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Coaxial Helicity Injection plasma start-up coupled to inductively driven sustainment on the National Spherical Torus Experiment*

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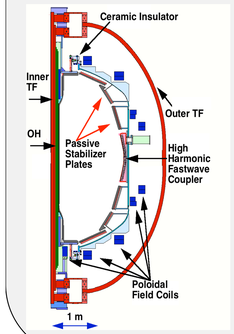
* Work supported by US DOE Contract No. DE-AC02-76CH03073

Presented at the 50th APS-DPP meeting in Dallas, TX on November 16-21, 2008

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

NSTX is designed to explore low aspect-ratio toroidal confinement

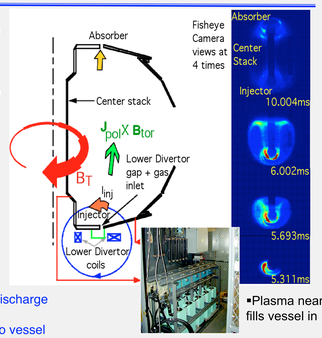


Parameters

Major Radius 0.85m	} A ≥ 1.27	
Minor Radius 0.68m		
Elongation		2.5
Triangularity		0.8
Plasma Current		1.5 MA
Toroidal Field		≤0.6T
Heating and Current Drive		
-Induction		0.6Vs
-NBI (100keV)		7 MW
-HHFW (30MHz)		6 MW
-CHI		0.4MA
Pulse Length		1.8 s

Machine components for transient CHI in NSTX

- The limited space for the center column in an ST necessitates alternative start-up and current drive.



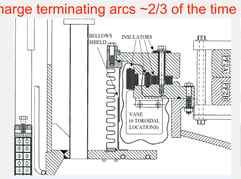
- Starts as helical discharge following B
- J_{pol} X B_{tor} is up into vessel

- Plasma nearly fills vessel in 1 ms
- 2 kV 50 mF capacitor bank

Insulator and external circuit reduce arcing

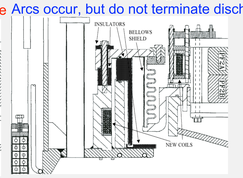
Old design

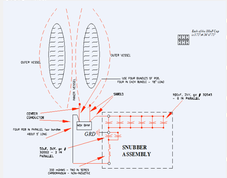
Discharge terminating arcs ~2/3 of the time



New design

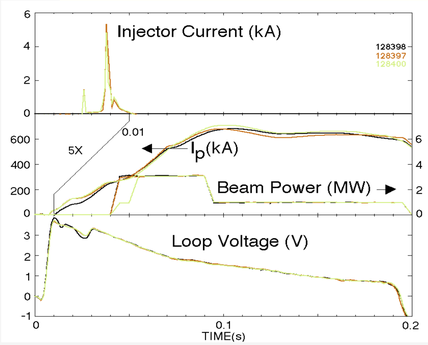
Arcs occur, but do not terminate discharge





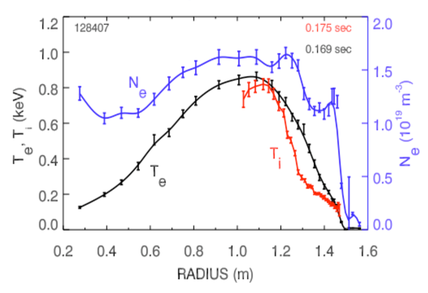
- Bigger insulator on high field side of gap
- No simple connection path between inner and outer vessel
- Transient plasma load produces large voltage spikes (>3kV with 1kV supply)
- Both AC and DC grounding are required
- With snubber circuit, inner voltage limited to 2.2 kV , outer to 0.5 kV with 1.75 kV on capacitor bank
- New absorber coils to null poloidal field

CHI initiated discharges coupled to NBI heated inductively sustained discharges (colors) and a reference no-CHI discharge (black)



- All three discharges have identical ohmic coil current programming throughout and all coil programming is identical until 0.040 s when a simple feedback control algorithm for R and z is used.
- So far no reliable increase in I_p has been found in the ramp-up experiments.
- Plasma performance following CHI is excellent with neutral beam injection.

CHI initiated plasmas exhibit good H-Mode performance



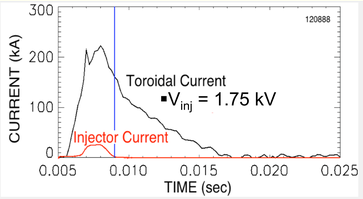
- CHI initiated discharge enters H-Mode at about 160 ms.
- Note broad n_e profile during H-Mode.
- Central T_i and T_e exceed 800 eV with 4 MW of NBI power at I_p = 550 kA.

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:

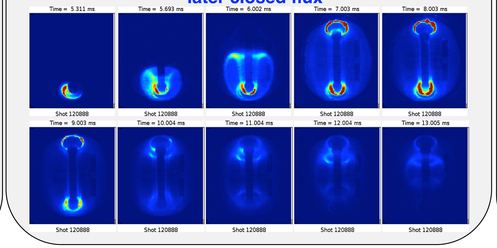
  $I_{inj} = 2\ \psi_{inj}^2/(\mu_0^2 d^2 I_{TF})$
  - For HIT-II, ψ_{inj} = 8mWb, d = 8 cm is flux footprint width
  - For NSTX, ψ_{inj} = 10mWb, d = 16 cm is flux footprint width
  - $I_{inj} \geq$ 15 kA for HIT-II, $I_{inj} \geq$ 2 kA for NSTX
- NSTX has achieved I_p > 60 I_{inj}
  - (HIT-II - I_p > 6 I_{inj})

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

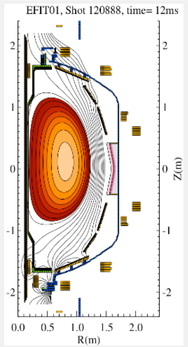


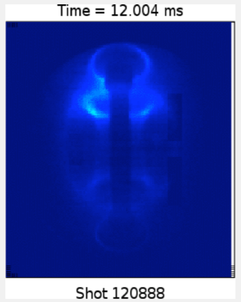
- I_p = 160 kA on closed flux surfaces when I_{inj} = 0.
- JT60U achieved 80 kA and PLT achieved 100 kA with RF start-up.
- Note an absorber arc raised the apparent injector current from a few to nearly 30 kA.

TV view of plasma showing absorber arc and later closed flux



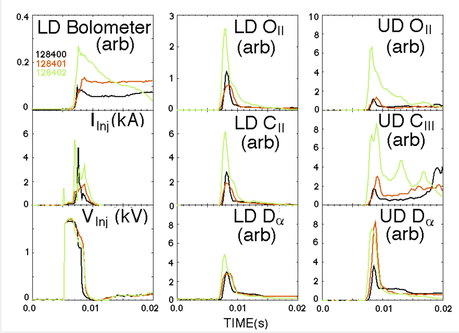
Equilibrium analysis confirms plasma position





- The plasma position from equilibrium analysis with EFIT agrees with images from the plasma TV.
- The calculated plasma position and size provide information for open loop control of the outer gap and z for the first 40 ms of the discharge.
- 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 with CHI only.
- These CHI produced plasmas are sufficient for ramp-up experiments.

With additional capacitors (energy) the spectroscopic line intensities increase



- The CHI capacitance used is indicated by the color.
  - 5 mF (black), 10 mF (red) and 15 mF (green)
- Need to reduce low-Z impurities.
  - Boronization and electrode conditioning have helped
- First attempts to use Li evaporation to reduce impurities were promising.
  - More repeatable discharges
  - Lower density
- Alternatively, provide additional heating power (~300 kW) early in the discharge

Status and Plans

- Successfully coupled induction to CHI discharge in NSTX and achieved excellent performance in those discharges.
- Further condition divertor plates to reduce impurities and allow use of more capacitance in the system.
- Use Li evaporation (LITER) to reduce recycling and impurities (a notable change with LITER in 2007 was a reduction in the oxygen impurity).
- Make first use of the CHI absorber coils to reduce absorber arcs that are a suspected source of impurity influx.