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NSTX PLASMA START-UP USING TRANSIENT CHI

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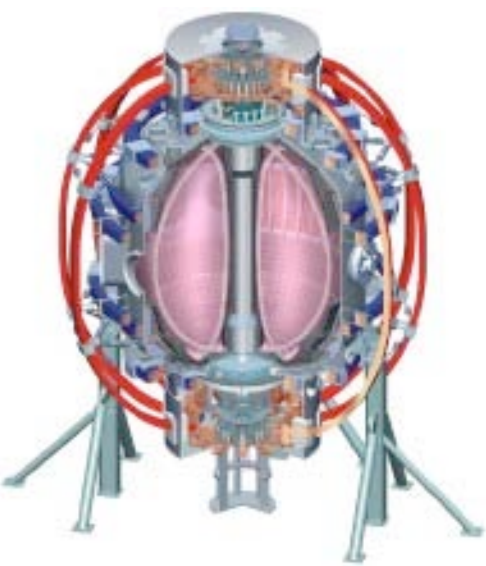

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Transient Coaxial Helicity Injection

Non-solenoid based start-up is essential for development of a fusion reactor based on the spherical torus concept. A method of non-inductive startup, referred to as transient coaxial helicity injection (Transient CHI), was successfully developed on the Helicity Injected Torus (HIT-II) experiment and employed on the National Spherical Torus Experiment (NSTX) to produce up to 160 kA of toroidal plasma current on closed flux surfaces without use of the central solenoid. In this method, plasma current is produced by discharging a capacitor bank between coaxial electrodes in the presence of toroidal and poloidal magnetic fields chosen such that the plasma rapidly expands into the chamber. When the injected current is rapidly decreased, magnetic reconnection occurs near the injection electrodes with the toroidal plasma current forming closed flux surfaces. Detailed experimental measurements made on NSTX include fast time-scale visible imaging of the entire process.

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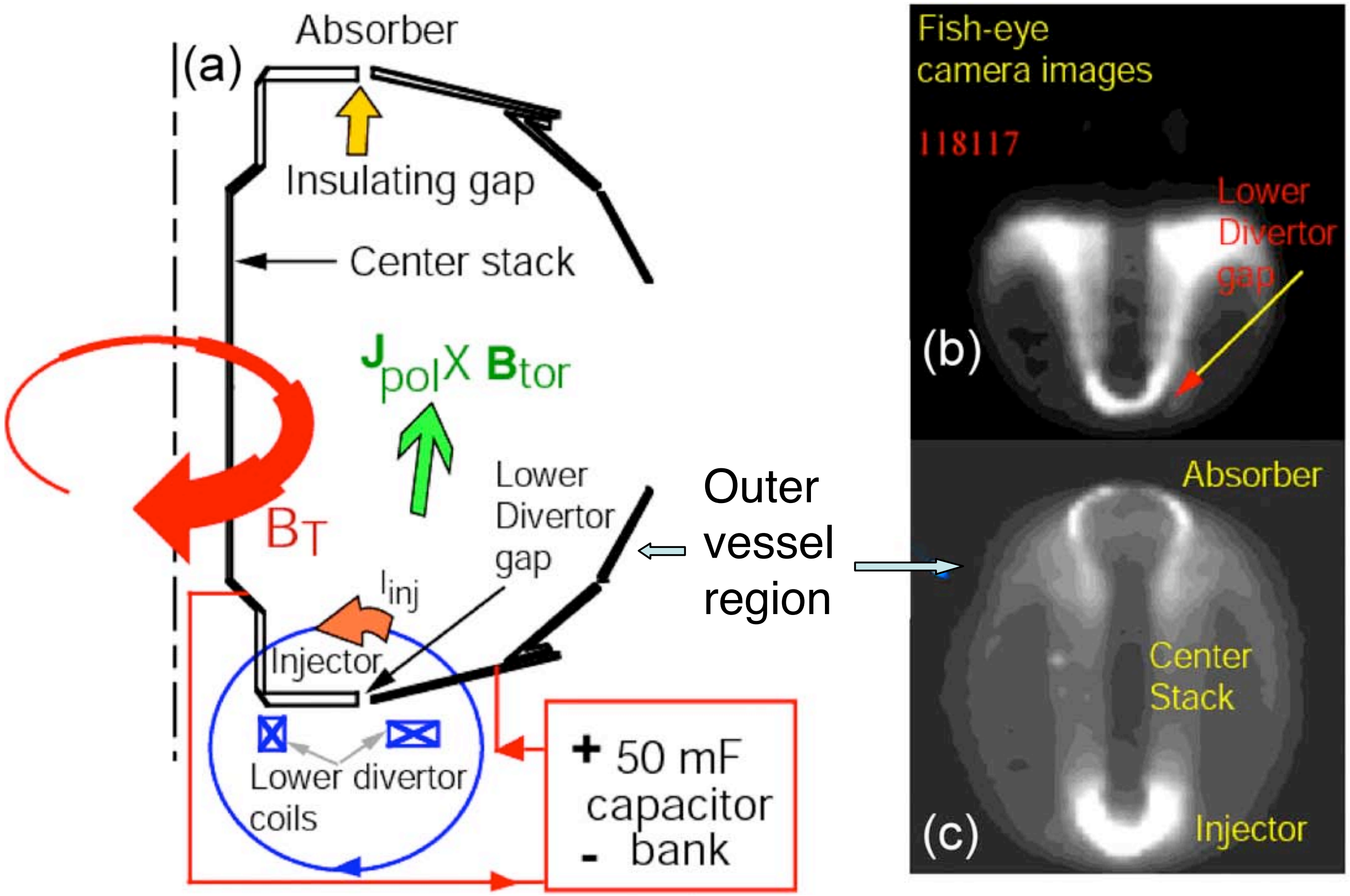
Solenoid-free start-up is important for the ST

- Limited space for the center column in an ST necessitates alternative start-up and current drive
- Favorable scaling of current multiplication for Transient CHI observed between HIT-II and NSTX

	HIT-II	NSTX
ϕ_{tor}	0.17Wb	1.5Wb
I_{inj}	≥15kA	≥2kA
I_p	~90kA	~120kA

- CHI extrapolates to larger, high-current machine, e.g. CTF, with low injector current if
  - Apparent scaling with toroidal flux is maintained
  - Plasma temperature is adequate to achieve reasonable injector voltage

Coaxial Helicity Injection (CHI) in NSTX



a) NSTX machine components for transient CHI

b) TV image early in discharge

c) Later when the discharge nearly fills vessel

- Starts as helical discharge following B
- J_{pol} X B_{tor} is up into vessel

Hardware modifications to NSTX facilitate CHI studies

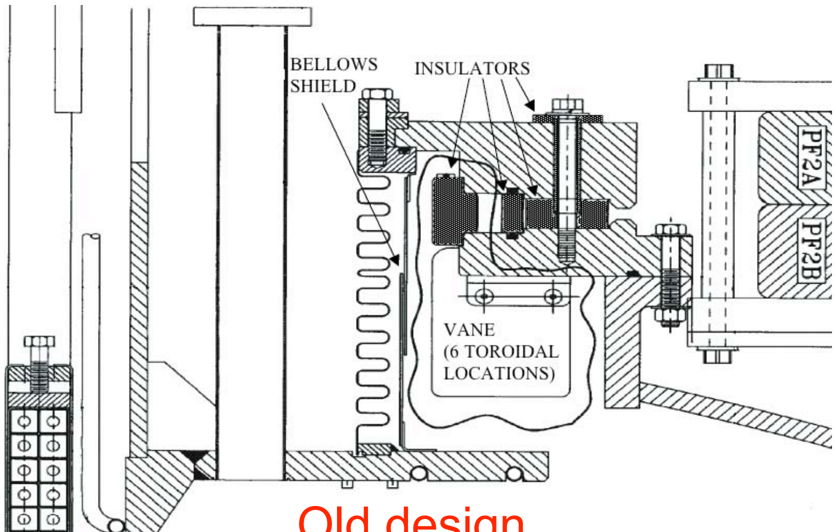
- HIT-II was designed to study CHI, NSTX is a normal ST that was modified
- Capacitor bank to supply CHI voltage
- Insulator design
- MOV circuit to limit voltage
- Snubber circuit to prevent Voltage spikes

Capacitor bank supplies injector voltage and current

NSTX

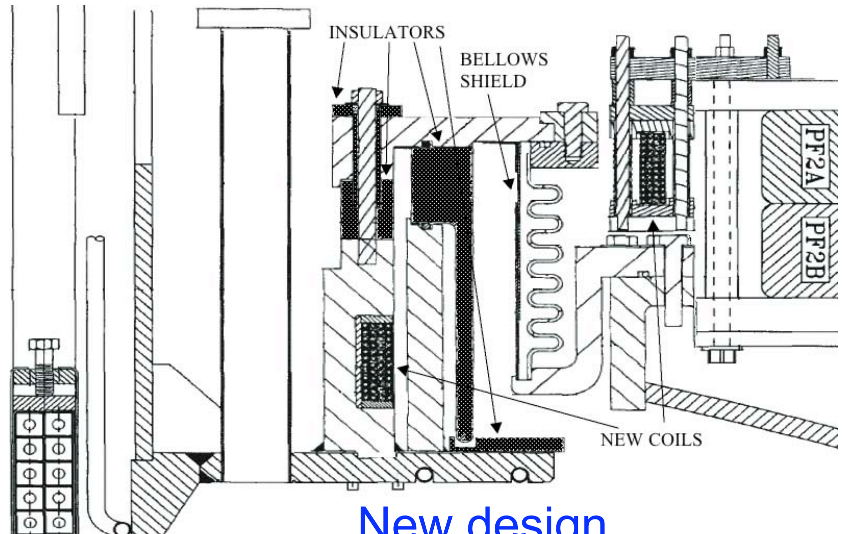
- 50mF, 2.0 kV capacitor bank
  15 to 45mF , up to 1.75 kV used in experiments
- Fast crowbar system to interrupt injector current
- Gas feed into injector region requires only as much gas as is used for a normal ohmic start-up

Insulator design prevents internal arcs that can terminate the discharge



Old design

Discharge terminating arcs ~2/3 of the time



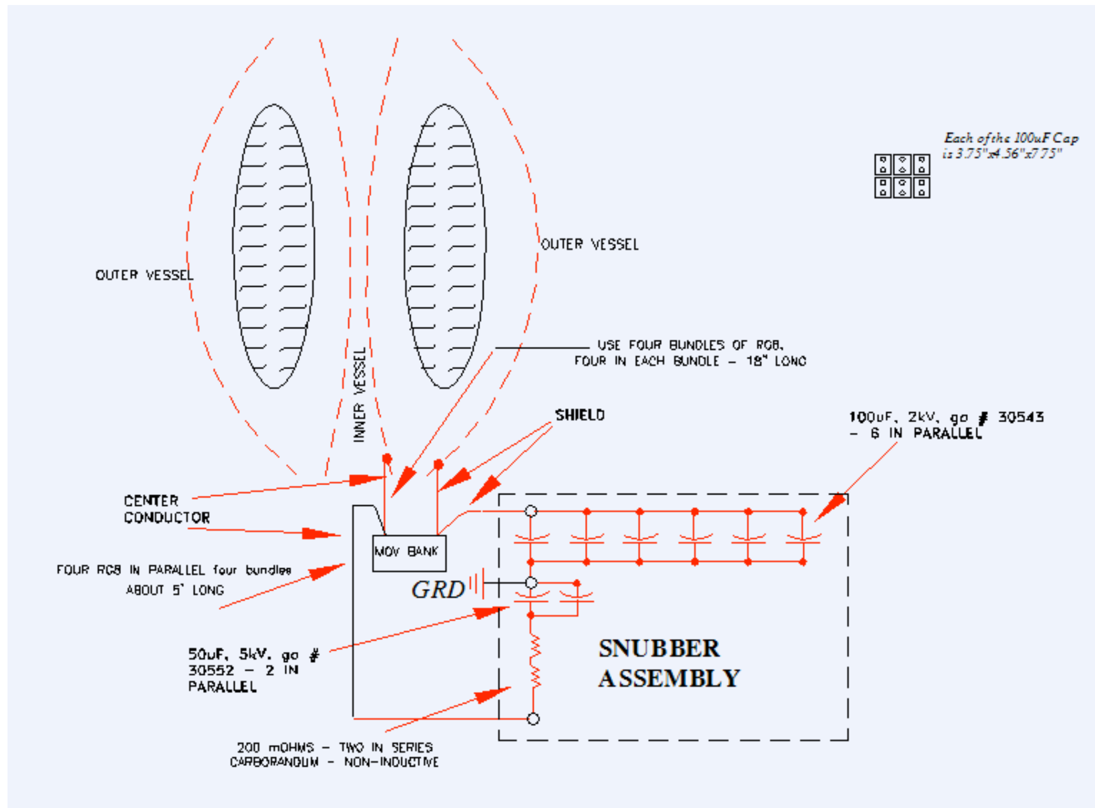
New design

Arcs occur, but do not terminate discharge

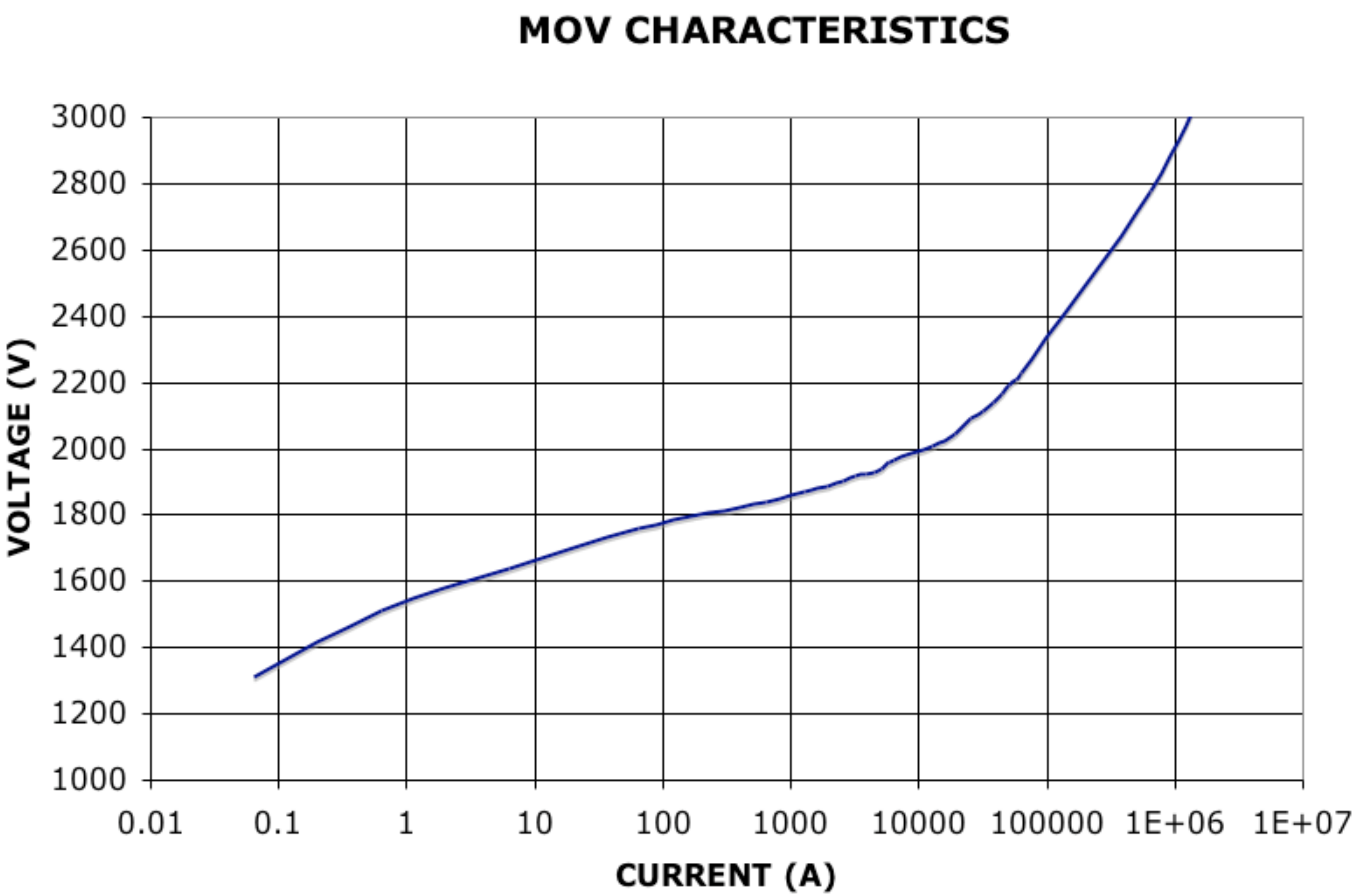
- New design
  - Bigger insulator
  - Insulator on high field side of gap
  - No short, simple connection path between inner and outer vessel

External arcs prevented by MOV s and snubber circuit

- Transient plasma load produces large voltage spikes (>3kV with 1kV supply)
- Analysis indicates both AC and DC grounding is required
- With snubber circuit, inner voltage limited to 2.2 kV , outer to 0.5 kV with 1.75 kV on capacitor bank



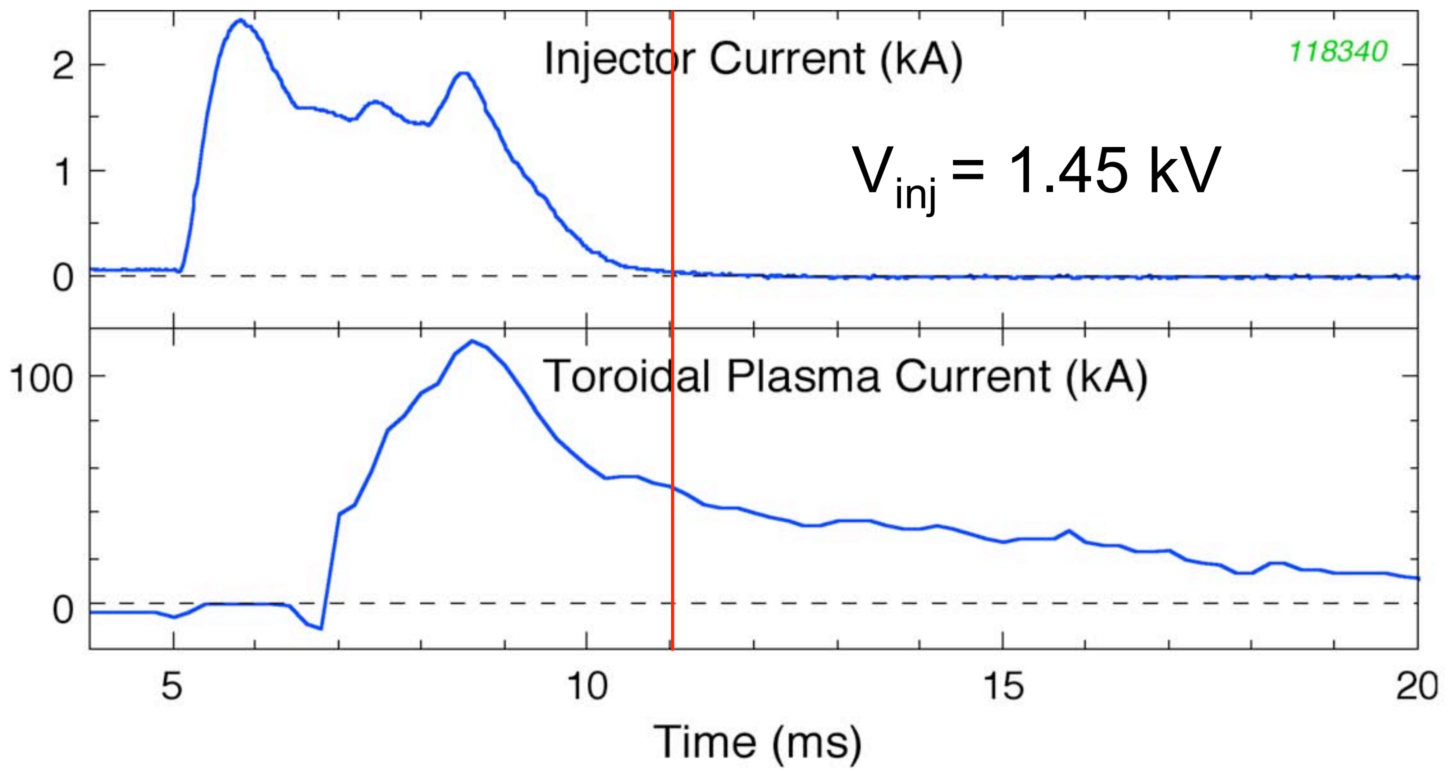
MOV circuit limits DC Voltage



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
- $Ip \leq I_{inj}(\psi_{tok} / \psi_{inj})$
- For similar B_T NSTX has 10 X 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

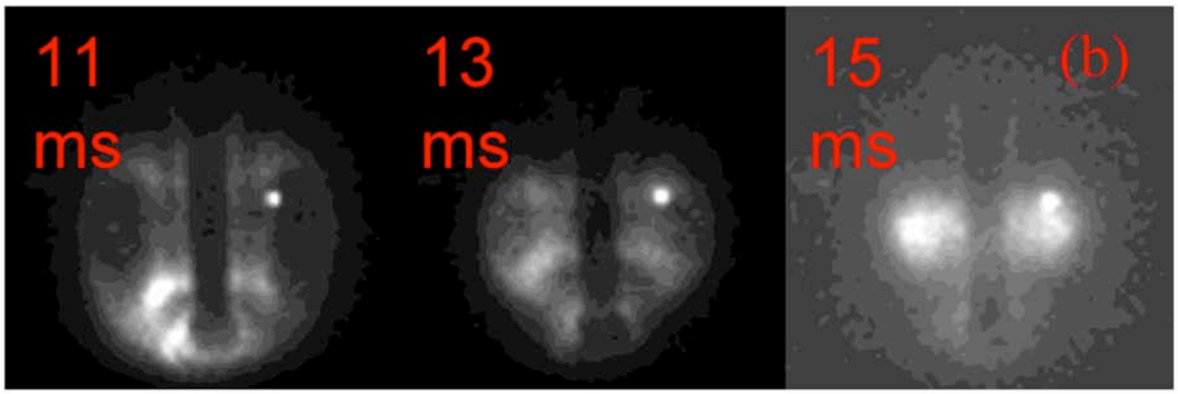
NSTX results in 2005 show clear evidence of current on closed field lines and high current multiplication

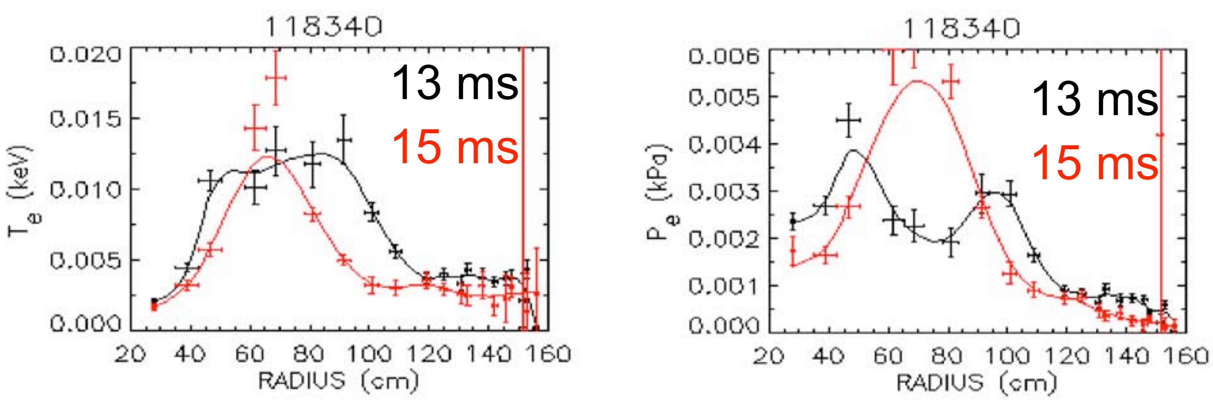


NSTX - $I_p > 60\ I_{inj}$

(HIT-II - $I_p > 6\ I_{inj}$)

TV images confirm detachment from injector

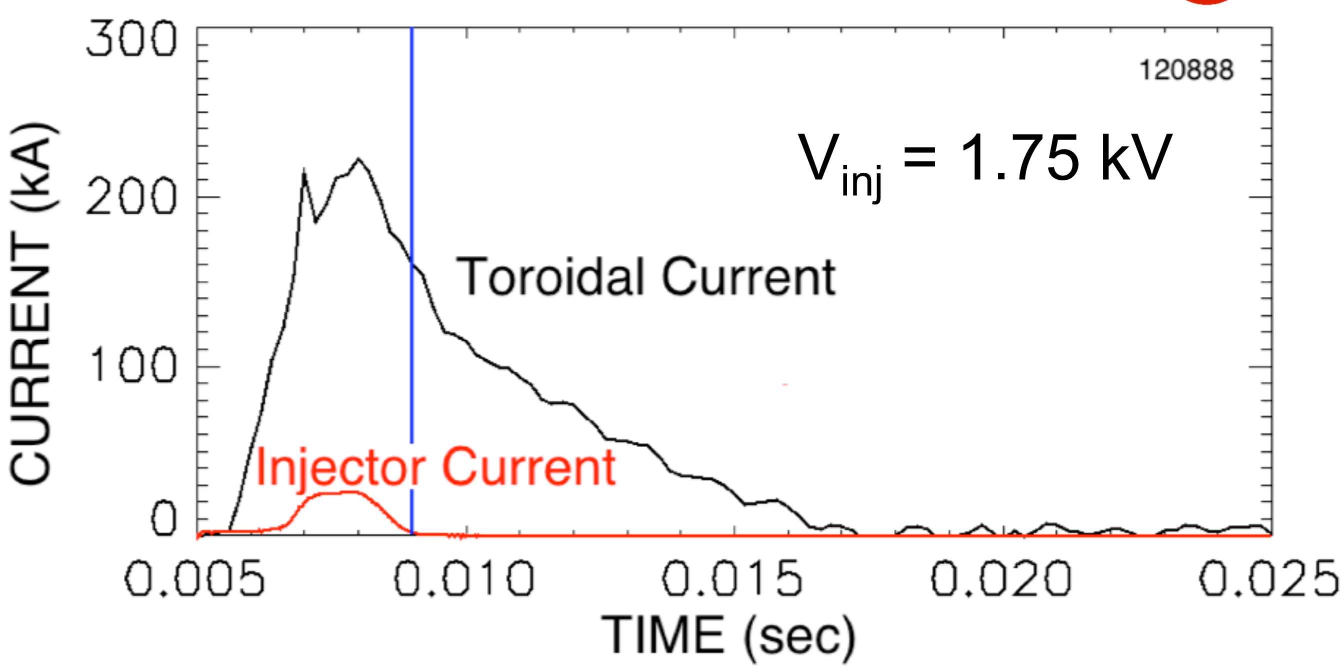




Temperature and pressure profiles

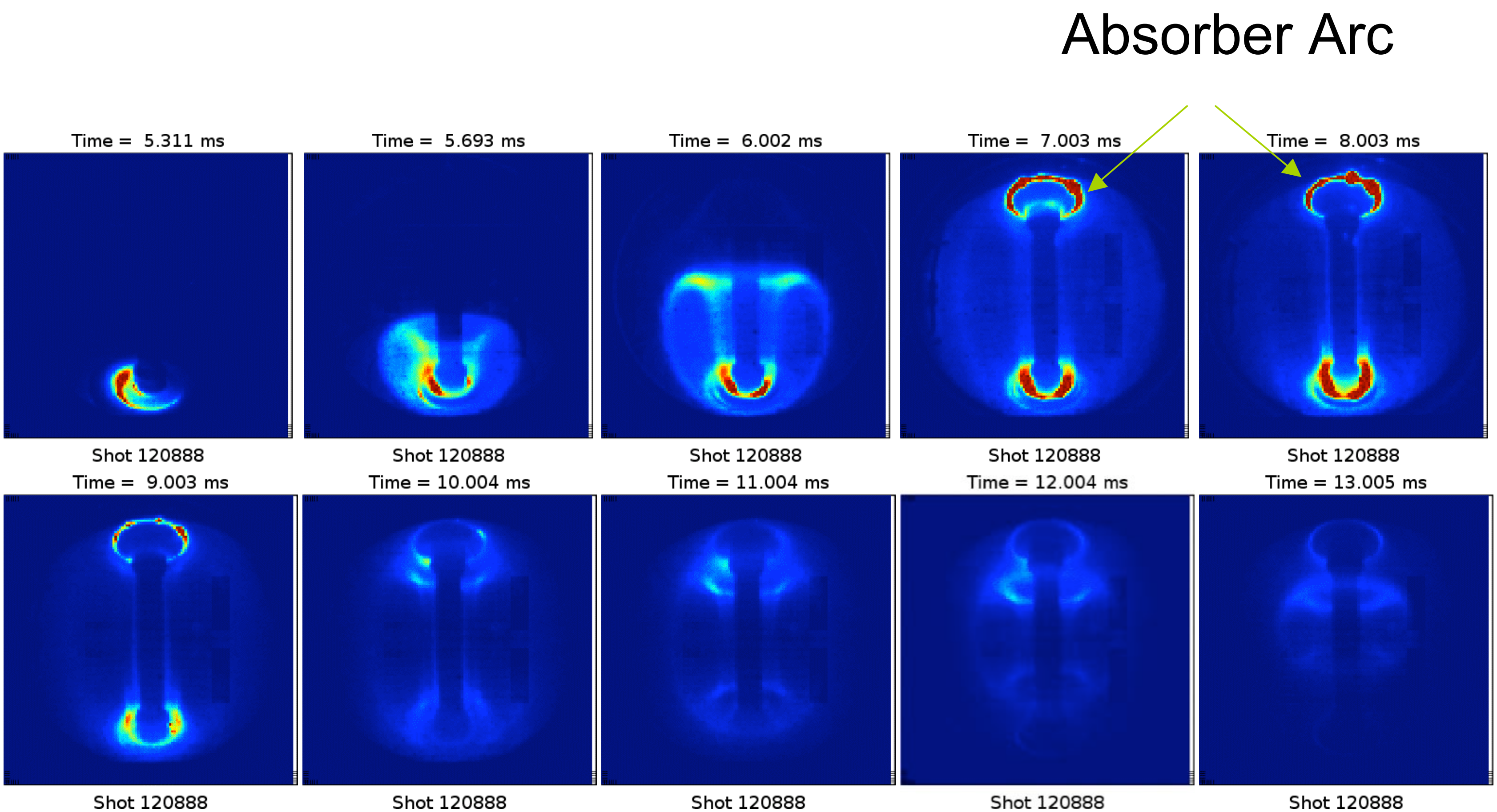
Plasma position agrees with magnetic analysis

World record non-inductive start-up 160 kA plasma current



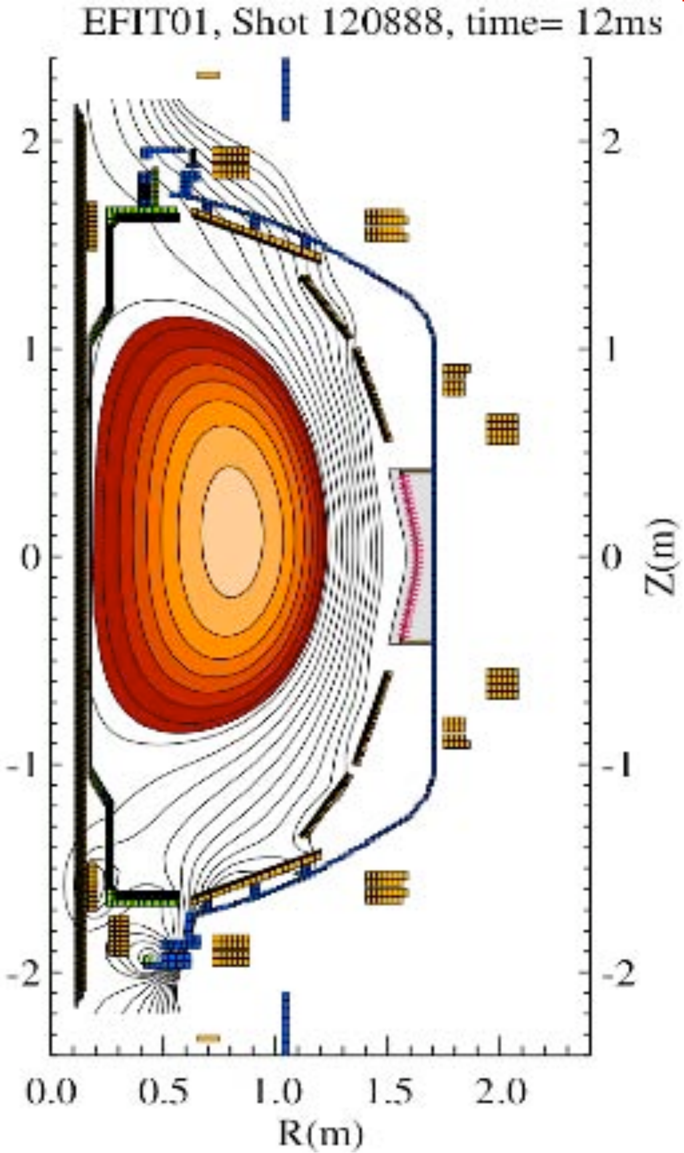
- I_p = 160 kA on closed flux surfaces with I_{inj} = 0
- JT60U achieved 80 kA and PLT achieved 100 kA with RF start-up
- Note an absorber arc raised the apparent injector current from a few to nearly 30 kA

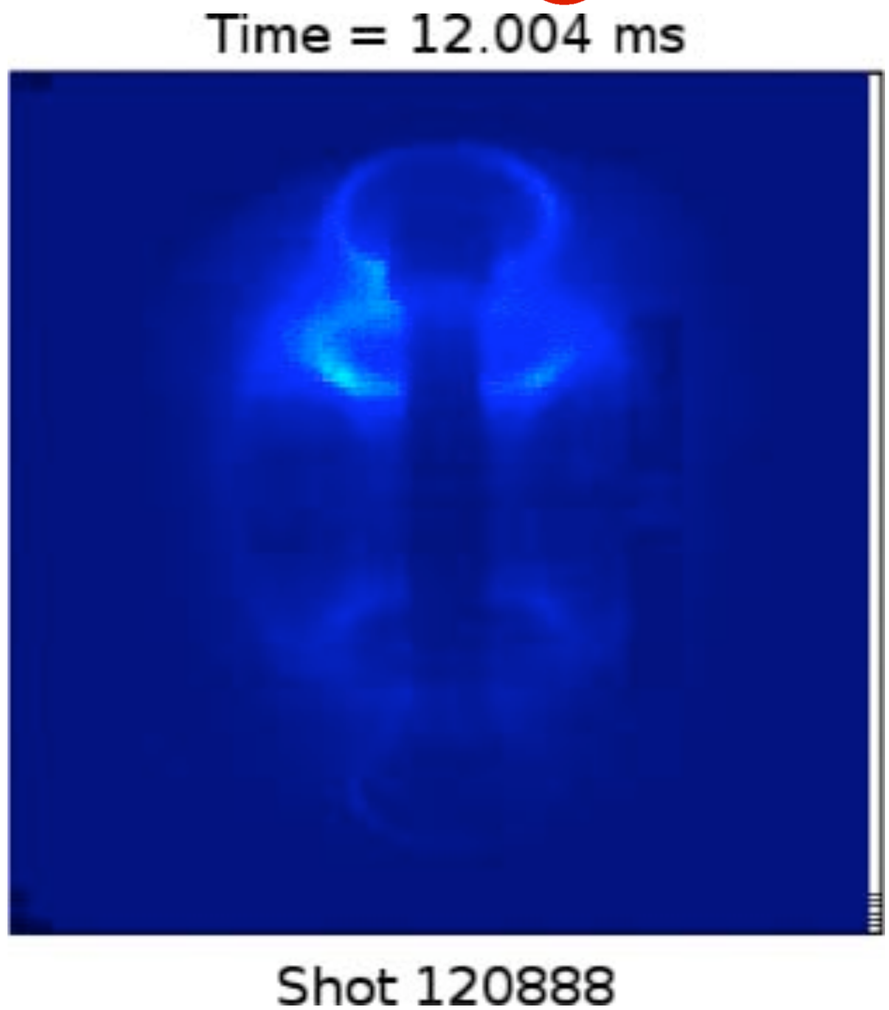
TV view of plasma showing absorber arc and later closed flux



- Ask to see the movies!

Equilibrium analysis confirms plasma position





Allowable injector currents are determined by maximum voltage

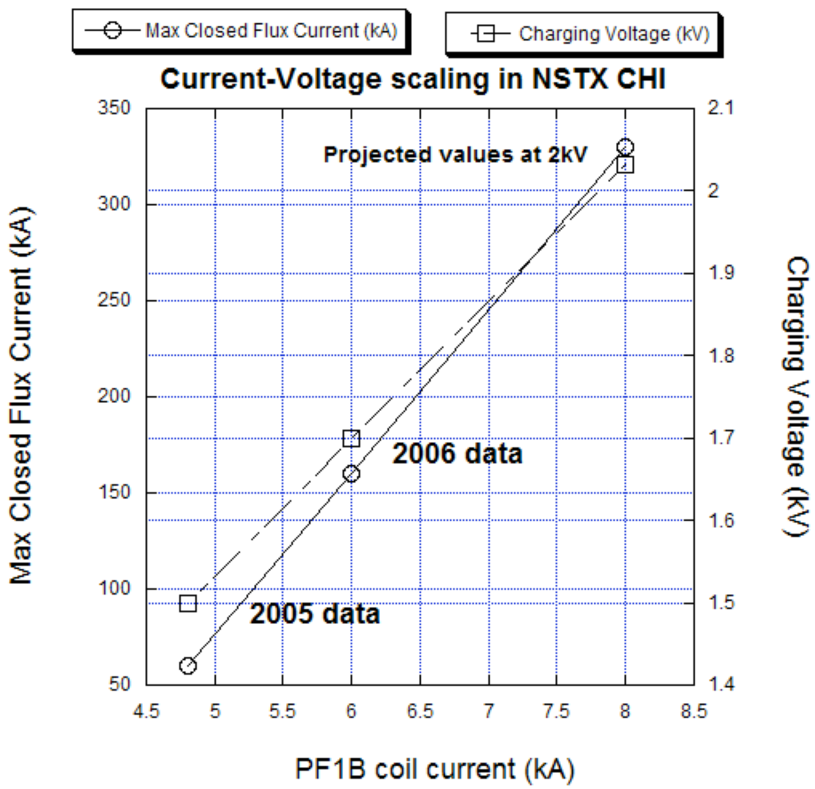
- Assuming constant resistivity,
  - $I_{inj} \propto V_{inj} (\psi_{inj} / \psi_{tok})$
- For similar values of ψ_{inj}, at the same voltage,
  - I_{inj} in HIT-II is about 10 times higher than in NSTX

    (I_{inj} ~15-20kA on HIT-II vs ~2kA in NSTX)
- Also consistent with the bubble burst relation,

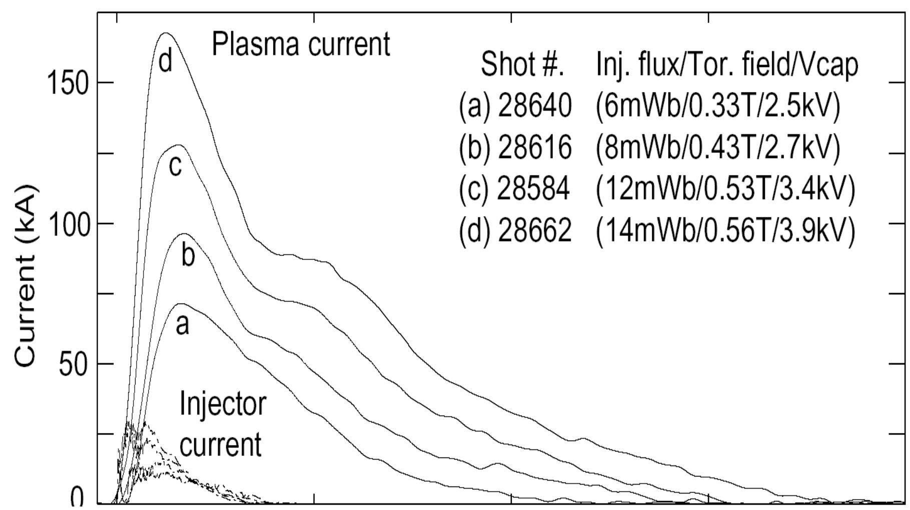
  $I_{inj} = 2\,\psi_{inj}^2/(\mu_0^2 d^2 I_{TF})$
- Which requires 10x more current in HIT-II than in NSTX

Full 2kV capability in NSTX would increase I_p to about 300kA

Best results from NSTX 2005 and 2006



HIT-II data: R. Raman, T.R. Jarboe et al., Nuclear Fusion, **45**, L15-L19 (2005)



Voltage, flux optimization allowed HIT-II to increase closed flux current as capacitor charging voltage was increased

CHI has initiated discharges with up to 160 kA of plasma current

NSTX

- Multiplication factor I_p/I_{inj} is ~10 times greater in NSTX than in HIT-II as expected
- Plasmas with substantial current have been produced
- CHI produced plasmas are sufficient for future current ramp-up experiments
- Will increase V_{inj} to full 2 kV for future experiments
- Handoff to inductive drive will be explored during the next campaign.