ABSTRACT

Measurement of Current in Scrape-off Layer (SOL) Plasma in DIII-D Tokamak.[1]

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Current in SOL plasma is measured in DIII-D using its tile current monitor diagnostic. The work is motivated by a hypothesis based on experimental observations in TFTR tokamak (see H. Takahashi, et al., APS DPP, 1998, K6Q.07) that an SOL current exists that magnetically mimics MHD phenomena, e.g., **Stationary Magnetic Perturbations** (SMP's) or **Locked Modes,** among others. 'Base' SOL current can be several times as large as previously reported, and is often not axi-symmetric, contrary to a common assumption. Base current increases during **Resistive Wall Modes.** 'Spiky' current, coincidental with **Edge Localized Modes** (ELM's), is also often not axi-symmetric. Current that oscillates like MHD modes is also found. Spiky or oscillating SOL current can be bi-polar, quickly reversing its flow direction. The lack of axi-symmetry and bi-polar nature of observed current challenge theoretical explanations of the origin of SOL current. SOL current will be examined as **'edge current'** in equilibrium and stability, and as a provider of **'field errors'** for slowing down and locking of MHD modes.

[1] Supported by DoE contract No. DE-AC02-76-CHO-3073 and DE-AC03-89-ER-51114

MOTIVATION

- **Overcome major hurdles to Advanced Tokamak (AT) plasmas.**

  On the one hand, stationary or low-frequency magnetic activity, such as Locked Modes (**LM's**) and Resistive Wall Modes (**RWM's**), which are here collectively called Stationary Magnetic Perturbations (**SMP's**), and Edge Localized Modes (**ELM's**) often degrade or terminate Advanced Tokamak discharges.

  On the other hand, current flows in SOL plasma concurrently with SMP's and ELM's.

- **Study possibly causal relationships between SOL current on one hand, and SMP's and ELM's on the other.**

  SOL current can:

  – Produce an 'error field' for locking MHD modes that comes in and out of existence *dynamically* (in contrast to a *static* structural error field conventionally associated with LM's).

  – Mimic magnetic signals (in part or whole) conventionally identified as evidence for the presence of MHD *modes* (such as LM's and RWM's).

  – Provide 'edge current' affecting equilibrium reconstruction (and hence equilibrium and stability).

SCHEMATIC OF POSSIBLE CAUSALITY RELATIONSHIPS

SOL current, which we also refer to as **'halo current,'** comprises a component that is toroidally **axisymmetric** and another that is **not axisymmetric.** Each may have consequences in different aspects of plasma performance.

$$I_{\text{SOL}} \begin{cases} I_{\text{asym}} \xrightarrow{\text{Produce}} \begin{cases} \text{Dynamic 'Error' Field} \xrightarrow{\text{Lock}} \text{MHD Modes} \\ \text{Detector Response} \xrightarrow{\text{Mimic}} \text{MHD Signals} \end{cases} \\ I_{\text{sym}} \xrightarrow{\text{Mean}} \text{Edge Current} \xrightarrow{\text{Affect}} \text{Equilibrium} \\ I_{\text{both}} \xleftrightarrow{\text{Concurrent}} \text{Large ELM's} \end{cases}$$

HIGHLIGHTS

An **unconventional view is put to test** that some magnetic perturbations, routinely considered to be generated by an MHD mode, in fact:

– Are not what they first appeared to be,

– Involve instead (or in addition) current flowing in SOL plasma, and

– May therefore be amenable to a remedy totally different from what conventional wisdom may suggest.

This investigation began when some MHD activity observed in TFTR, SMP's in particular, could not be explained in terms of MHD modes alone, and needed to postulate 'halo current,' or current in SOL plasma.

DIII-D TILE CURRENT DIAGNOSTIC

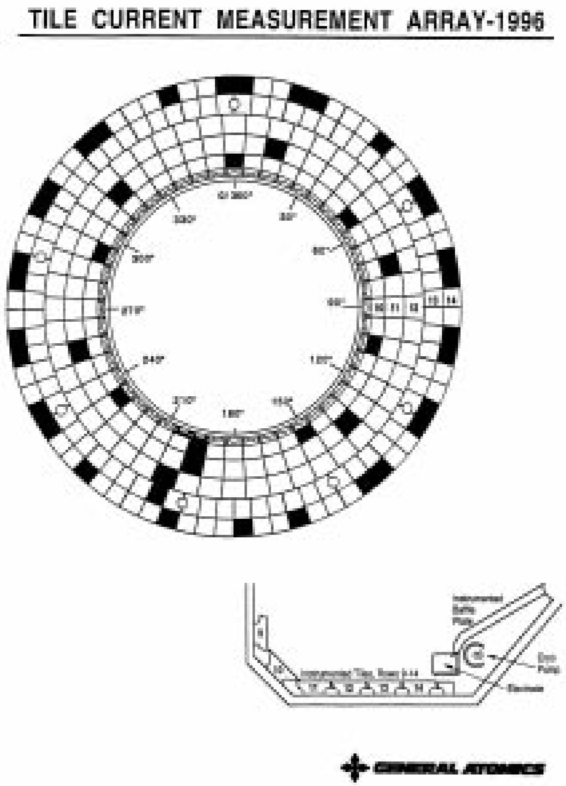

Fig. 1 Divertor bottom tiles are laid in rings. Forty eight tiles in **Ring#12B** carries most current (for this study). Each tile spans 7.5 deg toroidally and 13.9 cm radially. The data system bandwidth is 15 kHz for the tile current diagnostic, and is significantly slower than for the Mirnov and D_α systems referred to later.

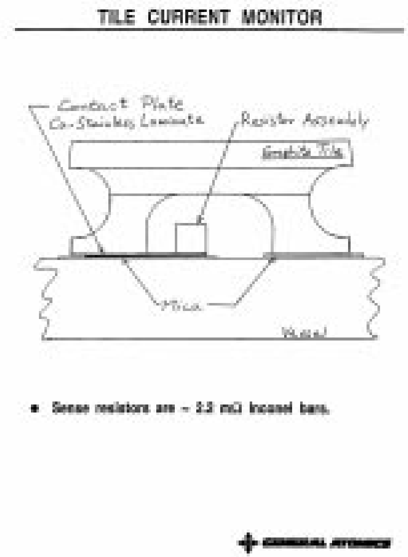

Fig. 2 Some divertor tiles are fitted with a 2.2 $m\Omega$ resistive element to measure current through it (five tiles in Ring#12B). Locations of instrumented tiles changed from time to time.

PART-I: PHENOMENOLOGY

DISCHARGE

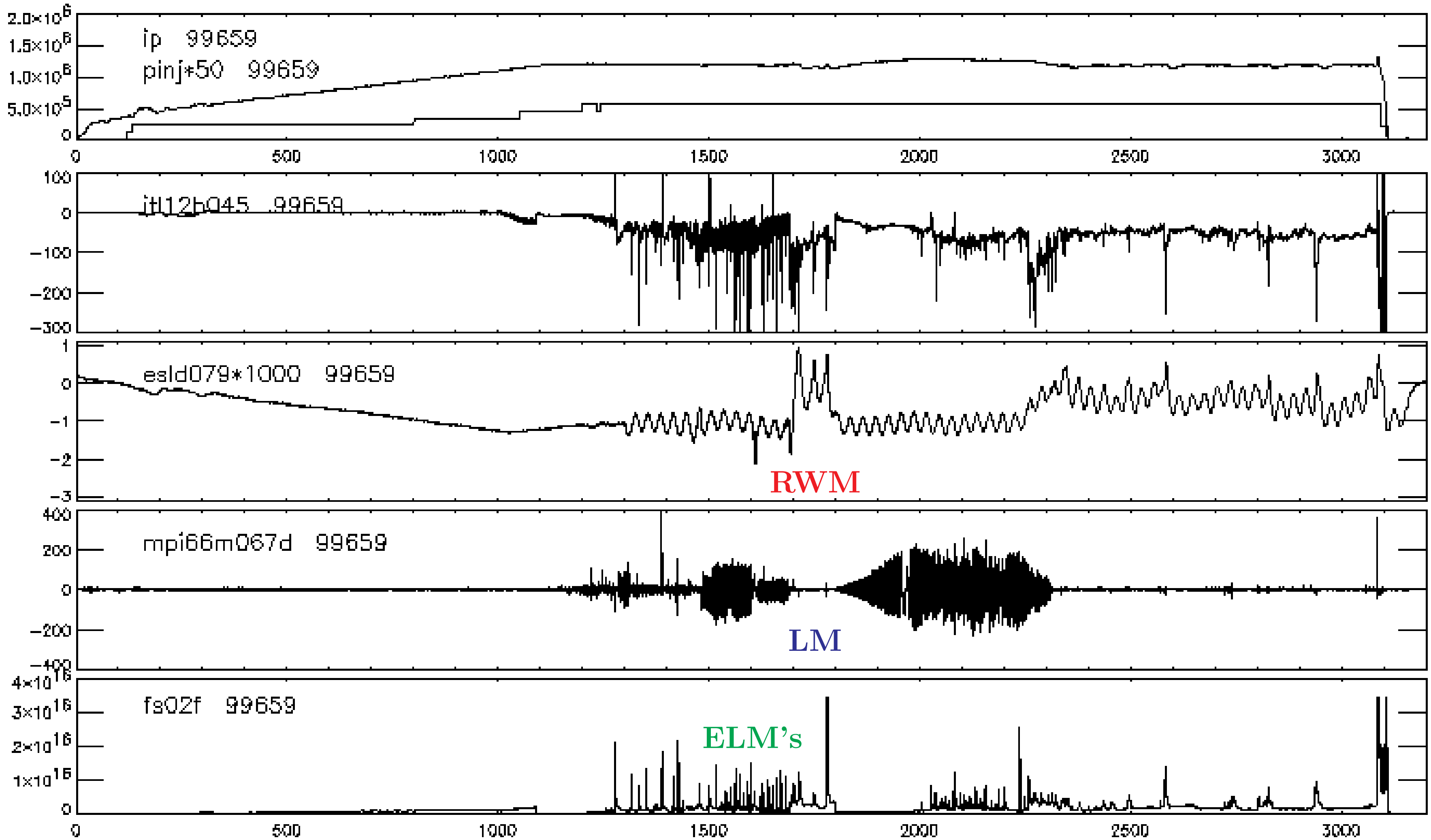

Fig. 4 A typical discharge with many types of interesting magnetic activity: (from top) I_p and P_{inj}, Tile Current, Saddle Loop (with driven oscillations), Mirnov, and D_α signals.

EQUILIBRIUM PARAMETERS AND FLUX SURFACES

Shot:	99659
Time:	1700.00
chi**2	22.616
Rout(m)	1.677
Zout(m)	-0.086
a(m)	0.612
elong	1.918
utri	0.543
ltri	0.848
indent	0.000
V (m**3)	21.203
A (m**2)	2.108
W (MJ)	0.895
betaT(%)	2.721
betaP	1.076
betaN	2.257
In	1.206
Li	0.768
error(e-4)	2.563
q1	9.150
q95	5.093
dsep(m)	0.049
Rm(m)	1.775
Zm(m)	-0.007
Rc(m)	1.704
Zc(m)	-0.023
betaPd	1.199
betaTd	3.033
Wdia(MJ)	0.997
Ipmeas(MA)	1.200
BT(0)(T)	-1.595
Ipfit(MA)	1.190
Rmidin(m)	1.065
Rmidout(m)	2.290

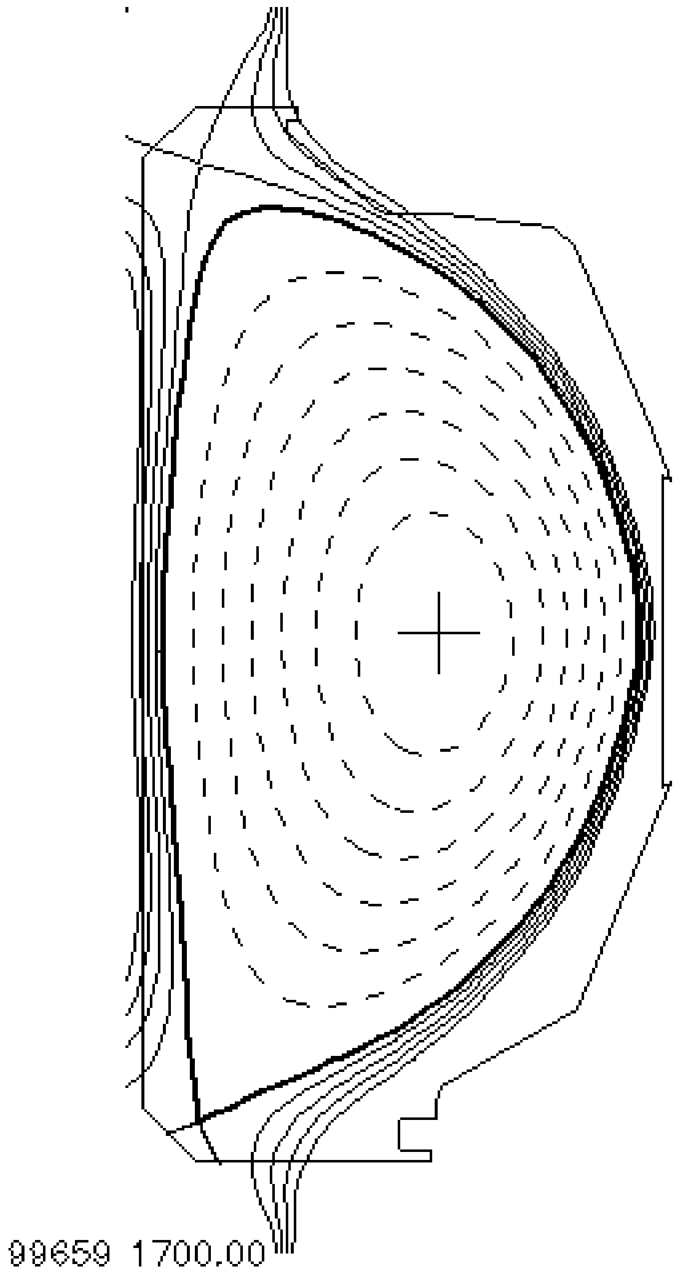

Fig. 5 Parameters and flux surfaces of a typical equilibrium studied. Flux surfaces in SOL intersect tiles in Ring#12B and other rings.

TEMPORAL VARIATION OF HALO CURRENT

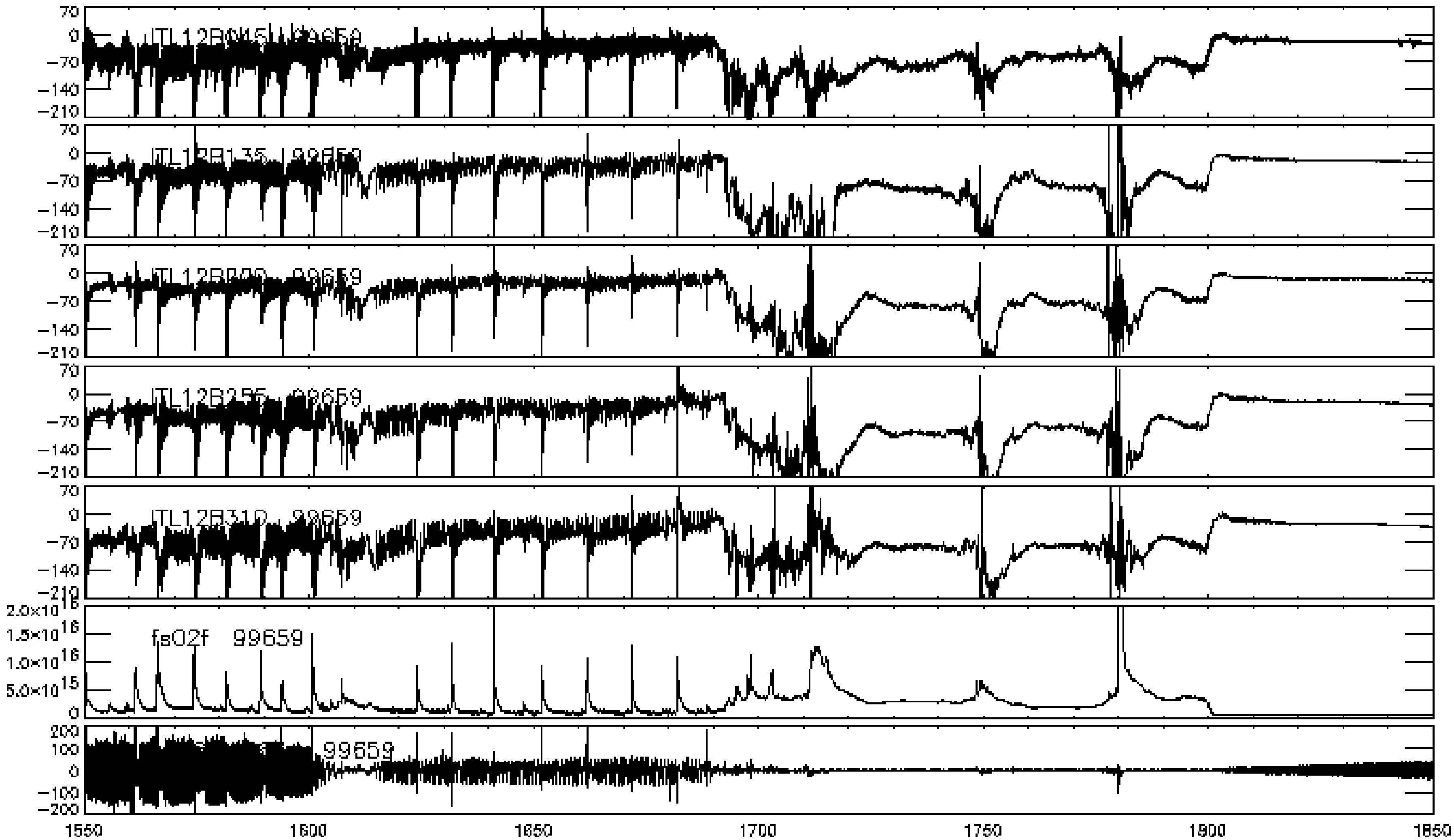

Fig. 6 Current through five tiles in Ring#12B around a period of magnetic activity. D_α and Mirnov signals are also shown at bottom.

HALO CURRENT DENSITY IN RWM/LM EVENT

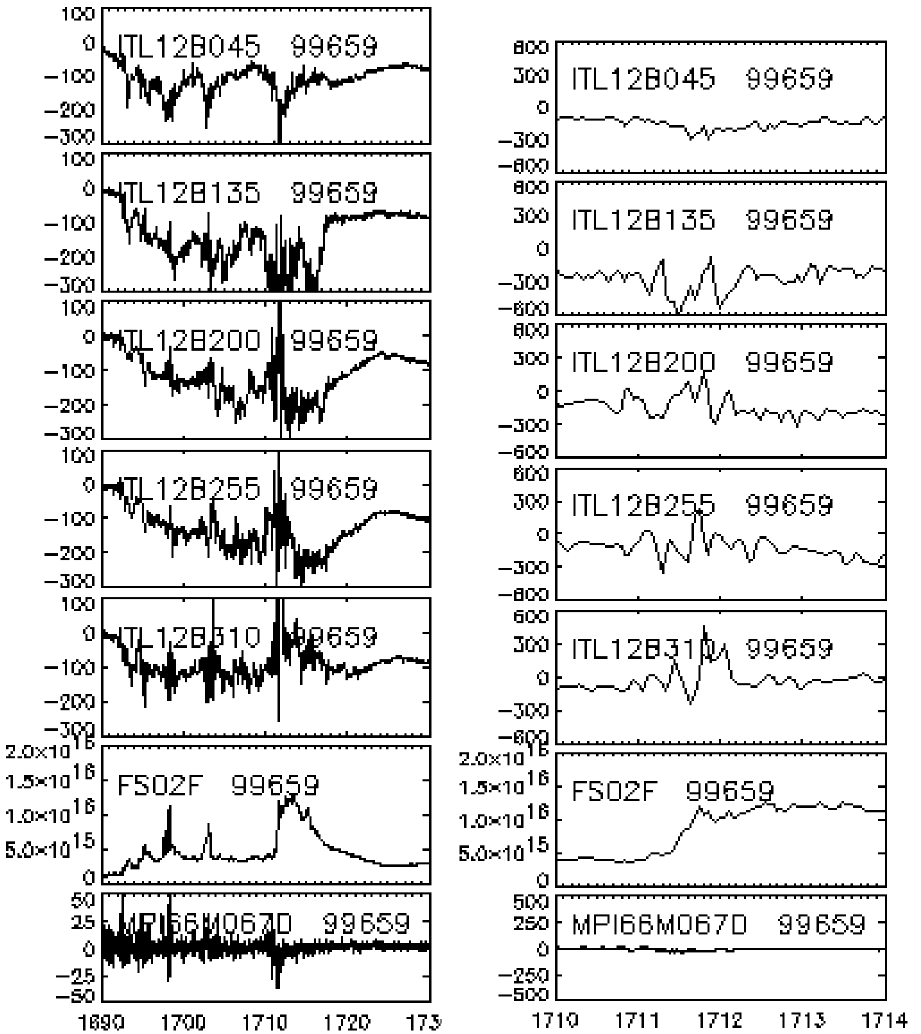

Fig. 7 Current is large generally (left), but especially at spiky peaks (right).

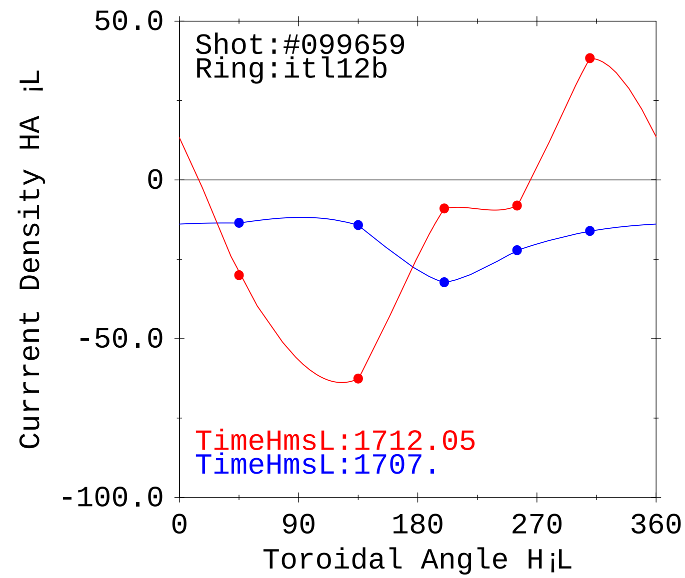

Fig. 8 Current is **'uni-polar'** with an axisymmetric base of around 15 A/deg and not axisymmetric toroidal variation of 15-20 A/deg. A much stronger variation up to 65 A/deg appears at spikes, where current is sometimes (as is here) **'bi-polar,'** and flows in opposite directions from one toroidal location to another.

HALO CURRENT DENSITY IN ELM EVENT

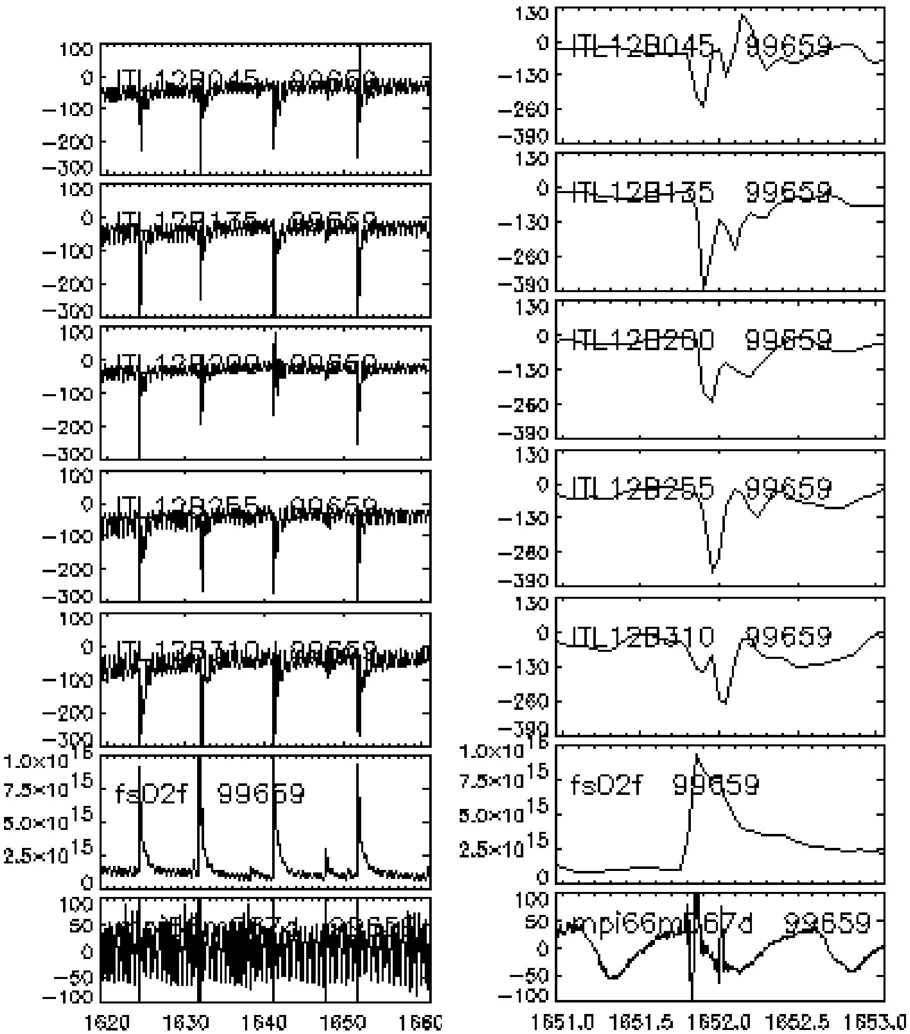

Fig. 9 Current is small and largely axi-symmetric between spikes (left), but can rise up to -400 A per tile at spikes (right).

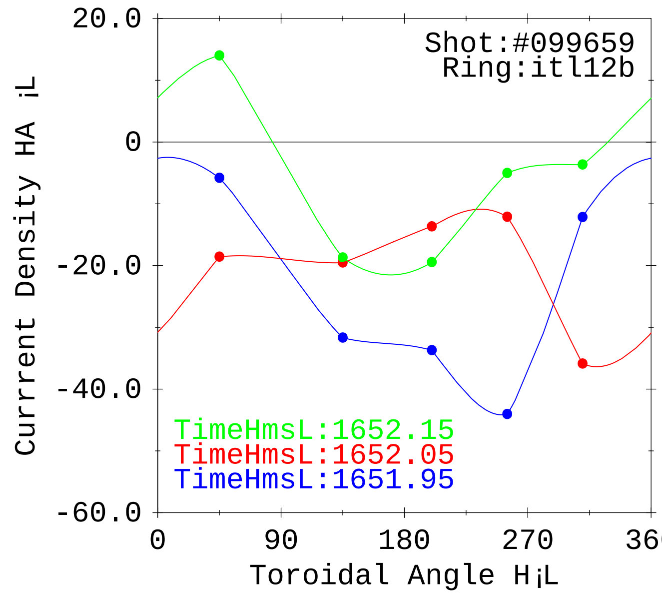

Fig. 10 Current is strongly not ax-isymmetric during an ELM event, contrary to a conventional assumption. It is sometimes (as is here) **'bi-polar,'** and flows in opposite directions from one toroidal location to another.

HALO CURRENT DENSITY IN AXISYMMETRIC PHASE

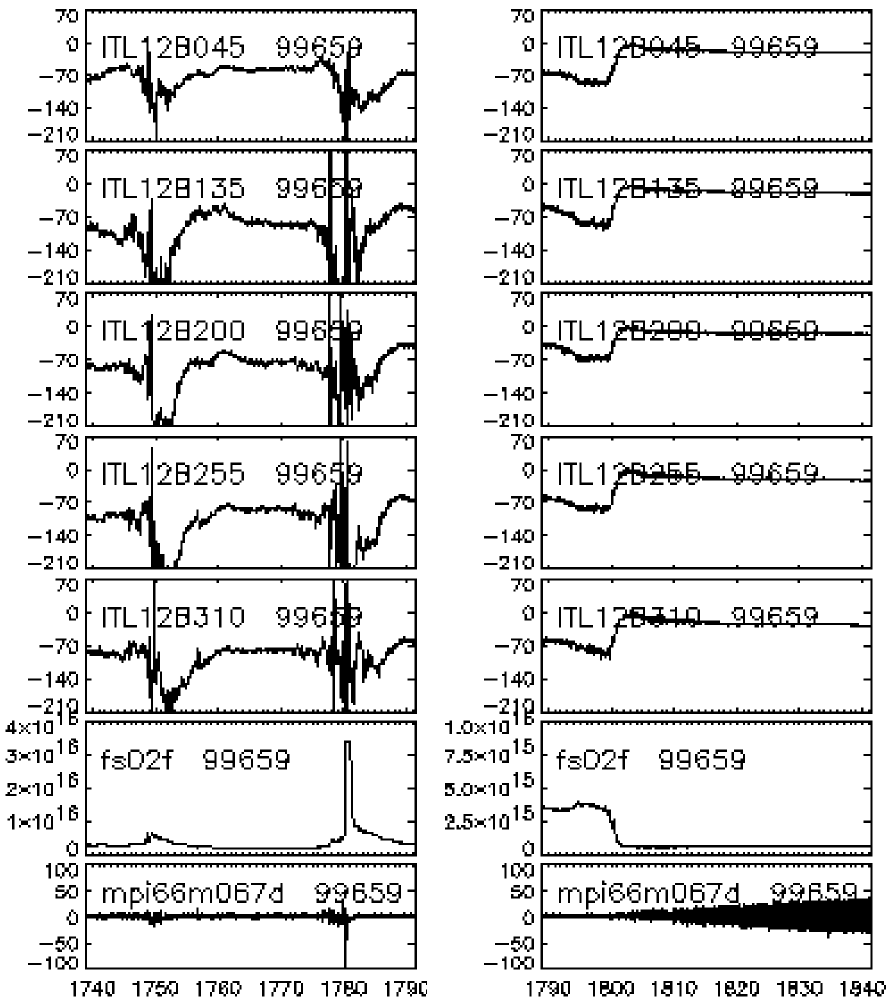

Fig. 11 Current is moderately large (left) between spikes during, but quite small (right) after, RWM.

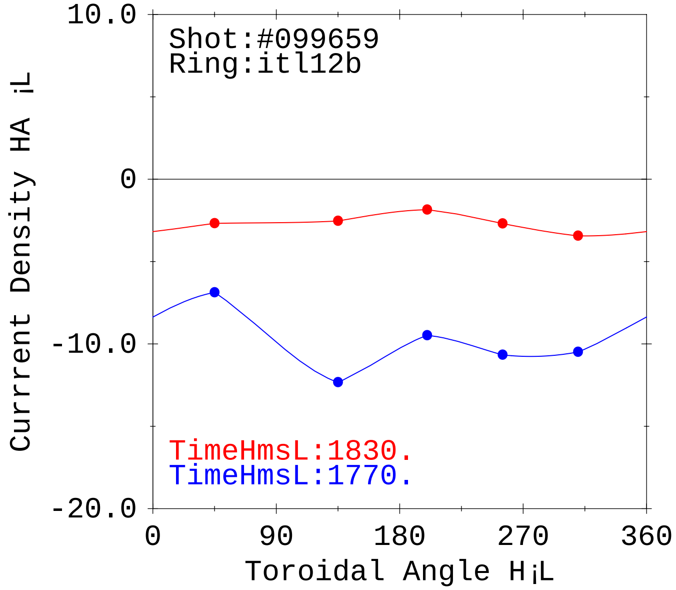

Fig. 12 Current can be fairly axisymmetric in some parts of an RWM event. It is closely axisymmetric after an RWM.

OSCILLATING HALO CURRENT

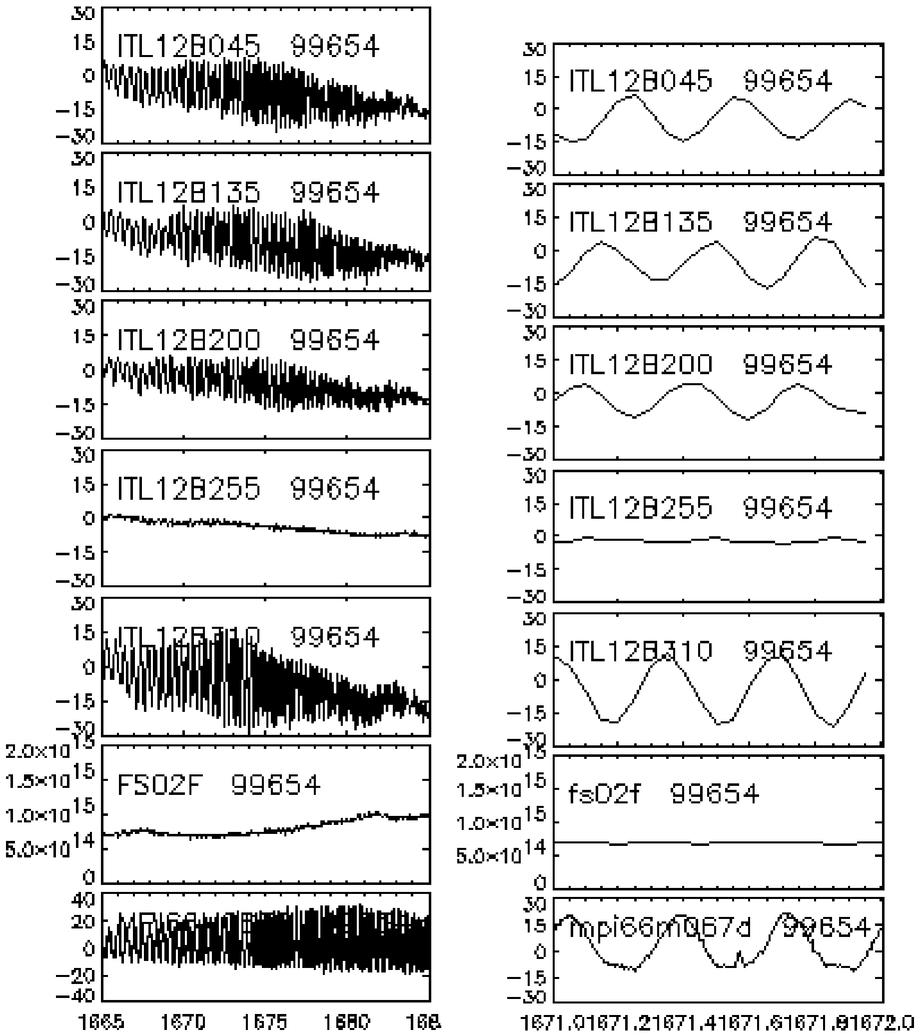

Fig. 13 Current oscillates at the same frequency (about 3 kHz) as MHD mode, but oscillations are clearly bi-polar.

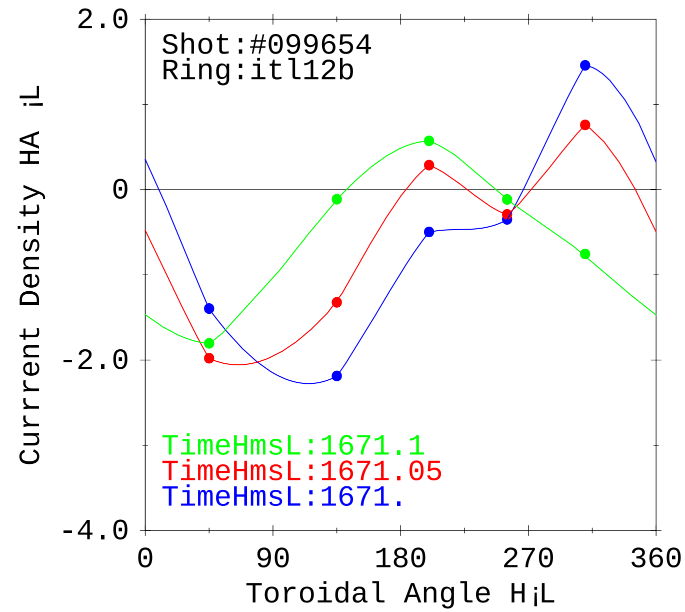

Fig. 14 Two toroidal 'nodal' points are evident as if in a **standing wave** pattern, one around 45 deg (here at a finite amplitude!) and the other around 270 deg. Apparent progressive phase inbetween seems to suggest, however, a **travelling wave** pattern — a curious situation.

EQUILIBRIUM RECONSTRUCTION

A common procedure in equilibrium reconstruction is to let the current density vanish on the separatrix. Important changes in reconstructed equilibrium can result if this condition is altered. Under some conditions SOL current measurement can indicate current density on the separatrix.

We do not yet know whether the observed SOL current flowed just outside the separatrix as a 'continuous extension' of the main plasma's current density profile, or as an 'independent bump' separated from the main plasma current by a radial region of little or no current. The SOL current measurement is relevant to equilibrium reconstruction in the case of 'continuous profile.'

On the basis of measured axisymmetric part of SOL current of about 100 A per tile (15 A/deg) and an assumed SOL width of 4 cm, the current density at the separatrix is about 300 kA/m^2.

A preliminary estimate indicates that this finite separatrix current density would result in a noticeable change in the x-point locations and other associated equilibrium properties.

PART-II: FIELD PRODUCED BY HALO CURRENT

FIELD PRODUCED BY LINE HALO CURRENT

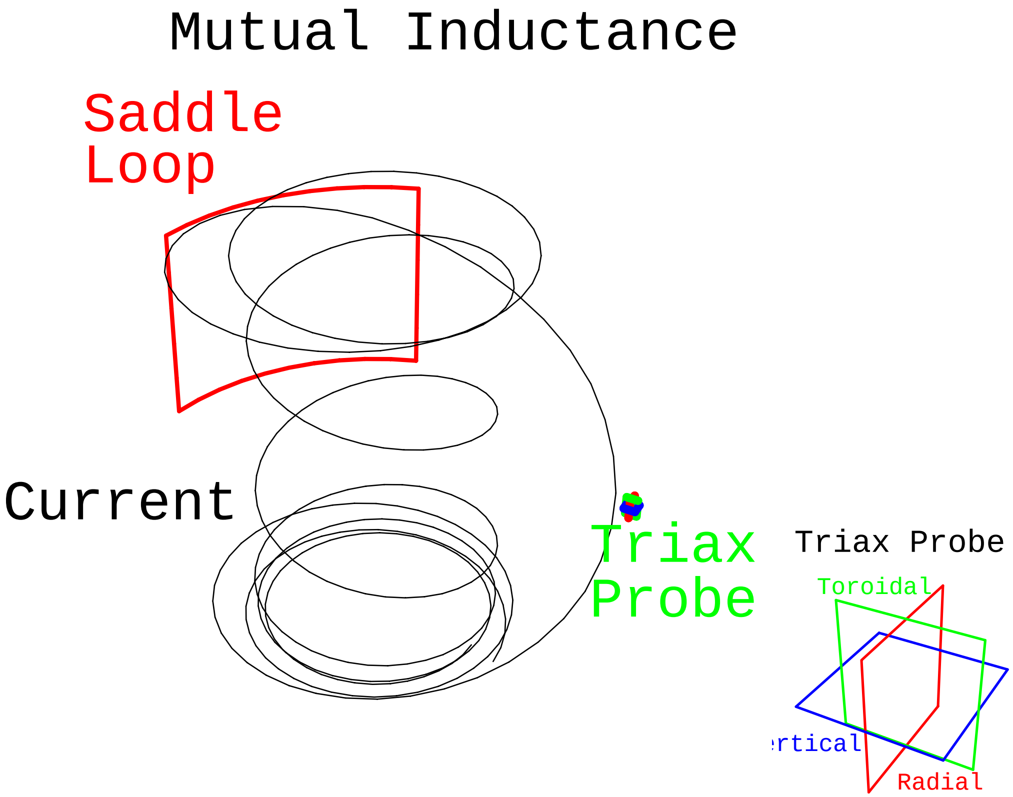

Fig. 15 Field is determined from calculations of mutual inductance between current following a helical field line obtained from an equilibrium and magnetic sensors (actual or fictitious).

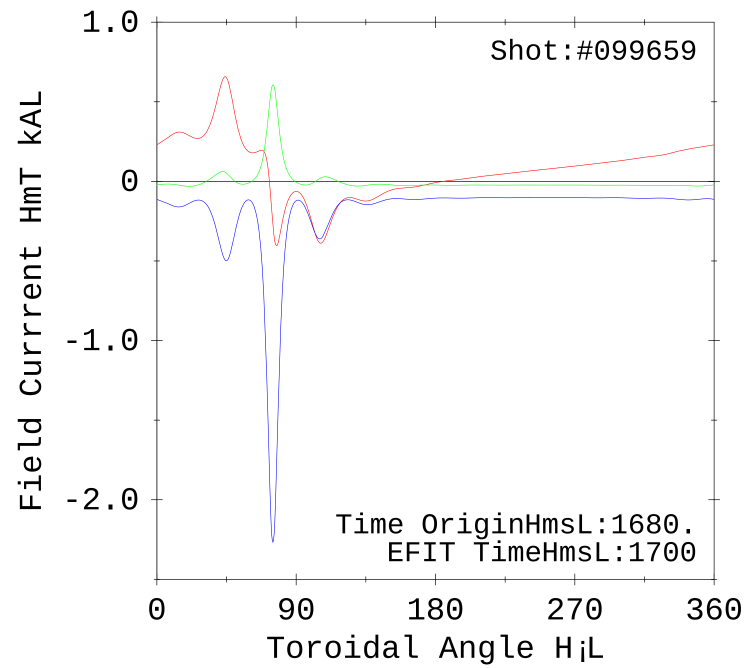

Fig. 16 Toroidal variation of field is obtained by rotating either the line current or the sensors. Field shown here is for a unit current (1 kA).

FIELD PRODUCED BY SHEET HALO CURRENT

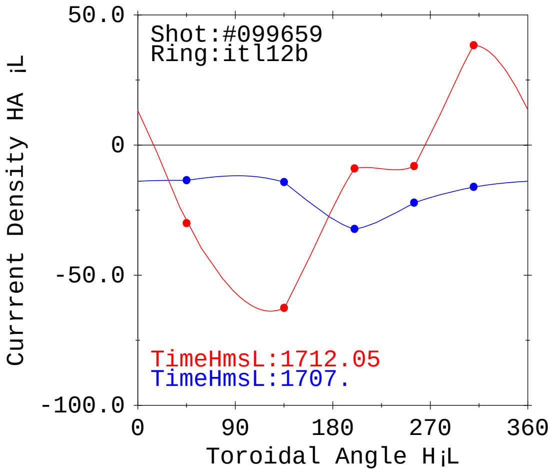

Fig. 17 Ring 12B current density.

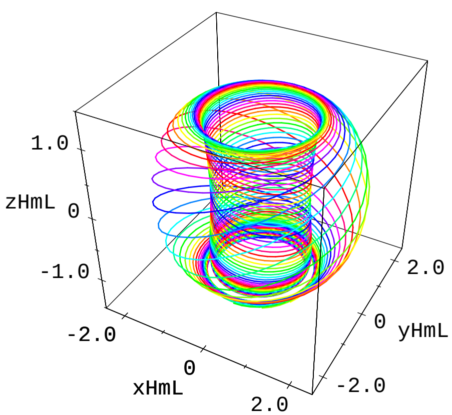

Fig. 18 Convolve each helix with measured current.

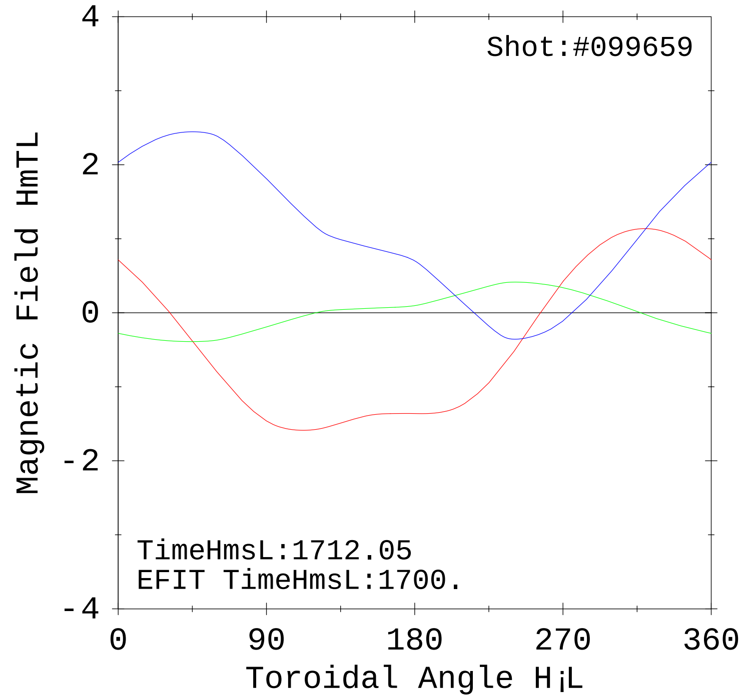

Fig. 19 Toroidal variation, up to a few **tens of Gauss at spiky peaks** (here nearly 30 G) and **several Gauss between peaks,** is comparable to structural error fields associated with locking MHD modes, and is large enough to account for parts of field attributed to LM's and RWM's.

PART-III: CONCLUSIONS AND DISCUSSION

CONCLUSIONS

- Temporal variation of SOL current was measured in DIII-D, and found to:
  - Rise often when Mirnov signals disappear (LM event).
  - Rise often when saddle loop signals rise (LM and/or RWM event).
  - Have a spike nearly always when D_α signals have a spike (ELM event).
  - Be sometimes oscillatory at the same frequency as MHD modes (but not oscillatory at other times even in the presence of MHD oscillations).
  - Be sometimes bi-polar when it is spiky or oscillatory, with current quickly reversing its flow direction with time (at the same toroidal location).
- Toroidal variation of SOL current was determined, and found to:
  - Be not axisymmetric often during SMP's and ELM's.
  - Be sometimes bi-polar, with current reversing its flow direction from one part of torus to another (at an instant of time).
- Not axisymmetric magnetic field produced by SOL current was calculated[2], and found to be often large enough to:

[2]Based on an assumption of a toroidal current sheet for want of more complete radial structural information, and on measured toroidal current density variation.

– Act as a *dynamical* ‘error field’ that is comparable to a *static* structural error field conventionally considered strong enough for locking a rotating MHD mode.

– Account for parts of magnetic perturbations that are usually attributed to LM’s and/or RWM’s.

DISCUSSION

Halo current measurement has been reported relatively scantly for a normal part of discharge[3] in contrast to a post-disruption period[4].

We have reported in this paper primarily on the phenomenology of halo current during a normal part of the discharge, some preliminary analysis of its significance in mimicing MHD-generated magnetic perturbations — an unconventional viewpoint, and briefly on equilibrium reconstruction.

Both observations and analysis suggest that this is an area of practical importance, because SMP's and ELM's are a major hindrance in achieving high performance plasmas. Clear understanding of these phenomena could lead to a remedy that is far different from those based upon conventional thinking.

For example, if locked modes are indeed locked by a halo-generated 'error field,' instead of a structural error field as conventionally believed, a remedy could be just a matter of limiting or eliminating halo current, which appears to be far simpler and economical than building coils to an extremely high degree of symmetry. A similar argument can be advanced also for RWM's and ELM's.

Finding of bi-polar oscillations suggests strongly that oscillations in current are not a simple consequence of plasma properties, such as resistivity, being modulated by MHD modes. Driving mechanism must reverse its polarity for the current to reverse its flow direction.

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[3]See M.J. Schaffer and B.J. Leikind, NF(1991)1750 and citations therein.
[4]See T.E. Evans, et al., J. Nucl. Mat.(1997)241 and citations therein.

Oscillating halo curent is particularly intriguing in light of magnetic perturbation data[5] from TFTR that are difficult to interprete without postulating something like it. Oscillating current found so far in DIII-D is, however, rather small in amplitude.

We have not addressed in this paper the subject of mechanisms that drive observed halo current, but provided experimental 'boundary conditions' or framework within which candidate mechanisms must be sought. Traditionally suggested mechanisms, such as loop voltage and thermo-electric effect, will have a significant challenge in explaining: (a) strong departure from axisymmetry, (b) temporal bi-polar variation, (c) spatial bi-polar variation, and (d) oscillating halo current.

Some data appear to suggest, though not discussed here, that halo current has a localized structure, for example, a helical bundle-like structure, rather than (or in addition to) a global structure, such as an n=1-like variation. Our next task is therefore to determine the spatial structure of halo current in more detail, both in radial and toroidal directions.

[5] H. Takahashi, et al., APS DPP, 1998, K6Q.07, and citations therein.

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Figures

FIG. 1.

FIG. 2.

FIG. 3.

FIG. 4.

FIG. 5.

FIG. 6.

FIG. 7.

FIG. 8.

FIG. 9.

FIG. 10.

FIG. 11.

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FIG. 15.

FIG. 16.

FIG. 17.

FIG. 18.

FIG. 19.

FIG. 20. Islands evident in T_e profiles.

FIG. 21. Island width determination method.

FIG. 22. Comparisons of magentic perturbations expected theoretically from measured width of islands and magnetic perturbations observed experimentally on Mirnov diagnostic.

FIG. 23.