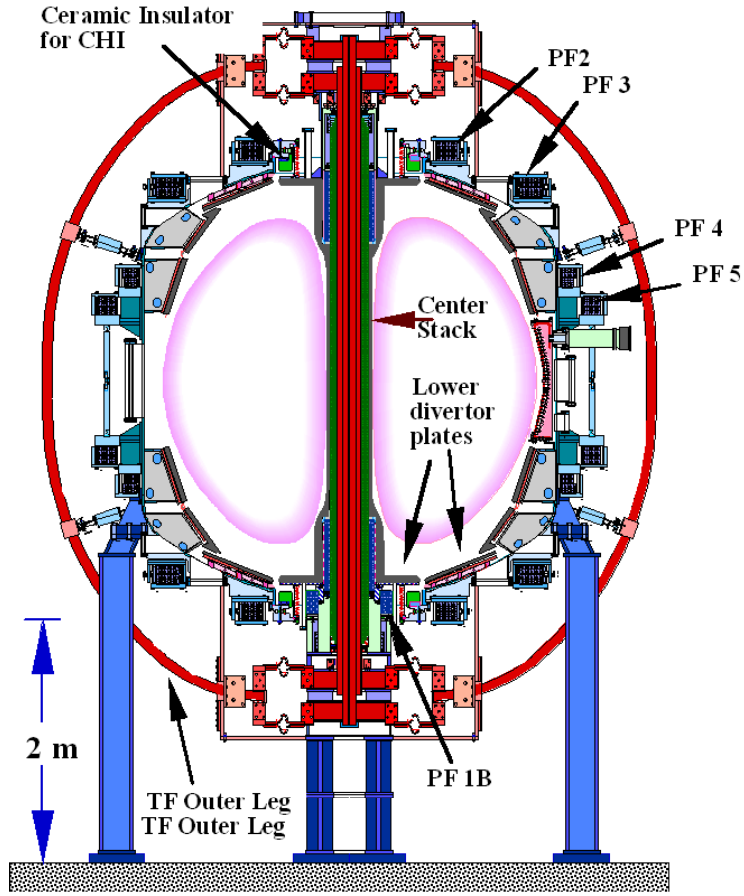
NSTX CHI Research Follows Concept Developed in HIT-II



Concept exploration device HIT-II

- Built for developing CHI
- Many close fitting fast acting PF coils
- 4kV CHI capacitor bank

NSTX plasma is ~30 x plasma volume of HIT-II

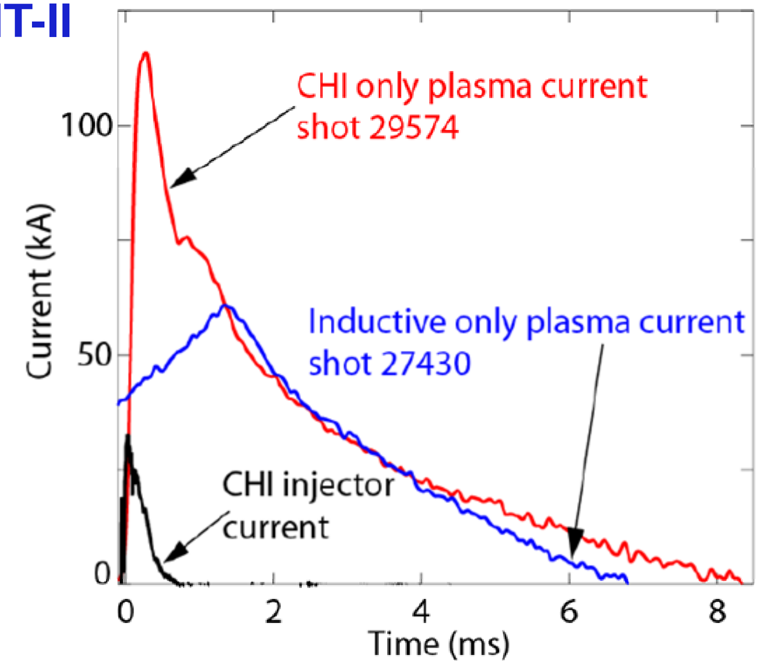


Proof-of-Principle NSTX device

- Built with conventional tokamak components
- Few PF coils
- 1.7kV CHI capacitor bank

Very High Current Multiplication (Over 70 in NSTX) Aided by Higher Toroidal Flux

HIT-II

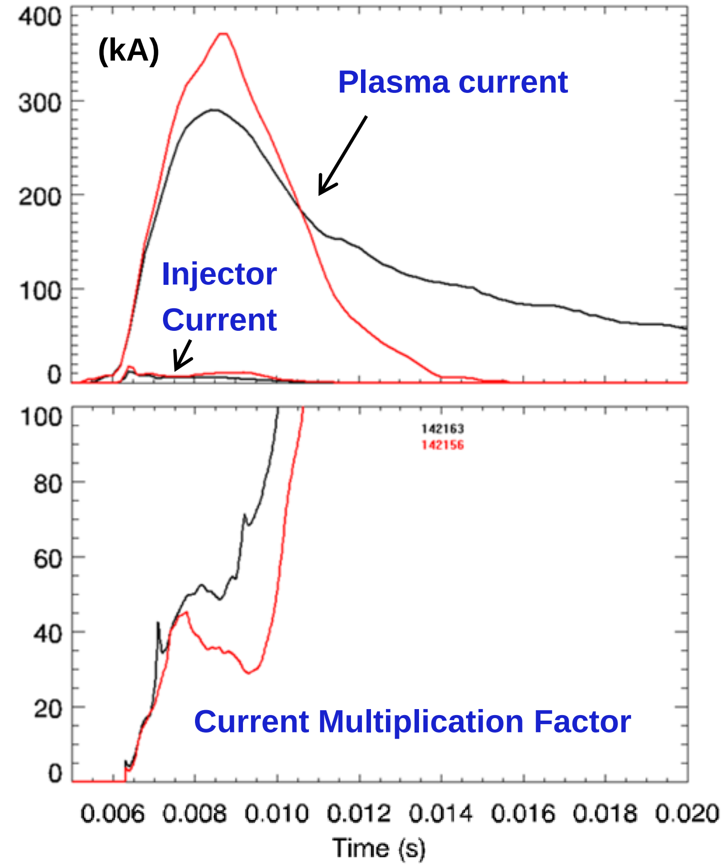


-30kA of injector current generates 120kA of plasma current

-Best current multiplication factor is 6-7

-Current multiplication factor in NSTX is 10 times greater than that in HIT-II

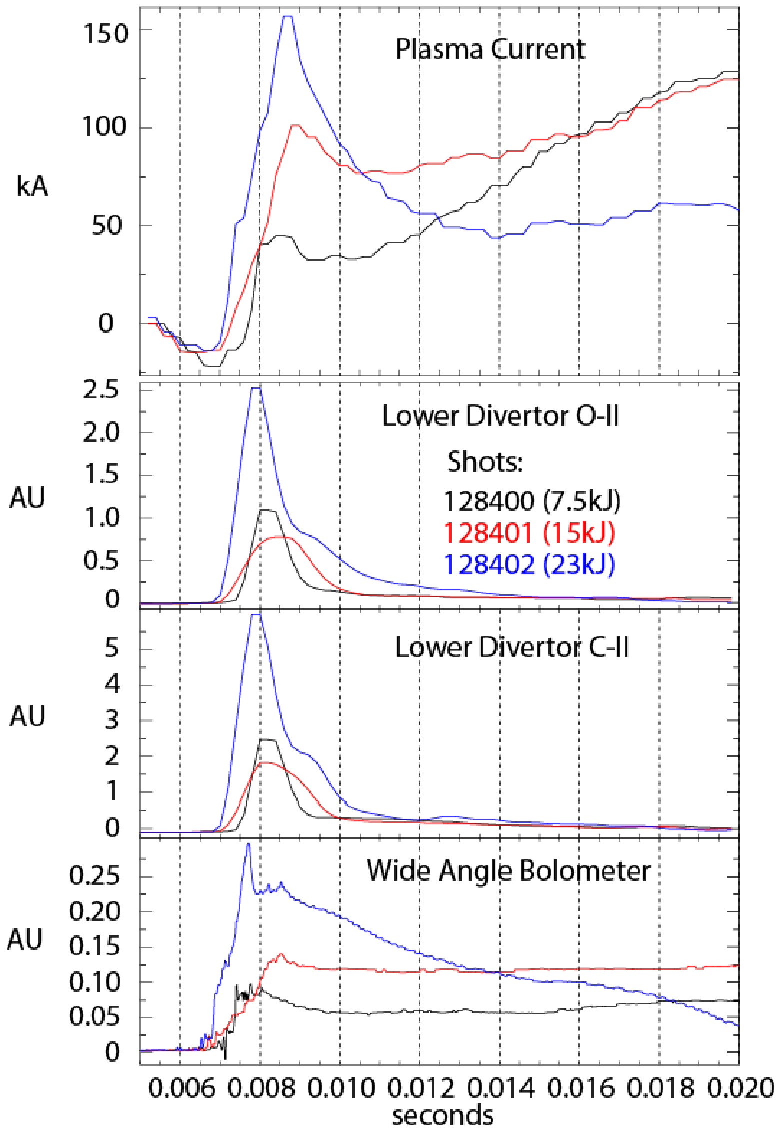
NSTX



- Over 200kA of current persists after CHI is turned off

R. Raman, B.A. Nelson, D. Mueller, et al., PRL 97, (2006) 17002

Low-Z Impurity Radiation Needs to be Reduced for Inductive Coupling

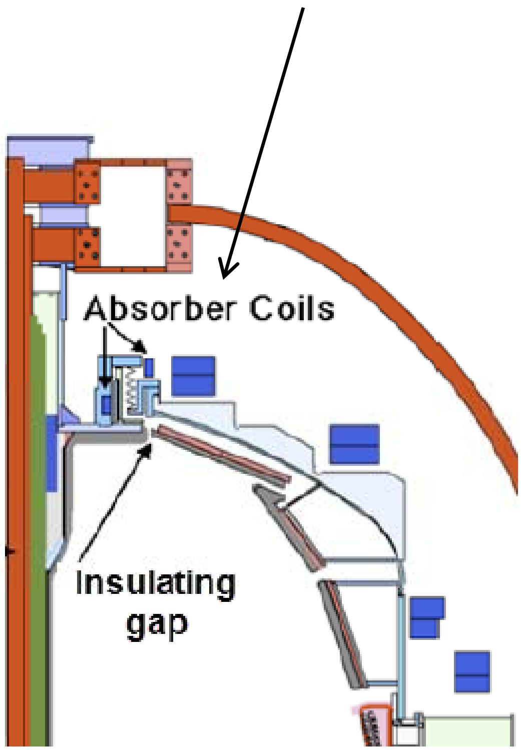


- Low-Z impurity radiation increases with more capacitors
- Possible improvements
  - Metal divertor plates should reduce low-Z impurities
    - High Te in spheromaks (500eV) obtained with metal electrodes
  - Discharge clean divertor with high current DC power supply
  - Use auxiliary heating during the first 20ms

Filter scopes: **V. Soukhanovskii**

Flux Savings on NSTX Now Realized After Low-Z Impurity Reduction

Absorber coils provide buffer field



Long-pulse (400ms) CHI discharges with high injector flux to avoid “bubble-burst”

- ablate low-Z impurities from lower divertor

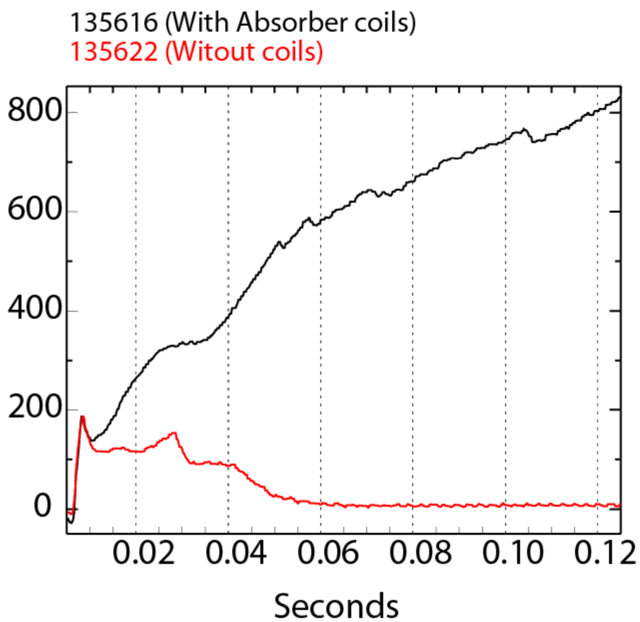
Deuterium glow discharge cleaning employed to chemically sputter and reduce oxygen levels

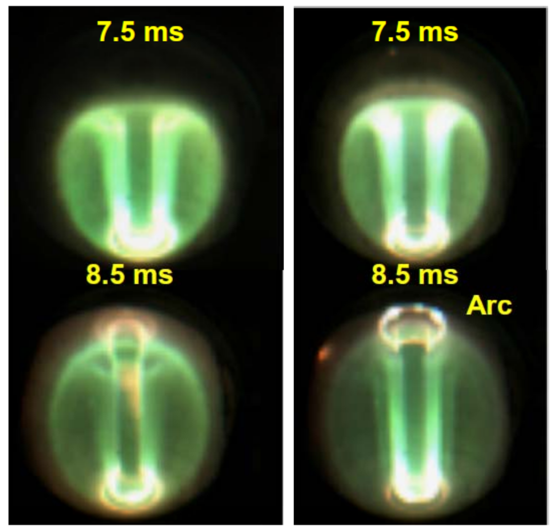
Lithium evaporation on lower divertor plates improved discharge performance

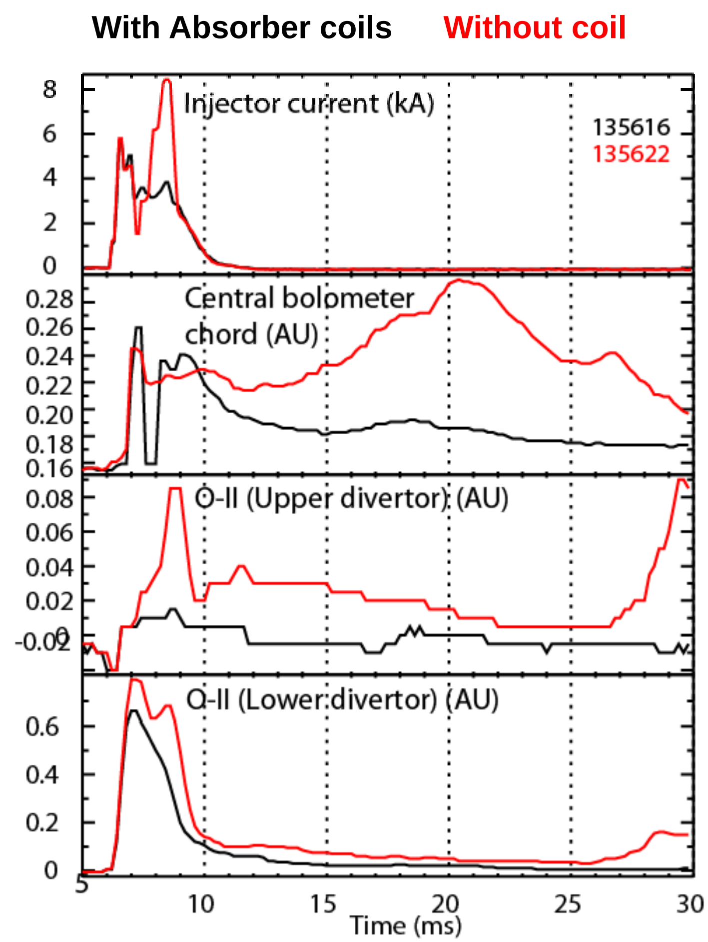
A buffer field was provided using new PF coils located in the upper divertor region

- reduced interaction of CHI discharge with un-conditioned upper divertor plates

Absorber Coils Suppressed Arcs in Upper Divertor and Reduced Influx of Oxygen Impurities





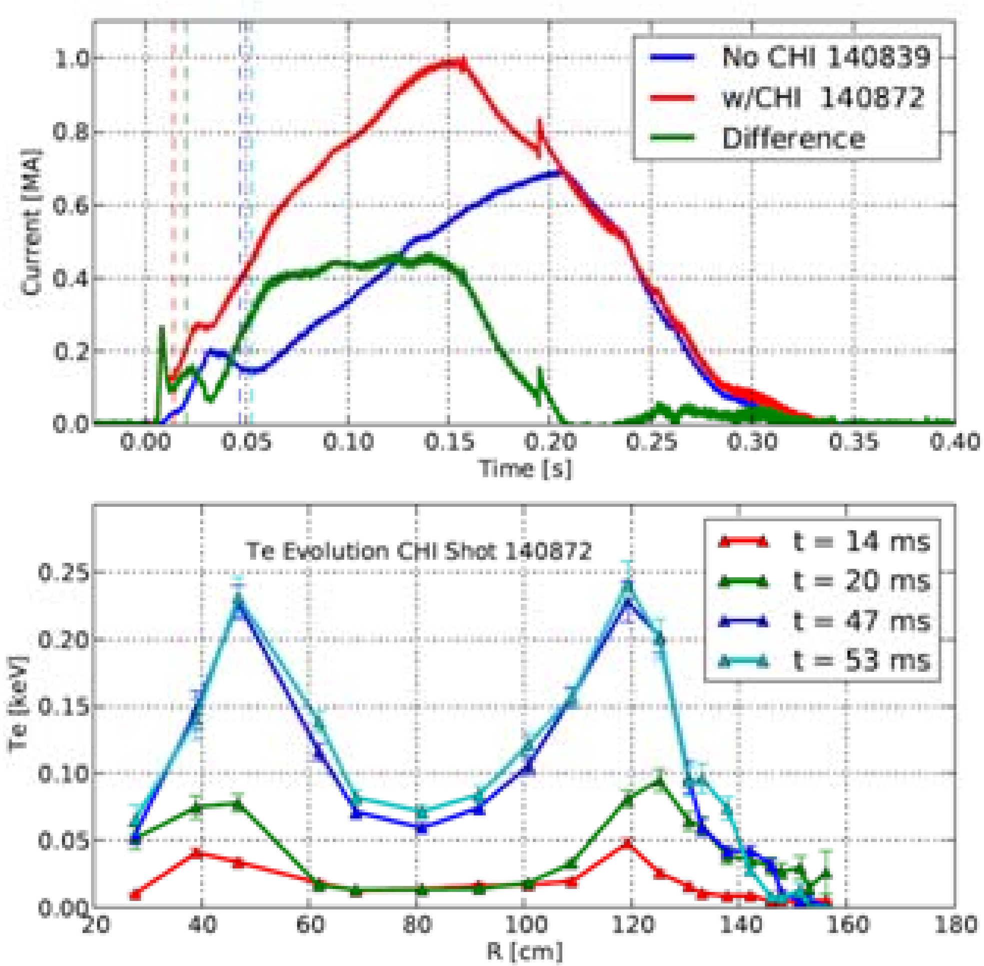


- Divertor cleaning and lithium used to produce reference discharge

- Buffer field from PF absorber coils prevented contact of plasma with upper divertor

R. Raman, D. Mueller, B.A. Nelson, T.R. Jarboe, et al., PRL 104, (2010) 095003

Using Only 27kJ of Capacitor Bank Energy CHI Started a 300kA Discharge that Coupled to Induction

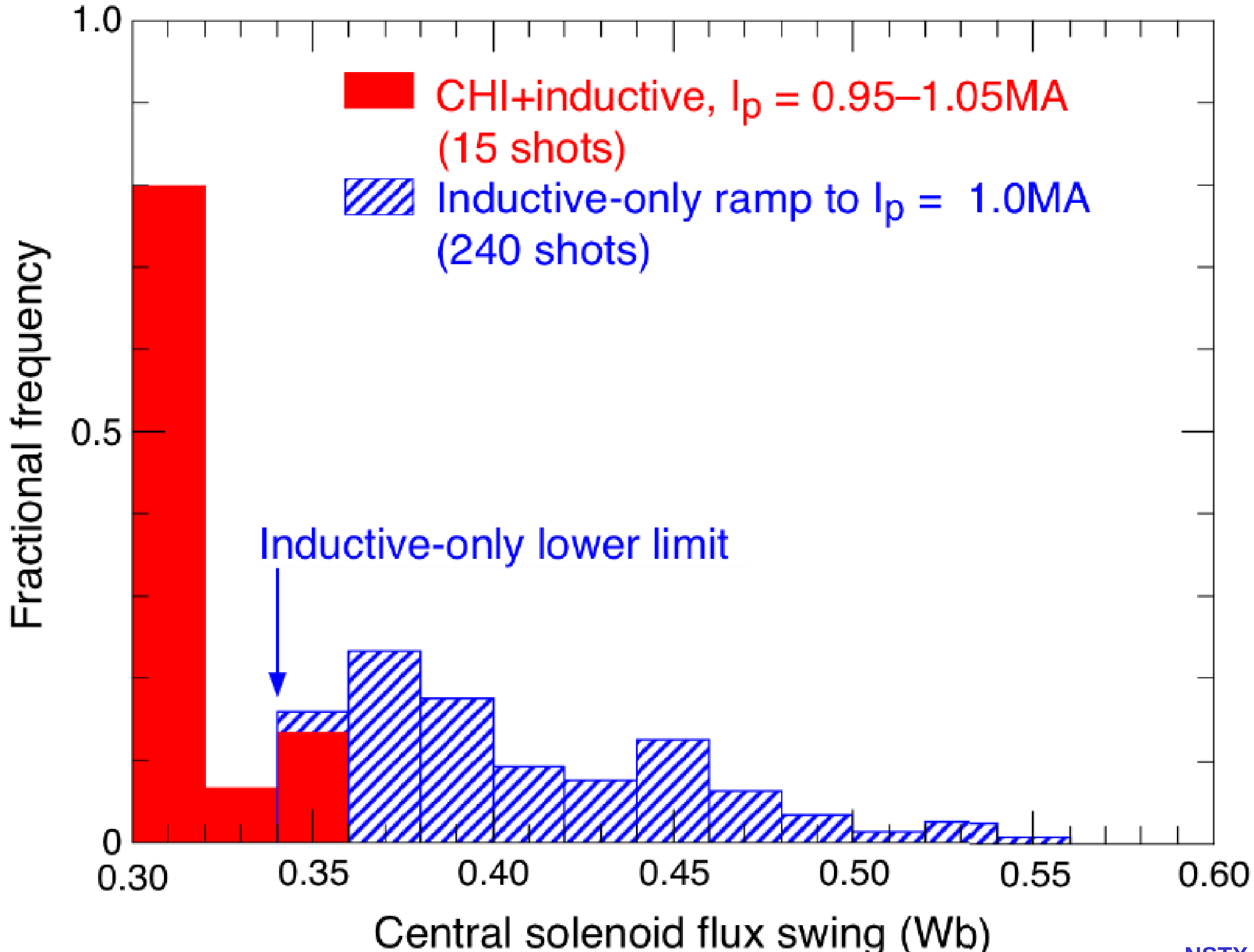


- Ramped up to 1MA after startup, using 0.3Wb change in solenoid flux
- Hollow electron temperature profile maintained during current ramp
  - Important beneficial aspect of using CHI startup

- Discharges with early high T_e ramp-up to higher current

CHI Started Discharges Require Less Inductive Flux than Discharges in NSTX Data Base

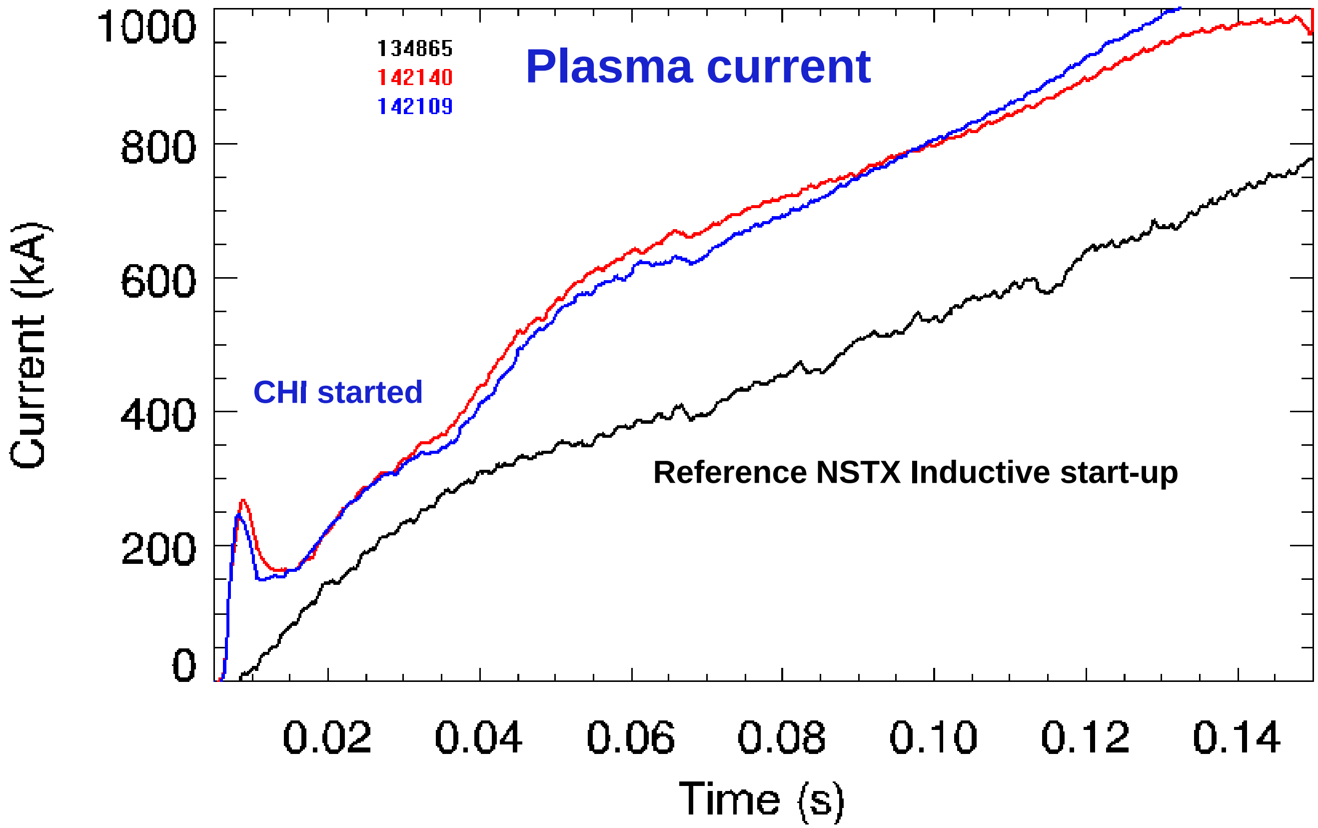
Comparison of CHI Startup to H-modes using more than 1 NBI source



Most recent CHI-started discharges require less flux than shown here

NSTX Data Base Analysis: **M. Bell**

Standard L-mode NSTX Discharge Ramps to 1MA Requiring 50% More Inductive Flux than a CHI Started Discharge

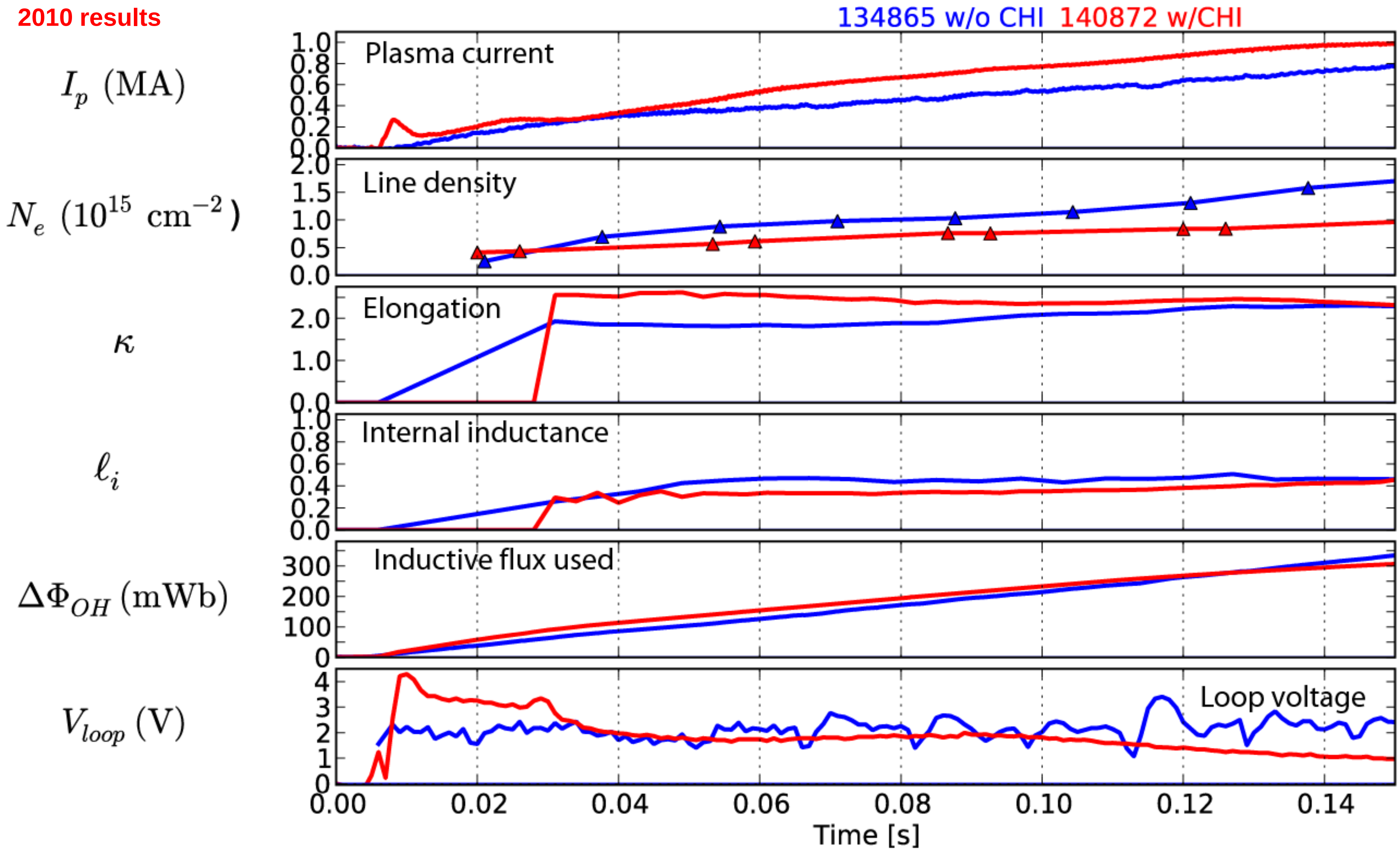


2010 results
Post IAEA

- **Reference Inductive discharge**
  - **Uses 396mWb to get to 1MA**
- **CHI started discharge**
  - **Uses 258 mWb to get to 1MA (138 mWb less flux to get to 1MA)**

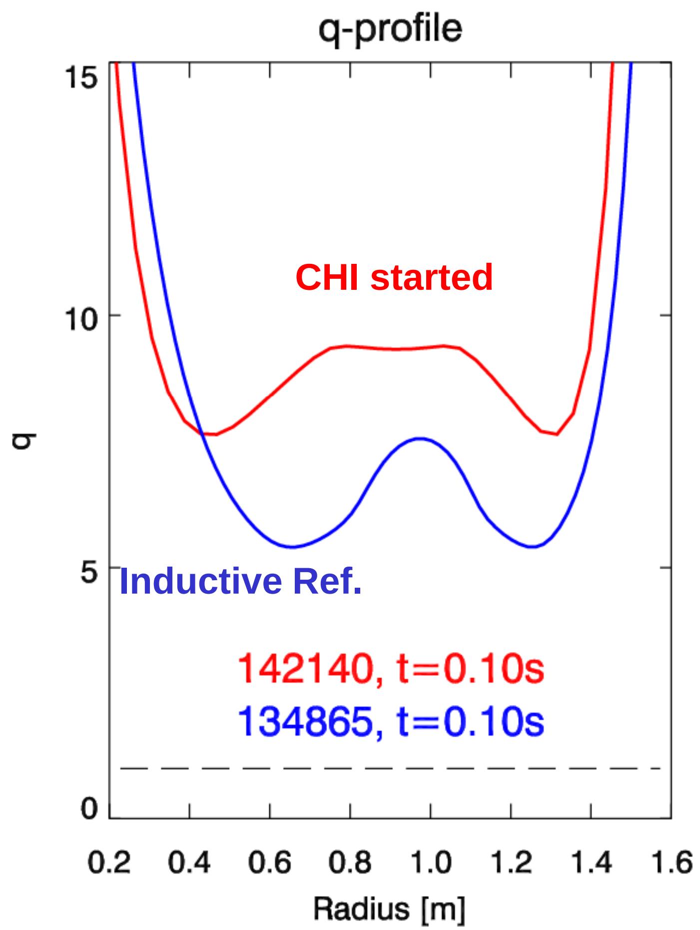
CHI Start-up Discharges have low Internal Inductance and Electron Density Starting from Early in the Current Ramp

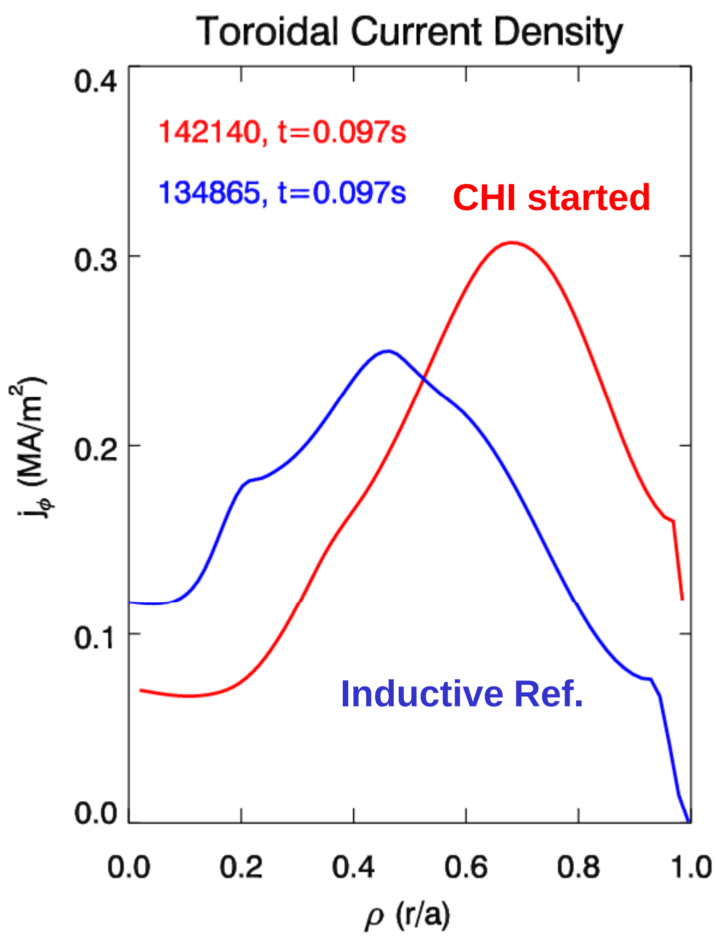
2010 results



These are the type of plasmas needed to increase the neutral beam current drive fraction

CHI Start-up Discharges Show Plasma Current Driven at Large Radius





2010 results

These are the type of plasmas needed for advanced scenario operations

MSE & LRDFIT: H. Yuh, J. Menard, S. Gerhardt

Research Priorities

Research Priorities:

- Minimize reliance on central solenoid flux to achieve 0.8-1MA plasma currents using early NBI/HHFW heating and by reducing impurities
- Assess heating and current drive in inductive low plasma current discharges using HHFW
- Determine maximum achievable closed flux currents with CHI start-up
- Start CHI discharges with a pre-charged central solenoid

Research Milestone

R(12-2): Assess confinement, heating, and ramp-up of CHI start-up plasmas

Responsible TSGs: Solenoid-Free Start-up, Wave-particle Interactions, Advanced Scenarios and Control

"Elimination of the ohmic heating (OH) solenoid is essential for proposed ST-based nuclear fusion applications. Coaxial helicity injection (CHI) is a leading candidate method for plasma initiation without an OH solenoid. Understanding CHI plasma confinement is important for projecting non-inductive start-up and ramp-up efficiency to next-steps. CHI initiated plasmas have been successfully coupled to induction H-mode plasmas with Neutral Beam Injection (NBI) heating. While these results are favorable, the confinement properties of CHI start-up plasmas have not been characterized. High-Harmonic Fast Wave (HHFW) and more recently NBI heating of low-current ohmic targets has been demonstrated and will be further developed. HHFW and/or early NBI heating will be applied to CHI targets coupled to induction to compare the confinement and heating versus non-CHI plasmas. Early NBI and HHFW heating and CD will be applied progressively earlier in the target to assess non-inductive sustainment, and the degree to which the OH flux consumed can be reduced will be quantified. Utilization of an all metal divertor could further improve CHI start-up and will also be characterized if such a divertor is present in NSTX. TRANSP and/or TSC will be used to both analyze and simulate the CHI experiments. This milestone informs the early auxiliary heating requirements for non-inductive start-up for NSTX Upgrade and for next-step ST facilities."

Goals & Objectives for SFPS Research in FY11/12

- Maximum CHI started plasma current
  - Maximum injector current consistent with acceptable low-Z impurities
  - Improvements due to metal electrodes
- Can HHFW increase Te of CHI discharges?
  - Can the current decay time be increased?
- How well does NBI couple to CHI started and ramped discharges?
  - As plasma current varies
  - As density varies
  - NBI power and application time (MHD modes)
  - NBI tangency
- Does early NBI & RF application improve CHI started discharges
- Properties of CHI started discharges vs. normal inductive plasmas
- How much NI current can be driven in low Ip OH and CHI started discharges
- CHI start-up capability ineeded in NSTX-U for directly coupling to NBI

New Hardware Improvements for FY11/12 Research

- Variable voltage charging capability for the CHI cap bank
  - Should help improve control of absorber arcs
- Higher currents in the PFAB1 and 2 coils
  - For improved absorber arc suppression
- Metal inner divertor plates
  - Reduce low-Z impurities as the injector current is increased
- Dual LITER system
  - Reduce low-Z impurities due to more complete divertor coverage
- Functioning Li-dropper system
  - For improved absorber arc suppression

Run Plan – XP1034, Raman et al., (1 –day in FY11) (obtain time from electrode conditioning time)

- Reproduce FY11 discharges using 4 capacitors
  - To verify machine is able to support higher current discharges
  - This may take more than a day as the CHI electrodes seem to require some time to condition

Run Plan – CHI Only, Nelson et al., (1 to 2 –days in FY11, 1 day in FY12)

- Generate CHI only discharges (No induction) to increase the CHI start-up current level
  - Higher injector currents will be needed as both the capacitor bank size and the injector flux will be increased at BT=0.55T
  - The variable voltage capability of the cap bank will be used to adjust the voltage programming to reduce absorber arcs
  - The dual LITERS will be used to reduce low-Z impurities from the injector
  - The PFAB1 and 2 coil current duration and current magnitude will be improved
  - After a limit is reached the upper divertor will be coated with Li using the Li-dropper in an inductive discharge (FY12)
  - In FY12 use boronization & improved vessel conditions to increase Ip
  - Assess current persistence time, electron temperature profile, CHI current locations on divertor plates, spectroscopic lines for reduction on O & C.

Run Plan – CHI Only + RF, Taylor et al., (0.5 to 1 days in FY11, 0.5 to 1 days in FY12)

- Heat the CHI generated discharges (No induction) with HHFW
  - Run after the HHFW XP on heating a low Ip target
  - Use 20-30ms pulses of stable RF at maximum reliable power level (>1 MW)
  - Assess improvements to the electron temperature
  - Assess current persistence time, electron temperature and density profile, changes to O & C lines and compare to No HHFW case

Ramp-up of CHI started discharges with zero pre-charge Raman et al., (2 days FY11, 4 days FY12)

- Use induction with zero pre-charge to ramp the CHI target to 1MA
  - If improvements are seen with RF application and if RF power is stable use the RF heating pulse and extend the RF pulse duration in these discharges. Otherwise do the initial ramp without RF
  - Initially use similar gas programming as in FY10, then repeat with +/- 50% variation in gas quantity (LFS and CS) to optimize at an improved gas injection level for these higher current discharges
  - Test with SGI (instead of LFS and CS) [FY12]
  - Using NBI at 60keV apply all three sources staring at 40ms & move pulses earlier in time [for TRANSP analysis]
  - Repeat above steps with NBI at 75keV and 90keV [TRANSP analysis]
  - Based on TRANSP results improve the NBI power & timing for FY12
  - Determine lowest density needed to access H-mode (FY12)
    - At the high beam power increase the density to access H-mode

Run Plan (CHI + OH, zero pre-charge)

- Equilibrium control
  - Adjust the PF1, 2 and 3 coil currents in the pre-programmed phase to improve the equilibrium control and reduce the Ip dip usually seen around 30ms (reduce plasma wall contact)
  - Adjust the PF5 preprogrammed current for these higher current discharges to improve equilibrium during the feedback controlled phase
  - Assess improvements over FY10 results
- Assess confinement improvement (FY12)
  - Using the improved vessel conditions further improve the initial CHI start-up current magnitude as it should now be possible to operate at higher injector currents
  - Based on the methods developed in FY11, re-establish ramp-up using induction and appropriate NBI and RF conditions
  - Assess confinement, heating and ramp-up of CHI started plasmas
    - Repeat reference discharges with No RF
    - Repeat reference discharges with No NBI (but short NBI for MSE)

Run Plan (CHI + OH, zero pre-charge)

- Analysis
  - In discharges with and without NBI and with NBI time variations use TRANSP analysis to determine & compare to OH-only discharges
    - thermal confinement (& for discharge with and without RF)
    - NBI coupling efficiency & NI current fraction
      - With electron density
      - With IP
      - Beam power
      - Beam tangency
  - Use magnetics & q-profile evolution to determine evolution in internal inductance and elongation of CHI stated and non-CHI started discharges
  - Assess MHD modes in CHI started and reference OH-only discharges
    - Low and high densities cases for stable operation
    - In low density L-mode and higher density H-mode

CH+OH, Zero pre-charge

- Assess benefits of metal cathode
  - Compare to discharges in FY10 to determine lower divertor oxygen and carbon intensities with injector current
  - Improvements to maximum injector current consistent with acceptable low-Z impurity levels
  - Possible metal influx into long-pulse discharge
  - Repeat discharges after a recent boronization to assess benefits of covering larger area of vessel with boron (to further reduce carbon and oxygen)

NIMROD & TSC simulations will be used for understanding the detailed reconnection physics and scaling to NSTX-U

TRANSP will be used to determine how best to maximize the NI fraction and to compare confinement properties of discharges with and without CHI

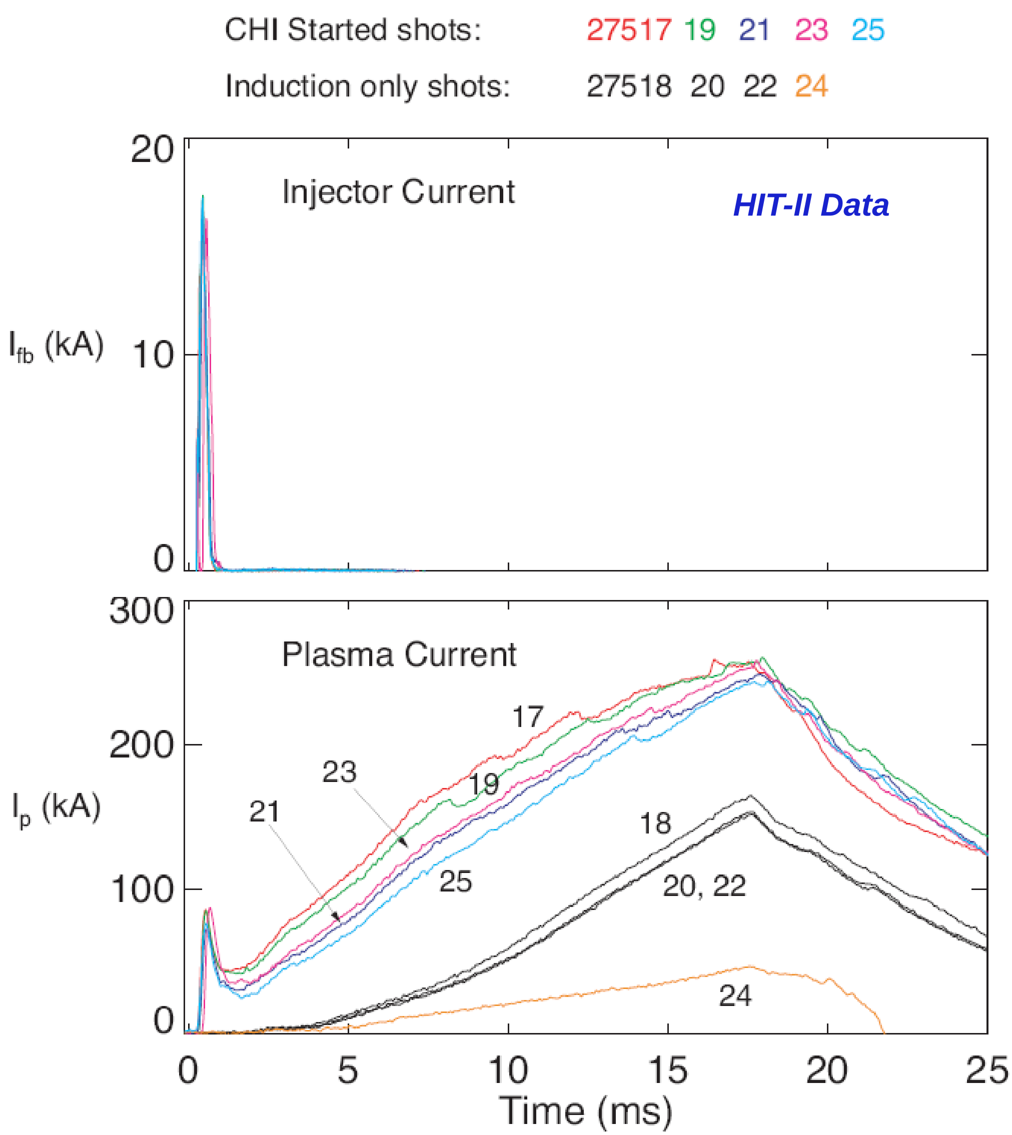
700kA Discharge with Flat-top, Mueller et al., (0.5 to 1.5 days) [May run this in ASC]

- Take a reference discharge from the previous XP that has transitioned to H-mode and limit the maximum Ip to 700kA
  - Use remaining inductive flux to maintain a current flat-top
- Time permitting
  - Transition the discharge to iso-flux control

CHI start-up with pre-charged CS, Mueller et al., (1 to 2 days)

HIT-II routinely operated with fully pre-charged central solenoid

NSTX pre-charged discharges use PF1 & PF3 coils to reduce OH fringing fields and to create a large field null



CHI start-up with pre-charged CS, Mueller et al., (1 to 2 days)

- Restore inductive discharge No. 120406 (OH at 4kV, No PF2, No PF1B – DN, 3 NBI sources).
  - -Increase BT to 0.55T and repeat
  - -Reduce the pre-charge in CS to +2.5kA (10% of nominal value), self consistently reduce the other coil current
- Now add in the CHI injector waveforms as follows:
  - - Superimpose CHI injector coil currents from a recent shot
  - - Current pre-programming in PF3s may not needed for CHI start-up
  - - Improve after running a vacuum calculation using LRDFIT
- If there is difficulty in attaining a breakdown, increase current in PF1A in steps to reduce fringing field from the OH
  - -After successful discharge initiation and ramp-up, increase the magnitude of the pre-charge in 10% increments
  - -Use the CHI voltage and gas programming from a recent CHI started discharge

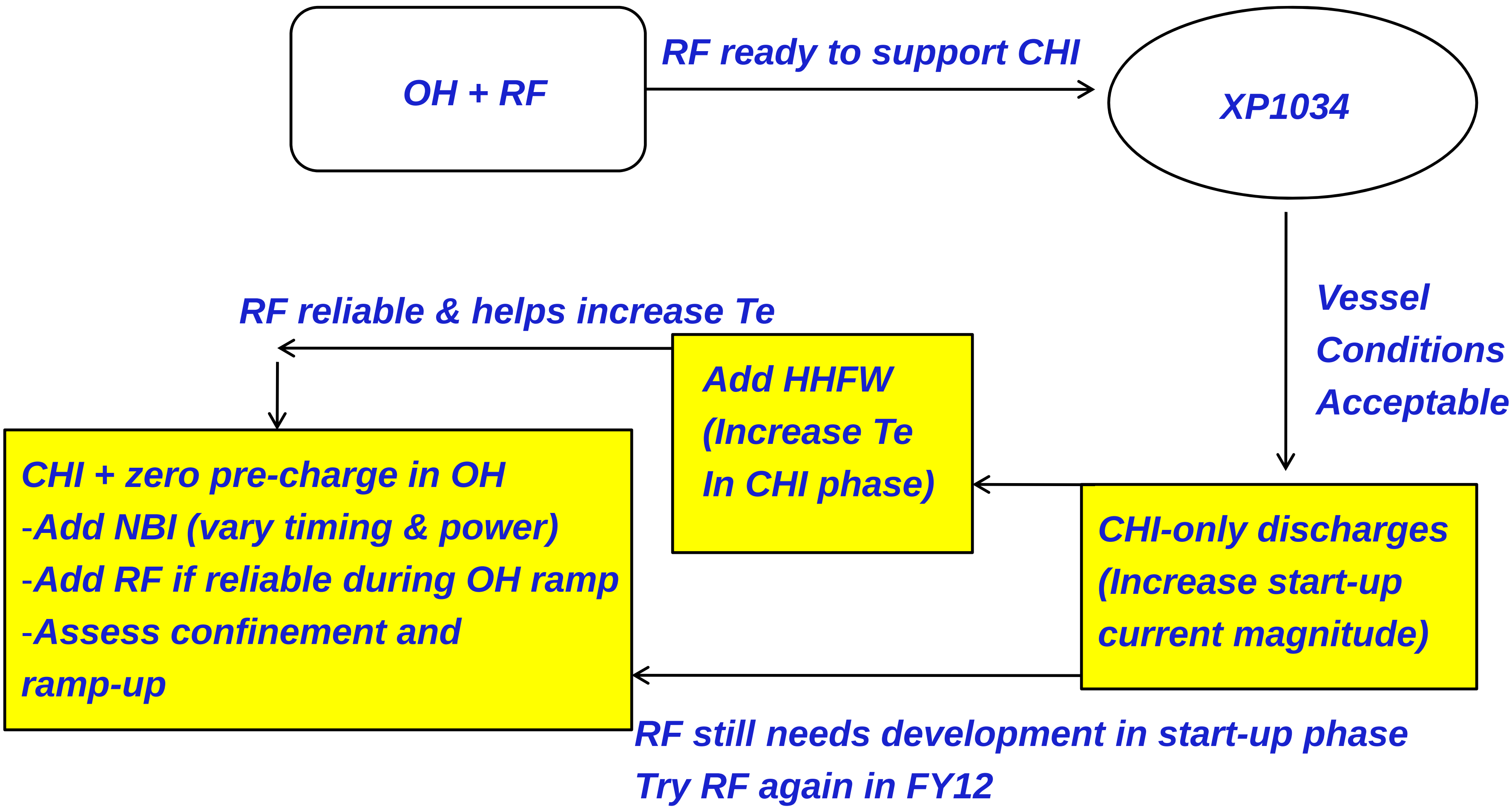
Overall Run Plan – FY11 (4 to 6 days)

- Taylor (OH+RF) 0.5 – 1 day
- Raman, XP1034 – Assess vessel conditions >1- day
- Nelson (CHI-only) startup 1 day
- Taylor (CHI-only + RF) 0.5 – 1 day
- Raman, (CHI + Zero pre charge OH + RF +NBI) >1 days
  - May need to defer much of this to FY12
- Mueller, CH+OH to 700kA 0.5 to 1 day (in ASC or SFPS)
  - Time permitting or run in ASC

Overall Run Plan – FY12 (5.5 to 7.5 days)

- Taylor (Full non-inductive) 0.5 – 1 day
- Nelson (CHI-only) startup 1 day
- Taylor (CHI-only + RF) 0.5 – 1 day
- Raman, (CHI + Zero pre charge OH + RF +NBI) >3 days
- Mueller, (CHI + pre charged OH) > 2 days
  - Time permitting

Milestone related XPs: XPs shown in Yellow Boxes to be run during same run-campaign



SFPS XPs Prioritized to Meet Milestones and Support Required Information for NSTX-U

Significant Improvements in CHI startup capability for SFPS Research

2008: Transitioning to an H-mode

2009: CS flux savings

2010: Low inductance & density (needed for NSTX-U Advanced Scenarios)

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  - Maximum injector current consistent with acceptable low-Z impurities
  - Improvements due to metal electrodes
- Can HHFW increase Te of CHI discharges?
  - Can the current decay time be increased?
- How well does NBI couple to CHI started and ramped discharges?
  - As plasma current varies
  - As density varies
  - NBI power and application time (MHD, fast ion modes)
  - NBI tangency
- Does early application of NBI & RF improve CHI started discharges?
- Properties of CHI started discharges vs. normal inductive plasmas
- How much NI current can be driven in low current OH and CHI started discharges?
- How much CHI start-up capability is needed in NSTX-U for directly coupling to NBI?