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Solenoid-free Start-up and Ramp-up

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For the NSTX Research Team

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Motivations for Solenoid-free Plasma Startup

- The development of methods for solenoid-free current initiation would improve the prospects of the ST as a CTF
- Could result in a more compact tokamak
- Of the three large machines in the US (DIII-D, NSTX, C-Mod) only NSTX is engaged in solenoid-free plasma startup research
- NSTX is exploring CHI and Outer PF Startup as methods for plasma current initiation

Goal: Initiate solenoid-free plasma currents, couple to non-inductive CD methods and ramp-up to high beta, high bootstrap current fraction discharges

PAC-21 action items in Solenoid-free Plasma Startup

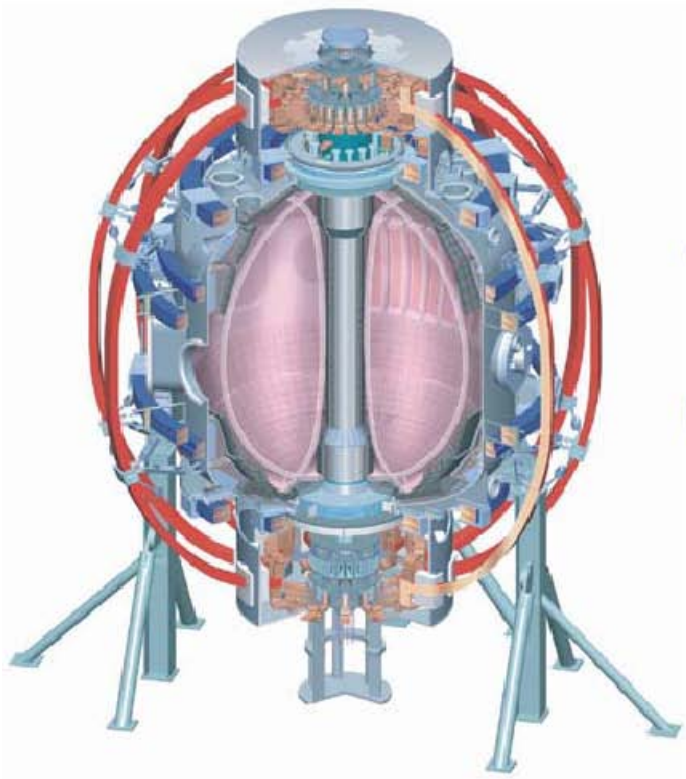
- ✓PAC21-25: Demonstration of solenoid-free plasma formation and current ramp-up is one of the defining issues for ST research.
- ✓PAC21-26: NSTX should consider incorporating CHI into its routine operation. Fully diagnose including current profile measurements.
- ✓PAC21-27: Further optimizations such as low density and low impurities might also be required.
- ✓PAC21-28: If possible Li capability should be incorporated with CHI.
- ✓PAC21-29: Test synergetic effects of CHI with other startup methods.
- ✓PAC21-30: 2-D or 3-D modeling of Transient CHI and follow-on current drive.

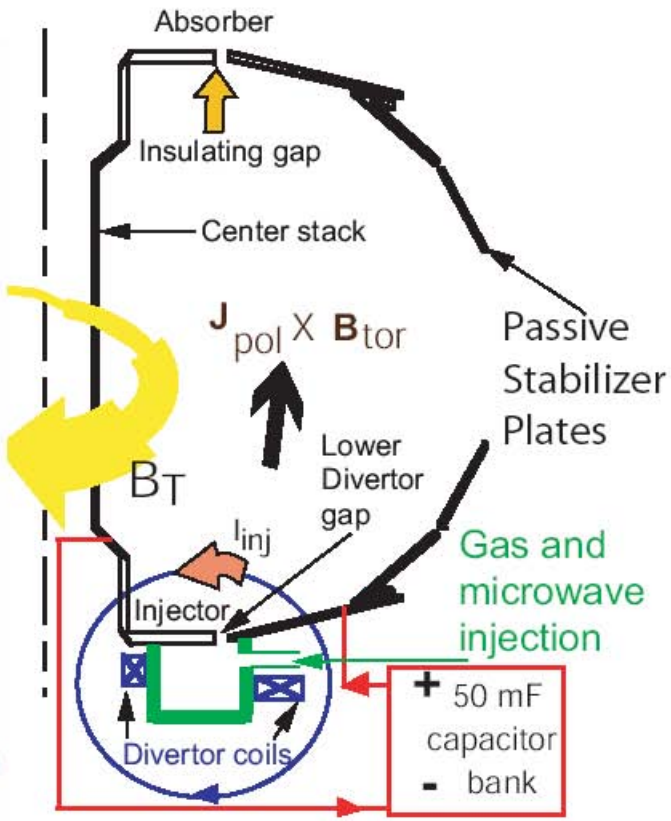
Methods for Solenoid-free Plasma Start-up that can be tested in NSTX

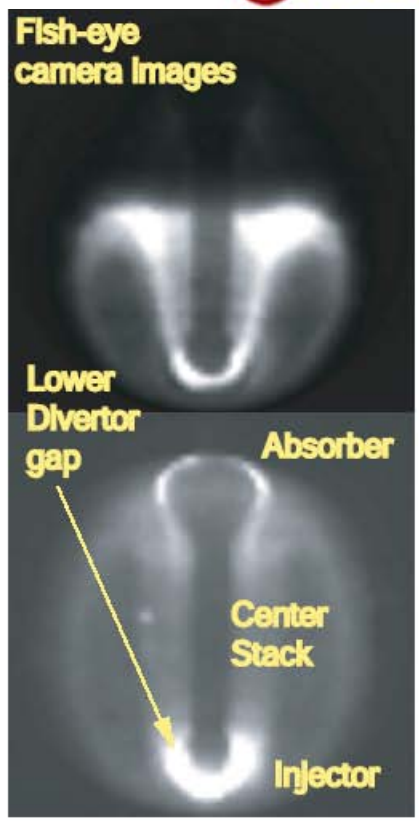
NSTX

- Coaxial Helicity Injection (Developed on HIT-II)
  - Applicable to STs & tokamaks with superconducting PF coils
- Outer PF Start-up (Developed on START & MAST)
  - Requires a test with PF coils located outside vacuum vessel
    - NSTX unique with PF coils located outside vacuum vessel
  - Also being tested in a small ST in Tokyo (UTST)
- Plasma Gun Start-up (Developed on Pegasus)
  - Plasma Gun could be withdrawn after plasma initiation

NSTX Incorporates Toroidal Insulation Breaks to Enable CHI Operation





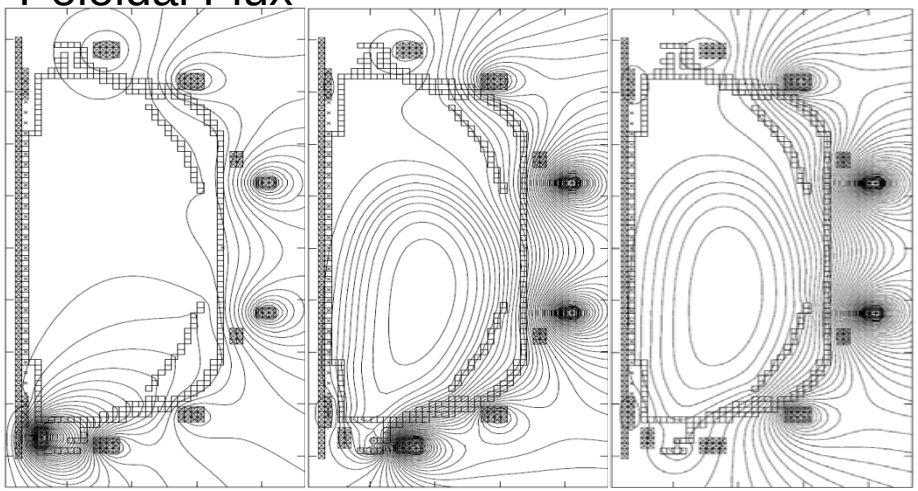


Transient CHI: Axisymmetric reconnection leads to formation of closed flux surfaces.

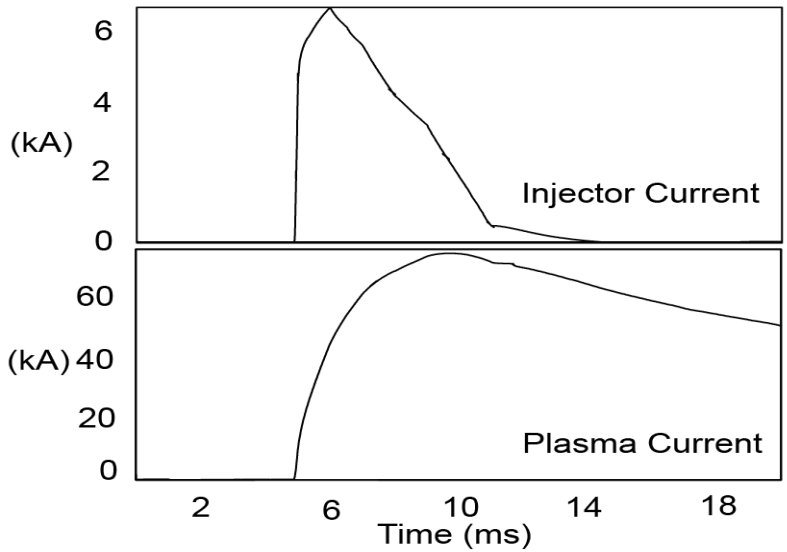
*CHI for an ST: T.R. Jarboe, Fusion Technology, **15** (1989) 7*
*Transient CHI: R. Raman, T.R. Jarboe, B.A. Nelson, et al., PRL **90**, (2003) 075005-1*

Simulated Transient CHI Discharges using TSC [PAC21-30]

Poloidal Flux



4.2 ms 11.6 ms 16 ms



After having successfully reproducing the 60kA discharge, the 160kA discharge will be simulated for benchmarking TSC and for understanding the full potential in NSTX and scaling to ST-CTF

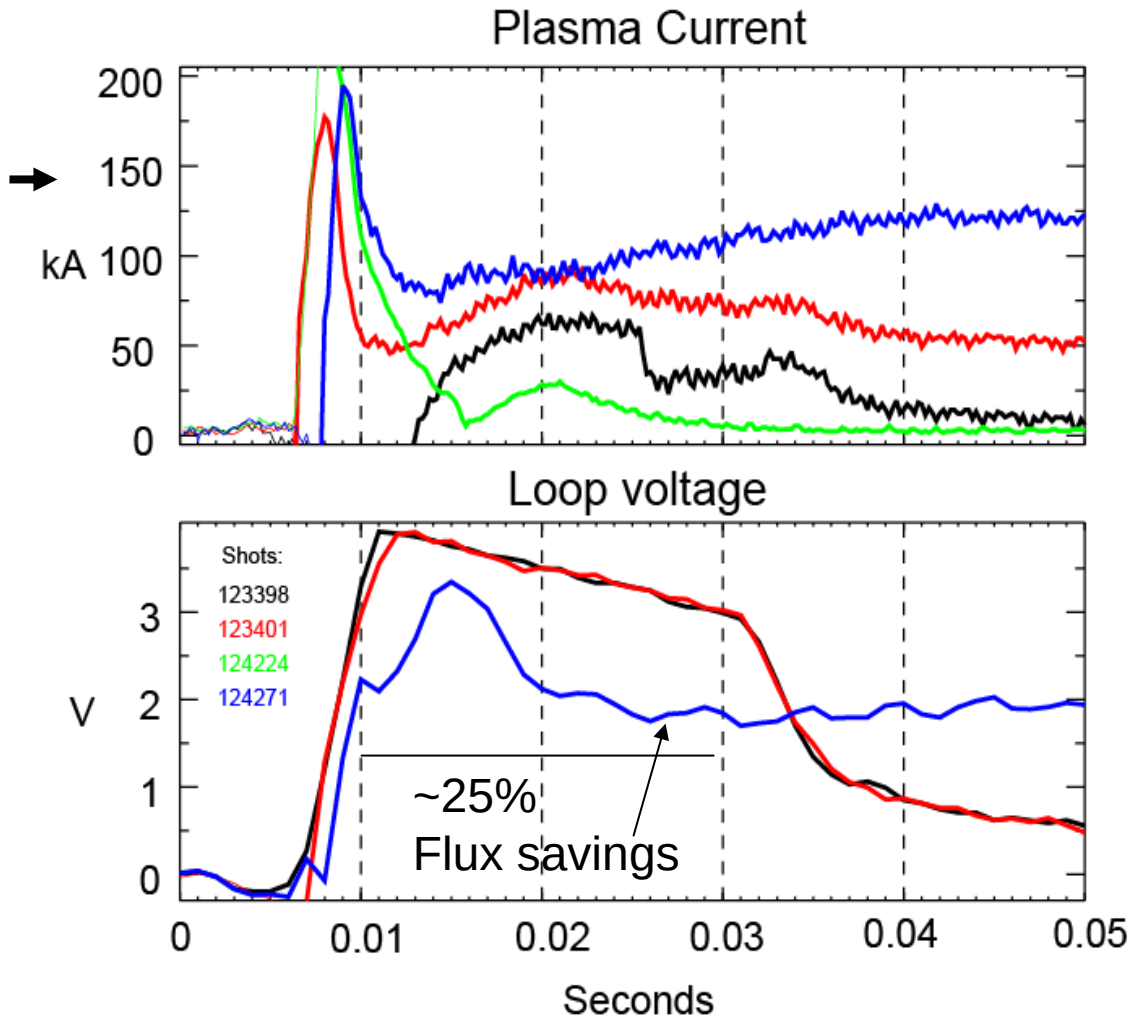
TSC: Developed by S.C. Jardin, PPPL

CHI plasmas successfully couple to transformer induction in NSTX for first time

CHI only

Induction only

CHI + induction



CHI + induction: I_P =120kA

(Boronization & improved PF programming)

- FUTURE optimization [PAC21-27]:
  - Improved divertor conditioning
  - Reduce absorber arcs
    - Staged cap. banks (FY08)
    - Abs. coils (FY09)
    - Use 350kW ECH (FY10-incremental)

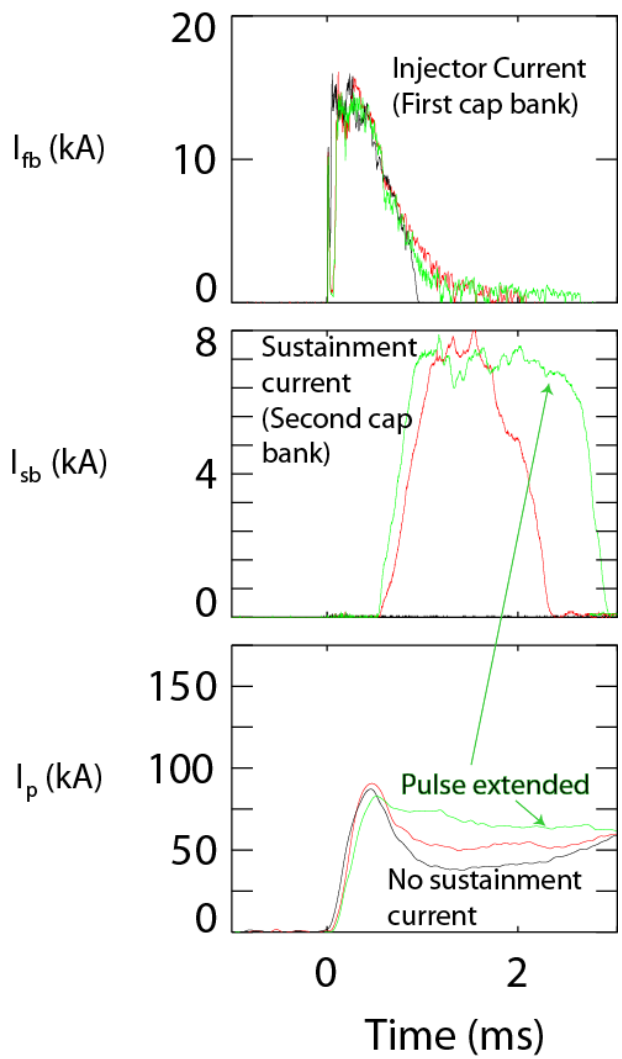
FY 08 Plans [Optimize Transient CHI Startup]

- Improve coupling to induction to show CS flux savings [FY08 milestone]
  - Operate with improved divertor surface conditions
  - Use Staged Capacitor bank to improve coupling (extends CHI pulse length during hand-off to OH)
  - Initially ramp OH solenoid unidirectionally from zero current
- Produce a reference CHI initiated long pulse discharge [PAC21-26]
  - Later use a pre-charged solenoid to extend pulse length

Run Plan

- Initial 4 day campaign to show CS flux savings (~ 1 day for conditioning)
- Second 4 day campaign for optimization

HIT-II data (PoP 2004)



Plasma Startup Using Outer Poloidal Field Coils

NSTX

Outer PFs have been used to startup the plasma

- MAST (START) - poloidal field coils + radial compression
- JT-60U - Aggressive application of RF heating and current drive
- NSTX – 20kA plasmas produced with large outboard field null + HHFW

Four important conditions for "Inductive" plasma startup:

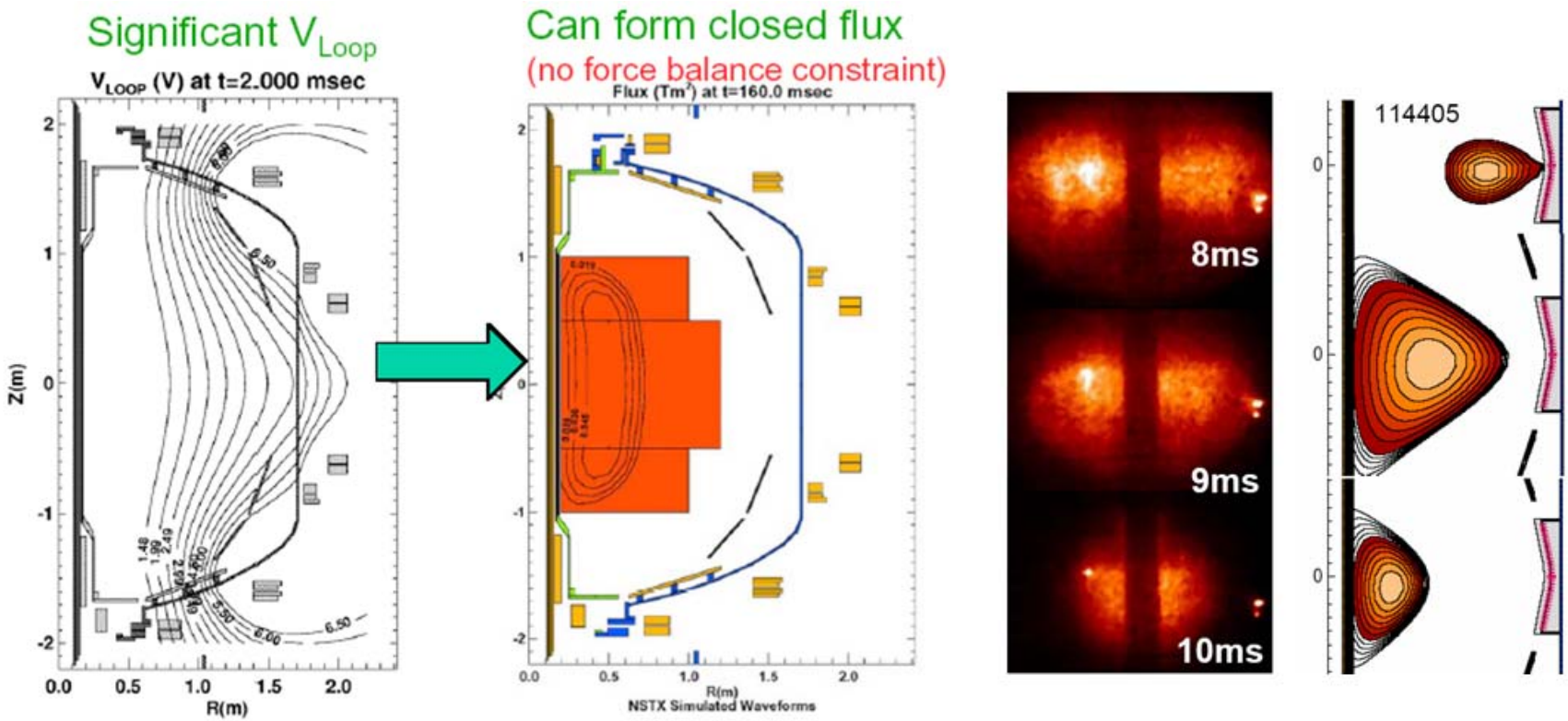
1. Satisfy the "Lloyd condition" for plasma startup.
   With strong ECH (in DIII-D), $E_T \cdot B_T / B_P \geq 0.12$ kV/m.

2. The field null must be maintained for a sufficient duration.
   2 – 3 ms in the presence of wall eddy currents.

3. Need sufficient voltage or heating to get through radiation barrier.

4. Sufficient available flux for subsequent current ramp up to ~ 500 kA.
   - At this current NBI becomes an effective non-inductive current drive tool.

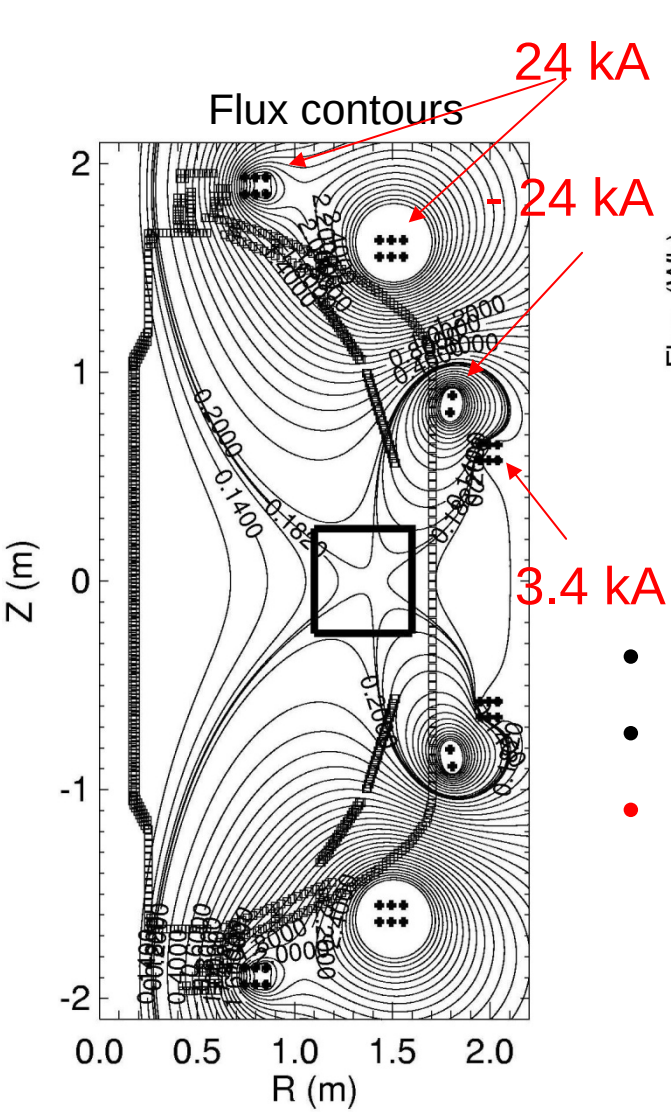
Outer-PF ramp from near zero current/flux

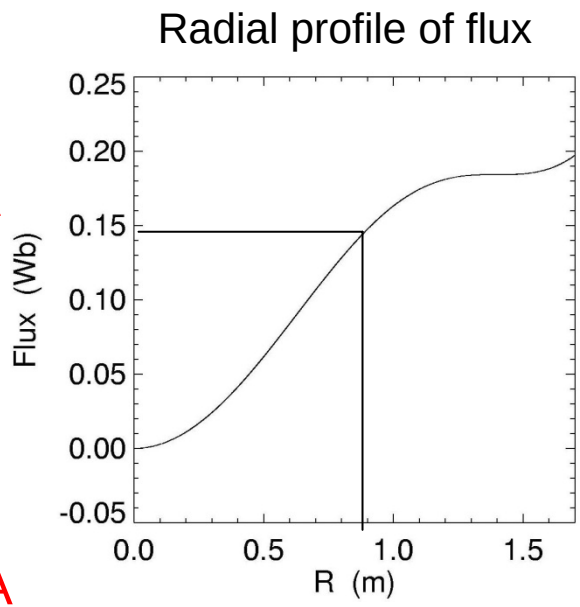


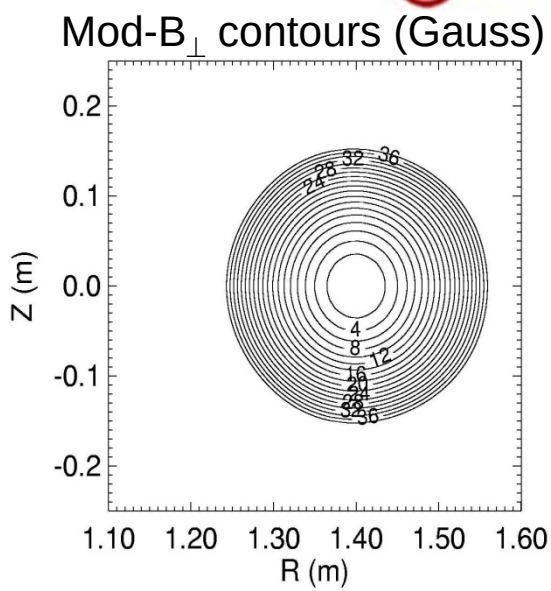
- 20kA produced in NSTX using this configuration
- Requires improved pre-ionization for optimizations

J. Menard, PPPL

Creation of High-Quality Field-Null with Significant Poloidal Flux is Possible with NSTX PF Coils





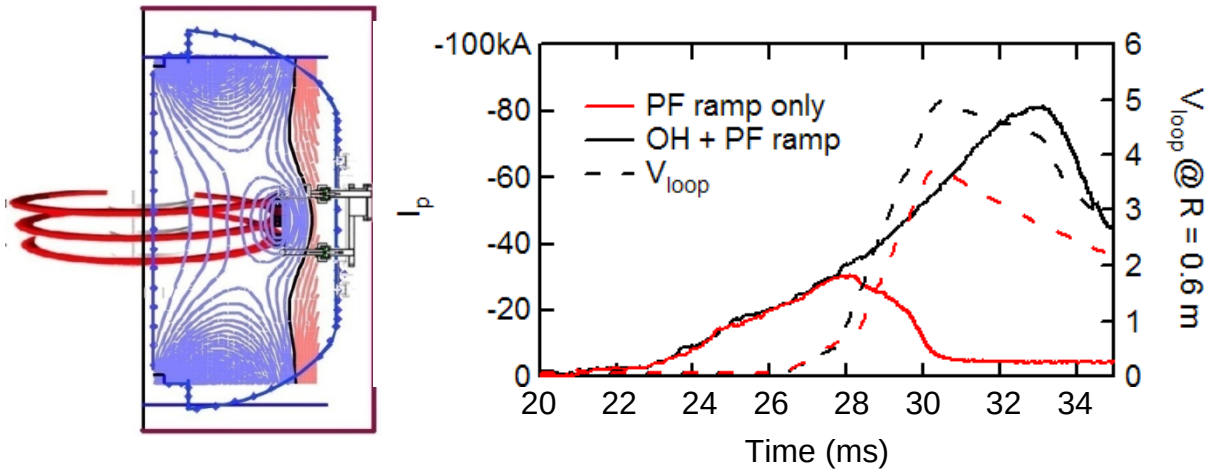


- ~0.15 Vs available on NSTX
- 1 MA achieved with ~0.3 Vs from solenoid
- Sugggests possibility of ~ 500 kA in NSTX
  - Improvements to pre-ionization are needed
    - CHI [PAC21-29]
    - plasma Gun, 350kW ECH (Incremental)

*W. Choe, J. Kim and M. Ono, NF **45** (2005) 1463*

Plasma Gun Startup (FY10)

- Results from single gun source in Pegasus are promising
- Estimated installation on NSTX (FY 10).



New triple gun array installed on Pegasus

- All hardware tested
- Currently learning how to use 3 guns simultaneously
- Will assess scaling relations for current build up in NSTX

FY 09-10 Plans

CHI

- Increase Transient CHI produced current [PAC21-27]
  - Use higher Voltage
  - Reduce absorber arcs (PF control)
  - Improve coupling to OH
  - Looking forward to LLD (initial integration with metal plates, then including Lithium) [PAC21-28]

FY10

  - Extend performance of OH shots
  - Test CHI / PF Synergism [PAC21-29]

Outer PF Startup

FY10

- Test outer PF Startup
  - Use CHI pre-ionization/current
  - 350 kW ECH (incremental)

Gun Startup

FY10

- Test Plasma Gun Startup
  - Assessing requirements & schedule

FY 11-13 Plans

NSTX 5yr Goal: Full Non-inductive startup and sustainment

CHI

- Develop Edge current drive
  - Upgrade control magnetics
  - Study the effect of edge current on ELMs, SOL flows, MHD (basic physics also applicable to tokamaks)
- Investigate relaxation current drive potential in NSTX
  - Can the startup current be enhanced beyond what is possible with Transient CHI?
  - Is steady-state current drive possible?
  - Requires DC PS & Improved Abs. Arc control
- Develop CHI / PF synergism
  - Maximize solenoid-free startup currents
  - Use ECH (incremental) to heat CHI for ramp-up with HHFW

Outer PF Startup

- Test alternate outer PF Startup techniques
  - Large field null scenarios
  - Small field null scenarios
  - Use Gun Pre-ionization
  - ECH Pre-ionization (incremental)
  - What is the potential for outer PF startup in a ST?

Gun Startup

- First test of plasma guns in a large ST
- What is the scaling for Gun Startup currents in a large ST?

NSTX is the only Large Machine Studying CHI & Outer PF Startup (with coil outside Vacuum Vessel)

- Transient CHI to be optimized by FY10
  - Successful initial development on HIT-II
  - Produced record non-inductive startup currents in NSTX
  - Scaling to larger machines is attractive
  - FY 08 Milestone is to produce a OH coupled long pulse discharge & show flux savings
  - GOAL: Incorporate CHI into normal operations
- Test plasma startup using outside PF induction (FY 09-13)
  - Potential to produce MA level startup currents in large STs
  - CHI & Guns for pre-ionization, ECH (incremental)
  - Can significantly benefit from NSTX operation beyond FY10
- New non-inductive CD Methods could significantly benefit from operations beyond FY10
  - Edge & Relaxation CD
  - Gun Startup
  - Synergism between methods leading to a realization of full non-inductive startup and sustainment

Solenoid-free Plasma Startup Time Line FY08 – FY10

NSTX

| FY08 | FY09 | FY10 | FY 11 | FY12 | FY13 |

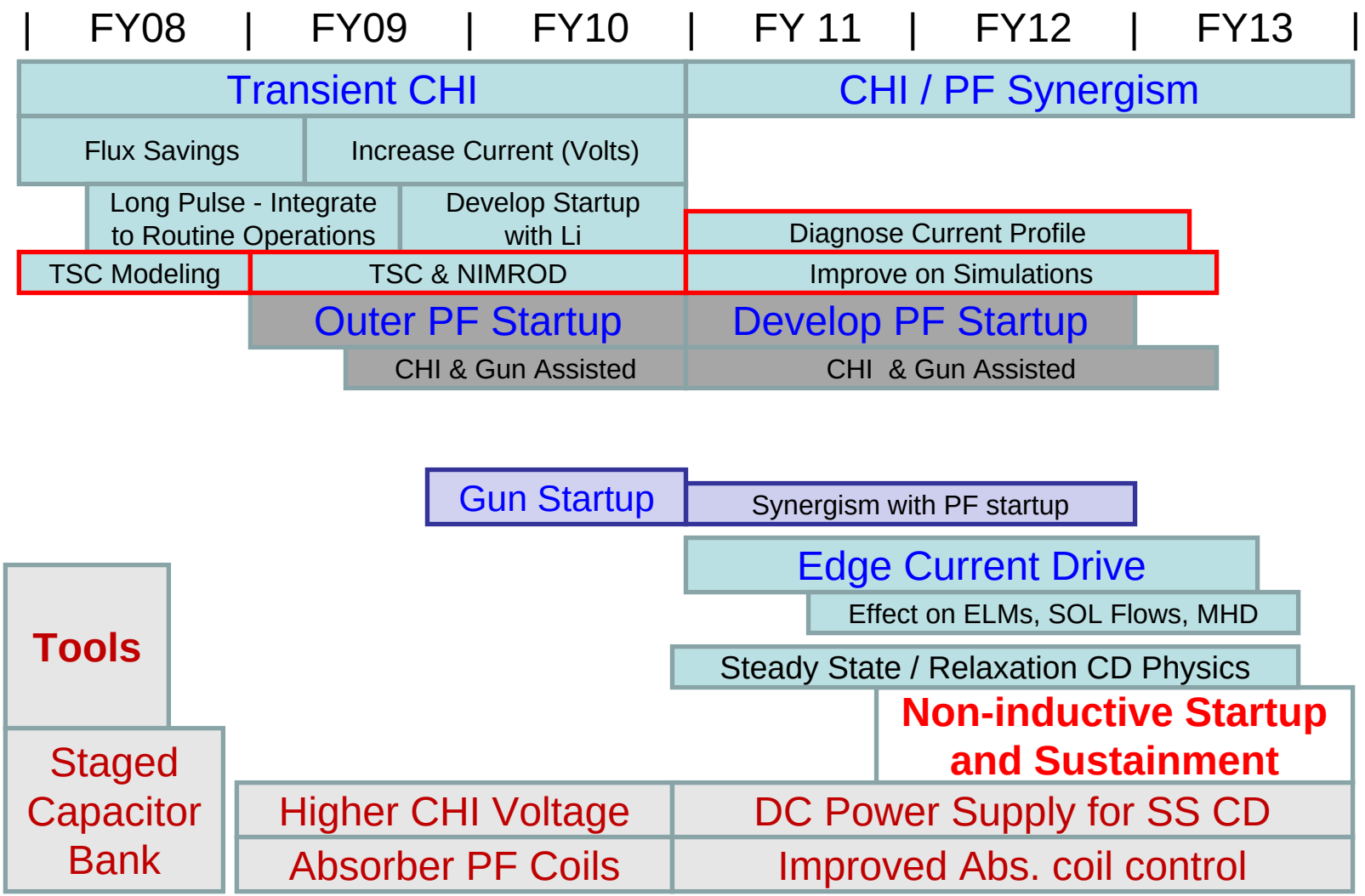
- Transient CHI
  - Flux Savings
  - Increase Current (Volts)
  - Long Pulse - Integrate to Routine Operations
  - Develop Startup with Li
- TSC Modeling
- TSC & NIMROD
- Outer PF Startup
  - CHI & Gun Assisted
- Gun Startup

Will not test outer PF startup & Gun startup in a FY08-09 only plan

Tools

- Staged Capacitor Bank
- Higher CHI Voltage
- Absorber PF Coils

Solenoid-free Plasma Startup Time Line FY08 – FY13



Solenoid-free Plasma Startup Time Line FY08 – FY13 + 10% Budget Increment