NSTX

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Draft Solenoid-free Start-up and Ramp-up Progress and Plans for 2014-18

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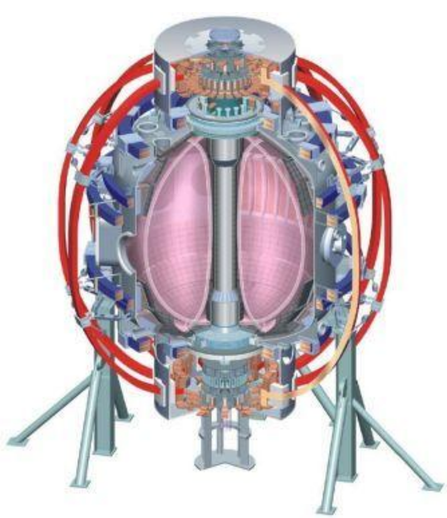
R. Raman, D. Mueller, S.C. Jardin

For the NSTX Research Team

September 1, 2011



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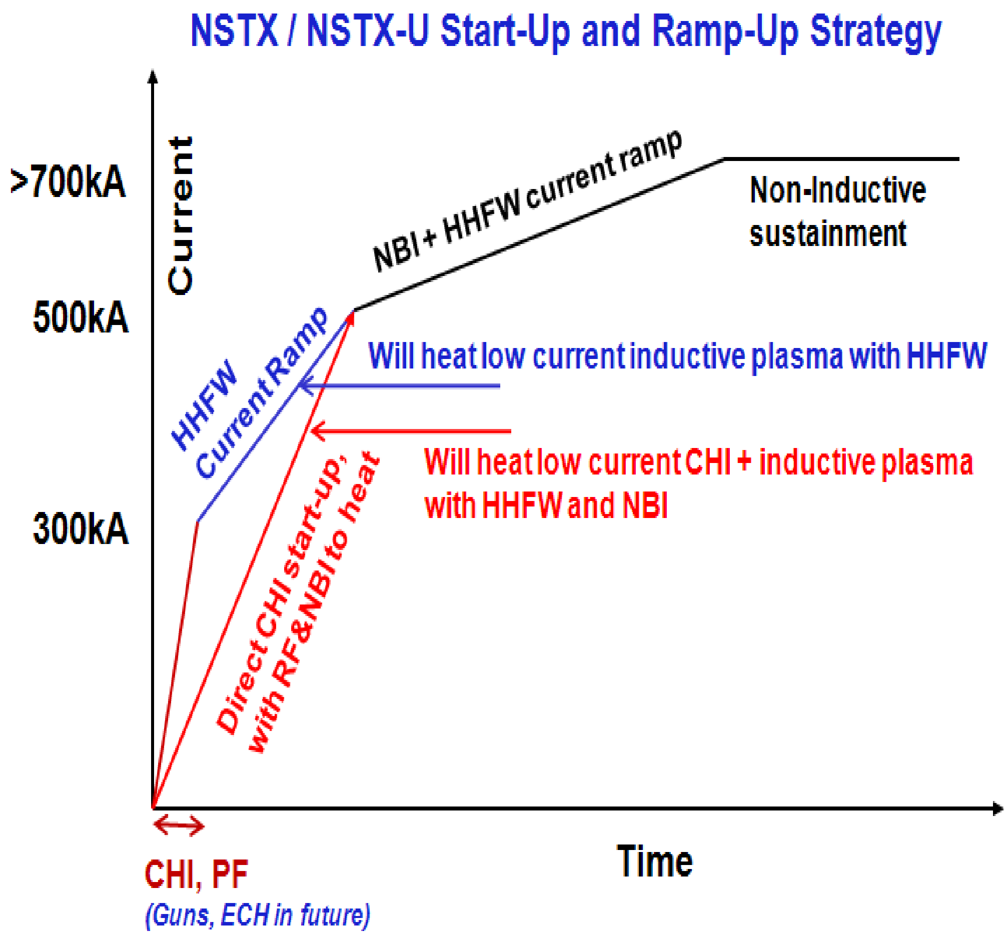
U Quebec

Motivation for Solenoid-free Plasma Startup

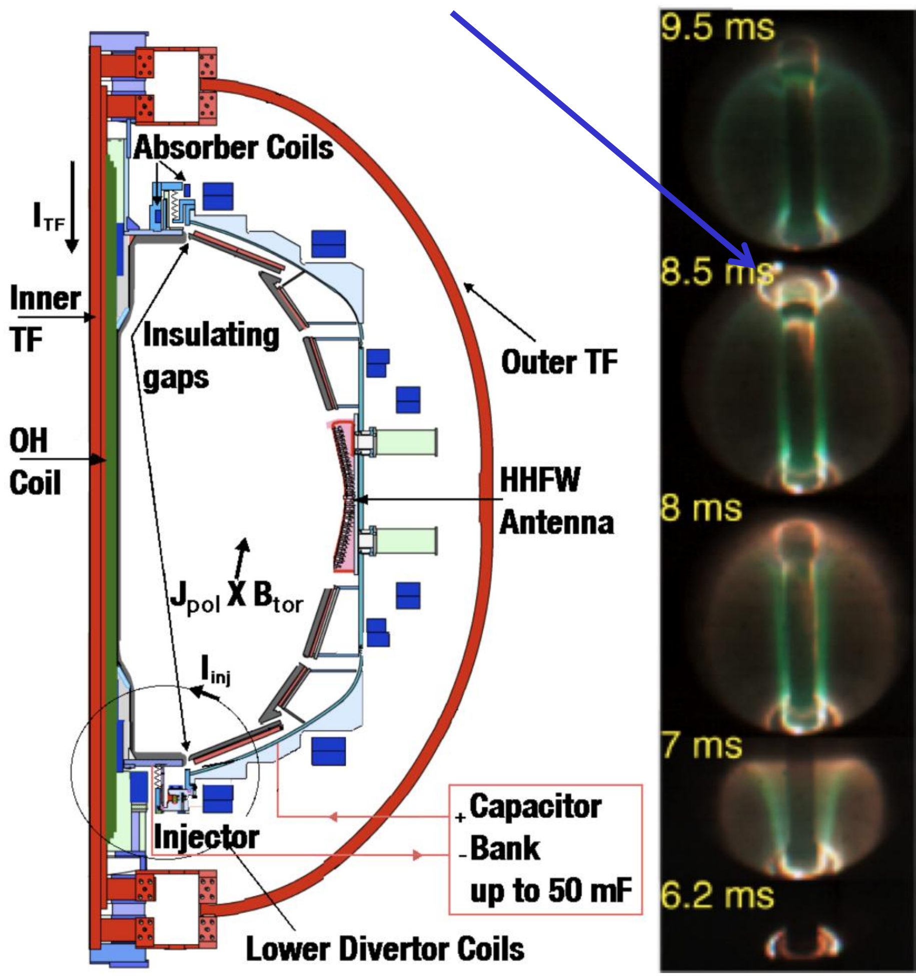
- The development of methods for solenoid-free current initiation would improve the prospects of the ST as a CTF and fusion reactor
- Could aid ARIES-AT design
- Of the three large machines in the US (DIII-D, NSTX, C-MOD) only NSTX has a dedicated solenoid-free plasma startup research program
- NSTX 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

<u>Goal</u>: Non-inductive Start-up and Sustainment Demonstration in NSTX-U

CHI Generates Closed Flux Equilibrium by Driving Current on Poloidal Flux that Connects Inner Divertor Plates



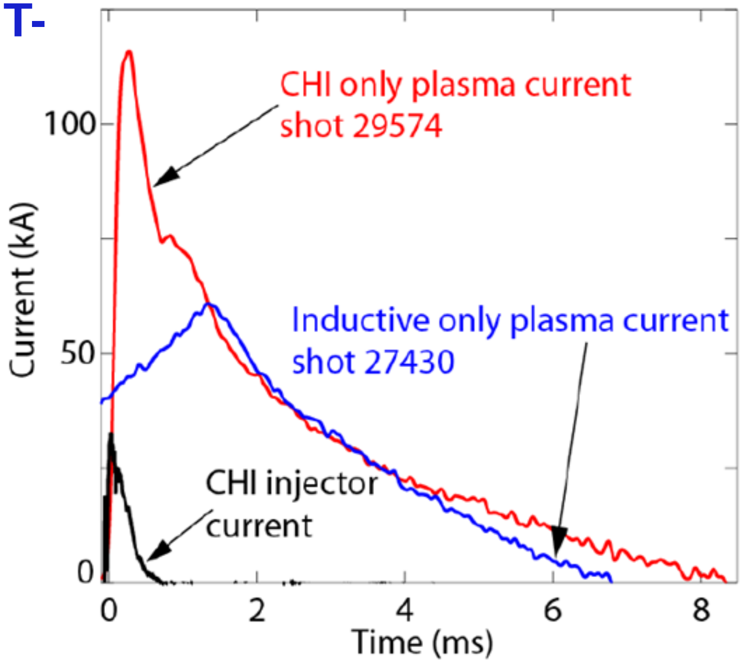
•Absorber Arc



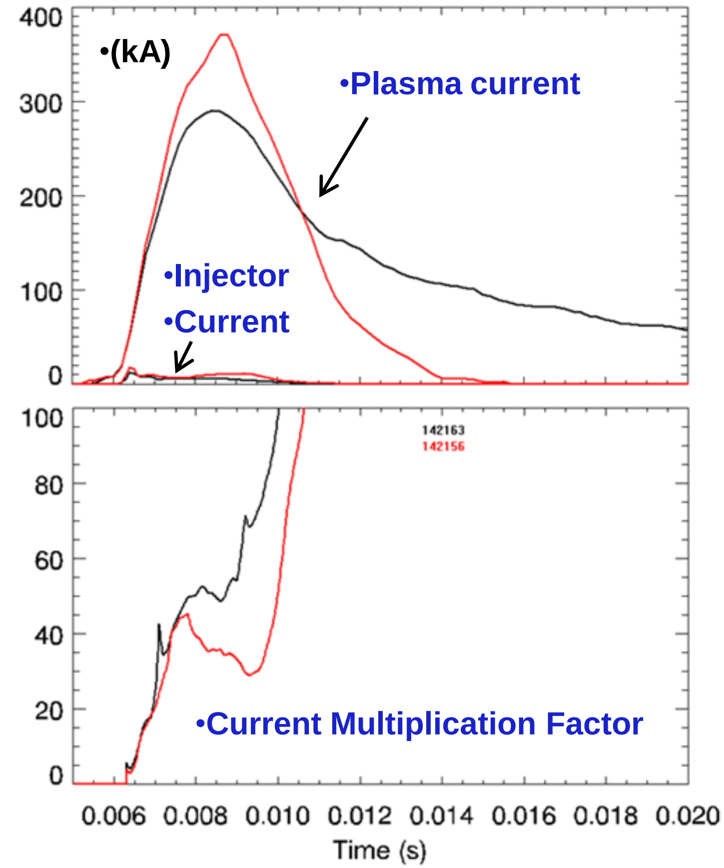
Direct CHI ramp-up to 500kA projected to be possible at 1T in NSTX-U

Very High Current Multiplication (Over 70 in NSTX) Aided by Higher Toroidal Flux

•HIT-II



•NSTX



-30kA of injector current generates 120kA of plasma current

-Best current multiplication factor is 6-7

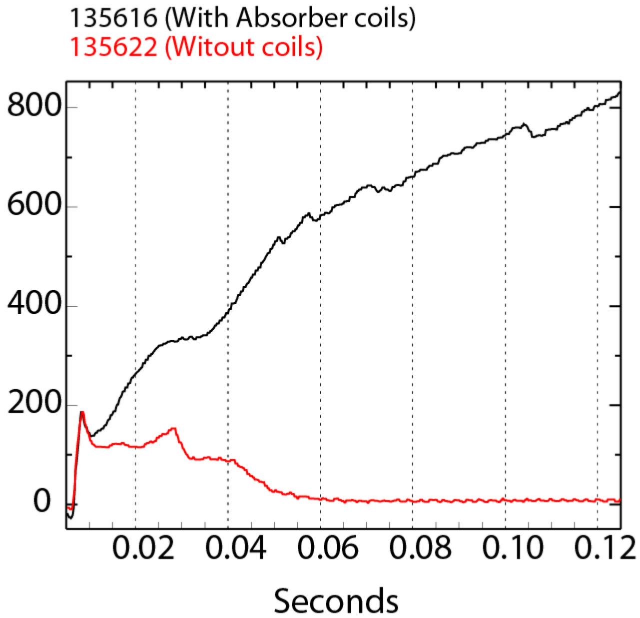
-Current multiplication factor in NSTX is 10 times greater than that in HIT-II

- Over 200kA of current persists after CHI is turned off

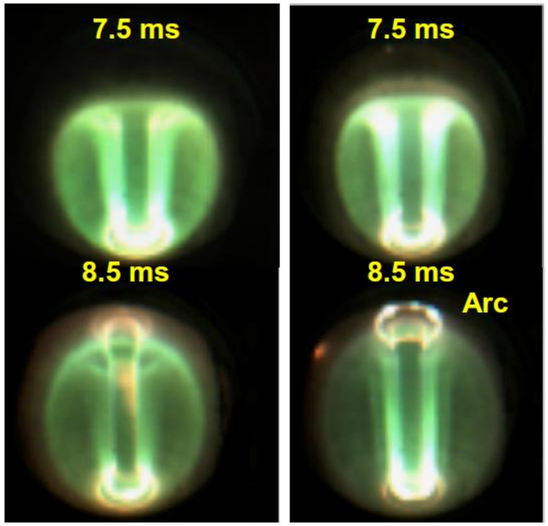
•R. Raman et al, Nuclear Fusion 45, L15-L19 (2005)

•R. Raman, B.A. Nelson, D. Mueller, et al., PRL 97, (2006) 17002

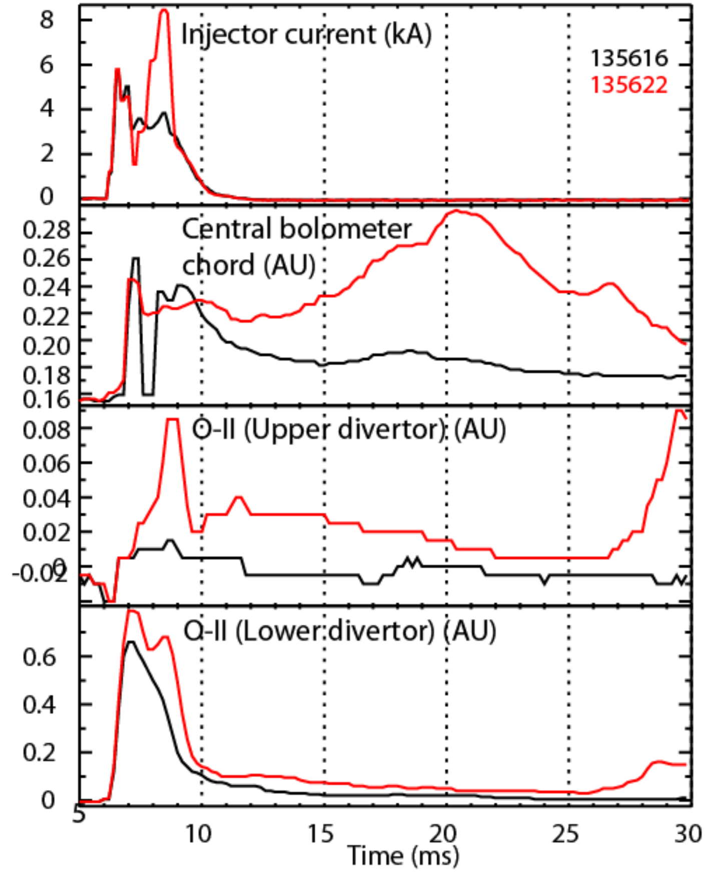
Absorber Coils Suppressed Arcs in Upper Divertor and Reduced Influx of Oxygen Impurities



•With Absorber coils •Without coil



•With Absorber coils •Without coil

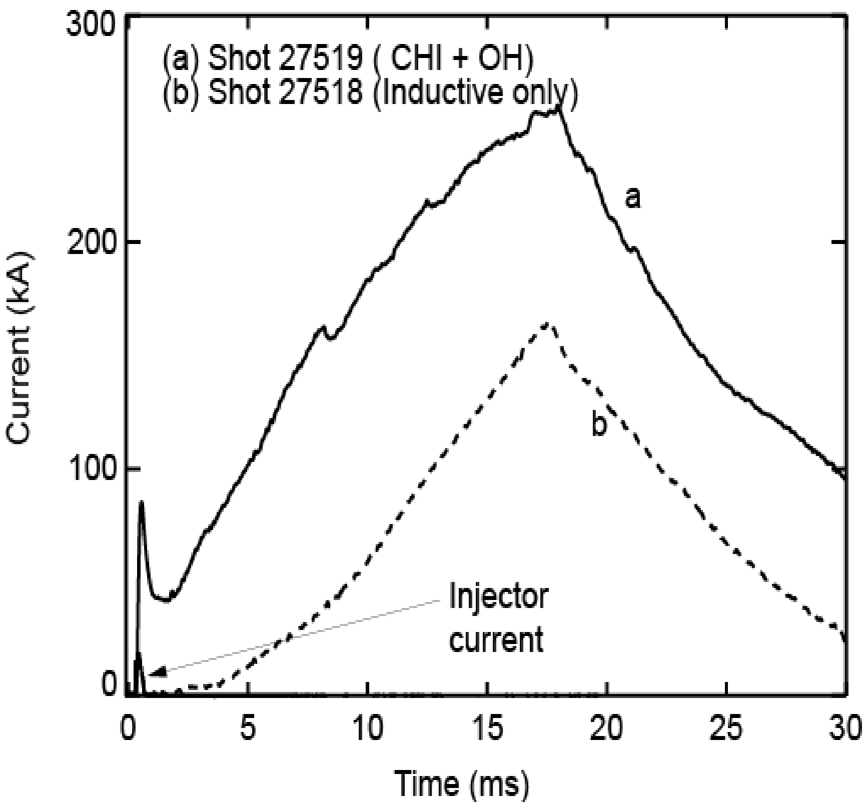


- Divertor cleaning and lithium used to produce reference discharge
- Buffer field from PF absorber coils prevented contact of plasma with upper divertor

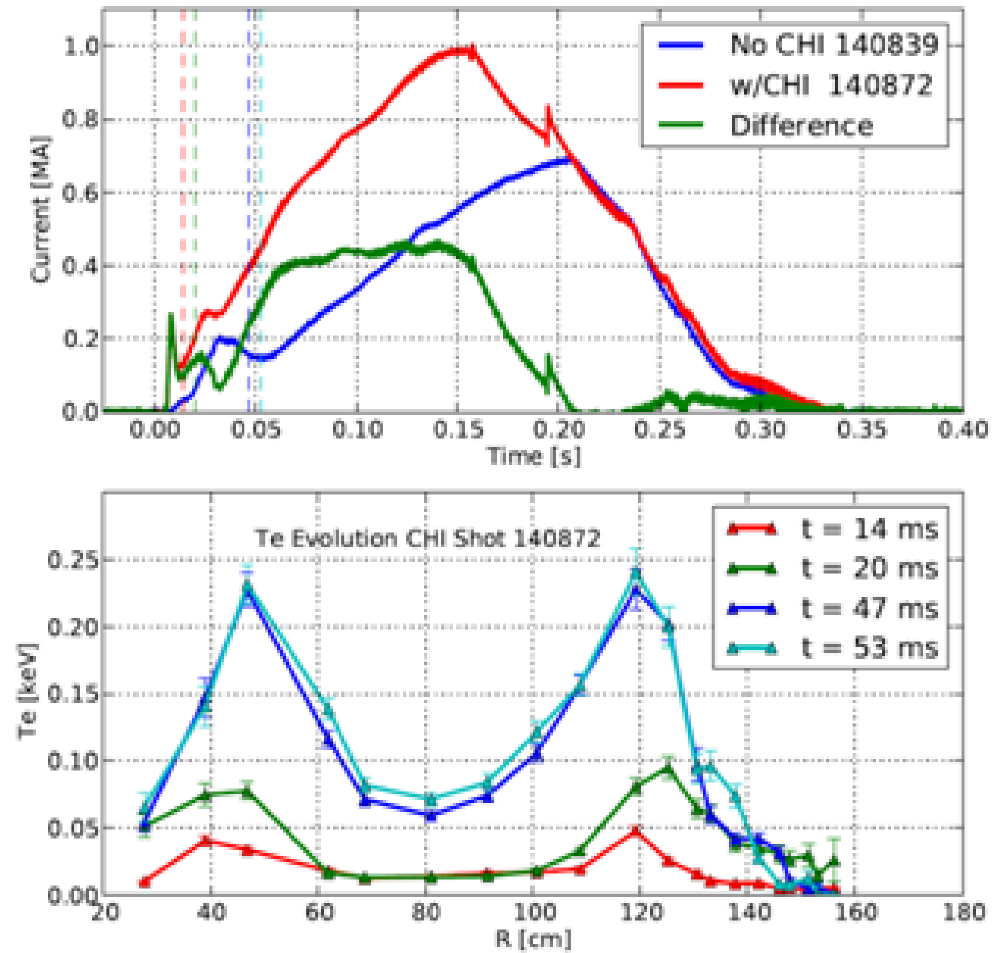
•R. Raman, D. Mueller, B.A. Nelson, T.R. Jarboe, et al., PRL 104, (2010) 095003

In NSTX Using Only 27kJ of Capacitor Bank Energy CHI Started a 300kA Discharge that Coupled to Induction

HIT-II



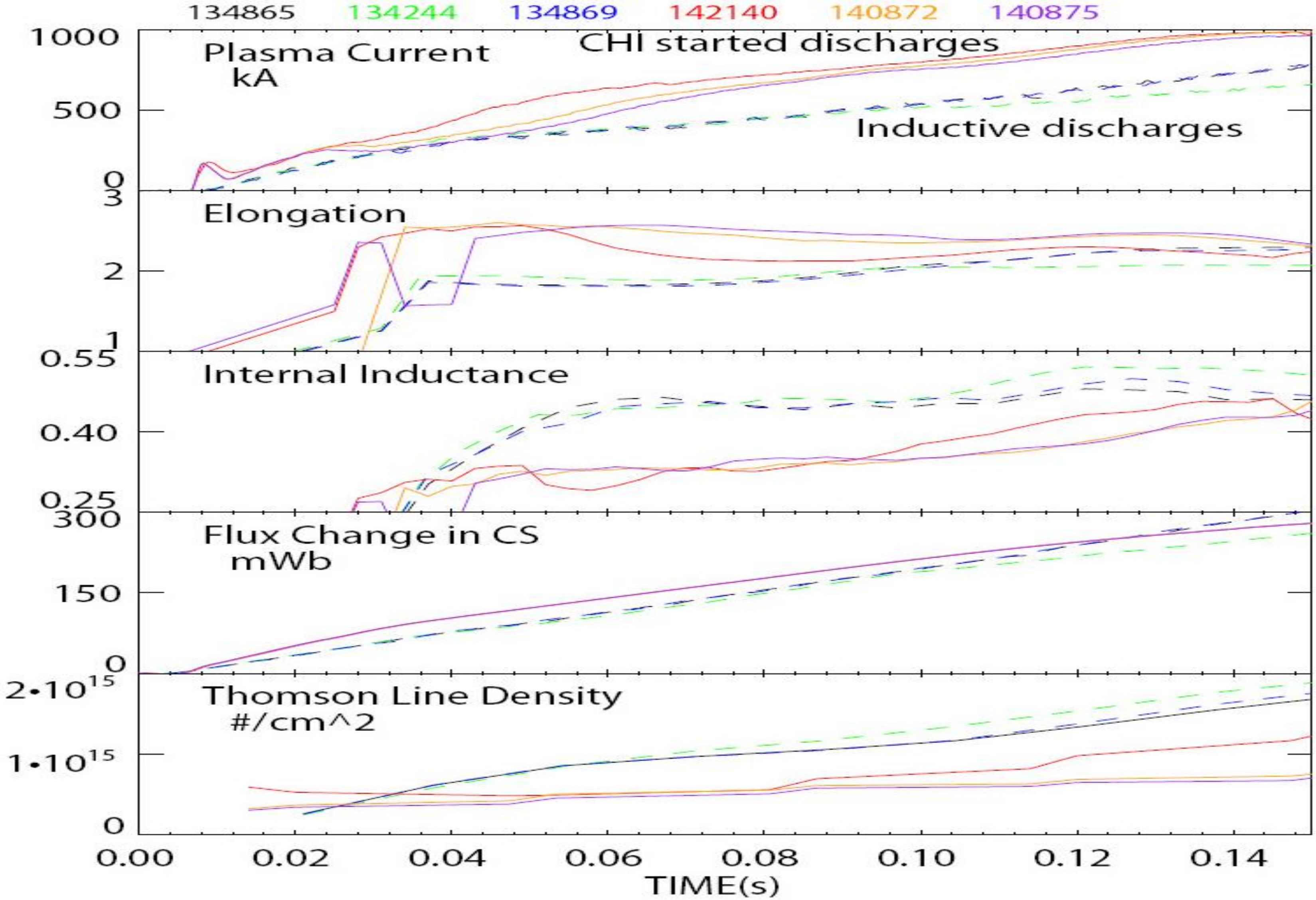
NSTX



•R. Raman, T.R. Jarboe, B.A. Nelson et al, Phys. Plasmas 14, 022504 (2007)

•B.A. Nelson et al, Nuclear Fusion 51, 063008 (2011)

CHI Start-up Discharges have low Internal Inductance and Electron Density Starting from Early in the Current Ramp



•These are the type of plasmas needed to increase the neutral beam current drive fraction

NSTX-U has the Potential for 1 MA CHI Start-up

•CHI Start-up Parameters in NSTX and NSTX-U

Parameters	NSTX	NSTX-U
R/a (m)	0.86 / 0.68	0.93 / 0.62
Toroidal Field (T)	0.55	1.0
Planned Non-Inductive sustained Current (MA) I_{PS}	0.7	1.0
Poloidal flux at I_{PS} (mWb)	132	206
Required Injector flux for 50% I_{PS} (mWb)	66	103
Peak current multiplication for 50% I_{PS}	53	48
Injector current for 50% I_{PS} (kA)	8.6	13.6
Maximum available injector flux (mWb)	80	340
Maximum startup current potential (MA)	0.4	~1
Req. Injector current for max. current potential (kA)	10	27*

•* HIT-II routinely operated with 30kA injector current without impurity issues

•R. Raman, D. Mueller T.R. Jarboe et al. PoP (2011) - accepted

FY14-18 Plans for CHI

2014-15

- Operate at 1T and higher levels of Injector flux to increase Ip
- Coils permitting Increase CHI start-up closed flux current to 400kA (600 kA peak current)
- Couple to Induction and asses improvements over NSTX discharges
- Assess NB & HHFW coupling to a CHI started target & assess confinement
  - Test the benefits of metal divertor plates
  - Use of Li & Absorber coils for performance improvement
  - Use higher voltage in NSTX-U

2016

- Use ECH to heat the initial CHI target
- Maximize CHI start-up current potential
  - Injector current & voltage permitting, 1MA peak current is projected
- Assess direct coupling of NBI to a CHI-only target
- Generate a CHI started target for other TSGs
- Electrodes permitting - Test edge current drive

2017

- Using (ECH, HHFW, High CHI Start-up currents, Lithium, Absorber coils) ramp-up a CHI started target to 1MA using NBI for full NI start-up and sustainment
- Generate reference start-up scenarios that do not use OH (for other TSGs)

2018

- Test synergism with other start-up methods, optimize NI ramp-up and support other TSGs

Plasma start-up using biased Plasma Guns

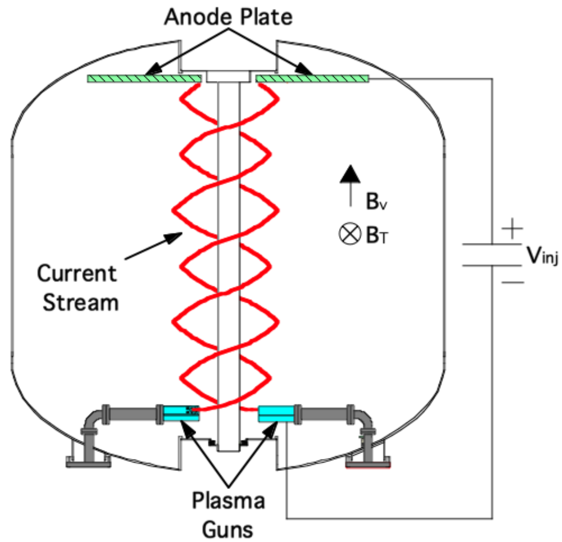
- DC helicity injection rate is given by:

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

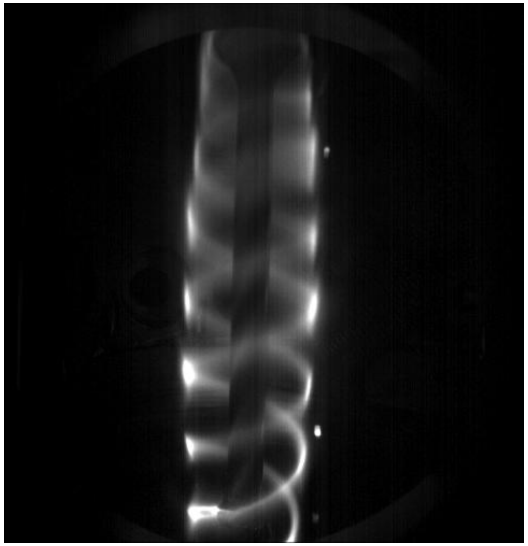
- The helical filaments can relax and form a tokamak if:
  1. Plasma-generated B_p greater than vacuum B_v
  2. Radial force balance is satisfied
  3. Sufficient input power

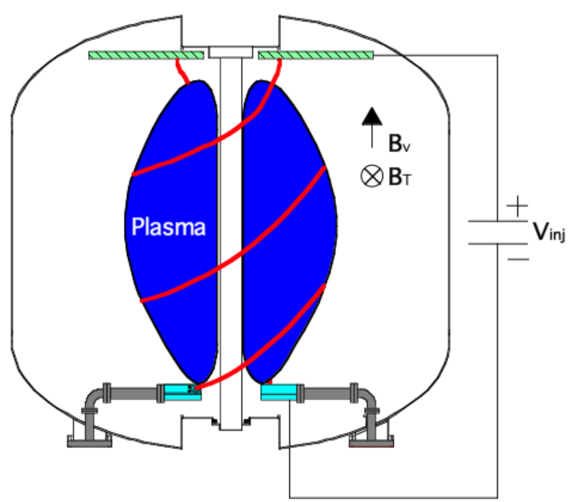
- Relaxed-plasma I_p is 10-15 times greater than I_{bias} multiplied by vacuum field windup (total multiplication up to 50)

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



Filaments





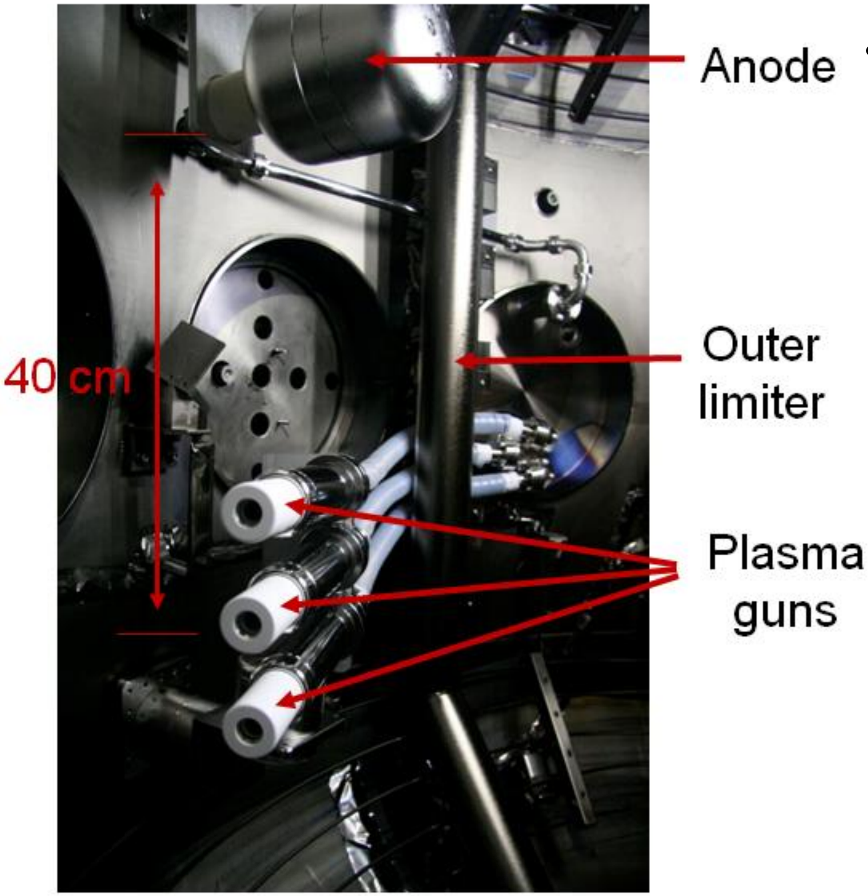
Relaxed State

PEGASUS ST

A.J. Redd, ICC Conference 2008

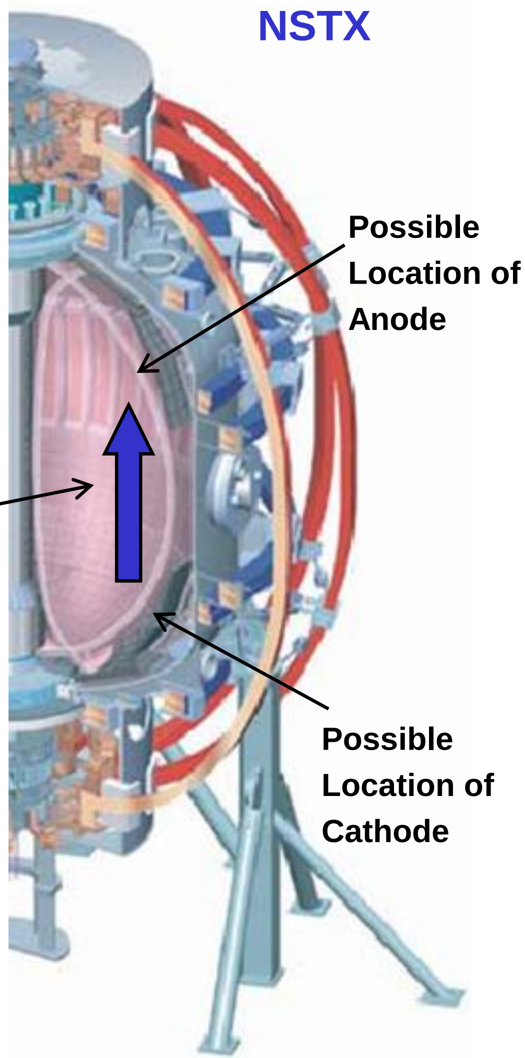
New larger surface area guns mounted on the outboard side being tested on Pegasus

Pegasus



- Guns on NSTX *could 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

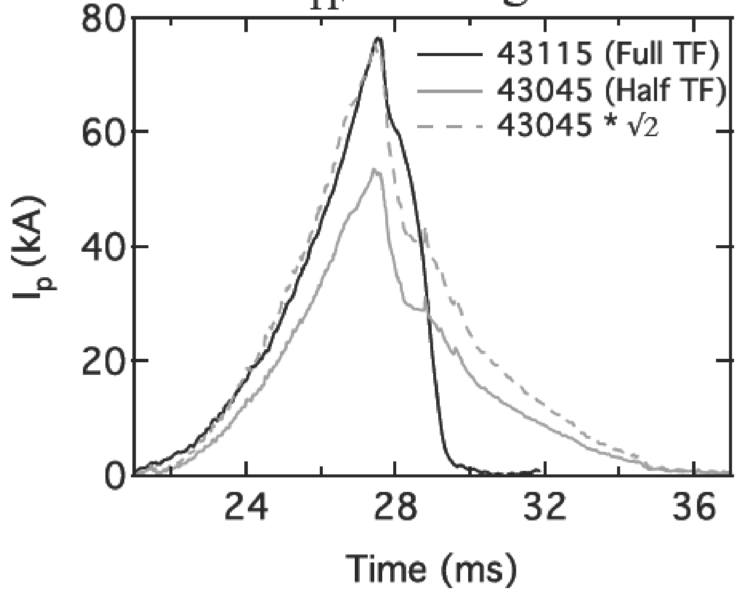


D.J. Battaglia, ICC Conference 2008

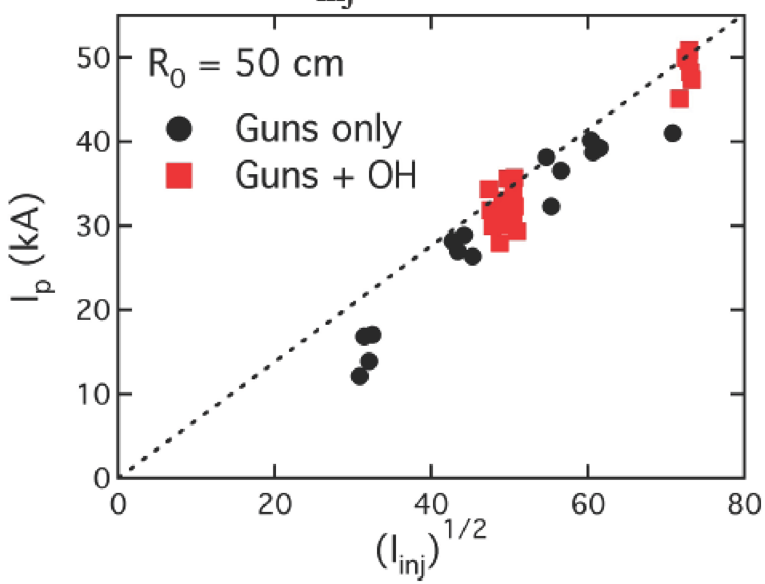
Experiments Confirm Relaxation Limit Scaling with Toroidal Field and Injector Current

- The relaxation limit I_p scales with: $I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$
- Experimental plasma currents appear to follow these scalings:

I_{TF} Scaling:



I_{inj} Scaling:



RJF APS/DPP 2010

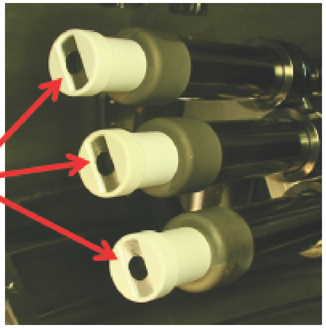
THE UNIVERSITY of WISCONSIN MADISON

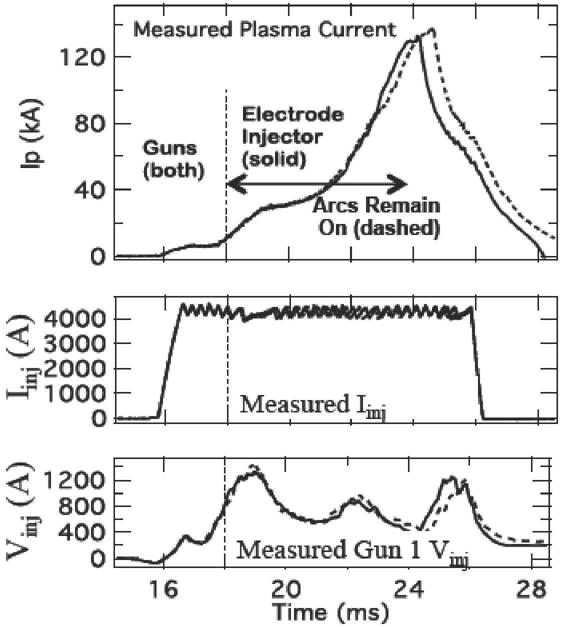
D.J. Battaglia et al, PRL 102, 225003 (2009)

D.J. Battaglia et al, NF 51 (2011) 073029

Active Gun / Passive Electrode Assembly Points to Simpler, Higher Ip operation

- Potential for much higher I_{inj} without need for larger guns
  - Helicity injection physics = agnostic to source of edge charge carriers
  - Passive electrodes = allow shaping to optimize helicity input *and* Taylor limit
- 2-step process
  - 1. Create initial tokamak-like plasmas with minimal active arc gun
  - 2. Grow to much larger I_p with passive electrodes fed by charge carriers in tokamak edge region.
- First tests are promising
  - Arc current off after relaxation
  - I_p rise = *same* whether arc current or edge losses provide charge carriers
  - Presently under study…





RJF APS/DPP 2010

Ip ~ 170kA obtained using helicity injection and outer PF-ramp up

Required Information for Gun Start-up on NSTX

- Promising results from Pegasus, but no data from NSTX
- Need additional information for projection on NSTX
- Hardware differences between Pegasus and NSTX
- Required vacuum limits and operating voltage (longer field line length)
- Scaling of generated current with
  - Number of guns
  - Area of guns / electrodes (Max I_{inj} as width is minimized)
  - Inclination of guns
  - Installation location and available access on NSTX (gap between primary and secondary plates adequate?
  - Do the guns need to be pulled back as current ramps-up in the presence of NBI?

D. Mueller to visit Pegasus to work out these details and provide a plan

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

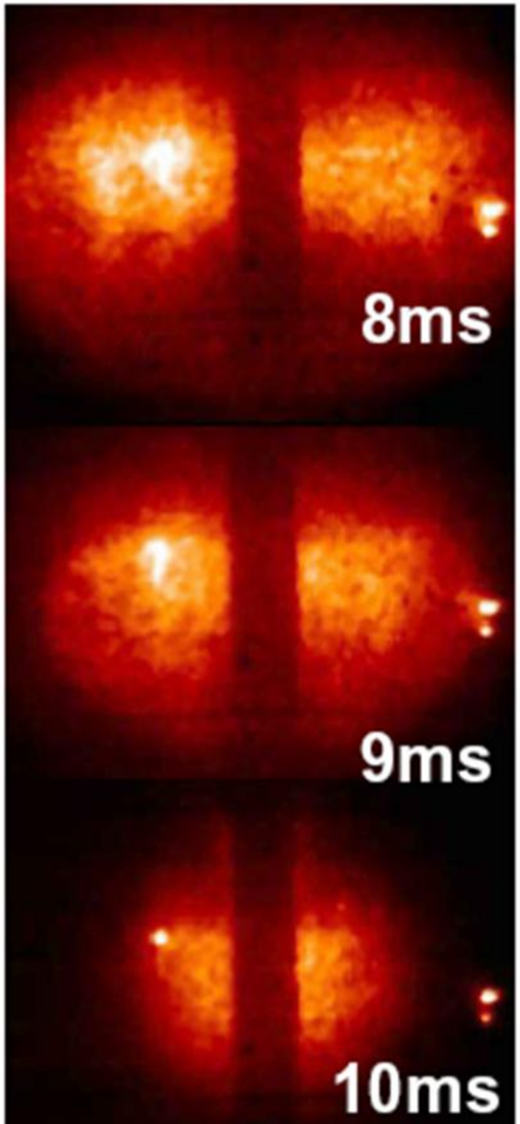
 # 3. Error field minimization to satisfy the "Lloyd condition" for plasma start up with strong preionization, $E_T \cdot B_T / B_P \geq 0.12$ kV/m achieved while retaining as much flux as possible for subsequent current ramp

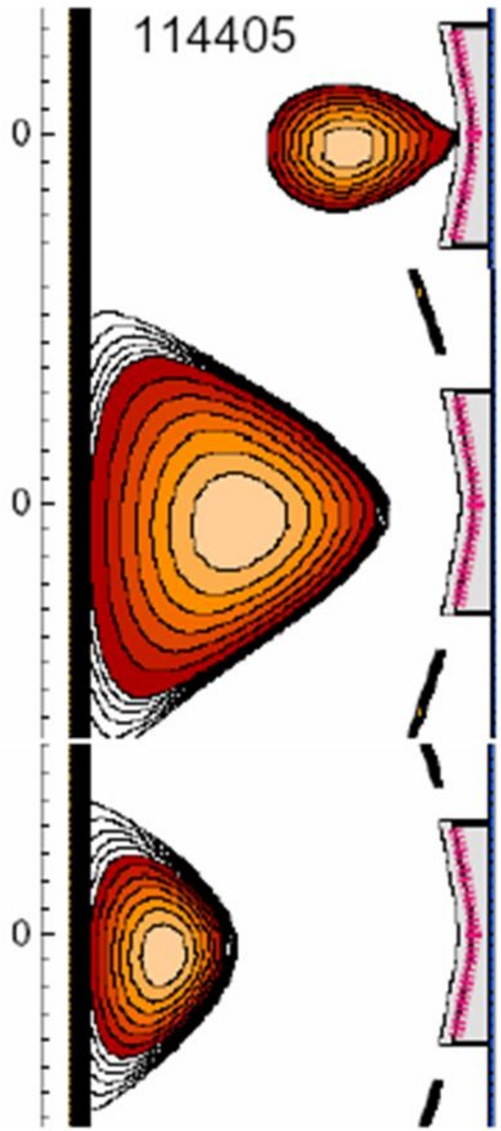
- Maintain field null for 2-3 ms in the presence of wall eddy current

- 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

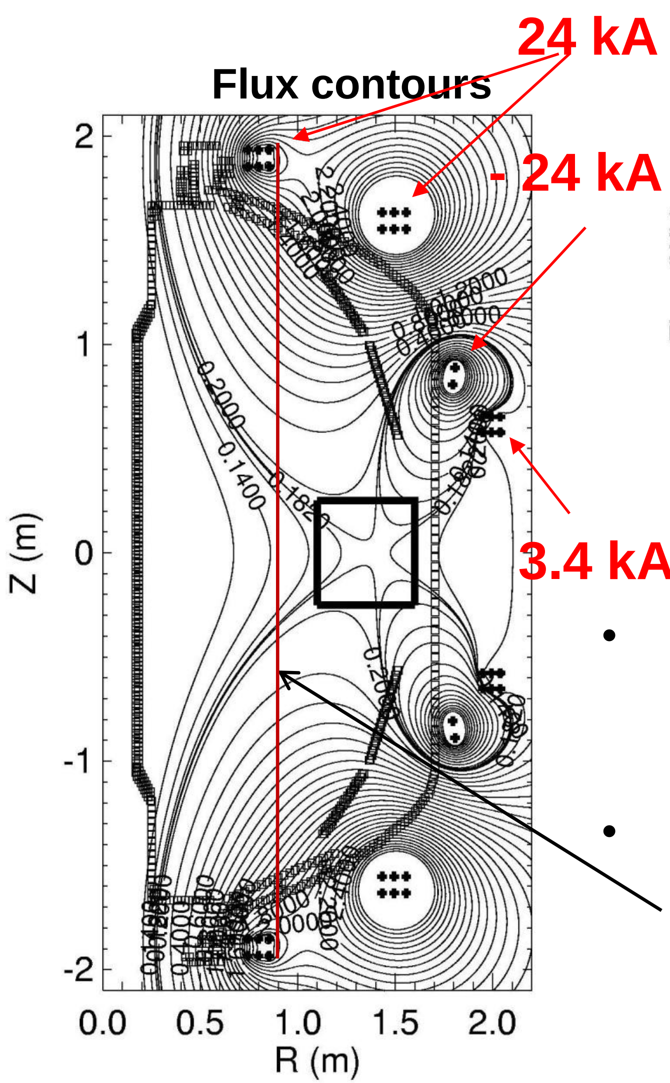


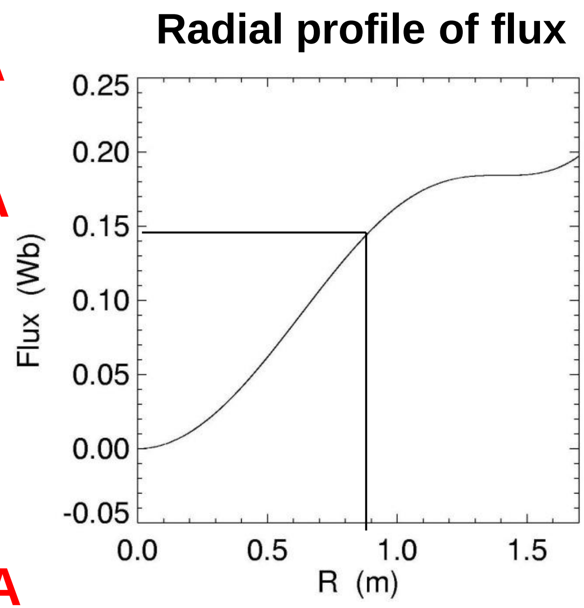


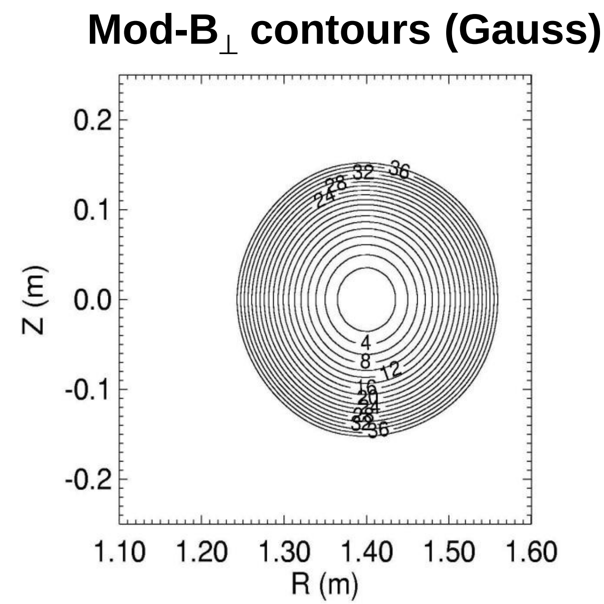
- LRDFIT code used for reconstructions
  - I_{vessel} ~ 10 x I**p**
- Careful control of B_Z after breakdown helped raise I**p** from 10kA to 20kA
  - More B_z evolution optimization possible
  - This satisfied $E_T.B_T/B_P$ ~1kV/m over good fraction of vacuum cross section
- Improved preionization and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

Outer PF Startup and Low Loop Voltage Startup

Now Assessing results from other machines

- D. Mueller participating on DIII-D experiments
- Experiments on Tokyo ST with PF coil located outside vessel
- Additional experiments on MAST

2014-15

- Test pre-ionization capability of ECH and or Plasma Guns
- Initial breakdown and current initiation studies using the existing uni-polar supply for PF 5
- Test low loop voltage startup

2016-18

- Based on results from FY14-15 and results from other machines

Ip Ramp up with HHFW and NBI

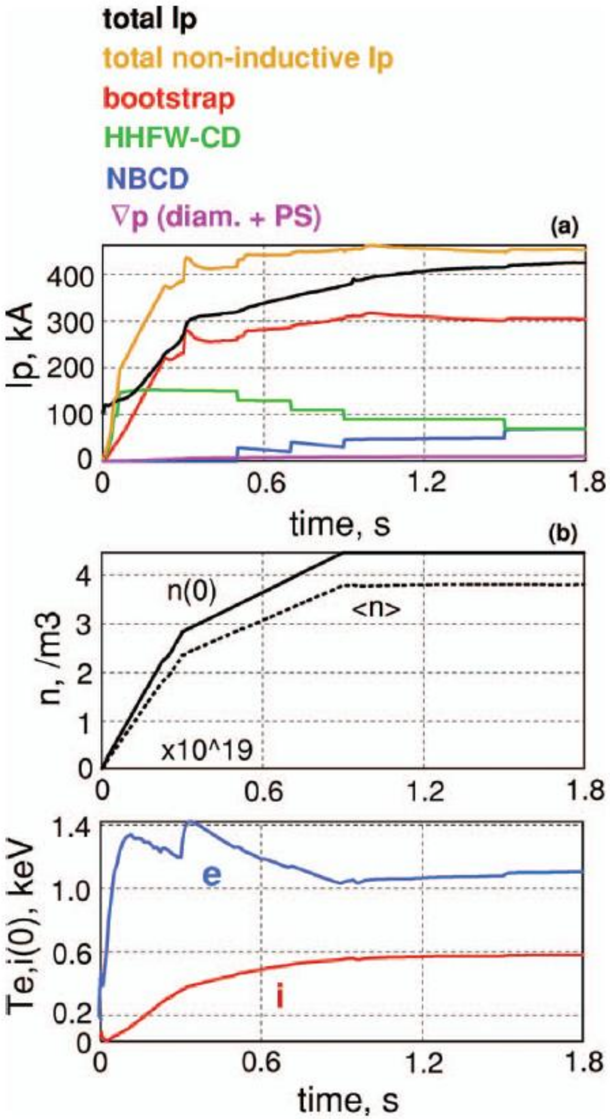
2014-15

- Fully NI driven inductively generated discharges
- Heating and improving CHI discharges
- Ramp-up of low Ip CHI target (If required)

2016-18

- Support CHI and other Plasma start-up research

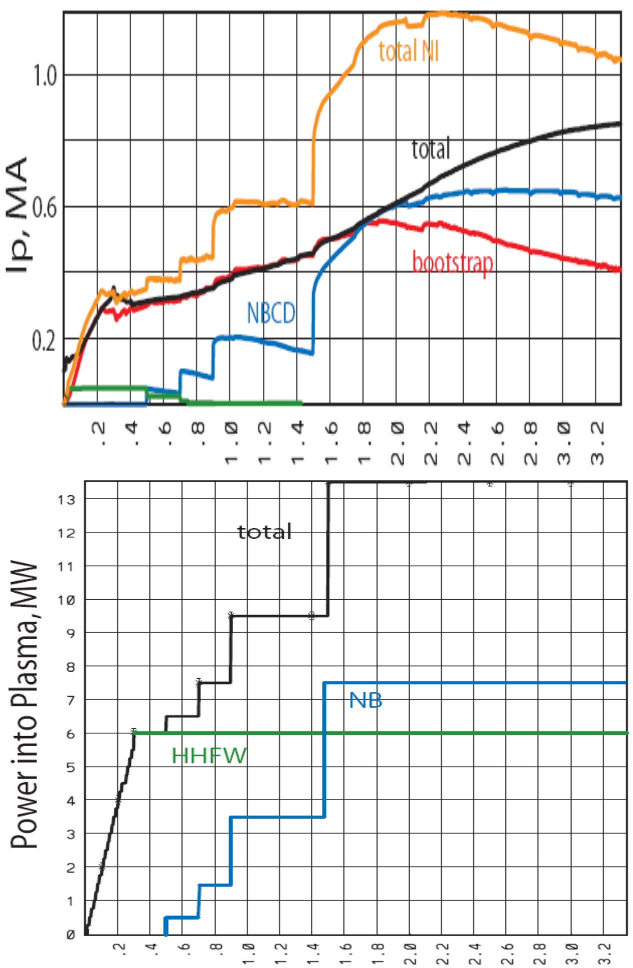
With 6MW HHFW Power Current Ramp up should be Achievable in NSTX



- 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

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

FY14-18 Plans for Non-Solenoidal Ramp up and Sustainment

2014-15

- Attempt Ip ramp-up from 200-250kA to 400-500kA using HHFW heating and CD + BS
- Generate high current CHI target with minimal OH usage
- Possible test of Gun start-up and outer PF start-up

2016-17

- Try nearly full sustainment and ramp-up at 500-1000kA using inductively produced target and compare to targets produced using CHI and other available method that show promise (Plasma guns, Outer PF, EBW start-up)
- Test generation of high current non-inductive target for routine use (Zero OH)
- 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.
- Study scaling to a 2T device

2018

- Conduct supporting experiments needed to design a solenoid-less 2T device

Diagnostics Needs for SFPS

- **Primary Diagnostics**
  - Magnetics
  - Electron Temperature and density profiles (especially in the outer regions) (Thomson)
  - Current profile evolution (MSE)
  - Impurities in the plasma and sources (Filter scopes, SPRED, other spectroscopic diagnostics)
  - Visible fast camera
  - Bolometer arrays
  - Soft X-ray arrays

- **Desirable diagnostics**
  - Current footprint on electrodes & electrode temperature response (Langmuir probes, fast IR camera, eroding thermocouples, tile halo currents)
  - Other current profile diagnostics (especially edge current) (Zeeman polarimetry)
  - Confinement of fast ions in start-up targets (FIDA, ssNPA)
  - Edge neutral density
  - Vessel neutral pressure measurements
  - Edge/Core rotation diagnostics (ERD, CHERS)
  - Edge density fluctuations (Edge reflectometer)
  - Divertor Thomson, Edge Thomson, Transmission grating spectrometer
  - Surface contaminants (Laser ablation)

NSTX/NSTX-U is Leading the Effort to Develop Startup Techniques for STs

- **Transient CHI is a proven method for generating a high current start-up plasma**
  - 0.3MA current generation in NSTX validates capability of CHI for high current generation in a ST
  - Successful coupling of CHI started discharges to inductive ramp-up & transition to an H-mode demonstrates compatibility with high-performance plasma operation
  - CHI start-up has produced the type of plasmas required for non-inductive ramp-up and sustainment (low internal inductance, low density)
  - Favorable scaling with increasing machine size (from two machines of vastly different size and in TSC simulations)
- **Plasma Gun startup to be tested in NSTX-U**
  - Startup and inductive coupling at 160kA demonstrated on Pegasus
  - Physics and scaling is being studied on Pegasus ST
  - Work underway to assess system installation requirements on NSTX-U
- **Outer PF startup is being considered (pending results from other machines)**
- **Low Loop Voltage startup to be tested**
  - To assess iron core start-up needs
- **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 (1MA CHI startup a possibility)