CDX-U Equilibrium Reconstructions

CDX-U

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Abstract

CDX-U

LTX

Lithium plasma facing components possess several traits that make them desirable for use in fusion relevant plasma. The recent focus of CDX-U research has been the investigation of the effects on plasma performance due to liquid lithium limiters and thin lithium coatings. Energy confinement times derived from plasma equilibrium reconstructions in the presence of clean lithium surfaces indicate an improvement in plasma performance over that expected by energy confinement time scalings based on earlier tokamak results and previous CDX-U energy confinement time measurement where lithium surfaces were not present. As part of the effort to create equilibrium reconstructions in CDX-U, a novel calibration technique for magnetic field sensors involving eddy current response function analysis was implemented for the first time. This talk will include a discussion of the response function calibration process, examples of CDX-U equilibrium reconstructions, and energy confinement time estimates for CDX-U plasmas in the presence of clean lithium surfaces.

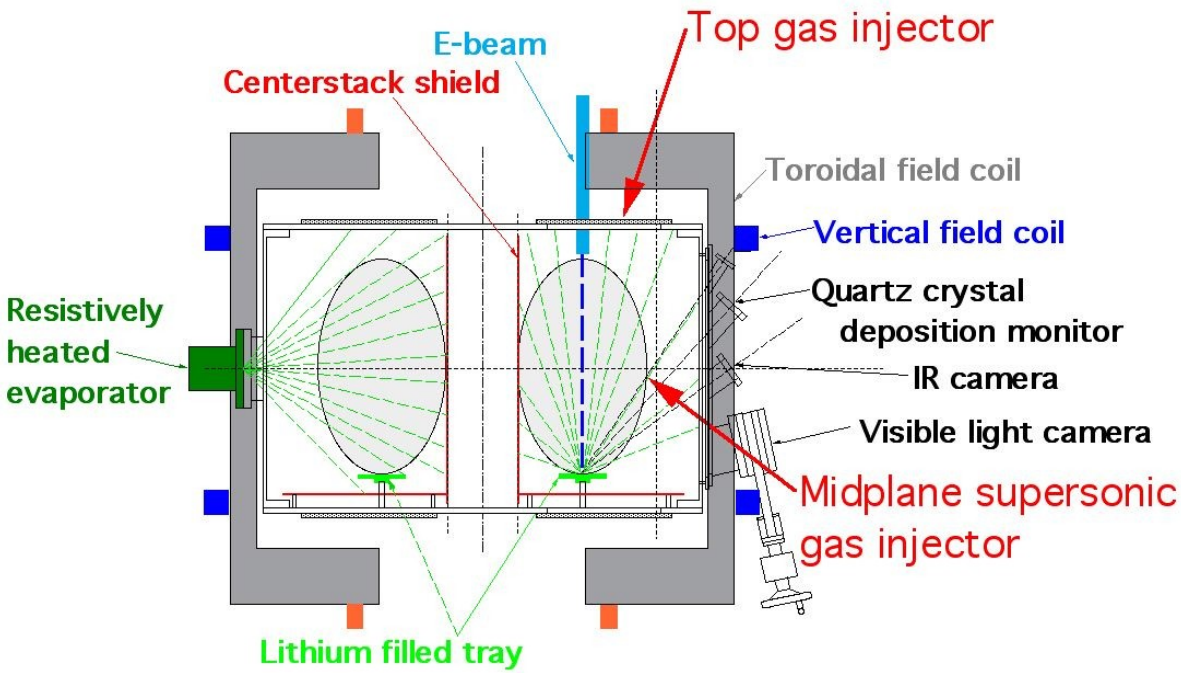
Outline

CDX-U

LTX

1. CDX-U lithium operations overview
2. Summary of CDX-U magnetic diagnostics capability
3. Response function aided calibration
4. CDX-U equilibrium examples using the Equilibrium and Stability Code (ESC)
5. CDX-U energy confinement analysis for lithium surface experiments from the week of 08-18-05
6. Implications for LTX

CDX-U Lithium Operations



Elevation of CDX-U

R_0=34 cm
a = 22 cm
$\kappa \leq 1.6$
$B_T(0)$2.2 kG

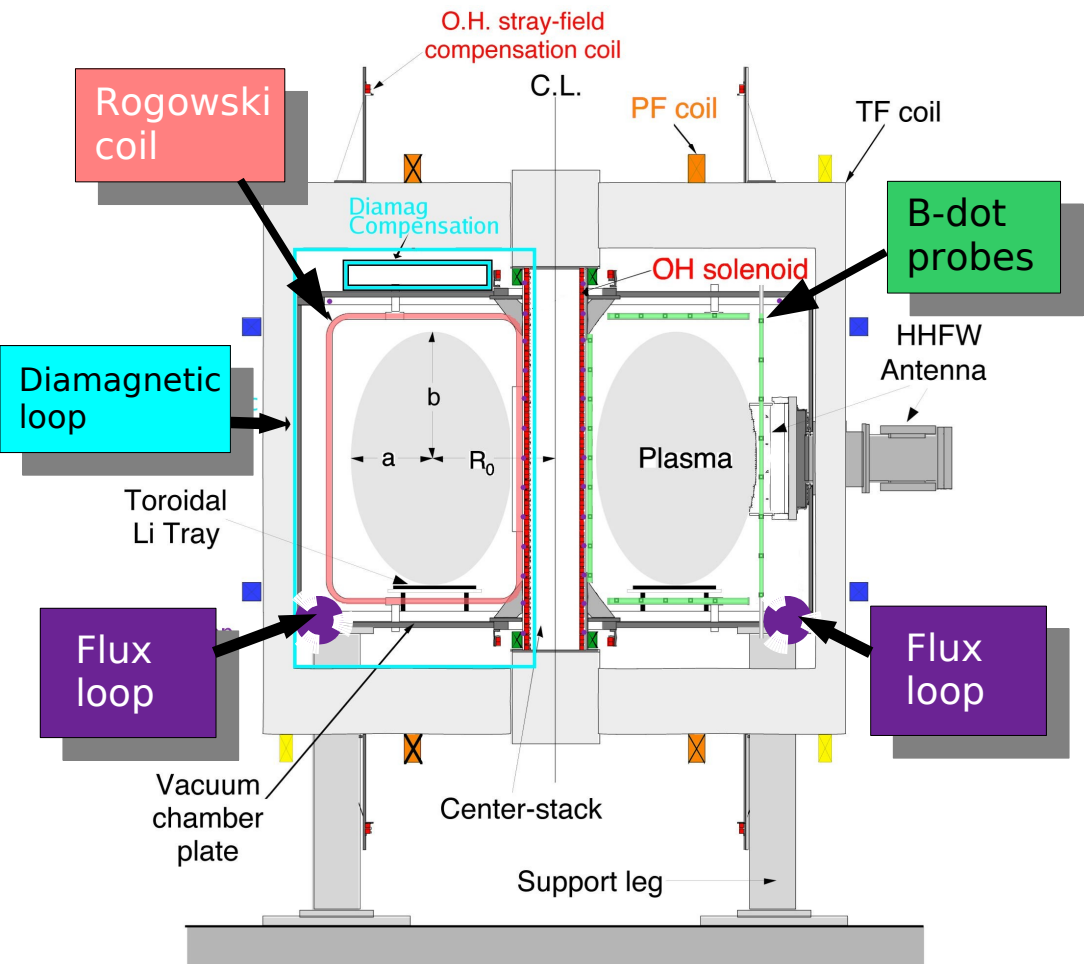
$T_e(0)$~100 eV
$n_e(0)<6\times10^{19}$ m^{-3}
$I_P \leq 80$ kA

τ_{disch}<30 msec

CDX-U

- **Lithium tray limiter**
  - 300 g of lithium in a toroidal tray
  - 120° toroidal coverage
- **Electron beam**
  - high heat flux, lithium coating system
  - Used lithium tray inventory as source
  - Line of sight coverage of most of vessel
- **Resistively heated lithium evaporator**
  - NSTX prototype

CDX-U Magnetics

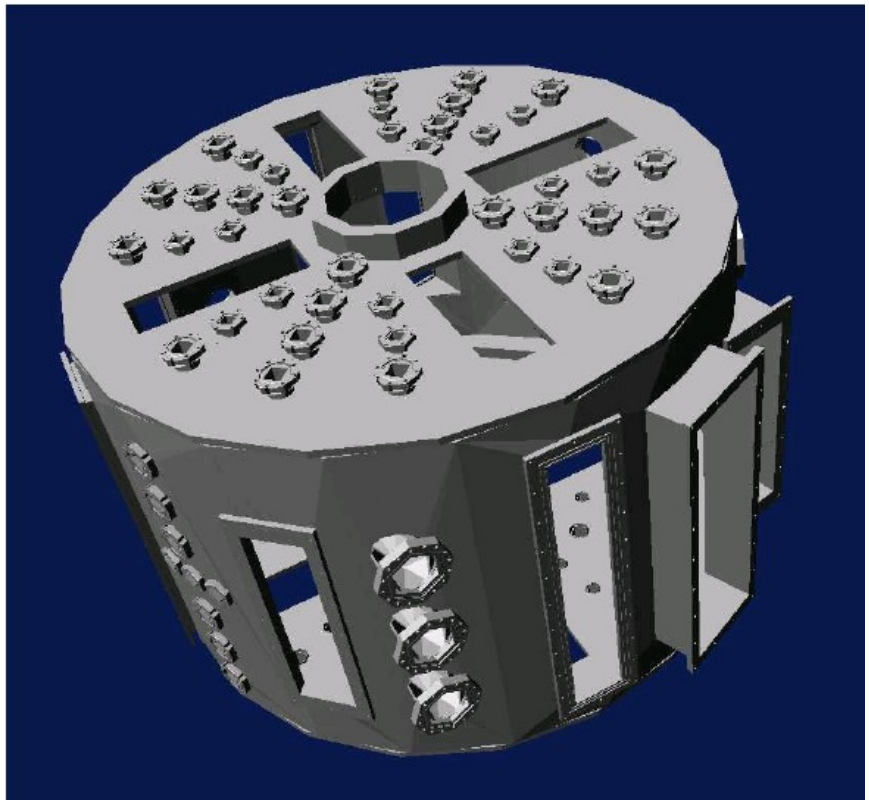


Unable to neglect vessel wall eddy currents generated by time-changing **PFCoil** currents.

- **Plasma Rogowski coil**
  - Toroidal plasma current
- **Diamagnetic loop**
  - Measurement of plasma induced toroidal flux (<1% TF-Coil flux)
  - In series with external TF-Coil flux compensation coil
  - Includes contribution from OH solenoid accounted for with field only shots
- **Poloidal array of B-dot probes**
  - local magnetic field measurements
  - Several toroidal locations
- **Poloidal flux loops**
  - Located along center stack and near outboard vessel corners

CDX-U Challenges

CDX-U



- Conductive shell with many port openings
- B-dot probes in several toroidal locations
- Pulsed plasma with short duration on the order of eddy current timescales
- Potentially large wall eddy currents with localized non-axisymmetric components near B-dot probes

Eddy Current Response Functions

CDX-U

- The response function $r^i_j(t)$ captures time history of all eddy current contribution from PFCoil current j at sensor i

$$V^i_j(t) = \int_0^t r^i_j(t-\tau)\frac{dI_j(\tau)}{d\tau}d\tau$$

I_j: Current at PFCoil j

V^i_j: Recorded voltage from sensor i due to current I_j

Limiting Case: Isolated current source with no other conducting surfaces

$r^i_j(t)$ = step function and $V^i_j(t) = r^i_j(\infty)I_j(t)$

Eddy Current Contributions To Response Functions

CDX-U

- The eddy current contribution to the recorded voltage at sensor *i* due to coil current *j* is:

$$Veddy^{i}_{j}(t)=\int_{0}^{t}\left(r^{i}_{j}(t-\tau)-r^{i}_{j}(\infty)\right)\frac{dI_{j}(\tau)}{d\tau}d\tau$$

- The asymptotic limit of the response function $r^{i}_{j}(\infty)$ describes the voltage expected if no eddy currents were present.

Limiting Case: $I_j(t)$ = step function

$$Veddy^{i}_{j}(t)=r^{i}_{j}(t)-r^{i}_{j}(\infty)$$

Response Functions and Sensor Calibrations

CDX-U

- Asymptotic behavior of response function provides a means of in-situ cross-calibration for each magnetic sensor against all available field coils for arbitrary current waveform shape (even capacitor driven coils!)
- Calibration requires signal and current to be non-zero for a time longer than required for the response function to reach its asymptotic value.

$$C^i = \frac{G^i_j C_j}{r^i_j(\infty)}$$

- G^i_j is Green's table value for isolated sensor-coil geometry
- C_j is physical sensitivity of PFCoil (MA/V)
- C^i is physical sensitivity of sensor (eg. Telsa/V or Weber/V

Cross-calibration provides measurement redundancy for statistical accuracy estimates for all calibration factors involved:
N PFCoils, M sensors → N*M equations to solve for M+N unknowns

Response Functions Work

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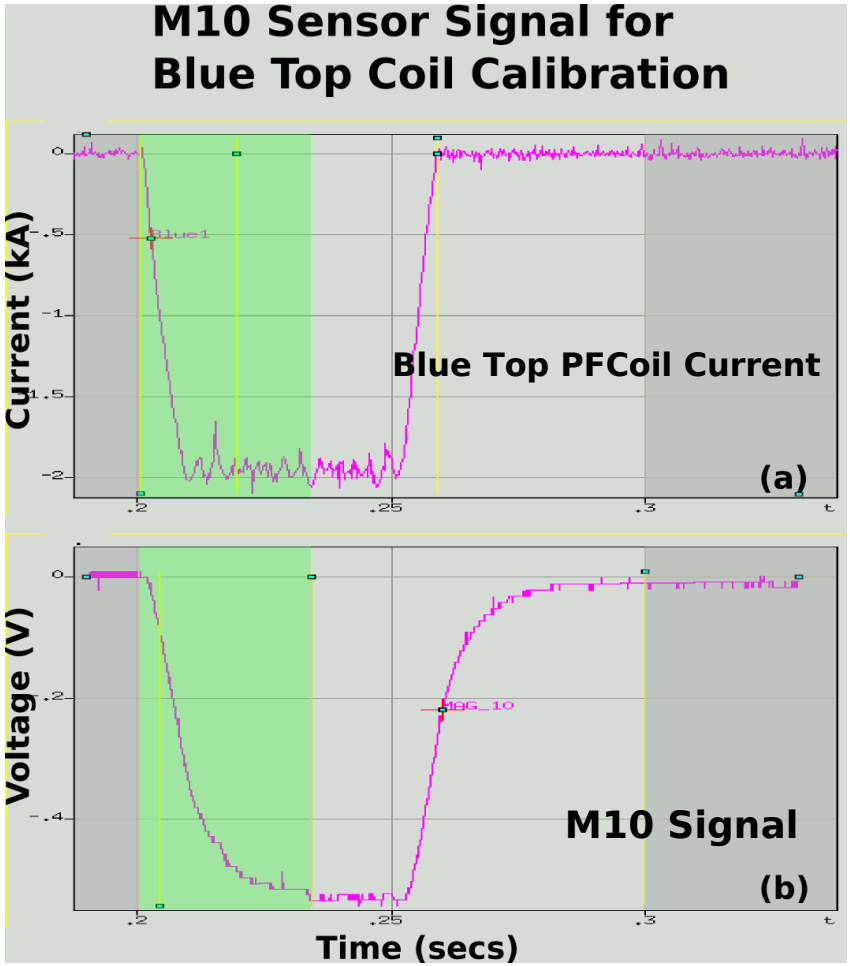
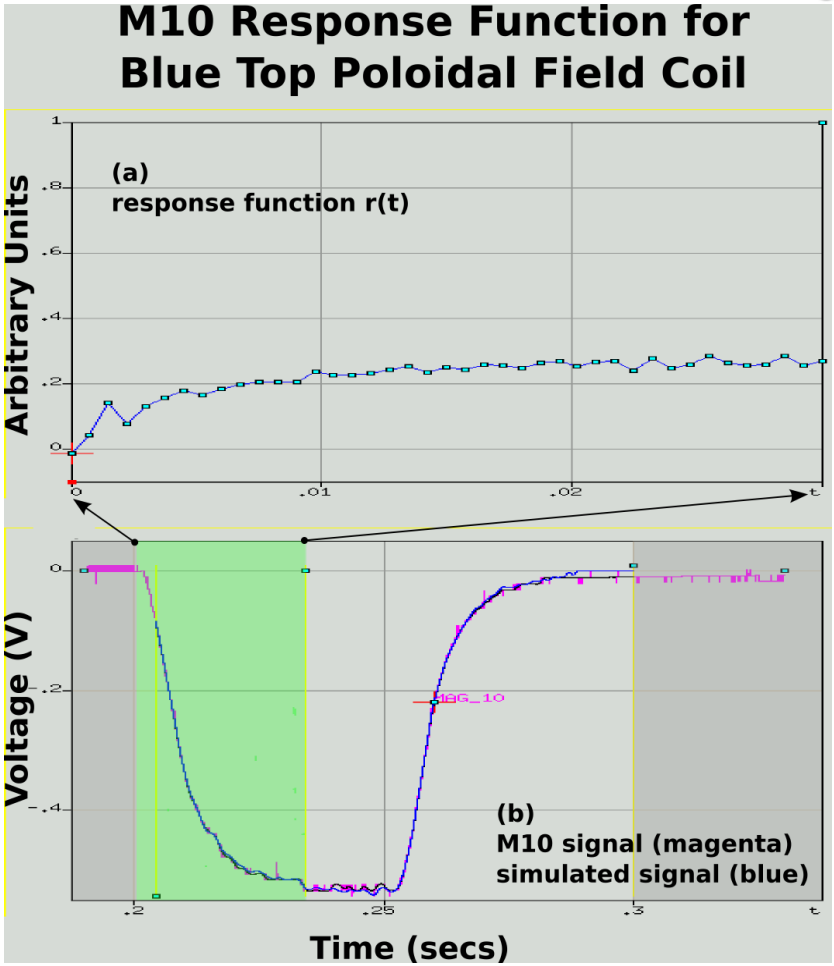
- M10 B-dot probe located at mid-plane behind center-stack heat shield.

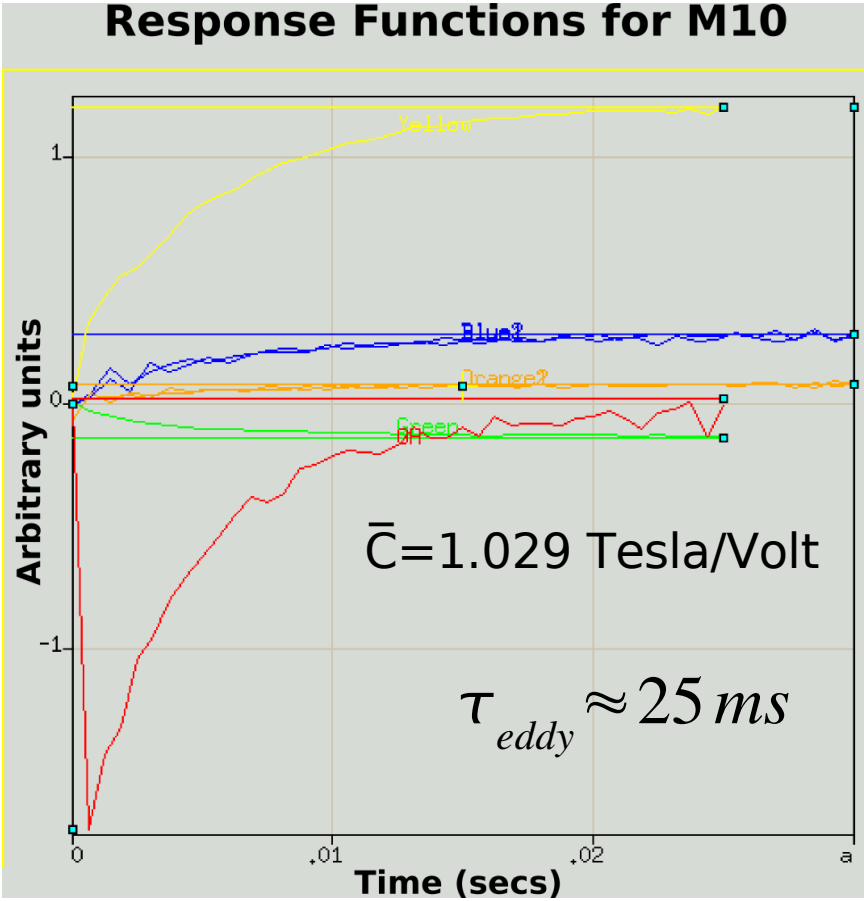




- Response function calculated from first 30 ms of sensor signal (green region).
- Simulated signal constructed from response function fits actual signal for entire signal waveform ~ 100 ms.

First Implementation of Response Function Cross-Calibration

CDX-U



Comparison of response functions for cross-calibration of all PFCoils for M10 sensor.

CbC2E code developed for response function cross-calibration for CDX-U

Sensitivity found to agree with 10% for most sensors across all PFCoils including pulsed, capacitor driven coils.

Uncovered historic errors in CDX-U PFCoil calibration

No model of the conducting surfaces required.

No assumption of axisymmetric eddy currents.

Equilibrium and Stability Code

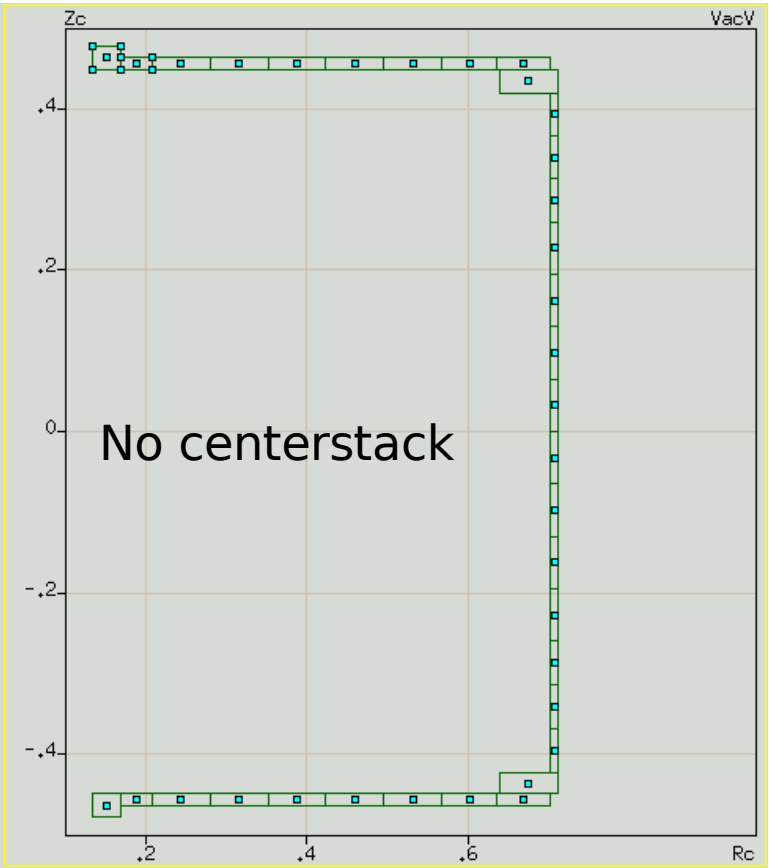
CDX-U

- Developed by L. E. Zakharov
  [Zakharov, Pletzer, Phy. of Plasmas, 1999]
- Designed to be a fast equilibrium solver for 2-D and 3-D geometries useful for real time forecasting of plasma discharges
  - Uses natural flux coordinate system internally
  - Uses a perturbed equilibrium approach to linearize the Grad-Shafranav equation for fast convergence of Newton's method iteration loops.

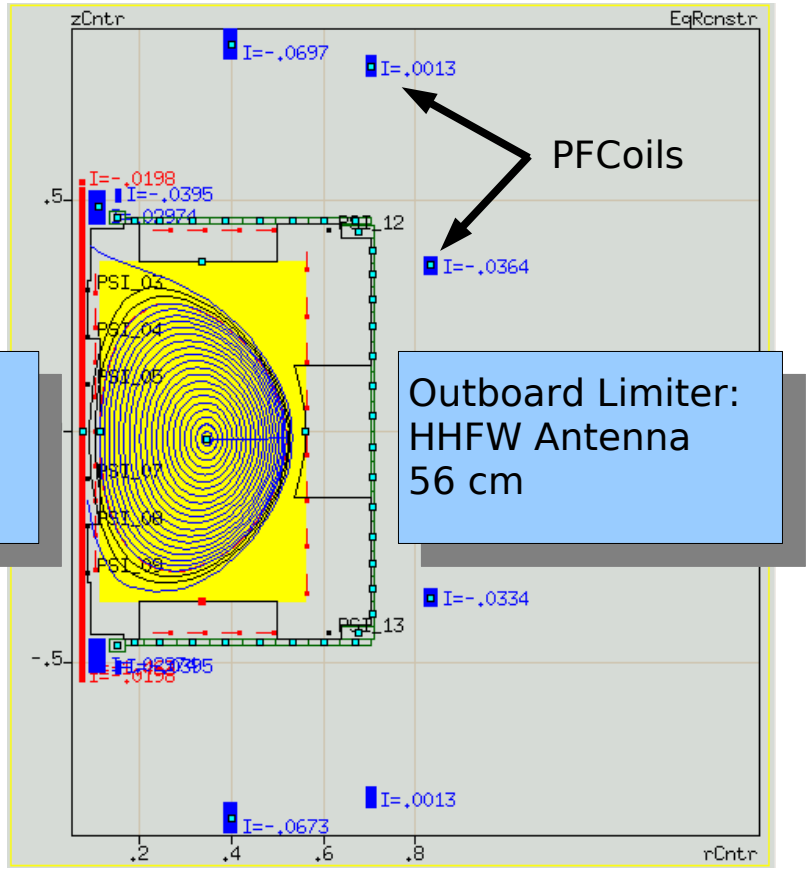
  ➔ New: Incorporates response function information from **CbC2E** code developed as part of CDX-U sensor calibration

The CDX-U Representation in ESC

CDX-U conductive wall model



The full CDX-U system representation



Using Response Function Information in ESC

CDX-U

- Flux loops are only sensitive to axisymmetric currents.
  - Flux loops can be used to fit equilibrium wall currents in ESC without invoking response function information.
  - Flux loop response function information can be used as a consistency check on wall current signal contribution.
- B-dot probes are sensitive to non-axisymmetric currents, which are not described in the equilibrium formulation.
  - B-dot response function information can be used to isolate plasma signal at each B-dot probe.

$$B_{total} = B_{plasma} + \underbrace{B_{plasma-eddy}}_{\text{neglected}} + \sum \underbrace{\left(B_{PFC} + B_{PFC-eddy}\right)}_{\text{response function}}$$

  - Note: B-dot probes are not used to fit the axisymmetric wall currents, when response function analysis is enabled.

Estimate of Plasma Induced Eddy Currents

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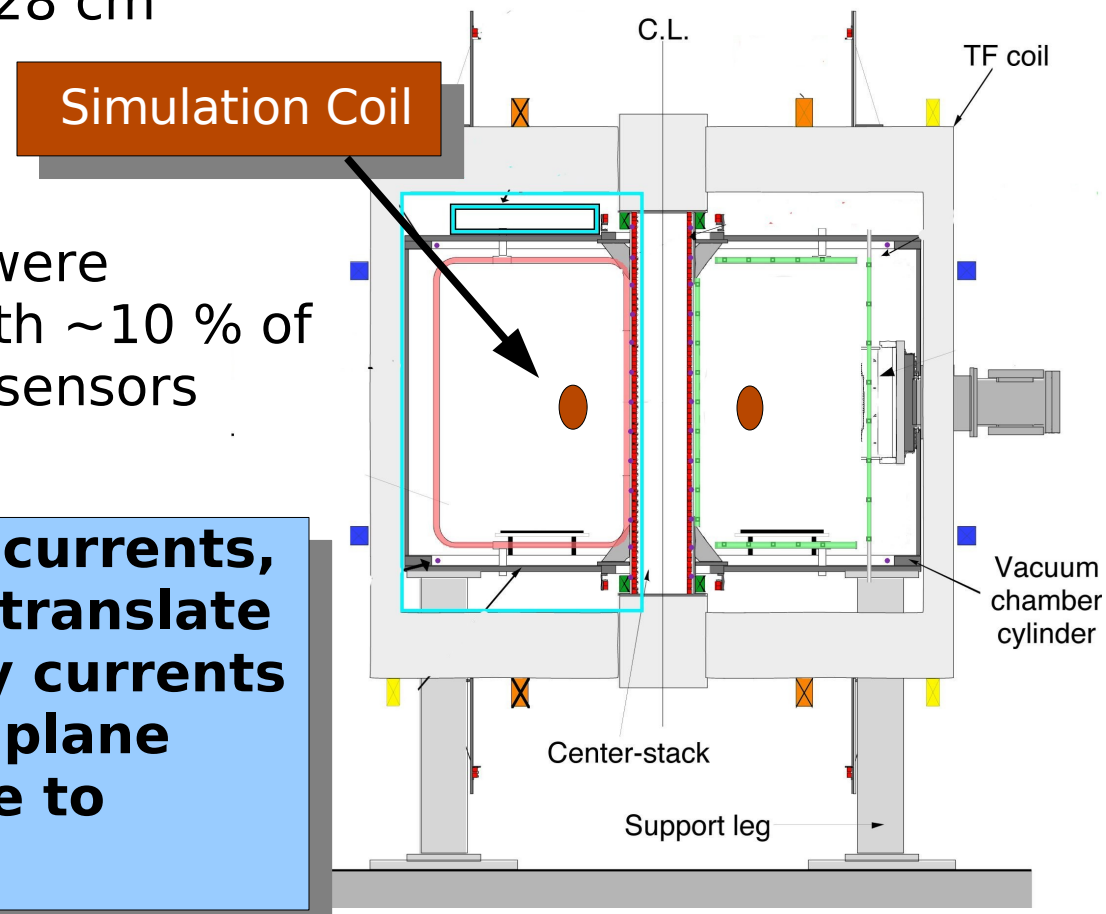
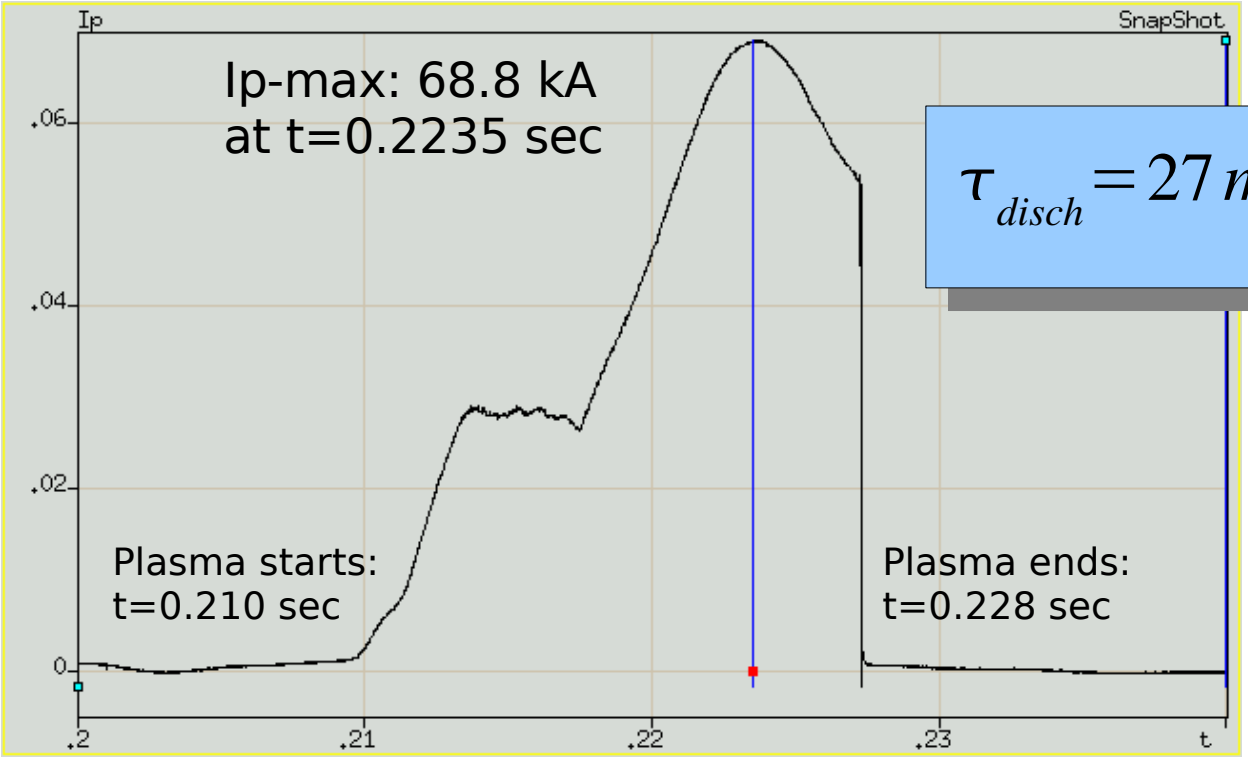
- Wound a simulation plasma coil inside CDX-U vacuum vessel to produce ~4 kA current channel at R=28 cm
- Applied response function analysis used for PFCoils
- Only outboard B-dot probes were sensitive to eddy currents with ~10 % of the total signal for midplane sensors (M23 and M24)



For typical CDX-U plasma currents, simulated plasma results translate into plasma induced eddy currents < 5% of full signal for midplane sensors and is comparable to calibration error.

CDX-U Equilibrium Example: 0818051234

CDX-U LTX



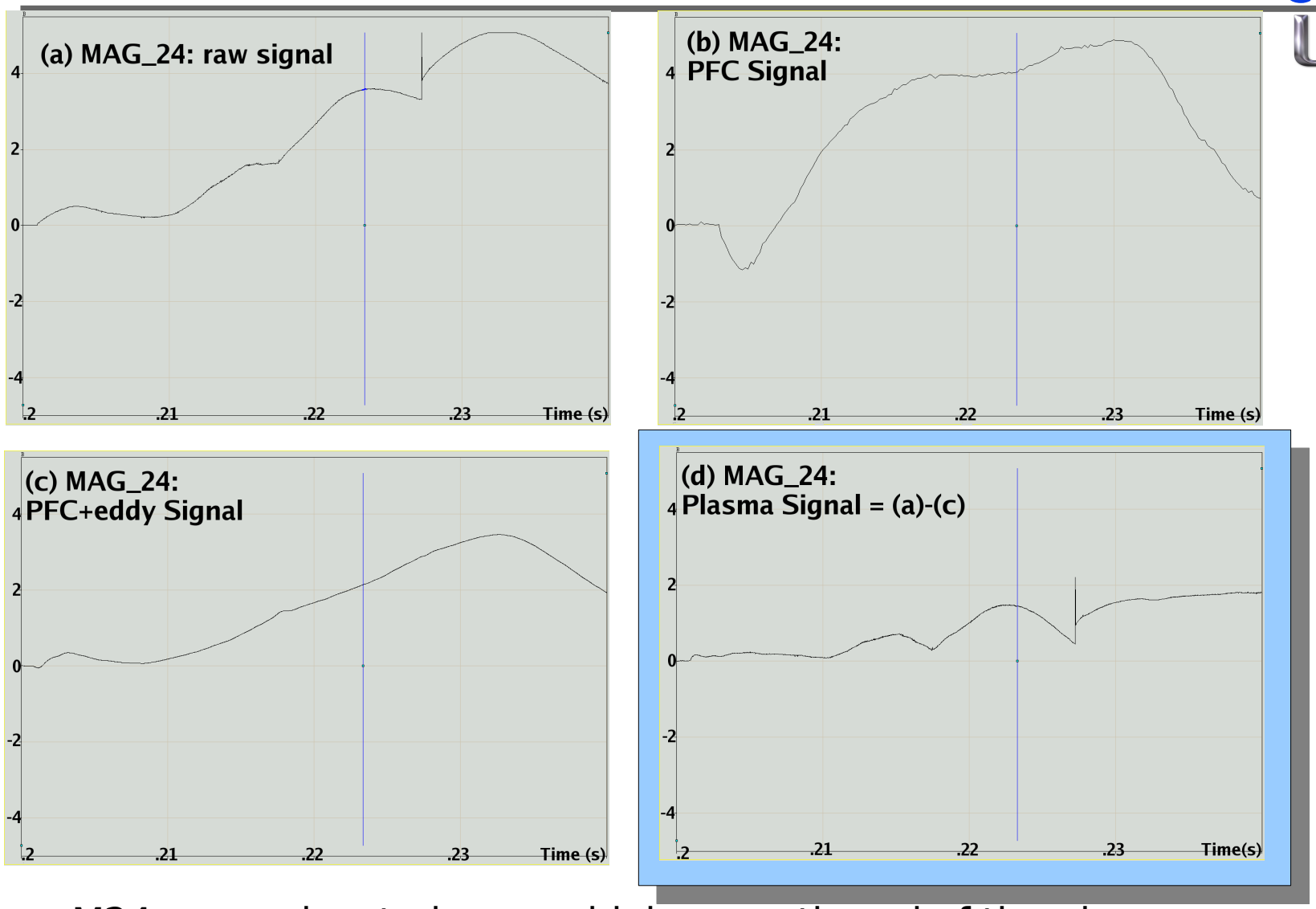
$$\tau_{disch} = 27\,ms \simeq \tau_{eddy}$$

Plasma current waveform for CDX-U shot: 0818051234

Active lithium evaporative coating via E-beam deposition into liquid lithium tray limiter ~ 400 C°

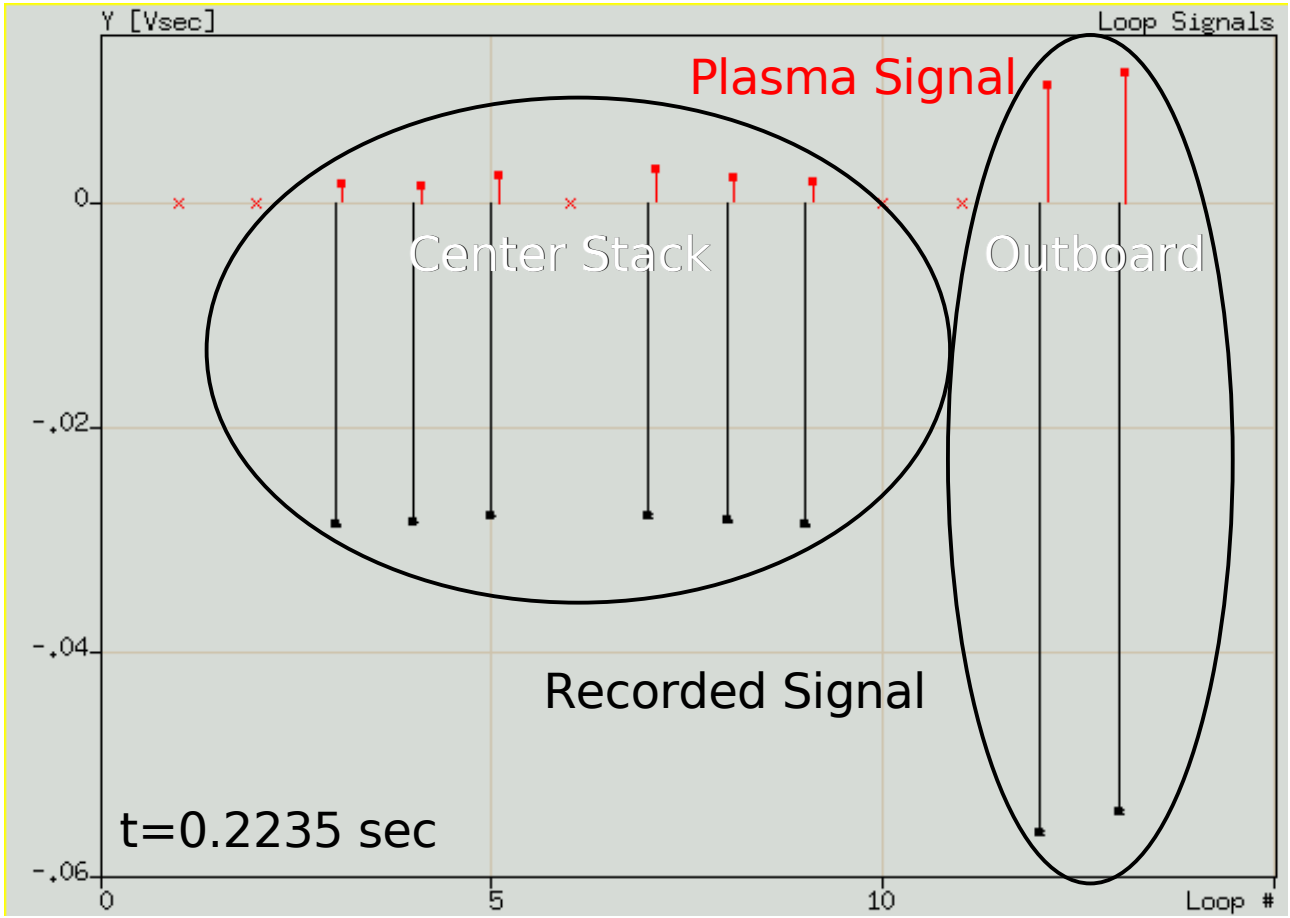
Extracting Plasma Signal Using Calibration Response Function

CDX-U



M24 sensor located near midplane, outboard of the plasma
Plasma contribution ~ 30% of total signal

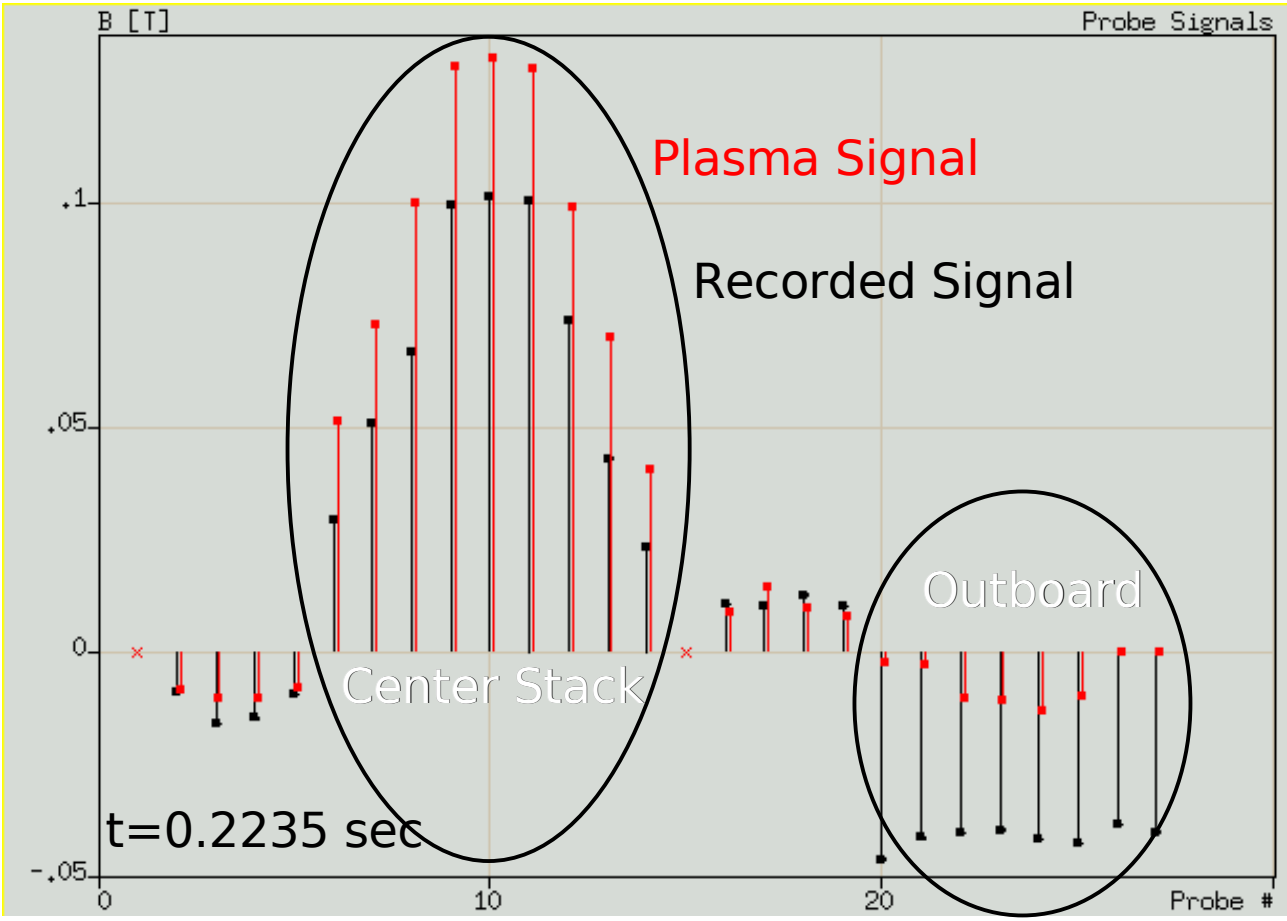
CDX-U Equilibrium Example 0818051234: Flux Loops



Signal from plasma is only a small fraction of the recorded flux loop signal at all flux loop locations

CDX-U Equilibrium Example 0818051234: B-dot Probes

CDX-U

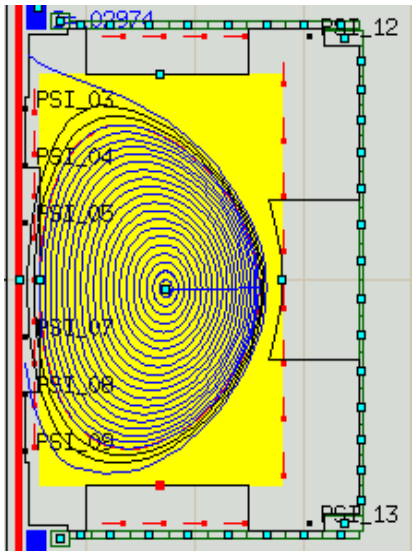


Signal from plasma dominates external contributions for B-dot probes along the center stack

CDX-U Equilibrium Example 0818051234

CDX-U

Analysis without response functions



R_0 =0.345 m

Area =0.187 m^2

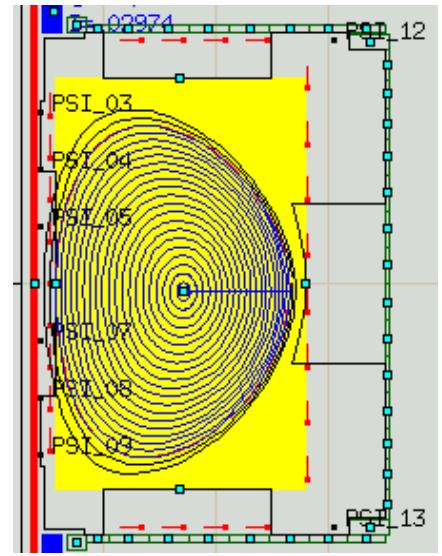
$W_{kinetic}$ =1.613E-4 MJ

$W_{magnetic}$ =3.347E-4 MJ

Using the same ESC weighting parameters

Convergence of either analysis technique is sensitive to weighting parameter choices

Response function aided analysis



R_0 =0.348 m

Area =0.182 m^2

$W_{kinetic}$ =1.615E-4 MJ

$W_{magnetic}$ =3.340E-4 MJ

Ψ_{edge} =-2.617E-2 Vsec

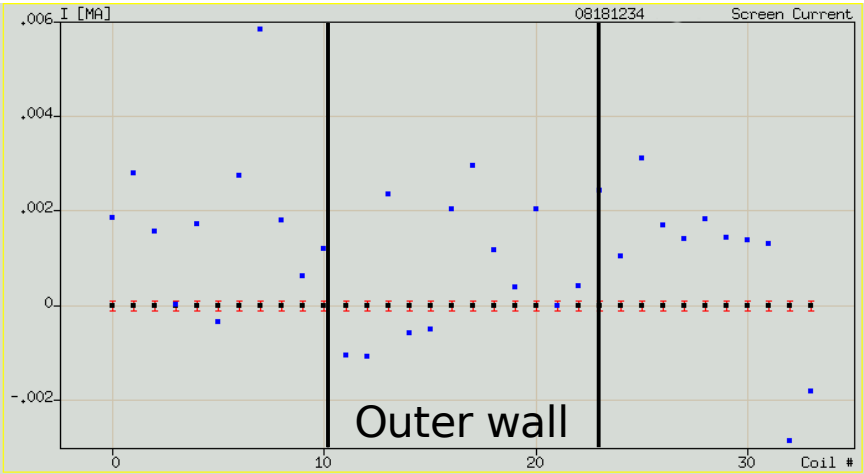
Ψ_{edge} most sensitive to weighting parameters

Ψ_{edge} =-2.650E-2 Vsec

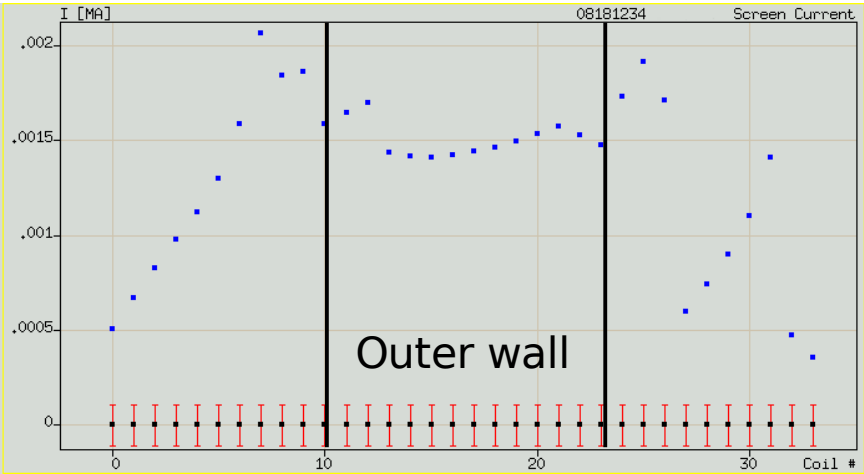
CDX-U Equilibrium Example 0818051234: Wall Currents

CDX-U

Analysis without response functions



Response function aided analysis

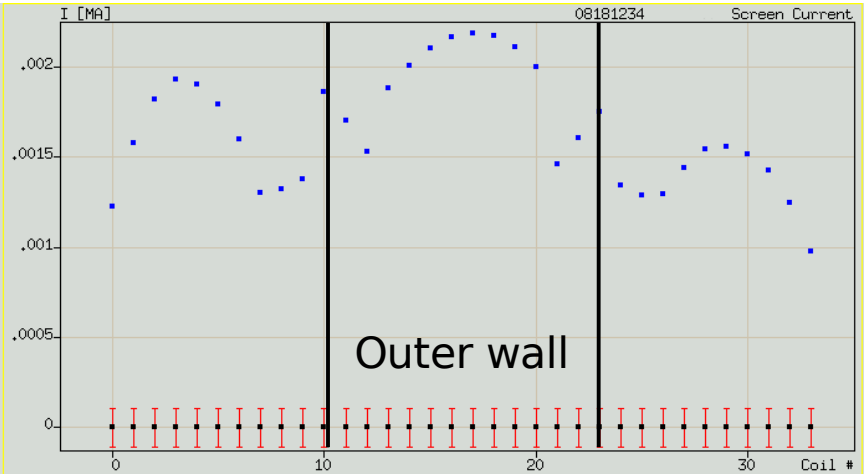


Response function aided analysis recovers smoothly varying wall currents along the conductive wall regions in the ESC plasma reconstructions.

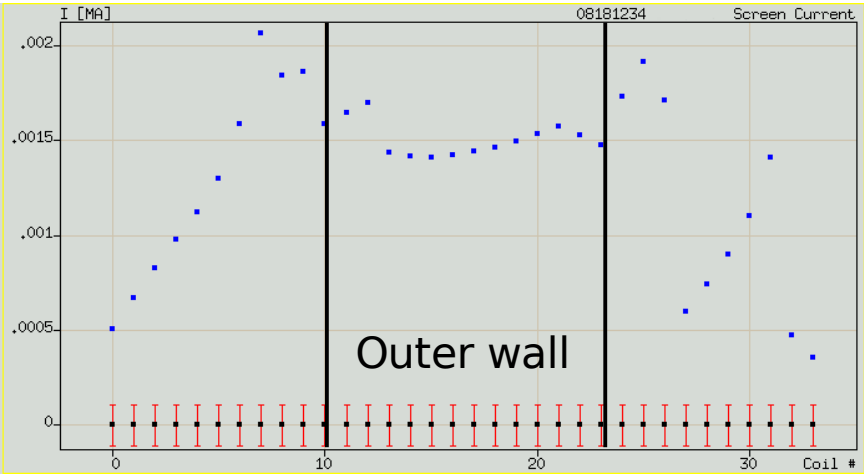
CDX-U Wall Currents Under-Constrained

CDX-U

Response function aided analysis with 'reduced' wall current weight



Response function aided analysis with 'normal' wall current weight



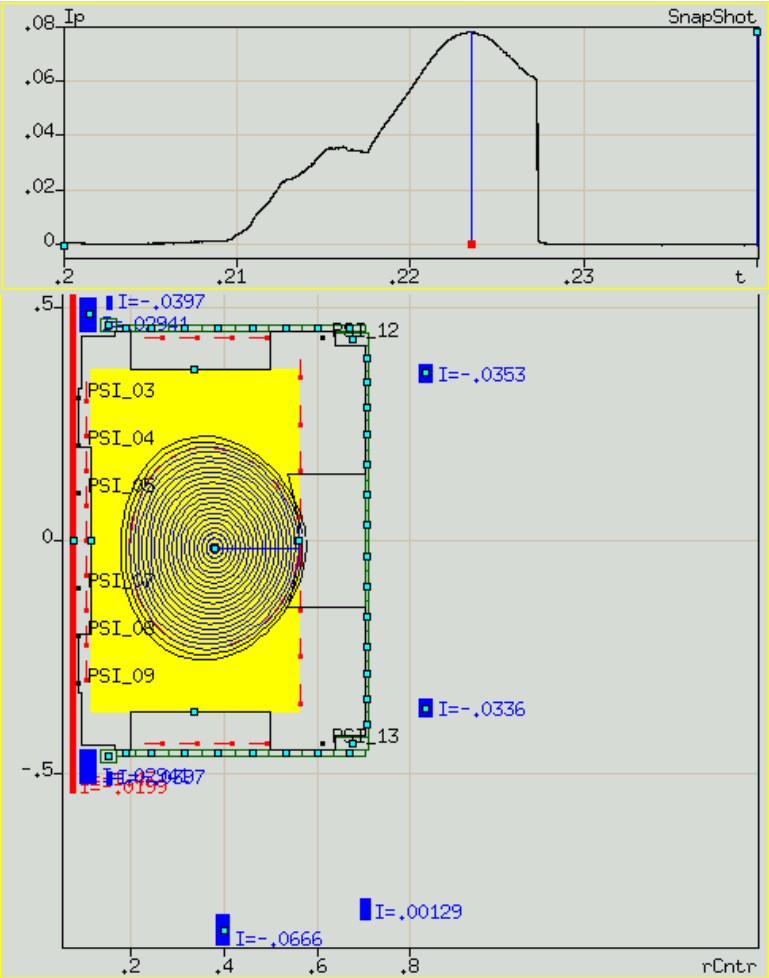
- Adjusting the relative weights of the wall currents in ESC results in two different wall current distribution patterns.

Results Indicate the wall currents are under-constrained.

- Can be addressed in LTX diagnostic enhancements to measure wall currents along the vessel wall or with additional flux loops.

CDX-U Plasmas Demonstrate Limited Equilibrium Control

CDX-U



- Shot: 0818051316
- I_p > 70 kA
- Detaches and reattaches to center-stack
- Enjoy the movie

Energy Confinement Time Analysis

CDX-U

- Energy Confinement Time [Hutchinson 1978]

$$\tau_e = \frac{W_{kinetic}}{P_{kinetic}}$$

  - For Ohmically heated plasmas, kinetic power input, $P_{kinetic}$, is resistive heating power, $I_p^2 R_p$.
  - Plasma can be approximated as a simple LR circuit to determine contribution to kinetic power and magnetic power.

$$P_{kinetic} = I_p^2 R = P_{incident} - P_{magnetic} = I_p V_{edge} - \frac{d(LI_p^2)}{dt}$$

  - $P_{incident} = I_p V_{edge}$ derived from surface integral of Poynting flux at plasma boundary

Energy Confinement Time Analysis

CDX-U

At time of peak I_p , $P_{magnetic} \approx 0$

$$\tau_e = \frac{W_{kinetic}}{V_{edge} I_p^{peak}}$$

V_{edge} derived from equilibrium Ψ_{edge} at multiple time points

$$V_{edge} = -\frac{d\Psi_{edge}}{dt}$$

V_{edge} modeled as linear fall-off near the peak CDX-U plasma, similar to diagnostic center-stack V_{loop} behavior

Observed large discontinuities in V_{edge} over very short time scales when plasma changes from being attached to center stack and outboard limiter. Interpreted as artifact of under-constrained wall currents.

Energy Confinement Time Example: 0818051234

CDX-U

LTX

I_p = 68.8 kA

V_{edge} = 1.14 V

V_{loop} = 1.08 V

}~5%

$P_{kinetic}$ = 7.84E-2 MJ/s

$W_{kinetic}$ = 1.613E-4 MJ

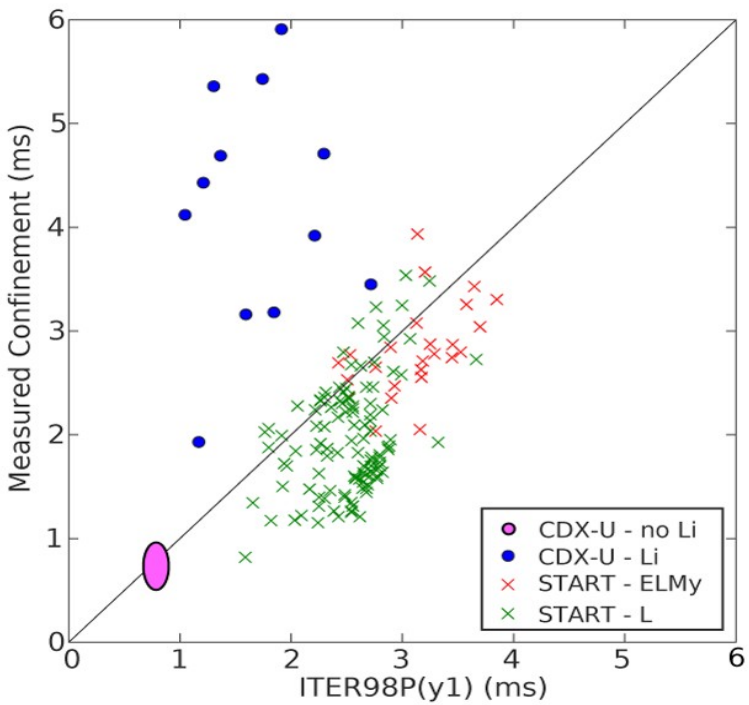
$W_{magnetic}$ = 3.347E-4 MJ

τ_e = 1.93E-3 ~ 2.07E-3 sec

- Performance improvement compared to previous energy confinement time estimates from kinetic measurements with no lithium present:
  - No Li: τ_e ~ 0.7 milliseconds [Munsat, 2002]

CDX-U τ_e Assessed for the First Time in Lithium Operations

CDX-U



The average energy confinement time is 3.5 times expected scaling

Scatter in results may be due to plasma irreproducibility or uncertainty in V_{edge} calculation

ITER98Py1 scaling chosen as a comparison,
as it provides a reasonable fit for previously available ST data.

[START data from Walsh, APS-DPP98]

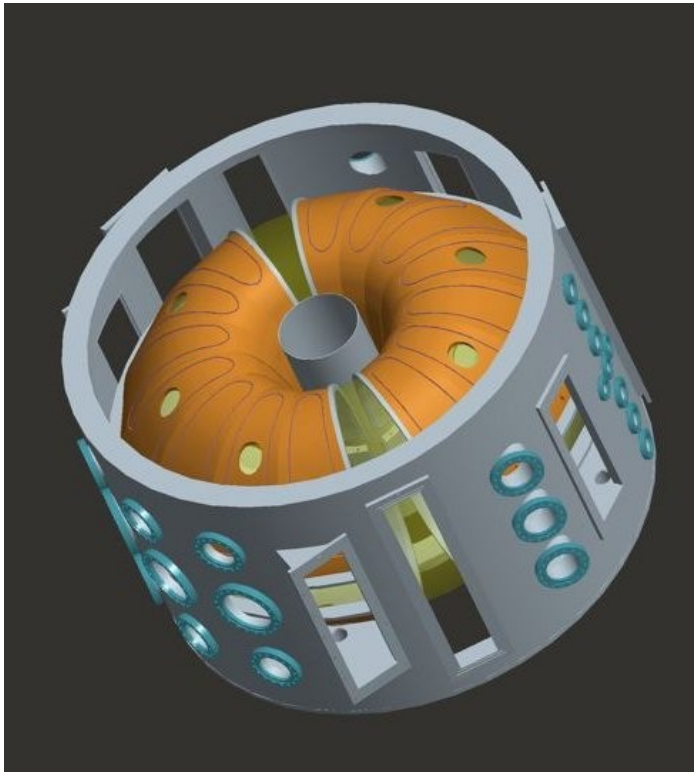
Summary of CDX-U Equilibrium Observations

CDX-U

- First implementation of response function cross-calibration of magnetic sensors.
- First CDX-U plasma equilibrium reconstructions resulting in estimates of τ_e.
    - During Lithium operation τ_e ~3.5 better than scaling predictions
- Observed limited equilibrium control with available OH capacitor system.
- Available analysis indicates areas of immediate diagnostic improvement:
    - Additonal outboard flux loop signals, closer to the plasma boundary
    - Direct measurement of wall current along outer vessel wall

Implications for LTX

CDX-U

LTX

- Equilibrium reconstruction capability demonstrated on CDX-U will be useful for baseline tool for developing field programming for LTX plasmas
- LTX diagnostic upgrades to better constrain equilibrium solution
  - Conformal flux loops near outboard plasma boundary for increased plasma flux sensitivity
  - Direct measurement of vacuum wall currents
  - Thomson scattering diagnostic to provide internal profile constraints for equilibrium profiles