Amplifying and Transforming of External Error Field by Scrape-Off-Layer Current (SOLC) in Tokamaks

H. Takahashi, E. Fredrickson, S. Gerhardt, and S. Zweben
Princeton Plasma Physics Laboratory

The 53rd Annual Meeting of Division of Plasma Physics
American Physical Society
Salt Lake City, Utah
November 14-18, 2011
Paper PP9.00040

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

ABSTRACT

Amplifying and Transforming of External Error Field by Scrape-Off-Layer Current (SOLC) in Tokamaks,* H. Takahashi, E. Fredrickson, S. Gerhardt, S.J. Zweben, *PPPL* – External error fields may induce a thermoelectrically driven SOLC, if the fields produce Te differences between the two ends of open field lines. SOLC may in turn generate an error field of its own that is greater in amplitude and more destructive in nature than the external fields. The SOLC-generated field tends to be symmetrized in the face of non-axisymmetry in the SOL plasma because of "phase mixing effect" arising from strong shear in the field line pitch angle. Near a "sweet spot," midway between primary and secondary separatrices, however, field lines tend to stay bundled together under opposite influences of the two separatrices, and current along these field lines can generate a low toroidal-harmonic error field in spite of the axisymmetry of the background field. A unit line SOLC (kA) in NSTX can generate an n=1 harmonic of amplitude in the magnetic axis plane of ~ 3 mT/kA at inboard q95, rapidly decaying to ~ 0.2 mT/kA at the axis, and to ~ 0.03 mT/kA at outboard q95, which may play a role in rotation slow-down/locking and other MHD phenomena.

*Supported in part by the US DOE under DE-AC02-09CH11466

Highlights

Does SOLC amplify or transform 3D error field?

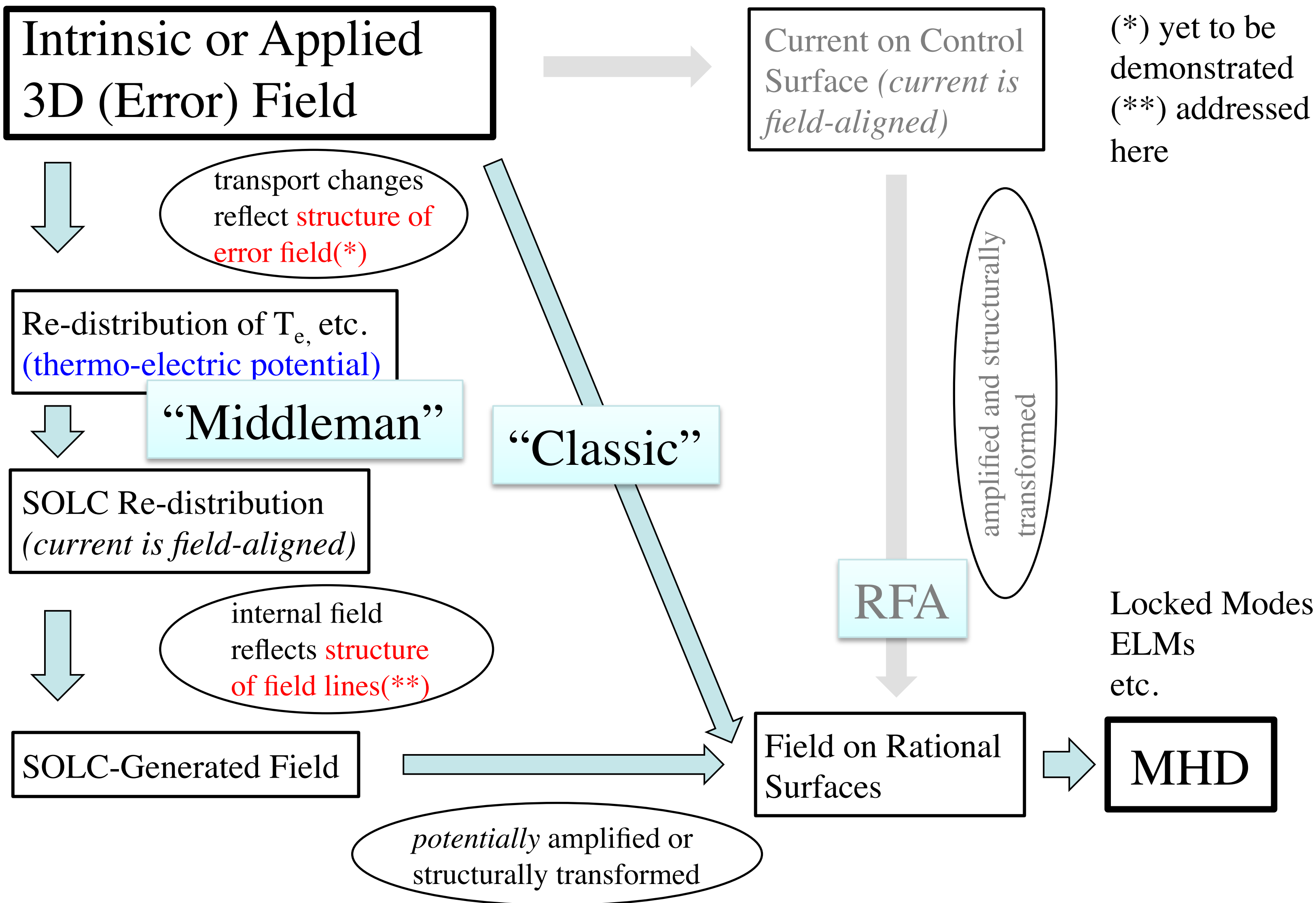
Need to demonstrate:

(i) External 3D field can alter a SOLC distribution
(ii) Field line structure imposes a transformed field pattern on rational surfaces

Only the second step is discussed here (*field line structure is the principal topic of this poster*).

This investigation is part of the work in progress to understand effects of SOLC on MHD phenomena, including rotation slow-down and stoppage, and ELM triggering.

SOLC as "Middleman" between Error Field and MHD



MEASUREMENT OF SOLC

Some measured SOLC data already reported in the APS '10 poster are repeated in this section.

Halo Current Diagnostic (2010)

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

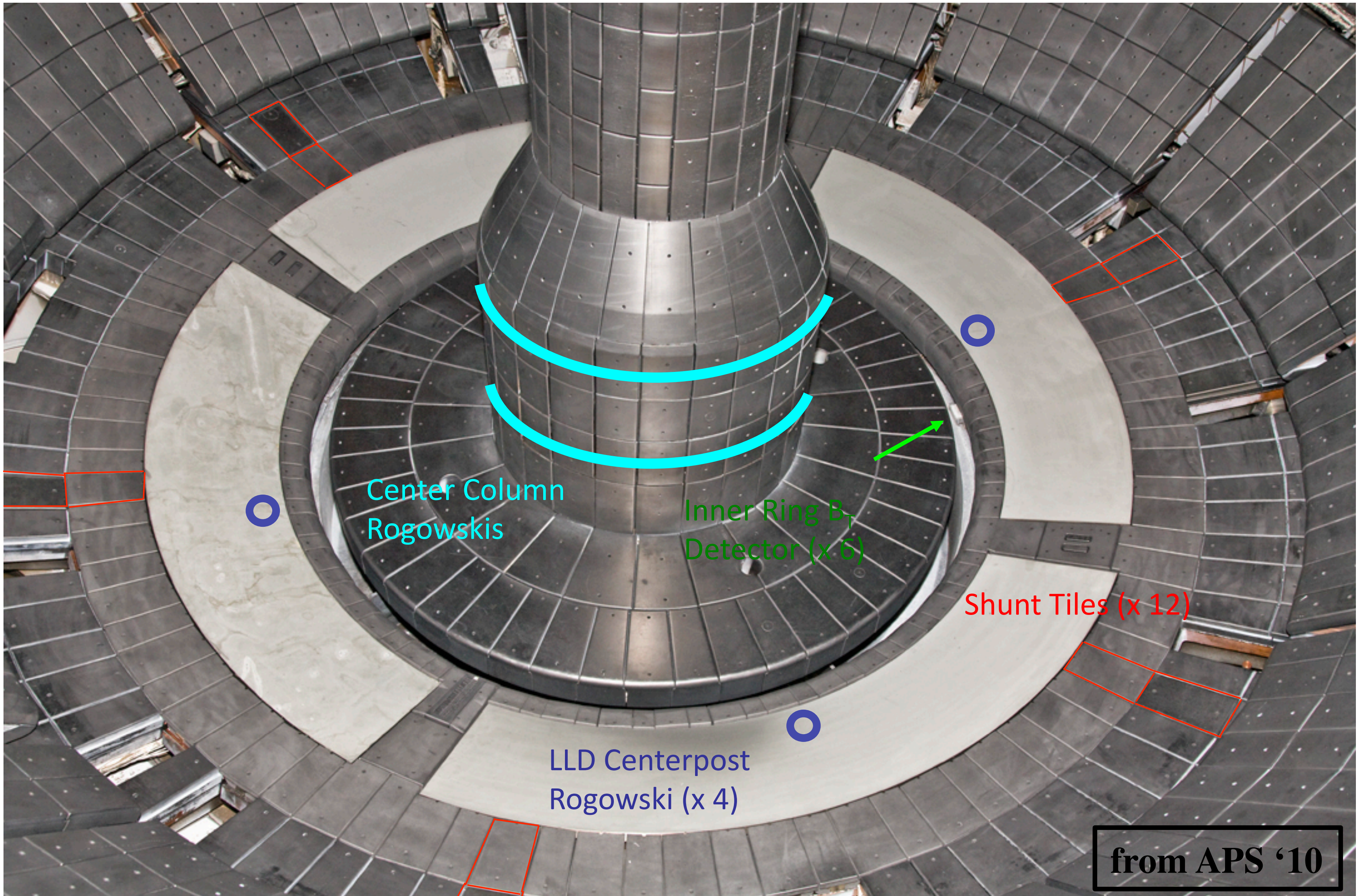
The diagnostic has two toroidal arrays of six equidistantly placed sensor tiles, one array each in "Ring-3" and "Ring-4" (each ring with a total of 96 tiles). Sensors in the two rings are radially aligned with each other (see next panel). A sensor tile is 3.75 deg (~ 6 cm) wide toroidally and ~ 11 cm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

from APS '10

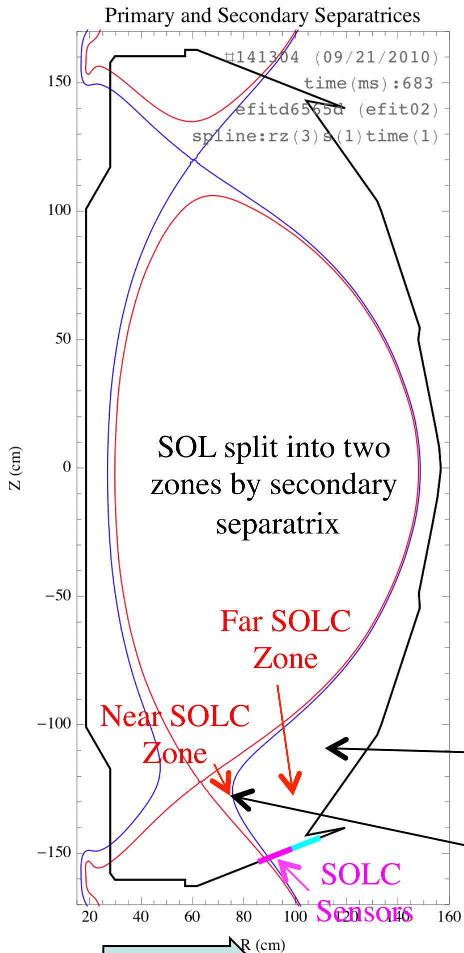
12 Tile Current Sensors (Indicated by Red Rectangles)



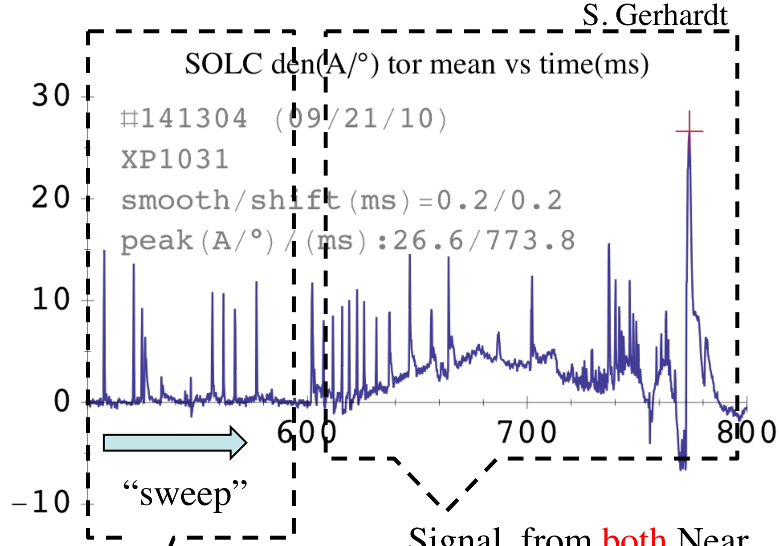
From Stefan Gerhardt, "Halo Current Diagnostics in 2010," Slide 6

Different SOLC Paths in Near and Far Zones

Near and Far SOLC Zones

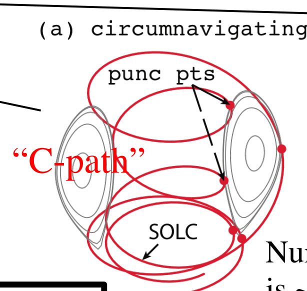


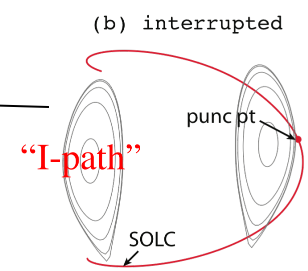
strike points "sweep"



Signal from both Near and Far SOLC Zones.

Signal from only Far SOLC Zone, devoid of current except during ELMs.





Number of field-line toroidal revolution is ~ 12 for NSTX (DIII-D shown here)

In "Near and Far SOLC Zones" SOLC flows along topologically distinct "C-path and I-path" respectively, which have their end points in different pairs of divertors with different thermal environments.

Consequently, thermo-electrically driven SOLC in the two zones may exhibit distinct temporal behaviors as well as magnetic consequences.

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

Explosively growing SOLC in Far Zone, spiky in time and non-axisymmetric, may serve as an ELM trigger.

from APS '10

Measurement Strategy and Plans

Measure SOLC with 3D field on/off in near and far SOLC zones; rotate 3D field toroidally; measure SOL parameters (yet to be attempted).

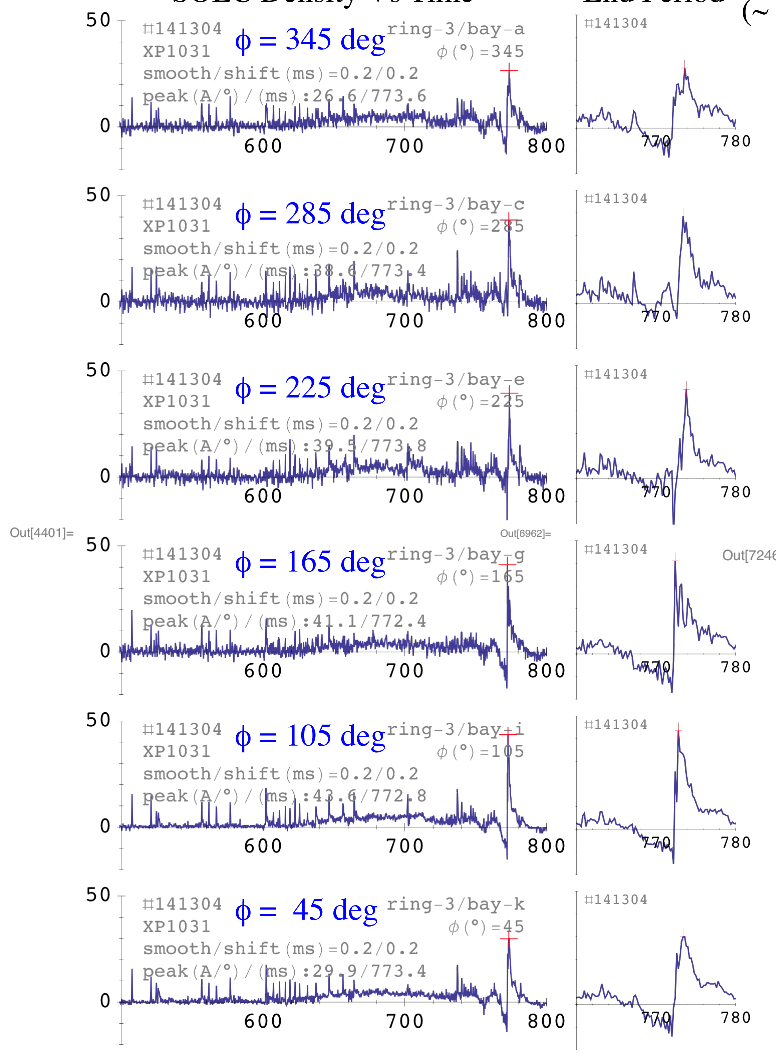
field applied / current measured:	3D field off	3D field on (n=3)
in near SOLC zone	n=0 current detected in quiescent state; spiky (n>0) current during ELMs.	no data(*)
in far SOLC zone	no or little current detected in quiescent state; spiky (n>0)current during ELMs.	no or little current detected in quiescent state; spiky (n>0) current during ELMs; little applied field effect on SOLC during ELMs.

(*) Planned experiments did not materialize because of NSTX shut-down earlier than originally planned in order to make way for NSTX-Upgrade construction.

Large Current Flows in Near SOLC Zones

Toroidal Spatial Variations

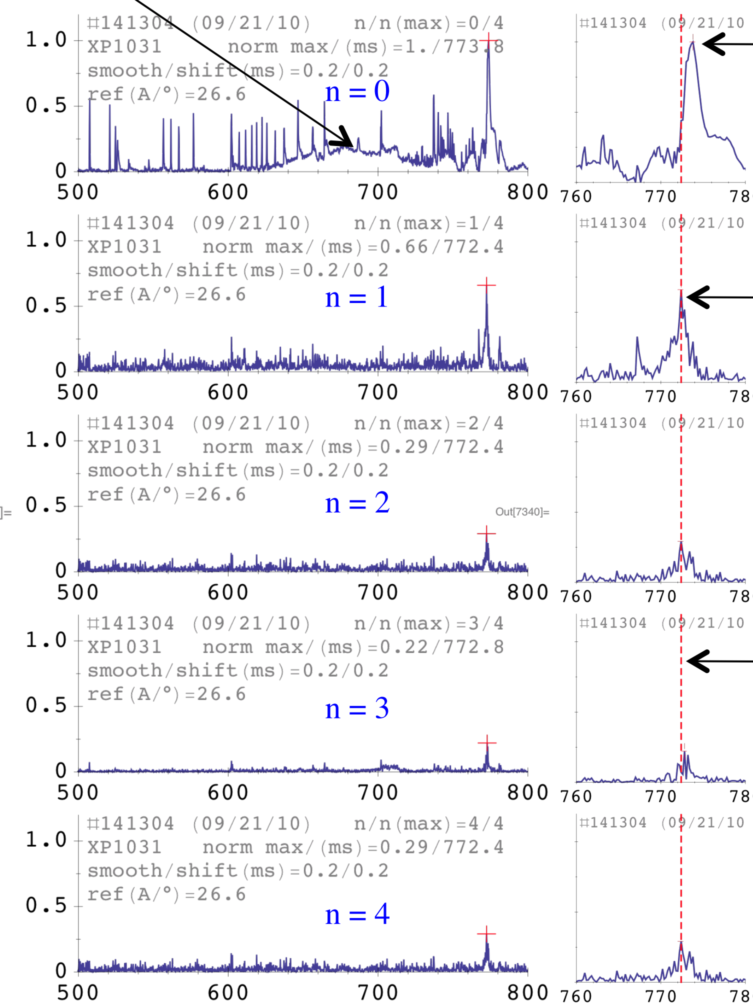
SOLC Density Vs Time — End Period



n = 0
~ 1.9 kA (pol)
~ 23 kA (tor)
(~ 3 %)

Toroidal Harmonic (SVD) Analysis

SOLC *Normalized* Harm Amp — End Period



n = 0
~ 10 kA (pol)
~ 120 kA (tor)
(~ 17 %)

n = 1 (RMS)
~ 4.5 kA (pol)
~ 54 kA (tor)
(~ 8 %)
MHD?
thermal instability?

n > 0 leads n = 0
causality?

from Results Review '10

NSTX

PPPL PRINCETON PLASMA PHYSICS LABORATORY

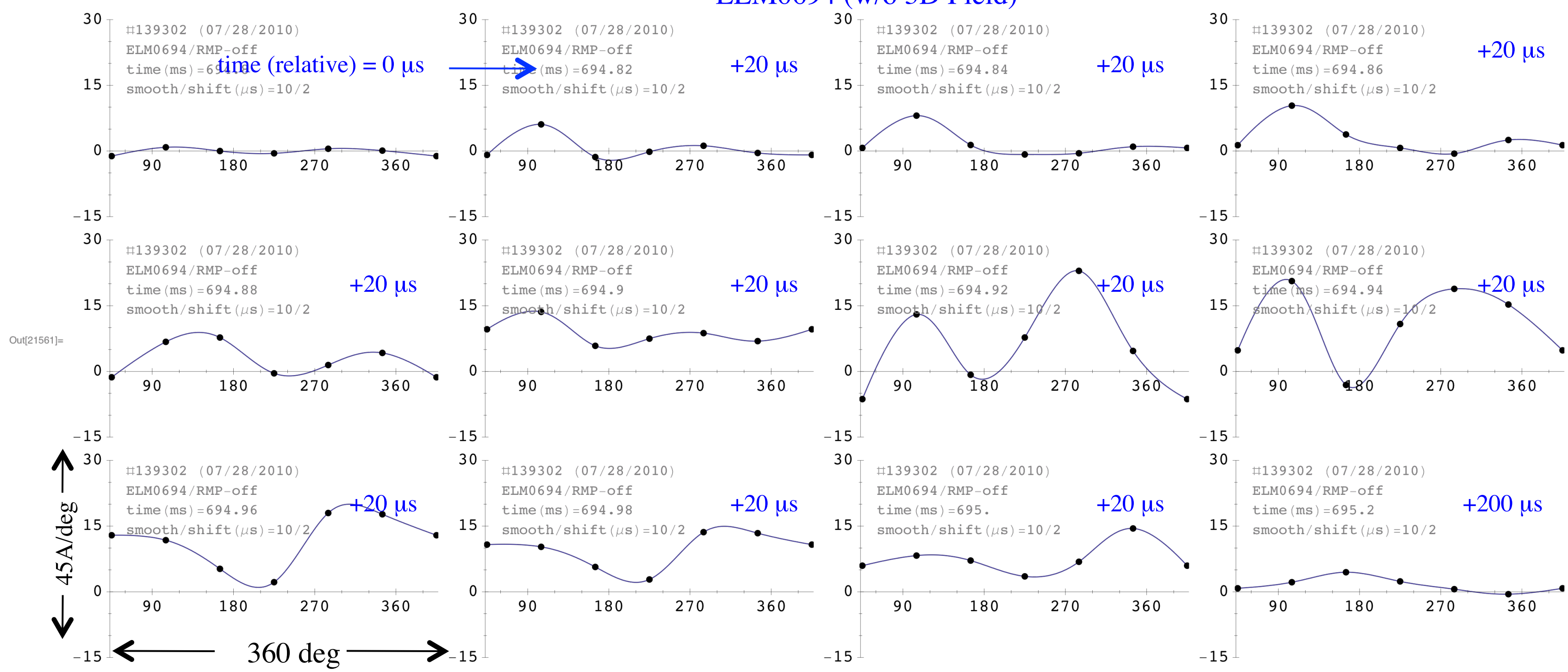
SOLC Strongly Non-Axisymmetric in ELMs in Far Zone - 1

bi-polar in space

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

w/o 3D field

ELM0694 (w/o 3D Field)



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

from Results Review '10

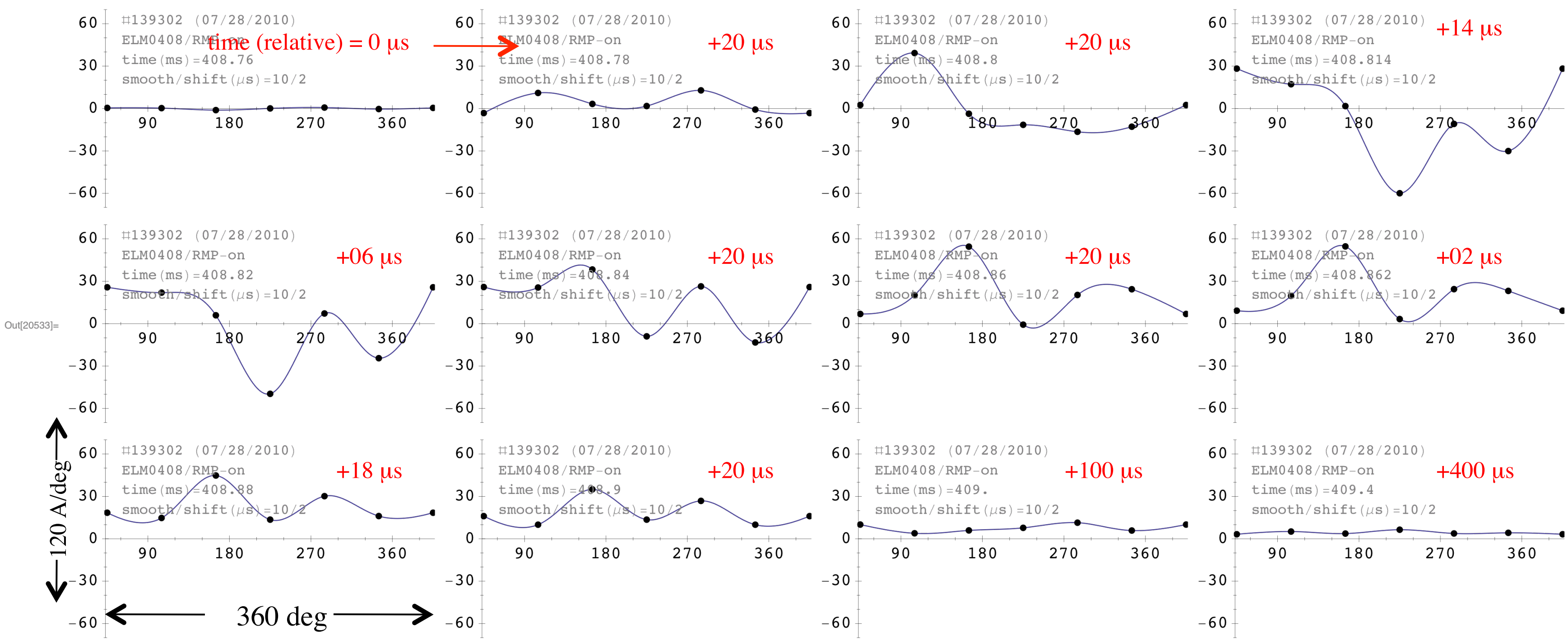
SOLC Strongly Non-Axisymmetric in ELMs in Far Zone - 2

bi-polar in space

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

with 3D field

ELM0408 (with 3D Field)



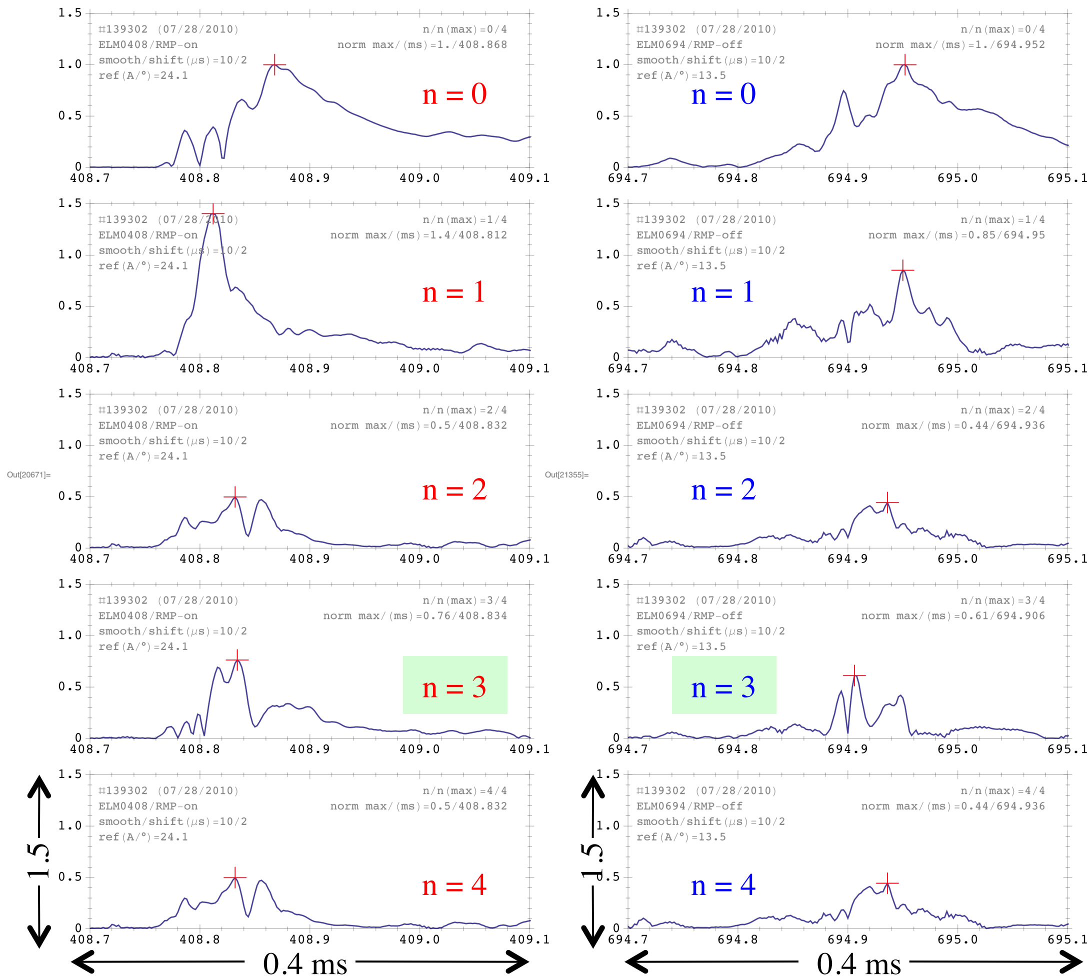
A strongly non-axisymmetric distribution fully develops in ~ 60 µs for this ELM with 3D field (n=3) applied. No significant effect of the field is evident, possibly because of a fast time-scale.

from Results Review '10

SOLC Toroidal Harmonics in ELMs in Far Zone

Time Variation of *Normalized* Toroidal Harmonic Amplitude (SVD)

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 (<u>*poloidal*</u> 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 a 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)).

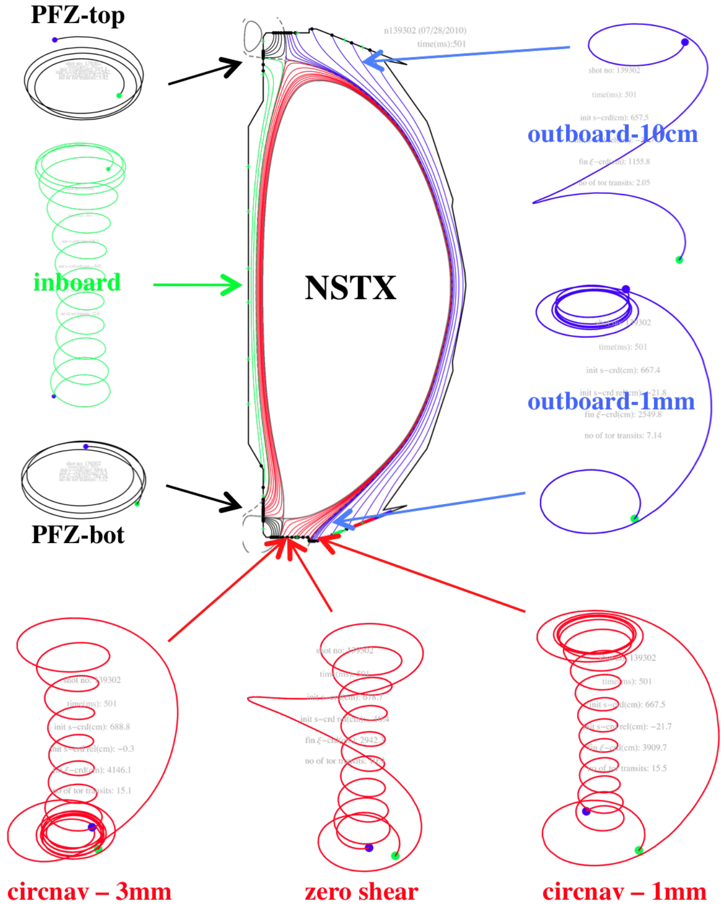
3D Field On/Off Comparisons: A lack of enhancement in n =3 *toroidal* harmonic is in contrast to *radial* striations observed (Ahn, NF 50 045010(2010)) by thermal imaging with 3D field (n = 3) that matched a homoclinic tangle pattern.

from Results Review ‘10

STRUCTURE of FIELD LINES and CALCULATION of SOLC-GENERATED FIELD

Field Line Geometry Varies in Different SOL Zones

#139302 (501 ms)



A field line executes a large number of toroidal transits, if it passes near an x-point – primary or secondary.

Primary and secondary separatrices demarcate the SOL volume into five distinct zones:

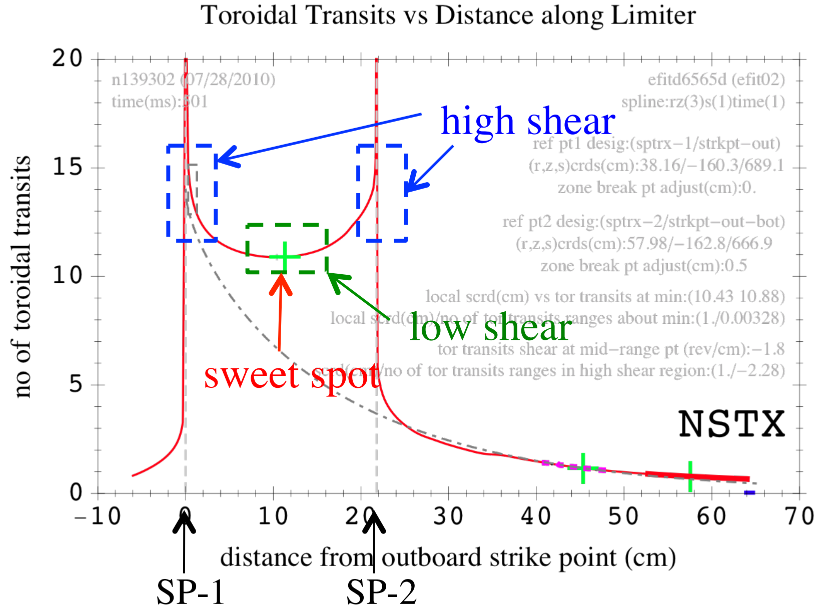
(i) Poloidally Circumnavigating Zone
(ii) Outboard Zone
(iii) Inboard Zone
(iv) Private Flux Zone - Top
(v) Private Flux Zone - Bottom.

Field line geometry differ qualitatively in these zones. Secondary separatrix (between red and blue zones) plays a particularly important role.

A circumnavigating field line traverses the outboard region in a single "sweeping arc," but forms a "multi-turn structure" in the inboard region.

High-Shear, Low-Shear, and “Sweet Spot”

Toroidal Transits Executed by a Field Line



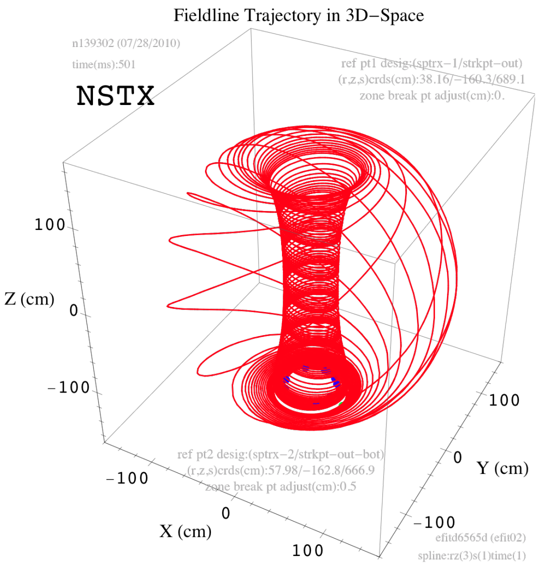
Number of toroidal transits that a field line executes, as it travels poloidally from a start point on a tile surface to an end point on another tile surface, is plotted as a function of the start-point distance measured along the limiter surface from the bottom outboard strike point of the primary separatrix. The plot covers three zones, bottom PFZ (d < 0), circumnavigating (0 < d < ~ 22 cm), and outboard (~ 22 < d cm) zones (see previous slide).

The rate of change of the number of transits with respect to the distance of field-line starting point is the “shear” of the transit number in analogy to the shear in the safety factor for field lines inside the main plasma.

The number of transits does not decrease monotonically (dotted exponential line) because of the presence of a secondary separatrix.

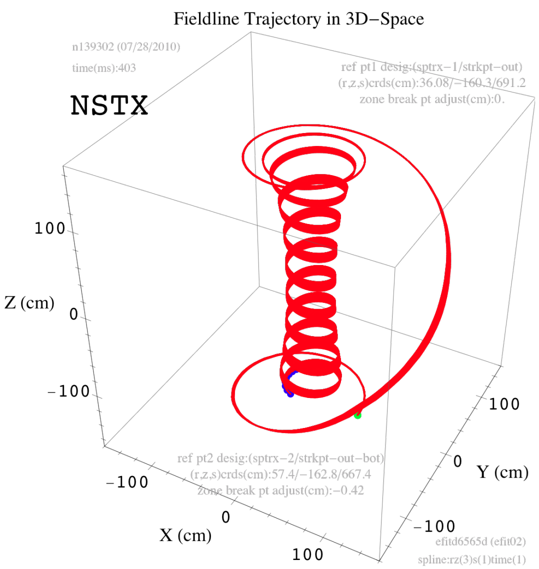
Instead, the number of transits possesses two regions of high shear (rapid variations with respect to the starting-point distance) near the primary (SP-1) and secondary (SP-2) strike points and a region of low shear about a zero-shear “sweet spot.”

SOLC Can Generate Symmetric or Asymmetric Field



High-Shear ⟺ Wide Band ⟺ Symmetric Field

Consider a bundle of field lines in a high-shear region, all starting at the same toroidal angle, but at slightly different distances from the strike point. These filed lines suffer strong toroidal angular dispersion, and become distributed over a "wide band" in toroidal angle. SOLC flowing along these field lines will produce magnetic field that is substantially toroidally symmetric, in spite of the fact current distribution at the starting points on the tile was strongly aymmetric (in fact, δ-function in toroidal angle).

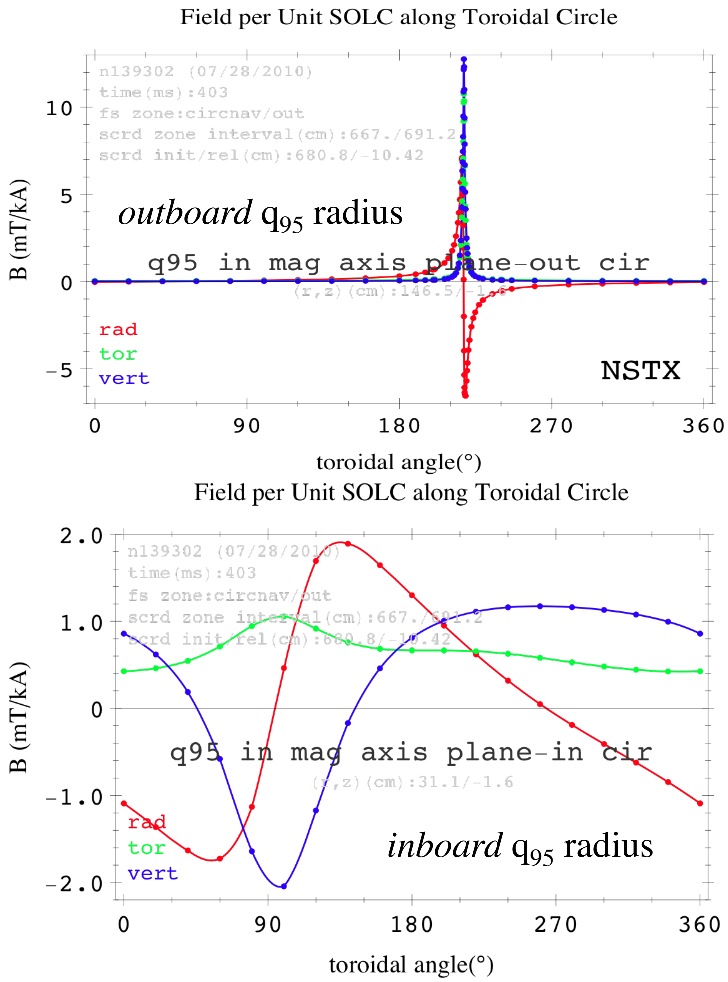


Low-Shear ⟺ Narrow Band ⟺ Asymmetric Field

Consider instead a bundle of field lines in a low-shear region clustered around a zero shear "sweet spot," again all starting at the same toroidal angle, but at slightly different distances from the strike point. These filed lines suffer little toroidal angular dispersion, and stay bundled together in a "narrow band" in toroidal angle. SOLC flowing along these field lines will produce toroidally asymmetric magnetic field.

Single SOLC Filament Can Generate Broad Field Pattern

Field (mT/kA) along Toroidal Circle



toroidal angle (deg)

Radial, toroidal, and vertical fields (mT) generated by a single SOLC filament carrying unit current (1 kA) is calculated using the Biot-Savart's law along toroidal circles in the magnetic axis plane at the major radii of outboard and inboard q_{95} surfaces.

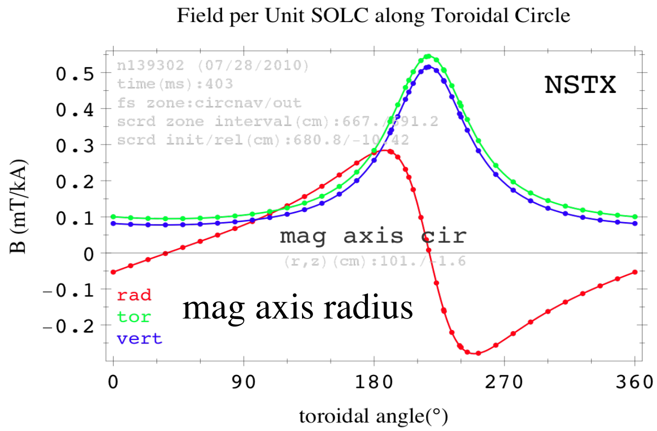
The wide "sweeping arc" of the filament crosses the outboard mid-plane at a high pitch angle, and, as expected, generates sharply concentrated field along the *outboard* q_{95} surface.

It is perhaps surprising, however, that field along the *inboard* q_{95} surface exhibits a broad distribution. This comes about because a SOLC filament runs at a shallow pitch angle on the inboard side, with the "multi-turn structure" (~ 12 turns) reinforcing the trend.

Interaction (e.g., momentum transfer in LM process) through flux coupling (mutual inductance) between SOLC and MHD current inside the plasma will be a subject to be explored in the near future.

Low-order Toroidal Harmonics Can Be Dominant

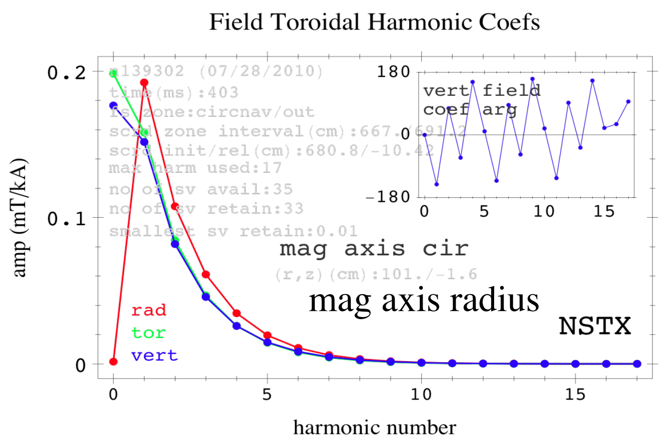
Field (mT/kA) along Toroidal Circle



toroidal angle (deg)

Amplitude of field generated by a single filament decays rapidly with the distance away from the inboard "multi-turn structure," reflecting the smallness of its horizontal spatial scale, but remains sizable even at the magnetic axis, with peak-to-peak variations up to ~ 0.5 mT/kA.

Toroidal Harmonics (mT/kA)



toroidal harmonic number

Toroidal Harmonic Analysis (THA) shows that the n=1 component, with amplitude up to ~ 0.19 mT/kA, is the dominant non-axisymmetric component even at the magnetic axis radius.

Spiraling Striations in Divertor in *Axisymmetric* Field

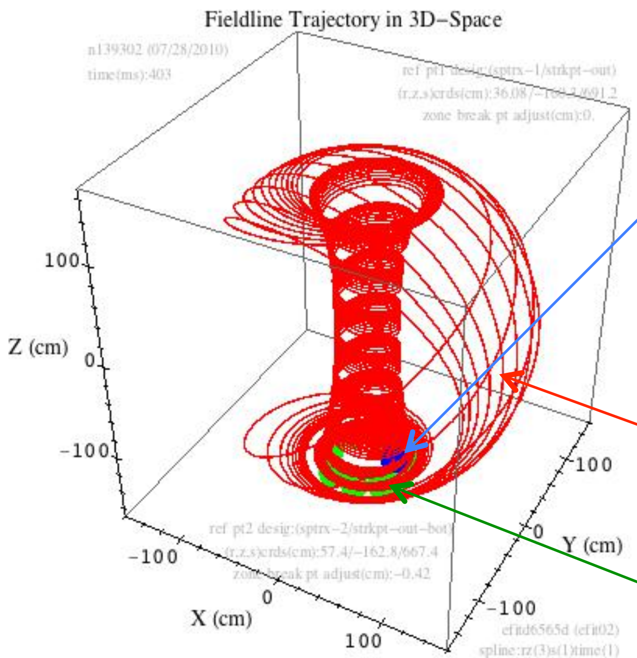
- *Not* through *Strike-Point Splitting* -

It is a common feature of field lines originating from a toroidally localized location in a divertor to disperse in toroidal angle, as they travel poloidally around the plasma column, and to terminate in another divertor with highly drawn-out "footprints," producing "spiraling striations" (unless field lines belong to an exception class originating at a "sweet spot").

The spiral, when viewed locally, may be seen as "striations" similar to those associated with strike-point splitting in a homoclinic tangle produced by applied 3D field.

Field Line Angular Dispersion Creates Spiral "Footprints"-1

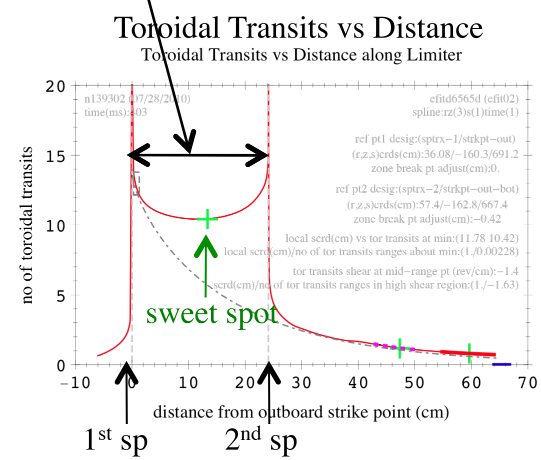
Field Lines in Circumnavigating Zone
(between Primary and Secondary Separatrices)

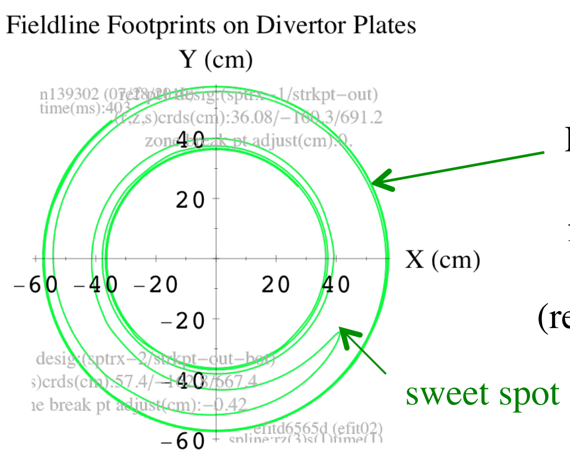


Field lines start in inboard divertor at the same toroidal angle but with a radial spread

Become widely dispersed in toroidal angle

Create a drawn-out "footprint" on outboard divertor





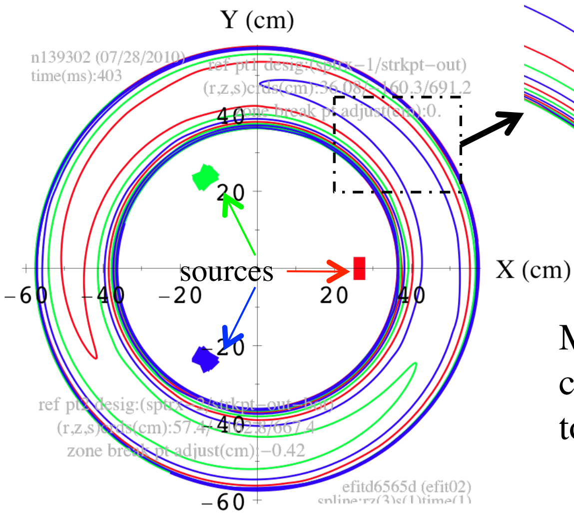
For a *large radial spread* at start, footprint can be a multi-turn spiral (reversing direction at "sweet spot")

A bundle of field lines originating in inboard divertor becomes widely dispersed in toroidal angle, and creates a drawn-out "footprint" in outboard divertor.

Multi-turn Spiral Footprints Locally Manifest as Striations-1

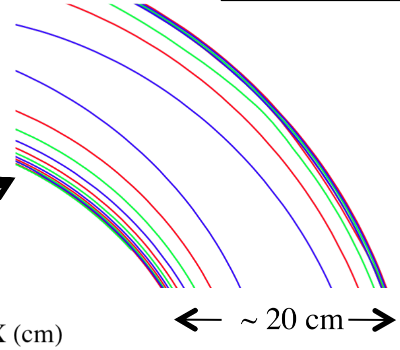
“n = 3” Current Source
Emulated by a δ-Function
at 3 Toroidal Angles

Fieldline Footprints on Divertor Plates



“striations”

Field Lines in Circumnavigating Zone
(between Primary and Secondary Separatrices)



Multi-turn spiral footprints could manifest as striations to localized observers.

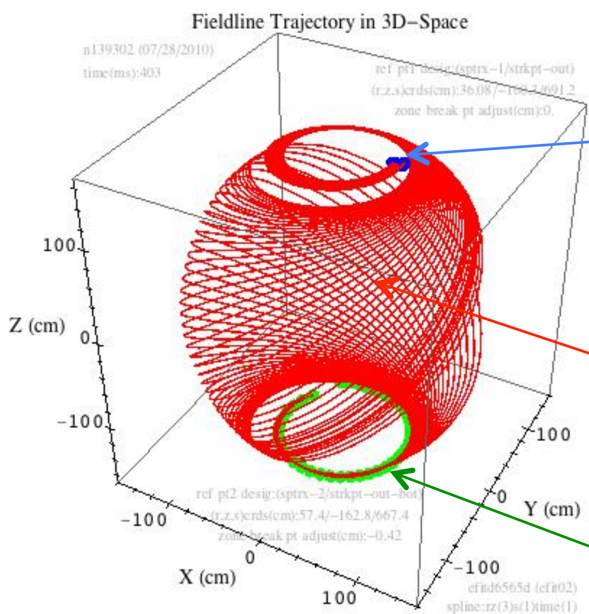
“Footprint” of a field line may become visible to optical sensors, as current flows through the sheath, interacting with neutrals and elevating the electron temperature through joule heating.

Striations observed on the divertor floor by infrared cameras under applied 3D field have been interpreted as a manifestation of strike point splitting due to the presence of a homoclinic tangle (Ahn, NF 50(2010)045010).

Another potential mechanism for creating striations is suggested here that occur in spite of the axisymmetry of background field, but in the presence of non-axisymmetric current source. The mechanism involves no strike point splitting.

Field Line Angular Dispersion Creates Spiral “Footprints”-2

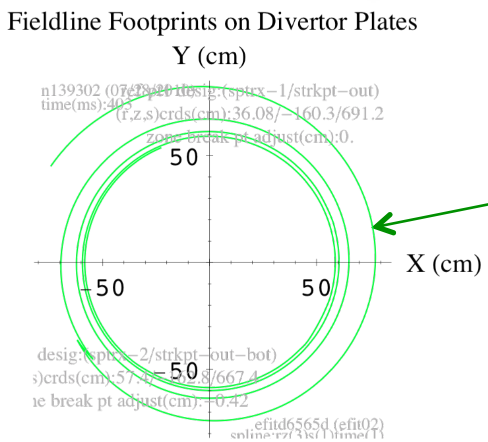
Field Lines in Outboard Zone
(outside Secondary Separatrix)



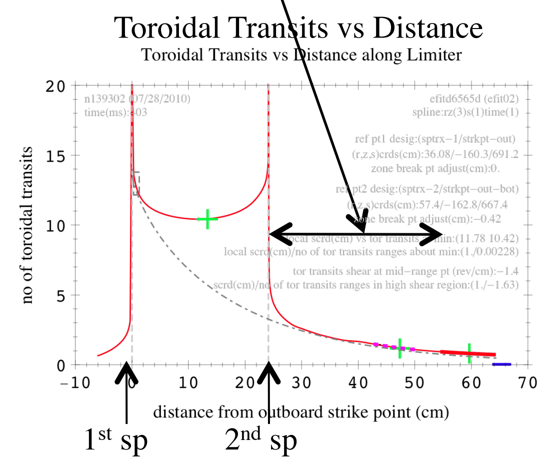
Field lines start in top divertor at the same toroidal angle but with a radial spread

Become widely dispersed in toroidal angle

Create a drawn-out “footprint” on bottom divertor



For a *large radial spread* at start, footprint can be a multi-turn spiral



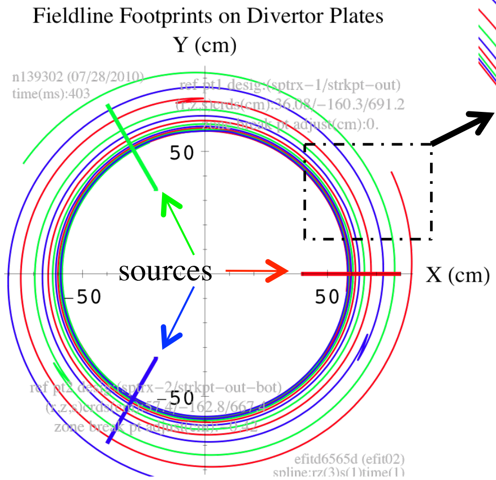
A bundle of field lines originating in top divertor becomes widely dispersed in toroidal angle, and creates a drawn-out footprint in bottom divertor.

Note the field line structure is relevant only when current indeed flows along these field lines (plasma may be too tenuous for significant current to flow in the far SOL except during MHD events, such as ELMs).

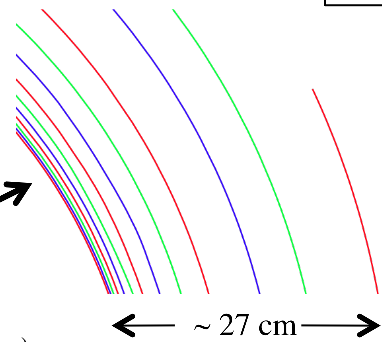
Multi-turn Spiral Footprints Locally Manifest as Striations-2

Field Lines in Outboard Zone
(outside Secondary Separatrix)

"n = 3" Current Source
Emulated by a δ-Function
at 3 Toroidal Angles



"striations"



Multi-turn spiral footprints could manifest as striations to localized observers.

"Footprint" of a field line may become visible to optical sensors, as current flows through the sheath, interacting with neutrals and elevating the electron temperature through joule heating.

Striations observed on the divertor floor by infrared cameras under applied 3D field have been interpreted as a manifestation of strike point splitting due to the presence of a homoclinic tangle (Ahn, NF 50(2010)045010).

Another potential mechanism for creating striations is suggested here that occur in spite of the axisymmetry of background field, but in the presence of non-axisymmetric current source. The mechanism involves no strike point splitting.

Summary-1

1. **Scrape-Off-Layer Current (SOLC) possesses the potential for acting as a "middleman," and transforming an error field pattern externally applied into a different field pattern actually acting on the plasma.**
2. **During quiescent discharge periods, mostly axisymmetric SOLC flows in the near SOLC zone and no or little SOLC flows in the far SOLC zone; During ELMs, highly non-axisymmetric SOLC flows in both near and far SOLC zones.**
3. **External 3D field has little effect on SOLC during ELMs in the far SOLC zone; External 3D field on SOLC in the near SOLC zone is yet to be studied.**

Summary-2.

4. SOLC can generate a field pattern that reflects the structure of field lines in the SOL, containing:
   a) "high shear" (large toroidal angular dispersion) regions, which tend to generate toroidally symmetric field, and
   b) "low shear" (small toroidal angular dispersion) regions about a zero-shear "sweet spot," which tend to generate toroidally asymmtric field.
5. SOLC can generate, in *axisymmetric* background field, spiraling striations of current attachment points ("footprints") that resemble spiraling striations attributed to "strike point splitting" in a complex magnetic structure known as a homoclinic tangle produced by externally applied 3D field.