Response of Thermo-electrically Driven Scrape-Off-Layer Current (SOLC) during ELMs to Discharge Manipulation in NSTX Tokamak

H. Takahashi, E. Fredrickson, S. Gerhardt, M. Jaworski, R. Kaita, J. Kallman, D. Mansfield, and S. Zweben, PPPL
S. Sabbagh, Columbia U.,
R. Maingi, ORNL
I. Joseph, LLNL

The 52ND Annual Meeting of Division of Plasma Physics
American Physical Society
Chicago, IL
November 8 - 12, 2010
Paper BP9.00056

Related Papers:
NF44(2004)1075
EPS(2005)4.018
PRL100(2008)205001

ABSTRACT

Response of Thermo-electrically Driven Scrape-Off-Layer Current (SOLC) during ELMs to Discharge Manipulation in NSTX Tokamak,* H. Takahashi, E. Fredrickson, S. Gerhardt, M. Jaworski, R. Kaita, J. Kallman, D. Mansfield, S. Zweben, *PPPL,* S. Sabbagh, *Columbia U.,* R. Maingi, *ORNL,* I. Joseph, *LLNL* – The halo current diagnostic in NSTX shows that SOLC abruptly rises to robust amplitude during ELMs out of near-noise-level pre-ELM background with dynamic range up to 10^2 in far SOL, while undergoing temporal and spatial polarity reversals. An examination of response of SOLC to manipulation of the discharge may reveal possible connections of SOLC to ELM triggering and suppressing mechanisms. In preliminary studies to date, limited only to far SOL (R-R(strike pt) > ~ 40 cm), application of n=3 Resonant Magnetic Perturbations resulted in no readily discernible n=3-like structure in SOLC, and ramping up or down of the plasma current made no correlated changes in SOLC. Effect of lithium injection and biasing electrodes imbedded in divertor tiles to drive current will also be studied. Extension of these investigations into near SOL is planned.

*Supported by the US DOE under DE-AC02-09CH11466, DE-AC02-09CH11466, DE-AC05-00OR22725, and DE-AC52-07NA27344.

Highlights

Progress toward
Unconventional Model for ELM Triggering and Evolution

Long Term Goals

Establish a physical model for ELM process based on thermo-electrically-driven Scrape-Off-Layer Current (SOLC) that rises abruptly and rapidly due to breakdown of sheath at the plasma divertor plate interface.

Immediate Goals

Determine temporal evolution and spatial structures of SOLC for better understanding of how conditions prone to robustly cyclical sheath breakdown come about, and for evaluation of impact of SOLC on MHD stability and stochastic field generation at plasma edge.

Use Discharge Manipulation Tools

Changing SOL conditions in a controlled manner allows SOLC examination from varied viewpoints, and may help elucidate SOLC's origin, structure, and effect.

a) Sweep Strike Point – *examine near and far SOLC zones*

b) Apply 3D Field – *help elucidate SOLC's origin*

c) Ramp Plasma Current – *change plasma edge profiles*

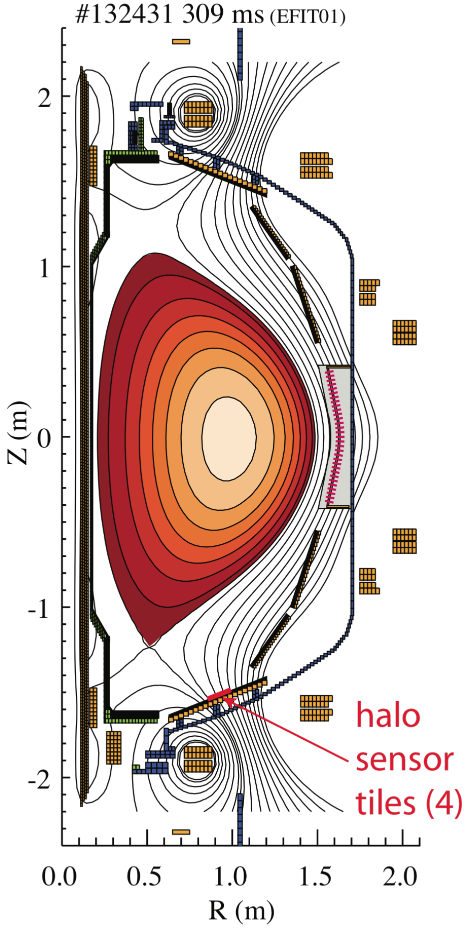
d) Bias Electrodes (BEaP) – *prospect for exciting ELMs*

e) Lithium/No Lithium – *vary SOL and tile surface conditions*

Swept strike point proved productive and led to better understanding of SOLC spatial structure. No obvious consequences have been identified *so far* from (b) through (d). No opportunity materialized to date to examine discharges without lithium injection.

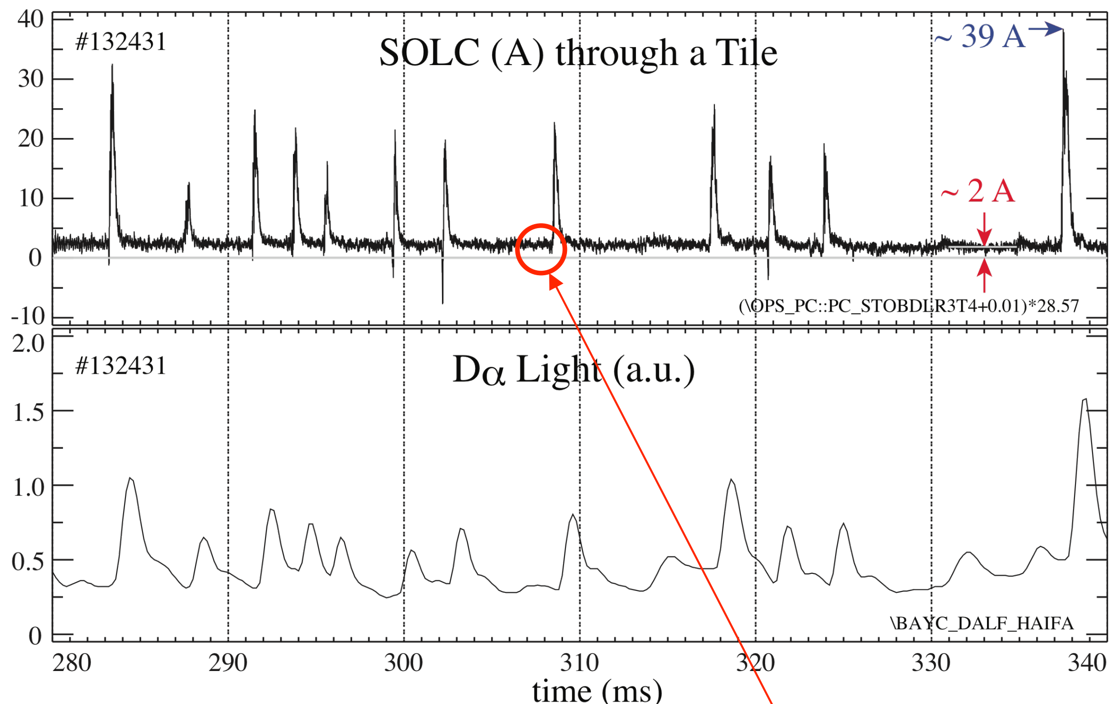
BACKGROUND

SOLC Begins to Rise Abruptly Just *before* ELM Onset



Data taken during pre-lithium period in 2009

NSTX



Halo current diagnostic in 2009 had 4 sensor tiles (out of 96 in a ring), each 6 cm (3.75 deg) wide toroidally and 12 cm long poloidally.

SOLC and D_α signals recorded on separate digitizers (with possible consequent error in relative timing).

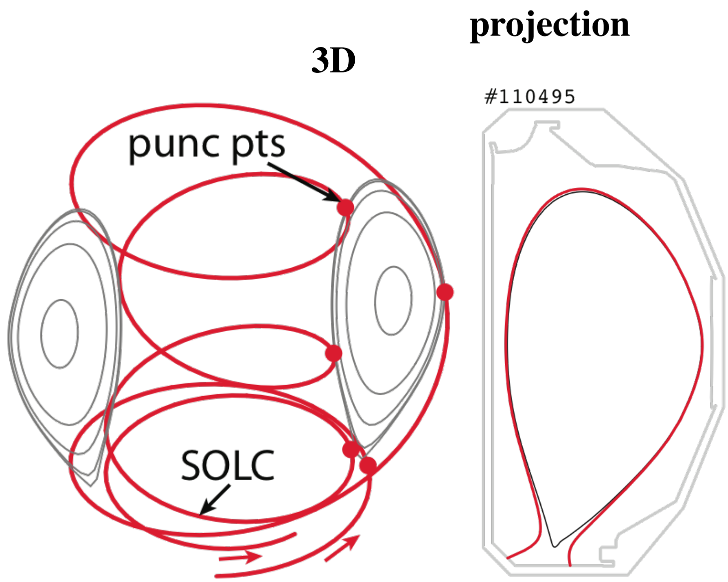
Why abrupt rise?

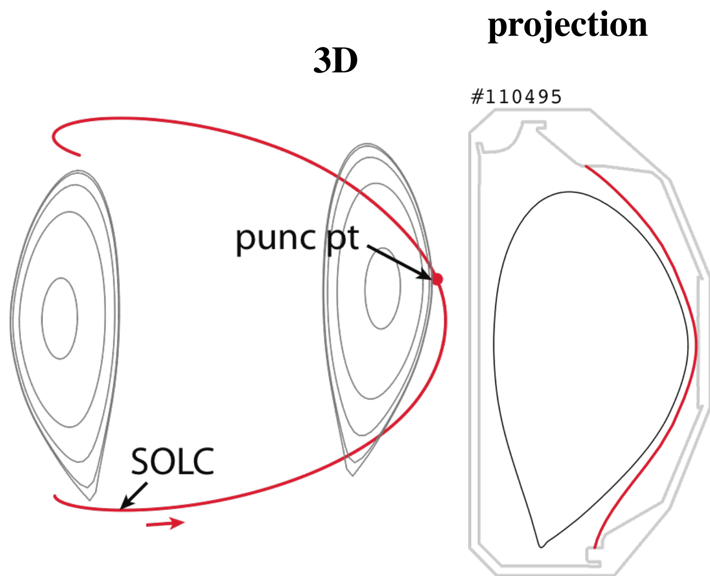
Rise begins ~ 100 μs *before* thermal collapse (based on DIII-D data - see EPS '05)

SOLC qualifies as a *candidate* mechanism for ELM triggering because it occurs before thermal collapse.

Two Types of SOLC Path

Circumnavigating **Path ("C-Path")** *Interrupted* **Path ("I-Path")**





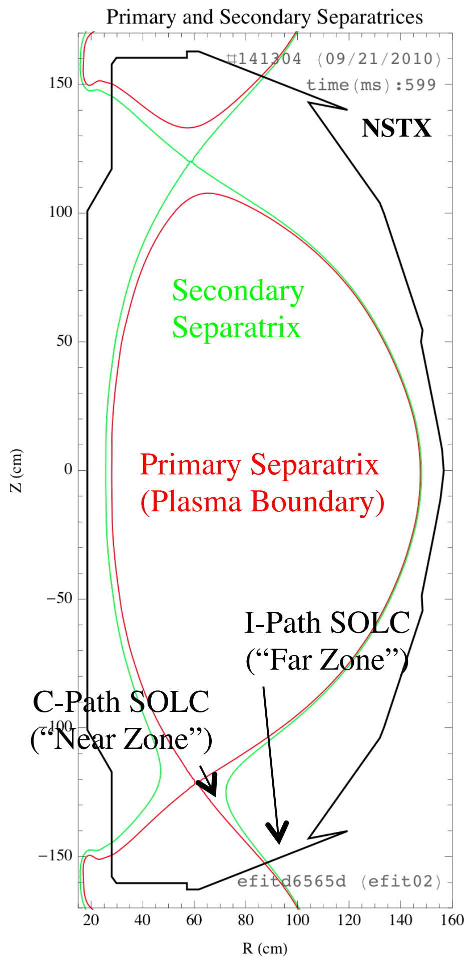
Line-current Representation of SOLC

These DIII-D pictures will be replaced by NSTX pictures (hopefully by the meeting).

SOLC completes its circuit through Tokamak Structure

Secondary Separatrix Demarcates SOLC Zones

Near and Far SOLC Zones



A secondary separatrix magnetically demarcates SOL into "Near SOLC Zone" and "Far SOLC Zone" wherein the two topologically different C-Path and I-Path SOLCs flow respectively.

Thermo-electrically driven SOLC may then exhibit distinct characteristics in the two zones because of likely different thermal environment in bottom-inboard and top-outboard divertors, with bottom-outboard divertor being shared by both (in LSN discharges).

A SOLC sensor, which is radially broad, may be placed to either straddle both near and far SOLC zones, or lie entirely within far SOLC zone, depending on the strike point location (*).

As will be seen, a straddling sensor registers a substantial signal in inter-ELM periods as well as during ELMs while a sensor entirely in the far zone records a strong signal only during ELMs – an observation helpful in re-constructing a SOLC spatial structure from measurement.

(*) EFIT02 analysis yields for some NSTX discharges an outboard strike point that is farther out in major radius than points suggested from interpretations of SOLC (see panel 14) and other divertor diagnostics signals. The discrepancy may arise from uncertainty in equilibrium reconstruction or incorrect interpretations. But it could also be due to effect of SOLC itself on equilibrium, in particular, strike point. EFIT02 prediction will be called "EFIT strike point."

Halo Current Diagnostic (2010)

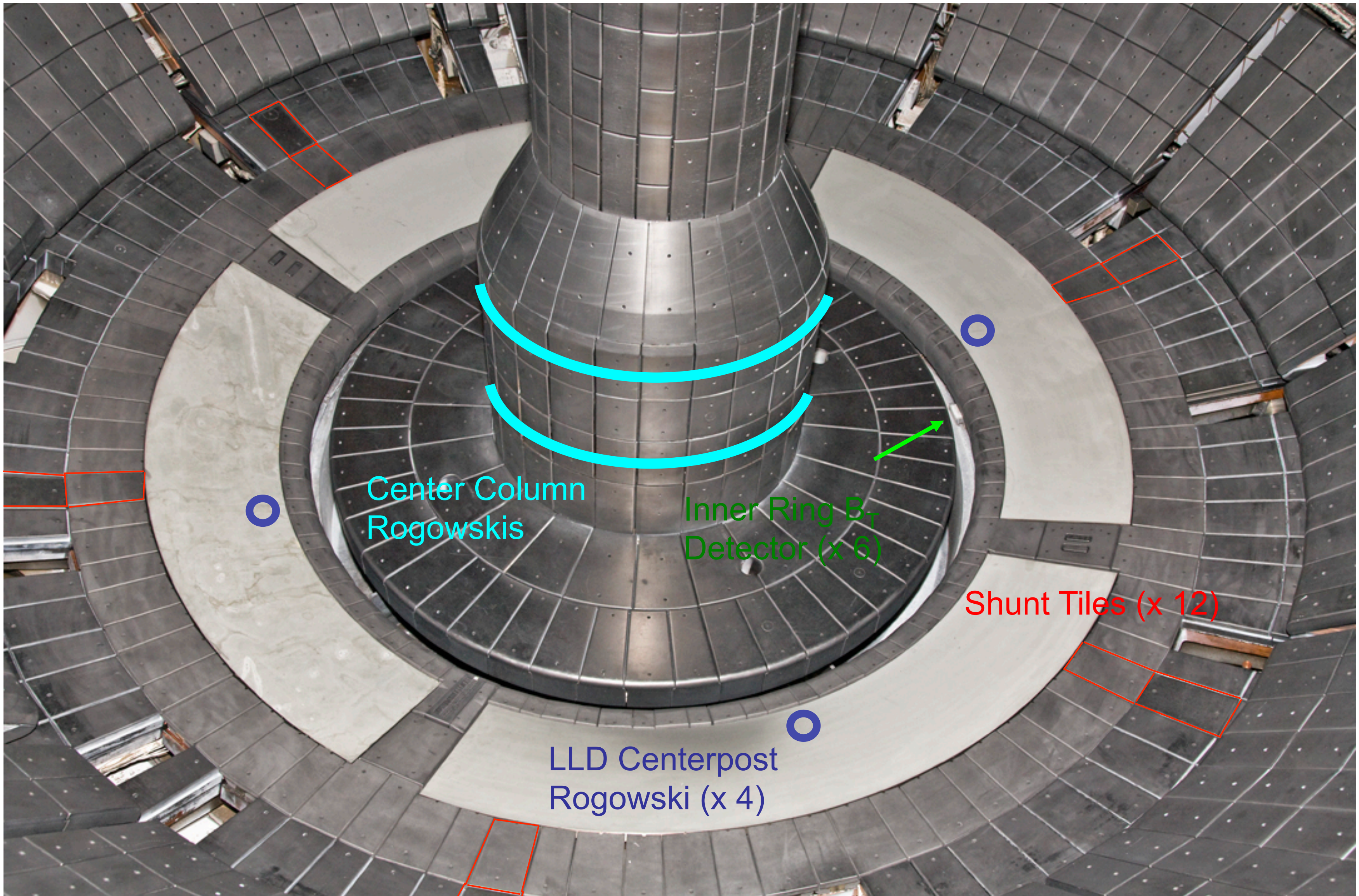
The halo current diagnostic (*) measures current through SOL and into a divertor tile instrumented with a resistive shunt (~ 3 mΩ).

The diagnostic has two toroidal arrays of six equidistantly placed sensor tiles, one array each in "Ring-3" and "Ring-4" (each ring with a total of 96 tiles). Sensors in the two rings are radially aligned with each other (see next panel). A sensor tile is 3.75 deg (~ 6 cm) wide toroidally and ~ 11 cm long poloidally. Current flowing out of a tile into the SOL plasma is defined as positive.

Each halo current signal, here interchangeably called a tile-current or SOLC signal, is usually recorded simultaneously on a slow digitizer (5 kHz) and on a fast digitizer (500 kHz).

(*) Stefan Gerhardt, "Halo Current Diagnostics in 2010"

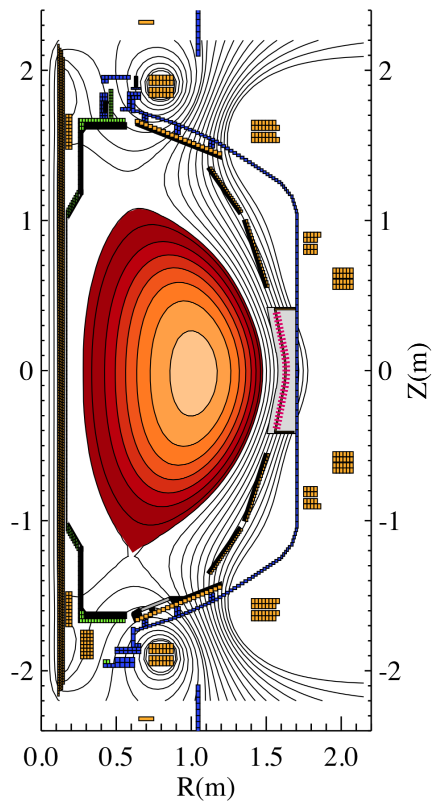
12 Tile Current Sensors (Indicated by Red Rectangles)

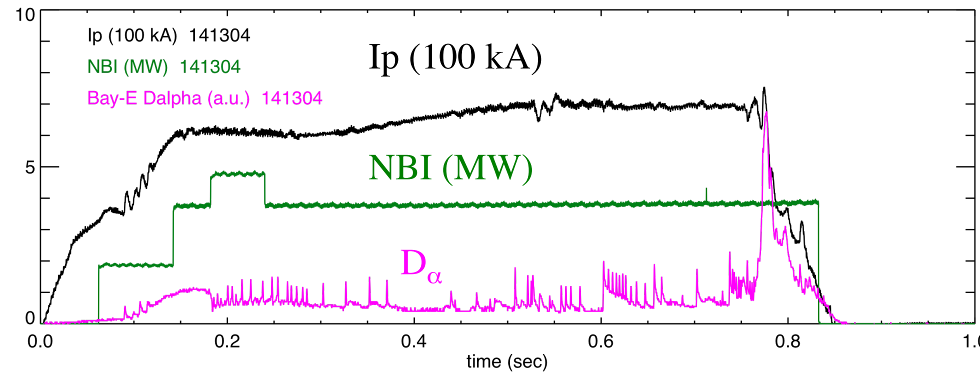


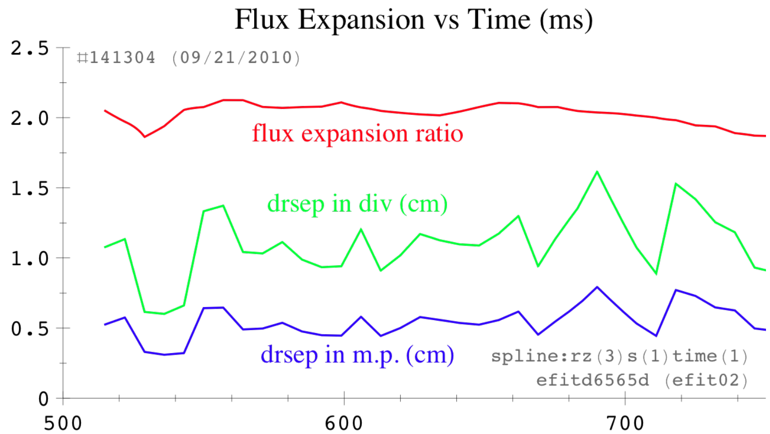
NEAR SOLC ZONE

WITH CIRCUMNAVIGATING SOLC PATH (C-PATH)

Low-Triangularity Shot for Near SOLC Zone Study







Ip ramp-up over 270 – 520 ms resulted in *no obvious* effect in SOLC behavior.

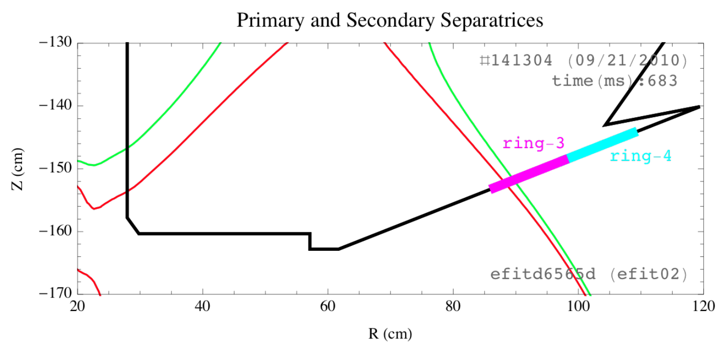
Inter-separatrix distance ("drsep") and flux surface expansion (from mid-plane to bottom outboard divertor) are small in this discharge.

A Lower-Single-Null, NBI-heated, lithium-injected, ELM'ing discharge in a "standard" NSTX configuration (Ip in CCW and Bt in CW direction) was examined.

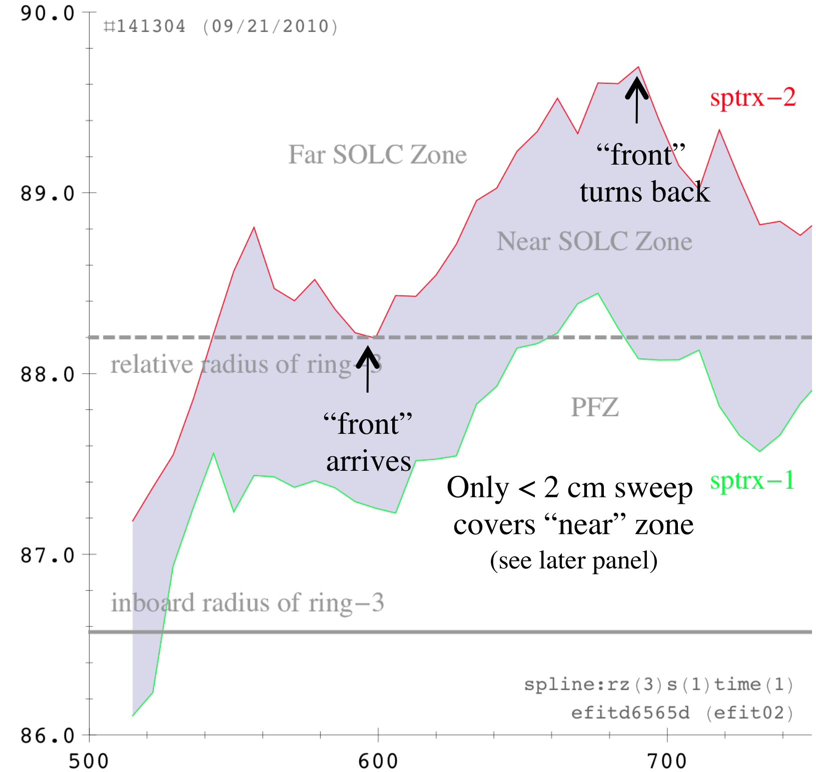
Current flows in a narrow (< 2 cm) Near SOLC Zone.

Sweep Strike Points for Finding SOLC Profile

Strike Points and SOLC Sensors in Bottom Divertor



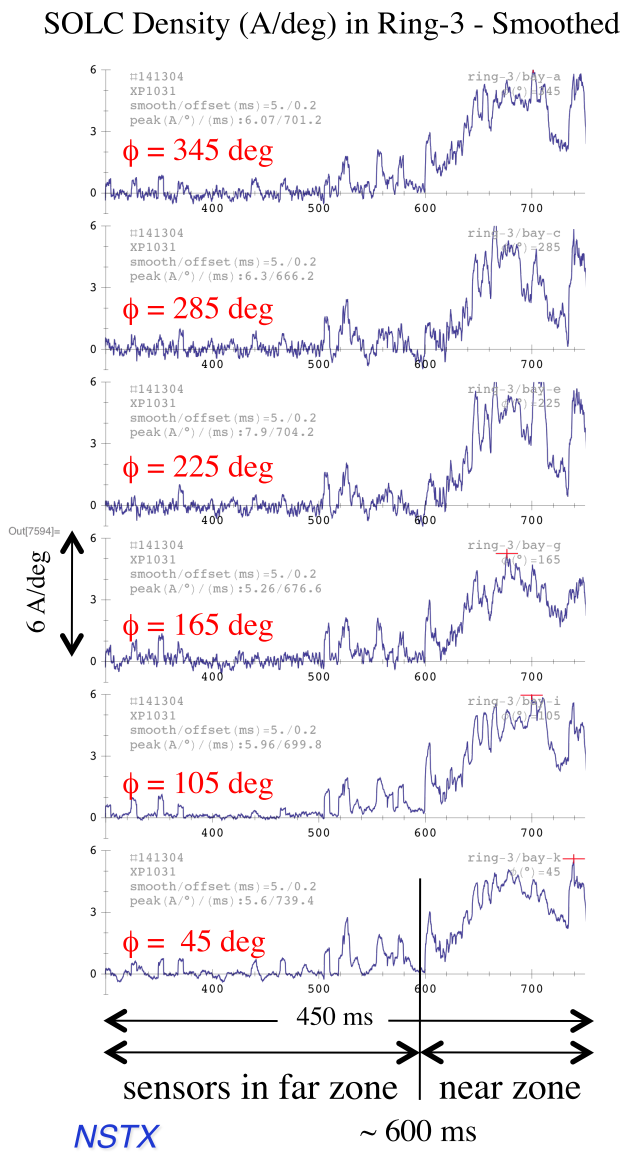
Radius (cm) of Strike Point−out vs Time (ms)



Under the assumption that a SOLC spatial profile is a time-independent function only of the distance measured from a strike point, the profile may be determined by moving ("sweeping") the strike point with respect to a stationery SOLC sensor.

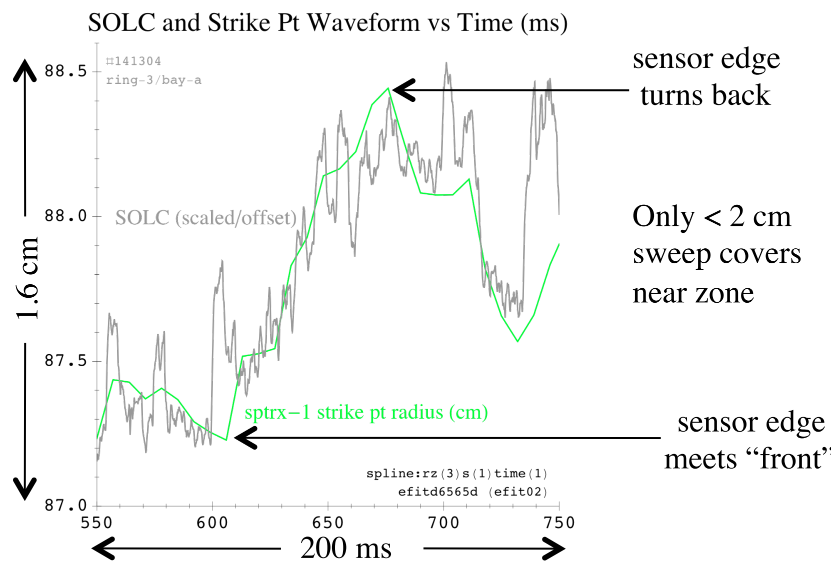
For the discharge examined here, EFIT strike points are farther out in major radius than the actual inboard edge of Ring-3 (solid horizontal line) from the beginning of the period shown above right, which would imply that Ring-3 sensors register signals, if there was any current in the Near SOLC Zone. Observations (next panel) contrary to this expectation, seem to suggest that strike points' locations relative to the ring edge were more like those with respect to the "relative radius" (dashed horizontal line). (In the plot, ring edge, not strike points, was moved by ~ 1.6 cm, for convenience of presentation.)

Inter-ELM SOLC Flows Only in Near SOLC Zone



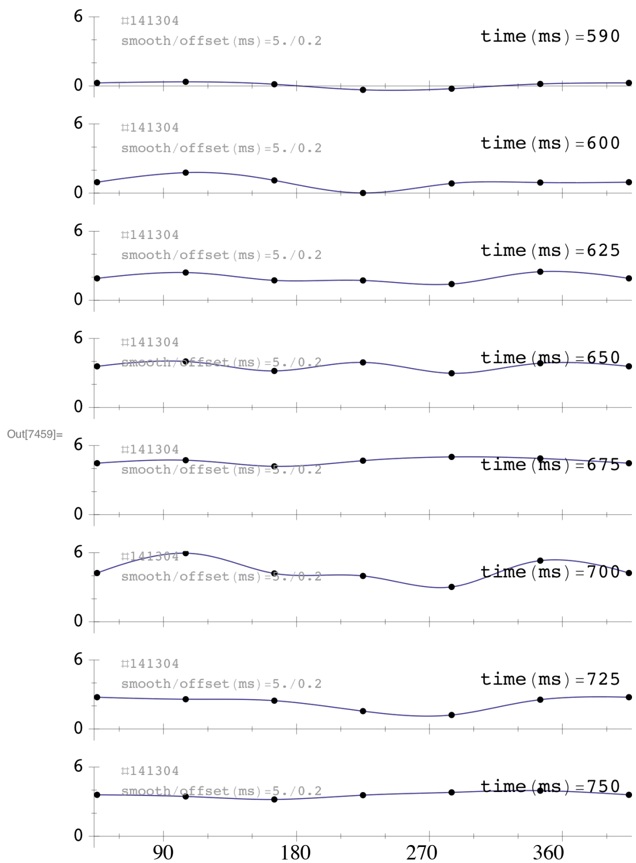
Signals (left) remain small while the sensors stay entirely within Far SOLC Zone, indicating the zone is devoid of SOLC that persists on a discharge evolution time scale.

Once Ring-3 inboard edge crosses into Near SOLC Zone (at ~ 600 ms), the sensors begin to "snow-plough" steadily present SOLC to yield rising signals. Abruptness of rise suggests the presence of a current-carrying region with a well-defined "front" (tentatively identified as a second separatrix). Overall resemblance (below) of waveforms of strike point motion and a sensor signal is supportive of such an interpretation.

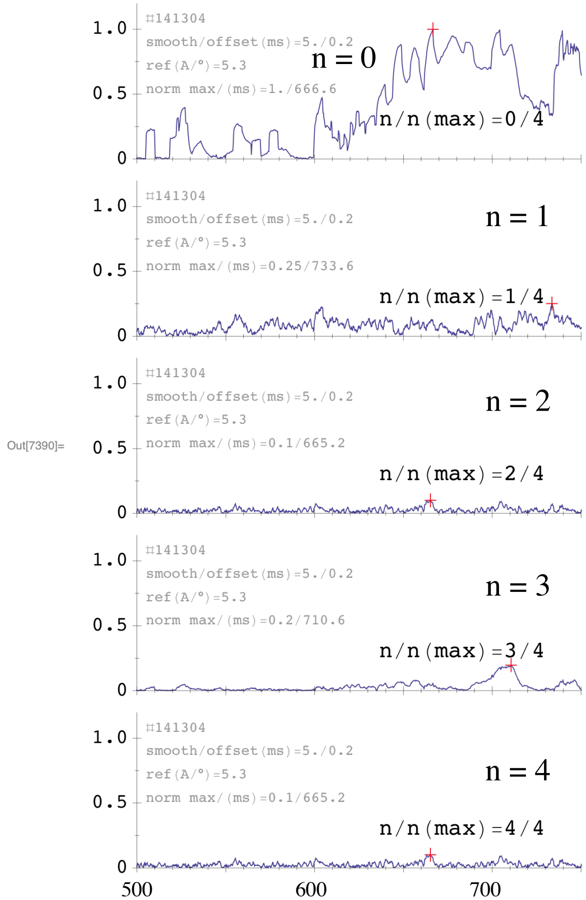


Near SOLC Zone Is Largely Axi-symmetric

Toroidal Variation of
SOLC Density (A/deg) in Ring-3



Time Variation of
Normalized Toroidal Harm Amp



Singular Value Decomposition (SVD), with max harmonic number of 4, is used for Toroidal Harmonic Analysis (THA).

Harmonic amplitudes are normalized by a peak value (in time) of n = 0 component.

Dominant n = 0 current density reaches 5.3 A/deg, or a total integrated SOLC (*poloidal* current), 1.9 kA (5.3 x 360) (possible effect on equilibrium is a subject of future work).

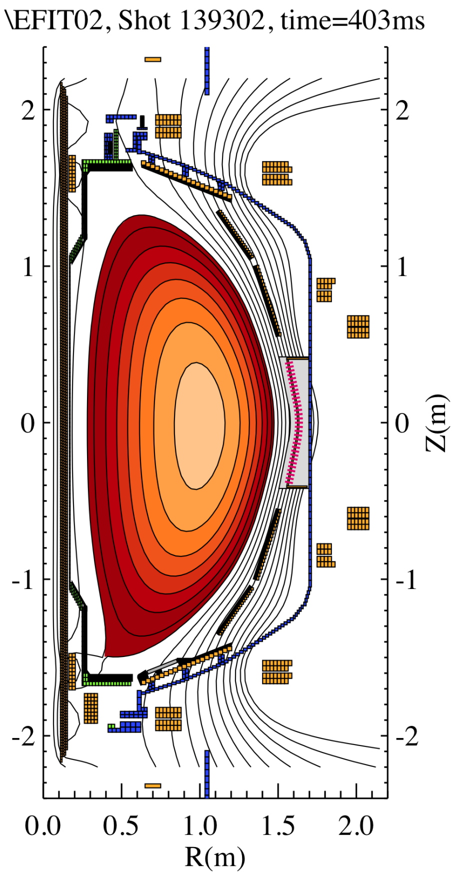
Axi-symmetric current in Near SOLC Zone, which persists over a discharge evolution time scale, may be driven by Te difference maintained by differential heat flux into in/outboard divertors.

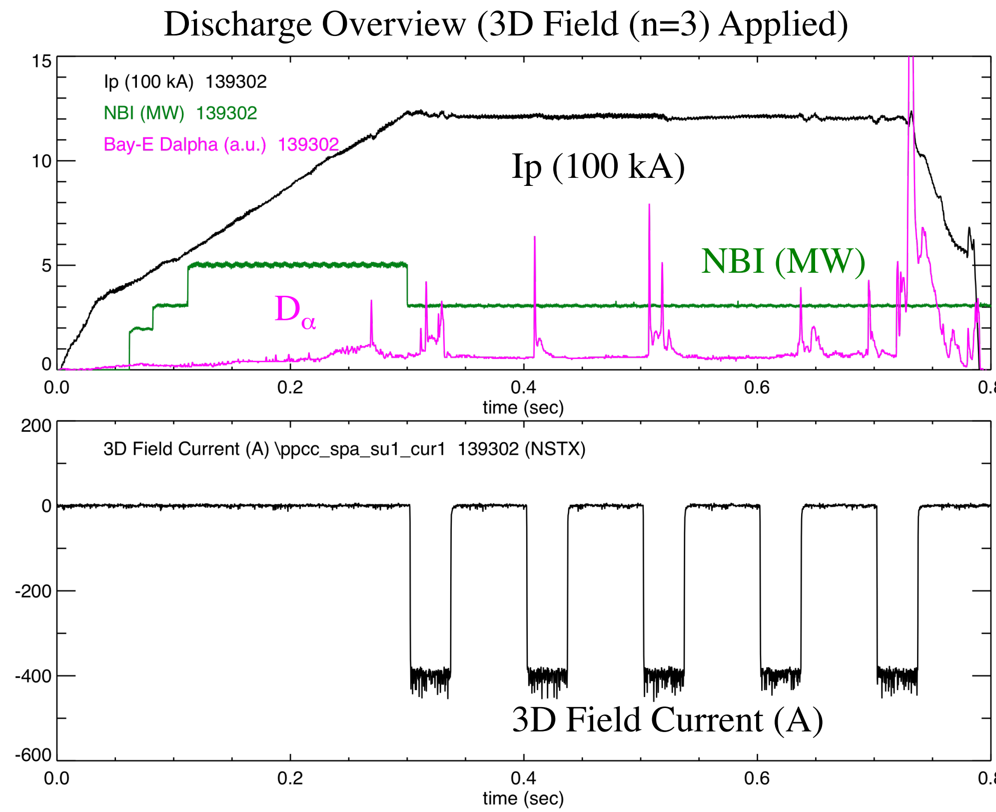
FAR SOLC ZONE

WITH INTERRUPTED SOLC PATH (I-PATH)

Also 3D Field On/Off Comparison

High-Triangularity Shot for Far SOLC Zone Study





A Lower-Single-Null, NBI-heated, lithium-injected, ELM'ing discharge in a "standard" NSTX magnetic configuration was examined. ELMs during 3D-field periods appeared to be induced by the field.

ELMs Manifest in Far SOLC Zone

•ELMs manifest as sharp *temporal* spikes in Far SOLC Zone, rising abruptly on a time scale of a few 10's of μs.

•SOLC spikes arise *in space hitherto essentially devoid of current*.

•SOLC is generally *bipolar* both in temporal and toroidal variations.

•SOLC spikes examined to date have been found to occur *before* the first "significant data point" of slowly-sampled (5 kHz) D_α rise indicating an arrival of an ELM. But a lack of diagnostics fast enough for following ELM onset in NSTX precludes positive determination. This comes from careful timing measurements in DIII-D (see EPS '05).

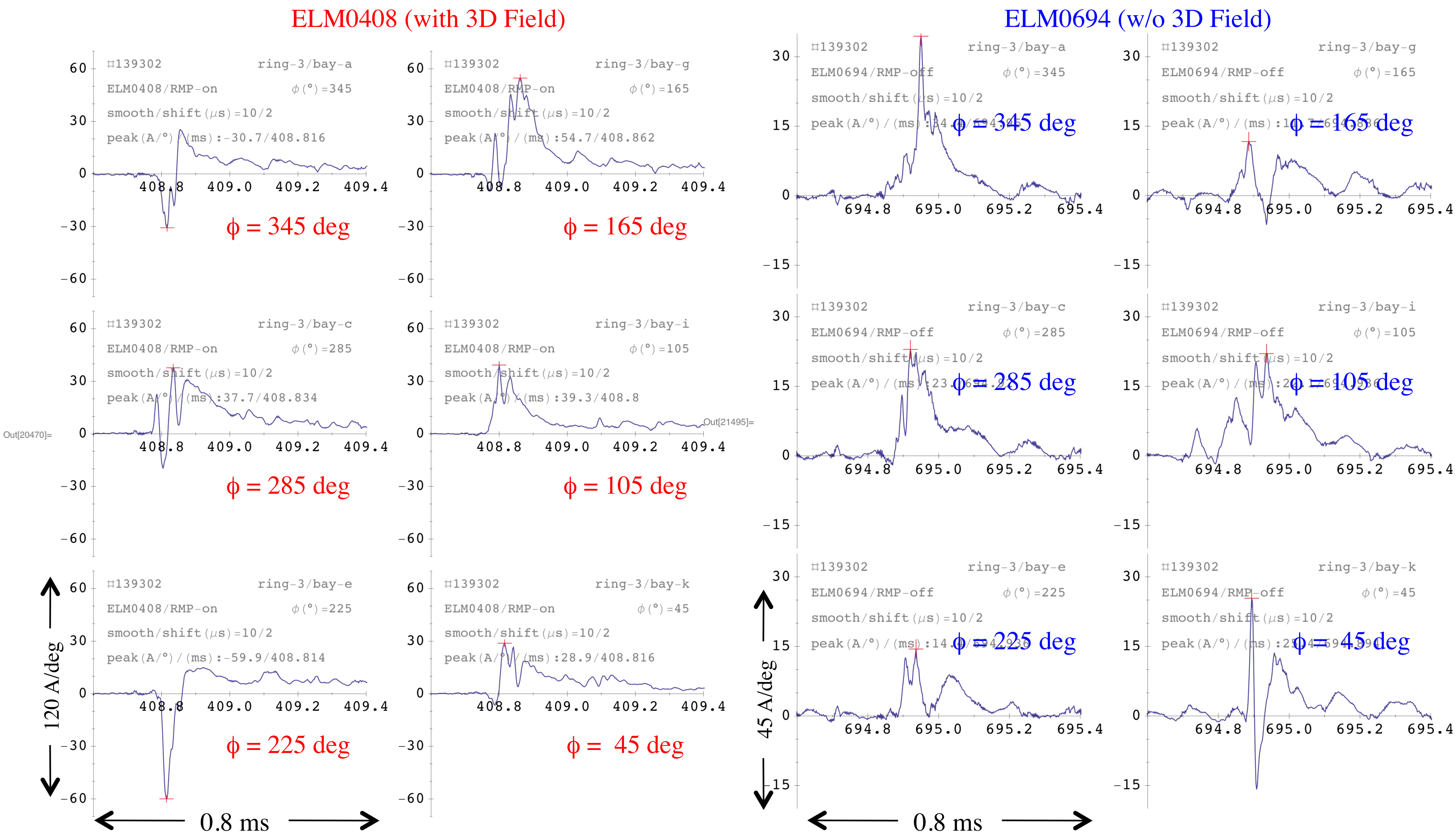
•Work is underway to identify the origin of current in Far SOLC Zone, consistent with all of the four "boundary conditions" stated above, and to assess effect of the observed SOLC on MHD stability and stochastic field generation at the plasma edge.

•Singular Value Decomposition (SVD), with maximum harmonic of 4, was used for Toroidal Harmonic Analysis (THA). Harmonic amplitudes are normalized by n = 0 amplitude to allow comparisons among ELMs of differing strengths.

The following 4 panels serve two purposes: (1) illustrate general features of current spikes in Far SOLC Zone and (2) compare SOLC spikes in the presence/absence of 3D field (n=3).

SOLC Manifests as Narrow Spikes in Far Zone

SOLC Density (A/deg) vs Time (ms) at Sensors

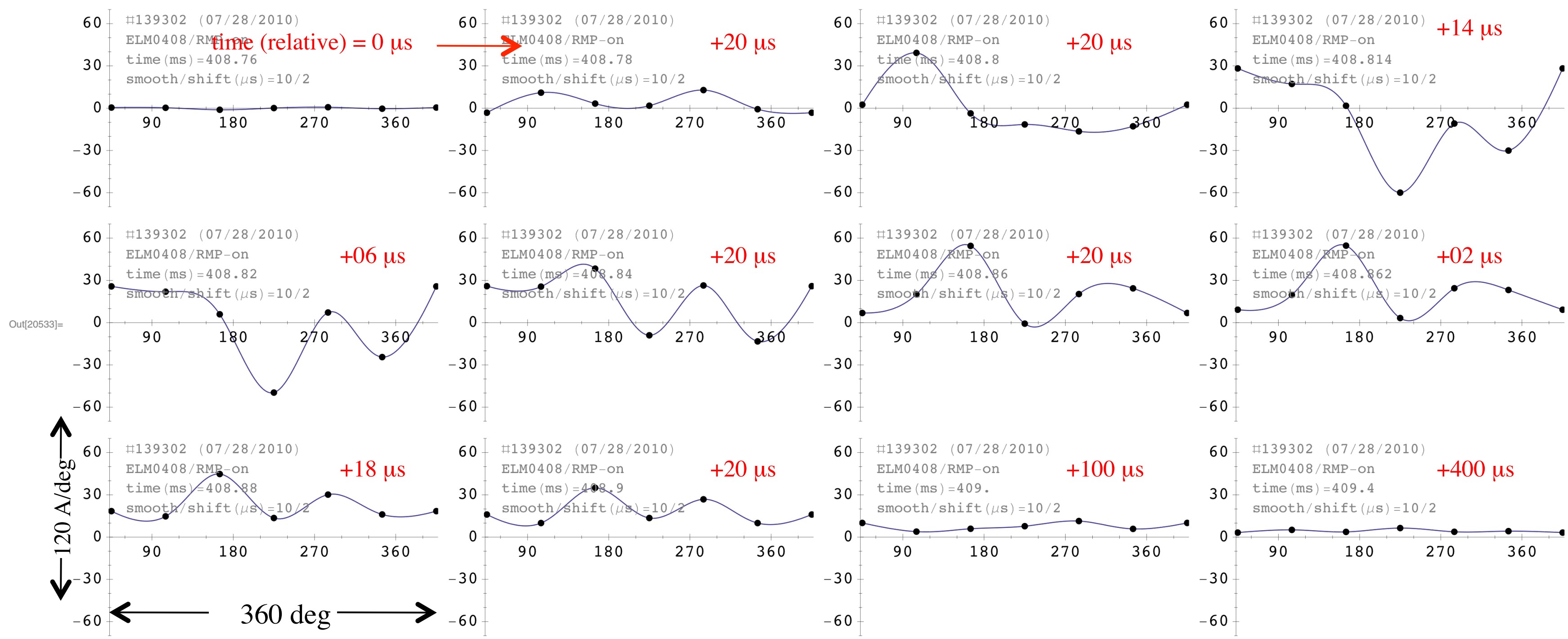


Application of 3D field makes no obvious change in SOLC behaviors in time domain.

SOLC Strongly Non-Axisymmetric in Far Zone - 1

SOLC Density (A/deg) vs Toroidal Angle (deg) at Multiple Times

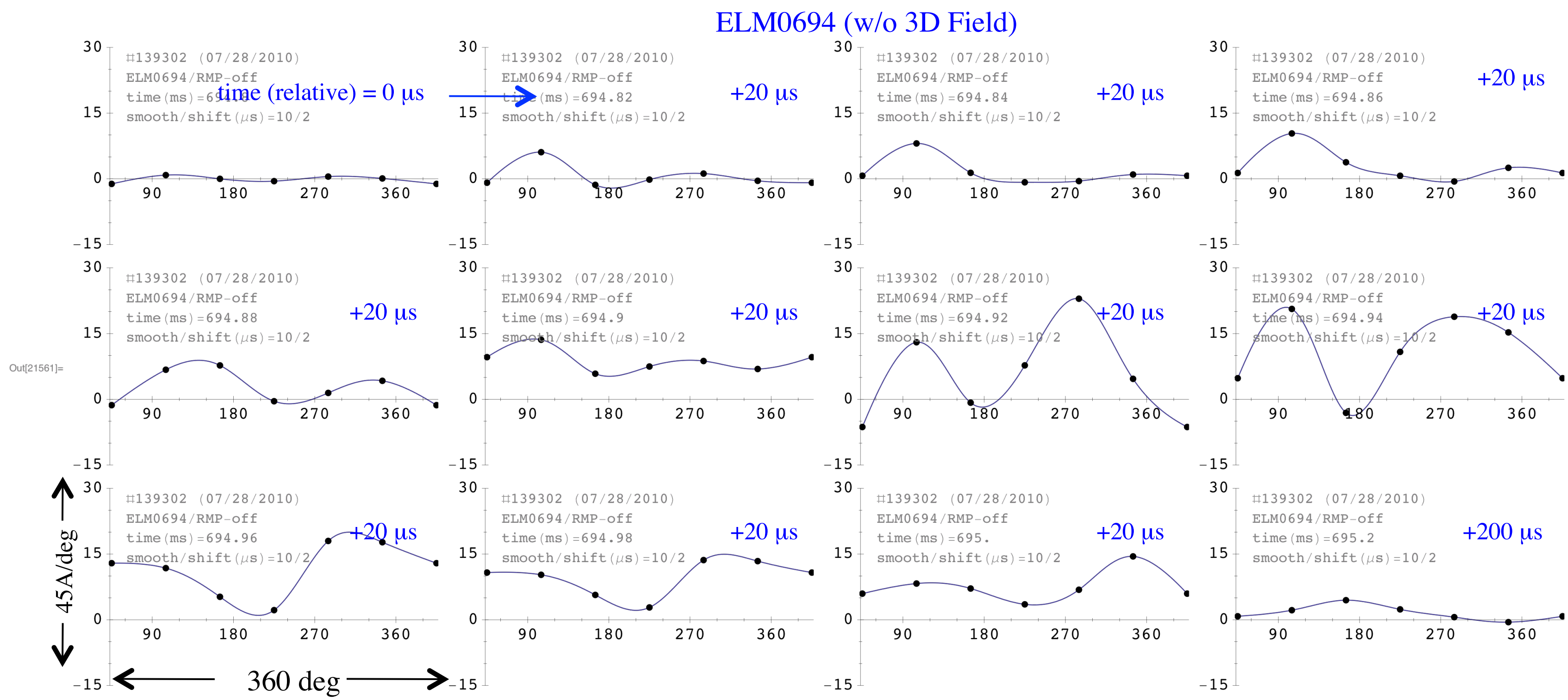
ELM0408 (with 3D Field)



A strongly non-axisymmetric distribution fully develops in ~ 60 μs for this ELM with 3D field (n=3) applied.

SOLC Strongly Non-Axisymmetric in Far Zone - 2

SOLC Density (A/deg) vs Toroidal Angle (deg) at Multiple Times

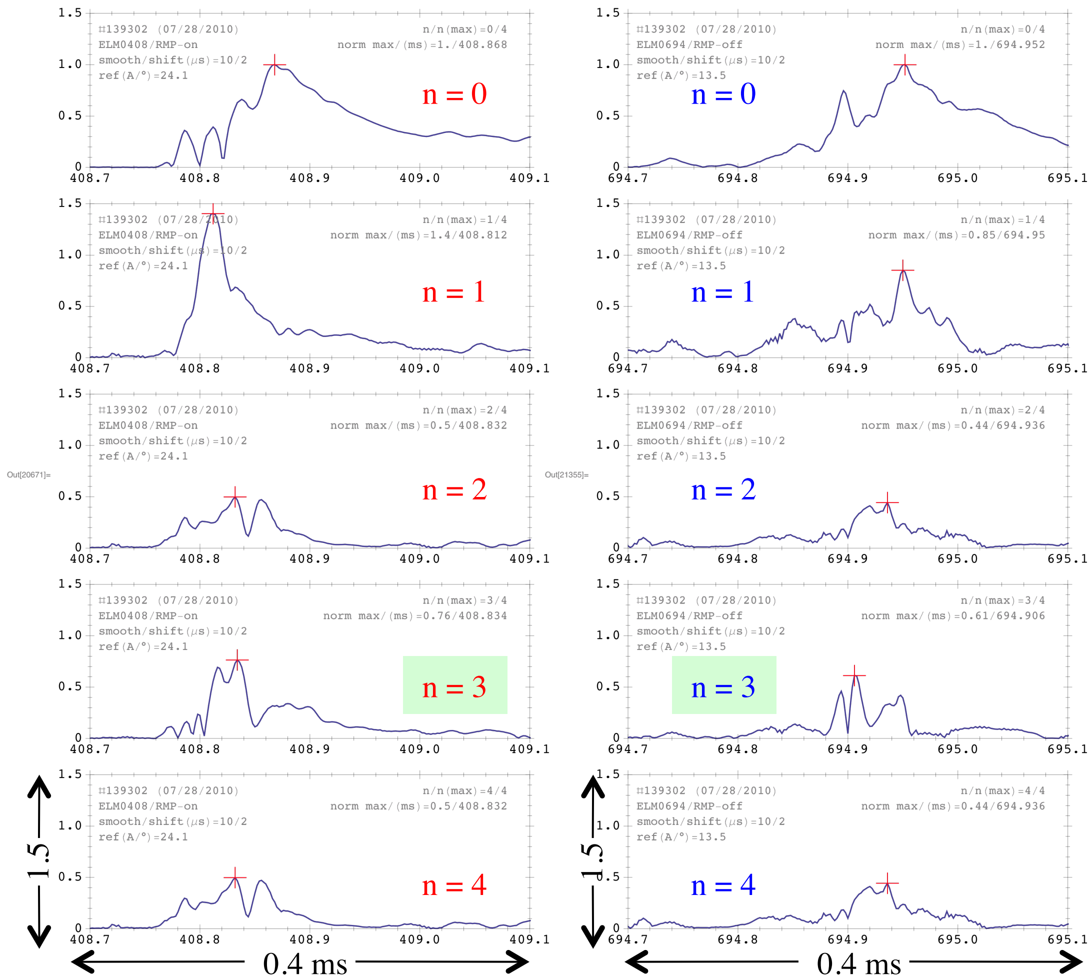


A strongly non-axisymmetric distribution fully develops in ~ 120 μs for this ELM without 3D field applied.

SOLC Toroidal Harmonics in Far Zone

Time Variation of *Normalized* Toroidal Harmonic Amplitude

ELM0408 (with 3D Field) ELM0694 (w/o 3D Field)



ELM0408 (with 3D Field)

n = 0 current density reaches 24.1 A/deg, or a total integrated SOLC (*poloidal* current), 8.7 kA (24.1 x 360), much greater, though for a very short duration, than current (1.9 kA) in Near SOLC Zone. (And this, just for Ring-3!)

n = 1 is a dominant non-axisymmetric harmonic (1.4 times n = 0), with RMS amp reaching 8.6 kA (8.7 kA x 1.4 / Sqrt(2)). This is the harmonic that peaks the earliest of all components computed for this ELM (but not universally seen feature).

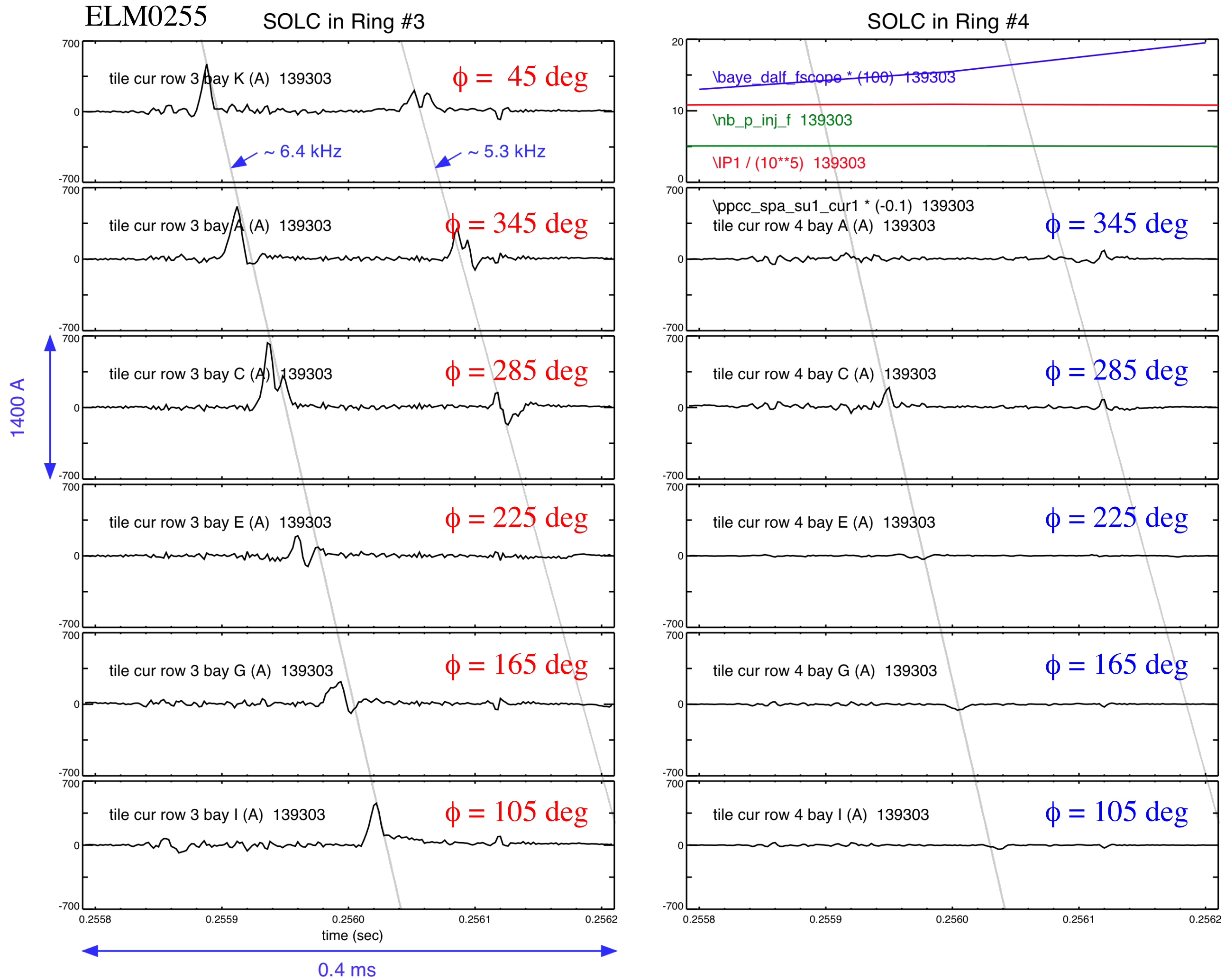
ELM0694 (w/o 3D Field)

n = 0 current density reaches 13.5 A/deg, or a total integrated SOLC, 4.9 kA (13.5 x 360), much greater, though for a very short duration, than current (1.9 kA) in Near SOLC Zone.

n = 1 is a dominant non-axisymmetric component (0.85 times n = 0), with RMS amp reaching 2.9 kA (4.9 kA x 0.85 / Sqrt(2)).

3D Field On/Off Comparisons: Lack of enhancement in n =3 *toroidal* harmonic is in contrast to *radial* striations observed (Ahn, NF 50 045010(2010)) by thermal imaging with 3D field (n = 3) that matched a homoclinic tangle pattern.

Rotating "Current-Carrying Patch" in Far SOLC Zone



A narrow "current-carrying patch," well-defined in its *toroidal* extent, executes, during some *Type-I ELMs* with or w/o 3D field, up to multiple revolutions in clockwise direction at up to several kHz rate - similar to filaments in Type-V ELMs (Maingi, PoP 092510 (2006)).

SOLC emerges on a sensor, just as it disappears from a neighbor. The patch has an estimated *FWHM ~ 25 deg* for this ELM.

SOLC in Ring-3 reached 600 A/tile during this ELM, leading to an estimated total current in the patch of up to 4 kA (triangular toroidal profile over ~ 13 tiles).

As a patch traverses over a succession of sensors, SOLC does not always maintain its temporal waveform, sometimes becoming even bipolar. It is thus the extent of a patch that remains nearly invariant, not current distribution in it.

Summary

•Two regions carrying different types of current, "Near SOLC Zone" and "Far SOLC Zone," have been identified; a secondary separatrix* may demarcates the zones, in which case they also have field lines of significantly different topology (*tentative, pending on resolution of strike point discrepancy).

• Near SOLC Zone carries during inter-ELM periods low-amplitude substantially *axisymmetric* current that persists on a discharge evolution time scale.

• Far SOLC Zone is nearly devoid of current during inter-ELM periods, and carries high-amplitude strongly *non-axisymmetric* spiky current during ELMs.

•A narrow "Current-Carrying Patch," well-defined in its *toroidal* extent, has been found to execute during some ELMs up to multiple toroidal revolutions in clockwise direction at up to several kHz rate.

•Applied 3D field (n = 3) generates no obvious effect on SOLC *toroidal* structures in Far SOLC Zone. (Near SOLC Zone has not yet been examined in this respect.)