Increased CHI Startup Currents through Imposed Non-axisymmetric Perturbations

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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)

Imposed Non-axisymmetric Perturbations Allow Flux Amplification

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- 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
  - IDCD scaling also consistent with self-generated non-axisymmetric perturbations and dI_p/dt rates during DIII-D radiative disruptions (Jarboe, submitted for publication)
- Asymmetric fields allow conversion of injected toroidal flux ($d\Phi_{TOR}/dt = -V_{CHI}$) to poloidal flux, increasing I_p

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

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- **Proposal:** Use RWM coils to produce asymmetric fields on Transient CHI start-up plasmas to evaluate current penetration, and flux amplification (higher I_p)
  - Need to determine *n* of perturbation and strength
  - RWM could be non-rotating to start
- 0.5 or 0.25 days; can run during Transient CHI operations
- If the IDCD model holds for Transient CHI current penetration there are other applications possible for NSTX-U (current ramp-up/ramp-down, disruption mitigation and control, *etc*.)

Backup Discussion

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

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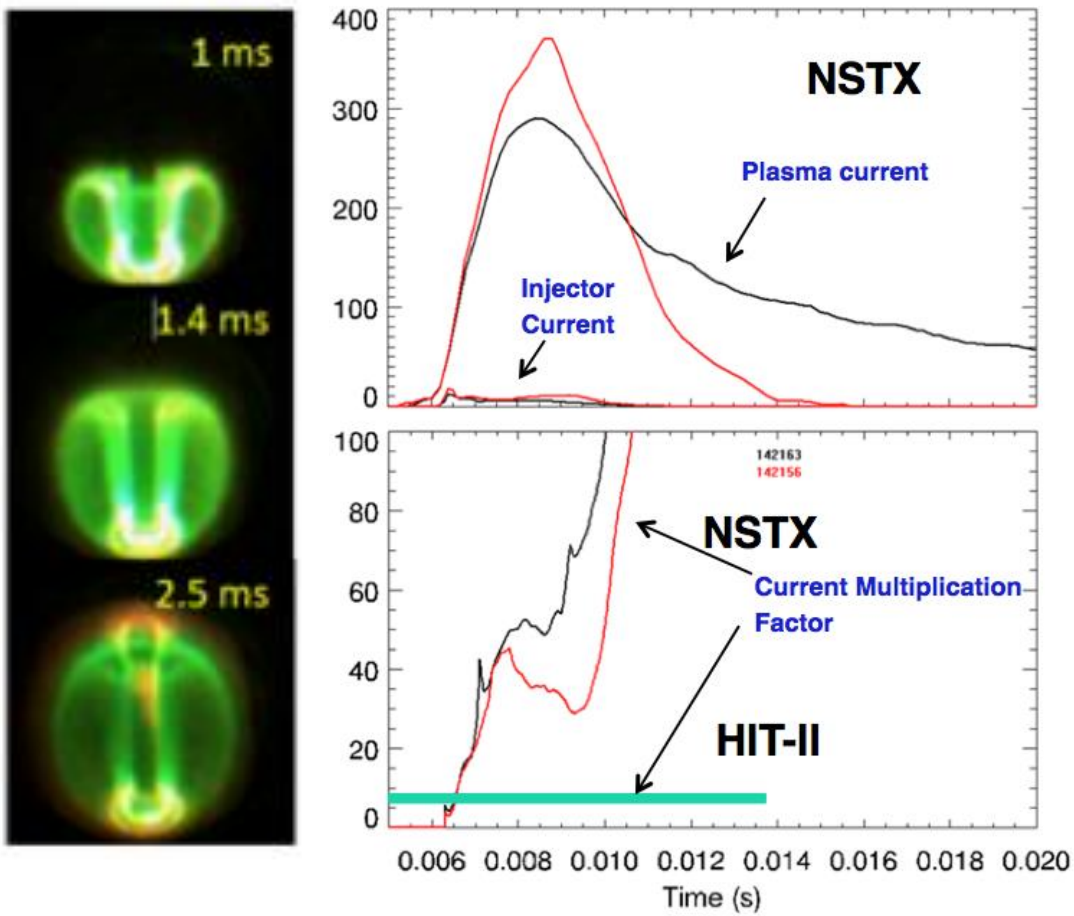

- Axisymmetric reconnection produces ~200 kA closed I_p
- High current amplification (I_p/I_{CHI}) achieved, but flux amplification (FA) requires non-axisymmetric motion

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

By
Tom Jarboe and the HIT team
To
The NSTX team

Outline

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

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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
- 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.

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- 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

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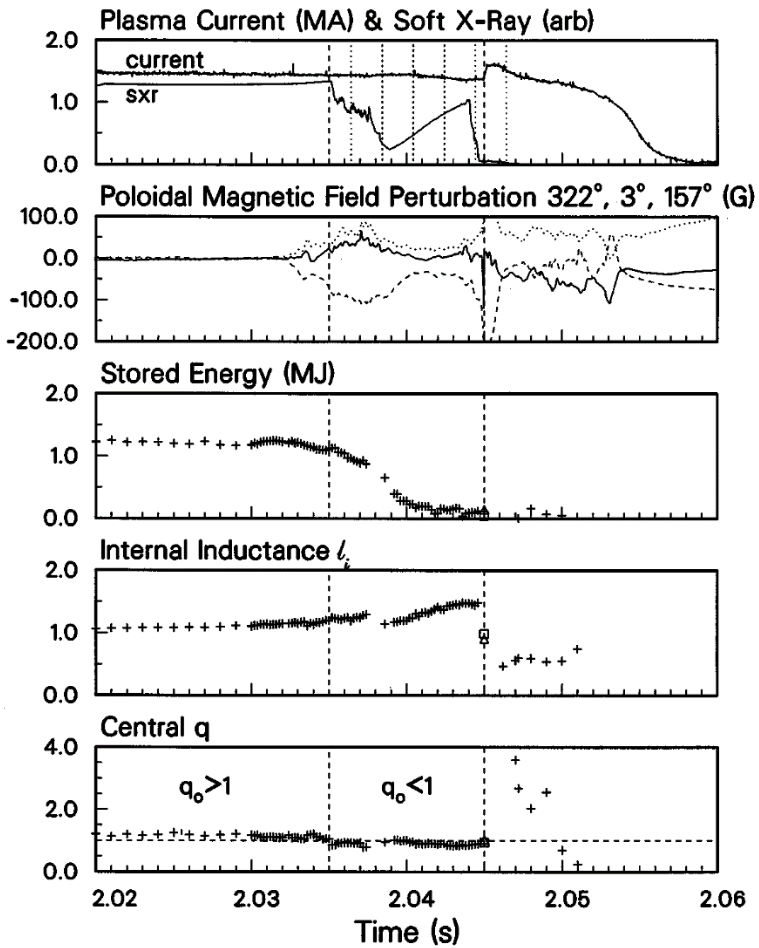

- Disruption created by argon injection.
- First: cold edge peaks the current until it is unstable. Instability cools plasma.
- Second: 1.5 MA profile is flattened in 1.2 ms

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

  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)

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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.

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

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- 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

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- At $n = 2.5\times10^{19}\ m^{-3}$, $T = 30$ 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.