

XP 833

Halo Current Dependencies on  
 $I_P/q_{95}$ , Vertical Velocity, and Halo  
Resistance

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Science Group

# Background

- Halo Current: When vertical position control of the plasma is lost during a disruption, the plasma comes in contact with the plasma facing components (PFCs). Decay of the poloidal and toroidal flux lead to voltages, and thus are driven currents that link the outer plasma region (halo) and PFCs
- Large electromagnetic loads on in-vessel component ( $J_{\text{halo}} \times B_T$ ) ...main load on ITER components for slow current quenches.
- New diagnostics installed for the FY08 run have motivated a new proposal.
- Goal of this XP: generate large halo currents and study their dependencies of various parameters.

*Works towards NSTX programmatic goal of understanding ST disruption dynamics.*

*Provides timely information for LLD design.*

# Halo Current Diagnostics For CY08 Run

Rogowskis on the CSC

CSCL1, CSCL2, CSCU1

Two Arrays of 6  $B_T$  coils

Inner Ring: Just Outside the CHI Gap

Outer Ring: Just Outside the OBD

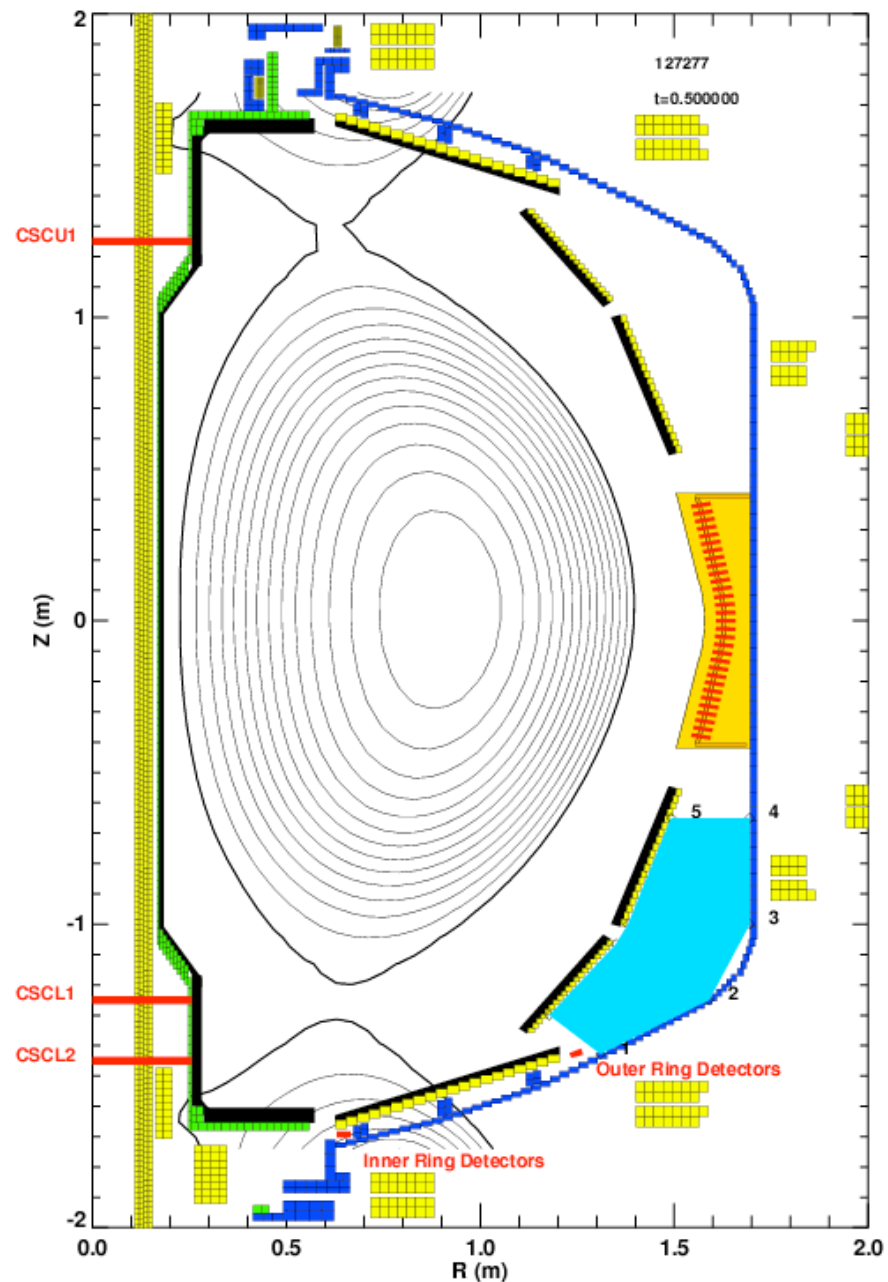
Difference Between These: Current into the OBD

Two Pearson CTs on CHI Bus

Current from inner to outer vessel

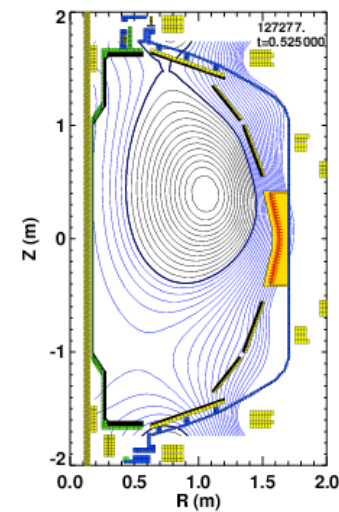
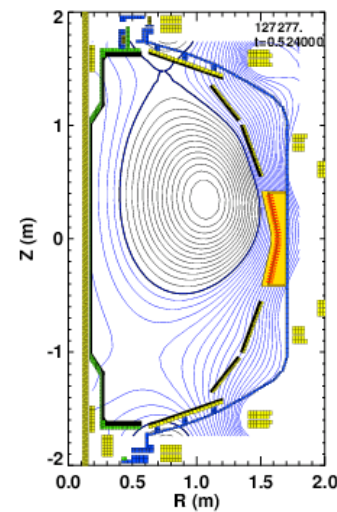
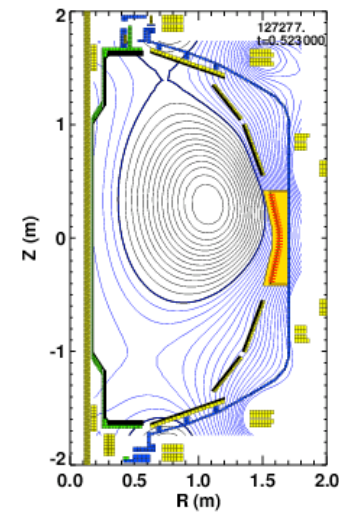
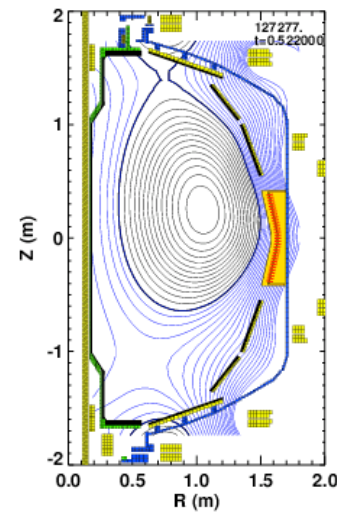
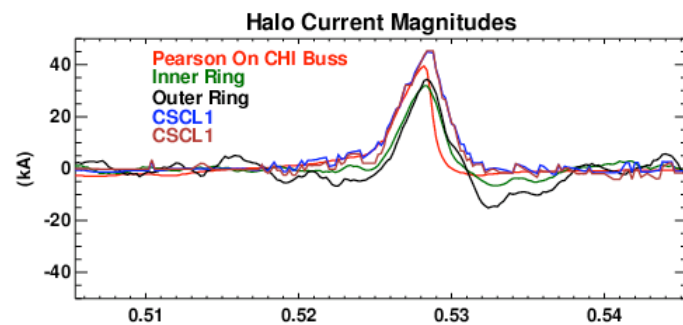
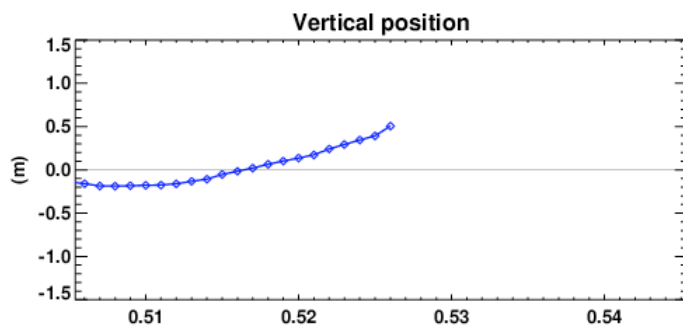
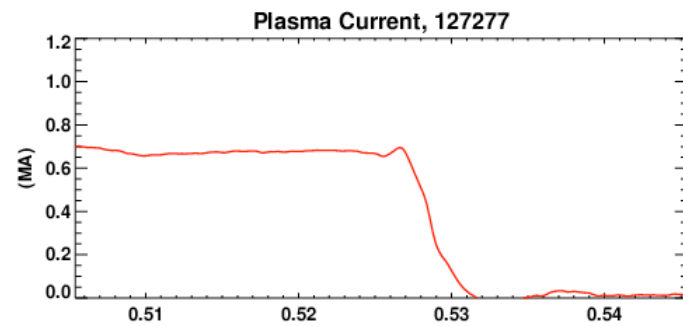
*NSTX Is Only Device with this Broken Halo Current Path*

*Part of XP is designed to study this "feature".*



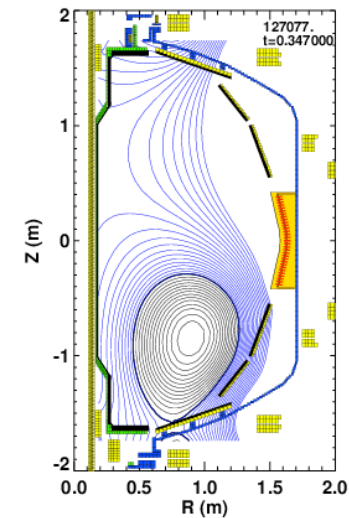
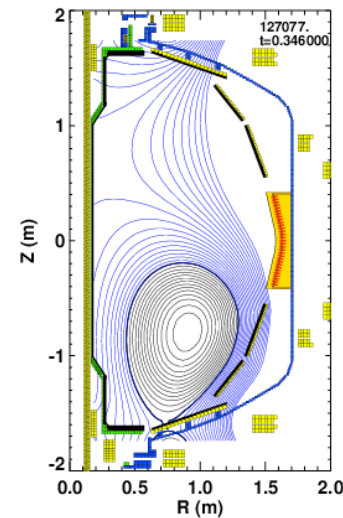
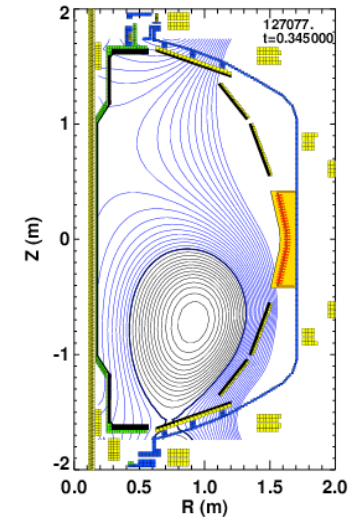
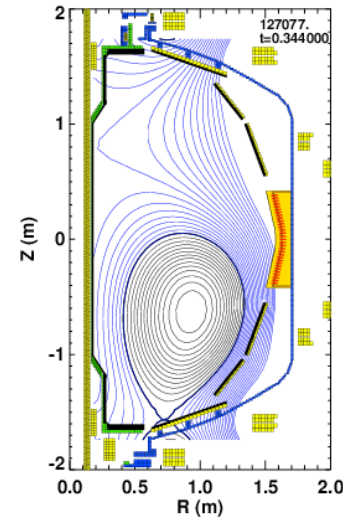
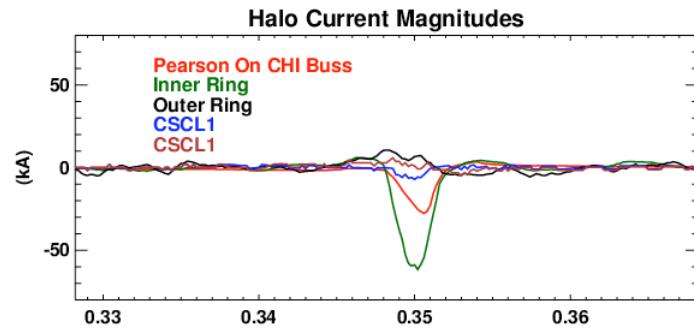
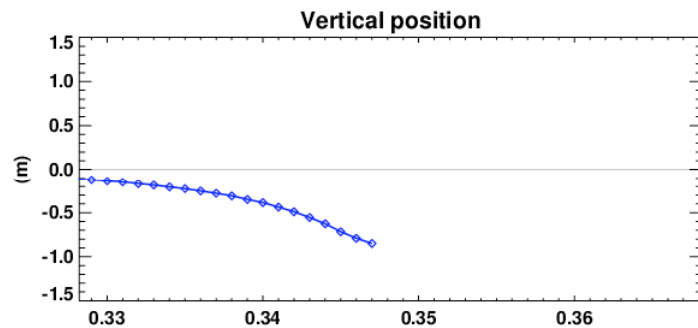
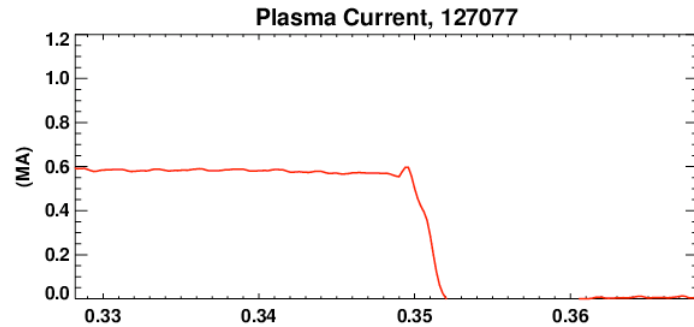
# Examples From NSTX

# Type 1: Shot 127277, Upward Going VDE Linking CHI Gap



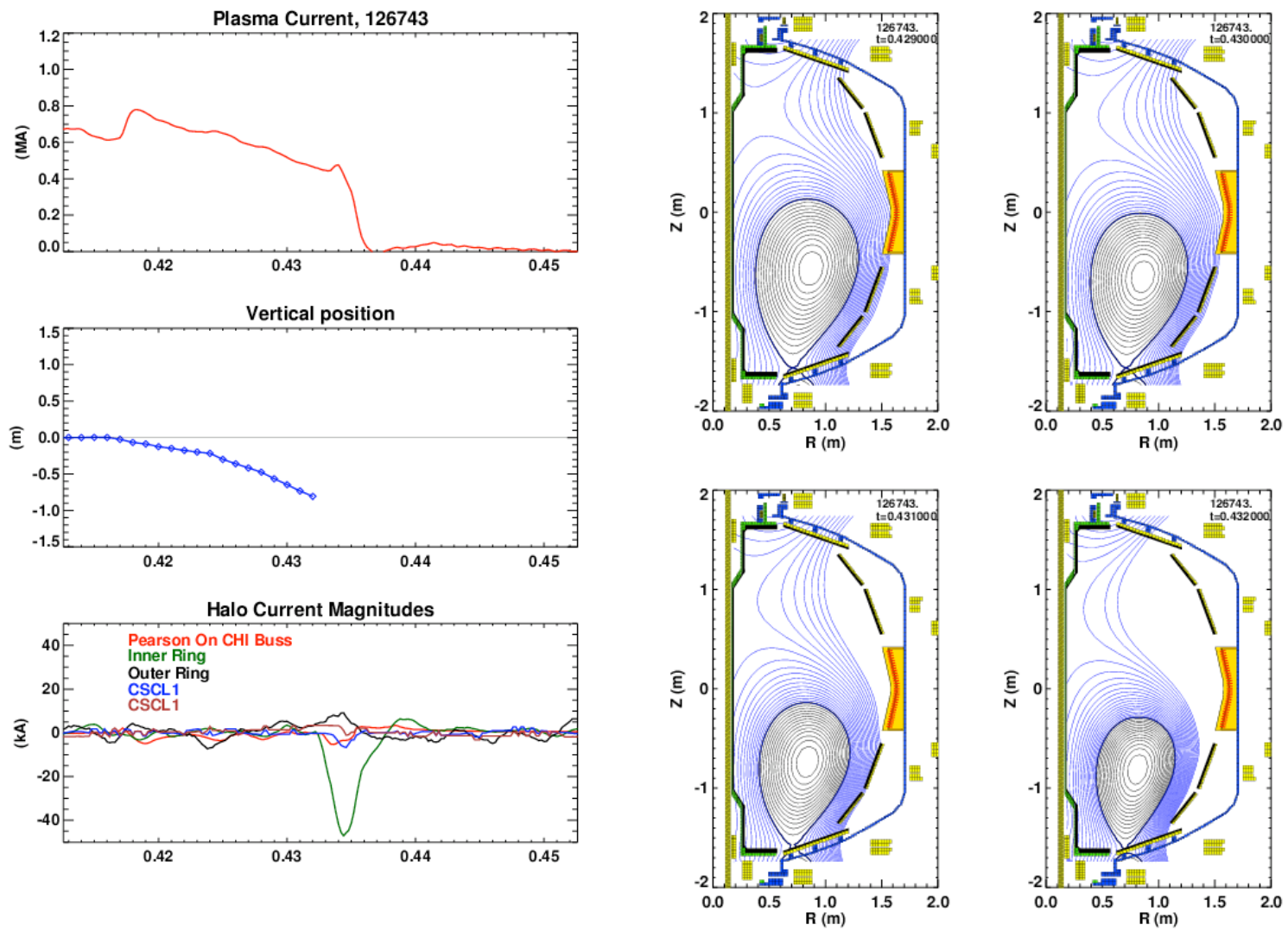
- Down the outer vessel, up the center column
- In vessel current is clockwise when facing in the positive toroidal angle

# Type 2: Shot 127077, Downward Going VDE Linking CHI Gap



- In vessel current is counter clockwise when facing in the positive toroidal angle*

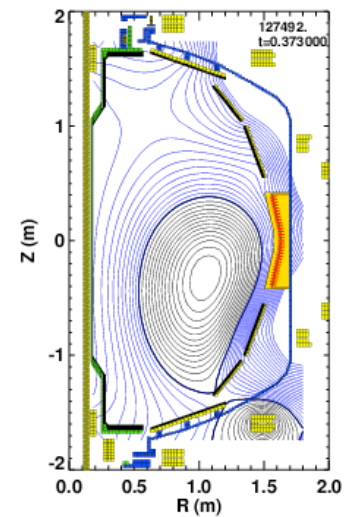
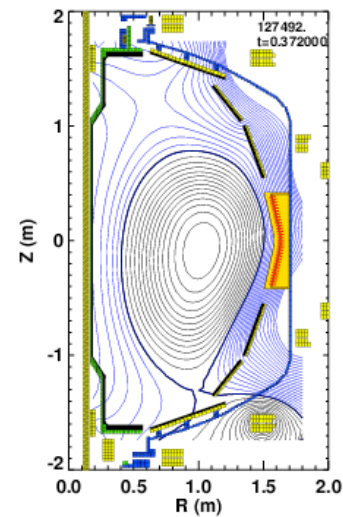
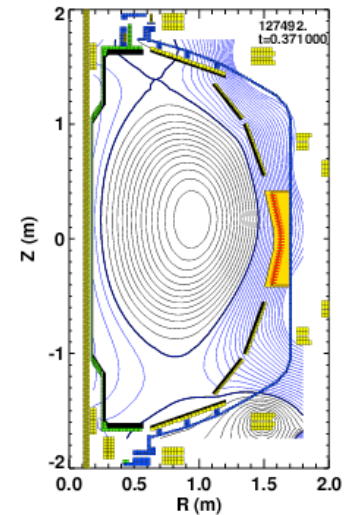
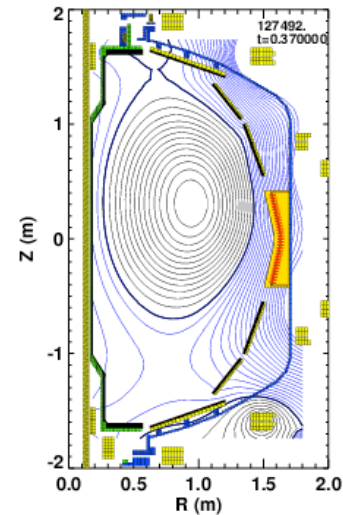
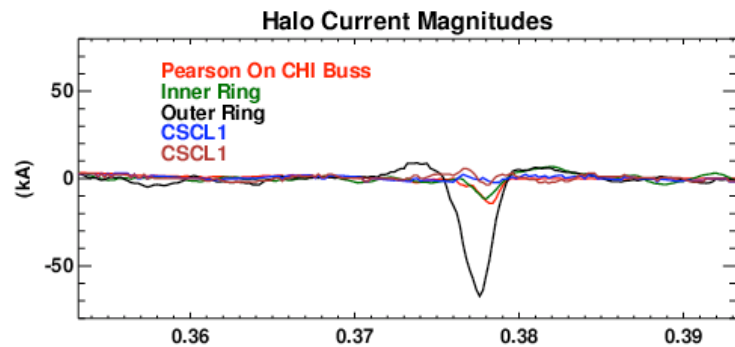
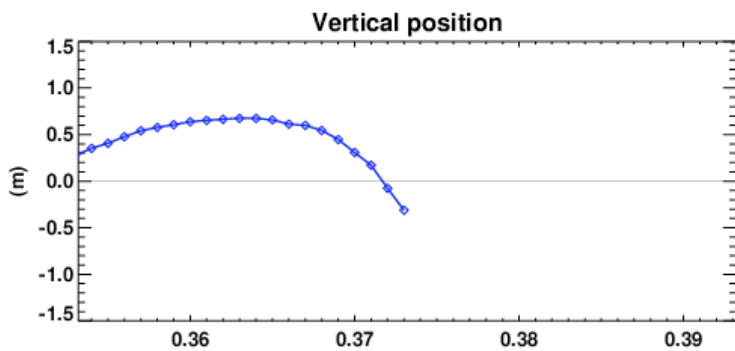
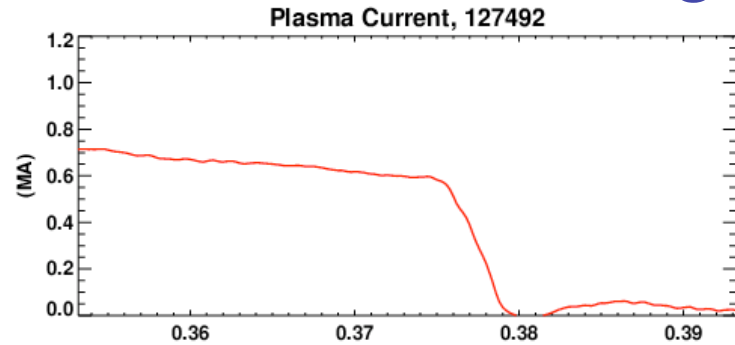
# Type 3: Shot 126743, Downward Going VDE Linking Inner Ring Only



• In vessel current is counter clockwise when facing in the positive toroidal angle



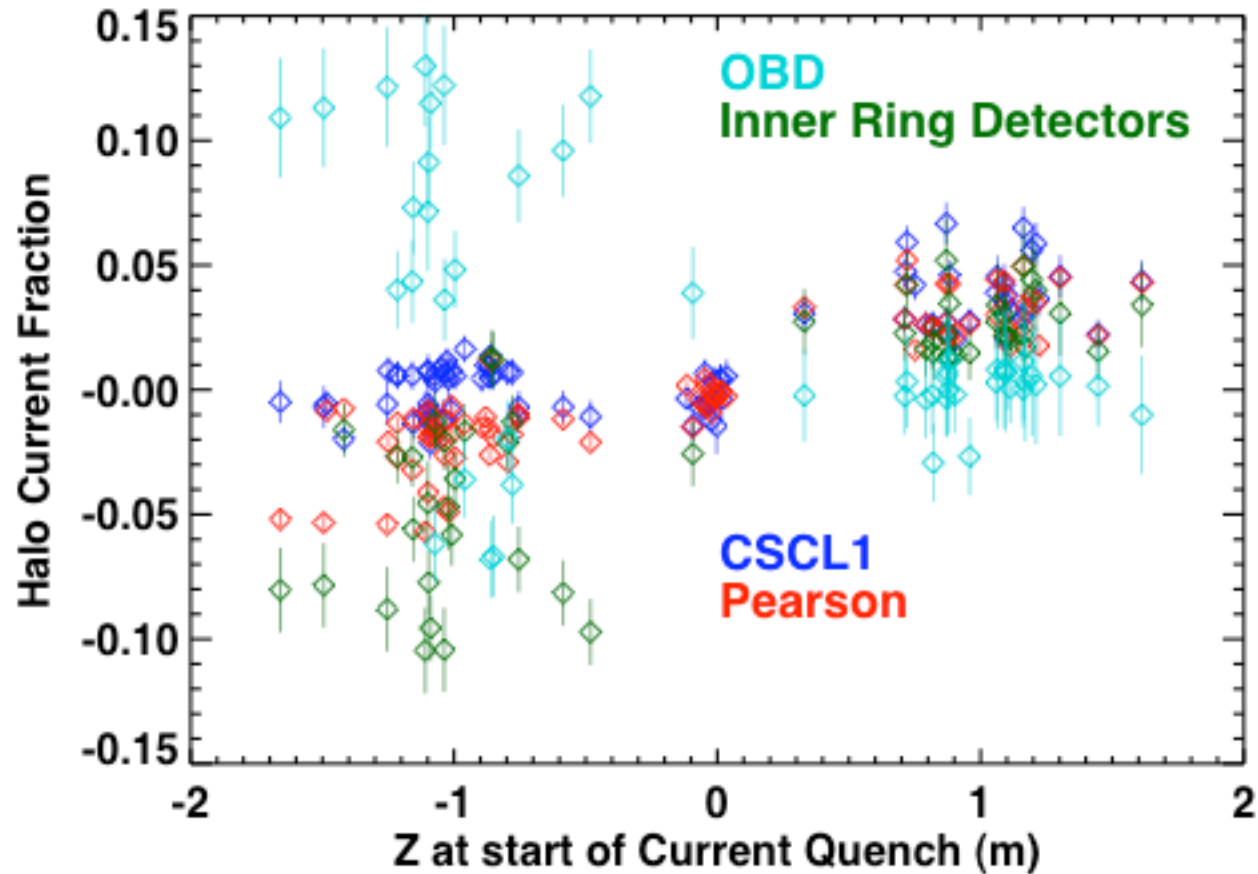
# Type 4: Shot 127492, Downward Going VDE Linking OBD and SPP



- In vessel current is counter clockwise when facing in the positive toroidal angle*



# Halo Current depends on Direction of Vertical Motion



**OBD=(Outer Ring)-(Inner Ring)**

Every Point has 1msec LRDFIT01

# Ohm's Law Explanation of Halo Currents (I)

Halo is force-free, so Ohm's law looks like:

$$J_{\parallel} = \sigma_{halo} (E_{\phi} \sin \alpha + E_{\theta} \sin \alpha)$$

$$\tan \alpha = \frac{B_{\phi}}{B_{\theta}} = qA$$

Relate the electric fields to voltages

$$E_{\phi} \sim \frac{V_{\phi}}{2\pi R_0}, \quad E_{\theta} \sim \frac{V_{\theta}^{PQ}}{2\pi a(1-\lambda)}$$

$\lambda$  ( $\ll 1$ ) is the fraction of the poloidal path in the wall  
Define the poloidal halo current as:

$$I_{\theta} = 2\pi w_{halo} R J_{\parallel} \cos \alpha$$

The Halo Ohm's law becomes:

$$\frac{I_{\theta} \mathfrak{R}_{Halo} (1-\lambda)}{A \cos^2 \alpha} = \frac{(1-\lambda) \tan \alpha}{A} V_{\phi} + V_{\theta}^{PQ}$$

The wall Ohm's law becomes:

$$V_{\theta}^{QP} = \frac{I_{\theta} \mathfrak{R}_{wall} \lambda}{A}$$

Combine these to form a total Ohm's law

$$A^{-1} [\mathfrak{R}_{wall} \lambda + (1-\lambda)(1+q^2 A^2) \mathfrak{R}_{Halo}] I_{\theta} = (1-\lambda) q V_{\phi} + V_{\theta}$$

\*P.J. Knight et al, Nuclear Fusion 40, 325 (2000)

Can Wall Resistance Be Neglected ?

$$\frac{\mathfrak{R}_{wall}}{\mathfrak{R}_{halo}} \ll \frac{q^2 A^2}{\lambda} \approx \frac{8 \cdot 8 \cdot 1.2 \cdot 1.2}{.2} = 460$$

$$\sigma_{wall} = 1,400,000 \text{ } (\Omega \cdot \text{m})$$

$$\mathfrak{R}_{wall} = (w_{wall} \sigma_{wall})^{-1} = 4.7 \times 10^{-5} \text{ } \Omega$$

$$\sigma_{Halo} = \frac{970 \cdot (T_e = 30)^{3/2}}{Z_{eff} = 3} = 8000 \text{ } (\Omega \cdot \text{m})$$

$$\mathfrak{R}_{halo} = (w_{halo} \sigma_{halo})^{-1} = 62 \times 10^{-5} \text{ } \Omega$$

$$\frac{\mathfrak{R}_{wall}}{\mathfrak{R}_{halo}} = .075$$

*Vessel Resistance Can Be Neglected When Current Avoids the CHI Bus*

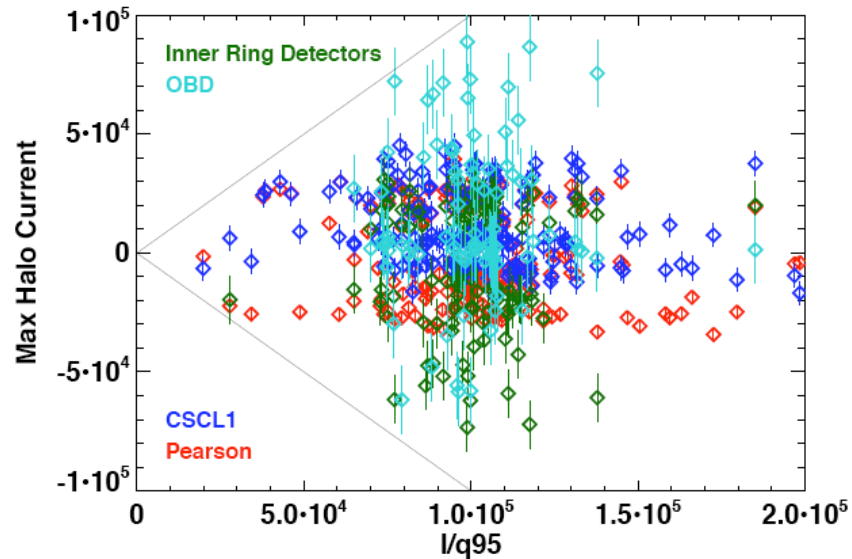
# Ohm's Law Explanation of Halo Currents (II)

Model Provides Estimate of Maximum Halo Current For Highly Conducting Halo

$$I_{\phi} = -\tau_{halo} (\dot{I}_{\phi} + \dot{I}_P)$$

$$I_P = I_{P0} e^{-(t/\tau_P)}$$

$$I_{\theta}^{\max} \leq \frac{1}{1-\lambda} \frac{I_p}{q}$$



This scaling observed in MAST, JET, JT-60, ALCATOR C-Mod, Compass-D...

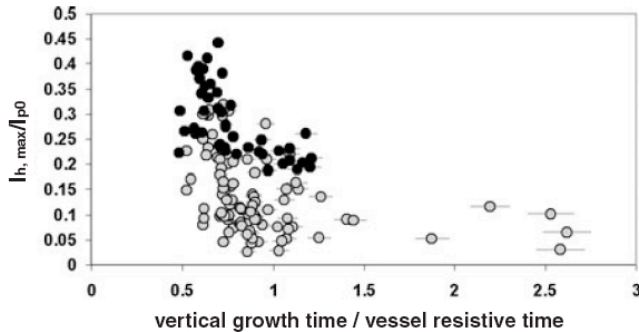
## Dependencies to Be Studied

$$A^{-1} [(1-\lambda)(1+q^2 A^2) \mathfrak{R}_{Halo}] I_{\theta} = (1-\lambda) q V_{\phi} + V_{\theta}$$

- Halo resistance with all else fixed.
- $I_p/q_{95}$  with all else fixed
- Variation with quench rate at all else fixed.

# The Halo Current Depends on the VDE Growth Rate at Conventional A.

V. Riccardo, Plasma Phys. Control. Fusion **46**, 925 (2004)

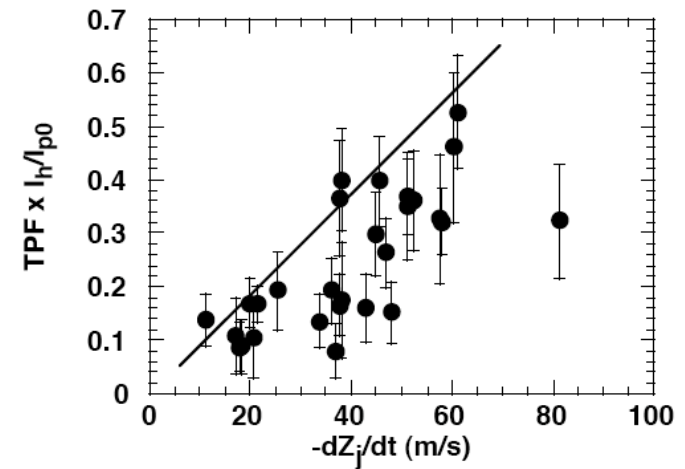


**Figure 7.** The halo fraction plotted versus the normalized analytical vertical growth time (i.e. the ratio of the vertical growth time and the vessel resistive time), which is displayed with its estimated accuracy; the darker dots represent discharges deliberate VDEs.

$$\frac{\tau_Z}{\tau_{shell}} = \left[ \left( \frac{(1 + \kappa)^3}{(\kappa - 1) \left( \frac{d_{shell}}{a^2} \right)} \right) - 1 \right]$$

This would correspond to large poloidal driving voltages...check in NSTX by varying the downward velocity.

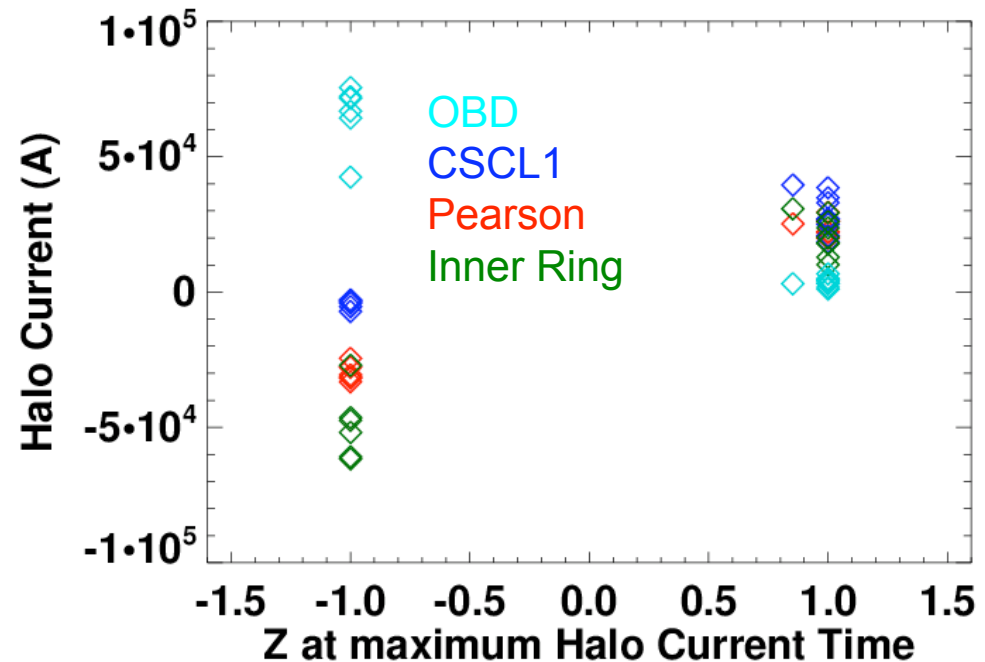
Y. Neyatani, et al, Nuclear Fusion **39**, 559 (1999)



**Figure 6.**  $TPF \times I_h/I_{p0}$  versus vertical shift velocity  $-dZ_j/dt$  at the time of maximum halo current.  $Z_j$  is the vertical position of the plasma current centre.

# XP811 data showed large Halo Currents

- Helium PF1A shot with  $k=1.8$ , vertical position control frozen at  $t=0.3$ .
- No scan over  $I_p$ ,  $B_T$ , or shape, only the duration of the freeze.
- Disruptions went up or down.
- Downward disruptions typically partially linked the CHI gap.
- Use this as one of two equilibria in a scan of  $I_p/q_{95}$  to test the case where the CHI buss is partially in the loop.



(Essentially unresolved  $\rightarrow$  binary up or down)

# Examples Show Main Requirements of XP

- Disruptions Must go DOWN
- Explore cases that link the CHI Buss, and cases that do not.
- Between shot reconstructions must be available with fast time resolutions (EFIT01 at 1 msec during the XP).
- Would like to have the fast camera viewing the entire lower divertor...correlation with toroidal peaking.

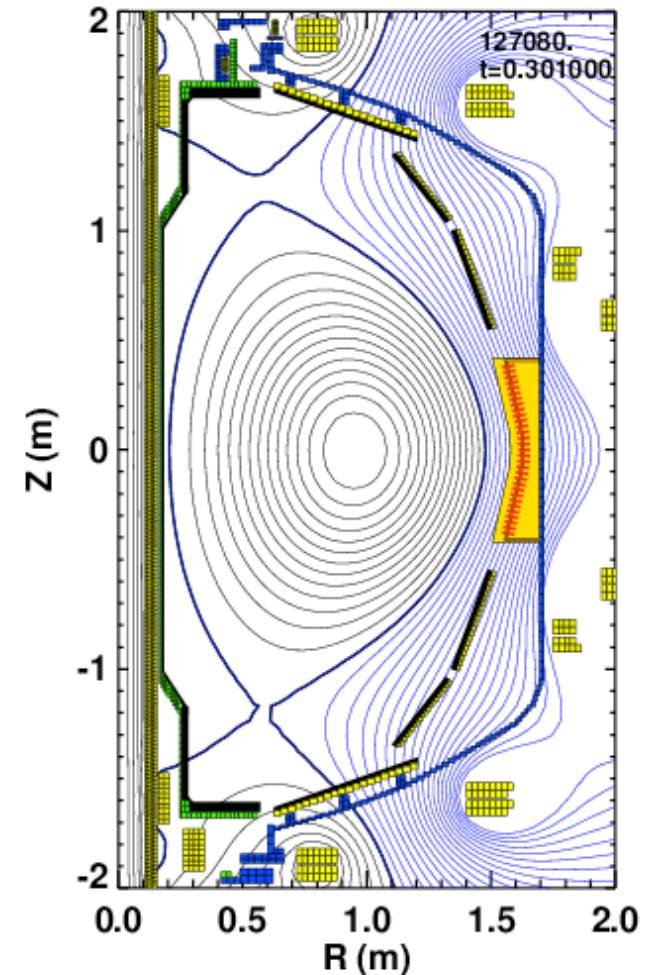
# Target is 127070: 600 kA Helium Gap-Control Shot From XP 811, Freeze Control at 250 msec

- Parameters

- 600 kA target
- $\kappa=1.9$
- $dr_{sep}=1\text{mm}$
- $R_0=.84\text{ m}$
- Outer Gap=10-12cm
- $\delta_i, \delta_t=.4$
- $W=30\text{kJ}$
- $B_T=0.45$

OH	-16862
PF1AU	7262
PF2U	4302
PF3U	-4725
PF5	-5724
PF3L	-4764
PF2L	4149
PF1AL	7502
PF1B	0
$R_0$ (m)	0.84
$a$ (m)	0.635
$I_p$ (kA)	600

- Freeze the PF3 voltages at 0.25 sec. for remainder of shot.
- Introduce 5msec step in PF3 voltages using the Voffset waveform to force plasma down. (*typically 150 V on PF3, use 10V kick*)





# Scan #1: $I_p/q_{95}$ scan at high $\delta_I$

- Motivation: Halo Current observed to scale like some fraction of  $I_p/q_{95} \propto I_p^2/B_T$ .
- Fill in a matrix to get a factor of 3 variation in  $I_p/q_{95}$ .
- Take points at end of scan twice.

# of shots	$I_p$	$B_T$	$I_p^2/B_T$ (MA <sup>2</sup> /T)
1	550	.45	.672
1	600	.45	0.8
1	650	.45	.94
1	700	.45	1.08
1	500	.45	0.55
1	700	.4	1.225
2	700	.35	1.4
2	500	.55	0.45
1	500	.5	0.5

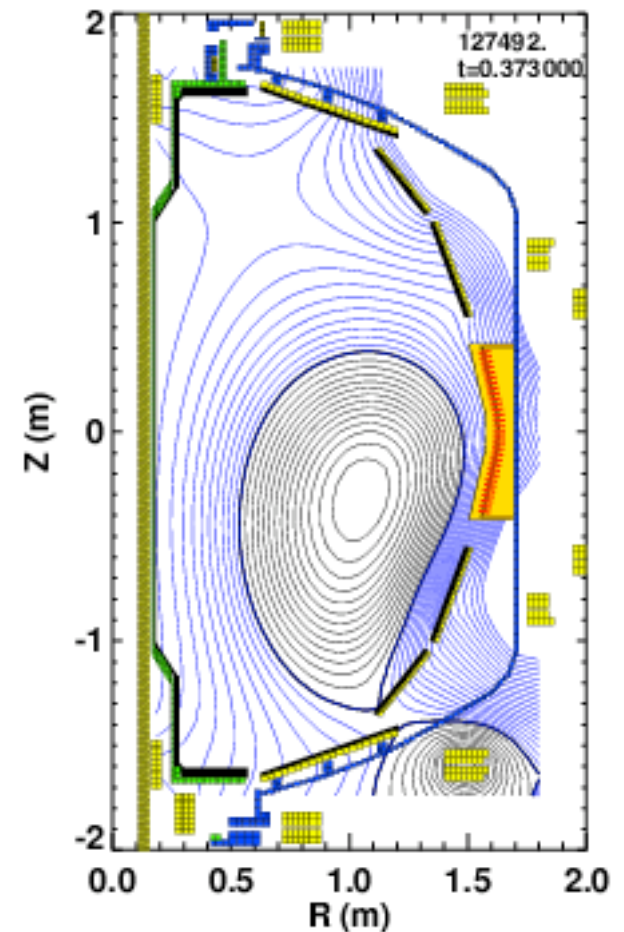
# Develop a shot where halo currents reliably link the SPP and OBD

## Implement series of step changes to the reference shot

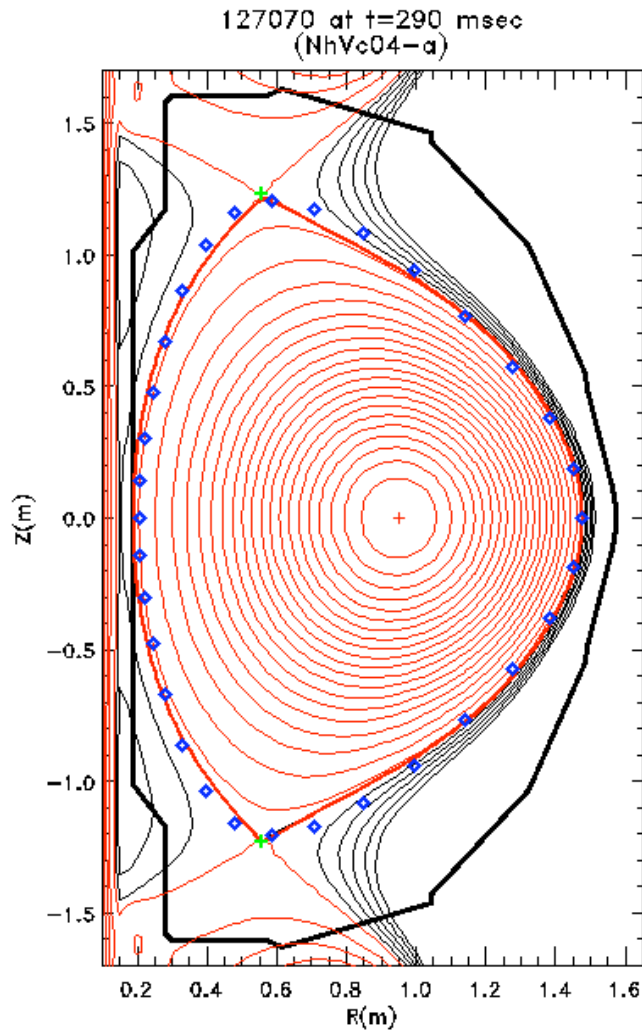
- Turn of PF1A
- Increase PF2 Pulling.
- Decrease PF3 Pushing (i.e. make less negative)
- Increase PF3I, so bias more downward.

*Keep Freeze On, to Get a Wide Scan of Halo Current Parameters*

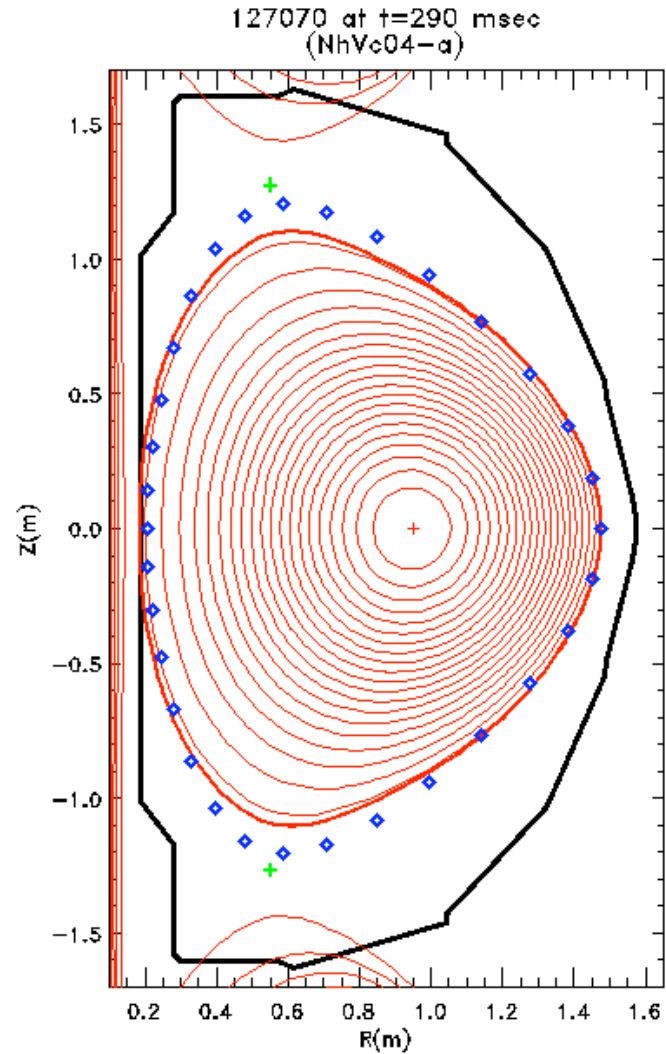
Try to get the plasma to land like this.



# Turn off PF1A

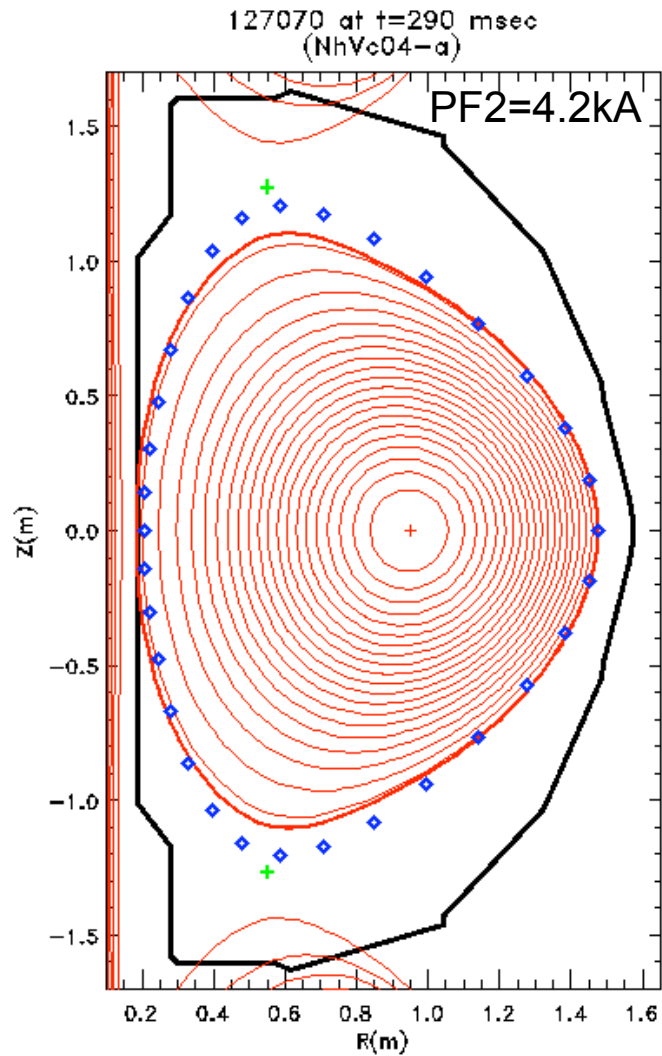


$$\kappa=1.9, \delta_l=.4, \delta_u=.4$$

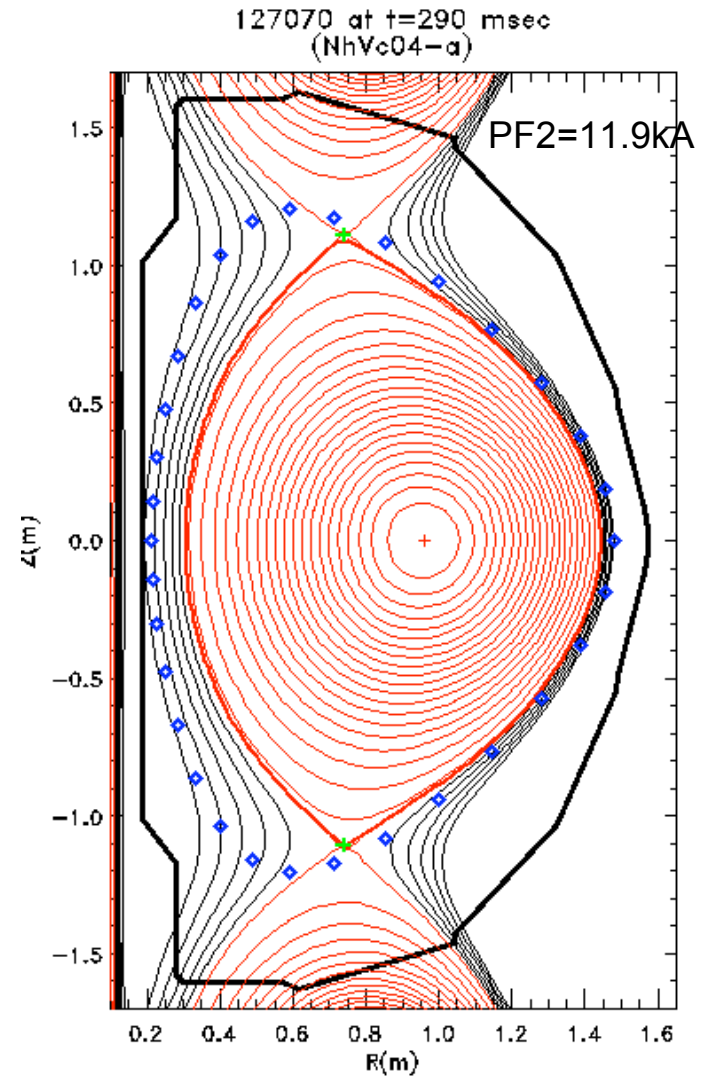


$$\kappa=1.68, \delta_l=.326, \delta_u=.326$$
$$R_0=0.84, R/a=1.31$$

# Increase PF2

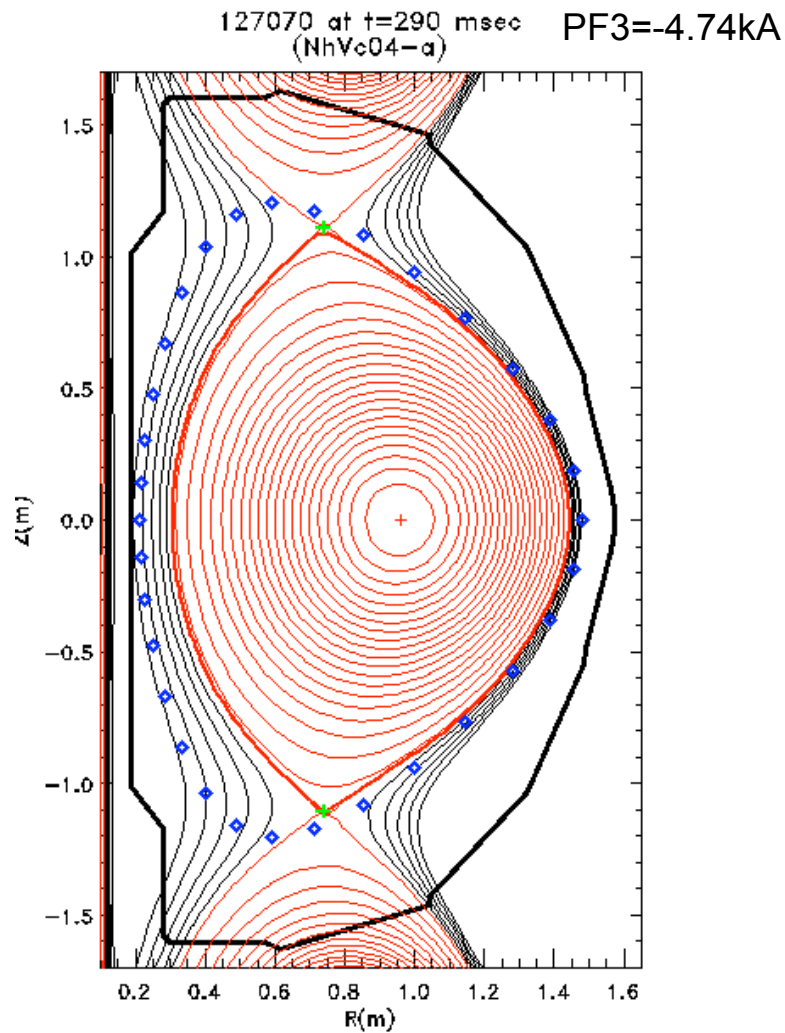


$$\kappa=1.68, \delta_l=.326, \delta_u=.326$$
$$R_0=0.84, R/a=1.31$$

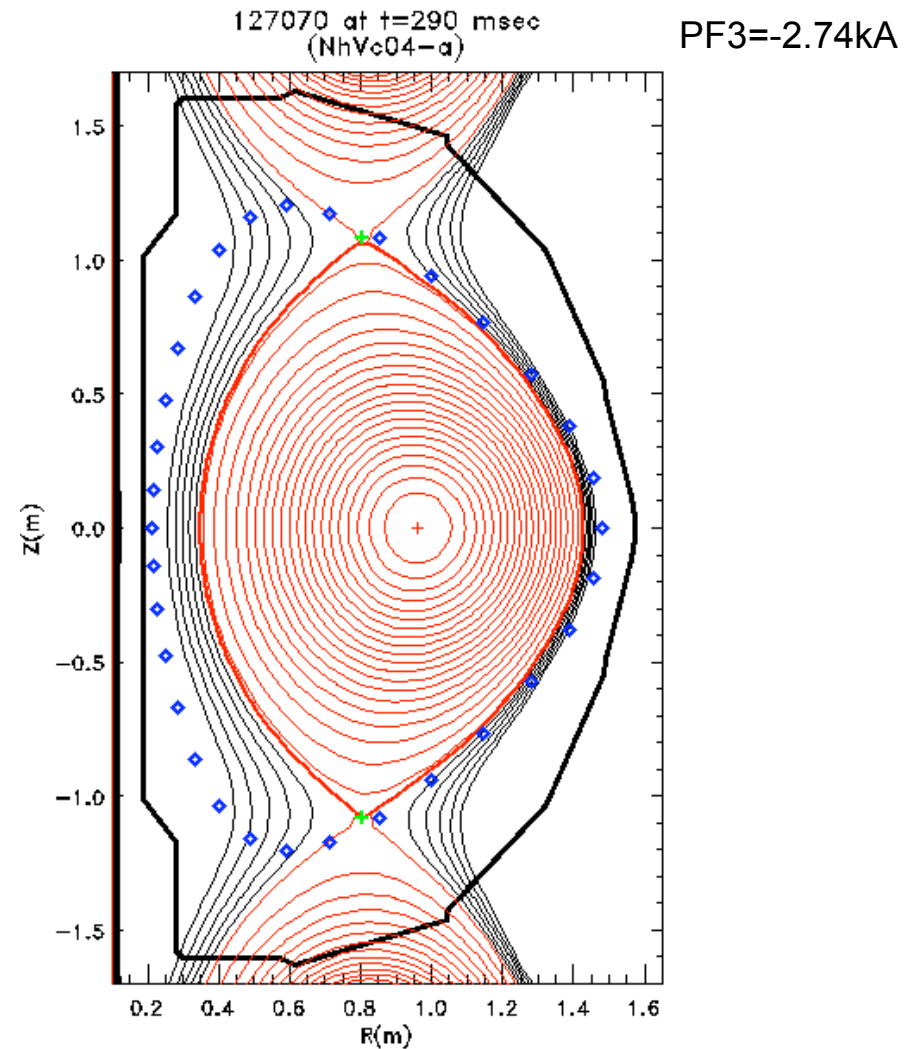


$$\kappa=1.80, \delta_l=-.173, \delta_u=.210$$
$$R_0=.878, R/a=1.56$$

# Reduce Pushing From PF3



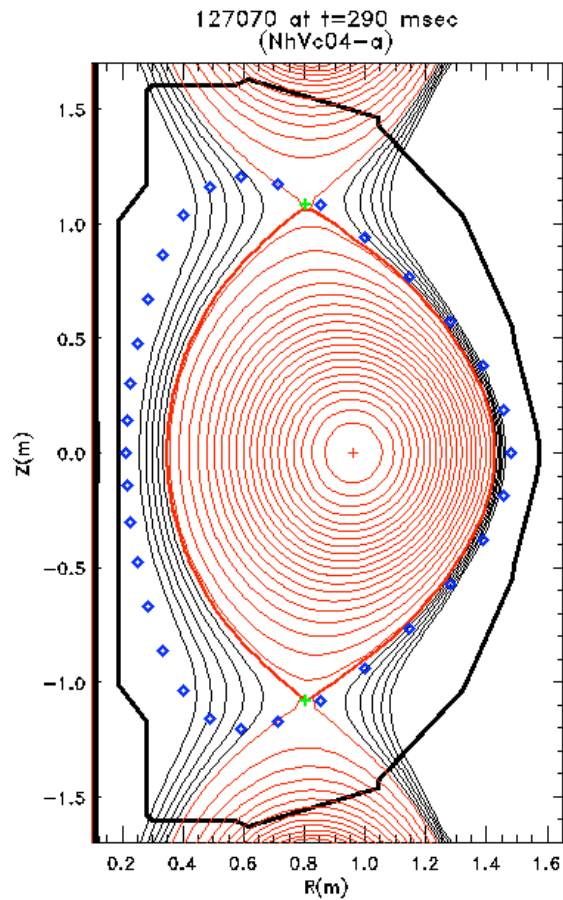
$\kappa=1.80$ ,  $\delta_l=-.173$ ,  $\delta_u=.210$   
 $R_0=.878$ ,  $R/a=1.56$



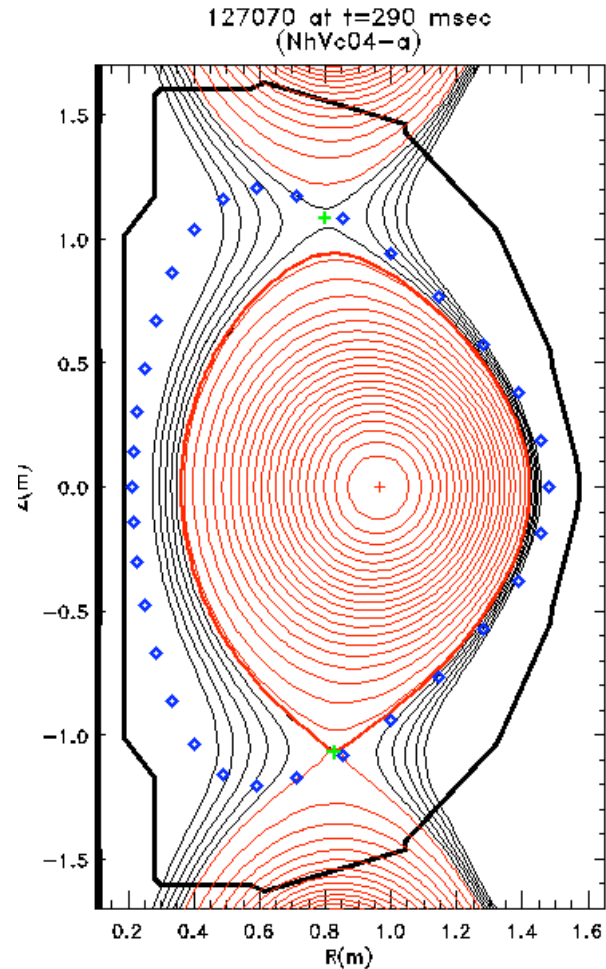
$\kappa=1.85$ ,  $\delta_l=-.153$ ,  $\delta_u=.163$   
 $R_0=.891$ ,  $R/a=1.67$

# Bias the Plasma Down With 600A in PF3L

PF3=-2.74kA



$\kappa=1.85$ ,  $\delta_l=-.153$ ,  $\delta_u=.163$   
 $R_0=.891$ ,  $R/a=1.67$ ,  $dr_{sep}=0$



PF3U=-2.74kA  
PF3L=-2.14kA

$\kappa=1.802$ ,  $\delta_l=-.08$ ,  $\delta_u=.118$   
 $R_0=.895$ ,  $R/a=1.7$ ,  $dr_{sep}=-7\text{mm}$

# Suggested Procedure For Change

- 1: Zero PF1A, Change PF2s as 4.2 kA→7.2kA (7kA/MA→1.2 kA/MA)
- 2: Change PF2s as 7.2kA →11.9 kA (1.2 kA/MA→2kA/MA)
- 3: Change PF3s as -4.74kA→-3.74kA (-7.9kA/MA →-6.23 kA/MA)
- 4: Change PF3s as -3.74 kA→-2.74 kA (-6.23 kA/MA → -4.56 kA/MA)
- 5: Bias Down: Add 600 A to PF3L (change of 1kA/MA)

*Keep Freeze On, and stop changes  
when currents link SPP and OBD*

Last Resorts:

Decrease the Outer Gap

Increase Freeze Voltage Offset



## Scan #2: $I_p/q_{95}$ scan at low $\delta_I$

- Motivation: Halo Current observed to scale like some fraction of  $I_p/q_{95} \propto I_p^2/B_T K$ .
- Fill in a matrix to get a factor of 3 variation in  $I_p/q_{95}$
- Take points at end of scan twice.

# of shots	$I_p$	$B_T$	$I_p^2/B_T$ (MA <sup>2</sup> /T)
1	550	.45	.672
1	600	.45	0.8
1	650	.45	.94
1	700	.45	1.08
1	500	.45	0.55
1	700	.4	1.225
2	700	.35	1.4
2	500	.55	0.45
1	500	.5	0.5

## Scan #3: VDE “Impact” Scan

- Want to scan the velocity of the downward going plasma....will it modify the halo current magnitude?
- Scan the duration and magnitude of the offset during the freeze time.
- Use high or low  $\delta$  configuration depending on which is more repeatable.

$I_p, B_T$	Duration Of Offset (reference Voltage)
600, 0.45	5 msec
600, 0.45	7 msec
600, 0.45	9 msec
600, 0.45	11 msec
600, 0.45	13 msec

...Or...

$I_p, B_T$	Voltage (For Reference Duration)
600, 0.45	5
600, 0.45	10
600, 0.45	15
600, 0.45	20
600, 0.45	25

## Scan #4: D<sub>2</sub> vs He Comparison

- Most operations are in D<sub>2</sub>, but this reference shot is in He...does this impact the result?
- Propose to redo parts of scan 1 or 2, depending on which is more interesting, in D<sub>2</sub>.
- 5 minute glow, maybe 10 minute cycle time (maybe 12?)
- First shot in this scan should be preceded by 2 minutes D<sub>2</sub> glow, then 7 minutes of He glow.

# of shots	I <sub>p</sub>	B <sub>T</sub>	I <sub>p</sub> <sup>2</sup> /B <sub>T</sub> (MA <sup>2</sup> /T)
1	600	.45	0.8
1	700	.45	1.08
1	500	.45	0.55
1	700	.4	1.225
1	700	.35	1.4
1	500	.55	0.45
1	500	.5	0.5

## Scan #5: $\sigma_{\text{halo}}$ scan to vary the halo resistivity

- Use Injector 1 system, to puff Neon into lower divertor during downward going VDE.
- Time neon wavefront to enter just as downward motion begins (require pre-XP evaluation of Neon Flow rate from injector 1, 100Torr-liter/sec typical).
- *Be careful of the prefill and the glow...don't use Neon for either.*
- Scan total amount of gas entering divertor, by varying the plenum pressure (typical particle inventory is 10-15 Torr-Liters).
- Need to calibrate the injector before the XP...have talked to Scott and Bill.
- Use high or low  $\delta$  configuration depending on which is more repeatable.

$I_p, B_T$	Gas Input (torr-liter)
600, 0.45	0.5
600, 0.45	1.0
600, 0.45	1.5

# Other Details of Setup

- Injector 1: Neon
- Injector 2: D<sub>2</sub> prefill, to about  $1.6 \times 10^{-5}$  torr for reference shot, also all fueling for D<sub>2</sub> cases.
- Injector 3: He fill and glow during D<sub>2</sub> period.
- NBI, CHI, HHFW: Not used
- B<sub>T</sub>: .3-.55 T
- I<sub>p</sub>: 500-700 kA

## Shot List, Min (+Contingency)

### Full Day (8hours\*6 shots/hour=48 shots)

- Startup: 1 (+1) shots
- $I_p/q_{95}$  scan at high  $\delta_1$  : 11 (+3) shots
- Low  $\delta_1$  Shot Development: 6 (+2) Shots
- $I_p/q_{95}$  scan at low  $\delta_1$  : 11 (+3) shots
- VDE Velocity scan: 6 (+2) shots
- $D_2$  Comparison: 7 (+2) shots
- Neon Injection: 3 (+2) shots
- Total: 45 (+60) shots

### 1/2 Day (4hours\*6 shots/hour=24 shots)

- Startup: 2 (+1) shots
- $I_p/q_{95}$  scan at high  $\delta_1$  : 8 (+3) shots
- Low  $\delta_1$  Shot Development: 6 (+2) Shots
- $I_p/q_{95}$  scan at low  $\delta_1$  : 8 (+3) shots
- Total: 24 (+9) shots