Magnetic Diagnostics for Equilibrium Reconstructions in the Presence of Non-axisymmetric Eddy Current Distributions in Tokamaks

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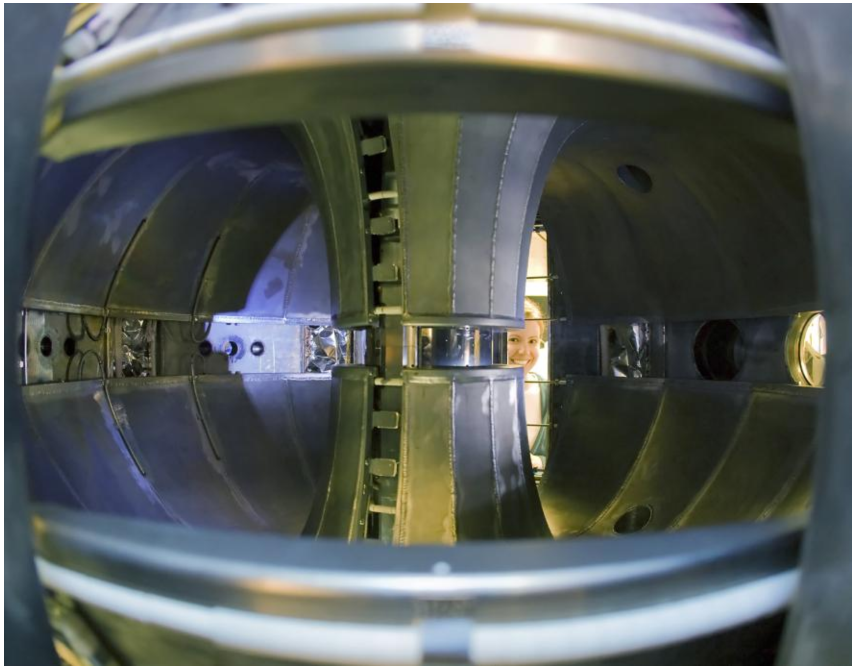
Outline

- Introduction to Magnetic Fusion Energy (MFE)
- Overview of the Lithium Tokamak eXperiment (LTX)
- Magnetic diagnostics for LTX
- LTX LRDFIT – 2-D code characterization
- LTX Cbshl – 3-D code development
- Summary



Fusion Energy

Goal: Generate power, like stars, through fusion reactions

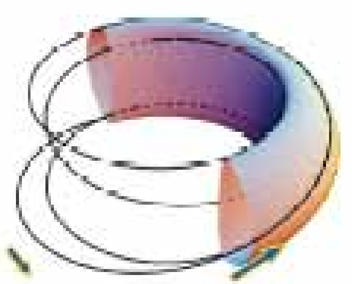
Example Reaction: $D + T \rightarrow n + \alpha + 17.6$ MeV

Benefits:

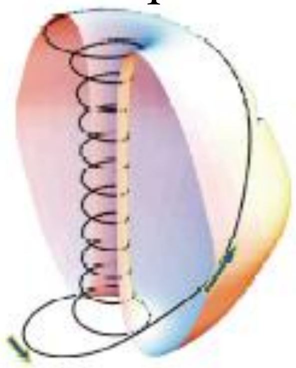
* Widely available input fuel source – sea water
* No risk of runaway chain reaction leading to nuclear accident
* Clean energy production – no greenhouse gas emission
* No high-level radioactive, nuclear waste

Magnetic Fusion Energy

* Fusion requires a balance of density, temperature, and confinement time
* Required temperature too high for physical containment → magnetic bottle
    * Form a plasma inside a physical vacuum vessel
    * Constrain plasma particles to closed magnetic field lines
    * Supply external heating in the form of neutral beam injection or radiofrequency heating
    * Highly energetic particles collide leading to fusion reactions and energy production
* Several potential magnetic bottle 'shapes':



Advanced Tokamak



Spherical Torus

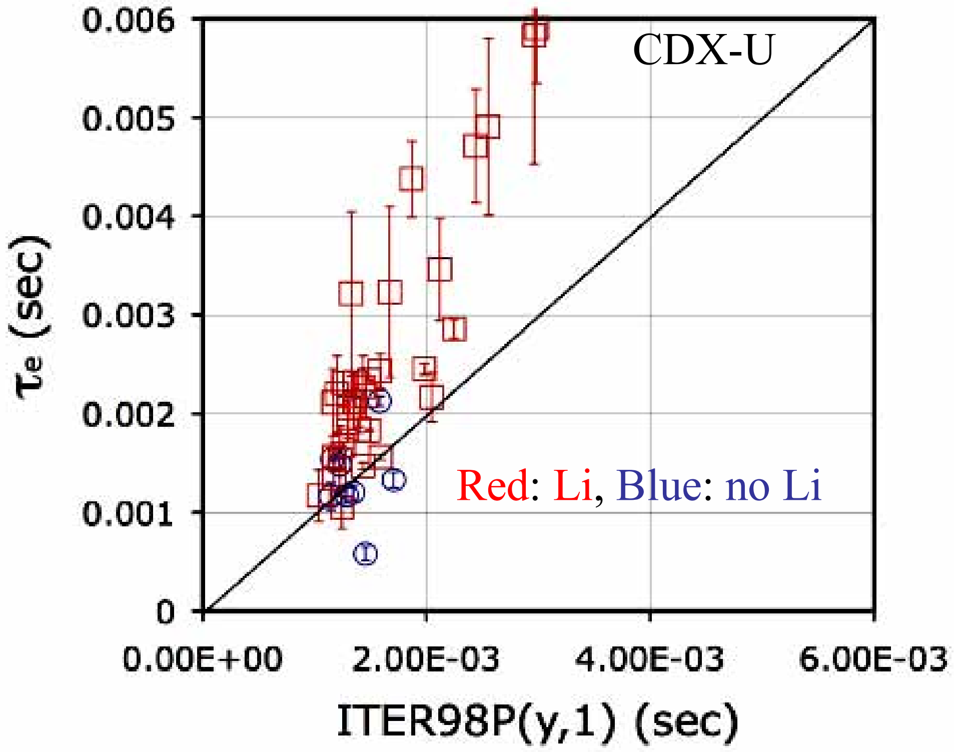
Compact Stellarator

Lithium acts as a getter → reducing recycling

- Experimental confirmation of plasma performance enhancement with lithium usage:
  - TFTR lithium wall-conditioning – solid Li
  - T-11M, FTU lithium rail limiter – liquid Li
  - CDX-U tray limiter filled with 2000 cm^2 liquid lithium – liquid Li PFC

CDX-U tray limiter

Largest improvement in energy confinement time for an Ohmic tokamak

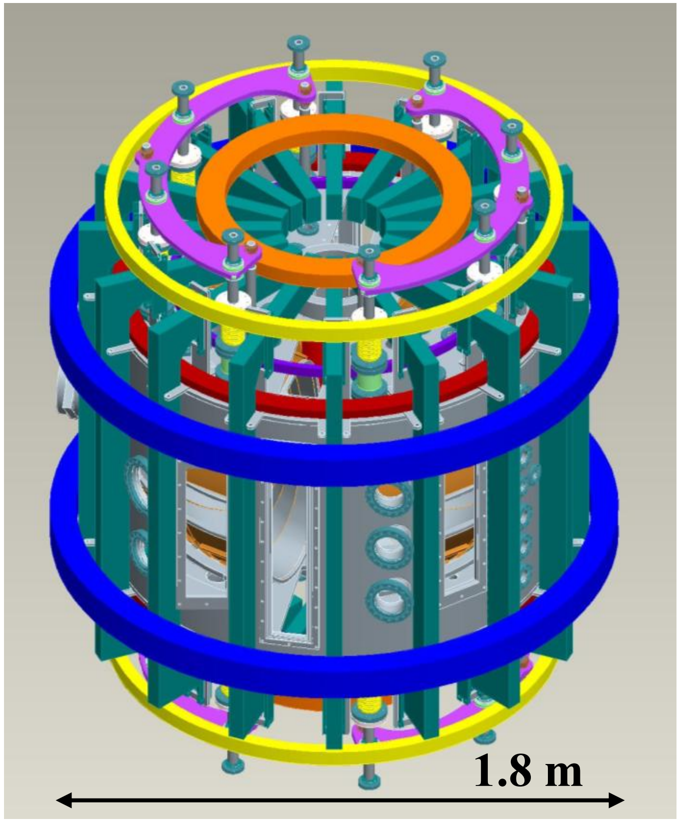


Lithium Tokamak eXperiment

- Extend previous lithium experimental results to operation with 85% liquid lithium coverage of last-closed-flux-surface

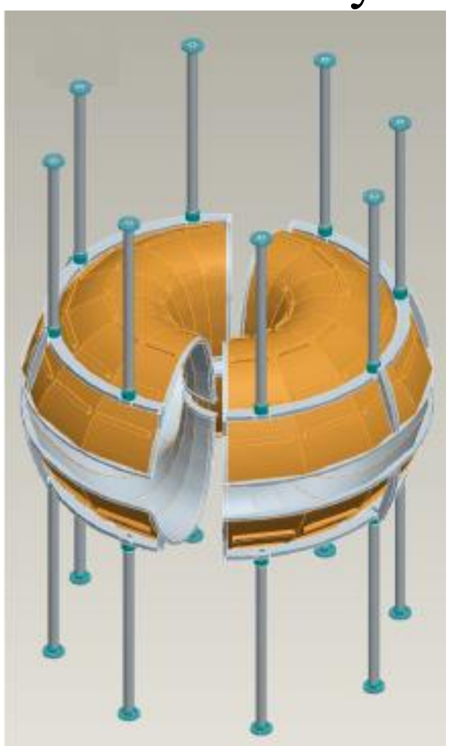
LTX parameters:

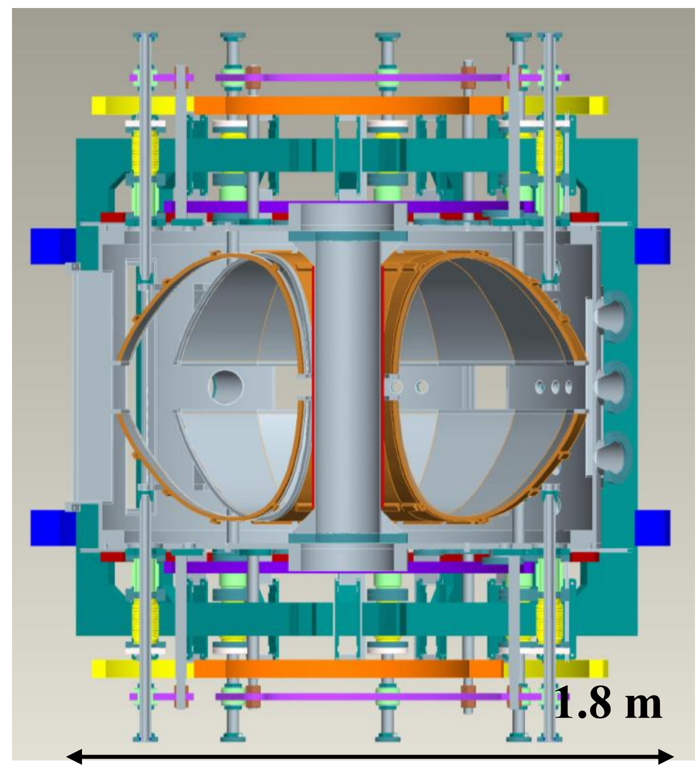
Major radius	0.4 m
Minor radius	0.26 m
Toroidal field	2 kG
Plasma current	15 kA → 150 kA
Discharge duration . . .	5 ms → 25 ms



LTX in-vessel, heated, conformal Cu shell

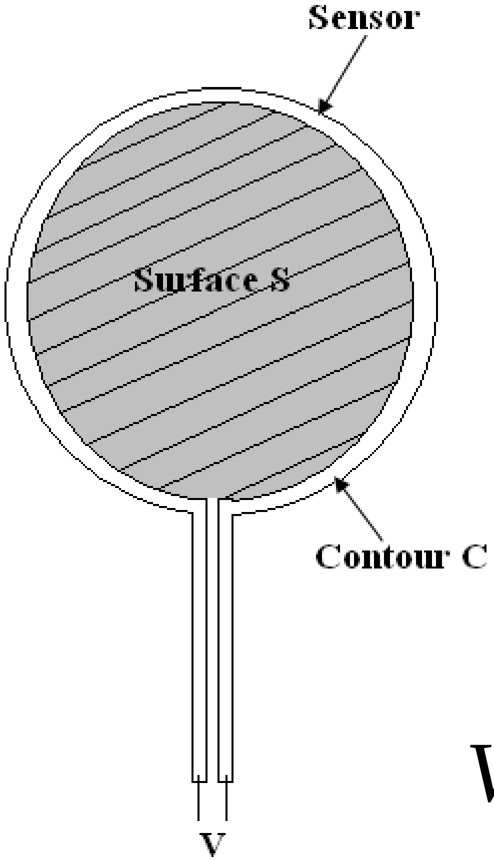
- 85% LCFS covered by liquid lithium when shell is lithium-coated
- Conformal with plasma last-closed-flux surface
- Two 22.5° toroidal breaks, and inboard and outboard poloidal breaks
- Can be heated up to 500 °C
- Mechanically and electrically isolated from the vacuum vessel



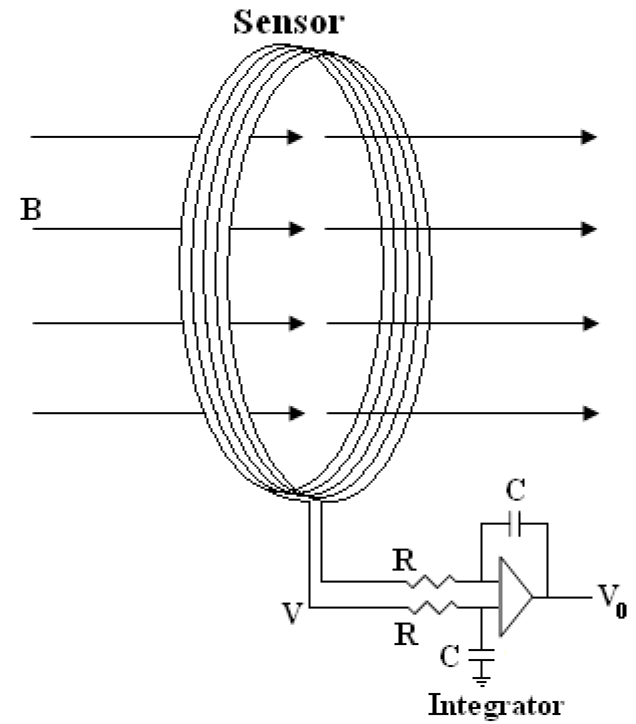


Basic theory of magnetic diagnostics

$$\oint_C E\cdot dl = \int_{coil} E\cdot dl + \int_{leads} E\cdot dl = 0 + V = -\int_S \dot{B}\cdot ds$$



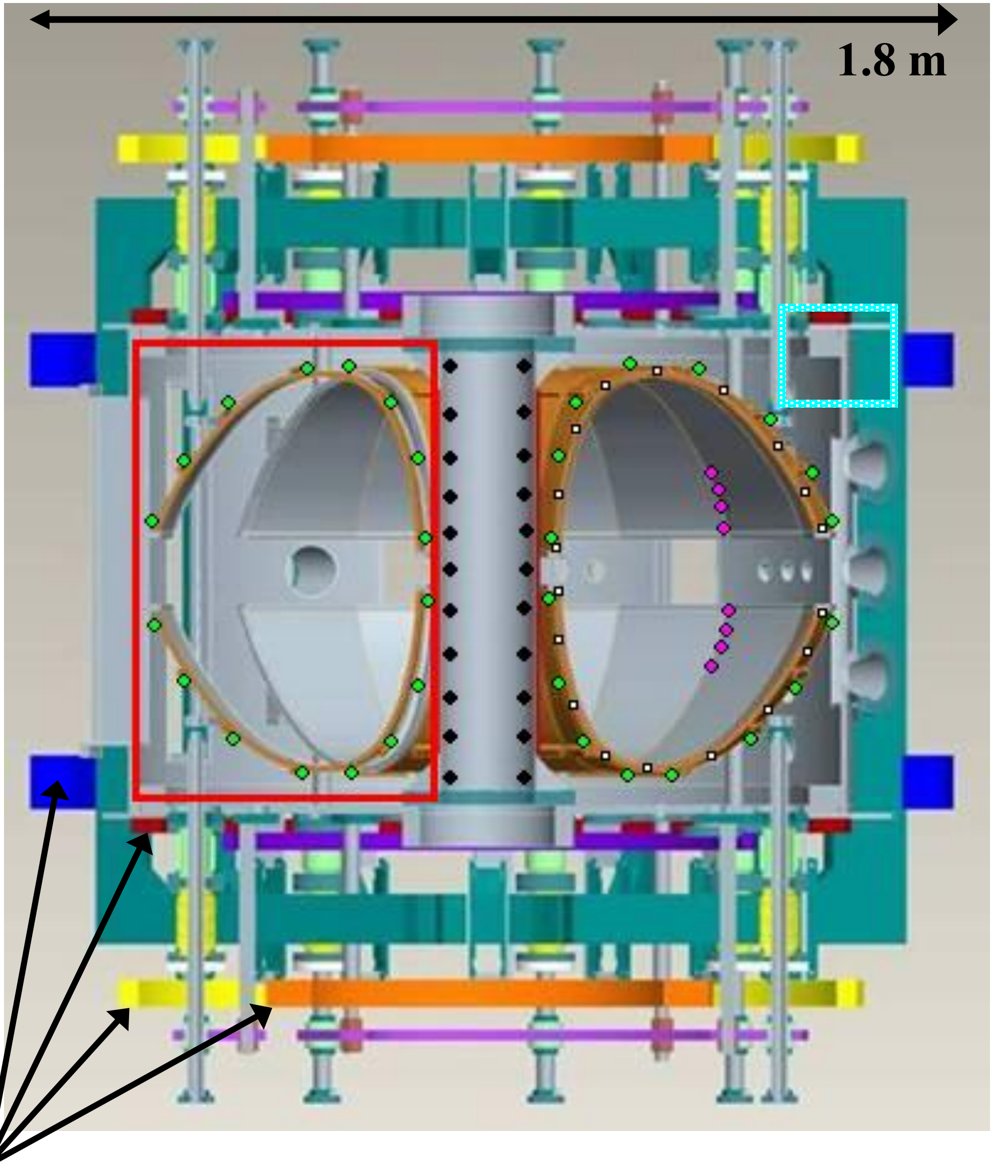
$$V = -\dot{B}\int_S ds$$



$$V_0 = \frac{N\Psi}{RC} = \frac{NAB}{RC}$$

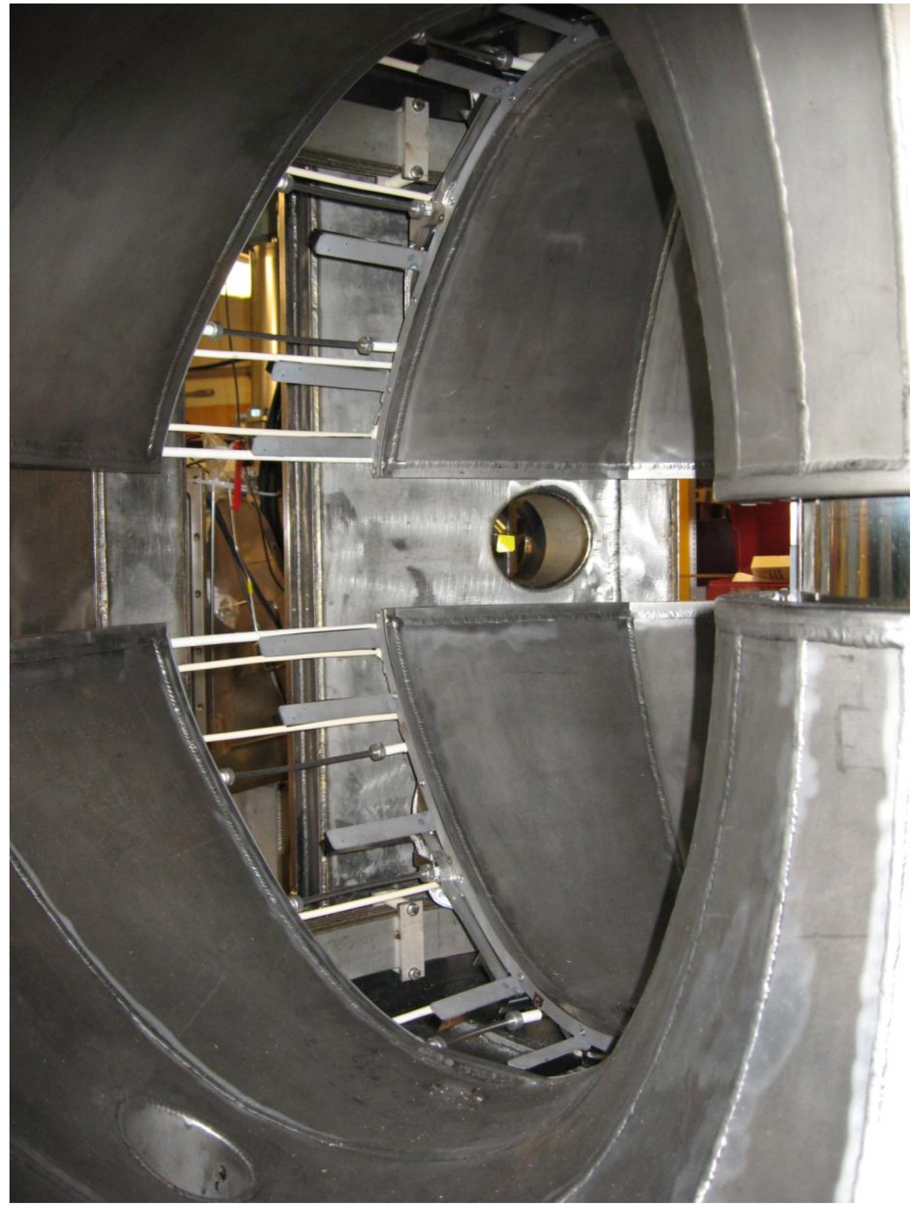
LTX has extensive set of magnetic diagnostics

- 11 centerstack flux loops
- 16 shell flux loops
- 4 saddle loops
- 30 in-shell B-dot coils
- 12 ex-shell B-dot coils
- 18 2-axis gap B-dot coils
- 26 B-dot coils in rectangular array
- 2 plasma current-measuring coils
- 1 vessel current-measuring coil
- Plasma stored energy measurement



Magnetic diagnostics design requirements

- Withstand high temperatures (500 °C) contact with lithium
- Maintain electrical isolation between shell quadrants and between shell and vacuum vessel
- Minimize distance between diagnostic and plasma
- Provide data on toroidal asymmetries
- Provide full coverage of poloidal cross-section
- Yield data for highly-constrained equilibrium flux surface reconstructions

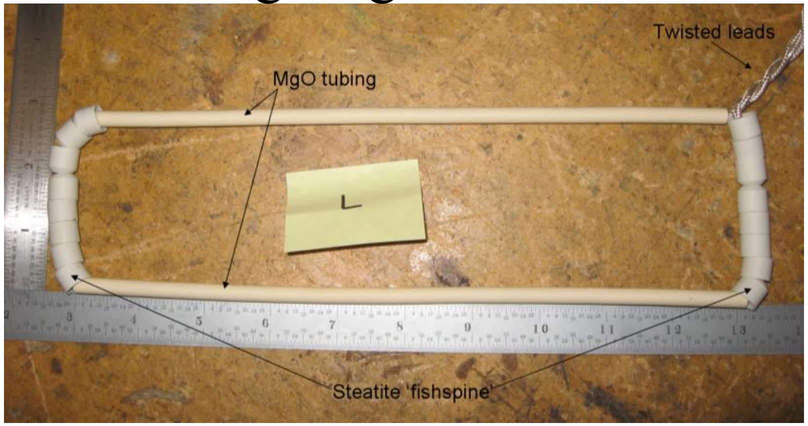


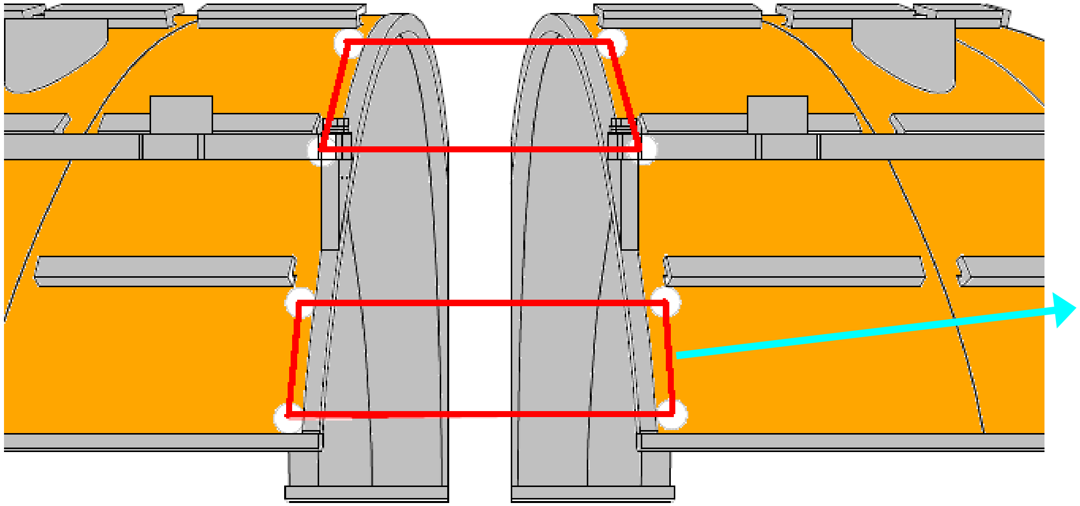
Shell flux loops – 8 on upper shells, 8 on lower

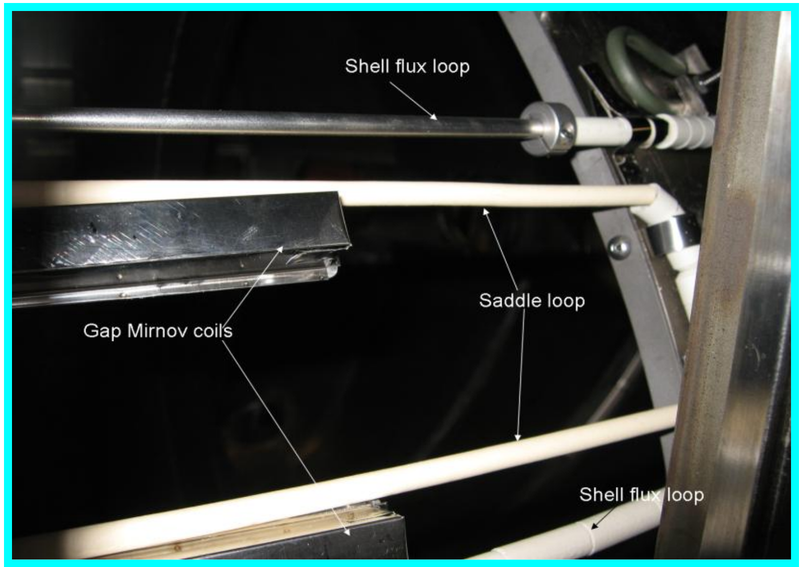
- 2-turn, center-tap grounded with separately grounded stainless steel housing for noise immunity
- SS housing covered with Steatite 'fishspine' and MgO to provide electrical isolation between diagnostic and shell and between shell quadrants
- Mounted directly to non-plasma facing side of shell to minimize distance to plasma and provide full poloidal coverage
- Signals valuable for code calibration, vertical null formation, constrained equilibrium reconstructions

Saddle loops – 4 total; outboard of vertical midplane

- Analogous materials and fabrication technique as shell flux loops
- Span toroidal gap, measure flux through gap from circulating shell currents
- Signals essential for determining magnitude and evolution of shell currents

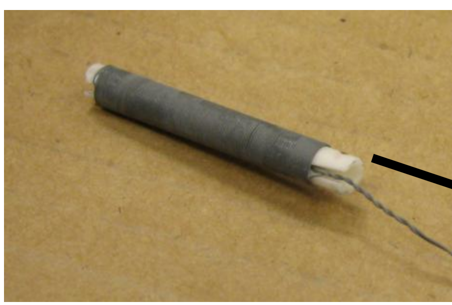






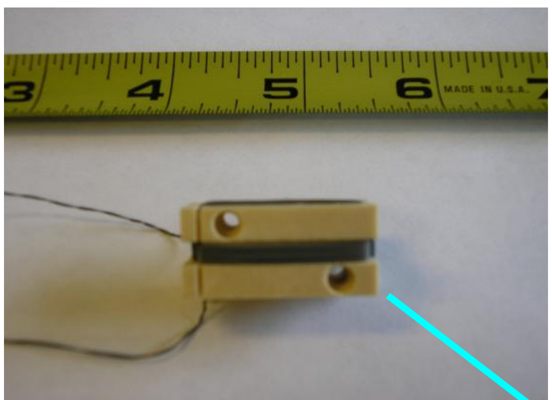
In- and ex-shell B-dot sensors

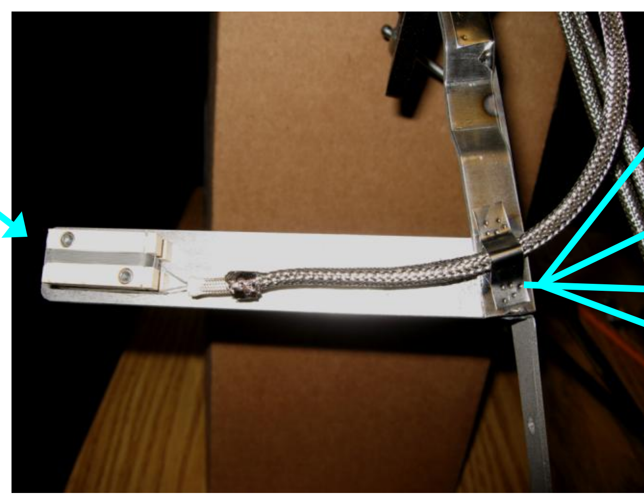
- 30 in-shell, 12 ex-shell; outboard coverage including poloidal gap at 3 toroidal locations
- Sensors mounted in SS housing to both plasma-facing side of shell and non-plasma-facing side of shell
- Signals provide measure of field extremely close to plasma; evidence of toroidal asymmetries
- Comparison between in and ex-shell sensors yields direct measurement of shell eddy currents

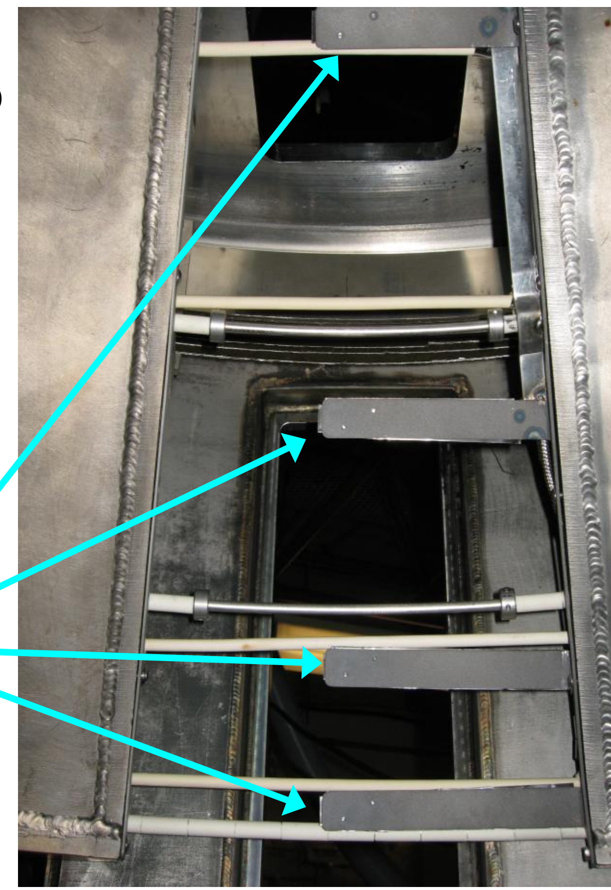


2-axis gap Mirnov coils – 9 probes upper, 9 lower

- Total of 36 probes mounted in toroidal gap; provide full poloidal coverage
- Mounting tabs plasma-sprayed with W; sensors covered by stainless steel protective caps, leads covered with fiberglass and stainless steel overbraid
- Signals provide dense measurement of poloidal and radial fields with minimal shell influence; yield measure of vertical field component and bulge of field into toroidal gap

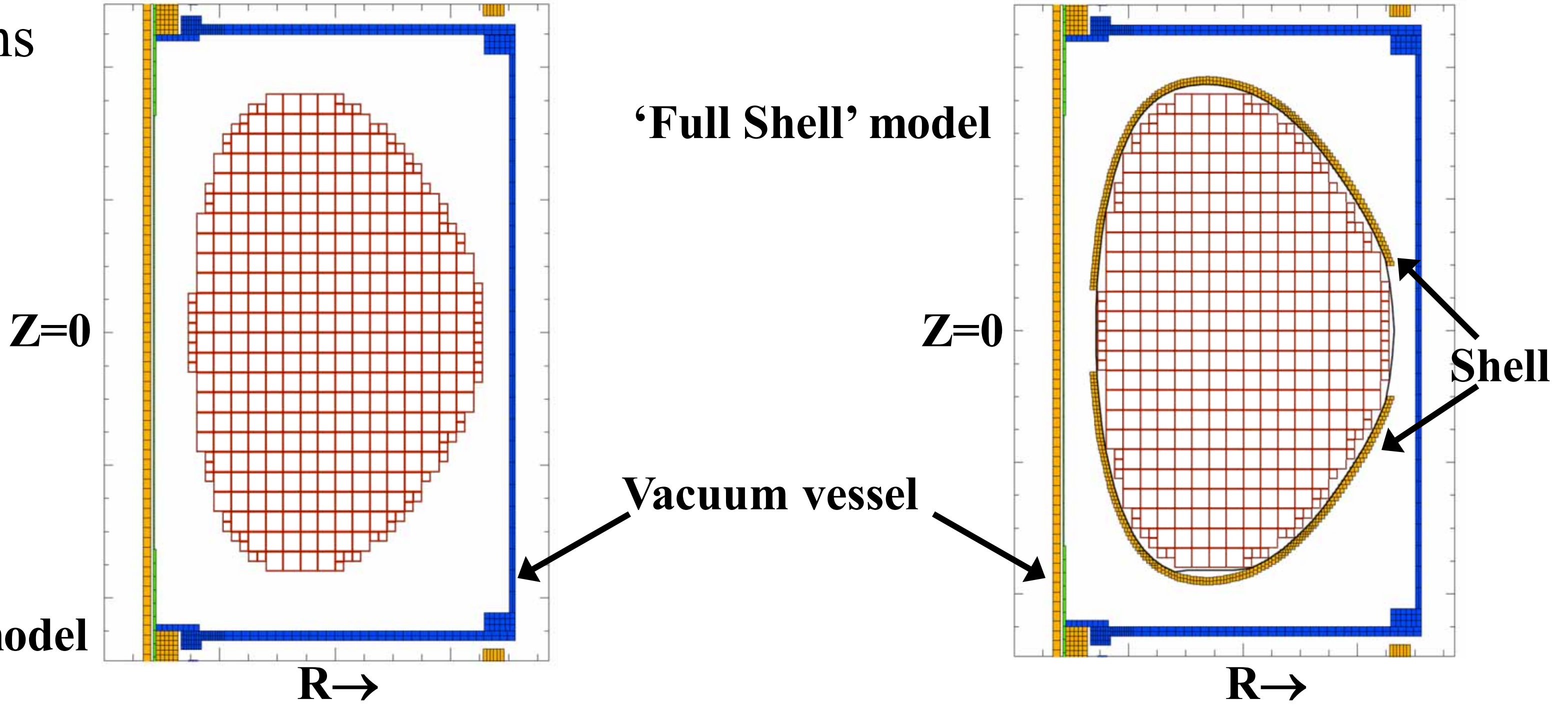




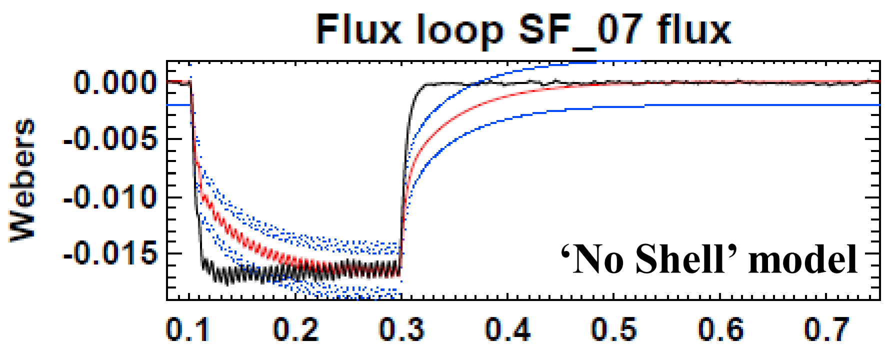


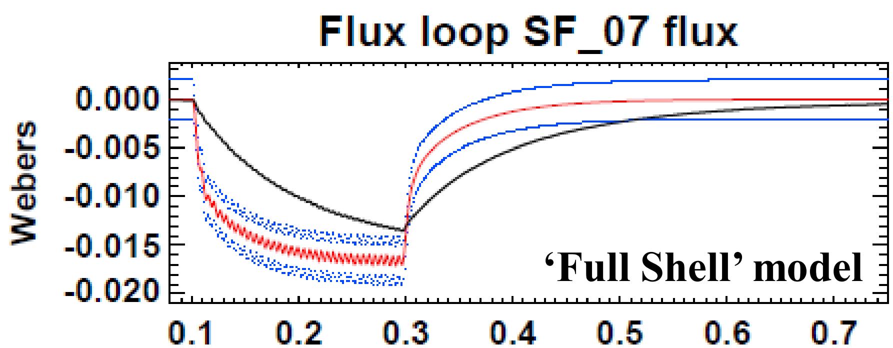
LTX LR circuit model with Data FITting capabilities

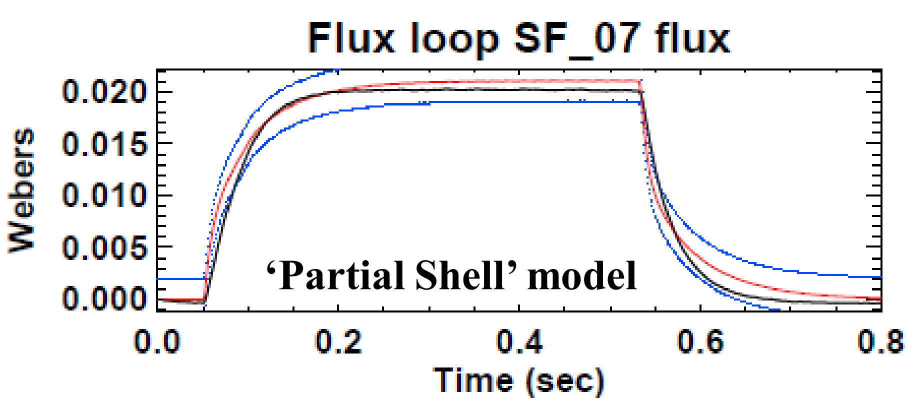
- Axisymmetric (2-D), non-filamentary code developed for NSTX (J. Menard) – now tailored for LTX
  - Solves circuit equations based on models of vacuum vessel, shell and plasma composed of individual conducting elements with assigned inductance and resistance values
- To reduce 3-D effects to a 2-D representation – inboard versus outboard shell elements' resistivity values adjusted to account for different current path lengths

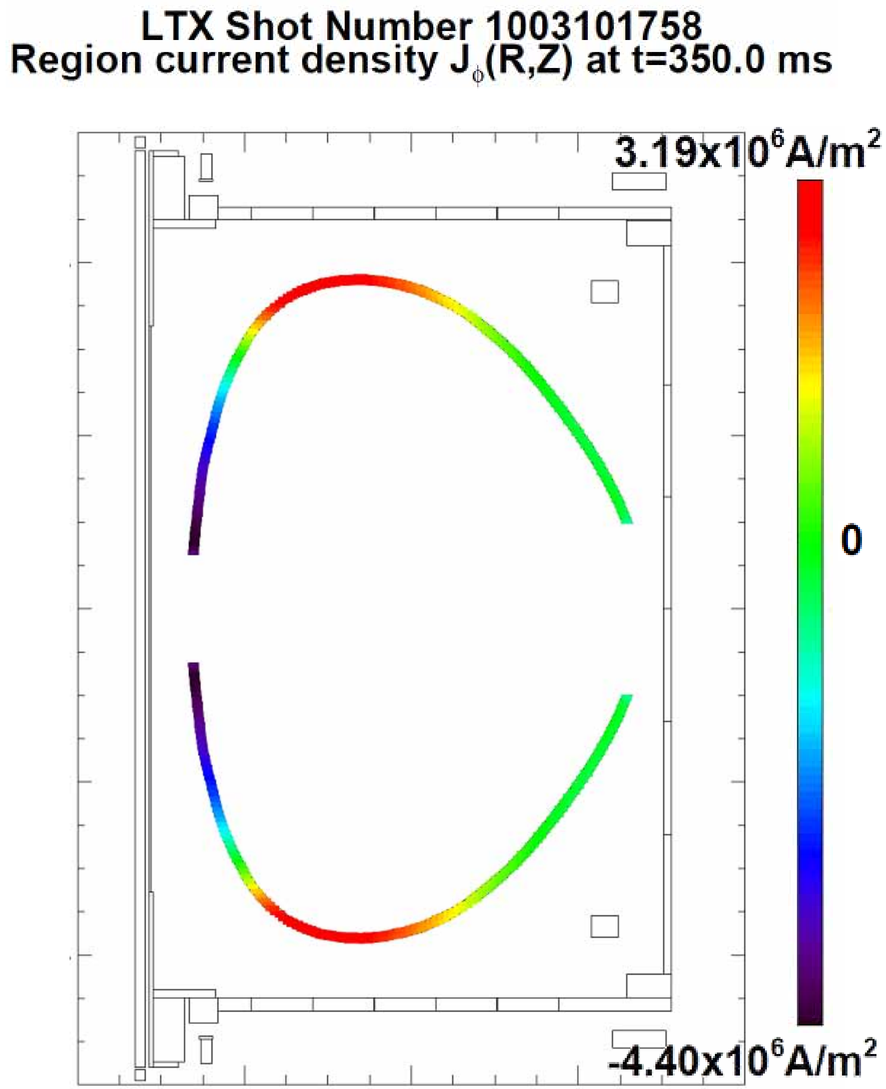


LTX LRDFIT



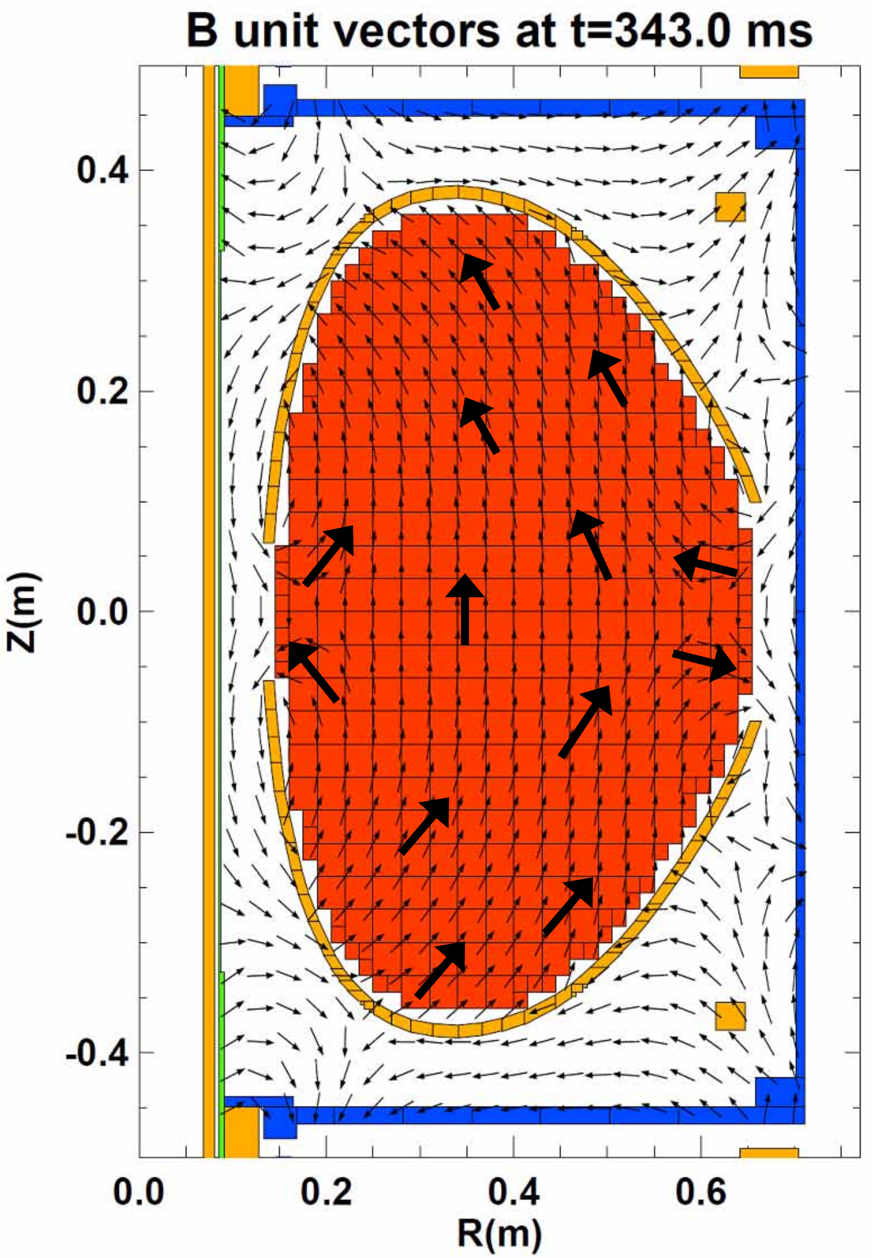




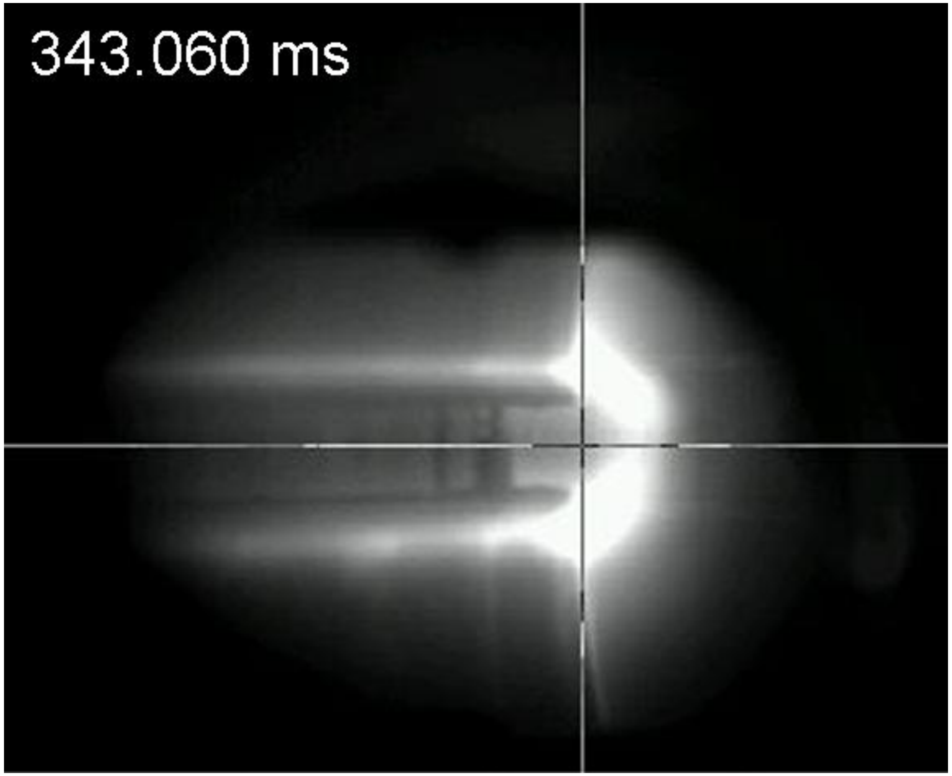


'Partial Shell' model

LTX LRDFIT validation, comparison with fast camera

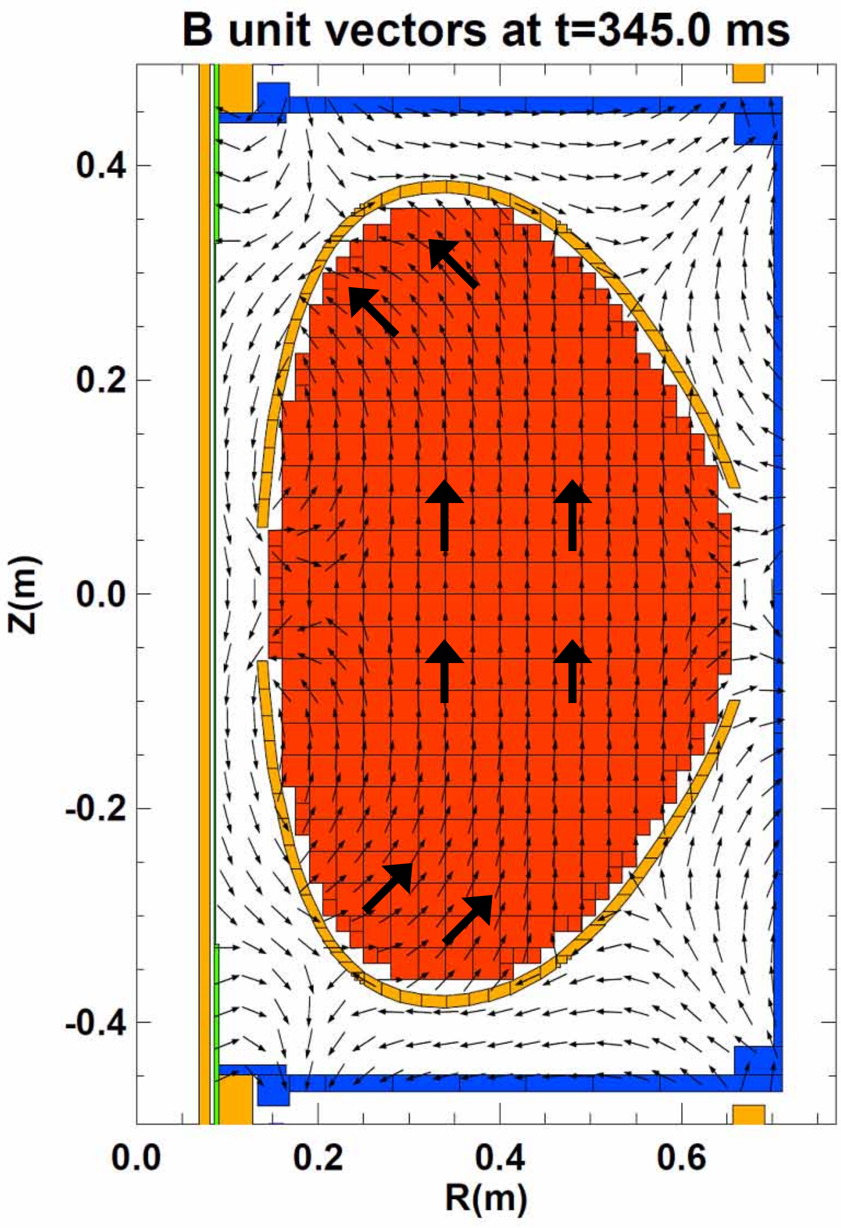


Visible fast camera frame



Discharge initiation

LTX LRDFIT field comparison at peak plasma current



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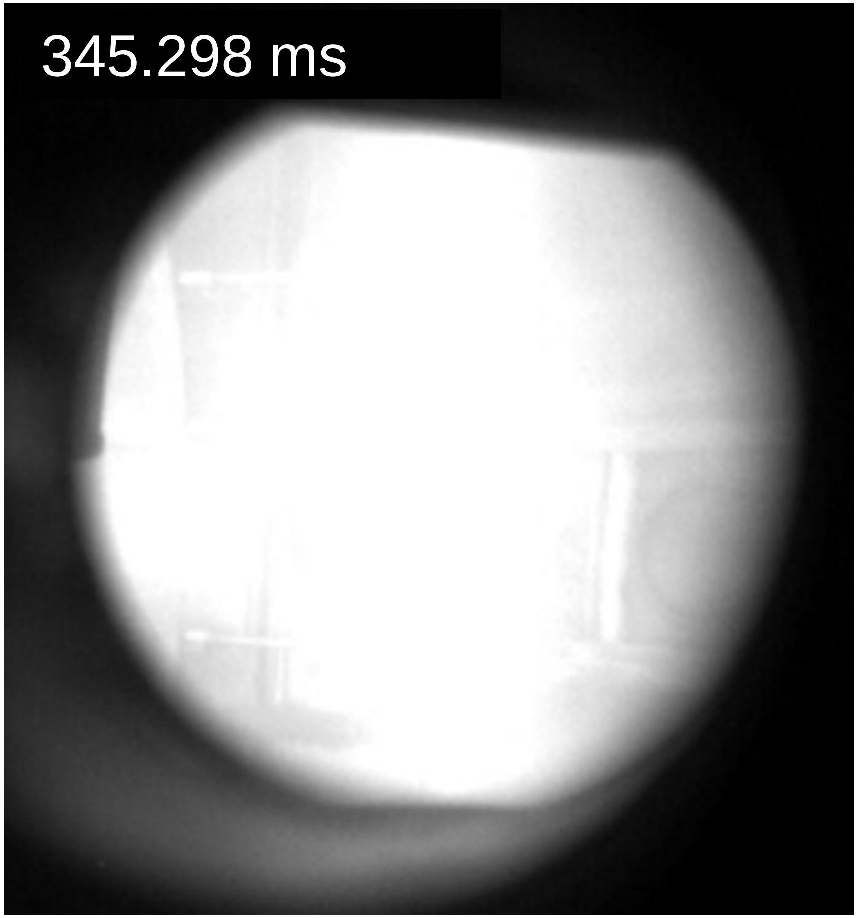
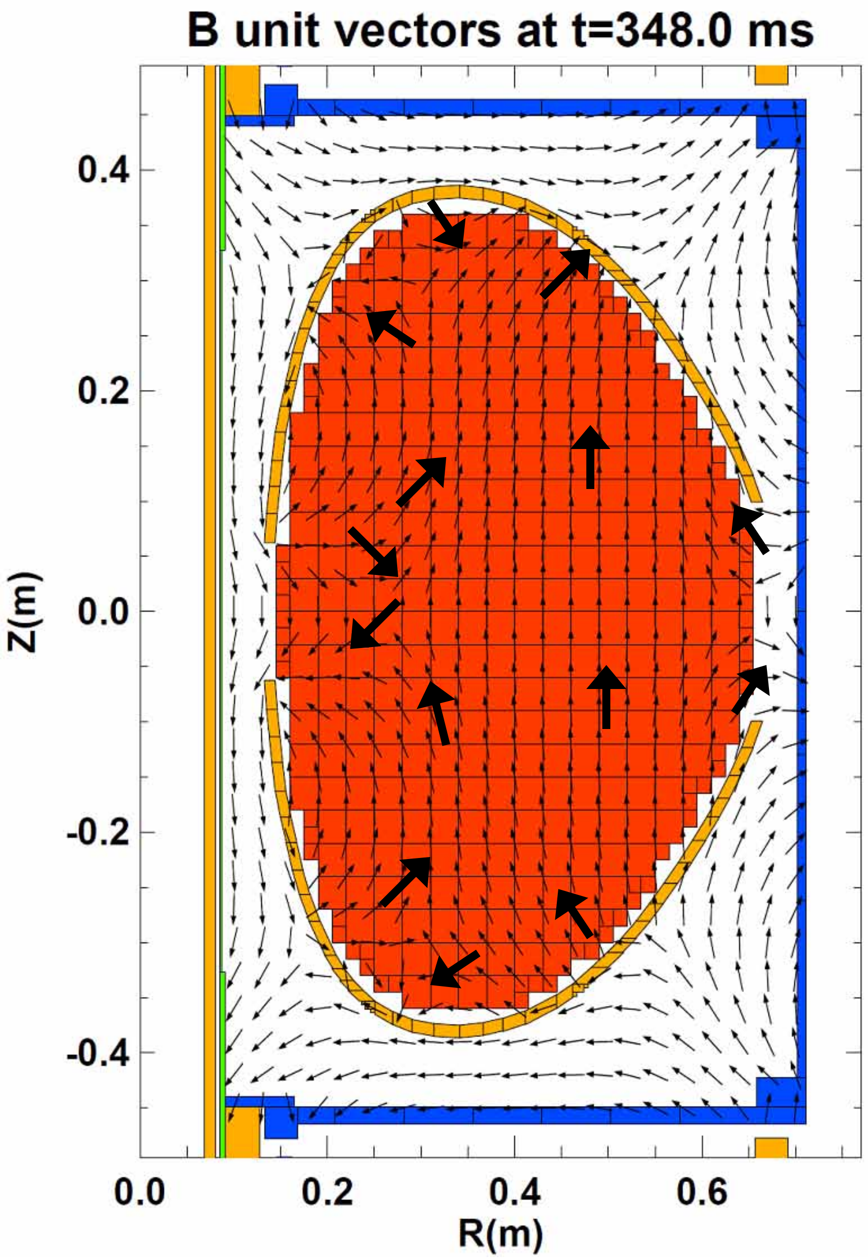


Discharge fully developed
Peak I_P

LTX LRDFIT field comparison at termination



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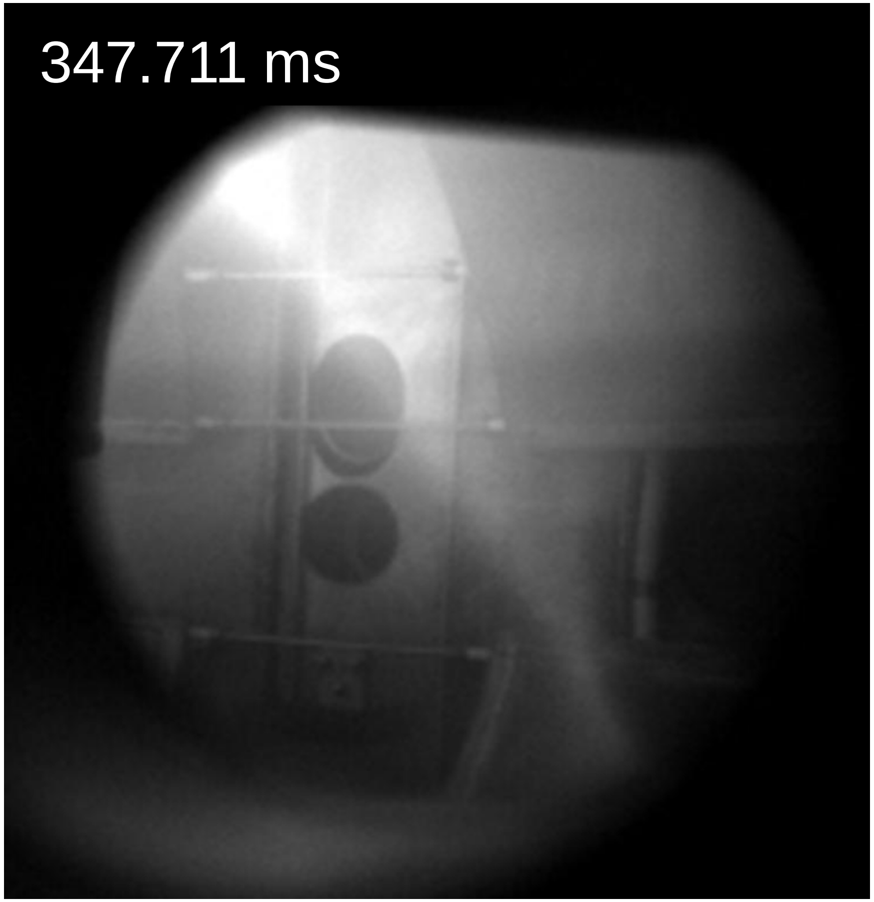
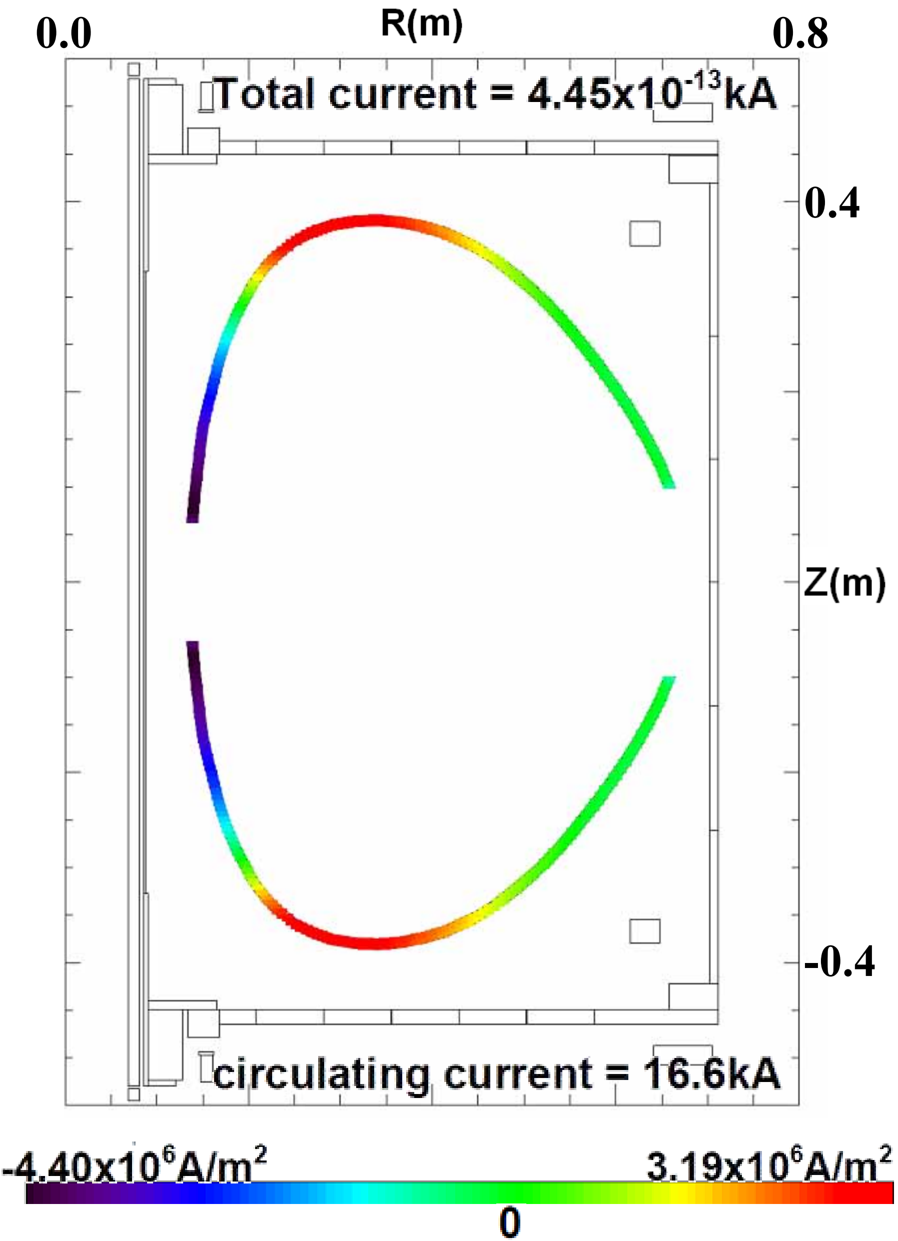
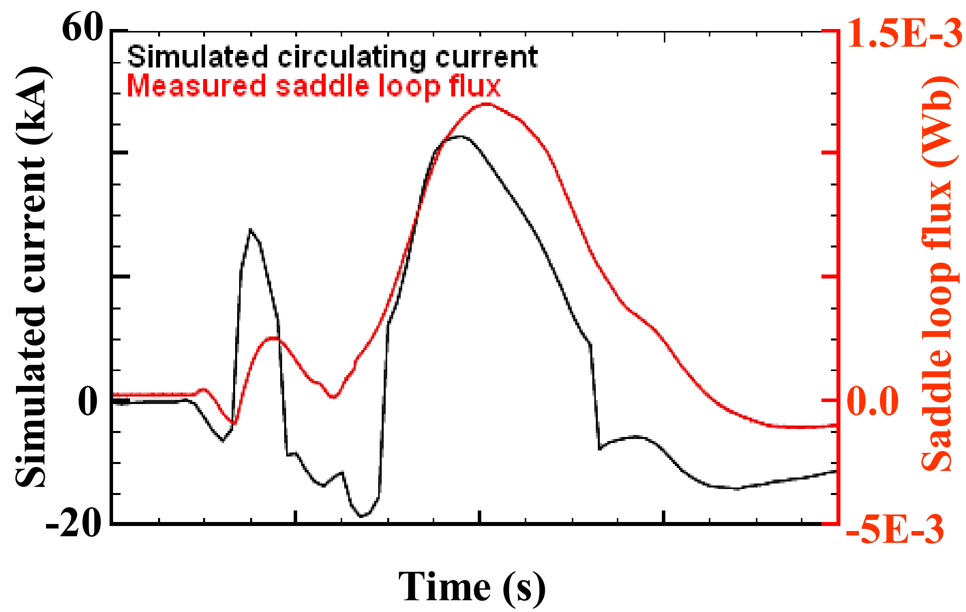
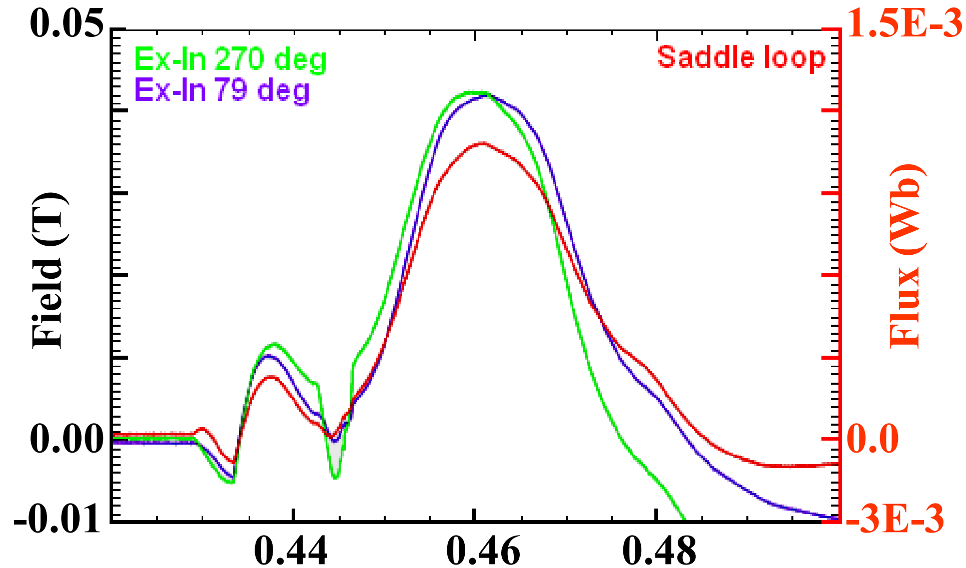


Discharge termination $I_P \rightarrow 0$

Inherently 2-D, LTX LRDFIT can simulate 3-D circulating shell currents

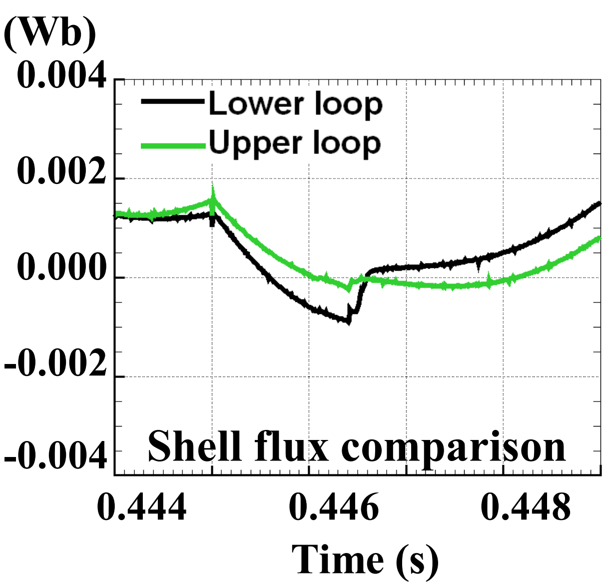


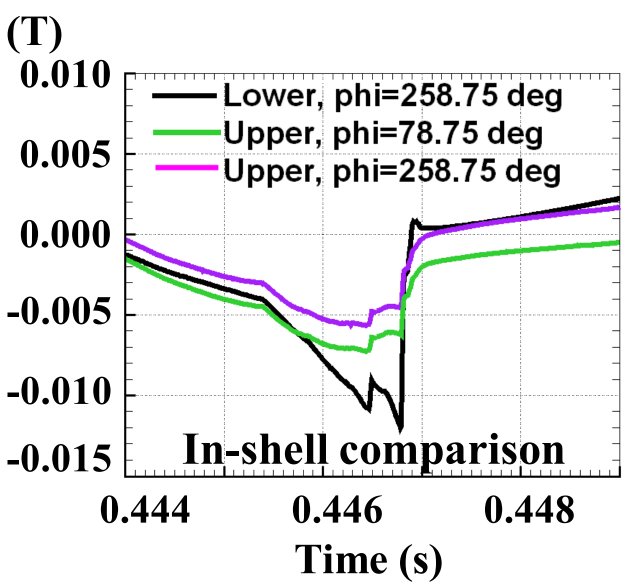


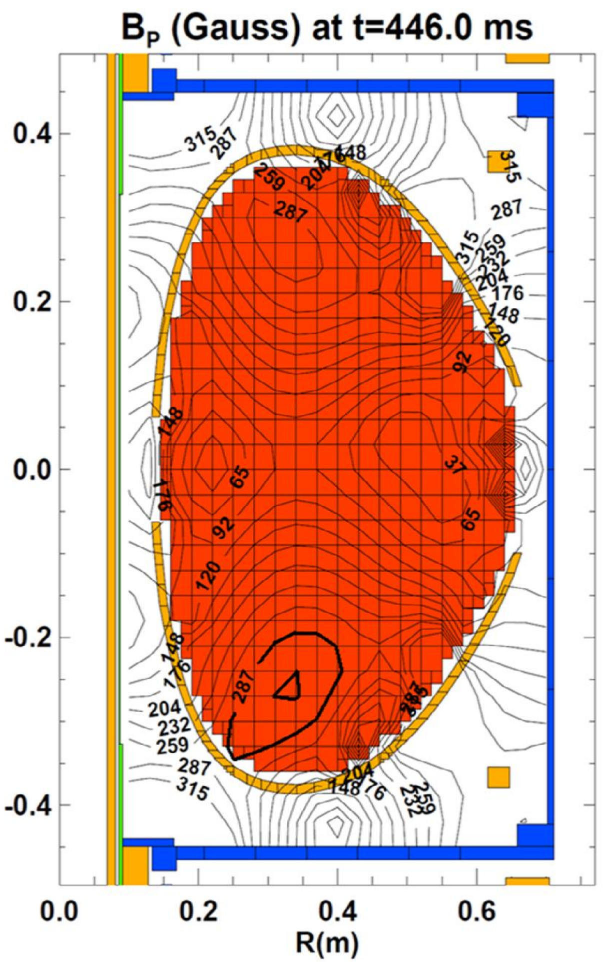


Shell currents act as additional set of PF coils

- Shell currents during plasma discharge ~20 kA
  - Provide field in opposite direction to main vertical field coils, elongates plasma, drives vertically unstable
- Up-down asymmetry observed on magnetic diagnostics signals
- Plasma reconstructions show solution high or low in plasma volume





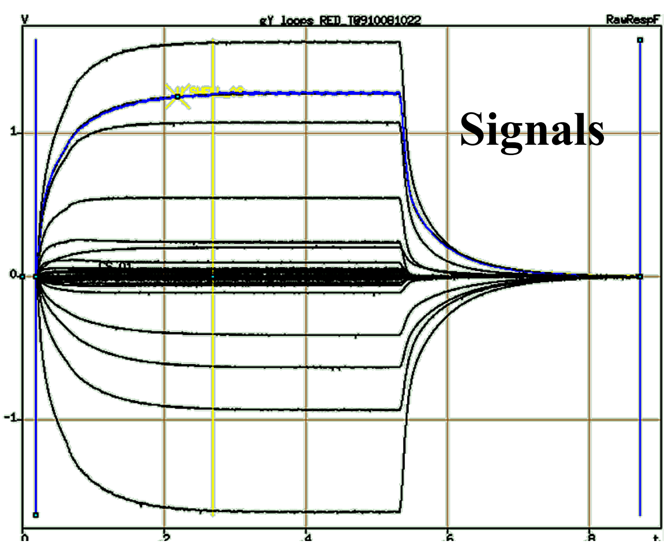


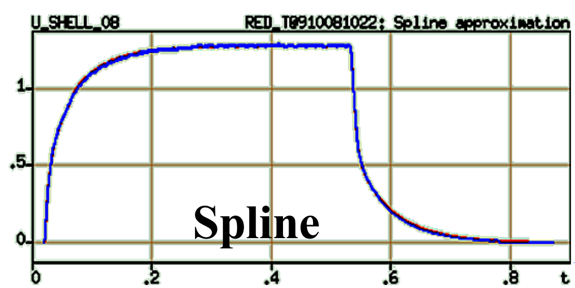
Next step: 3-D simulation of LTX double-walled conducting structure

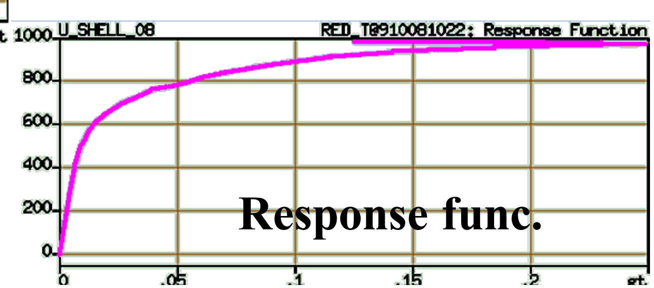
- Response function technique (L. Zakharov) coupled with three-dimensional electromagnetic model and circuit equations
  - Response functions – mathematical relationship between a **finite-size** sensor and an individual poloidal field coil through driving voltage applied to the field coil:

$$S(t) = B(t) + \int_{t_0}^{t} R(t-\tau)V'(\tau)d\tau$$

$$= B(t) + R(0)V(t) + \int_{0}^{t-t_0} R'(\tau)V_t(t-\tau)d\tau$$



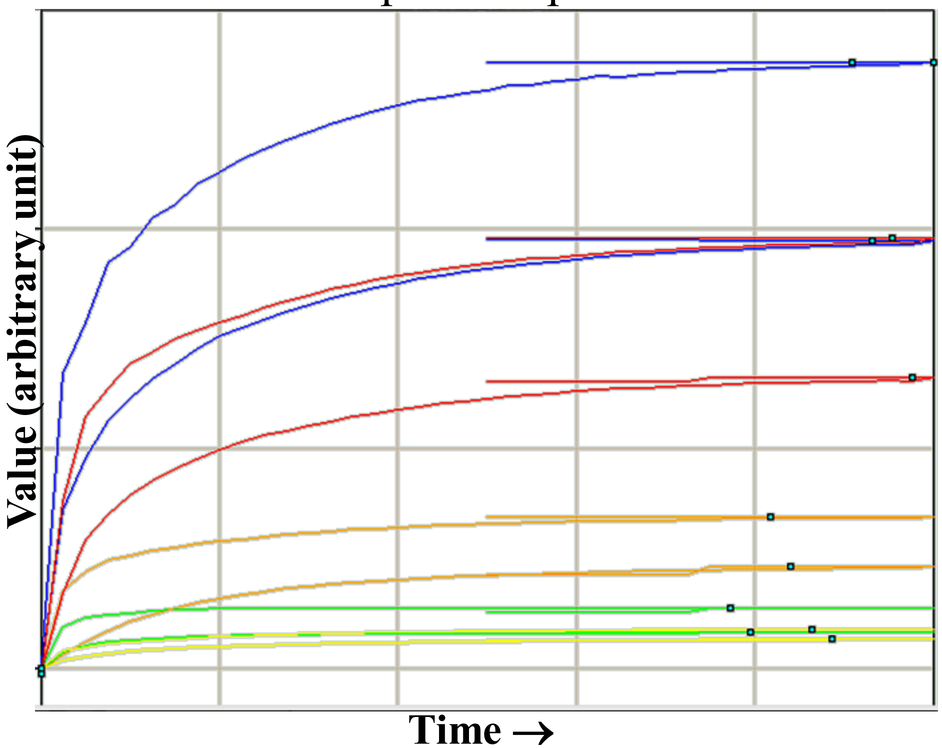




Response Function Technique

- Calibrate location of field coils and magnetic diagnostics by minimizing difference between theoretical saturation value and calculated asymptote from measured data response function

Shell flux loop #8 Response Functions

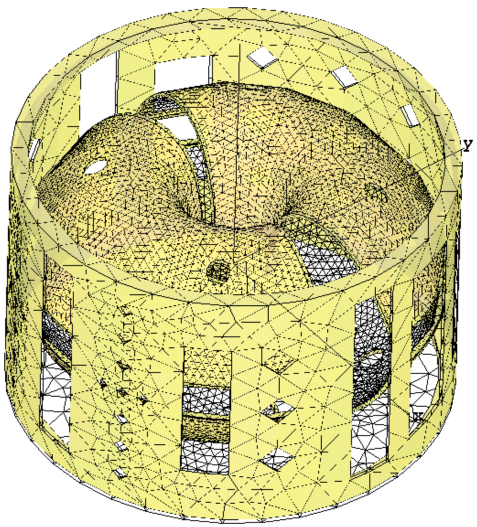


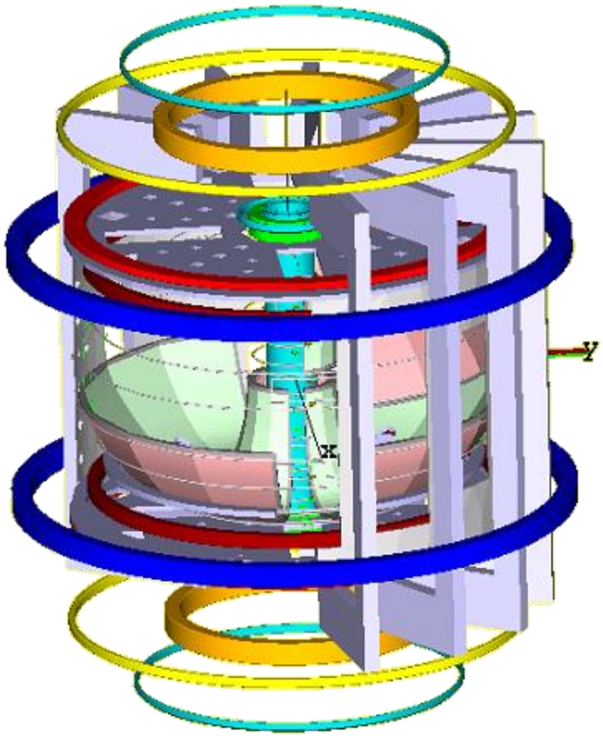
$$S(t)\big|_{t-t_0>T} = R(T)V(t-T) + \int_0^T R'(\tau)V_t(t-\tau)\,d\tau$$

- Matrix of response functions allows:
  - Non-plasma contribution to sensor signals to be removed
  - ‘Reverse’ solving for discharge design

Coupled with response functions, simulate eddy currents in shell and vessel

- Triangular mesh calculated for shell quadrants and vacuum vessel (>18,000 elements per shell quadrant, >8,000 elements for vacuum vessel)





- Derived (L. Zakharov): analytical representation of field due to the surface current on each triangle, **no** surface singularities AND linked circuit equations –

$$\sum_{i\subset T_{ia}}\left(0.1\sum_{j=0}^{j<N_T}\left\langle \phi_{Eij}\right\rangle_i (\nabla\dot{I}\times\mathbf{n})_j+\left\langle \dot{\mathbf{A}}^{ext}\right\rangle_i+\frac{(I_a\mathbf{r}_{cb}+I_b\mathbf{r}_{ac}+I_c\mathbf{r}_{ba})_i}{(2Sd\sigma)_i}\right)\cdot\mathbf{r}_{cb}^{i}=0$$

Conclusions

- Extensive need to diagnose eddy currents and 3-D effects, particularly as more experiments investigate alternative first wall and blanket concepts
- LTX magnetic diagnostics system permits quantification of eddy currents, provides path forward for mitigating operational issues introduced
- LTX LRDFIT has been tailored to include 3-D effects, essential for start-up design and discharge development
- Further work: continued development of a full, 3-D electromagnetic code
- **Double-walled conducting structure (shell and vacuum vessel) of LTX provides opportunity to explore liquid lithium PFCs and to develop magnetic diagnostics, 2-D, and 3-D codes of general applicability for: quantifying eddy currents and their effects on plasma behavior, and optimizing these effects**

Acknowledgements

I would like to sincerely thank my thesis advisors, Robert Kaita and Richard Majeski, for the opportunity to be part of the LTX team and for all of their patience, time, and guidance.

I would like to thank the LTX team as well for their support and help throughout my thesis work.

I would also like to thank the terrific people at Krell for all of their help and for the opportunity to be part of the SSGF program.

LTX

SSGF

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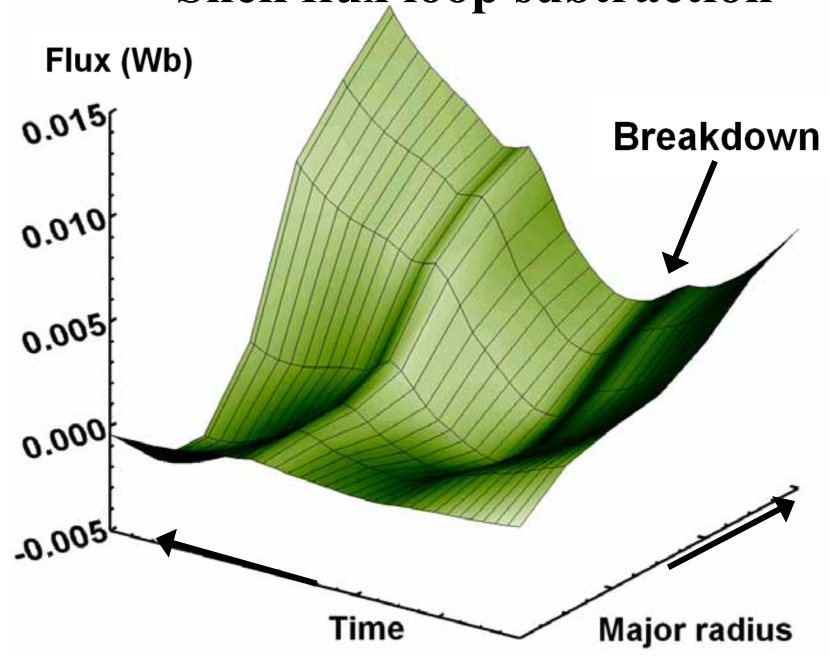
Magnetic diagnostics crucial for discharge development

- Basic Ohmically-driven tokamak start-up theory:
  - Provide Ohmic flux to drive plasma
  - Form vertical/poloidal field null near peak in Ohmic flux swing
  - Provide vertical field for confinement after initial electron avalanche and breakdown
  - Develop vertical fields for discharge control and shaping

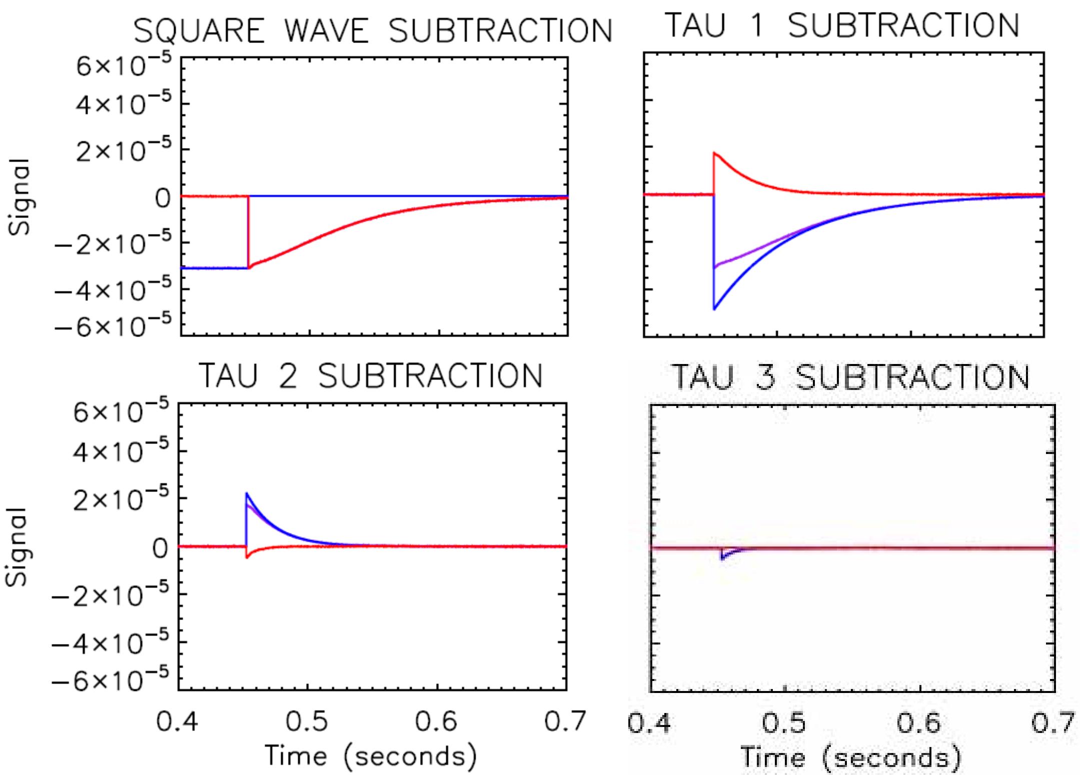
Shell flux loop subtraction

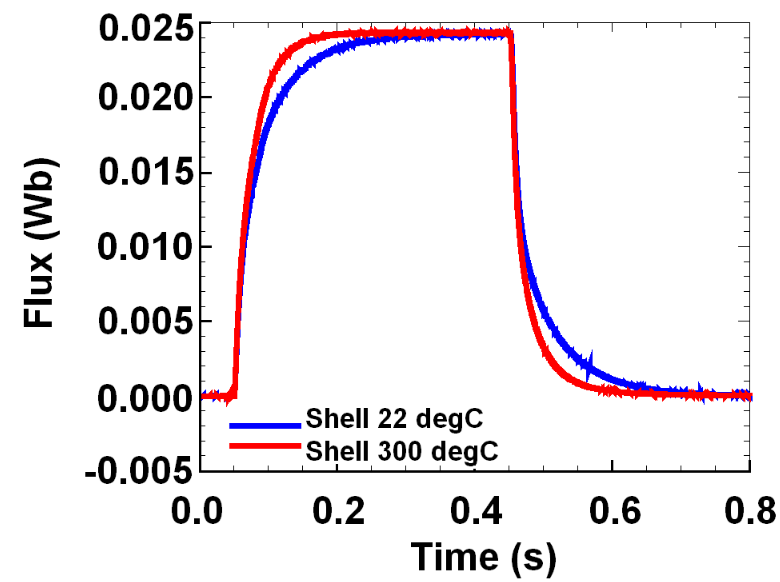


- Challenges in double-walled tokamak:
  - Minimizing required Ohmic flux
  - Quantifying eddy currents in conductive structures close to plasma

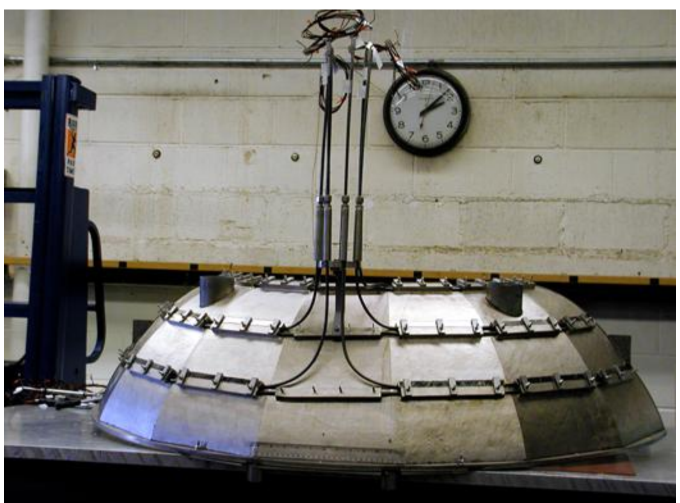
Quantifying eddy currents in the shell

- Calculation of decay times
  - Collect library of calibration shots: individual poloidal field coil pulses and pulses with operational pairs of coils, long-pulse (>300 ms) wherever possible
  - Expand library with poloidal field coil-only pulses during shell heating tests





Supplemental Slides



Supplemental Slides

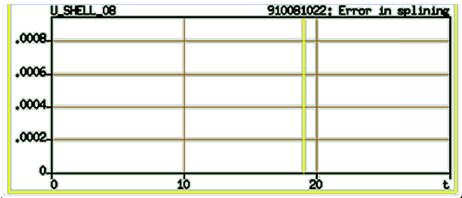
- Mathematically linearly superimpose poloidal fields to minimize vertical field near loop voltage peak

$$\sum_{i=1}^{6} A_i I(t - t_i) \approx 0$$

- Compare with LTX LRDFIT field contour simulations

Future Work – Interpretation of Reconstructions

- Use reconstructions to study energy confinement time
  - Examine changes in current profile with reduced recycling
  - Examine scaling of confinement time with various plasma parameters such as current, field, density, and temperature
- Compare results with ASTRA-ESC simulations
  - Simulations utilize the Reference Transport Model (RTM), which reflects elimination of anomalous electron transport in LiWall regime, and fits well with CDX-U data
  - RTM is sensitive to diffusion coefficients, not thermoconduction since only minimized temperature gradient is present – electron and ion transport become linked: $\chi_e = \chi_i = D_{i,e} = \chi_i^{neoclassical}$
  - Compare simulations with LTX data and reconstructions
  - If similar correspondence is observed, may permit first principles transport model of LTX


U_SHELL_08
910081022: Error in splining
.0008
.0006
.0004
.0002
0
0
10
20
t


U_SHELL_08
910081022: Error in reconstruction
.006
.004
.002
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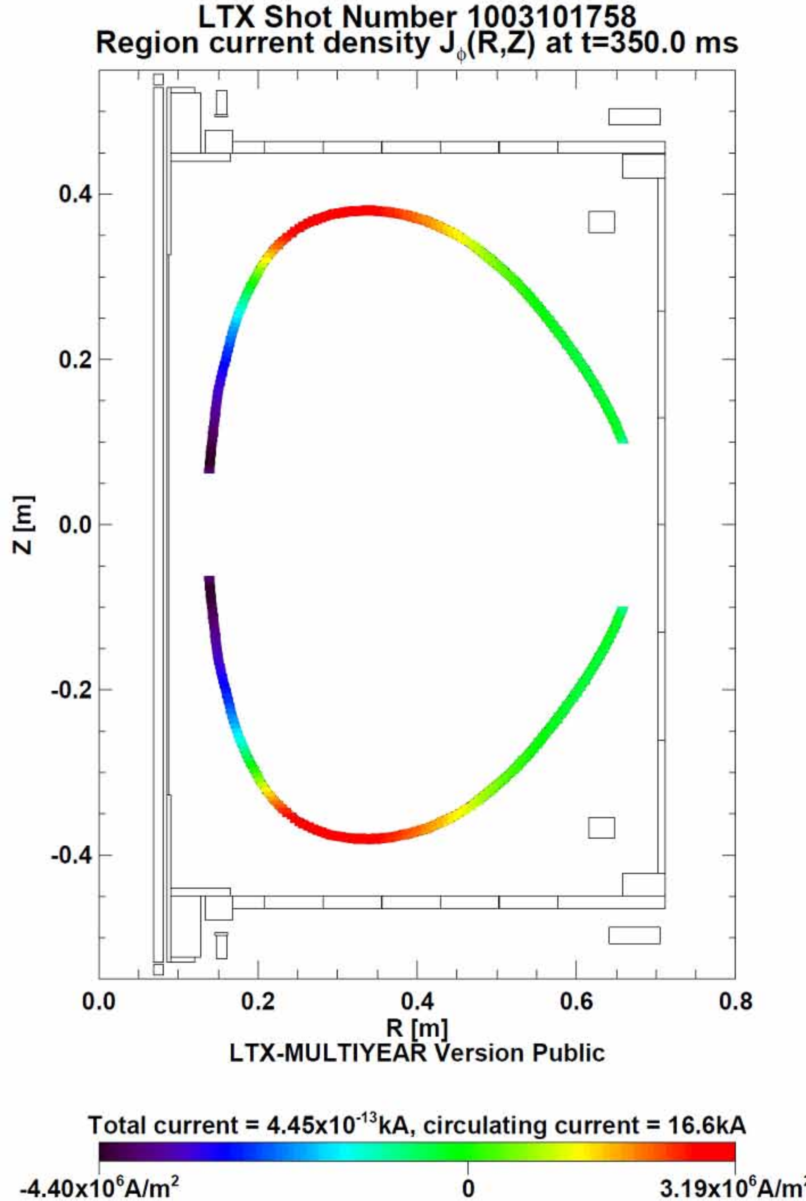
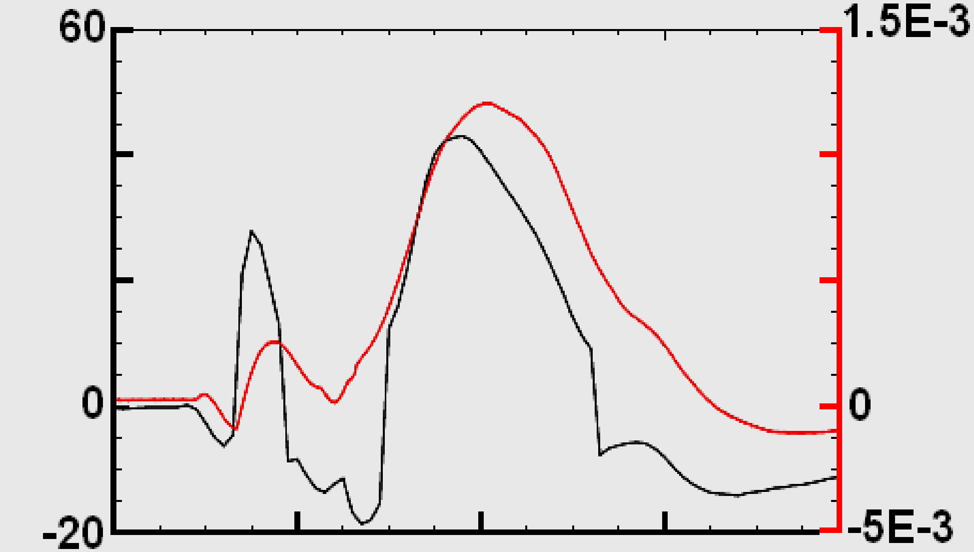
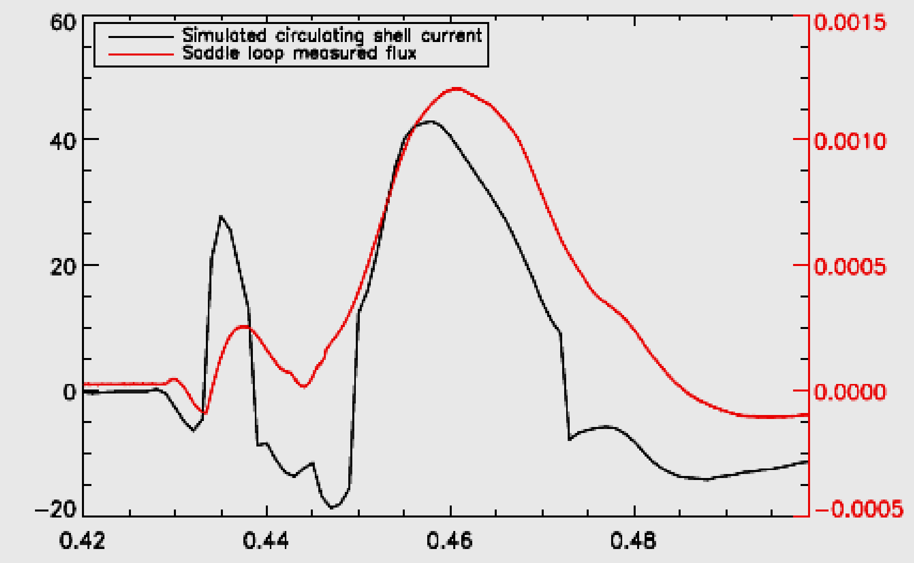
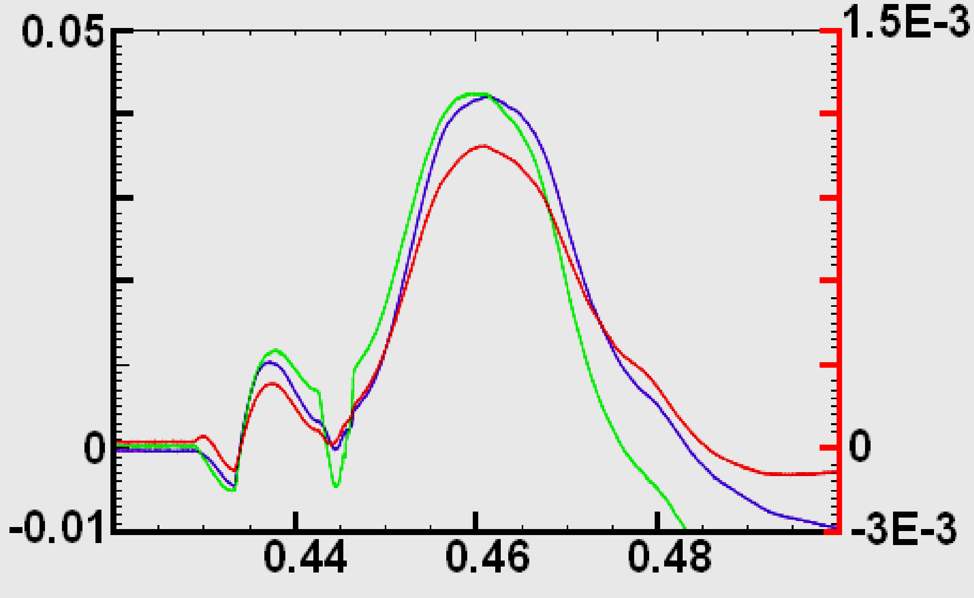
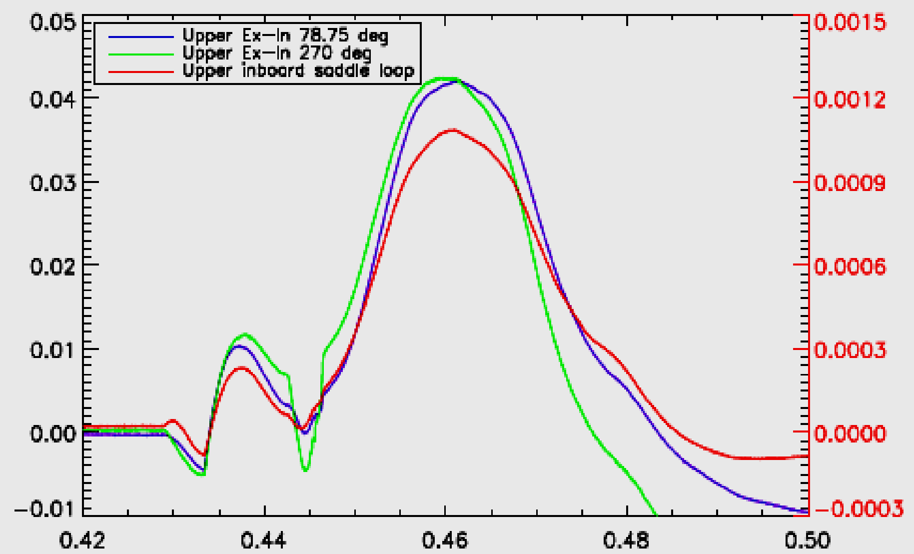

LTX Shot Number 1003101758
Region current density $J_\phi(R,Z)$ at t=350.0 ms
Z [m]
0.4
0.2
0.0
-0.2
-0.4
0.0
0.2
0.4
0.6
0.8
R [m]
LTX-MULTIYEAR Version Public
Total current = 4.45×10^{-13}kA, circulating current = 16.6kA
-4.40×10^{6}A/m^2
0
3.19×10^{6}A/m^2


60
0
-20
1.5E-3
0
-5E-3


60
40
20
0
−20
0.0015
0.0010
0.0005
0.0000
−0.0005
0.42
0.44
0.46
0.48
Simulated circulating shell current
Saddle loop measured flux


0.05
0
-0.01
1.5E-3
0
-3E-3
0.44
0.46
0.48


0.05
0.04
0.03
0.02
0.01
0.00
−0.01
0.0015
0.0012
0.0009
0.0006
0.0003
0.0000
−0.0003
0.42
0.44
0.46
0.48
0.50
Upper Ex-In 78.75 deg
Upper Ex-In 270 deg
Upper inboard saddle loop