Disruptions and Halo Currents on NSTX - Update

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For the

NSTX Macroscopic Stability Topical Science Group

3rd Meeting of the ITPA MHD Stability Topical Group

October 6 - 9, 2009

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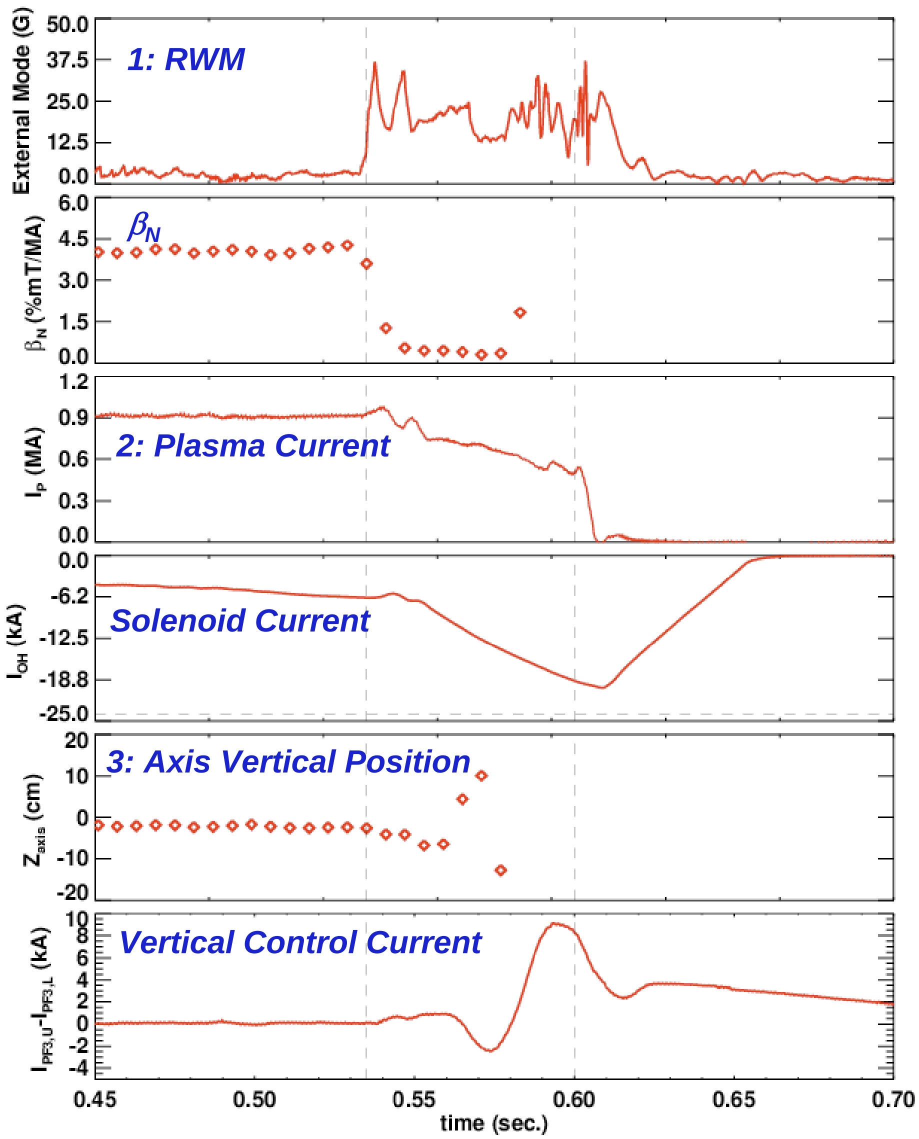
Disruptions and Halo Currents on NSTX - Update
OUTLINE

- General overview of disruption characteristics in NSTX.
- Pre-disruption energy loss in NSTX
- Current quench characteristics
- recent halo current results update from 2009 NSTX run
- summary of NSTX contributions to ITPA disruption database
- Future work and summary

Typical Time-Sequence of high-β Disruption in NSTX

Shot 128859: RWM Induced By Magnetic Braking



1: RWM grows

Triggers β-collapse and loss of H-mode

2: Plasma current begins to droop

Solenoid ramps harder to maintain I_P

3: Plasma develops rapid vertical motion

Vertical Control system attempts to maintain position

Disruption when plasma impacts vessel top

Comments on the sequence:

Representative of common H-mode RWM, Locked 2/1 mode disruptions

VDE is not:

"hot": full energy, before β-collapse

"cold": after the thermal quench

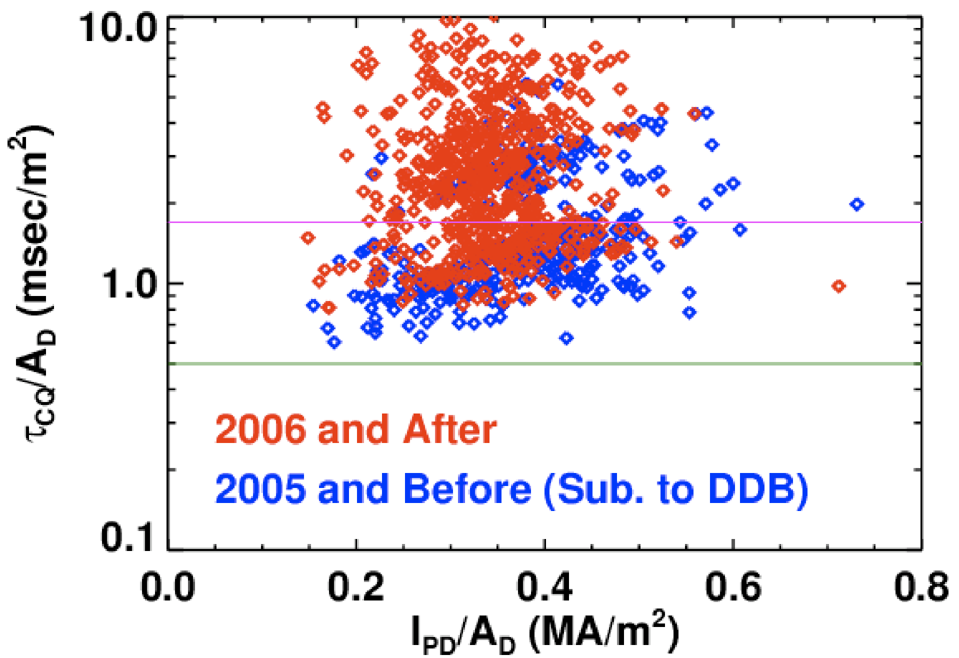
Can be large time lag between initial MHD and the final disruption

No mitigation or soft-landing techniques implemented in NSTX

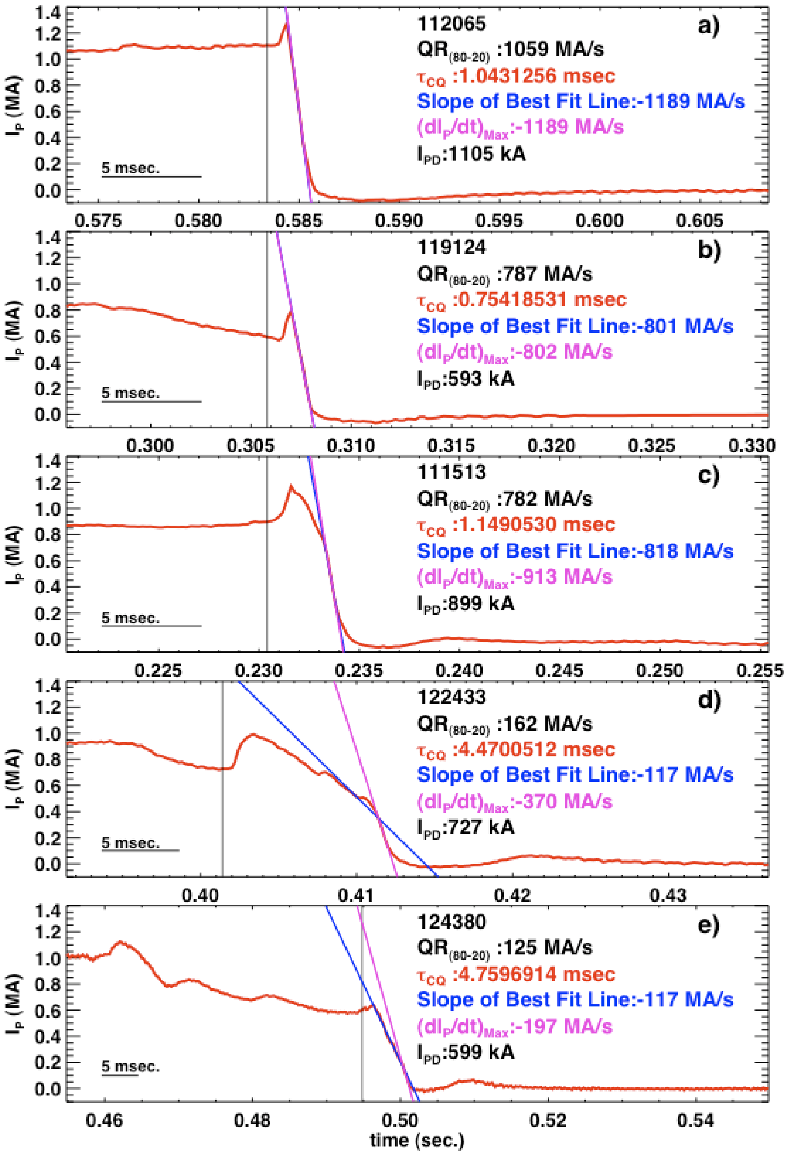
Current Quench Characteristics From 2005 DDB Submission Still Set the Quench-Rate Boundary

Area Normalized Quench Time vs. Average Current Density

- Limits for conventional aspect ratio and NSTX are apparently different
  - Conventional Aspect Ratio: ~1.7 msec/m^2
  - NSTX (and MAST): ~0.5 msec/m^2
- Difference likely due to the lower external inductance at lower aspect ratio
  - Wesley, et al., IAEA FEC, Chengdu (2006)
- All bounding cases occurred in 2005 and before
  - Are already in the DDB results published in above mentioned paper



Wide Range of I_P Quench Waveforms Observed



a-c) Fastest I_p quenches in NSTX database

Near linear I_p decay waveforms

No evidence of run-aways

***80-20 quench rate** and **maximum dI/dt** are similar*

d) Maximum quench rate is ~2.5 × the 80-20 metric.

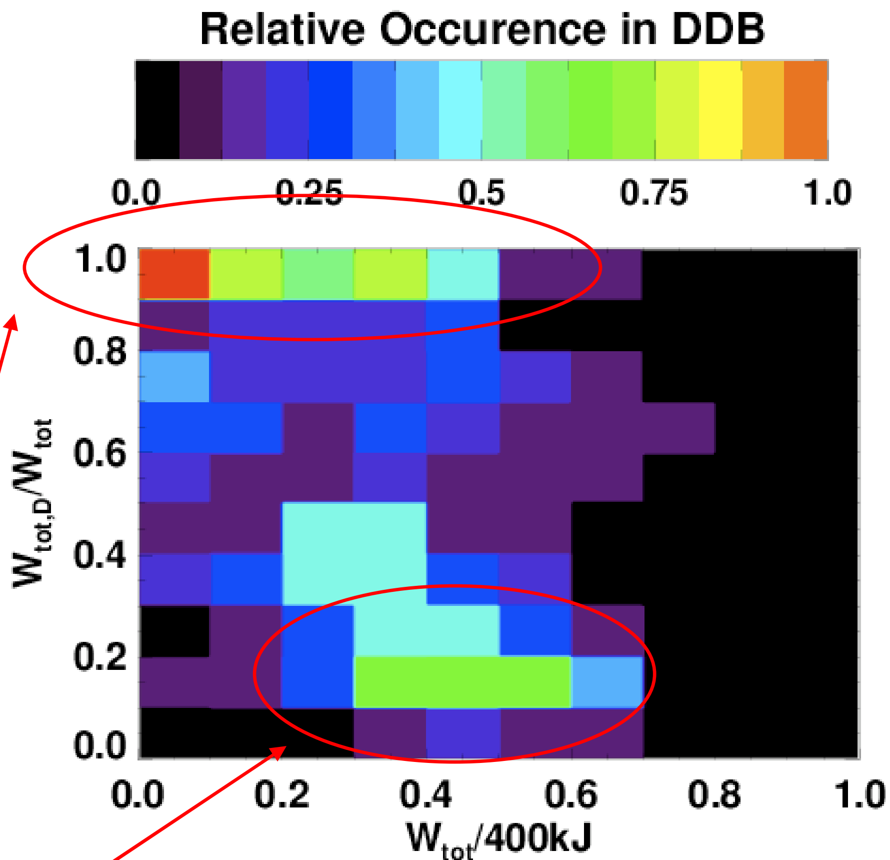
Period of slow I_P decay followed by rapid decay after plasma strikes vessel bottom

e) Plasma looses ~50% of it's current before the I_P quench

Poses the question: when does the "disruption" start?

Pre-Disruption Energy Loss: Database Shows Two Common Classes of Shots

- ***Stored energies from equilibrium reconstruction:***
  - *Record W_{MHD} at time of maximum stored energy*
  - *Record W_{MHD} just before disruption, as long as χ^2 is reasonable and reconstruction is within 15msec of disruption time*
  - *Criterion may lead some high stored energy shots to be discarded*
- ***1015 shots in database, including:***
  - *Shots with maximum I_P quench rates*
  - *Shots with highest pre-disruption stored energies*
  - *Shots with largest halo currents*
- ***Consider a 2D Histogram of the data***



Group 1:

- ***Little Pre-Disruption Loss, but low stored energy.***
- ***Typical of I_P ramp-up disruptions.***

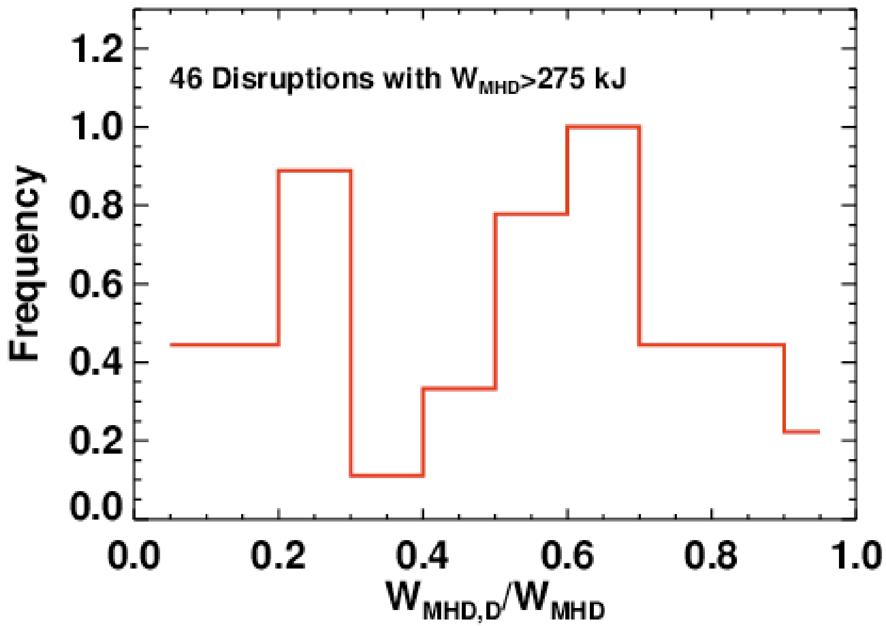
Group 2:

- **Large Stored energy, but also large loss before disruption.**
- **Typical of flat-top disruptions**

Interesting to Consider the Cases with Highest Stored Energy (W_{MHD}>275 kJ)

There is a Set of Highest Energy Disruptions Without Large Proceeding Energy Loss

- Rare high-energy cases with minimal pre-disruption energy loss.
  - These are potentially most troubling cases in NSTX
- Many cases occur just when negative V_{loop} is applied to ramp-down current in a high-energy discharge.
  - Need to develop better ramp-down scenarios to avoid these.



Halo Current Diagnostics in NSTX Have Been Continually Upgraded

Halo Current Detection in NSTX

3 Rogowskis on the Center Column (pre-2008)

- One rogowski (CSCL1) broken into three segments.
- The other two (CSCL2 and CSCU1) continuous

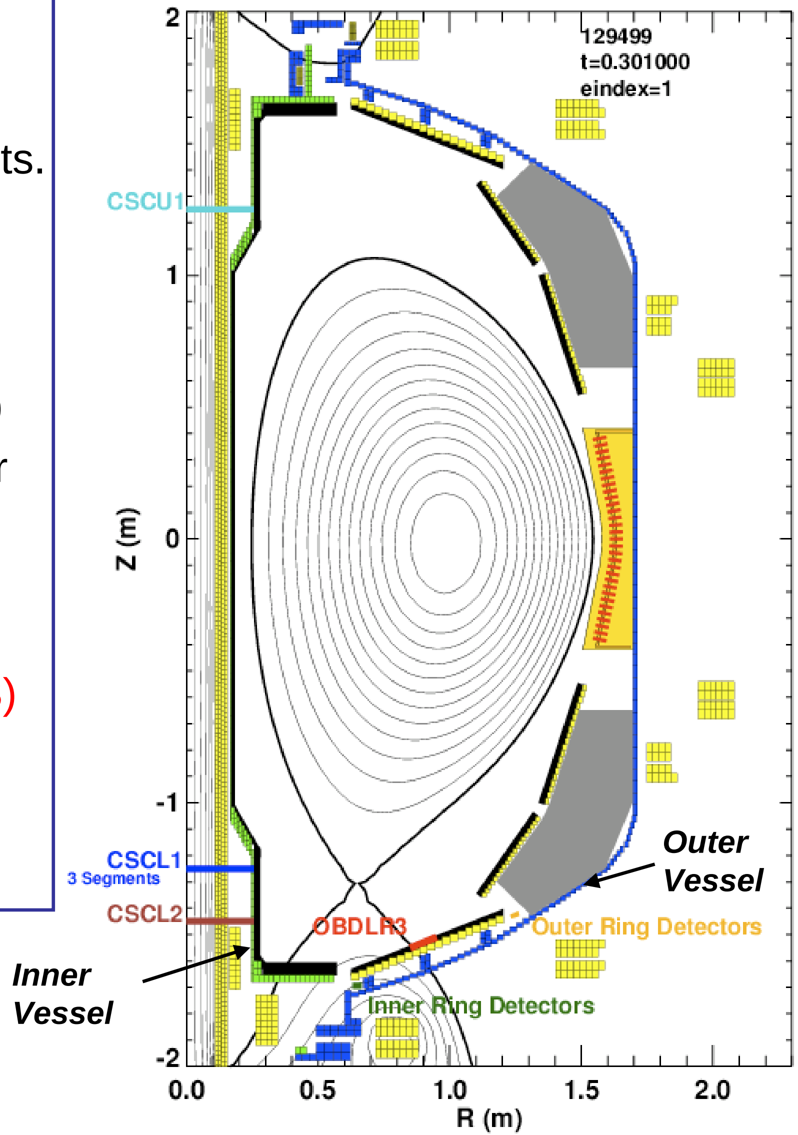
Arrays of Toroidal Field Sensors (2008)

- Poloidal current flowing in vessel wall
- One array of 6 sensors near CHI gap (Inner Ring)
- One array of 6 sensors between outboard divertor (OBD) and secondary passive plate (SPP) (Outer Ring)

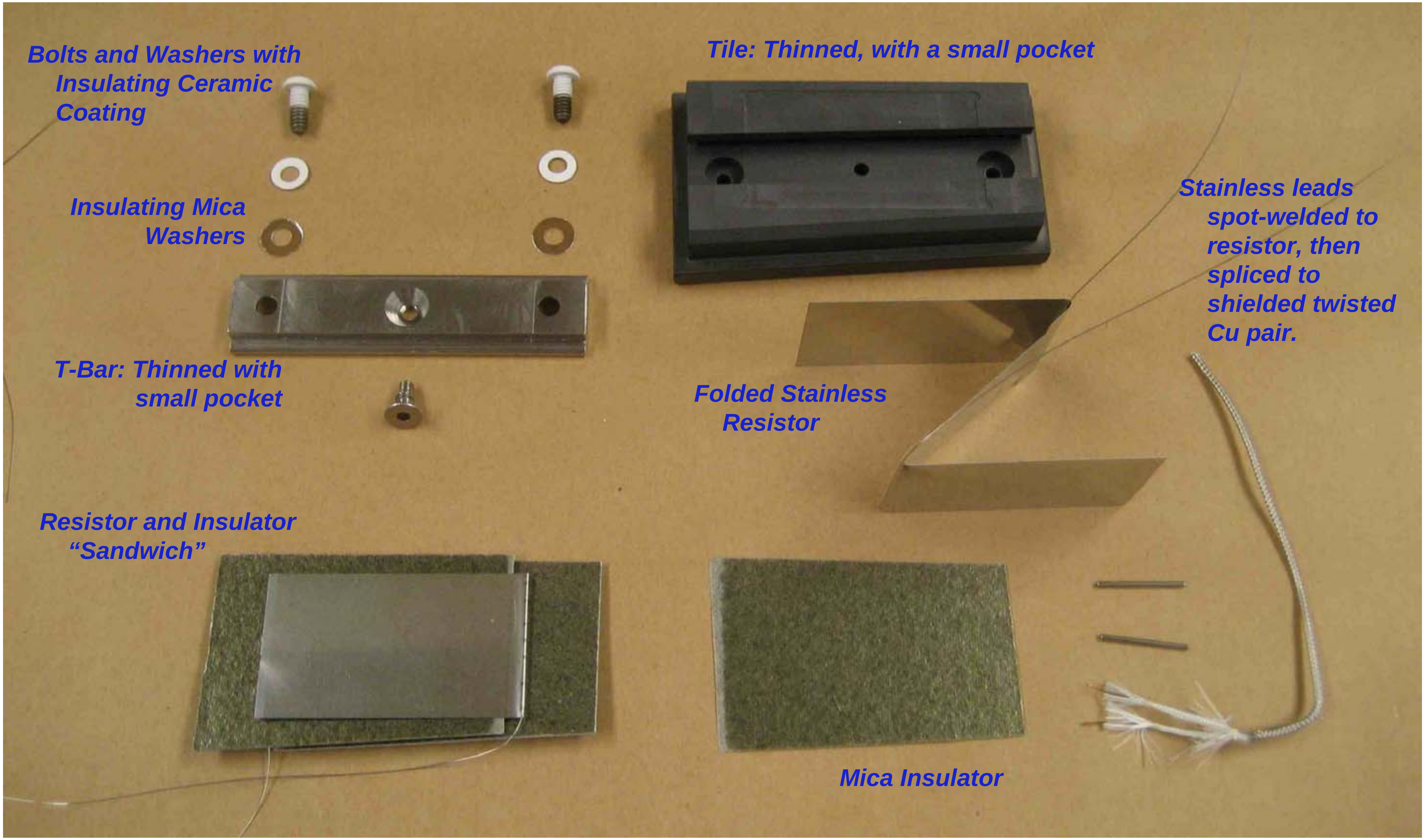
Arrays of Instrumented Tiles (2009)

- 4 Tiles in row 3 of the outboard divertor (OBDLR3)
- 90º Toroidal Separation
- Highly localized measurements of the current

NSTX has isolated inner and outer vacuum vessels. Only connection between them is via buss-work at the vessel bottom.

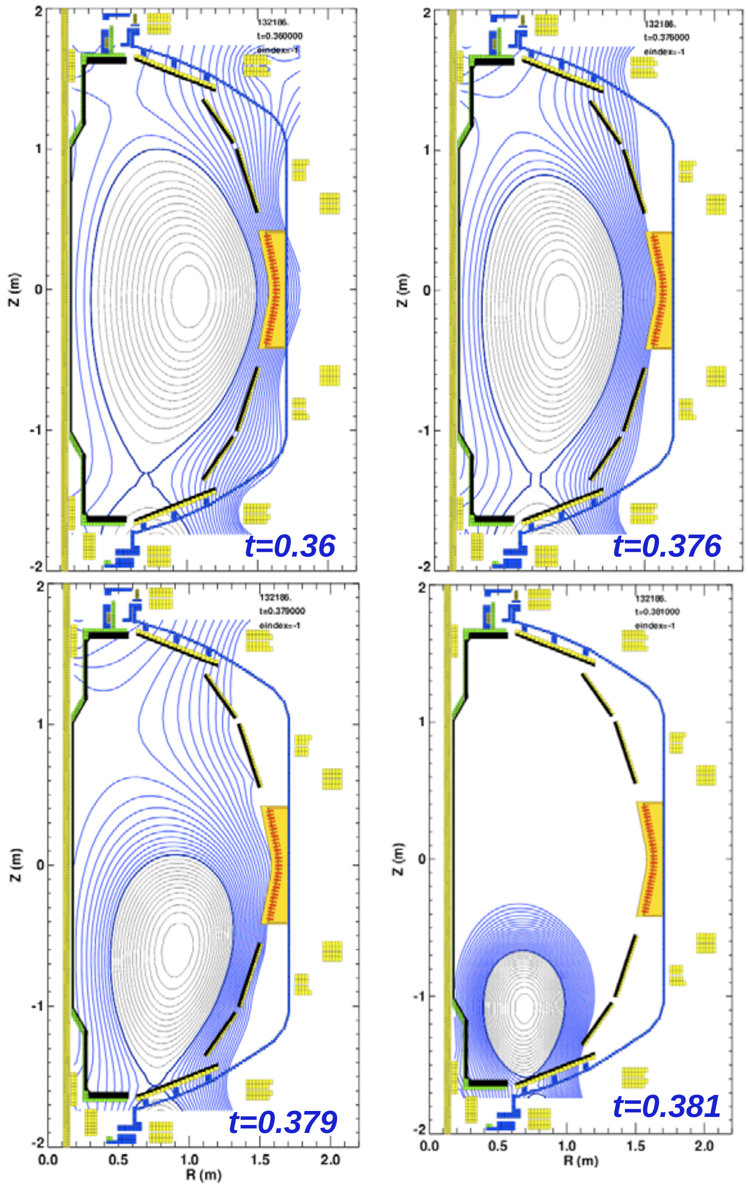


Novel Instrumented Tile Design Implemented in Four Tiles of 3rd Row of Lower Outboard Divertor

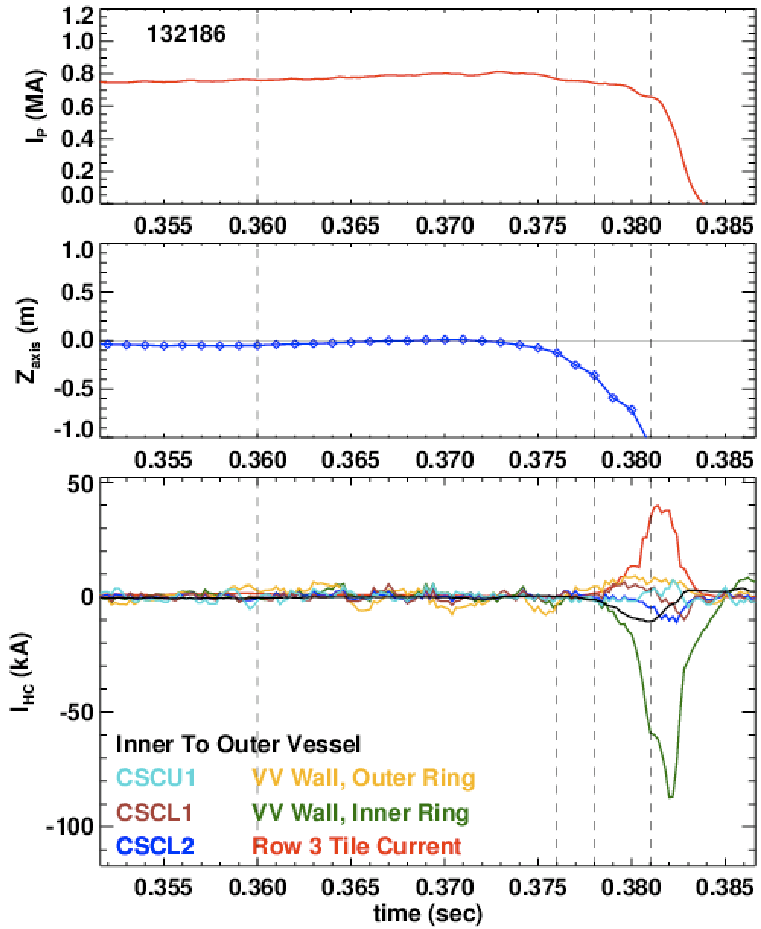


Design by S. Gerhardt, L. Guttadora, E. Fredrickson, and H. Takahashi

Downward-going VDE example (Currents Flowing Out of OBD, Row #3) Time Evolution and Spatial Distribution of Currents



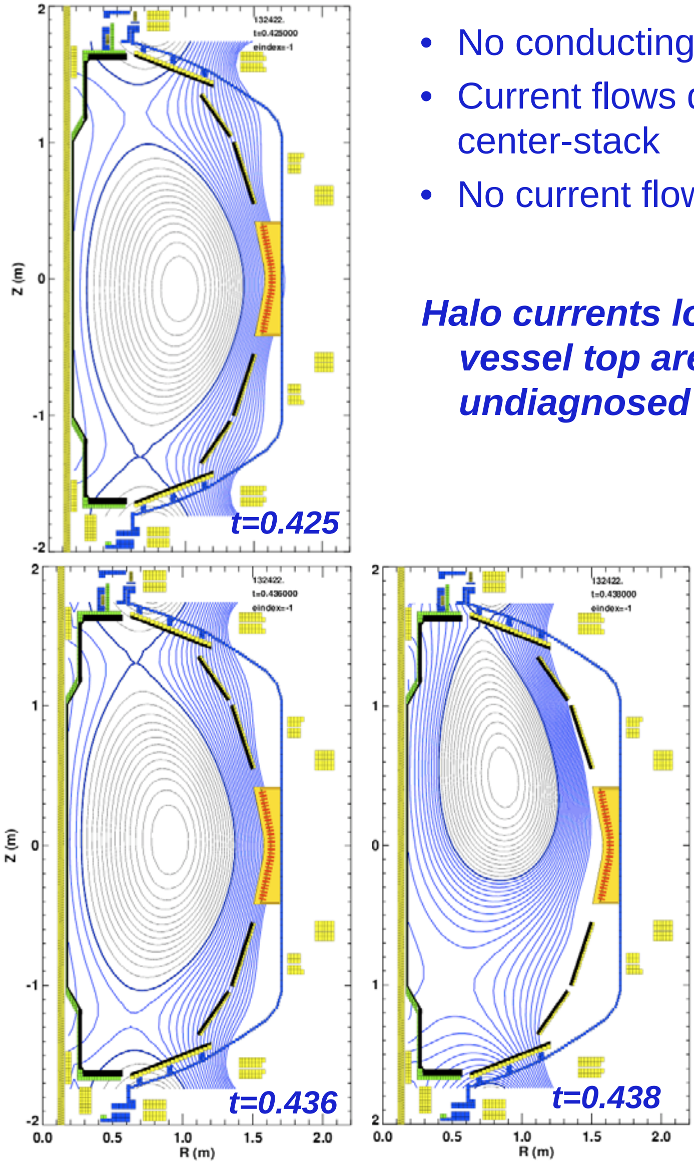
- Currents flow into the OBD near the CHI gap, and out of the OBD near tile #3
- Row-3 currents peak before the Inner-Ring currents
- Essentially no currents on the center-stack.

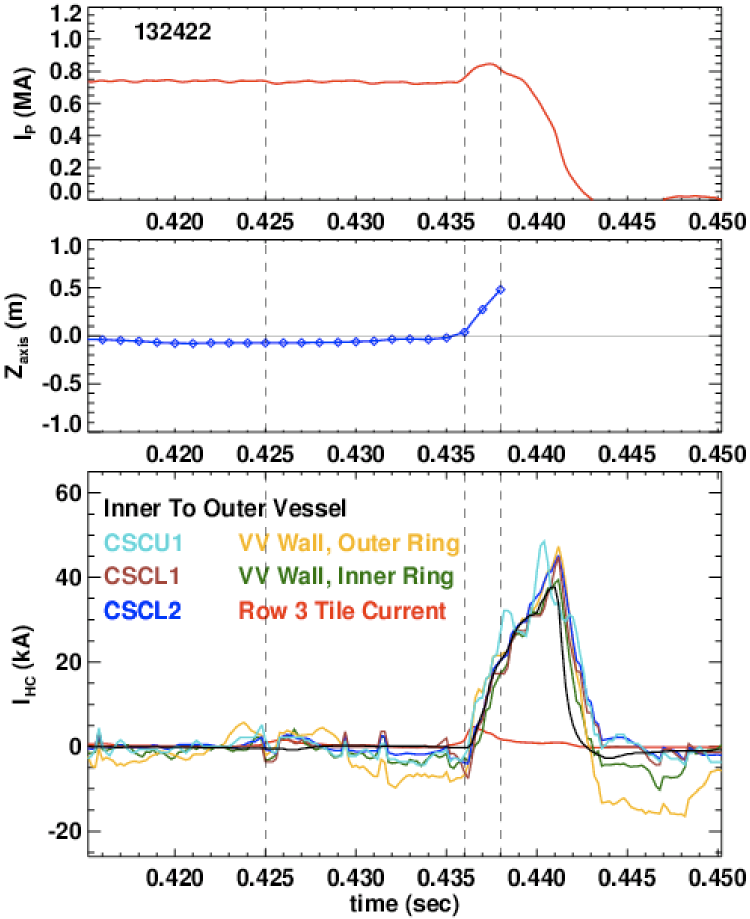


Upward-going VDE Example
Time Evolution and Spatial Distribution of Currents

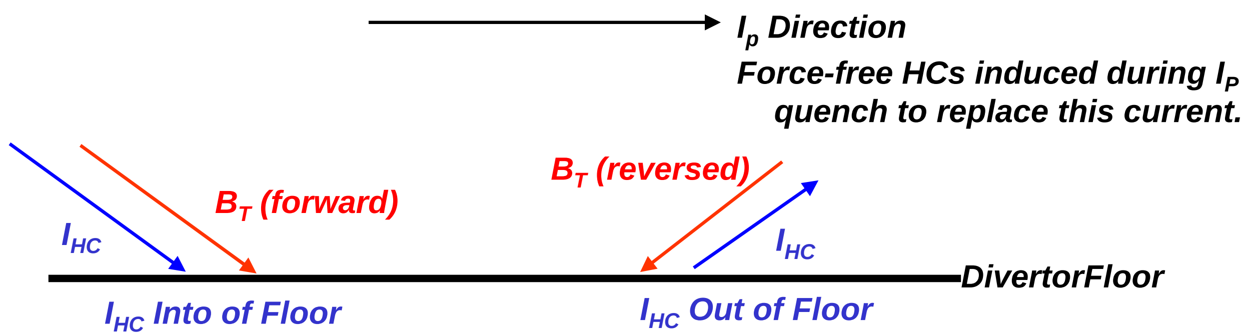
- No conducting path between machine inner and outer vessel at top of device.
- Current flows down the outer vessel, along the machine bottom, and up the center-stack.
- No current flow through row #3 tiles

Halo currents local to the vessel top are undiagnosed in NSTX

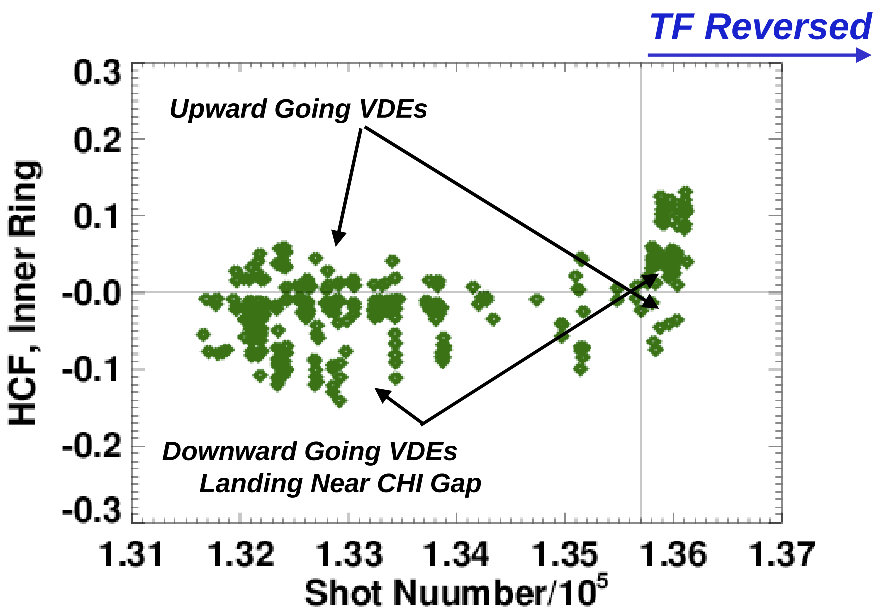




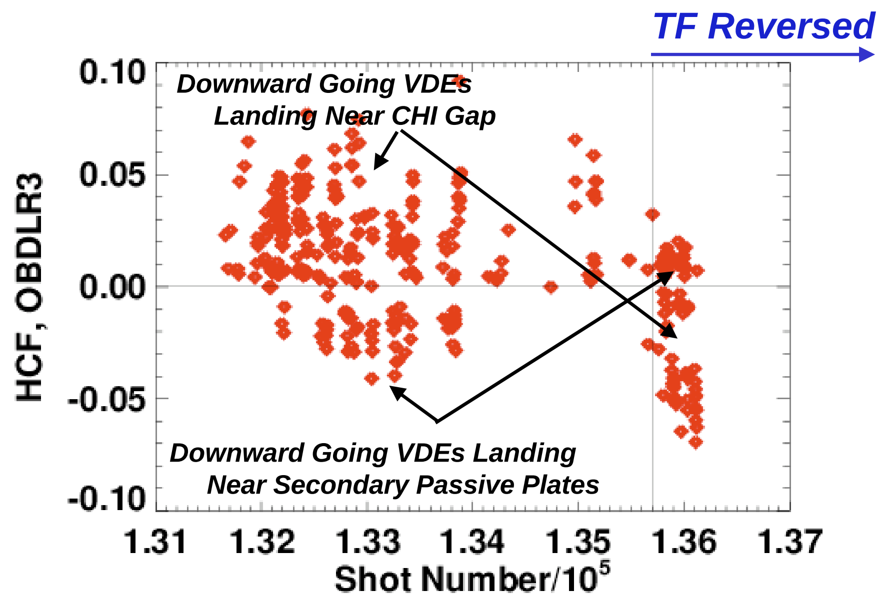
Axisymmetric Halo Current Directions Changed when Sign of Toroidal Field was Changed in 2009 (~135702)



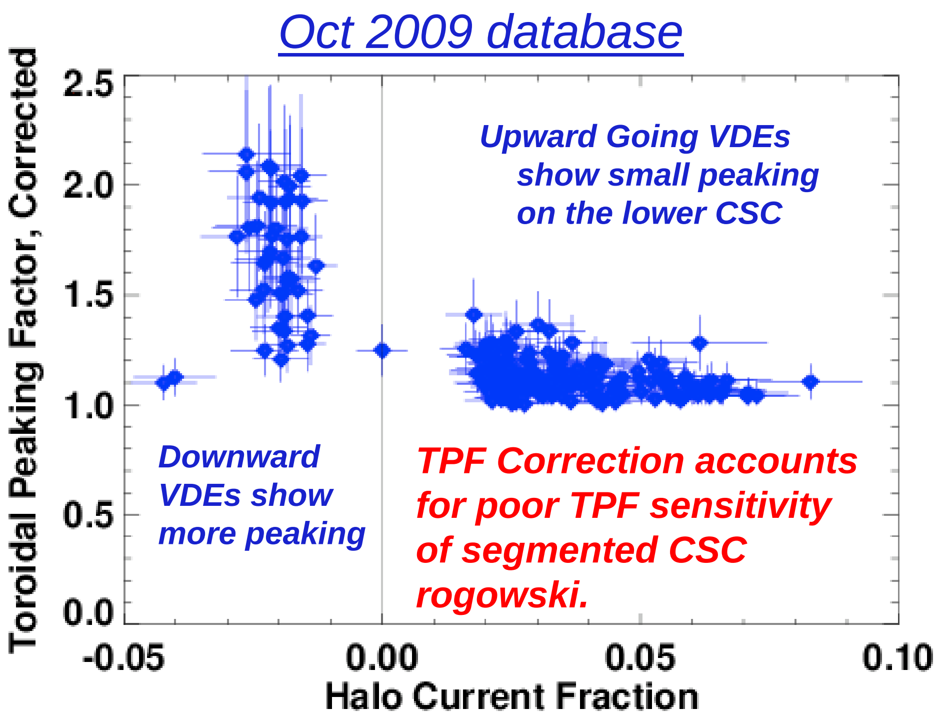
On Vessel Wall Near CHI Gap

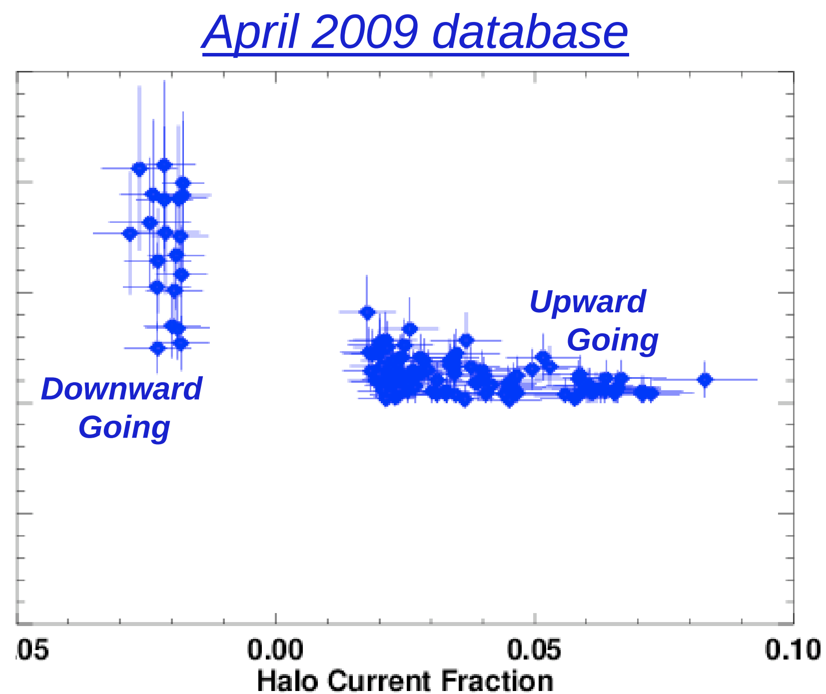


Shunt Tiles in Row #3 of Outboard Divertor



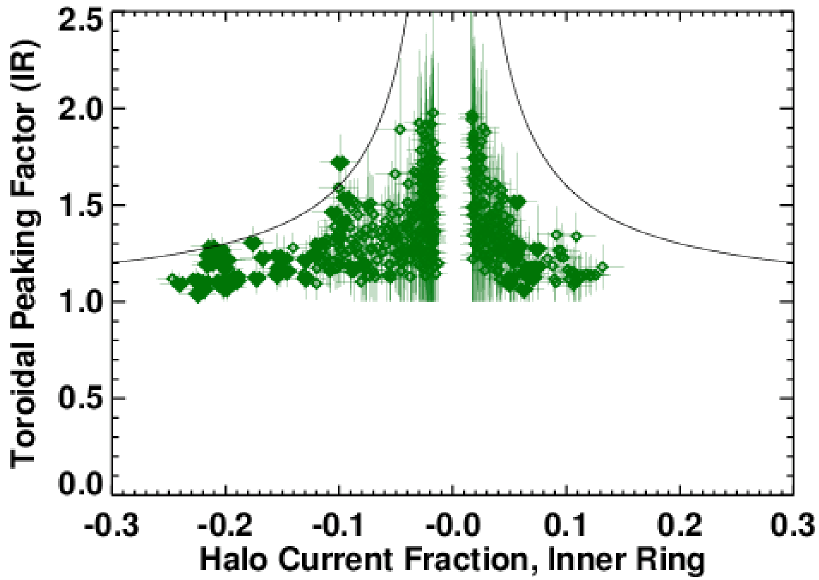
Recent Data Continues to Show Small Toroidal Peaking on Center Stack Casing (CSC)

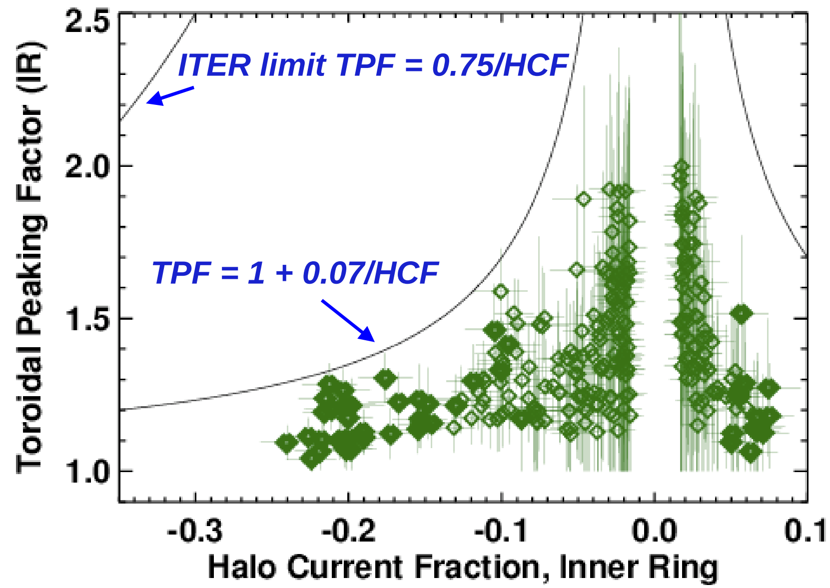




- Large B_T on inboard side of ST makes the center stack (CS) the most demanding region
  - Small observed halo current fraction (HCF) is encouraging for future devices
- Downward VDEs
  - Almost never limit on the lower center column => Low halo current fraction on the CS casing
  - Toroidal peaking factor as high as 2 observed after correction
- Upward going VDE
  - Currents typically flow along the vessel bottom, become toroidally uniform as they flow along vessel
  - Toroidal peaking factors (TPF) smallest in these cases

Recent Data for Lower Vessel Currents Continue to Show the Common TPF ∝ 1/HCF Scaling

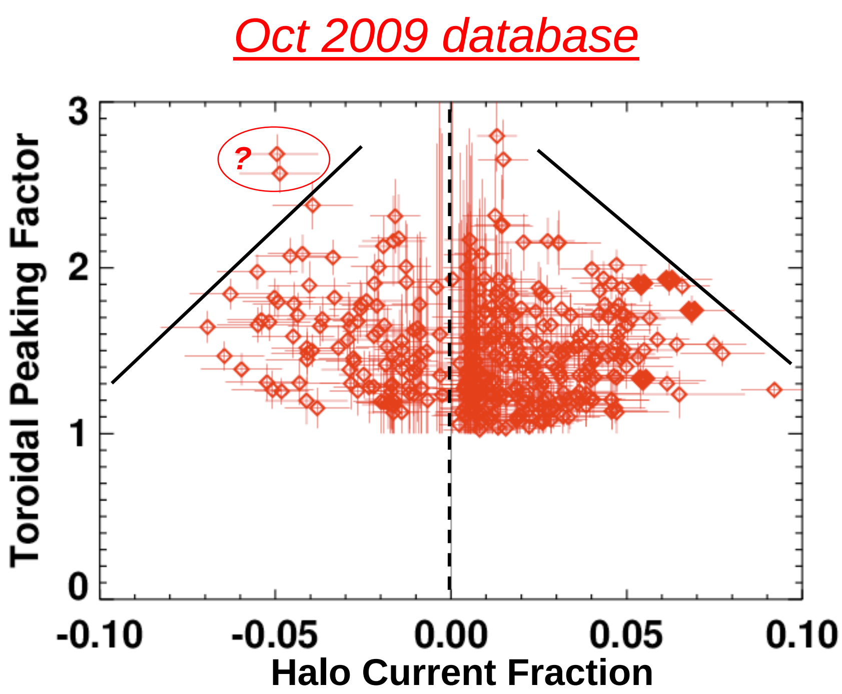


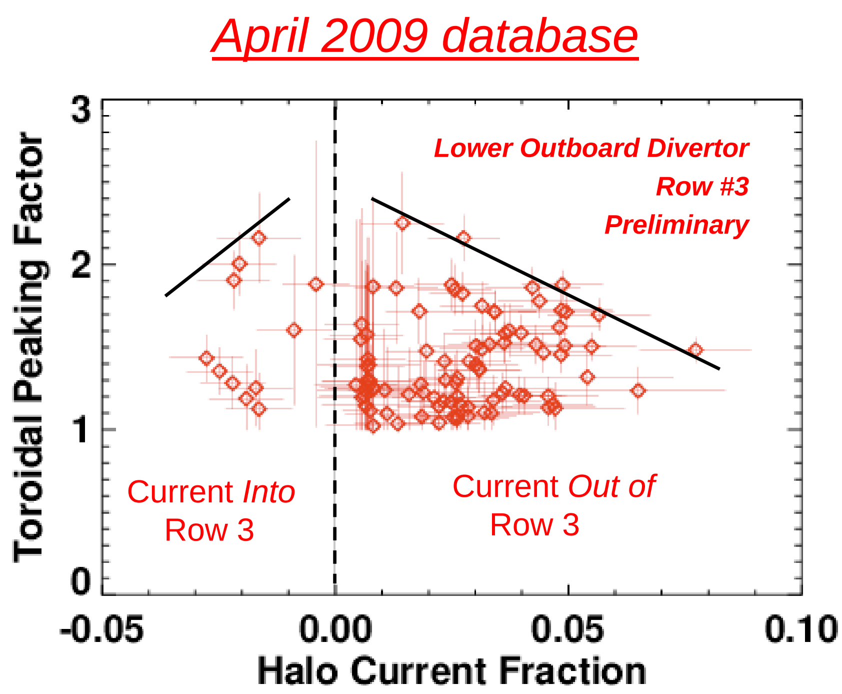


Halo Currents at Vessel Bottom

- TPF∝1/HCF, but absolute value far lower than guidance for ITER limit
- Downward VDEs show significantly larger halo currents
- For upward VDEs, halo currents small
- Deliberate VDEs (solid points) all show very small TPF

Recent Data for Lower Vessel Currents Continue to Show the Common TPF ∝ 1/HCF Scaling





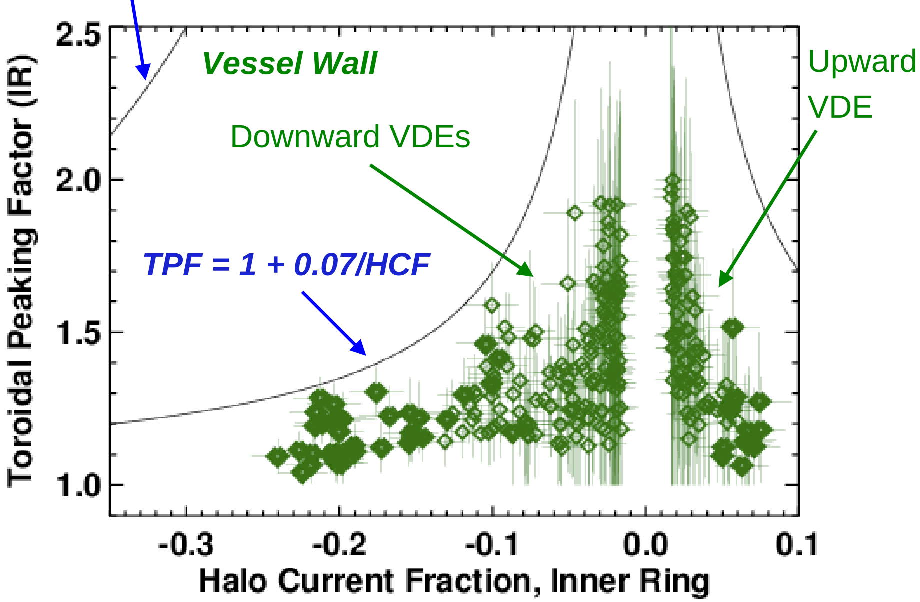
Halo Currents Through Outboard Divertor Row #3 Tiles

- New for 2009 campaign
- Tile subtends ~1/4 of the lower outboard divertor radial extent.
    - Not the full current into the lower divertor
- Apparent TPF∝1/HCF scaling

Currents in Lower Vessel Can be Much Larger, and Show the Common HCF ∝ 1/TPF Scaling

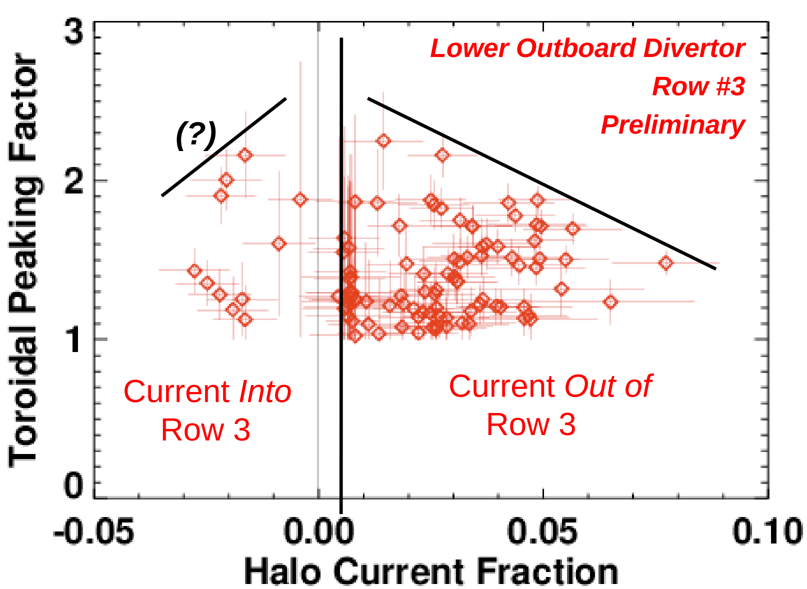
Vessel Bottom

- For upward VDEs, halo currents small, and TPF, though poorly resolved, is also small
- Downward VDEs show TPF∝1/HCF
- Deliberate VDEs all show very small TPF



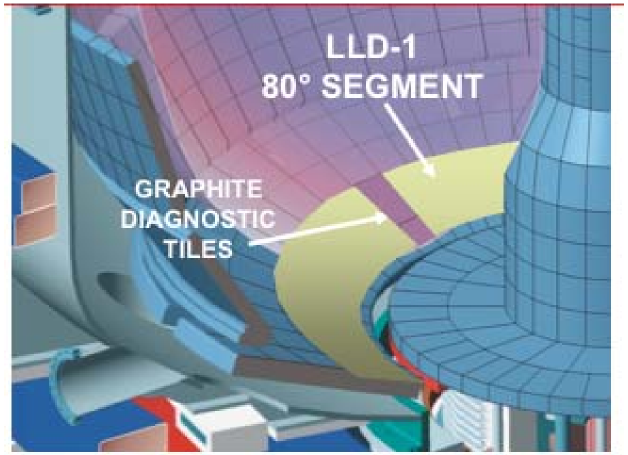
OBD Row #3 Tiles

- Upward VDEs are not detected
- Current flowing *out of* tiles is most common case
  - limiting point at smaller radius than the tiles
  - Clear TPF∝1/HCF scaling
- Current *into* tiles shows hints of TPF∝1/HCF scaling; more data necessary



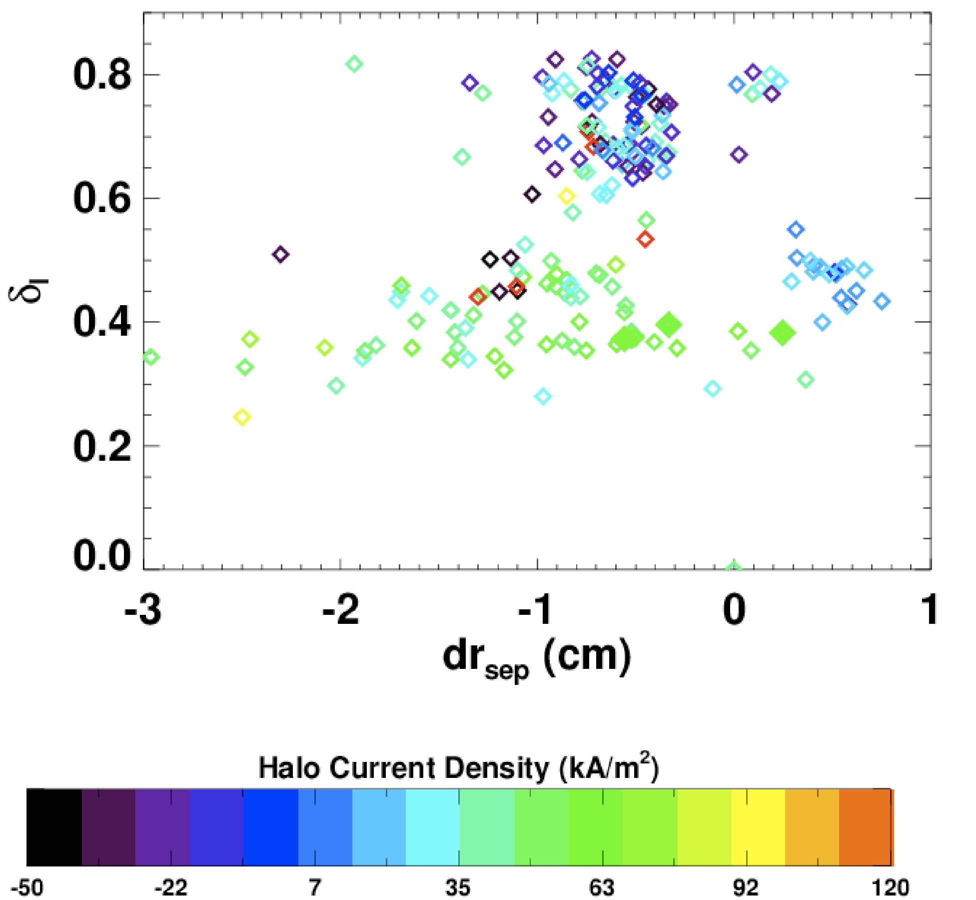
Error in TPF is large when the HCF is small

Liquid Lithium Divertor (2010): Currents of 20-30 kA per Segment Should Be Anticipated For Rare Events

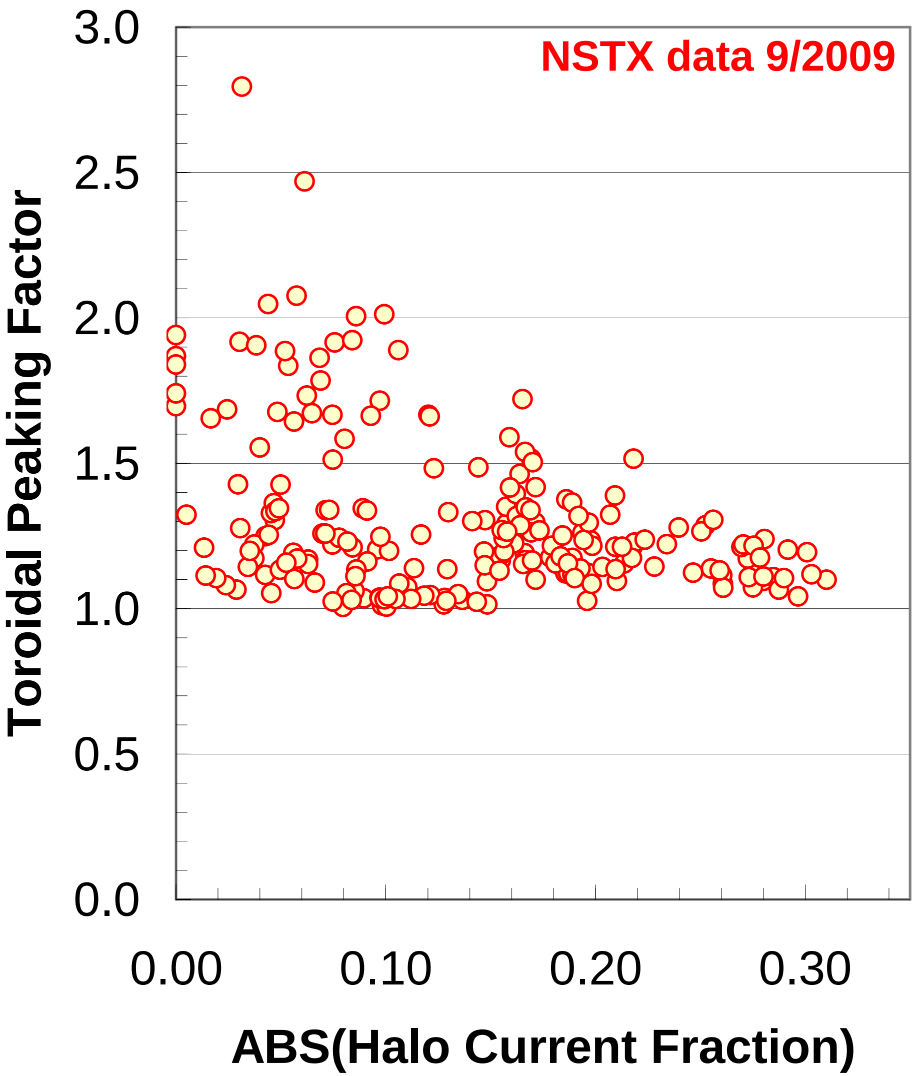


- Current density measured from shunt tiles in outboard divertor
- LLD Area is ~1m^2, divided into four quadrants
  - $A=2\pi R\delta R=2\pi \cdot 0.78 \cdot 0.2=1m^2$
- Halo currents of 20-30 kA/segment should be assumed for the rare worst case
  - Caveat, need to carefully look at the data for these worst cases
- Halo current measurements will be an important part of the LLD operational experience

Halo Current Density vs. triangularity and dr_{sep}



New NSTX Results Recently Contributed to ITPA Disruption Database



- 257 NSTX shots added
  - All shots taken during 2008 & 2009 campaigns.
  - Includes shots with fastest quench rates, largest pre-disruption stored energies, and largest halo current values and peaking.
- 58 variables for per shot
- HC related variables include:
  - IHMAX: max. in-vessel halo current
  - TIMEIHM: time of max. halo current
  - TPFATMAX: max. localized halo current
  - IPATMAX: total plasma current at IHMAX

NSTX Plans Continued Work in this Area

- Disruptivity
  - 2010 MHD milestone on efficacy of control techniques to suppress disruptions.
- Halo Currents
  - Upgrading to 12 Instrumented tiles in the outboard divertor, for improved TPF measurements, including rotating structures.
  - Small rogowski coils on the single point grounds of the LLD trays.
  - Comparison of NSTX data and TSC simulations (part of ITER TA).
- Disruption Thermal Quench/Loading Studies
  - Two interesting phases
    - β-collapse immediately after MHD events.
    - Disruption thermal quench.
  - Relevant NSTX Diagnostics
    - Fast equilibrium reconstructions, for magnitude of stored energy collapse.
    - USXR, for spatial evolution in the plasma and time-scales of thermal collapse.
    - Fast divertor IR, for spatial structure of heat flux.
  - Questions to be addressed
    - How does the energy leave the plasma in these events?
    - How much does the SOL spread during these events, and how fast are they?
    - Which events lead to the largest loading?

Disruptions and Halo Currents on NSTX - Update
SUMMARY

- STs can contribute to important disruption studies for both ST and AT devices
- Large pre-disruption energy losses are observed for the typical high-β disruptions (locked 2/1 islands, RWMs)
  - There remains a tail of high-energy disruptions
- The current quench can be faster in an ST than at conventional aspect ratio
  - Understood in terms of the lower inductance of the ST
- Halo current loading appear to be less than the conventional aspect limit derived for ITER
  - Similar to observations in MAST (Counsell, PPCF 2007)
  - Continued measurements and modeling should help confirm this finding

Backup Slides

Segmented Rogowski Coil on Center Column Can Significantly Underestimate Toroidal Peaking

- Model the currents on the CS as having an n=1 cosine theta dependence

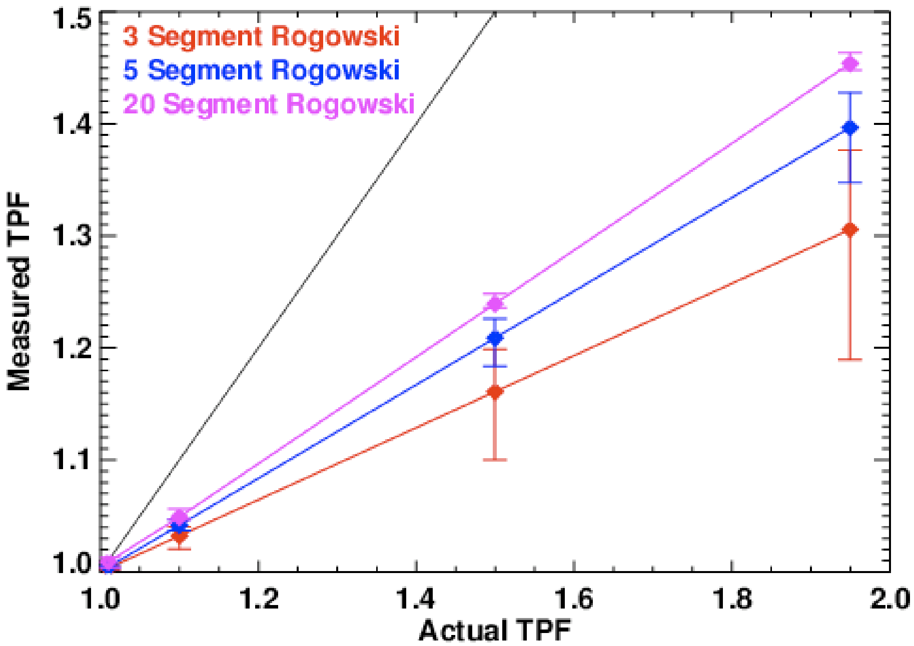
$$I_{Z,CSC}(\theta) = 1 + A_{HC}\cos(\theta - \theta_{HC})$$

- Calculate the average toroidal field seen by each segment of the N-segment rogowski: $B_{T,HC,i}$
- Calculate the "measured" and "actual" toroidal peaking factors

$$\textbf{Actual TPF} = 1 + A_{HC}$$

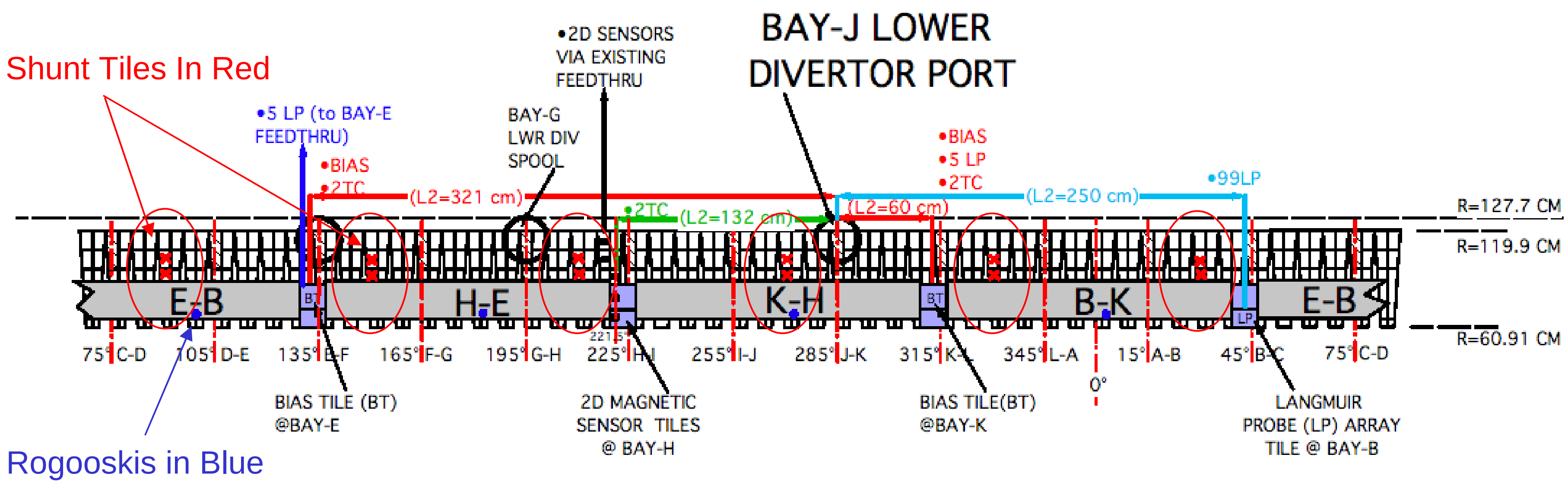
$$\textbf{Measured TPF} = \frac{N \cdot \max(B_{T,HC,i},\ i = 1:N)}{\sum_i B_{T,HC,i}}$$

- Repeat for many toroidal phases of the halo current (θ_{HC}) with respect to the toroidally fixed rogowski segments
  - Provides error bars



Calculations allow the measured rogowski TPF to be converted to the actual current TPF (assuming n = 1)

Substantial Upgrade to Halo Current Measurement Capability for 2010



- ***Keep the Old Diagnostics***
  - ***Center stack casing rogowskis***
  - ***Lower vacuum vessel current measurements***
- ***Add Some New Ones***
  - ***Each LLD Segment has a Small Rogowski on its single point ground***
  - ***6 shunt tiles in row 3 of the lower outboard divertor***
  - ***6 shunt tiles in row 4 of the lower outboard divertor***