NSTX

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Solenoid-free Start-up and Ramp-up Progress and Plans

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For the NSTX Research Team

NSTX PAC-27
February 3-5, 2010

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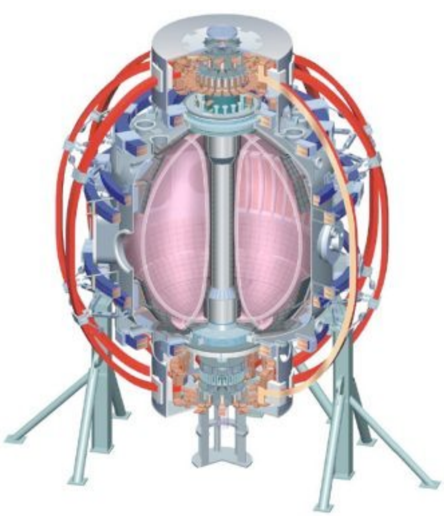

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2008 FESAC-Toroidal Alternatives Panel: for ST non-inductive start-up and ramp-up is priority #1

- Goal: Plasma start-up, ramp-up and sustainment with minimal use of the solenoid (aim for solenoid-free demonstration)

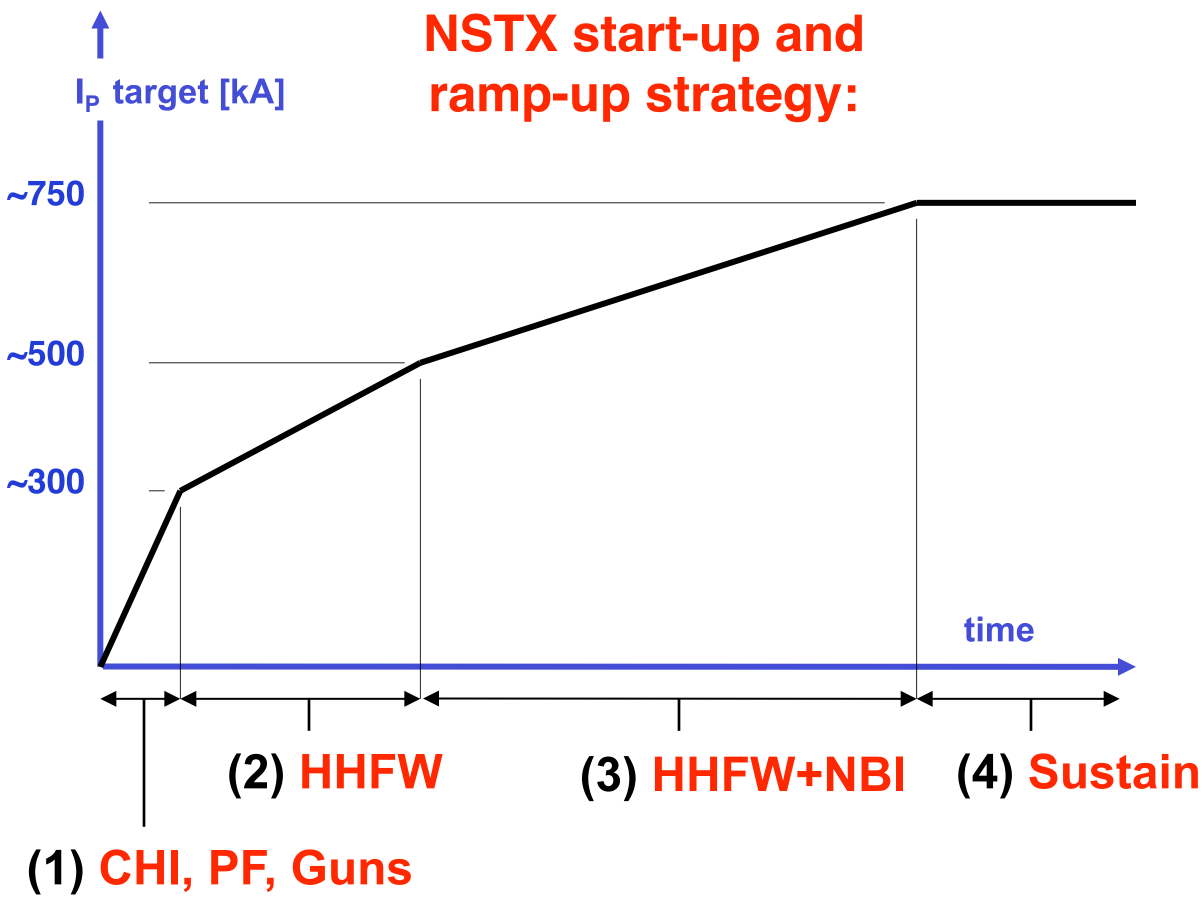
- Solenoid-free current initiation would improve the prospects of the ST as a CTF and fusion reactor; Could aid tokamak reactors, ARIES-AT design

- NSTX has explored CHI and Outer PF start-up for plasma current initiation
  - Collaboration with DIII-D on outer PF start-up with ECH

- DIII-D is exploring outer PF start-up and NBCD/ECCD ramp-up
  - Achieved ~175 kA start-up current

- UW PEGASUS program on plasma gun start-up will be tested on NSTX when technically ready
  - Achieved ~150 kA start-up current

Three Phases for Start-up and Ramp-up in NSTX



Start-up/ramp-up requirements:

(1→2) I_P, T_e, RF coupling must be sufficiently high for HHFW to be absorbed

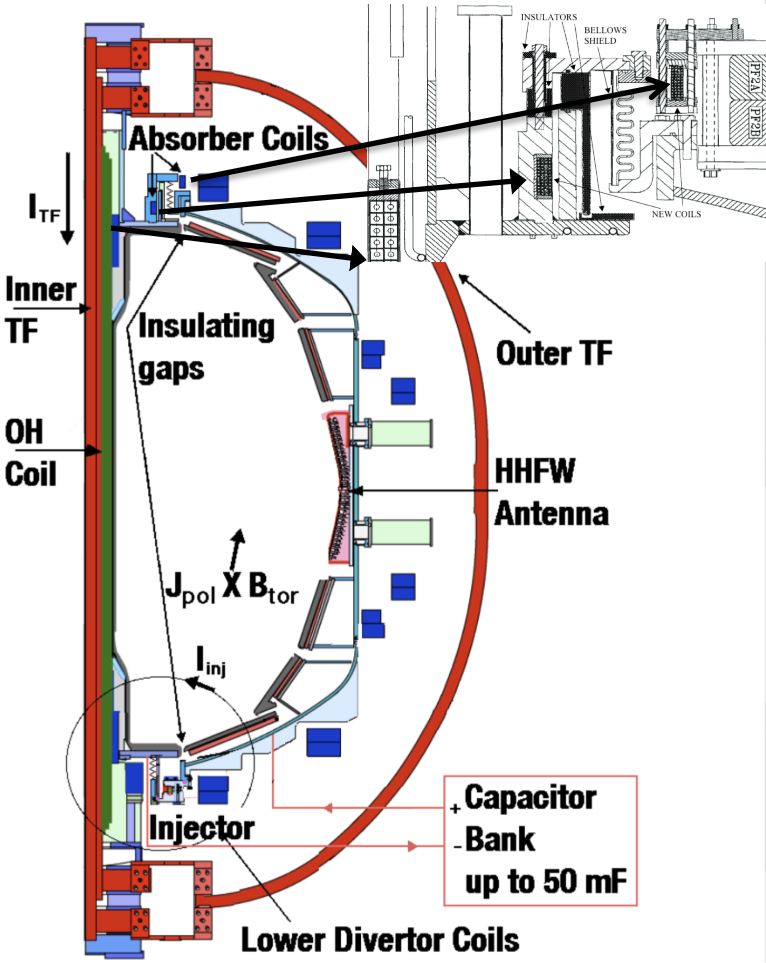
(2) Sufficiently high P_{RF}, τ_E must be achieved for I_P overdrive using BS and HHFW current drive

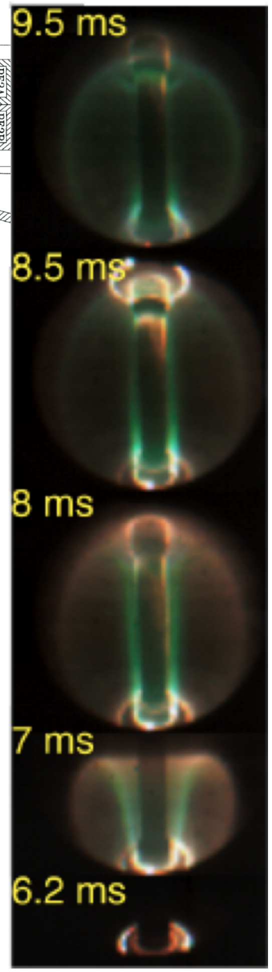
(2→3) Sufficiently high I_P needed to absorb NBI, high P_{HEAT}, τ_E, β_P needed for current overdrive

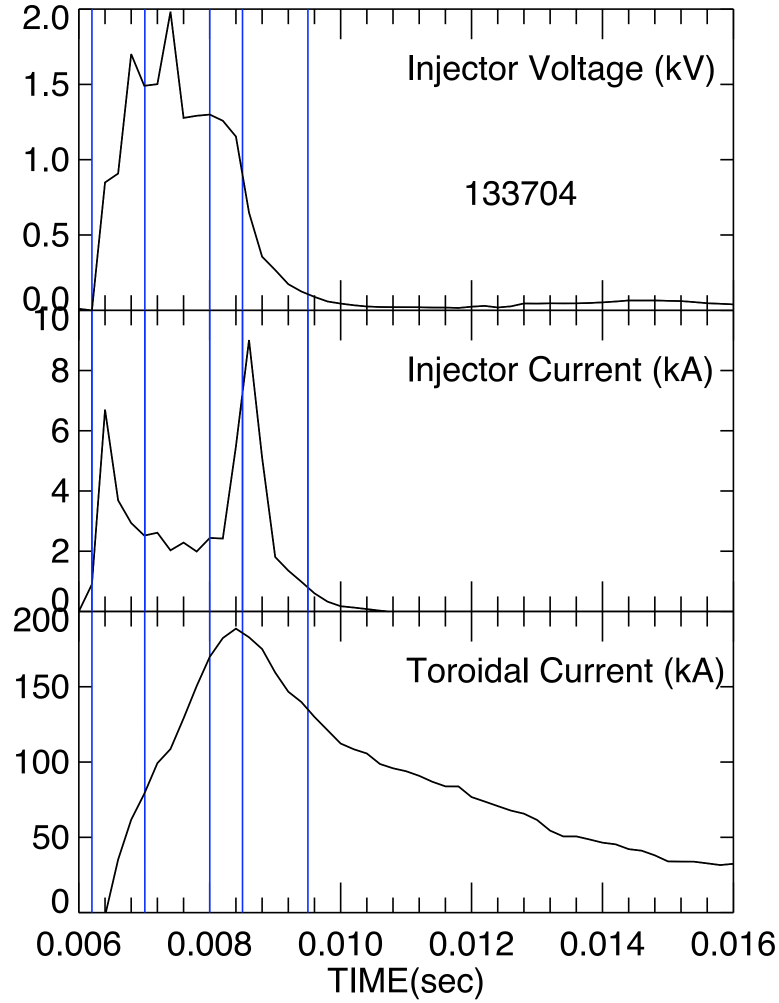
(3→4) Ramp-up plasma must be consistent with sustained high-f_{NI} scenario

NSTX FY2009-13 – Progressively reduce use of central solenoid

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



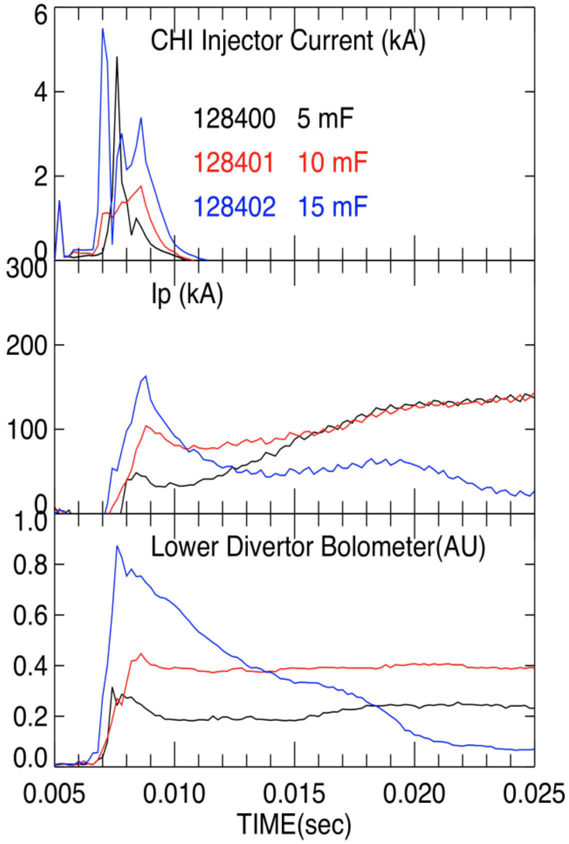


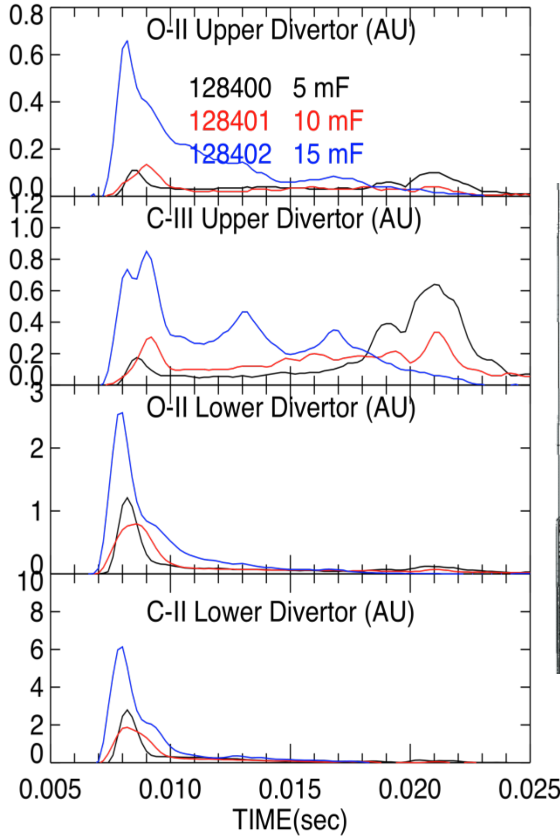


Demonstration of coupling to induction and NBI H-mode (2008)

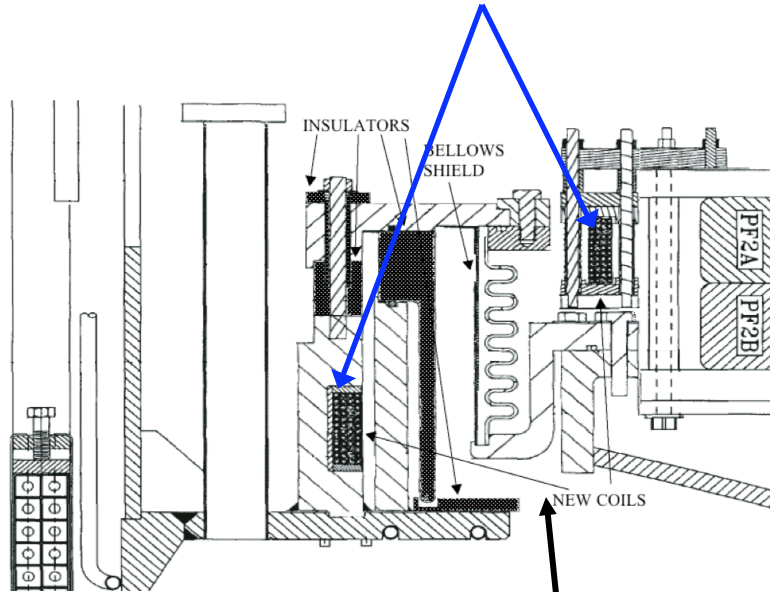
Improved coupling at higher injection current (2009)

In 2008, low Z impurities limited the ability to ramp-up a CHI discharge with central solenoid





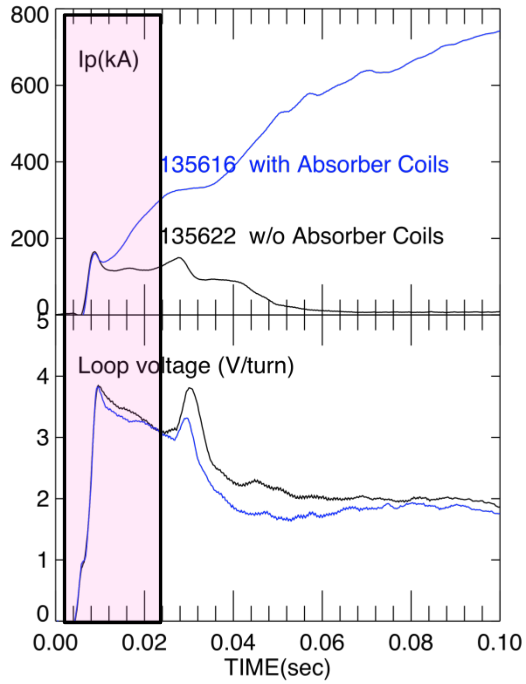
Absorber Coils

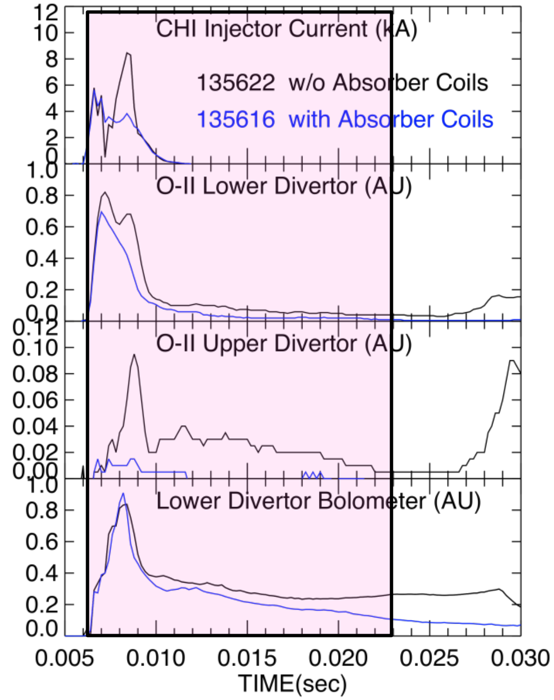


- CHI exhibits low Z impurities that increase with increasing capacitor energy.
- As the discharges grow upwards to fill the vessel absorber arcs occur
  - FY2009: Used absorber coils to provide buffer flux and prevent arcs

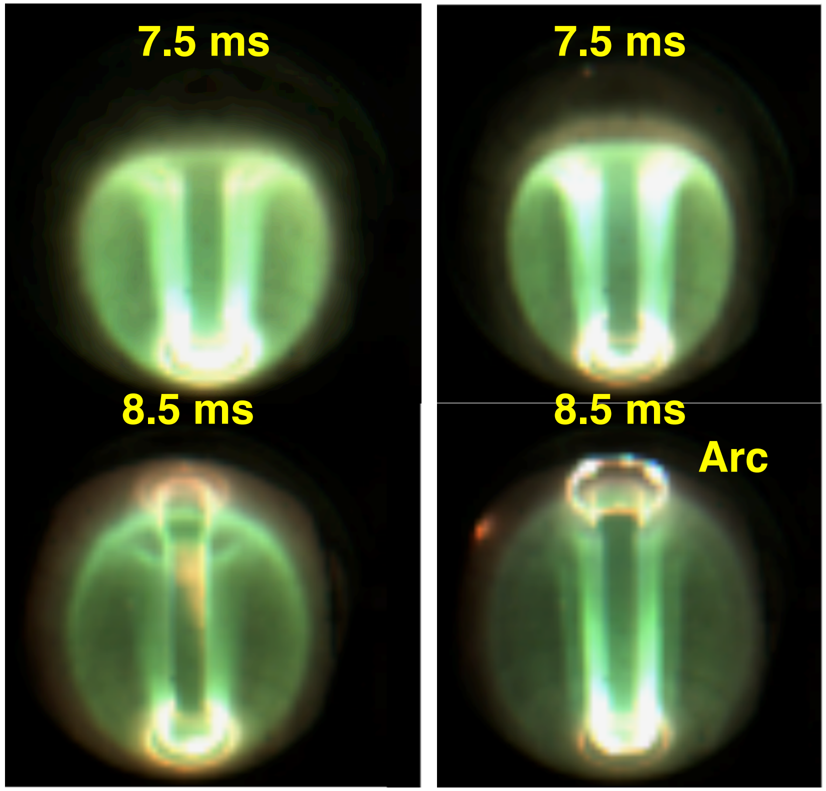
Radial field from absorber coils can prevent plasma from reaching absorber gap and arcing during CHI

•15 mF at 1.7 kV



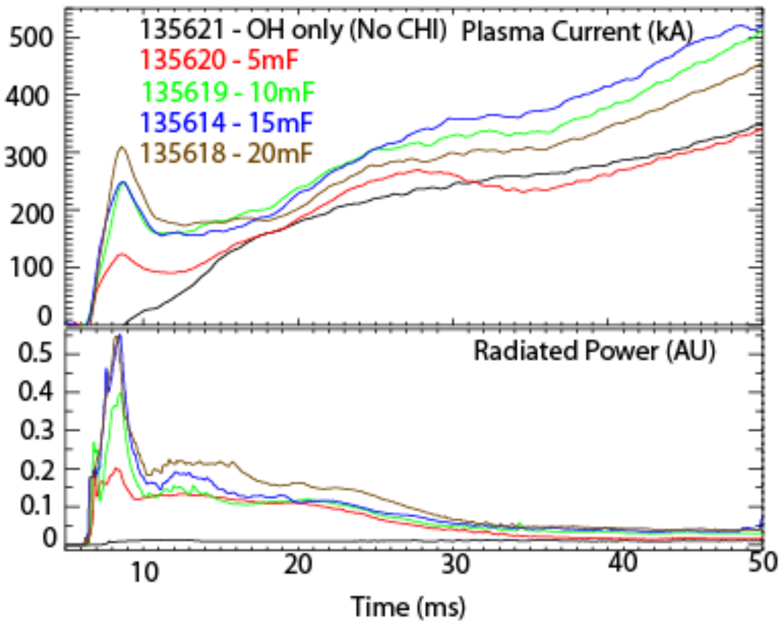


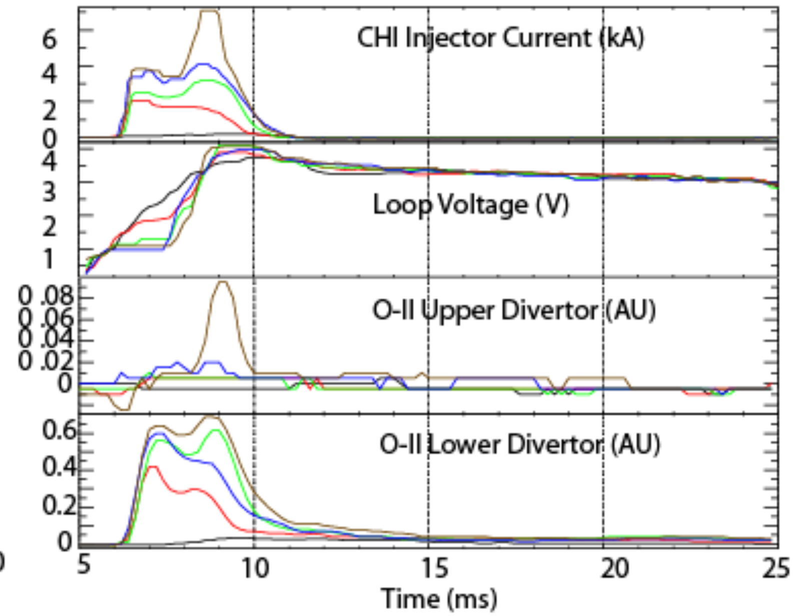
With Absorber Coils **Without**

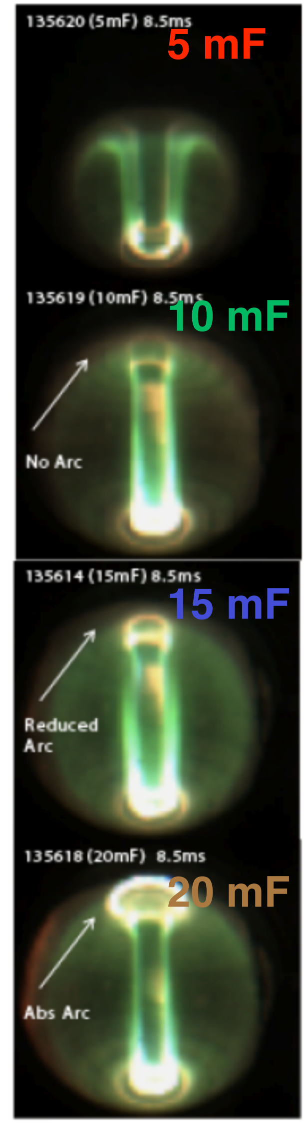


- Only the discharge without the absorber arc couples to inductive ramp-up
- Even without an arc, low Z impurities limit the ability to couple to ramp-up
- It is important to condition the lower divertors

Ip increases with CHI energy until absorber arc occurs







Before using absorber coils, CHI discharges using > 5 mF at 1.7 kV had absorber arcs

- I_p ~ 200 kA greater than ohmic only
  - Best in 2008 was ~ 50 kA, 4-fold improvement
- Successful coupling to induction using 20 mF (goal is 50 mF)
  - Ignoring impurity effects, expect current to scale with capacitor energy

FY10-12 Plans for CHI

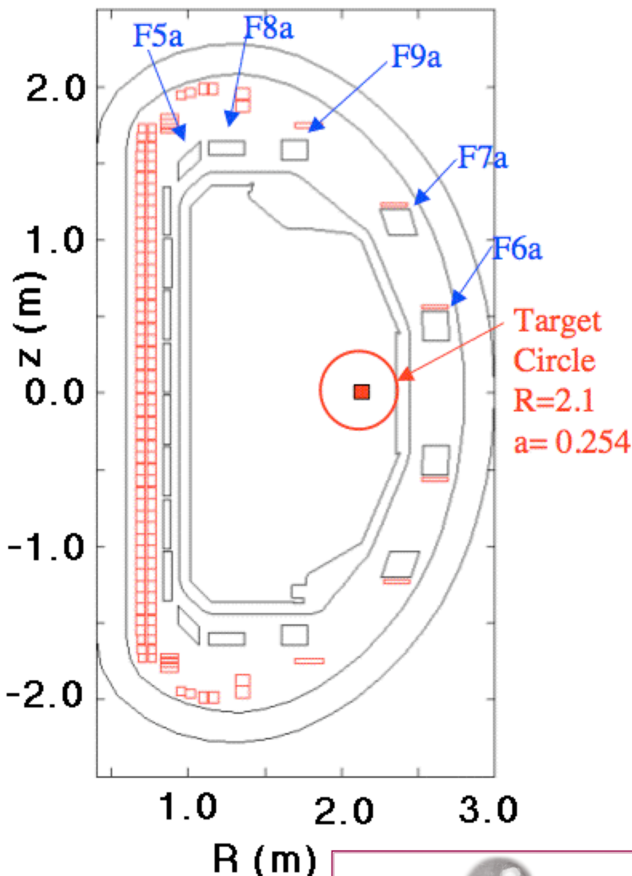
2010

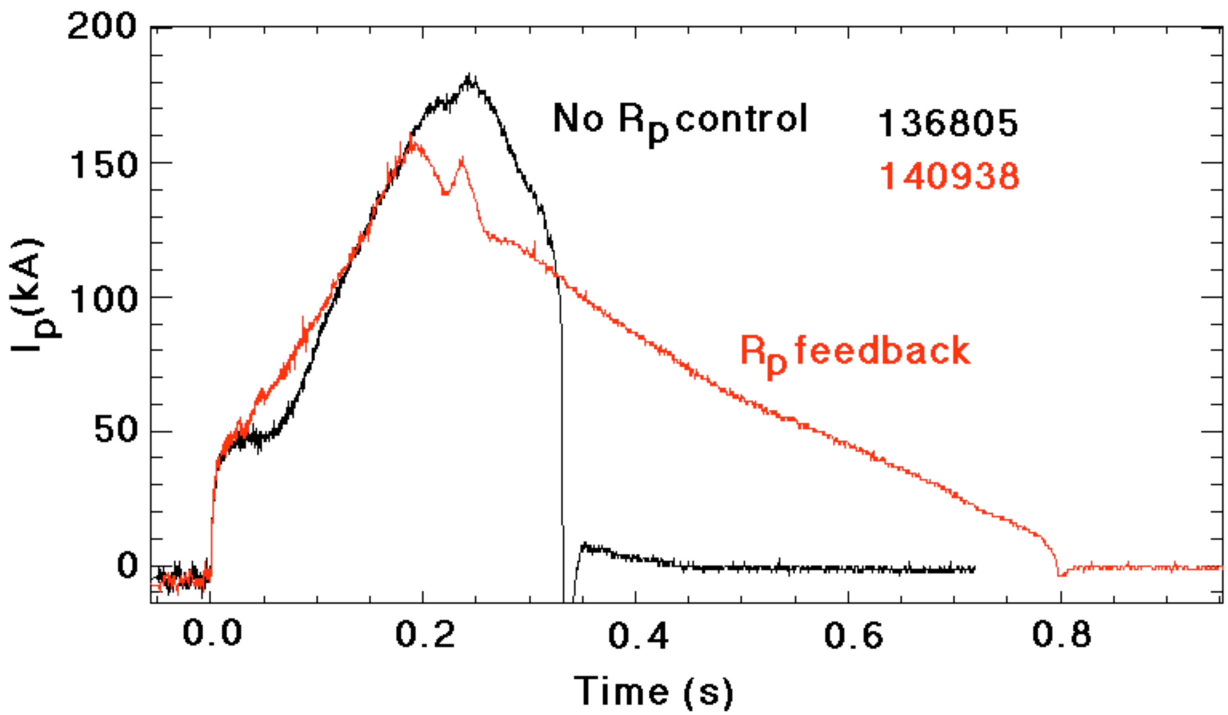
- Optimize current in CHI Absorber coils to reduce arcs
- Increase capacitor energy to try to increase flux savings
- Apply radial position control earlier (now at t=40ms, reduce to t=20ms)
- Test use of Li powder to coat upper divertor and limit low Z impurities
- Use long pulse CHI for conditioning
- Use HHFW heating to burn through impurities
- If reversed TF is available, test heated metal outer divertor plate (LLD) as cathode

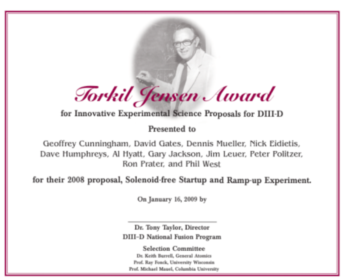
2011/2012

- R(12-3): Assess confinement, heating, and ramp-up of CHI start-up plasmas
- Utilize full metal divertor plates to improve CHI current start-up capability
- Tests PEGASUS plasma guns on NSTX if technically ready

Collaboration with GA, Culham and KSTAR tested outer PF start-up with R_p control using high-power ECH (6MW)







Torkil Jensen Award

for Innovative Experimental Science Proposals for DIII-D

Presented to

Geoffrey Cunningham, David Gates, Dennis Mueller, Nick Eidietis, Dave Humphreys, Al Hyatt, Gary Jackson, Jim Leuer, Peter Politzer, Ron Prater, and Phil West

for their 2008 proposal, Solenoid-free Startup and Ramp-up Experiment.

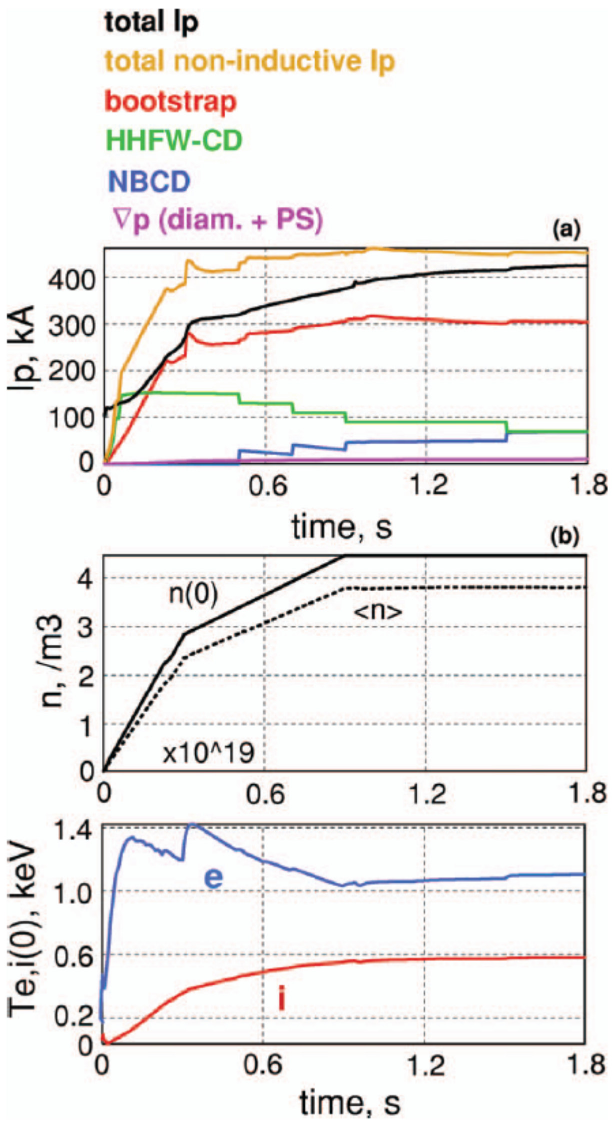
On January 16, 2009 by

Dr. Tony Taylor, Director
DIII-D National Fusion Program

Selection Committee
Dr. Keith Burrell, General Atomics
Prof. Ray Fonck, University Wisconsin
Prof. Michael Mauel, Columbia University

- ***Provides target for NB Current Drive***
- ***Simonen demonstrated sustainment of 0.34 MA with NBCD on DIII-D using H°→He***
- ***Planned experiments on DIII-D for D°→D***

With 6MW HHFW Power, Non-inductive Current Ramp up should be Achievable in NSTX



- TSC Simulation of current ramp up at 0.45T
  - HHFW is the heating and CD system at low I_p and low T_e
- I_p ramp up started at 100kA
  - 6MW HHFW ($8m^{-1}$) Co-CD Phasing
  - 6MW NBI added after I_p reaches ~400kA (only 2-3 MW confined due to low I_p)
- 5-6MW power coupling of HHFW could lead to bootstrap current overdrive
  - Requires improved ELM recognition and outer gap control for stable HHFW coupling
- Antenna upgrade (2009) and ELM recognition system (2010) now ready for use in HHFW ramp-up experiments

TSC simulations by C. Kessel

FY10-12 Plans for Non-Solenoidal Ramp up and Sustainment

2010-2011

- **Use higher power and ELM recognition to:**
  - **Heat a I_p 250-400 kA inductive discharge with HHFW**
  - **Assess current sustainment and ramp-up of a 250-400kA inductively generated discharge with HHFW + bootstrap overdrive**

2011/2012

- **Couple HHFW to CHI initiated plasma**

Milestone R(12-3): Assess confinement, heating, and ramp-up of CHI start-up plasmas

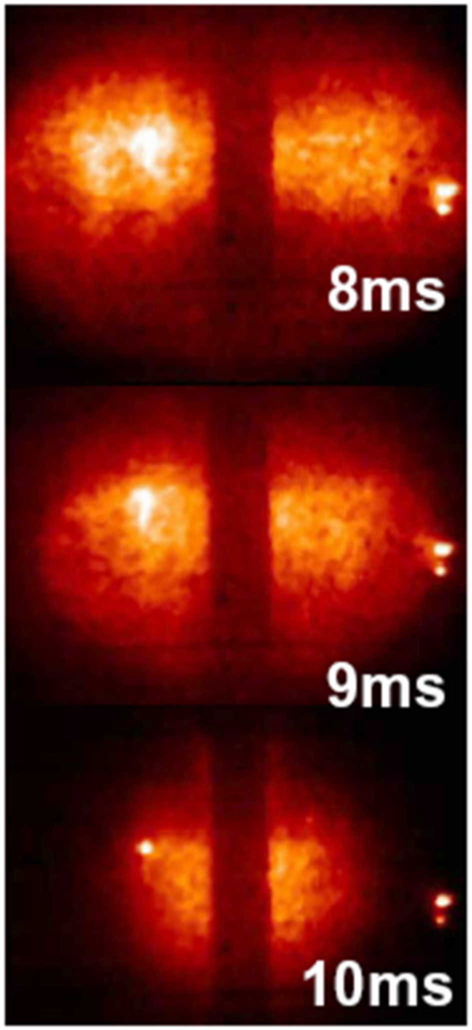
NSTX is a leader in developing start-up and ramp-up techniques for STs

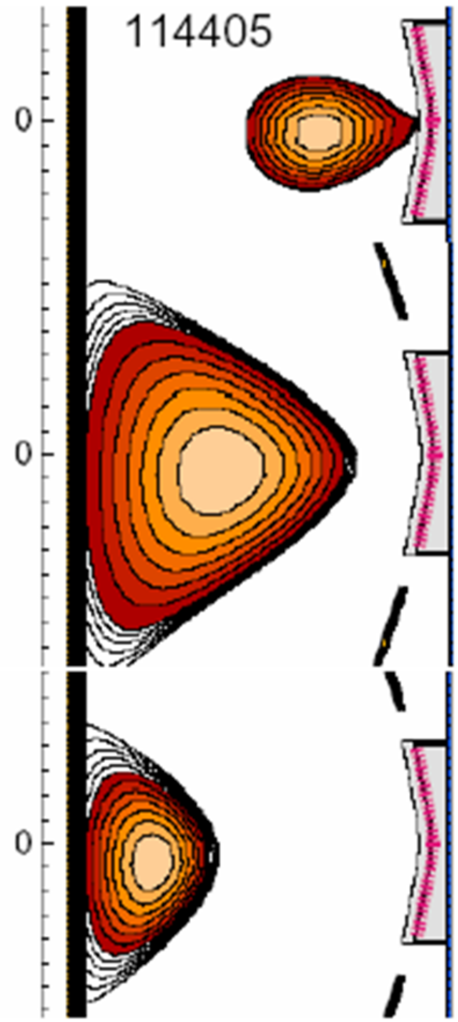
- **Transient CHI now a proven method to generate closed flux**
  - Startup & inductive coupling at 200kA demonstrated on NSTX
  - CHI initiated and inductively ramped current reached 700kA in H-mode plasmas reaching 800eV
  - Used absorber coils to reduce absorber arcs
  - Used Li to reduce impurities during CHI
  - Will investigate use of HHFW in CHI phase
  - Will test CHI performance implications of metal electrodes (from LLD)
- **HHFW Heating and Current Drive for Ramp-up**
- **Outer PF start-up was demonstrated on DIII-D and NSTX**
  - DIII-D experiment with high power ECH and NB current drive
- **Plasma Gun start-up being investigated on Pegasus**
  - Design/install on NSTX as progress on PEGASUS warrants, FY2012 or later

Solenoid-free start-up research will benefit greatly from new center stack and 2nd NBI

- Non-inductive current ramp-up experiments should significantly benefit from higher power HHFW, higher TF (~1T), longer pulse length (5s), ECH would help start-up
  - I T CS upgrade and 2nd tangential NBI particularly important for high-current ramp-up demonstration
  - Start-up currents of ~500kA relax requirements on subsequent ramp-up
  - 350kW ECH to heat CHI plasma for coupling to HHFW, but is limited by resource availability
- Consider 2kV capability to increase the magnitude of the CHI started currents
- Test relaxation current drive
- Use CHI startup for full integration with nearly full non-inductive operation, which includes startup with CHI, reaching Ip ~500kA followed by ramp-up with HHFW and NBI to current levels where it is non-inductively sustained.

Outer PF Startup has been tried, but was limited by available heating power and flux





- LRDFIT code used for reconstructions
  - I_{vessel} ~ 10 x **Ip**
- Control of B_Z after breakdown raised **Ip** from 10kA to 20kA
  - Satisfied $E_T.B_T/B_P$ ~1kV/m over good fraction of vacuum cross section
- Need improved preionization, heating and optimized PF coil waveforms
  - 350kW ECH resonance layer in large field null region
  - Need T_e control to get to high-enough I_P to meet PF coil programming