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Halo Current and Current Quench Rate Characteristics During Disruptions in NSTX

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For the

NSTX Macroscopic Stability Topical Science Group

12th Meeting of the ITPA MHD Stability Topical Group

October 20-22, 2008

CRPP, Lausanne, Switzerland

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Examining disruption eddy currents, halo currents, and I_p current quench in the spherical torus

Goals

- Provide electromagnetic loading data for future ST design
- Examine ST specific characteristics to enhance tokamak knowledge base

Considerations

- High elongation more subject to n = 0 instability during vertical motion (VDE)
  - General issue: disruption I_P quench drives eddy currents (I_C) in nearby conducting structures (C); currents lead to significant JxB forces on in-vessel components
    - τ_c (L_C/R_C time) long: total flux change matters
    - τ_c short: instantaneous flux change matters

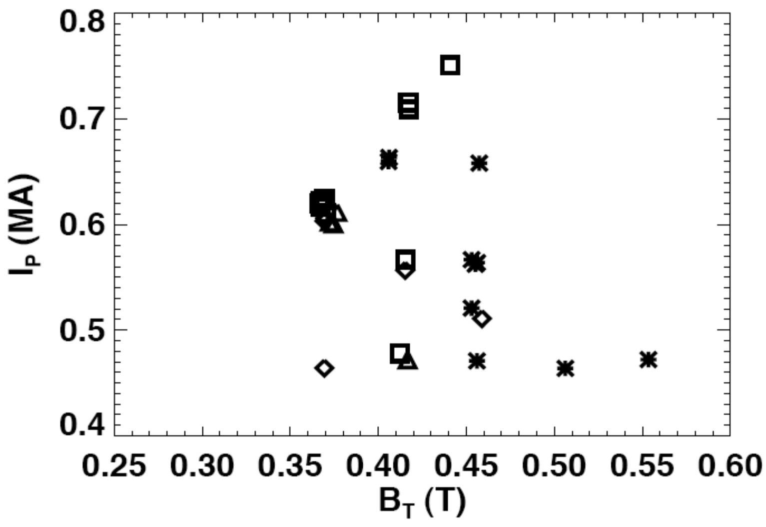
$$\frac{dI_C}{dt} + \frac{I_C}{\tau_c} = -\frac{1}{L_C}\frac{d\Phi}{dt}$$

  - Strong 1/R B_t variation in ST makes center column halo currents a large concern
- Halo currents can flow linking the plasma and in-vessel components when plasma comes in contact with plasma facing components
  - Currents are parallel to B in the plasma edge; distributed to vessel based on inductance/resistance
- Disruptions are faster in the ST vs. conventional aspect ratio
  - Expand studies to wider range of disruption conditions/plasma parameters

Disruptions analyzed over a wide range of plasma conditions

- Disruption database
  - Greater than 900 shots, covering all operational regimes
  - Select shots with fast current quenches, large halo currents
  - Maximum halo current in all measured paths, current quench characteristics
- Dedicated experiment in 2008
  - Triggered VDEs
  - I_P and B_T scans at fixed shape, NBI power
  - Detailed tracking of vertical motion
  - More accurate characterizations than in large database analysis

XP833 I_P & B_T Range



New measurements allow study of additional halo current paths

Rogowskis on the Center Stack Casing (CSC)
CSCL1, CSCL2, CSCU1
No Midplane Measurements

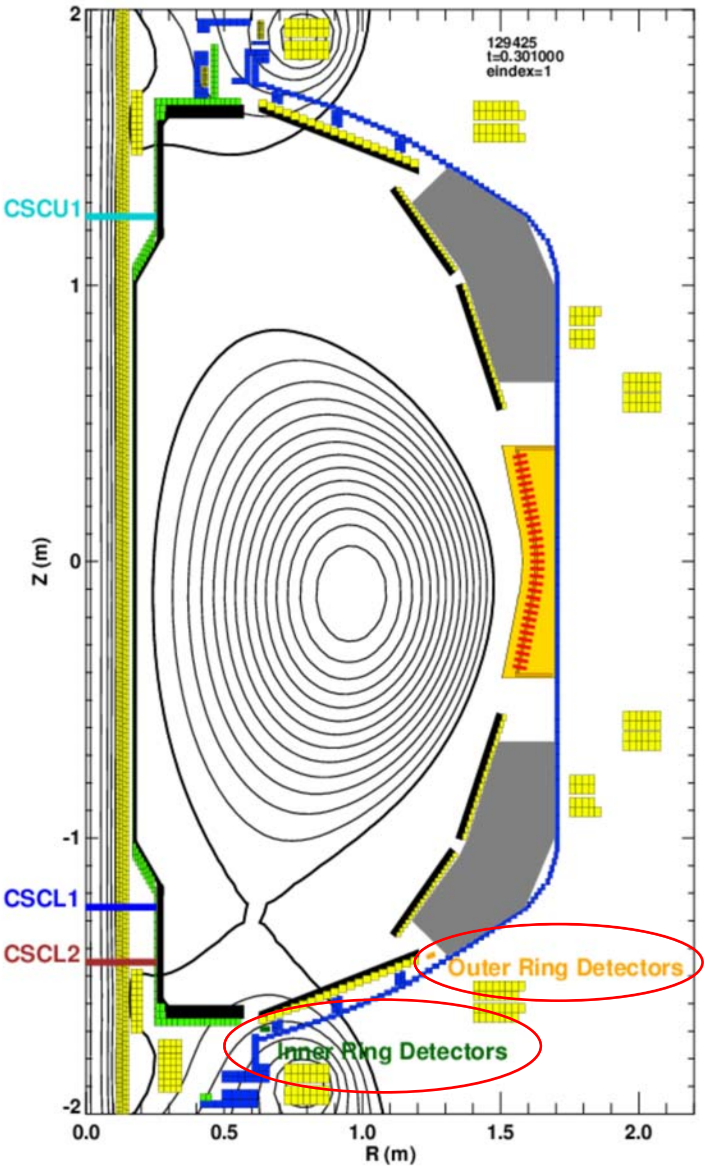
Two Pearson current transducers on CHI Bus

Current from inner to outer vessel

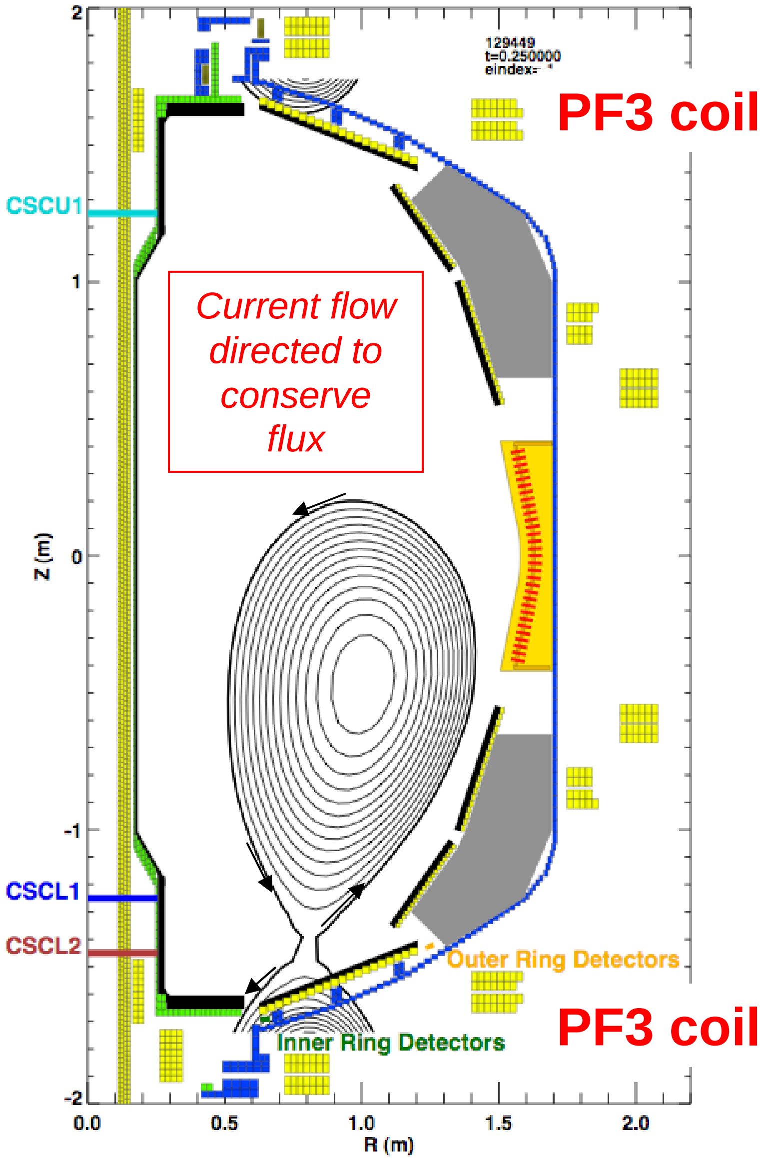
New For 2008

Two Arrays of 6 B_T coils

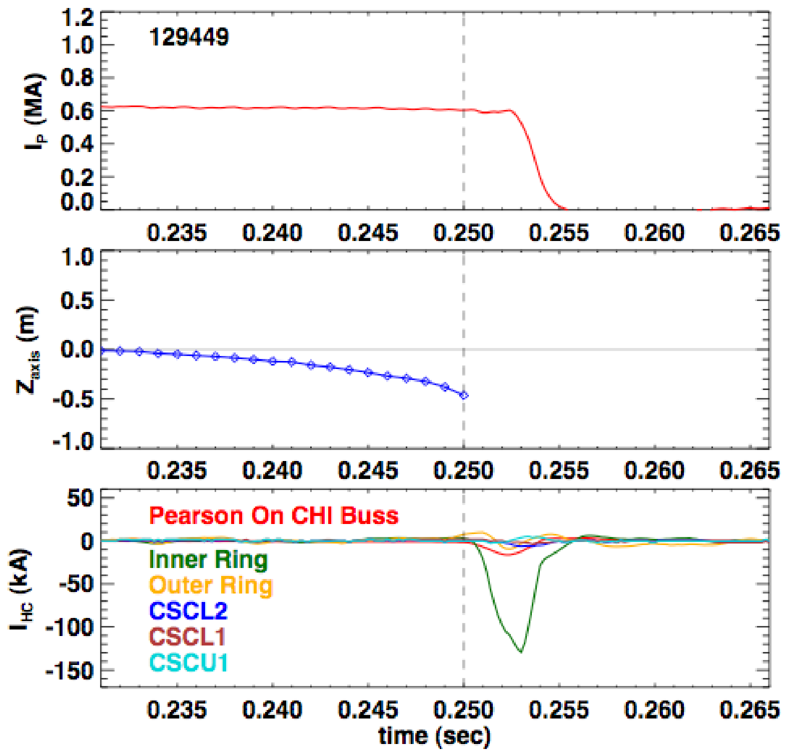
Inner Ring: Just Outside the CHI Gap
Outer Ring: Just Outside the OBD
Difference Between These: Current into the OBD



Downward Going Disruption With Large Halo Currents

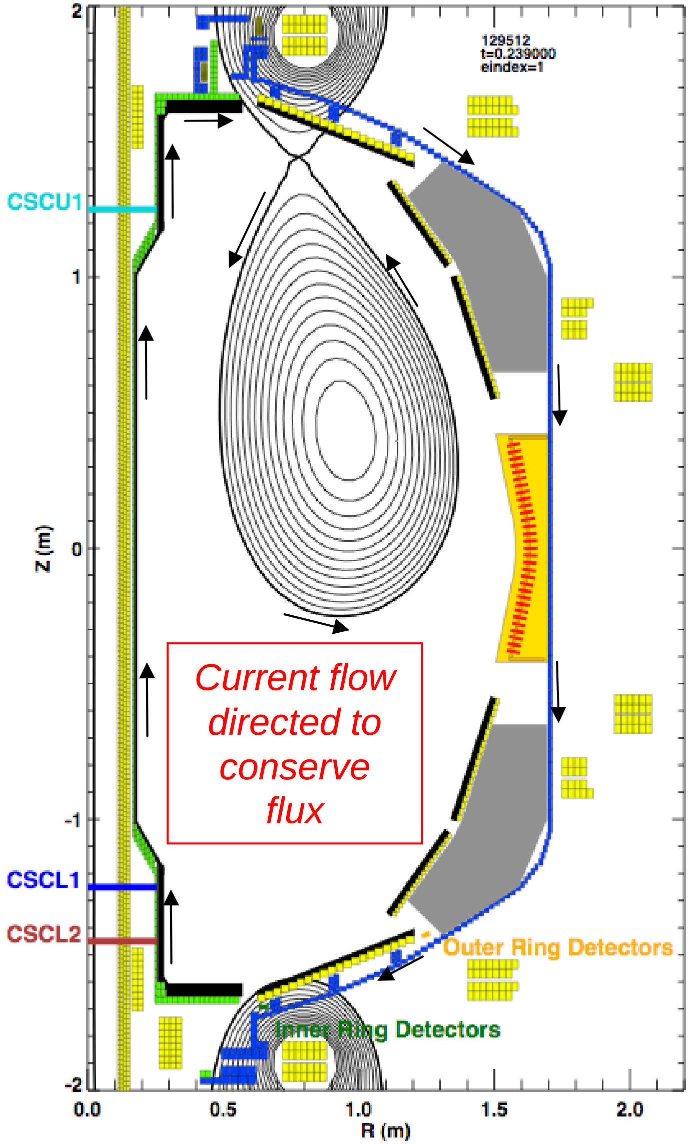


Shot 129449
Downward Going VDE
(PF3 Voltage Freeze + Offset)
Current Flows OUT of Divertor Plate

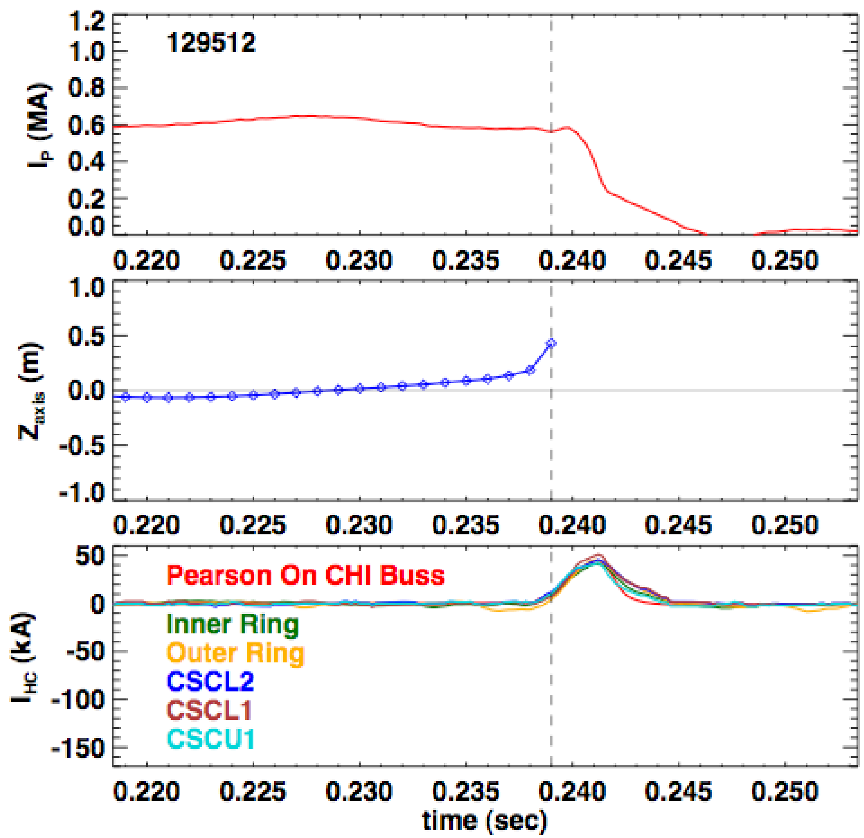


Typical Pattern for Dedicated VDE Experiment

More Limited Measurements for Upward Going VDE

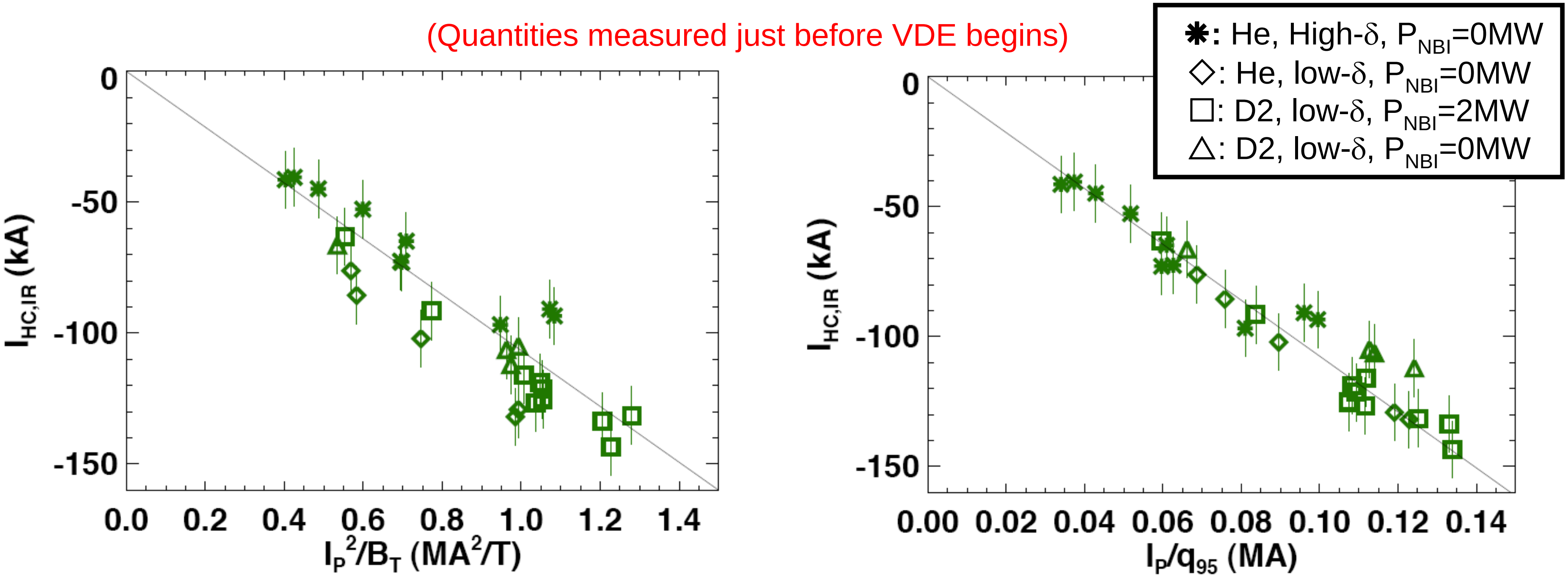


Shot 129512
Upward Going VDE



Leads to Largest Center Stack Casing Currents

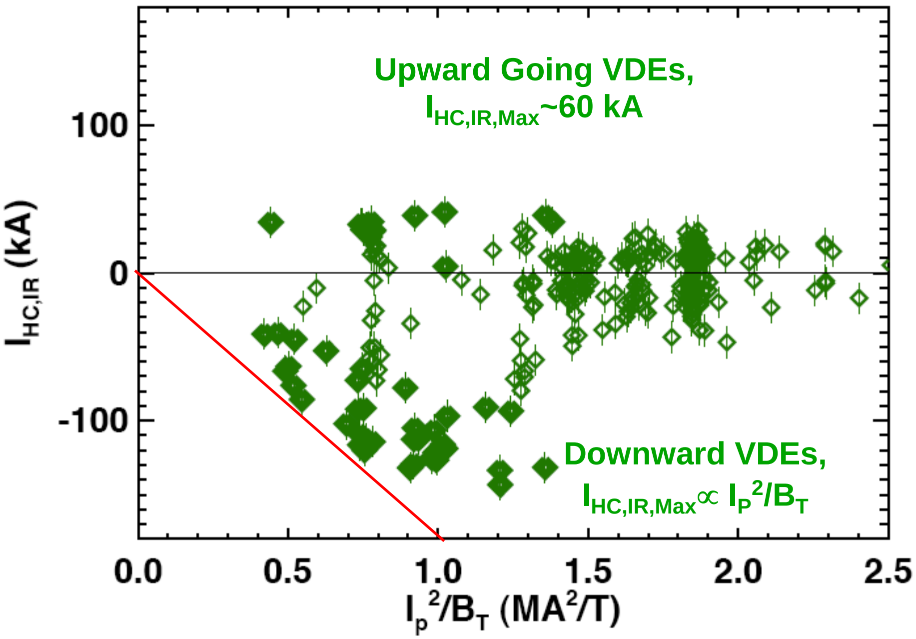
Halo Currents In Vessel Bottom Scale as I_P/q, Consistent With Simple Models



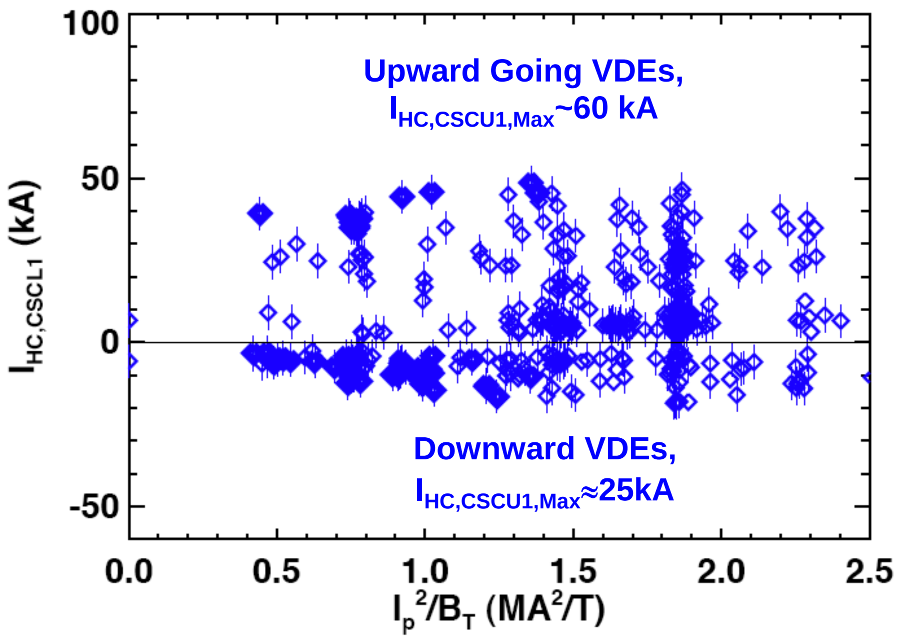
- Simple explanation of scaling (P.J. Knight, et al., Nucl. Fusion **40** (2000) 325.)
  - I_p: Halo currents increase with I_p
  - q: halo currents flow parallel to B, poloidal component increases if q decreases
- Scaling coefficient independent of working gas, P_{NBI}, shape

Vessel Bottom Currents Largest in Triggered VDE Experiments

Vessel Bottom, I_{HC} vs $I_P^2/B_T \sim I_P/q$



Lower PF1A Transition, I_{HC} vs I_P^2/B_T

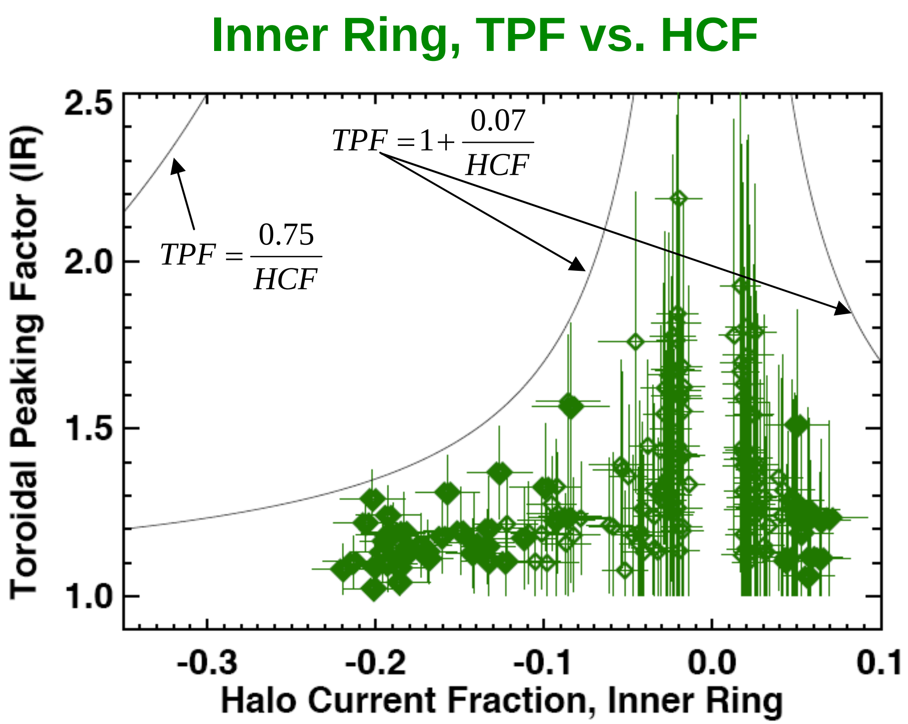


Solid Symbols: Deliberate VDEs (XP833 & XP811), Open Symbols: All Others

- Simplified conclusion
  - Upward VDEs: 60 kA max center stack casing current, no observed scaling with I_P^2/B_T, I_P/B_T, or I_P
  - Downward VDEs: I_P^2/B_T scaling for currents into outboard divertor

NSTX

Toroidal Peaking Factor Decreases With Halo Current Fraction

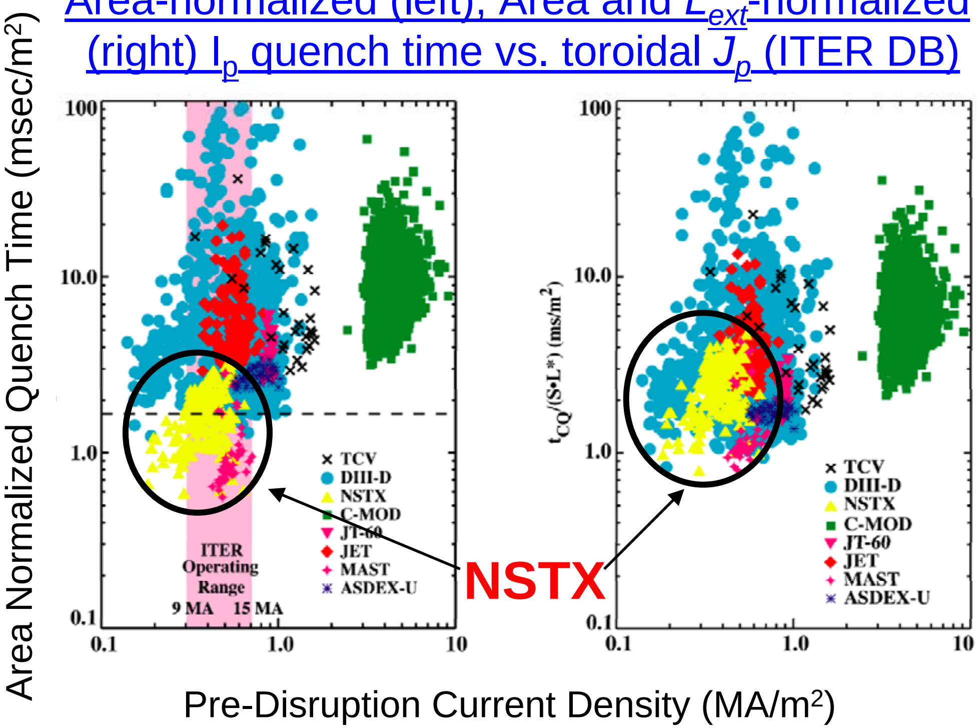


- Toroidal peaking factor TPF = 6*max(B_i=1:6) / ΣBi
  - Uncertainty larger at small halo current fraction (HCF)
- ITER Assumption: TPF×HCF < 0.75
  - NSTX Data Well Below This Scaling

Current Quench Rates Are Fast in the ST

Past ITPA result

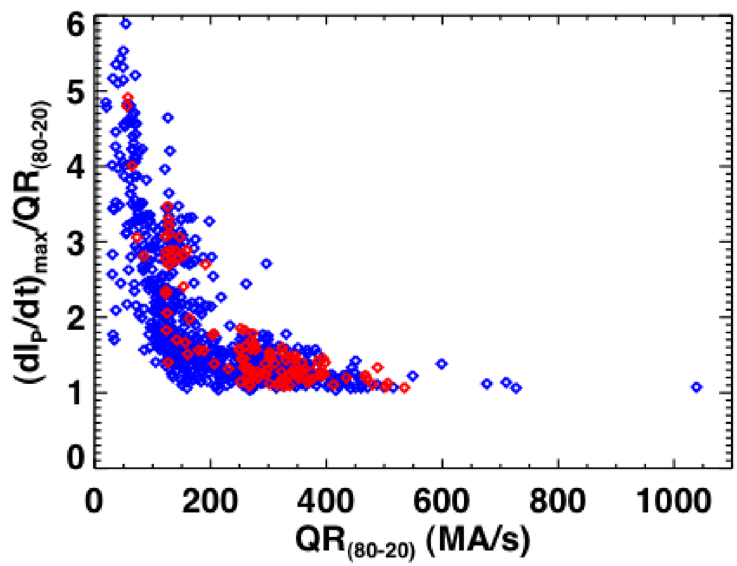
Area-normalized (left), Area and L_{ext}-normalized (right) I_p quench time vs. toroidal J_p (ITER DB)



- Fastest NSTX disruption quench times of 0.4 ms/m², compared to ITER recommended minimum of 1.7 ms/m²
- Reduced inductance at high-κ, low-A explains difference

$$\frac{\tau_{L/R}}{S} = \frac{\mu_0}{2\pi\eta}\left[\ln\left(8 \big/ \sqrt{\kappa\varepsilon}\right) - 7\big/4\right]$$

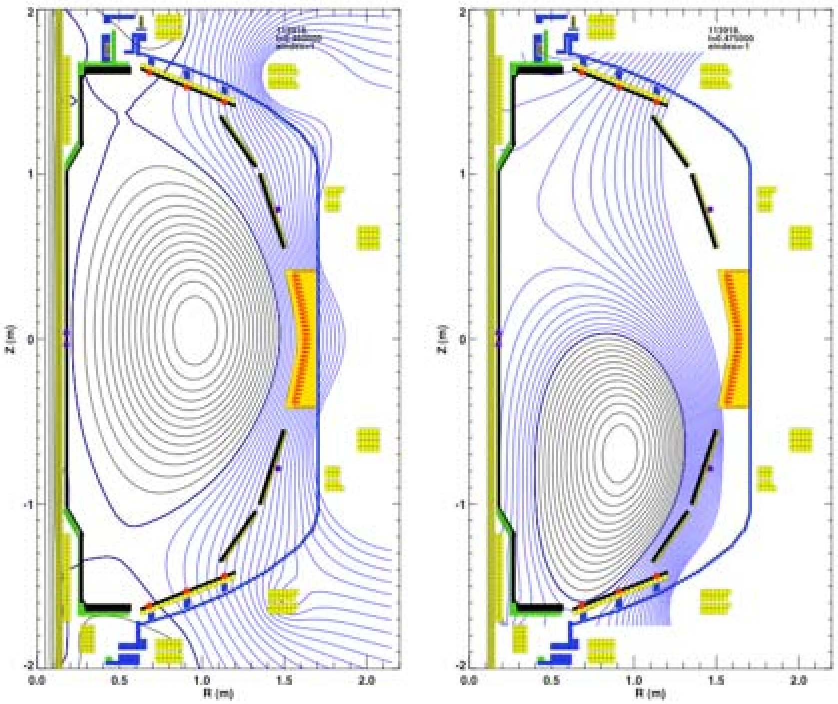
Maximum Quench Rates/Average Quench Rate vs. Average QR

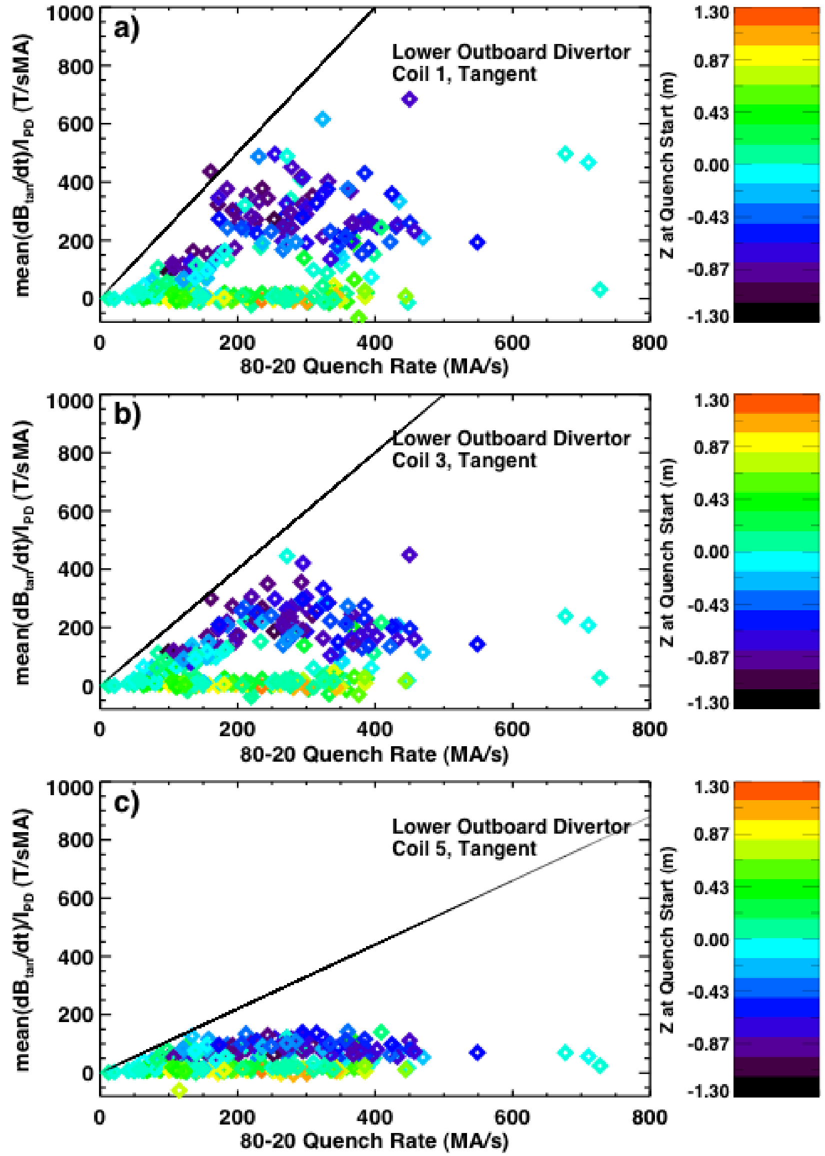


Average Quench Rate: $QR_{(80-20)} = -\frac{.6 * I_{PD}}{t_{20} - t_{80}}$

- Maximum quench rates often larger than average quench rates
  - Issue for components with short L/R time

Quench rate important in determining the eddy current drive

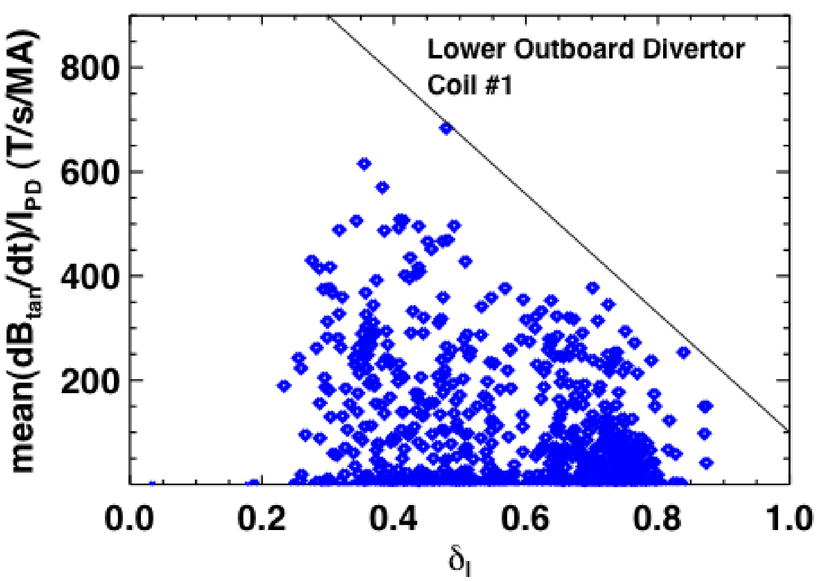




- dB/dt at Lower outboard divertor
  - Points sorted by the axis vertical position just before the disruption
  - Ip-normalized dB/dt increases with quench rate
  - Scatter in data due to details of plasma motion and shape

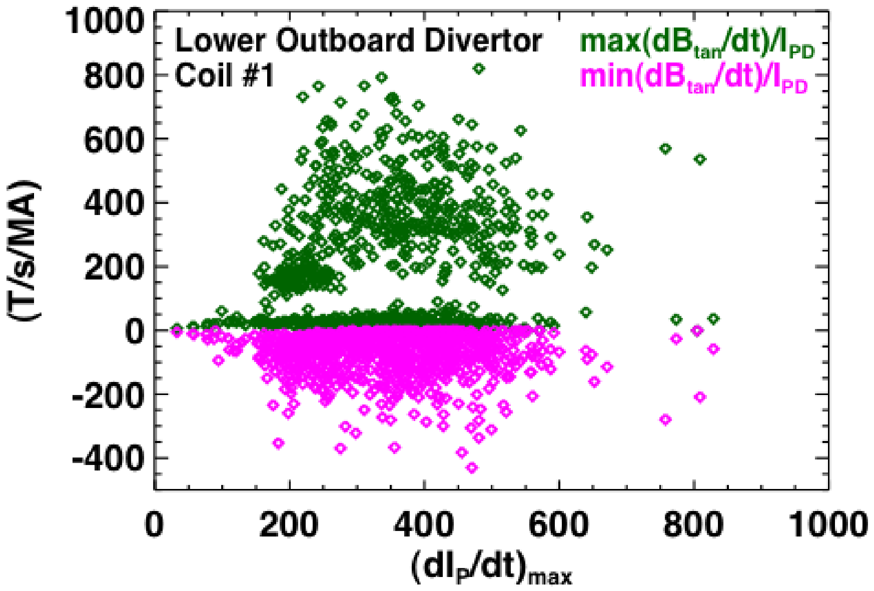
Geometry and plasma motion affects local field variation

Mean(dB/dt)/I_P vs Lower Triangularity Outboard Divertor



- At low δ, Shaping field coil current attracts plasma toward sensor coil during VDE
  - maximizes measured dB/dt
- Same result for upward-going VDE and upper sensor coil

(Max and min)(dB/dt)/I_P vs $(dI_P/dt)_{max}$ Outboard Divertor



- Large positive values due to large values of dIp/dt during quench
- Large negative values due to rapid downward plasma motion (~constant I_p)
- Current quench effect is dominant, but only factor 2 larger

Halo currents, eddy currents, and current quench rates investigated in ST geometry

- Large database relevant to disruption EM loading
- Halo currents up 150kA measured with new diagnostics, I_P/q_{95} scaling, in outboard divertor
- Halo currents up to 60 kA, and no observed scaling, on center stack casing
- Fastest I_P quenches of 1GA/s, with instantaneous rates often much faster than the average
- Current quench rate, plasma geometry, plasma motion important in determining the local eddy current drive

Planned for Next Run Campaign

- Toroidally extended halo current measurements into four liquid lithium divertor (LLD) sectors
- Toroidally localized halo current measurements at four positions at LLD
- Fast (> 1.5 kHz) IR thermography for thermal quench studies

Backup slides follow

NSTX Disruption Studies Contribute to ITER, Aim to Predict Disruption Characteristics & Onset For Future Large STs

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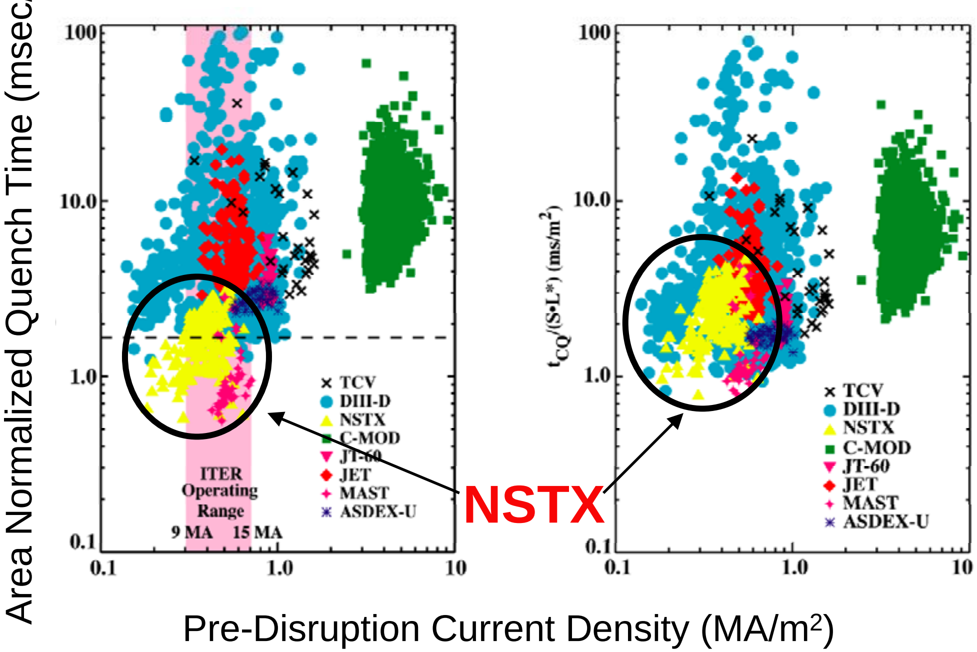
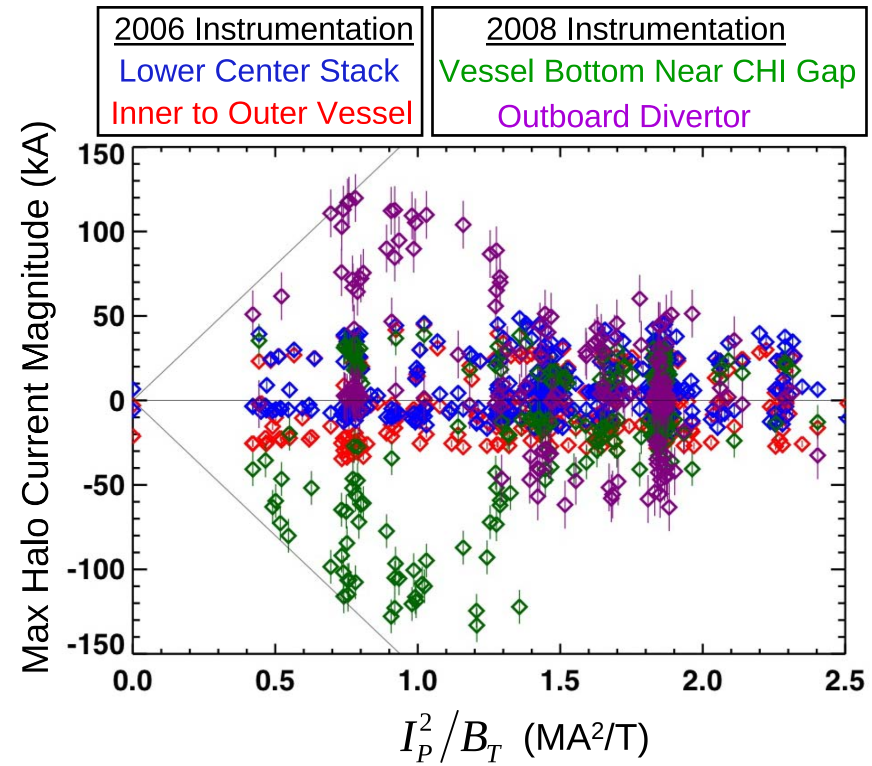


Halo Current Magnitudes and Scaling



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$$\frac{\tau_{L/R}}{S} = \frac{\mu_0}{2\pi\eta}\left[\ln\left(8/\sqrt{\kappa\varepsilon}\right) - 7/4\right]$$

- New instrumentation in 2008 yields significant upward revision of halo current fractions (now up to 20%)
  - reveals scaling with I_P and B_T
  - Mitigating effect: Largest currents for deliberate VDEs
- Toroidal peaking reduced at large halo current fraction

Expand Results For a Complete Characterization of Disruption Dynamics, Including Prediction Methods