Error Field in Ideal Magnetically Symmetric Tokamaks Generated through Asymmetric Shadows Cast by Neutral Beams on Divertor Floor

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

The 54th Annual Meeting of Division of Plasma Physics(*)
American Physical Society
Providence, Rhode Island
October 29 - November 2, 2012
Paper PP8.00015

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

ABSTRACT

Error Field in Ideal Magnetically Symmetric Tokamaks Generated through Asymmetric Shadows Cast by Neutral Beams on Divertor Floor ,* H. Takahashi, E. Fredrickson, S. Gerhardt, *PPPL* – The neutral beam intersects open field lines as it traverses the Scrape-Off-Layer (SOL), and casts its "shadows" on the divertor floor, where beam particles and heat lost in transit are deposited. These shadows are toroidally asymmetric in shape, reflecting the localized nature of the beam geometry and, unlike in the main plasma, a lack of symmetrizing field-line property (irrational surfaces) in the SOL. Thermoelectrically driven Scrape-Off-Layer Current (SOLC) due to a Te difference between these shadows is also toroidally asymmetric, and, when considered on a single flux-surface basis, generates an error field in an otherwise ideal magnetically symmetric tokamak. Spreading of the SOLC over flux surfaces has a symmetrizing effect on magnetic field produced due to field-line shear, except around a "sweet spot" midway between primary and secondary separatrices, necessitating calculations along the entire SOL beam path for a reliable field estimate. This study explores the possibility that error field due to a SOLC in the beam shadows may contribute to strong plasma rotation braking often observed when the SOL magnetic structure rapidly evolves in an early discharge phase. Similar considerations may apply to pellet paths, gas puff clouds, and other operational asymmetries.

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

Highlights

Do “Shadows” Cast by a Neutral Beam in SOL Lead to 3D Error Field?

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 possible presence of a dynamically produced 3D error field dependent on the SOL conditions.

Neutral beam intercepts open field lines in the SOL and casts its asymmetric shadows on the divertor floors, which may lead to thermoelectrically generated Scrape-Off-Layer Current (SOLC) and attendant 3D error field.

Contributions to Goals of NSTX-U Program

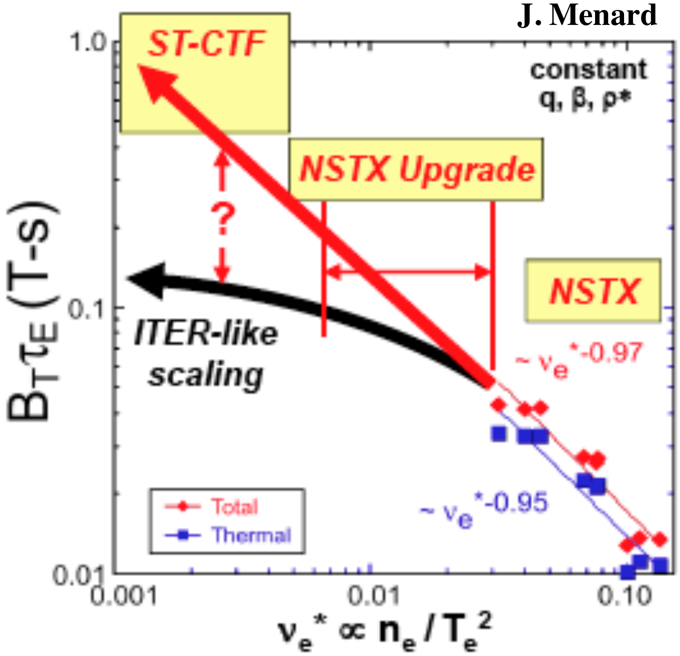
The capability to operate in low collisionality regimes is a matter of singular importance to the NSTX-U program, as it allows extrapolating to future tokamak and ST reactors physics understanding of today's most vexing problems in fusion and useful operational scenarios that may be gained through the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

Importance of Low Density for NSTX-U



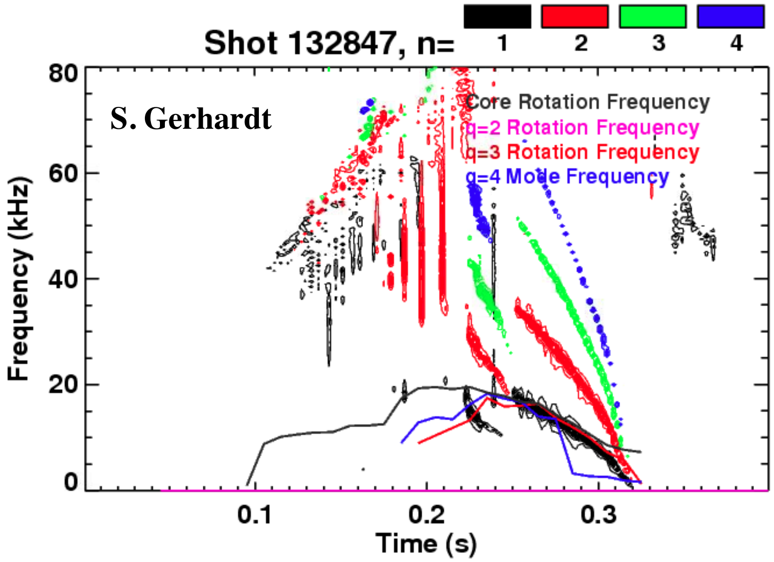
J. Menard

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 the 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 [Menard].

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.

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.

SOLC Measurement and Modeling

In NSTX most discharges start up in a high-triangularity configuration while SOLC sensors are installed for measurements in low-triangularity configurations. Efficacy of SOLC in causing locked modes in early discharge is therefore presently assessed based on modeling.

SOLC measurements in a discharge that evolved from a high to low triangularity configuration, extensively discussed earlier (APS '11) and also reproduced in the next slide, may be useful though not directly applicable to the discharge period of interest. Toroidal harmonic analysis, using a Singular Value Decomposition (SVD) method, of signals from a toroidal array of 6 SOLC sensors showed that poloidal current reached ~ 1.9 kA (n = 0) during a quiescent period while it peaked at ~ 4.5 kA (n = 1) shortly before disruption.

Field generated by a single filamentary current is first calculated (APS '11); fields by multiple filaments are aggregated into field by a sheet current (this poster); fields by multiple sheet currents are summed into field by a volume-distributed current (future). For a given total current (1 kA), each stage has a tendency to depress the peak and broaden the width of field's toroidal harmonic spectrum, and extend a field pattern further in space. This poster discusses field by a sheet current located at the "sweet spot" of the SOL field-line structure, and defers the study of field by volume-distributed current to a future opportunity.

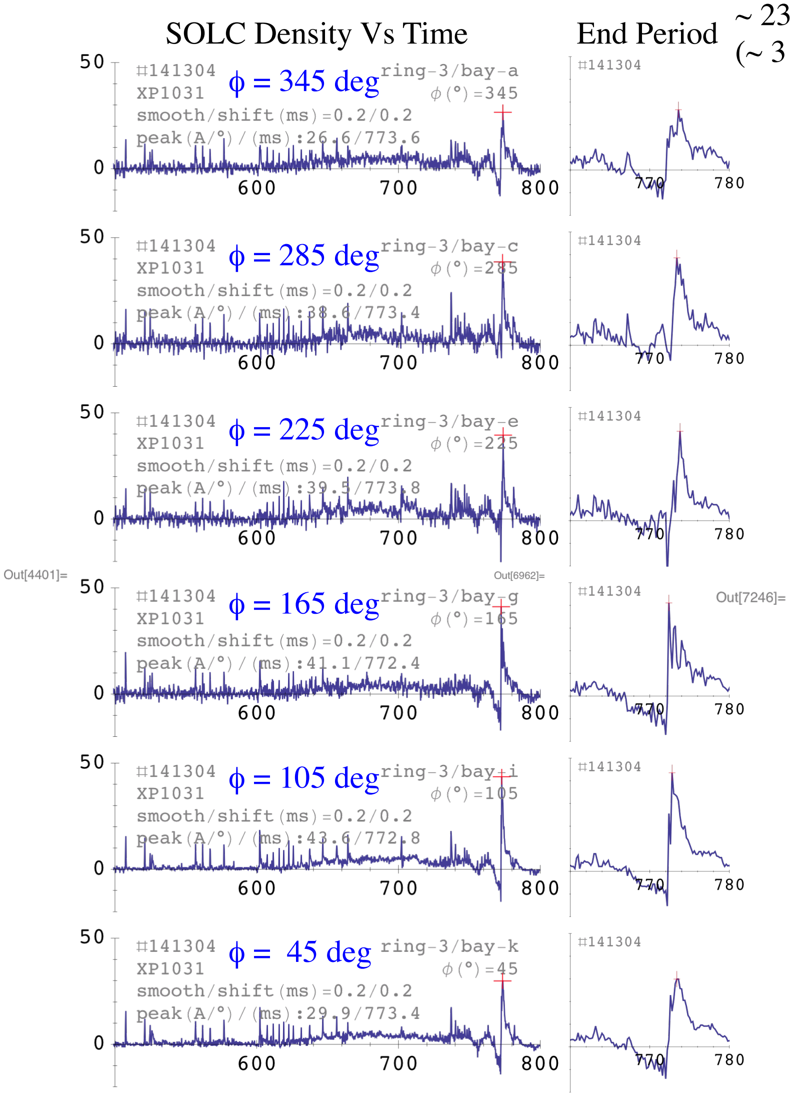
The relationship between SOLC and field is non-trivial, and the overall spatial structure, not just individual field lines, needs to be examined: a symmetric current distribution always leads to a symmetric field distribution, but an asymmetric current does not always yield an asymmetric field because of sheared toroidal angular dispersion of field lines.

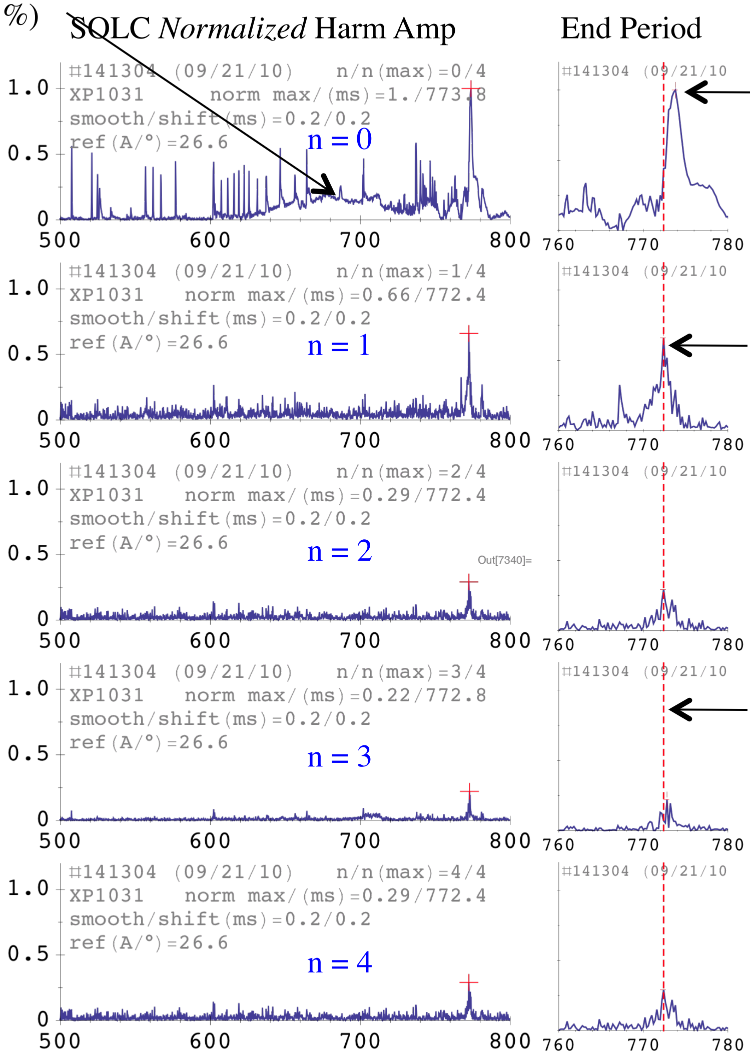
SOLC Measured in NSTX

Toroidal Spatial Variations

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

Toroidal Harmonic (SVD) Analysis


SOLC Density Vs Time
End Period


SOLC *Normalized* Harm Amp
End Period

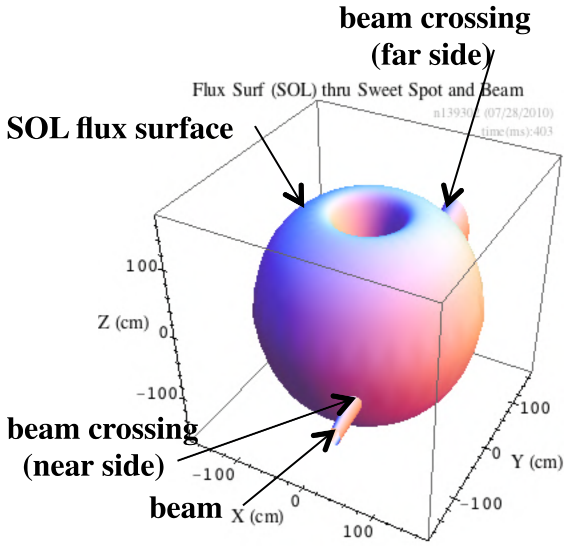
n = 0
~ 10 kA (pol)
~ 120 kA (tor)
(~ 17 %)

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

n > 0 leads n = 0
causality?

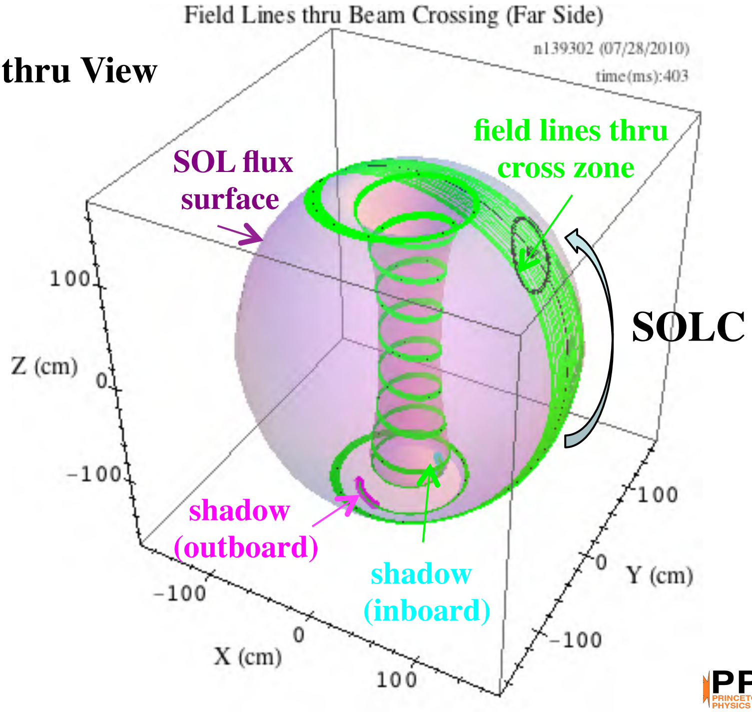
from Results
Review '10

Current Driven by NBI Charge Exchange Heat Loss in SOL



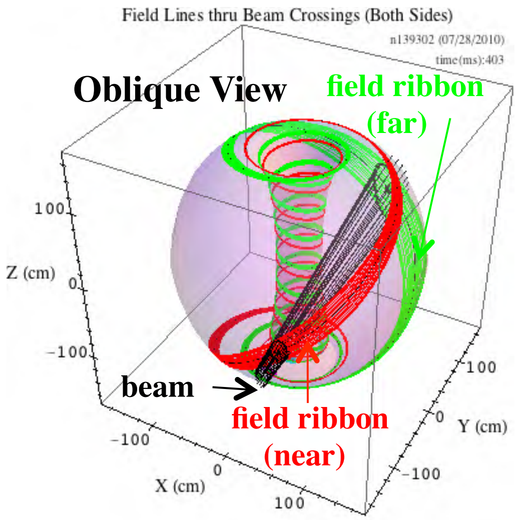
Charge exchange loss from NB while crossing the SOL may create a Te difference between the two "shadows" cast along open field lines onto in/outboard divertor floors, in part because of connection length difference, here, 21.2m/7.6m = 2.8, and drive a thermoelectric current. Localized gas puff into the SOLC regions, lithium, etc., may alter thermo-electric potential as well as electrical resistance, both ohmic and ion sheath (the latter being non-linear).

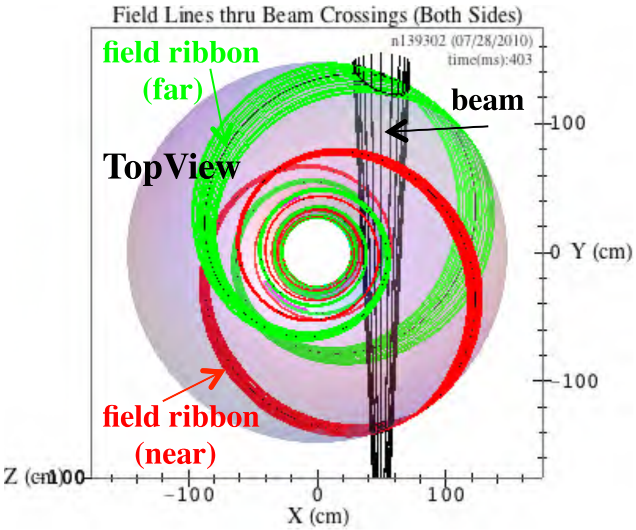
See-thru View



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 indicate that these geometrical properties may affect the current path and location (rapidly) and size of "shadows," offering tokamak operators a possibly useful tool.

Field Based on Single-Flux-Surface Model





A single ensemble of field lines ("field ribbon") on a single flux surface intercepted by the beam, either at a near or far crossing zone, would generate, if it indeed carries thermoelectric current, a wide-band toroidal harmonic field structure, reflecting the narrowness of the ribbon's toroidal width.

Field would be strong in the immediate vicinity of a field ribbon, but harmonic decomposition should reveal largely similar amplitudes for low to high harmonic components.

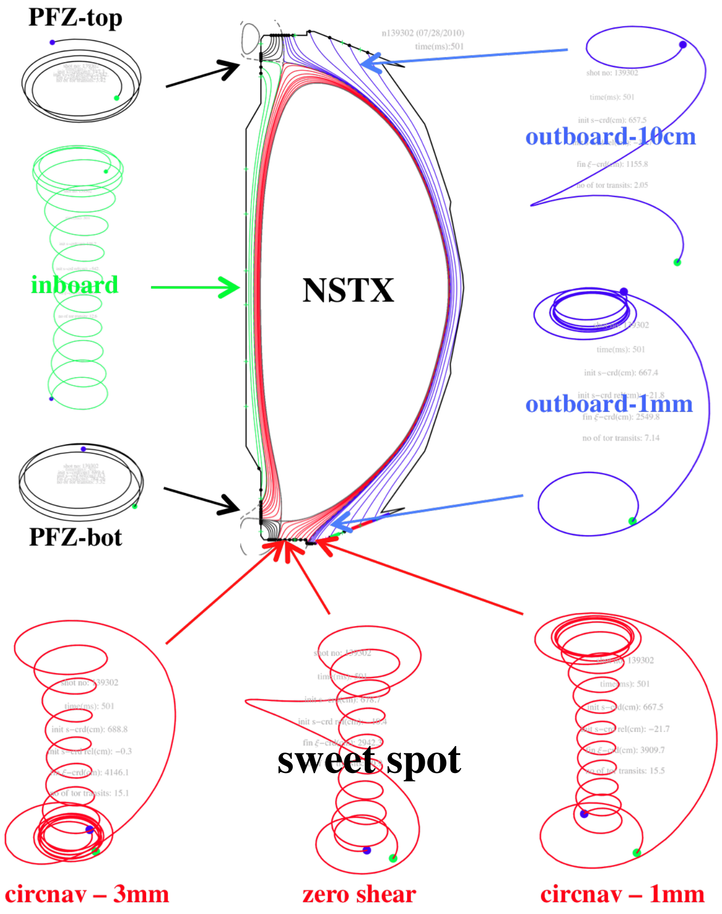
But a pair of field ribbons, passing through both near and far beam-intercepting zones, though still on a single flux surface, would enhance a low-n toroidal spectrum because the zones are apart by a distance comparable to the device diameter (here by ~ 115 deg or n ~ 3).

These are superficial expectations on field that may be generated by SOLC based on a model wherein it flows in an infinitesimally thin current sheet on a single flux surface.

Considerations of cooperative or destructive influence among field ribbons on neighboring flux surfaces would reveal (coming soon) a field-line structure with strong toroidally symmetrizing properties in parts of the SOL and an imbedded layer highly efficient in generating 3D error field, which are both a consequence of an opposing influence of the primary and secondary sepratrices.

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.

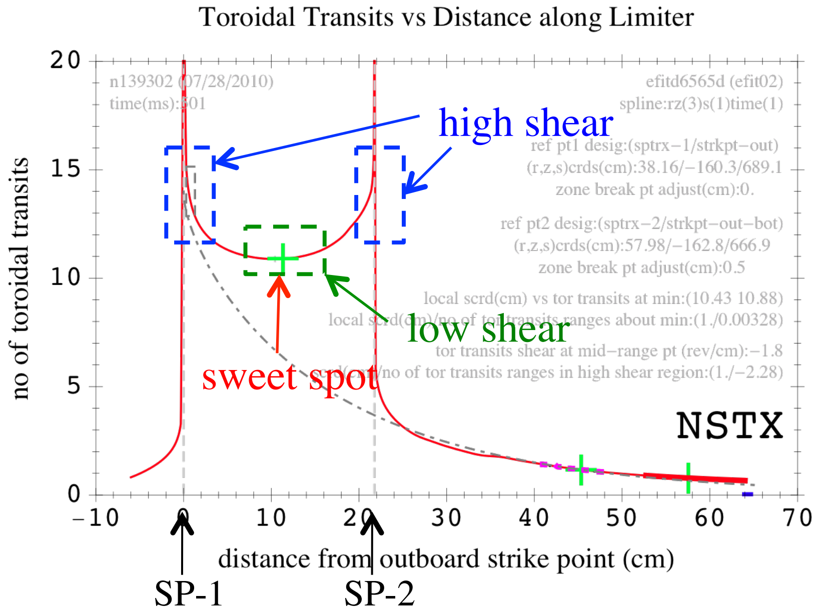
Field line geometry differs qualitatively in these zones. Secondary separatrix (between red and blue zones) plays a particularly important role.

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

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).

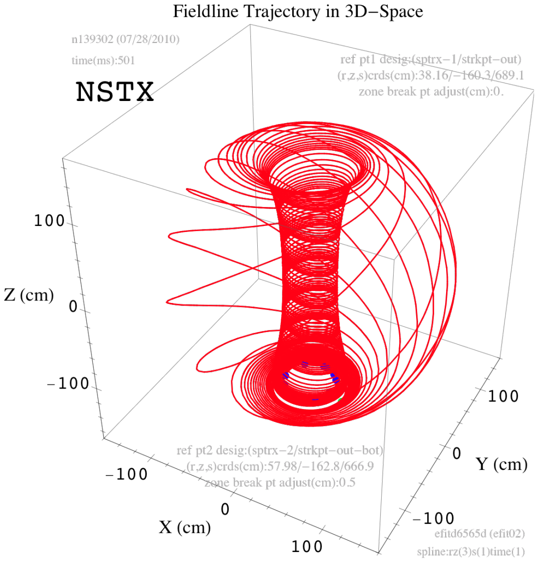
The rate of change of the number of transits with respect to the location of field-line starting point is the “shear” of the transit number in analogy to the shear in the safety factor for field lines inside the main plasma.

The number of transits does not decrease monotonically (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.”

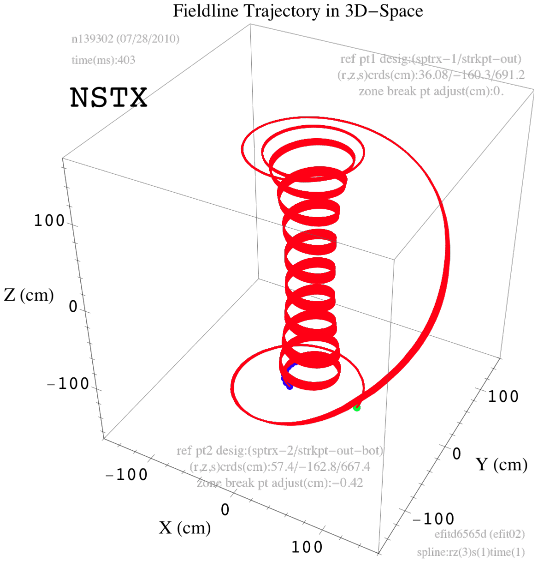
From APS ‘11

SOLC Can Generate Symmetric or Asymmetric Field



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. 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 aymmetric (in fact, δ-function in toroidal angle).

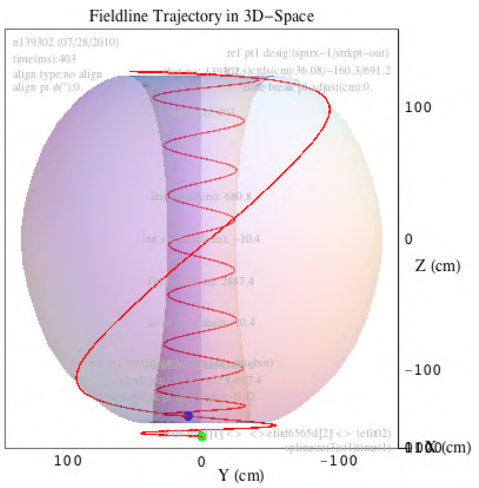


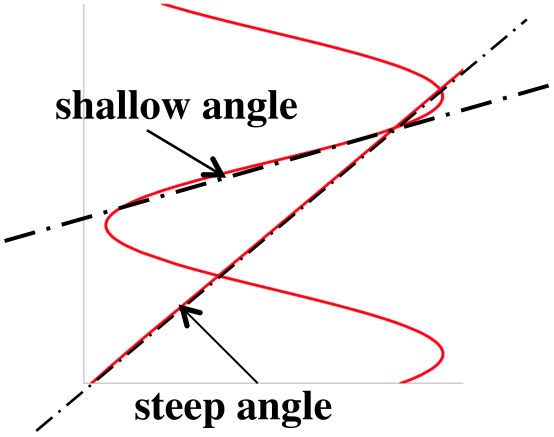
Low-Shear ⇔ Stay Together ⇔ Asymmetric Field

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. SOLC flowing along these field lines will produce toroidally asymmetric field.

From APS '11

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.

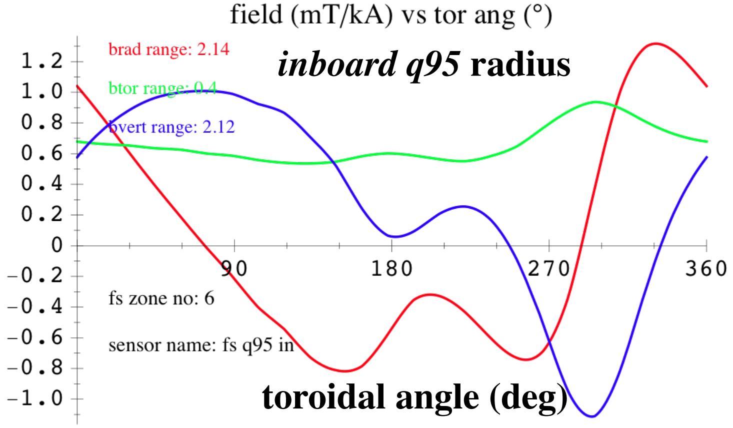
It may perhaps be counter-intuitive that the "multi-turn structure" on the inboard side efficiently generates along the *inboard* q_{95} surface a narrow low-n spectrum. This comes about because SOLC filament runs at a very shallow pitch angle on the inboard side. (When viewed at an extreme close range – 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.

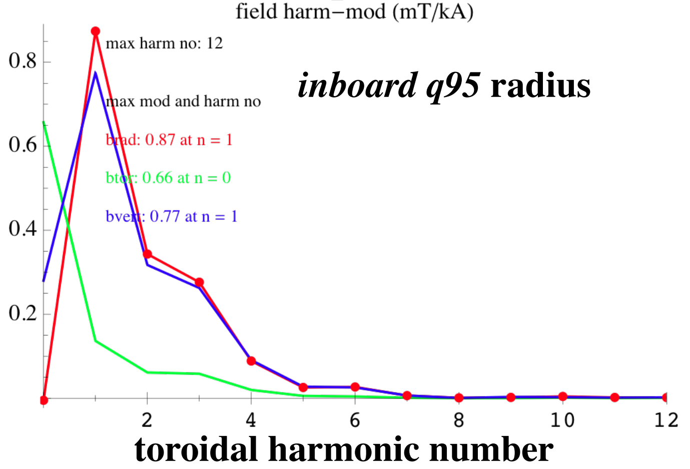
These differences may manifest in the nature and magnitude of drag forces acting on the plasma in the locked mode process.

SOLC Field Is Strong along Inboard q-95 Circle

Field (mT/kA) along Toroidal Circle



Harmonic Components (mT/kA)



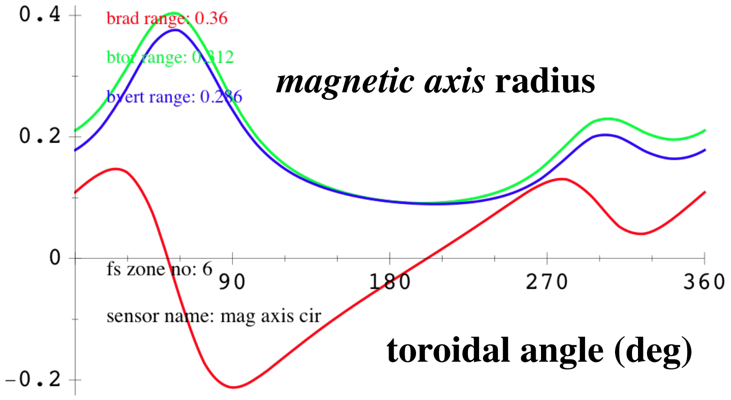
Radial, toroidal, and vertical fields (mT) generated by SOLC ribbons carrying unit current (1 kA) through the two crossing zones (0.5 kA for each zone) are calculated using the Biot-Savart's law along toroidal circle in the magnetic axis plane at the major radius of inboard q_{95} surface.

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 large enough to elicit a significant plasma response.

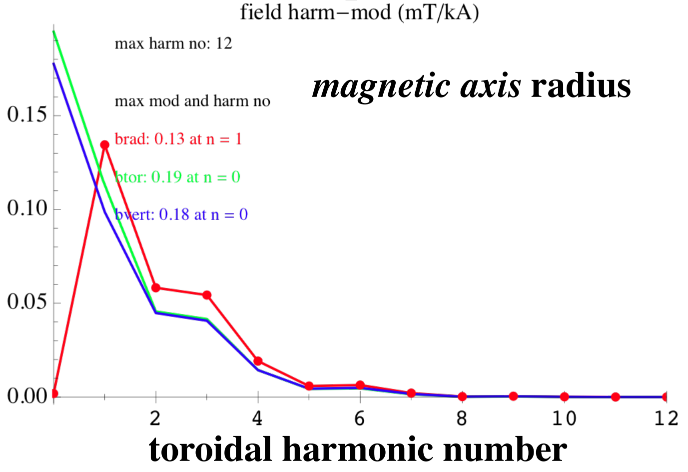
It may be on the *inboard* side where SOLC-generated field may be felt as an important contributor to drag forces acting on the plasma.

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

SOLC Field Is Still Large along Magnetic Axis Circle



Field (mT/kA) along Toroidal Circle



Harmonic Components (mT/kA)

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

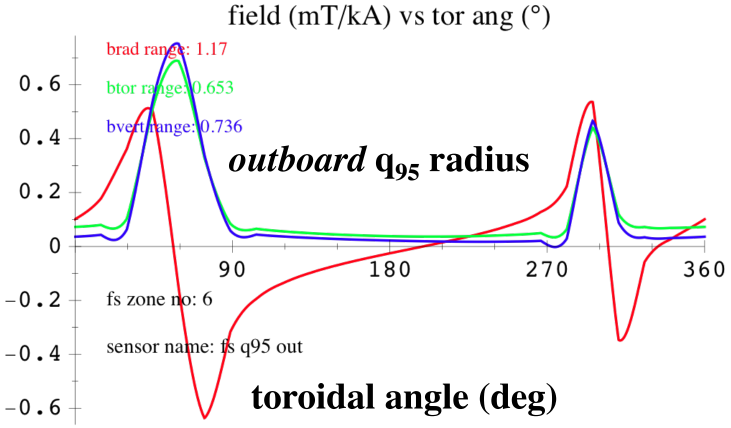
SOLC-generated radial field at magnetic axis has a harmonic structure peaked at n = 1 and ~ 0.13 mT/kA, which, at a unit current level, is comparable to RMP coil field (~ 0.1 mT on the *outboard* side) that is itself large enough to elicit a significant plasma response.

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.

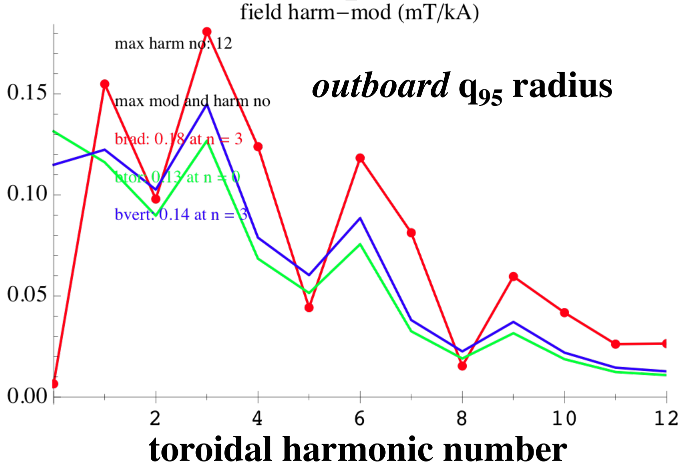
Interaction through flux coupling (mutual inductance) between SOLC and MHD current inside the plasma will be a subject to be explored in the near future.

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 carrying unit current (1 kA) through the two crossing zones (0.5 kA for each zone) 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, ~ 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 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.

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

Future Research Direction - 1

1. **Near Term**

Model SOLC-generated field based on geometrical parameters of individual sources within each of the two actual NSTX-U beams to identify differences in 3D error field patterns possibly exploitable for improving operational scenarios, for example, by canceling out residual structural error field.

Assess the requirement for a diagnostic system, consisting mainly of tile current and magnetic sensor arrays, capable of determining a *radial* SOLC distribution sufficient to resolve low and high shear regions and sweet spot.

2. **Medium Term**

Calculate a 2D distribution of SOLC-generated vacuum field on surfaces of interest, including the plasma, q95, pedestal top, and rational surfaces as well as magnetic sensing coil installation surfaces, and assess whether the calculated field, in magnitude and structure, warrants further investigations of effects of SOLC on MHD phenomena associated with these surfaces.

Assess the feasibility of building a experimental system for actively driving a small-amplitude SOLC for putting to a test physics models for MHD phenomena, e.g., rotation breaking, ELM triggering, RFA, NTMs, etc.

Future Research Direction - 2

3. Long Term

Evaluate modifications of SOLC-generated vacuum field by plasma response and assess the overall effect of SOLC on MHD phenomena.

Assess the amplitude of actively driven SOLC needed for influencing MHD stability, and design an experimental system for taking advantage of driven SOLC for improved performance for the present and future devices.

Summary

1. **A class of toroidally asymmetric *operational* procedures on tokamaks has been studied as a potential dynamic source of 3D error field through generation of an asymmetric distribution of Scrape-Off-Layer Current (SOLC) flowing in an unfavorable low-shear region centered about the sweet spot of SOL field-line structure.**

2. **Charge exchange heat loss from a Neutral Beam (NB) crossing the SOL is a possible source of an asymmetric SOLC distribution, as the loss could create unequal electron temperatures at the two "shadows" that the beam casts along open field lines onto the divertor floors, thus driving thermoelectric current between them.**

3. **Field generated by SOLC originating from NB crossing zones has a dominant n = 1 toroidal harmonic with its amplitude largest on the inboard side and steeply decaying outward, in sharp contrast to field generated by Resonant Magnetic Perturbation (RMP) coils. Neutral beam, with its *two* crossing zones, tends to produce a low-n (~ 3) spectrum on the outboard side.**