Rotating Coil Measurement Errors*

Animesh Jain
Superconducting Magnet Division
Brookhaven National Laboratory, Upton, NY 11973, USA

2nd Workshop on Beam Dynamics Meets Magnets (BeMa2014)

December 1-4, 2014

Park Hotel, Bad Zurzach, Switzerland

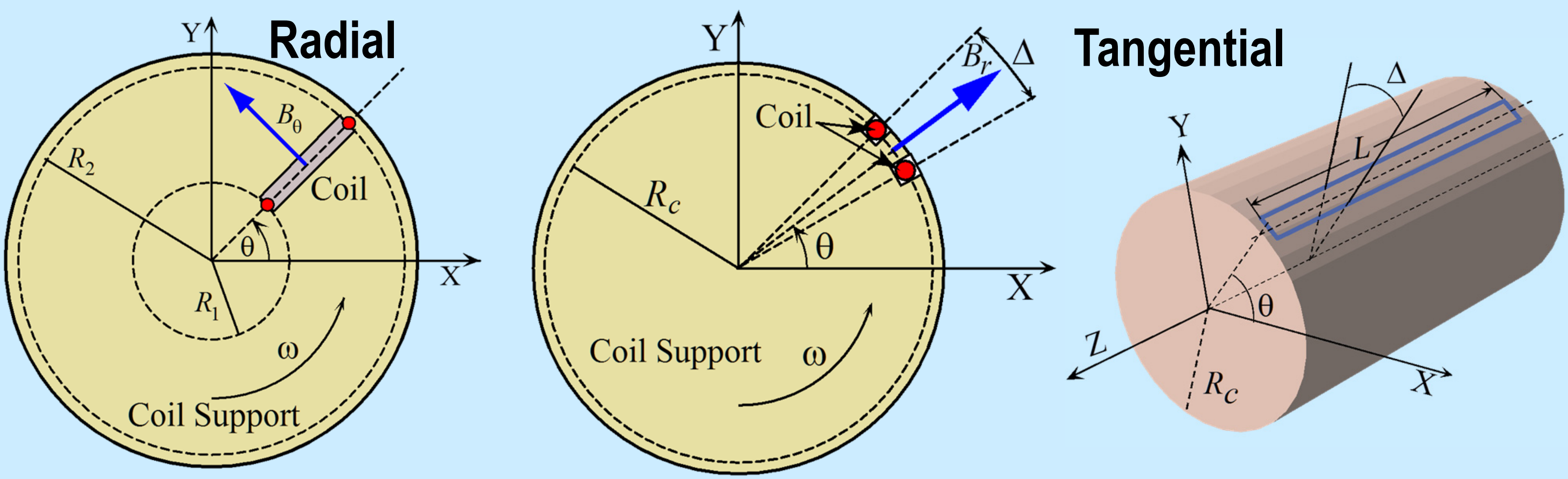
* Work supported by the U.S. Department of Energy under contract DE-AC02-98CH10886

Introduction

- Rotating coils are unmatched in their ability to accurately measure higher order field harmonics in accelerator magnets.
- Rotating coils also provide a means of measuring the strength of the main harmonic term (**transfer function** and **roll angle**), simultaneously with the measurement of **higher order terms**.
- With "good" systems, the measurements can be repeatable over long time periods (~0.01% for the main harmonic, ~10 ppm for higher order terms) $\Longrightarrow$ Good for monitoring production.
- Errors can arise in these measurements due to imperfections in fabrication, calibration and rotation of the measuring coil.
- The possible sources of errors will be reviewed in this talk.

What is a Rotating Coil?

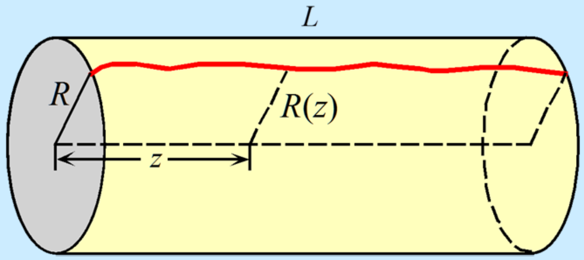
- It is essentially a loop of wire of certain geometry, rigidly held in place by a support bobbin, that is rotated in the aperture of the magnet being measured. (Can the bobbin be omitted?)
- The flux intercepted by the loop is measured as a function of angular position, which is then converted into field harmonics.
- Commonly used geometries are “Radial” and “Tangential” coils.



Sources of Measurement Errors

- Small deviations of as-built loop geometry from the design. This affects the sensitivity to various harmonics, and thus the conversion from flux to harmonics.
  - Can be taken care of by a detailed calibration of the as-built coil.
  - All coils must be treated as neither pure "radial" nor "tangential".
- Data acquisition system errors (integrators, voltmeters, angle encoders, tilt sensors, current transducers, …)
  - Use good quality components, calibrate frequently.
- Rotational imperfections (transverse and torsional vibrations) of the rotating coil $\Longrightarrow$ Most important for higher order harmonics.
  - **Need good "bucking" for immunity to such imperfections.**

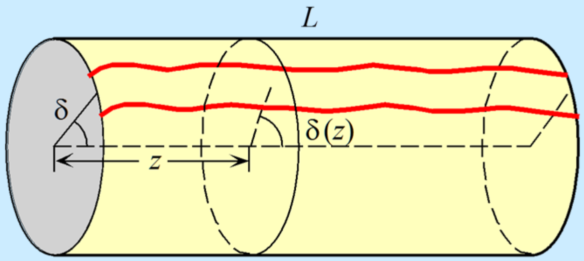
Typical Construction & Placement Errors



Random variation in coil radius:

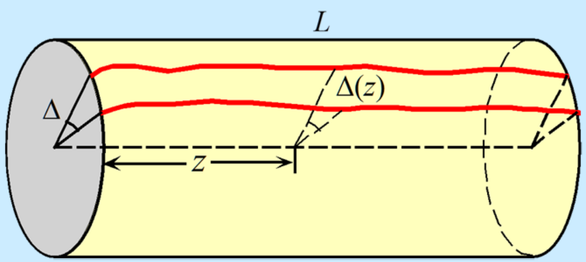
$$K_n \approx K_n^{ideal}\left[1+\frac{n(n-1)}{2}\left(\frac{\sigma_R}{R_c}\right)^2\right]$$

K_n = Sensitivity to $2n$-pole term (n = 1 is Dipole)



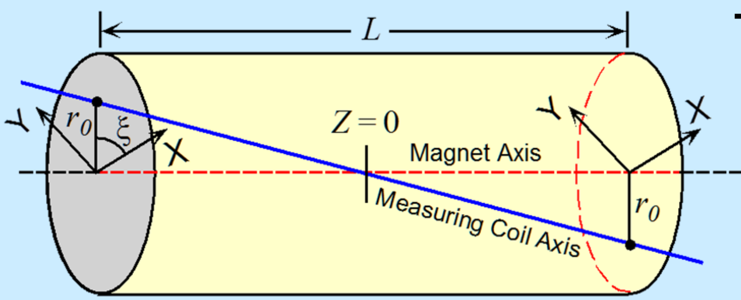
Random variation in coil angular position:

$$K_n \approx K_n^{ideal}\left[1-\frac{n^2}{2}\sigma_\delta^2\right]$$



Random variation in (tangential) coil opening angle:

$$K_n \approx K_n^{ideal}\left[1-\frac{n^2}{8}\sigma_\Delta^2\right]$$



Tilt in measuring coil axis (in axially uniform field):

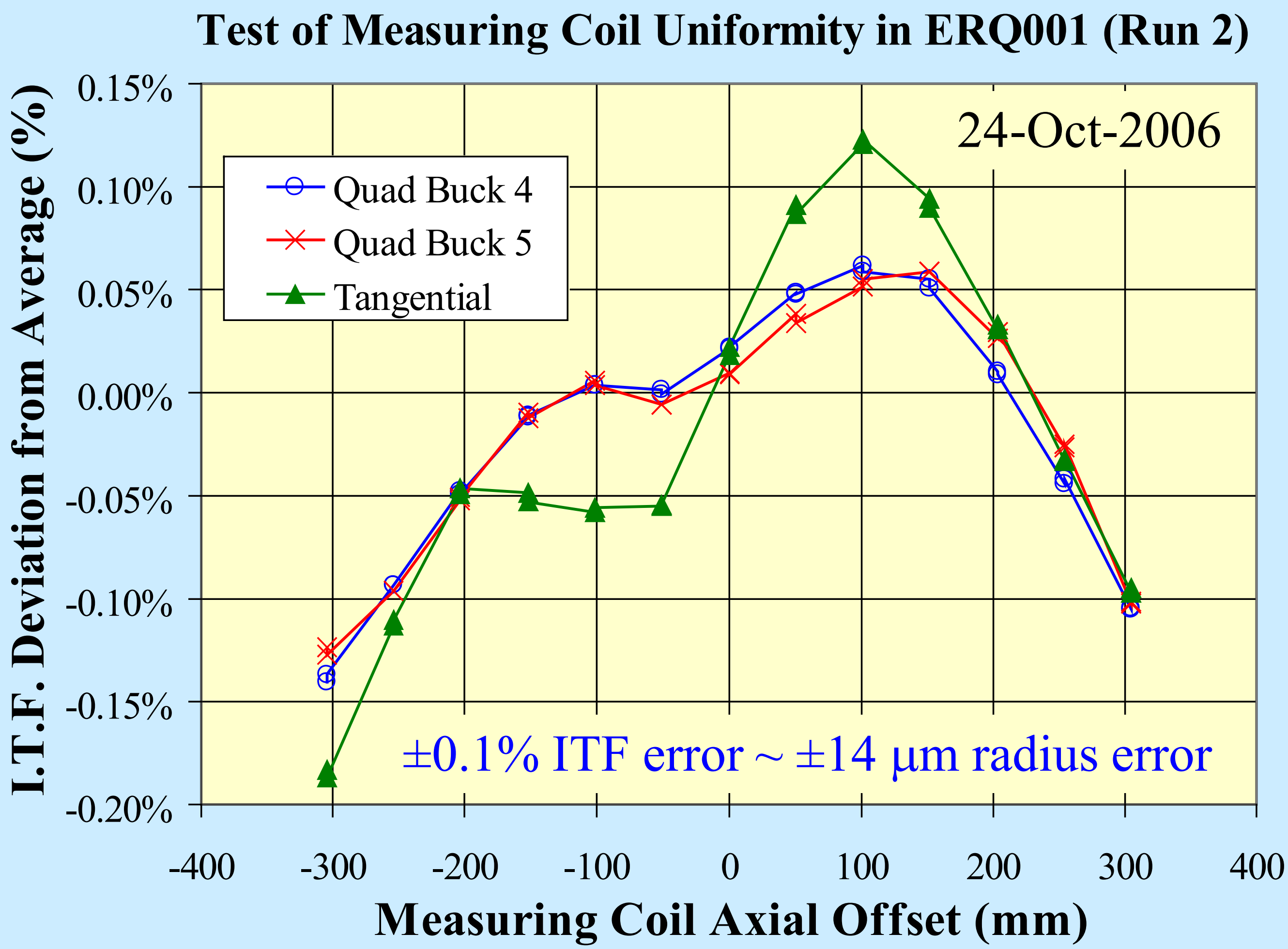
$$B_n' + iA_n' = \sum_{k=0}^{\infty}\frac{B_{n+2k}+iA_{n+2k}}{(2k+1)}\frac{(2k+n-1)!}{(n-1)!(2k)!}\left(\frac{r_0\exp(i\xi)}{R_{ref}}\right)^{2k}$$

(B_n, A_n) = $2n$-pole Normal & Skew

Coil Construction Errors

- Most coil construction errors (within reasonable limits) affect the measurement of harmonics at the level of a few percent or less.
- For magnets with good field quality, this is generally not a serious limitation for the higher harmonics (5% of 1 “unit” = 0.05 unit).
- The main field, however, may require much better accuracy than a few percent (better than 0.1%, say).
  - An independent calibration of the main field is required.
  - **Calibration is dependent on magnet size and axial placement due to axial non-uniformity in coil construction.**
  - Both field strength and roll angle calibration must be carried out in a magnet of similar characteristics (length and axial profile).

Axial Variations in Coil Construction



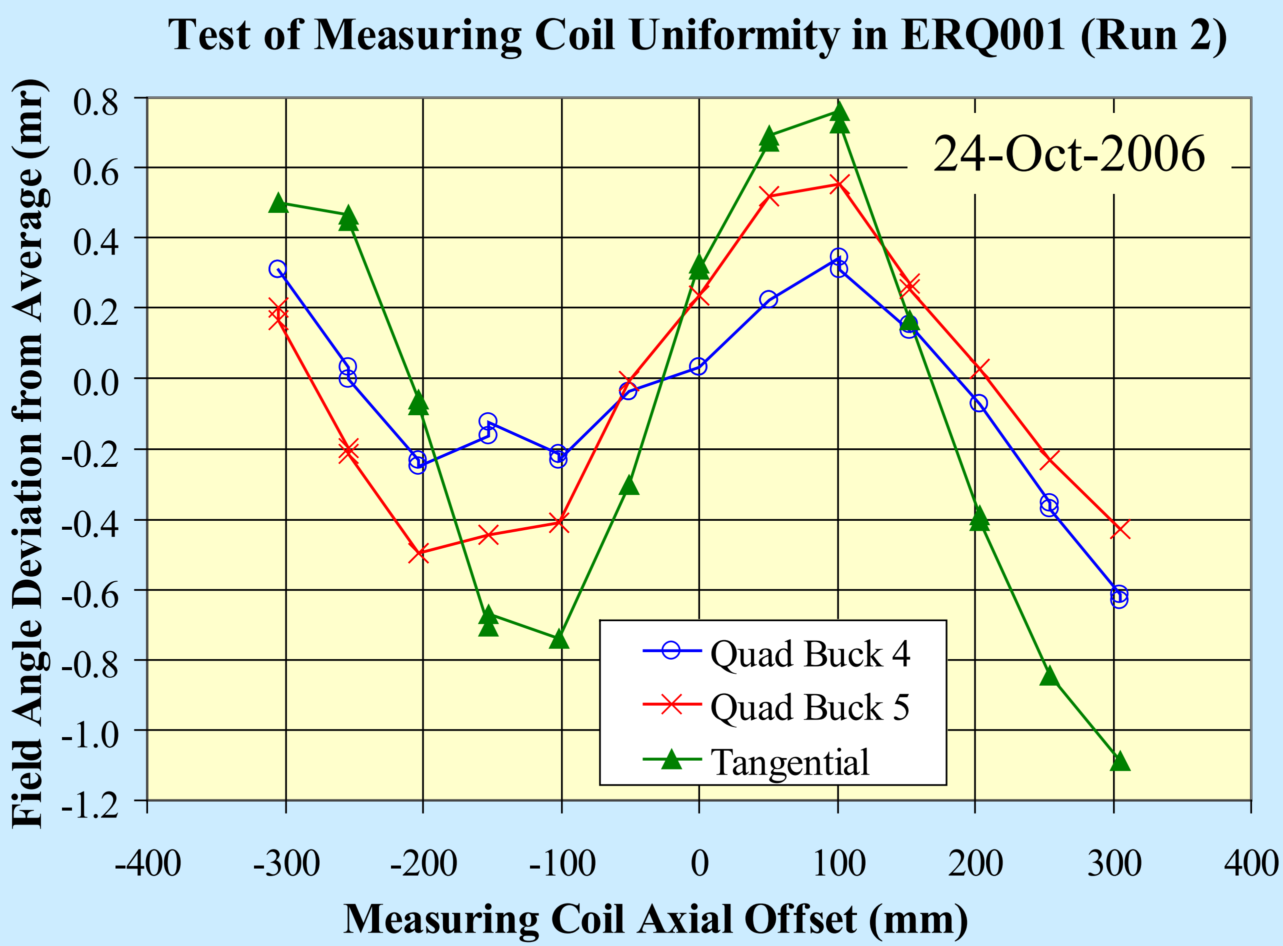
Magnetic length = 0.16 m

Measuring coil length = 1.0 m

Radius = 27.4 mm

(I.T.F = Integrated Transfer Function)

Axial Variations in Coil Construction



Magnetic length = 0.16 m

Measuring coil length = 1.0 m

Radius = 27.4 mm

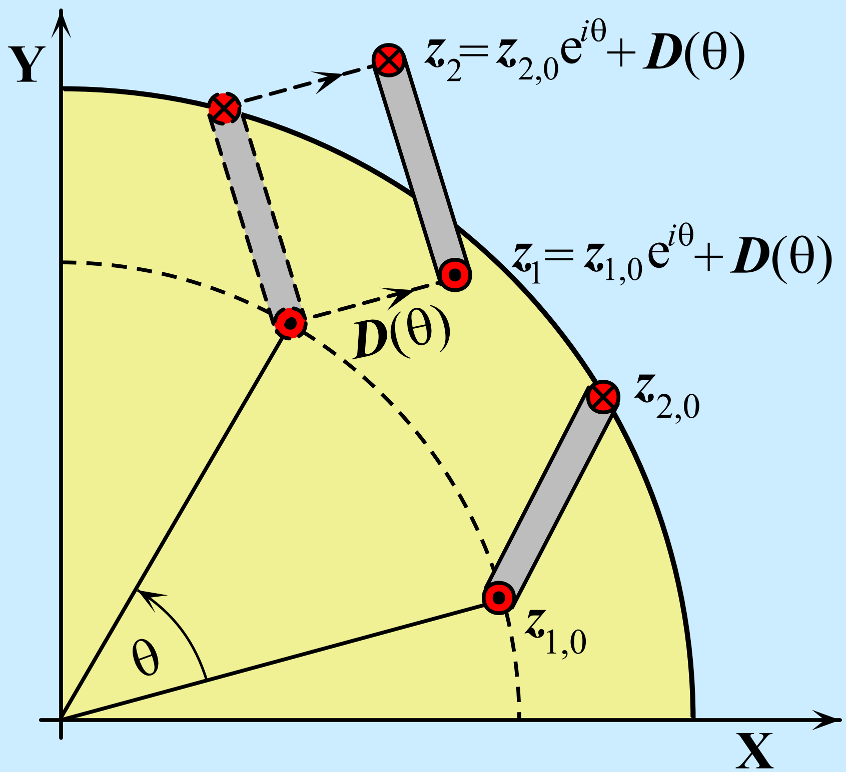
10 μm azimuthal error ~ 0.4 mr angle error.

It is clear that specific section must be calibrated to achieve < 0.1 mr error

Coil Transverse Placement Errors

- The axis of rotating coil may have an offset and a tilt relative to the magnetic axis of the magnet being measured.
- Any transverse offset leads to feed down terms, which can in fact be used to derive the offset. The measured data can be easily corrected for this offset. (precise alignment is not necessary)
- A tilt of the axis, on the other hand, causes only second order feed down, and is generally negligible, except in the case of
  - Measuring sextupoles, or higher order multipole magnets, where the main field can produce strong 2nd order feed down terms.
  - Magnets with asymmetric axial profiles (e.g. lead end differing from non-lead end), where 1st order feed down does not cancel.

Transverse Vibrations

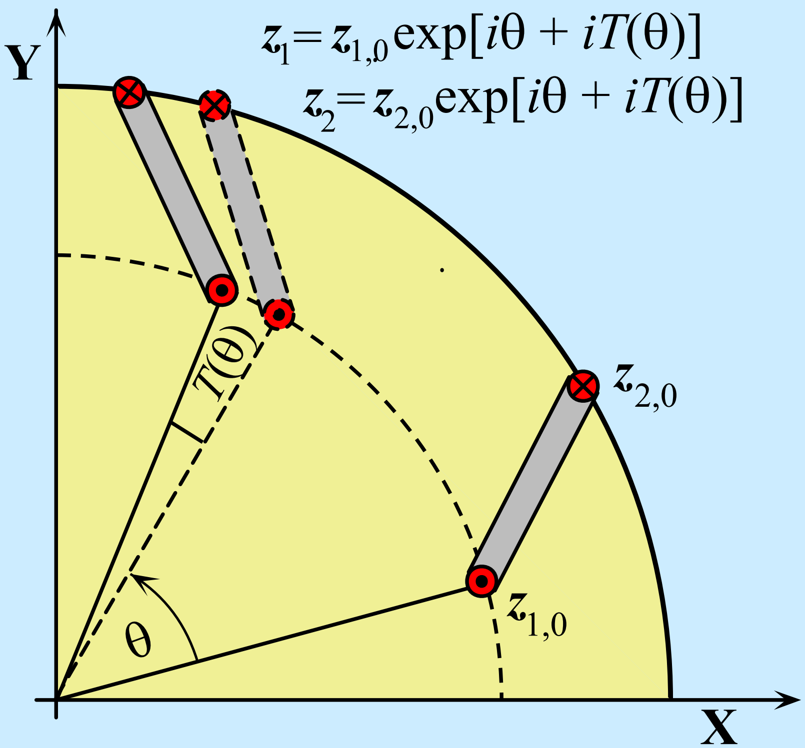


The coil is displaced from the ideal position by a vector $\boldsymbol{D}(\theta)$ when the coil rotates through θ.

In a pure 2*n*-pole field, the amount of spurious harmonics in the coil signal is roughly proportional to the sensitivity of the coil to the (*n* –1)th harmonic.

The effect of transverse vibrations in a 2*n*-pole magnet can be minimized by using a coil system whose sensitivity to the (*n*-1)th harmonic is zero.

Torsional Errors



The coil angular position is $\theta + T(\theta)$ when it should have been θ.

In a pure 2*n*-pole field, the amount of spurious harmonics in the coil signal is roughly proportional to the sensitivity of the coil to the *n*-th harmonic.

The effect of torsional errors in measuring a 2*n*-pole magnet can be minimized by using a coil system whose sensitivity to the *n*-th harmonic is zero.

Implementation of Bucking

- For precise measurements of harmonics, all rotating coils must implement bucking. This is often done by adding one or more loops of wire to the coil, in addition to a "main" coil.
- The additional loops are so chosen that a suitable combination of them (generally a simple sum) has the same sensitivity as the "main" coil for the harmonics to be bucked.
- Analog bucking: all coils are suitably connected in series such that harmonics to be bucked are cancelled out. This requires precise fabrication of various loops in the rotating coil.
  - **The "bucking ratio" for feed down term is often overlooked!**
- Digital bucking: all signals are digitized first, then summed
  - Allows weight factors to be adjusted; requires good DAQ system.

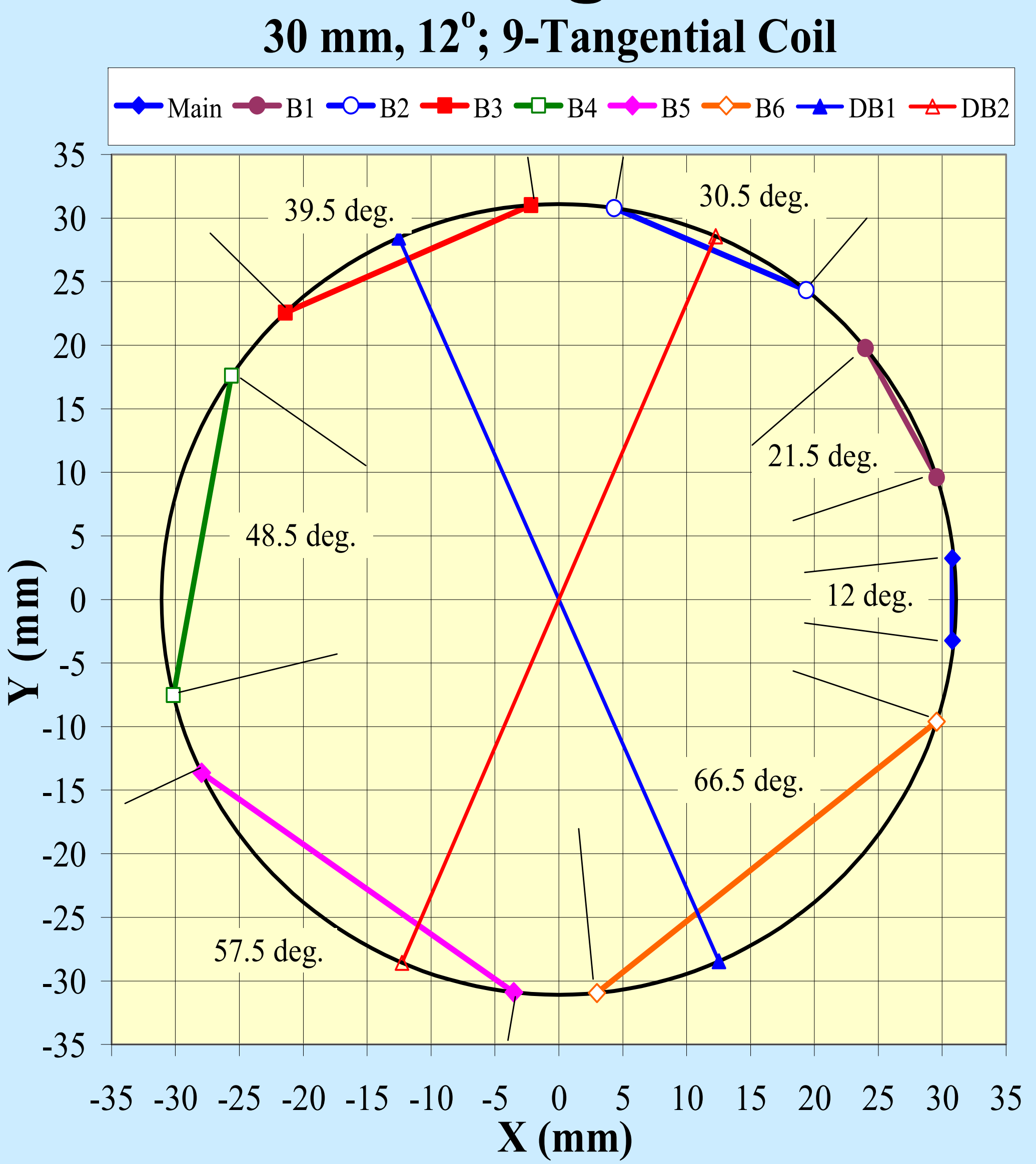
Validating Harmonics Measurements

- Errors in higher harmonics caused *directly* by coil fabrication tolerances are generally small, and can be neglected.
- But even small construction errors may significantly affect the quality of bucking when analog bucking is used. This is often the most important cause of unreliable field harmonics data.
- It is important to validate a measurement system for accuracy, particularly if magnets are to be shimmed to meet stringent field quality requirements. (Errors may lead to incorrect shimming!)
- It is generally not easy to verify accuracy because there is nothing against which the measurements may be compared.
  - Need for "well characterized" reference magnets.
  - Use consistency under coordinate transformations for cross-check.

In the Absence of Reference Magnets …

- It is very difficult to prove beyond doubt that a given set of measurements are accurate enough. However, certain tests may be performed to look for signs of problems.
- Measurements could be made with the magnet installed in both the normal orientation, as well as flipped end-for-end. Systematic errors in harmonics that should change sign with respect to the main field (e.g. b3, a4, b5, .. in a quadrupole, or b4, a5, b6, .. in a sextupole) can be detected by comparing the two sets of measurements. (n = 1 is Dipole)
- If available, measurements could be made using two independent systems, preferably with windings of different designs.
- *Best approach is to build redundancy in the measuring coil such that several independent measurements are made simultaneously. (Example: BNL 9-winding coil design using digital bucking)*

BNL "9-Tangential" Coil Design (IMMW16)



- 12 deg., 36 Turns "Main" coil.
- 16 turns in each of the six bucking windings.
- 18 grooves needed.
- Minimum groove separation is 12 deg. (quite comfortable).
- Coil parameters are manually optimized to ensure applicability to all magnet types. (12 free parameters)
- Very simple end design (No overlapping turns, except DB).
- Only 7 windings are essential.
- Dipole windings were added to help with calibration, but are also useful in providing more flexibility in measurements.

BNL 9-winding Coil Design

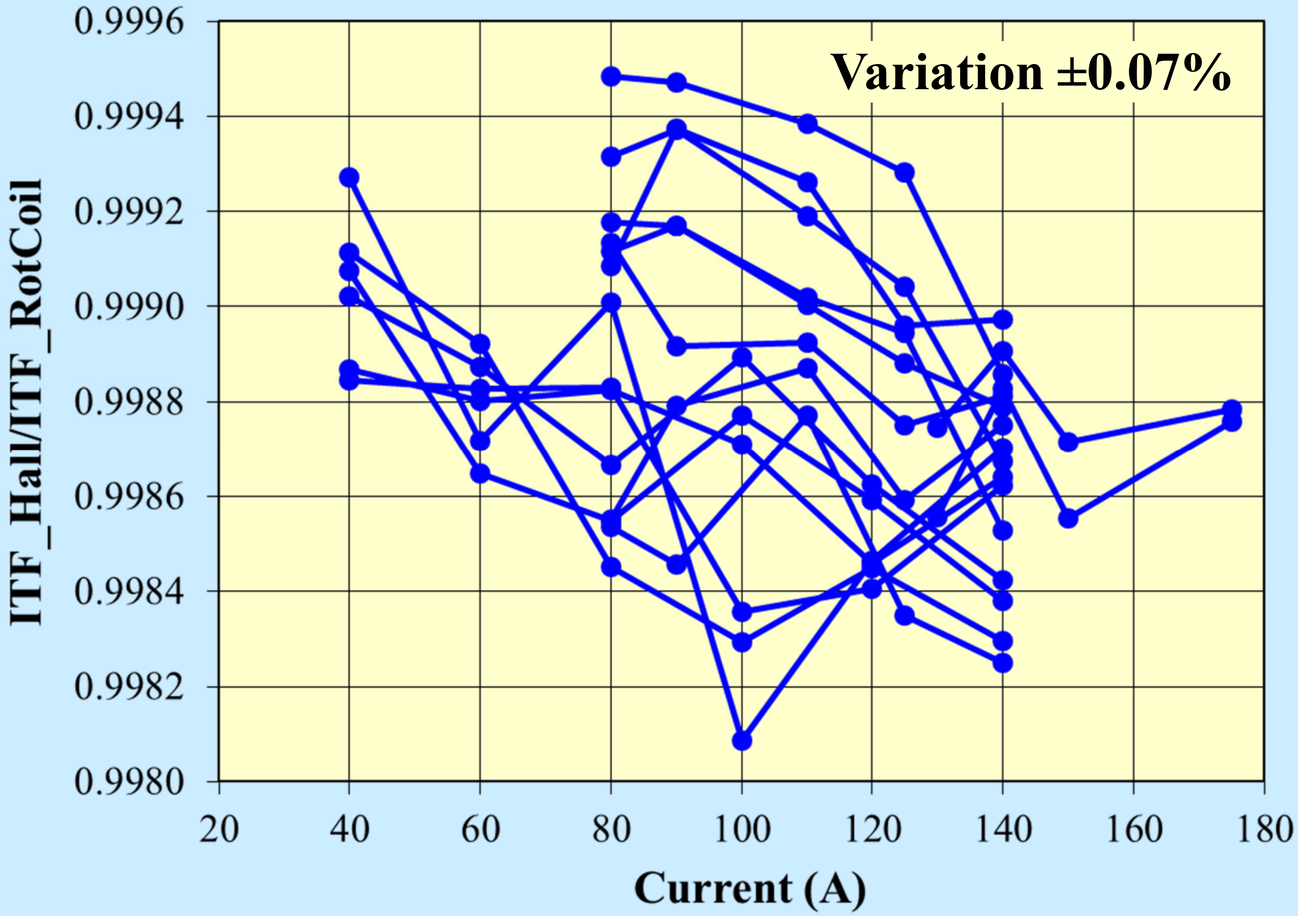
- 7 Tangential coils of different opening angles
- 2 "Dipole" windings (180 deg. Opening angle Tangential coils)
- Any combination of 5 windings can buck out any two arbitrarily chosen harmonics – same coil can be used for ALL magnet types.
- Any combination of 7 windings can buck out any three harmonics (e.g. dipole, quad, sextupole) – suitable for measuring multiple magnets together, e.g. for interference effects.
- There are up to 126 ways to pick 5 windings out of 9 available. *One can pick the most favorable combinations for each harmonic.*
- Equivalent to measuring the magnet with many different coil designs *simultaneously*. This allows an estimation of measurement accuracy.

For details, please see: A. Jain, *A New Versatile Rotating Coil Design Using Multiple Tangential Windings and Digital Bucking*, IMMW-16, Oct. 26-29, 2009

Measurement of Main Field Component

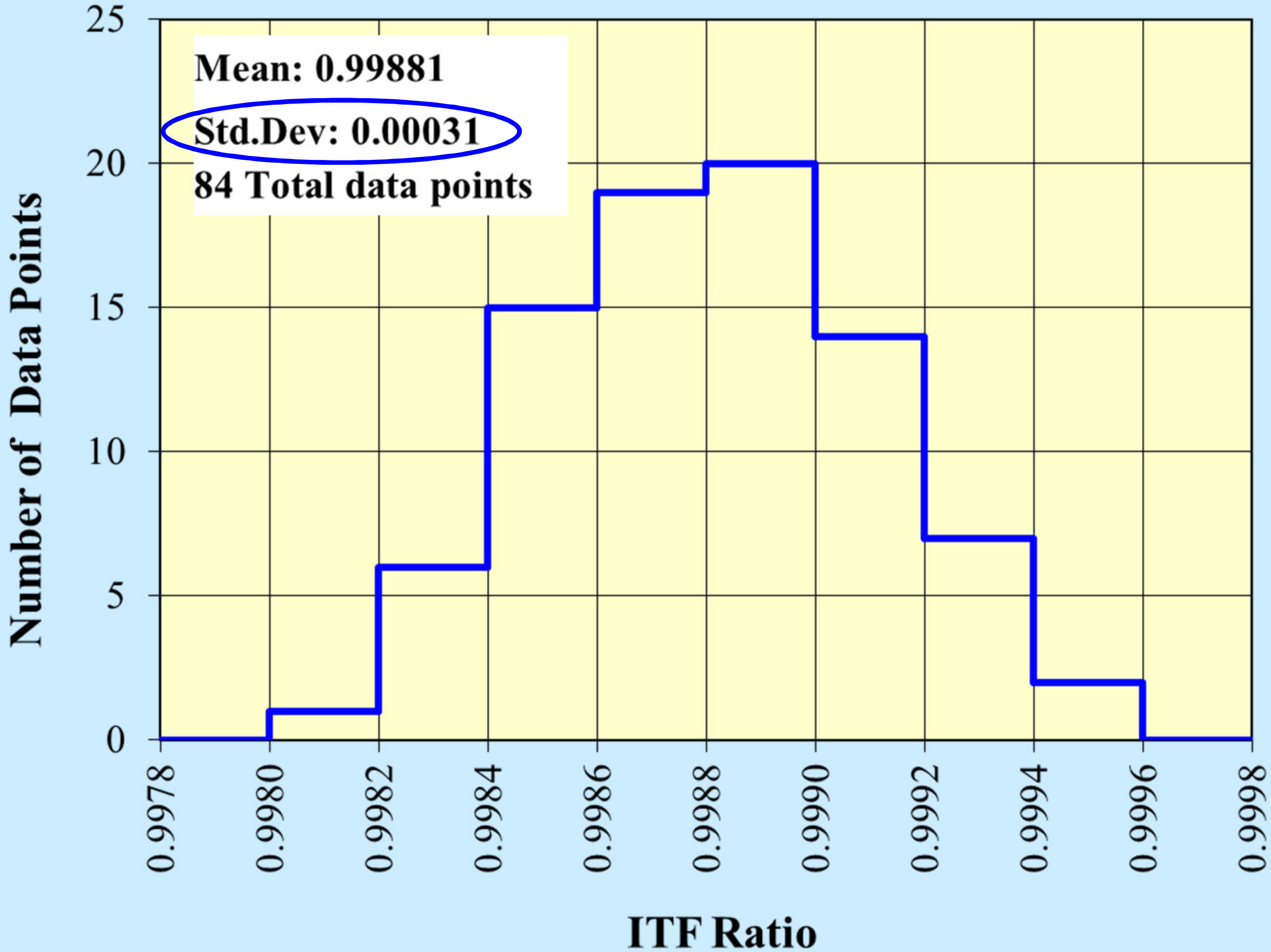
- The strength and roll angle of the main field is the quantity of most interest that needs to be measured as accurately as possible (Strength better than ±0.1%, angle better than ±0.1 mr).
- Strength calibration needs to be done against absolute measurements using other techniques, such as Hall probes, stretched wires, or NMR.
- Such a calibration must be carried out in magnets of the same type, length and field profile. (To account for axial non-uniformity of coil construction.)
- It should be possible to calibrate the absolute strength at the level of ~0.05% in magnets with not too small an aperture.
- If the rotating coil installation needs it to be removed from the drive, then special coil geometries should be used (e.g. J. DiMarco, IMMW15).
- Roll angle calibration needs to be performed almost daily to ensure measurement accuracies of better than ±0.1 mr (calibration drifts easily).

Calibration of Quadrupole Strength



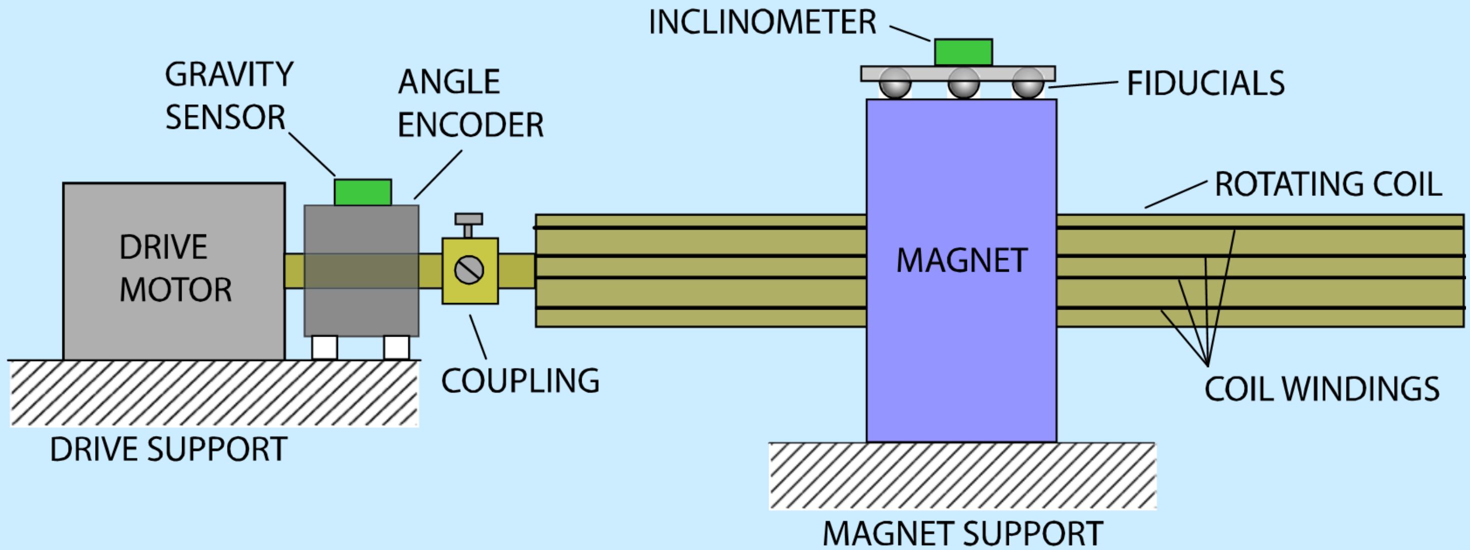
- 16 NSLS-II quadrupoles of 6 different types measured with a Hall probe at several currents.
- Hall probe was calibrated against NMR in a dipole magnet.

Calibration of Quadrupole Strength



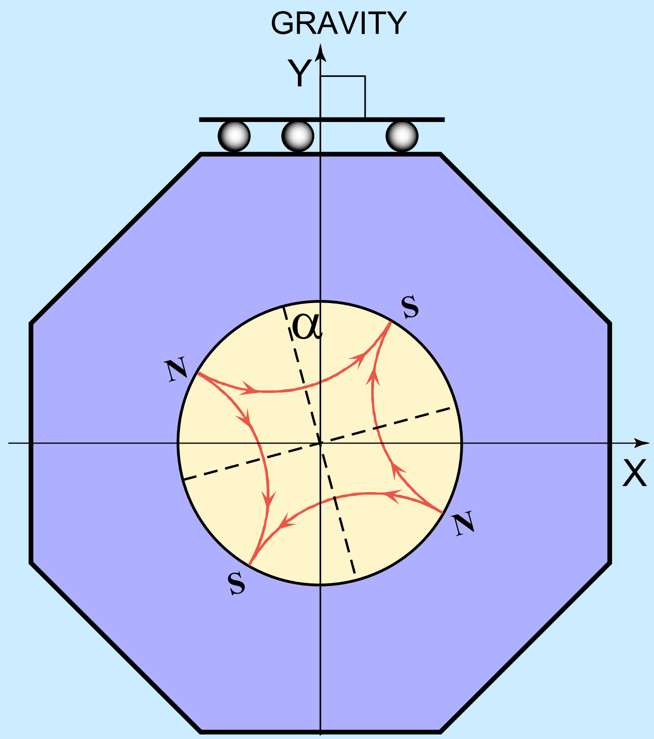
- 16 NSLS-II quadrupoles of 6 different types measured with a Hall probe at several currents.
- Hall probe was calibrated against NMR in a dipole magnet.

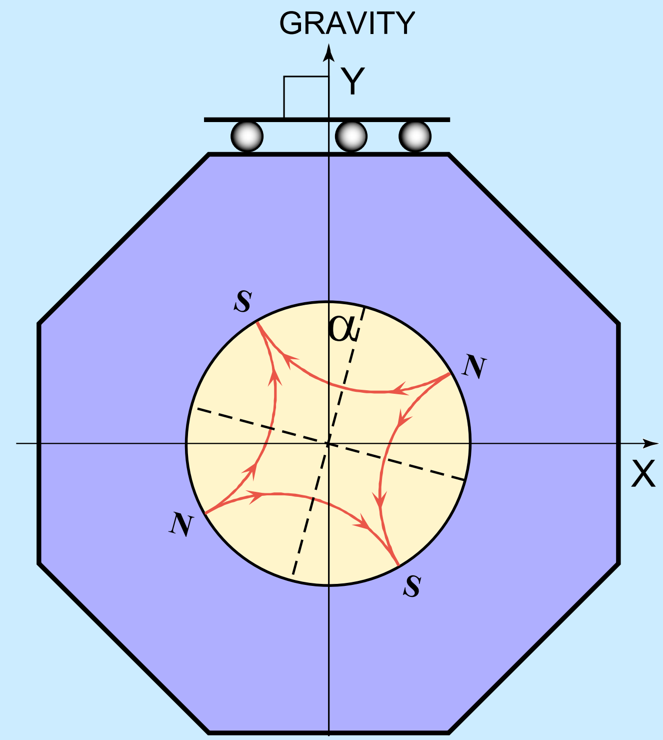
Magnetic Measurement of Roll Angle



- Measurement frame is defined by the index pulse from the angle encoder. One needs angular positions of windings in this frame.
- Calibration establishes the coil winding angles relative to the angle encoder index pulse ***as present at the time of calibration***.
- Gravity ties the measurement frame to the magnet fiducials.
- Error in roll angle measurement can occur due to drift of gravity sensor offset and slippage in the drive shaft coupling.

Roll Angle Measurement Error Correction





View from one end:

True Roll Angle = α

Meas. Roll Angle = $\alpha + \varepsilon = \alpha_1$

View from opposite end:

True Roll Angle = $-\alpha$

Meas. Roll Angle = $-\alpha + \varepsilon = \alpha_2$

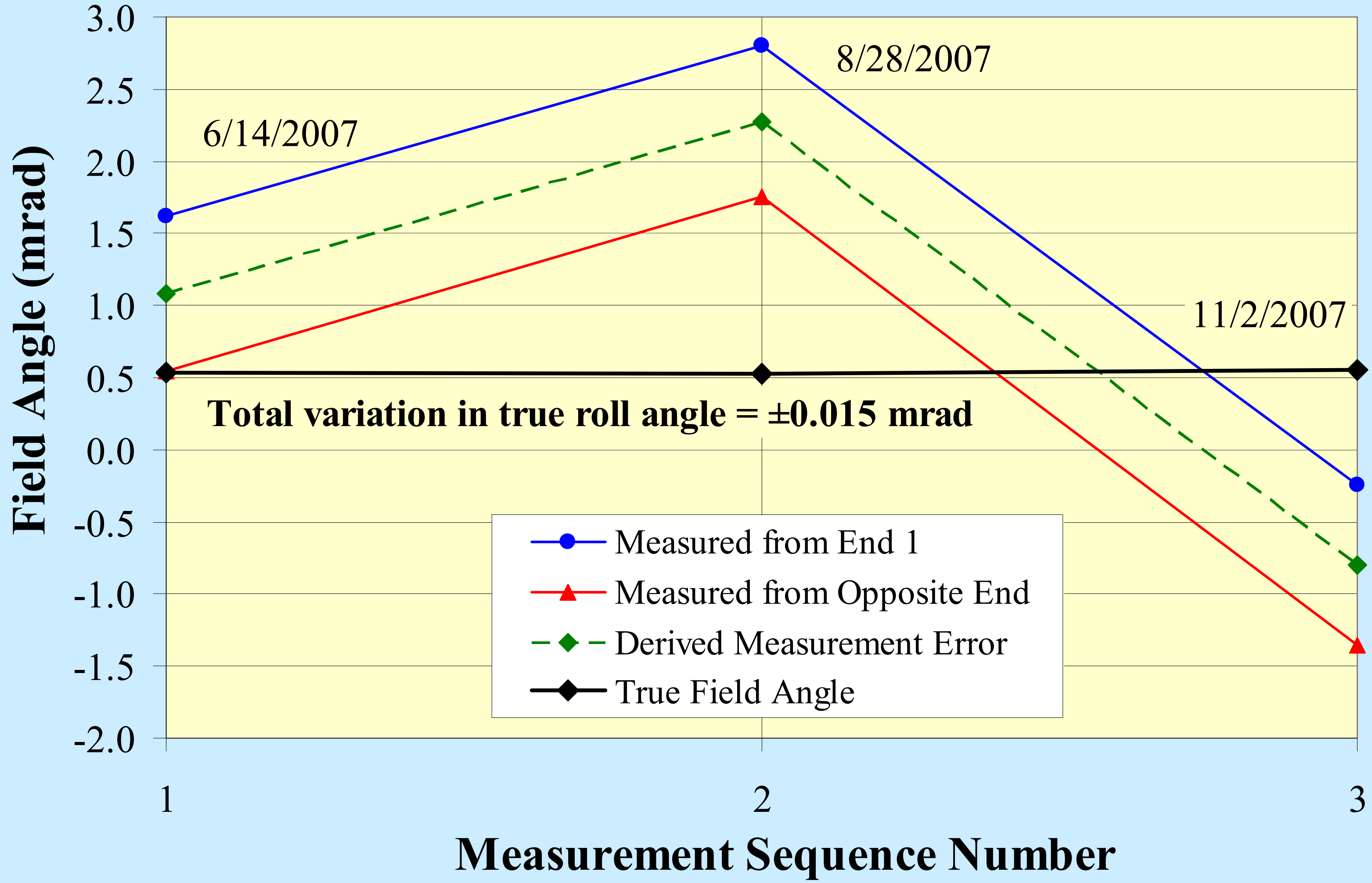
True Roll Angle = $\alpha = (\alpha_1 - \alpha_2)/2$

Meas. Error = $\varepsilon = (\alpha_1 + \alpha_2)/2$

Uncertainty in Roll Angle Error Correction

- Noise in each measurement ~ 0.03 mrad
- Resolution of gravity sensors ~ 0.02 mrad
- Total error ~ ±0.05 mrad can be achieved with careful measurements.
- Note that 0.05 mrad over a shaft of 20 mm diameter amounts to a slippage of only 0.5 micron! (removable coil connections?)
- Due to very small mechanical shifts needed to cause even large roll angle measurement errors, it is necessary to determine the roll angle correction for every magnet measured in order to ensure reliable measurements (at least once per day).

Various Roll Measurements in ERQ106



End-for-end measurements are very effective in correcting roll angle measurement offsets.

Summary

- Reasonable coil construction and placement errors generally do not affect harmonics measurements directly (i.e. via sensitivity).
- Primary reason for unreliable harmonics measurements is poor analog bucking due to even small construction errors.
- **Bucking of feed down term should not be overlooked.**
- Digital bucking can offer an advantage in terms of relaxed construction tolerances, but requires good data acquisition.
- Calibration of main field strength and roll angle must be done for the specific section of a rotating coil that is in magnetic field.
- Roll angle calibration tends to drift easily and must be checked almost daily for reliable roll angle measurements.