Results of Magnetic Measurements in LEReC Solenoids

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November 24, 2015

(Updated November 25, 2015)

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LEReC Compensating Solenoid Details

- 3 Solenoid coils – One *Main coil* and two *Bucking Coils:*
  - The Bucking Coils are expected to reduce the fringe field from the main solenoid to less than 1 Gauss at a distance of ~210 mm from the axial center.
  - Nominal operating current is < 15 A for all solenoid coils.
  - Goal is to get $\int [B_z(z)]^2 \, dz \geq 4 \times 10^{-5} \ \mathrm{T}^2 \cdot \mathrm{m}$
- Horizontal and vertical dipole correctors:
  - Operating current = 0.8 A (max.)
  - Expected dipole field integral ~ 10^{-5} T.m at 0.8 A.
  - Needed to correct transverse fields from any misalignment of the solenoid axis.
- 158.5 mm dia. clear aperture; 200.2 mm total length.

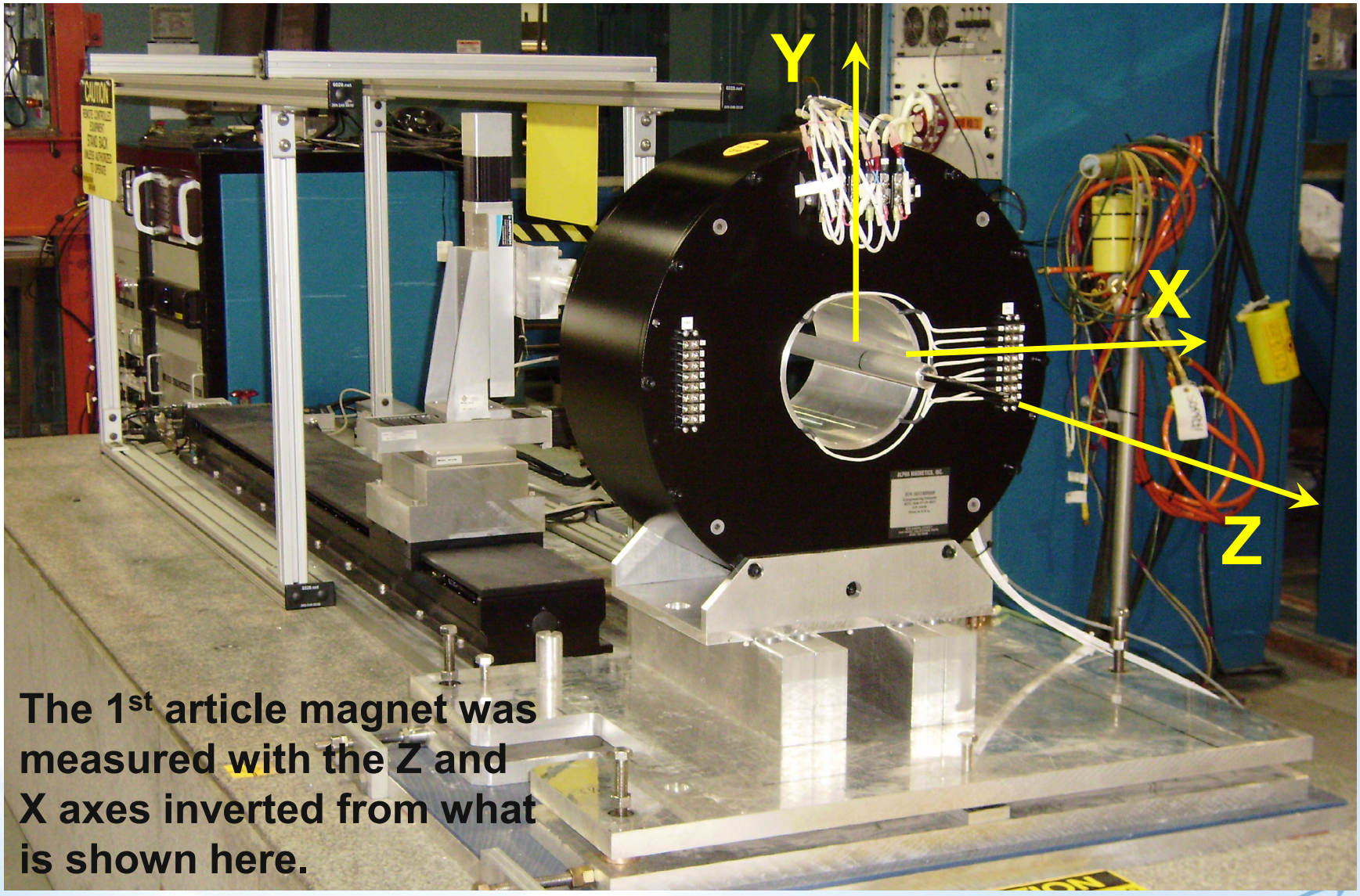
Hall Probe Measurements

- Magnets after the first article were measured with a new 3-axis probe. All axes were calibrated against NMR.
- Hall probe scans with both the main and the bucking solenoid coils powered together:
  - Measured B_x, B_y, B_z with a new 3-D Hall probe.
    - Main current = 14.0 A, Bucking coil current = 14.8 A (full field)
    - Main current = 7.0 A, Bucking coil current = 7.4 A (1/2 field)
    - Main current = 3.5 A, Bucking coil current = 3.7 A (1/4 field)
  - Z-values from –300 mm to +300 mm in 5 mm steps
  - On-axis (r = 0) and every 45 deg. off-axis at r = 15 mm.
- Hall probe loop 0 A to 15 A at axial and radial center, main solenoid only, with the bucking solenoid held at a fixed current of 14.8 A. (not done in 4 magnets).

Hall Probe Measurement Limitations

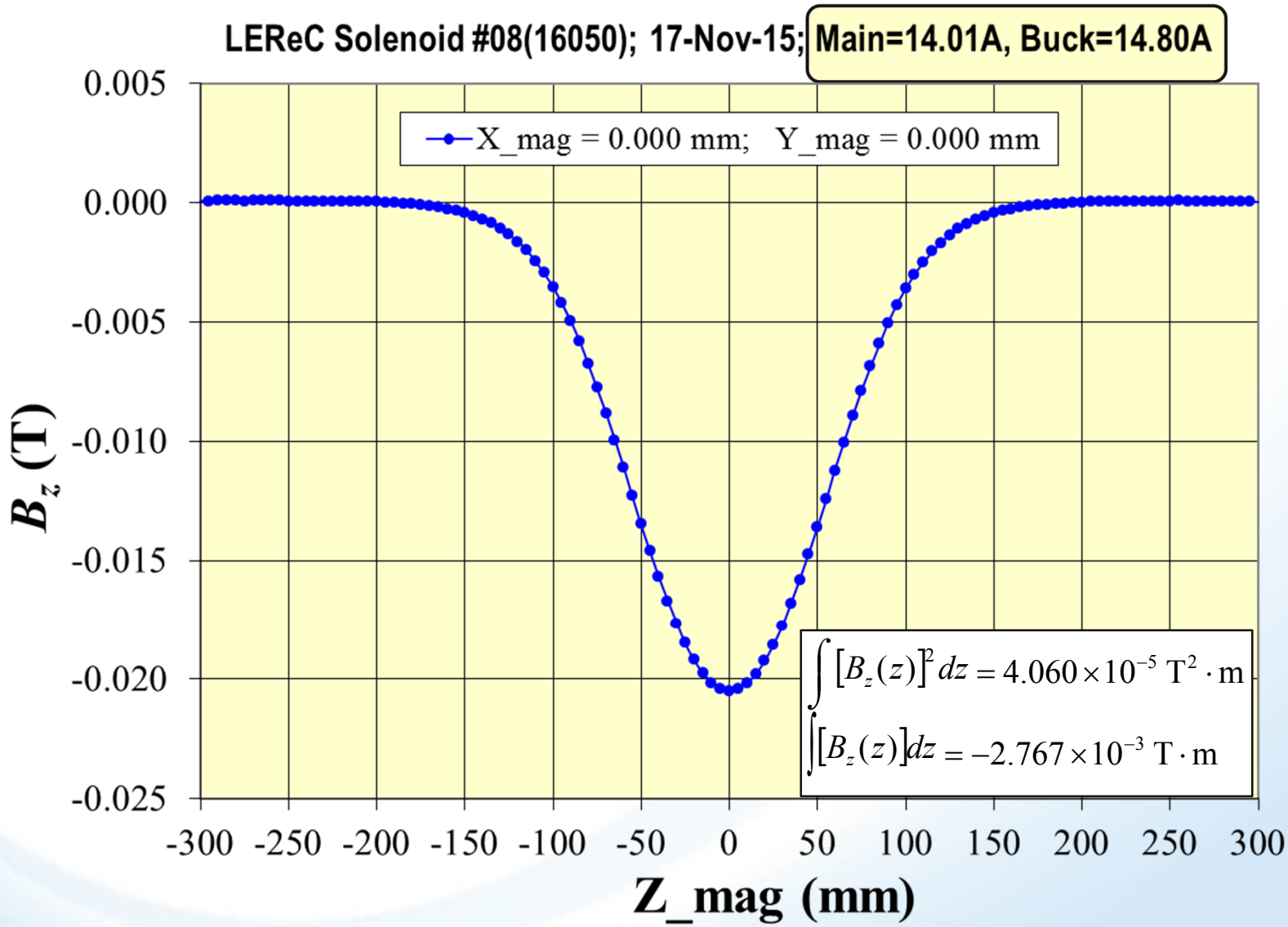
- Probe calibration is sensitive to temperature. Probe temperature varies with the ambient.
  - Offset is corrected to some extent by measuring in a mu metal shield just prior to each measurement.
  - Gain errors are unknown.
- Measurement of minor field components is not reliable (error could be up to 1% of the main field component):
  - Non-orthogonality of the 3 probe axes (specification is ~ 2 mr)
  - Misalignment of the probe axes with respect to the magnet coordinate system.
  - Imperfect motion of stages causing slight angular tilts as a function of position.
  - We do not have means to characterize these errors.

LEReC Solenoid: New Hall Probe Setup

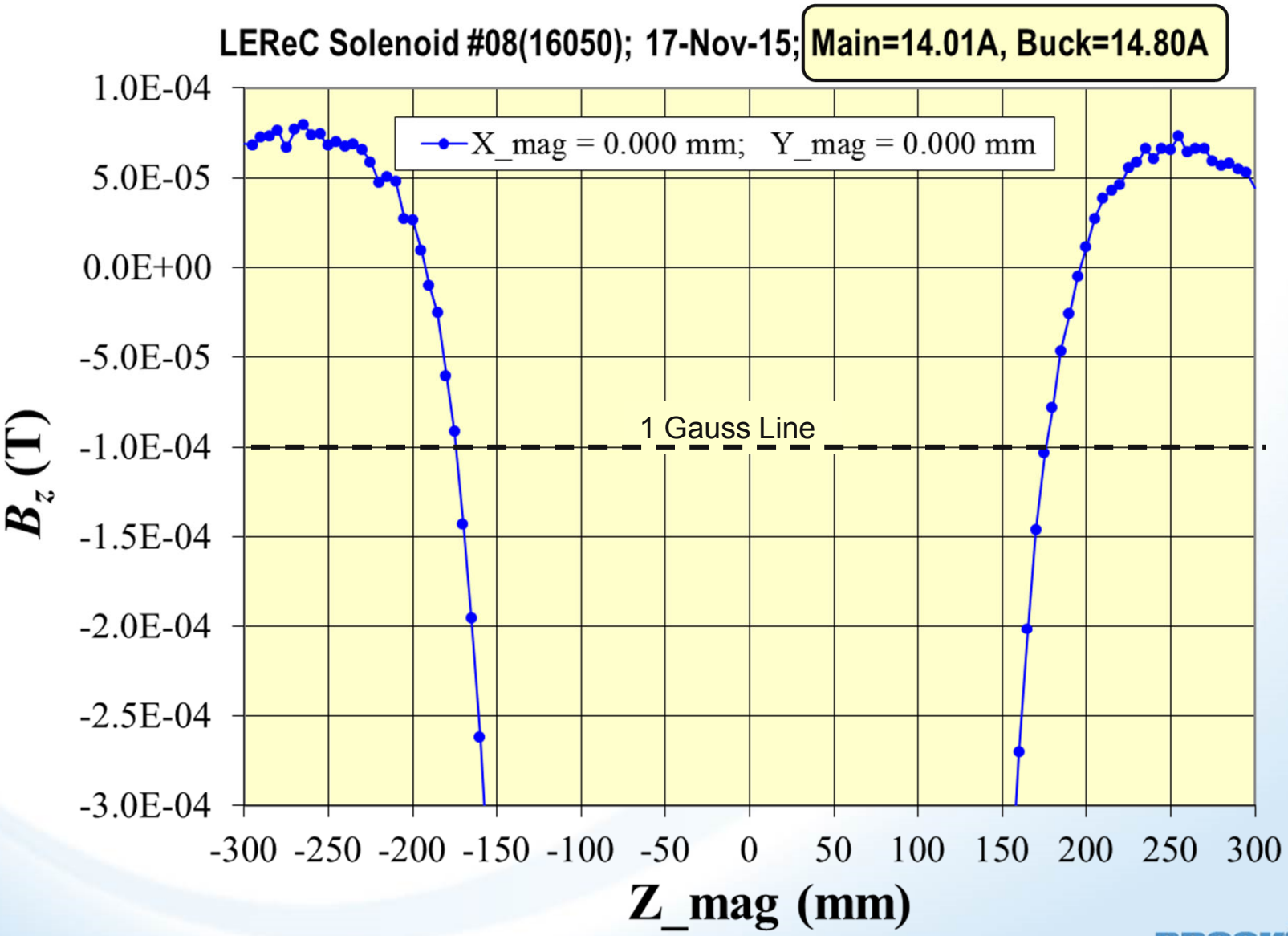


The 1st article magnet was measured with the Z and X axes inverted from what is shown here.

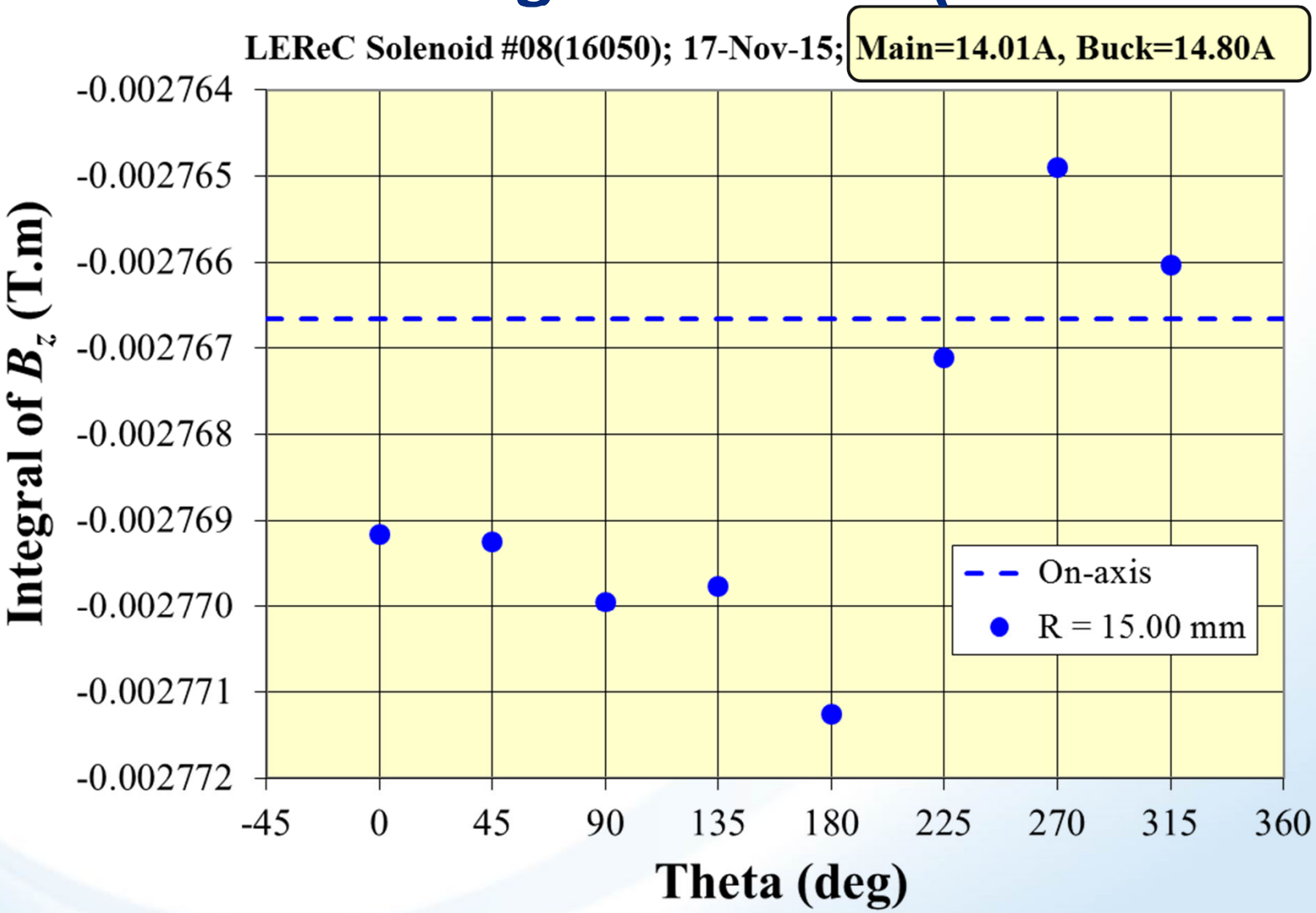
Solenoid Field Profile On-Axis (Main + Buck)



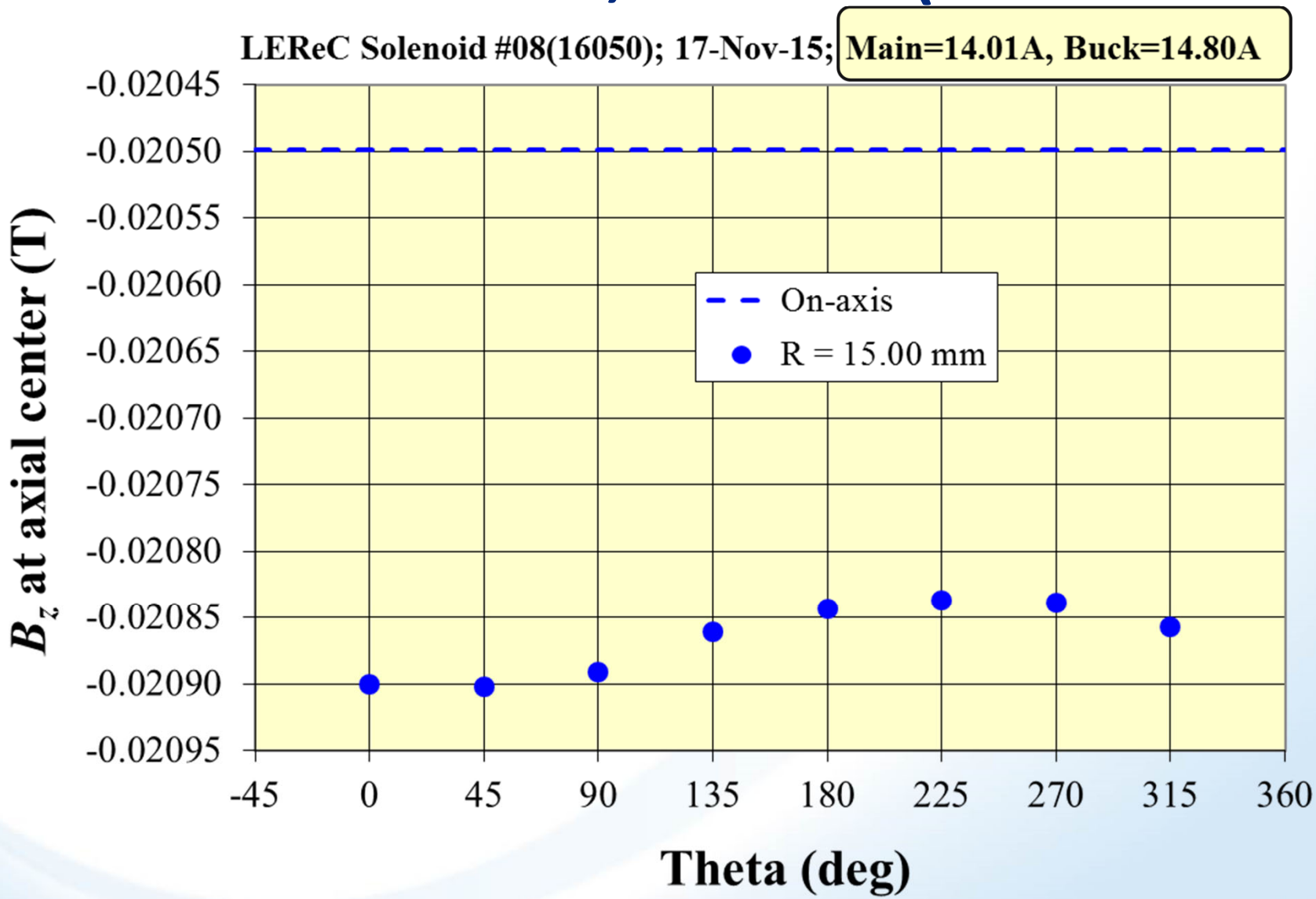
Solenoid Fringe Field On-Axis (Main + Buck)



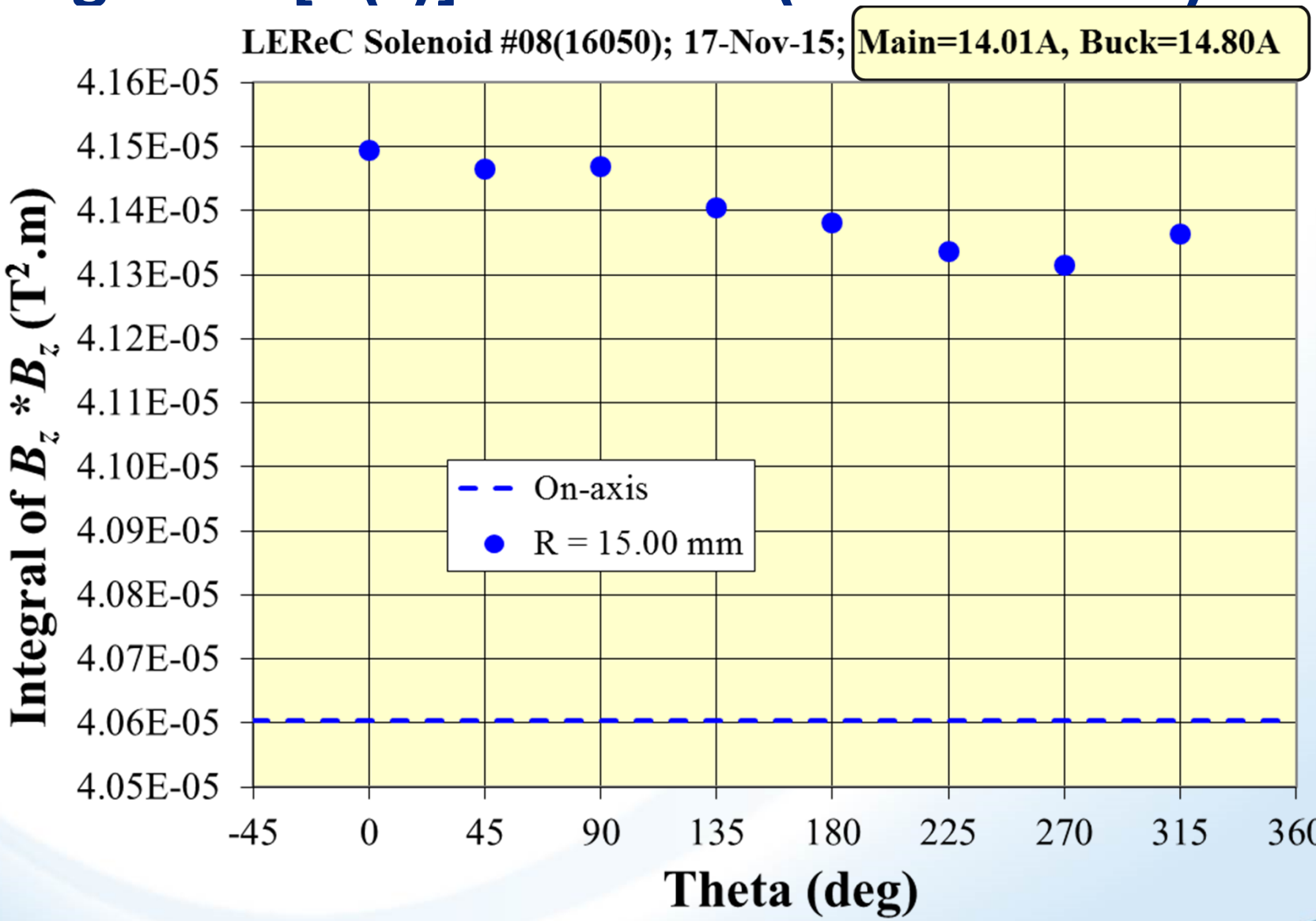
Solenoid Field Integral Off-Axis (Main + Buck)



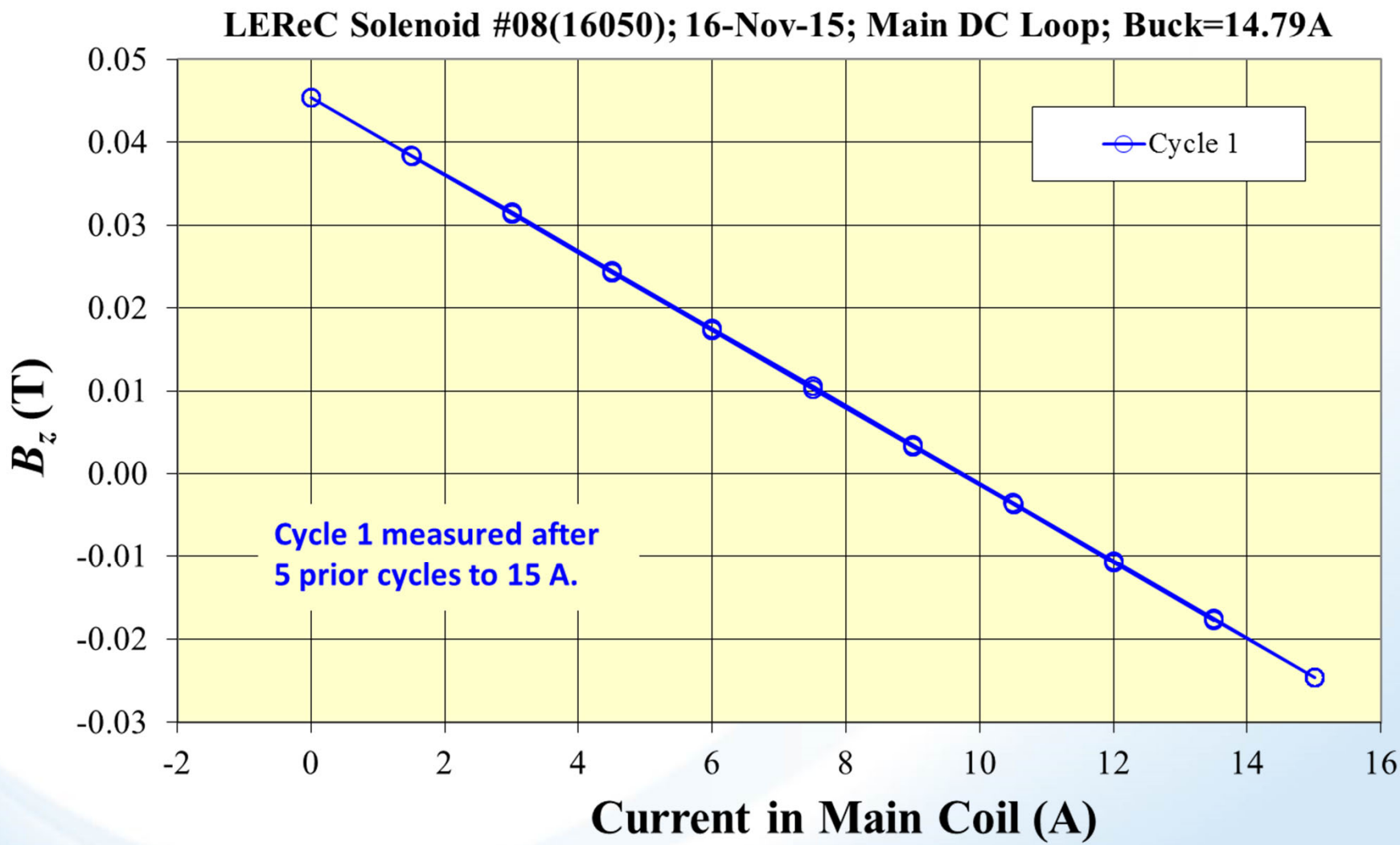
Solenoid Field at Z = 0, Off-Axis (Main + Buck)



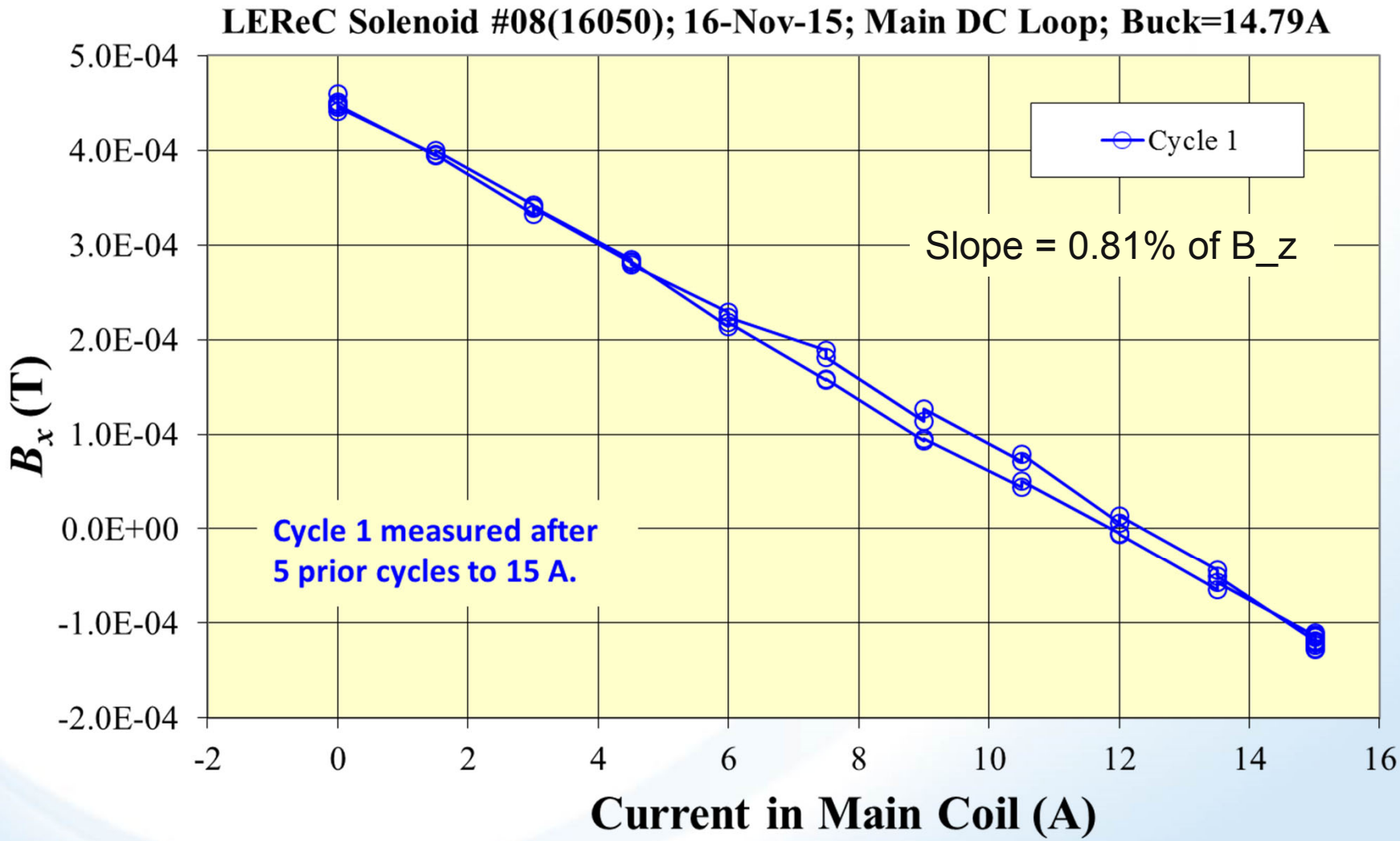
Integral of $[B(z)]^2$ Off-Axis (Main + Buck)



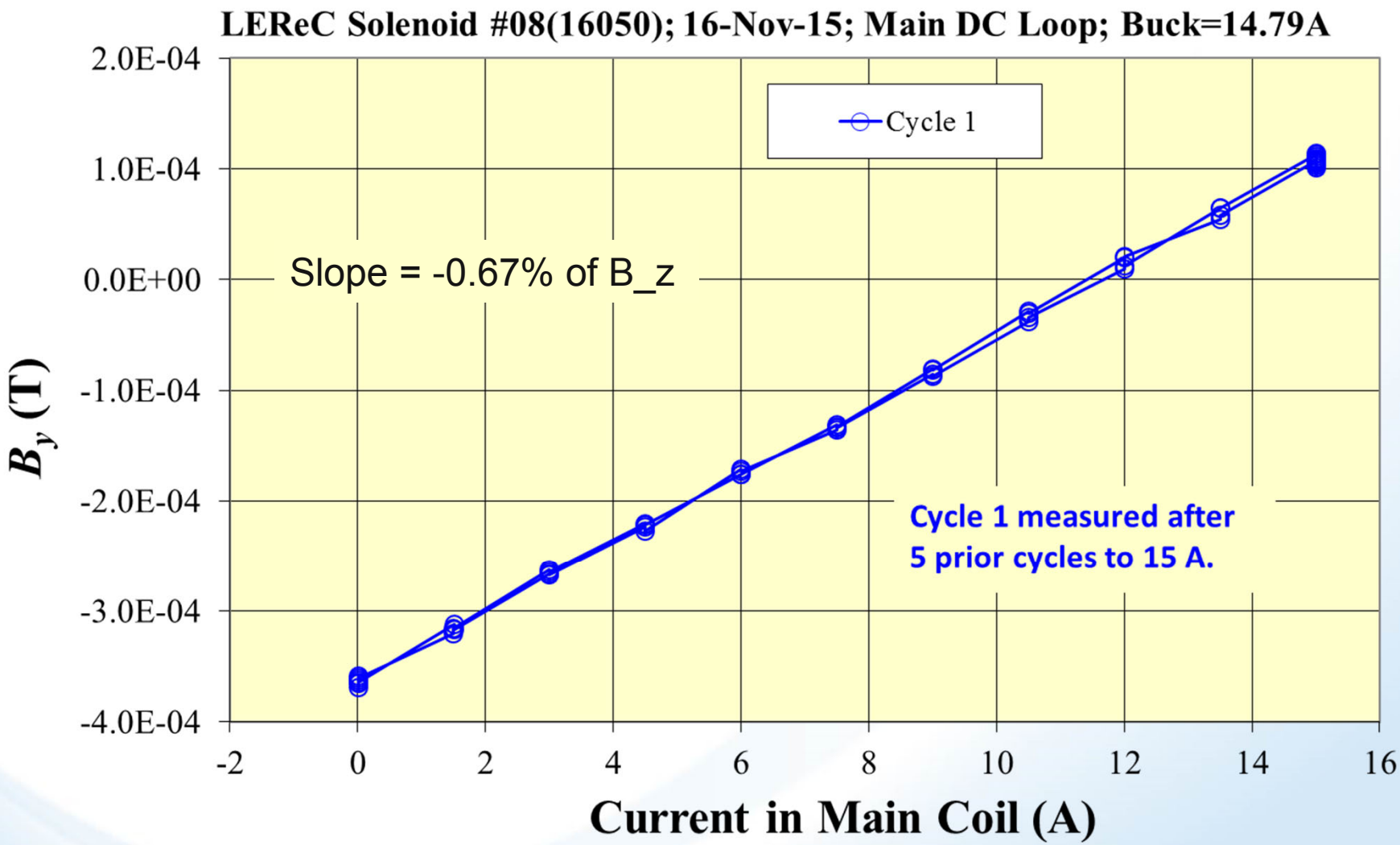
DC Loop in Main Coil at (*r*,*z*) = (0,0)



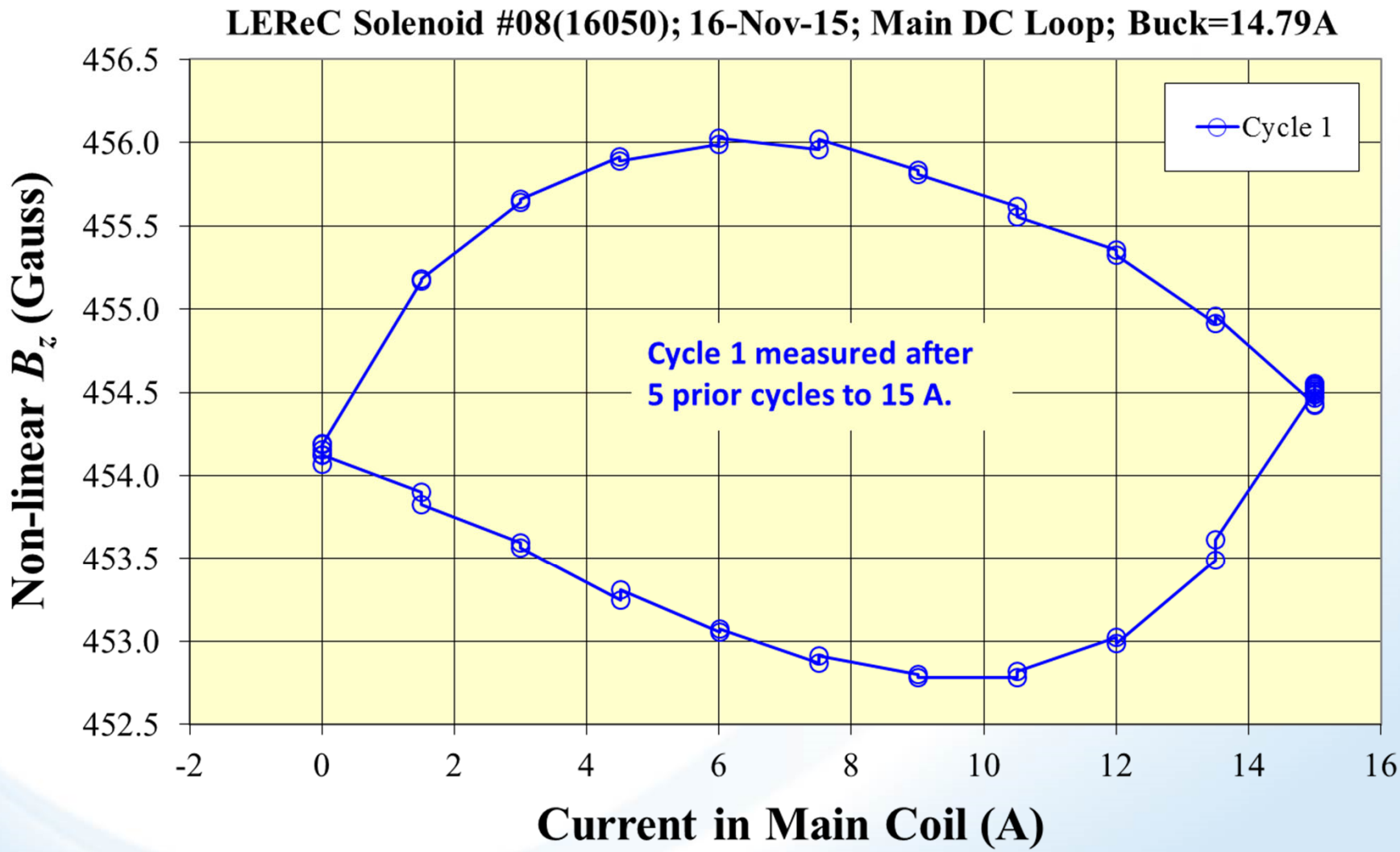
DC Loop in Main Coil at (*r*,*z*) = (0,0)



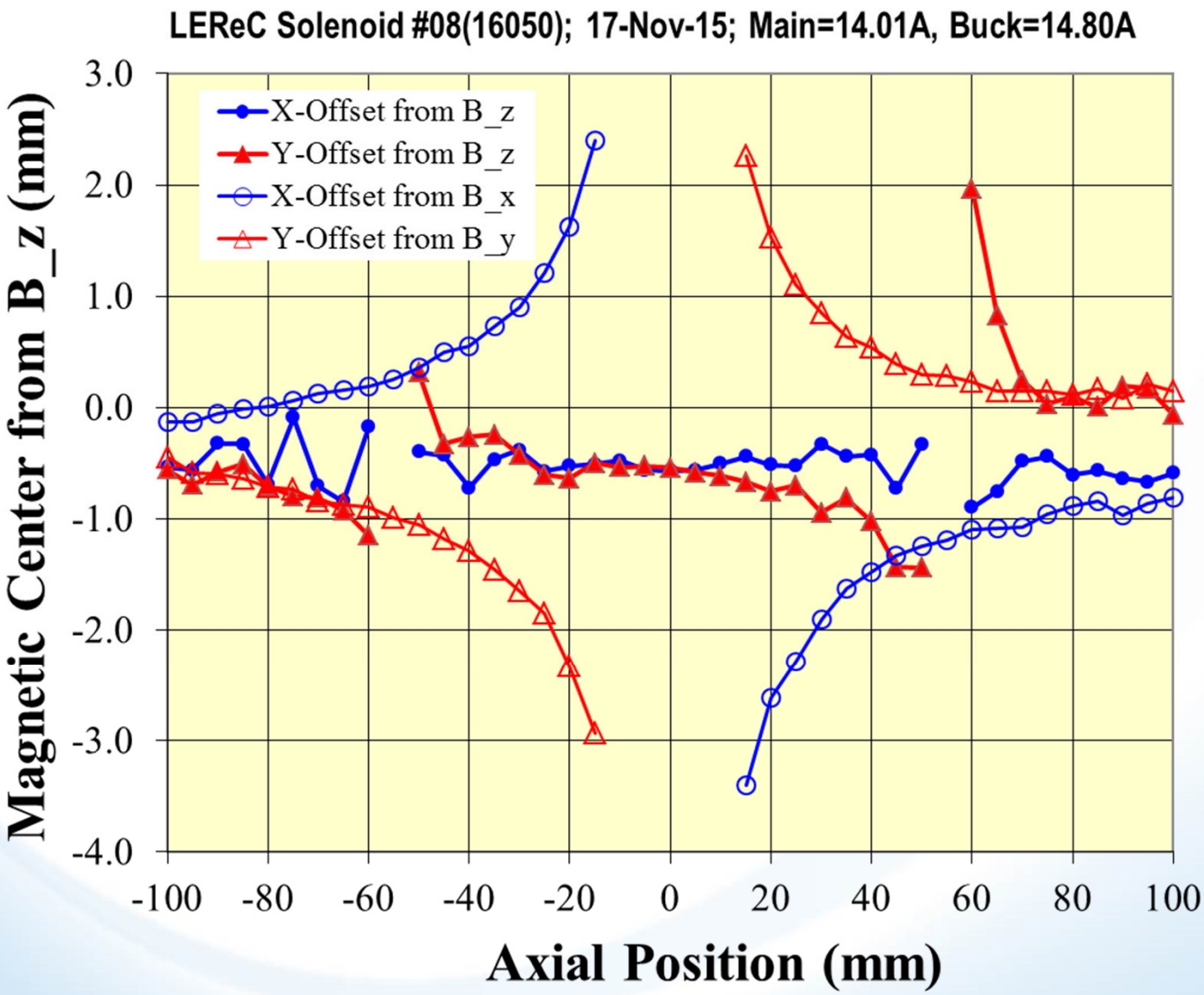
DC Loop in Main Coil at (*r*,*z*) = (0,0)



DC Loop in Main Coil at (*r*,*z*) = (0,0)



Attempt to find magnetic axis



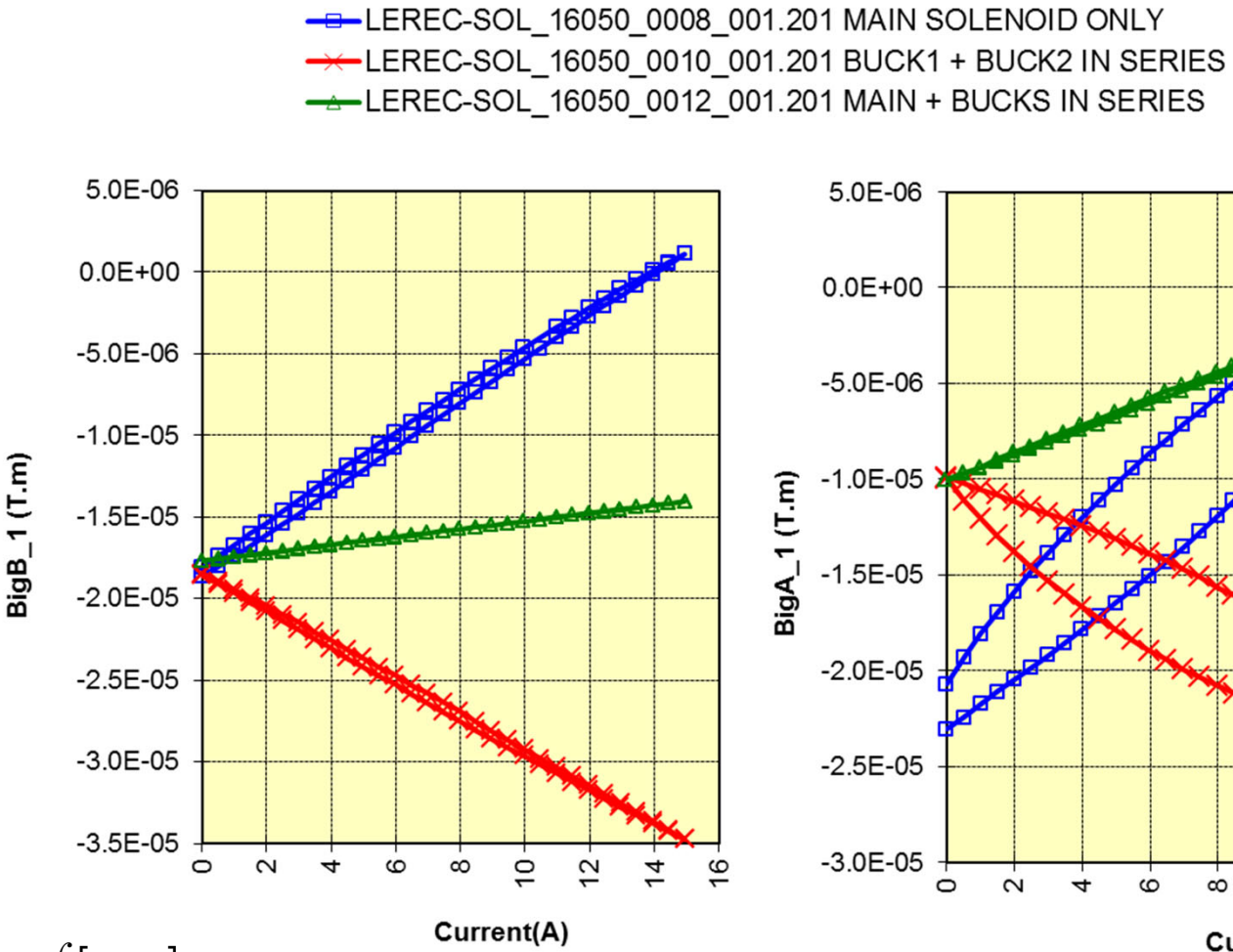
Transverse components of field at R = 15 mm are small compared to the axial component, even near the ends.

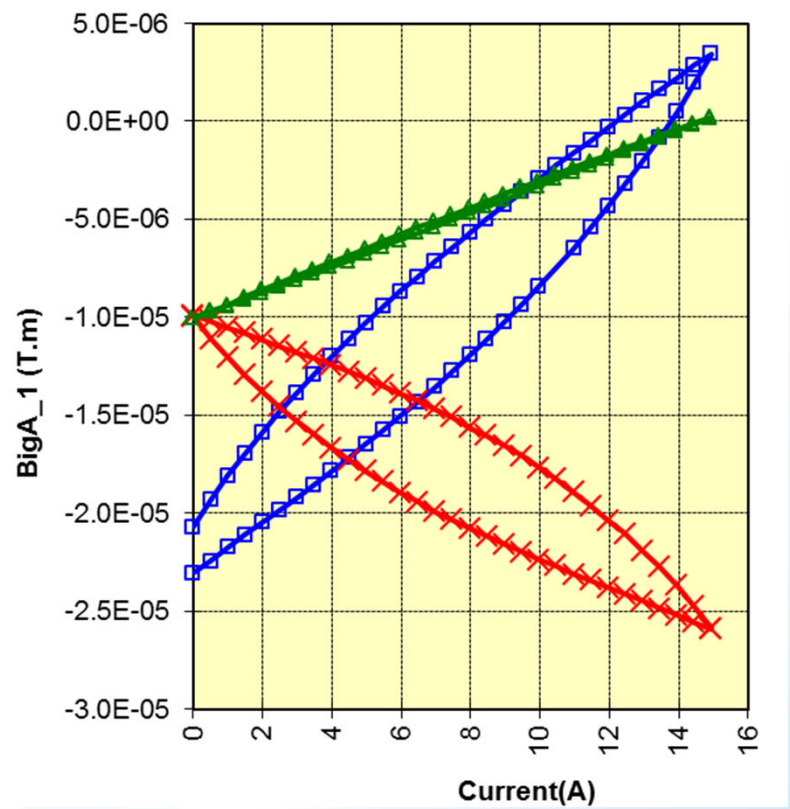
Center obtained from B_z Vs. X (or Y) is more reliable, particularly in the region away from the ends.

Rotating Coil Measurements

- Measuring coil is 0.914 m long, but the magnet is only 0.2 m
  - Good for capturing all the fringe field, but sees a lot of extra transverse field from earth's field.
  - Need to subtract background fields to get true contribution from the magnet
- Measurements were carried out in two ways:
  - Several measurements at two different currents (0 A and 15 A for solenoids and +0.8A and –0.8 A for the correctors). True fields obtained by the slope of a straight line fit to two currents.
  - Full excitation curves measured from I_{min} to I_{max} (0 A to +15 A for solenoids and –0.8 A to +0.8 A for the correctors). True fields obtained by the slope of a straight line fit to both the up ramp and down ramp data.
    - This also gives non-linearity such as hysteresis.
  - Results from both methods are very similar.
  - Main and bucking solenoids measured separately, and in series. (Measured only in series for 3 magnets.)
- Only the full excitation curve results are presented here.

Solenoid Transverse Field Integrals

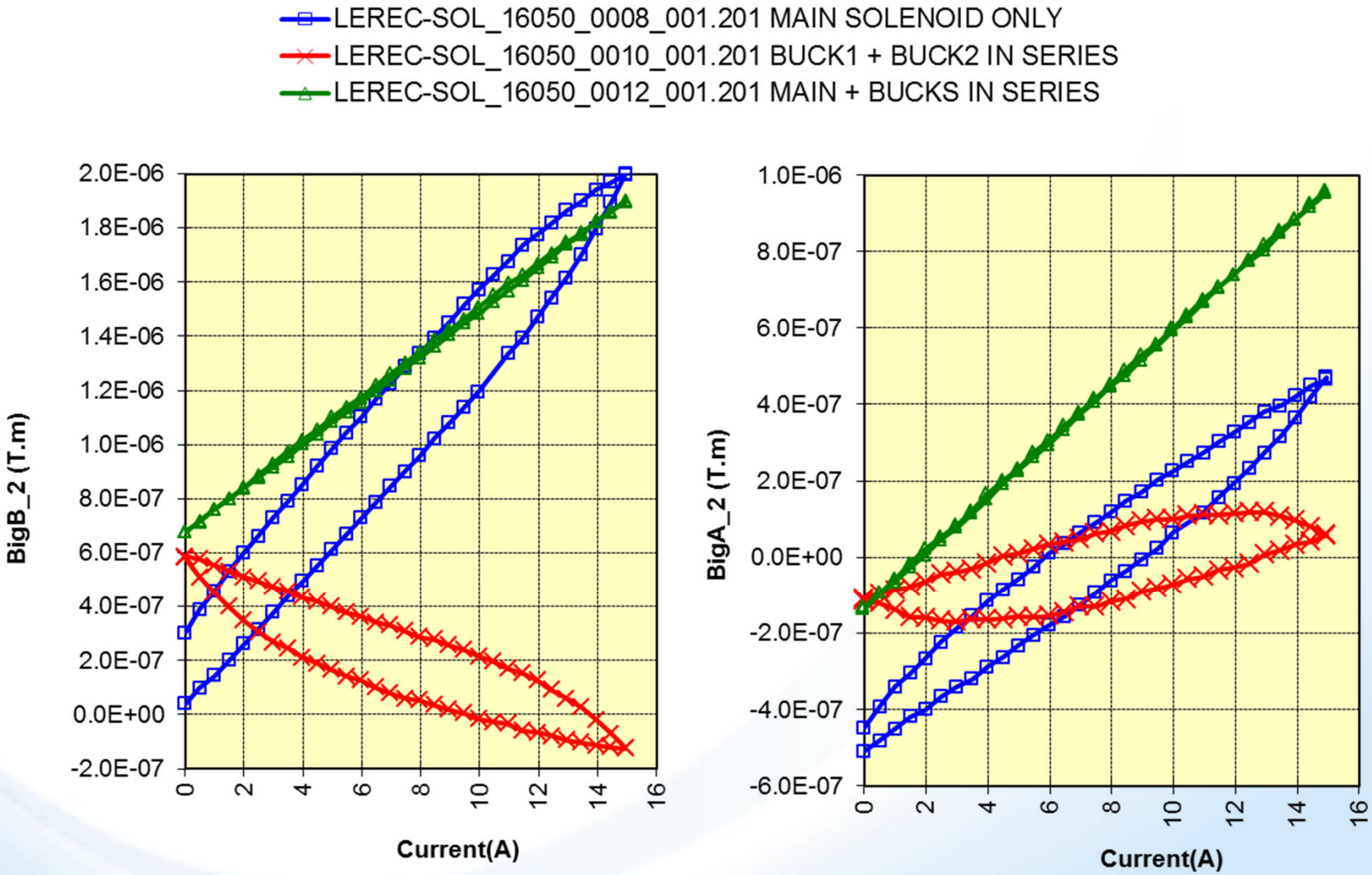




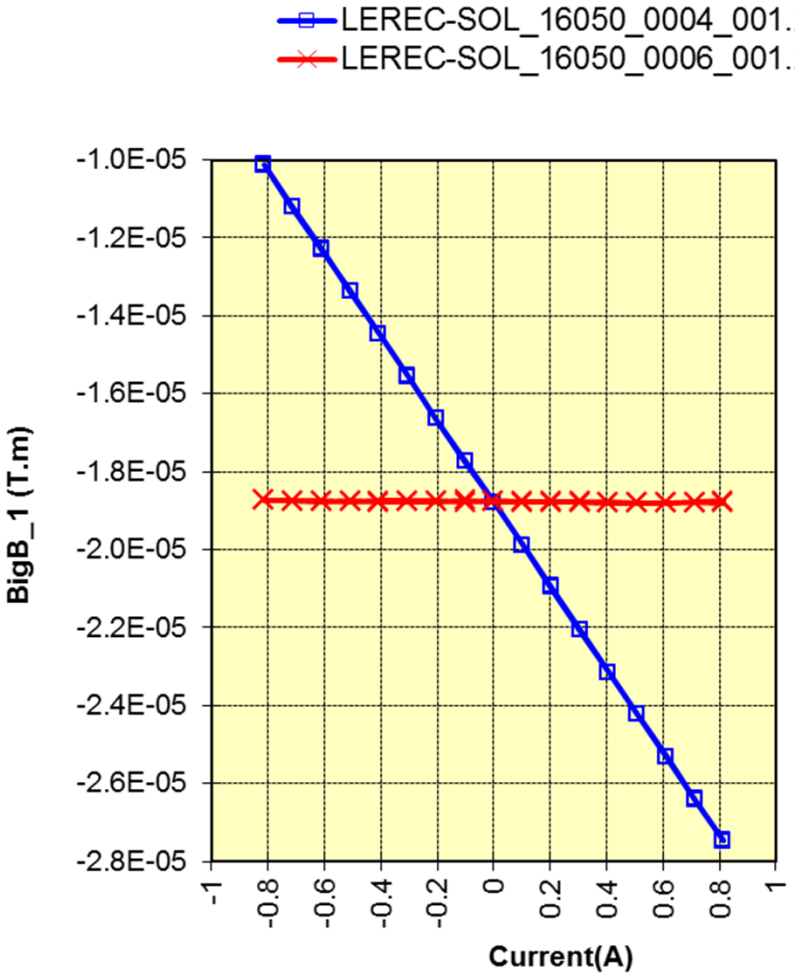
$$\int [B_y(z)]dz = 1.317\times10^{-6}\ \mathrm{T\cdot m/A\ (Main)}$$
$$= -1.096\times10^{-6}\ \mathrm{T\cdot m/A\ (Bucks)}$$
$$= 2.44\times10^{-7}\ \mathrm{T\cdot m/A\ (Main + Bucks)}$$

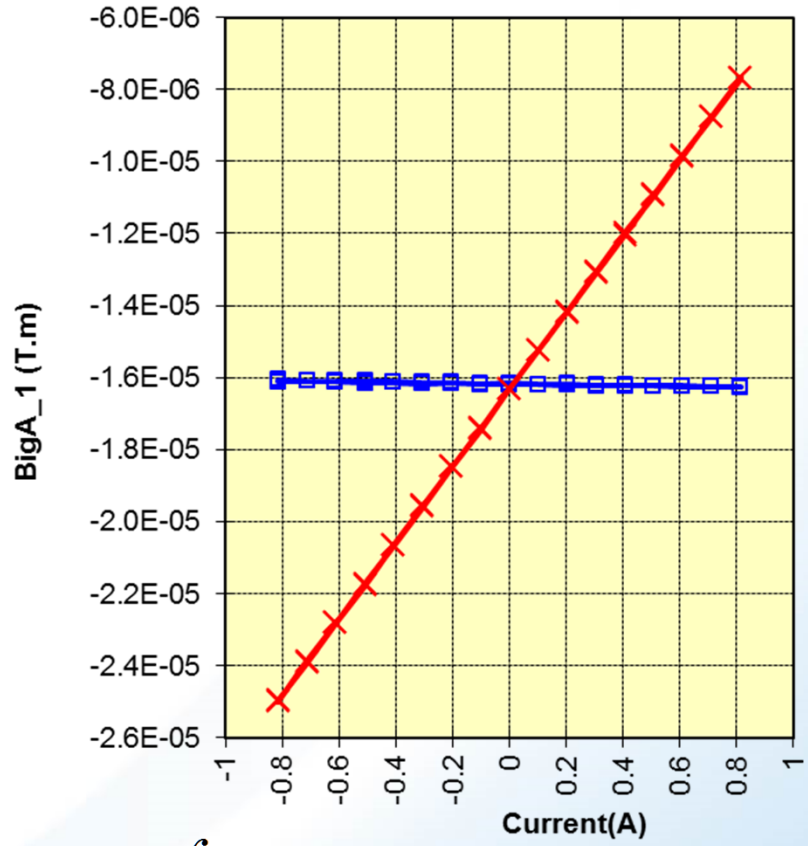
$$\int [B_x(z)]dz = 1.636\times10^{-6}\ \mathrm{T\cdot m/A\ (Main)}$$
$$= -9.99\times10^{-7}\ \mathrm{T\cdot m/A\ (Bucks)}$$
$$= 6.90\times10^{-7}\ \mathrm{T\cdot m/A\ (Main + Bucks)}$$

Solenoid Transverse Field Integrals: Quadrupole



Corrector Field Integrals





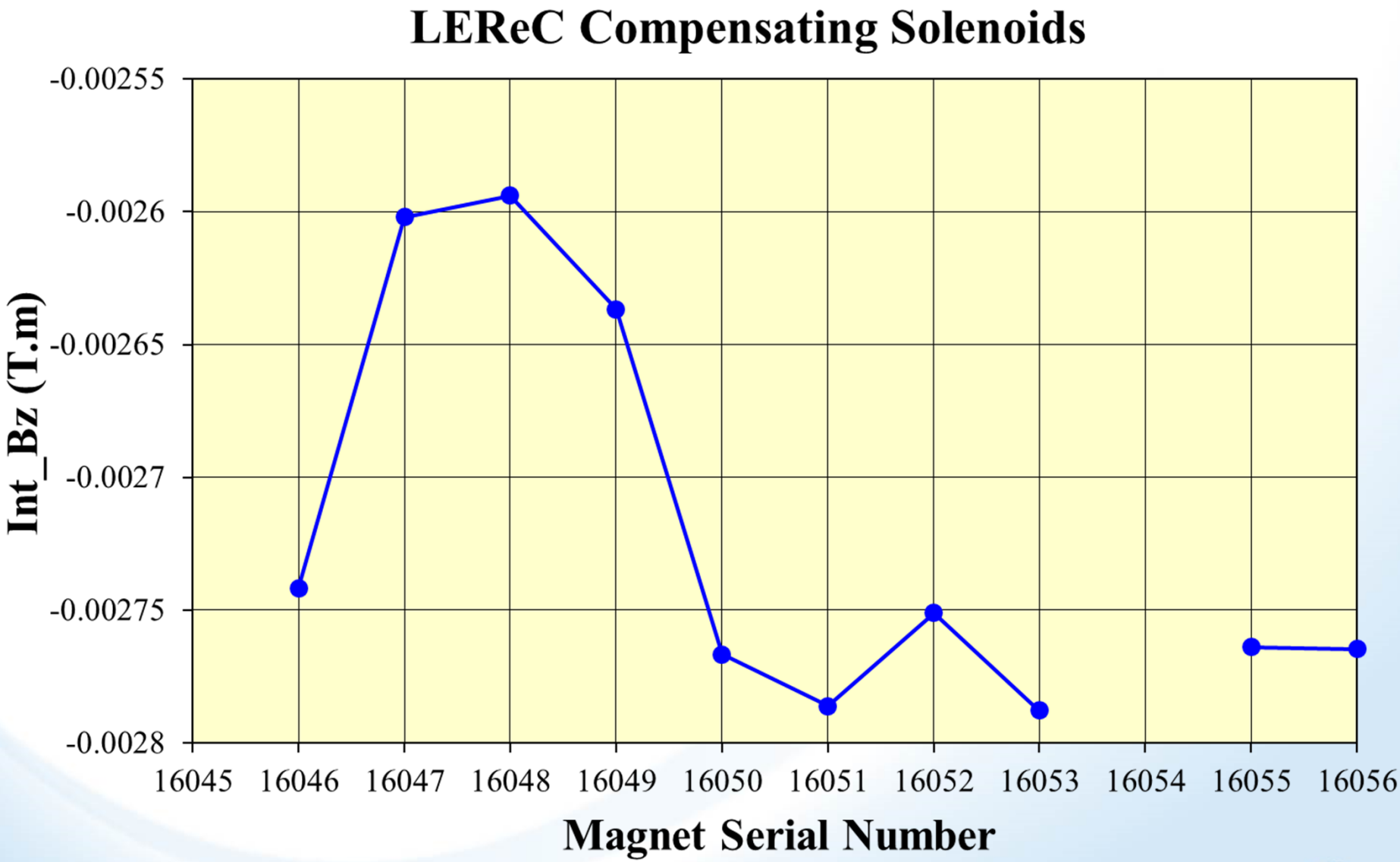
$$\int [B_y(z)]dz = -1.066 \times 10^{-5}\ \mathrm{T \cdot m/A}$$

$$\sim 8.53 \times 10^{-6}\ \mathrm{T \cdot m\ at\ 0.8\ A}$$

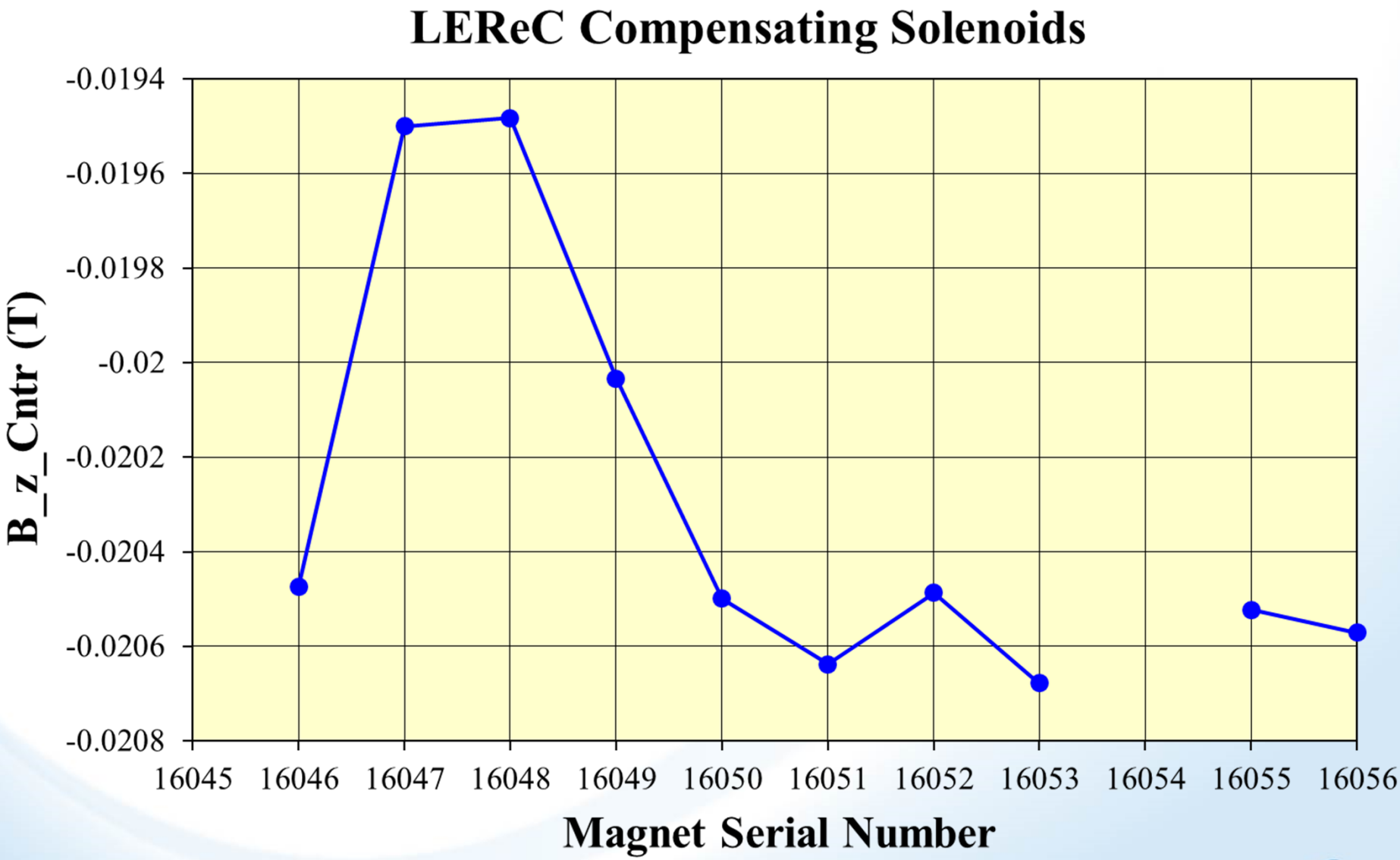
$$\int [B_x(z)]dz = 1.062 \times 10^{-5}\ \mathrm{T \cdot m/A}$$

$$\sim 8.50 \times 10^{-6}\ \mathrm{T \cdot m\ at\ 0.8\ A}$$

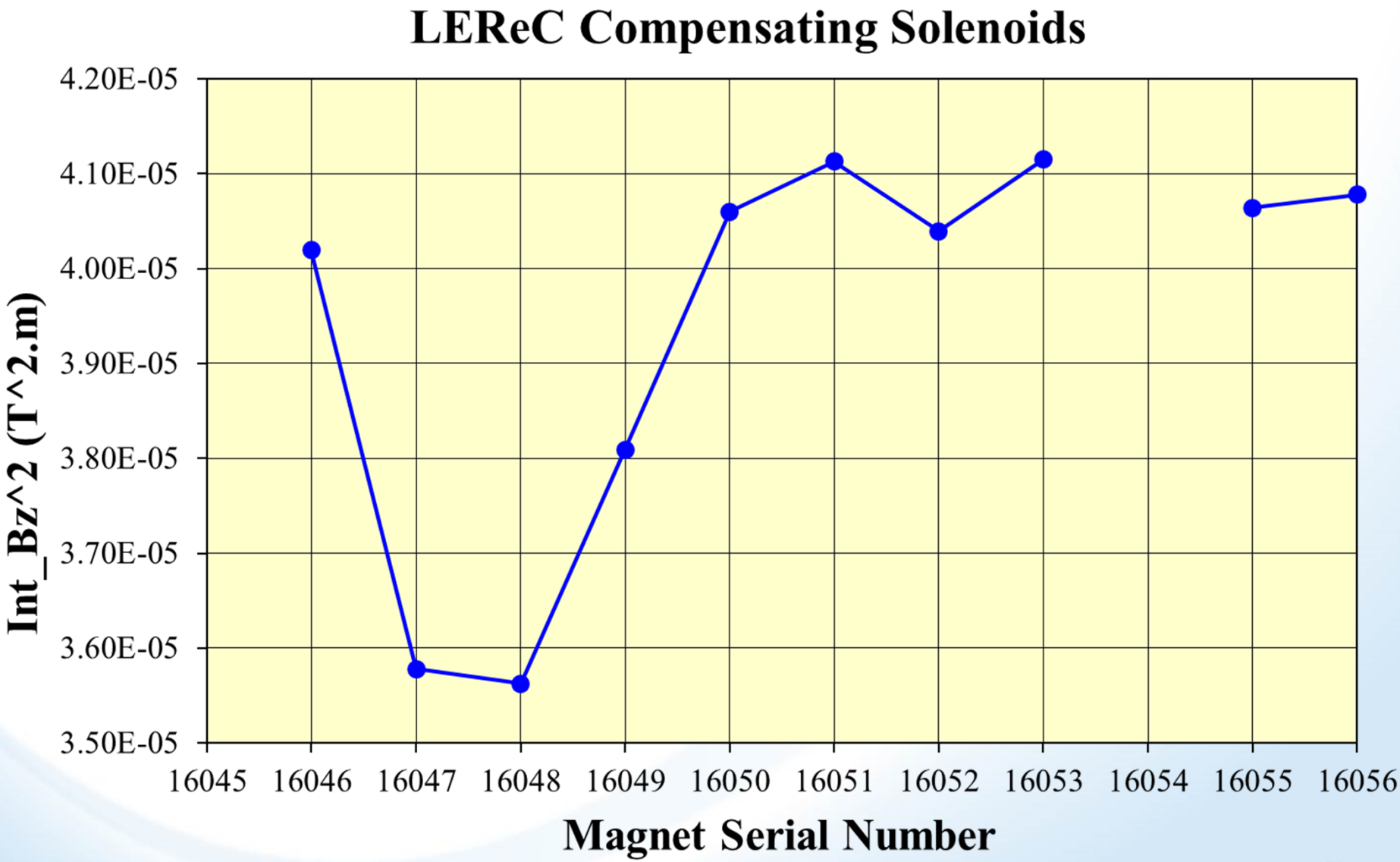
Integral of axial field in all magnets



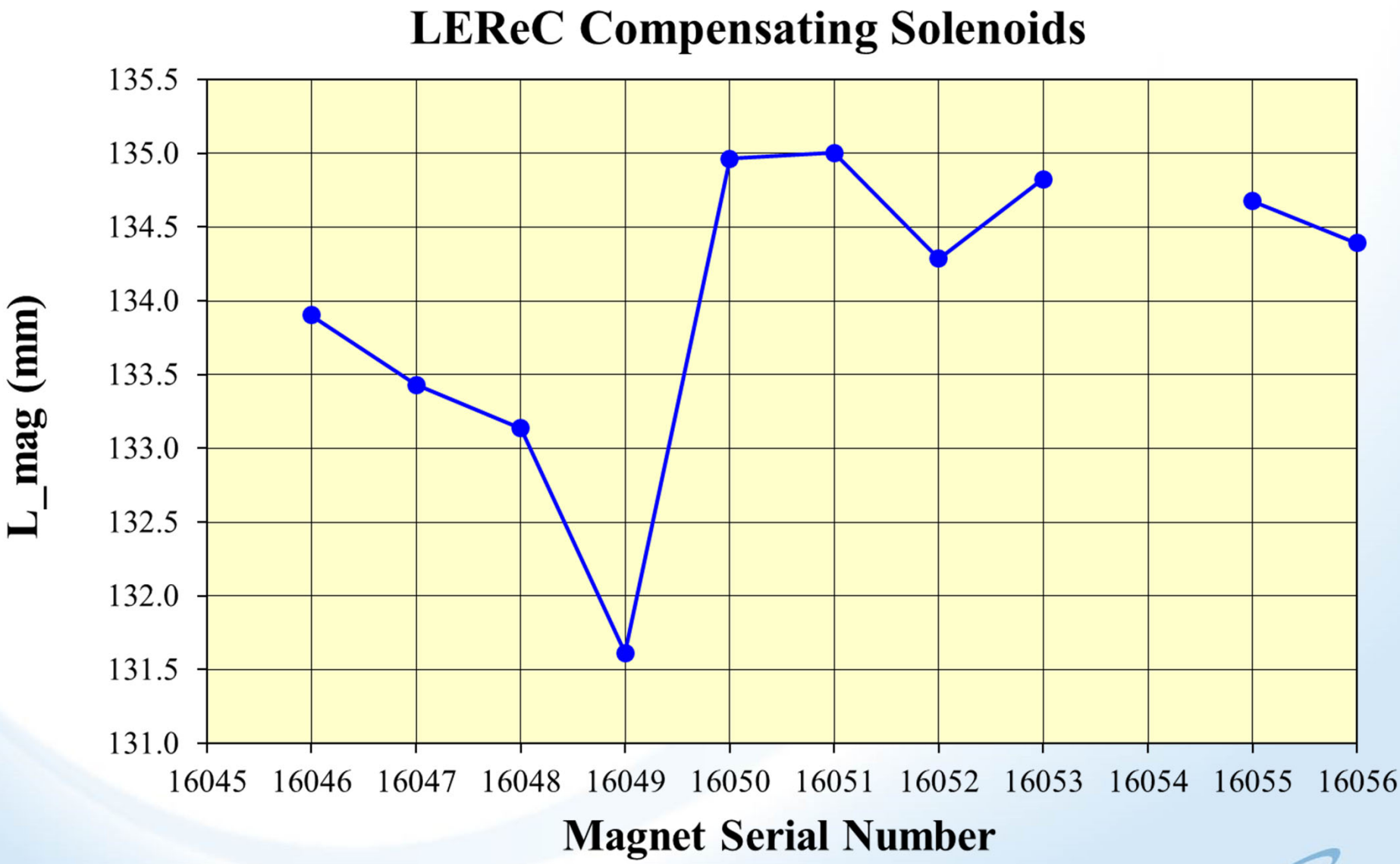
Central field in all magnets



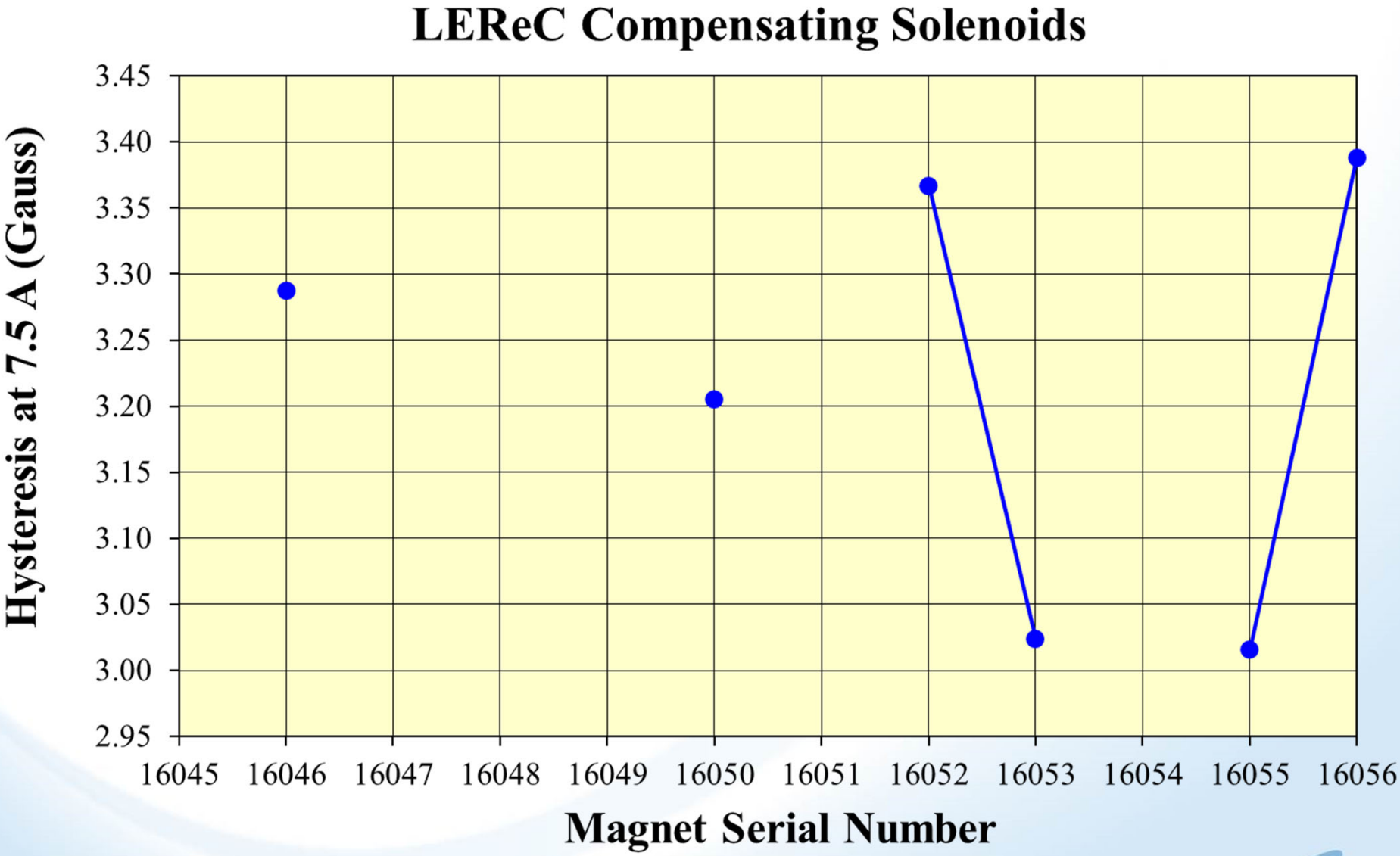
Integral of (B_z*B_z) in all magnets



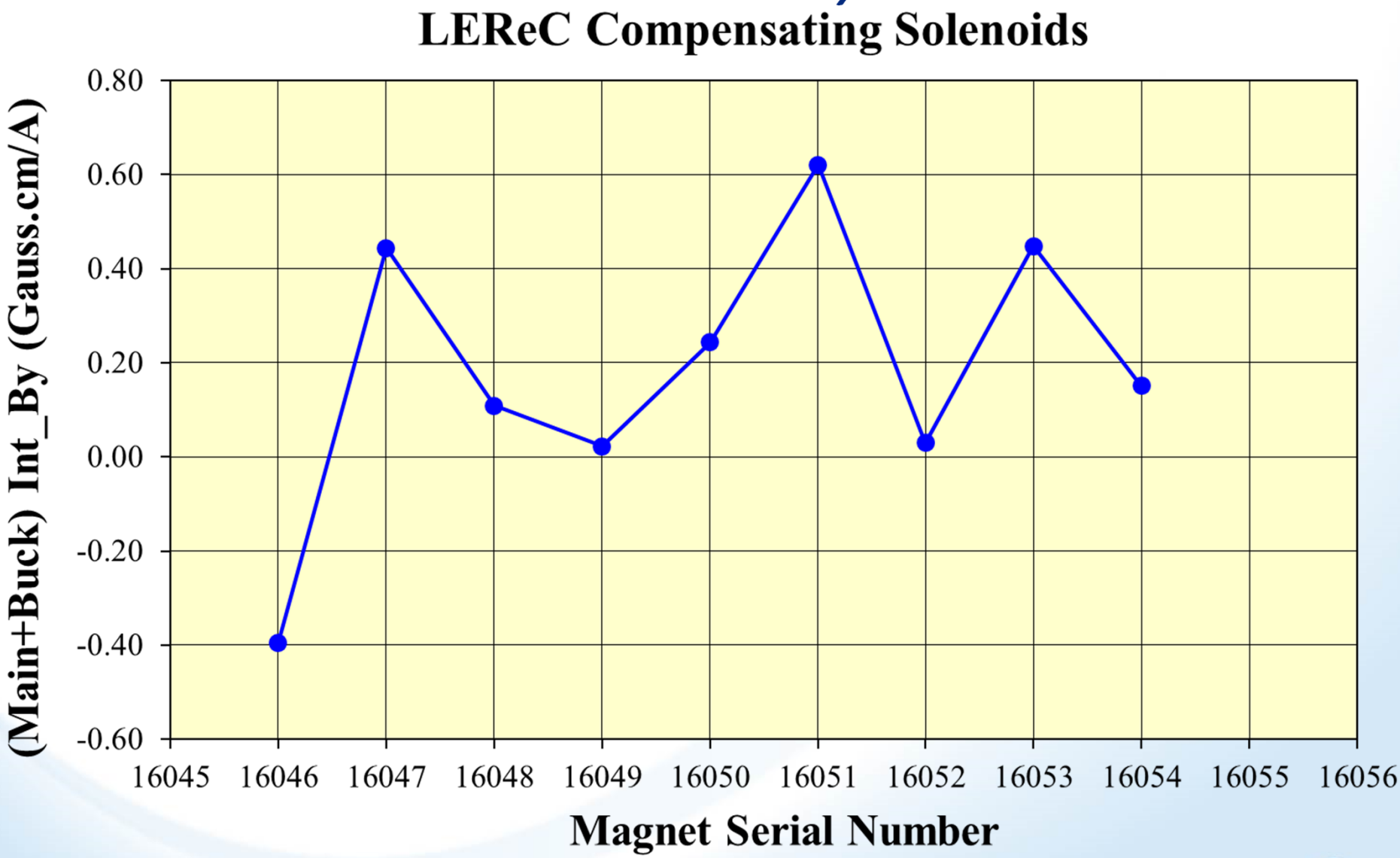
Magnetic length in all magnets



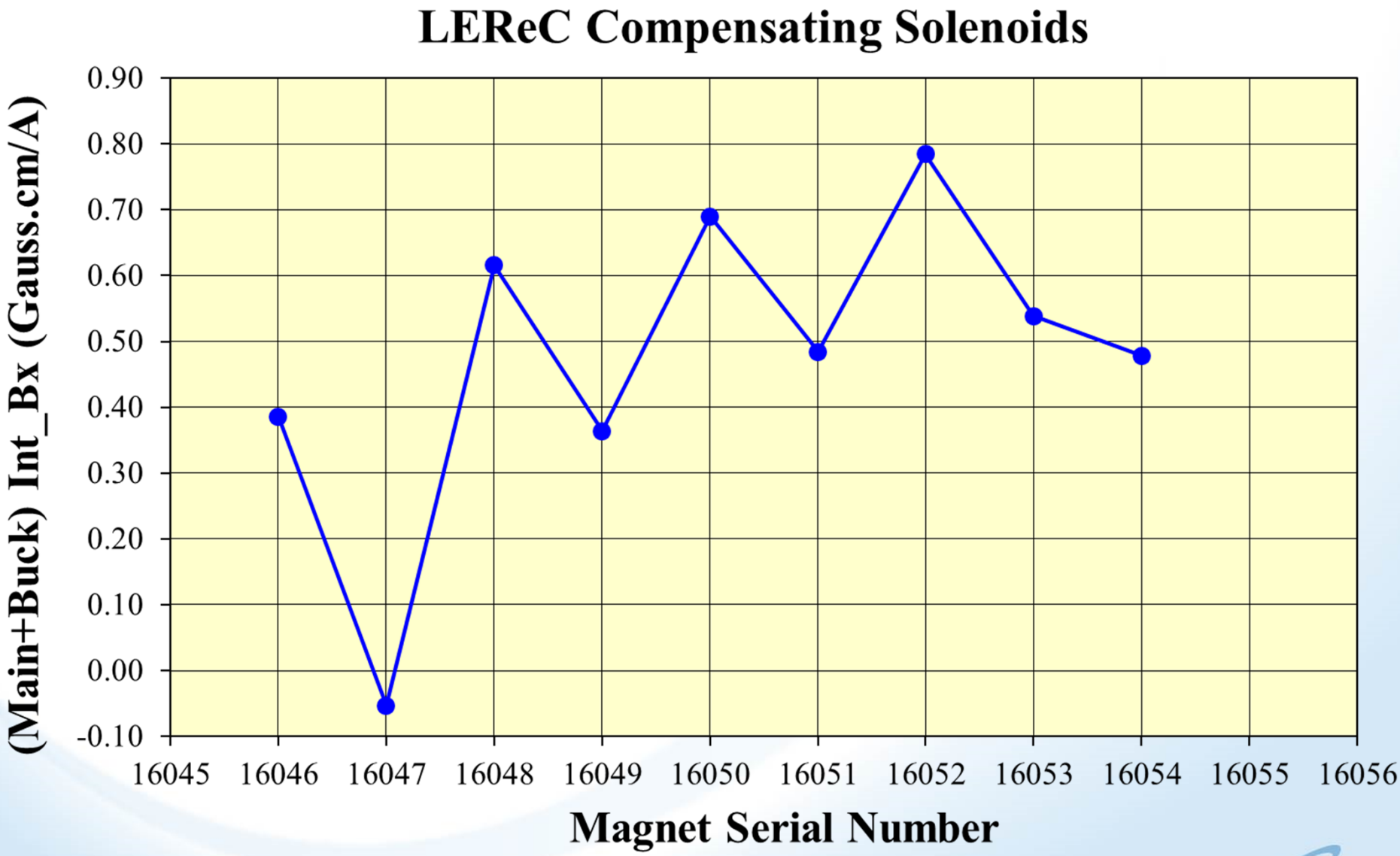
Hysteresis in all magnets



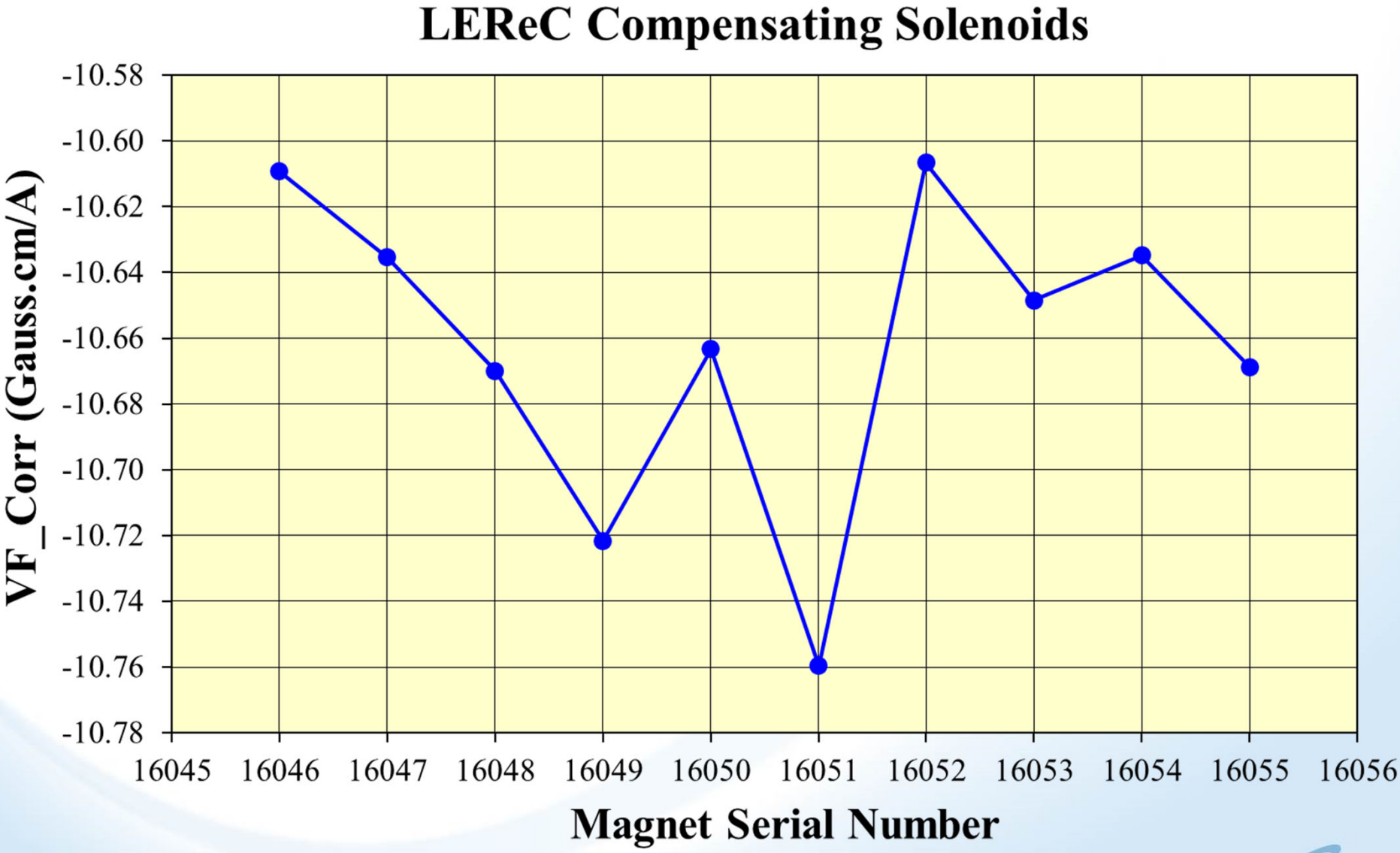
Solenoid transverse field, B_y (rotating coil)



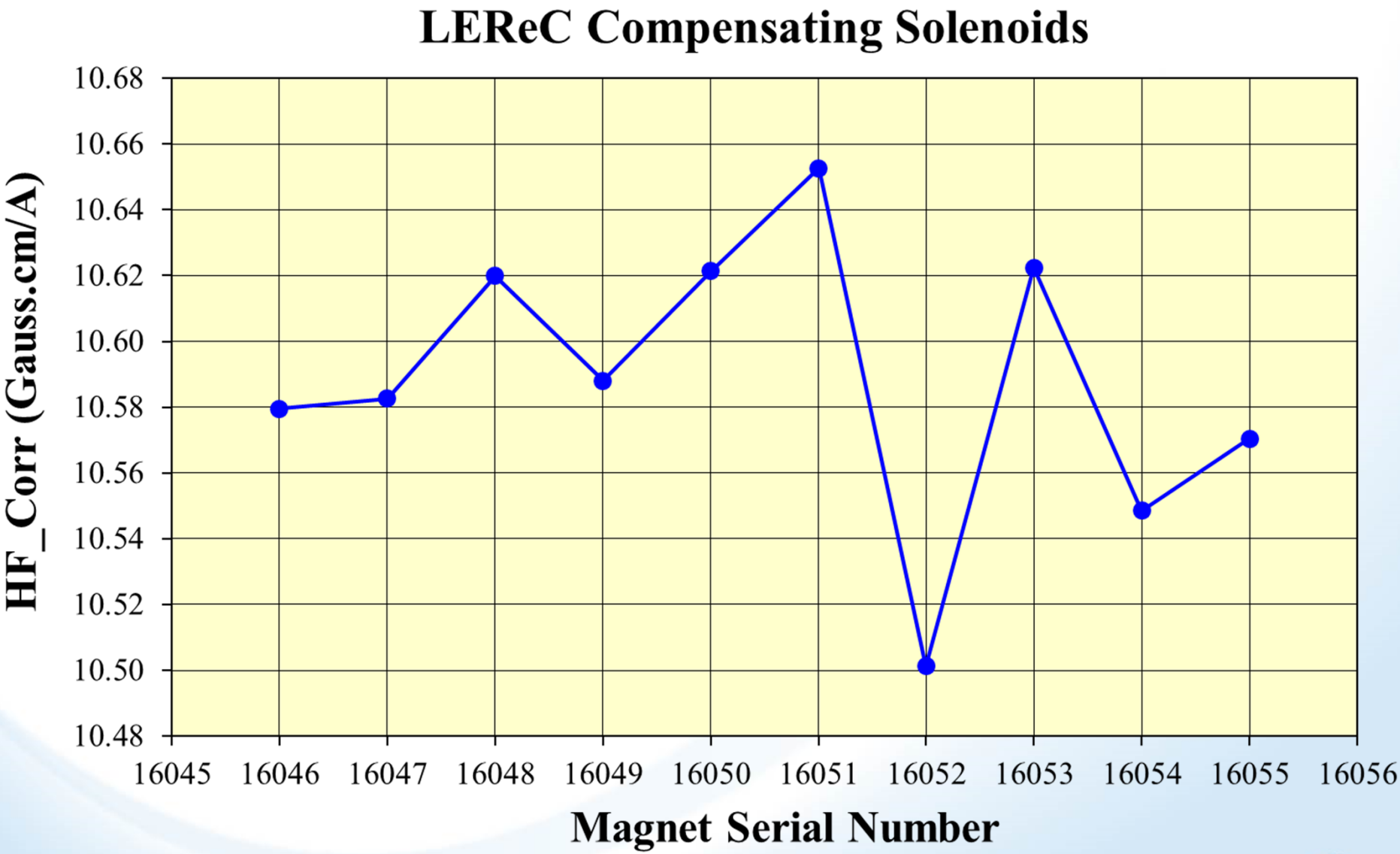
Solenoid transverse field, B_x (rotating coil)



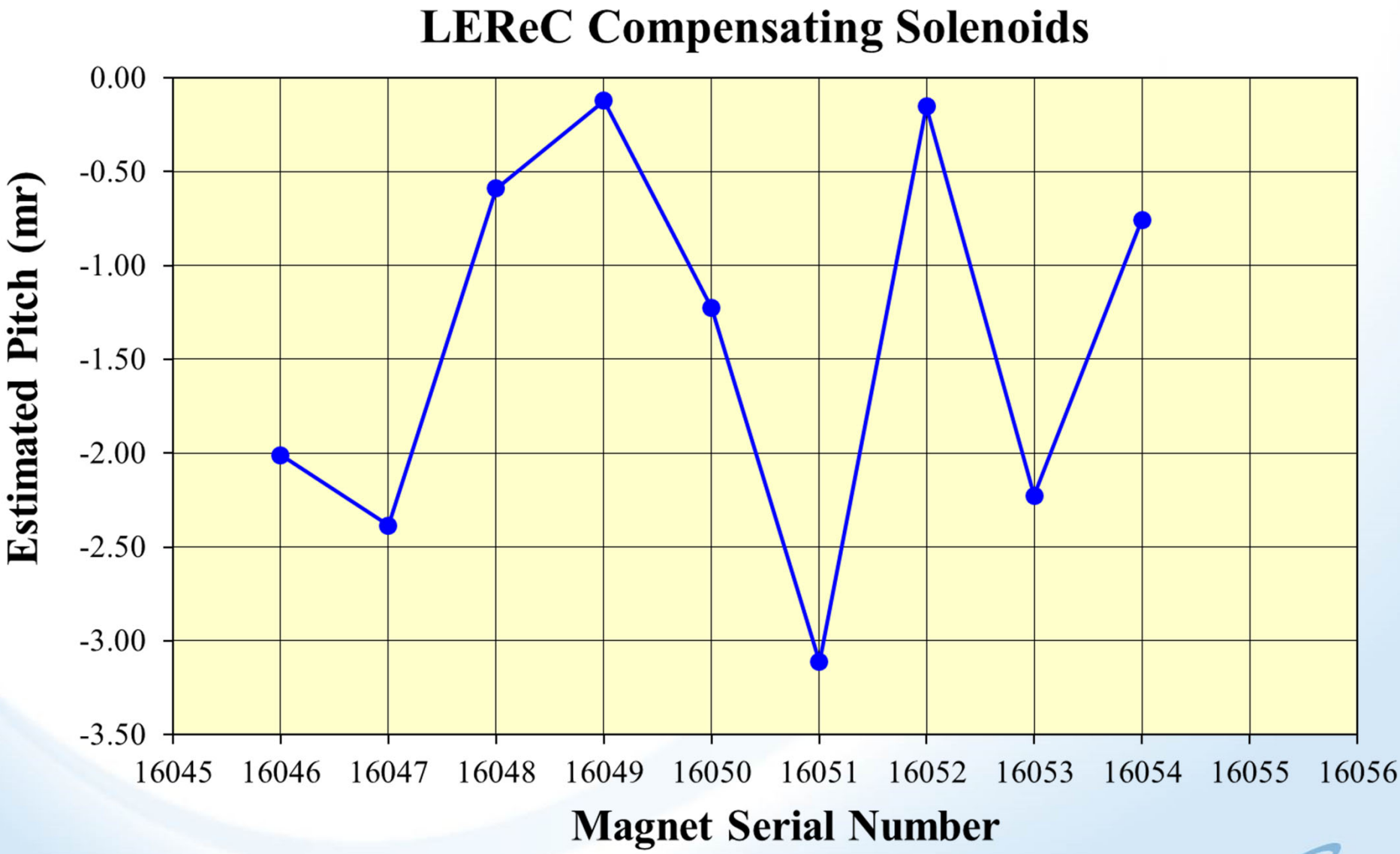
Vertical field corrector strength (rotating coil)



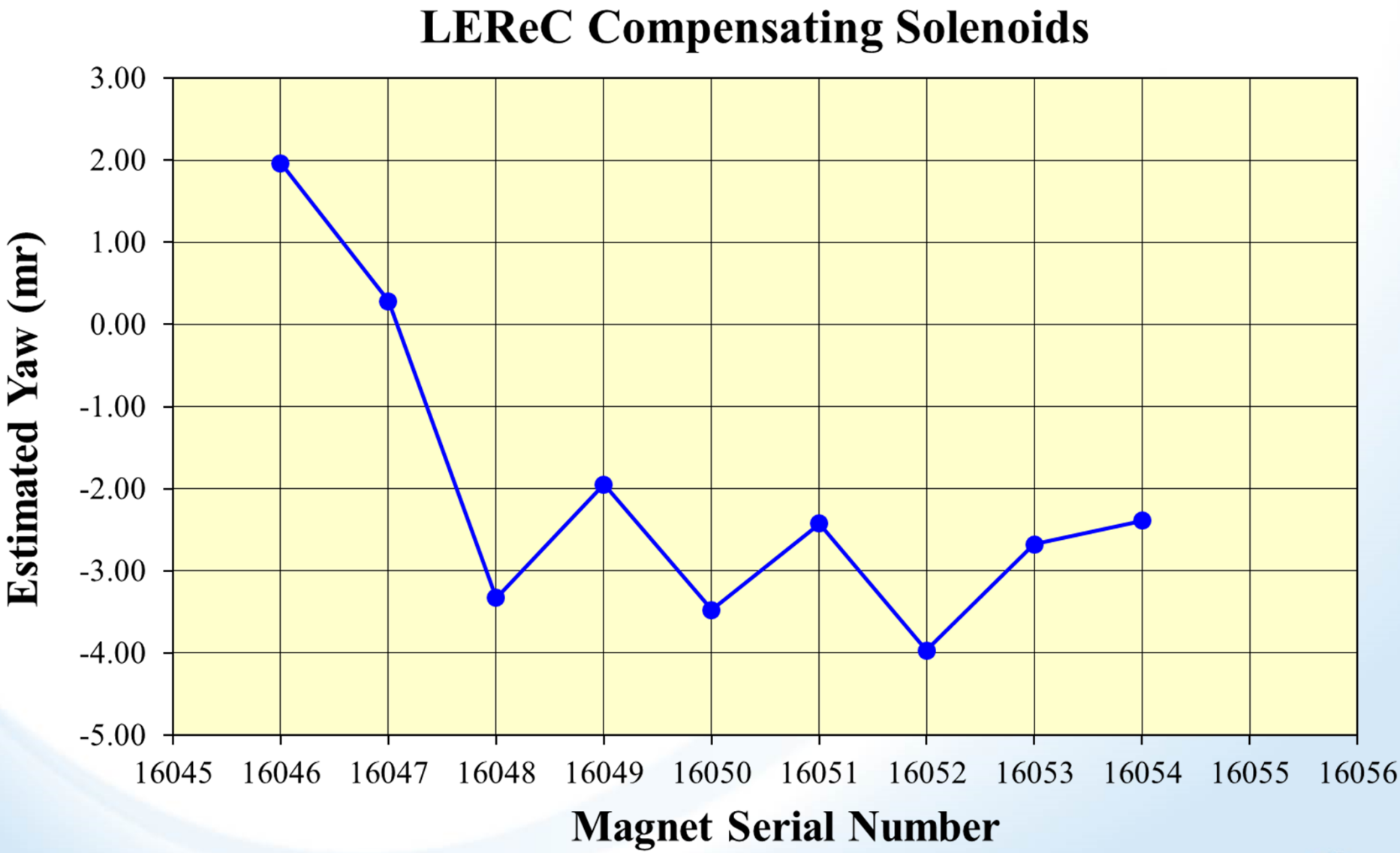
Horizontal field corrector strength (rotating coil)



Estimated Pitch of Magnetic Axis (Int_By/Int_Bz)



Estimated Yaw of Magnetic Axis (Int_Bx/Int_Bz)



Summary of compensating solenoids data

Summary of On-axis Field Measurements in LEReC Compensating Solenoids

Data at Full Field (Main Solenoid = 14.0 A, Bucking Solenoid = 14.8 A)

	Quantity	Mean	Std. Dev.	Min	Max	Ncount
Hall Probe	Int_Bz (T.m)	-2.719E-03	7.694E-05	-2.788E-03	-2.594E-03	10
	Int_Bz^2 (T^2.m)	3.944E-05	2.151E-06	3.562E-05	4.115E-05	10
	B_z at Center (T)	-2.029E-02	4.548E-04	-2.068E-02	-1.948E-02	10
	L_mag (mm)	134.024	1.058	131.614	135.005	10
	Hysteresis at Center, at 7.5 A (Gauss)	3.21	0.16	3.02	3.39	6
Rotating Coil	MainSolenoid Int_By (Gauss.cm/A)	0.747	0.602	-0.230	1.317	6
	MainSolenoid Int_Bx (Gauss.cm/A)	0.715	0.700	-0.237	1.637	6
	BuckSolenoid Int_By (Gauss.cm/A)	-0.685	0.519	-1.282	0.032	6
	BuckSolenoid Int_Bx (Gauss.cm/A)	-0.270	0.657	-1.183	0.360	6
	(Main+Buck) Int_By (Gauss.cm/A)	0.186	0.301	-0.395	0.621	9
	(Main+Buck) Int_Bx (Gauss.cm/A)	0.476	0.241	-0.054	0.785	9
	VF_Corr (Gauss.cm/A)	-10.662	0.048	-10.760	-10.607	10
	HF_Corr (Gauss.cm/A)	10.589	0.043	10.501	10.653	10

Summary of matching solenoids data

LEReC Matching Solenoids (On-axis data)			
Data at Full Field (18.2 A)			
	Quantity	98383	98384
Hall Probe	Int_Bz (T.m)	2.5234E-02	2.5234E-02
	Int_Bz^2 (T^2.m)	2.2460E-03	2.2450E-03
	B_z at Center (T)	0.11552	0.11549
	L_mag (mm)	218.45	218.49
	Hysteresis at Center, at 7.5 A (Gauss)	-2.16	-2.15
Rotating Coil	MainSolenoid Int_By (Gauss.cm/A)	-2.436	0.251
	MainSolenoid Int_Bx (Gauss.cm/A)	-1.468	1.148
	Estimated Pitch Int_By/Int_Bz (mr)	-1.76	0.18
	Estimated Yaw Int_Bx/Int_Bz (mr)	-1.06	0.83

Summary

- Measurements of LEReC solenoids is well underway.
- Data from the new 3-axis Hall probe show sufficient resolution, but numerous issues exist for measuring the minor field components.
- It is desirable to have temperature stabilization for the probe to further improve resolution and stability of calibration.
- All but 2 magnets meet the focussing strength specification at the nominal current.
- Horizontal and vertical field correctors may not have sufficient strength to fully compensate the transverse fields in some solenoids.
- Rotating coil measurements are more accurate, but still suffer from uncertainty in alignment at the level of ~ 1-2 mr.