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

D. Mueller and R. Raman

For the NSTX Research Team

NSTX PAC-25
February 18-20, 2009

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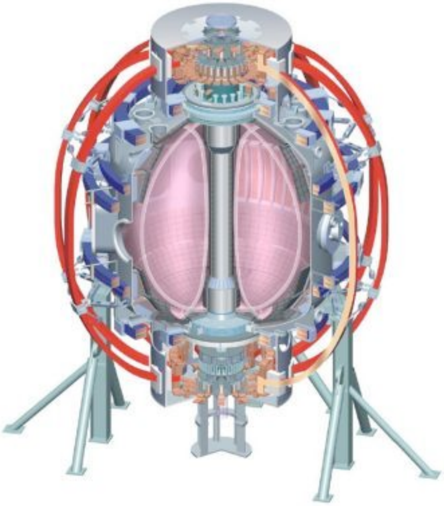

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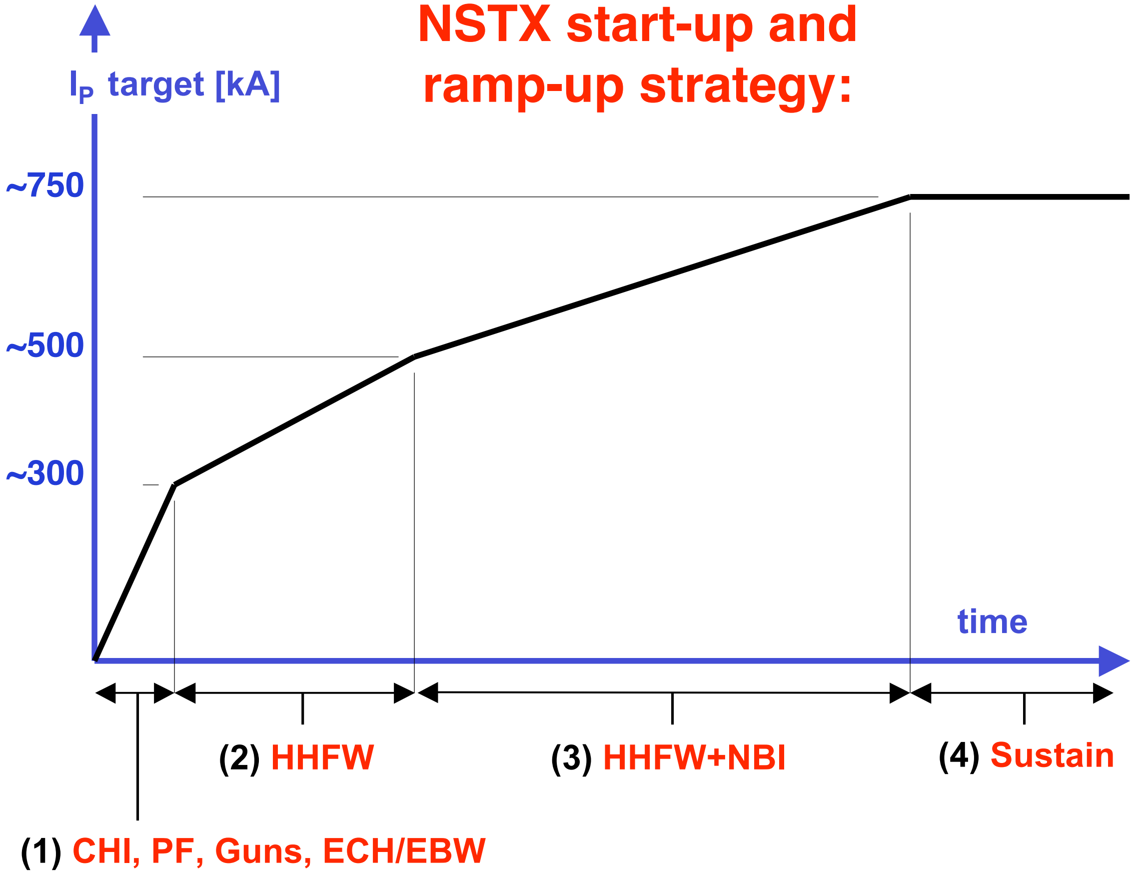
Motivation for Solenoid-free Plasma Startup

- Non-inductive start-up and ramp-up is FESAC-TAP priority #1 for ST
- Solenoid-free current initiation would improve the prospects of the ST as a CTF and fusion reactor; Could aid ARIES-AT design
- Of the three large machines in the US (DIII-D, NSTX, C-MOD)
  Only NSTX has engaged in solenoid-free plasma start-up research
  DIII-D collaboration plans to explore outer PF start-up this spring
- NSTX has explored CHI and Outer PF start-up for plasma current initiation
  - •*PAC23-19* NSTX PAC recommended start-up concept research in addition to CHI
  - •*PAC23-20* Collaboration with DIII-D on outer PF start-up with ECH
  - Need scaling from UW PEGASUS plasma gun start-up

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

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

NSTX start-up and ramp-up strategy:



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

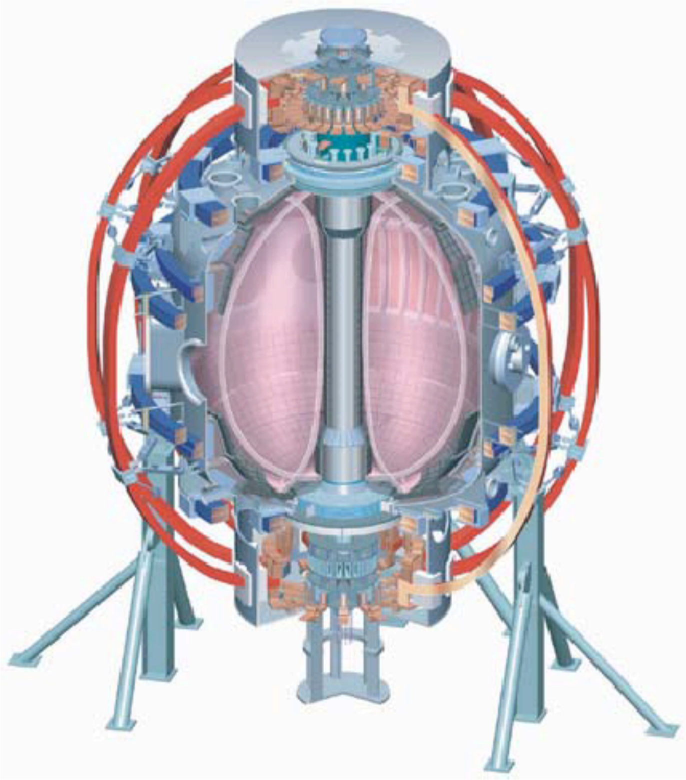
(2→3) Sufficiently high I_P needed to absorb NBI, high P_{HEAT}, τ_E, β_P needed for current overdrive

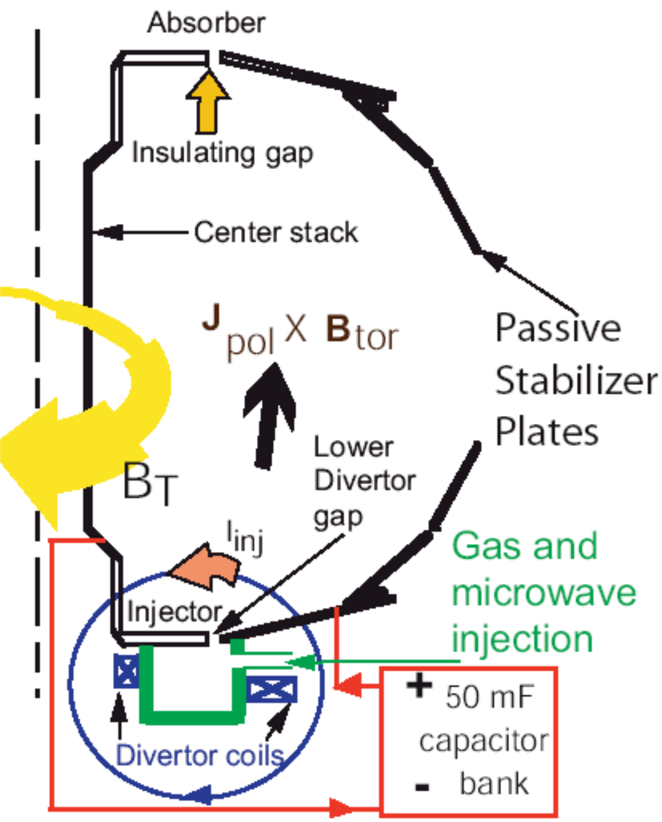
(3→4) Ramp-up plasma must be consistent with sustained high-f_{NI} scenario

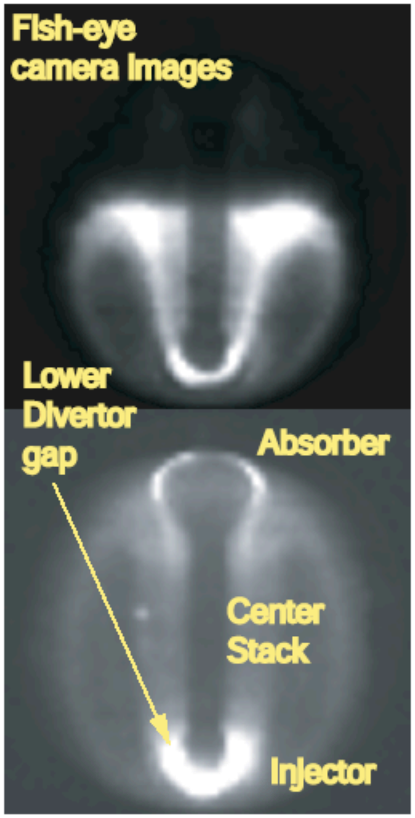
In ST-CTF/DEMO, iron core and possibly mineral insulated conductor transformer could provide portion of flux needed for I_P ramp-up

NSTX FY2009-13 - Use OH as needed to simulate I_P ramp-up

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







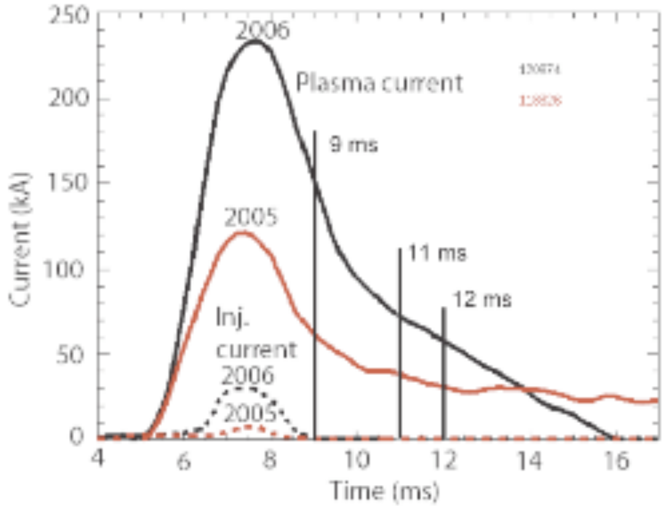
- Demonstration of closed flux current generation
  - Aided by gas and EC-Pi injection from below divertor plate region
- Demonstration of coupling to induction and NBI H-mode (2008)
  - Aided by staged capacitor bank capability

CHI for an ST: T.R. Jarboe, Fusion Technology, 15 (1989) 7

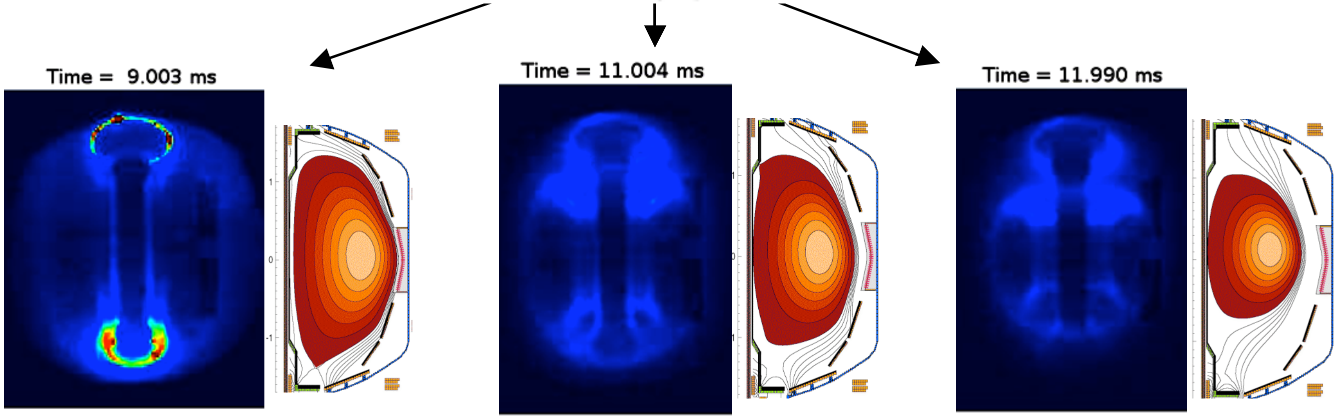
Transient CHI: R. Raman, T.R. Jarboe, B.A. Nelson, et al., PRL 90, (2003) 075005-1

Very high current multiplication (>50) aided by higher Toroidal Field: $I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})$

Toroidal plasma current after $I_{CHI} \rightarrow 0$ flows on closed surfaces



Used LRDFIT reconstructions to account for large vessel eddy currents



2006 discharges had higher B_T and injector flux

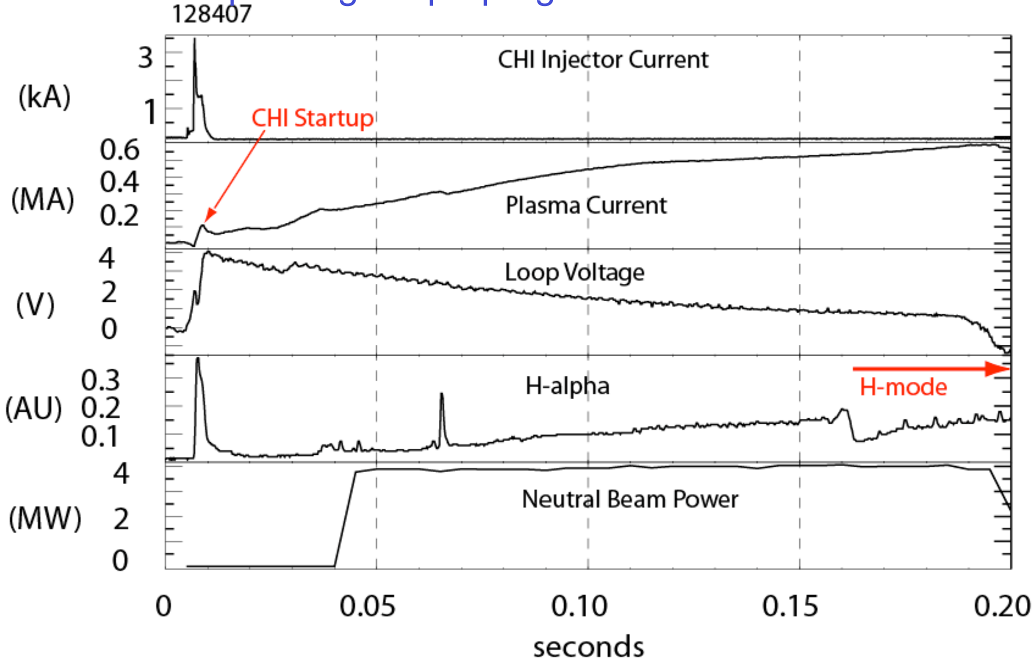
Record 160kA non-inductively generated closed flux current in ST or Tokamak produced in NSTX

R. Raman, B.A. Nelson, M.G. Bell et al., PRL 97, 175002 (2006)

LRDFIT (J. Menard)

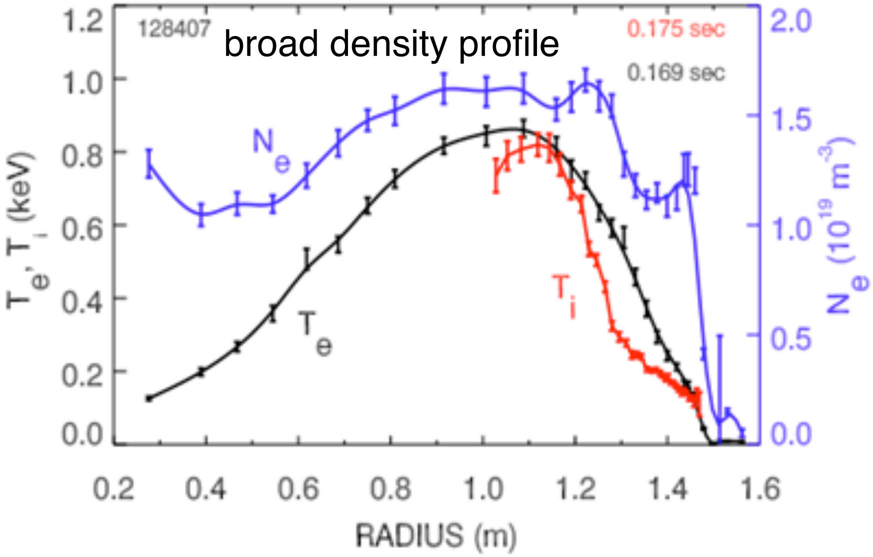
CHI started discharge couples to induction and transitions to an H-mode demonstrates compatibility with high-performance plasma operation

- Discharge is under full plasma equilibrium position control
  - Loop voltage is preprogrammed



Te & Ne from Thomson

Ti from CHERS



Central Te reaches 800eV

Central Ti > 700eV

- *PAC-23*

- Projected plasma current for CTF > 2.5 MA $[I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})]^*$
  - Based on 50 kA injected current (Injector current densities achieved on HIT-II)
  - Current multiplication of 50 (achieved in NSTX)
  - In HIT-II nearly all CHI produced closed flux current is retained in the subsequent inductive ramp

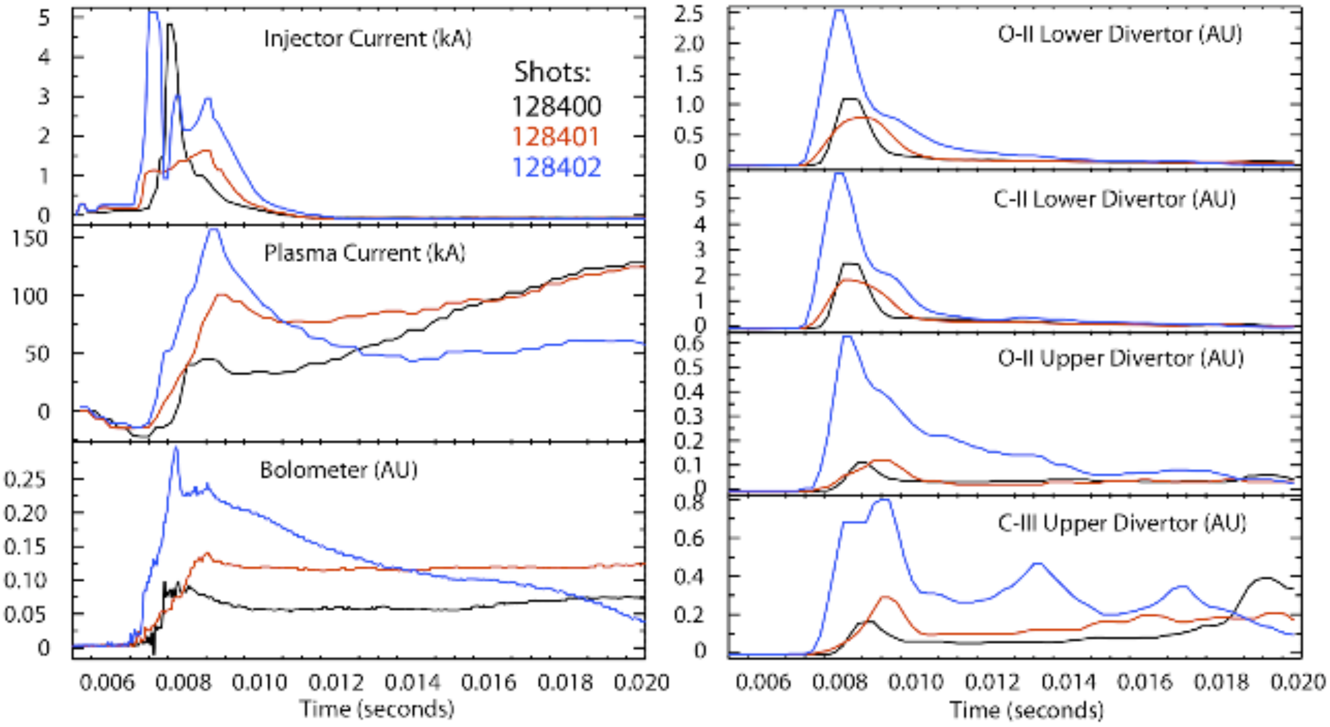
CHERS: R. Bell, Thomson: B. LeBlanc

***T.R. Jarboe, Fusion Technology, 15 (1989) 7**

Need auxiliary heating or metal divertor plates to compensate for increased radiated power with more capacitors

Low-z impurity radiation increases with increased injection energy in both upper and lower divertor regions

128400: 5mF (7.6kJ) **128401: 10mF (15.3kJ)** **129402: 15mF (22.8kJ)**



- ***Lower Divertor** - condition surfaces with long CHI discharges, Lithium, try metal cathode (LLD with reversed TF in 2010)*
- ***Upper Divertor** - Suspected source is arcing at top, Use absorber field nulling coils to reduce arcs*
- ***Both** - Revisit HHFW heating of CHI discharge, use 350 kW ECH when available*

D. Mueller et al., EPS 2008

FY09-13 Plans for CHI

2009

- Use the SPAs to power CHI Absorber coils and reduce absorber arcs
- Test use of Li powder and evaporated Li for performance improvement
- Test long pulse CHI for conditioning
- Use HHFW heating to burn through impurities

2010

- Test heated metal outer divertor plate (LLD) as cathode (reverse TF)
- Consider 2kV capability to increase the magnitude of the CHI started currents

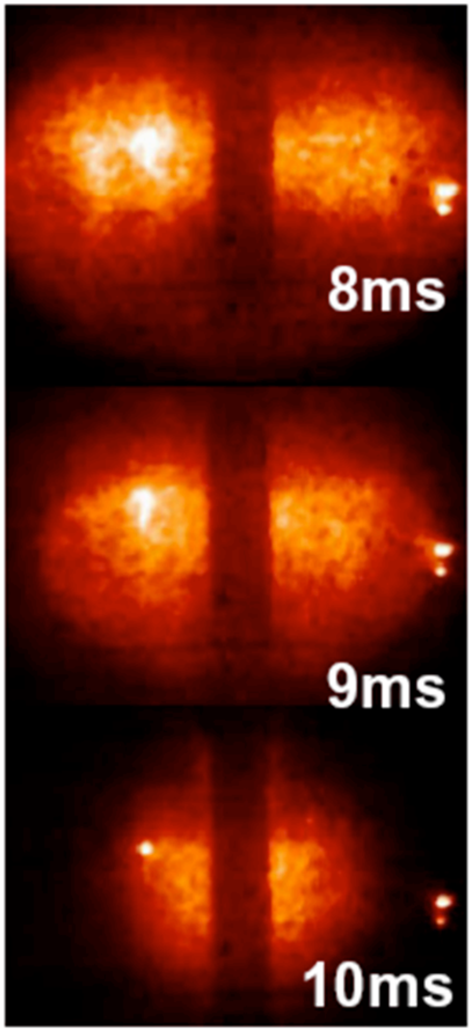
2011

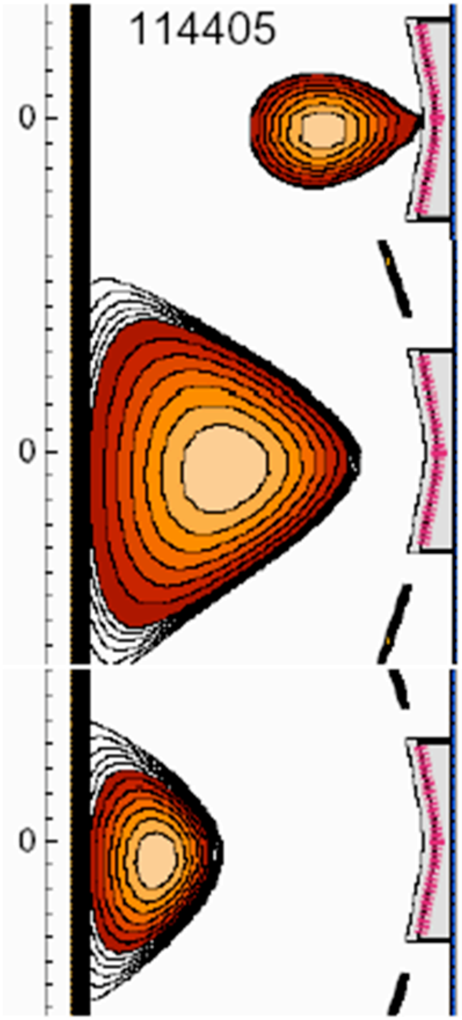
- Consider full metal divertor plates to improve CHI current startup capability
- Test relaxation current drive.

Research utilizing new CS and/or 2nd NBI and/or ECH (2012-2013)

- Operate at 1T to maximize CHI startup currents
- Use 10ms, 350kW ECH to heat CHI plasma for coupling to HHFW
- Maximize startup currents using synergism with outer PF coil startup
- 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 is possible in NSTX, but is limited by available heating power





- LRDFIT code used for reconstructions
  - I_{vessel} ~ 10 x **Ip**
- Careful control of B_Z after breakdown helped raise I_p from 10kA to 20kA
  - More B_z evolution optimization possible
  - This satisfied $E_T.B_T/B_P$ ~1kV/m over good fraction of vacuum cross section

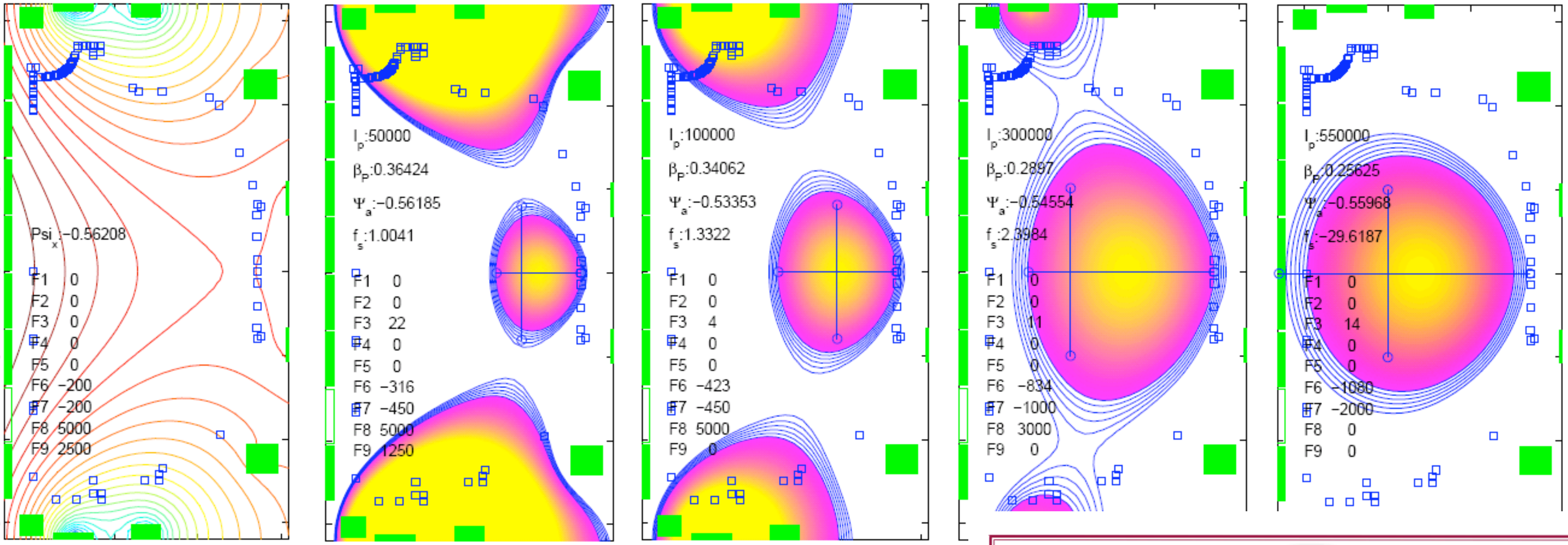
Need improved preionization, heating and optimized PF coil waveforms

  - 350kW ECH resonance layer in large field null region
  - Need Te control to get to high-enough I_P to meet PF coil programming

- Collaboration with Culham and GA on DIII-D outer PF start-up

•PAC23-19

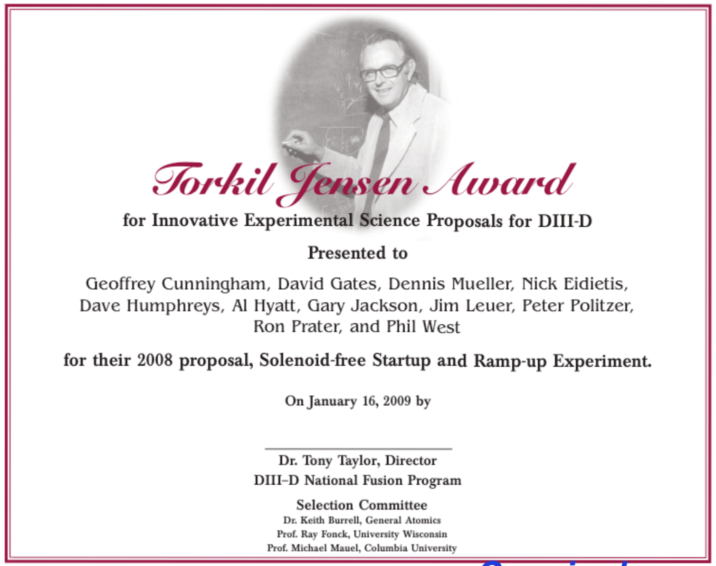
Collaboration with Culham and GA will test outer PF start-up on DIII-D using high-power ECH (4MW) and NBI (10 MW)



The initial configuration becomes vertically controllable only at finite I_p : 50KA shown here for F8=+5KA. This is the most tricky phase.

The plots have roughly constant ψ(a) (Ejima coefficient=1) giving final Ip=550KA

Torkil Jenson Award is a run day on DIII-D



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

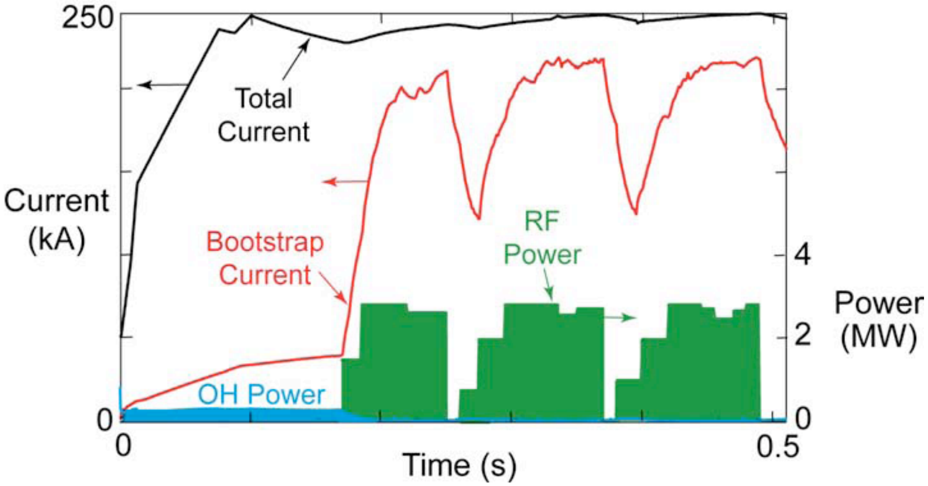
Selection Committee
Dr. Keith Burrell, General Atomics
Prof. Ray Fonck, University Wisconsin
Prof. Michael Mauel, Columbia University

•*Cunningham*

Progress on Ip Ramp up with HHFW and NBI

2005

- Produced HHFW heated ($k_{||}$ = 14 m^{-1}) plasmas at Ip = 250 kA with 85% bootstrap current
- Transiently produced $V_{loop} \leq 0$ and $dI_{OH}/dt \approx 0$
- Identified the need for H-mode for effective replacement of inductive current



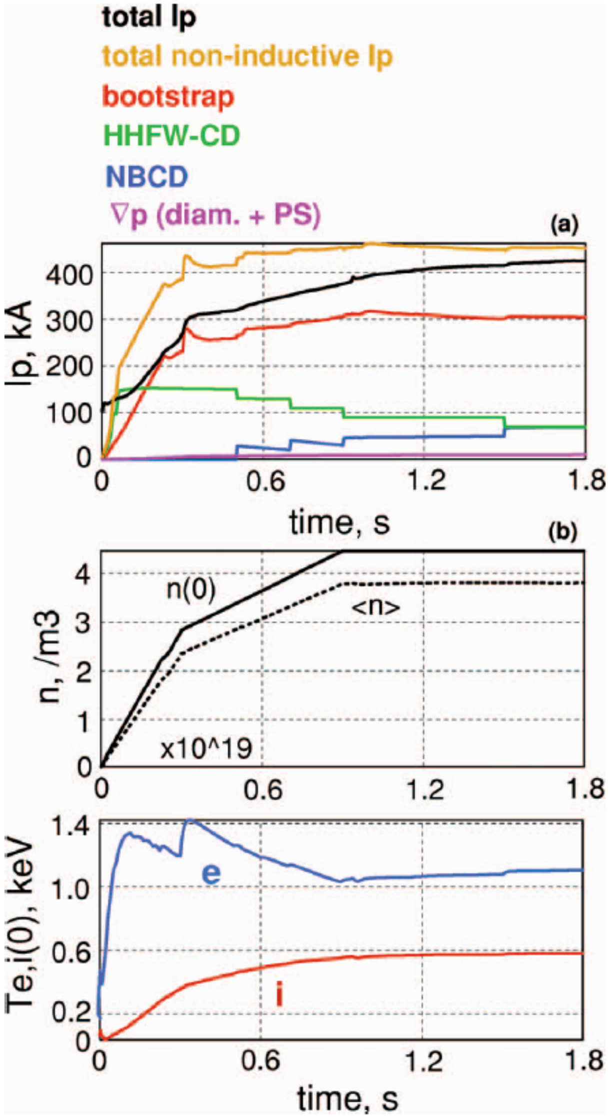
2006

- Demonstrated that higher B_T makes HHFW more efficient for heating

2007

- Improved HHFW coupling efficiency, including CD phasing
- Demonstrated that increased antenna voltage stand-off and ELM resilience needed to make HHFW work reliably
- This , in large part, motivated the HHFW voltage stand-off upgrade (FY2009) and ELM resilience (FY2010-2011)

With 6MW HHFW Power, 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 Ip and low Te
- Ip ramp up started at 100kA
  - 6MW HHFW (7m-1) Co-CD Phasing
  - 6MW NBI added after Ip reaches ~400kA (only 2-3 MW absorbed due to slow Ip ramp rate in 1.8s plasmas)
- 5-6MW power coupling of HHFW could lead to bootstrap current overdrive (instead of 85% BS)
  - Requires improved ELM and outer gap control for stable HHFW coupling

C. Kessel

FY09-13 Plans for Non-Solenoidal Ramp up and Sustainment

2009-10

- First sustain I_p~400 kA with HHFW Heating and Current Drive and possibly NBI
- FY10 HHFW milestone is to use higher power (x2) and ELM resilience to attempt Ip ramp-up from 200-250kA to 400-500kA using HHFW heating and CD + BS

2011

- Try nearly full sustainment and ramp-up at 500kA using inductively produced target

Research utilizing new CS and/or 2nd NBI (2012-2013)

- 1T expected to reduce normalized beta required to achieve high bootstrap fraction for overdrive, also expected to increase target Te for increased HHFW absorption and higher CD efficiency. NBI also should become more effective at higher field and current.
- Try more tangential NBI and higher NBI power for improved CD ramp-up above 500kA
- Understand lower current limit for ramp-up and sustainment at 1T and scaling to 2T (Needed to establish start-up requirements)

NSTX is Developing Start-up and Ramp-up Techniques for STs

- **Transient CHI is a proven method to generate closed flux (160kA to date)**
  - Startup & inductive coupling at 100kA demonstrated on NSTX & HIT-II
  - CHI initiated and inductively ramped current reached 700kA in H-mode plasmas reaching 800eV
  - Use absorber coils to reduce absorber arcs
  - Investigate use of Li to reduce impurities during CHI
  - Investigate use of HHFW in CHI phase
  - Test CHI performance implications of metal electrodes (from LLD)
- **HHFW Heating and Current Drive for Ramp-up**
- **Outer PF start-up will be tested using new tools for pre-ionization**
  - DIII-D experiment with high power ECH and NBI
- **Plasma Gun start-up being investigated on Pegasus**
  - Design/install on NSTX as progress on PEGASUS warrants, FY2011 or later
- **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

BACKUP SLIDES

CHI Scaling

- From helicity and energy conservation, for a Taylor minimum energy state $\lambda_{inj} \geq \lambda_{tok}$

  -$\lambda_{inj} = \mu_0 I_{inj}/\psi_{inj}$; ψ_{inj} = poloidal injector flux

  -$\lambda_{tok} = \mu_0 I_p/\psi_{tok}$: ψ_{tok} = toroidal flux in vessel

- $I_p \leq I_{inj}(\psi_{tok} / \psi_{inj})$
- For similar B_T NSTX has 10 times ψ_{tok} of HIT-II
- Bubble burst condition:

  $I_{inj} = 2\, \psi_{inj}^2/(\mu_0^2 d^2 I_{TF})$

  -For HIT-II, ψ_{inj} = 8mWb, d = 8 cm is flux footprint width

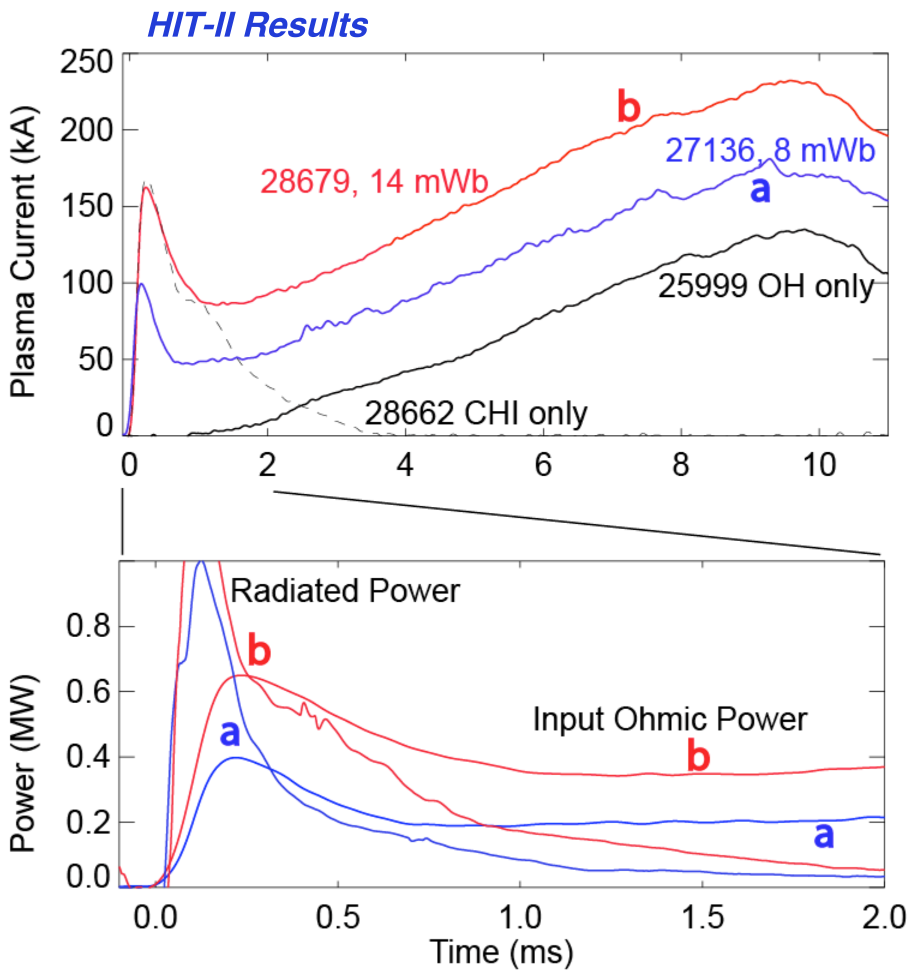
  -For NSTX, ψ_{inj} = 10mWb, d = 16 cm is flux footprint width

  -$I_{inj} \geq$ 15 kA for HIT-II, $I_{inj} \geq$ 2 kA for NSTX

- NSTX has achieved $I_p > 60\ I_{inj}$
- HIT-II has achieved $I_{inj} \sim 50$ kA

  ⇨ I_p over 2.5 MA is possible for CTF if $I_{inj} \sim 50$ kA

In HIT-II nearly all CHI produced closed flux current is retained in the subsequent inductive ramp

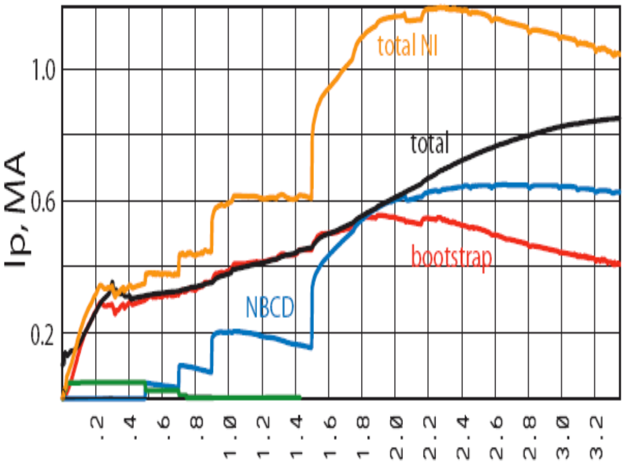


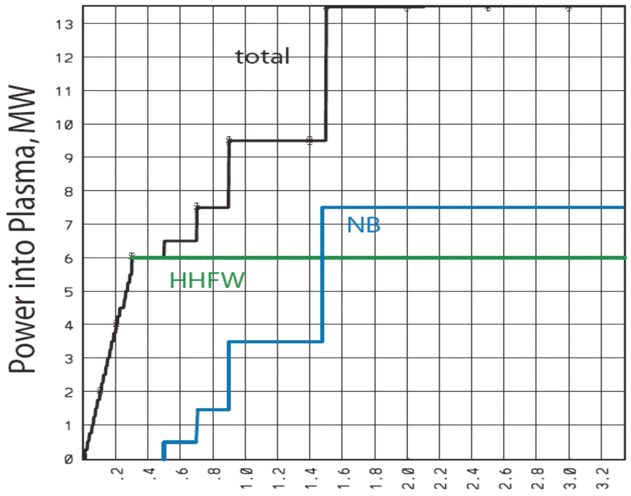
- All three discharges have the identical loop voltage programming
- Coupling current increases as injected flux is increased
- Ip ramp-up begins after input power exceeds radiated power
  - Auxiliary heating would ease requirements on current ramp-up system
- Radiated power can be decreased by using W or Mo target plates
  - Start-up plasma (inductive or CHI) is cold (few 10s of eV)
  - Reduce Low-Z line radiation

R. Raman, T.R. Jarboe, R.G. O'Neill, et al., NF 45 (2005) L15-L19

R. Raman, T.R. Jarboe, W.T. Hamp, et al., PoP 14 (2007) 022504

With 1T and 6MW HHFW + 7MW NBI Power, Current Ramp up to 800-900kA Should be Achievable in NSTX





- TSC Simulation of current ramp up at 1T
  - HHFW is the heating and CD system at low Ip and low Te
  - Current ramp up to 1MA should be possible
- Ip ramp up started at ~350kA
  - 6MW HHFW (7m-1) Co-CD Phasing
  - 7MW NBI added after Ip reaches ~600kA
  - 3s pulse needed for ramp-up to higher current
- Higher HHFW and NBI power absorption at higher TF eases requirements on ramp up
  - New CS is needed for 3s 1T operation to get to end of ramp up at 3s
- Simulation is on-going effort and un-optimized

C. Kessel

Plasma start-up using biased Plasma Guns

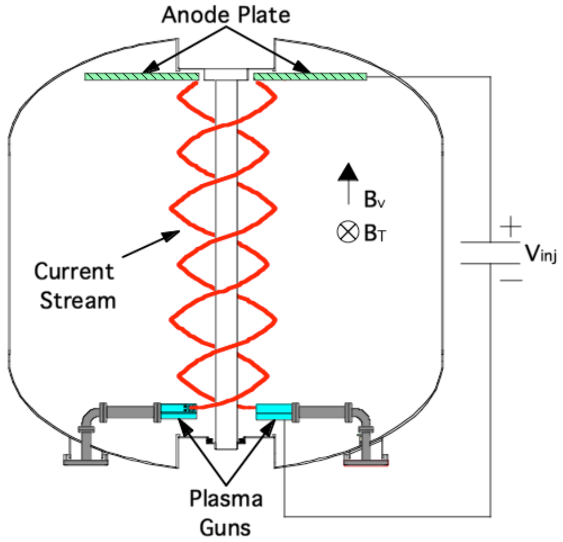
- DC helicity injection rate is given by:

$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

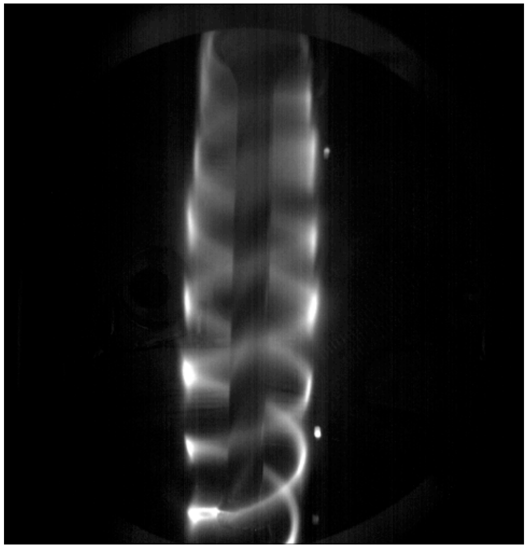
- The helical filaments can relax and form a tokamak if:
  1. Plasma-generated B_p greater than vacuum B_v
  2. Radial force balance is satisfied
  3. Sufficient input power

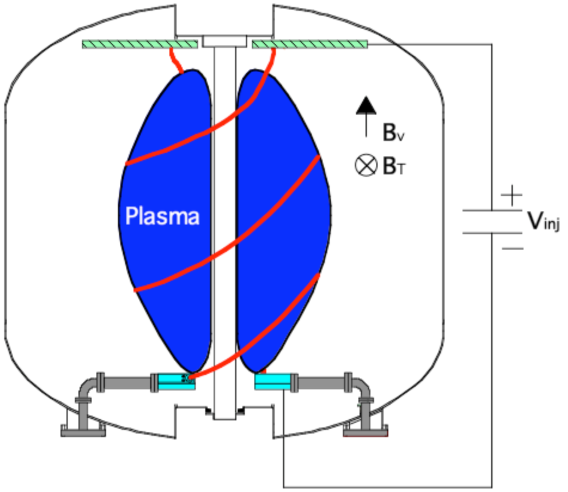
- Relaxed-plasma I_p is 10-15 times greater than I_{bias} multiplied by vacuum field windup (total multiplication up to 50)

- Can be easily mounted between primary and secondary passive plates on outboard region



Filaments





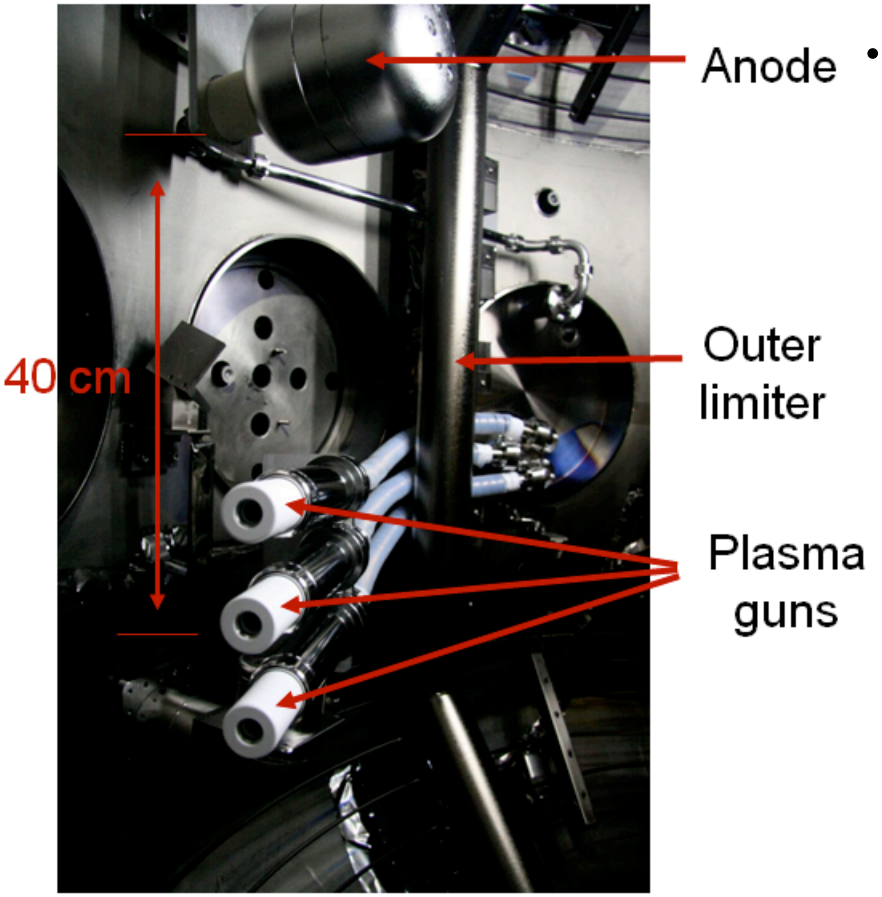
Relaxed State

PEGASUS ST

A.J. Redd, ICC Conference 2008

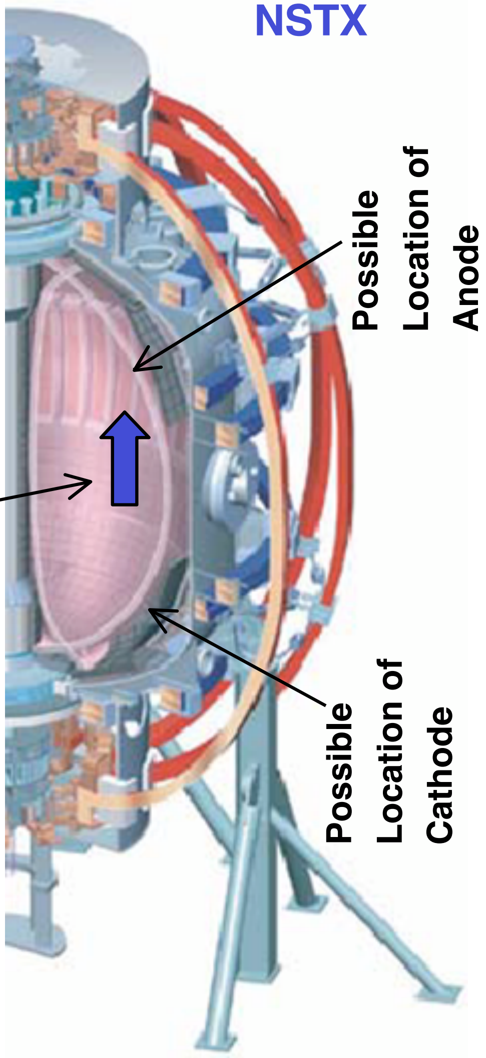
New larger surface area guns mounted on the outboard side being tested on Pegasus

Pegasus



- Guns on NSTX to be installed in the gap region between the primary and secondary passive plates
  - Electron flow channel should intersect field null produced during outer PF startup experiments

NSTX

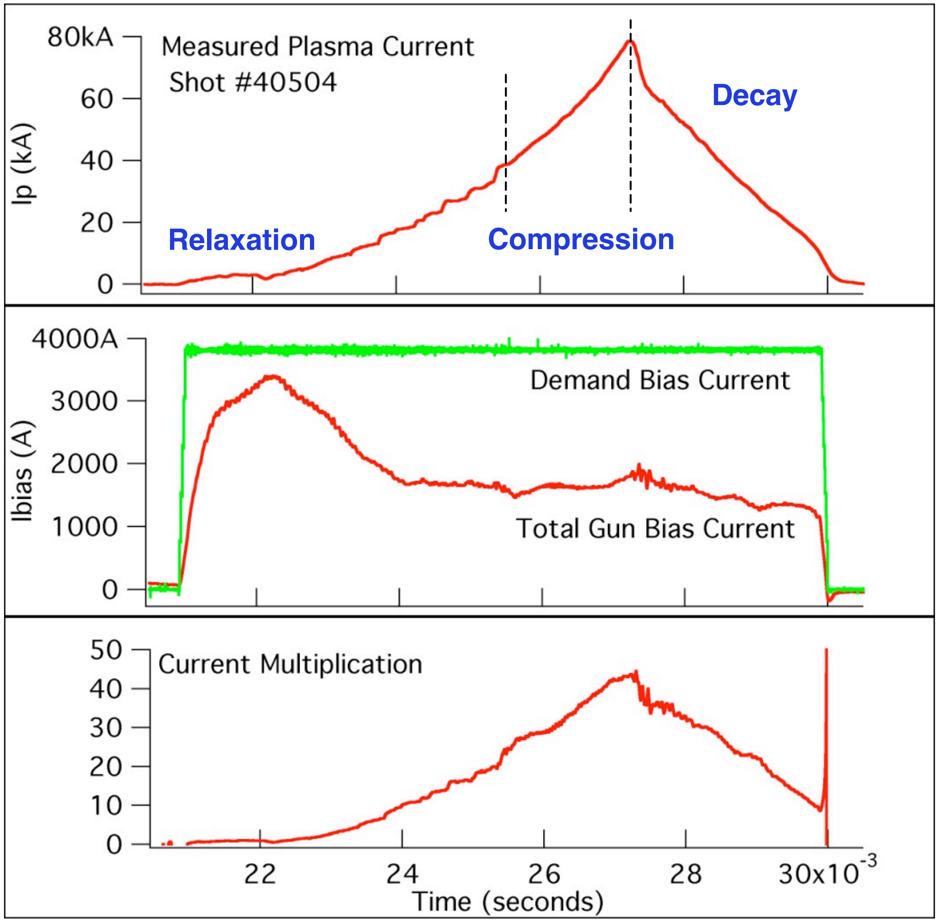


D.J. Battaglia, ICC Conference 2008

Relaxation Enhances the Driven Current Beyond the Vacuum-Field Windup

- Current multiplication through relaxation and outer-PF ramp
  - Up to 80kA obtained with additional induction from outer PF coils
- Ip evolves through three stages
  - Relaxation of gun-driven plasma + outer PF ramp
  - Radial compression of detached tokamak
  - Tokamak decay, limited by central column

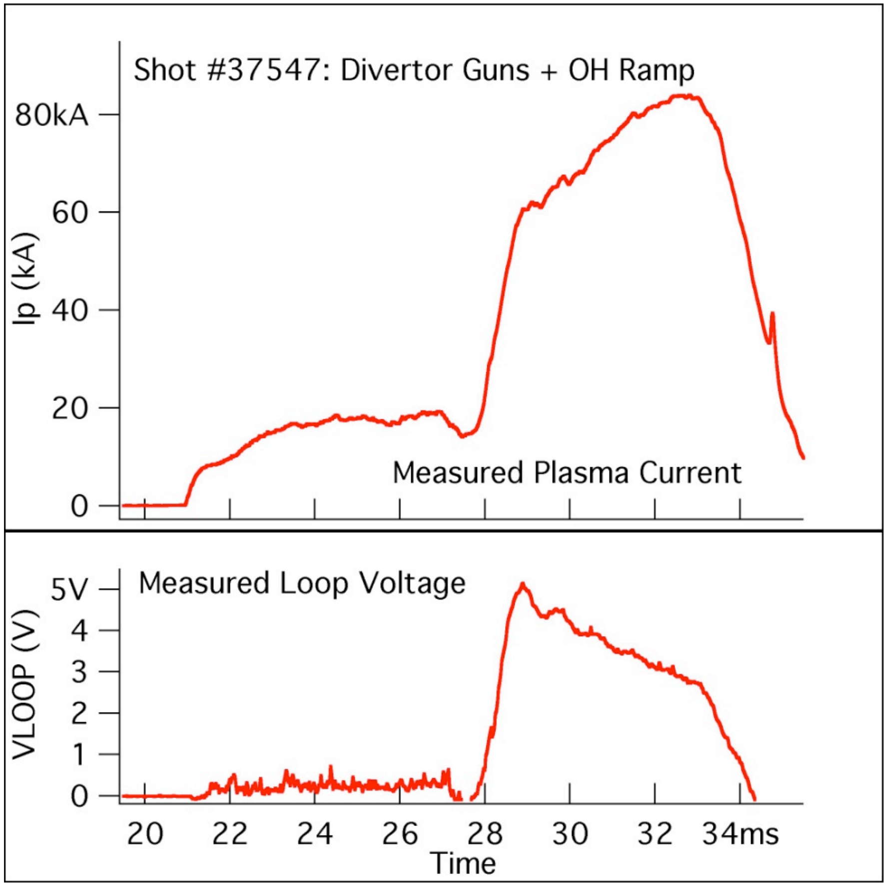
Results from mid-plane Guns (PEGASUS)



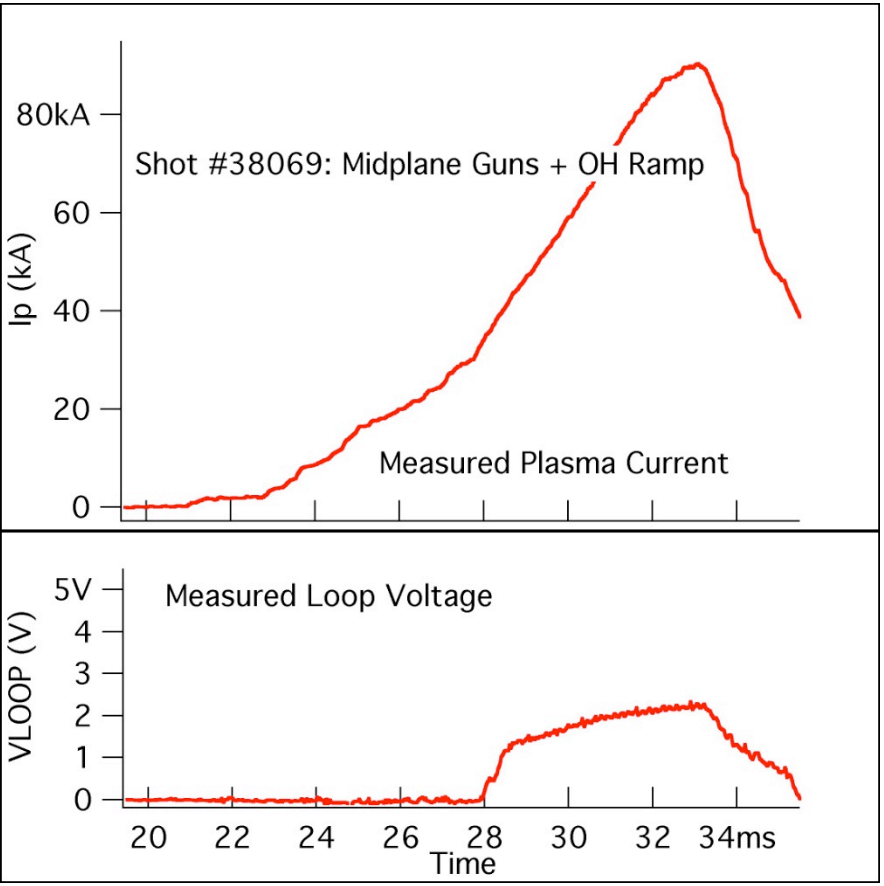
A.J. Redd, D.J. Battaglia, ICC Conference 2008

Midplane-Driven Plasmas Couple More Easily to Induction From the Central Solenoid

Divertor Guns



Midplane Guns



- Both discharges had guns, outer-PF ramps, and applied OH drive
- The midplane-driven discharge required less Ohmic flux to reach 90kA

A.J. Redd, D.J. Battaglia, ICC Conference 2008

FY09-13 Plans For Plasma Gun Startup

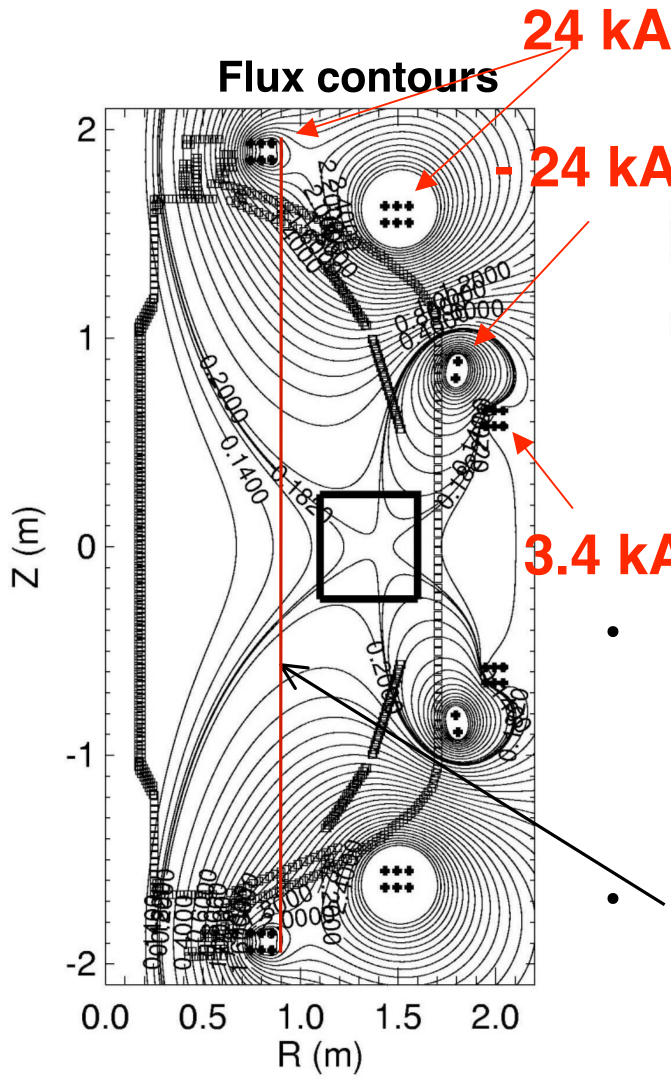
2009-10

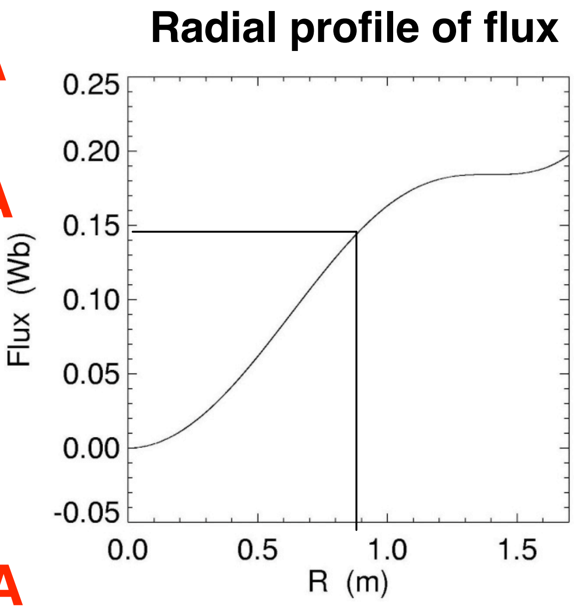
- **Conduct supporting experiments on PEGASUS to understand scaling to higher current**
- **Design the system for NSTX and identify hardware components and installation details**

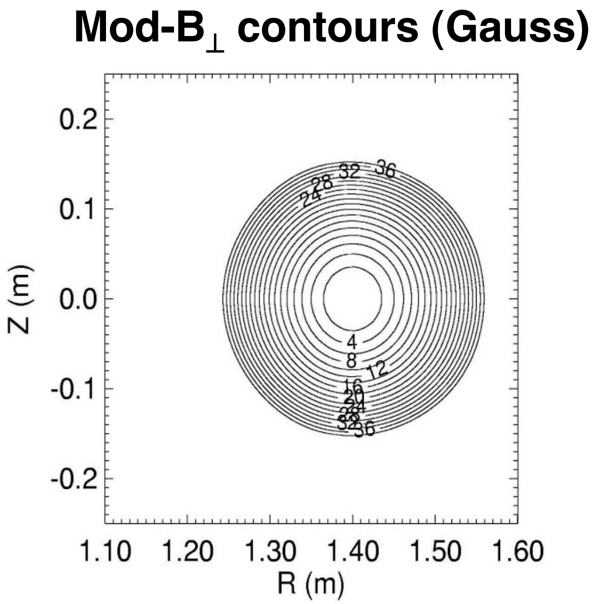
2011-2013

- **Installation on NSTX based on success of PEGASUS**
- **Support outer PF start-up experiments, by injecting plasma into the region of field null**
- **Low loop voltage startup using plasma guns**
- **Test of plasma startup using guns installed in the gap region between the primary and secondary passive plates**
- **Upgrade the system to higher current levels as progress warrants**

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







- ~0.15 Vs available in NSTX
  - 1MA achieved in NSTX with ~0.3 VS from solenoid, suggesting possibility of 500kA in NSTX
- Calculation at 0.5T, $\mathbf{E_T \cdot B_T / B_P}$ up by X 2 at 1T
  - 28GHz ECH at 1T puts resonance layer near field null, also good for Plasma Gun Startup

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

Plasma Startup Using Outer PF Coils

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
  - Got to 700kA with LHCD

DIII-D outer PF start-up experiment, few MW ECH, good tools to control fields.

Three approaches for outer PF start-up are explored:

 # I. Outer PF ramp from near zero flux and current. Use variety of non-inductive current drive for ramp-up assist (HHFW, NBI, BS, etc.)

 # 2. Approach based on the JT-60U experience. Strong heating & CD for initiation and ramp-up could relax the Lloyd condition

 # 3. Error field minimization to satisfy the "Lloyd condition" for plasma start up with strong preionization, $E_T \cdot B_T / B_P \geq 0.12$ kV/m achieved while retaining as much flux as possible for subsequent current ramp

- **Maintain field null for 2-3 ms in the presence of wall eddy current**
- **Without strong PI, Lloyd condition is 1 kV/m (very difficult to achieve)**
- **1 T (FY12) and 350kW ECH relaxes Lloyd condition startup requirements**