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Coupling of Coaxial Helicity Injection plasma start-up to inductive ramp-up on the National Spherical Torus Experiment

D. Mueller, R. Raman, M. G. Bell, T.R. Jarboe, B.P. LeBlanc, B.A. Nelson, A.L. Roquemore, S.A. Sabbagh, and V.A. Soukhanovskii

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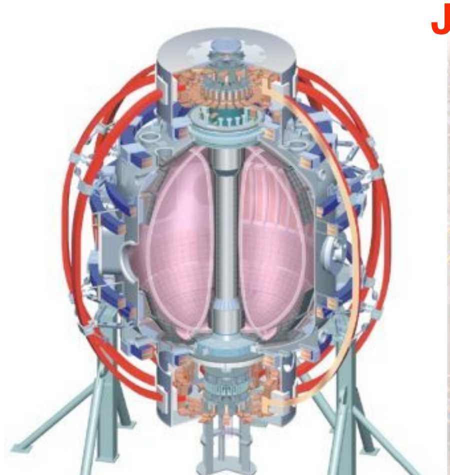

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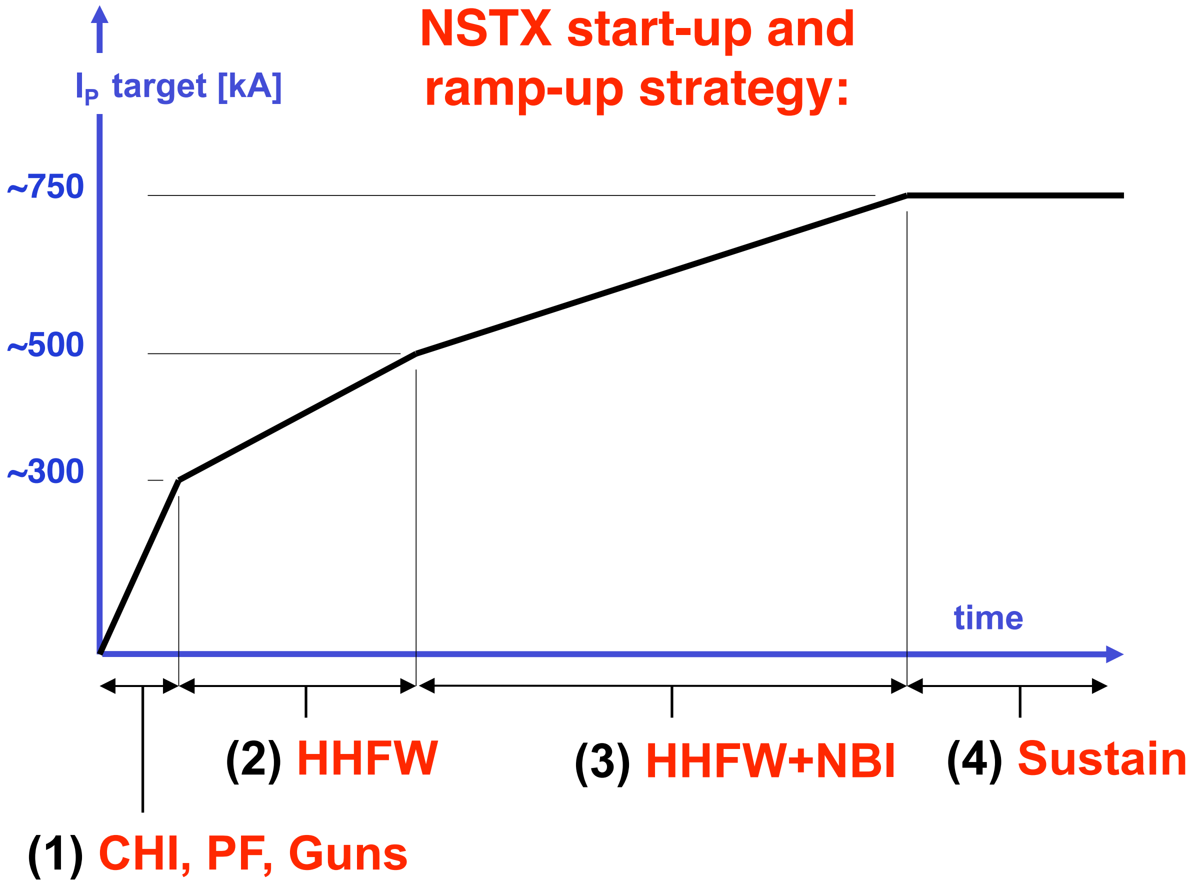
Non-inductive start-up and ramp-up is a high priority for the future of the ST

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

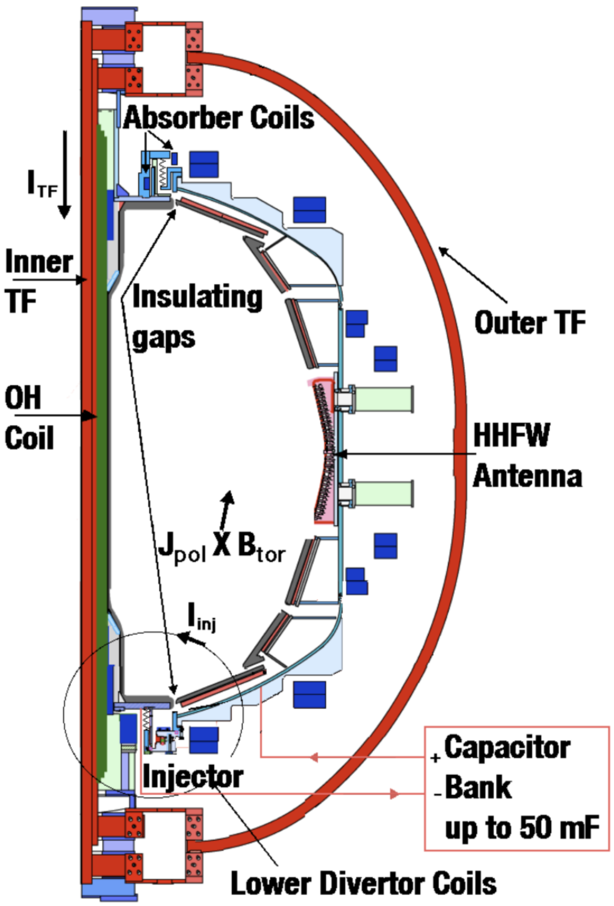
(2) Sufficiently high P_{RF}, τ_E must be achieved for I_P overdrive using BS and HHFW current drive

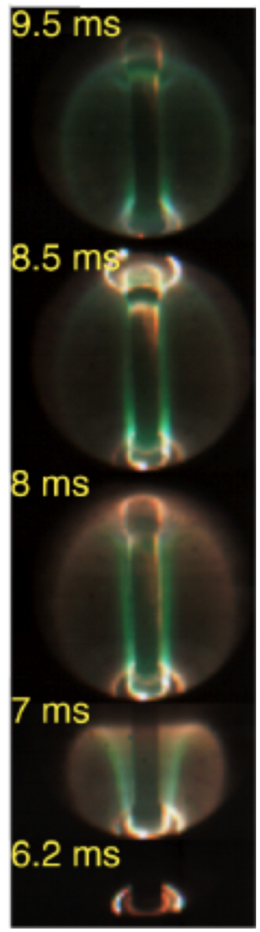
(2→3) Sufficiently high I_P needed to absorb NBI, high P_{HEAT}, τ_E, β_P needed for current overdrive

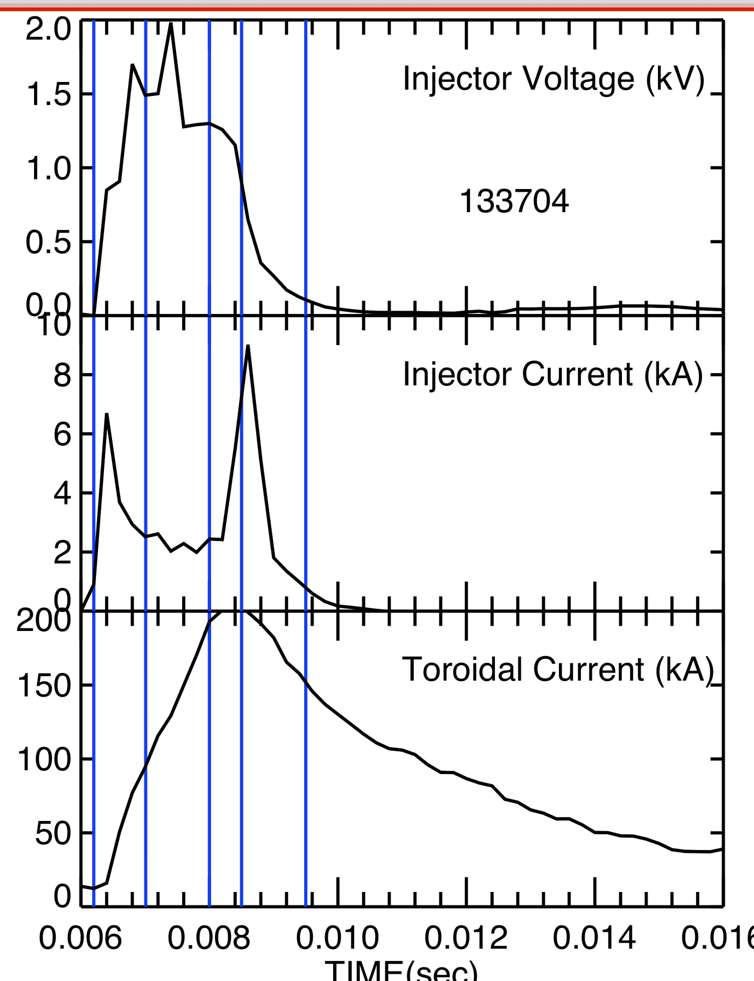
(3→4) Ramp-up plasma must be consistent with sustained high-f_{NI} scenario

The NSTX non-solenoid plans are to progressively reduce the use of the central solenoid to investigate fully non-inductive discharges

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

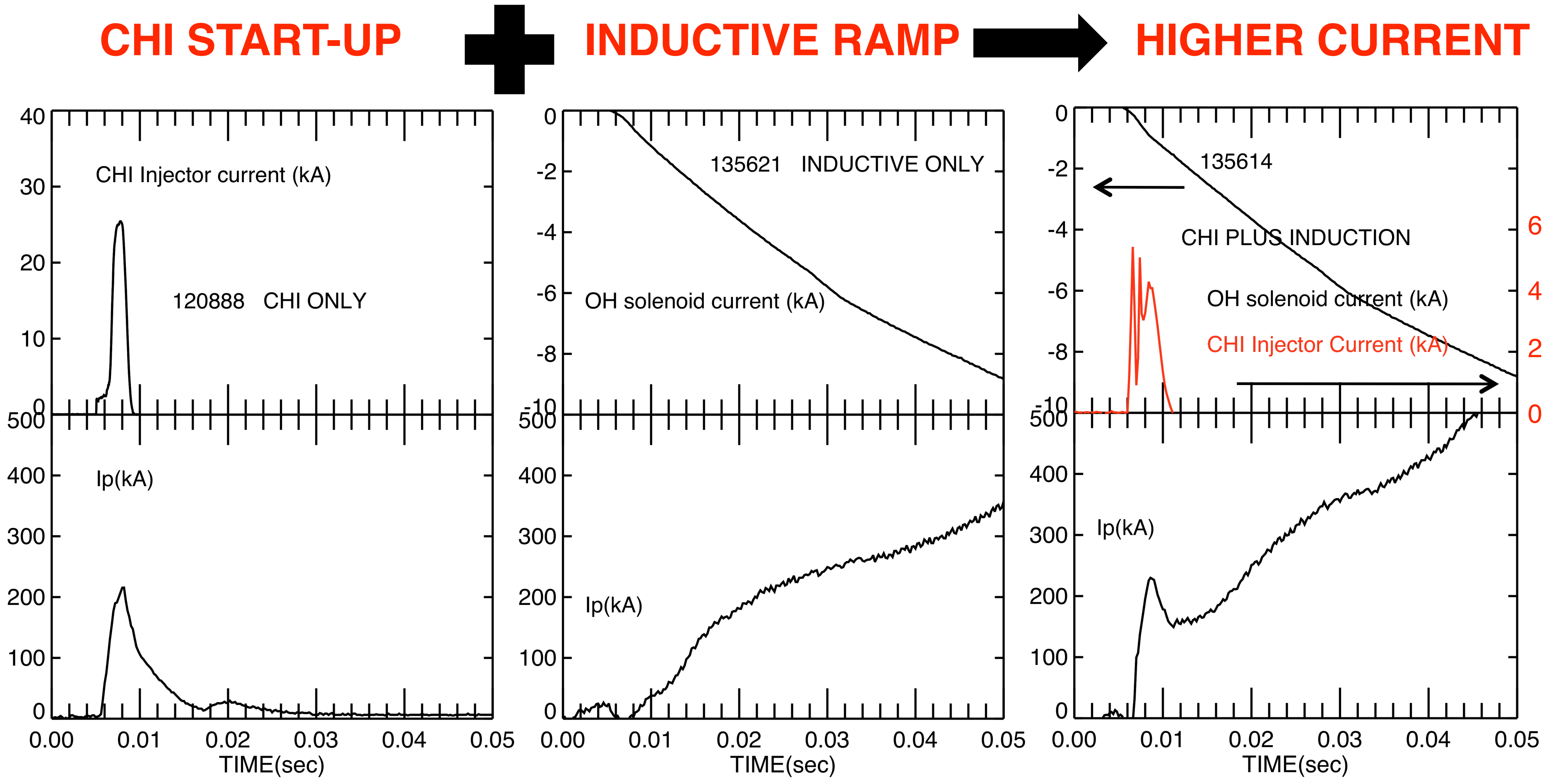






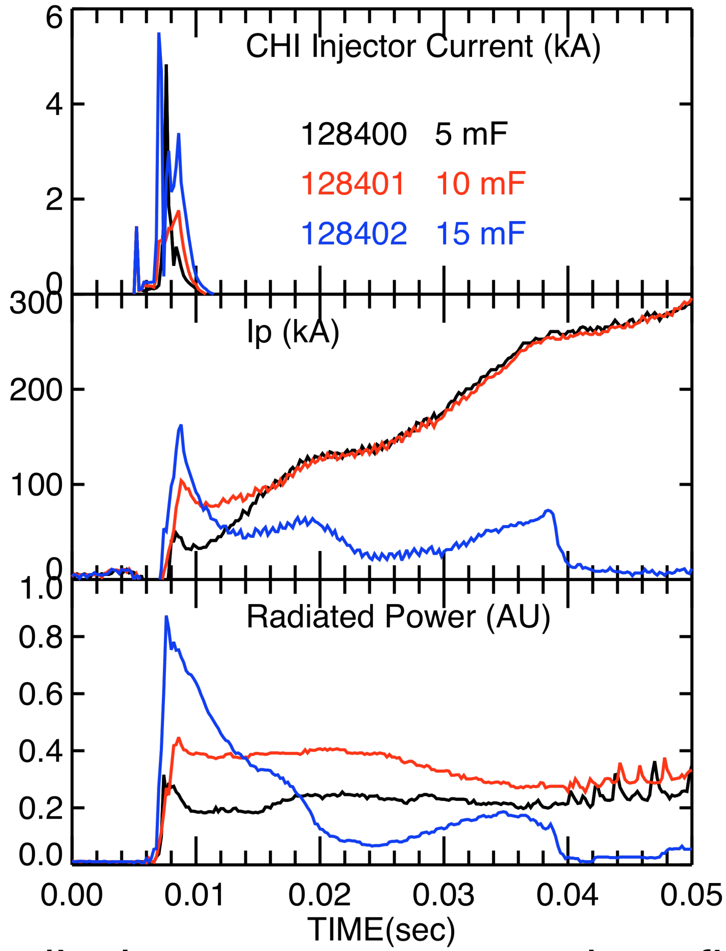
- Initial plasma on helical field lines in the injector region expands upward due to the $J_{pol} \times B_{tor}$ to fill the vessel
- Removing the injector voltage brings the injector current quickly to zero

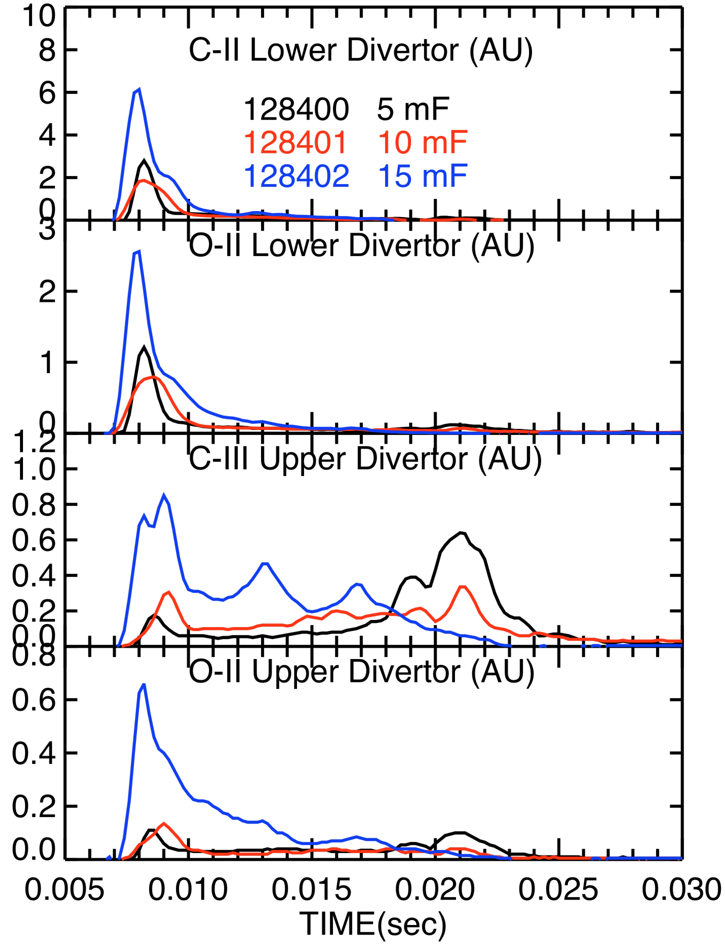
Add inductive drive to CHI formed plasma



- ***The goal is to use CHI to establish a discharge that can be ramped up by other means***

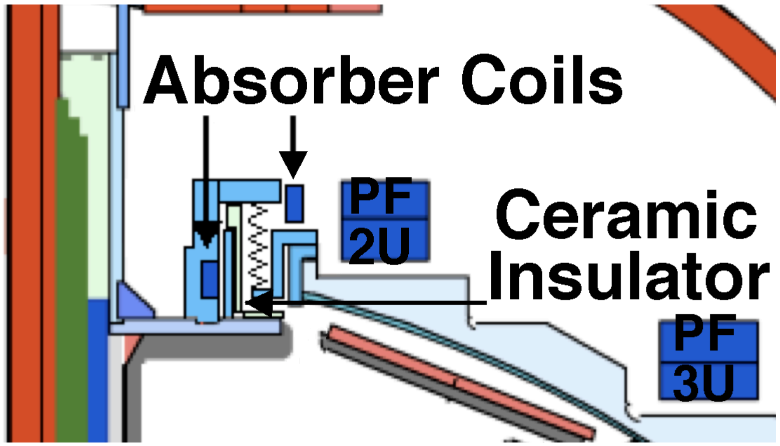
Low-Z impurities can limit the ability to ramp-up a CHI-initiated discharge with the central solenoid

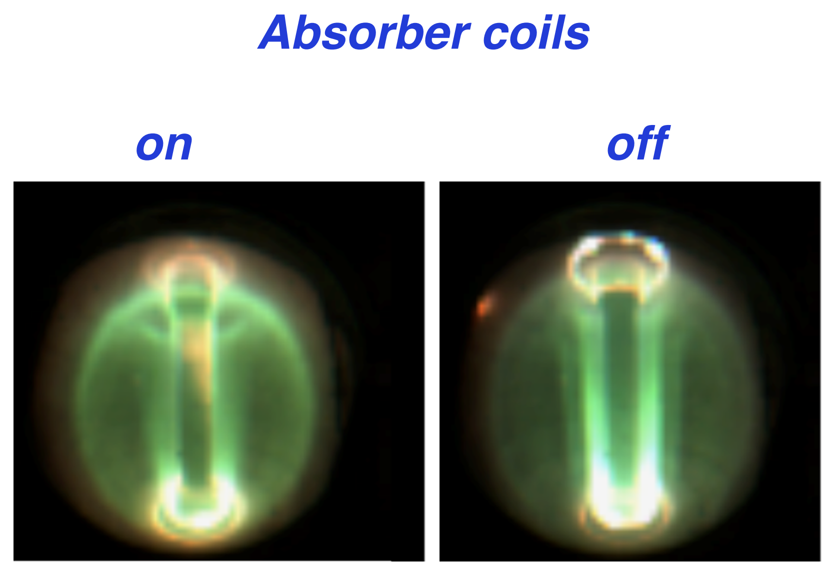




- As the discharges grow upwards to fill the vessel absorber arcs occur.
- Applied V_{loop} ~ 3.5 V/turn
- Low-Z impurities increase with increasing injector current and capacitor energy

Use of the Absorber Coils can limit vertical growth of the plasma and prevent unwanted arcs in the absorber

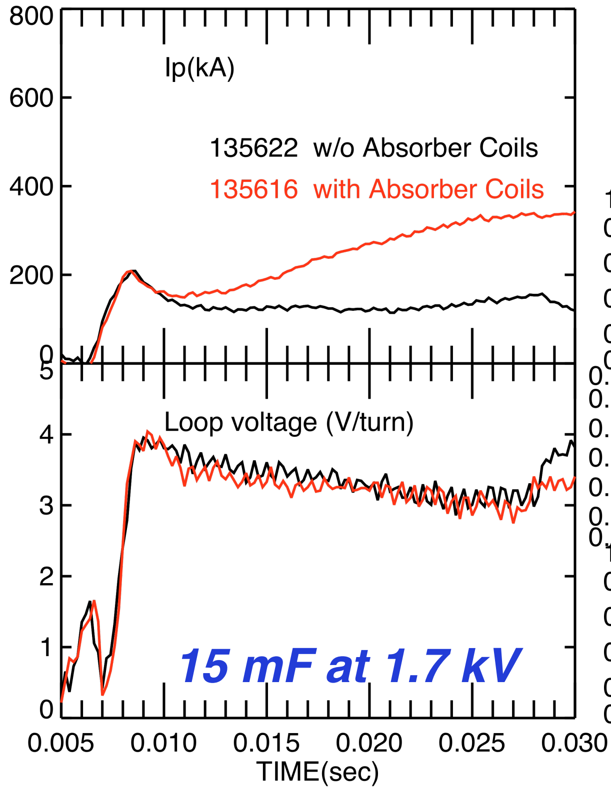


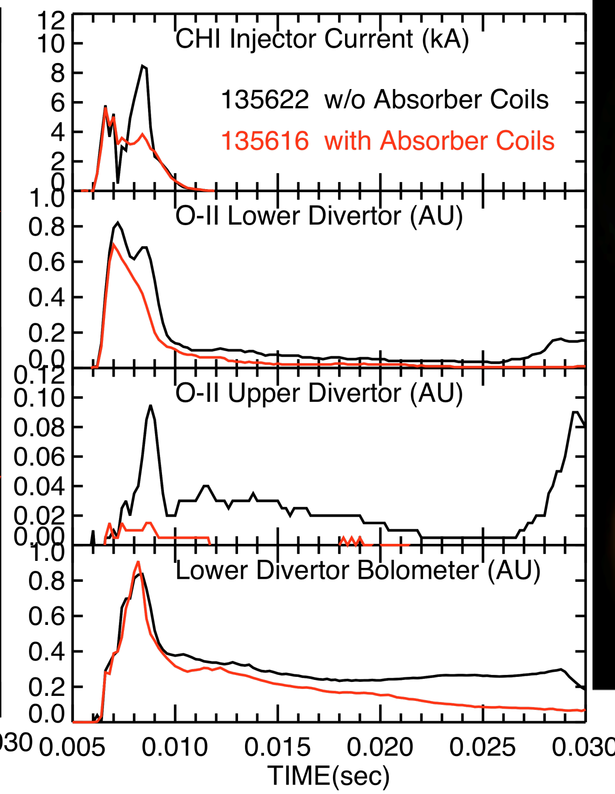


- Providing a buffer flux prevents the plasma from growing into the absorber gap and eliminates arcs
- When arcs occur, low-Z impurities, primarily carbon and oxygen, are introduced into the discharge

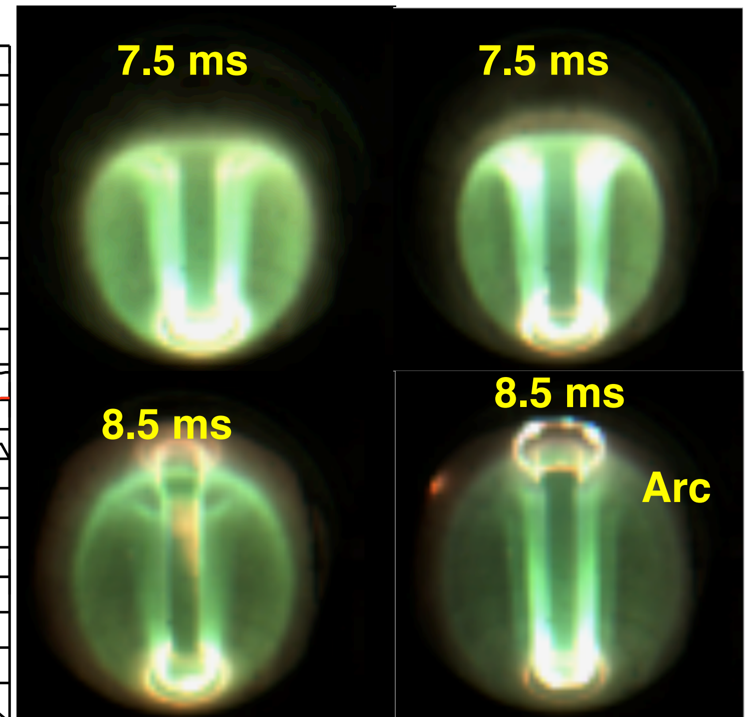
Radial field from absorber coils prevent plasma from reaching absorber gap and reduces impurity influx

Red with Absorber Coils ***Black without***





With Absorber Coils **Without**



- Only the discharge without an absorber arc couples to inductive ramp-up
- Absorber arcs raise low-Z impurities, limit the ability to couple to ramp-up
- Use of the absorber coils reduces arcs, reduces impurity influx and improves coupling to inductive ramp-up

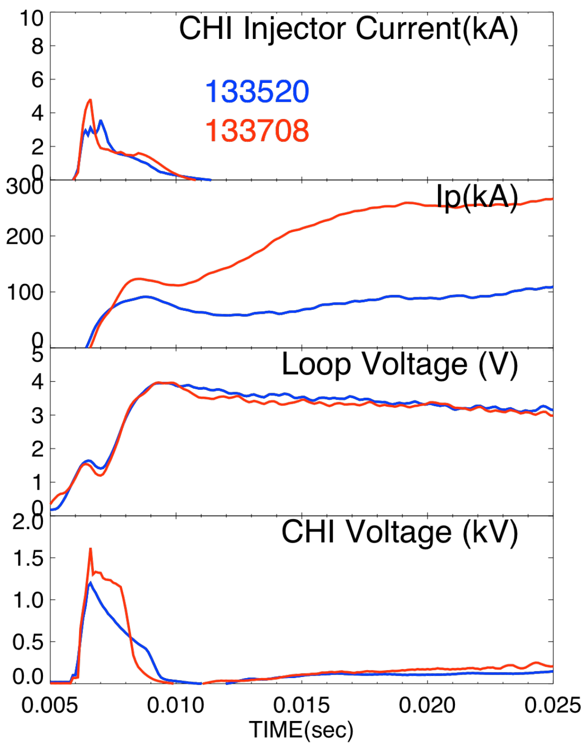
Discharge cleaning and lithium evaporation reduce low Z impurities and improve the coupling to inductive ramp-up

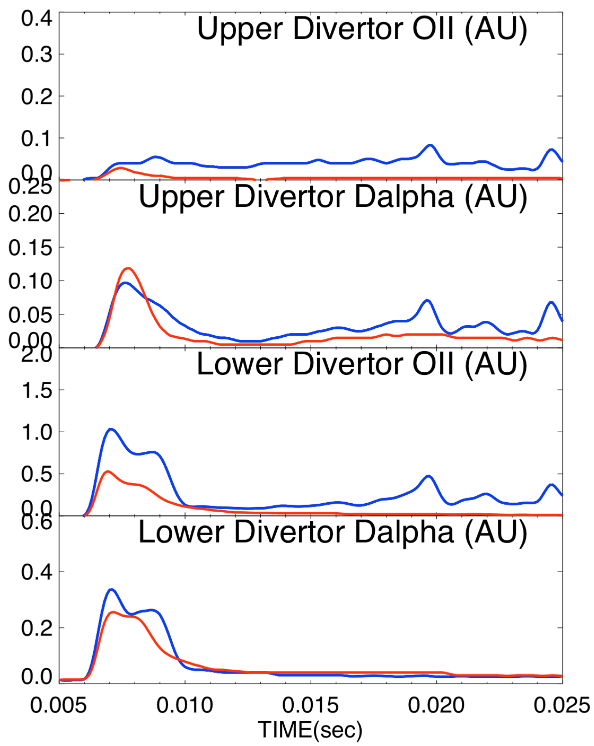
- ***Blue before conditioning***
- ***Red after conditioning and with lithium evaporation***

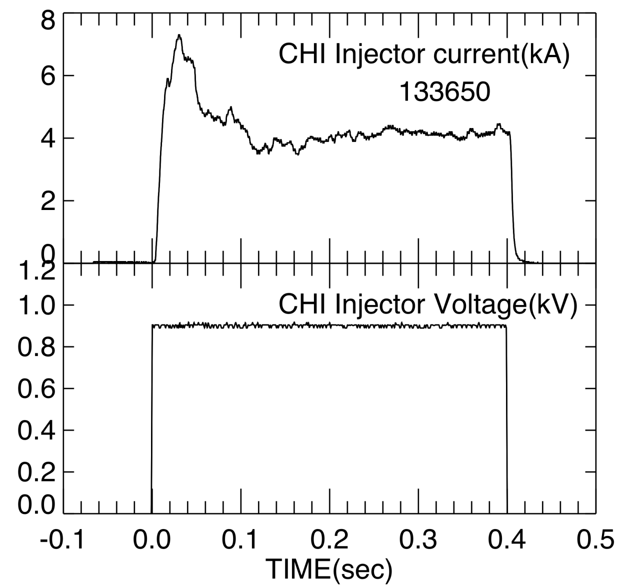
Conditioning Discharge

CHI rectifier supply – long pulse

High poloidal flux – limits expansion



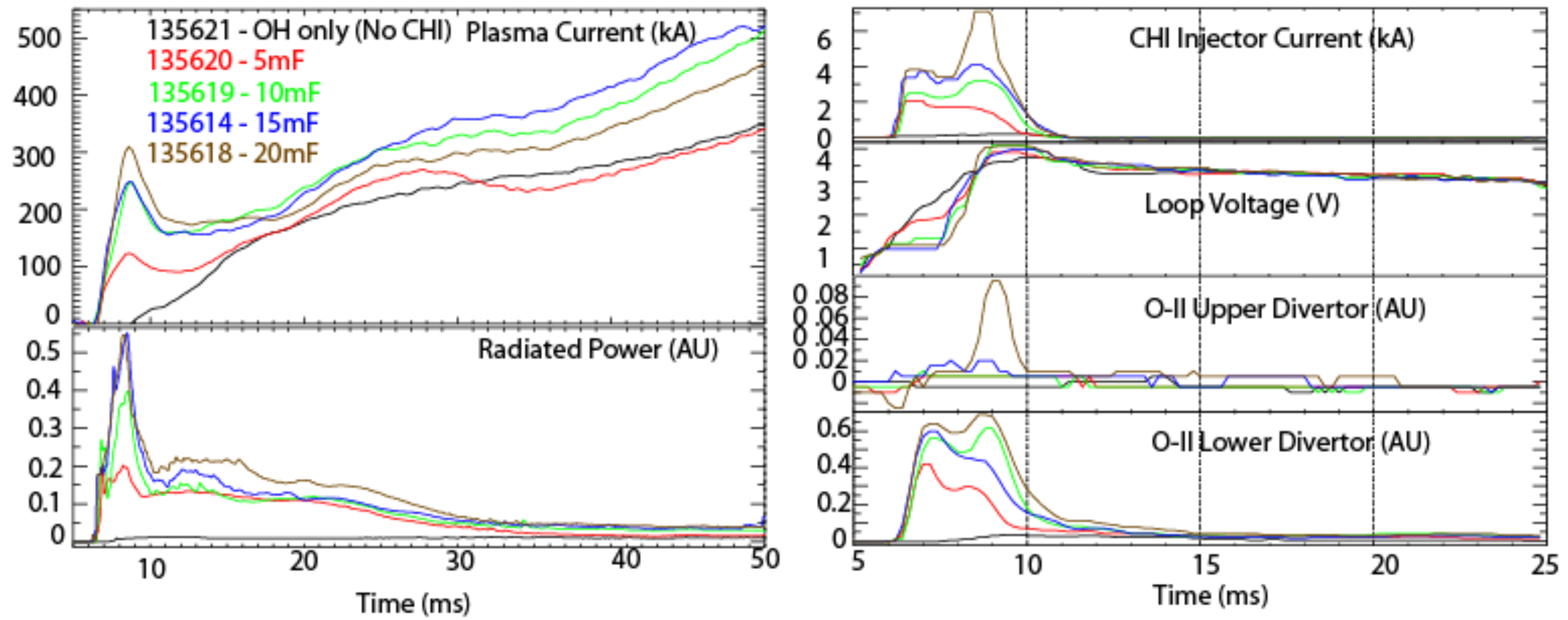




- Conditioning of the lower divertor is also important

Final plasma current increases with CHI energy until absorber arc occurs

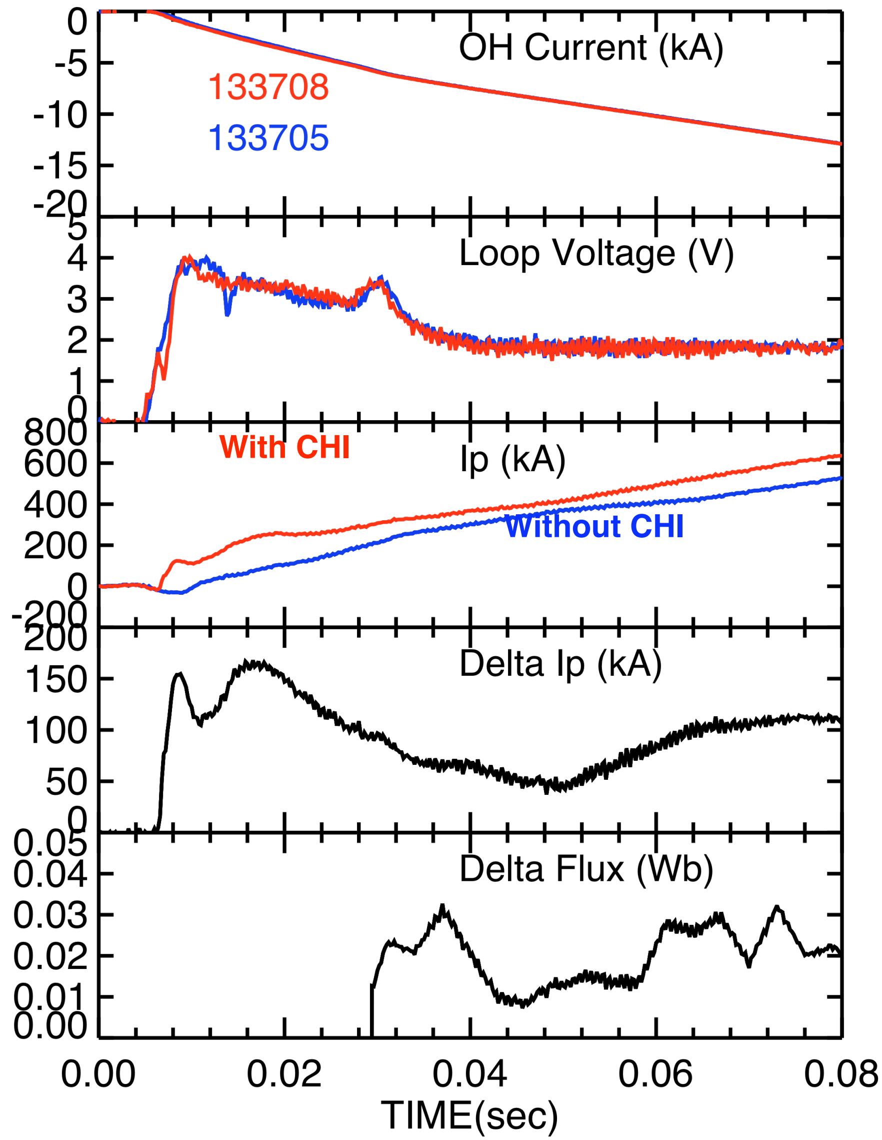
All discharges had identical solenoid (OH) current programming



- With CHI, I_p ~ 200 kA greater than ohmic only
- Successful coupling to induction using 20 mF (goal is arc-free with 50 mF)
  - Ignoring impurity effects, expect current to scale with capacitor energy

Comparison of well-controlled shots demonstrates higher I_p and greater internal poloidal flux with CHI initiation

- **Compare discharges with identical solenoid current programming**
  - **Discharge in red with CHI (10 mF, 1.65 kV)**
  - **Discharge in blue is purely inductive**
  - **Both had low levels of O_{II} emission**
  - **Density of CHI initiated discharge ~ 25% greater**
- **Final I_p is 110 kA greater in the CHI initiated discharge**
- **Internal inductance, plasma shape and radius from EFIT analysis are essentially identical**
- **Internal flux = $1/2\ \mu_0 I_p l_i R_p$**



NSTX is developing non-inductive start-up and ramp-up techniques for STs

- **Transient CHI a proven method to generate current on closed flux**
  - Start-up & inductive coupling of 200 kA non-inductive current demonstrated on NSTX Goal: 500 kA start-up current
  - Used absorber coils to reduce/eliminate absorber arcs
  - Used Li to reduce impurities during CHI
  - CHI initiated reached 700 kA in NBI heated H-mode plasmas
  - Will test CHI performance implications of metal electrodes (LLD plates); Can reducing the source of low Z impurities improve the start-up and coupling?
- **HHFW Heating and Current Drive for Ramp-up**
  - NSTX is investigating low current, low temperature targets for HHFW Goal: replace inductive drive
- **NBI Current Drive and Bootstrap Current routinely sustain about 65% of the plasma current non-inductively**
  - NSTX upgrade will increase that fraction Goal: replace inductive drive

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:

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

  -For HIT-II, ψ_{inj} = 8mWb, d = 8 cm, for NSTX, ψ_{inj} = 10mWb, d = 16 cm

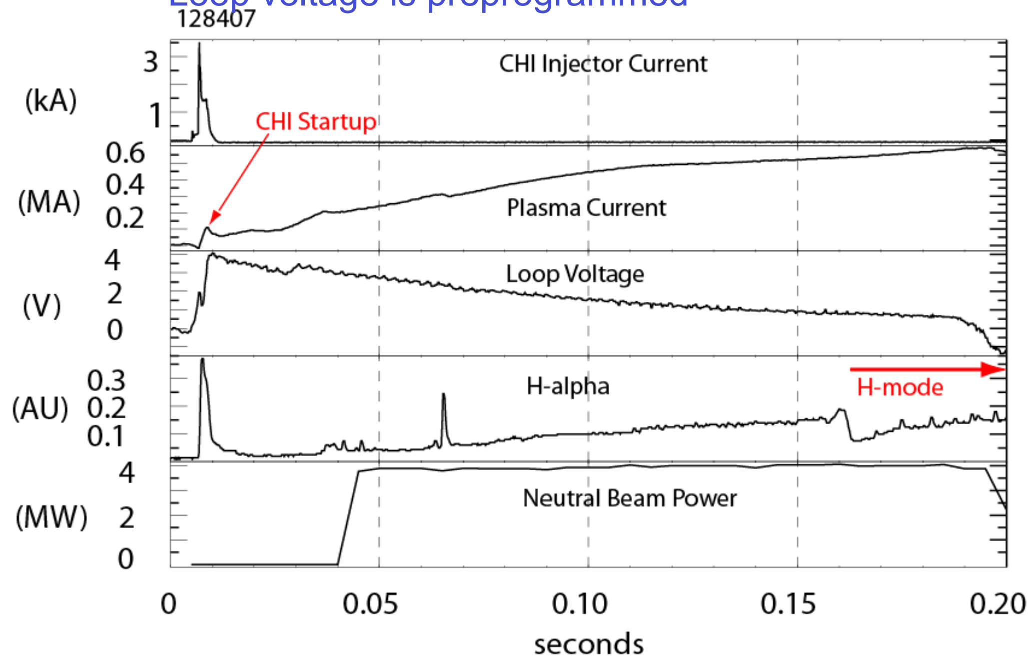
  -$I_{inj} \geq$ 15 kA for HIT-II, $I_{inj} \geq$ 2 kA for NSTX

- Sufficient energy to produce CHI discharge $W_{cap} > W_{plasma}$; $½\, CV^2 > ½\, L_p I_p^2$
  - L_p plasma inductance ~ 0.5 μH, and C= 50 mF limits I_p to ~ 500 kA for present NSTX system
- NSTX has achieved $I_p > 60\, I_{inj}$; HIT-II has achieved I_{inj} ~ 50 kA

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

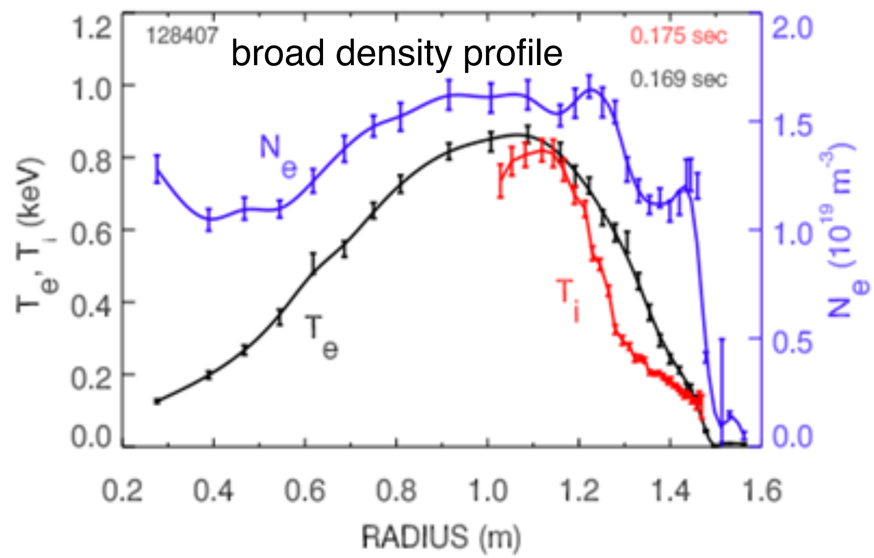
CHI started discharge couples to induction and transitions to an H-mode
demonstrates compatibility with high-performance plasma operation

- 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

- 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**