ABSTRACT

Stationary Magnetic Perturbations ('Locked Modes') and Edge Phenomena in TFTR Tokamak[1]

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Stationary Magnetic Perturbations (SMP's), commonly known as 'locked modes,' are investigated in TFTR. Ealier studies[2] suggested the possibility that the response of SMP sensors ('locked mode detectors') was in part produced by 'halo currents' that flow in the plasma scrape-off layer over part of their path and in the tokamak structure over the rest of the path. In the present study, the relationship is investigated between SMP's and an edge phenomenon called 'blooms,' which is thought to be caused by a concentrated power flow to a limiter surface. 'Blooms' are found to be almost always accompanied by an SMP (magnetic phenomenon), suggesting that they carry an electrical current, contrary to a traditional expectation. (Not all SMP's are accompanied by a 'bloom,' however.) These new observations are consistent with the notion that SMP's more generally are a consequence of 'halo currents.'

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[1]Supported by DoE contract No. DE–AC02–76–CHO–3073

[2]Several types of SMP's were reported earlier — APS DPP, 1994(6R28), 1995(9P29), 1996(1S27); 7th Int. Toki Conf. on Plasma Physics and Nuclear Fusion, Toki City, Japan, Nov. 28 - Dec. 1, 1995, Paper T7-I4.

MOTIVATION

- Stationary Magnetic Perturbations (**SMP's**), which are traditionally interpreted as **locked modes,** occur concurrently with adverse effects on tokamak discharges, such as loss of confinement and disruptions.
- If SMP's are indeed locked modes caused by error fields, as a prevailing view claims, avoiding them in future tokamak reactors (such as **ITER**) would require a confining field that is uniform to 10^{-5} — a technically challenging and economically costly requirement.
- We study the SMP phenomenon in the hope that its thorough understanding leads to a different, possibly far less costly, solution for avoiding adverse discharge effects associated with SMP's.

HIGHLIGHTS

- **SMP's** and an edge phenomenon called **'blooms'** are observed together with a high degree of concurrence.
- 'Blooms' are traditionally thought to be an 'edge atomic physics phenomenon.' These new observations that 'blooms' are correlated with a *magnetic* signal suggest that 'blooms' carry electrical currents (i.e., akin to an electrical breakdown).
- External and internal diagnostic data show that the SMP phenomenon more generally must involve **a second source of magnetic signals** in addition to MHD modes.
- In the model proposed in earlier reports[3] **'halo currents'** serve as a second source of magnetic signals. ('Blooms' may involve such currents that cause 'atomic physics processes' on a limiter surface, perhaps because the currents become 'anchored' to particular locations on it.)
- In our 'halo current model,' **MHD modes,** though usually observed prominently, are a secondary element in the SMP phenomenon.

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[3] SMP's have been discussed in: APS DPP, 1994(6R28), 1995(9P29), 1996(1S27); 7th Int. Toki Conf. on Plasma Physics and Nuclear Fusion, Toki City, Japan, Nov. 28 - Dec. 1, 1995, Paper T7-I4.

LOCKED MODE PICTURE (CONVENTIONAL)

1. Slow down of the frequency of MHD modes[4].
2. 'Locking' of MHD modes.
3. Growth of the amplitude of MHD modes while locked.

Oscillating perturbation currents of MHD modes generate oscillating eddy currents in surrounding structures, which are retarded in phase due to finite resistivity of structures, and exert secular (non-periodic) electromagnetic forces on MHD modes, causing them (and plasma) to slow down.

External error fields, which exert only periodic forces to MHD modes while the plasma is rotating, trap the modes in a 'potential well' once the plasma momentum becomes too small to overcome the forces.

Error fields, which are prevented by the skin effect to enter the plasma while it is rotating, can penetrate the plasma as it slows down and stops rotating. Destabilizing resonant components of error fields reach relevant rational surfaces, and cause MHD modes to be excited, or render MHD modes more strongly unstable, if they already exist.

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[4] So-called purely growing locked modes lack oscillating precursors.

'LOCKED MODE' PICTURE[5] FOR *TFTR*

1. Slowing and stationary (or 'locked') perturbations, both internal and external, do exist (**no quarrels here**).
2. Low-order tearing-type MHD modes are responsible for only a fraction of measured signals of 'locked mode' detectors.
3. Slow down of the frequency, or cessation of rotation, has little effects on the amplitude of MHD modes.
4. Error fields are not directly involved in 'locked modes.'
5. Detailed plasma properties, probalbly in the scrape-off, but not directly bulk plasma properties, determine generation of locked modes.
6. A second phenomenon exists that has powerful influences on transport, and also generates a bulk of 'locked mode' detector response. We think the phenomenon is 'halo currents.'

Since MHD modes are argued here to be only a secondary element of *locked modes*, a more general term, Stationary Magnetic Perturbations (SMP's), is used in our model.

[5]The model was constructed from observations described in this report as well as earlier ones.

DISCHARGE WITH SMP AND 'BLOOM'

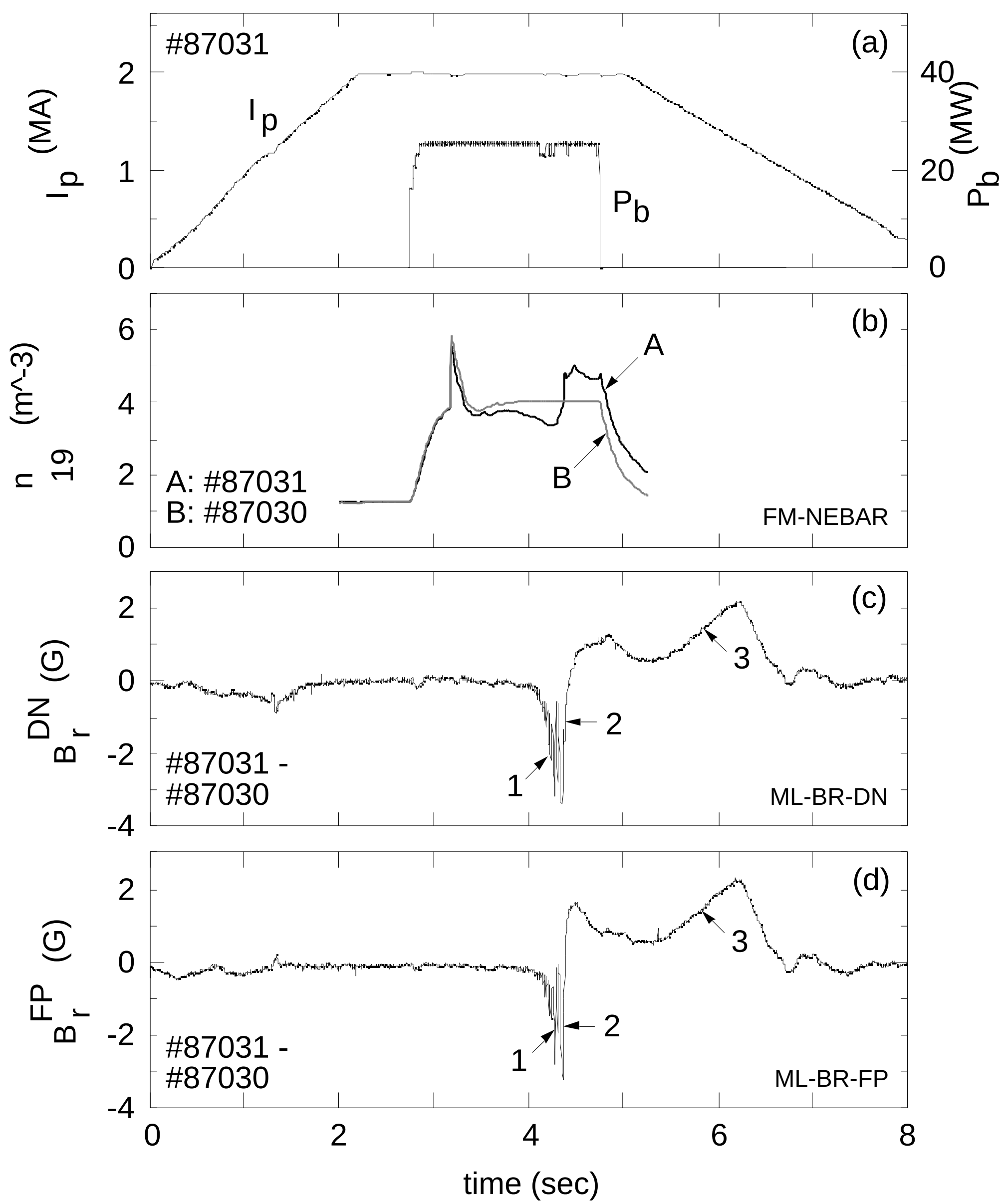


Fig. 1 An overview of discharges with SMP and 'bloom' events (see below for details). (a) Two discharges had identical I_p and P_b waveforms. (b) In Discharge A, an edge event, termed 'bloom' in TFTR lingo, took place around 4.2 sec when density rose strongly. (An earlier density peak was caused by unrelated Li-pellet injection.) In Discharge B, no bloom occurred. (c) and (d) An SMP event at '1' and '2' occurred concurrently with bloom.

'COMPOUND' SMP

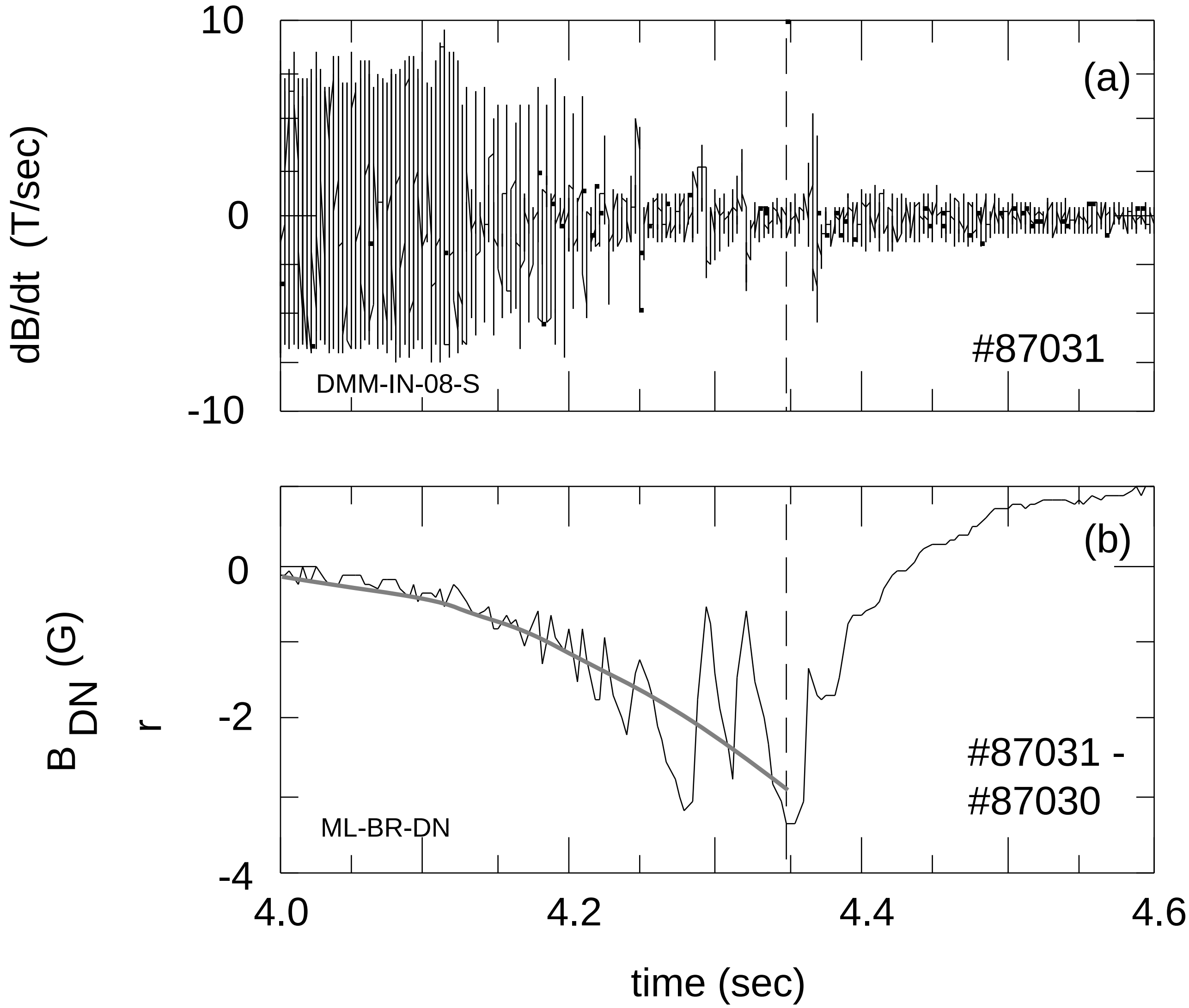


Fig. 2 Mirnov coil and SMP sensor signals in an SMP event. (a) Oscillation frequency of Mirnov signal slows down. (b) SMP signal builds up *secularly* while *oscillating* at the same time. We call this type a 'compound' SMP for this reason.

'BLOOMS' IN TFTR

- In some TFTR discharges an unusual edge phenomenon occurs that causes a rapid increase in light emission from hydrogenic atoms and carbon impurity ions. A concomitant increase in plasma density first appears at the plasma edge and then propagates inward. Radiated power and visible Bremsstrahlung also increase. Energy confinement degrades significantly.
- The 'bloom' has *traditionally* been considered to involve only particles and energy, but not electrical currents.
- But concurrent observations of 'blooms' almost always with an SMP, which is a *magnetic* phenomenon, suggest that 'blooms' carry electrical currents. 'Blooms' may be a phenomenon akin to an electrical breakdown in scrape-off plasmas.

'BLOOMS' IN TFTR

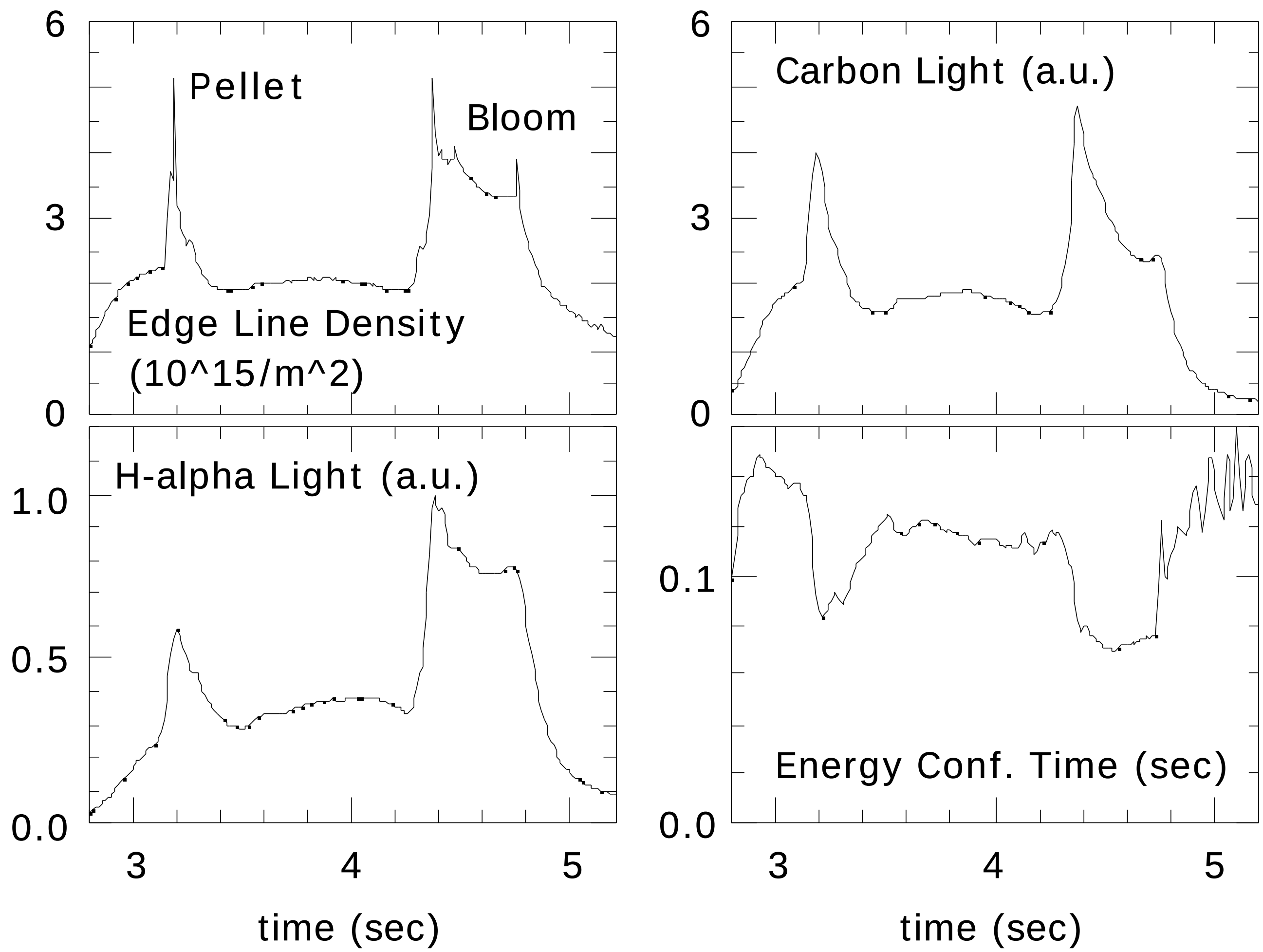
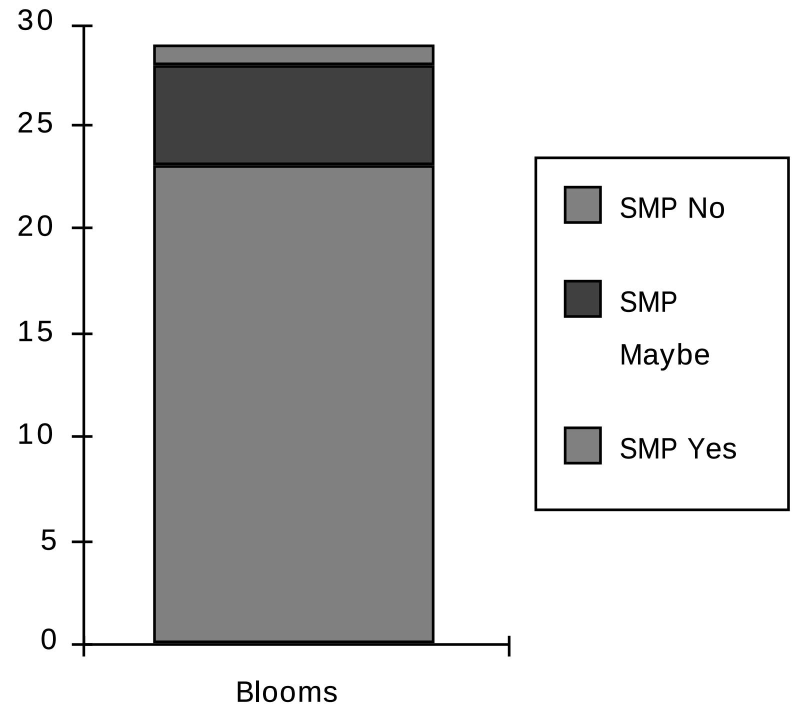


Fig. 3 In a 'bloom' light emission increases from hydrogenic atoms and carbon impurity ions. Density increases first at edge. Energy confinement degrades. (The peak at 3.2 sec is an unrelated Li-pellet injection.)

CONCURRENCE OF SMP'S AND BLOOMS



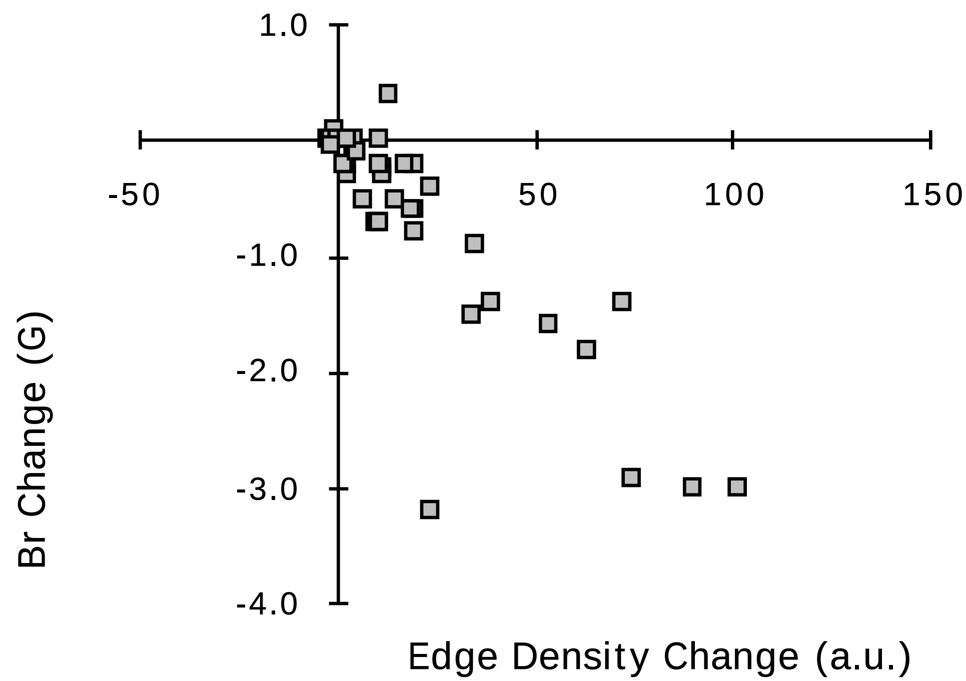


Fig. 4 Nearly all 'bloom' shots had a concurrent SMP (but not all SMP's have a 'bloom').

Fig. 5 Increase in *edge* density during a 'bloom' event is correlated with increase in SMP signals.

EVIDENCE FOR SOURCE OF MAGNETIC SIGNALS

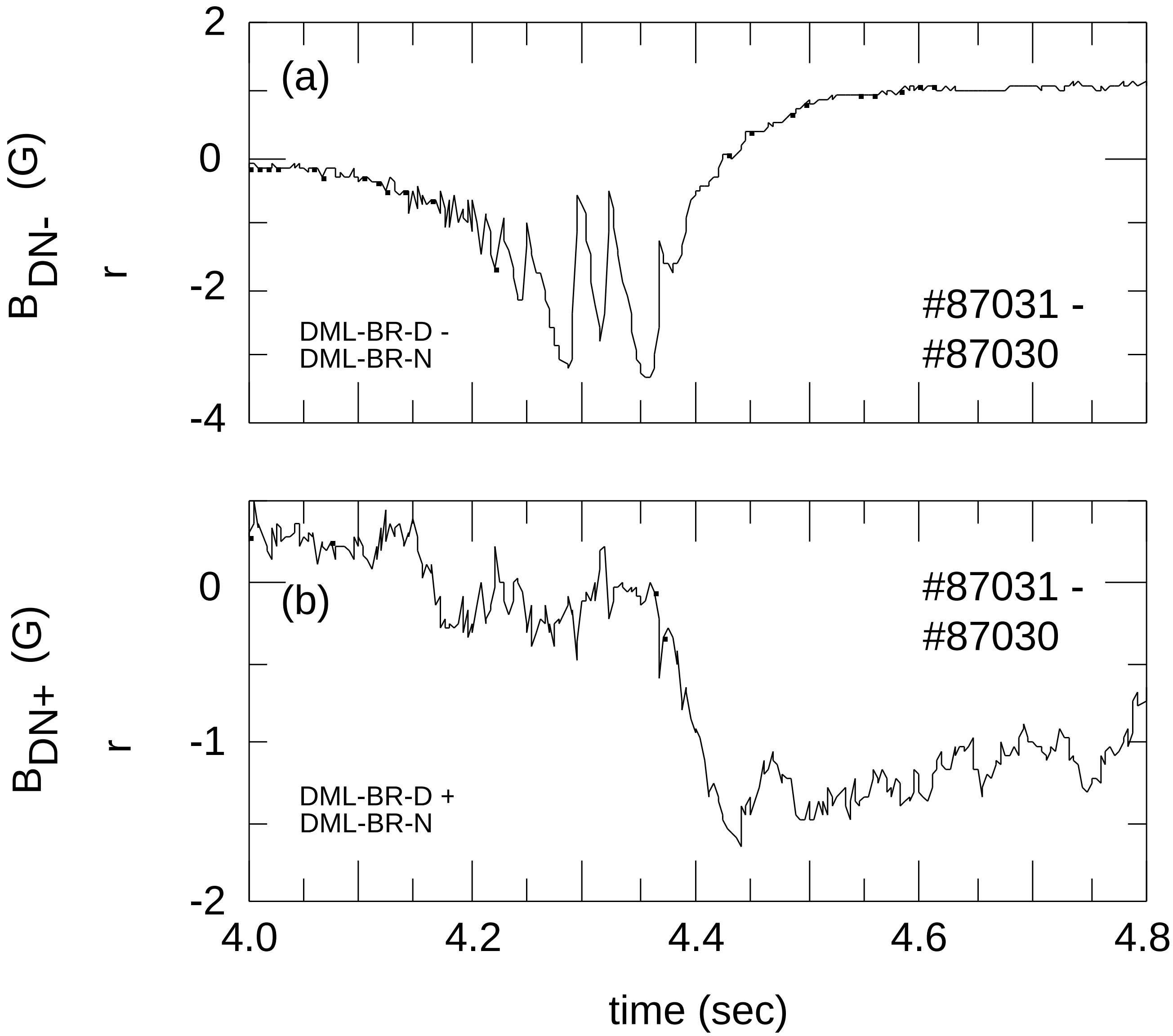


Fig. 6 Both difference and sum of SMP signals from a toroidally opposite sensor pair are examined. The sum and difference signals contain a *secularly* growing component. The difference signal contains also a slow oscillating component. The secular component *cannot* be produced by MHD modes alone. The SMP signal must have contributions from an additional source.

MODEL OF SMP AND 'HALO CURRENTS'

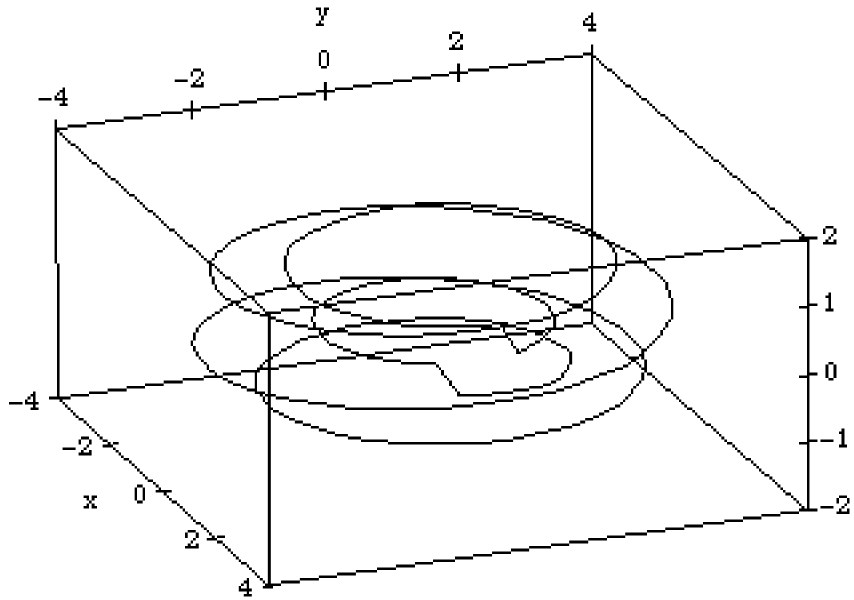
- We postulate 'halo currents' flowing through scrape-off plasmas and tokamak structures. They may sometimes be rotating at small amplitudes, but may get 'anchored' at some preferred limiter points at large amplitudes.

- 'Halo currents' fit the bill in explaining many aspects of the SMP phenomenon, but not 'MHD perturbation currents.'

- 'Halo currents,' interrupted by limiters, are incomplete helices and unidirectional while 'MHD perturbation currents' (placed at x- and o-points) are complete helices and bi-directional. These different geometrial characteirstics result in important differences in effects the currents produce.

- First, 'halo currents' can produce secular and oscillating components in both difference and sum signals, but not 'MHD perturbation currents.' Second, 'halo currents' produce a much greater radial field than 'MHD perturbation currents' (see below). Third, 'halo currents' act like dynamically introduced error fields, and serve as a mechanism to slow down and lock MHD modes.

'INTERRUPTED' HALO CURRENTS



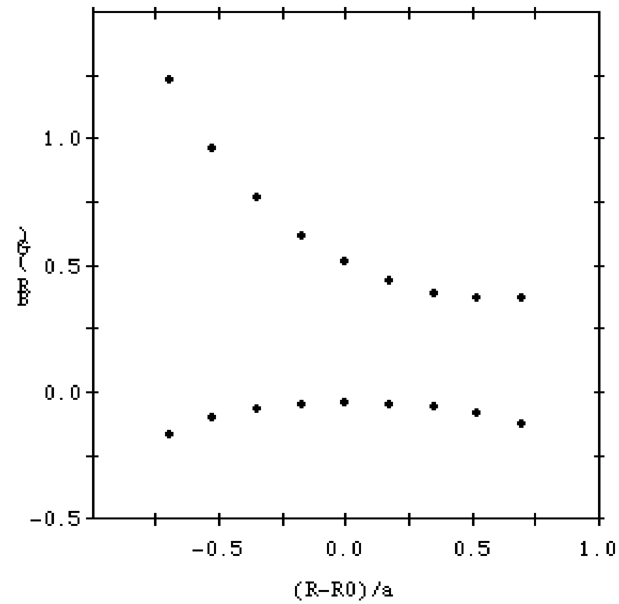


Fig. 7 Halo currents that are interrupted by structures are discrete and incompletely helical 'bundles.'

Fig. 8 'Interrupted' halo currents produce much greater B_r (top 'curve') than completed helical currents (bottom) for a unit current (1 kA).

We think that several kA of 'interrupted halo currents' flow in a tokamak with a few MA of plasma current. Currents of such a size are compatible with observed SMP detector signals.

EVIDENCE FOR SOURCE OF MAGNETIC SIGNALS — Cont.

- We observe that waveforms (i.e., *time* variation) of Mirnov signals resembled a regular sinusoid well before the 'mode locking' time, but became distorted at later times. This can be evidence for the presence of a source of magnetic signals in addition to, or in place of, MHD modes.
- We note, however, that waveforms can be distorted either because a spatially regular perturbation structure rotates at irregular speeds, or because a spatially irregular structure rotates at a regular (or irregular) speed.
- A Lissajous diagram of a pair of Mirnov signals can be used to eliminate the time as a variable, and hence to discern the *spatial* coherence of a perturbation structure to distinguish between these possibilities.
- We will conclude that the waveform distortion of external magnetic signals was a result of spatial distortion due to an additional source of magnetic signals, for example, 'halo currents.' Comaprisons with Lissajous diagrams of internal perturbations will reinforce this conclusion.

MIRNOV SIGNALS 'WELL BEFORE' LOCKING

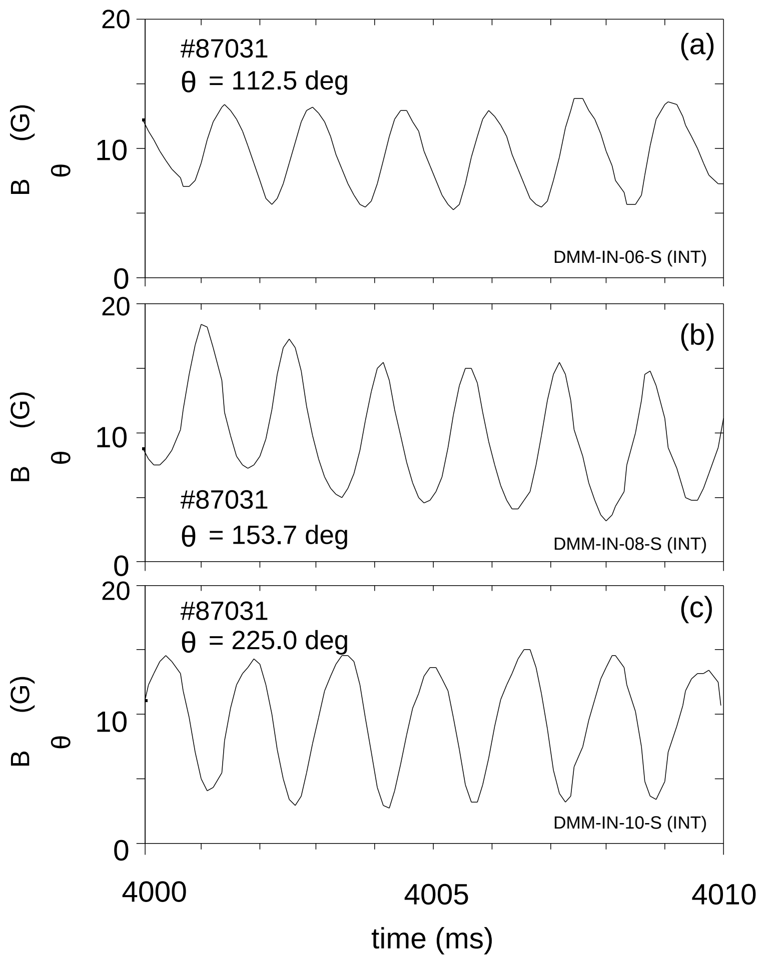


Fig. 9 Waveforms of Mirnov signals show time coherenece at all poloidal locations.

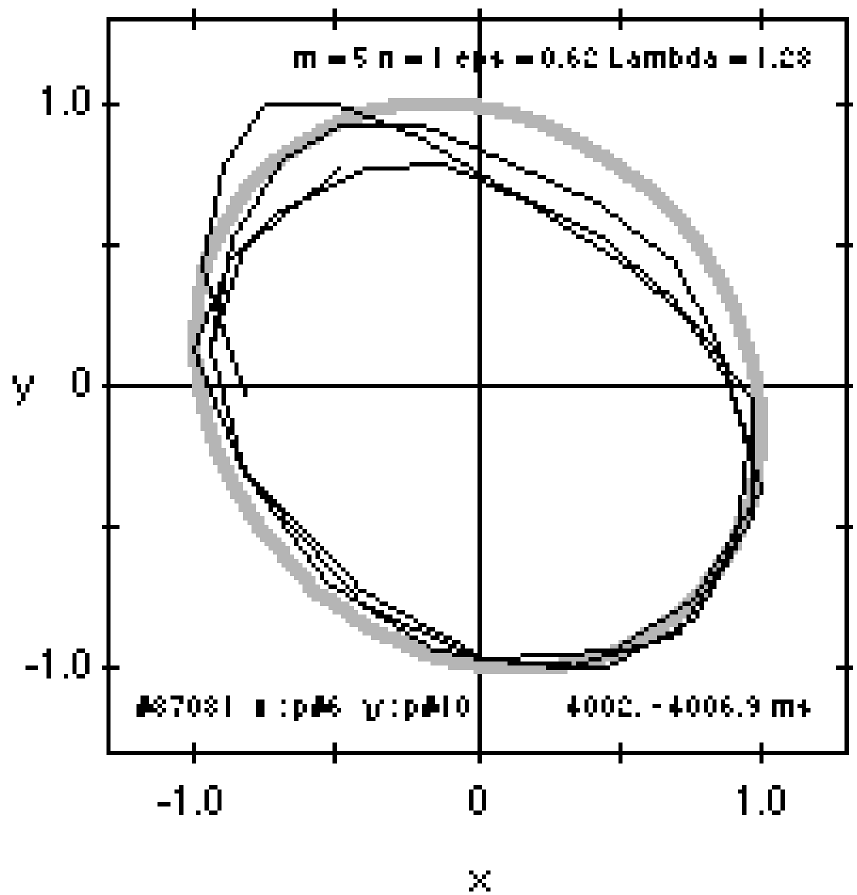


Fig. 10 Lissajous diagrams of a pair of Mirnov signals (δB_1 vs. δB_2) show space coherence over many cycles.

MIRNOV SIGNALS ‘JUST BEFORE’ LOCKING

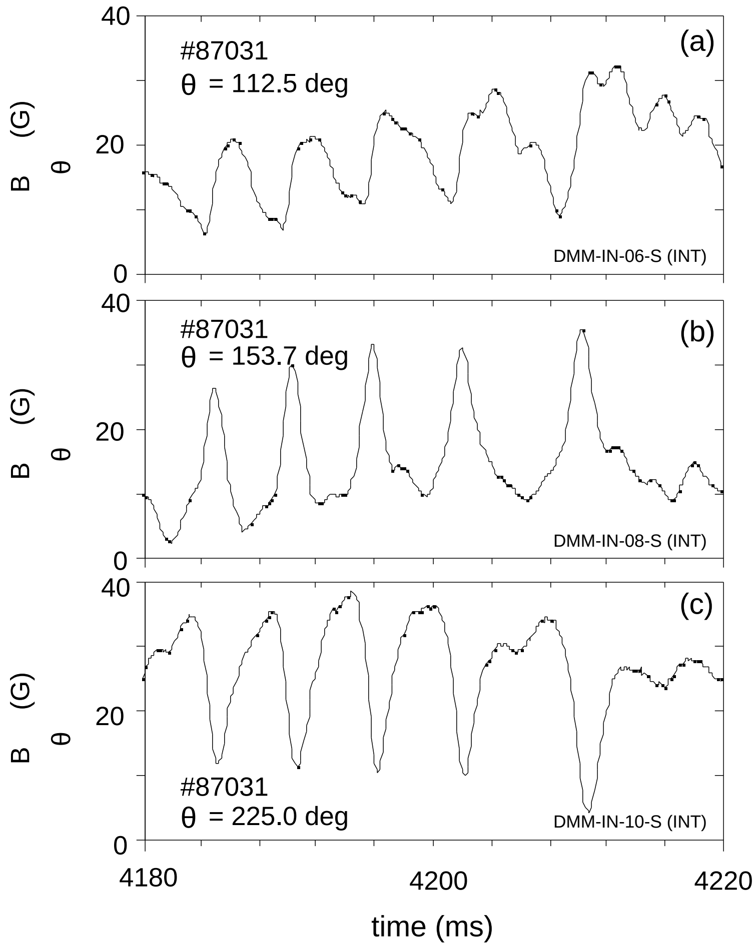


Fig. 11 Waveforms of Mirnov signals show distorted time coherenece at all poloidal locations.

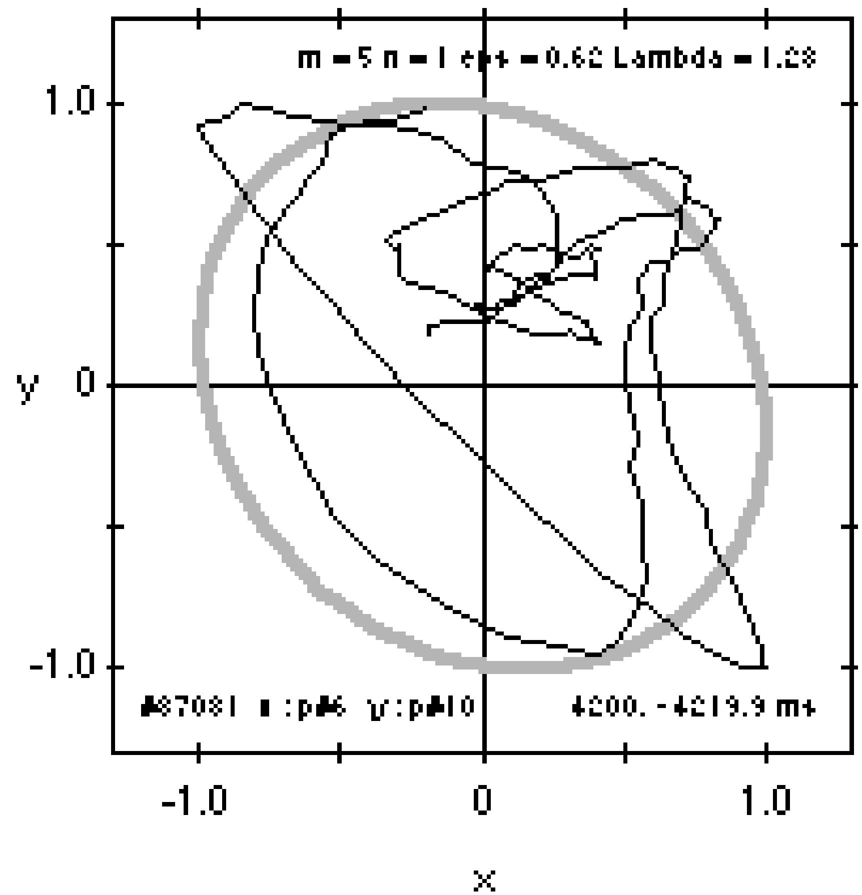
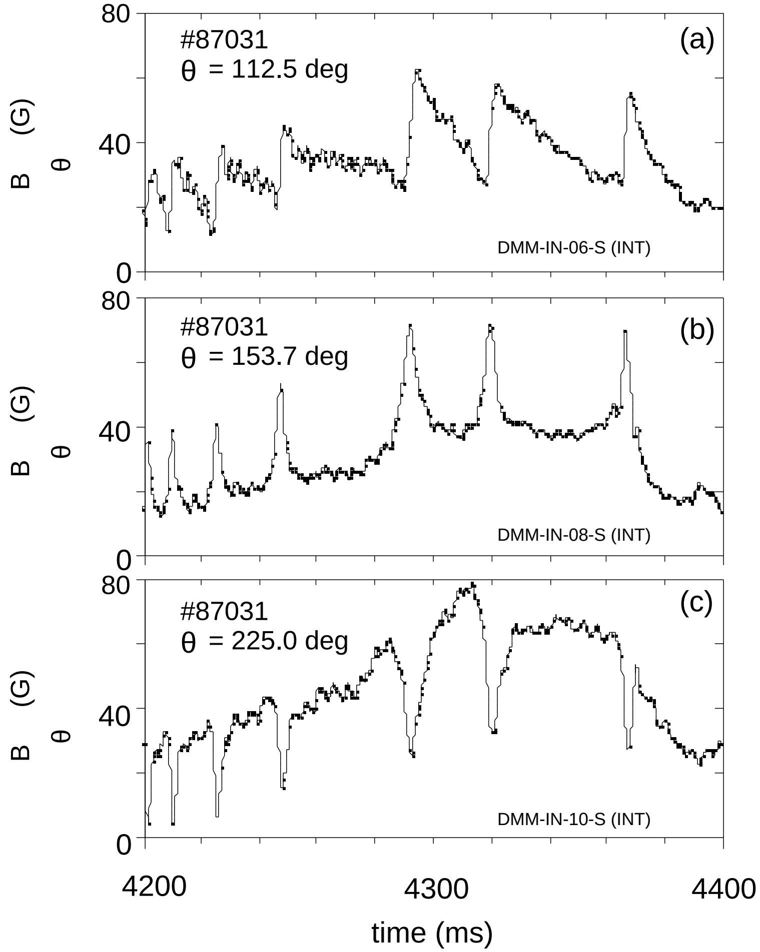


Fig. 12 Lissajous diagrams of a pair of Mirnov signals (δB_1 vs. δB_2) show distorted space coherence.

MIRNOV SIGNALS 'AROUND' LOCKING



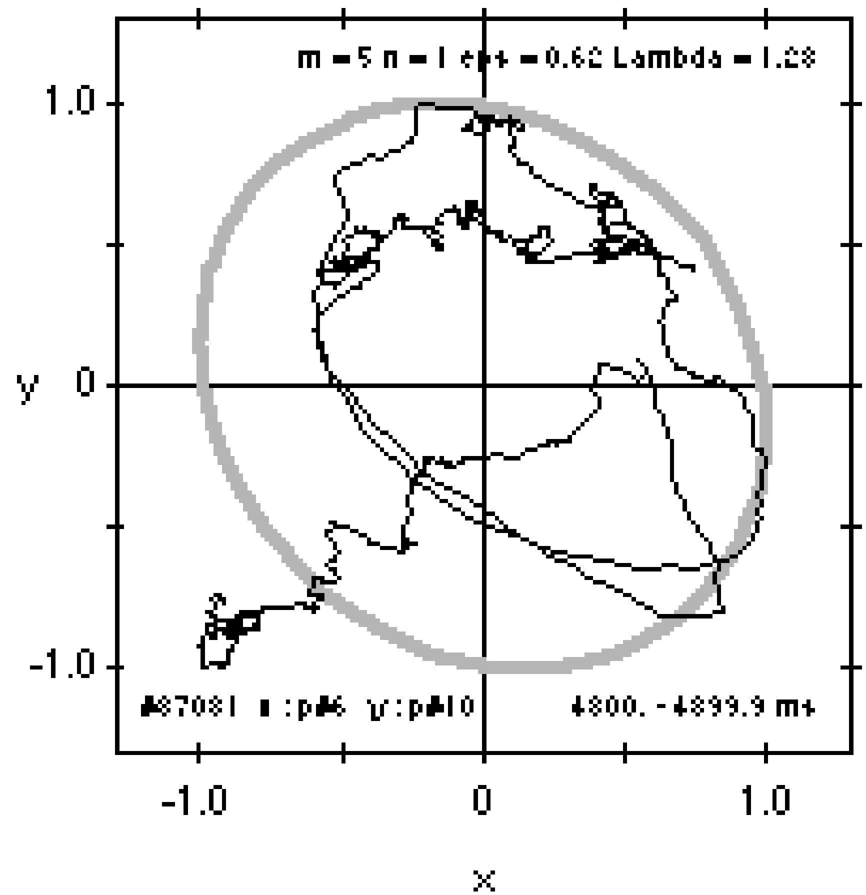


Fig. 13 Waveforms of Mirnov signals show strongly distorted time coherenece at all poloidal locations.

Fig. 14 Lissajous diagrams of a pair of Mirnov signals (δB_1 vs. δB_2) show strongly distorted space coherence.

INTERNAL PERTURBATIONS — ISLANDS

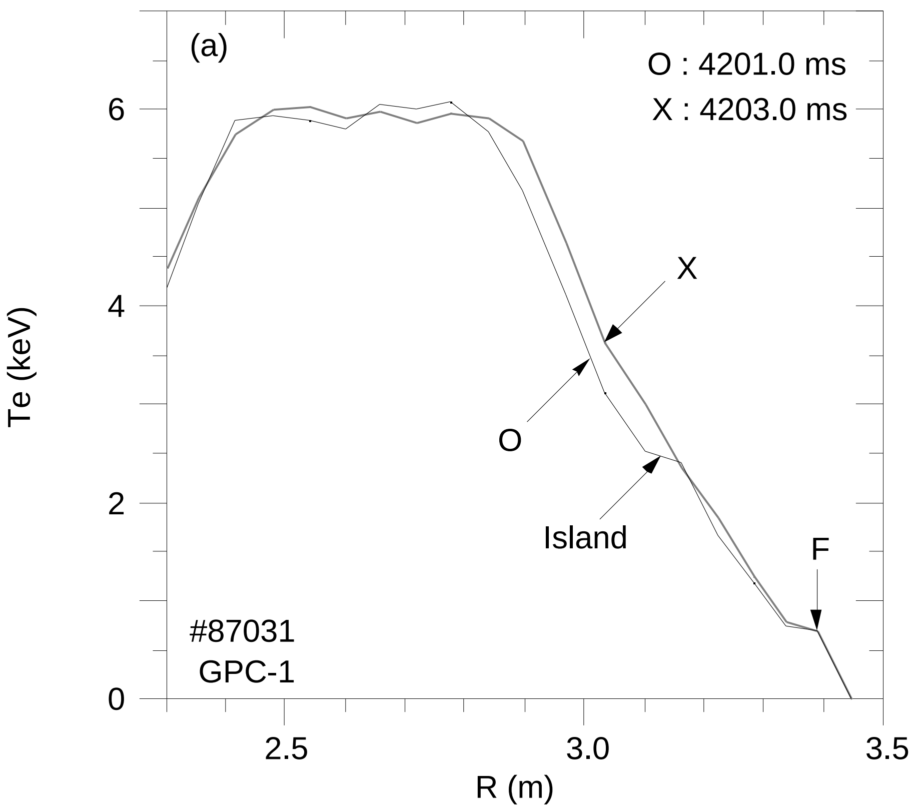


Fig. 15 T_e profiles from GPC-1 signals show an island structure 'just before locking time.'

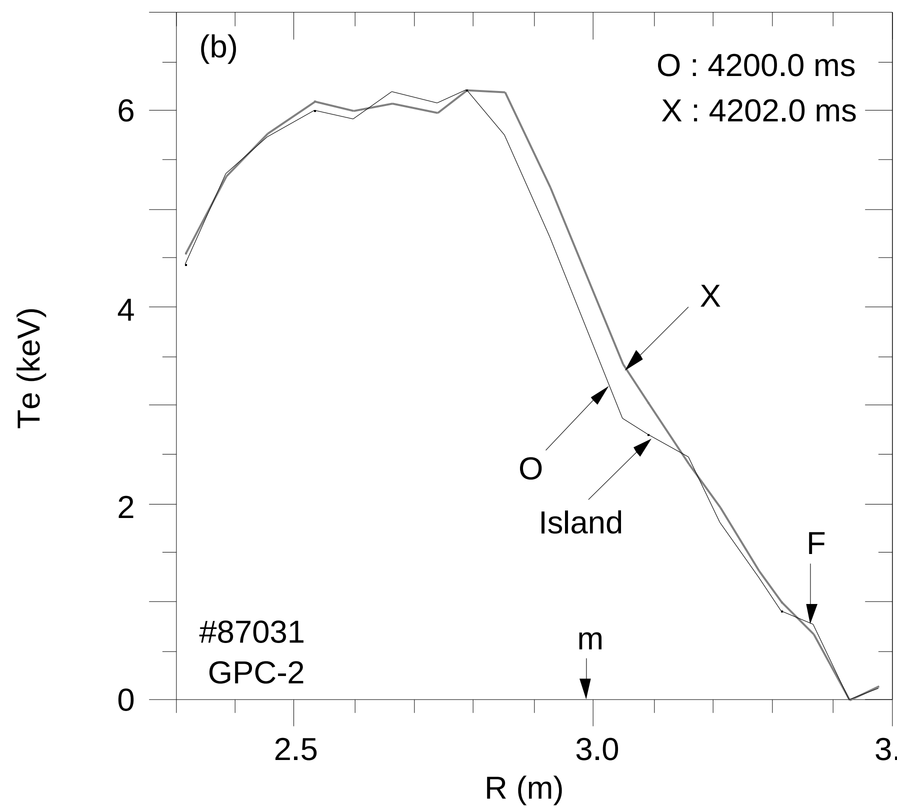


Fig. 16 T_e profiles from GPC-2 signals show an island structure 'just before locking time.'

SPACE COHERENCE OF INTERNAL PERTURBATIONS

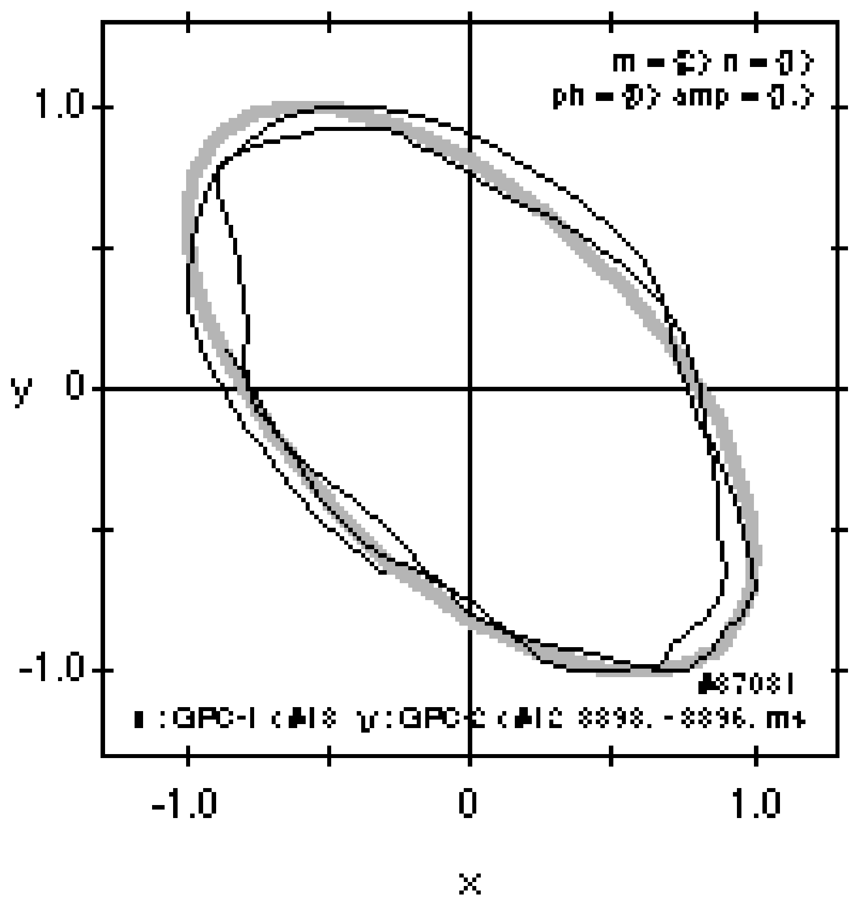


Fig. 17 Lissajous diagrams of a pair of T_e perturbation signals (δT_{e1} vs. δT_{e2}) 'well before locking time'—good space coherence.

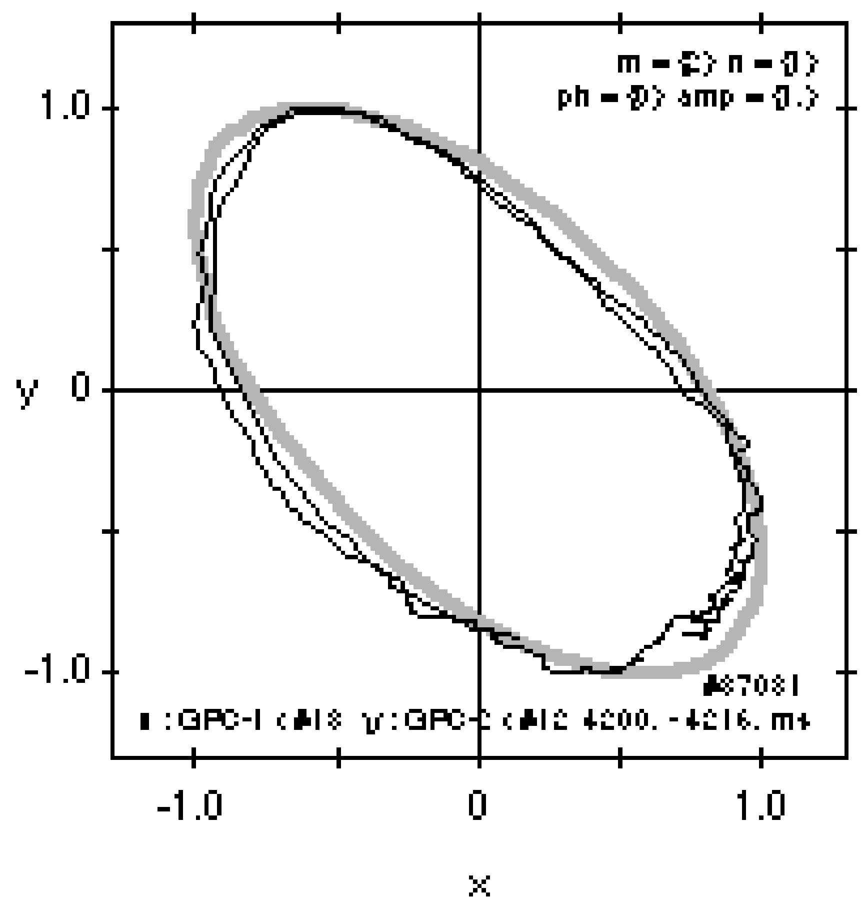


Fig. 18 Lissajous diagrams of a pair of T_e perturbation signals (δT_{e1} vs. δT_{e2}) 'just before locking time'—still good space coherence *unlike* external magnetic signals.

ISLAND GROWTH

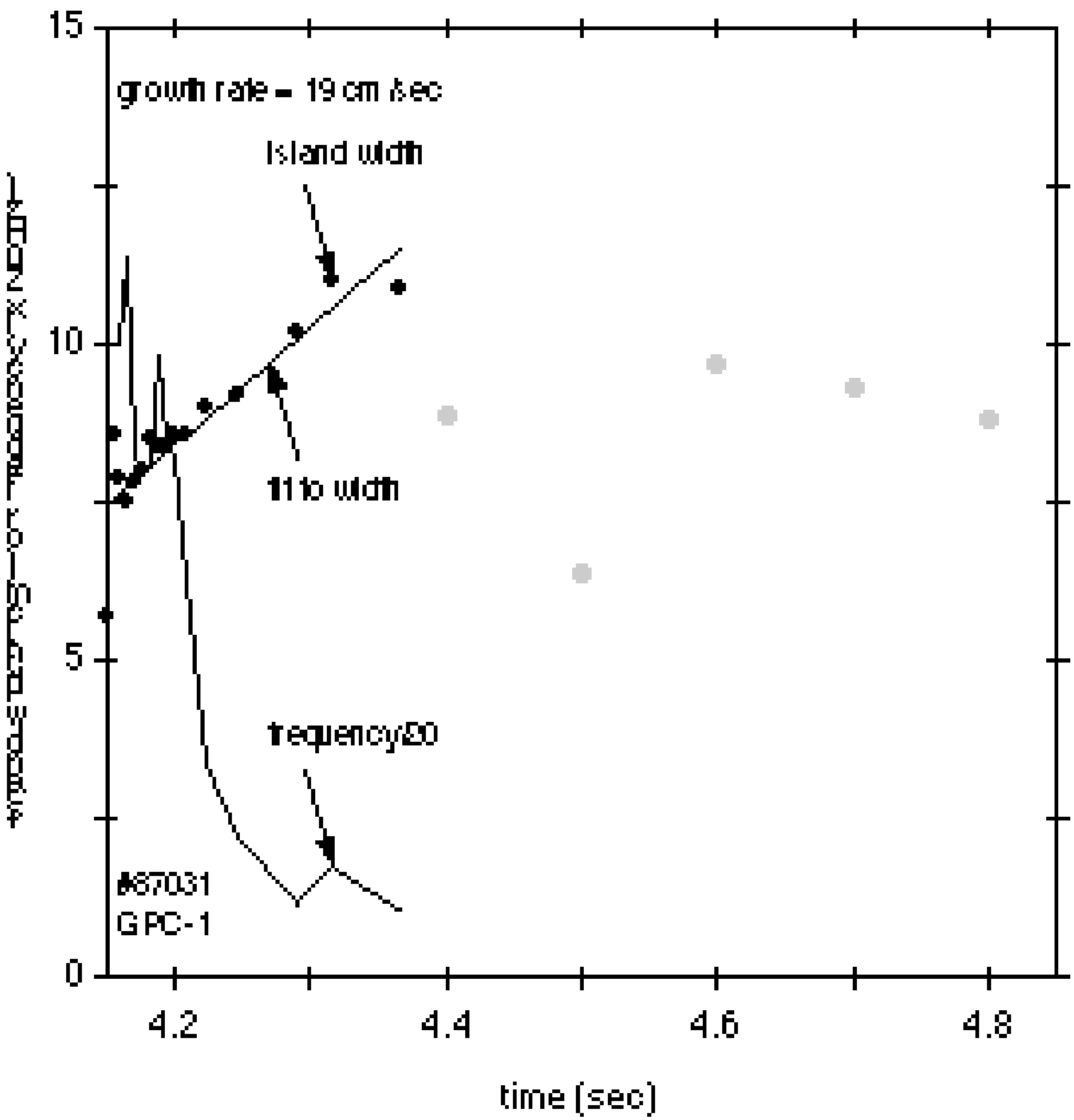


Fig. 19 Island width and rotation frequency measured by ECE. Island is growing before 'mode locking,' with a growth rate that is little affected by mode slow down. Island does not grow after locking (points after locking in gray), contrary to a theoretical expectation.

SUMMARY

1. A source of magnetic signals in addition to, or in place of, MHD modes is involved in the SMP phenomenon.
2. 'Halo currents' in a scrape-off plasma are a possible additional source of magnetic signals in the SMP phenomenon.
3. A 'bloom' is nearly always accompanied by an SMP (but the converse is not true), and hence involves electrical currents; A 'bloom' is akin to an electrical breakdown in a scrape-off plasma.