ABSTRACT

Effect of the I-coil on the Low Density Locked Mode Threshold in DIII-D

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In DIII-D Ohmic discharges, the low density limit of the tokamak is defined by the onset of locked modes. These non-rotating instabilities are driven by the presence of an intrinsic tokamak error field created by small errors in coil locations and coil symmetries. For several years, the DIII-D external error field correction coil system (C-coil) has been used to partially correct the tokamak's error field, leading to better plasma stability. Installation of the new internal coil set (I-coil) has allowed further exploration of the error field by using the I-coil to apply a variety of poloidal mode spectra and field helicities, capabilities that the C-coil does not have. A systematic scan over I-coil parameters that include amplitude, phase, and poloidal mode spectrum has recently been performed, documenting the effects on the low density locked mode threshold. We present the results of these experiments, compare them to C-coil results, and discuss what is revealed about the error field component resonant with the locked mode instability.

INTRODUCTION

- Stability in Ohmic low density plasmas is modified by the application of externally generated radial magnetic fields.

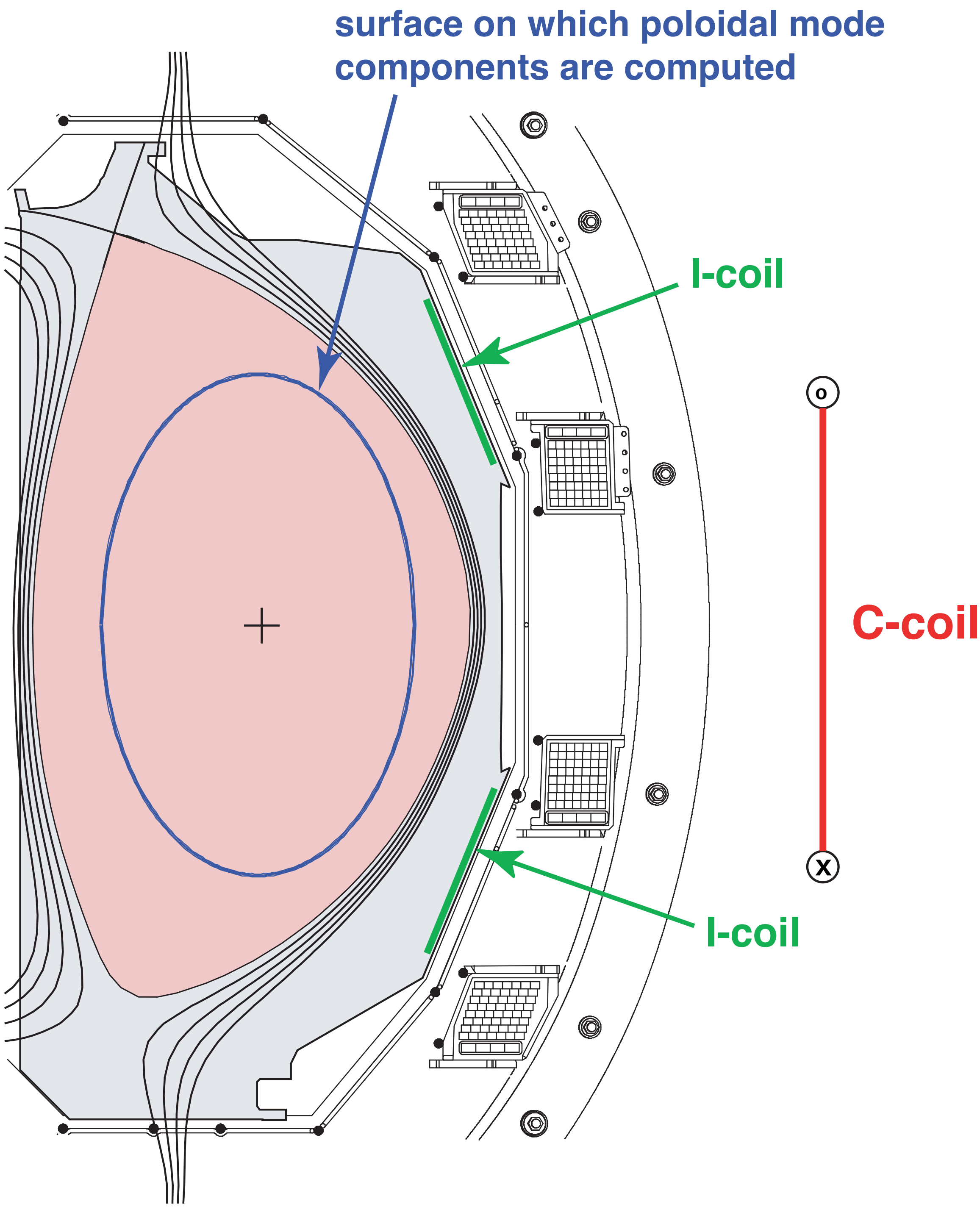
- Unlike the C-coil, the 12 in-vessel I-coils allow modifying the helicity and poloidal mode spectrum of the applied radial field.

- Using the I-coils, the low density locked mode threshold was investigated to help answer the following questions:

  – What do the experimental results reveal about the error field components that couple to the locked mode instability?

  – What can we deduce about the nature of the inherent error field of the tokamak?

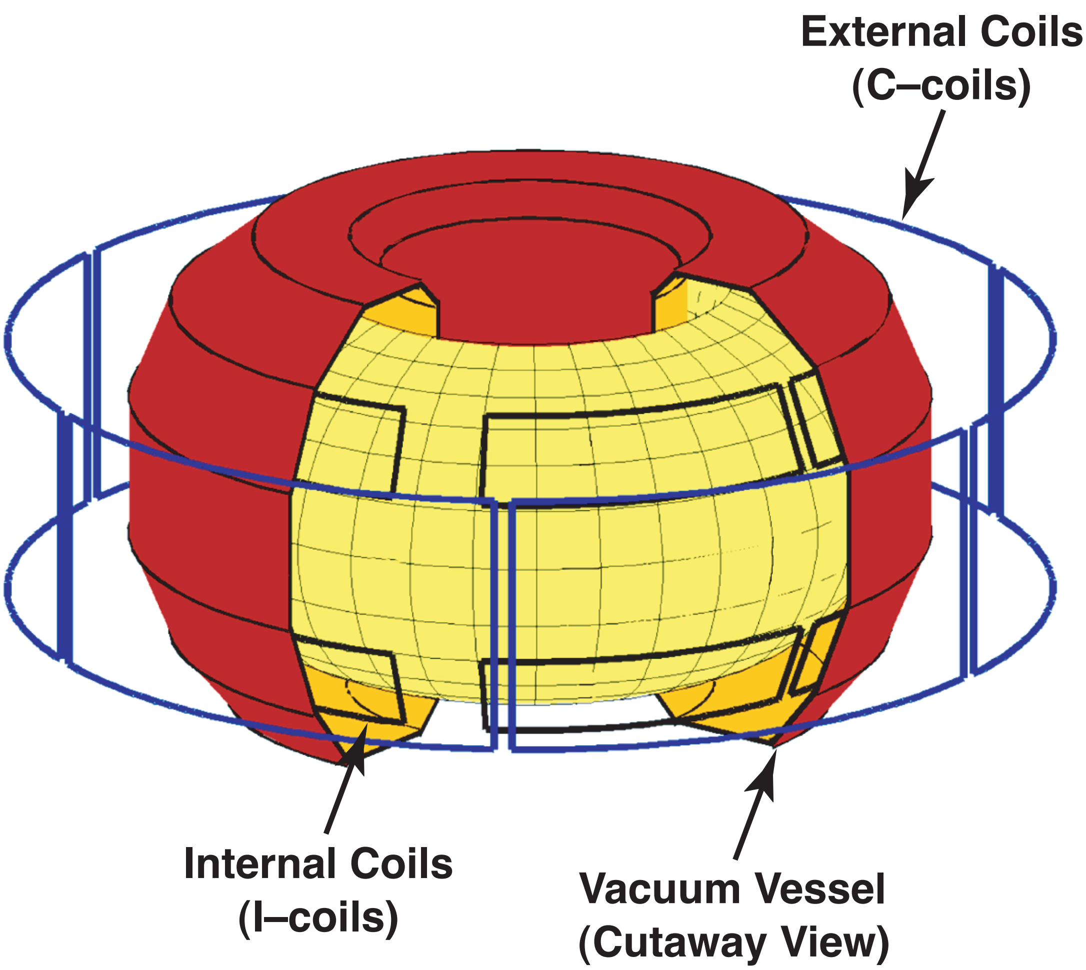
MAGNETIC FIELD PERTURBATIONS ARE APPLIED TO THE PLASMA USING THE 6 EXTERNAL C-COILS OR THE 12 INTERNAL I-COILS



ISOMETRIC VIEW OF MAGNETIC FIELD PERTURBATION COILS SHOWING EXTERNAL C-COILS AND INTERNAL I-COILS

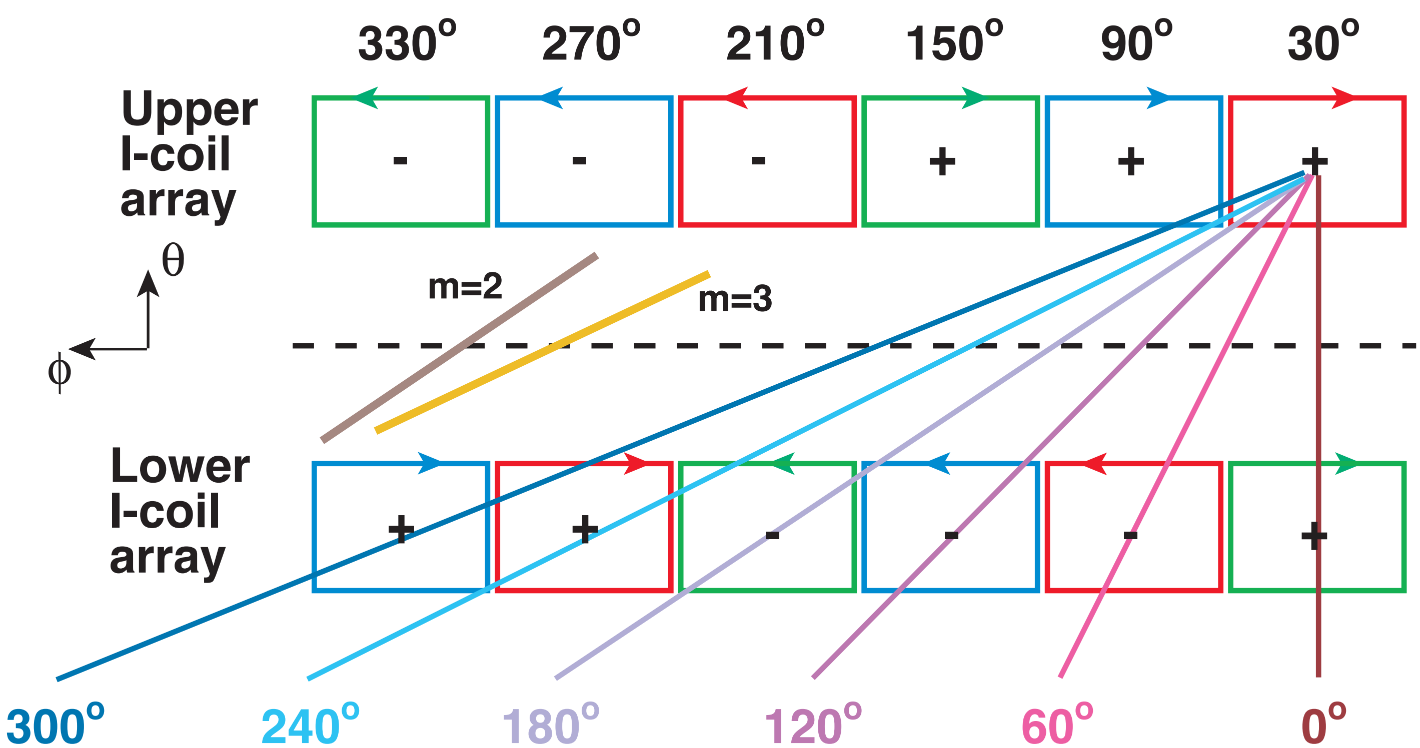
- **C-coil has 6 external 4-turn coils at midplane. Max current 28 kA-turns.**

- **I-coil has 12 internal single-turn coils, 6 above midplane and 6 below. Max current 7 kA-turns.**



DIFFERENT I-COIL CONFIGURATIONS PRODUCE A FIELD WITH A VARIETY OF PITCH ANGLES TO ALTER THE POLOIDAL MODE SPECTRUM

- **Three sets of 4 I-coils each (red, blue, green) are connected in series to make "quartets".**
  - **180° pairs connected in antiseries for n=1.**
  - **top pair connected to bottom pair with a phase shift of $\Delta\phi$ = 0°, 60°, 120°, 180°, 240°, 300° (240° phasing shown).**

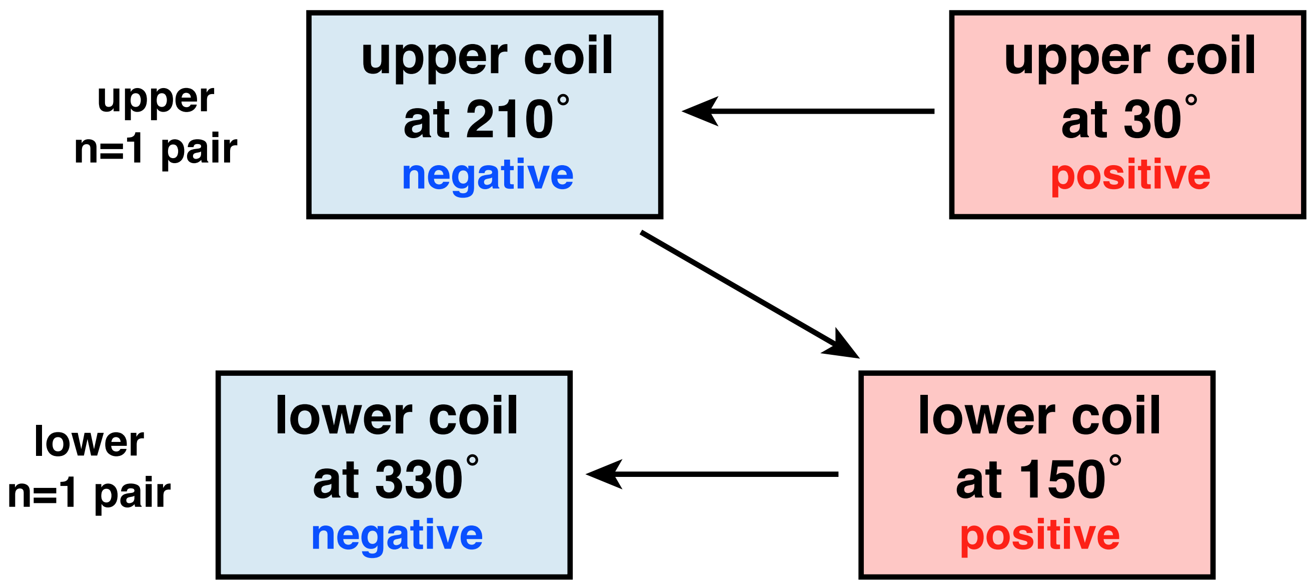


- **Poloidal mode m ~ $\Delta\phi/\Delta\theta$ for toroidal mode n=1. $\Delta\theta$ is fixed. Larger $\Delta\phi$ shifts spectrum to higher m.**
  - **left-handed (resonant) m/n = 2/1 and 3/1 approximate pitches shown**

TERMINOLOGY

- "Phasing" - difference, $\Delta\Phi$, in toroidal angle between top n=1 pair and bottom n=1 pair of I-coils making up a quartet. PHASING DETERMINES THE HELICITY.

current path for quartet with 120° phasing:



- "Phase" - the toroidal angle, at midplane, of the maximum of the applied quartet field.

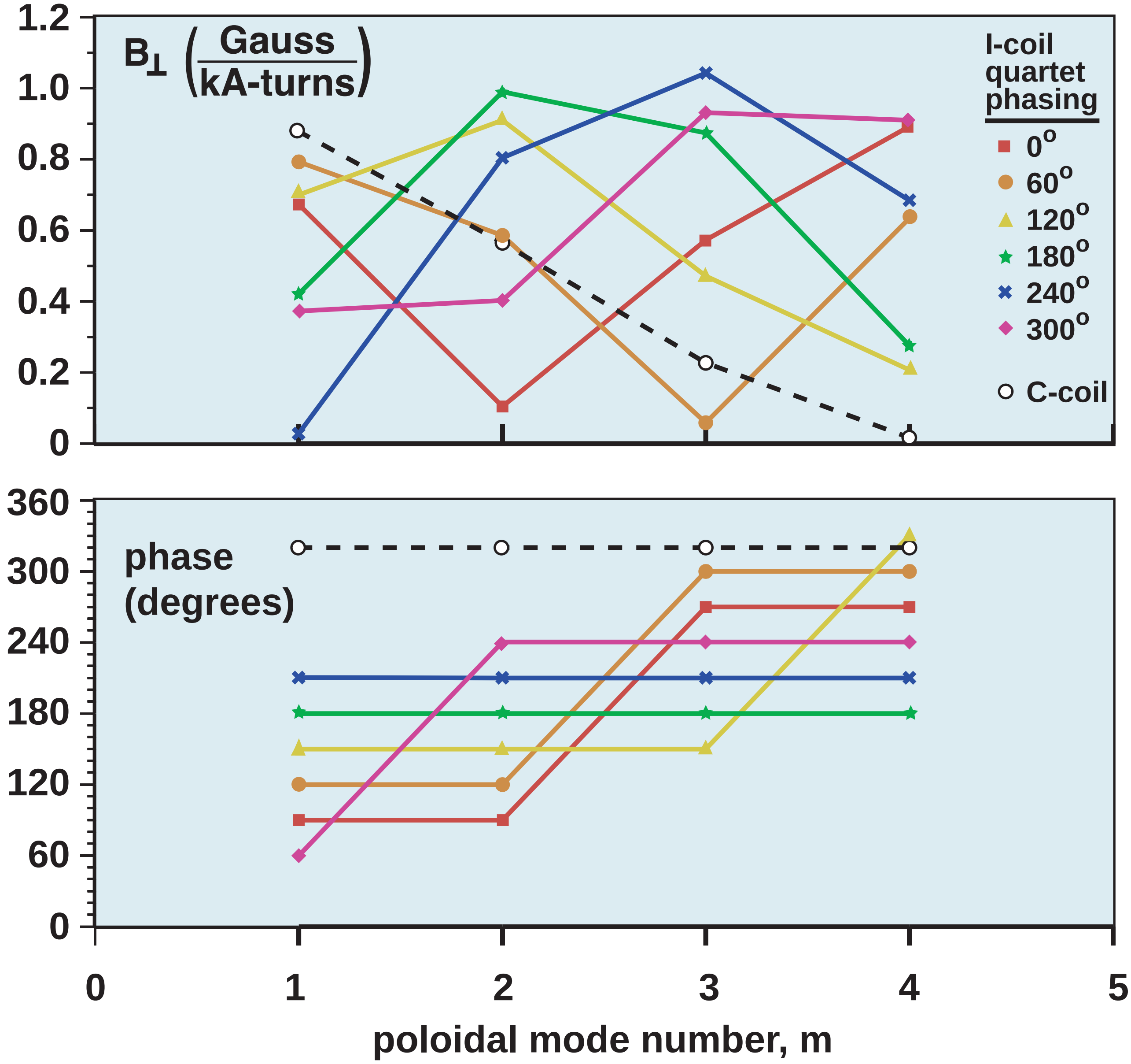
$$\phi_{mid} = \phi_{up} + \frac{\Delta\Phi}{2}$$

- phase of field applied with quartet example above is 90°

THE n=1 POLOIDAL MODE SPECTRUM OF I-COIL QUARTETS IS VARIABLE USING PHASE SHIFTS BETWEEN UPPER AND LOWER PAIRS

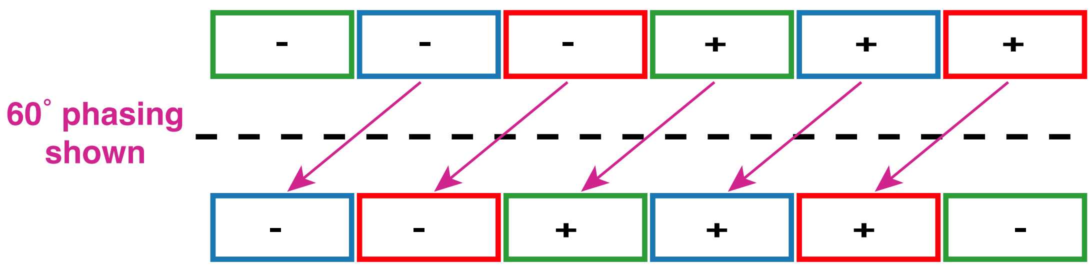
- **For the spectra below, all coil current magnitudes are 1 kA-turn. Upper coil polarities + + + - - -. Lower coil polarities determined by phasing.**

- **Note phase "flip" of some mode components.**

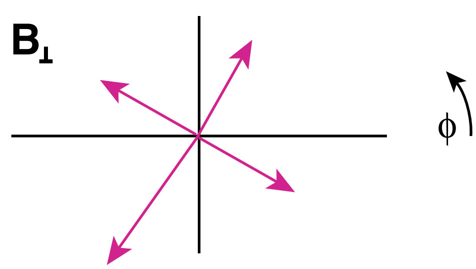


EXPERIMENTAL METHOD: SCAN I-COIL PARAMETERS AND DOCUMENT LOW DENSITY LOCKED MODE THRESHOLD

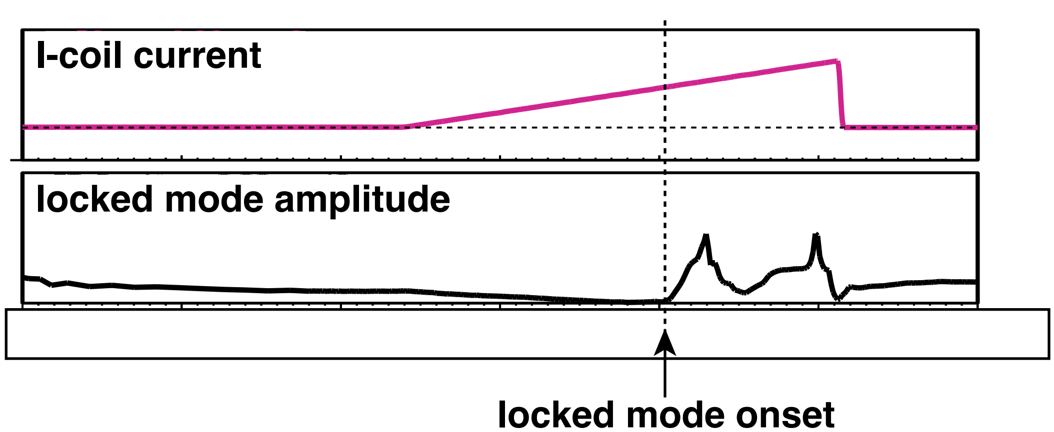
- Six I-coil quartet "phasings", i.e., the phase shift between the upper n=1 pair of I-coils and the lower n=1 pair.



- For each quartet phasing, scan the toroidal phase. Four shots - one in each quadrant.

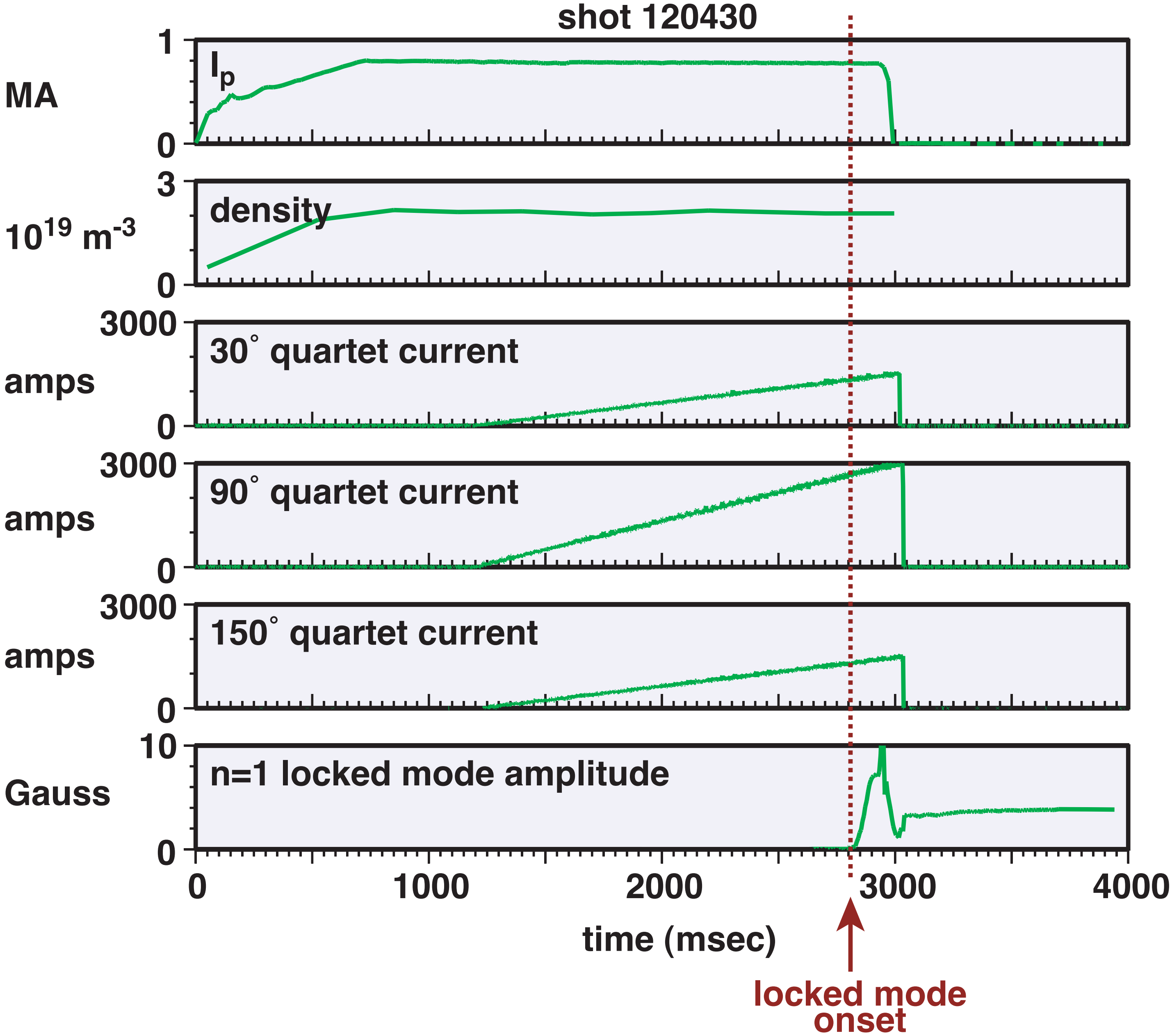


- Ramp the amplitude of the applied field until the locked mode is triggered.

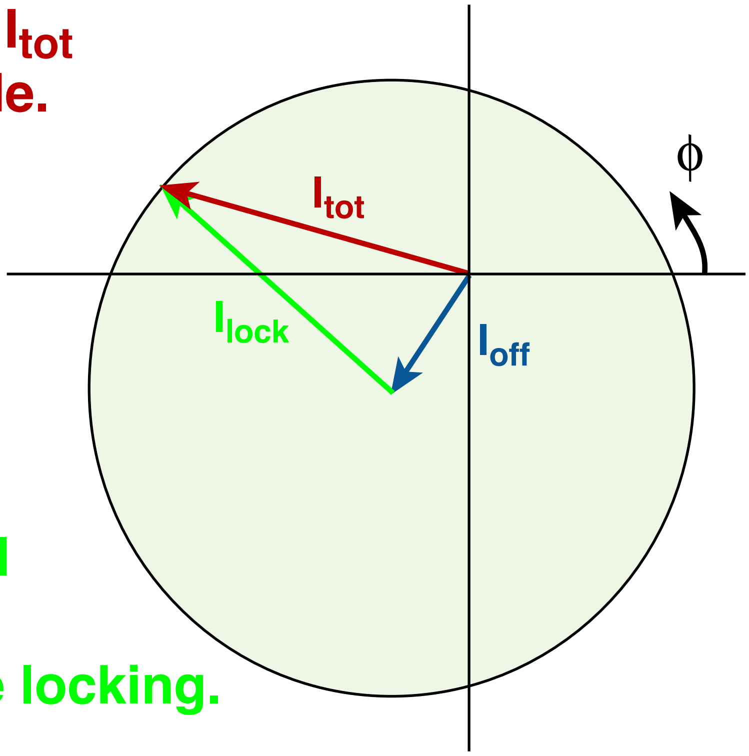


LOCKED MODE THRESHOLD DATA OBTAINED BY RAMPING I-COIL CURRENTS AT FIXED DENSITY UNTIL LOCKED MODE ONSET

- I-coil quartet currents ramped in fixed ratio to apply n=1 field with desired toroidal phase.
- Current ratios chosen to eliminate n=3.



THE APPLIED I-COIL FIELD IS RESOLVED INTO "OFFSET" AND "LOCKING" COMPONENTS



- Total current vector I_{tot} induces locked mode.
- Offset current I_{off} accounts for the inherent error field of the tokamak.
- I_{lock} is the additional current (after offset) necessary to induce locking.
- For each quartet phasing, I_{off} is calculated by averaging over the four discharges, one in each toroidal quadrant:

$$f \equiv \sum_{i=1}^{4} \left| \bar{I}_{tot,i} - \bar{I}_{off} \right|^2 \quad , \qquad \frac{df}{dI_{off}} = 0$$

- Locking current I_{lock} is average difference between total and offset:

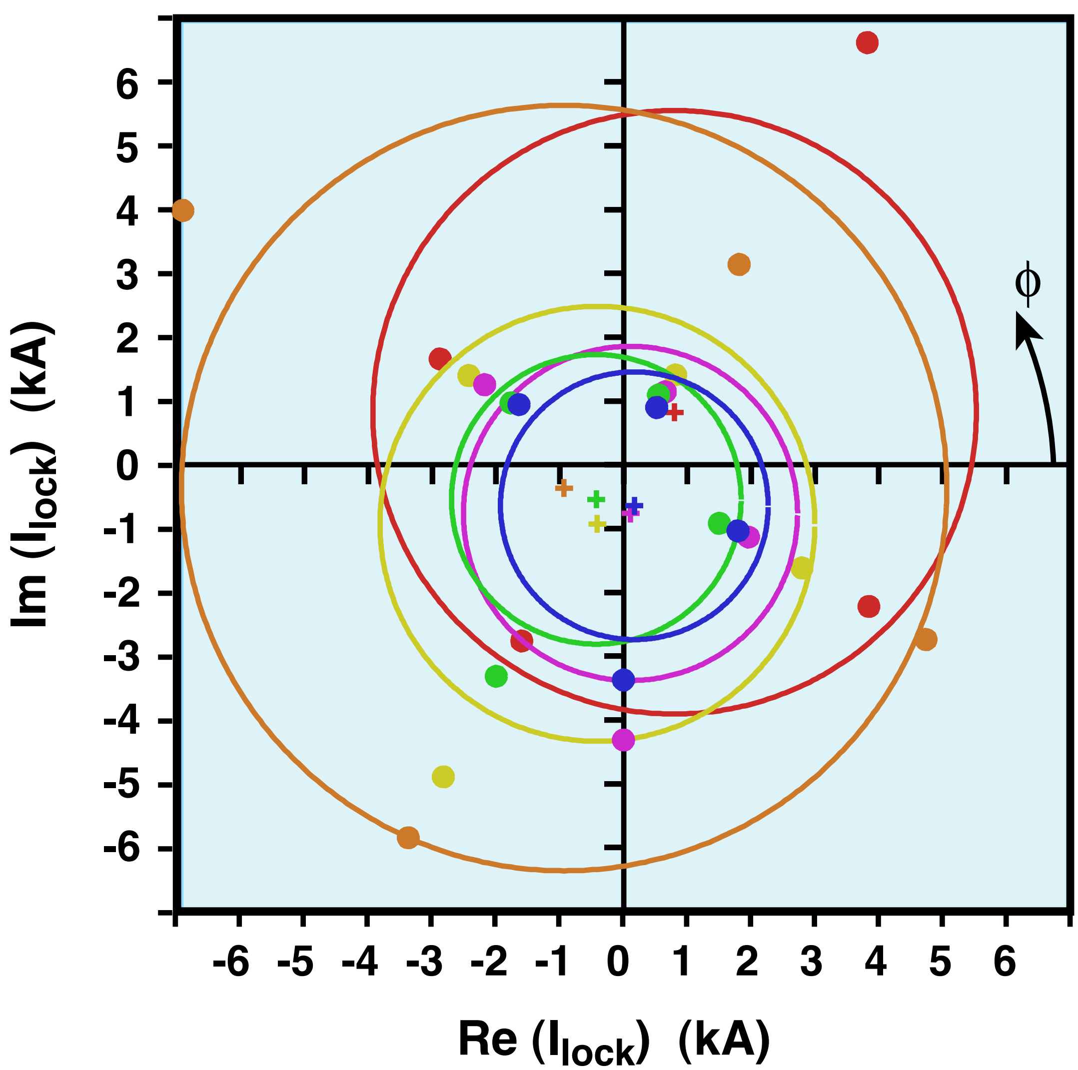
$$\vec{I}_{lock} = \frac{1}{4} \sum_{i=1}^{4} \left(\vec{I}_{tot,i} - \vec{I}_{off} \right)$$

EACH QUARTET PHASING DEFINES A PARAMETER SPACE FOR THE LOCKED MODE

- Each quartet phasing predicts locked modes outside the circle fit to each dataset.
- Center of circle (cross) is defined by the offset current.
- Radius of circle is defined by the locking current.

quartet phasing:

0° phasing
60° phasing
120° phasing
180° phasing
240° phasing
300° phasing

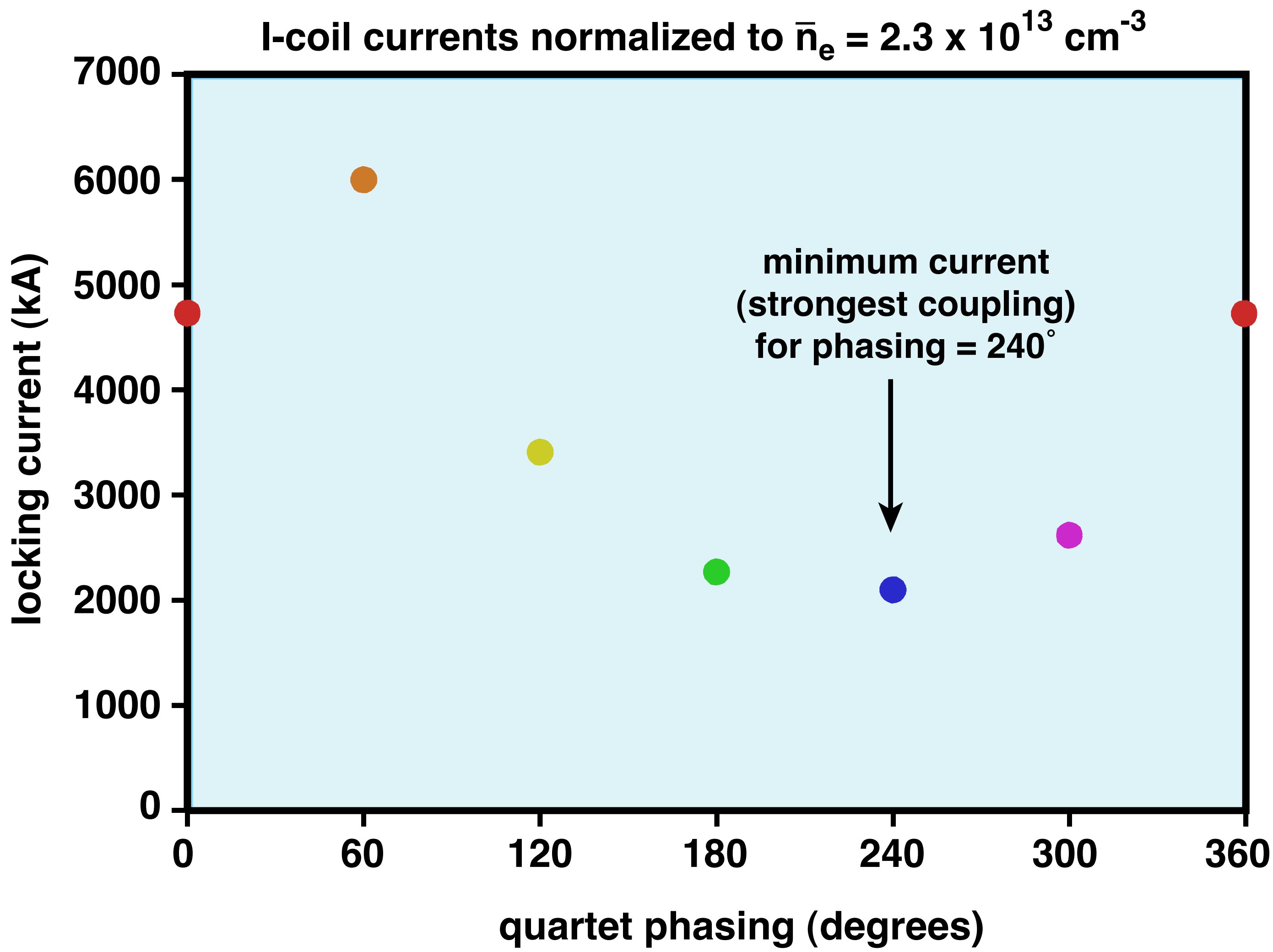


LOCKING CURRENT

I-COIL CURRENT REQUIRED TO INDUCE LOCKED MODE IS STRONG FUNCTION OF QUARTET PHASING

- Locking current is effective n=1 I-coil current, corrected for offset, required to produce locked mode.

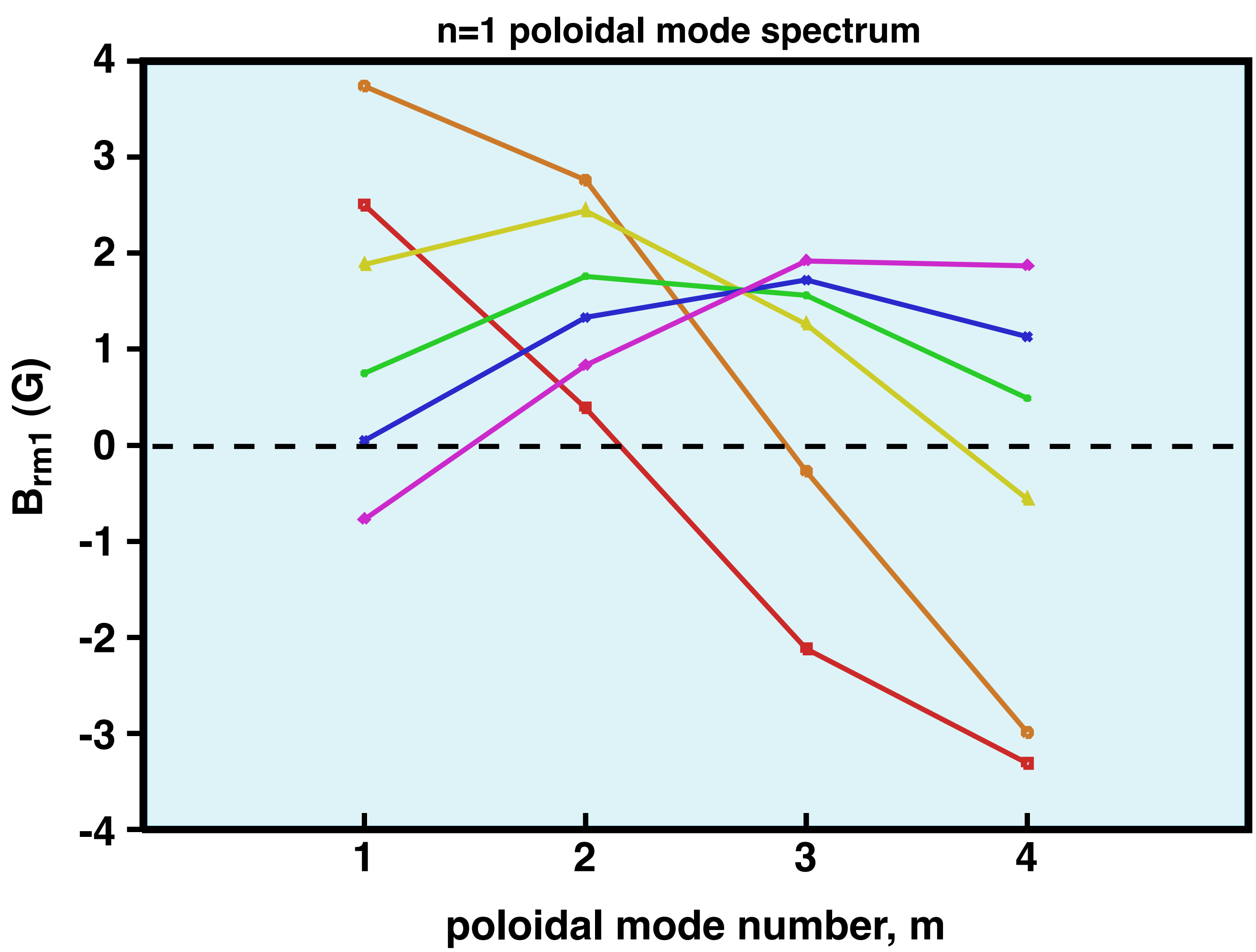
- Quartet phasing determines pitch angle of applied field. Good coupling when pitch angle similar to that of m/n=2/1 and m/n=3/1 modes.



POLOIDAL MODE SPECTRUM OF THE AVERAGE "LOCKING" CURRENT FOR EACH QUARTET PHASING

- **Lowest amplitudes for 180˚, 240˚, and 300˚ quartet phasings.**
- **Note 120˚, 180˚, 240˚, 300˚ spectra have nearly identical amplitude between m=2 and m=3.**

quartet phasing:
0˚ phasing
60˚ phasing
120˚ phasing
180˚ phasing
240˚ phasing
300˚ phasing



THE FIT TO THE MODE-COUPLING FORM OF THE PENETRATION FIELD USING I-COILS IS DIFFERENT THAN THAT OF THE C-COILS

- **The penetration field, B_{pen}, is the field that resonates at the q=2 surface to produce a locked mode.** [Scoville & La Haye, Nucl. Fus. 43 (2003) 250-257.]

- **B_{pen} includes the effects of both viscous and direct mode coupling between the m=1 and m=3 modes to the m=2 mode.**

$$B_{pen} = \left[w_1 b_{11}^2 + \left(u_1 b_{11s} + b_{21s} + u_3 b_{31s} \right)^2 + \left(u_1 b_{11c} + b_{21c} + u_3 b_{31c} \right)^2 + w_3 b_{31}^2 \right]^{1/2}$$

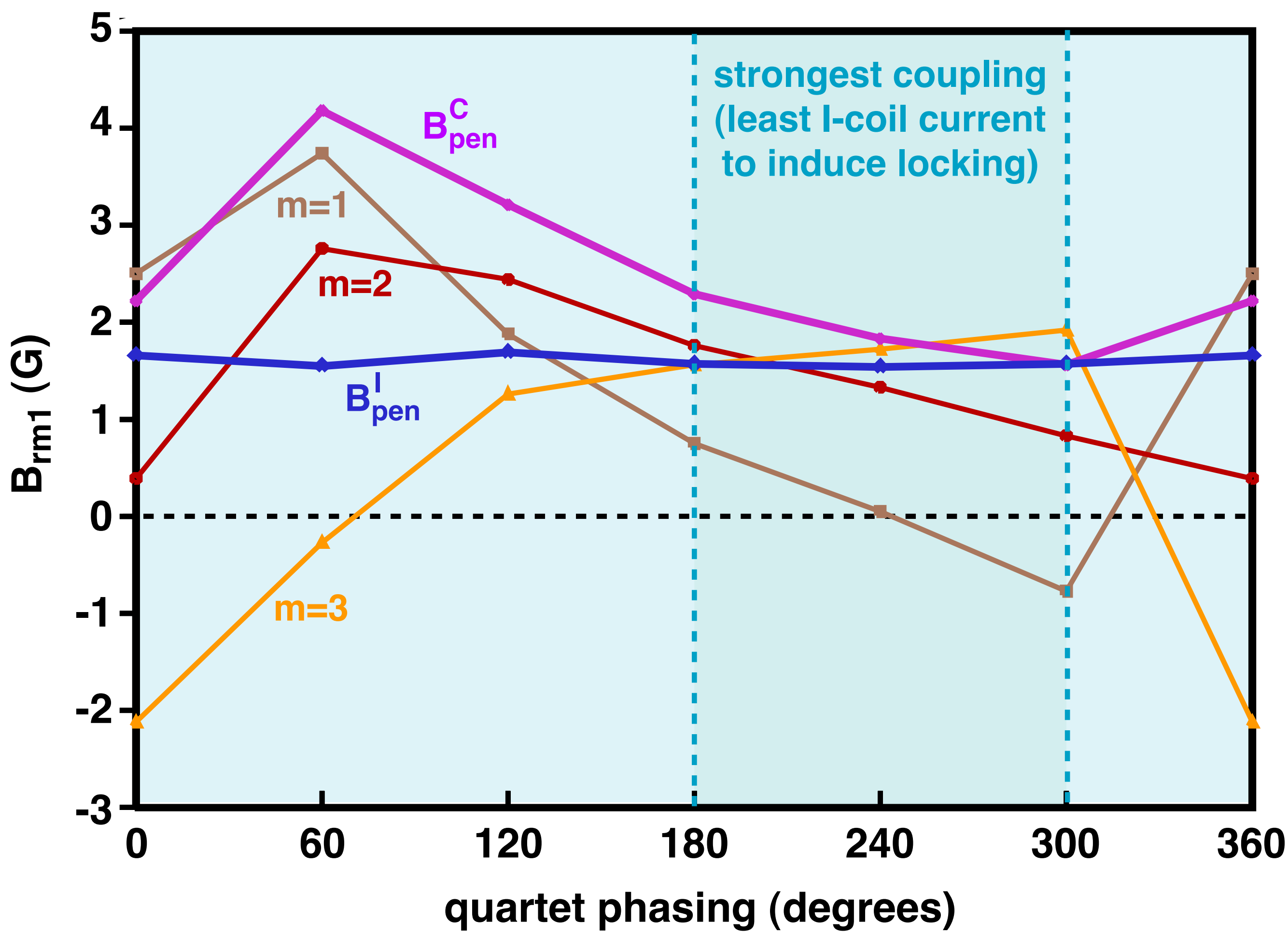
- **The mode-coupling coefficients (w_1, u_1, u_3, w_3) are determined by fits using low density locked mode threshold data.**

- **C-coil data and I-coil data give much different results:**

	w_1	u_1	u_3	w_3
C-coil	0.29	0.24	0.02	0.49
I-coil	0.15	-1.01	-1.64	0.00

POLOIDAL MODE AMPLITUDES VS. QUARTET PHASING FOR AVERAGE "LOCKING" CURRENT

- B_{pen} calculated from old C-coil locked mode database is compared to B_{pen} calculated from new I-coil data.
- Negative amplitude indicates mode phase "flipped" 180˚.
- Least locking current required when both m=2 and m=3 amplitudes significant.



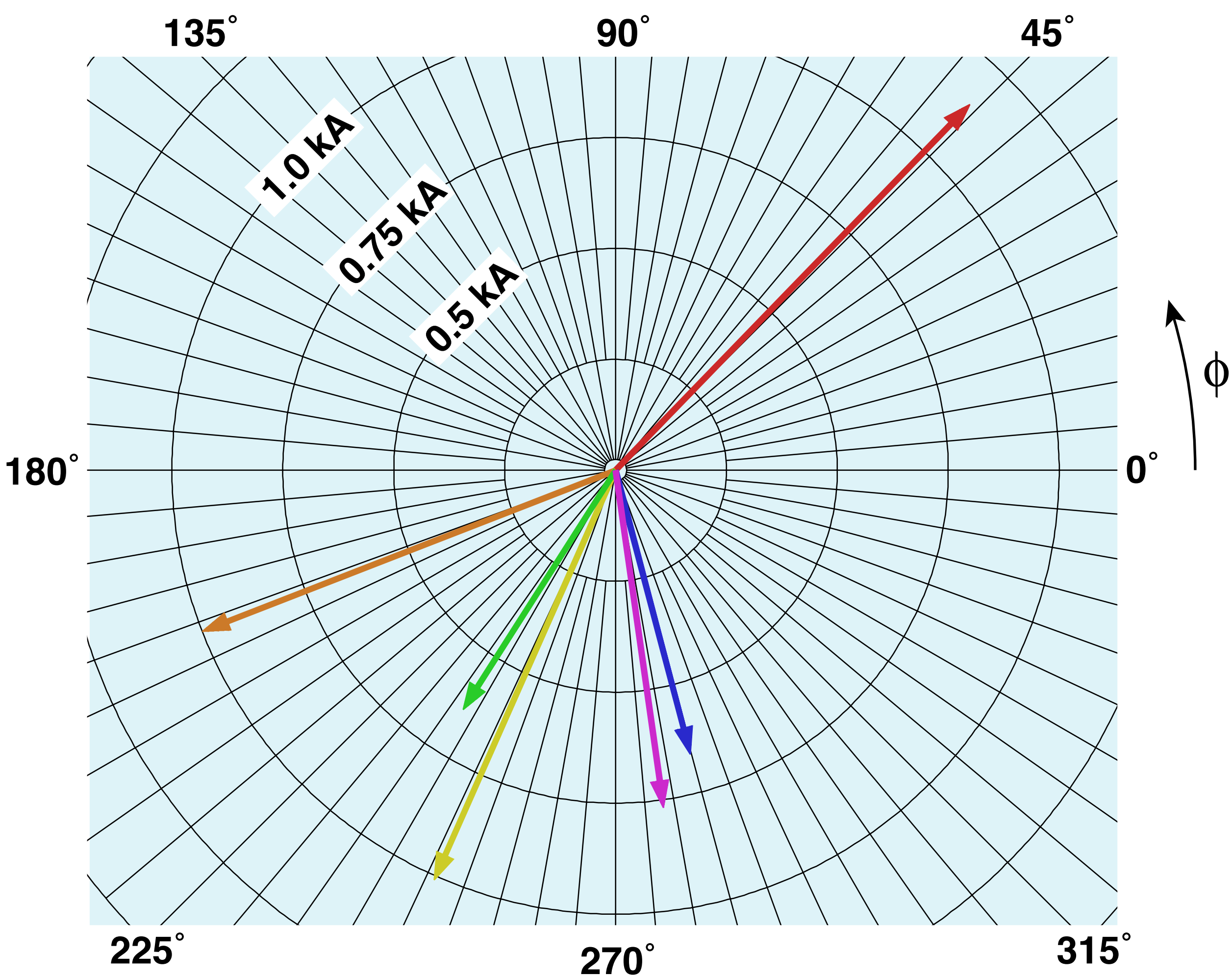
OFFSET CURRENT

OFFSET CURRENTS CALCULATED FOR EACH QUARTET PHASING ARE SIMILAR, EXCEPT FOR 0°

- Offset vectors are averages over each quartet phasing.
- Offset vectors are due to the inherent error field.
- Why is 0° so different?

quartet phasing:

0° phasing
60° phasing
120° phasing
180° phasing
240° phasing
300° phasing

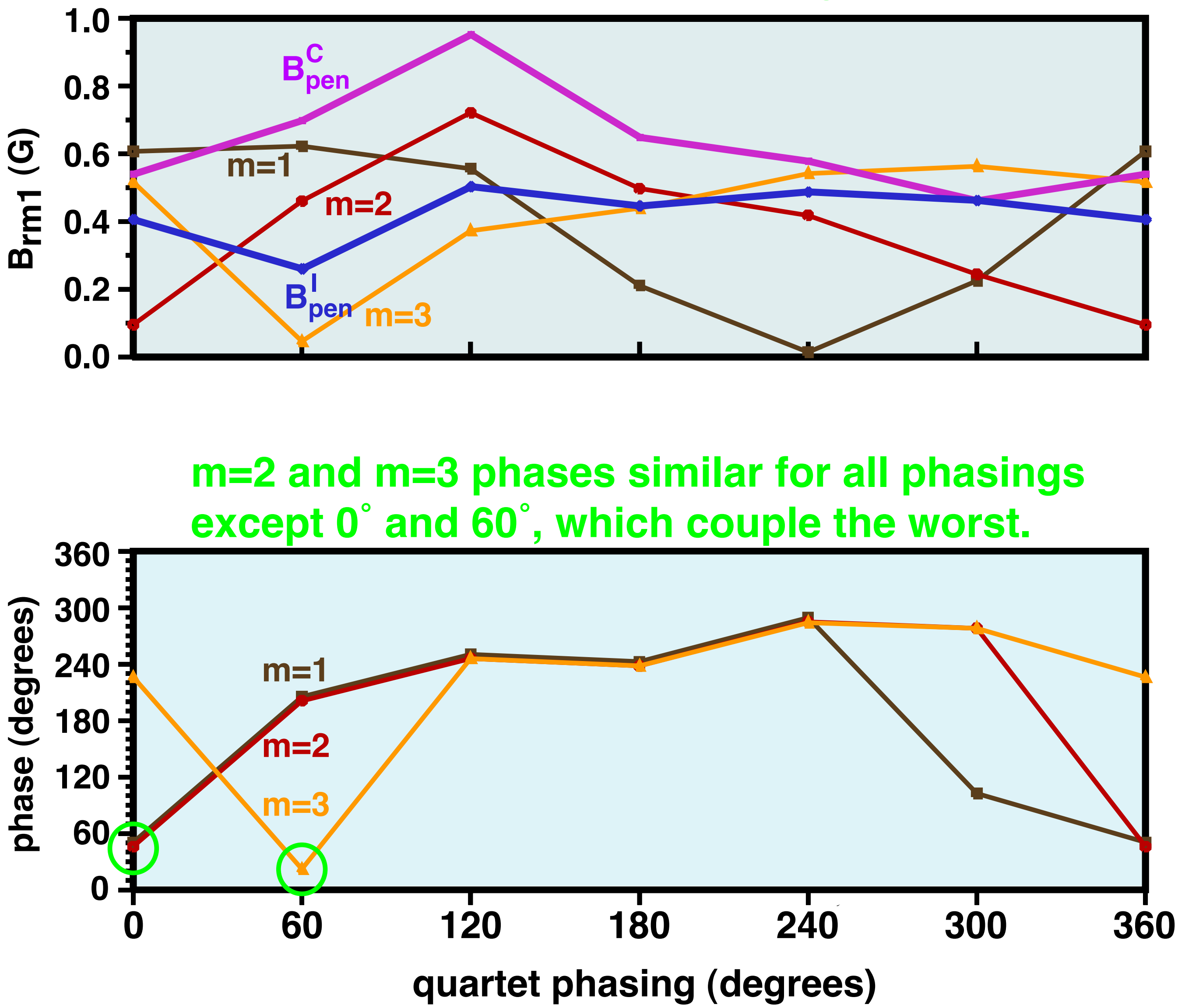


POLOIDAL MODE SPECTRUM OF THE OFFSET CURRENT FOR EACH QUARTET PHASING

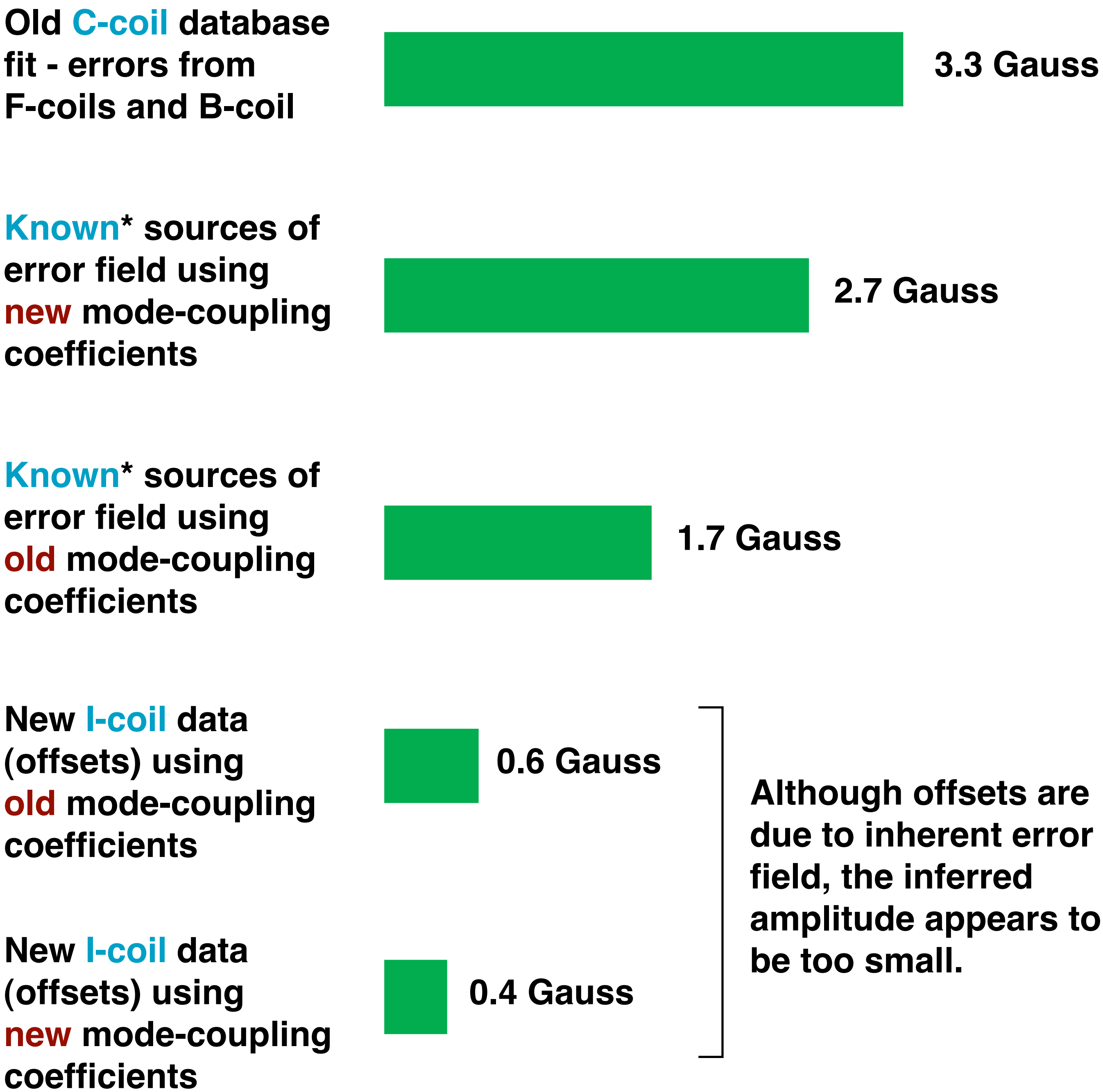
- **Offset current spectrum is caused by the inherent error field of the tokamak.**
- **If offset current is used to infer inherent n=1 error field, B_{pen} :**

B_{pen} is similar for most phasings, using either old or new mode-coupling coefficients.

m=2 and m=3 phases similar for all phasings except 0° and 60°, which couple the worst.



THE INHERENT ERROR FIELD INFERRED FROM NEW I-COIL DATA OFFSETS IS SMALLER THAN FROM KNOWN SOURCES



* Luxon, Nucl. Fus. 43 (2003) 1813-1828.

CONCLUSIONS

- **The helicity of the externally applied field affects the coupling to the plasma locked mode instability.**

  - lowest locking currents for quartet phasings 180°, 240°, 300°.

  - helicities matching m/n = 2/1 and m/n = 3/1 couple best.

- **The inherent error field of the tokamak is:**

$$\frac{B_{pen}}{B_T} = 3.3 \times 10^{-4}$$

from old C-coil error field multi-mode fit

$$\frac{B_{pen}}{B_T} = 2.7 \times 10^{-4}$$

from known sources using new multi-mode fit from I-coil data