Magnetic Measurements

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Magnetic Measurement Goals

- Measurement of field quality in magnets:
  - Ensure that field quality meets specified requirements
  - Detect any gross construction errors
  - Monitor trends and provide timely feedback to ensure uniformity in a large production run (e.g. RHIC).
  - Provide feedback during construction (using interim measurements) to improve field quality (e.g., shims for RHIC insertion quads and SNS magnets; pattern modulation in direct-wound magnets)
  - Provide data needed for use of the magnets in accelerator (e.g., excitation curves, superconductor magnetization effects at injection, ramp rate effects, iron yoke saturation effects)
- Measurement of field center and field direction:
  - Provide data needed for magnet installation and alignment
- Superconducting Magnet Division (SMD) has been active in developing new techniques, as needed, to meet these goals.

Field Quality Measurement Basics

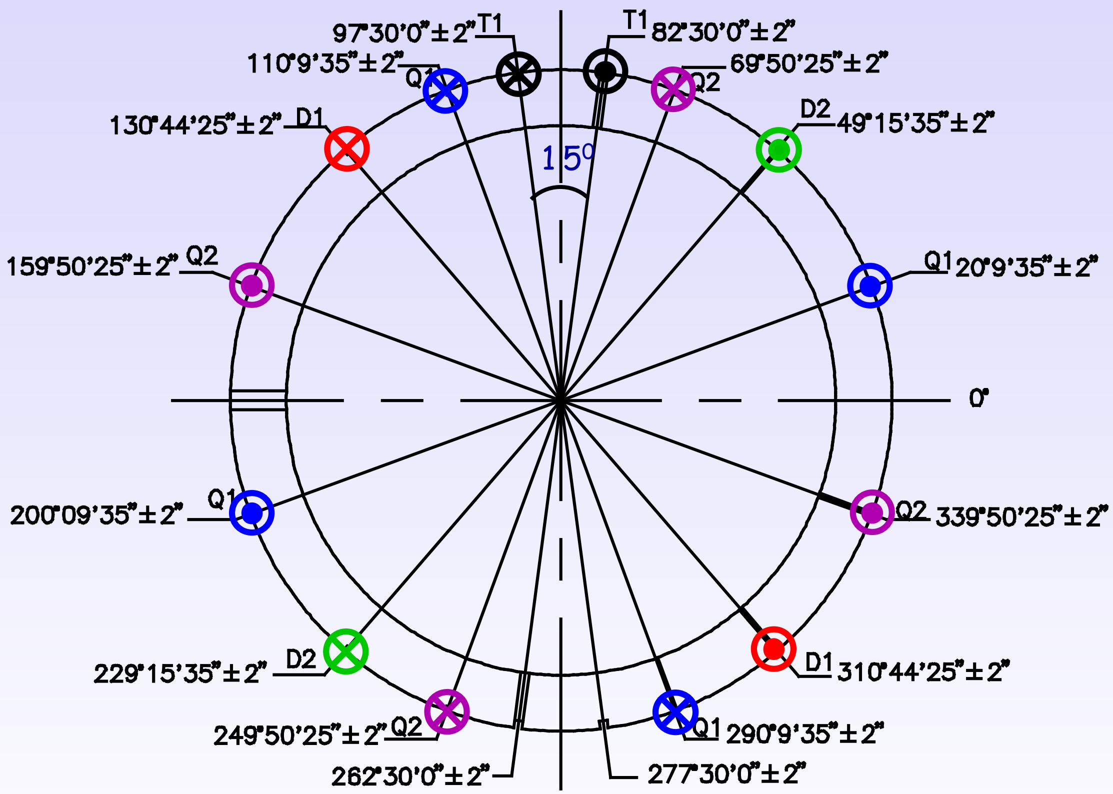
- Field quality in accelerator magnets is expressed in terms of harmonics (coefficients B_n and A_n in a series expansion of 2-dimensional field):

Radial component:	Azimuthal component:
$B_r(r,\theta)=\sum_{n=1}^{\infty}\left[B_n\sin(n\theta)+A_n\cos(n\theta)\right]\left(\frac{r}{R_{ref}}\right)^{n-1}$	$B_\theta(r,\theta)=\sum_{n=1}^{\infty}\left[B_n\cos(n\theta)-A_n\sin(n\theta)\right]\left(\frac{r}{R_{ref}}\right)^{n-1}$

  R_{ref} is an arbitrary "Reference radius", typically ~50-70% of coil inner radius.

- These coefficients are most conveniently and accurately measured using rotating coils.
- The angular dependence of field is picked up by a rotating coil and a Fourier analysis of the signal gives all the harmonics.
- A rotating coil system typically has several different loops to "buck out" certain harmonics. This is done to minimize errors caused by imperfections in the rotational motion of the coil.
- SMD uses a tangential coil design with a total of 5 windings.

Cross Section of a Typical Measuring Coil in SMD



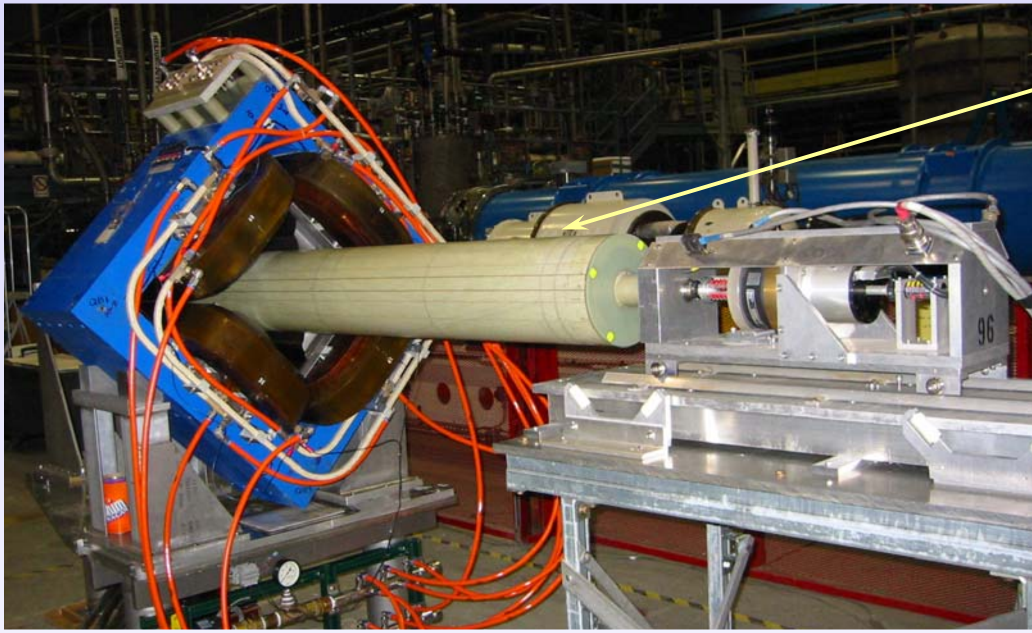
All SMD coils are wound in grooves machined into cylinders. Most coils have a similar cross section, with 5 active windings.

2 Dipole (3 turns each)
2 Quad (3 turns each)
1 Tangential (30 turns, 15^0)

Many coils of different radii and lengths have been built to suit different magnet sizes.

Although primarily designed for dipoles and quadrupoles, the same coil design can be used to measure practically all types of magnets (dipole through 12-pole, except octupole) by adjusting the weight factors in a digital bucking scheme.

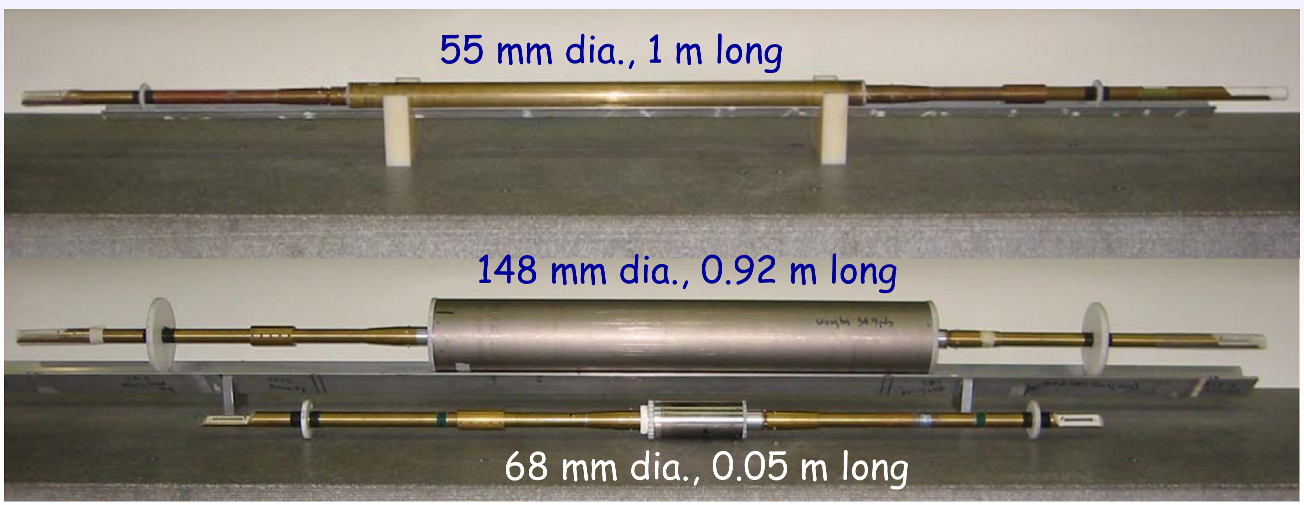
Examples of Rotating Coils



247 mm Diameter,
3 m Long,
External Drive Coil
in a SNS Quadrupole

Smallest coil available is 15 mm in diameter.

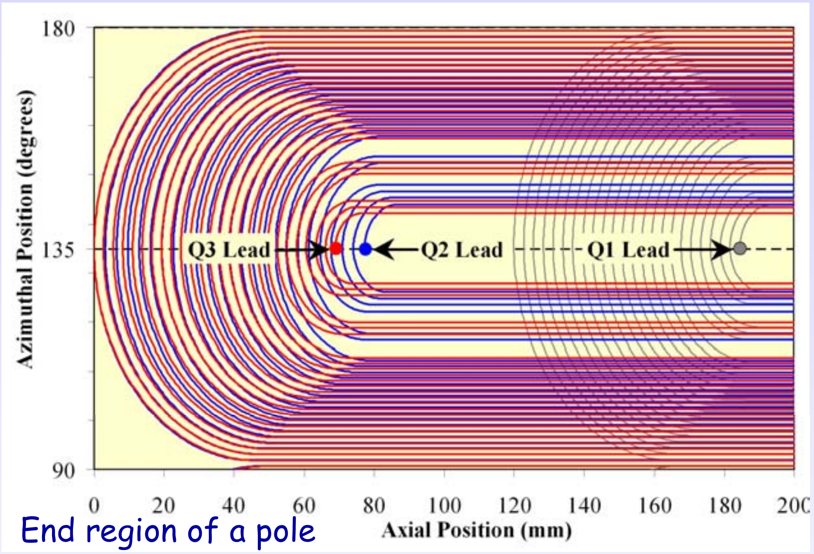
Shortest coil available is 51 mm long.



"Moles" for measuring long magnets in several short sections.

- Developed for SSC
- R&D100 Award 1988

Application: Electrical Short in HERA Quadrupole



End region of a pole

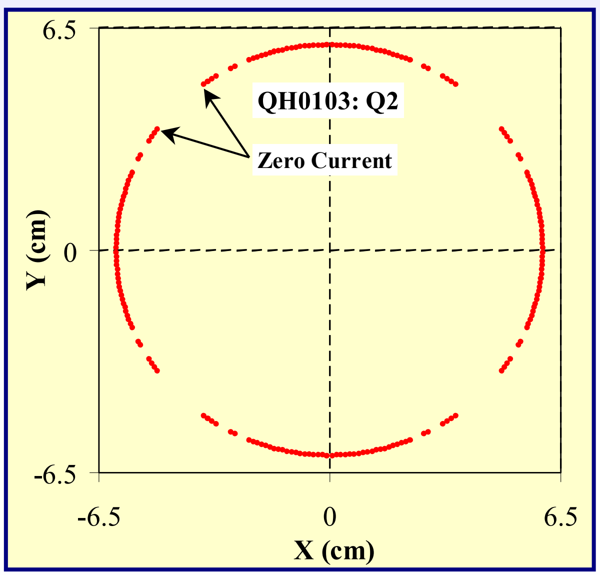
Large changes in harmonics were seen in the Q2 layer after it was buried under three more layers.

A repair was performed without sacrificing any layer

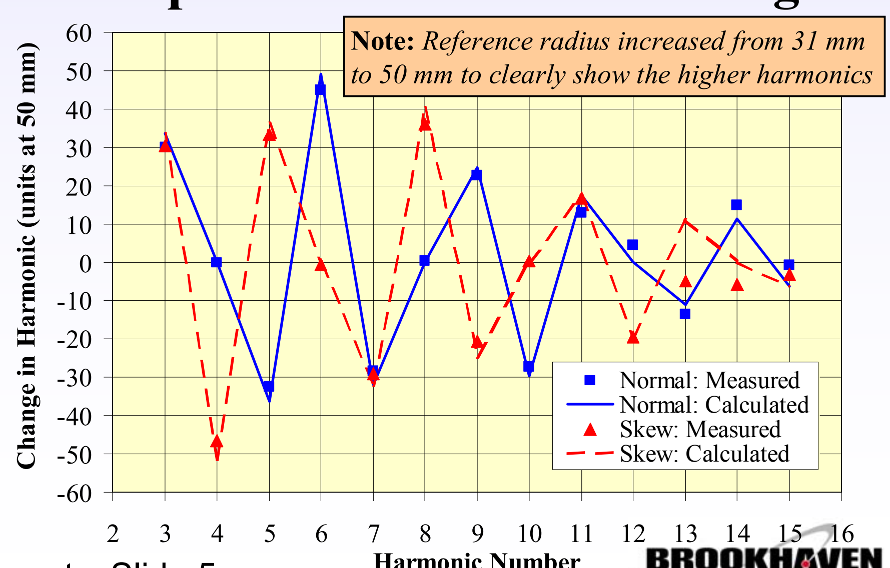
2 turns of Q2 exposed for repair

Most likely cause was a short between the lead and a pole turn.

This model explained all changes.



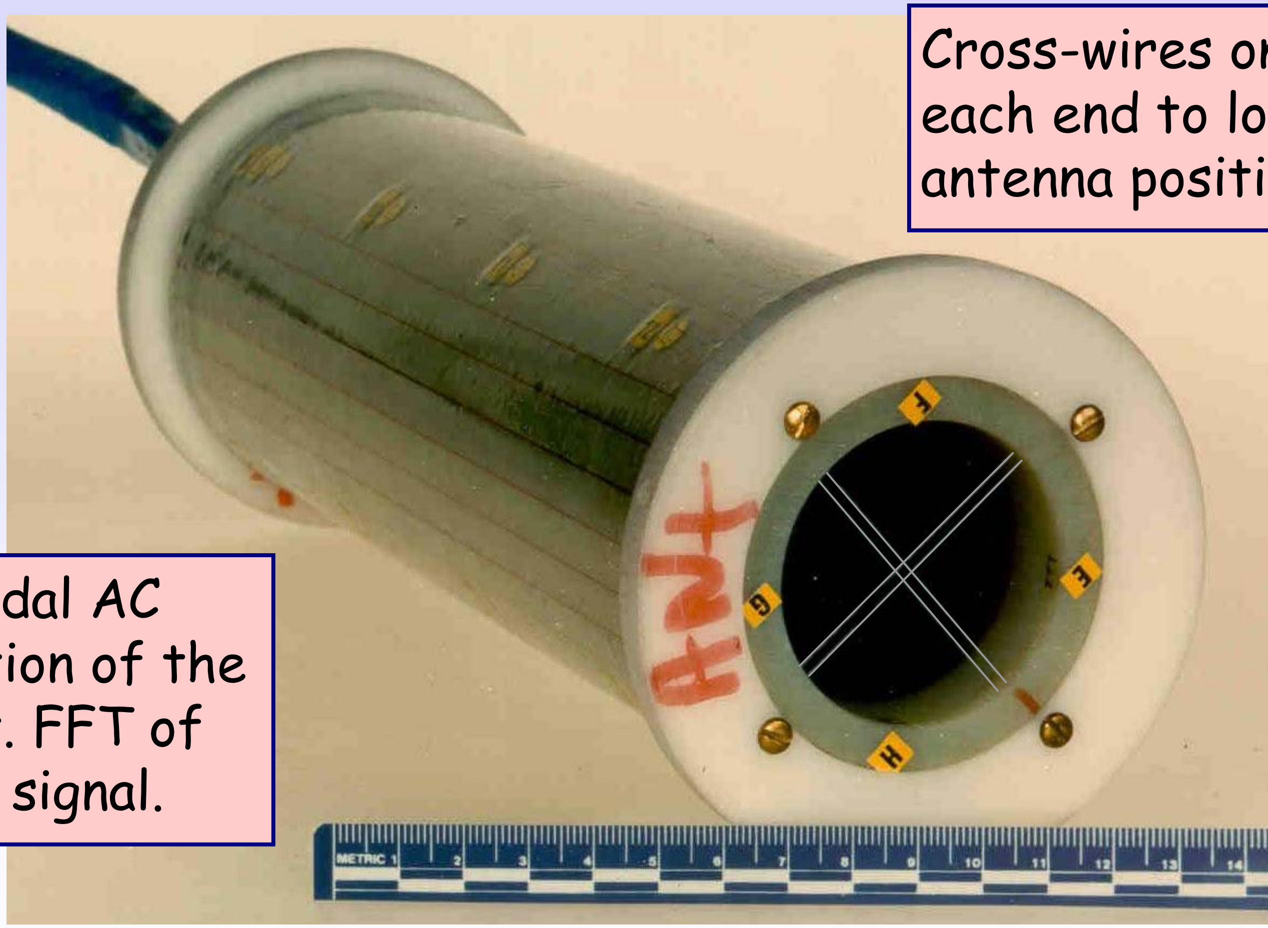
Computed Vs Measured Changes



Measurement of Magnetic Field Center

- Field center needs to be measured relative to external fiducials in order to install and align the magnets.
- Rotating coils can measure the magnetic axis relative to the rotation axis (typical noise ~ 2-5 μm in quadrupoles).
- It is often difficult to locate the rotation axis relative to the fiducials, particularly for short coils inside long magnets.
- The technique of "Harmonic Antenna" was developed at SMD for RHIC magnets
  - Uses stationary pick up coils and AC excitation of magnet at ~10-50 Hz
  - Special coil geometries measure only the relevant harmonics
  - Fiducials on the antenna to measure its location in external frame

Non-rotating Harmonic Coil (Antenna)



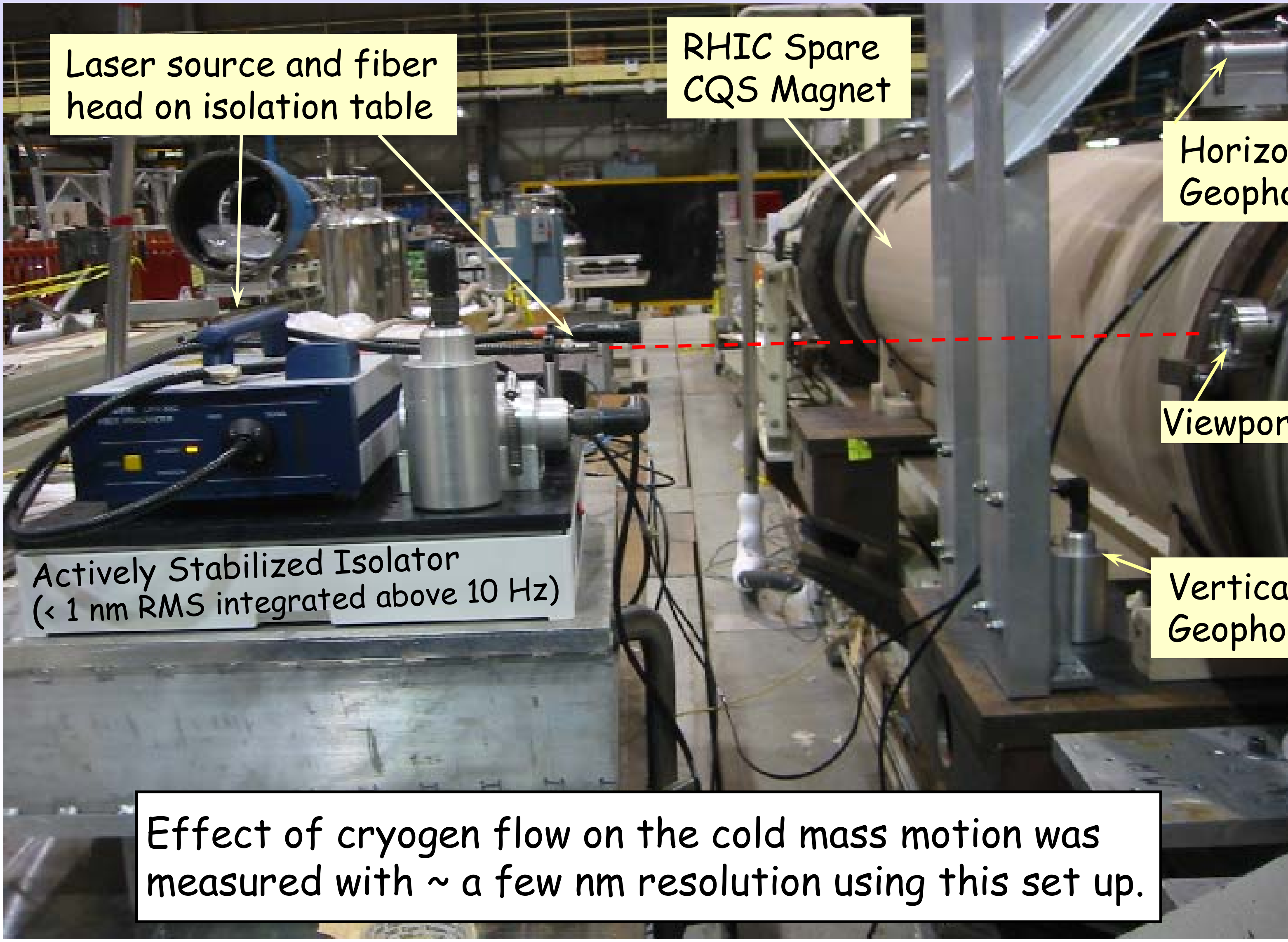
Cross-wires on each end to locate antenna position

Sinusoidal AC excitation of the magnet. FFT of pick up signal.

A similar concept was adopted later at CERN for the LHC

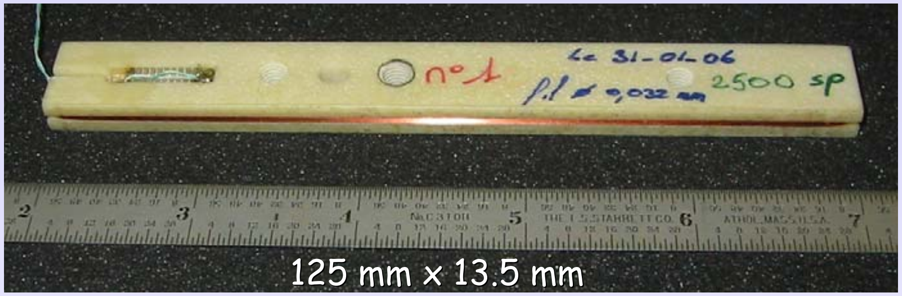
6 Windings (2 Dipole; 2 Quadrupole; 2 Octupole):
Can measure Quadrupoles through 12-pole magnets

Quadrupole Vibration Measurements at 4.5 K

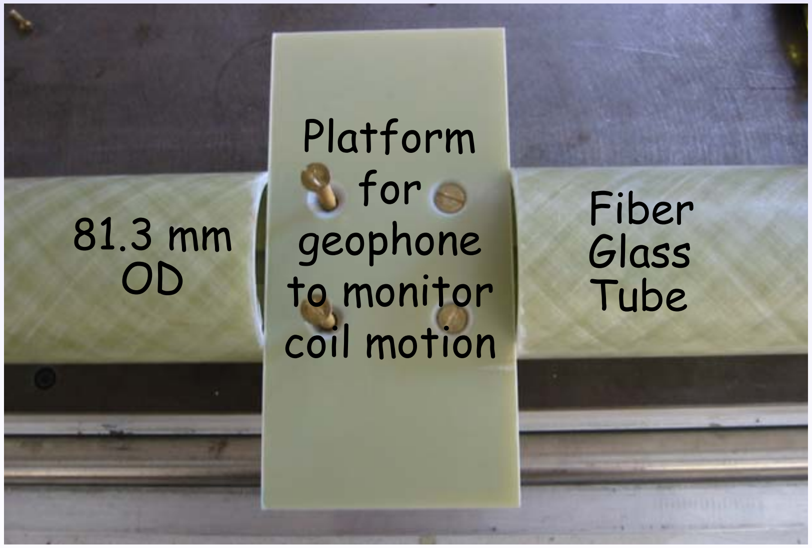


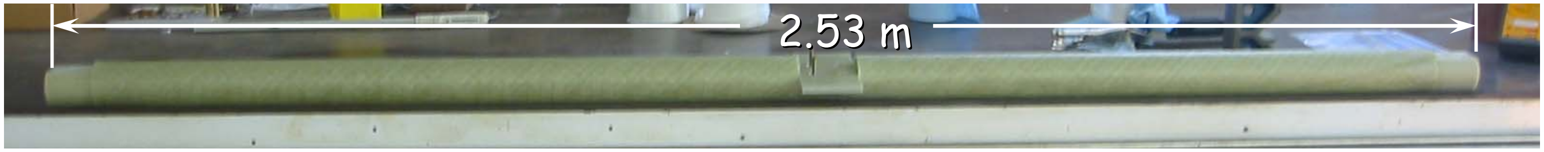
Effect of cryogen flow on the cold mass motion was measured with ~ a few nm resolution using this set up.

Quad Center Motion at nm Level in Linear Collider
(Work is in early stage)



2500-turn coil from CERN (32 µm wire)

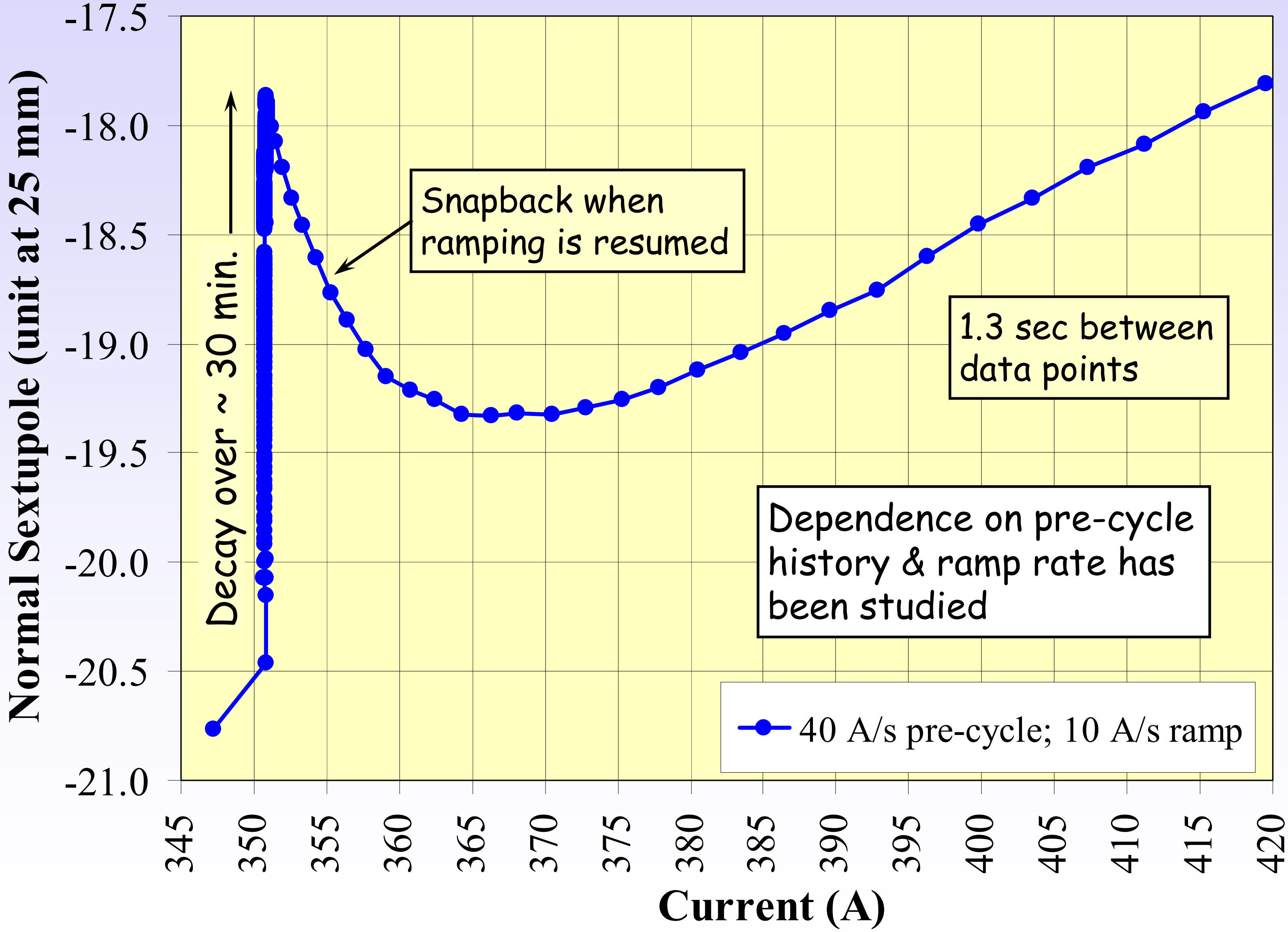




Harmonic Measurements in Time Varying Fields

- Rotating coils are ideally suited only for DC fields.
- In many instances, it is necessary to measure the field quality under dynamic conditions.
  - Time decay and snapback due to persistent current effects
  - Eddy current induced harmonics while ramping
- Typical rotating coil speed is ~3.5 sec per revolution.
  - 128 angular positions; 1 power line cycle integration at each reading.
- A time resolution of 1.3 sec has been achieved with 64 angular positions (useful for time decay and snapback studies).
- A new iterative analysis procedure was developed to allow rotating coil measurements during ramping at relatively low rates (below ~0.1 T/s).
- An entirely new system consisting of many coils was developed for very high ramp rates (> 1 T/s) for two recent projects.

Sextupole Time Decay & Snapback in a LHC Dipole

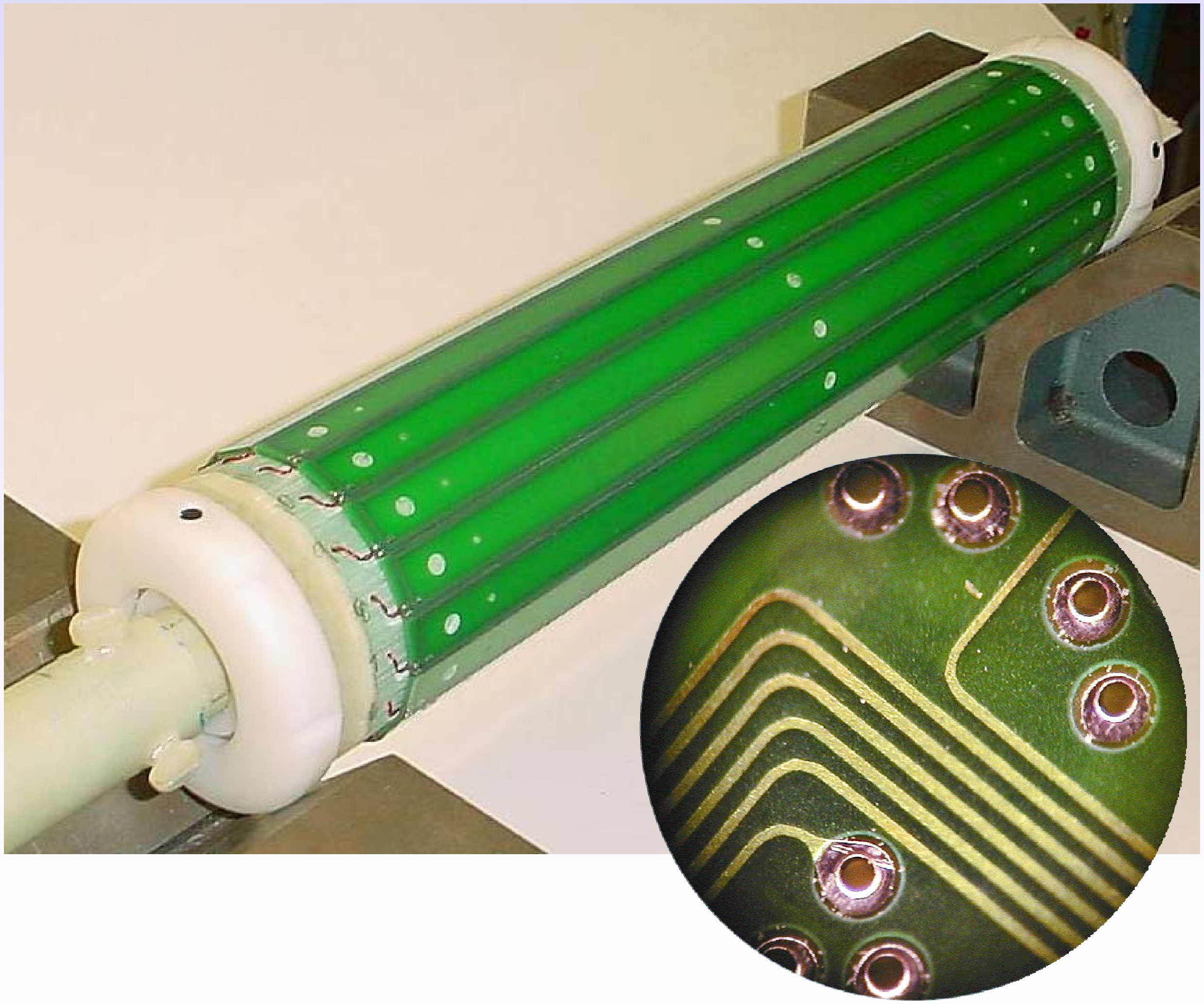


Rotating coil data with an iterative analysis for slowly varying fields

10 A/s = 7 mT/s in this magnet

Harmonic Measurements at Very High Ramp Rates

System of Coils Used in Stationary Mode



16 Printed Circuit coils

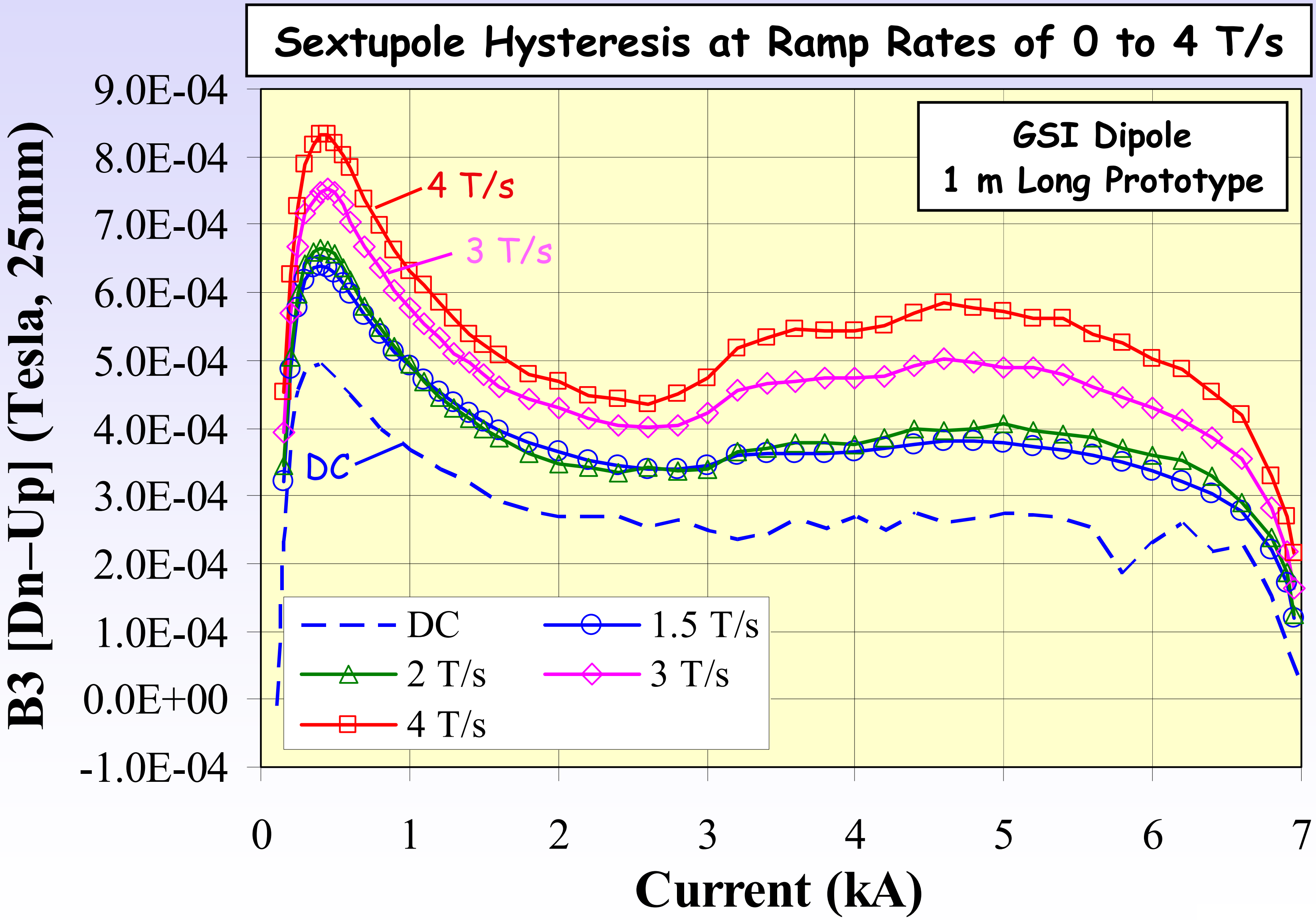
6 turns/layer; 10 layers

300 mm long

0.1 mm lines with
0.1 mm gaps

Radius =
26.8 mm (GSI)
35.7 mm (BioMed)

Harmonic Measurements at Very High Ramp Rates



Summary

- The Superconducting Magnet Division is well equipped to carry out field quality measurements in most accelerator magnets.
- Rotating coils are the primary tools employed for magnetic measurements, although other techniques, such as Hall probes and NMR, are also used where needed (not covered in this talk).
- New measurement and analysis techniques are developed to meet measurement challenges
  - e.g., Harmonic Antenna; Fast Rotating Coil; Stationary Coil
- SMD has successfully measured large production runs, such as for the RHIC and SNS, meeting all the measurement goals.
- We look forward to new measurement challenges
  - Electron Cooling, NSLS-II, Rapid Cycling Synchrotron, ILC, ...