Highlights From Recent Disruption Studies in NSTX

Piggyback + XP 833

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Many More Results Available At
http://w3.pppl.gov/~sgerhard/NSTX.html

Rev. 0

Eddy Currents, Halo Currents and the Spherical Torus

- The disruption I_P quench drives eddy currents (I_C) in nearby conducting structures (C).
  - τ_c (L_C/R_C time) long: total flux change matters
  - τ_c short: instantaneous flux change matters

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

- Previous studies have found that disruptions in an ST are faster than at conventional aspect ratio.
  - Expand these studies to a wider range of characteristics and look for dependence on discharge parameters.
- Highly elongated plasmas, while otherwise desirable because of their high q values, are typically unstable to vertical motion.
  - The vertical motion is controlled by PCS feedback; almost always fails during NSTX disruptions.
- When the plasma come in contact with the top or bottom of the VV, currents can flow linking the plasma and in-vessel components.
  - Currents are ||B in the plasma edge (“Halo”), and distributed in the vessel as per the appropriate inductive/resistive distribution.
- These currents lead to large JxB forces on the in-vessel components.
  - *Anticipated to be the largest source of EM loading for slow I_P-quench vertically unstable disruptions in ITER.*
- Strong 1/R toroidal field variation in the ST.
  - *Halo currents on center column are the biggest concern.*

Goal: Provide EM Loading Data for the Design of Future STs

What data has been analyzed?

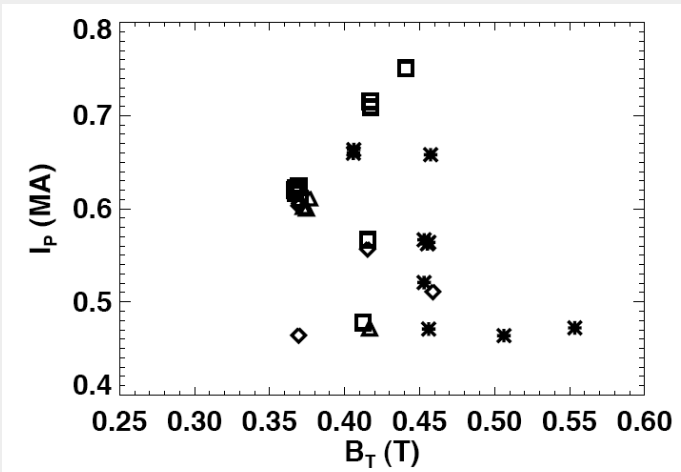
Database analysis of interesting disruptions

- Analysis goes back to 102169
- Select shots with fast current quenches, large halo currents,…
- Maximum halo current in all measured paths
- All important current quench characteristics
- Plasma equilibrium parameters, both at time of disruption and time of maximum stored energy.

Devoted Experiment in XP833

- PF3 Voltage Freeze +Offset for triggered VDEs
- Scans of I_P and B_T at fixed shape and NBI power.
- Detailed tracking of vertical motion (no multiple bounces).
- More accurate characterizations than in large database analysis.

XP833 I_P & B_T Range



New Measurements Allow The Study of Additional Halo Current Paths

Rogowskis on the CSC
CSCL1, CSCL2, CSCU1
No Midplane Measurements

Two Pearson CTs on CHI Bus

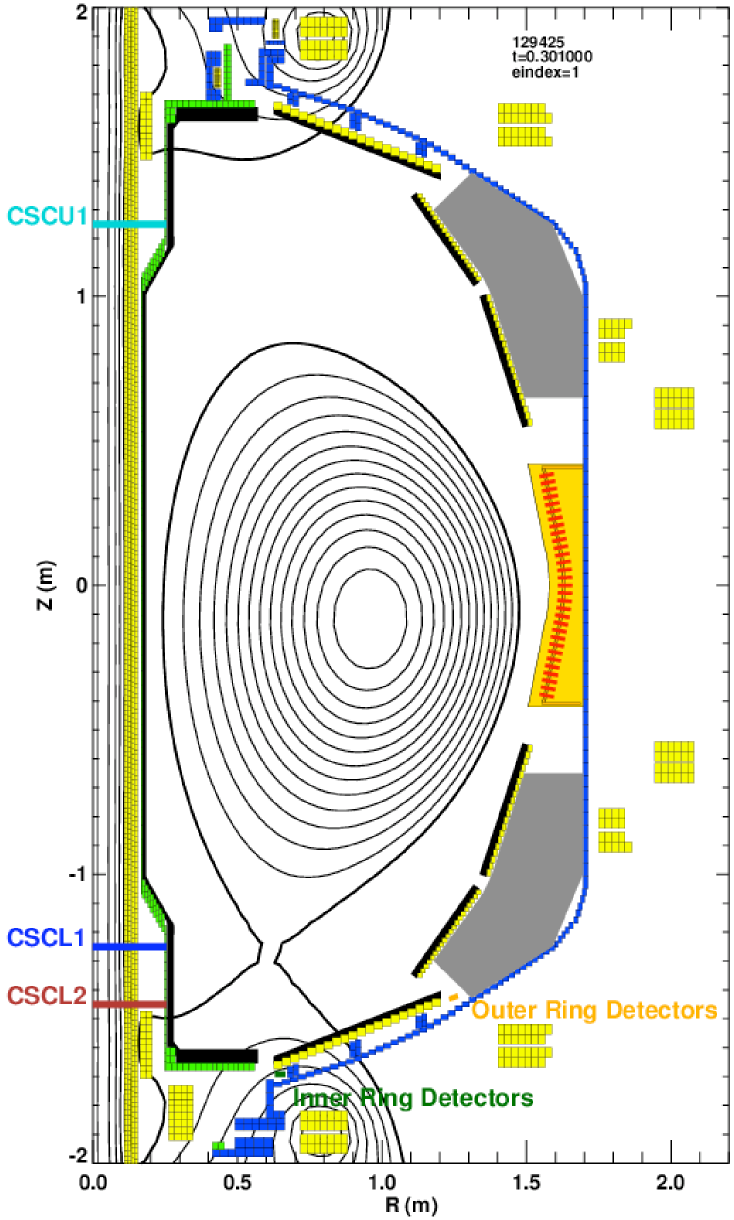
Current from inner to outer vessel

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

Colors Above Consistent With Plots on Following Pages



XP 833 Produced I_P and B_T Scans With Different Species, Shape, and Injected Power (I)

Shot	Species	I_P (MA)	B_T (T)	q_{95}	κ	δ_l	P_{inj}
129415	He	0.6	0.46	9.6	1.96	0.37	0
129416	He	0.56	0.46	9.4	1.93	0.42	0
129417	He	0.66	-.46	7.78	1.93	0.4	0
129419	He	0.52	0.45	10.01	1.9	0.35	0
129420	He	0.47	0.46	11	1.89	0.39	0
129421	He	0.66	0.41	6.67	1.93	0.3	0
129423	He	0.66	0.41	6.871	1.95	0.37	0
129425	He	0.47	0.55	13.9	1.9	0.4	0
129426	He	0.46	0.51	12.4	1.91	0.35	0
129427	He	0.56	0.46	9.87	1.95	0.3	0
129446	He	0.56	0.42	6.22	1.96	0.33	0
129448	He	0.51	0.46	7.44	1.94	0.33	0
129449	He	0.61	0.37	5.09	1.96	0.32	0
129450	He	0.46	0.37	6.12	2.02	0.31	0
129511	He	0.6	0.37	4.87	1.94	0.32	0

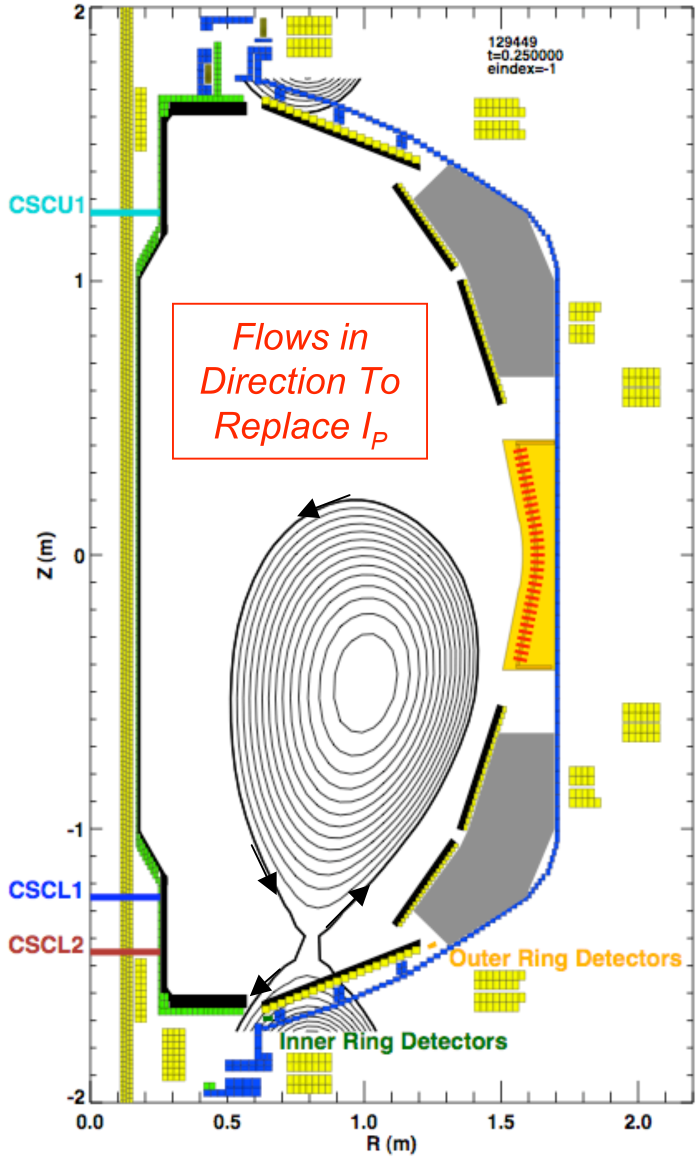
Some Shots in Scan Went Up

not included above, but are included in larger database

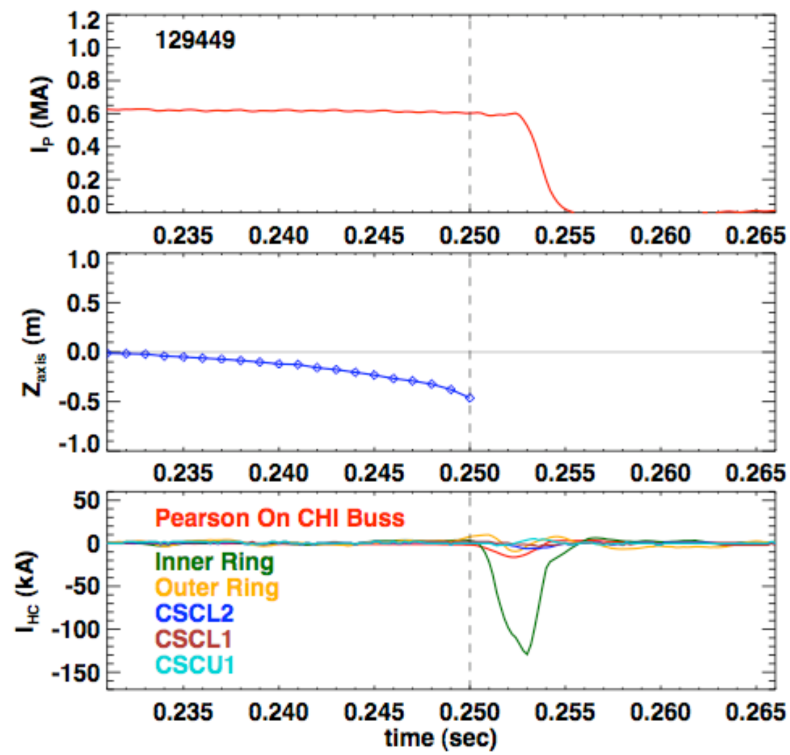
XP 833 Produced I_P and B_T Scans With Different Species, Shape, and Injected Power (II)

Shot	Species	I_P (MA)	B_T (T)	q_{95}	κ	δ_l	P_{inj}
129512	D_2	0.62	0.38	5.68	2.12	0.32	0
129513	D_2	0.57	0.38	5.04	2.09	0.31	0
129821	D_2	0.61	0.38	5.4	2.2	0.32	0
129826	D_2	0.6	0.37	5.3	2.1	0.32	0
129832	D_2	0.6	0.37	4.85	2.11	0.25	0
129835	D_2	0.47	0.42	7.13	2.08	0.32	0
129831	D_2	0.61	0.37	5.46	1.96	0.35	2.06
129836	D_2	0.48	0.41	8.02	1.91	0.36	2.12
129837	D_2	0.57	0.42	6.77	1.96	0.36	2.03
129839	D_2	0.71	0.42	5.33	2.0	0.35	2.0
129840	D_2	0.74	0.45	6.61	2.14	0.33	2.11
129842	D_2	0.62	0.37	5.53	1.98	0.35	2.09
129846	D_2	0.75	0.45	6.75	2.14	0.33	2.07
129847	D_2	0.72	0.42	5.35	2.05	0.34	2.13
129848	D_2	0.62	0.37	5.8	2.0	0.37	3.99
129849	D_2	0.62	0.37	5.72	1.98	0.37	4.0
129850	D_2	0.62	0.37	5.7	2.0	0.35	4.0

Downward Going Disruption With Large Halo Currents

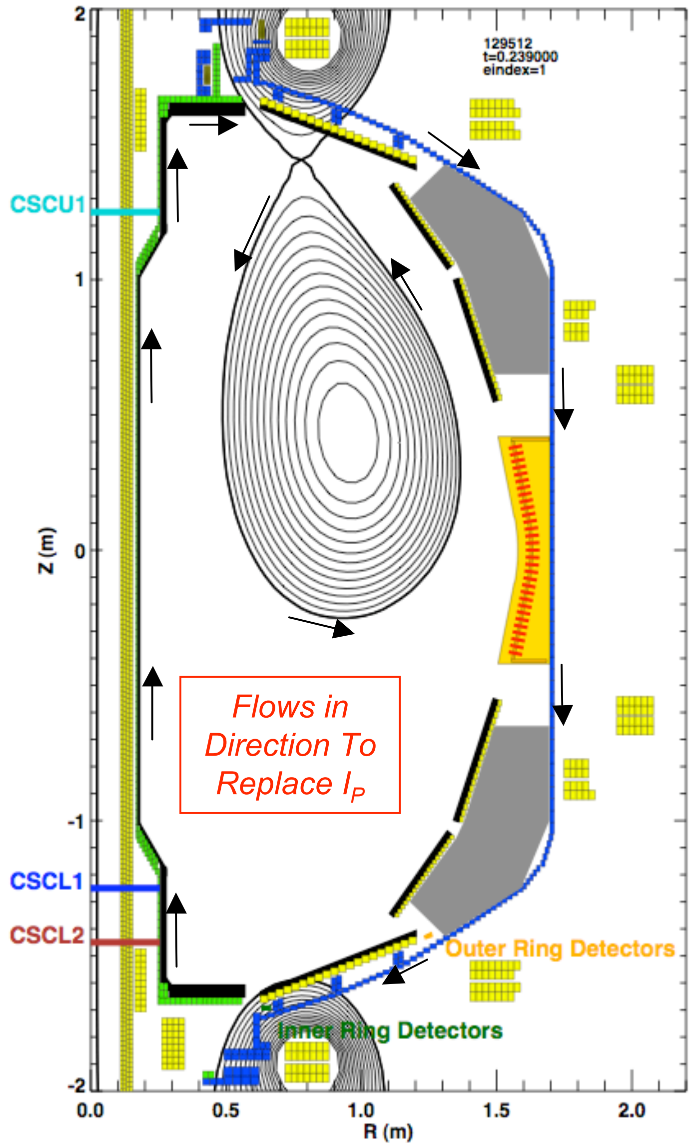


Shot 129449
Downward Going VDE
(PF3 Voltage Freeze + Offset)
Current Flows OUT of Divertor Plate

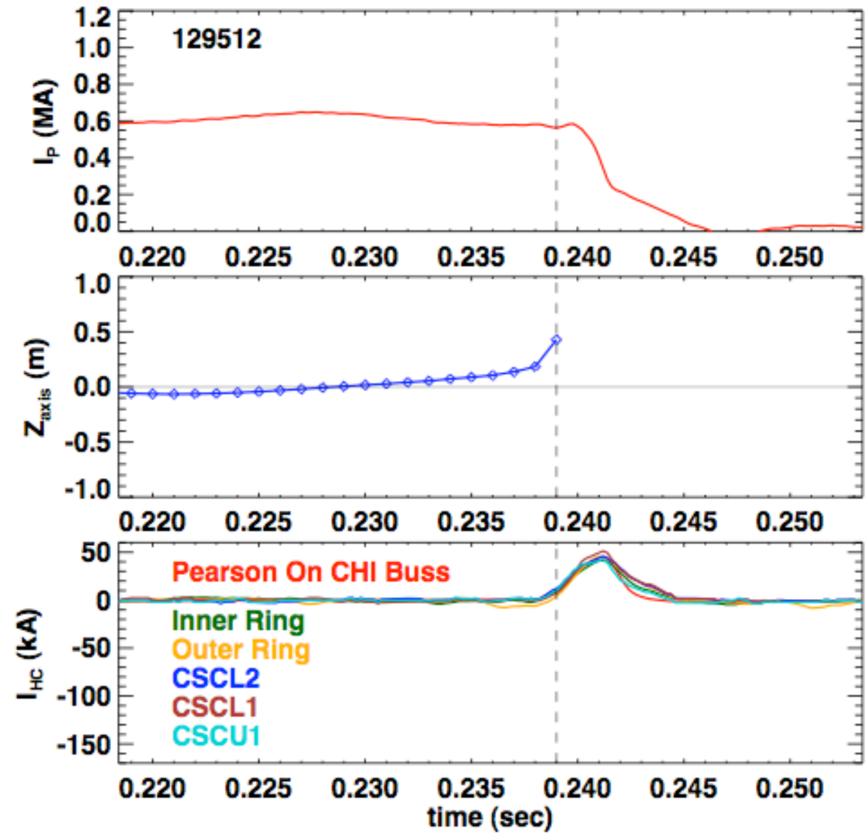


Typical Pattern for Devoted Experiments in XP833

More Limited Measurements for Upward Going VDE



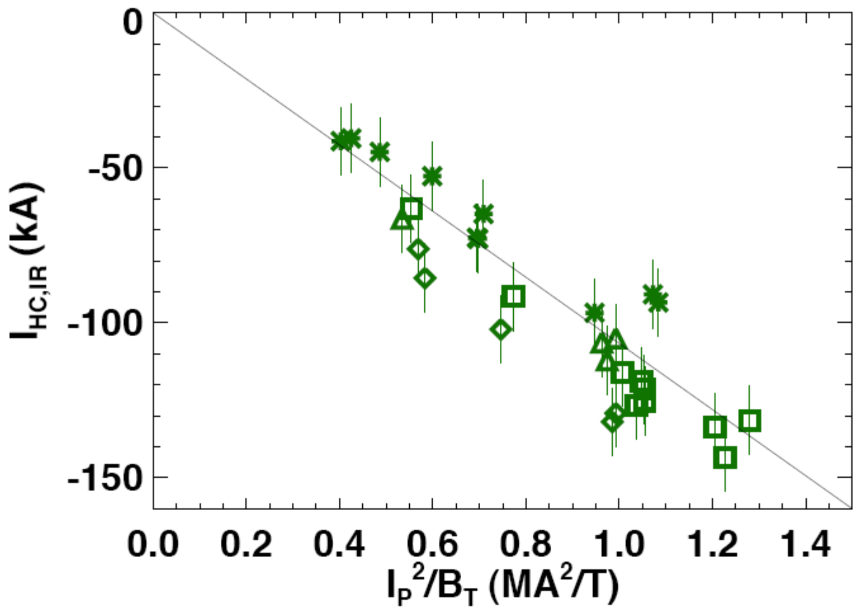
Shot 129512
Upward Going VDE

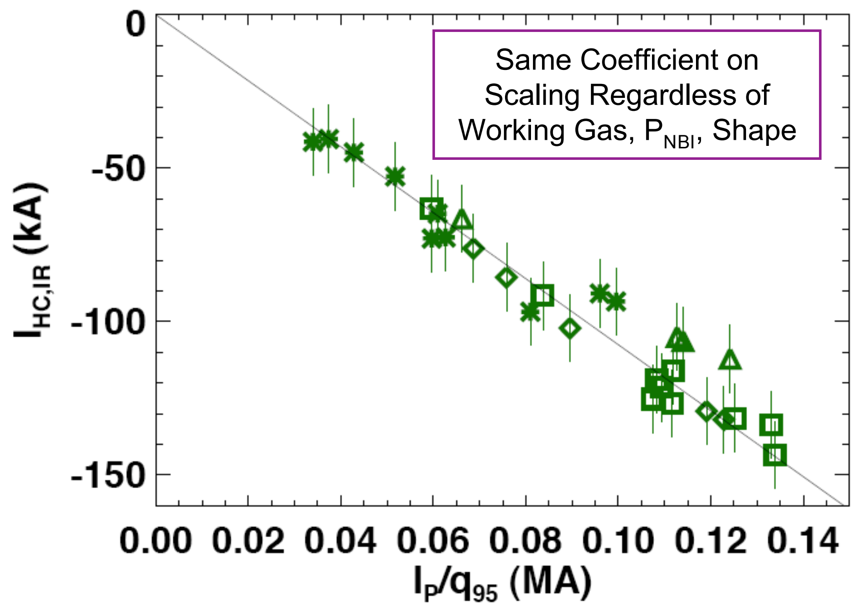


This Condition Leads to the Largest Currents on the Center-Stack Casing

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

For XP833 Analysis, Measure All Quantities Just before VDE Begins





✱: He, High-δ, P_{NBI}=0MW
◇: He, low-δ, P_{NBI}=0MW
□: D2, low-δ, P_{NBI}=2MW
△: D2, low-δ, P_{NBI}=0MW

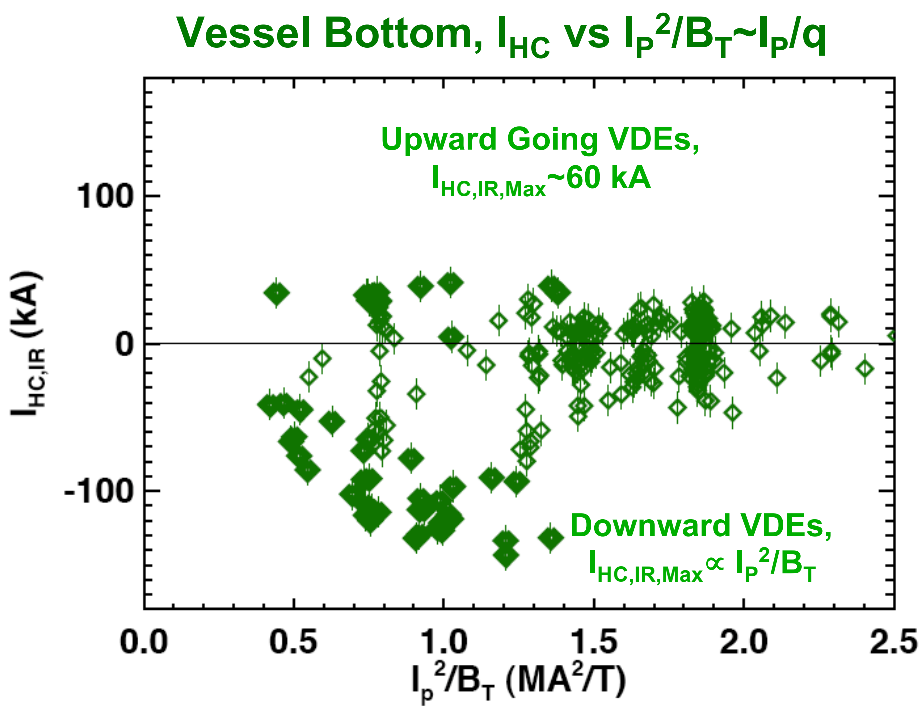
<u>Simple Explanation of Scaling:</u> (See P.J. Knight et al, for more thorough explanation)

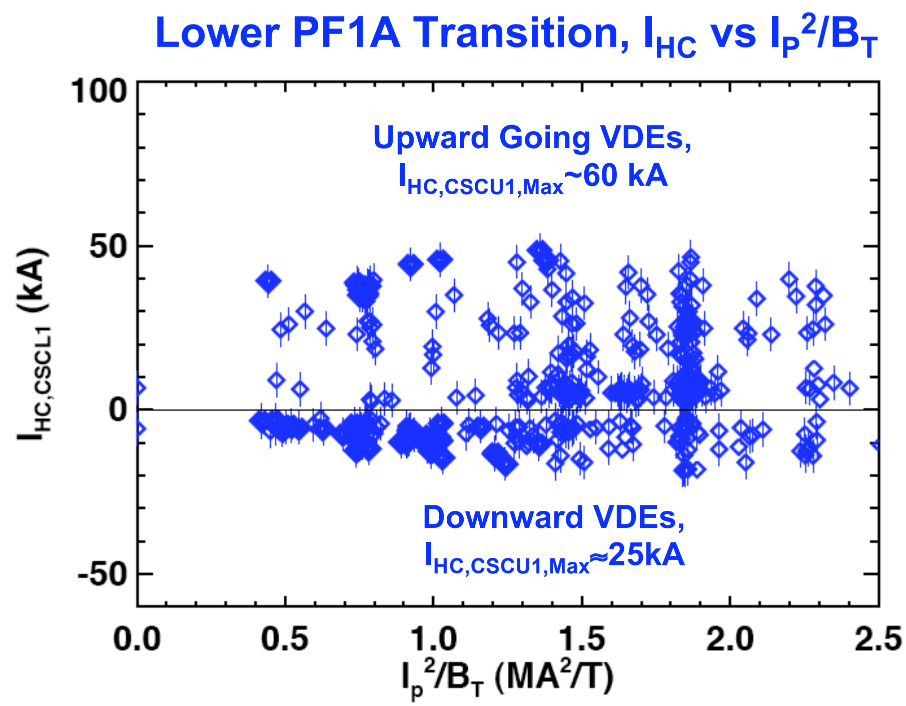
I_P: Halo currents increase if I_P increases

q: halo currents flow parallel to B, poloidal component increases if q decreases

Vessel Bottom Currents Are Largest in the Triggered VDE Experiments

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





Simplified Conclusion

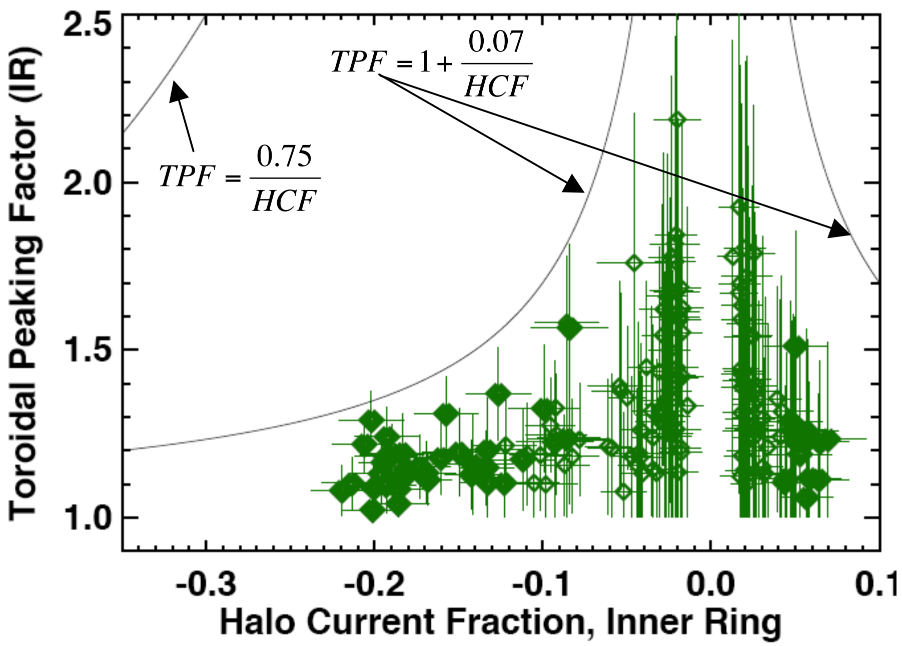
Upward VDEs: 60 kA max CSC current, no observed scaling observed with I_P^2/B_T, I_P/B_T, or I_P.

Downward VDEs: I_P^2/B_T scaling for currents into OBD

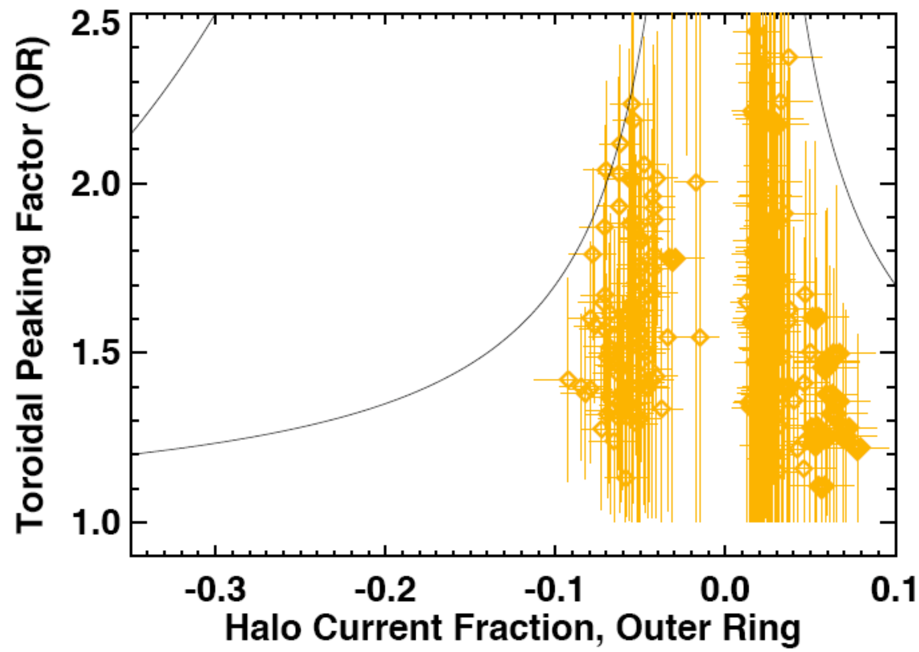
TPF Decreases With HCD

TPF=6*max($B_{i=1:6}$) / ΣB_i
Uncertainty will be Larger at Small |HCF|

Inner Ring, TPF vs. HCF



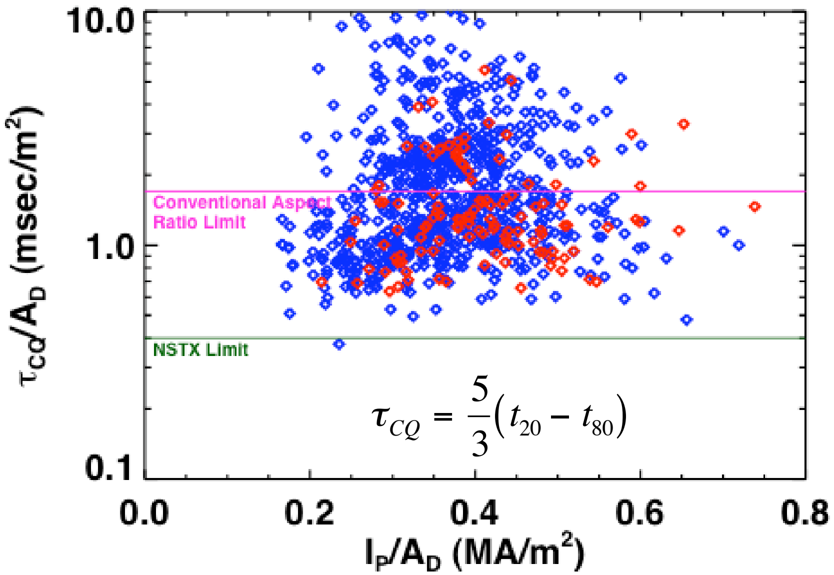
Outer Ring, TPF vs. HCF



ITER Assumption: TPF×HCF<0.75
NSTX Data Well Below This Scaling ("Good News")

Current Quench Rates Are Fast in the ST

Area Normalized Quench Times Vs Pre-Disruption Current Density



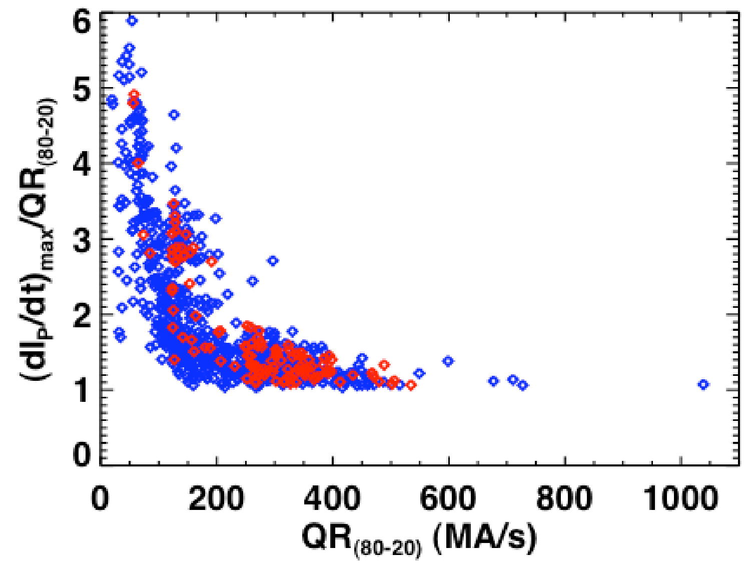
Assume That the Current Quench is Just an L/R Decay $\tau_{L/R} = L_P^{eff}/R_P$

$$R_P = 2\pi\eta R_0/A \qquad L_P^{eff} = \mu_0 R_0\left[\ln\left(8/\sqrt{\kappa\varepsilon}\right) - 7/4\right]$$

Area Normalized Decay Rate Depends Mainly on Electrical Resistance

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

Maximum Quench Rates Often Much Larger than Average Quench Rates



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

Maximum Quench Rate: $\left(\frac{dI_P}{dt}\right)_{max}$

Quench Rate Is Important in Determining the Local Field Variation

Method

• Calculate the mean dB/dt during the I_P quench, at various locations around the device.

• Normalized the field derivative to I_P just before the disruption.

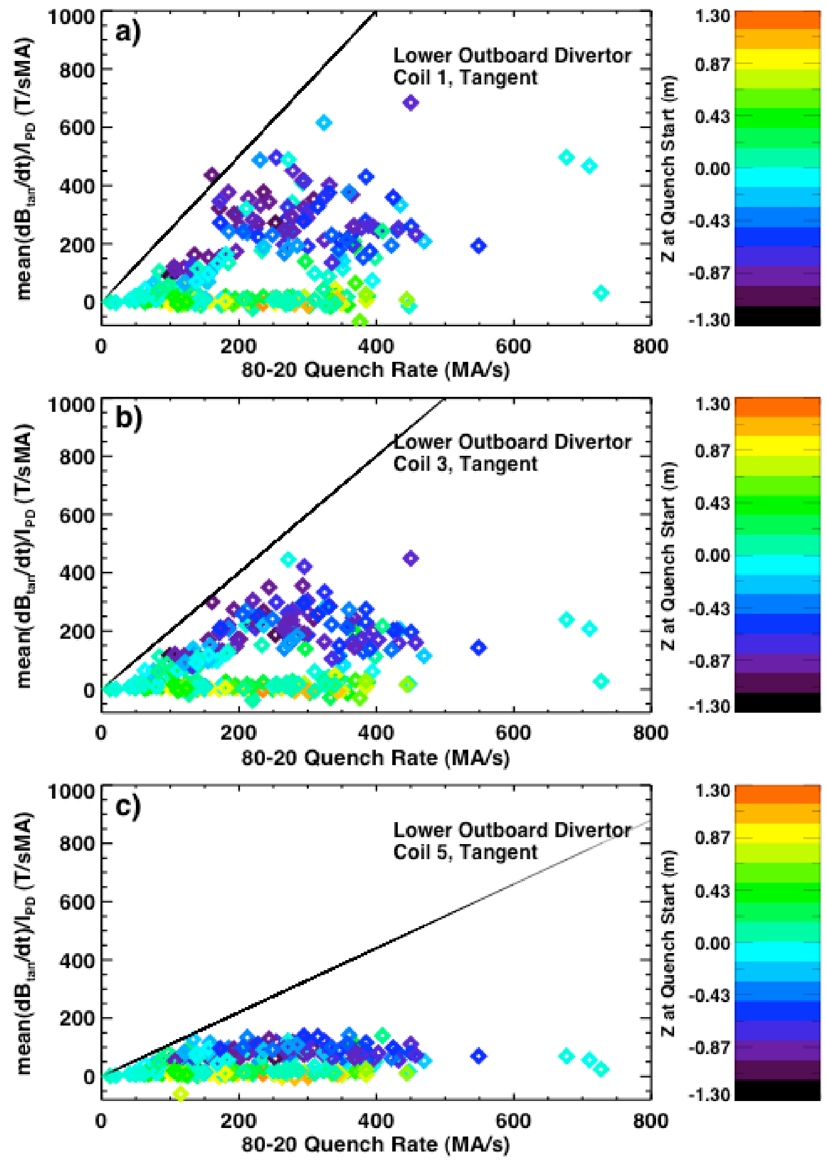
• Have these for CS midplane, upper and lower OBDs, upper and lower PPP.

Example Result: Lower Outboard Divertor

•Points sorted by the axis vertical position just before the disruption.

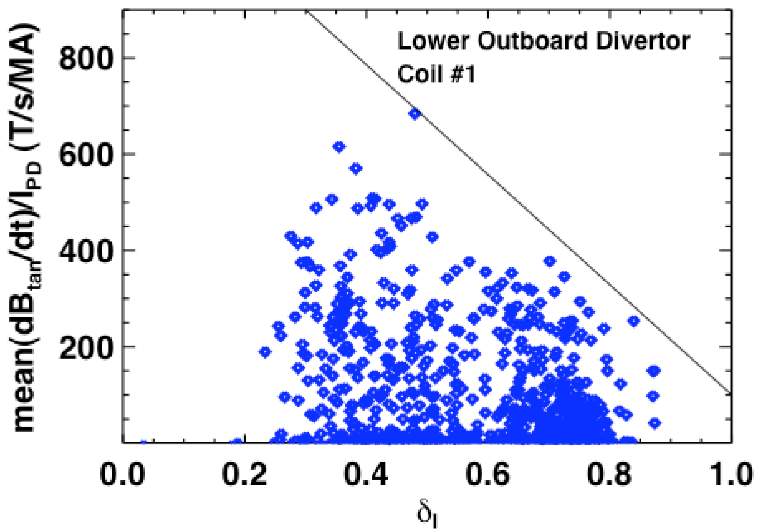
•I_P-normalized dB/dt is proportional to the quench rate.

•But, lots of scatter in the data…



But Geometry and Plasma Motion Matters

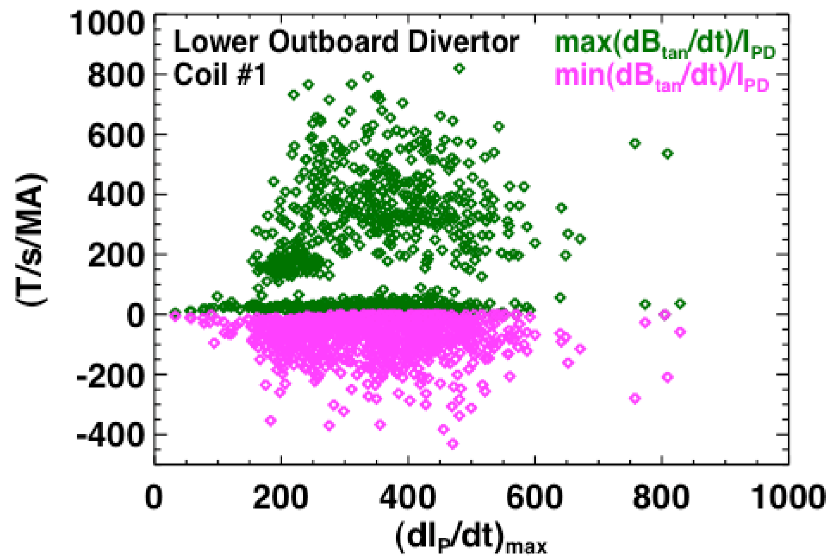
mean(dB/dt)/I_P vs Lower Triangularity
Outboard Divertor



Explanation

- Lower triangularity shots often have large PF 2 pulling current, “attracts” the VDE motion.
- This location (coil #1) sits above PF2, sees the plasma private flux just before the VDE.
- When the I_P quench occurs, the tangent field changes sign from the plasma direction to the vacuum direction, leading to a large dB/dt.

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



Explanation

- Large Positive Values: Due to large values of dI_P/dt during the current quench.
- Large Negative Values: Due to rapid downward plasma motion at near fixed I_P.
- *Only a factor of 2 difference!*

Summary

- We have a large database relevant to disruption EM loading.
- Halo currents of to 150kA & I_P/q scaling, in OBD.
- Halo currents up to 60 kA, and no observed scaling, on CSC.
- Fastest I_P quenches of 1GA/s, with instantaneous rates often much faster than the average.
- All of dI_P/dt, plasma geometry, and plasma motion important in determining the local eddy current drive.

For the Next Campaign

Halo currents into the four LLD sectors

Four prototype instrumented tiles (Halo Currents + SOL Currents, CHI)

Fast IR thermography, for thermal quench studies

Many More Results Available At

http://w3.pppl.gov/~sgerhard/NSTX.html