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Overview of Transient CHI Plasma Start-up in NSTX

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Acknowledgment

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and the NSTX/NSTX-U Research Team

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Session 2: Overview & Fusion/Reactor Research

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Outline

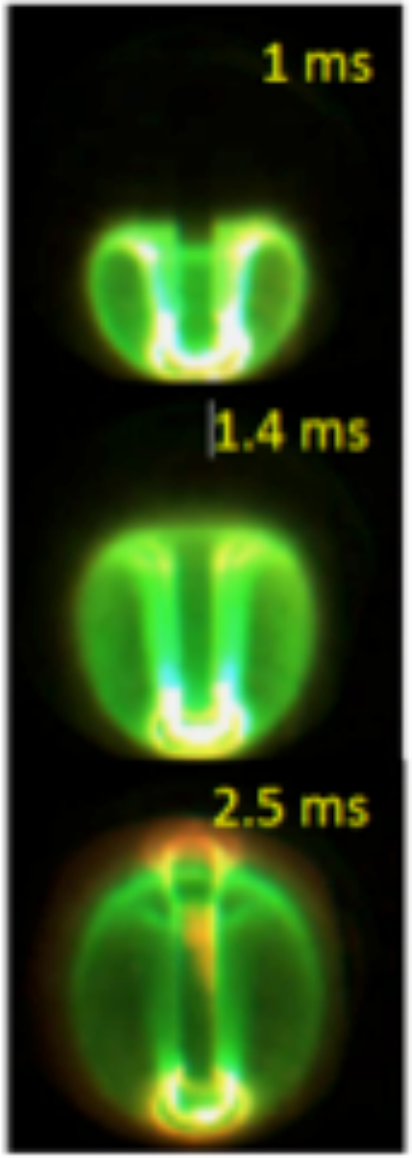
- Motivation for CHI in a ST/Tokamak
- Implementation and results from NSTX
- CHI research goals on NSTX-U
- Fusion reactor considerations

Solenoid-Free Current Initiation Would Improve the Prospects of the ST as a FNSF and Fusion Reactor

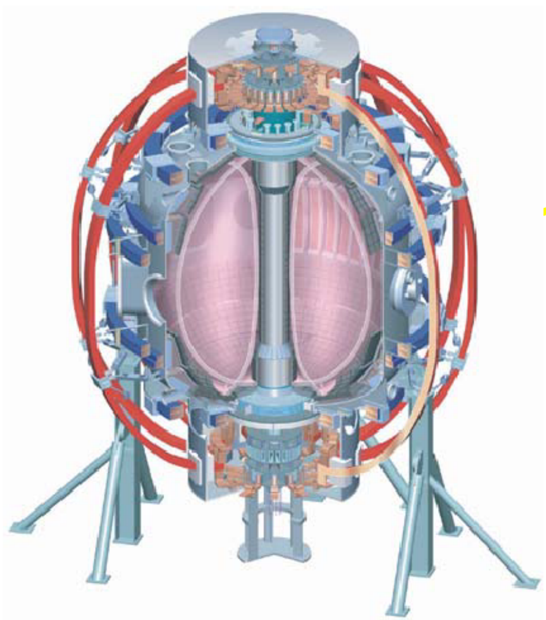
- Of the large machines, only NSTX/NSTX-U actively engaged in solenoid-free plasma startup research

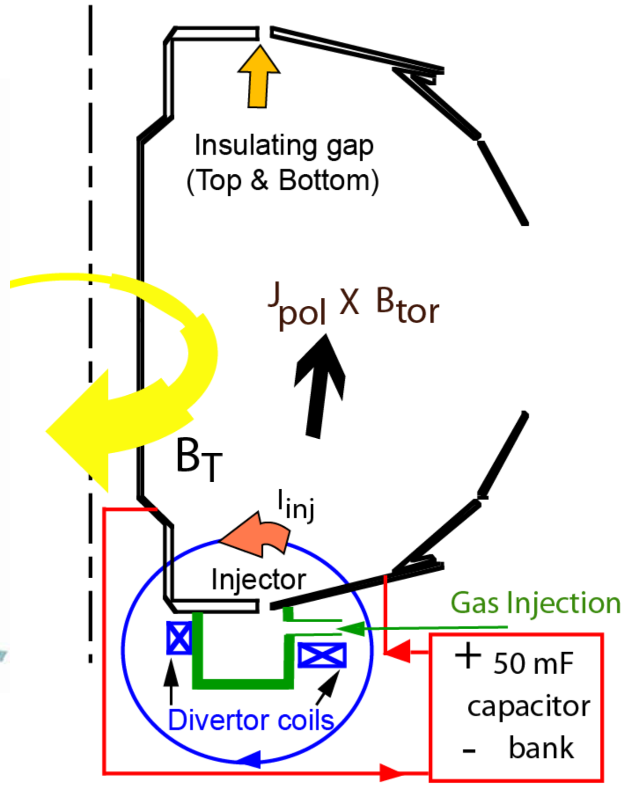
- Transient Coaxial Helicity Injection plasma startup method developed on HIT-II at U-Washington is the most developed concept
  - For plasma start-up, CHI is *now* unique to NSTX-U
  - QUEST ST in Japan, now implementing CHI capability

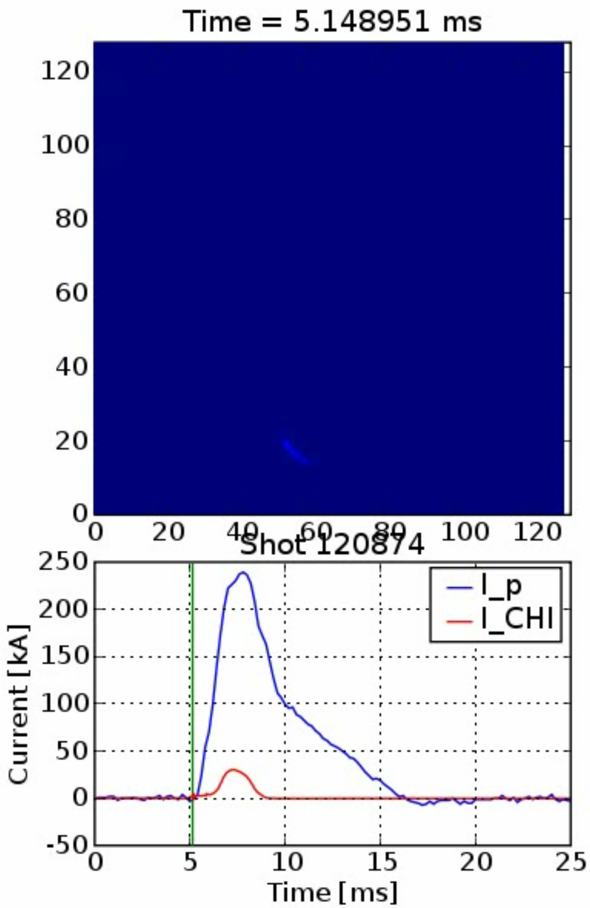
- Enables lower aspect ratio Spherical Tokamak (ST) configurations
  - Also simplifies conventional tokamak design



Transient CHI: Axisymmetric Reconnection Leads to Formation of Closed Flux Surfaces







- Parameters to consider
  - Current multiplication factor
  - Effect of toroidal field
  - Magnitude of generated plasma current
  - New desirable features?

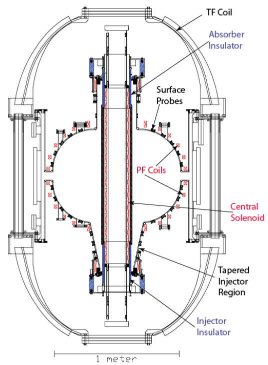
Fast camera: F. Scotti, L. Roquemore, R. Maqueda

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

Movie of CHI Start-up

NSTX CHI Research Follows Concept Developed in HIT-II

University of Washington

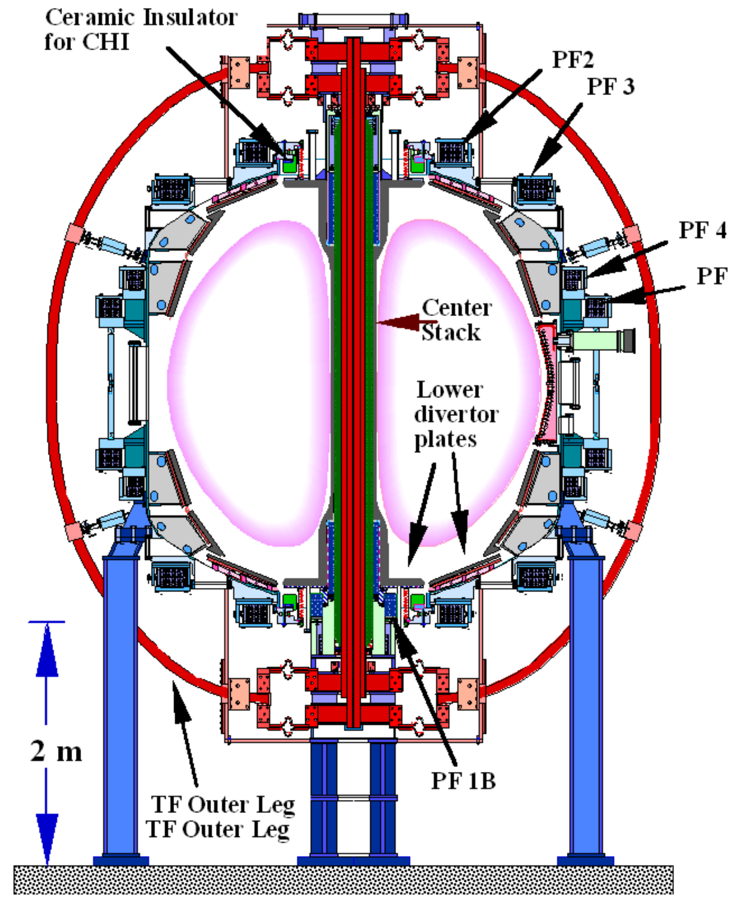


Concept exploration device HIT-II

- Built for developing CHI
- Many close fitting fast acting PF coils
- 4kV CHI capacitor bank

NSTX plasma is ~30 x plasma volume of HIT-II

PPPL

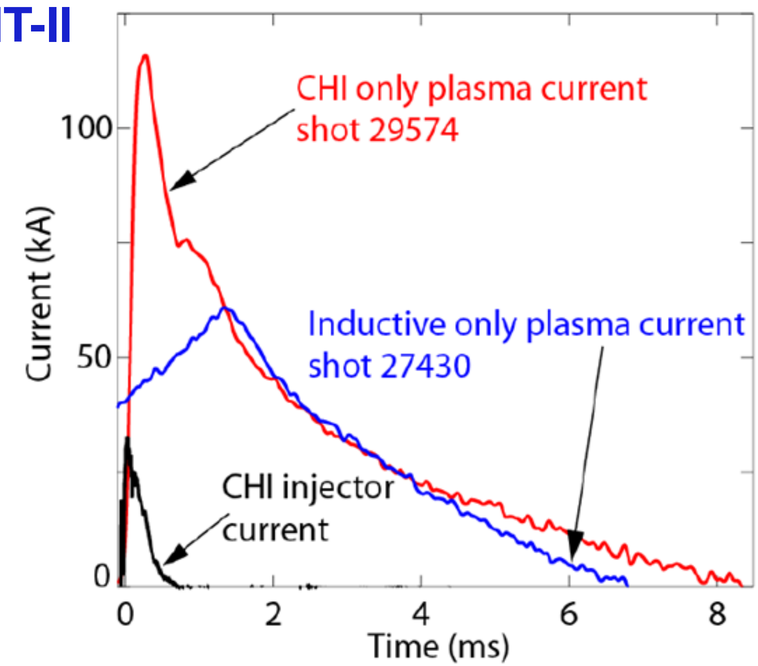


Proof-of-Principle NSTX device

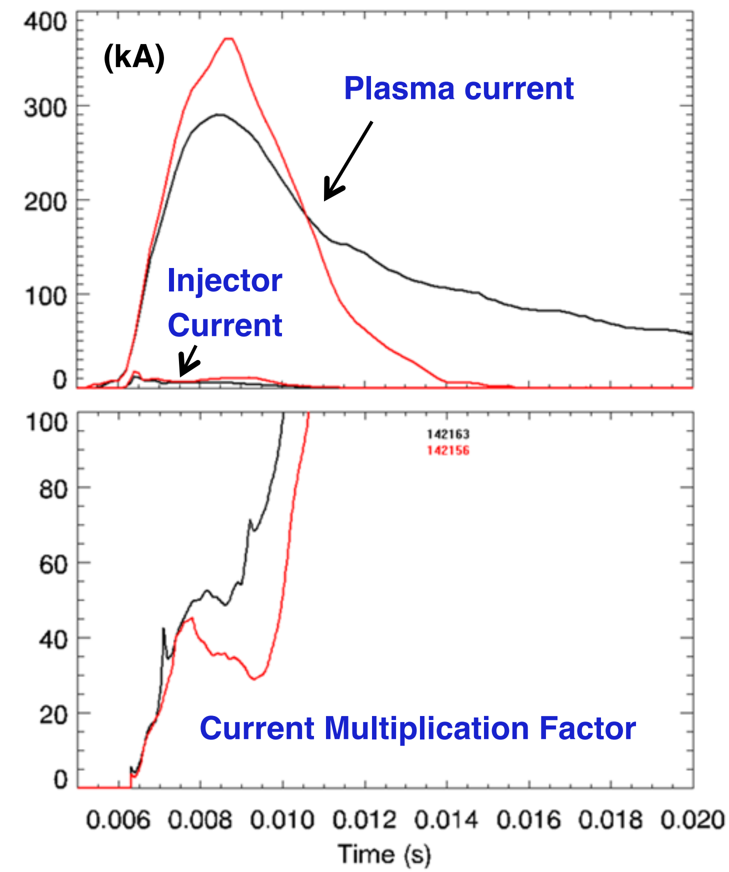
- Built with conventional tokamak components
- Few PF coils
- 1.7kV CHI capacitor bank

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

Externally Produced Toroidal Field makes CHI much more Efficient in a Tokamak

- Bubble burst current*: $I_{inj} = 2\psi_{inj}^2 / (\mu_o^2 d^2 I_{TF})$

  ψ_{inj} = injector flux

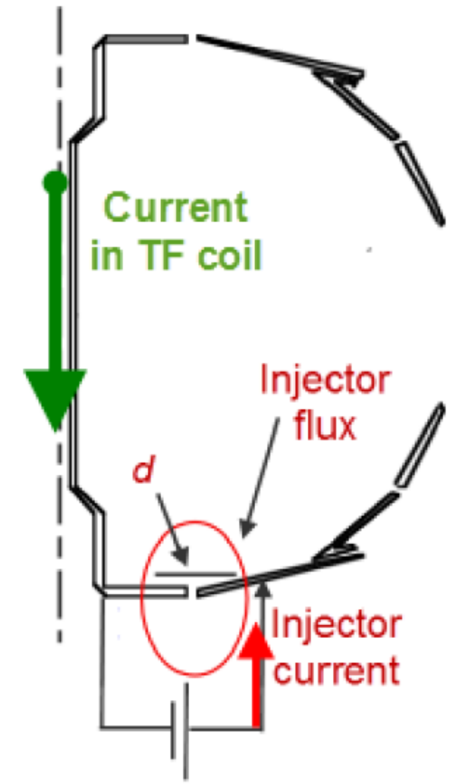
  d = flux foot print width

  I_{TF} = current in TF coil

Injector current **Toroidal flux**

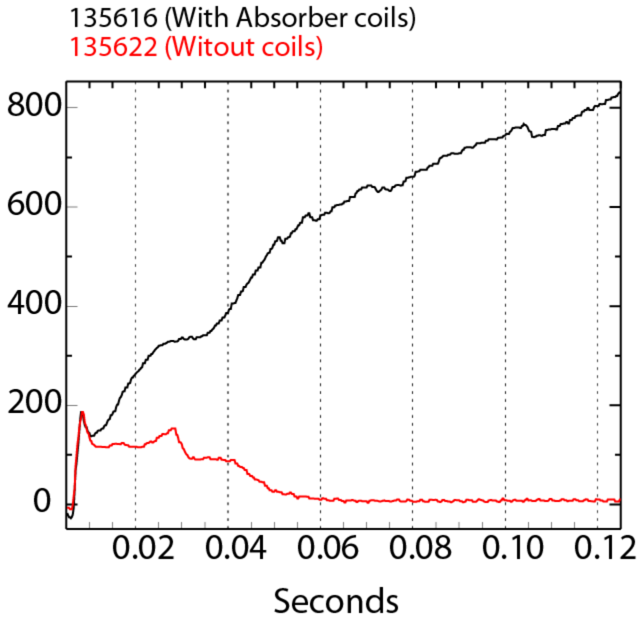
$$I_P = I_{inj}(\psi_T / \psi_{inj})$$

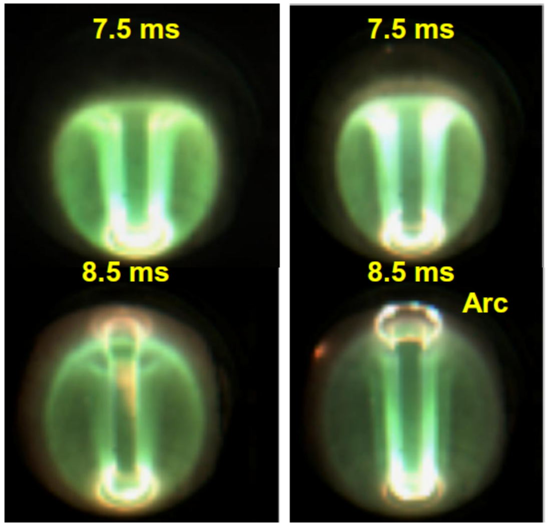
- Current multiplication increases with toroidal field
  - Favorable scaling with machine size
  - Increases efficiency (10 Amps/Joule in NSTX)
  - Smaller injector current to minimize electrode interaction

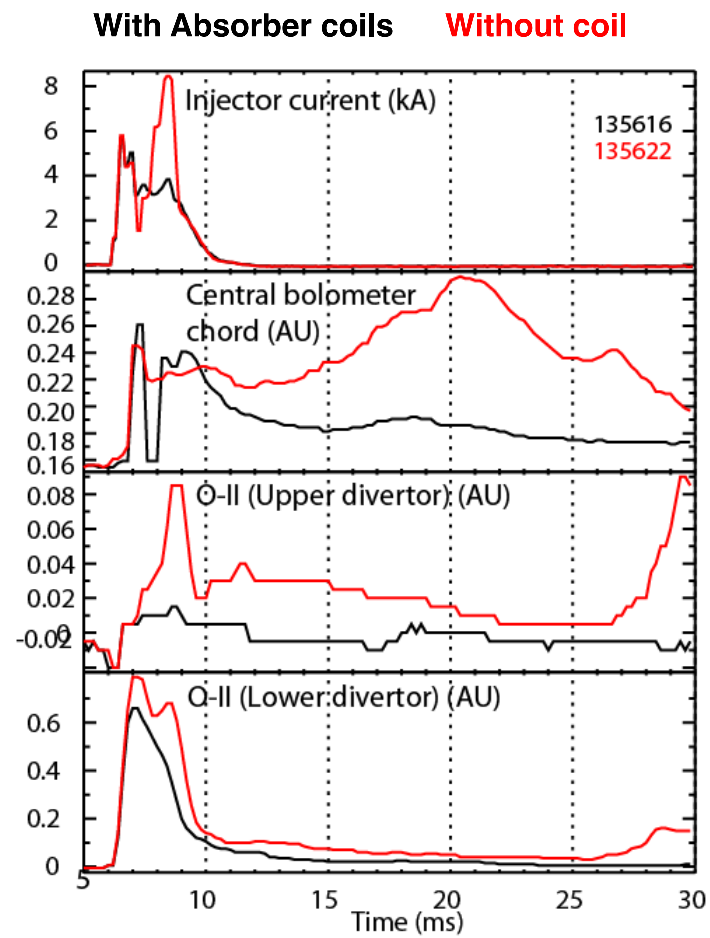


* T.R. Jarboe, Fusion Tech. 15, 7 (1989)

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



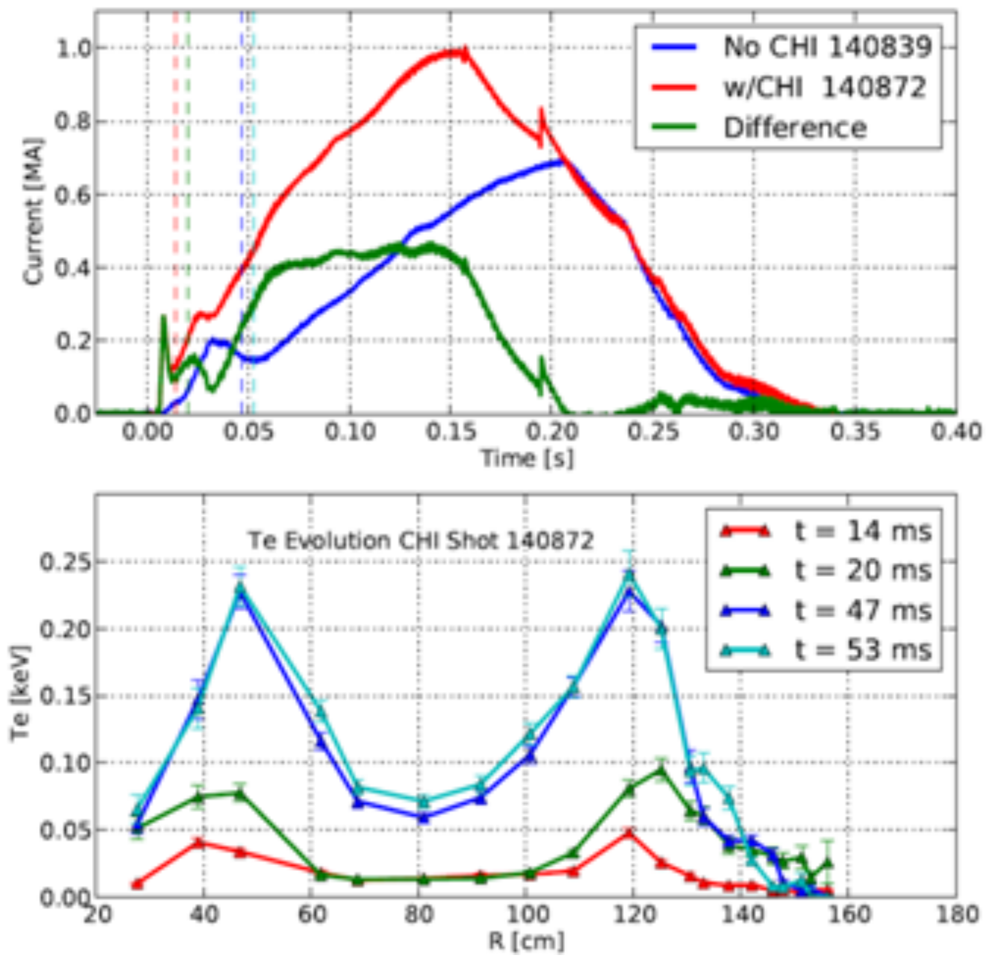




- Divertor cleaning and lithium used to produce reference discharge
- Buffer field from PF absorber coils prevented contact of plasma with upper divertor

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

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

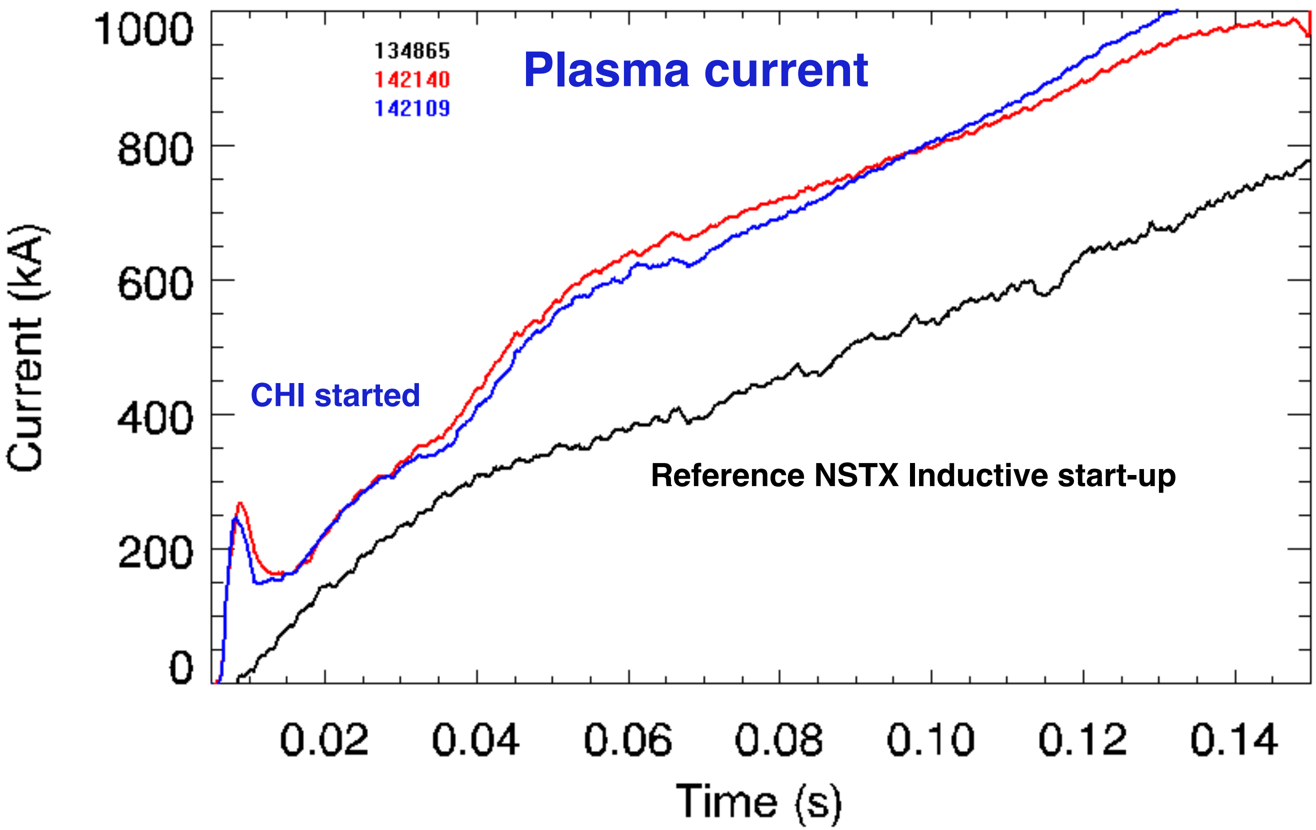


- Ramped up to 1MA after startup, using 0.3Wb change in solenoid flux

- Hollow electron temperature profile maintained during current ramp
  - Important beneficial aspect of using CHI startup

- Discharges with early high T_e ramp-up to higher current

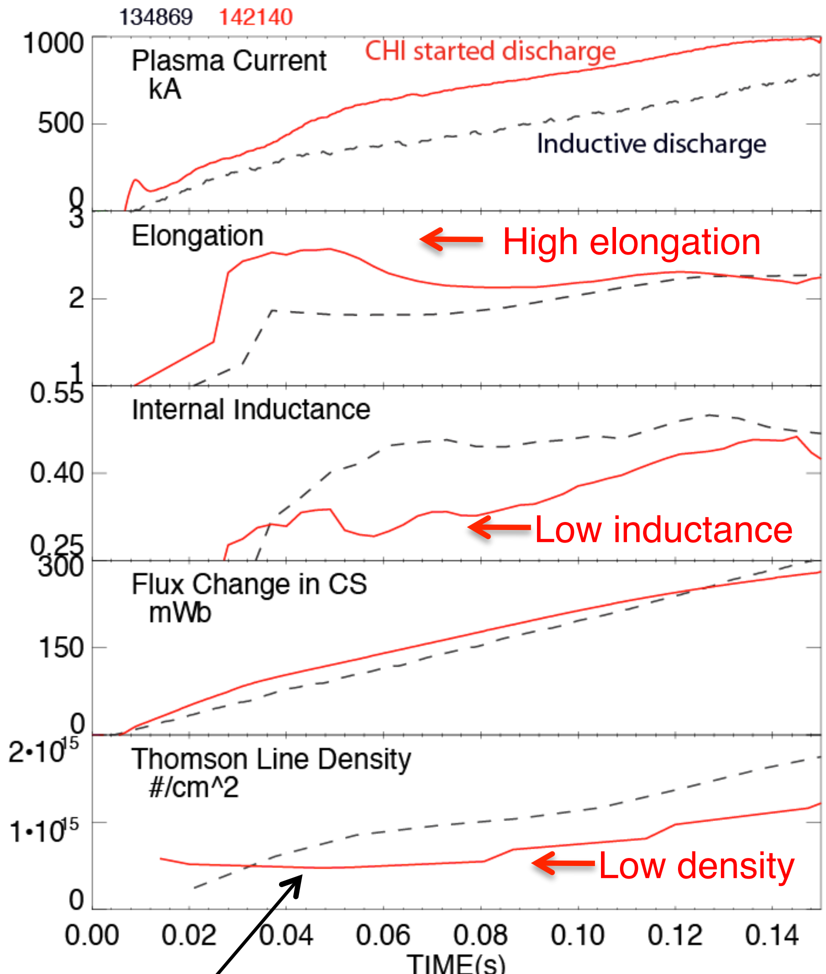
Standard L-mode NSTX Discharge Ramps to 1MA Requiring 50% More Inductive Flux than a CHI Started Discharge



- **Reference Inductive discharge**
  - **Uses 396mWb to get to 1MA**
- **CHI started discharge**
  - **Uses 258 mWb to get to 1MA (138 mWb less flux to get to 1MA)**

CHI Started Discharges have Favorable Properties needed for subsequent Non-inductive Current Ramp-up

CHI assisted startup in NSTX



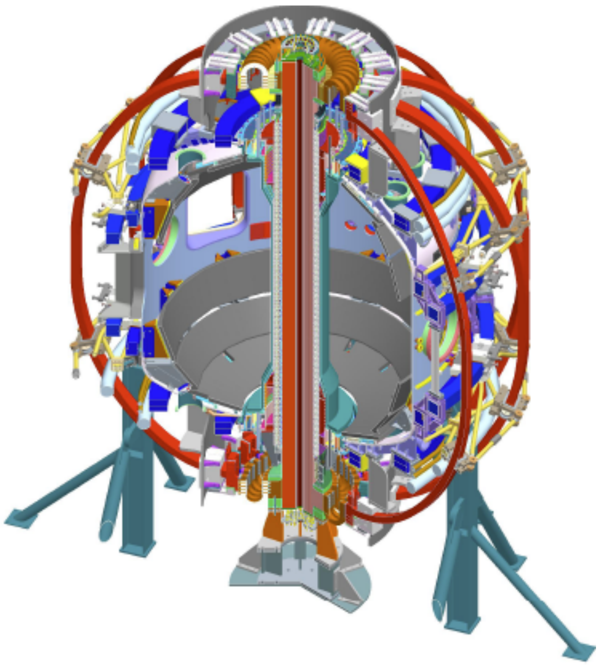
CHI generates plasmas with low n_e so that ECH could be used to heat these plasmas

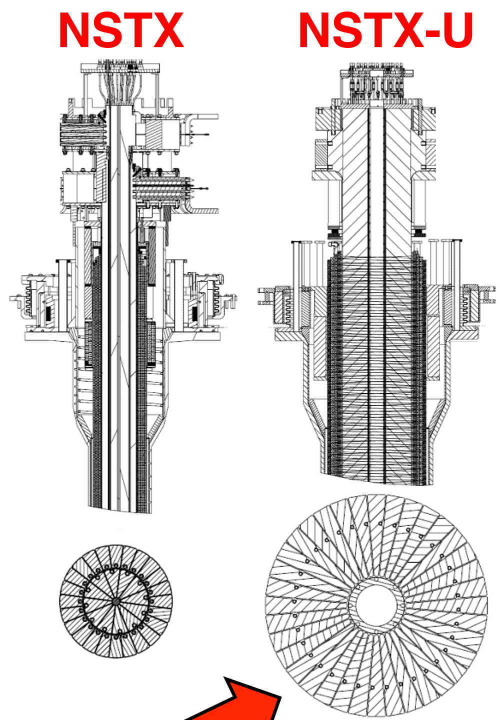
27 kJ of stored capacitor bank energy used for CHI plasma start-up

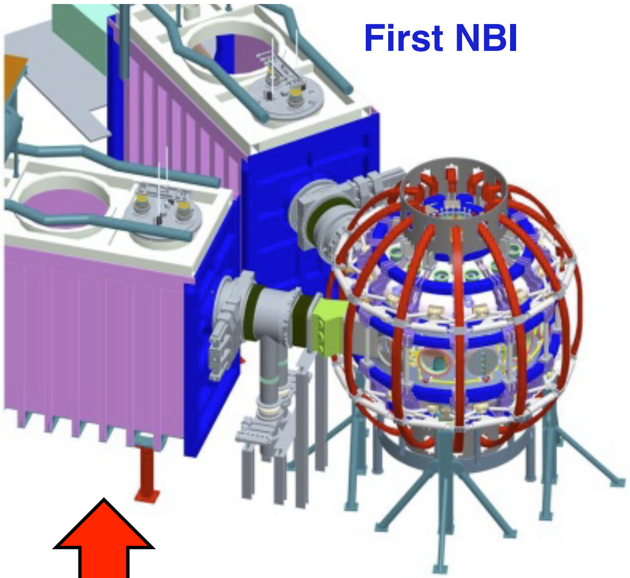
CHI produced plasma is clean

(Discharges have transitioned to H-mode after coupling to induction)

NSTX-U Research will Advance the ST as a Candidate for a Fusion Nuclear Science Facility (FNSF)







New large center stack in NSTX-U enables

- B_T: Increases from 0.55 to 1 T
- Plasma current: 1 to 2 MA
- Discharge pulse duration: 1s to 5 s

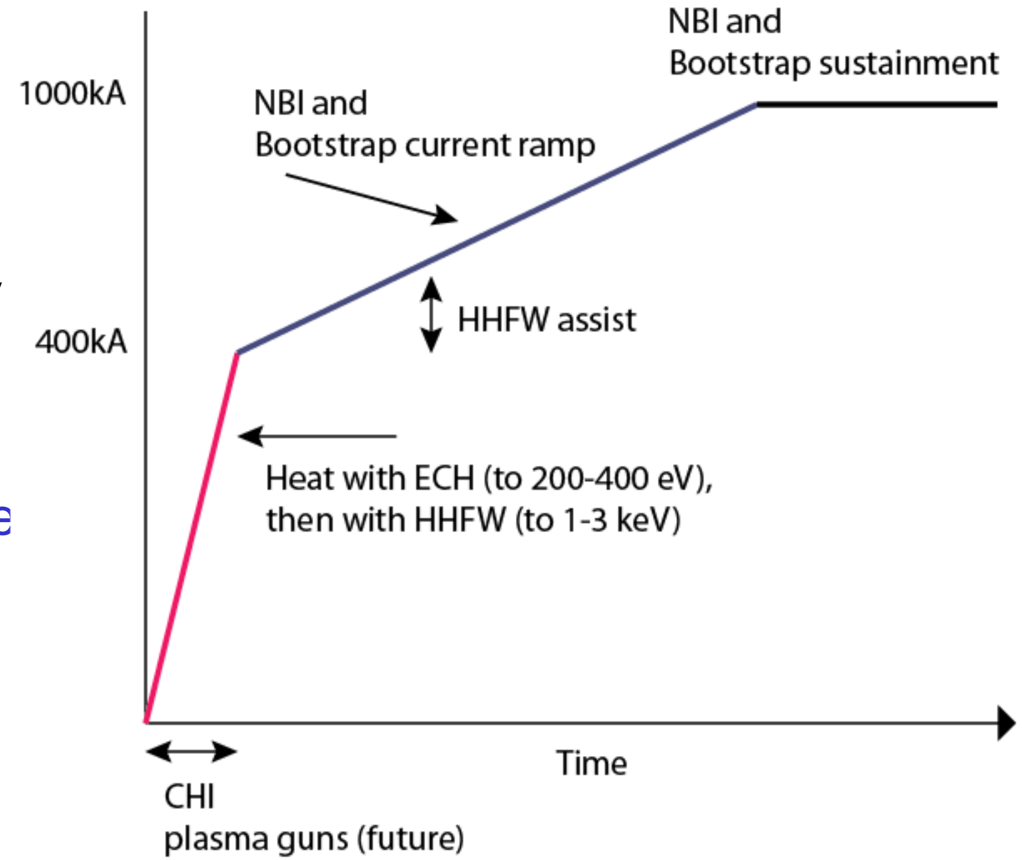
Second tangential Neutral Beam in NSTX-U enables development of

- Non-inductive current ramp-up and 100% NI sustained operation

NSTX-U Aims to Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation

- Establish physics basis for ST-FNSF, and solenoid-free start-up is essential in ST
- NSTX-U is striving for fully non-inductive operations
  - Transient Coaxial Helicity Injection (CHI) start-up is the front end of that objective
  - Plasma guns and EWB will be tested after those systems are technically ready

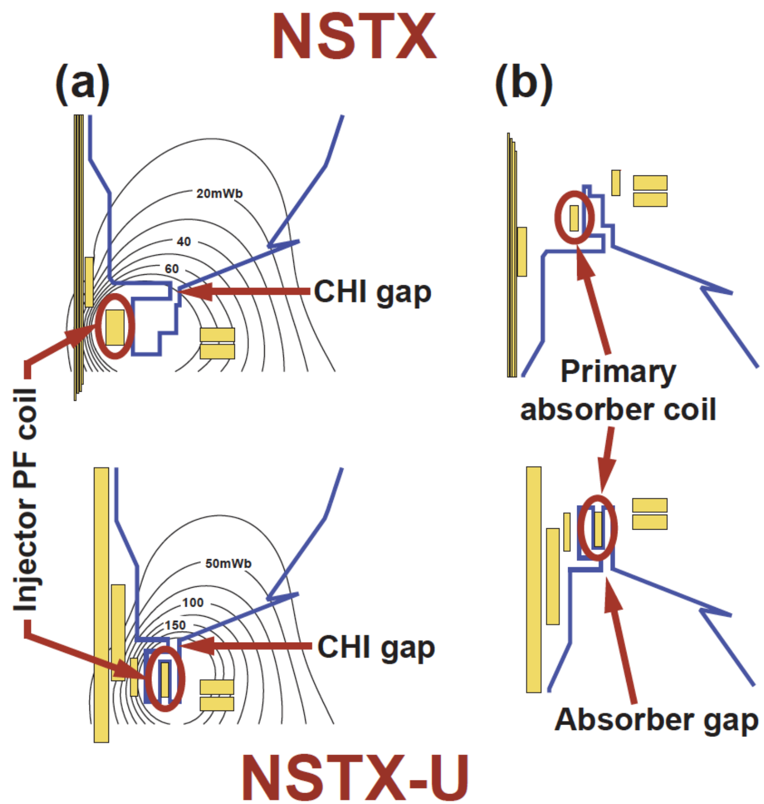
NSTX-U Start-up & Ramp-up strategy



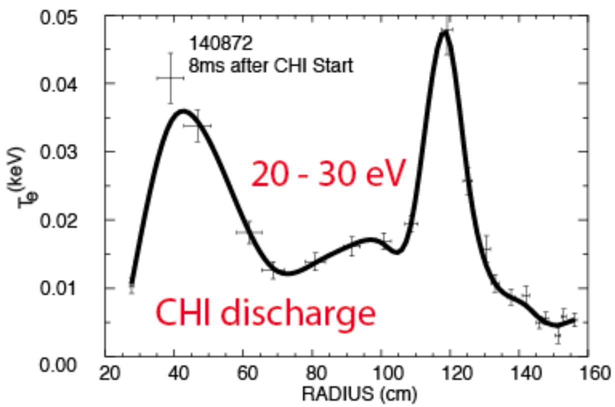
NSTX-U Upgrades that Facilitate CHI Start-up

NSTX-U Machine Enhancements for initial CHI

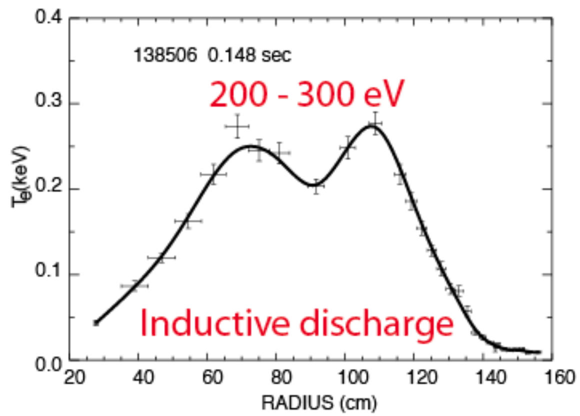
- > 2.5 x Injector Flux in NSTX (proportional to I_p)
- About 2 x higher toroidal field (reduces injector current requirements)



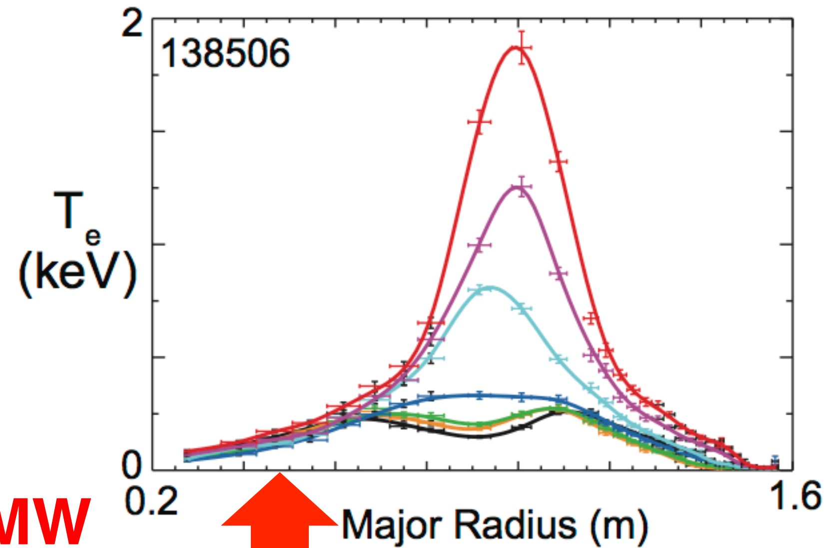
Bridge Electron Temperature Gap Between CHI Start-up and Current Ramp-up Requirements with ECH Heating

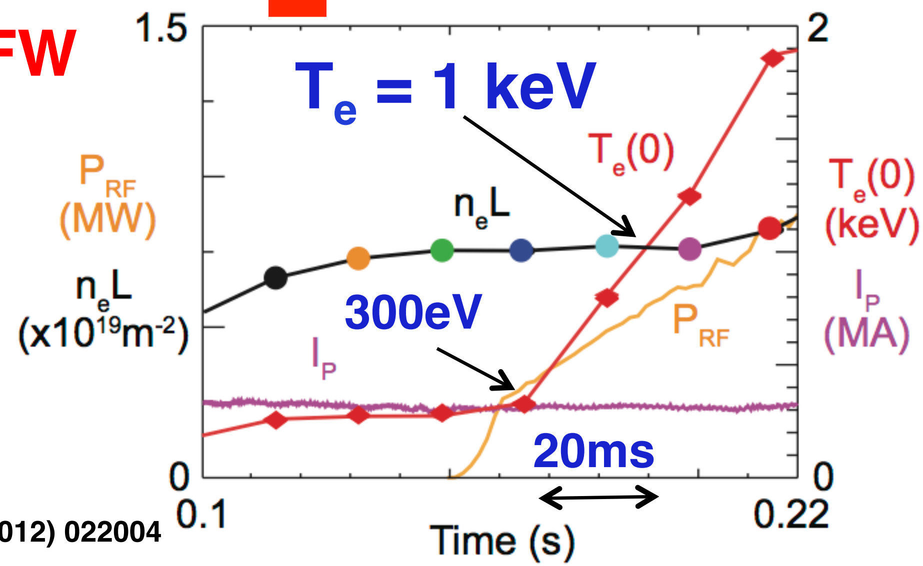


1MW ECH



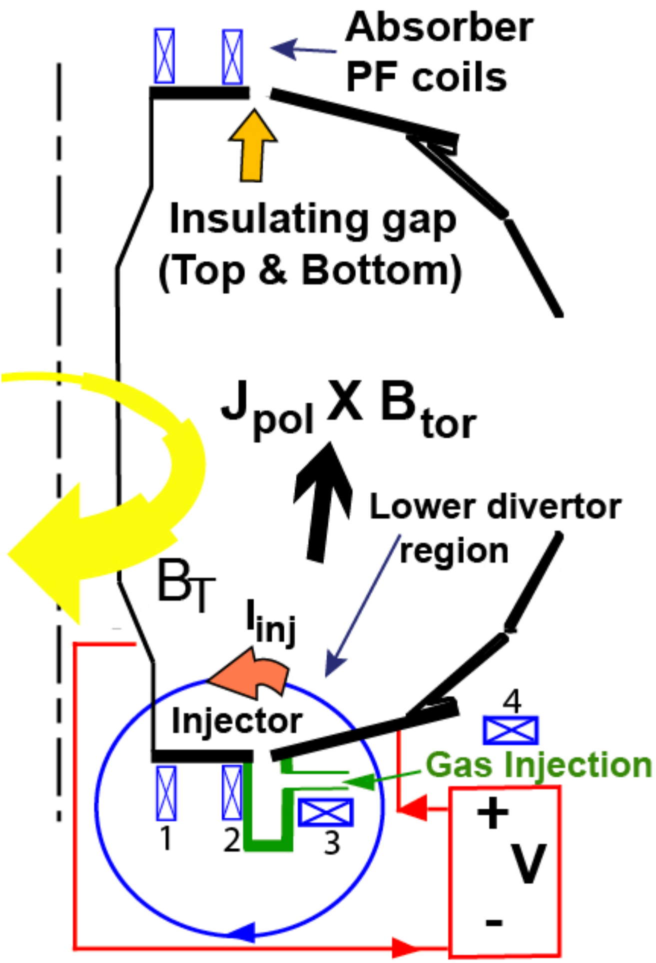
1-2 MW HHFW



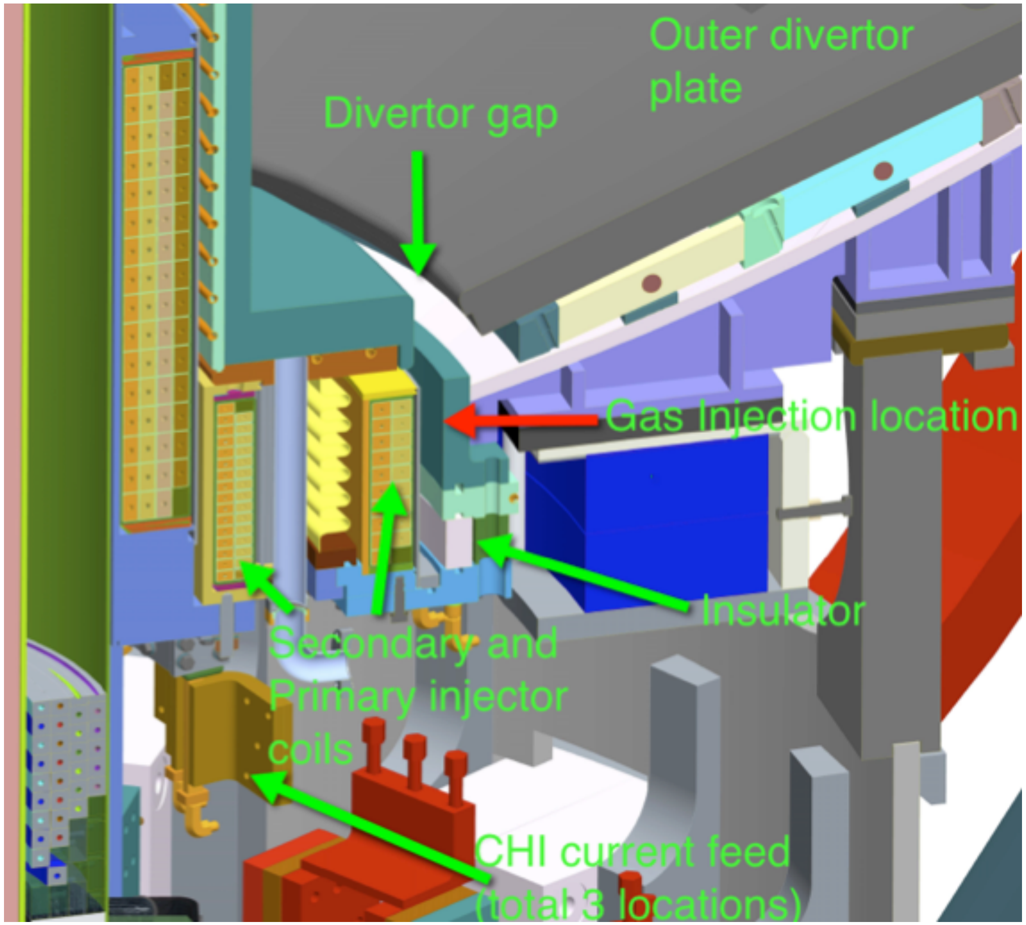


G. Taylor, et al.,
Phys. Plasmas 19 (2012) 022004

CHI Insulator and Electrode Configuration on NSTX-U

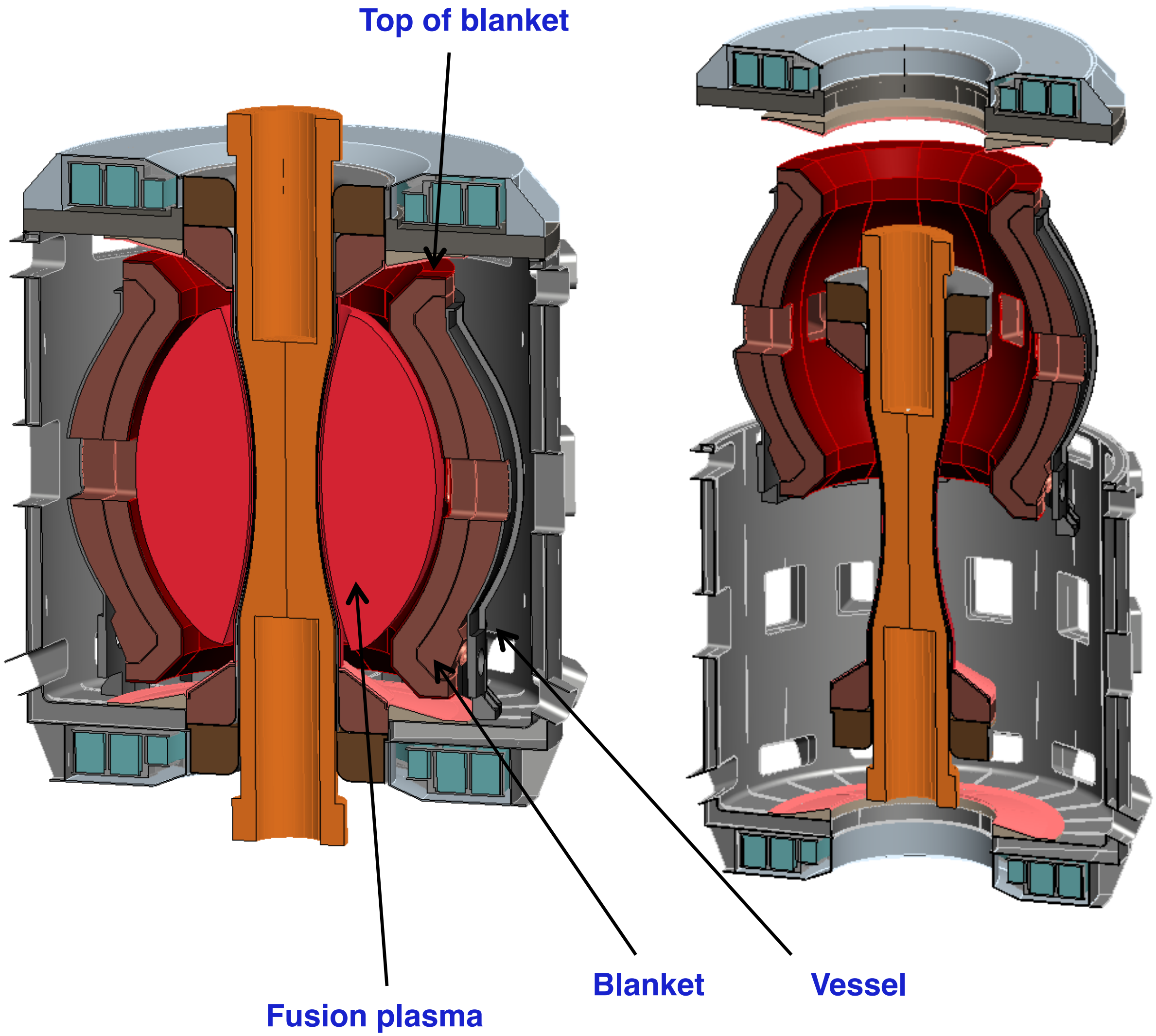


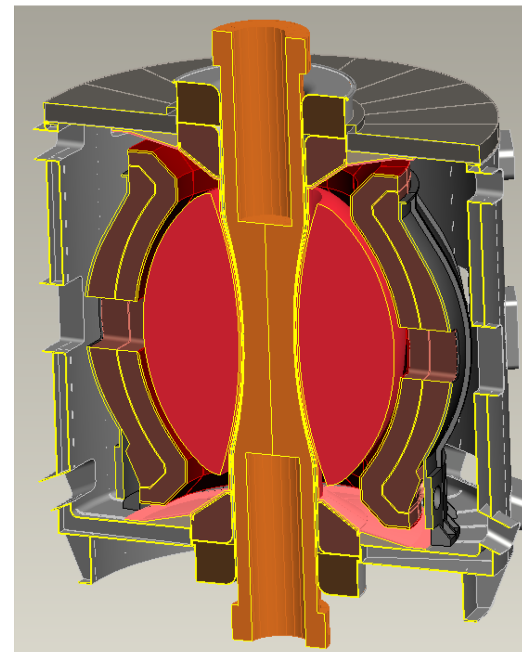
1,2: Injector coils
3,4: Flux shaping coils



ST FNSF Configuration

(R_{maj} = 1.7m, A=1.5, B_T = 3T, I_p = 10MA)



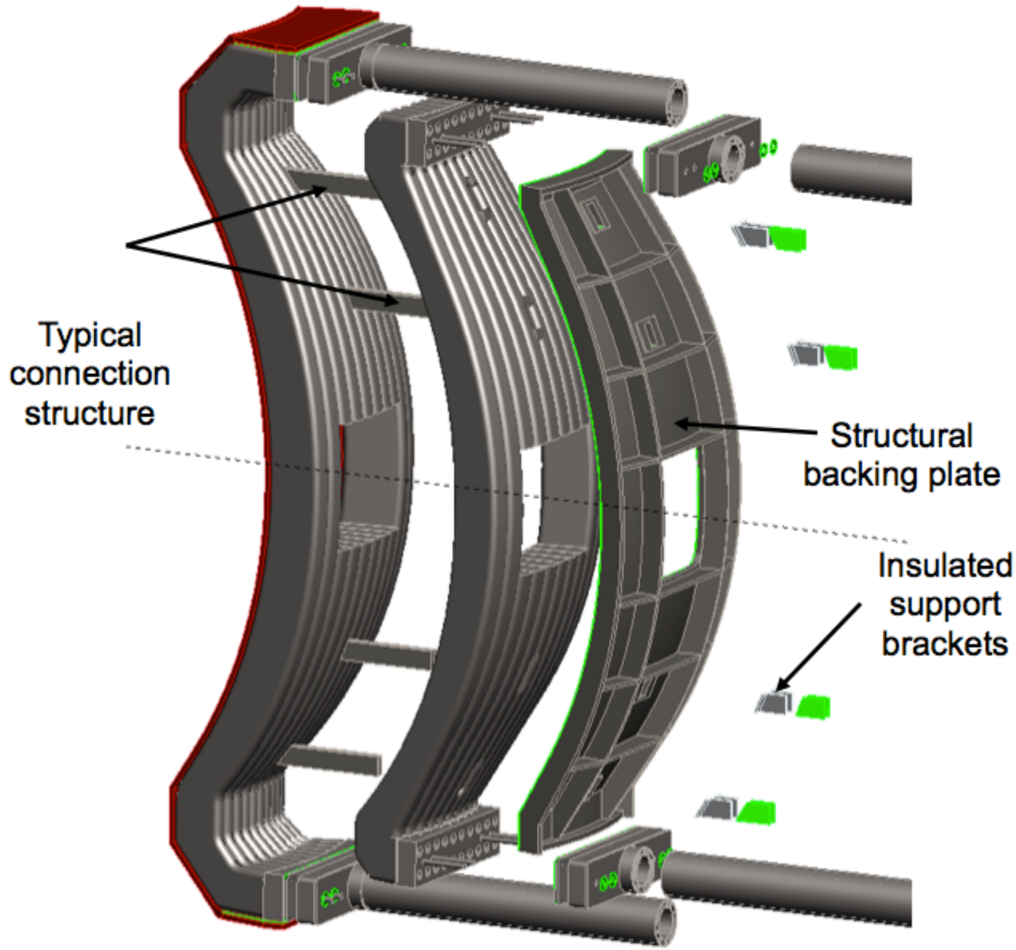


3-D Neutronics model

CHI Design Studies for ST-FNSF have Identified Two Designs with > 2MA Start-up Current Generation Potential

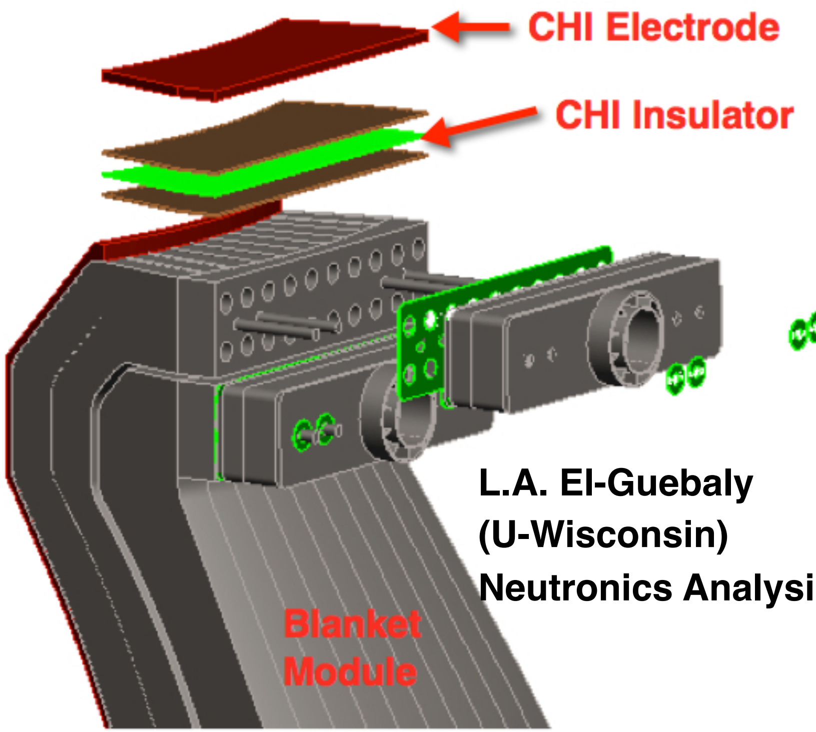
Concept – I (NSTX-like)

***Blanket modules and piping insulated from rest of vessel**



Concept – II (QUEST-like)

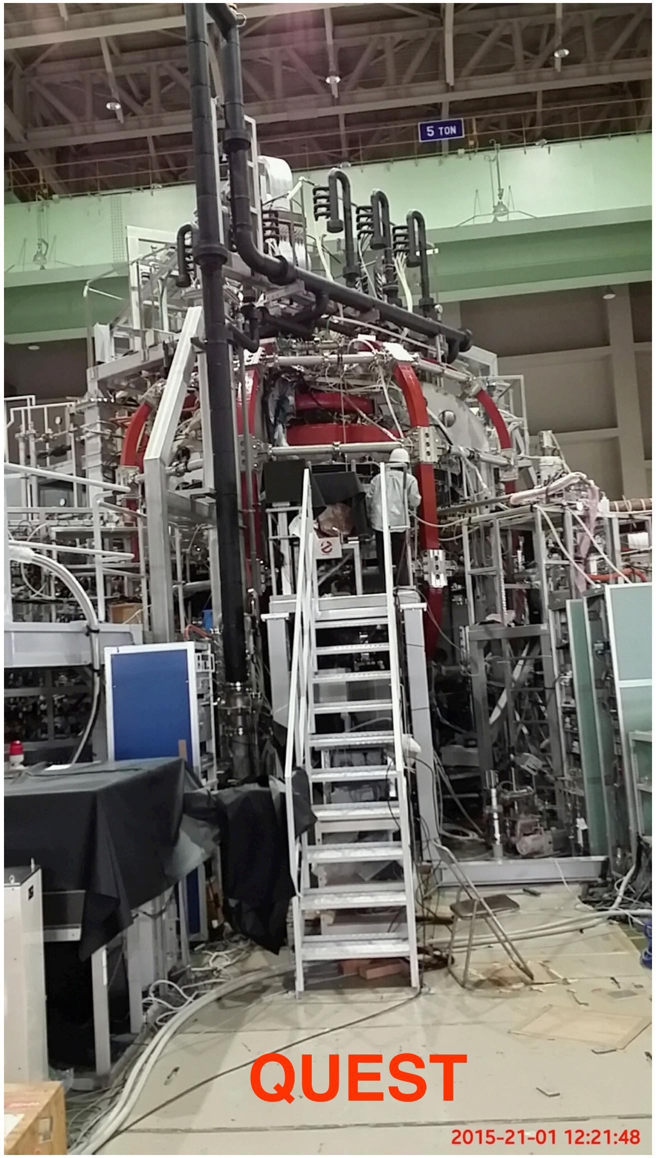
Toroidal electrode on top of blanket structure, analogous to CHI ring electrode previously used on DIII-D



L.A. El-Guebaly (U-Wisconsin) Neutronics Analysis

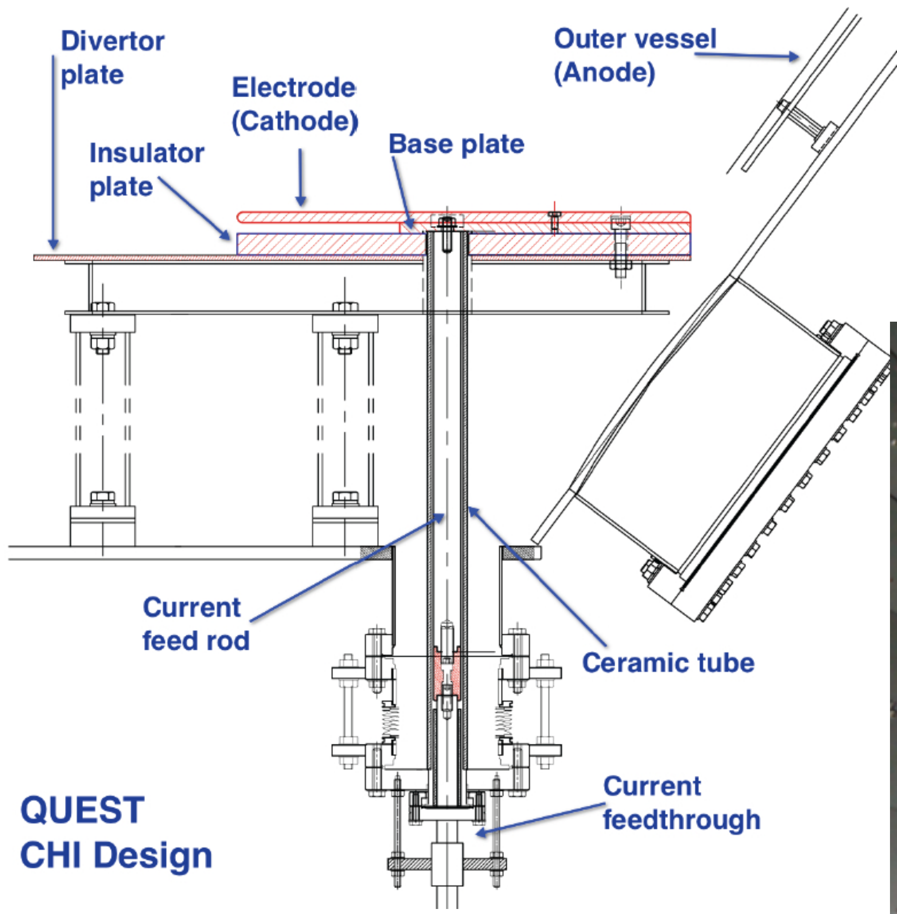
R. Raman, T. Brown, L.A. El-Guebaly, et al., Fusion Science & Technology (2015)

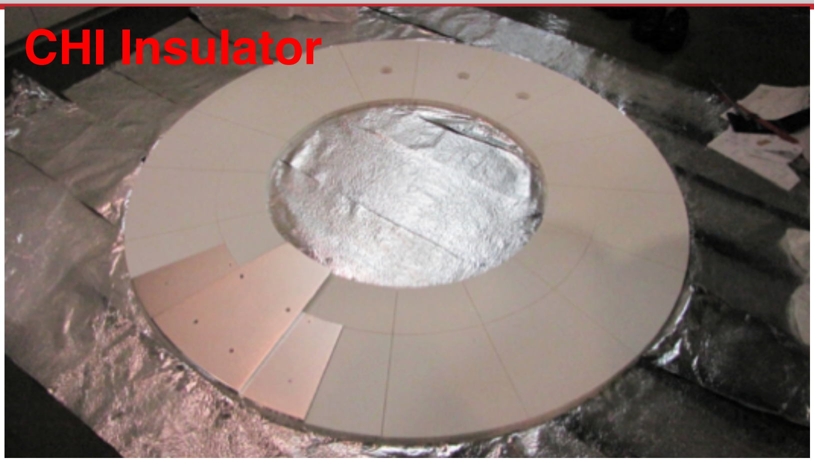
CHI Research on QUEST in Support of NSTX-U and ST-FNSF

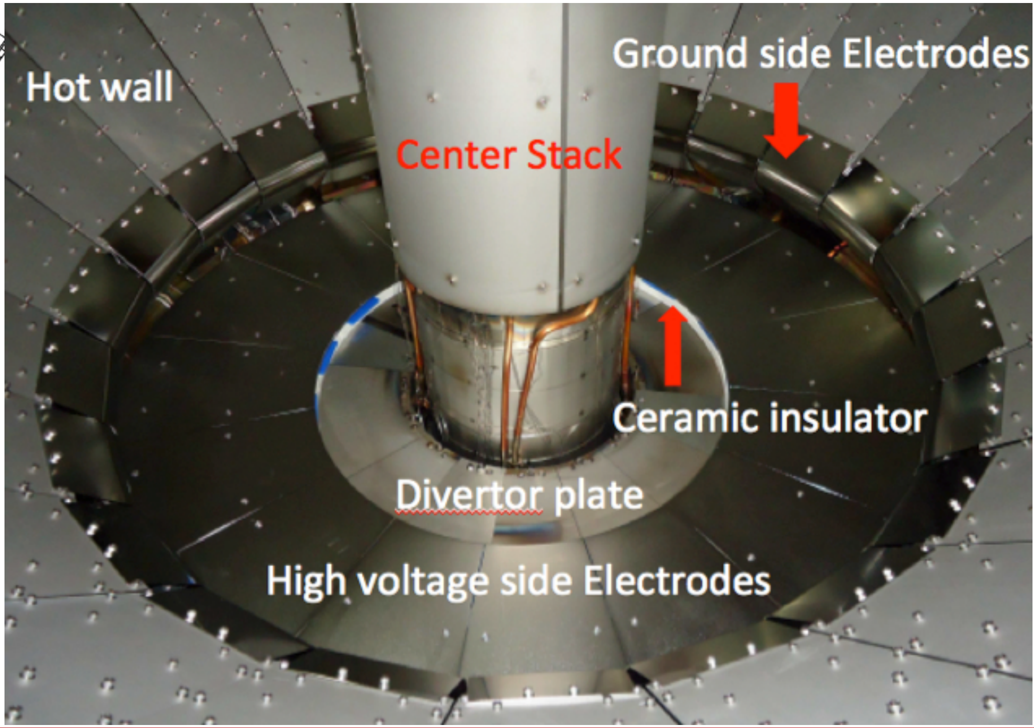


- Test ECH heating of a CHI Target
  - QUEST is equipped with ECH
- Test CHI start-up using metal electrodes
  - Clean metal electrodes should reduce low-Z impurity influx
- Test CHI start-up in an alternate electrode configuration that may be more suitable for a ST-FNSF installation
  - CHI insulator is not part of the vacuum vessel

CHI Configuration on QUEST will Test ST-FNSF Relevant Electrode Design







CHI start-up to ~0.4MA is projected for NSTX-U, and projects to ~20% start-up current in next-step STs

Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Major radius [m]	0.86	0.93	1.2	2.2
Minor radius [m]	0.66	0.62	0.80	1.29
B_T [T]	0.55	1.0	2.2	2.4
Toroidal flux [Wb]	2.5	3.9	15.8	45.7
Sustained I_p [MA]	1	2	10	18
Injector flux (Wb)	0.047	0.1	0.66	2.18
Projected Start-up current (MA)	0.2	0.4	2.0	3.6

Transient CHI Scaling:

Generated Toroidal Current is proportional to Injector Flux

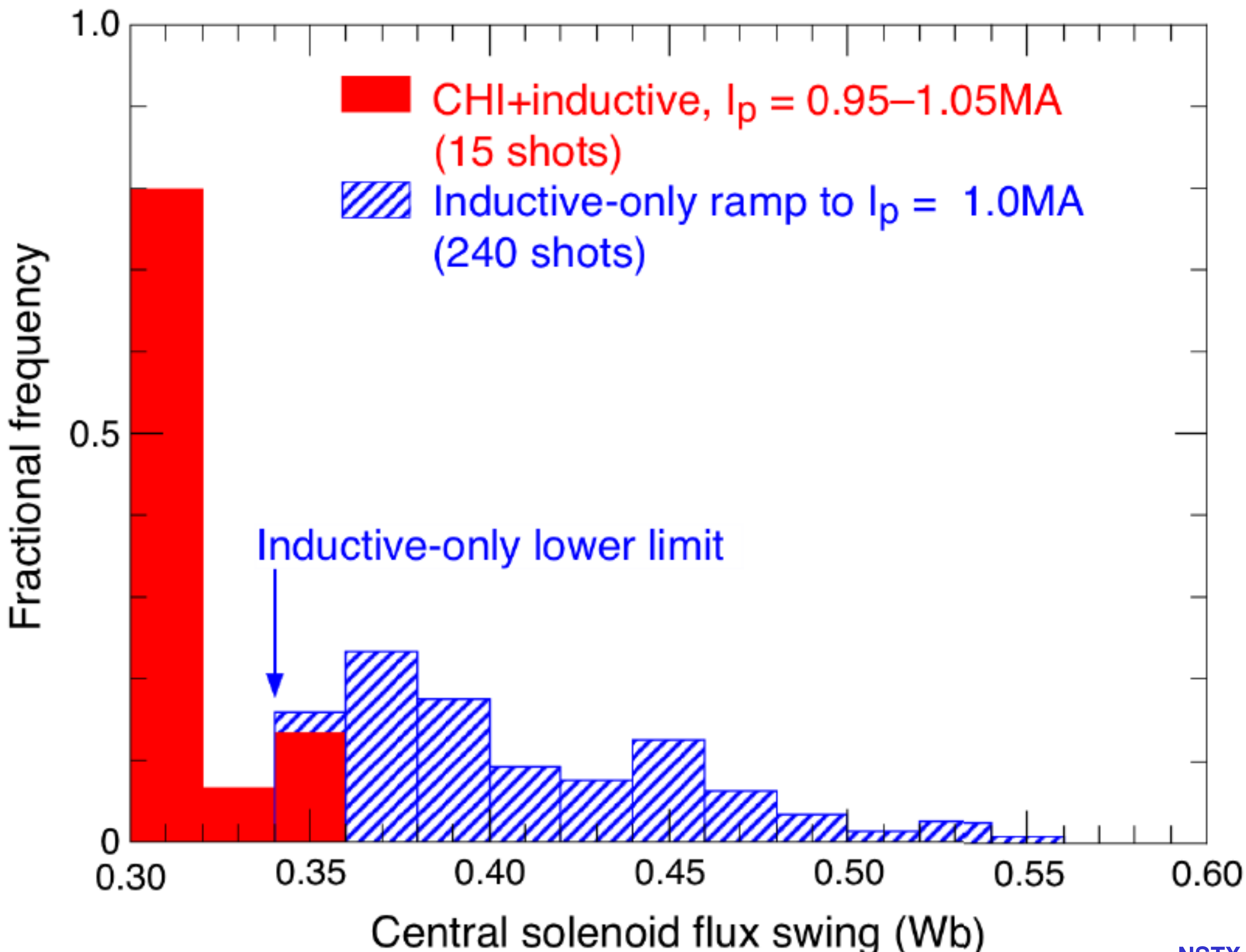
NSTX has Made Considerable Progress Towards Developing a Viable Solenoid-Free Plasma Startup Method

- 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 observed experimentally and in numerical simulations
- NSTX-U is well equipped with new capabilities to study full non-inductive start-up and current ramp-up (2x Higher TF, 1MW ECH, Second Tangential NBI for CD, 2x higher CHI voltage, >2.5x more injector flux, Improved upper divertor coils)

Back-up Slides

CHI Started Discharges Require Less Inductive Flux than Discharges in NSTX Data Base

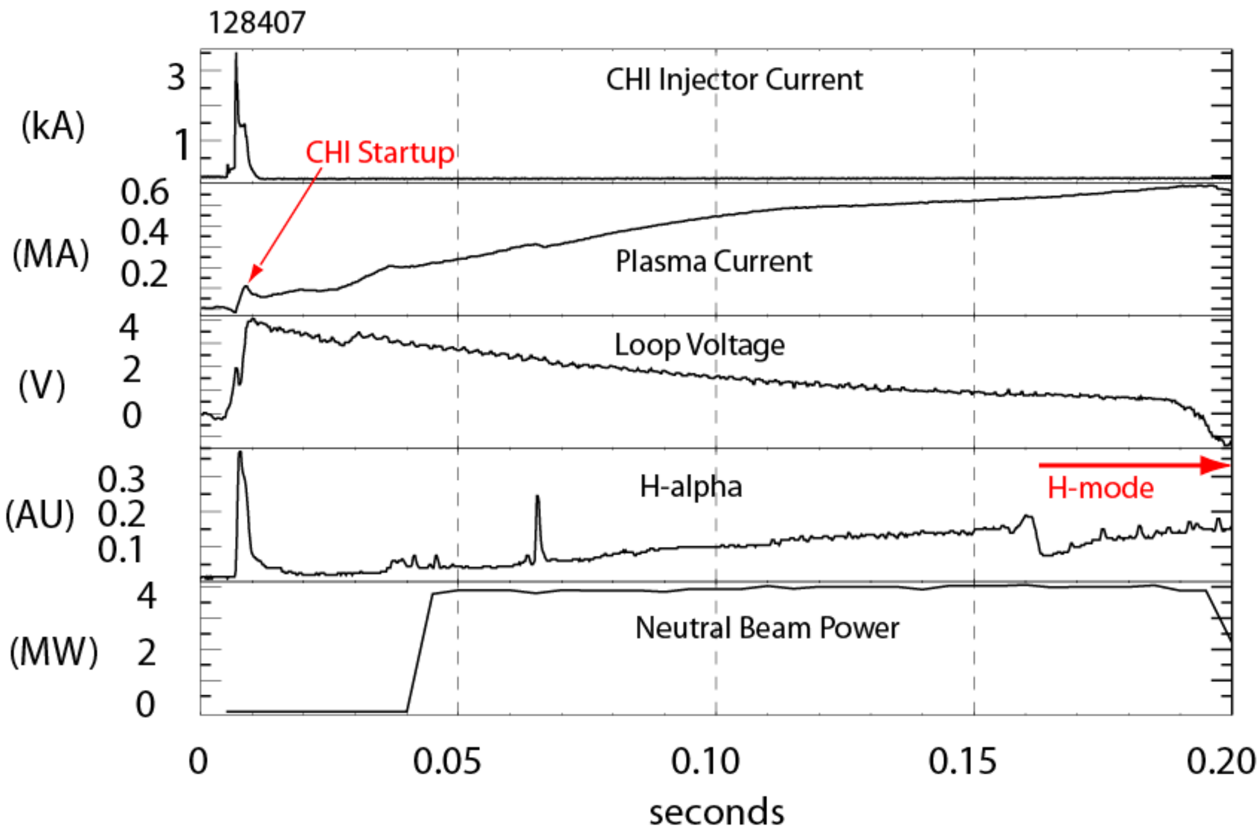
Comparison of CHI Startup to H-modes using more than 1 NBI source



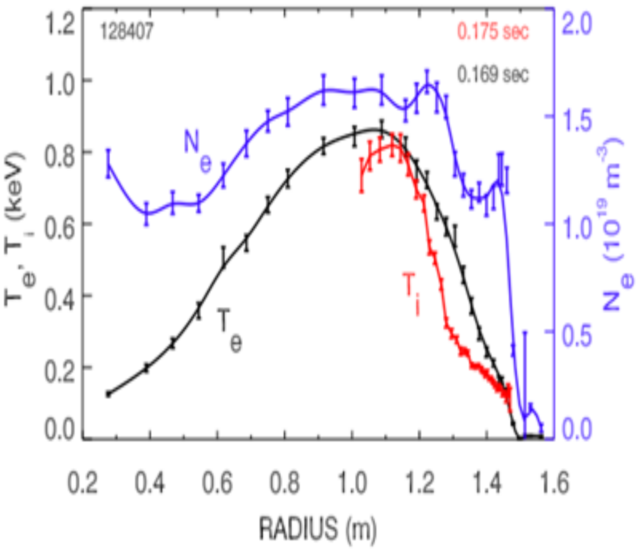
Most recent CHI-started discharges require less flux than shown here

NSTX Data Base Analysis: **M. Bell**

CHI Started Discharge Couples to Induction and Transitions to an H-mode Demonstrating Compatibility with High-performance Plasma Operation



T_e & N_e from Thomson
T_i from CHERS

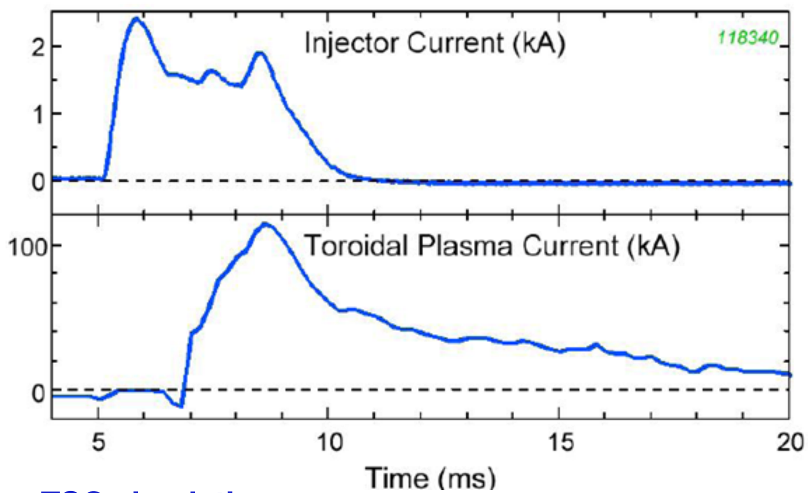


- Discharge is under full plasma equilibrium position control
  - Loop voltage is preprogrammed

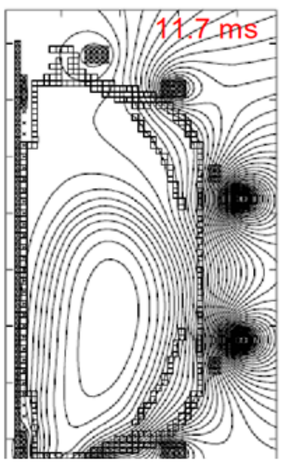
CHERS : R. Bell
Thomson: B. LeBlanc

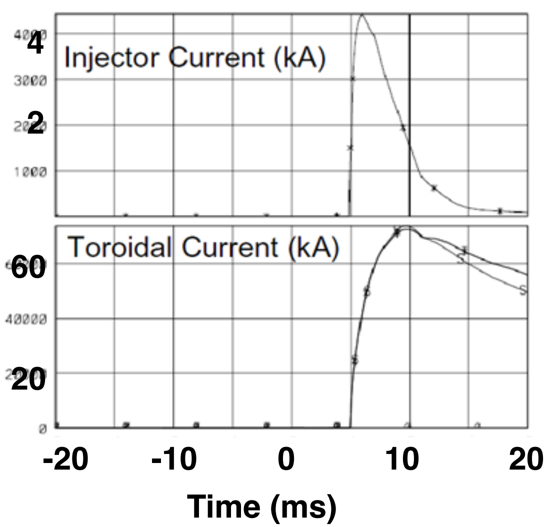
TSC Simulations are being Used to Understand CHI-Scaling with Machine Size

NSTX Experimental result



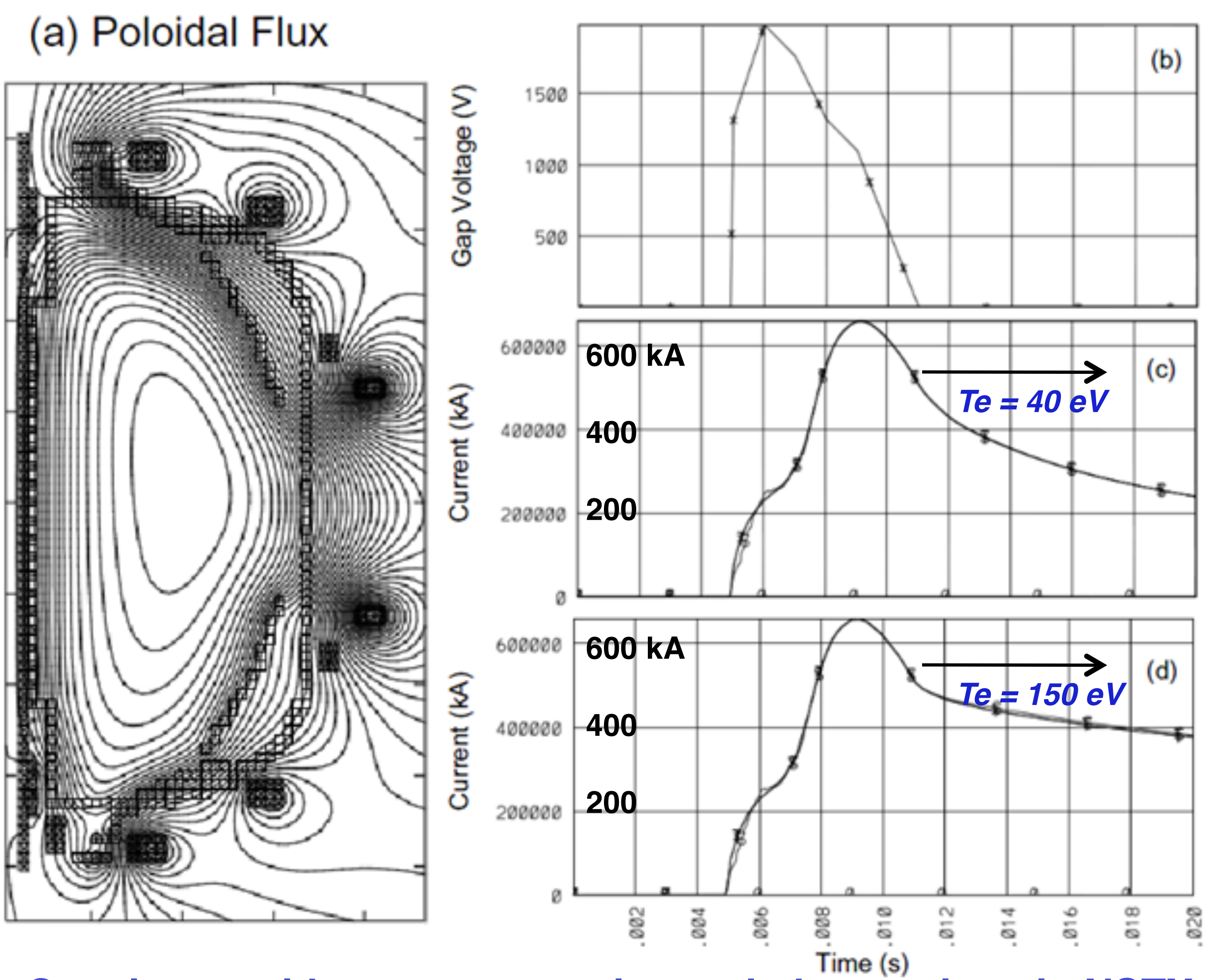
TSC simulation





- **Time-dependent, free-boundary, predictive equilibrium and transport**
- **Solves MHD/Maxwell's equations coupled to transport and Ohm's law**
- **Requires as input:**
  - **Device hardware geometry**
  - **Coil electrical characteristics**
  - **Assumptions concerning discharge characteristics**
- **Models evolutions of free-boundary axisymmetric toroidal plasma on the resistive and energy confinement time scales.**
- **NSTX vacuum vessel modeled as a metallic structure with poloidal breaks**
  - **An electric potential is applied across the break to generate the desired injector current**

TSC Simulations Show 600kA CHI Start-up Capability in NSTX as TF is Increased to 1T

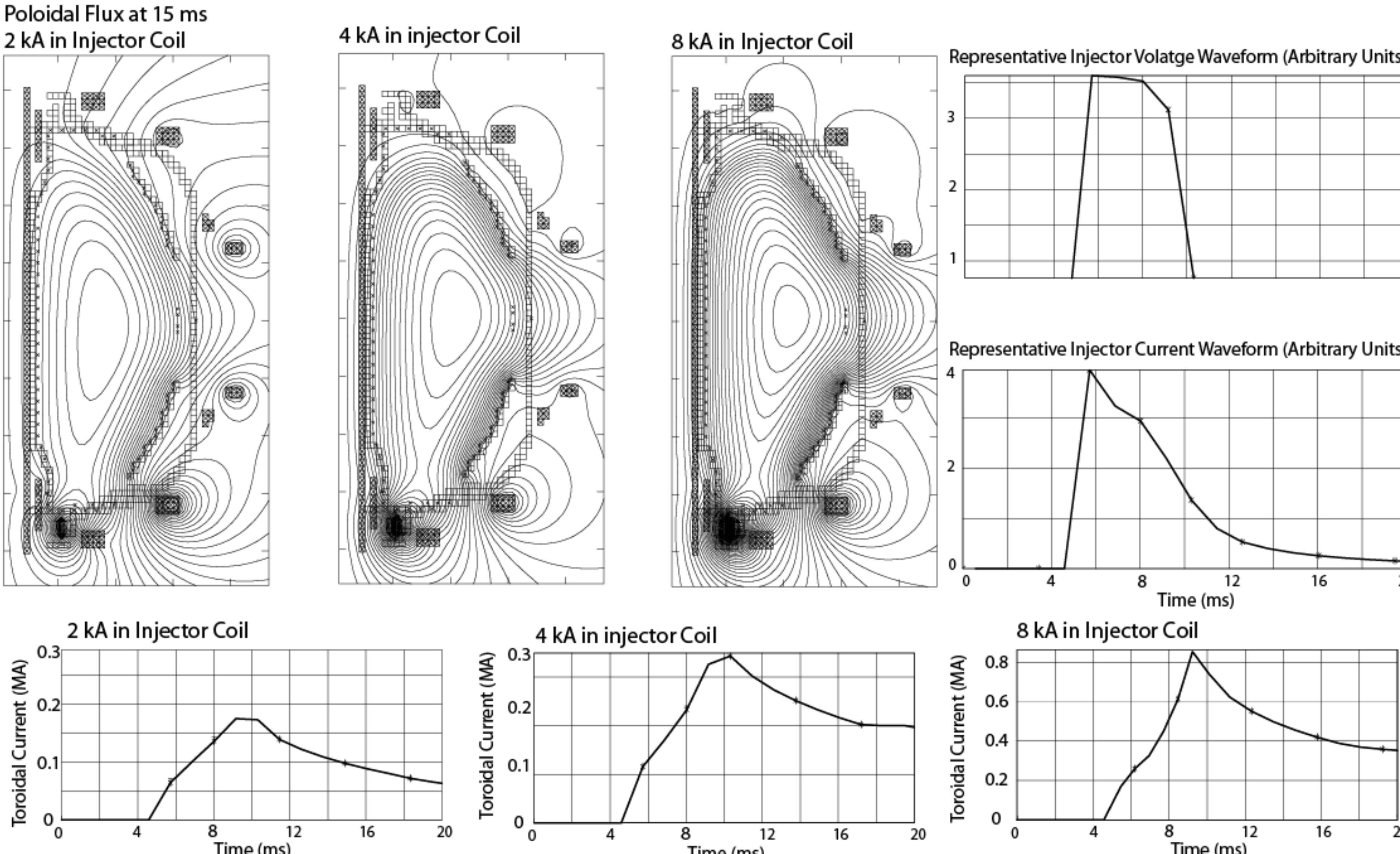


Projected plasma current for CTF >2.5 MA [$I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})$]

- Based on 50 kA injector current (1/5th of the current density previously achieved)
- Current multiplication of 50 (achieved in NSTX)

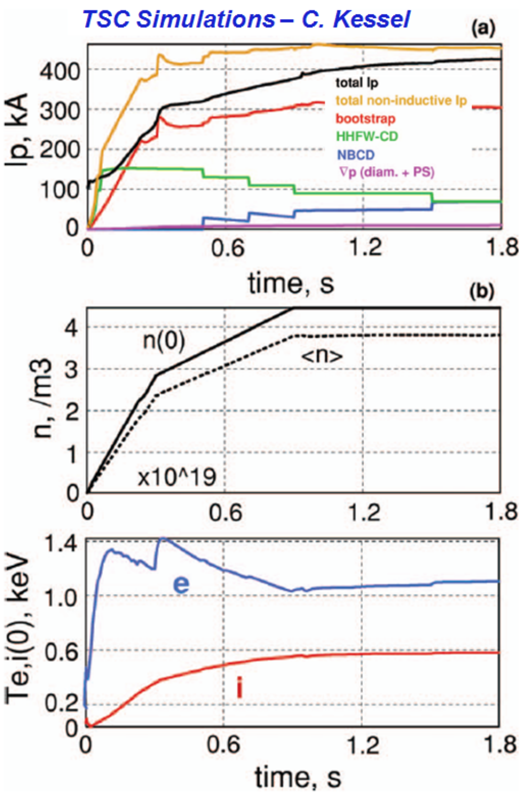
- **Consistent with present experimental observations in NSTX that attain >300kA at 0.5T**
- **NSTX-U will have B_T = 1T capability, ST CTF projected to have B_T about 2.5T**

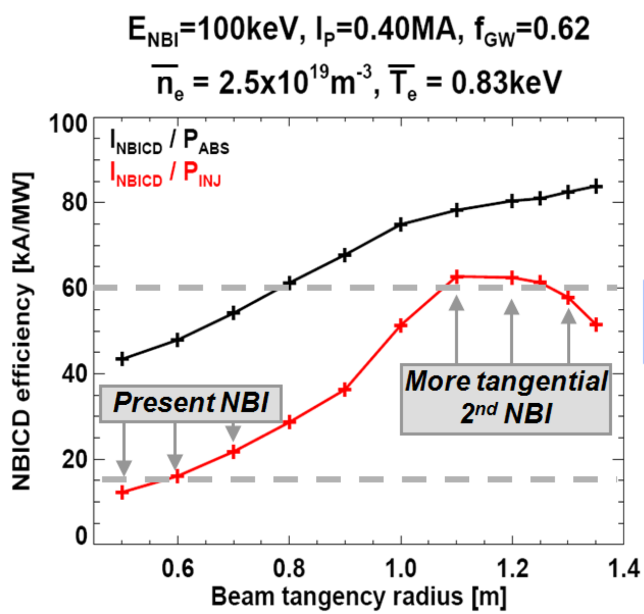
CHI Produced Toroidal Current Increases with Increasing Levels of Current in the CHI Injector Coil (NSTX-U)

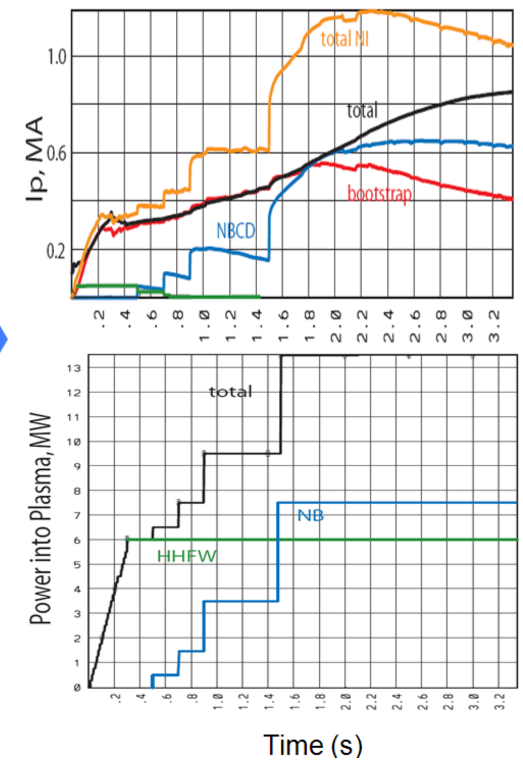


Raman, et al., IEEE Transactions on Plasma Science, Vol 42, No. 8 2154 (2014)

TSC Simulations Indicate 100kA Target could be Ramped-up to 800kA Using HHFW and Tangential NBI in NSTX-U





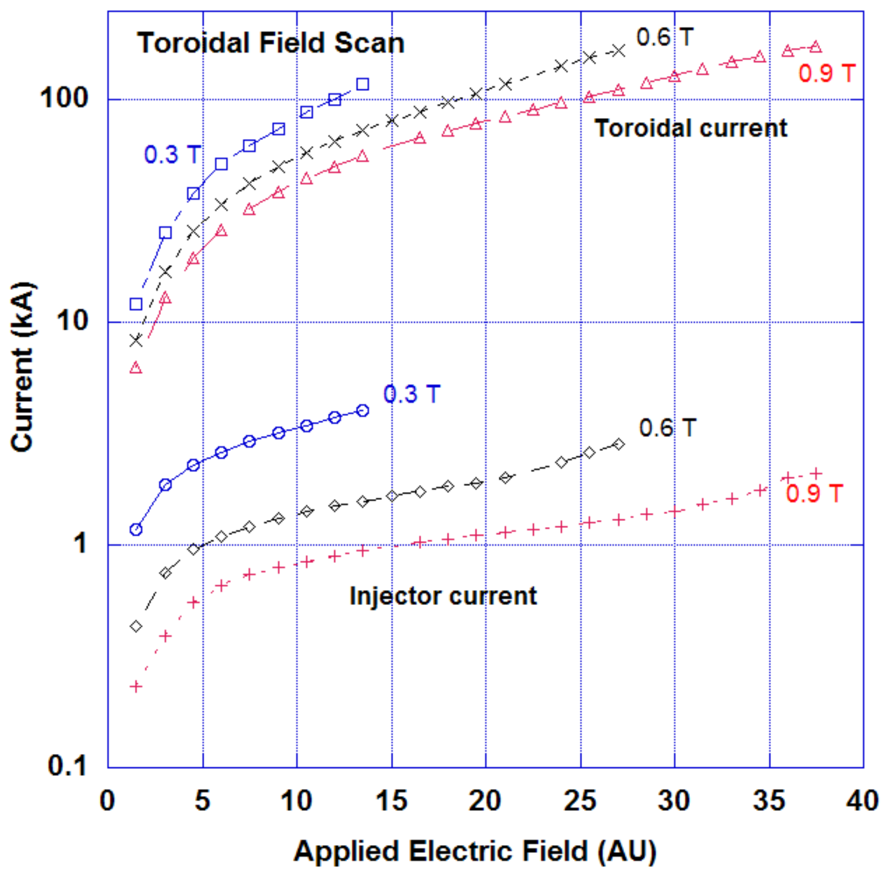


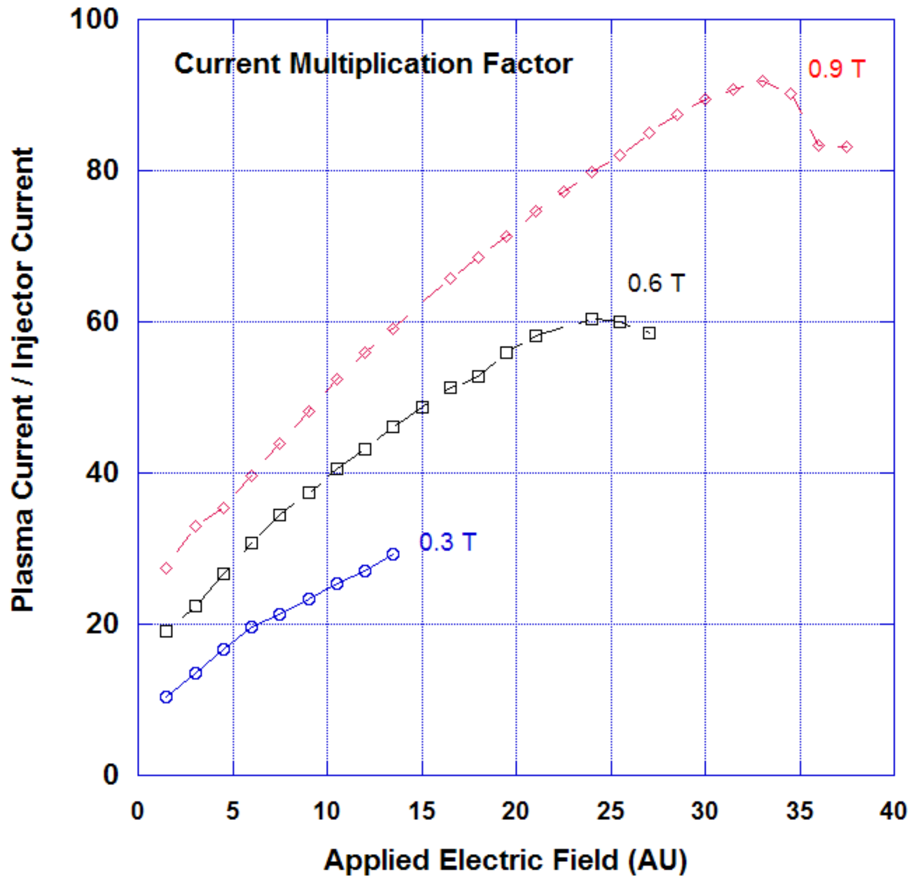
Contributions to the different toroidal currents & required electron density

Toroidal current generated per unit of absorbed neutral beam power and per unit of injected neutral beam power as the beam tangency is varied

Evolution in I_p as it is non-inductively ramped up from an initial 100 kA to more than 800 kA

TSC Simulations Show Increasing Current Multiplication as TF is Increased (NSTX geometry)

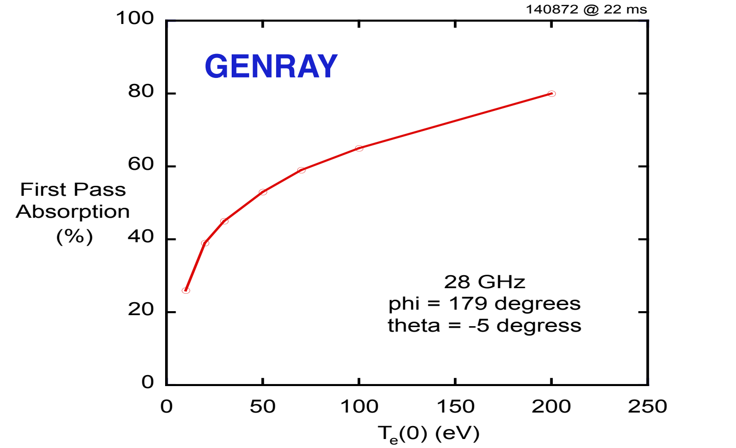


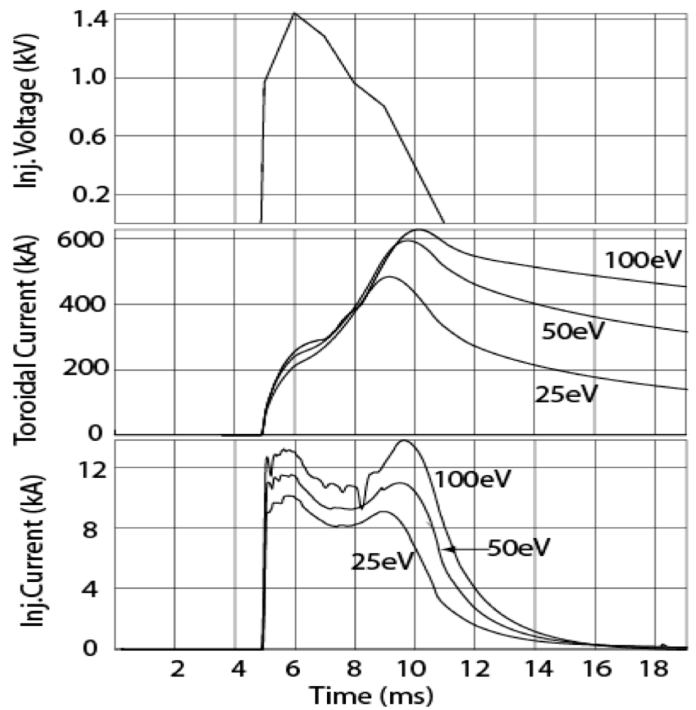


- Observed current multiplication factors similar to observations in NSTX
  - Higher toroidal field important as it reduces injector current requirement

Ramp-up strategy significantly benefits from 1-2 MW ECH to heat CHI plasma

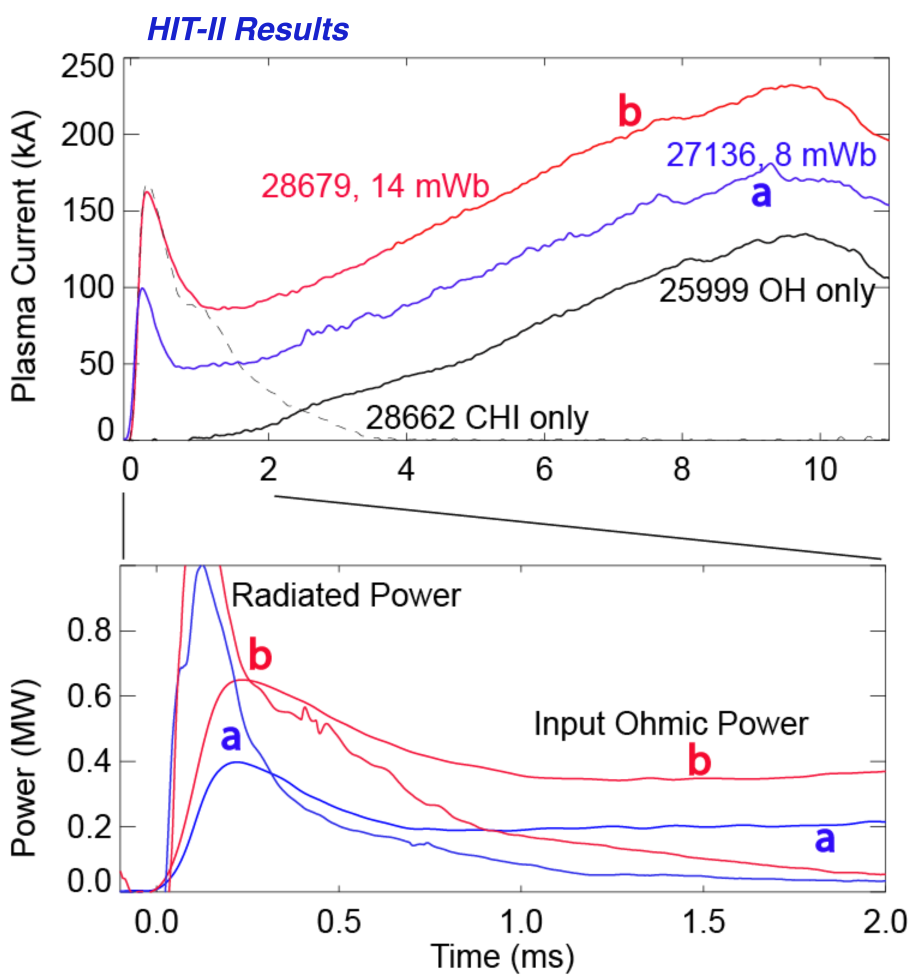
- In a 500kA decaying inductive discharge, TSC* simulations indicate 0.6MW of absorbed ECH power could increase T_e to ~400eV in 20ms (with 50% ITER L-mode scaling)
  - ECH absorption and deposition profile being modeled using GENRAY
  - CHI discharge densities at T_e = 70 eV would allow 60% first-pass absorption by 28 GHz ECH in NSTX-U
- Increased T_e predicted to significantly reduce I_p decay rate
  - ECH heated plasma can be further heated with HHFW
  - Maximum HHFW power < 4MW, higher B_T in NSTX-U would improve coupling
  - HHFW has demonstrated heating a 300 kA / 300 eV plasma to > 1 keV in 40ms





*S.C. Jardin., et al., J. Comput. Phys. 66, 481 (1986)

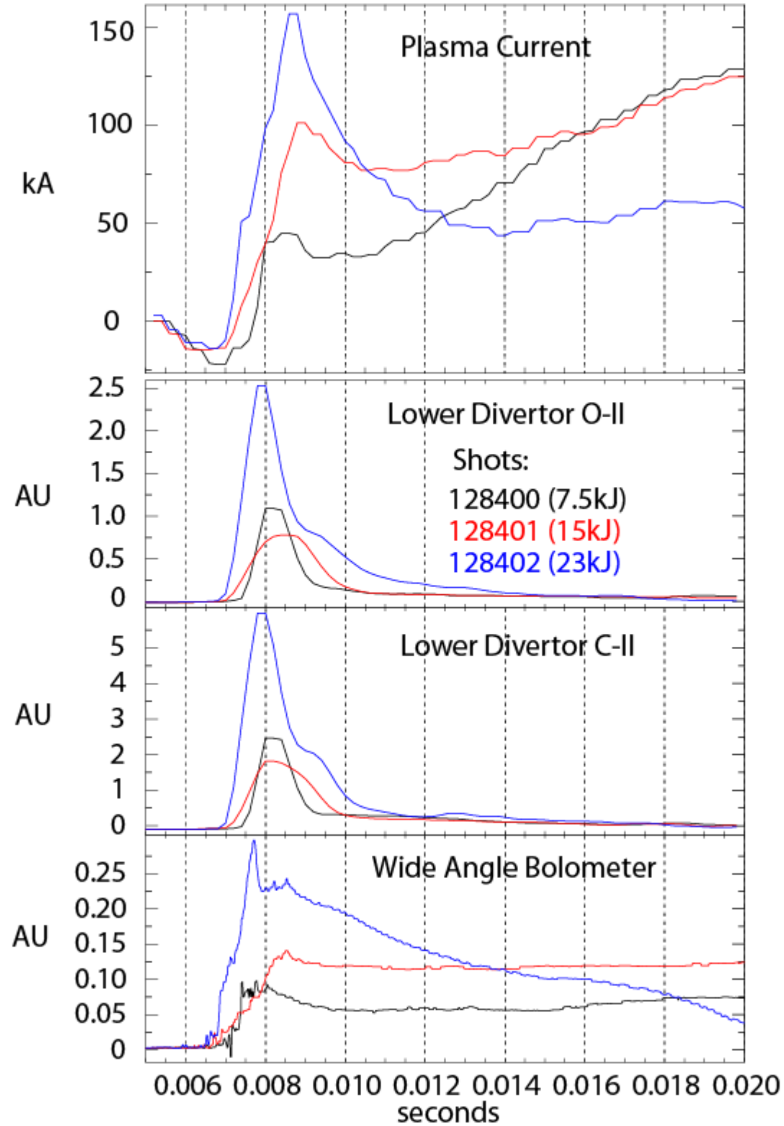
Inductively Coupled Current Ramps-up After Input Power Exceeds Radiated Power



- Identical loop voltage programming for all cases
- Coupling current increases as injector flux is increased
- 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
  - Auxiliary heating would ease requirements on current ramp-up system

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

Low-Z Impurity Radiation Needs to be Reduced for Inductive Coupling

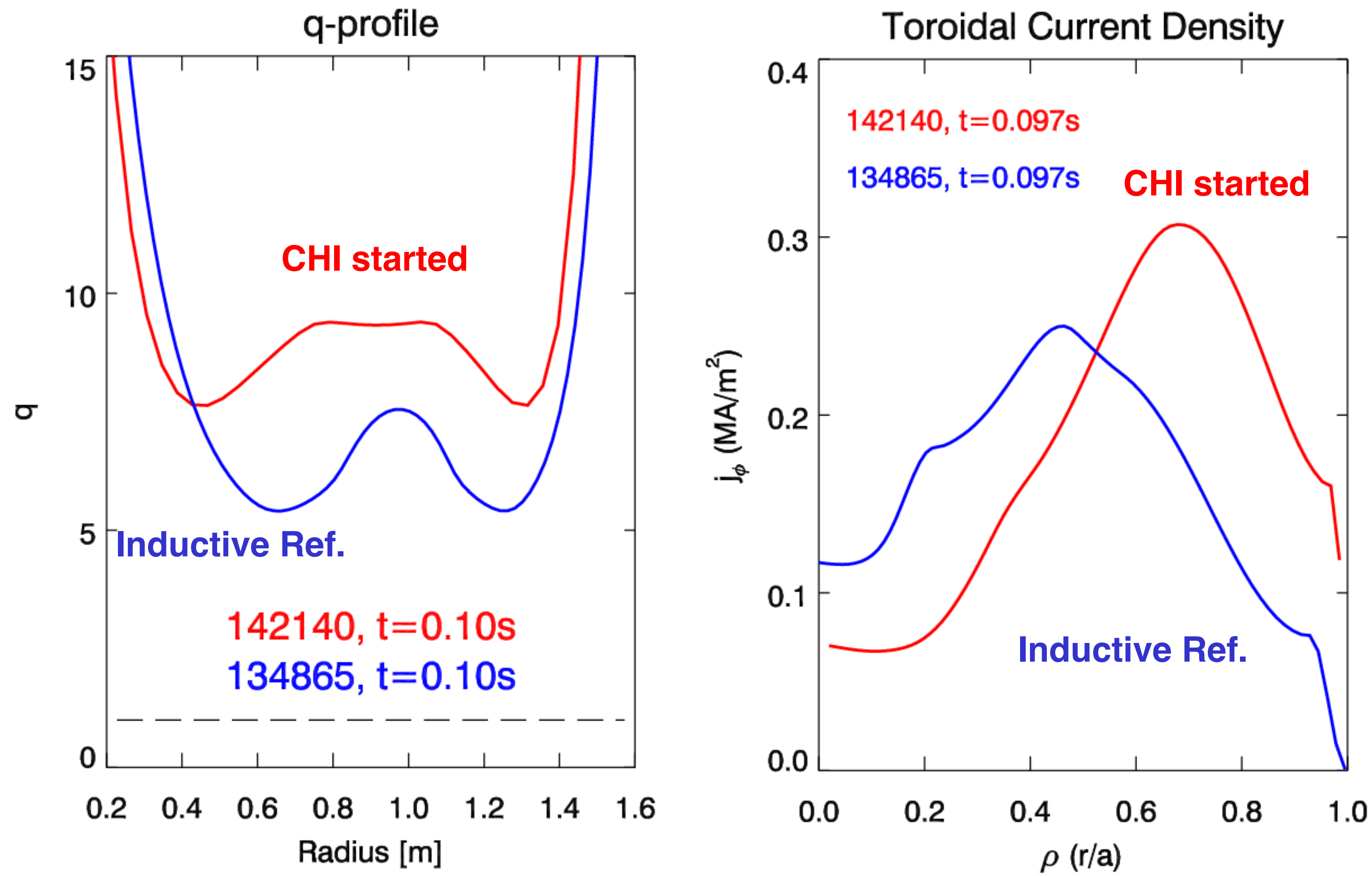


- Low-Z impurity radiation increases with more capacitors
- Possible improvements
  - Metal divertor plates should reduce low-Z impurities
    - High Te in spheromaks (500eV) obtained with metal electrodes
  - Discharge clean divertor with high current DC power supply
  - Use auxiliary heating during the first 20ms

Filter scopes: **V. Soukhanovskii**

CHI Start-up Discharges Show Plasma Current Driven at Large Radius

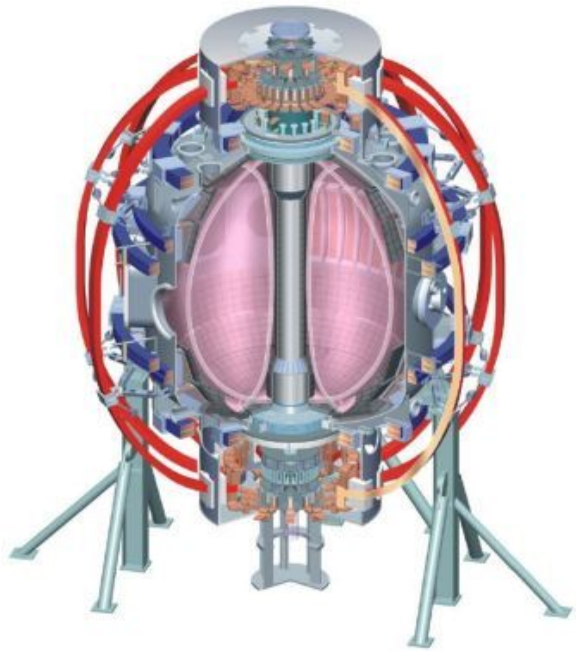
2010 results



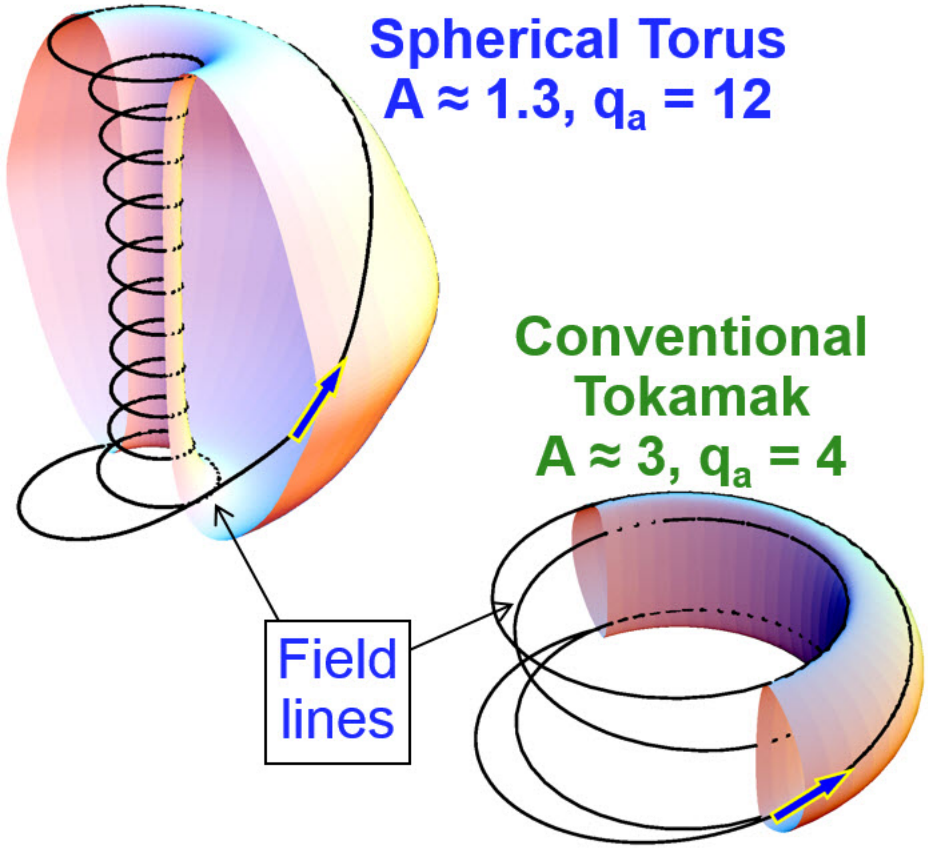
These are the type of plasmas needed for advanced scenario operations

MSE & LRDFIT: H. Yuh, J. Menard, S. Gerhardt

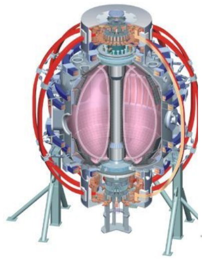
NSTX Studies Toroidal Confinement Physics at Low Aspect-Ratio & Supports ITER Research

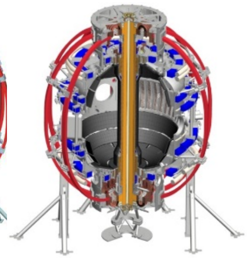


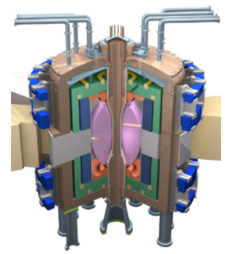
Aspect ratio A	1.3 – 1.6
Elongation κ	1.8 – 3.0
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field	0.55 T
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW

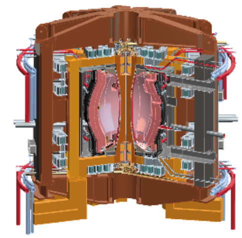


NSTX Upgrade will access next factor of two increase in performance to bridge gaps to next-step STs

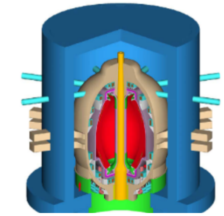




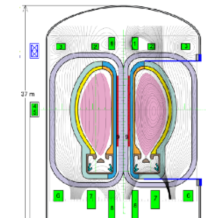




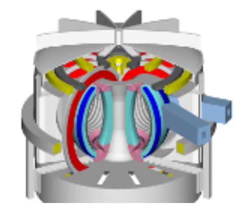
Low-A Power Plants



ARIES-ST (A=1.6)



JUST (A=1.8)



VECTOR (A=2.3)

Parameter	NSTX	NSTX Upgrade	Fusion Nuclear Science Facility	Pilot Plant
Major Radius R_0 [m]	0.86	**0.94**	1.3	1.6 – 2.2
Aspect Ratio R_0 / a	≥ 1.3	**≥ 1.5**	≥ 1.5	≥ 1.7
Plasma Current [MA]	1	**2**	4 – 10	11 – 18
Toroidal Field [T]	0.5	**1**	2 – 3	2.4 – 3
Auxiliary Power [MW]	≤ 8	**≤ 19***	22 – 45	50 – 85
P/R [MW/m]	10	**20**	30 – 60	70 – 90
P/S [MW/m^2]	0.2	**0.4**	0.6 – 1.2	0.7 – 0.9
Fusion Gain Q			1 – 2	2 – 10

- **** Includes 4MW of high-harmonic fast-wave (HHFW) heating power***

Key issues to resolve for next-step STs

- **Confinement scaling (electron transport)**
- **Non-inductive ramp-up and sustainment**
- **Divertor solutions for mitigating high heat flux**
- **Radiation-tolerant magnets (for Cu TF STs)**