U.S. MAGNET DEVELOPMENT PROGRAM

First field quality measurements of a 15 T Nb3Sn Dipole Demonstrator

September 24, 2019

Thomas Strauss, E. Barzi, J. DiMarco, V.V. Kashikhin, I. Novitski, M. Tartaglia, G. Velev, A.V. Zlobin

US Magnet Development Program

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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

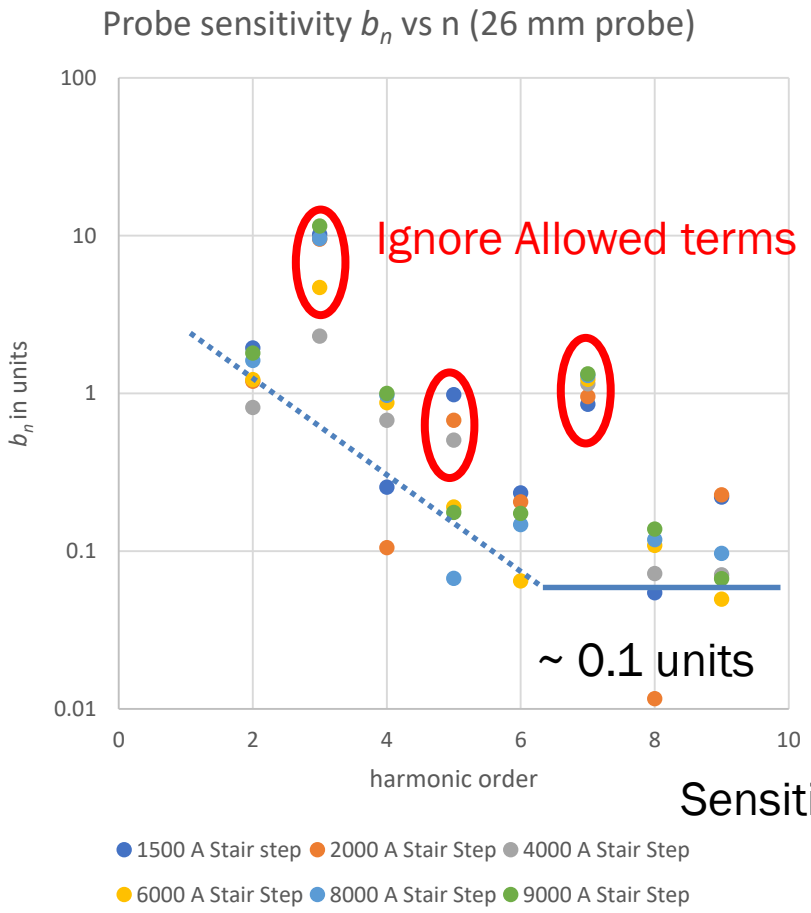
- Rotating Coil Measurement System at Fermilab Vertical Magnet Test Facility
  - 0.75 – 1 Hz rotation
  - R_{ref} set to 17 mm (56% of aperture)

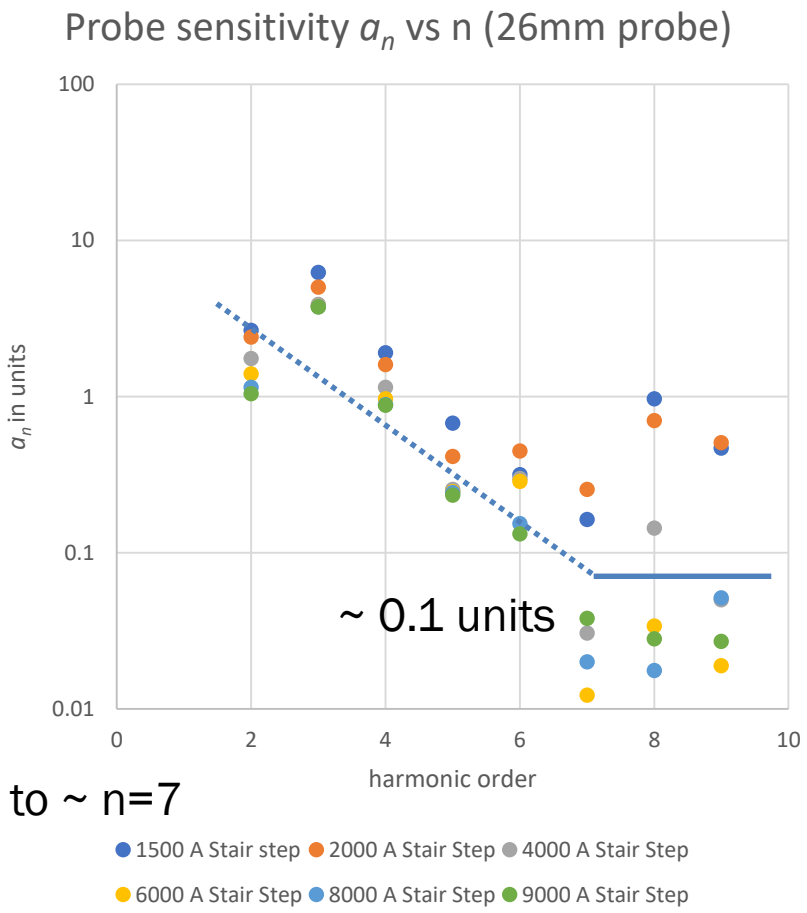
- Shaft with attached probe to scan 'warm bore' of the magnet, 3 m stroke

- 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



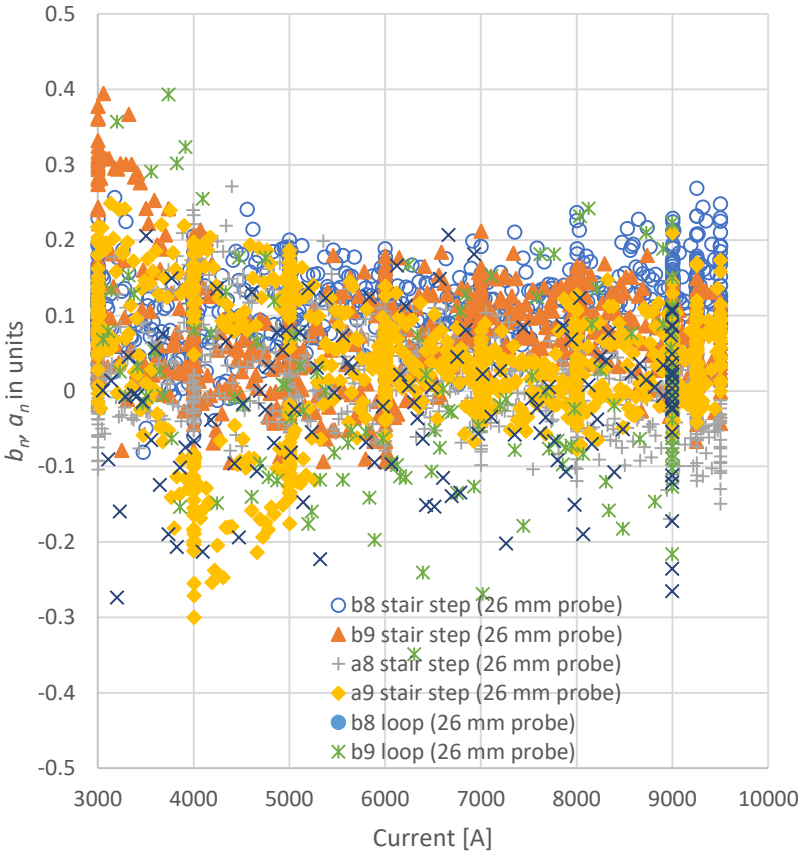


Sensitive to ~ n=7

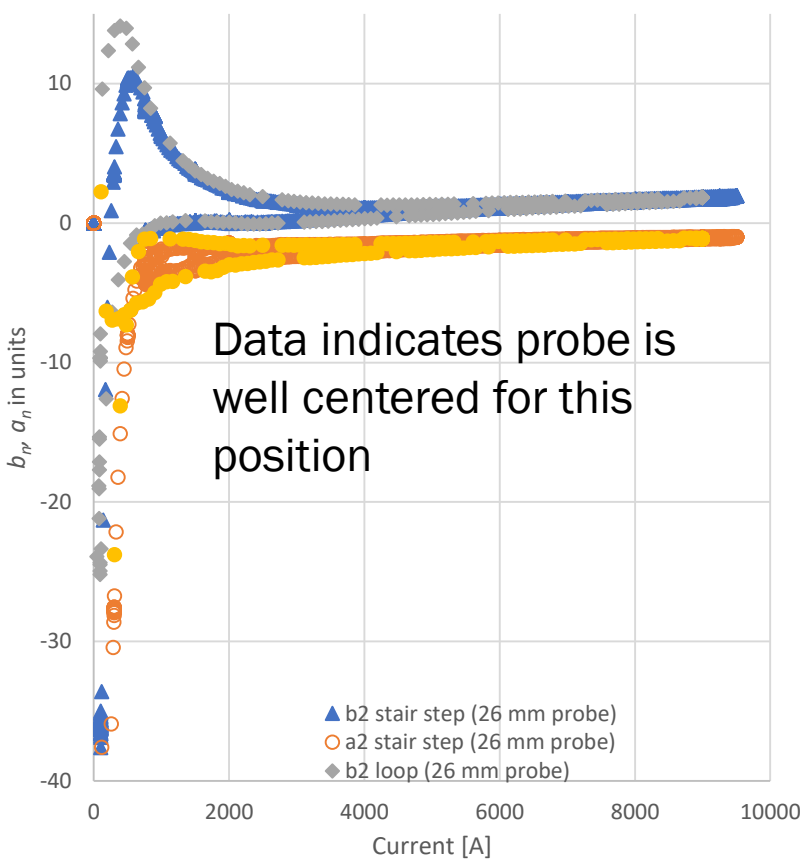
$$B_y + iB_x = B_1 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1}$$

Centering Correction

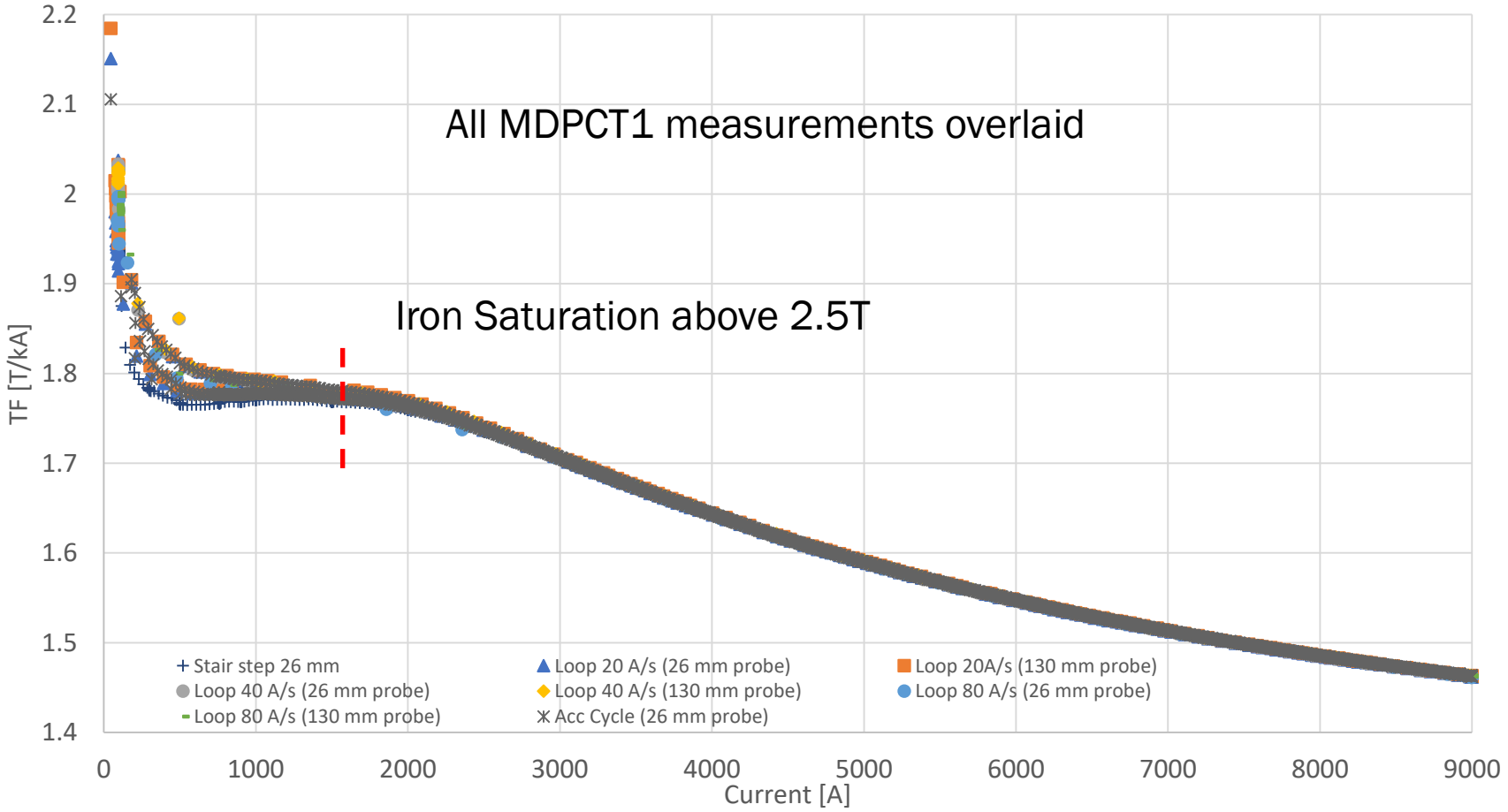
Higher order units versus current



Hysteresis feed-down from b_3

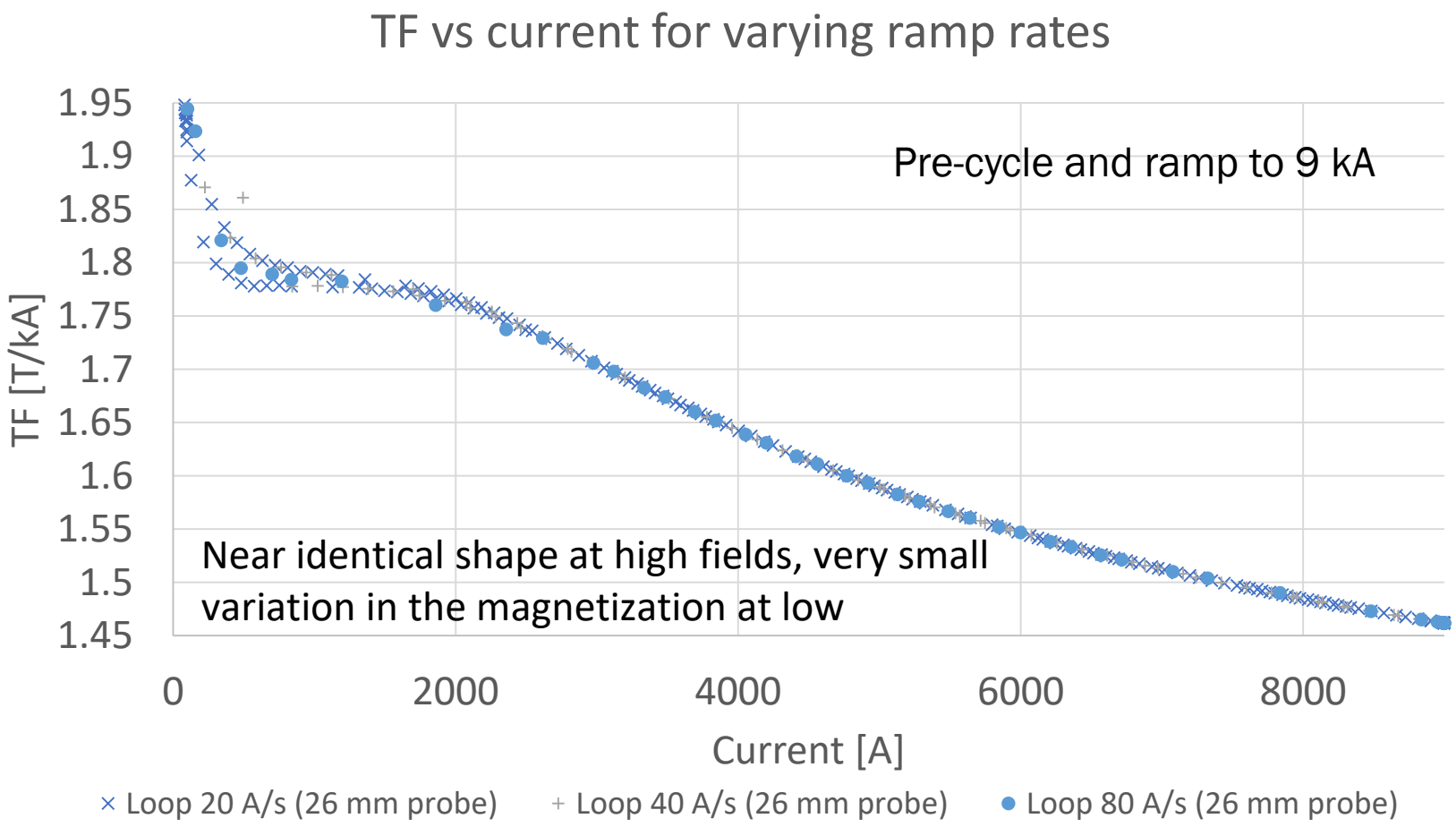


Transfer Function for multiple measurements

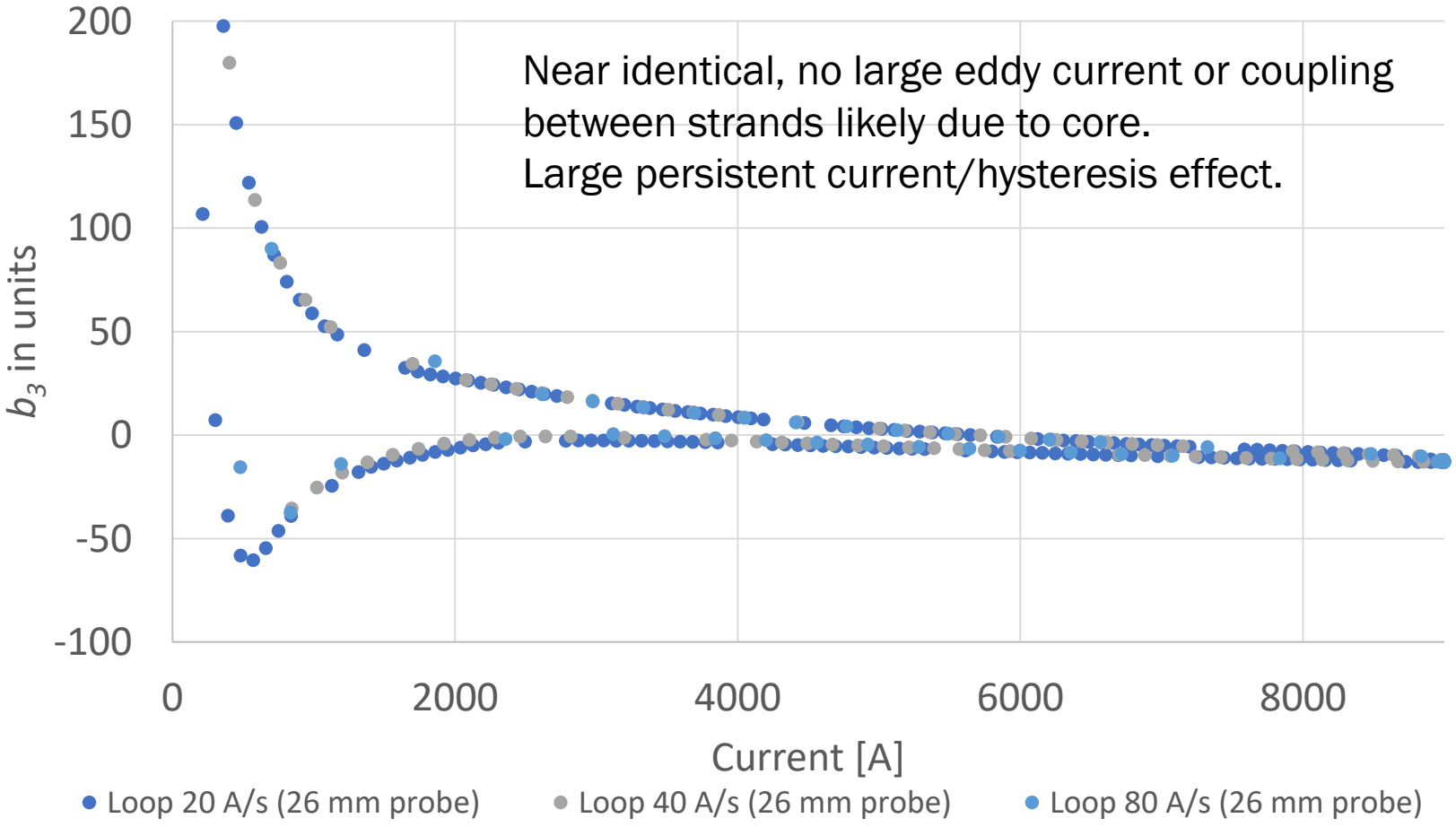


Loop measurements

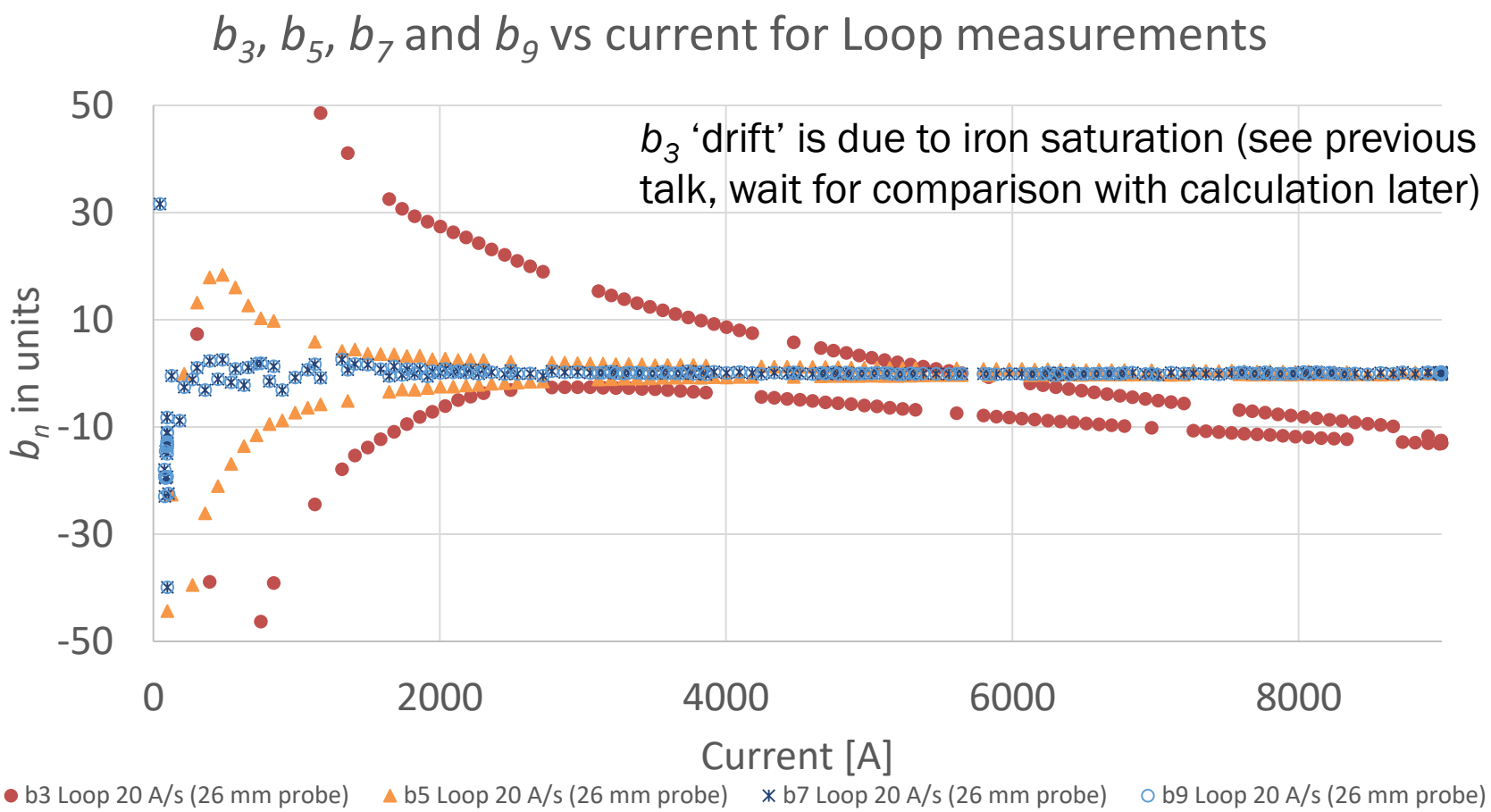
Conductor uses 11 mm width stainless core (nearly full width of cable)



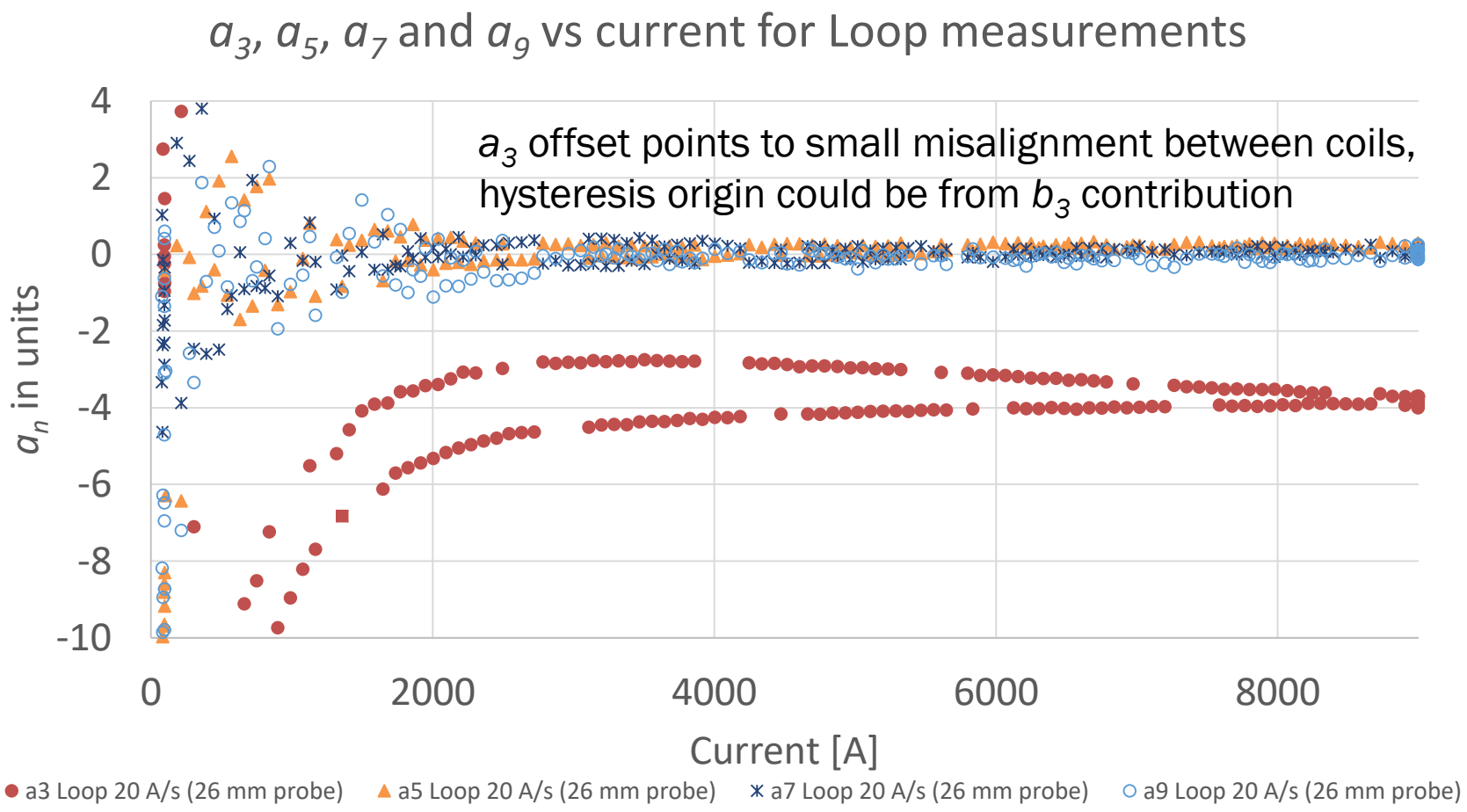
Loop harmonic *b3* vs current for various ramp rates



20 A/s Loop measurements normal harmonics

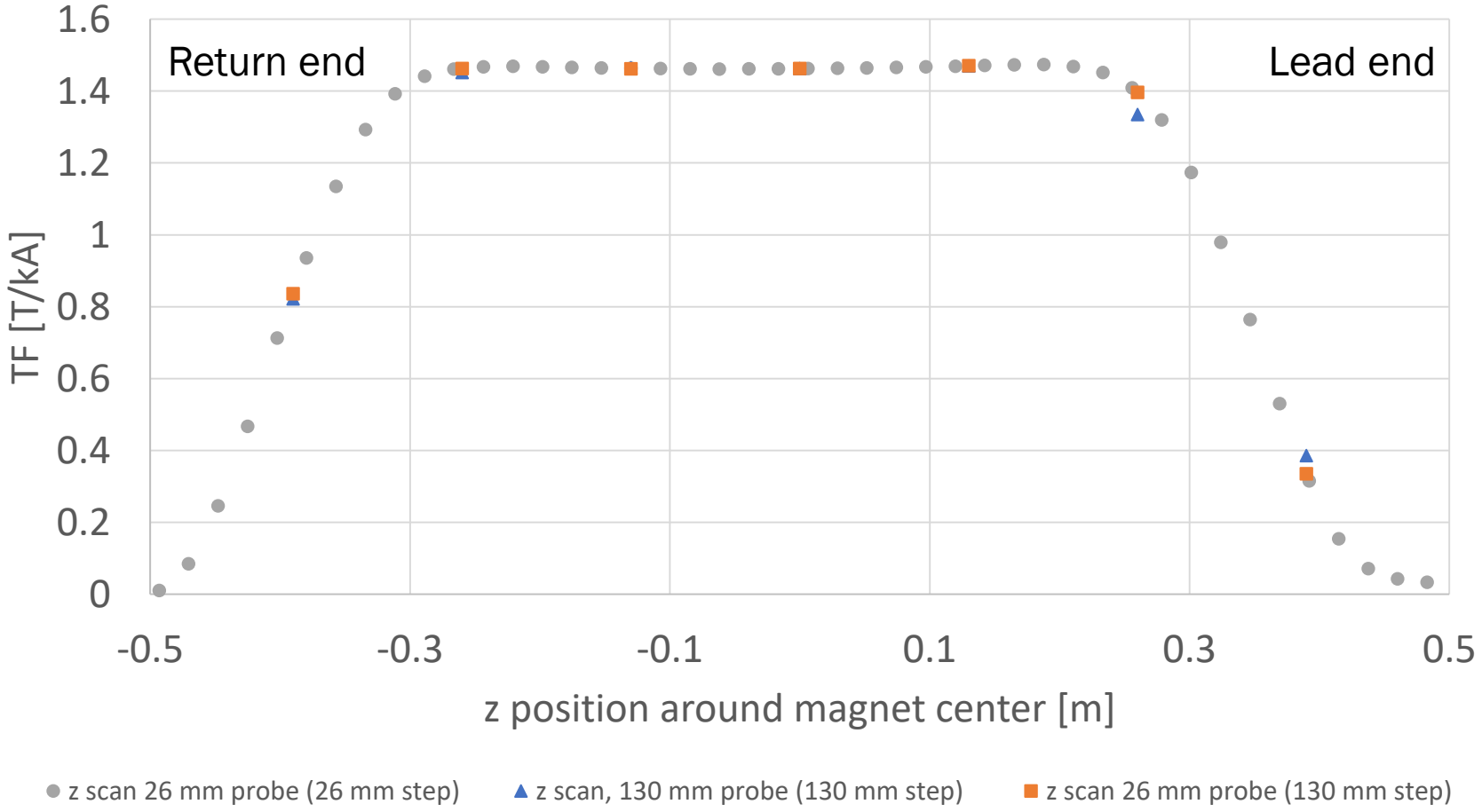


20 A/s Loop measurement skewed harmonics



Z scan TF along magnet bore

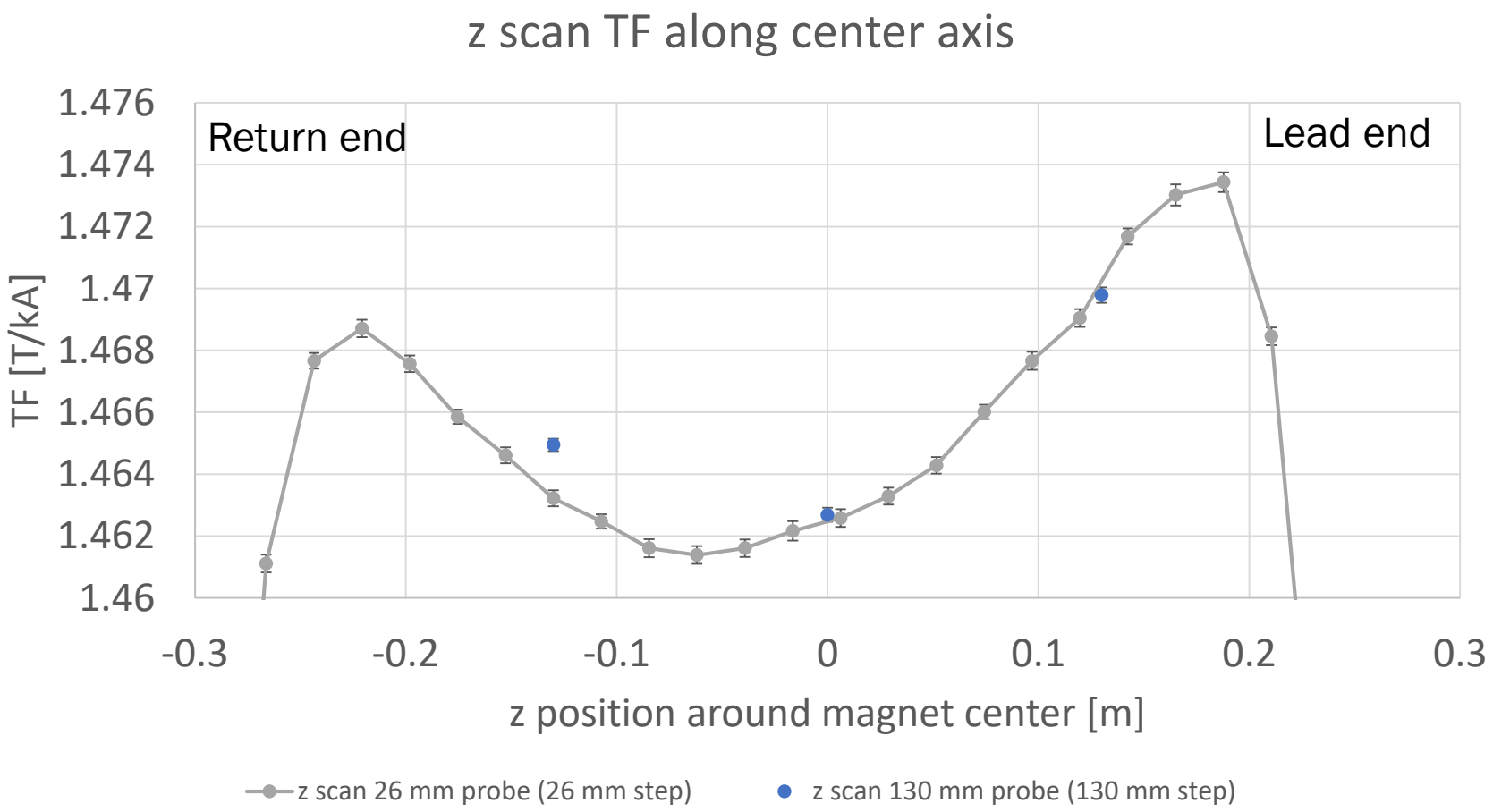
Measured at 9kA



Z scan TF, zoom

Measured at 9kA

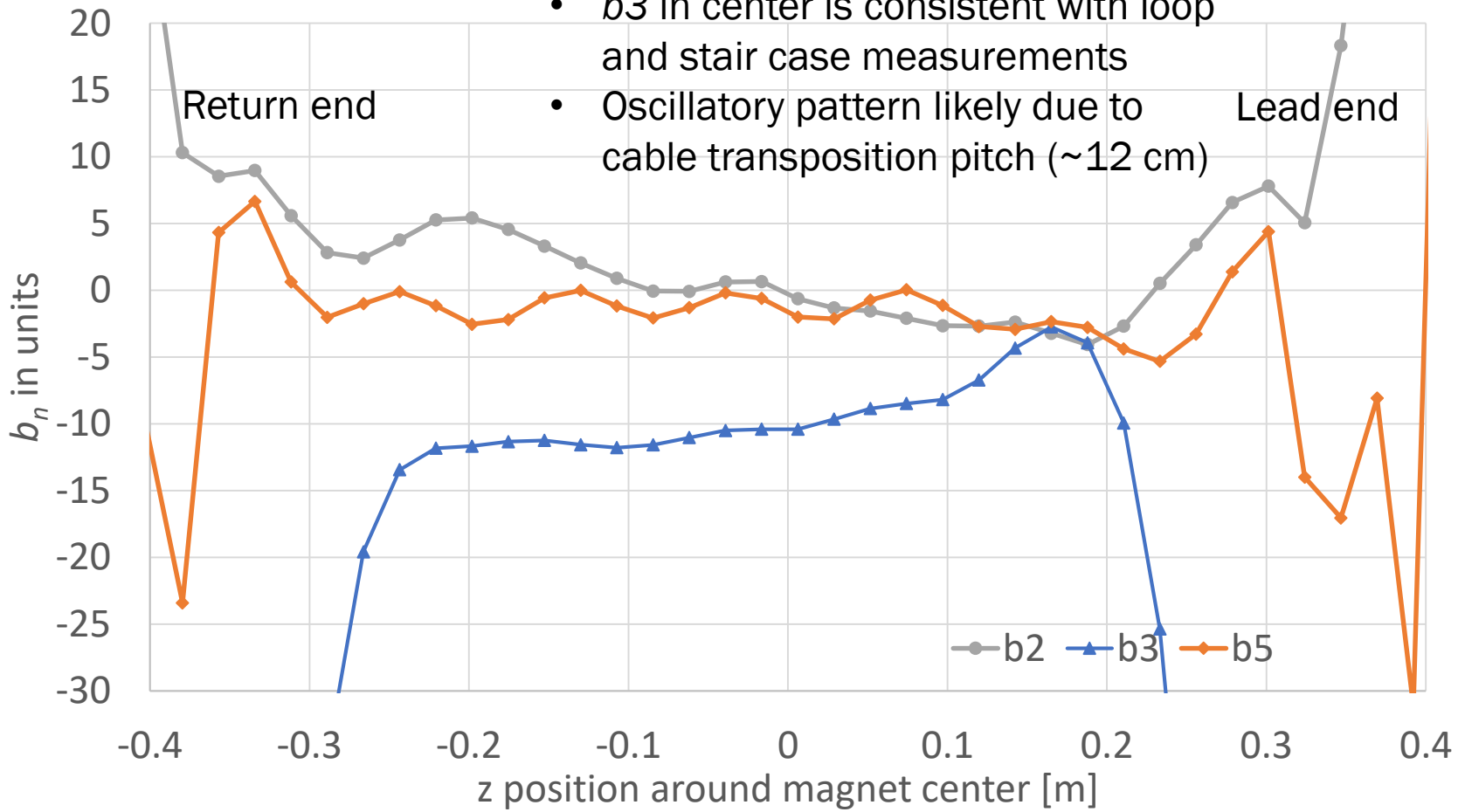
Variations due to end field contributions



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)

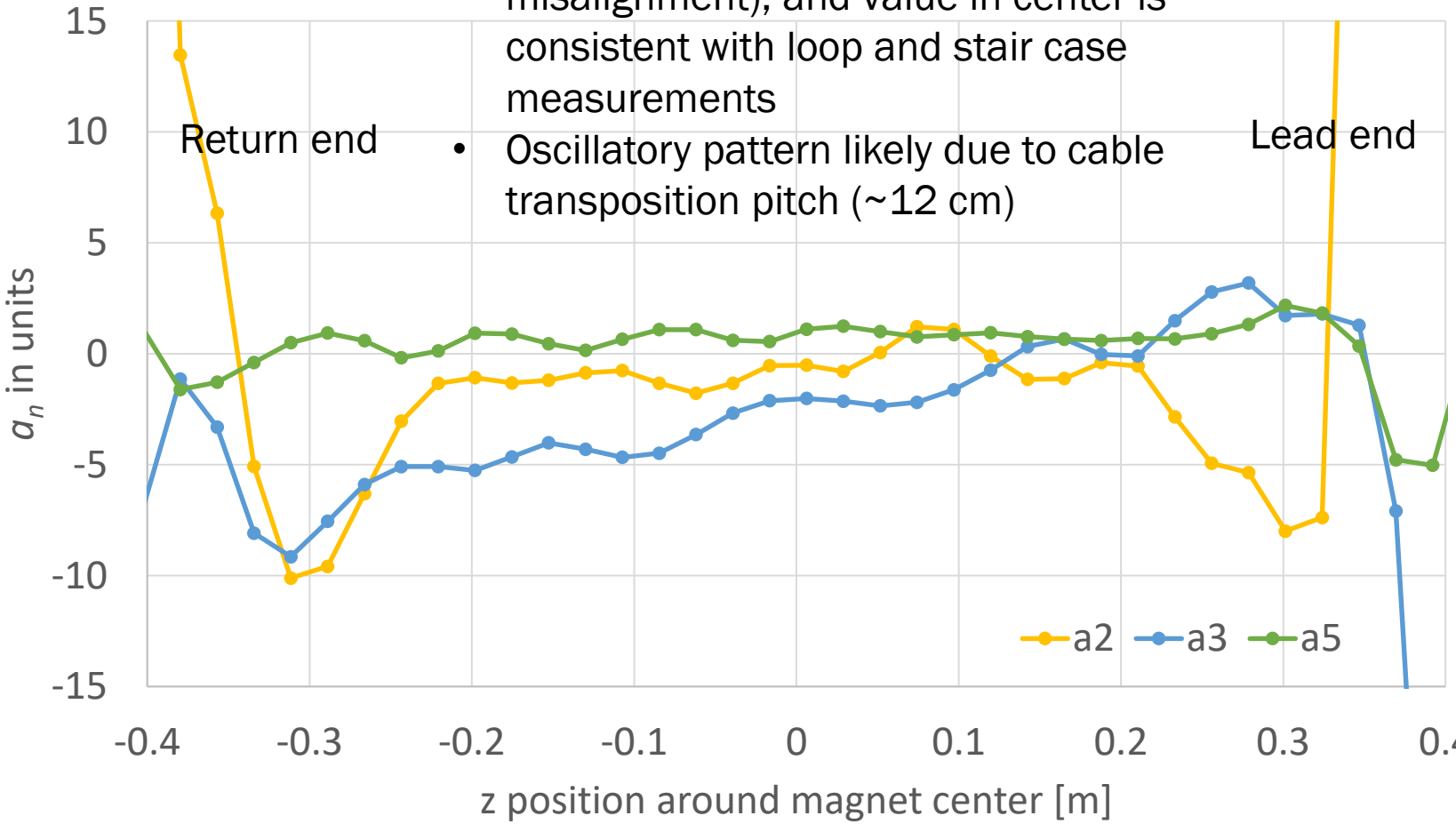


Errors smaller than symbols

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

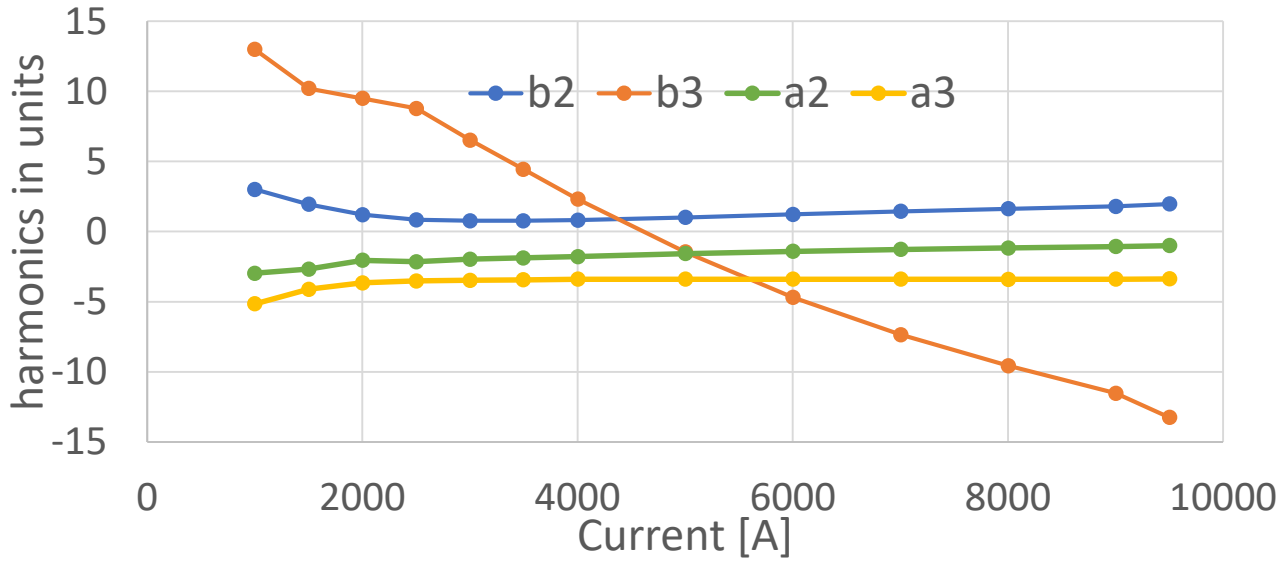
- **Stair step, 26 mm probe**

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**

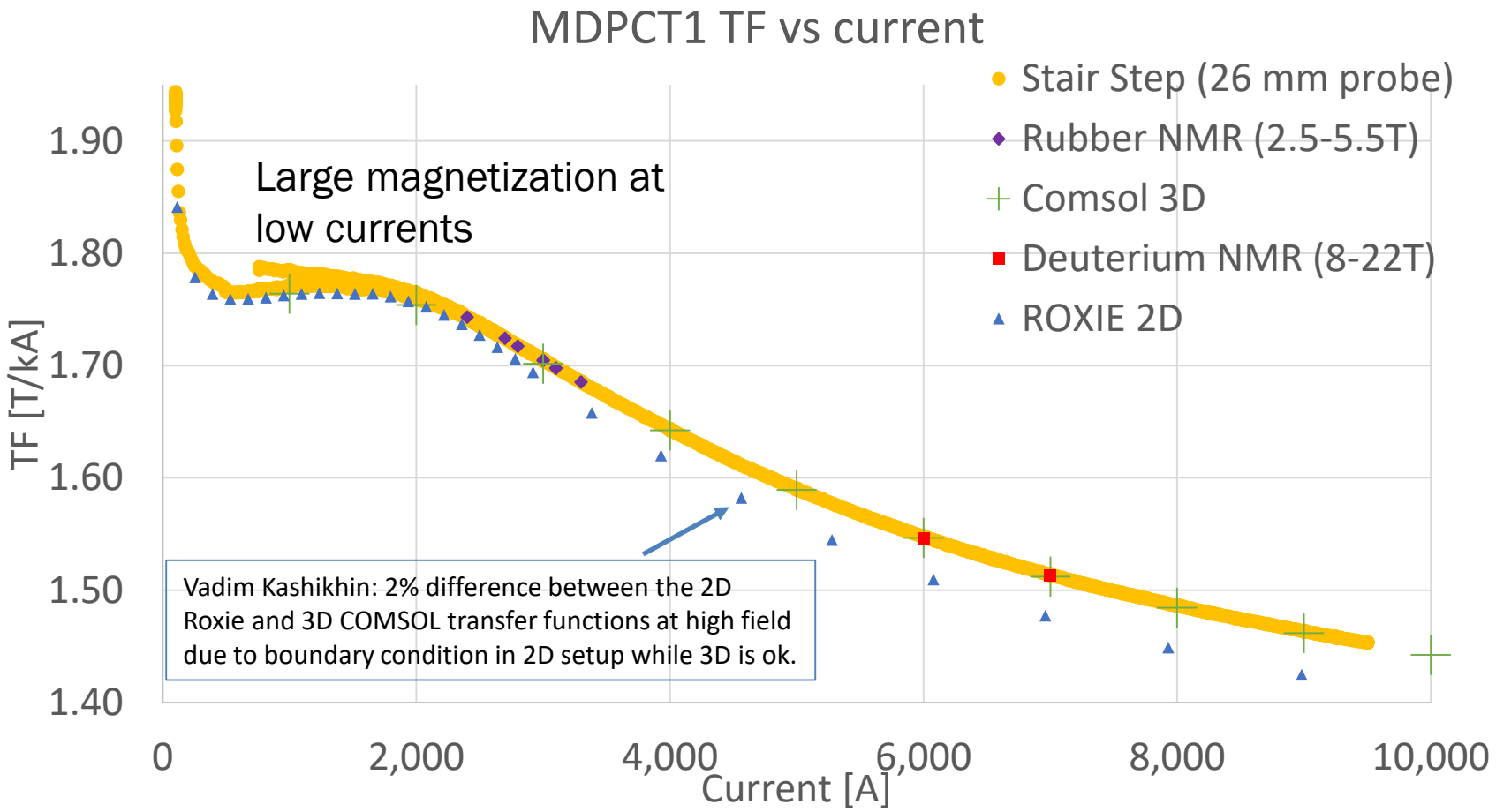
Loop 20 A/s 26 mm																			
6996		1.512	1.4	-7.6	-1.0	0.2	-0.2	1.4	0.1	-0.2		-1.4	-3.7	0.8	0.2	0.2	0.1	0.0	0.0
Loop 20 A/s 130 mm																			
6996.030		1.514	-1.2	-7.2	-1.8	-1.3	-0.1	0.7	0.2	0.0		-1.5	-3.0	2.4	1.2	0.1	0.1	-0.1	0.0



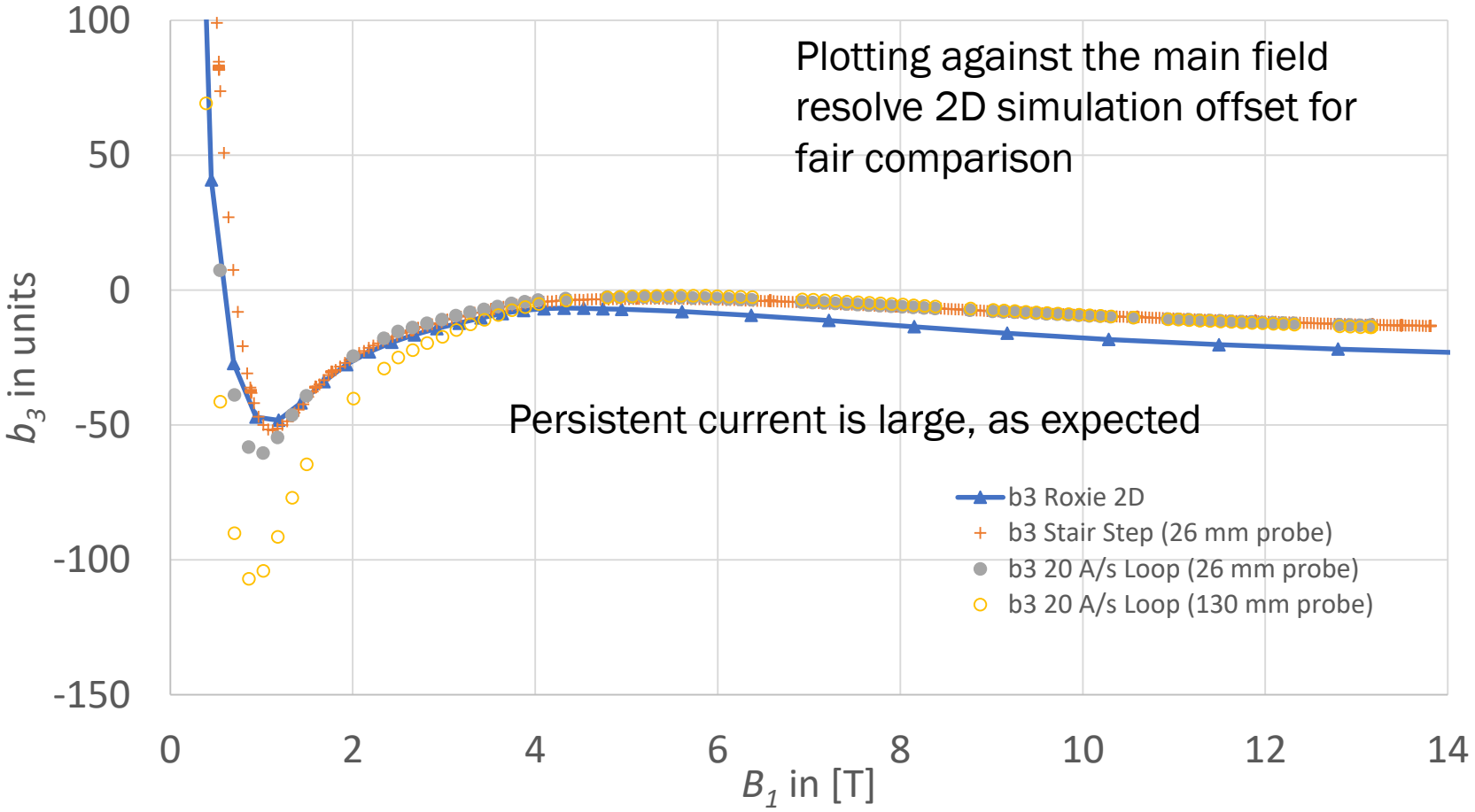
Harmonics averaged from up and down ramp

Transfer Function

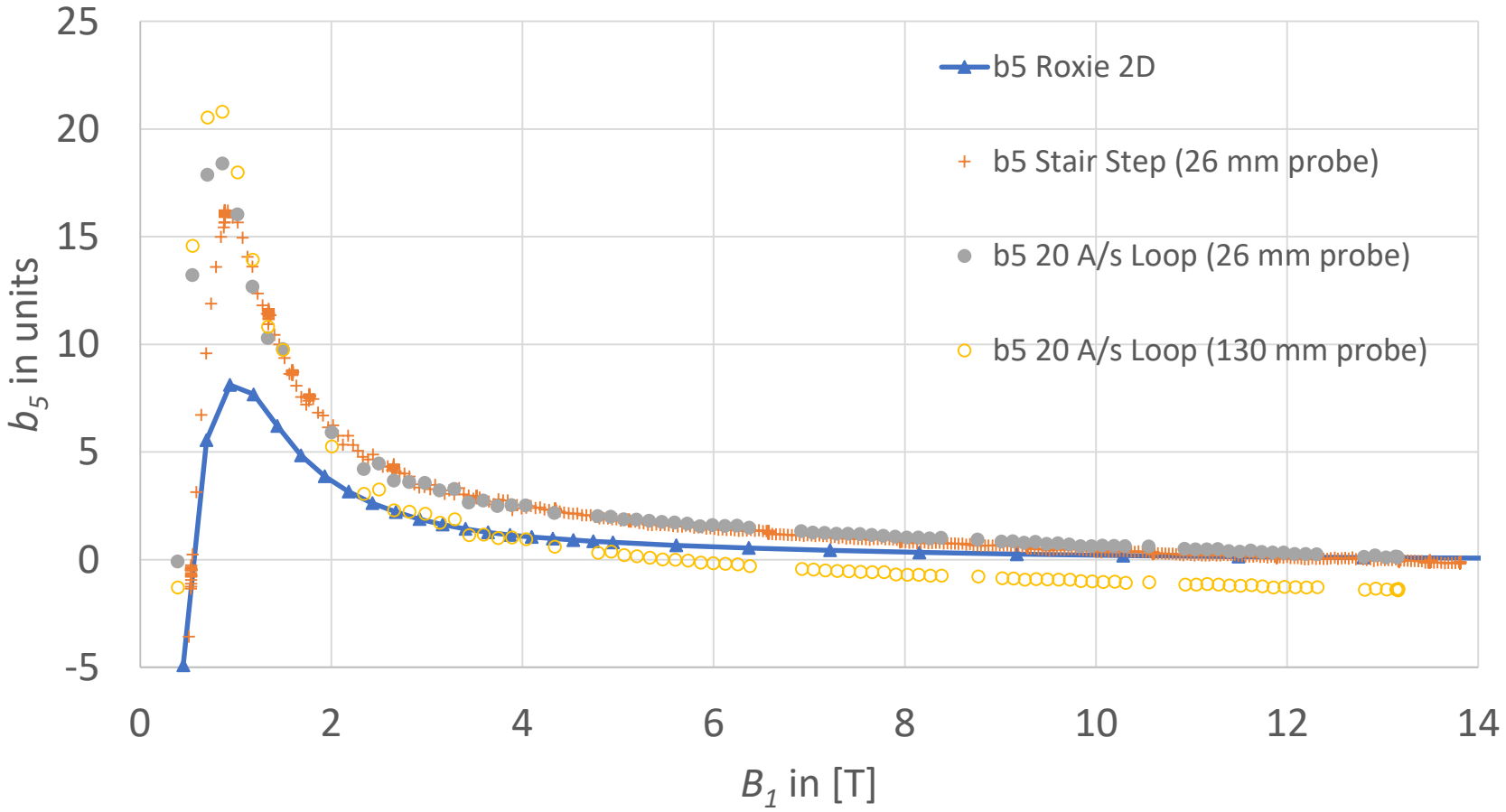
Deuterium probe was loaned to FNAL by GMW



b_3 versus dipole field

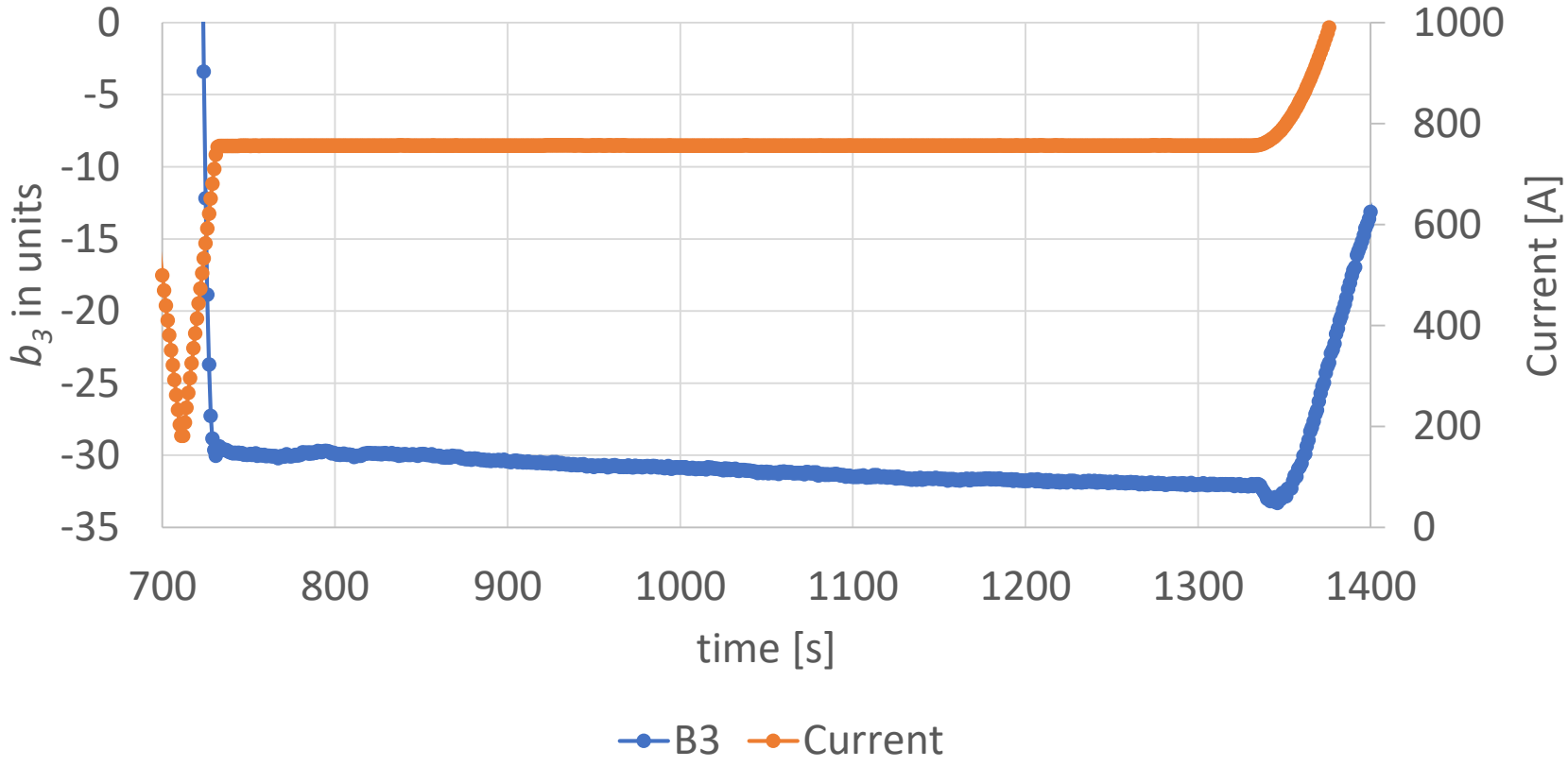


b_5 versus dipole field

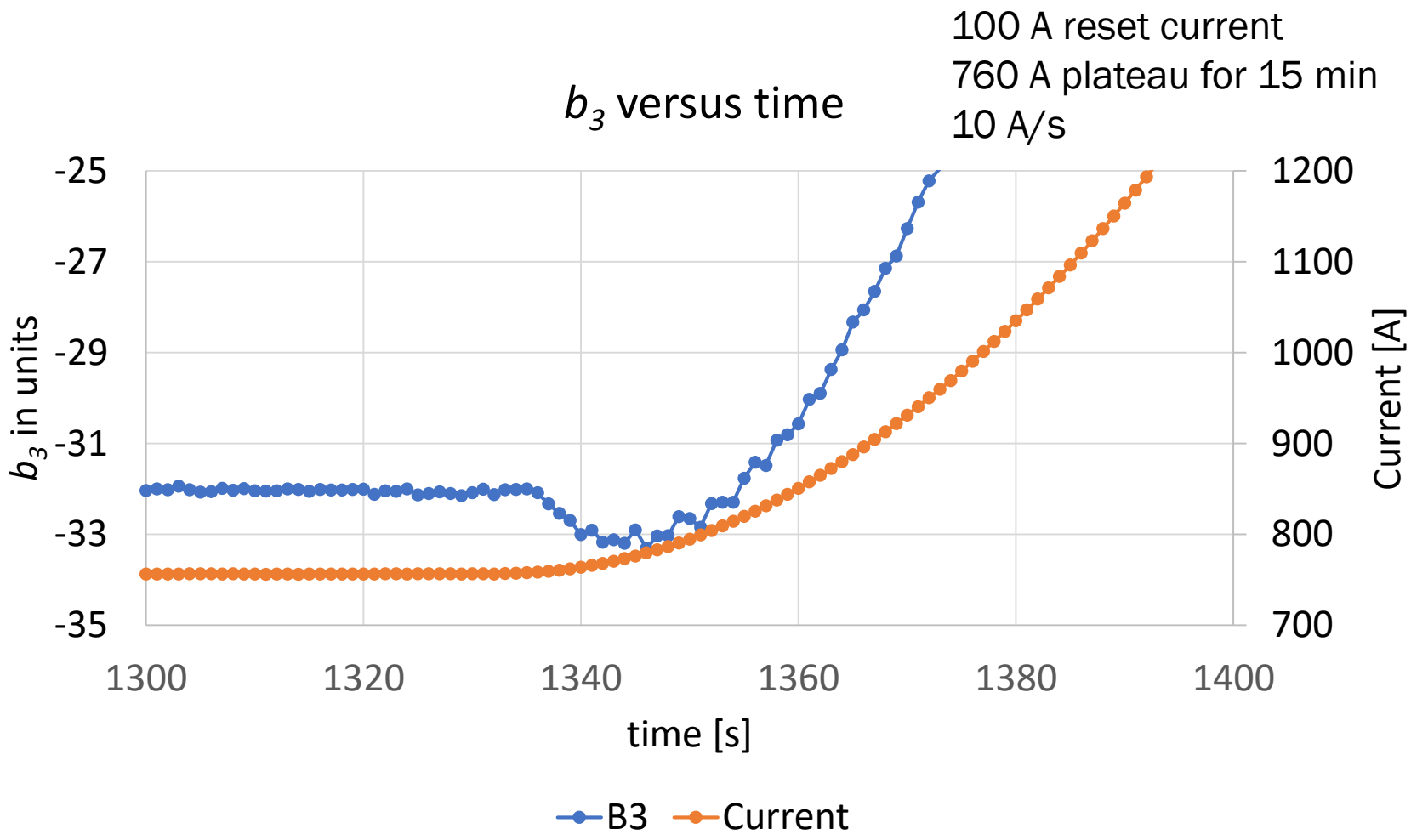


Decay and Snapback

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

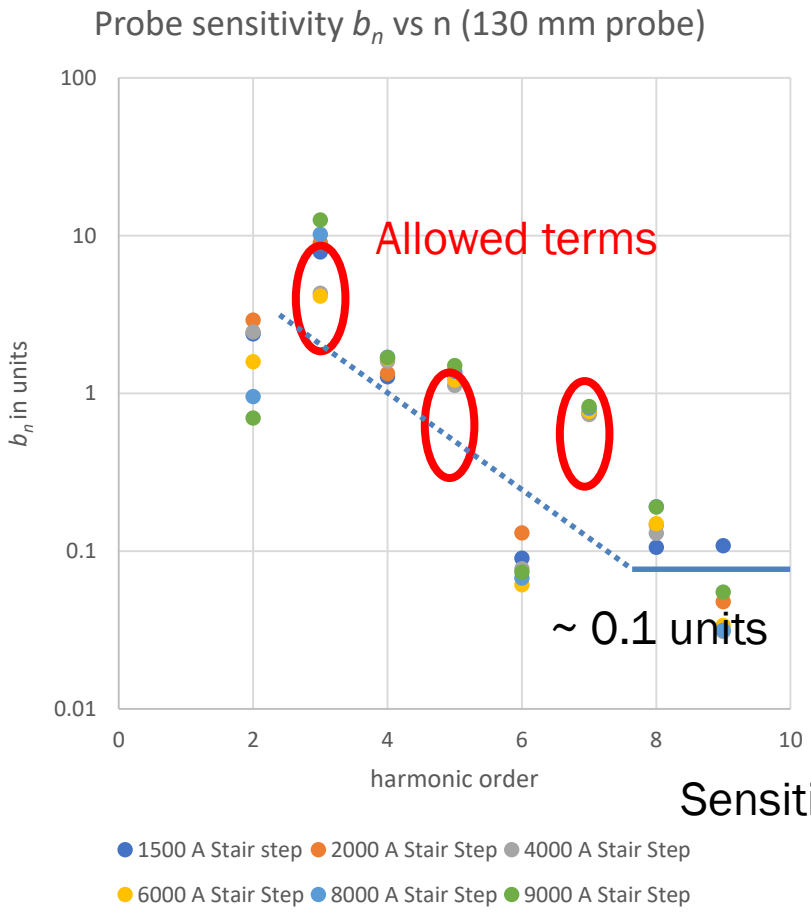
- Magnet *TF* and low-order field harmonics were measured using 26 mm and 130 mm long rotating coils in the field range up to ~14 T.
- The measurements included geometrical components and contributions from the coil magnetization and iron yoke saturation effects.
- All the measured geometrical harmonics, 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

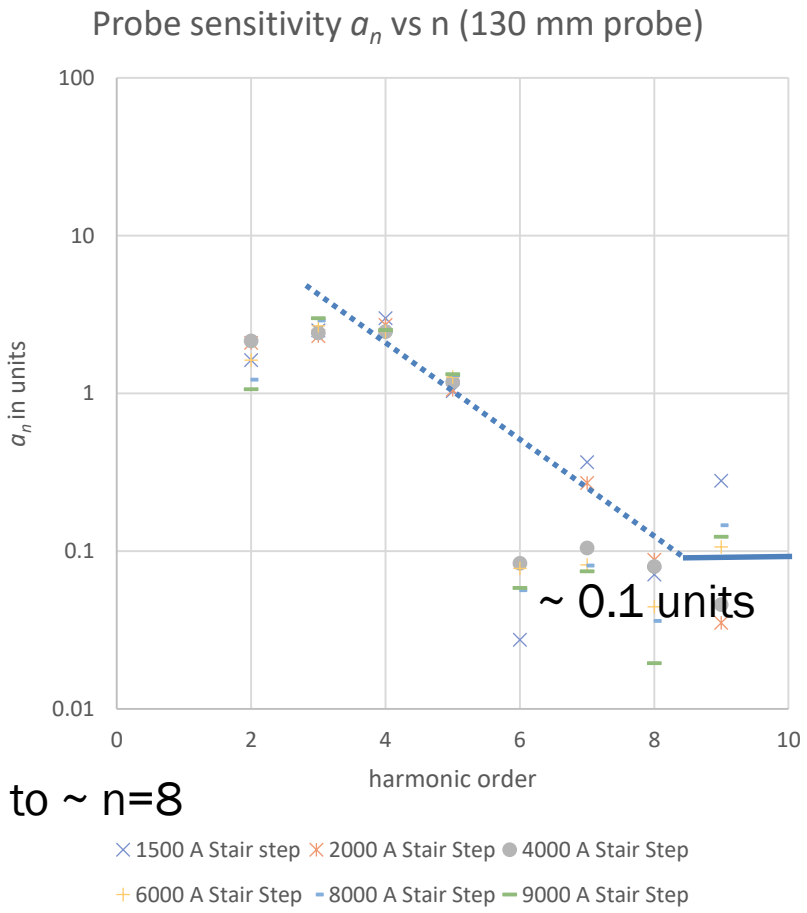
Acknowledgment

- 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