The Structure of Flux Tubes for Generating Toroidal Asymmetry in the Tokamak Scrape-Off-Layer (SOL)

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ABSTRACT

The Structure of Flux Tubes for Generating Toroidal Asymmetry in the Tokamak Scrape-Off-Layer (SOL),* H. Takahashi, E. Fredrickson, PPPL – Creating and maintaining a tokamak discharge involve toroidally localized operations, including particle and heat inputs through gas puffing and neutral beam and pellet injections. In the main plasma, the injected particle and heat distributions become toroidally symmetric through rapid transport along infinitely long field lines forming irrational magnetic surfaces. But in the SOL, rapid transport along open finite-length field lines, which end on a structural component, can result in a toroidally asymmetric region (flux tube) with properties distinguishable from those of its surroundings. Of particular interest is a flux tube carrying field-aligned current, thermoelectrically driven by an electron temperature difference between its two ends. This work investigates the efficacy of such Scrape-Off-Layer Current (SOLC) in generating error field in an otherwise magnetically symmetric tokamak as a function of the flux tube structure, and explores the possibility that SOLC-generated error field contributes to strong plasma rotation braking often observed when the SOL magnetic structure rapidly evolves in an early discharge phase.

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Highlights

Could Gas Puff, NBI, Pellet, and Other Asymmetric *Operations* Lead to 3D Error Field in Tokamaks?

Operational procedures commonly practiced in tokamaks that are not toroidally symmetric could compromise even an ideal magnetic symmetry painstakingly attained through engineering perfection.

The sequence of operational procedures, including carefully tailored temporal profiles of Neutral Beam Injection (NBI), gas puffing, plasma cross-sectional shaping, and H-mode timing in relation to plasma current ramping, have been important tools in the arsenal of tokamak operators for avoiding or ameliorating rotation slow-down/locking and disruption in the early discharge evolution*. This may suggest the presence of a 3D error field due to thermoelectrically driven currents dynamically produced dependent on the SOL conditions.

*** S. Gerhardt, priv. comm.**

Contributions to Goals of NSTX-U Program

The capability to operate in low collisionality regimes is a matter of singular importance to the NSTX-U program, as it allows extrapolating to future tokamak and ST reactors physics understanding of today's most critical unsolved problems in fusion and useful operational scenarios that may be gained through the program.

Locked modes, conventionally thought to result from structural magnetic asymmetry, and attendant disruptions are the single most important impediment to attaining desired collisionality regimes through *low density* in many tokamaks. A large performance improvement has in fact resulted from correcting gross structural asymmetry in NSTX. Locked modes nevertheless remain to be a potent obstacle.

A study has been underway to examine 3D error field generation from an unconventional perspective: currents flowing along open field lines in the SOL may play an important role in the process. Specifically, this poster addresses the question whether or not *asymmetric operational procedures may lead to a distribution of SOLC with a propensity for producing error field.*

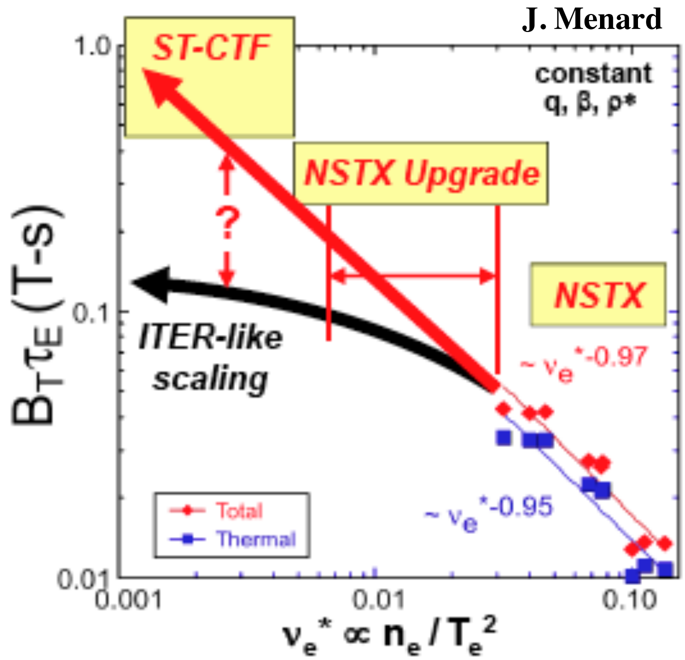
It would be a significant contribution to the NSTX-U program and beyond, if this study bears fruit in helping to understand origins of locked modes and develop ways for preventing or ameliorating them.

Adapted from APS '12

INTRODUCTION AND MOTIVATION

(*) This introduction/motivation section is largely adapted from APS ’11 and ‘12.

Importance of Low Density for NSTX-U



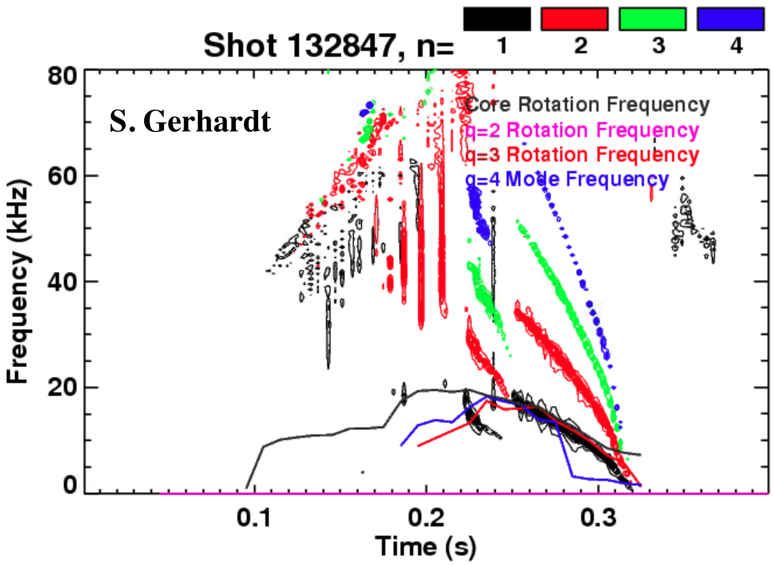
An important programmatic goal of NSTX-U is to provide environment for a broad range of studies at low collisionality. Major hardware upgrade of NSTX-U for doubling Bt and Ip are powerful tools in achieving low collisionality through higher Te. It is necessary, however, to also maintain low density to achieve low collisionality.

Operating at ever-lower collisionality (~ ne/Te^2) is imperative for maintaining the relevance of any present-day device to future generation fusion facilities, as dominant physics may depend on this parameter in many key areas influencing the device performance, including confinement, stability, non-inductive start-up, and current sustainment.

Measurements at intermediate collisionality expected in NSTX-U would help to infer whether the favorable inverse scaling achieved in NSTX holds at much lower collisionality, thereby enabling compact and economical ST-based Fusion Nuclear Science Facility (FNSF) and Component Test Facility (CTF), with high fusion neutron flux and fluence, or instead be replaced by less favorable ITER-like scaling [J. Menard].

Adapted from APS '12

Locked Modes in Early Discharge in NSTX



Toroidal harmonic amplitude (n = 1-4) of magnetic signals shows rapid rotation slow-down and stoppage in a low density discharge, which ended in a β-collapse and disruption.

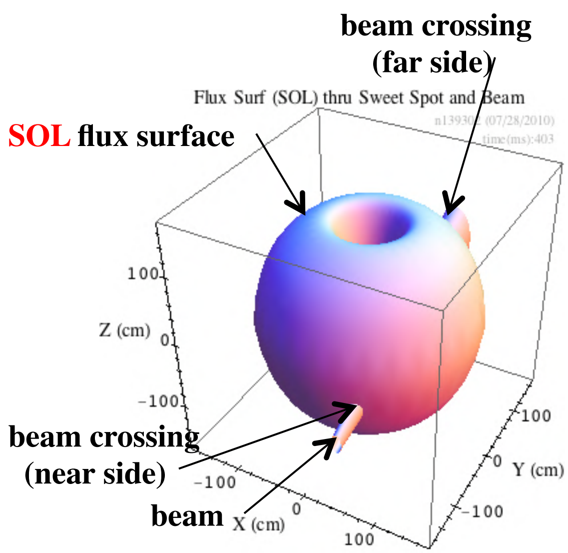
At sufficiently low densities, a likely early-phase discharge evolution in NSTX (and many other tokamaks) is rapid slowing down of plasma rotation to complete stoppage on a ~ 100 ms time scale even in the face of steady momentum input from NBI, often leading to a severe β-collapse or disruption.

Rotation slow-down can sometimes be arrested before complete stoppage through operational procedures, such as changes in evolution of plasma current, shape, fueling, heating, H-mode transition timing, optimizing Resistive Wall Mode (RWM) control, error field correction, and lithium pumping [S. Gerhardt].

A second NBI in NSTX-U at a more tangential injection angle should help maintain plasma rotation in the face of ill-understood drag forces by simply increasing momentum supply. Understanding the mechanisms draining momentum would contribute to producing low-density discharges for widely varying requirements. Developing active means of preventing slow-down based on physics understanding is also imperative, as the inability to routinely operate at low densities could undermine the important programmatic goals of NSTX-U.

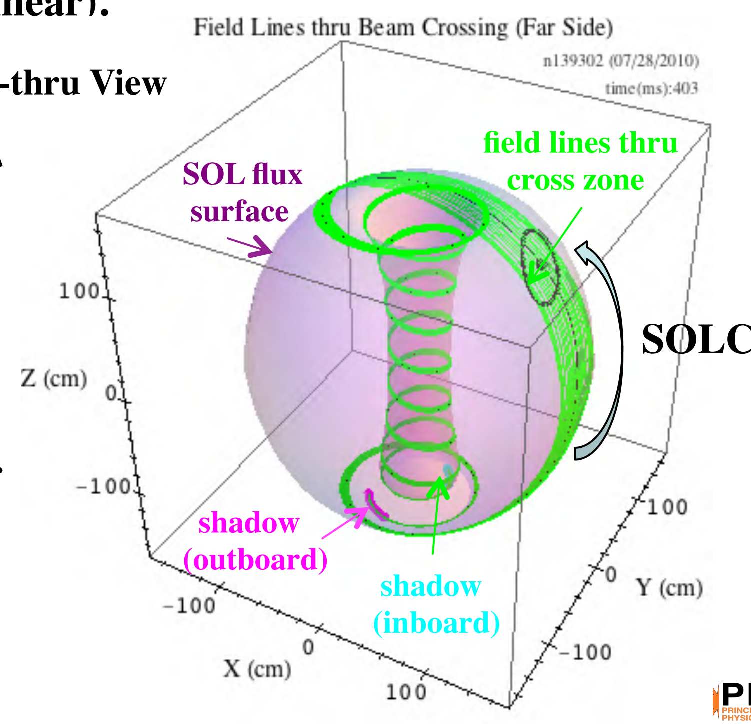
Adapted from APS '12

Asymmetry in SOL by Local Operation Processes



Localized tokamak operations may interact with the SOL (NB crossings illustrated here), create a Te difference between the two "shadows" of the interaction zones cast along open field lines onto in/outboard divertor floors (in part because of connection length difference, here, 21.2m/ 7.6m = 2.8), and drive thermoelectric currents. Localized lithium coating may alter thermo-electric potential as well as electrical resistance, both ohmic and ion sheath (the latter being non-linear).

See-thru View



A hypothetical ("cartoon") beam, with its axis at a small tangency radius and tilted upward off the horizontal and elliptical diverging cross section, is shown here to suggest that these geometrical properties may affect the current path and location (rapidly) and size of "shadows," offering tokamak operators a possibly useful tool.

Adapted from APS '12

STRUCTURES OF FLUX TUBES

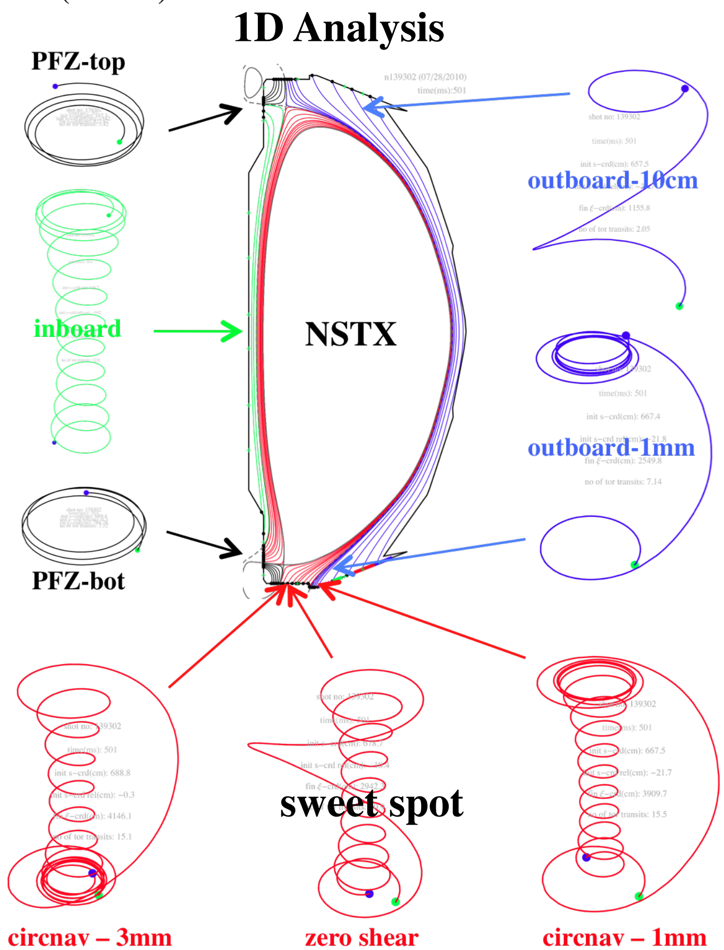
This work has been progressing in stages along the increasing dimensionality in representing field line structures in the SOL :

Field Lines (1D) → Field Ribbons (2D) → Flux Tubes (3D)

The work plan is to investigate the flux tube structures in all field line zones (see next slide), but particularly the outboard zone (this poster) and circumnavigating zone (coming soon).

Primary and Secondary Separatrices Demarcate SOL

#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 non-communicating zones:

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

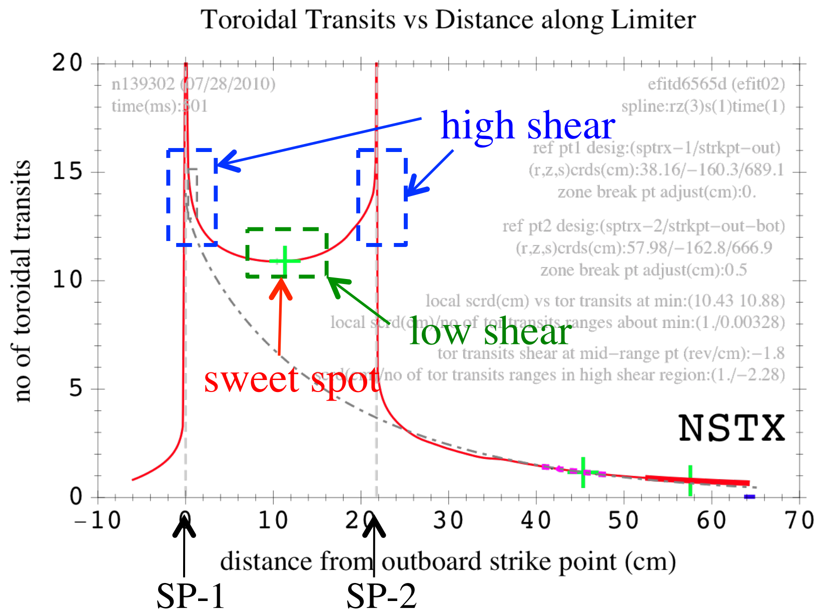
Field line geometry differs qualitatively in these zones. Important roles played by secondary separatrix (between red and blue zones) have seldom been discussed.

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

Adapted from APS '11

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 toroidal transits with respect to the location of field-line starting point is the "shear" in 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 (as dotted exponential line) because of the presence of a *secondary separatrix*.

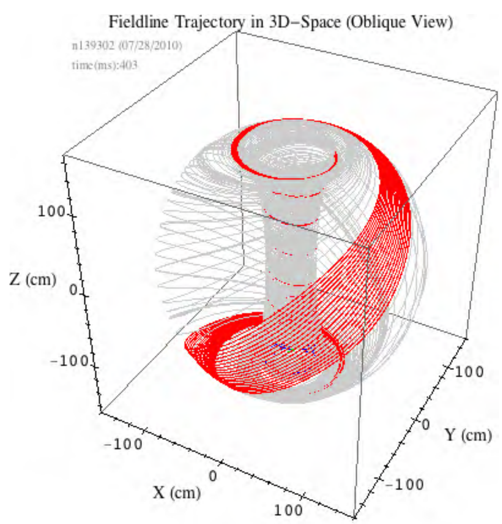
Instead, the number of transits possesses two regions of high shear (rapid variations with respect to the starting-point distance) near the primary (SP-1) and secondary (SP-2) strike points and a region of low shear about a zero-shear "sweet spot."

Adapted from APS '11

SOLC Can Generate Symmetric or Asymmetric Field

2D Analysis

A field "ribbon" is finite in length and in an additional lateral dimension, usually either radial or toroidal, but is infinitely thin in the third dimension.



Two field "ribbons" are shown: one toroidally widely dispersed (gray) and another stayed bundled together (red).

High-Shear ⟺ Dispersed ⟺ Symmetric Field

A bundle of field lines in a high-shear region, all starting at the same toroidal angle but slightly different distances from the strike point, suffers strong toroidal angular dispersion, and become widely distributed around the torus (gray filaments). SOLC flowing along these field lines produces field that is substantially toroidally symmetric in spite of the fact the current distribution itself at the starting points was strongly asymmetric (in fact, a δ-function in toroidal angle).

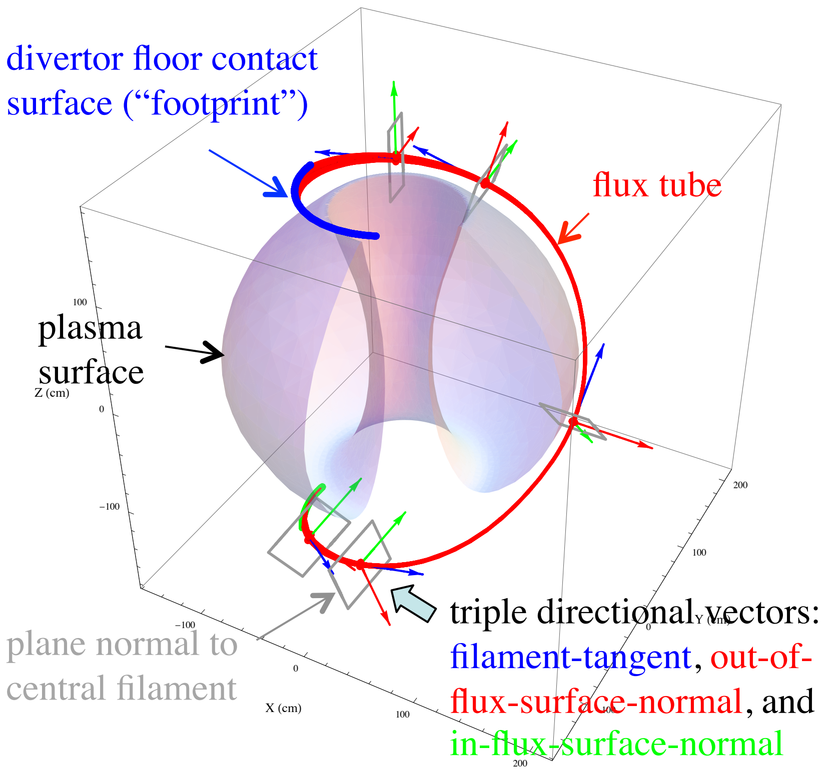
Low-Shear ⟺ Stay Together ⟺ Asymmetric Field

A bundle of field lines in a low-shear region clustered around the zero shear "sweet spot," again all starting at the same toroidal angle but slightly different distances from the strike point, suffers little toroidal angular dispersion, and remains bundled together (red filaments). SOLC flowing along these field lines will produce toroidally asymmetric field.

Adapted from APS '11

Flux Tube Geometry Analysis

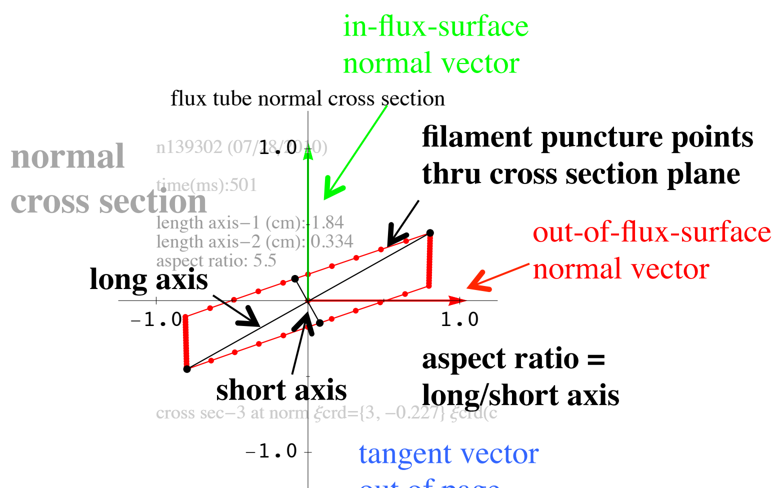
3D Flux Tube (*)



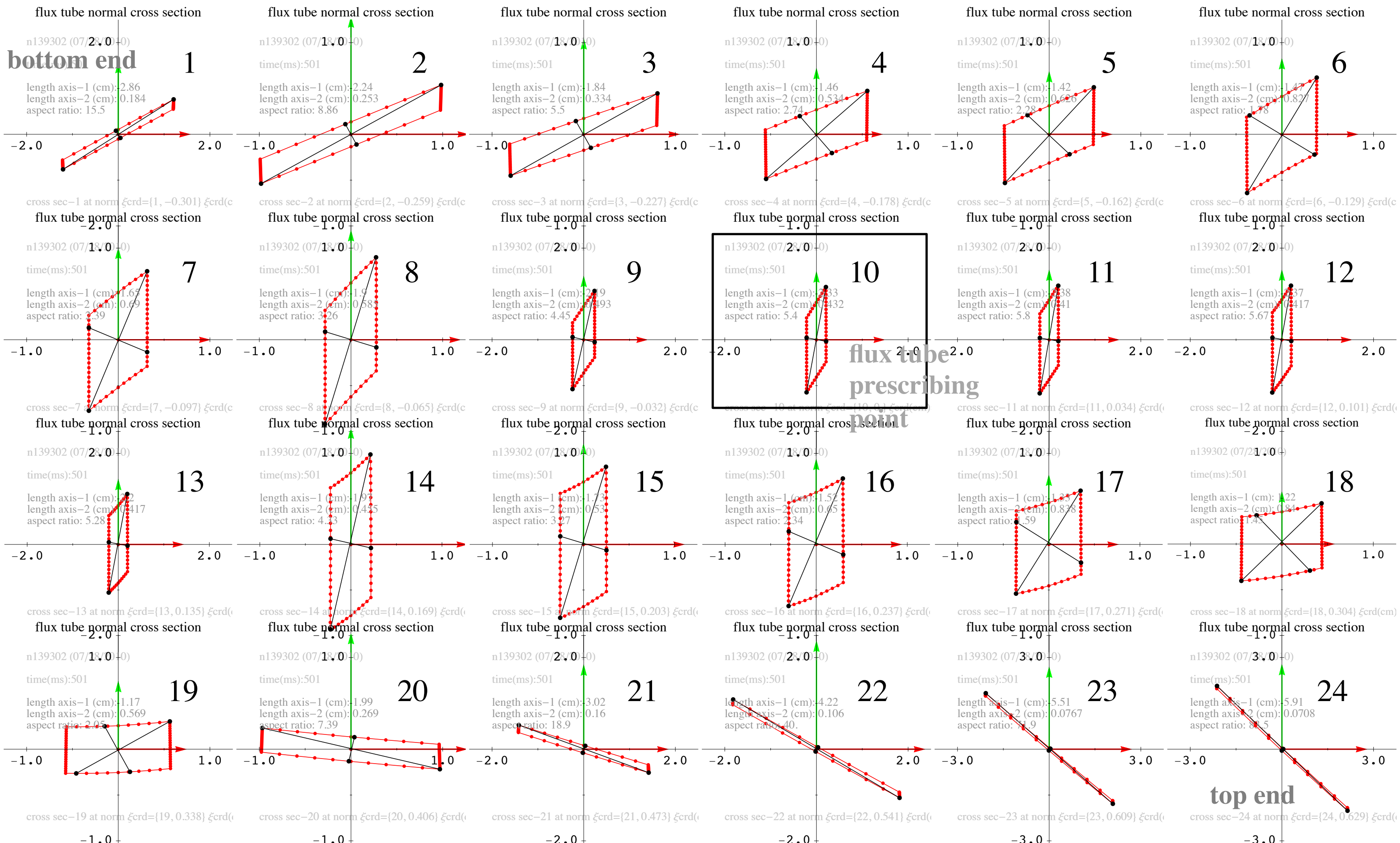
(*) The flux tube in this explanatory drawing has a circular normal cross section at the magnetic axis plane when viewed head-on along its central filament, and is different from the flux tube discussed below with a more rectangular cross section.

A flux tube in the SOL is a 3D volume bounded by filaments on its side surfaces and structural components on its end surfaces. A flux tube is meaningfully identifiable as such, only if some properties of the volume, such as particle, heat, and current densities, differ from those of the surrounding regions.

Any surface, planar or not, that intersects the flux tube may be defined as its cross section. But a sensible choice is a plane normal to a central filament of the flux tube, if its lateral dimensions are to be compared with the ion gyro-radius as has been done elsewhere.



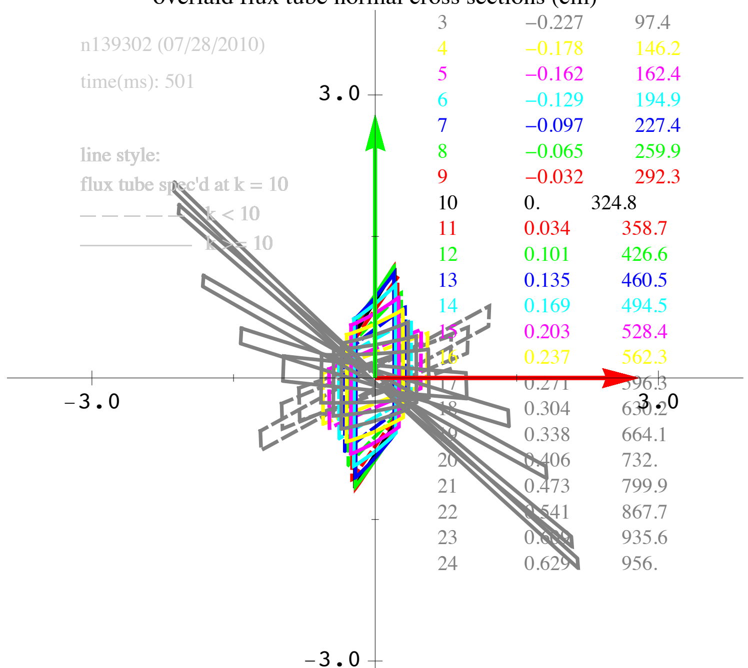
Cross Sections along Flux Tube Central Filament

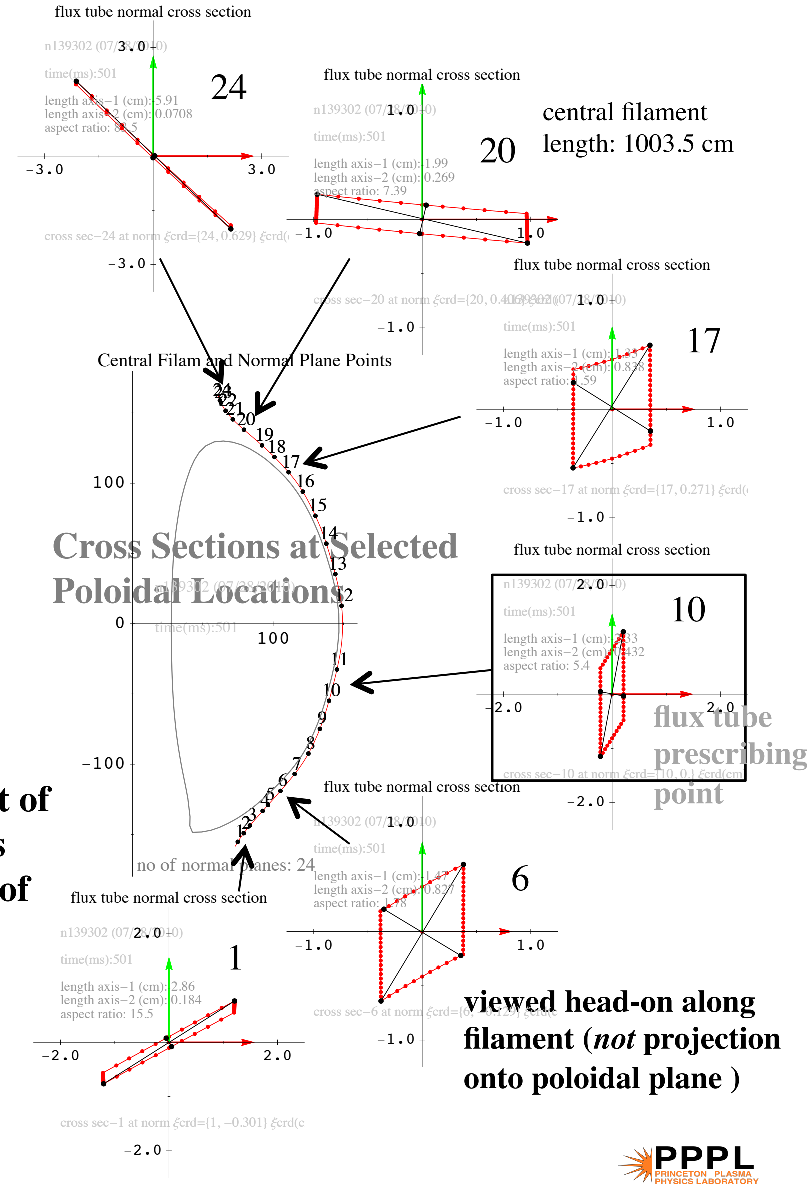


The flux tube was prescribed at (R, Z) = (139.7, -54.9) cm, just outside (2 cm) secondary separatrix as a “pie-shaped” space curve, 1 deg by 2 cm wide, in a plane normal to the plasma surface (see also next slide).

In-Flux-Surface Compression Prominent

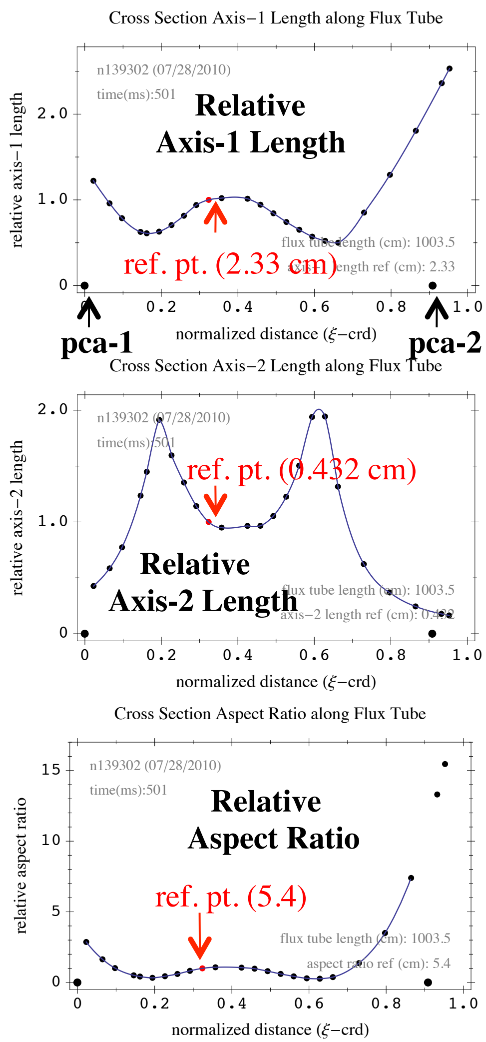
All Cross Sections Overlaid





The direction tangent to the flux tube central filament is out of the plane of the page, the direction normal to flux surface is along the horizontal axis, and the direction normal to both of these directions and hence within flux surface is along the vertical axis. ***Compression in the in-flux-surface direction,*** **accentuated only in part by shearing is the most prominent cross section deformation from mid-plane region to either divertor.**

Cross Section Axes Lengths and Aspect Ratio



Normalized Distance

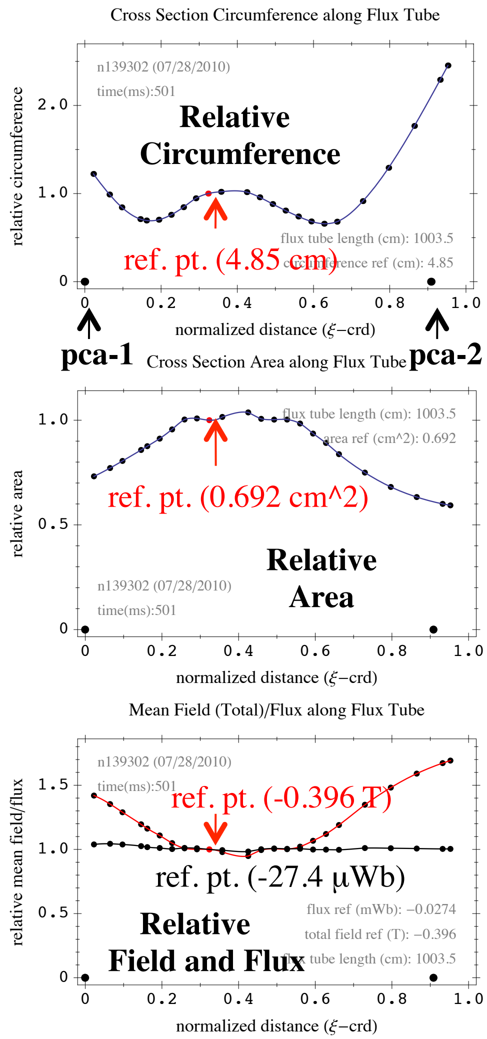
Axis-1 is the longest axis that a cross section can accommodate. Axis-2 is the cross section width in a direction perpendicular to the axis-1. The aspect ratio of a cross section is the length of axis-1 divided by that of axis-2.

Variations of the axis-1 and axis-2 lengths and aspect ratio, all relative to their values at the flux tube prescribing reference point, are shown as a function of the distance along the central filament normalized by its length (1003.5 cm).

The axis-1 length varies within a factor of ~ 2 from its reference value. The axis-2 length becomes shorter by a factor of 5 toward the Points-Of-Closest-Approach (PCAs) between the central filament and either the primary (pca-1) or secondary (pca-2) x-point.

The smallest axis-2 length (~ 1 mm) could become comparable to the deuteron gyro radius (1.6 mm at 0.4 T and 10 eV), if a flux tube of rather small (~ 1 cm) lateral dimensions is considered, as in this example. The important question is what physics dictates the consideration of flux tubes of a particular dimension.

Cross Section Circumference Length and Area



Normalized Distance

The circumference length and area of a cross section, both relative to their values at the flux tube prescribing reference point, are shown as a function of the distance along the central filament normalized by its length (1003.5 cm). The variations in these parameters are modest (~ 2) over the entire flux tube length.

This tiny flux tube contains magnetic flux of ~ -27.4 μWb, whose constancy along the flux tube length is demonstrated through approximate calculations (total field integrated over the cross section).

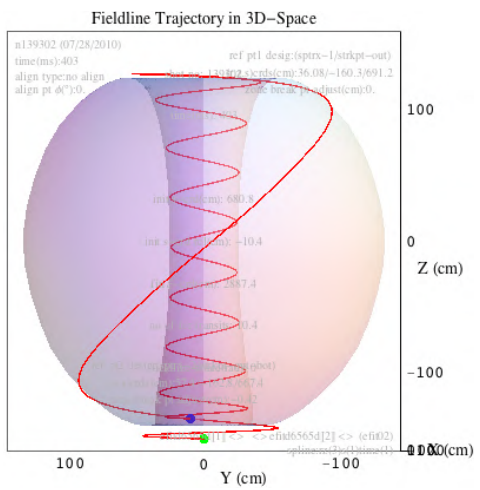
A similar set of calculations is yet to be performed for flux tubes within the circumnavigating zone (coming soon).

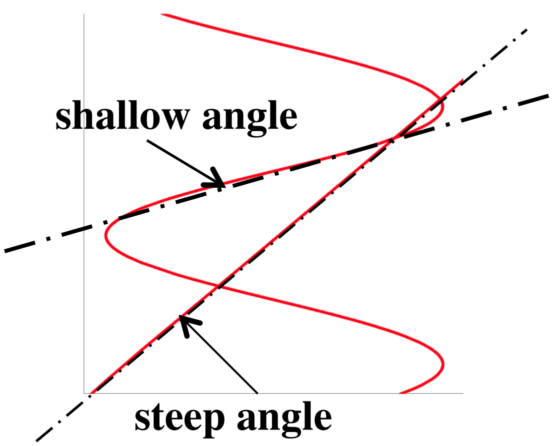
FIELD GENERATED BY RIBBON CURRENT SHEET

The research described in this poster is a work in (slow) progress, which has reached a point of being able to analyze the structures of flux tubes, but not yet field generated by a 3D volume distribution of SOLC as promised in the abstract.

For completeness, field calculations for a 2D ribbon current sheet reported in APS '12 are excerpted here. These calculations were for a ribbon in the circumnavigating zone (but the flux tube analyzed above in the present poster is for the outboard zone).

SOLC Generates Low-n Harmonics on Inboard Side





The single 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 and a *wide-band* toroidal harmonic spectrum.

It may perhaps be counter-intuitive that the "multi-turn structure" on the inboard side efficiently generates along the *inboard* q_{95} surface a narrow *low-n* spectrum. This comes about because SOLC filament runs at a very shallow pitch angle on the inboard side. (When viewed at an extreme close range – with "your nose nearly touching it"– the filament would appear to fill your entire field of view.)

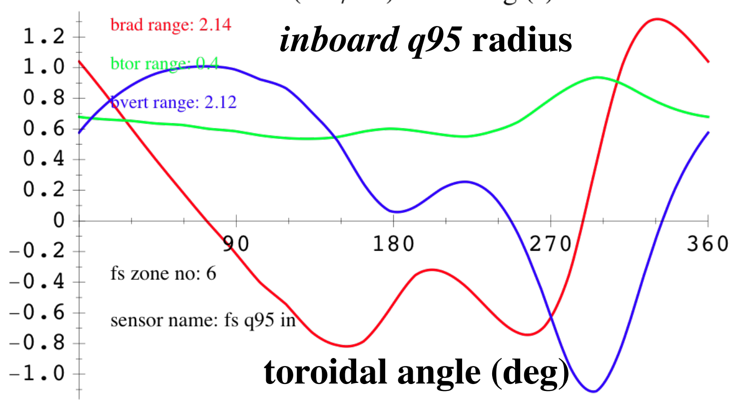
SOLC-generated field consequently has low-n harmonics that peak at the inboard side and decay rapidly toward magnetic axis and further onto the outboard side. This is in sharp contrast to field generated by external RMP coils.

These differences may manifest in the nature and magnitude of drag forces acting on the plasma in the locked mode process.

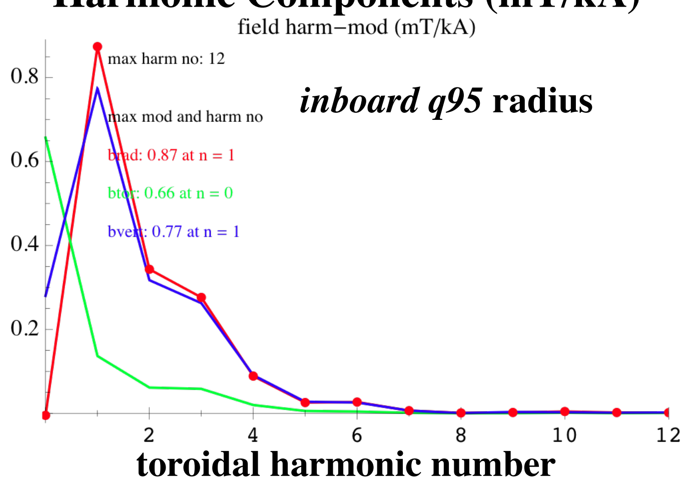
Adapted from APS '12

SOLC Field (n = 1) Large along Inboard q-95 Circle

Field (mT/kA) along Toroidal Circle



Harmonic Components (mT/kA)



Radial, toroidal, and vertical fields (mT) generated by SOLC ribbons (see slide-8) carrying unit current (1 kA) through the two NBI crossing zones (0.5 kA each) are calculated using the Biot-Savart's law along toroidal circle in the magnetic axis plane at the major radius of inboard q_{95} surface.

SOLC-generated radial field on the inboard side has a harmonic structure peaked at n = 1 and ~ 0.87 mT/kA, which, at a unit current level, is far bigger than RMP coil field (~ 0.1 mT on the *outboard* side) that is itself thought to be large enough to elicit a significant plasma response.

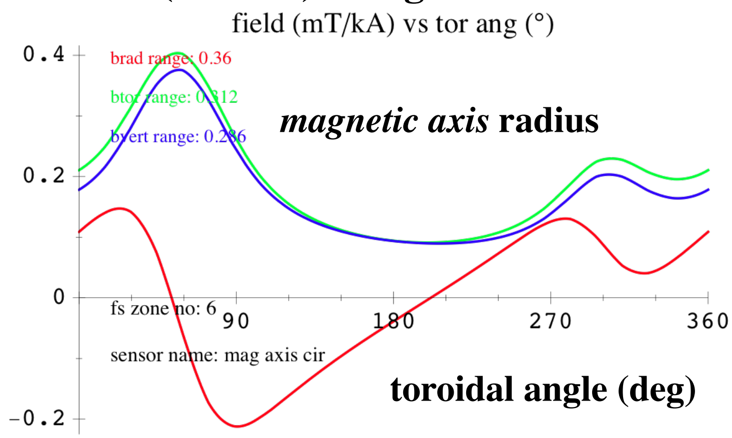
It may be on the *inboard* side where SOLC-generated field may be felt as an important contributor to drag forces acting on the plasma.

Interaction through flux coupling (mutual inductance) between SOLC and MHD current inside the plasma will be a subject to be explored in the future.

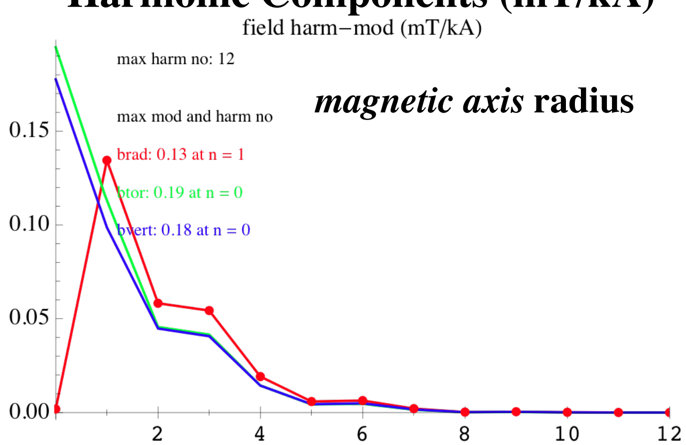
Adapted from APS '12

SOLC Field (n = 1) Still Large on Magnetic Axis Circle

Field (mT/kA) along Toroidal Circle



Harmonic Components (mT/kA)



Radial, toroidal, and vertical fields (mT) generated by SOLC ribbons (see slide-8) carrying unit current (1 kA) through the two crossing zones (0.5 kA each) are calculated using the Biot-Savart's law along toroidal circle in the magnetic axis plane at the major radius of magnetic axis.

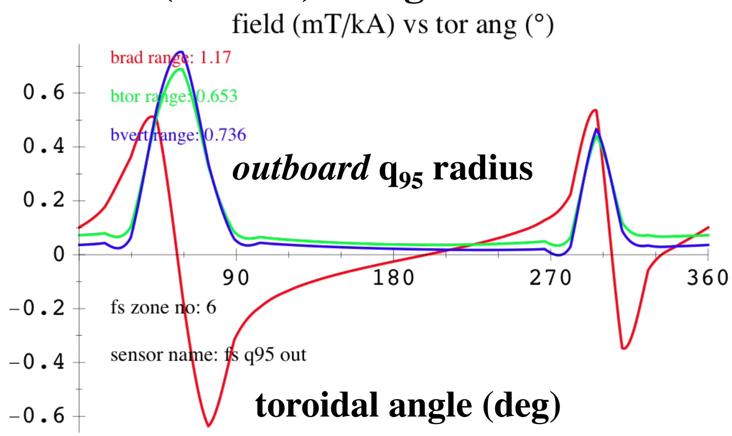
SOLC-generated radial field at magnetic axis has a harmonic structure peaked at n = 1 and ~ 0.13 mT/kA, which, at a unit current level, is comparable to RMP coil field (~ 0.1 mT on the *outboard* side) that is itself thought to be large enough to elicit a significant plasma response.

More than half of the plasma thus comes under SOLC-generated low-n field that is, at a unit current level, comparable to or greater than RMP coil field.

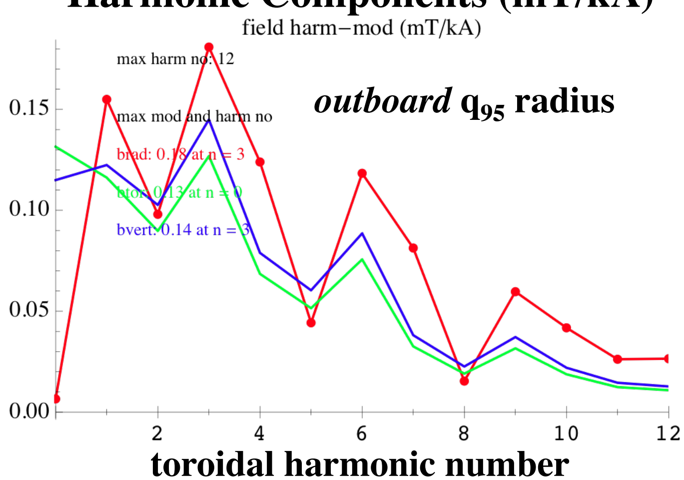
Adapted from APS '12

SOLC Field Peaks at n = 3 along Outboard q-95 Circle

Field (mT/kA) along Toroidal Circle



Harmonic Components (mT/kA)



Radial, toroidal, and vertical fields (mT) generated by SOLC ribbons (see slide-8) carrying unit current (1 kA) through the two crossing zones (0.5 kA each) are calculated using the Biot-Savart's law along toroidal circle in the magnetic axis plane at the major radius of outboard q_{95} surface.

Interference of the "near" and "far" ribbons (see slide-8), ~ 115 deg apart, results in a harmonic structure peaked at n = 3 and ~ 0.18 mT/kA, which, at a unit current level, is comparable to RMP coil field (~ 0.1 mT on the *outboard* side) that is itself thought to be large enough to elicit a significant plasma response.

Important contributions to drag forces acting on the plasma, however, may arise from SOLC-generated field in the inboard and interior regions.

Adapted from APS '12

Summary

1. **Constructed a set of tools for analyzing the structures of flux tubes in the tokamak Scrape-Off-Layer (SOL) with an ultimate goal in mind for determining whether or not a class of toroidally asymmetric *operational* procedures is a potential dynamic source of 3D error field through generation of an asymmetric distribution of Scrape-Off-Layer Current (SOLC).**

2. **The initial analysis, so far in a limited class of flux tubes, revealed considerable narrowing in a lateral dimension of the cross section of a flux tube prescribed in an outboard mid-plane region when the cross section is traced from there toward and past either primary or secondary x-point.**

3. **The question is yet to be addressed of whether or not field generated by SOLC in a 3D flux tube replicates the interesting features reported earlier of field generated by SOLC in a 1D filament or a 2D field ribbon.**