U.S. MAGNET DEVELOPMENT PROGRAM

First field quality measurements of a 15 T Nb3Sn Dipole Demonstrator

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US Magnet Development Program

Outline

- Data collection
  - Magnetic Measurement System
  - Measurement sensitivity
  - Centering Corrections
- Measurement discussion
  - Transfer Function (magnitude of the field)
  - Loop (Dynamic effects, eddy current)
  - Z-scan (behavior along magnet length)
  - Harmonics from Stair Step (geometric harmonics)
  - Comparison with Simulation
  - Decay and Snapback
- Summary

Magnetic Measurement System

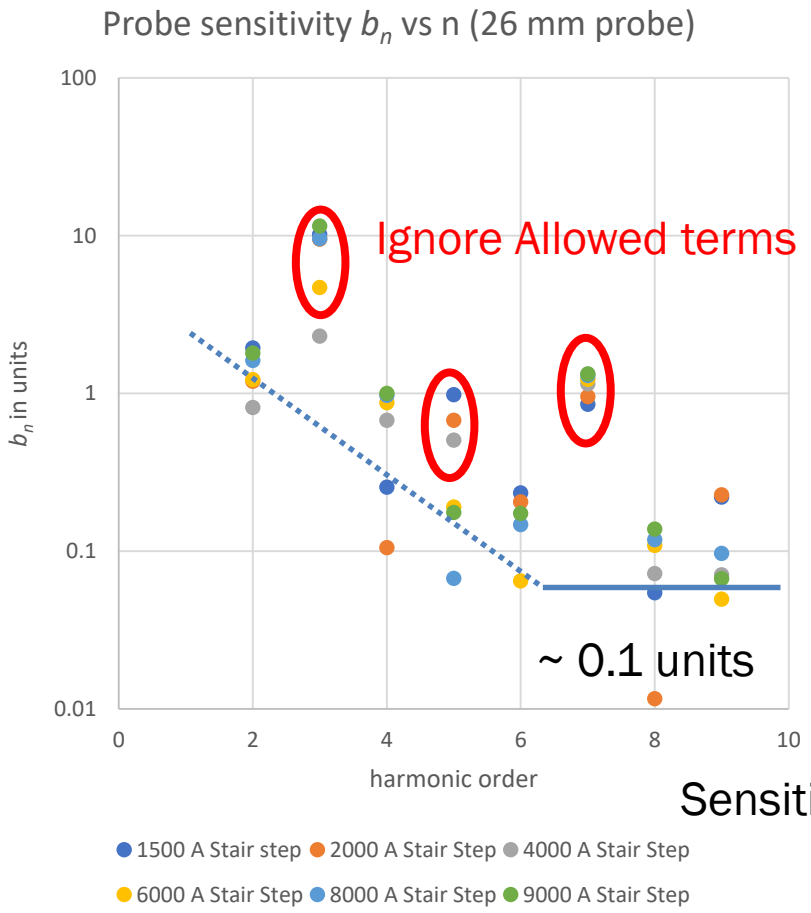
- Rotating Coil Measurement System at Fermilab Vertical Magnet Test Facility
  - 0.75 – 1 Hz rotation
  - R_{ref} set to 17 mm (56% of aperture)

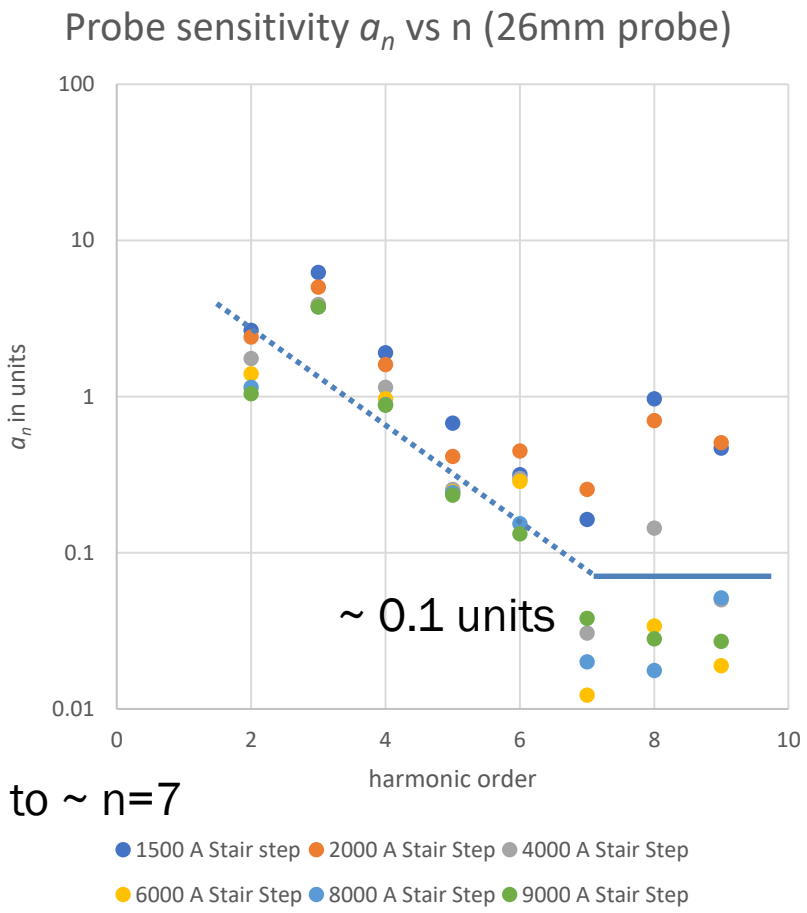
- Shaft with attached probe to scan 'warm bore' of the magnet, 3 m stroke

- Two probes, offset by 130 mm (16 layers, 2 Loops, 13 Windings each)
  - 130 mm x 22.25 mm PCB probe
  - 26 mm x 22.25 mm PCB probe
  - Dipole bucked signal

26 mm Probe sensitivity

130 mm probe sensitivity similar



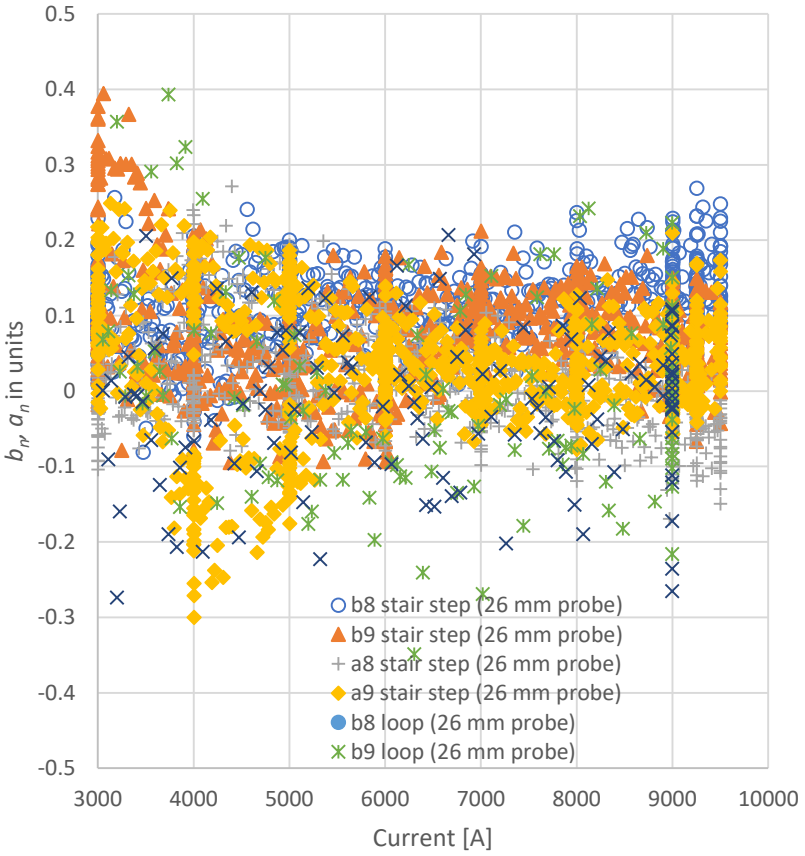


Sensitive to ~ n=7

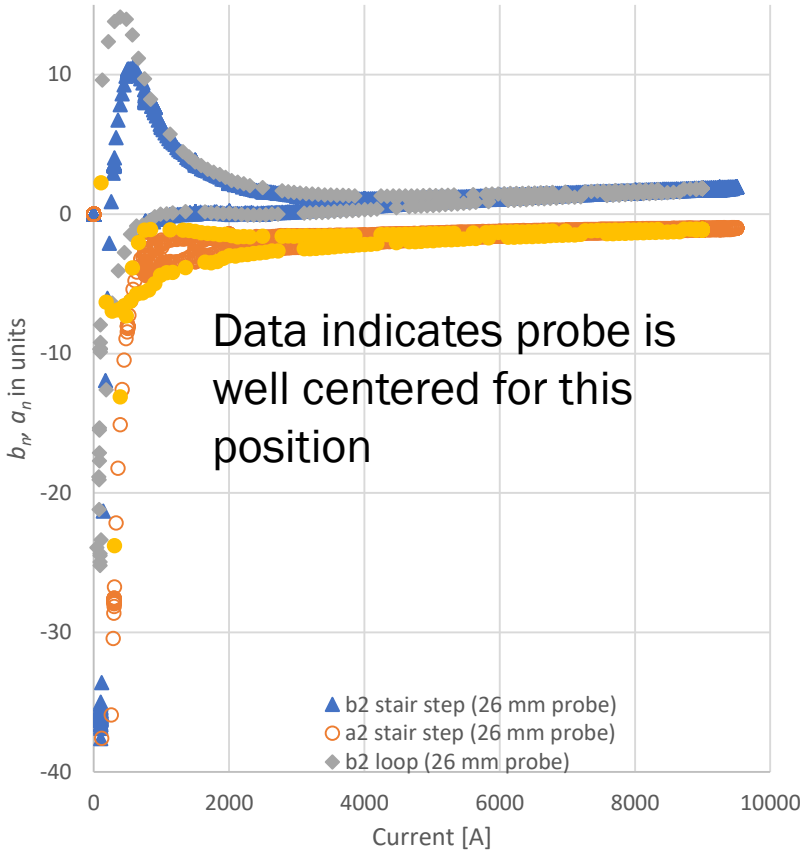
$$B_y + iB_x = B_1 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

Centering Correction

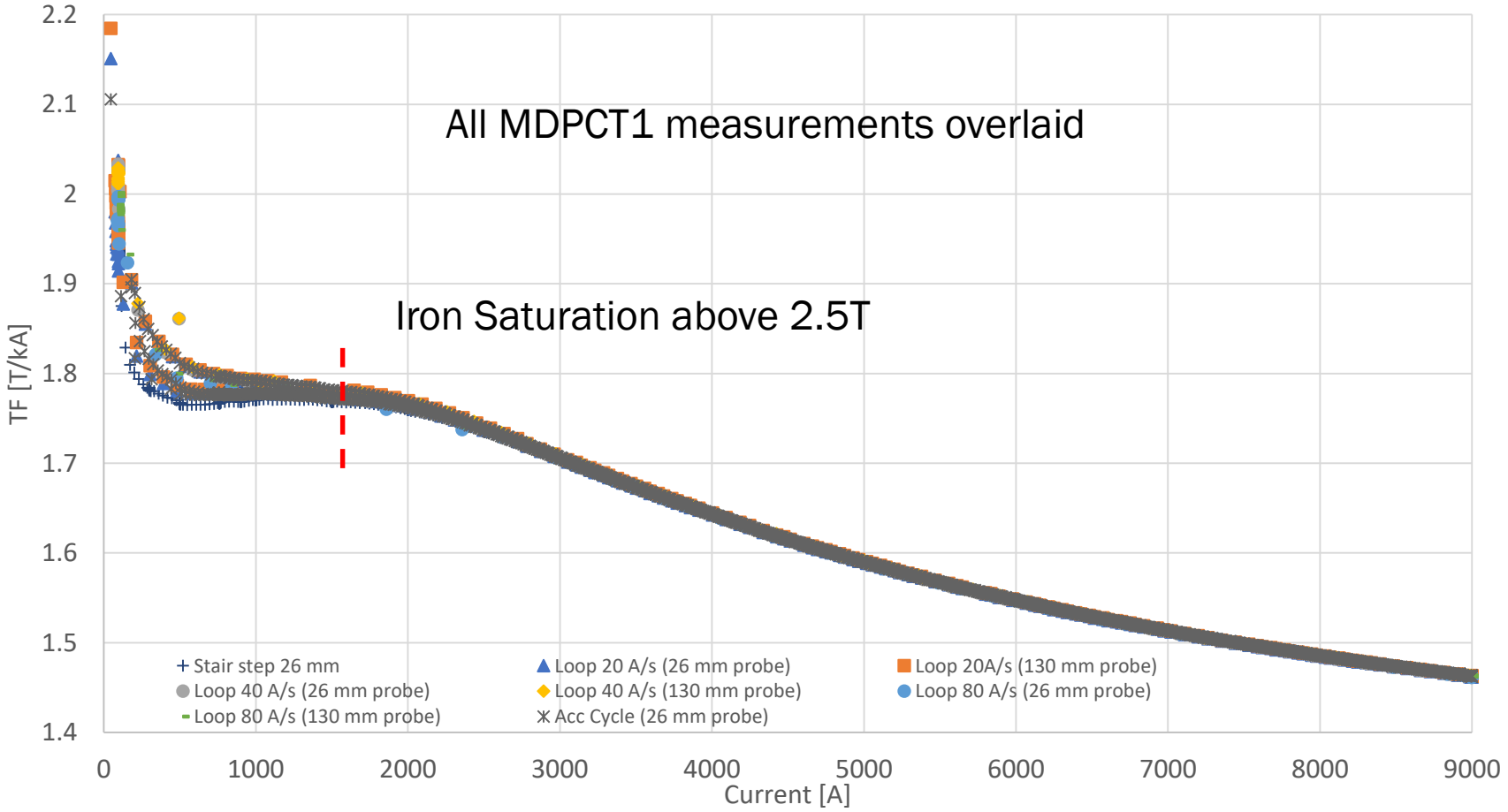
Higher order units versus current



Hysteresis feed-down from b_3

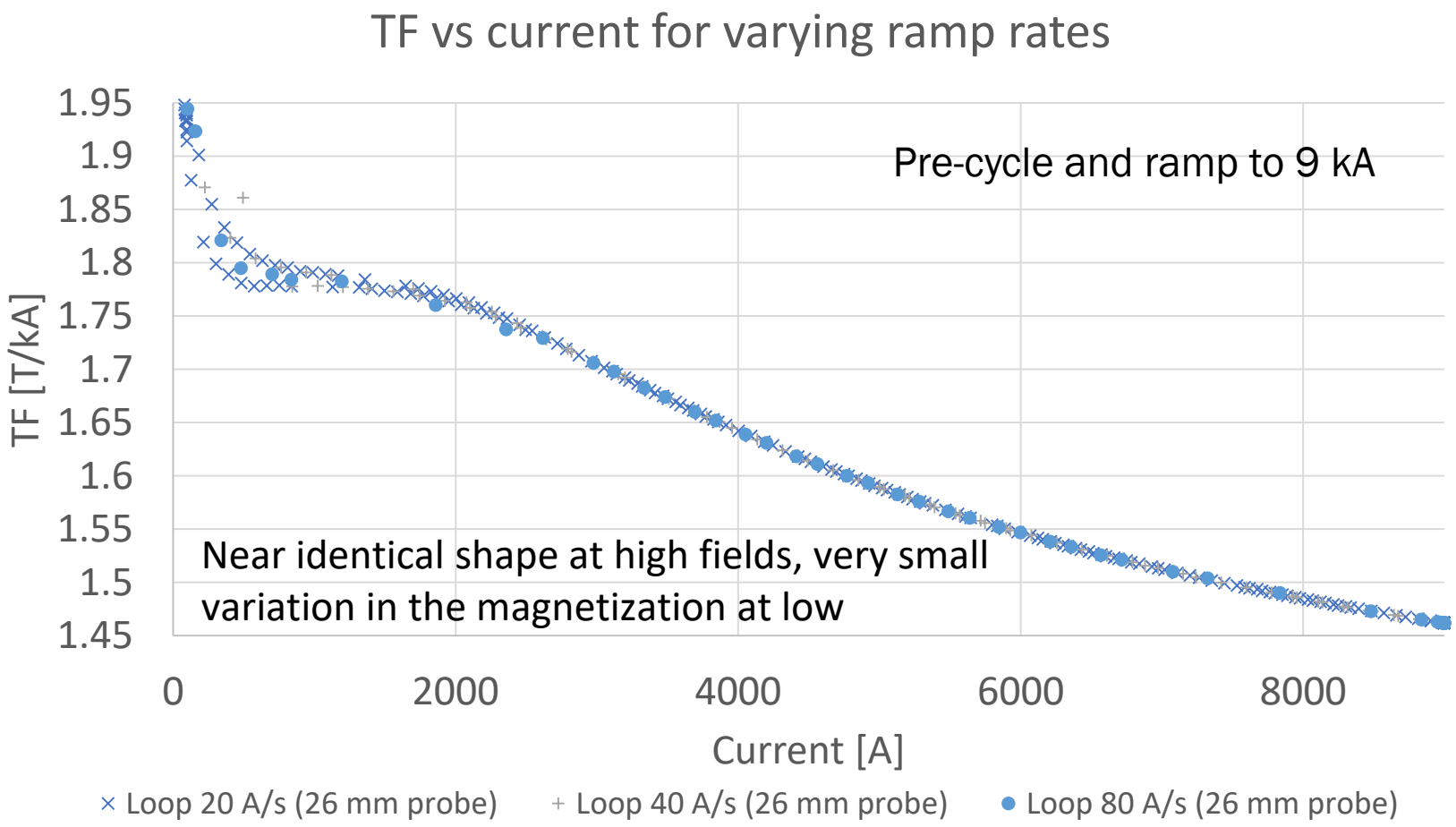


Transfer Function for multiple measurements

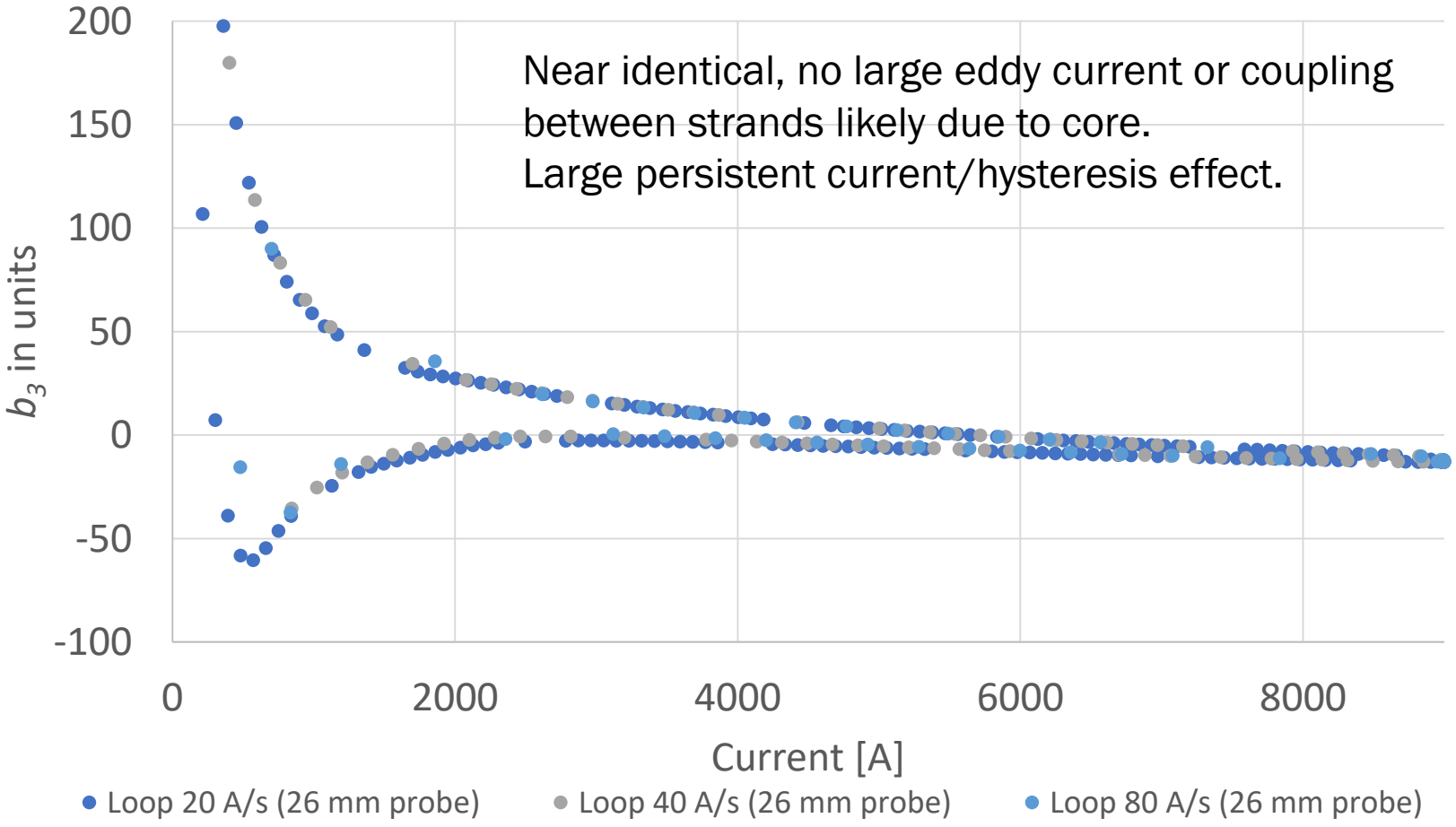


Loop measurements

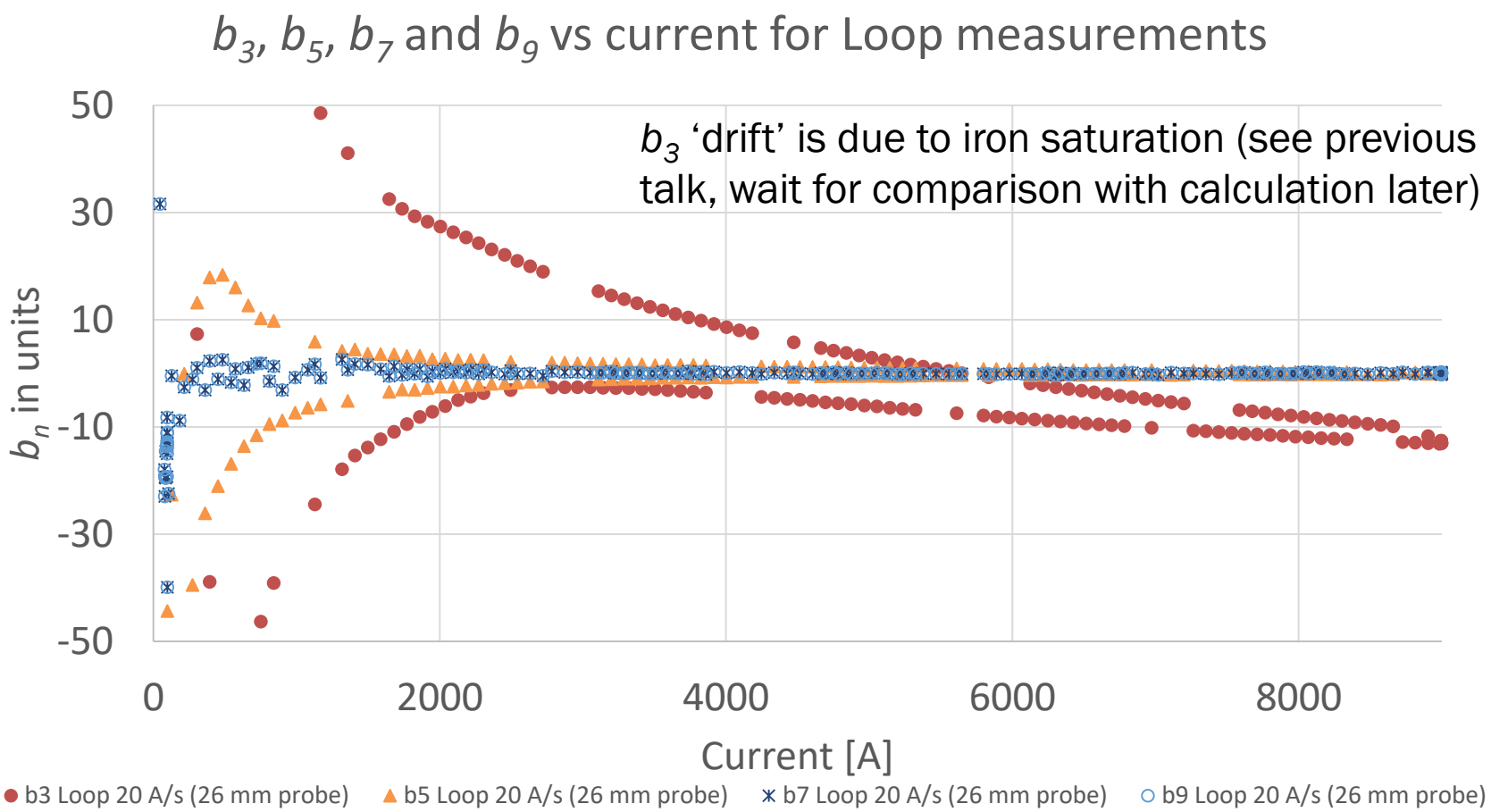
Conductor uses 11 mm width stainless core (nearly full width of cable)



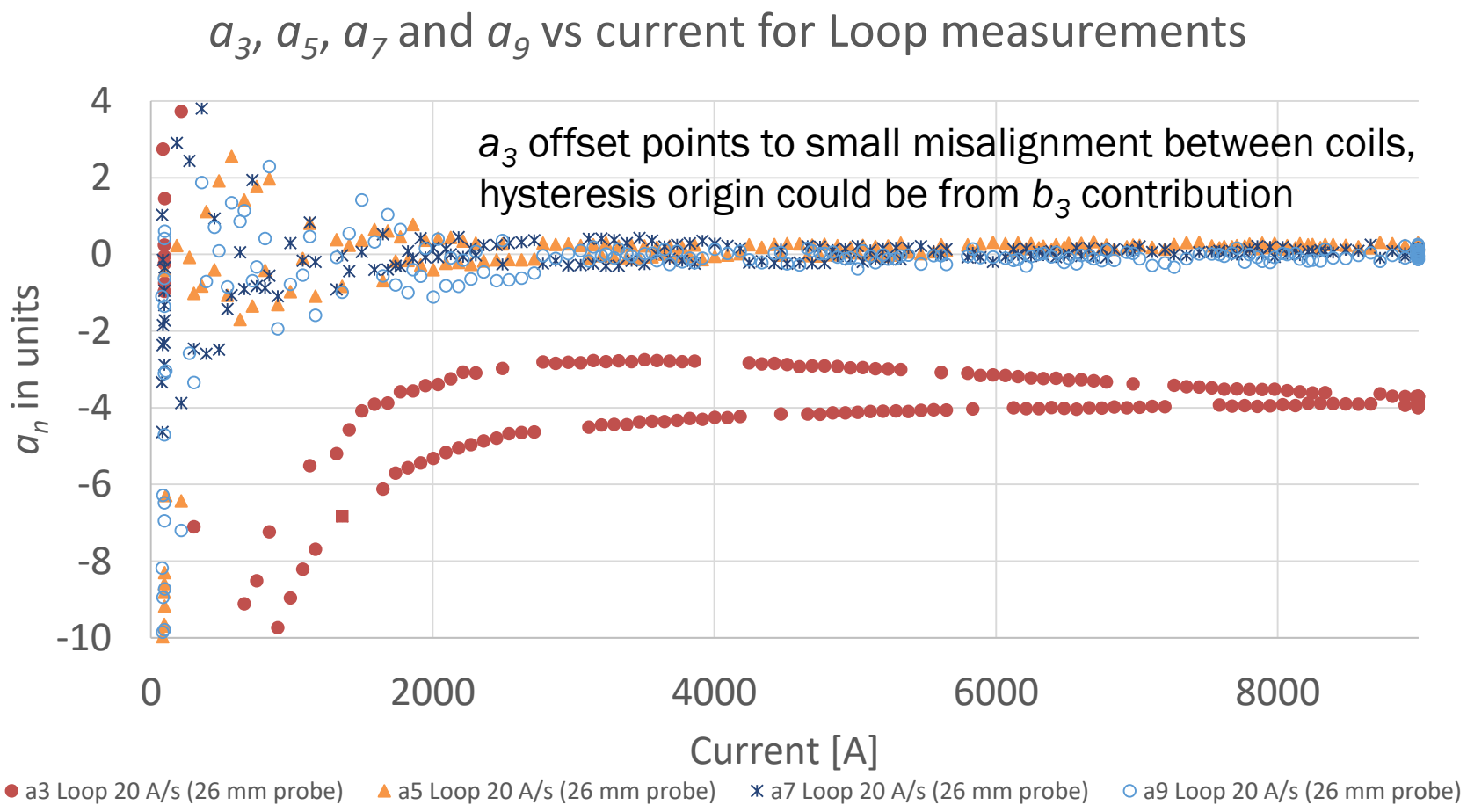
Loop harmonic *b3* vs current for various ramp rates



20 A/s Loop measurements normal harmonics

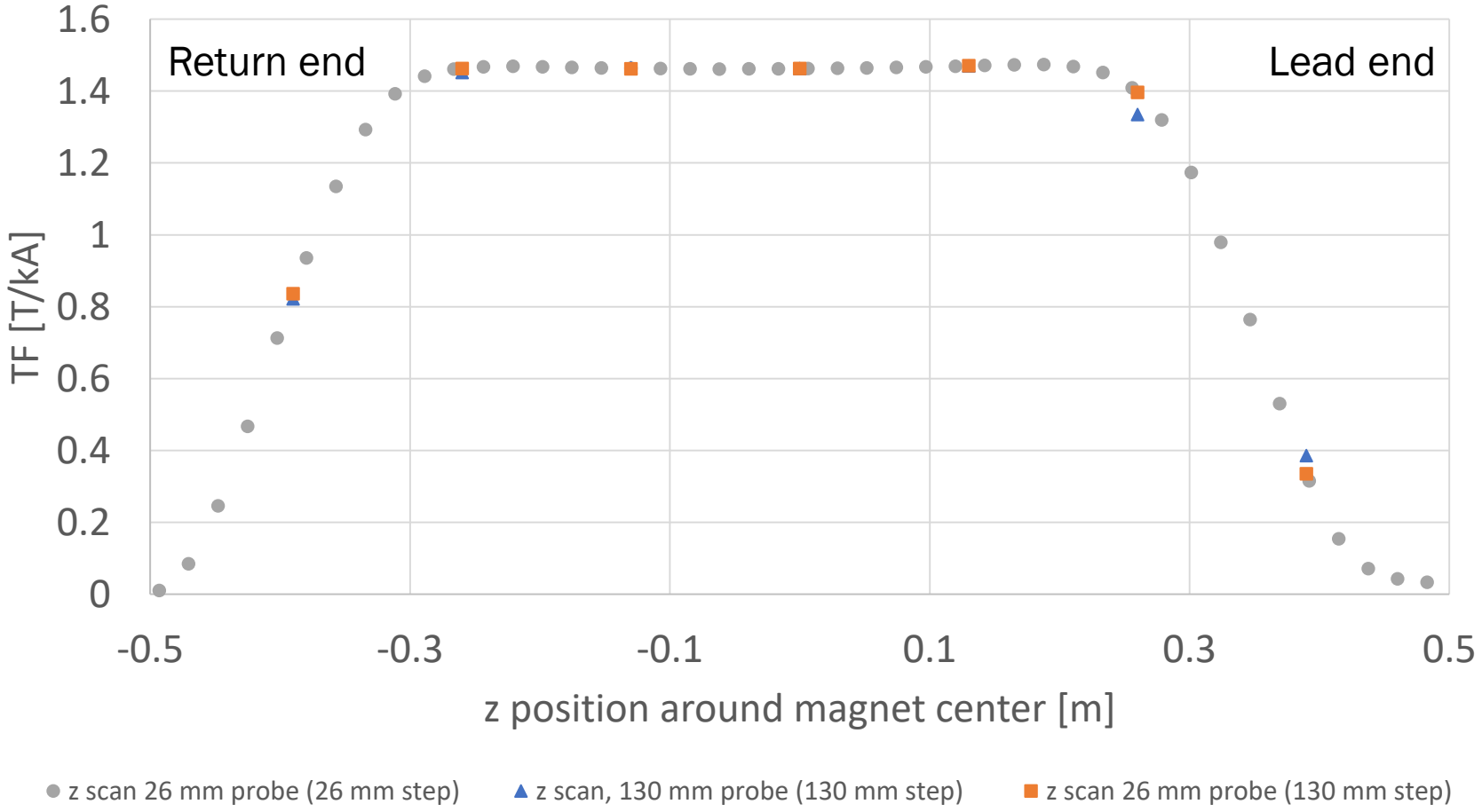


20 A/s Loop measurement skewed harmonics



Z scan TF along magnet bore

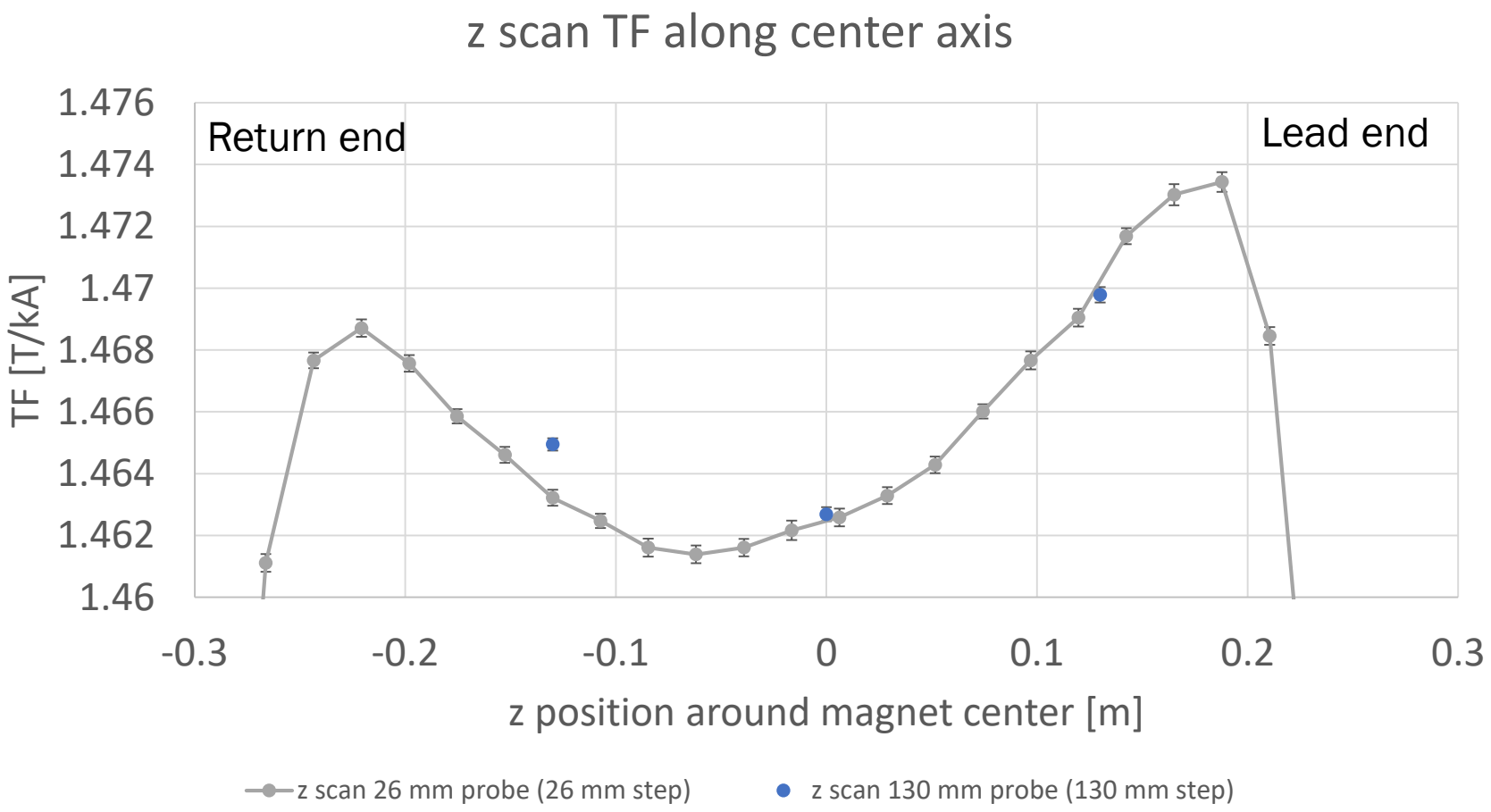
Measured at 9kA



Z scan TF, zoom

Measured at 9kA

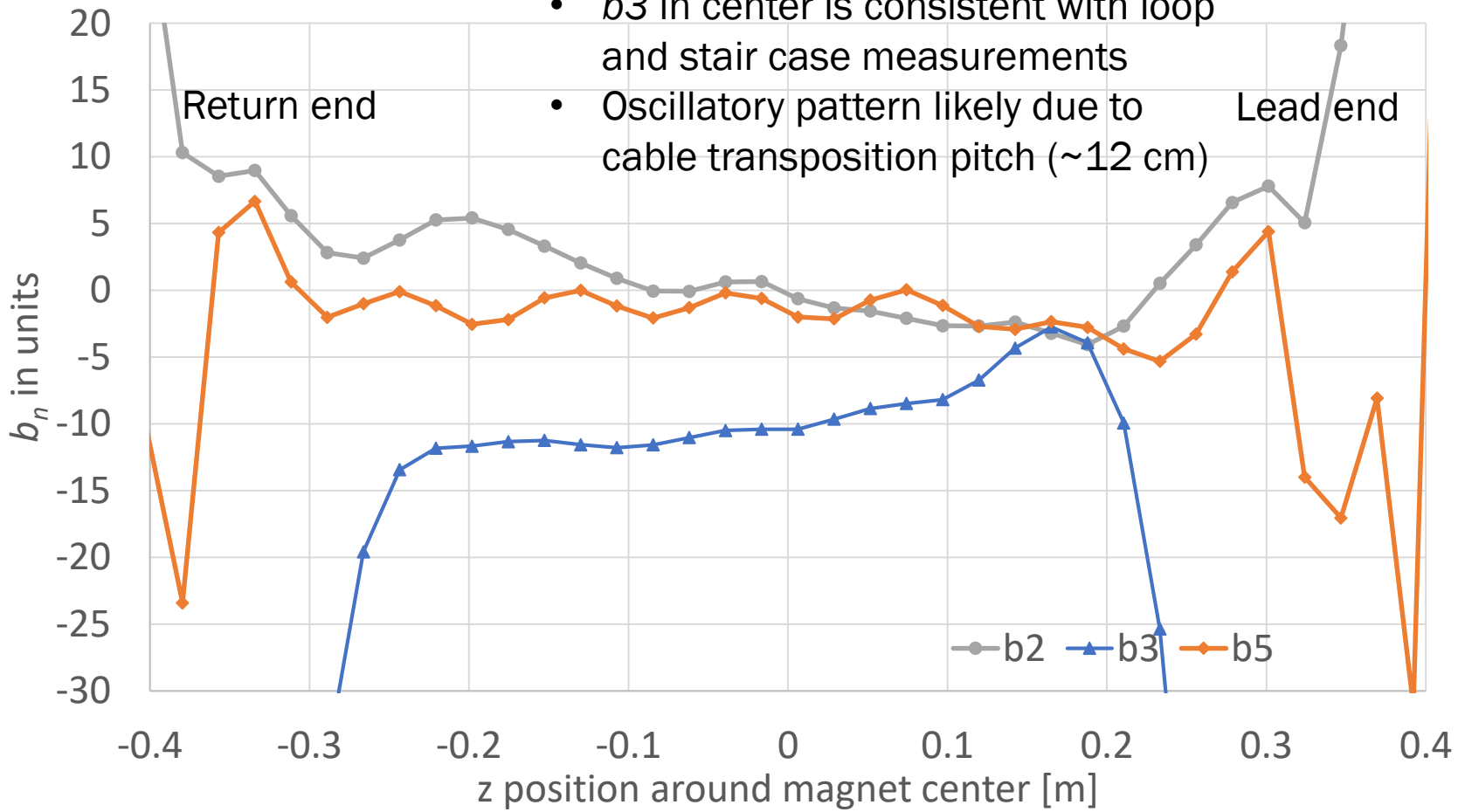
Variations due to end field contributions



Z scan harmonics

Measured at 9kA, 26 mm probe

- *b3* in center is consistent with loop and stair case measurements
- Oscillatory pattern likely due to cable transposition pitch (~12 cm)

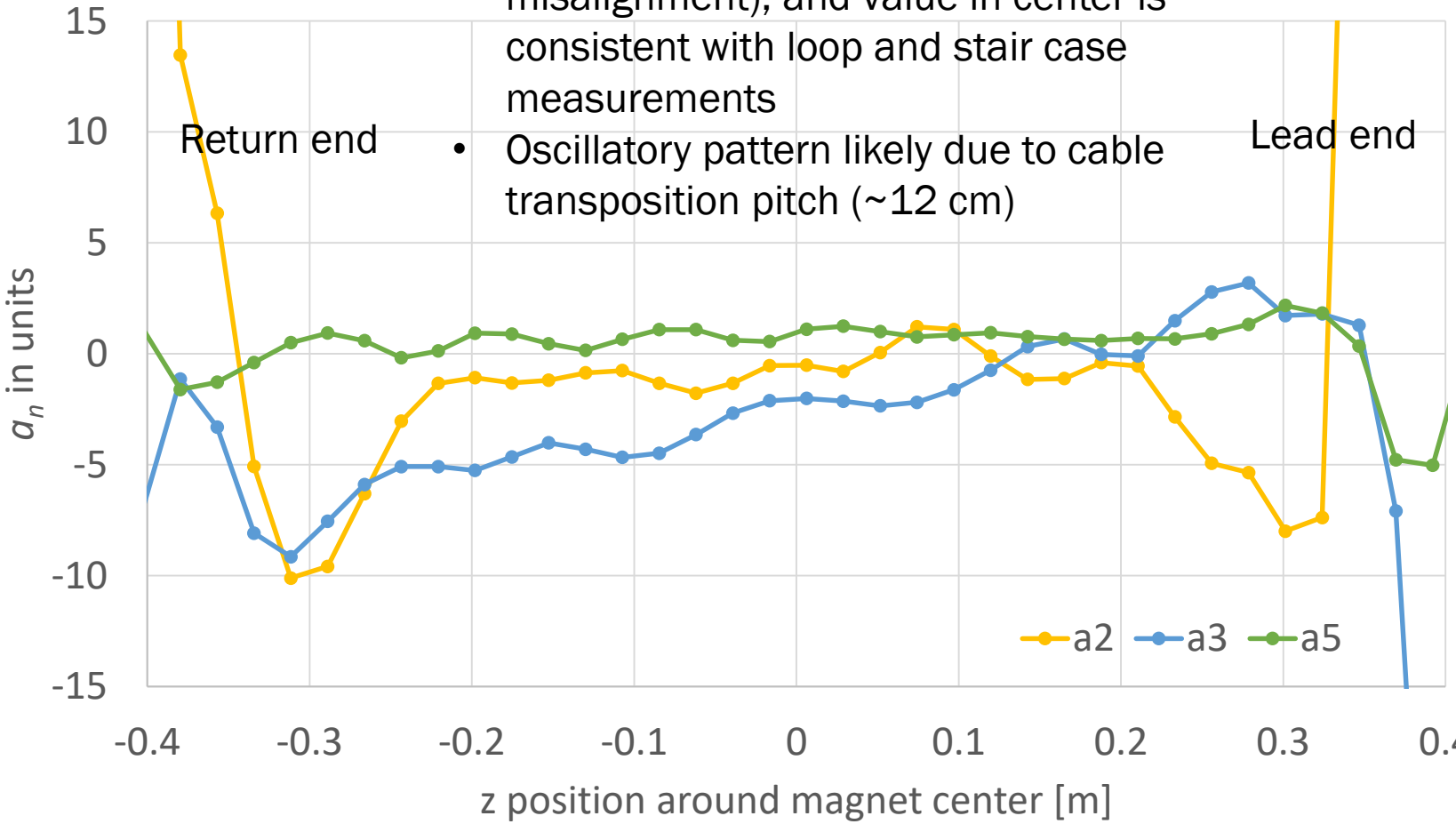


Errors smaller than symbols

Z scan harmonics

- *a3* depends on z-axis (possible misalignment), and value in center is consistent with loop and stair case measurements
- Oscillatory pattern likely due to cable transposition pitch (~12 cm)

Measured at 9kA



Errors smaller than symbols

Geometrical Harmonics

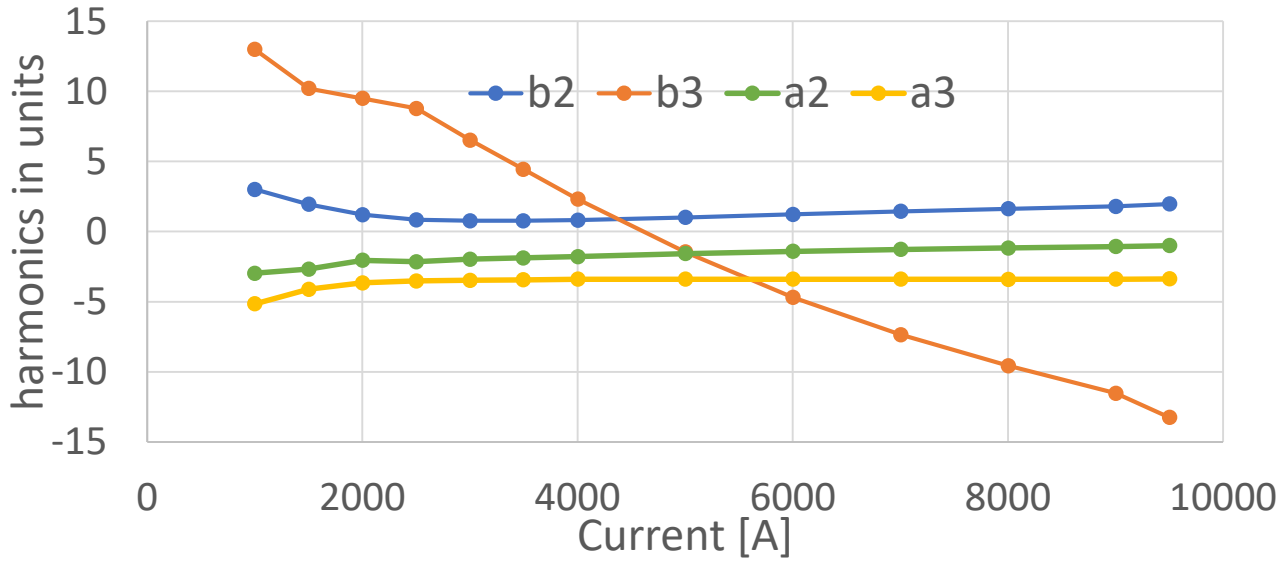
- **Stair step, 26 mm probe**

Geometric harmonics nearly identical in stair step and loop, small except for a2,a3,b2, and b3

current	B main	TF	b2	b3	b4	b5	b6	b7	b8	b9		a2	a3	a4	a5	a6	a7	a8	a9
7003	10.599	1.514	1.4	-7.4	-0.9	0.1	-0.1	1.3	0.1	0.1		-1.3	-3.4	0.6	0.1	0.1	0.0	0.0	0.0

- **Loop, 20 A/s, both probes, 130 mm offset in between**

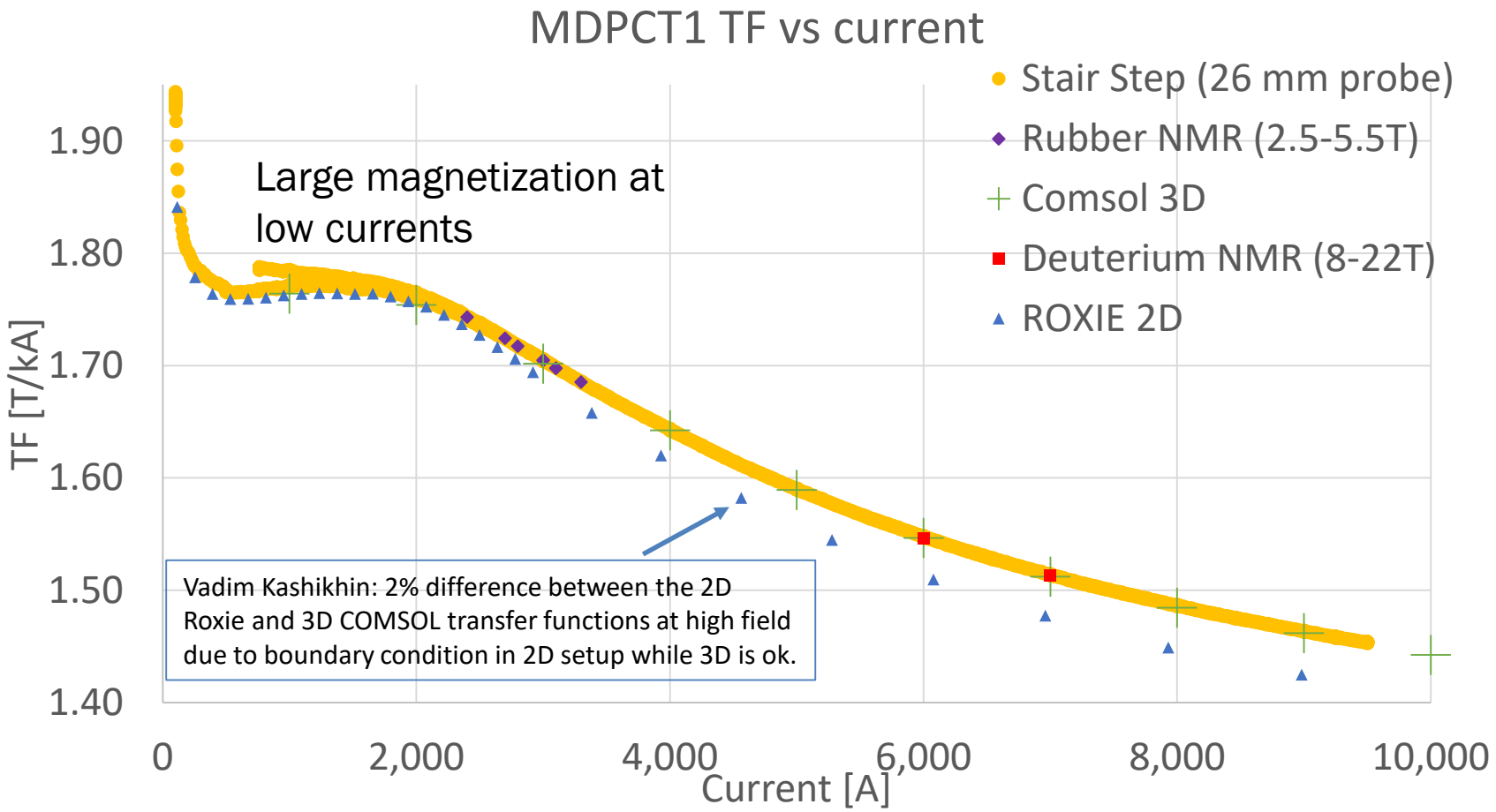
Loop 20 A/s 26 mm																			
6996		1.512	1.4	-7.6	-1.0	0.2	-0.2	1.4	0.1	-0.2		-1.4	-3.7	0.8	0.2	0.2	0.1	0.0	0.0
Loop 20 A/s 130 mm																			
6996.030		1.514	-1.2	-7.2	-1.8	-1.3	-0.1	0.7	0.2	0.0		-1.5	-3.0	2.4	1.2	0.1	0.1	-0.1	0.0



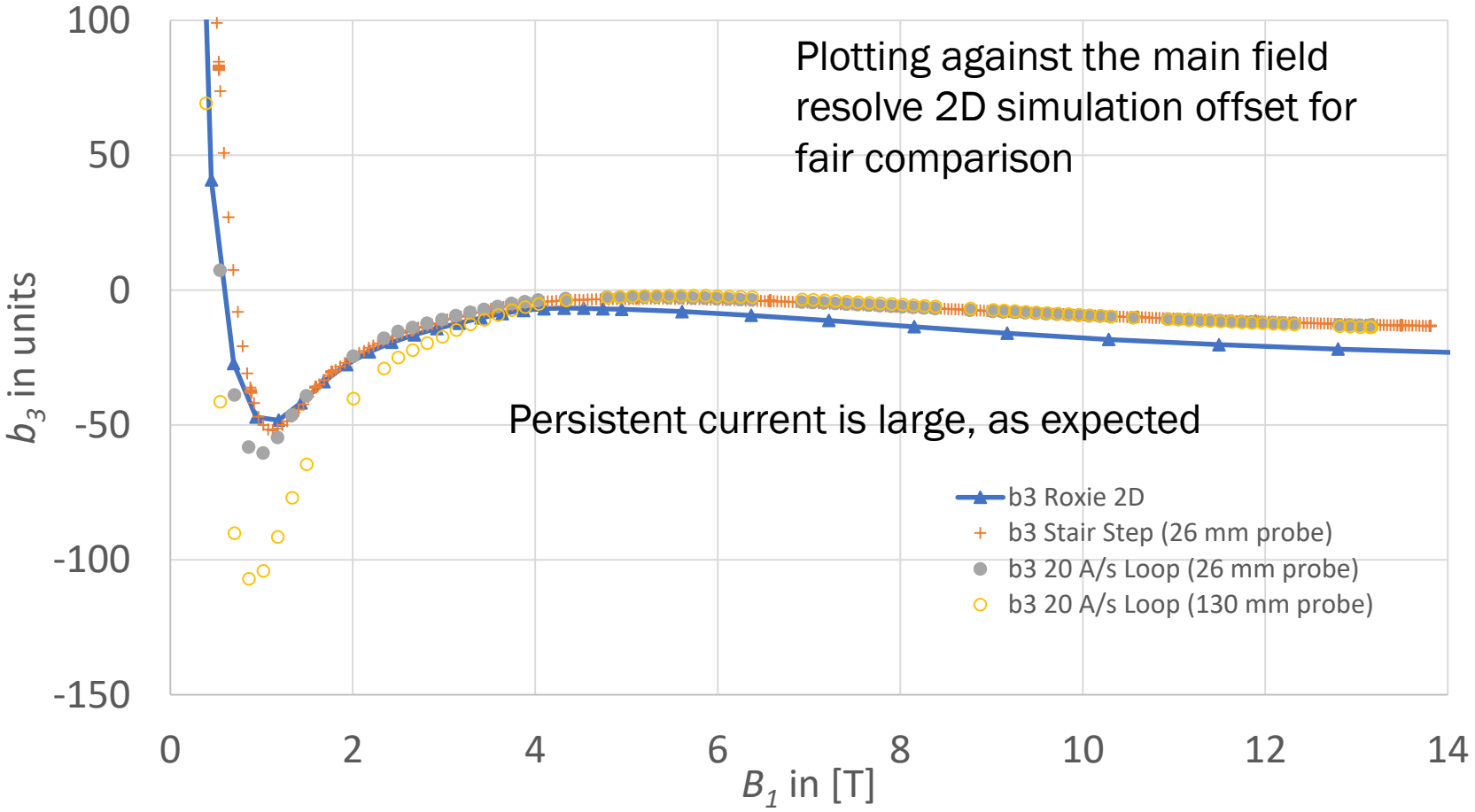
Harmonics averaged from up and down ramp

Transfer Function

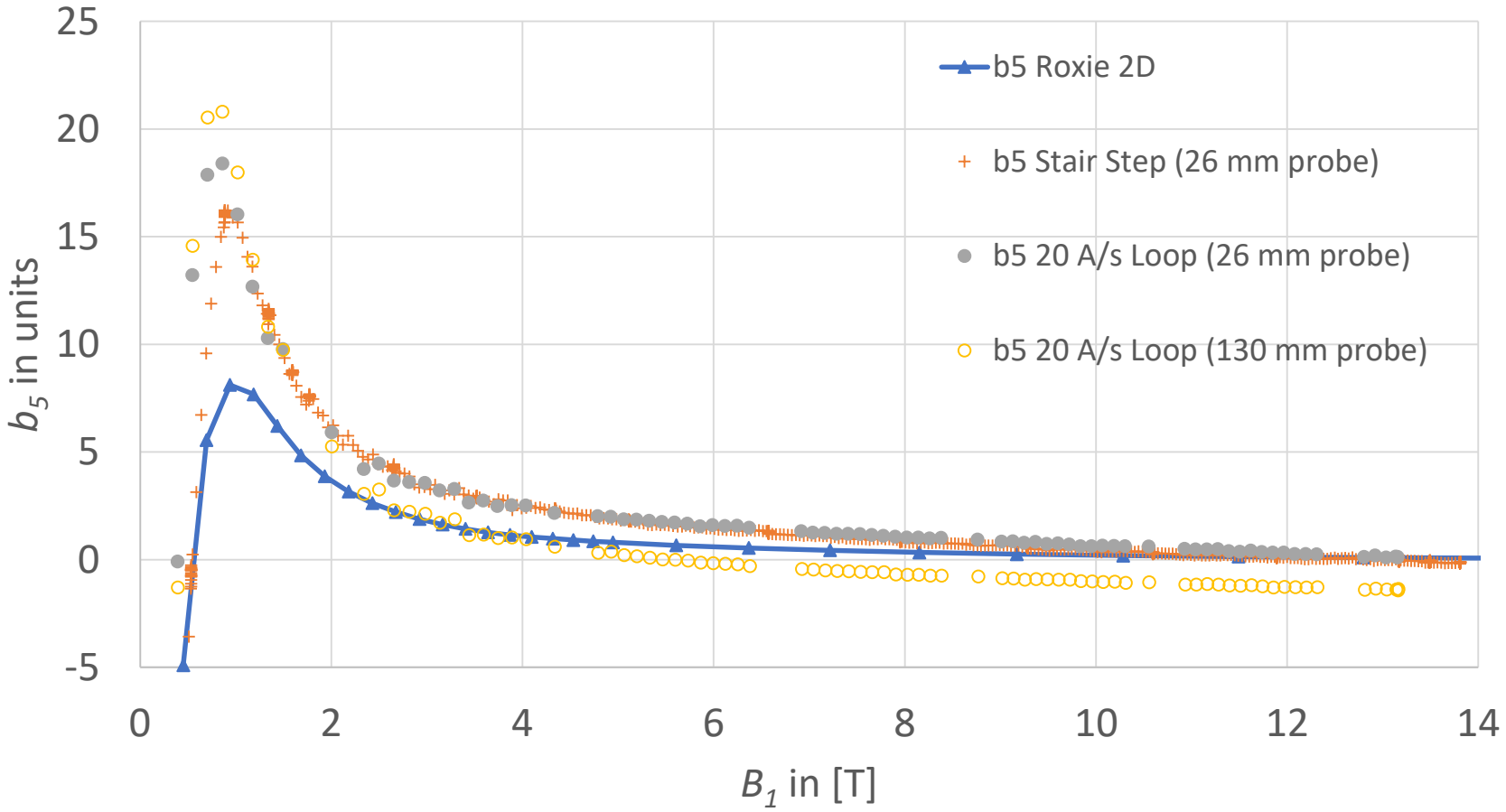
Deuterium probe was loaned to FNAL by GMW



b_3 versus dipole field

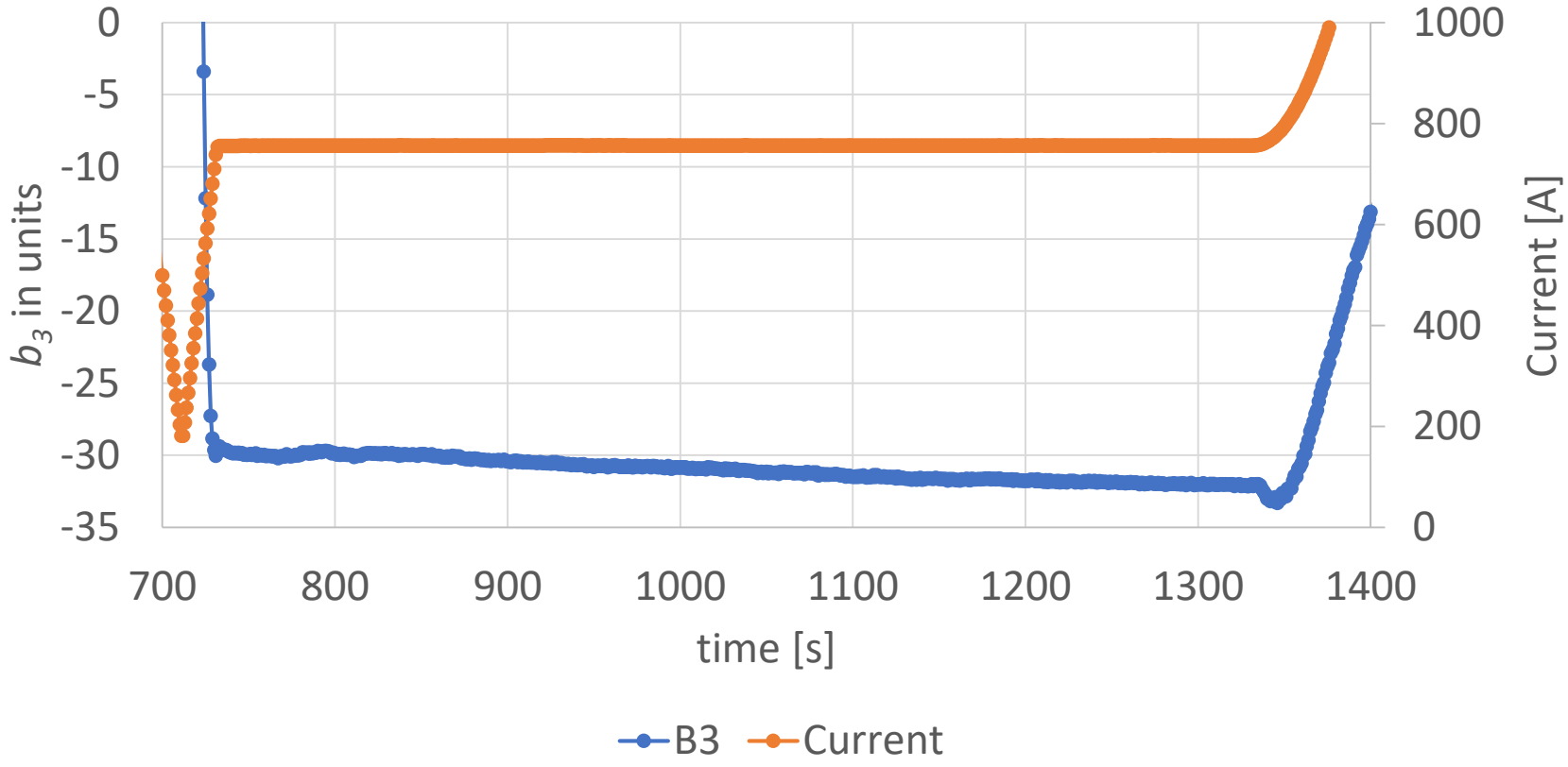


b_5 versus dipole field

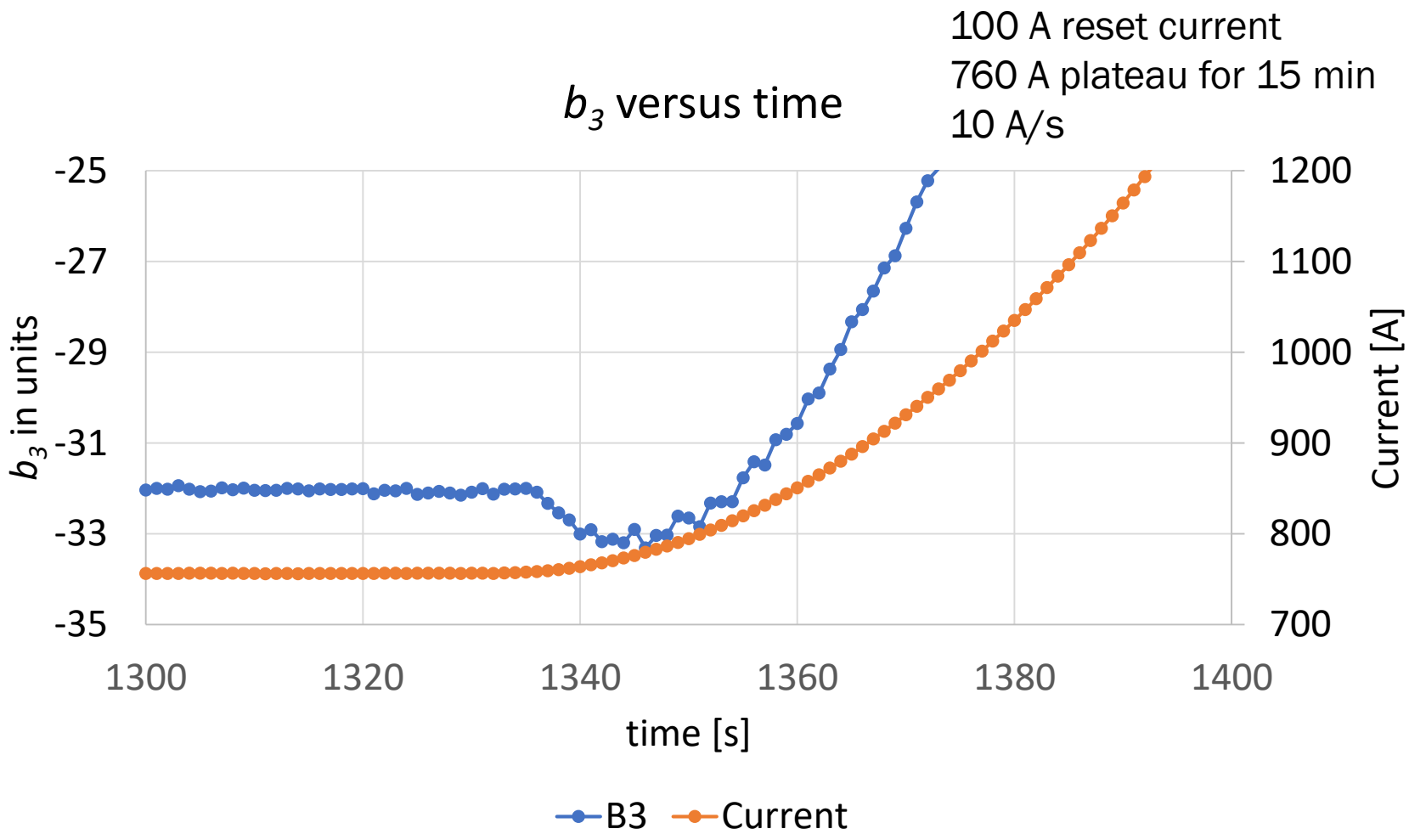


Decay and Snapback

100 A reset current
760 A plateau for 15 min
10 A/s



Snapback


100 A reset current
760 A plateau for 15 min
10 A/s
b_3 versus time
-25
-27
-29
-31
-33
-35
b_3 in units
1200
1100
1000
900
800
700
Current [A]
1300
1320
1340
1360
1380
1400
time [s]
B3
Current

Summary

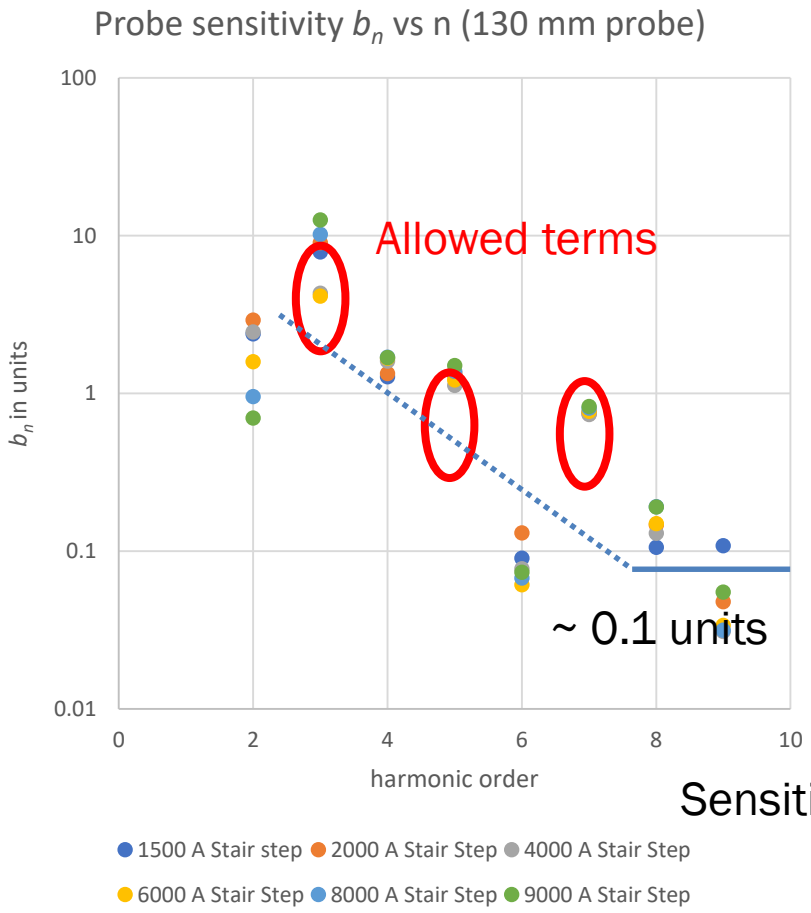
- Magnet *TF* and low-order field harmonics were measured using 26 mm and 130 mm long rotating coils in the field range up to ~14 T.
- The measurements included geometrical components and contributions from the coil magnetization and iron yoke saturation effects.
- All the measured geometrical harmonics, except for a_2, a_3, b_2, b_3, are small, on the level of 1 unit or less at R_{ref}=17 mm.
- The coil magnetization effect in MDPCT1 at low fields is large due to the high critical current density and relatively large sub-element size in the contemporary Nb_3Sn strands.
- The iron yoke saturation effect in MDPCT1 starts at fields above 2.5 T and is also large.
- Both coil magnetization and iron saturation effects are in good agreement with theoretical predictions for TF and b3
- The eddy current effect in the cable on the *TF* and field harmonics in MDPCT1 was suppressed by using a stainless-steel core inside the cables
- A first glimpse at Decay and snapback showed no new surprises assuming an LHC type accelerator profile

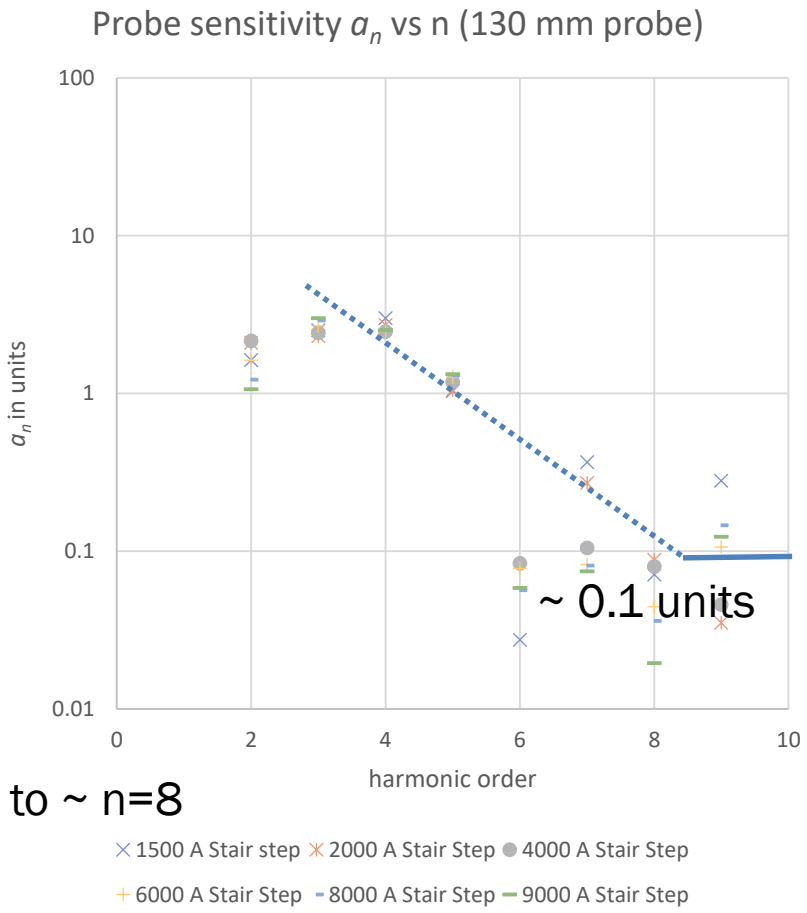
Acknowledgment

- We thank the technical staff of FNAL APS-TD for contributions to magnet design, fabrication and test, and US-MDP Management Group and Technical Advisory Committee for the support of this project.

- We thank GMW (www.gmw.com) for providing us with a Metrolab 1226 8-22T NMR probe for our PT2026 Teslameter

130 mm Probe sensitivity





Sensitive to ~ n=8