Solenoid Free Plasma Start-up Progress and Plans

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and the NSTX Research Team

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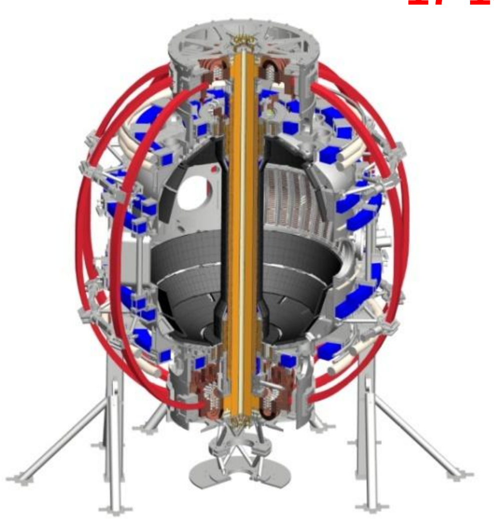

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Overview

Outline:

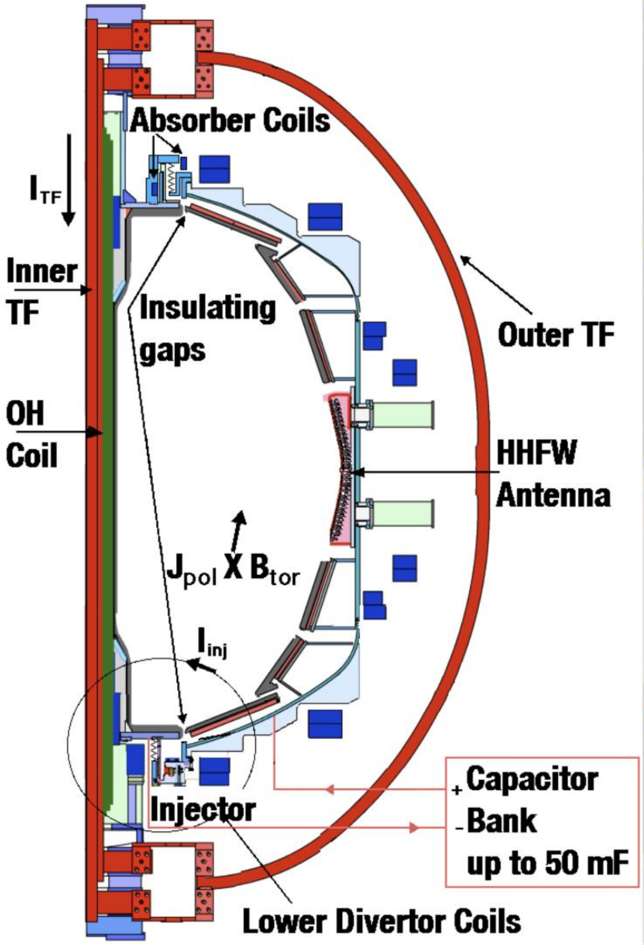
- Motivation
- Highlights from NSTX operations
- MHD Simulation studies
- Experimental plans on NSTX-U
- Plans for modeling work
- Plans for external collaboration activities
- Summary

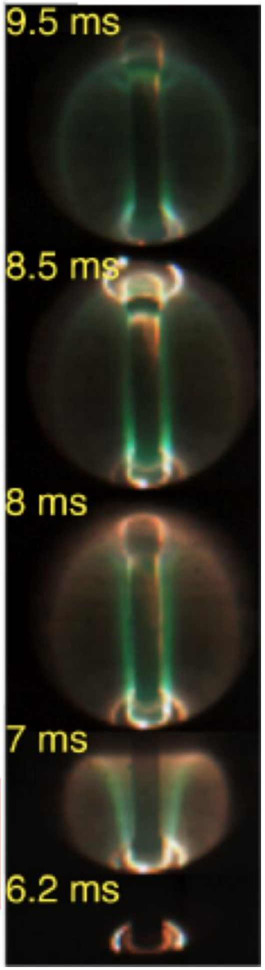
Milestones:

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

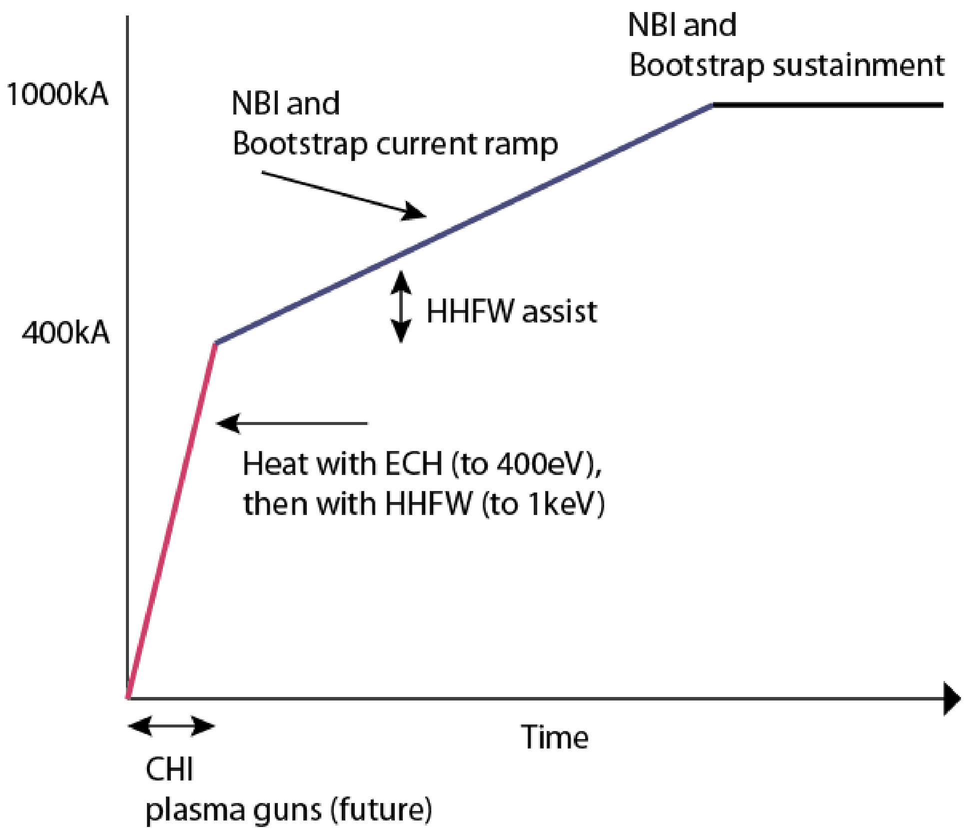
CHI is planned to be used as initial current seed for subsequent non-inductive current ramp-up in NSTX-U

CHI in NSTX/NSTX-U





NSTX-U Start-up and Ramp-up strategy



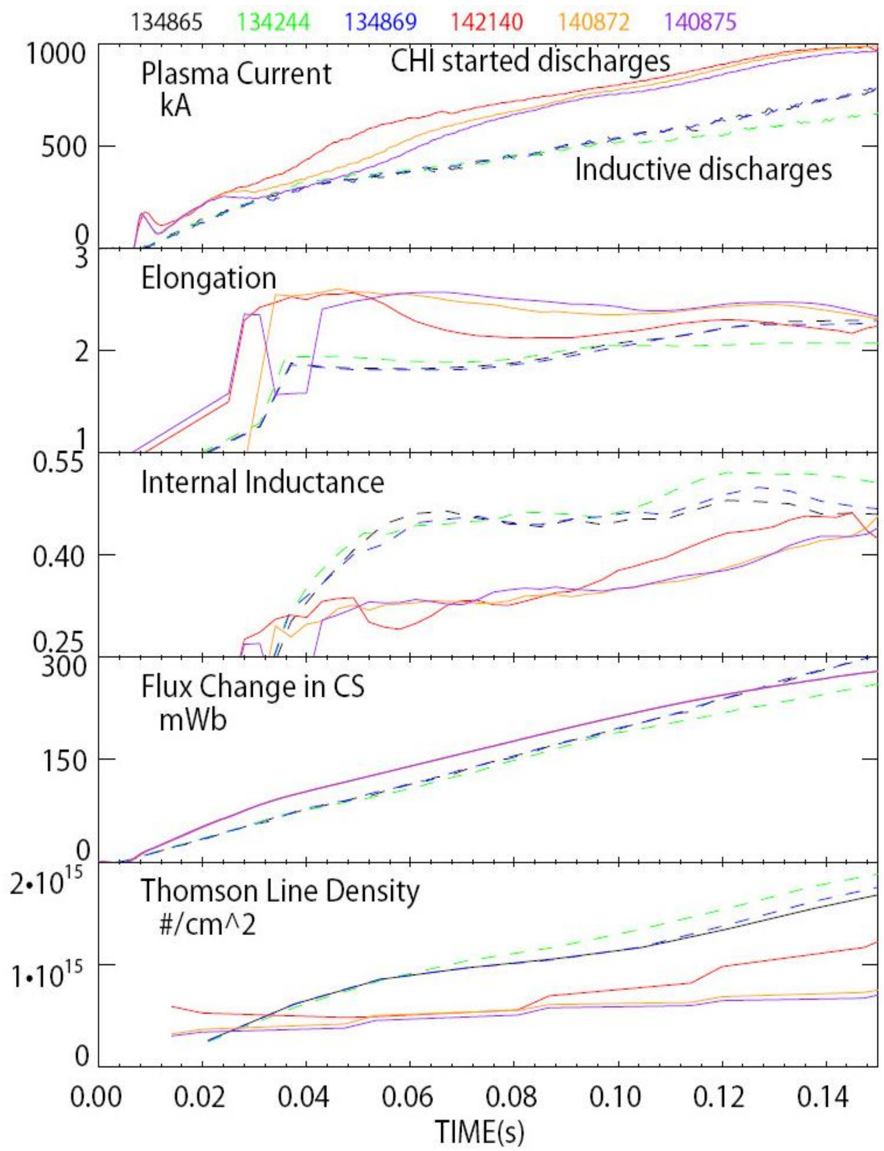
NSTX-U goal is to demonstrate and understand solenoid-free current start-up and ramp-up

NSTX has made considerable progress in developing CHI as a method to start-up an ST

- Best inductive plasma (from 10 YR NSTX data base) uses 340 mWb of solenoid flux to get to 1MA

- Un-optimized CHI started discharges require 258 mWb

- Full non-inductive start-up and ramp-up will be developed on NSTX-U



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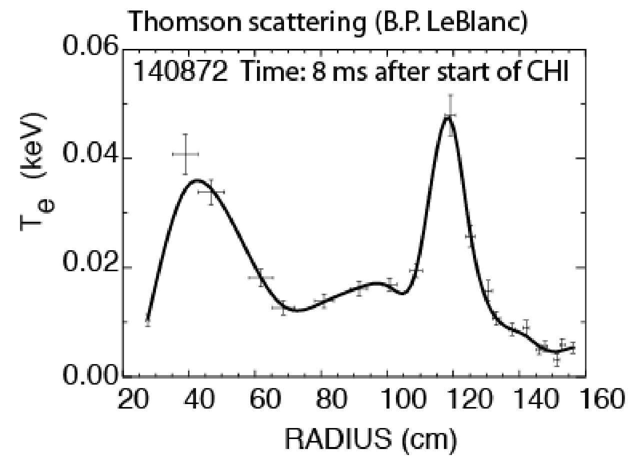
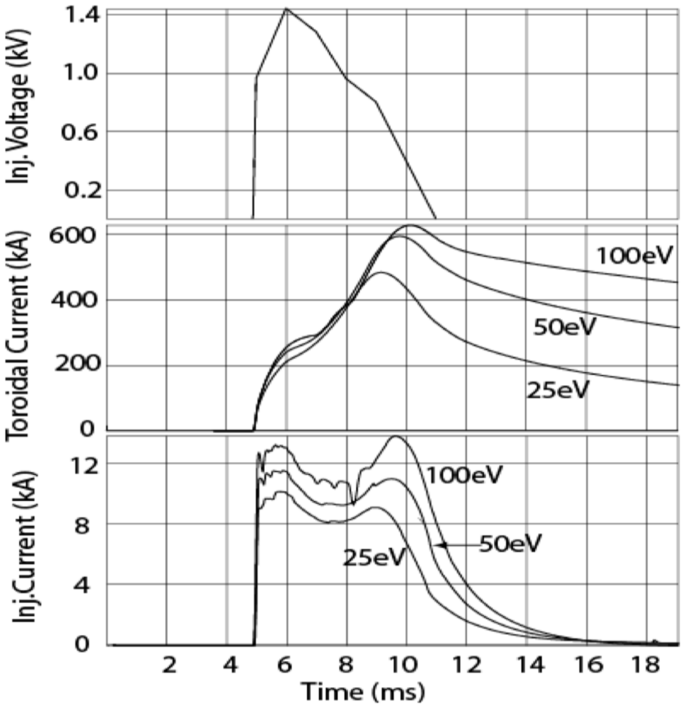
Additional electron heating of CHI plasma is needed to increase start-up current and duration

- Both NSTX and HIT-II CHI discharges have attained 20-50eV during CHI phase
  - 200kA (NSTX), 100kA (HIT-II)
- Issues:
  - This T_e likely too low for HHFW to be efficiently/reliably absorbed
  - I_P likely decays too quickly for NBI fast-ions to remain confined
- Increased T_e predicted to significantly increase CHI closed flux current & reduce I_P decay rate
  - TSC simulations show I_p stays above 400kA for 10-15ms for $T_e \geq$ ~100eV
  - Even higher T_e is highly desirable





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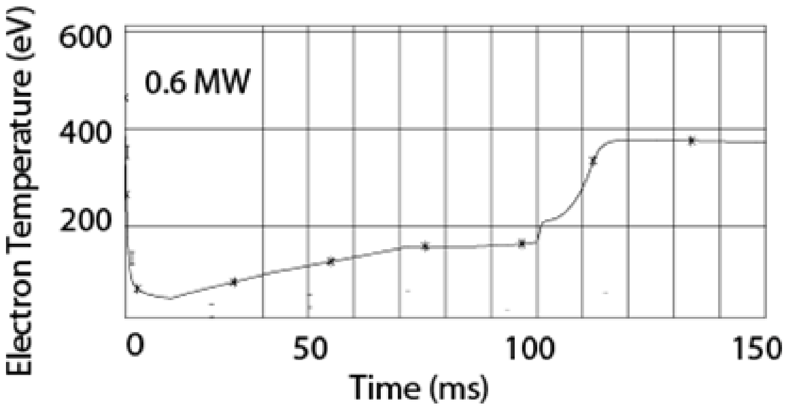
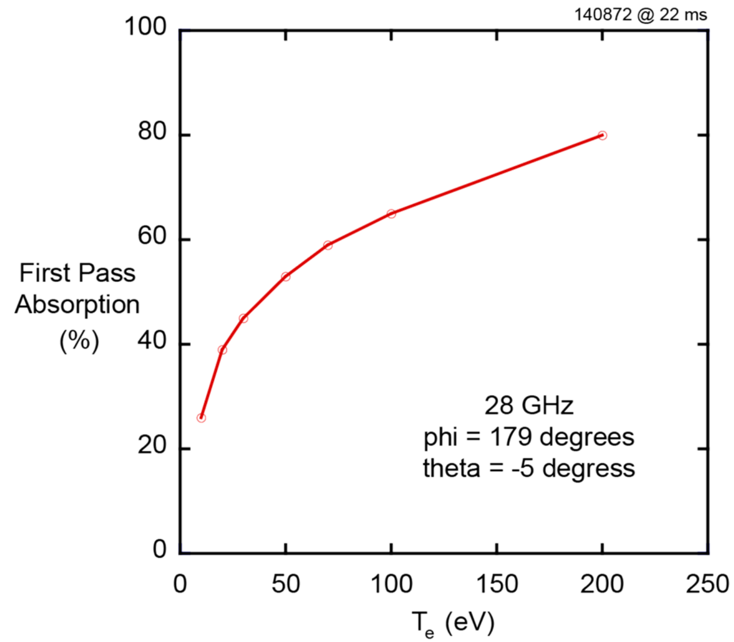
Ramp-up strategy significantly benefits from 1-2 MW ECH to heat CHI plasma

- In a 500kA decaying inductive discharge, TSC simulations indicate 0.6MW of absorbed ECH power could increase T_e to ~400eV in 20ms
  - ECH absorption and deposition profile being modeled using RF codes
  - CHI discharge densities at T_e = 70 eV would allow 60% first-pass absorption by 28 GHz ECH in NSTX-U
- ECH enables improved ramp-up strategy:

  (a) ECH heating for direct coupling to NBI, or
  (b) Pre-heat with ECH and heat to > 400 eV using HHFW
  - Maximum HHFW power > 4 MW, higher B_T in NSTX-U would improve coupling
  - HHFW has demonstrated heating a 300 kA / 300 eV plasma to > 1 keV in 40ms*

ECH applied at 100 ms to a 500kA plasma with CHI-like density with 50% ITER L-mode confinement at 100ms





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***G. Taylor, et al., PoP 19, 042501 (2012)**

CHI start-up to ~0.4MA is projected for NSTX-U, and is projected to scale favorably to next-step STs

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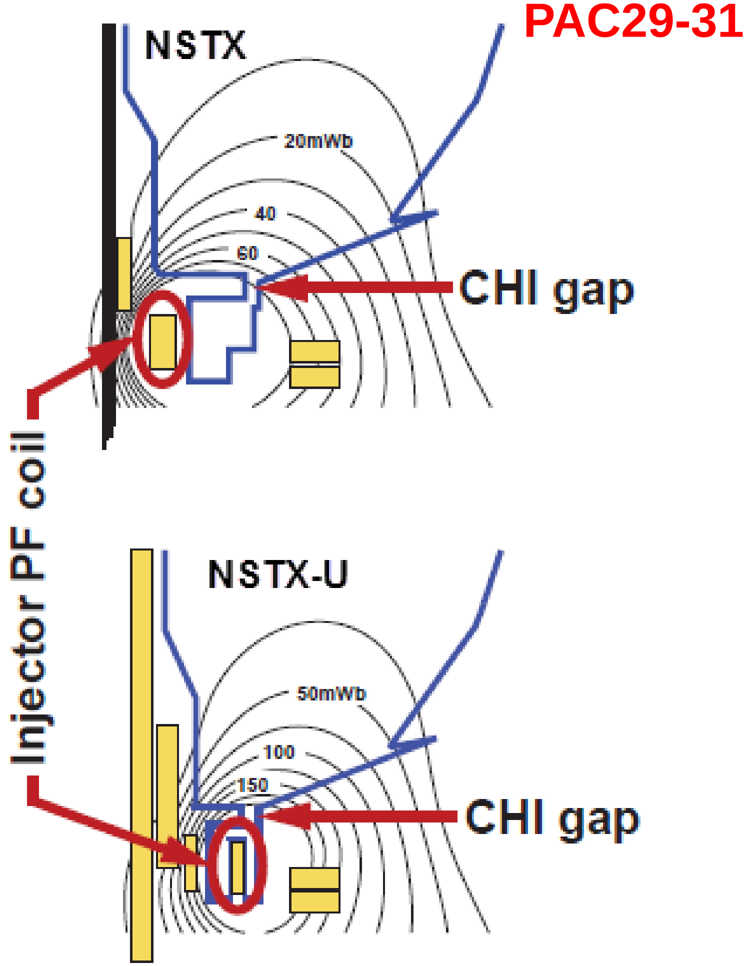


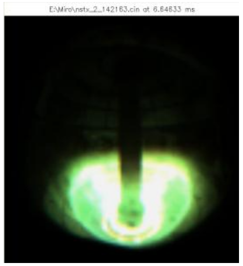
Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Aspect ratio: A	1.30	1.50	1.50	1.70
Elongation: κ	2.6	2.8	3.1	3.3
Major radius: R_0 [m]	0.86	0.93	1.2	2.2
Minor radius: a [m]	0.66	0.62	0.80	1.29
Toroidal field at R_0: B_T [T]	0.55	1	2.2	2.4
TF rod current: I_{TF} [MA]	2.4	4.7	13.2	26.4
Toroidal flux: Φ_T [Wb]	2.5	3.9	15.8	45.7
Reference maximum sustained plasma current: I_{PS} [MA]	1	2	10	18
Start-up plasma normalized internal inductance: l_i	0.35	0.35	0.35	0.35
Injector flux footprint: d [m]	0.6	0.56	0.73	1.17
Injector flux for projecting start-up current: ψ_{inj} [Wb]	0.047	0.10	0.66	2.18
Bubble-burst current: I_{bb} [kA]	3.3	9.0	79	165
Injector current: I_{inj} [kA]	4.0	10.8	95	198
Start-up plasma flux: ψ_p [Wb]	0.04	0.08	0.53	1.74
Start-up plasma current achieved or projected: I_P [MA]	0.20	0.40	2.00	3.60
Current multiplication: I_P / I_{inj}	50	37	21	18
Multiplication limit: Φ_T / ψ_{inj}	53	38	24	21
Injector current density [kA/m^2]	4.9	12	63	39

Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

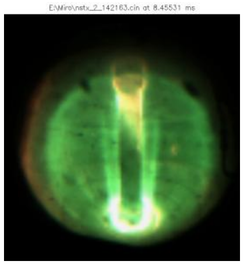
J.E. Menard, et al., Nuclear Fusion (submitted)

Resistive MHD simulations beginning to reproduce aspects of NSTX CHI discharges

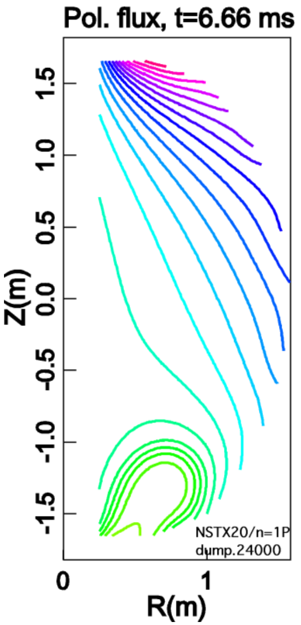
- Objective is to understand the importance of the initial non-axisymmetric dynamics of plasma growth and reconnection
- Reproduces experimental open flux evolution and current
- Experiment: EFIT and Fast camera images show detached large volume closed flux region
- Simulations (work in progress): show resistive reconnection generates smaller closed flux volume
  - Localized to region near injector
  - Now understanding requirements for generation of large volume closed flux regions
- Simulations show a n=1 mode

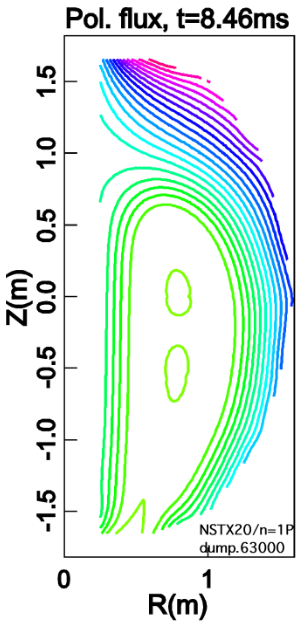


6.65 ms



8.46 ms





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E.B. Hooper (LLNL), C. Sovinec (Univ. of Wisconsin)

Preliminary scenario for ramping to 1MA in NSTX-U

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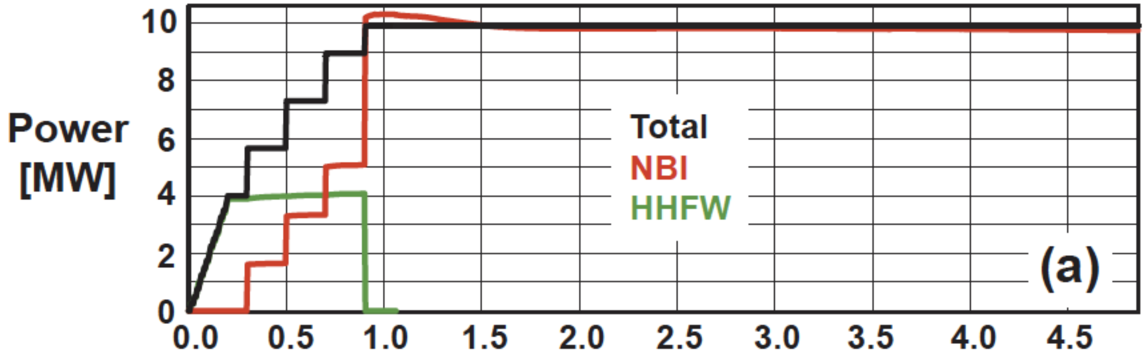
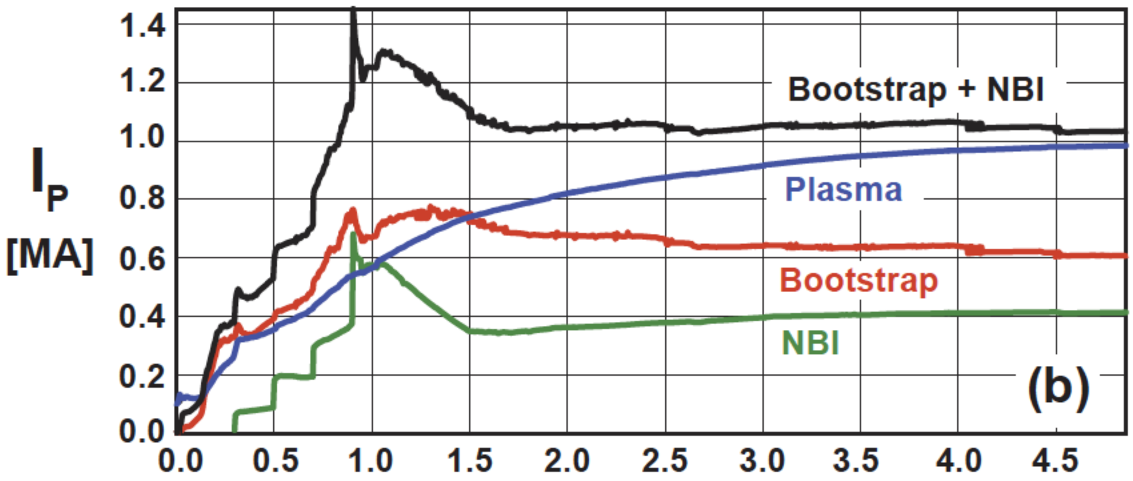
- Initial 100 kA target is heated by HHFW
  - H-mode initiated at 150ms
  - Bootstrap current increases I_p to 400 kA
- At I_p = 400kA NBI is injected (at 0.3s)
  - NBI power programmed to increase with I_p
  - HHFW is turned off at 0.9s at I_p = 550kA
  - Starting from 1.5s, f_{GW} of 0.5 and central temperature of 1.7 keV is maintained until 5s
  - Bootstrap current overdrive and NB current increases I_p to 1 MA at 5s

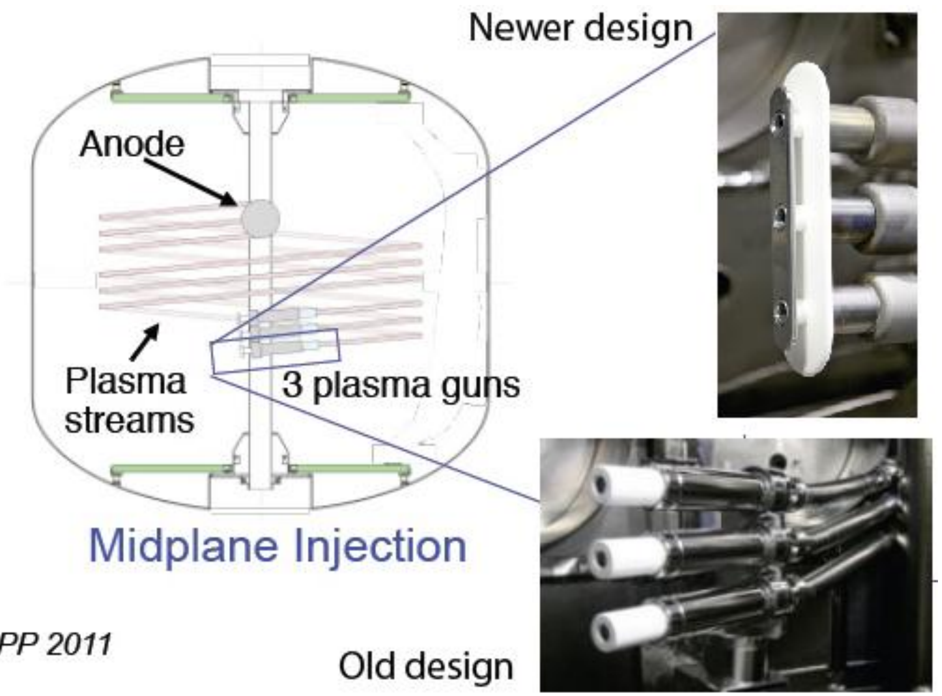




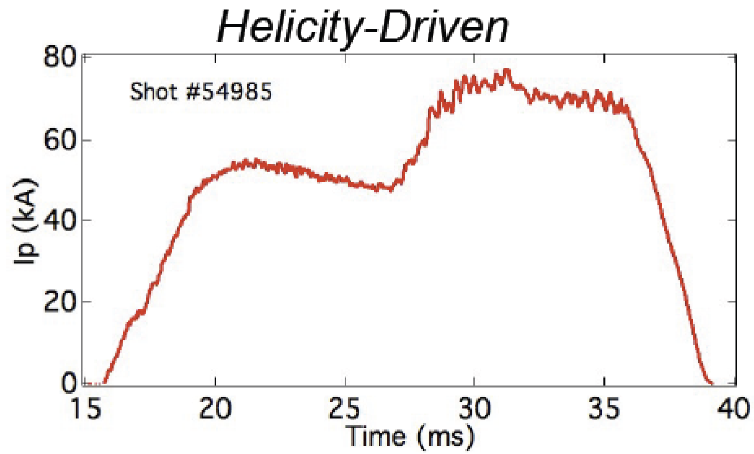
Alternate scenario to be investigated in 2012-13 using TSC simulations: Start with 400 kA seed target and minimize reliance on HHFW

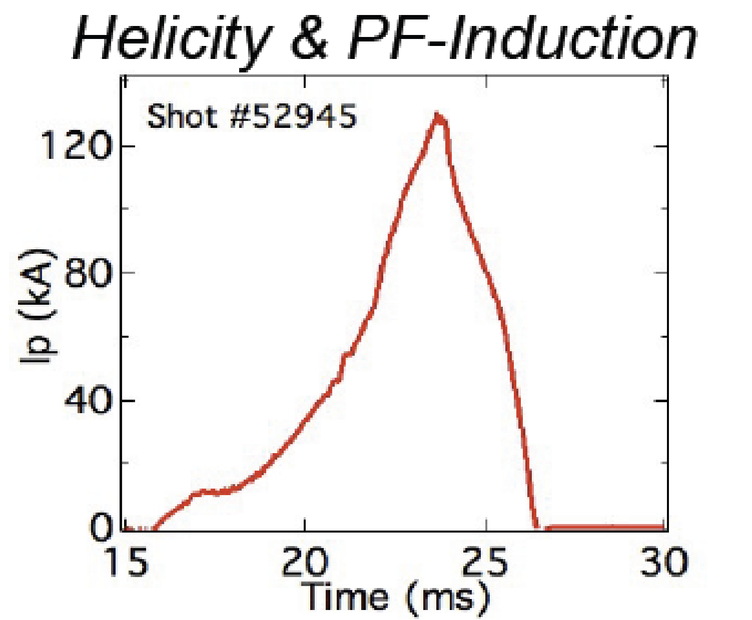
Point source helicity injection being developed by PEGASUS is an alternate method for plasma start-up in NSTX-U

- Retractability of guns potentially advantageous in FNSF/Demo nuclear environment
- Plasma guns(s) biased relative to anode
  - Helicity injection rate: $\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$



RJF APS/DPP 2011





Hardware preparations for NSTX-U Start-up

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- Diagnostics [FY12-13]
  - New additional fast voltage monitors for upper divertor
  - Additional dedicated current monitors near injector
  - Special set of EMI shielded inner vessel magnetics
  - Additional flux loops and Mirnov coils on lower and upper divertor
    - Langmuir probe array on lower divertor
  - Multipoint Thomson scattering, Filter scopes, multi chord bolometers and SXR arrays
- PF Coil configurations [FY 12]
  - Prioritizing bi-polar supplies and voltage limits for high slew rates
- Capacitor bank power supply [FY 13] – Baseline capability
  - Voltage increased to ~2 kV & improve voltage snubbing systems
  - NSTX-U to support 4kV Ops. including transients
- Capacitor bank power supply [YR 3-5] – Upgraded capability
  - Voltage increased to ~3 kV, bank energy increased to 200 kJ (in design stage)
  - Additional modules for improved voltage control (in design stage)

SFPS Run Plan on NSTX-U

- Years 1 – 2 of NSTX-U Operations
  - Re-establish initial transient CHI discharges
    - Using graphite divertor plates
    - Use full Li coverage to reduce low-Z impurities
    - Test benefits of upper metal divertor* and Lithium during absorber arcs
    - Initially couple to induction, then assess coupling to NBI
    - **1 MW ECH may allow coupling to NBI during Year 2 [incremental funding]**
- Years 3 - 5
  - Establish discharges using metal divertor plate electrodes **PAC29-34**
    - Assess benefits and compare to QUEST results (if available)
    - Assess benefits of cryo pumping in the absorber region*
  - Maximize current start-up
    - Use 1 MW ECH, then HHFW to increase T_e to ~ 1keV for coupling to NBI
  - Test plasma gun start-up on NSTX-U
    - Collaboration with PEGASUS

*** Resources permitting**

Plans for 2-D MHD simulations (TSC)

- FY12 [Ramp-up of CHI-started discharge – IAEA 2012 & R12-2]
  - Assess requirements for electron heating by ECH
    - Use TRANSP analysis of NSTX CHI discharges with inductive ramp to obtain electron transport model
    - Improve simulations using NSTX CHI discharges with inductive ramp to obtain ECH absorption and heat deposition profiles and extend to 1T
  - Assess requirements for electron heating by HHFW (with ECH heating)
  - Requirements for NBI ramp-up to1 MA of CHI target with ECH + HHFW
    - Now developing high resolution T-CHI start-up for hand-off to NBI CD
    - Requirements on density, temperature
- FY13-14 [Extend above work to NSTX-U vessel geometry]
  - Initial focus on developing start-up scenarios for Year 1-2 NSTX-U Ops.
  - Couple TSC directly to TRANSP & RF codes to calculate ECH, HHFW and NBI deposition profiles
- Years 15-18 [Extend to FNSF and ST Demo]
  - Initial work will start in FY13 and continue

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Plans for 3-D MHD NIMROD simulations

- FY12-13 [Improved comparison with experiment]
  - Requirements for the generation of large volume closed flux surfaces
    - Quantify influence of time-changing boundary flux on dynamics of CHI
    - Requirements for gap width, crowbar time, T_e, n_e and Z_{eff}
    - Requirements on injector voltage and programming requirements
    - Plasma growth rate implications for electron heating

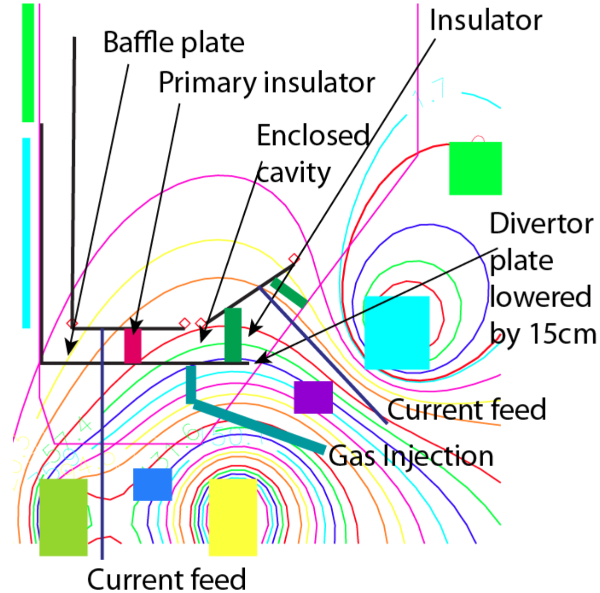
PAC29-34

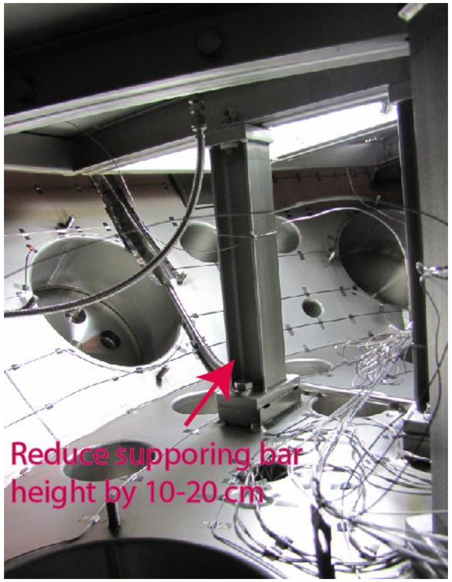
- FY 14 – 16 [Extend modeling to NSTX-U]
  - Understand mechanisms that lead to closed flux generation
    - Role of MHD fluctuations & toroidal field
  - Importance of vessel geometry
    - Benefits of PF1C vs PF1B operation for inducing reconnection
  - Examine current drive using NBI
    - **F. Ebrahimi (Univ. of New Hampshire)**
- Years 17-18 [Develop 3-D model for FNSF and ST Demo]

R.H. Weening (Thomas Jefferson University) may provide part-time theory support for CHI (Now investigating use of M3D-C1 code to support some of above FY12-13 activities)

CHI design for Quest supports NSTX-U research

- Design uses two floating electrodes
  - Insulators not part of vacuum structure
  - CHI operation at up to 5kV **PAC29-34**
  - Metallic electrodes (SS + Mo, Ta or W)
    - Provides early data for NSTX-U metal electrodes
    - Will also explore steady-state CHI & edge CD
- >100 kA current generation potential
  - Ip ~200kA with lower baffle plate height
- Initial design completed (March 2012)
  - R. Raman invited by QUEST to conduct design study (March 2012)
  - Finish Engineering design of electrodes & insulator (June 2012) & rest of design (September 2012)
  - Design appears feasible for installation





Plans for external collaboration & design studies

- FY12
  - Preliminary design study of CHI for QUEST completed (looks feasible)
    - Develop detailed engineering design of CHI system
- FY 13-14
  - CHI system design for FNSF, ST Demo
  - Planned participation with HIST device for Transient CHI test for comparison with HIT-II and NSTX results (Raman)
  - Participation with PEGASUS on plasma gun start-up (Mueller)
    - Assessment of requirements for NSTX-U
  - Possible installation of CHI capability on QUEST*
    - Establish Transient CHI discharges on QUEST
- Years 15-17*
  - Assessment of benefits of metal electrodes on QUEST (for NSTX-U)
  - Assessment of new design CHI installation on QUEST
  - Test of edge current drive & steady-state CHI on QUEST

*** Subject to CHI installation on QUEST**

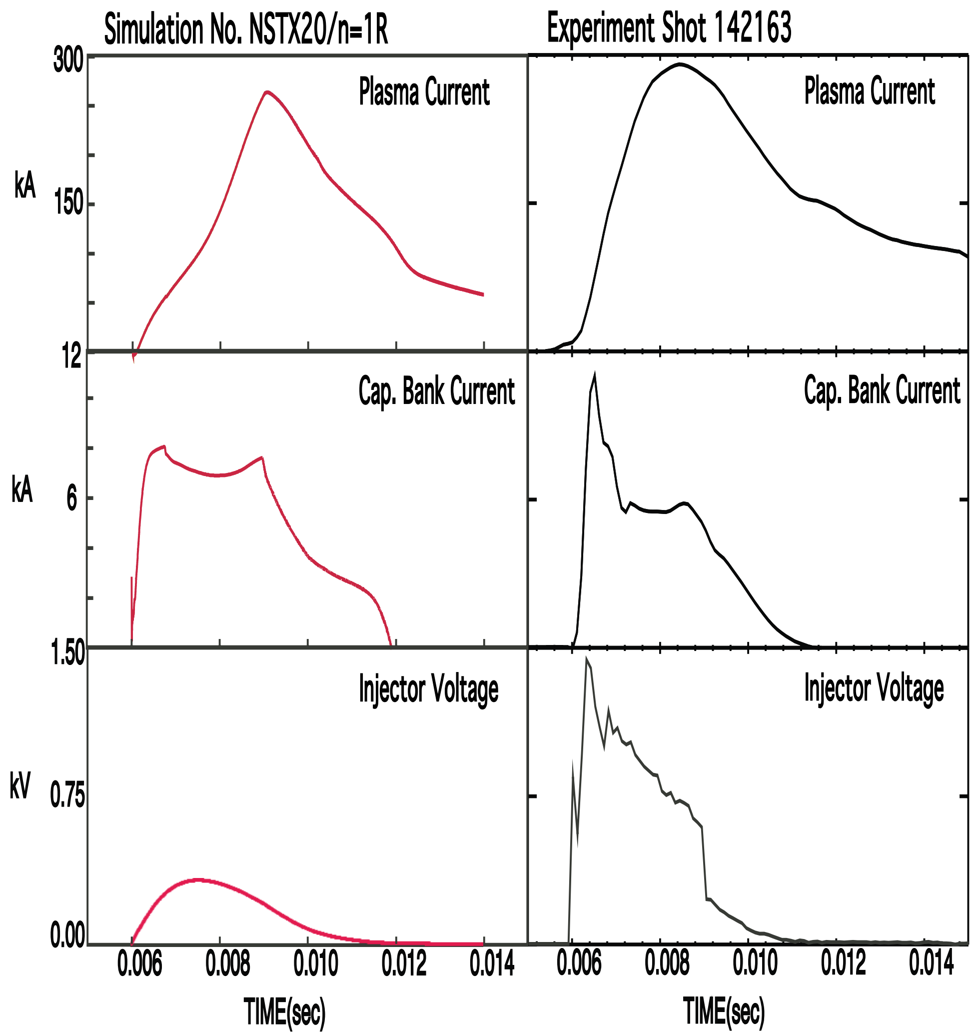
Summary: SFPS research plan supports development of solenoid-free current formation and ramp-up to the 1MA level

- CHI start-up achieves record-low flux consumption on NSTX to get to 1MA
  - Discharges coupled to induction transition to H-mode demonstrating compatibility with high performance operation
  - Generates discharges with low internal inductance and density needed for ECH heating and non-inductive ramp-up with NBI on NSTX-U
  - Favorable scaling with machine size (HIT-II, NSTX)
- ≥ 1MW 28 GHz ECH would greatly benefit start-up/ramp-up capabilities
- MHD codes now starting to reproduce NSTX CHI discharges
  - TSC being used to develop initial start-up scenarios for NSTX-U
  - NIMROD (and possibly M3D-C1) to understand flux closure mechanisms and the early dynamic phase of CHI
- External collaboration aids NSTX-U, FNSF & ST Demo
  - Plan to test metal electrodes and new electrode design on QUEST
  - PEGASUS developing plasma gun start-up for a future test on NSTX-U

Back-up slides

3-D MHD simulations with the NIMROD code reproduces injector and plasma current

- Time-dependent boundary conditions used as input
  - Current amplification in approximate agreement with experiment
- Voltage rise time different as there is no pre-breakdown phase in simulation
  - Power supply inductance limits rate of rise
  - Added power supply damping for stability reasons



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E.B. Hooper (LLNL) with support of C. Sovinec (U-Wisconsin)