NSTX

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Solenoid-free Start-up and Ramp-up Progress and Plans for 2009-13

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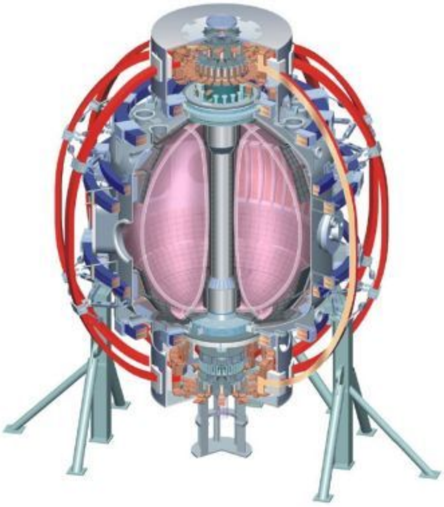
R. Raman and D. Mueller

For the NSTX Research Team

NSTX 5 Year Plan Review for 2009-13
Conference Room LSB-B318, PPPL
July 28-30, 2008



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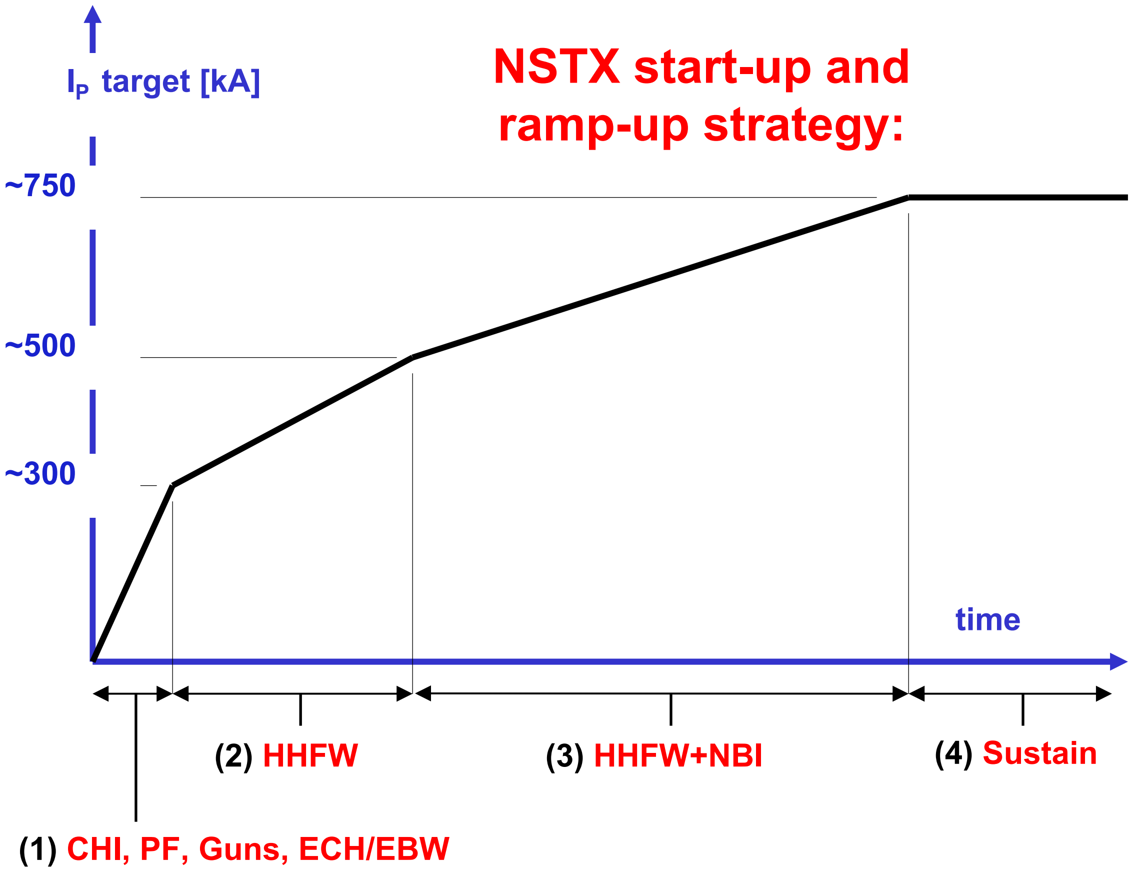
Motivation for Solenoid-free Plasma Startup

- The development of methods for 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 is engaged in solenoid-free plasma startup research
- NSTX has so far explored CHI and Outer PF startup for plasma current initiation
  - NSTX PAC has recommended additional start-up concept research in addition to CHI

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

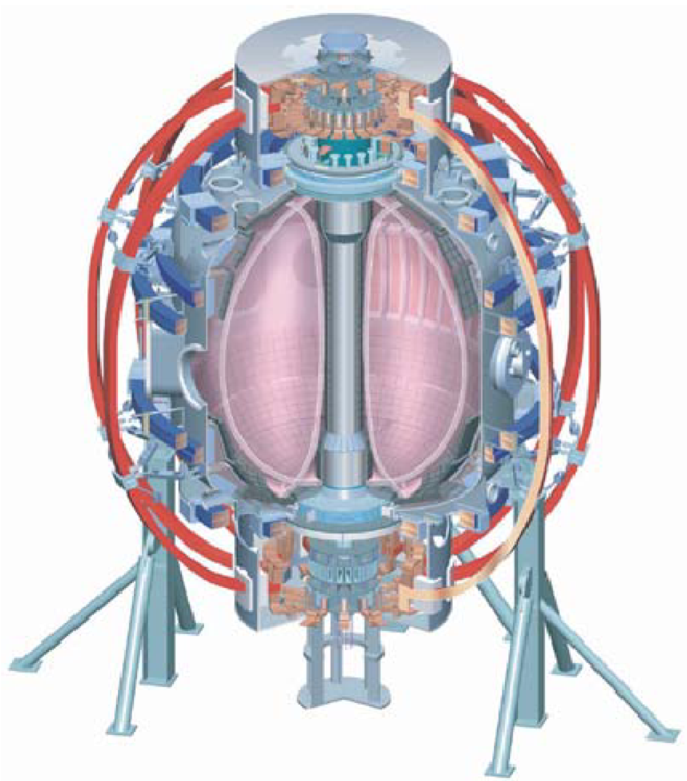
(2→3) Sufficiently high I_P needed to absorb NBI, high P_{HEAT}, τ_E, β_P needed for current overdrive

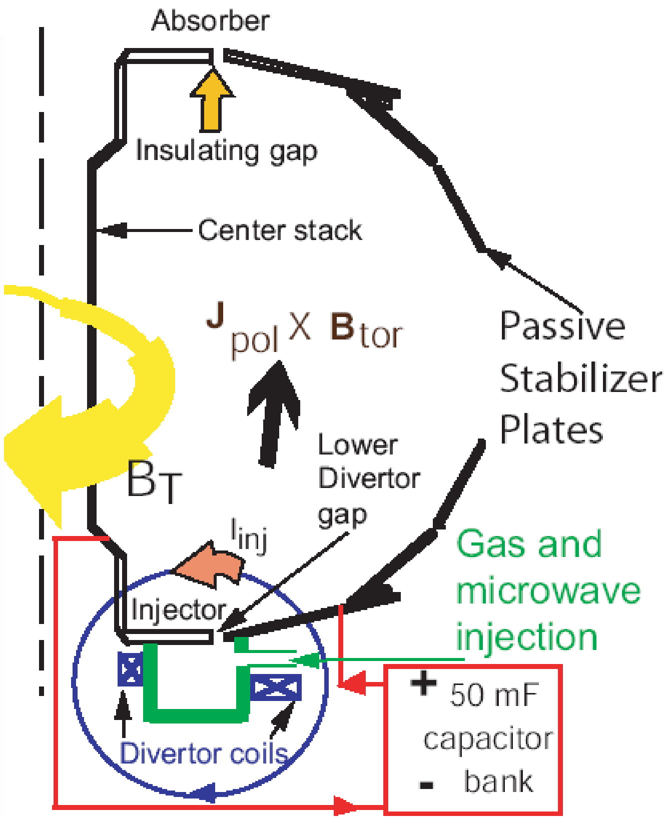
(3→4) Ramp-up plasma must be consistent with sustained high-f_{NI} scenario

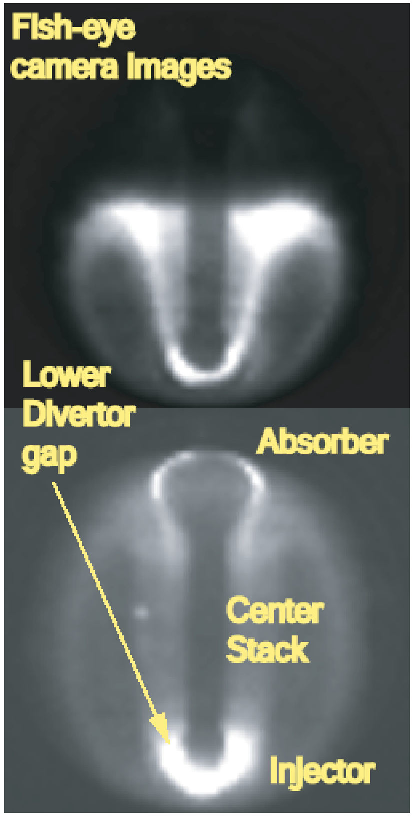
In ST-CTF/DEMO, iron core and possibly mineral insulated conductor transformer could provide portion of flux needed for I_P ramp-up

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

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



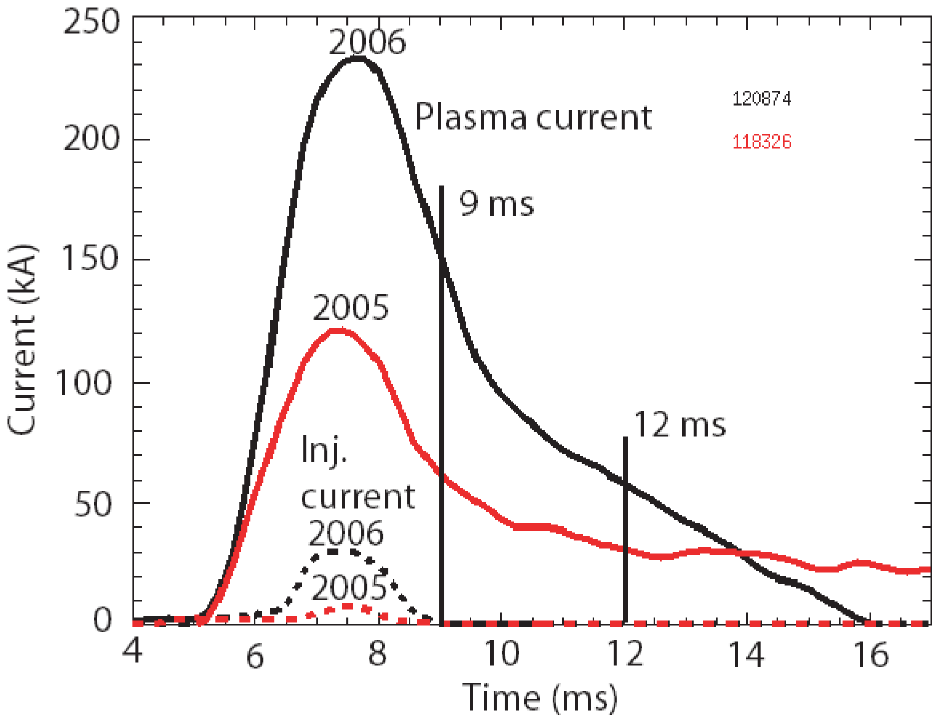


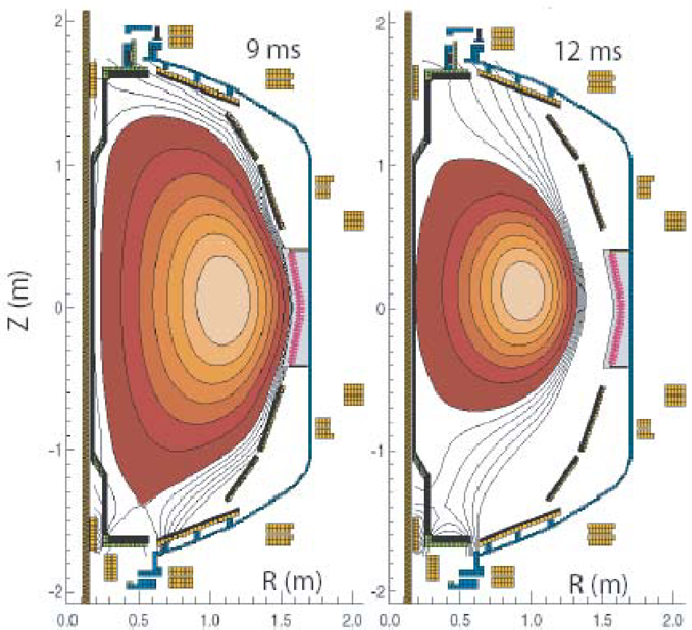


- Demonstration of closed flux current generation
  - Aided by gas and EC-Pi injection from below divertor plate region
- Demonstration of coupling to induction (2008)
  - Aided by staged capacitor bank capability

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 (~60) aided by higher Toroidal Field: $I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})$



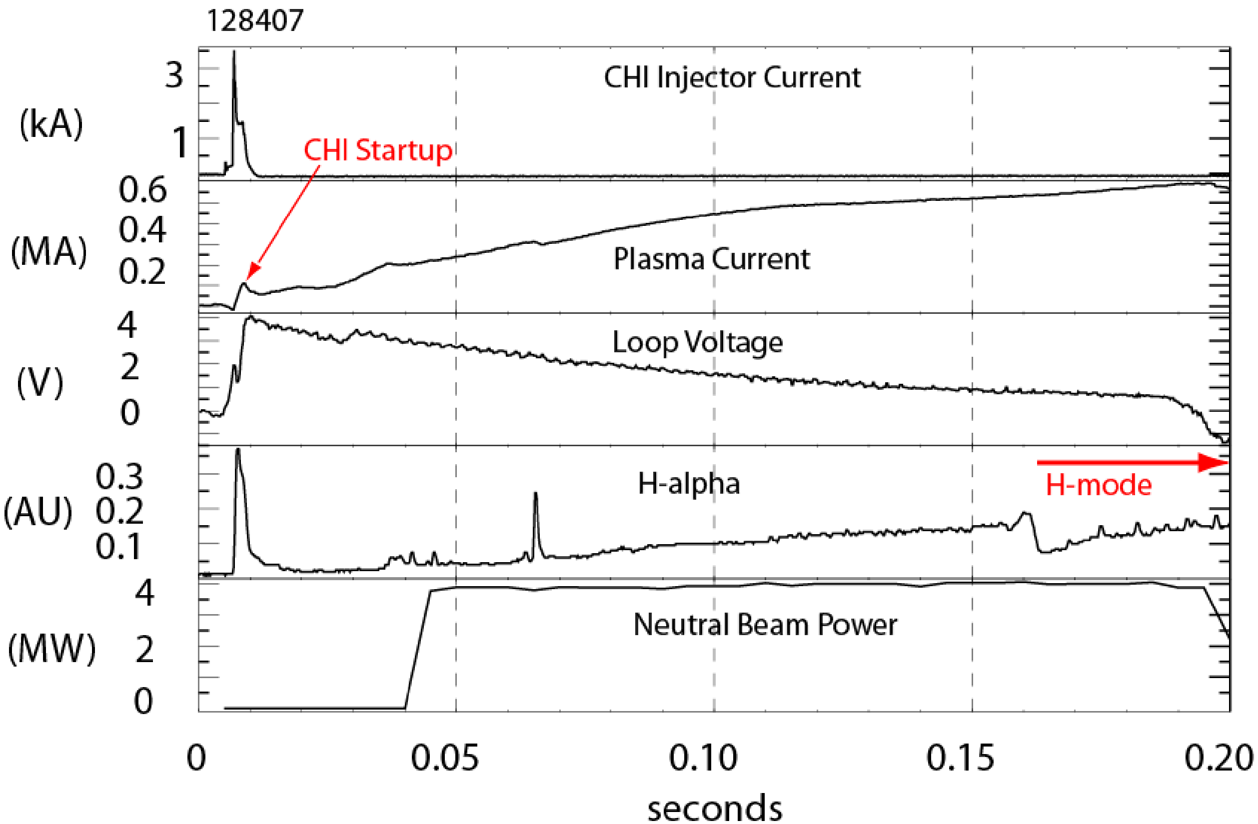


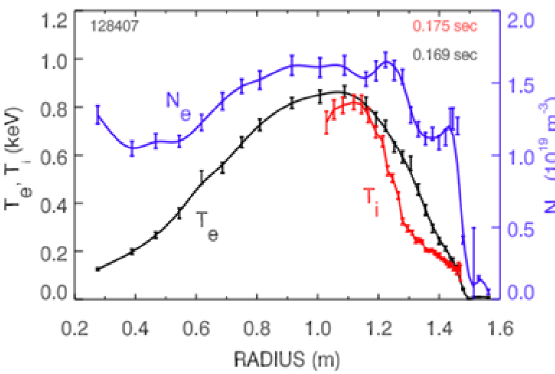
- 2006 discharges operated at higher toroidal field and injector flux
  - Record 160kA non-inductively generated closed flux current in ST or Tokamak produced in NSTX
- Used LRDFIT reconstructions to account for large vessel eddy currents

LRDFIT (J. Menard)

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

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





Te & Ne from Thomson

Ti from CHERS

- Central Te reaches 800eV
- Central Ti > 700eV

Note the broad density profile during H-mode phase

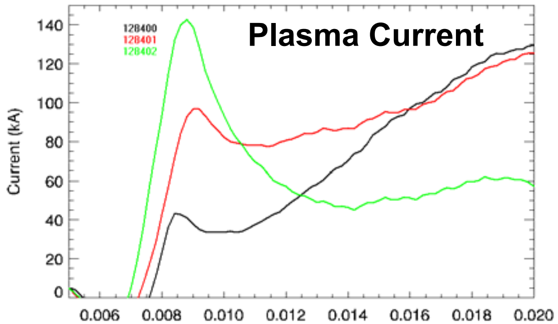
CHERS: R. Bell

Thomson: B. LeBlanc

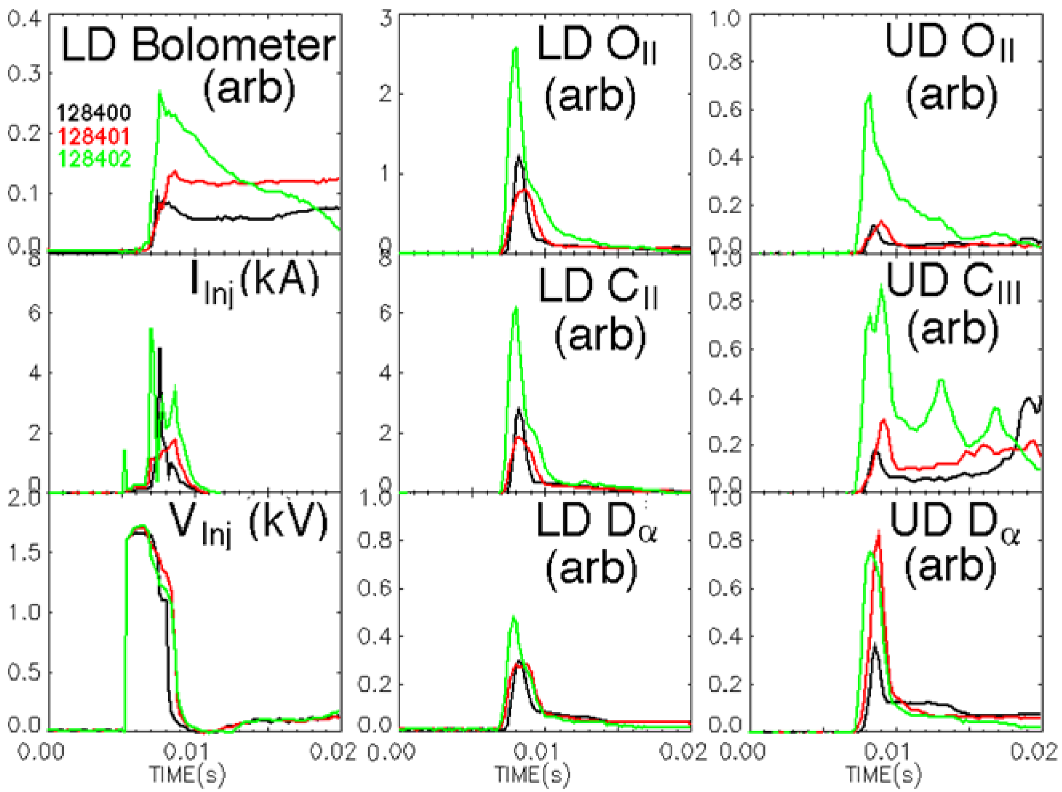
- Discharge is under full plasma equilibrium position control
  - Loop voltage is preprogrammed
- Projected plasma current for CTF >2.5 MA $[I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})]$*
  - Based on 50 kA injected current (Injector current densities achieved on HIT-II)
  - Current multiplication of 50 (achieved in NSTX)

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

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



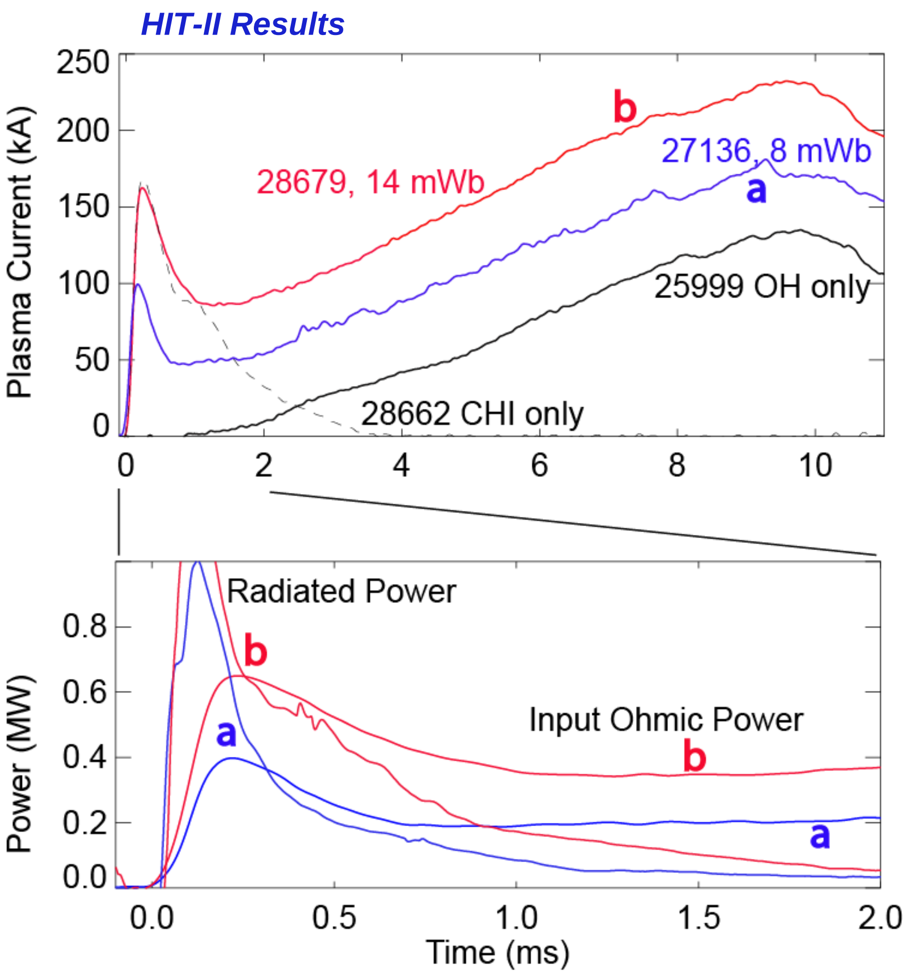
128400: 5mF (7.6kJ)
128401: 10mF (15.3kJ)
129402: 15mF (22.8kJ)



- Low-z impurity radiation increases with more capacitors
  - High Te in spheromaks (500eV) obtained with metal electrodes
  - Test with partial metal outer divertor plates during FY09
  - Reverse TF polarity to make outer vessel cathode
- Upper divertor radiation also increases with more capacitors
  - Need to reduce absorber arcs
  - Absorber field nulling coils to be used during FY09
- Assess benefits of partial metal plates + Absorber coils
  - Discharge clean divertor with high current DC power supply
  - Use 350kW ECH during FY11

D. Mueller et al., EPS 2008

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

FY09-13 Plans for CHI

2009

- Test heated metal outer divertor plate as cathode (reverse TF)
- Use the CHI Absorber coils to reduce the intensity of absorber arcs
- Test use of liquid Li for performance improvement

2010

- Consider 2kV capability to increase the magnitude of the CHI started currents
- Test edge current drive

2011

- Use 10ms, 350kW ECH to heat CHI plasma for coupling to HHFW
- Consider full metal divertor plates to improve CHI current startup capability
- Test relaxation current drive.

2012

- Operate at 1T to maximize CHI startup currents
- Maximize startup currents using synergism with outer PF coil startup

2013

- 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.

Plasma start-up using biased Plasma Guns

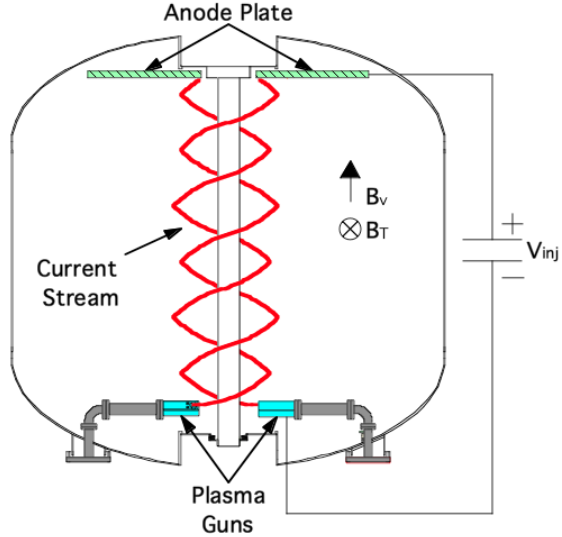
- DC helicity injection rate is given by:

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

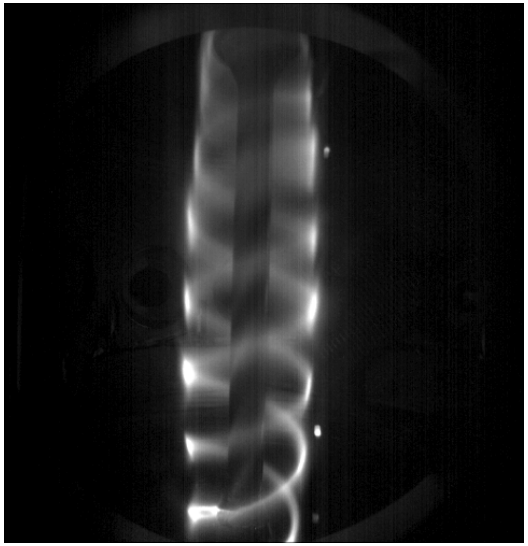
- The helical filaments can relax and form a tokamak if:
  1. Plasma-generated B_p greater than vacuum B_v
  2. Radial force balance is satisfied
  3. Sufficient input power

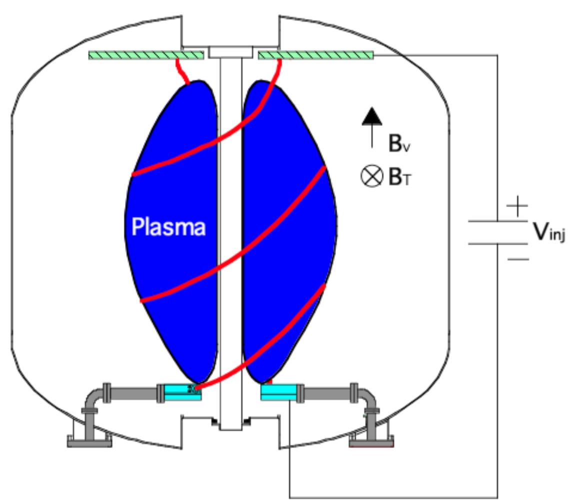
- Relaxed-plasma I_p is 10-15 times greater than I_{bias} multiplied by vacuum field windup (total multiplication up to 50)

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



Filaments





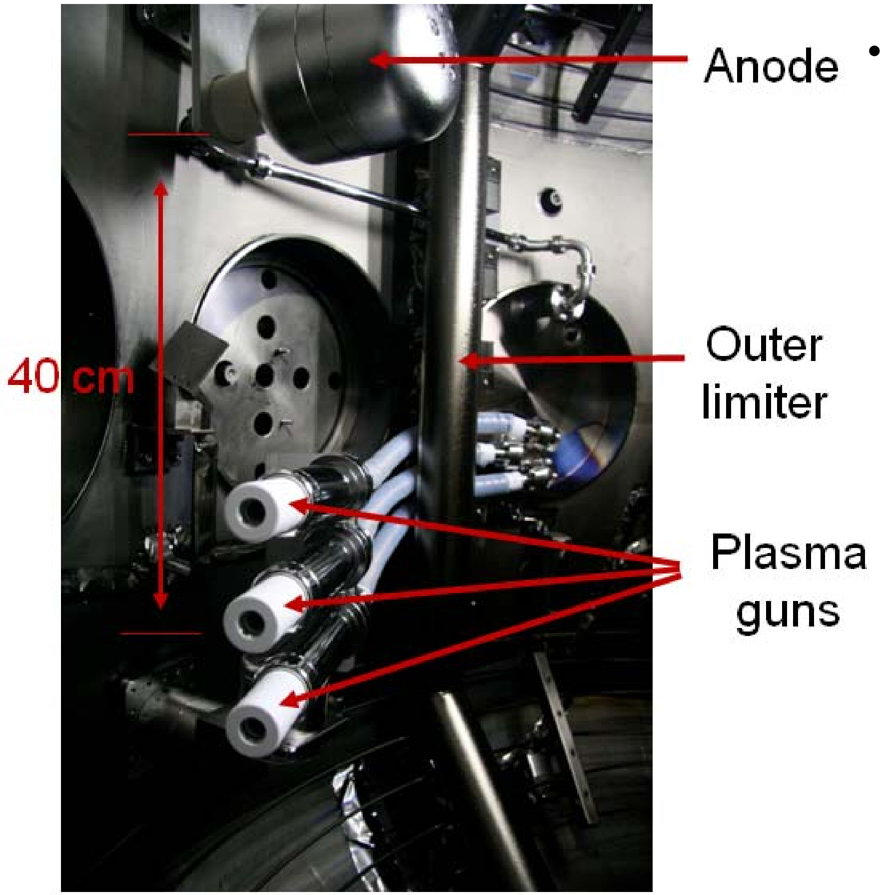
Relaxed State

PEGASUS ST

A.J. Redd, ICC Conference 2008

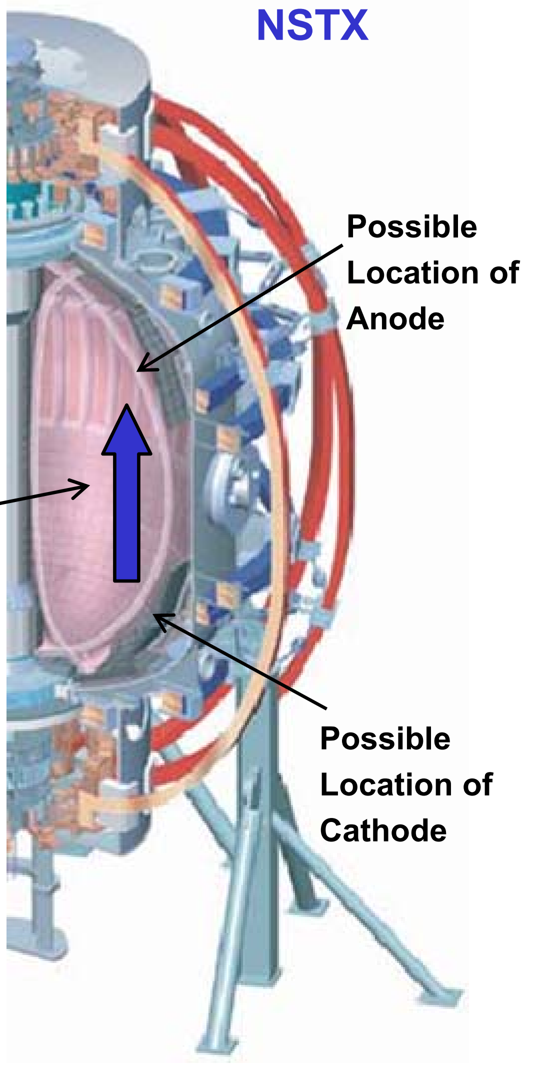
New larger surface area guns mounted on the outboard side being tested on Pegasus

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

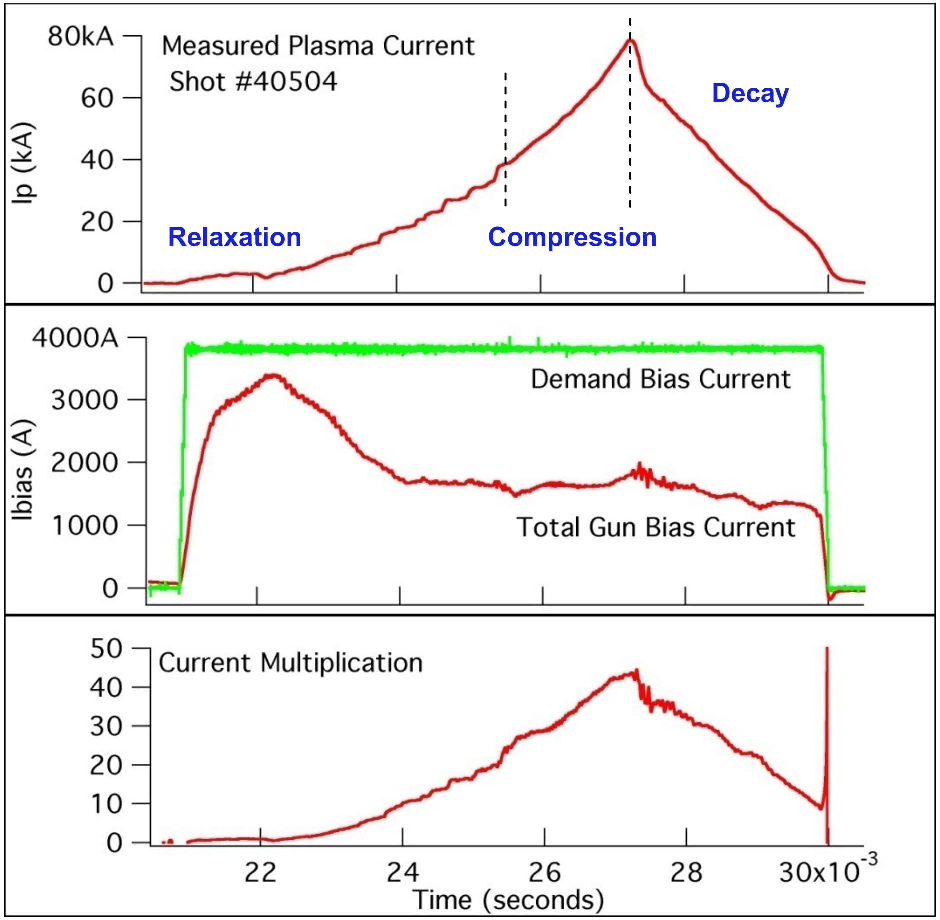


D.J. Battaglia, ICC Conference 2008

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

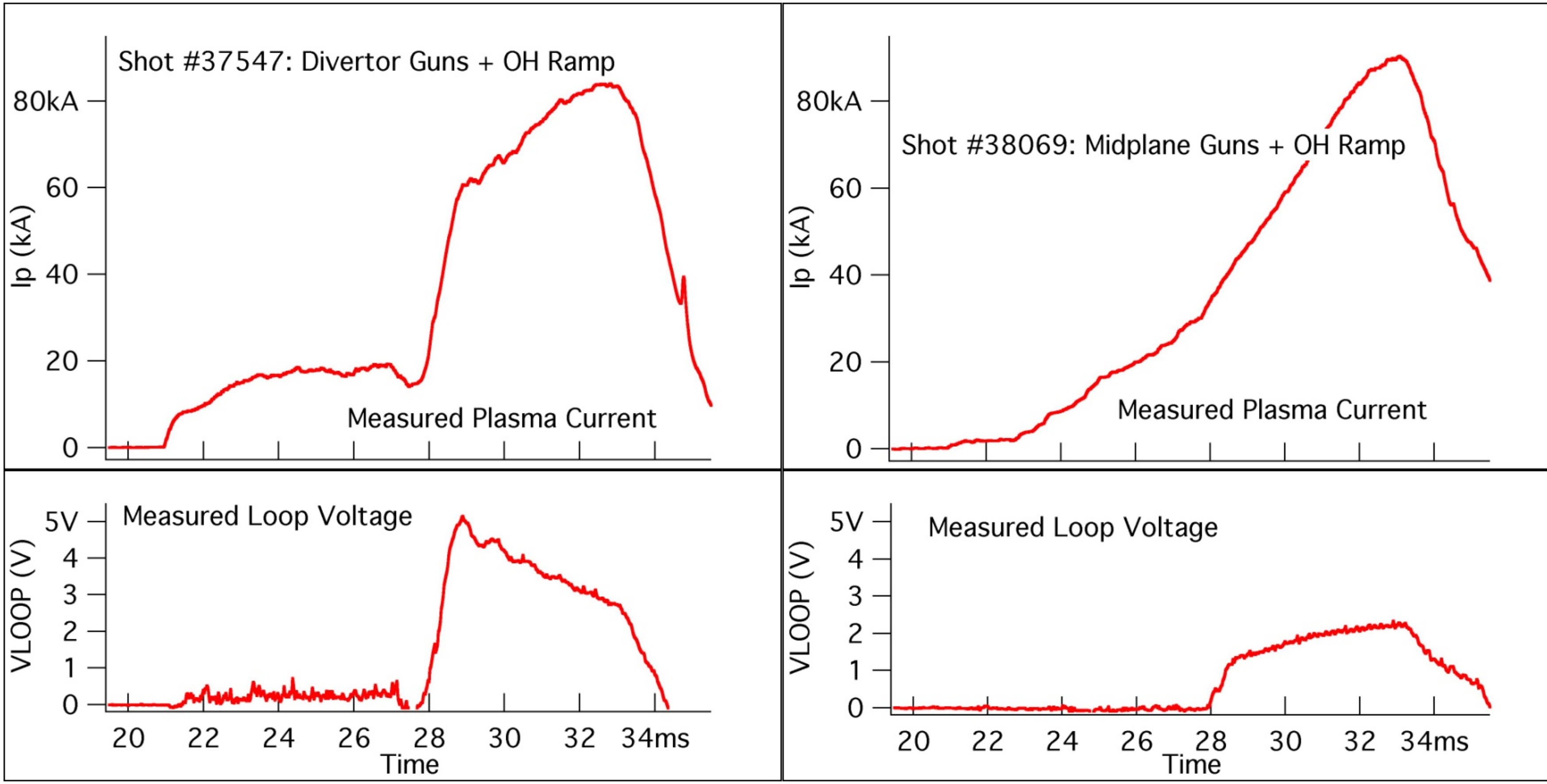
Results from mid-plane Guns (PEGASUS)



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

FY08-13 Plans For Plasma Gun Startup

2008-09

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

2010

- Installation on NSTX and commissioning tests
- Support outer PF start-up experiments, by injecting plasma into the region of field null
- Low loop voltage startup using plasma guns

2011

- Test of plasma startup using guns installed in the gap region between the primary and secondary passive plates

2012-2013

- Based on 2011 results, upgrade the system to higher current levels

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

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

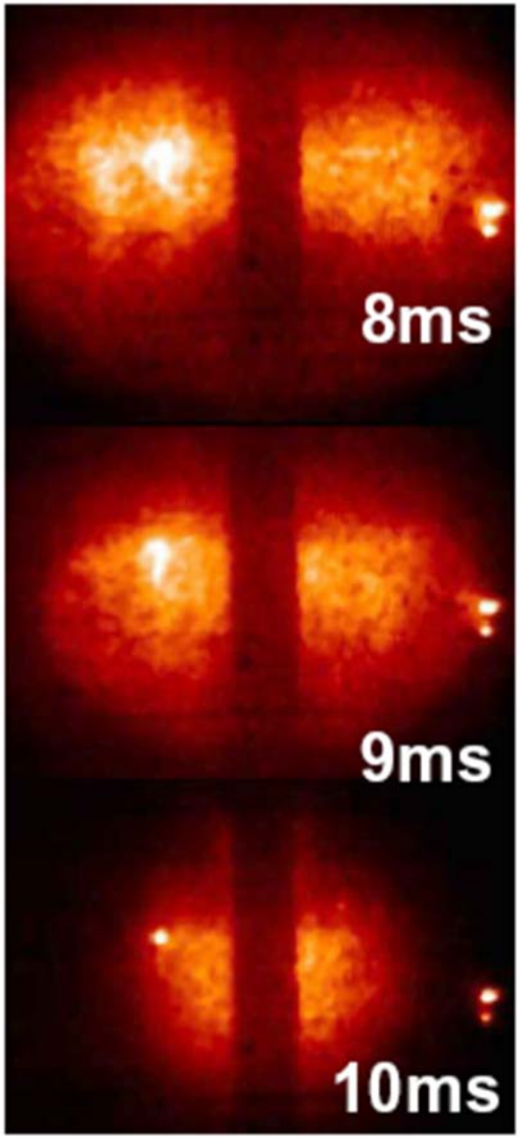
 # 3. Error field minimization to satisfy the "Lloyd condition" for plasma start up with strong preionization, $E_T \cdot B_T / B_P \geq 0.12$ kV/m achieved while retaining as much flux as possible for subsequent current ramp

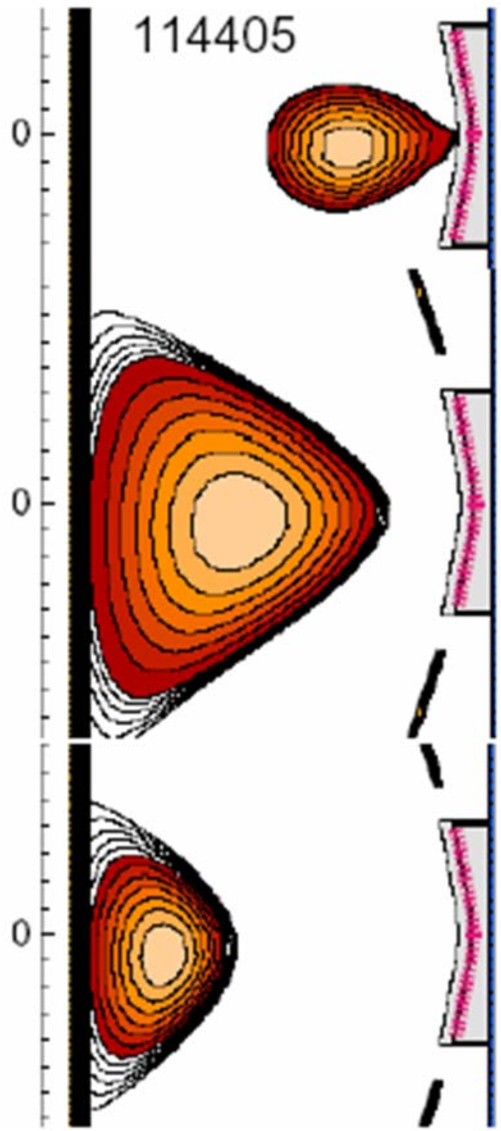
- Maintain field null for 2-3 ms in the presence of wall eddy current

- Without strong PI, Lloyd condition is 1 kV/m (very difficult to achieve)

- 1 T (FY12) and 350kW ECH relaxes Lloyd condition startup requirements

#1 Outer PF Ramp From Near Zero Current/Flux

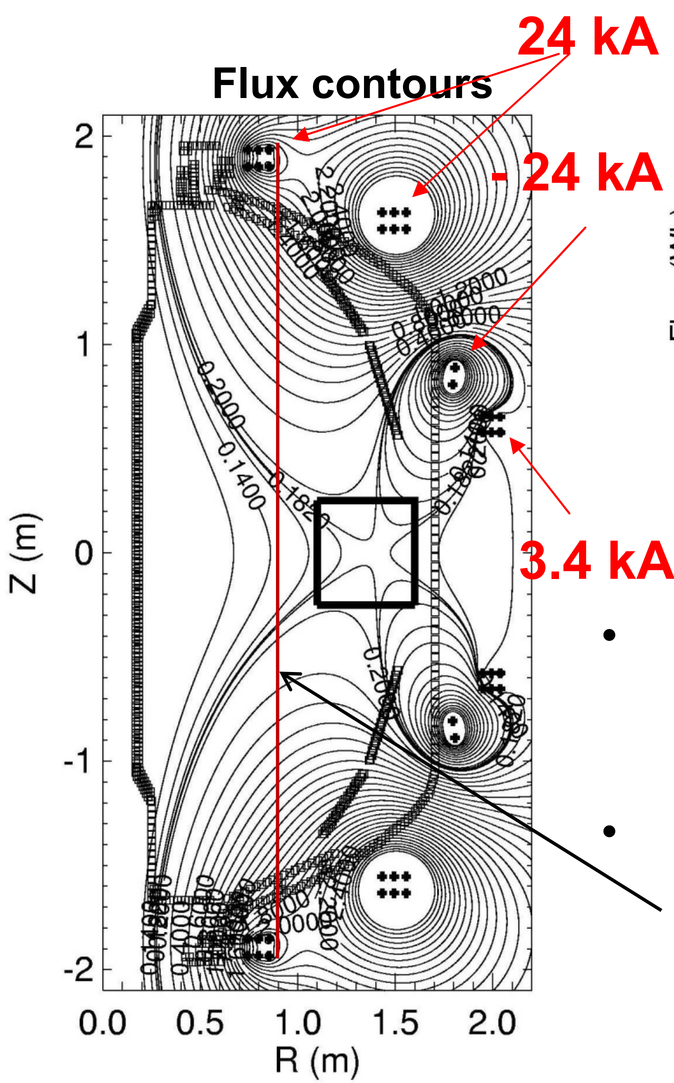


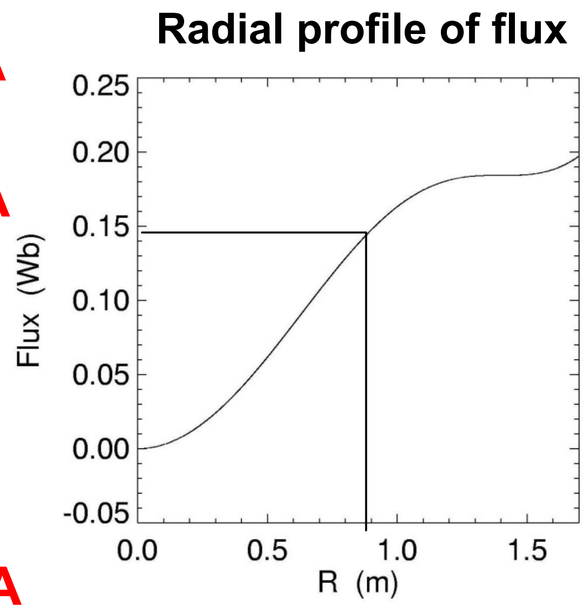


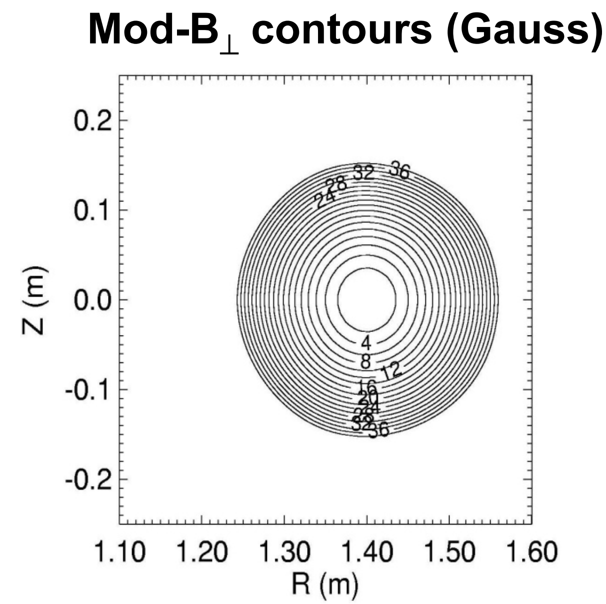
- LRDFIT code used for reconstructions
  - I_{vessel} ~ 10 x **Ip**
- Careful control of B_Z after breakdown helped raise I_p from 10kA to 20kA
  - More B_z evolution optimization possible
  - This satisfied $E_T.B_T/B_P$ ~1kV/m over good fraction of vacuum cross section
- Improved preionization and PF coil waveforms to be optimized
  - 350kW ECH resonance layer in large field null region
  - Plasma Guns should inject plasma in to field null region
  - Need Te control to get to high-enough I_P to meet PF coil programming

J. Menard

#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

FY09-13 Plans for Outer PF Startup and Low Loop Voltage Startup

2009

- Test pre-ionization capability of CHI
- Initial breakdown and current initiation studies using the existing uni-polar supply for PF 5
- If successful breakdown confirmed, implement needed hardware changes including the bi-polar capability of PF5
- Test low loop voltage startup using CS

2010

- Test pre-ionization capability of the washer gun plasma sources with some assist from CS

2011

- Use 350kW ECH for pre-ionization, and use higher power HHFW to test high current capability of outer PF startup (Ip ~ 300 - 500 kA)
- Use 350kW ECH to improve low loop voltage startup

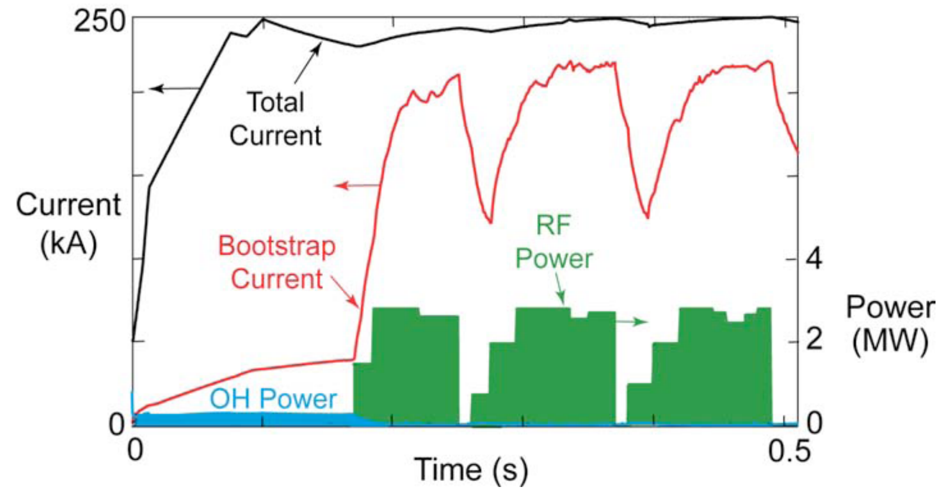
2012-13

- Using a combination of CHI start-up or Plasma Gun, ECH and outer PF start at higher B_T to ramp-up to a high beta target

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



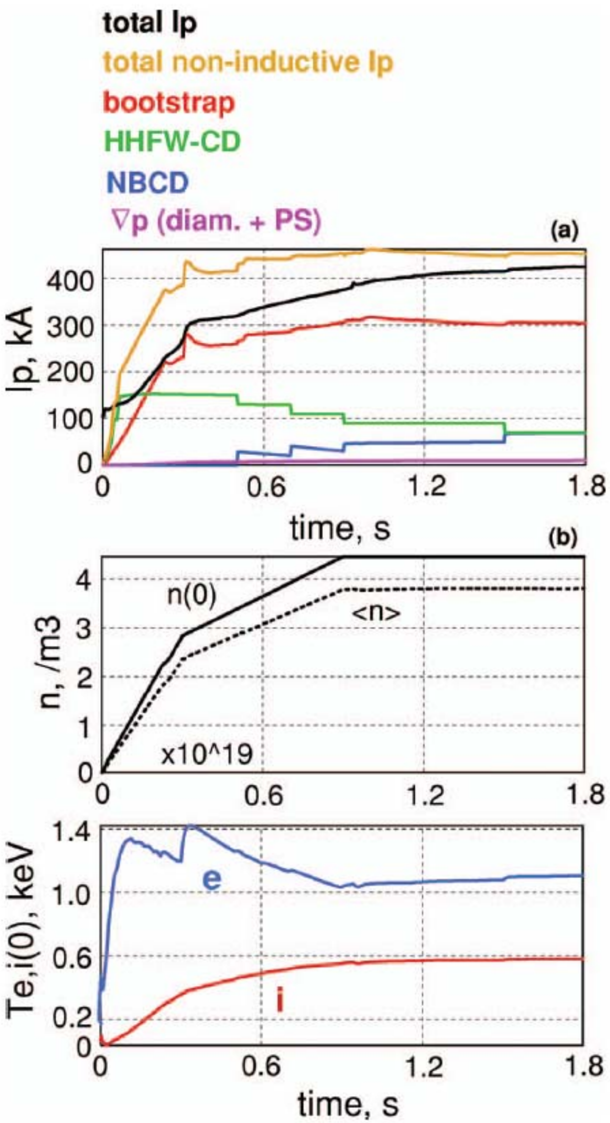
2006

- 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

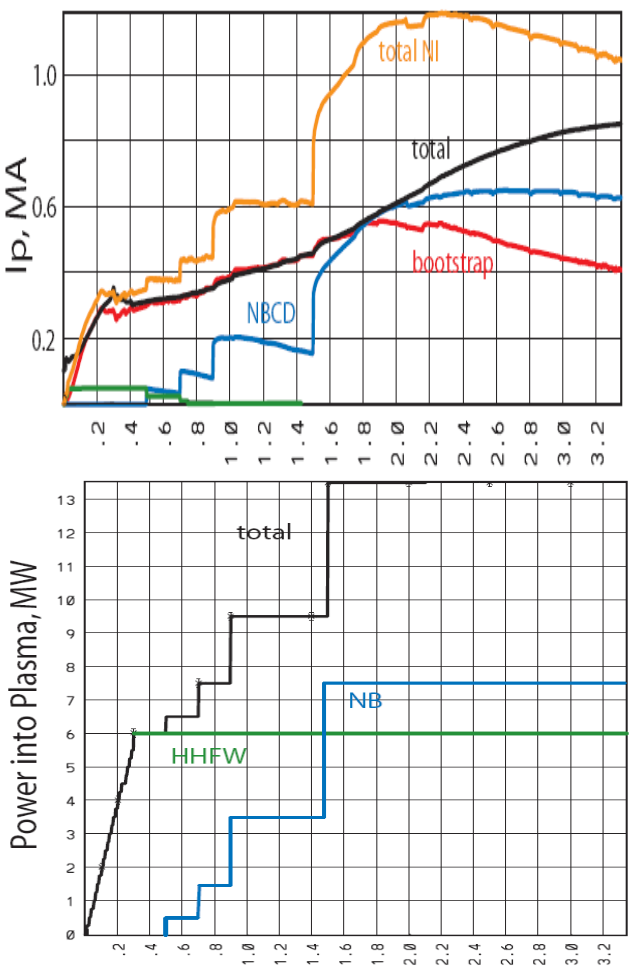
With 6MW HHFW Power, Current Ramp-up to ~400kA is Simulated to be Achievable in NSTX



- 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

With 1T and 6MW HHFW + 7MW NBI Power, Current Ramp up to 800-900kA is Simulated to 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

FY09-18 Plans for Non-Solenoidal Ramp up and Sustainment

2009-10

- 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

2012

- 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.

2013

- Try more tangential NBI *(incremental)* 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 Leading the Effort to Develop Startup 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
  - Will test CHI performance implications of metal electrodes (from LLD), higher TF (1T), modest increases to cap bank voltage, and absorber arc control
- Plasma Gun startup to be tested in NSTX
  - Startup and inductive coupling at 60kA demonstrated on Pegasus
  - Physics and scaling is being studied on Pegasus ST
- Outer PF startup will be tested using new tools for pre-ionization
  - CHI, Gun Plasma, 350kW ECH + higher power HHFW
- Low Loop Voltage startup will be tested in conjunction with Outer PF startup and Plasma Gun startup
- Non-inductive current ramp-up experiments would significantly benefit from higher TF (~1T), longer pulse length (5s) and higher power HHFW
  - 1T CS upgrade and 2nd tangential NBI particularly important for high-current ramp-up demonstration
  - Startup currents of ~500kA relax requirements on subsequent ramp-up

Solenoid-free Start-up and Ramp-up Timeline FY08-13

FY07 | 08 | 09 | 10 | 11 | 12 | 13

CHI
- Test metal electrode operation Reduce absorber arcs, Use Liquid Li
- Test Edge CD
- Heat CHI target using ECH, then with HHFW. Test Relaxation CD
- Increase current using 1T. Test synergism with Outer PF
- Full integration with HHFW, NBI and outer PF startup

Plasma Guns
- Supporting experiments on Pegasus. Design system for NSTX
- Commission Plasma Guns
- Test Plasma Gun Startup
- Increase generated current using 1T TF. Test synergism with outer PF startup. Integrate with HHFW & NBI.

Outer PF
- Use CHI PI
- Plasma Gun PI
- Use ECH PI
- Use Low Loop Voltage with Outer PF and Plasma Guns
- Use 1T + ECH to adequately satisfy Lloyd parameter

Ramp-up
- Ramp from 250kA to 400-500kA with HHFW (FY10 milestone)
- Sustain Ip at 500kA
- Use 1T to achieve bootstrap overdrive
- Use 2nd NBI + 1T for Current Ramp-up demonstration

Tools
- Supports CHI, Plasma Guns, Outer PF Start-up and Ramp-up
- 10ms 350kW ECH
- 1 Tesla operation

CHI
- Absorber Field Nulling Coils, Heated Outer Metal divertor Plate Reversed TF, Liquid Li
- Consider 2kV

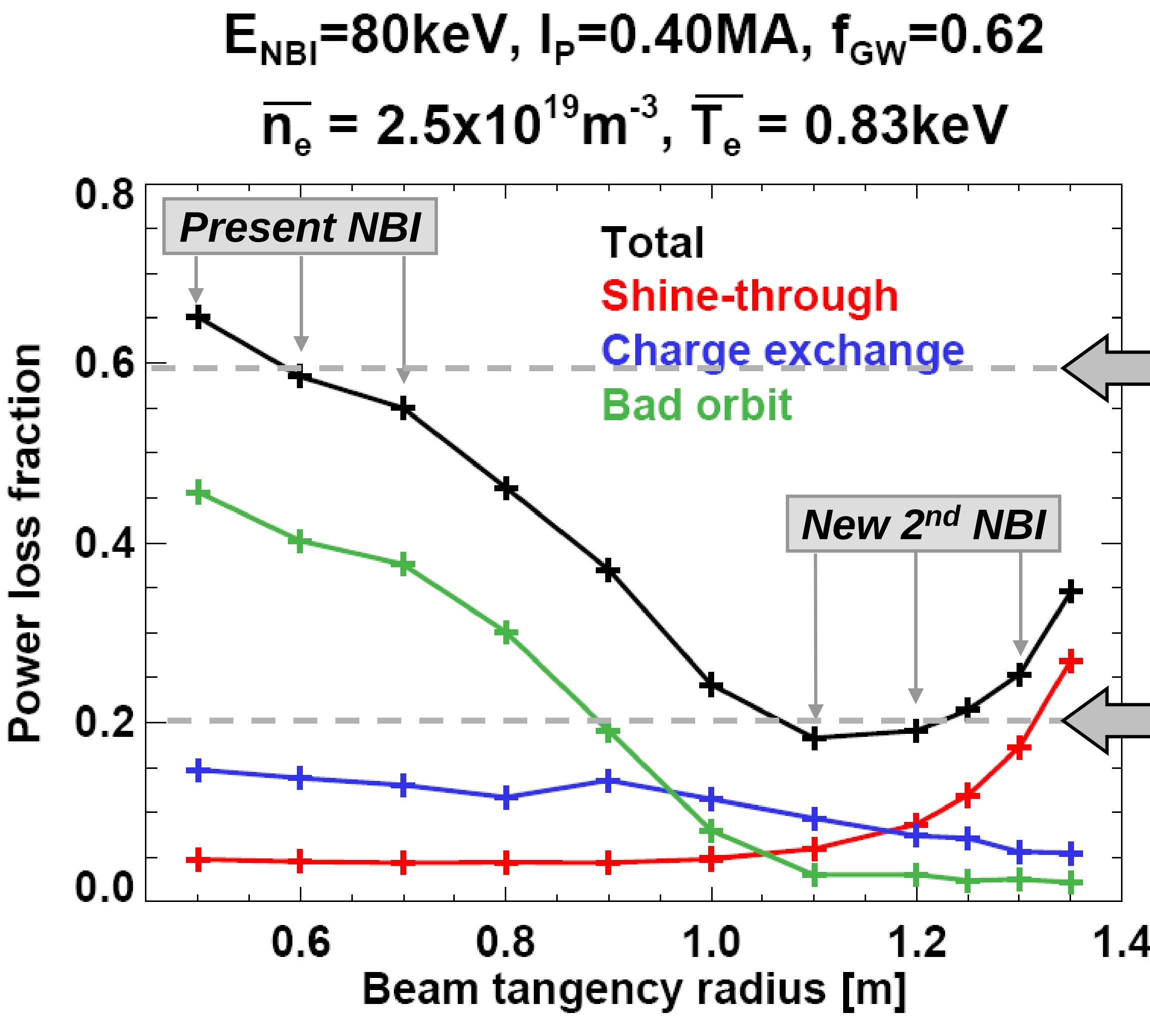
Plasma Guns
- Install Plasma Guns
- Upgrade Plasma Guns

Outer PF
- CHI PI
- Plasma Gun PI
- ECH Pi

Ramp-up
- Higher Power HHFW
- 2nd Tangential NBI *(Incremental)*

Backup

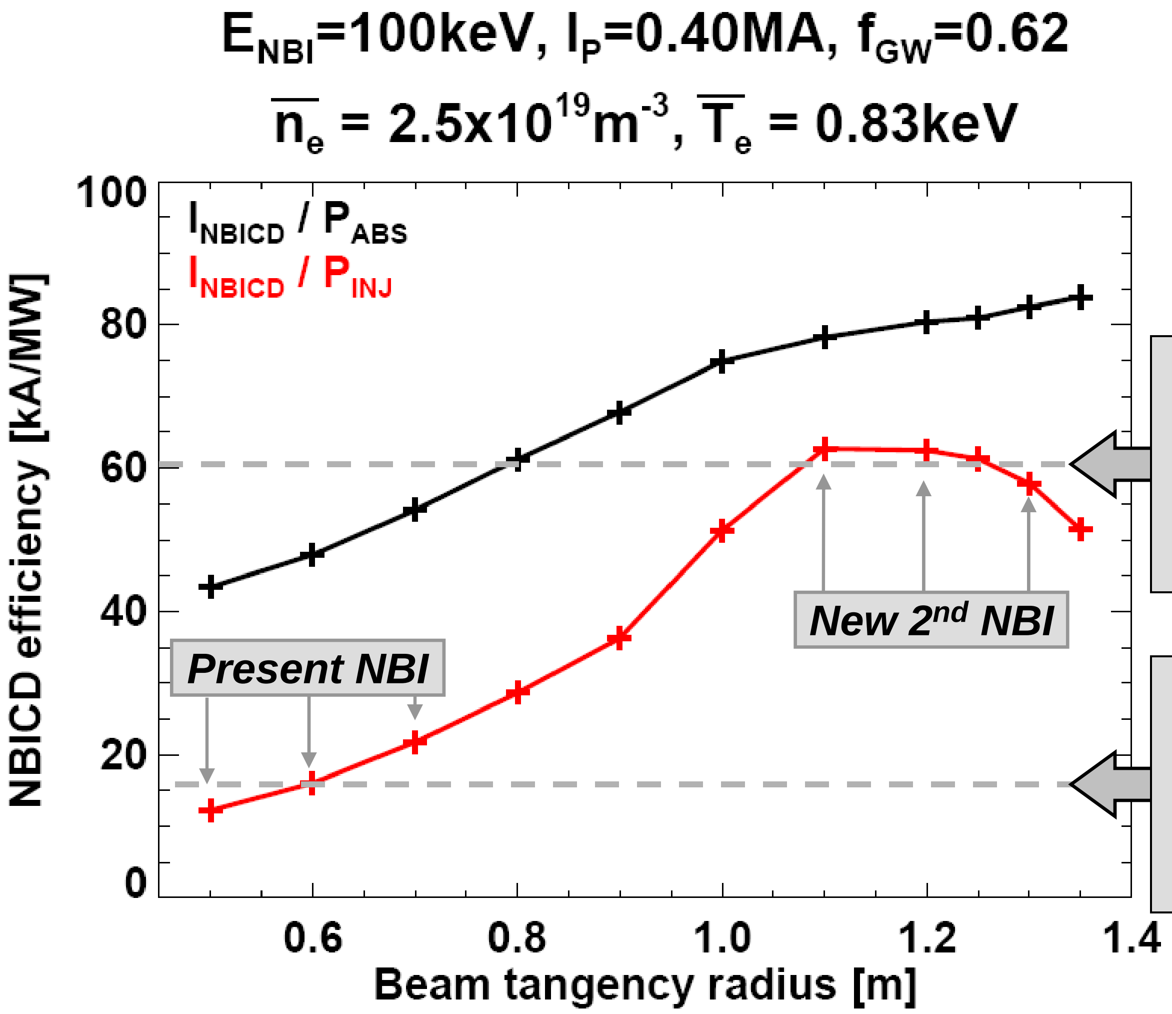
More tangential 2nd NBI has 3× lower power loss than present NBI at low I_P = 400kA



- 60% of power of present NBI lost
  - Absorb 2 of 5 MW (80kV)
- 20% of power of new 2nd NBI lost
  - Absorb 4 of 5 MW (80kV)

→ *2nd NBI can efficiently heat 400kA HHFW-driven ramp-up plasma*

More tangential 2nd NBI has 4× higher NBI current-drive than present NBI at low I_P = 400kA



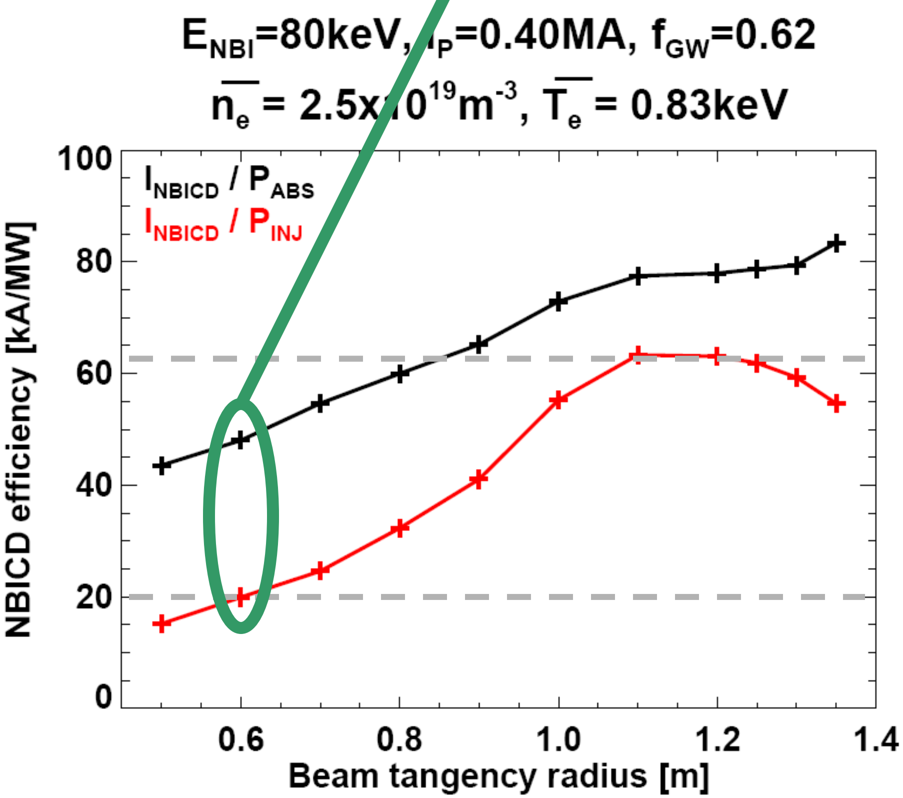
- 2nd NBI → 60kA/MW current drive efficiency
  - 450kA CD for 7.5MW injected at E=100keV
- Present → 15kA/MW current drive efficiency
  - 110kA CD for 7.5MW injected at E=100keV

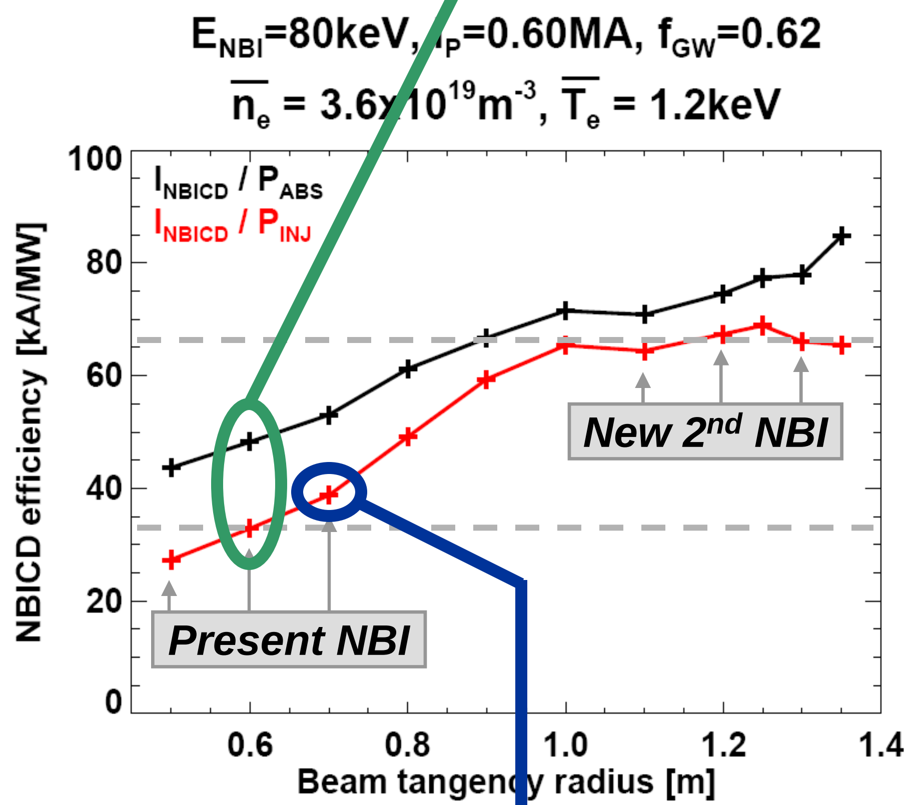
→ *2nd NBI can provide sufficient current for ramp-up to ~800kA*

Absorbed fraction and CD of present NBI increases by factor of 1.7 for plasma current = 400kA→600kA

- I_P = 400kA, present NBI:
  - 60% loss, 20kA/MW

- I_P = 600kA, present NBI:
  - 32% loss, 33kA/MW





Most tangential of present sources has > 70% absorption for $I_P \geq$ 600kA and would be the most effective of the present sources for ramp-up