Increased CHI Startup Currents through Imposed Non-axisymmetric Perturbations

Brian A. Nelson, Thomas R. Jarboe,
Roger Raman, and Derek A. Sutherland
University of Washington

Aeronautics and Astronautics
University of Washington
College of Engineering

Perturbations Crossing Flux Surfaces Give Cross-field Current Drive Effect

- The HIT-SI data show that perturbations generate a cross-field viscosity in the electron fluid. The viscous force per unit area between adjacent equilibrium flux surfaces is simply $(\delta B_{\perp})^2/2\mu_o$, where $\delta B_{\perp}$ is the magnetic perturbation perpendicular to the flux surface.*

- The j/B profile is flattened

- Model agrees with tokamak rotation, disruption ramp down rates and allowable field-errors.

*T. R. Jarboe *et al.*, Nucl. Fusion, **52,** 083017 (2012)

XP: Apply Asymmetric Fields on Transient CHI to Produce Flux Amplification (FA)

Aeronautics and Astronautics
University of Washington
College of Engineering

- Previous experiments depended on non-axisymmetric *instabilities* to produce FA (e.g. SSPX)
- Imposed Dynamo Current Drive (IDCD: Jarboe NF 2012) applies non-axisymmetric fields to a *stable* equilibrium producing high-β spheromaks (HIT-SI: Victor PoP 2014)
- Hollow NSTX Transient CHI plasmas allow imposed perturbations to flatten edge J/B; IDCD scaling for NSTX CHI startup-up plasmas show scaling > 1 MA
- Asymmetric fields allow conversion of injected toroidal flux ($d\Phi_{TOR}/dt = -V_{CHI}$) to poloidal flux, increasing I_p

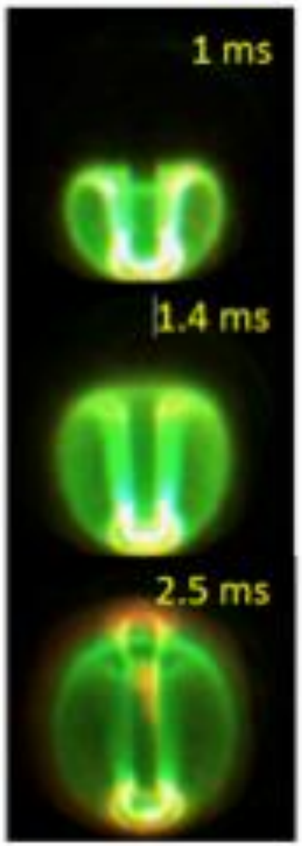
- **Proposal:** Use RWM coils to produce asymmetric fields on Transient CHI start-up plasmas to evaluate current penetration, and flux amplification (higher I_p)
  - 0.5 or 0.25 days; can run during Transient CHI operations

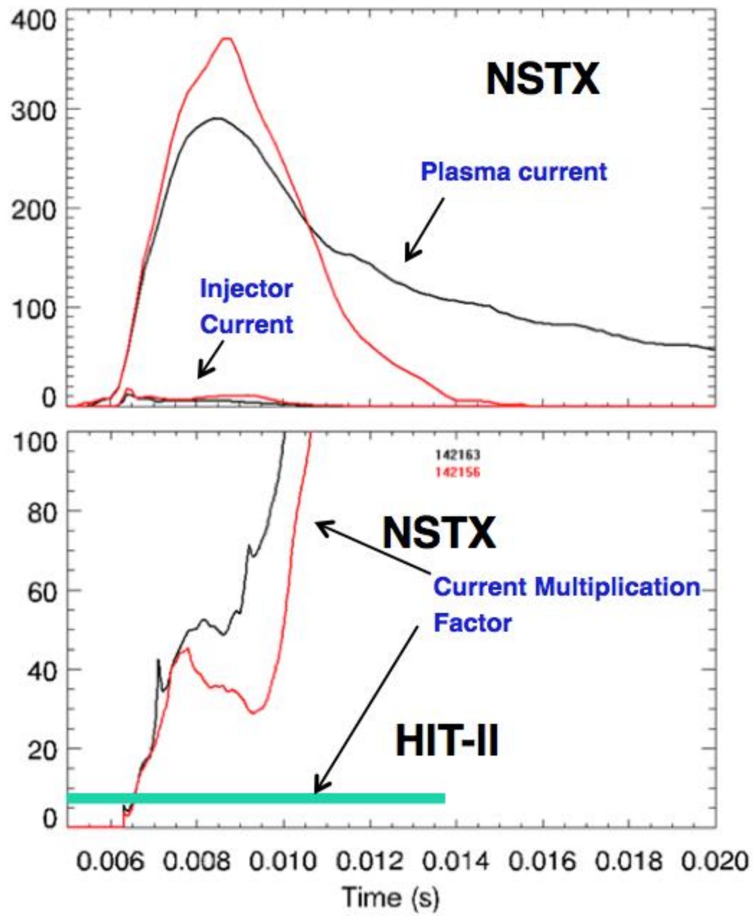
Aeronautics and Astronautics
University of Washington
College of Engineering

Backup Discussion

CHI Start-up Plasma Polodial Flux is Limited to Initial Injector Flux Value

Aeronautics and Astronautics
University of Washington
College of Engineering





- Axisymmetric reconnection produces ~200 kA closed I_p
- High current amplification (I_p/I_{CHI}) achieved, but flux amplification (FA) requires non-axisymmetric motion

Aeronautics and Astronautics
University of Washington
College of Engineering

An effect of perturbations on the current profile and how to use it

By
Tom Jarboe and the HIT team
To
The NSTX team

Aeronautics and Astronautics
University *of* Washington
College of Engineering

Outline

- Perturbations flattening the j/B profile and cause rotation
- Agreement with tokamak data
- NSTX-U tests

Perturbations crossing flux surfaces give cross-field current drive effect

Aeronautics and Astronautics
University *of* Washington
College of Engineering

- The HIT-SI data show that perturbations generate a cross-field viscosity in the electron fluid. The viscous force per unit area between adjacent equilibrium flux surfaces is simply $(\delta B_{\perp})^2/2\mu_o$, where $\delta B_{\perp}$ is the magnetic perturbation perpendicular to the flux surface.*
- The j/B profile is flattened
- In the externally-driven regions dynamo force brakes electrons so the force is in the direction of the current giving plasma velocity in that direction
- In the dynamo driven region the force is with the electron flow resulting in plasma flow against the current

*T. R. Jarboe *et al*., Nucl. Fusion, **52,** 083017 (2012)

The cross-field current drive is consistent with observations on tokamaks.

Aeronautics and Astronautics
University of Washington
College of Engineering

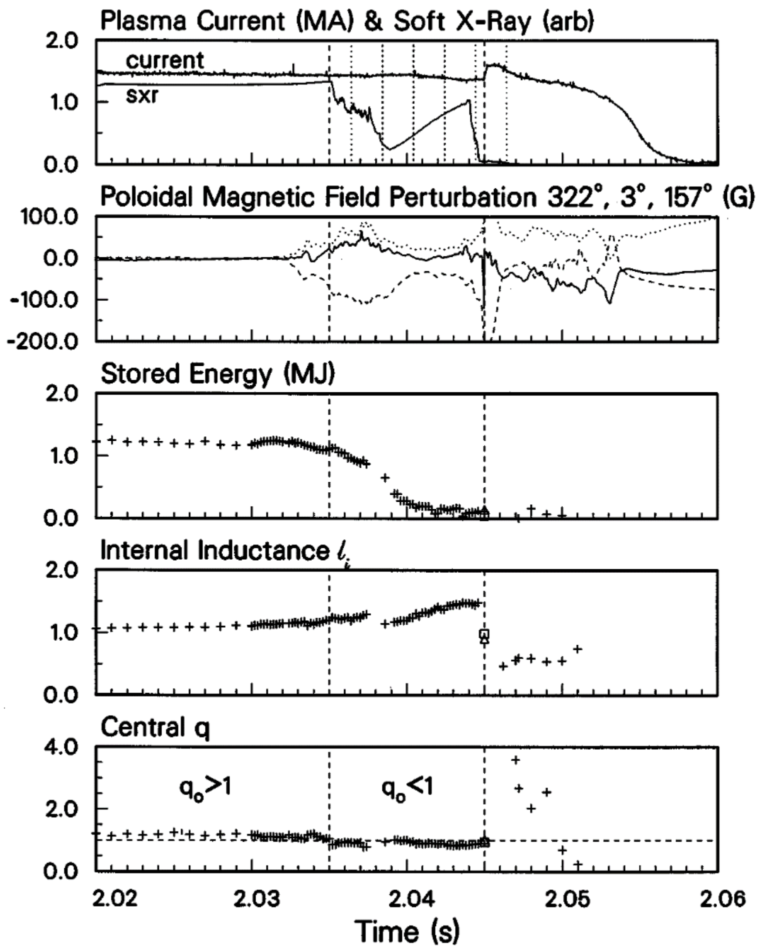
- Plasma rotates with current in normal tokamak and against the current when LHCD is used in the edge*
- Low level perturbations have a large effect on performance probably because they flatten j/B that flattens q-profile, on a tokamak, and decreases shear
- Maxwell stress tensor analysis for flux surface (given in the Imposed Dynamo Current Drive (IDCD) paper**) yields the $\delta B_{\perp}$ required to drive the current:

$$\frac{(\delta B_{\perp rms})^2}{\mu_o} \geq (\eta j\| - E\|) n e r; \quad \frac{\mu_o}{4\pi}\frac{d(l_i I)}{dt} \simeq -E\|; \quad \delta B_{\perp rms} \geq \left(\frac{\mu_o^2}{4\pi}\frac{\Delta(l_i I)}{\Delta t} n e r\right)^{1/2}$$

*J. E. Rice *et al.,* Nucl. Fusion **49** 025004 (8pp) (2009)
T. R. Jarboe *et al.*, Nucl. Fusion, **52, 083017 (2012)

IDCD equation agrees with radiative disruption* perturbations on DIII-D

Aeronautics and Astronautics
University *of* Washington
College of Engineering



- Disruption created by argon injection.
- First: cold edge peaks the current until it is unstable. Instability cools plasma.
- Second: 1.5 MA profile is flattened in 1.2 ms

$$\Delta(l_i I)/\Delta t = 0.92 GA/s$$

IDCD requires δB of 190 G (at 2.045-6 s)

- Third: 10 ms current quench.

$$\Delta(l_i I)/\Delta t = 0.08 GA/s$$

IDCD requires δB of 60 G. (at 2.046-56 s)

*P. L. Taylor *et al.*, *Phys. Rev. Lett*, **76**, 916-919 (1996)

On a reactor and ITER the perturbation levels required to drive the current are a little higher than considered acceptable (confirming the effect). They are small.

Aeronautics and Astronautics
University of Washington
College of Engineering

Parameter	Present tokamaks	ARIES-AT	ITER
I_{tor} (MA)	4.5	12.8	15.
Temp. (keV)	2	18	8.1
a (m)	1	1.3	2
$\tau_{L/R}$ (s)	15	605	454
$\delta B_{\perp rms}/B$	0.0004	0.0001	0.0001

- If they can drive the current they flatten the j/B profile which flattens the q-profile leading to poor performance.

Summary of the impact of perturbations flattening the j/B profile on a tokamak

Aeronautics and Astronautics
University of Washington
College of Engineering

- Low-level (10^{-4}) perturbations seriously damage performance. Uniform j/B gives low β.
- With an extensive low-j/B edge plasma or locked modes, higher levels (10^{-2}-10^{-3}) cause a disruption.

Solutions

- Drive the edge current high and impose a perturbation profile that sustains the desired reversed-shear current profile.
- Solves the sustainment problem. (400 times more efficient than RF)
- High edge current prevents the edge from using perturbations to drag down the current in disruptions.

Possible related experiments on NSTX-U

Aeronautics and Astronautics
University of Washington
College of Engineering

- At $n = 2.5 \times 10^{19}\ m^{-3}$, $T = 30$ eV, $a = 0.6$ m, $\delta B_{\perp} = 50$ G
  - I = 1.5 MA can be sustained
  - dI/dt = 80 MA/s ramp up or down, depends on edge current.
- Use RWM coils to augment CHI startup.
- Tie down the edge current with an argon puff and then demonstrate control of ramp down using RWM coils.
- Do not tie down the edge and generate halo currents.
- For current drive: The edge currents can be driven by CHI and the perturbations imposed by RWM coils. The only restriction for current drive is that j/B must be monotonically decreasing from the edge.
- Drive the edge with CHI for disruption control.