An Encapsulated Rotating-coil Test System at Fermilab

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IMMW17

Acknowledgements:

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Goal

- A general-purpose, portable measurement system to measure strength and multipole harmonics for low or high field magnets.

A 'mole'-type device…

Design for such a system was presented at IMMW16

A Name

FERmilab Rotating-coil Encapsulated Test System
("Ferret" System)

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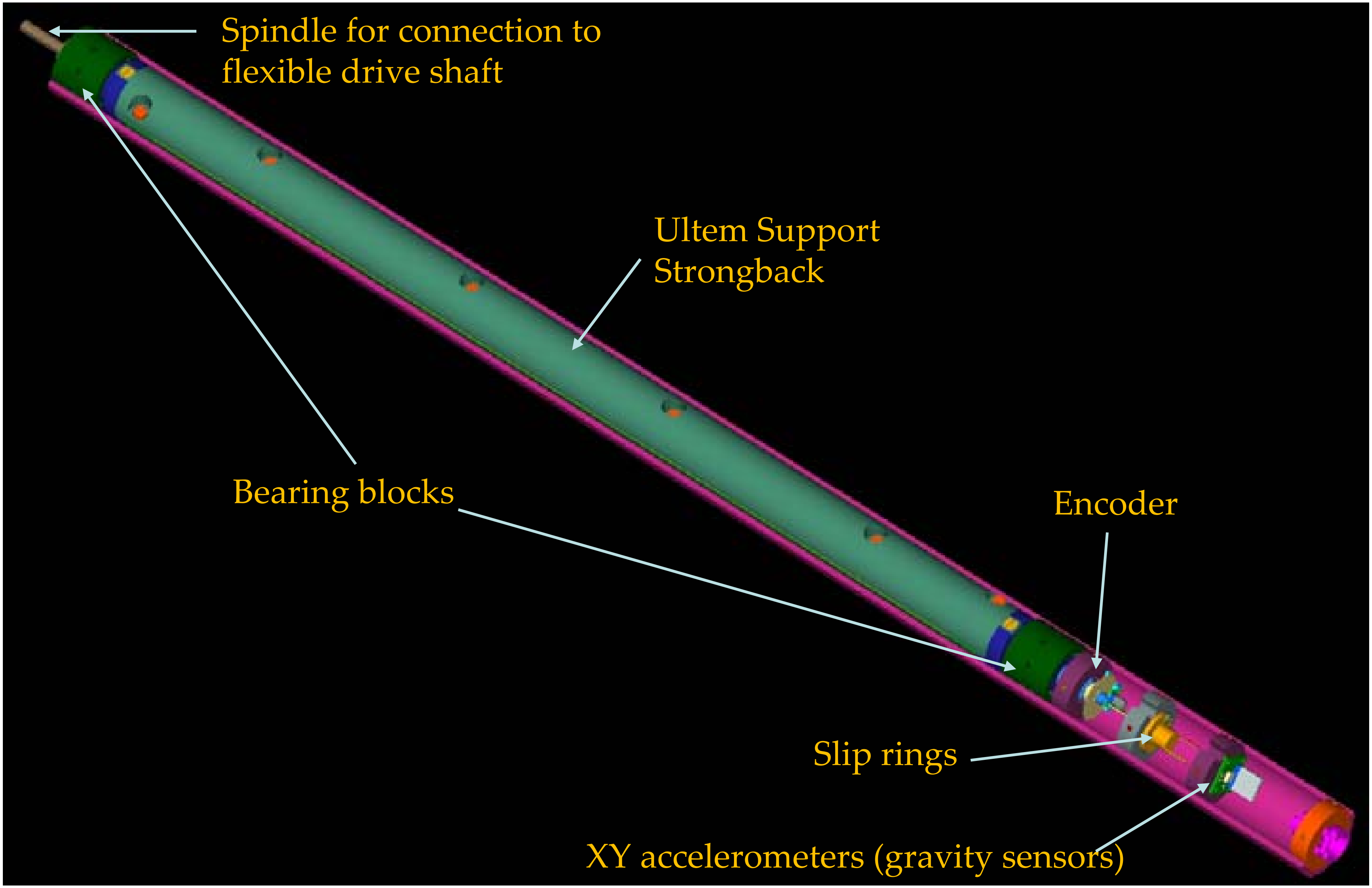
… also in recognition of Fermilab’s history of using particular tunnel denizens to perform magnet work!

Probe Concept

- Flexible non-magnetic drive shaft with motor external to magnet
- Circuit board probe supported on ‘strongback’ with bearings at each end
- Different diameter circuit boards could be used to optimize measurement radius for particular magnet.
- On-board encoder and slip-rings
- On-board signal amplifier
- Gravity sensor
- Thermometer


Spindle for connection to
flexible drive shaft
Ultem Support
Strongback
Bearing blocks
Encoder
Slip rings
XY accelerometers (gravity sensors)

Timeline

Fabrication ➔ Summer 2010

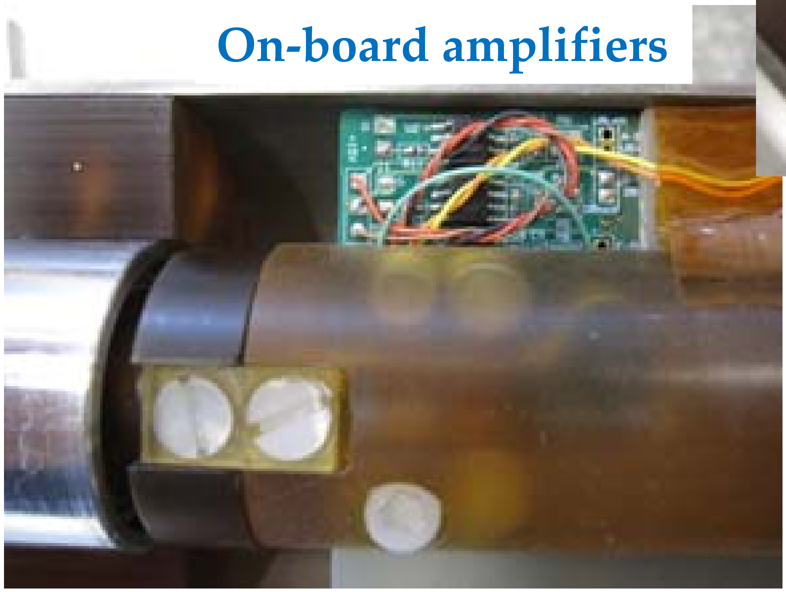
Commissioning (low-field) ➔ Fall 2010 (warm measurements of LQS02b)

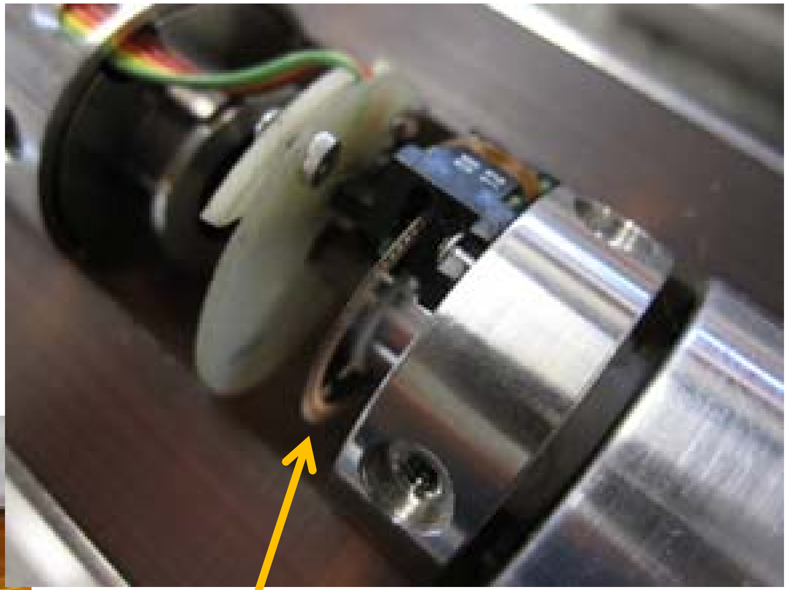
High-field ➔ Summer 2011 (**ongoing**) (cryogenic testing of Tevatron dipole to ~5T)

As-built Probe

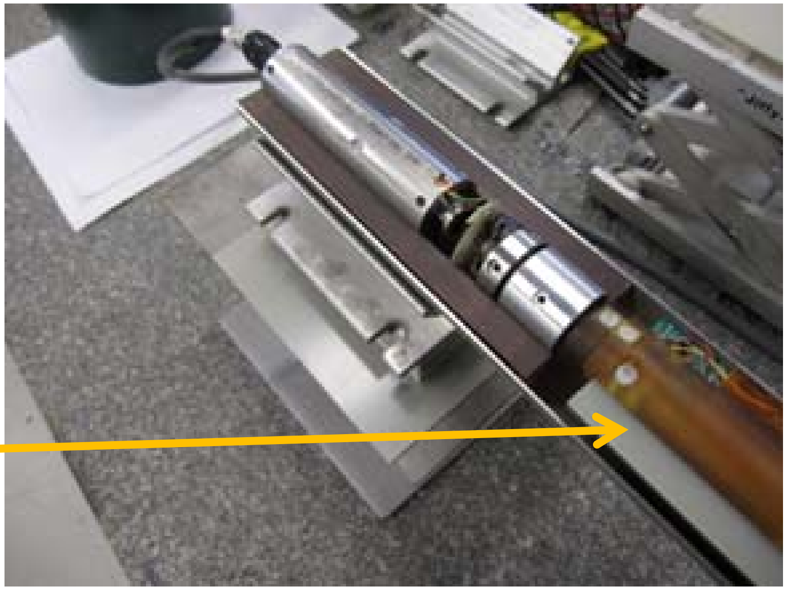
59mm dia. pcb

On-board amplifiers

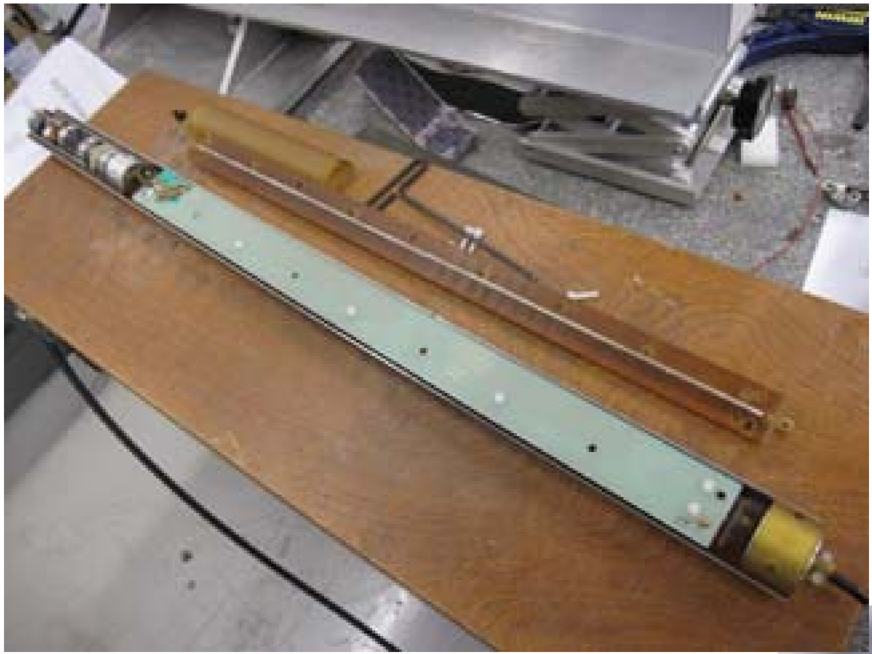


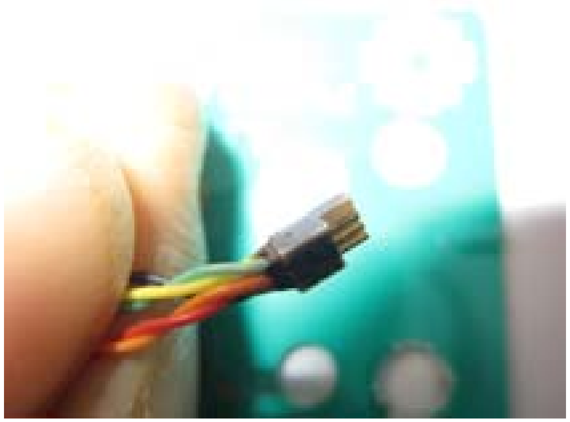


Encoder wheel and read head



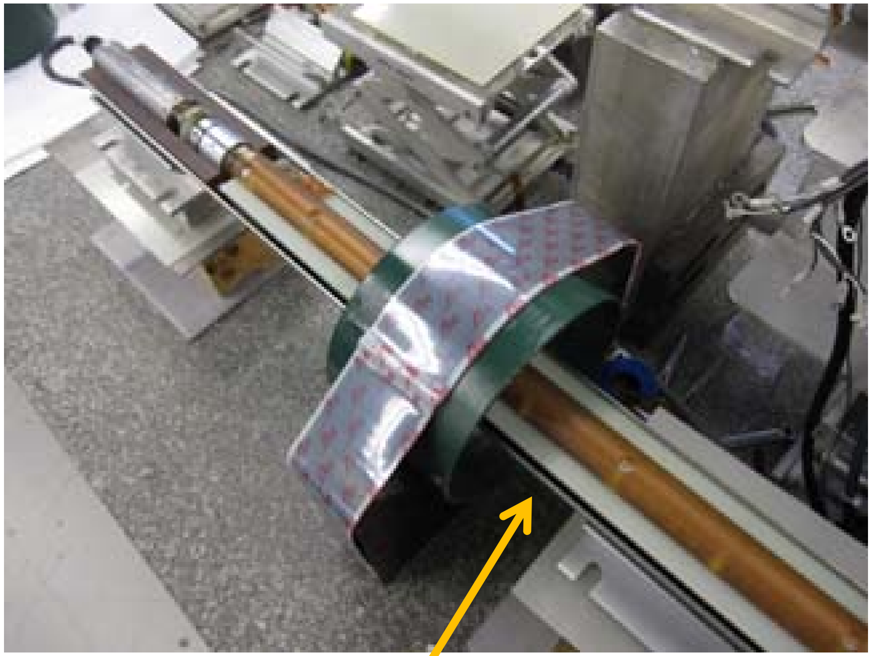
pcb extends beyond strongback



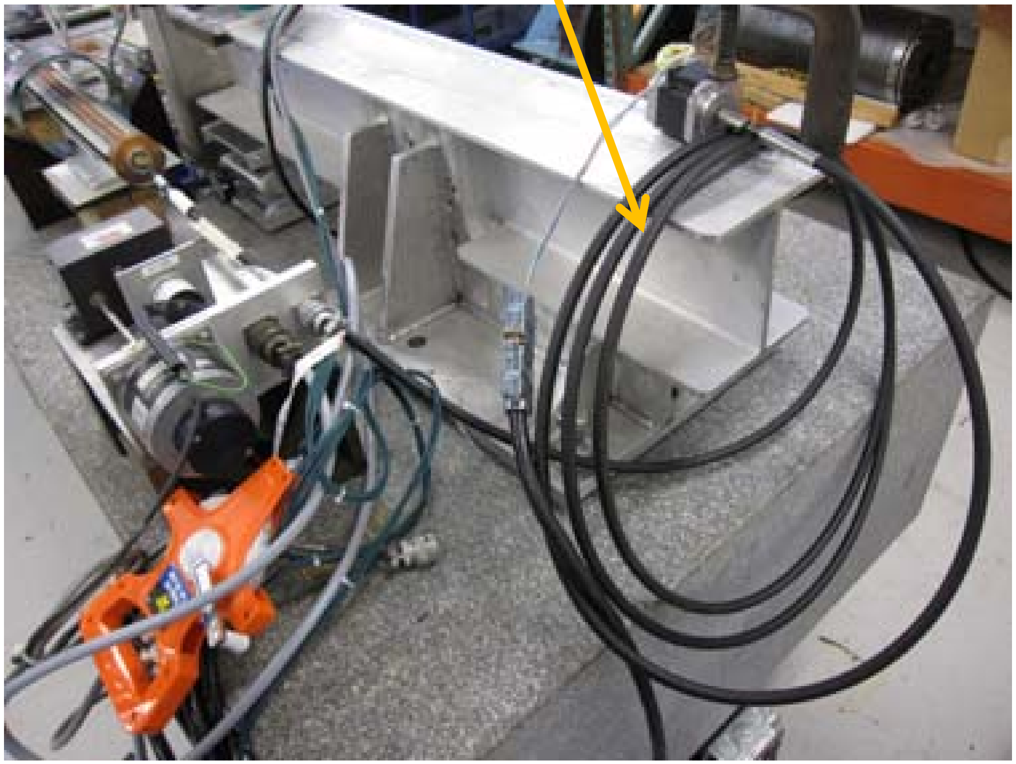


12-wire slip-ring

Gravity sensor



Test of tightly coiled flex drive to spin probe (this flex shaft is 5m long 304SS – it is slightly magnetic)



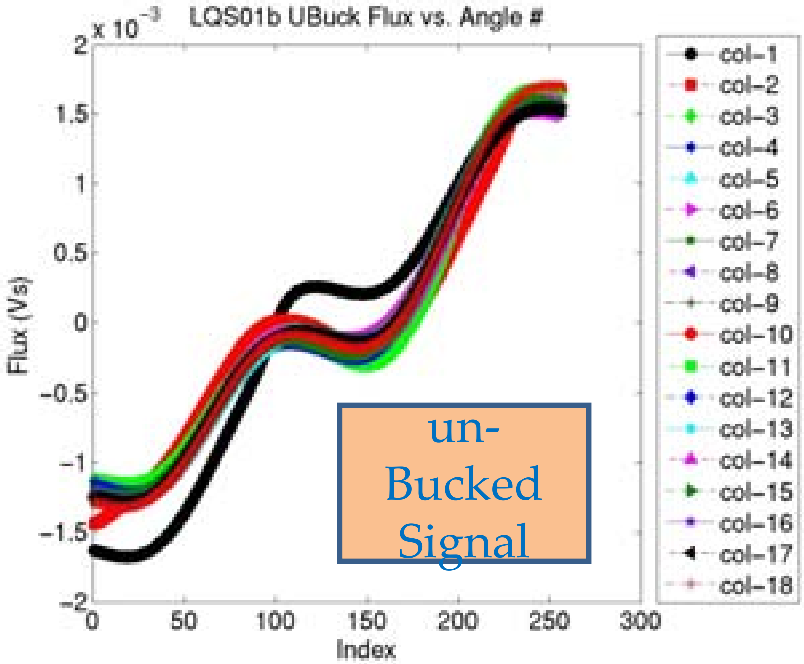
Probe testing in 'coffee-can' magnet

Low-field Tests

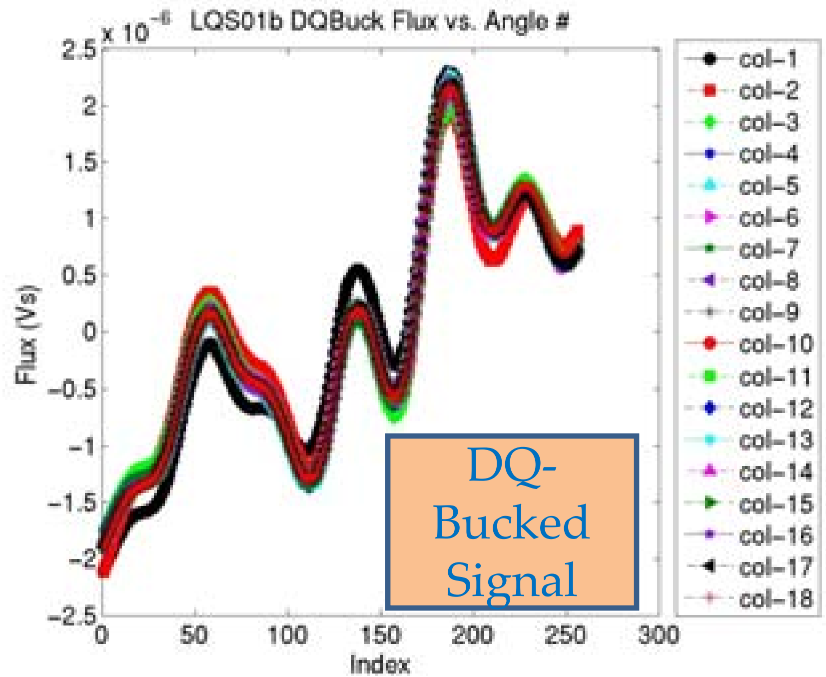
LQS01b measurements 14Oct2010

- **4Hz rotation rate** with external flex shaft
- Simultaneous sampling at 40kHz with NI-4472b (DSA) card.
- 8 channels of input (**Index, Encoder**, **UnBucked(UB), DipoleBucked(DB), DipQuadBucked(DQB) probe signals**, magnet current, gravity sensor
- 10A magnet current (→ **gradient ~ 0.185 T/m** → 5mT at UB radius → 1 unit of harmonics is ~0.5μT)
- Measurements every 0.25m (probe length ~0.5m)
- On board **amplifier** has gains 10/1000/1000 for UB/DB/DQB respectively.
- 5m flex shaft (7.5m flex shaft LQS02 May 2011)

Raw flux data



18 rotations



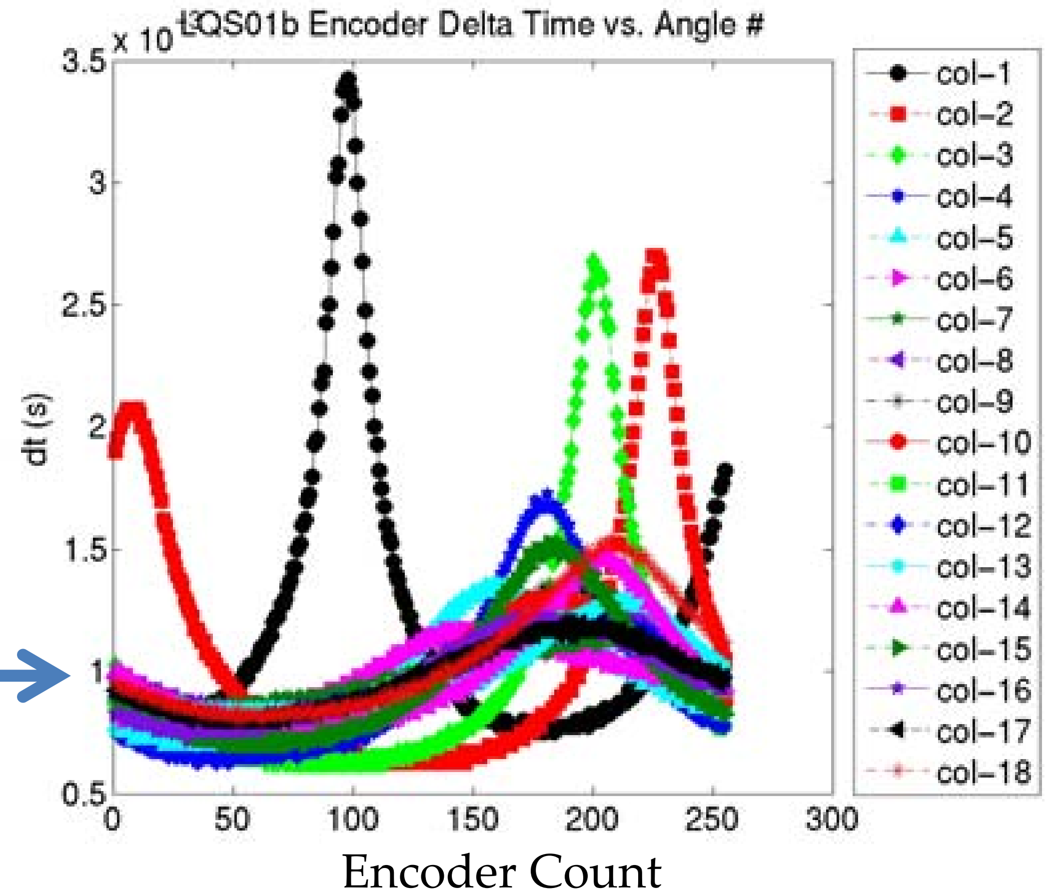
Signals look ‘clean’ – low noise

… but large variation in flux between rotations (even if correct for flux drift)…

Rotation stability

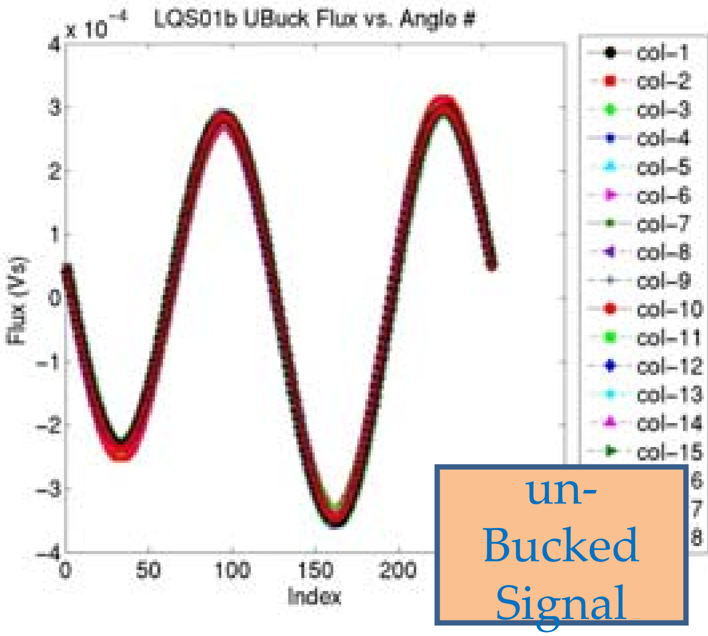
256 encoder counts in ~250ms (4Hz rotation rate) → **~1ms/pulse**

Average dt per encoder count for one rotation at 4Hz



Rotation speed variation should not matter since probe rigidly coupled to encoder ➔ flux (which is path independent) is measured at fixed angles. But since this time variation during rotation is occurring in the presence of voltage offsets (which integrate into flux drift), need to correct for dt effects.

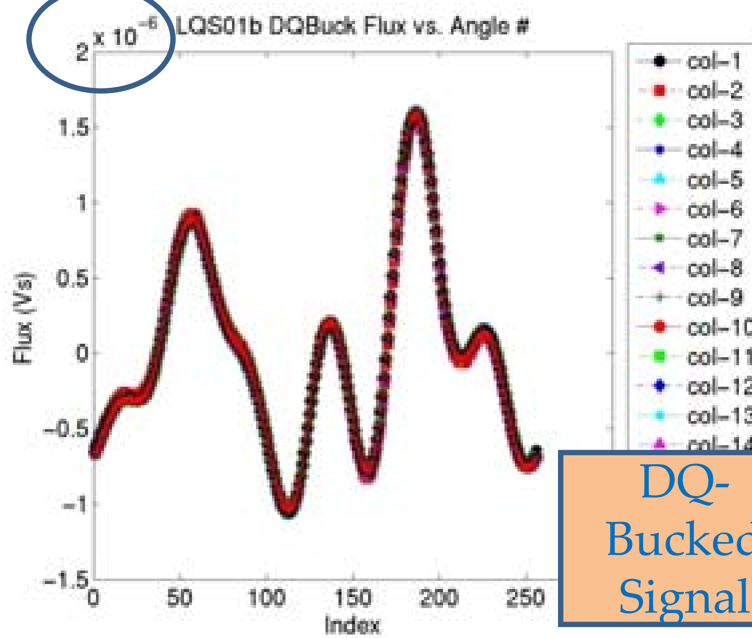
LQS01b **dt-corrected** data



un-Bucked Signal

18 rotations

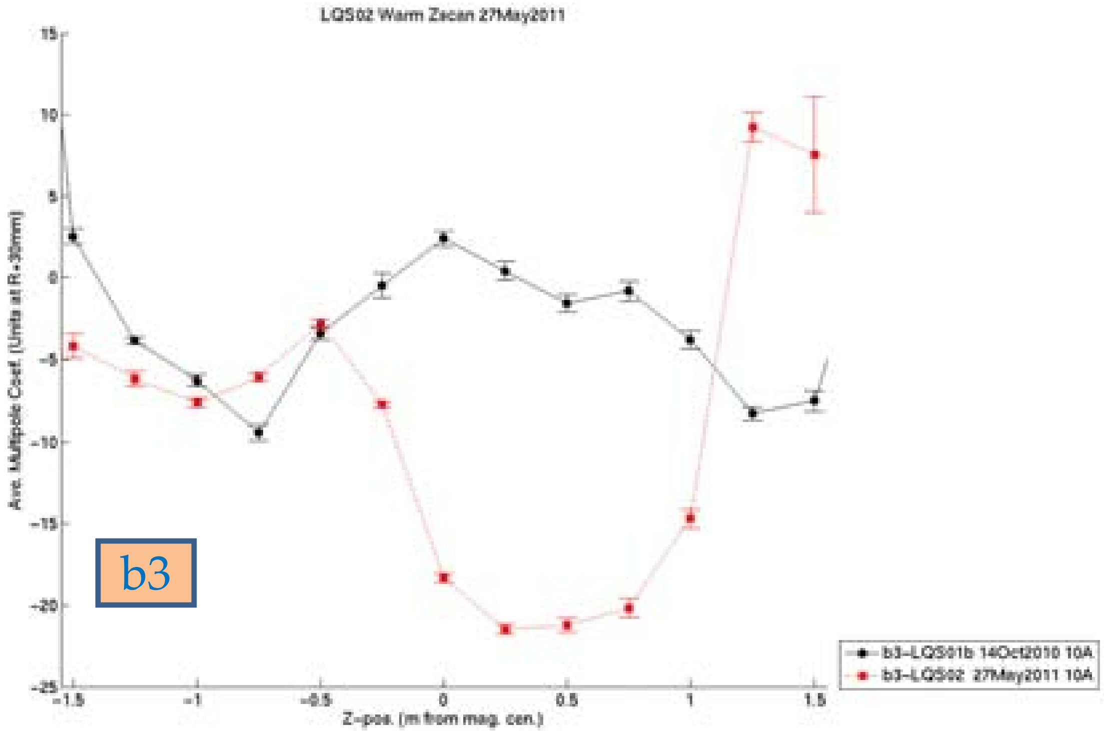
Full scale 2uVs

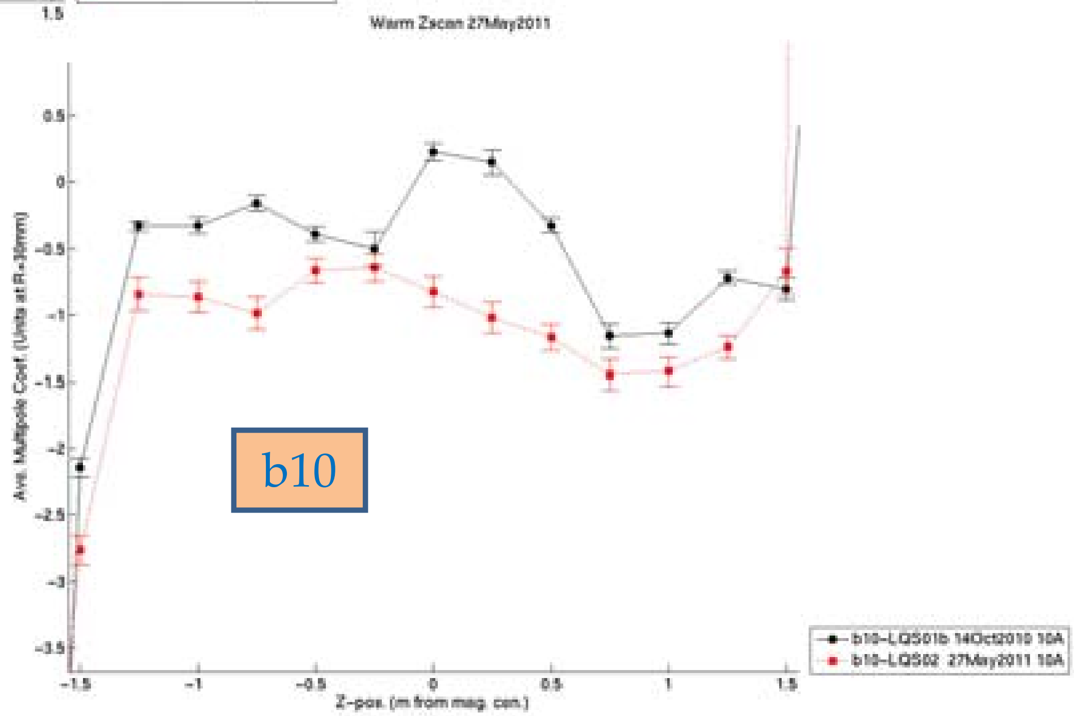


DQ-Bucked Signal

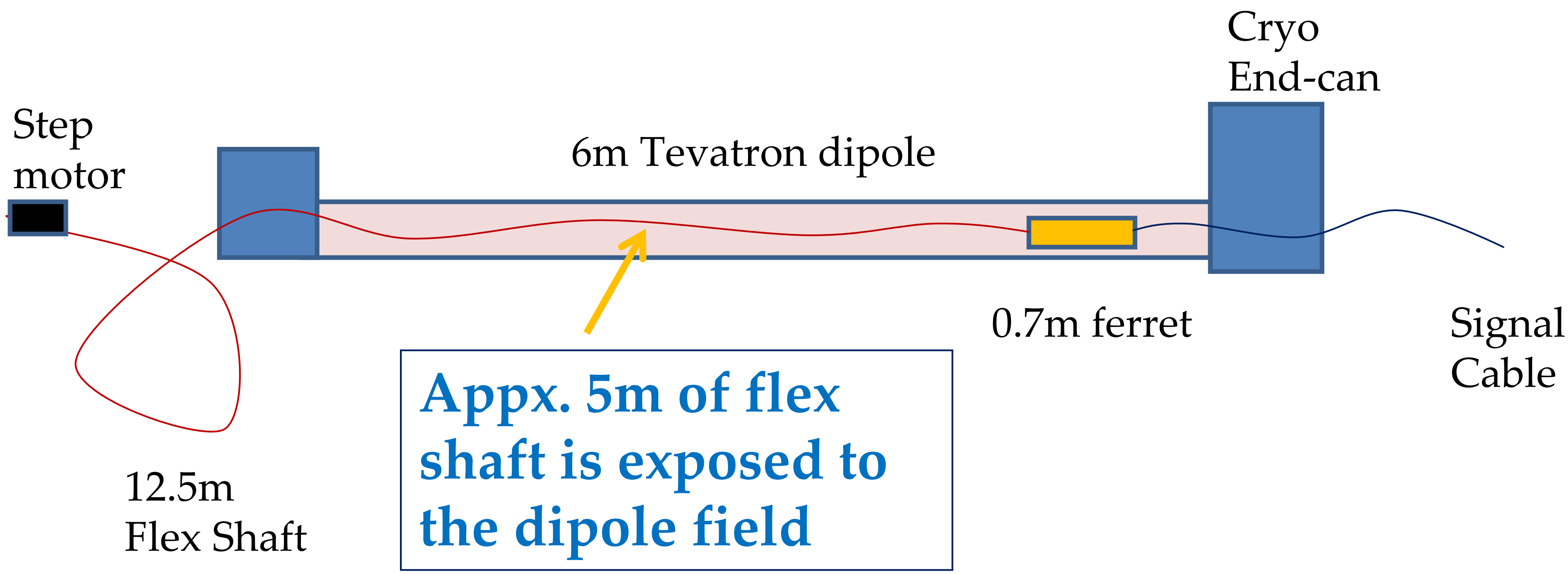
…even first rotation now looks ok…

Sample LQS01b and LQS02 Warm measurement data





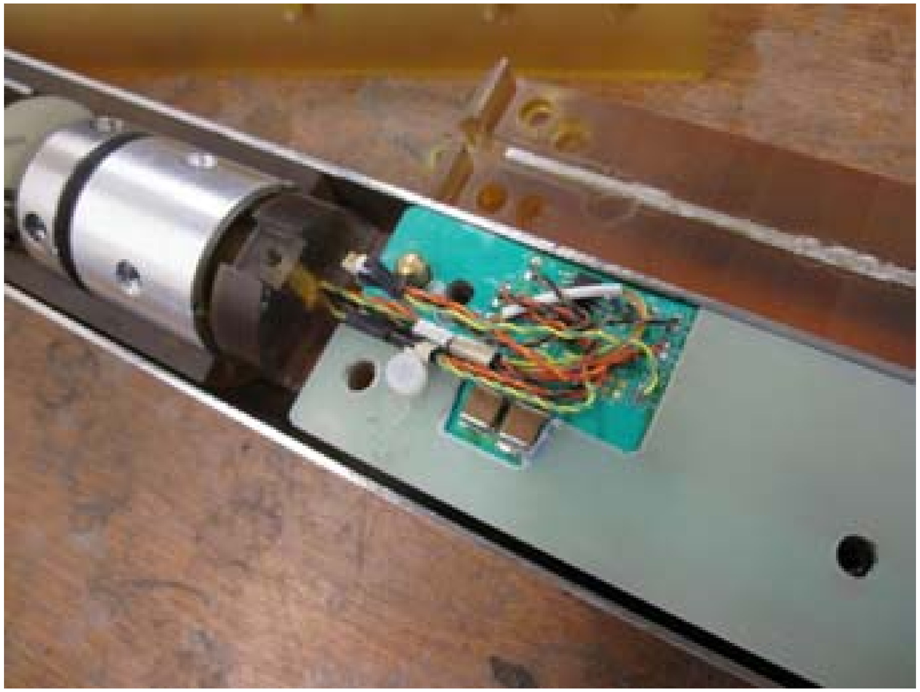
High-field Test



Tevatron dipole field TF ~1T/kA

Change PCB for high-field test

- Tevatron warm bore tube ID is about 45mm
- Use trimmed 46mm board (25cm length)

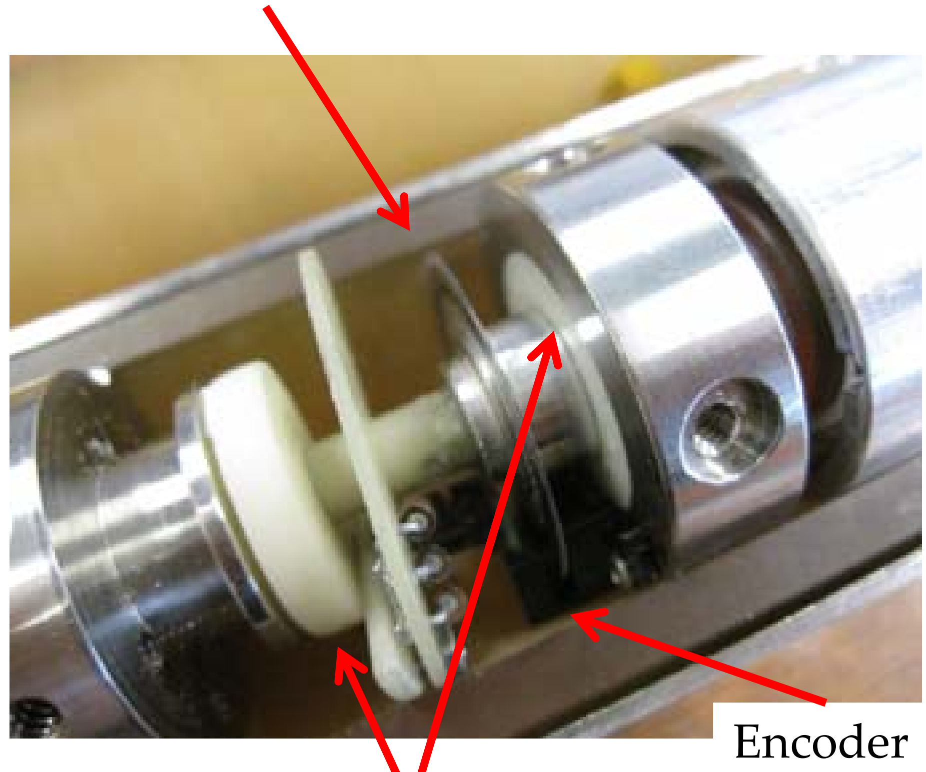


43mm pcb

59mm pcb

Encoder

- Hard to find a small one with through-shaft for probe signals! (~35-38mm seems to be the minimum diameter available)
- We used separate encoder wheel and read head (25mm) – but observed large false quad harmonics in the UnBucked signal during the dipole tests. Realized that this was from radial 'run-out' of the shaft that the encoder wheel was connected to.
- Modified the encoder implementation so that shaft was supported by bushings. Run-out now at the level of < 0.025mm
- The large (~100 unit) quad harmonics in the UB signal disappeared.

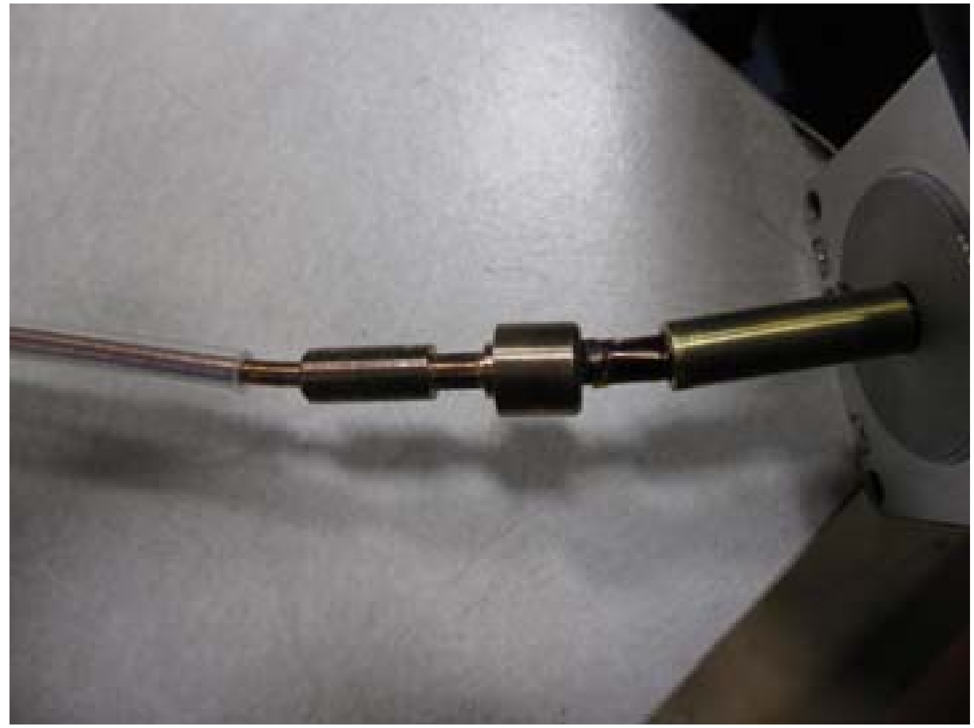


Motor/Flex-drive

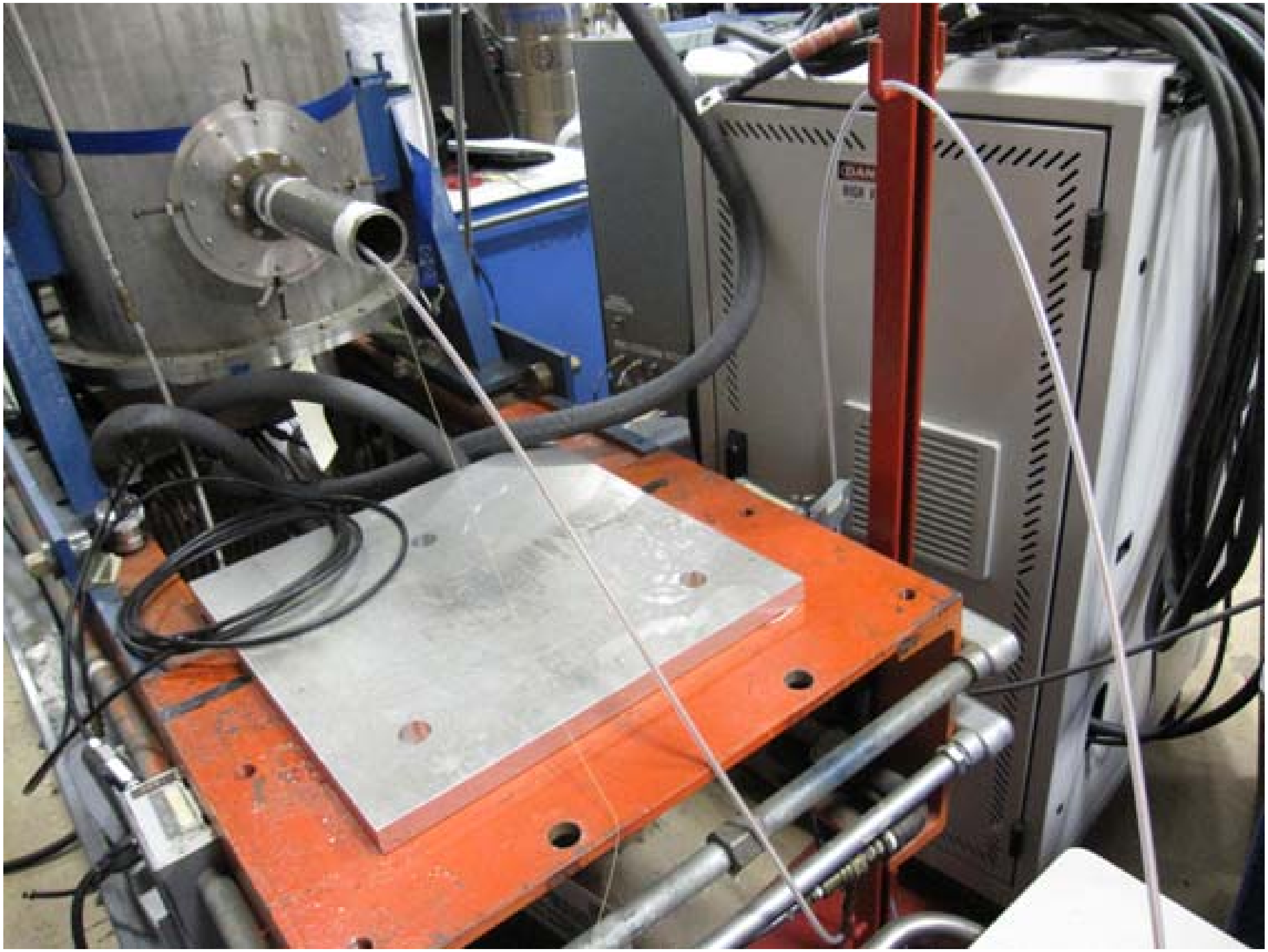
Phosphor-bronze ('non-magnetic') flexible shaft within Teflon housing driven by step motor.

Procured two 5 meter-long and one 2.5m-long sections (SS White Corp. – also had bid from Suhner for 316L SS shaft).

These can be coupled end-to-end via set screws on the phosphor-bronze end-fittings. (Torque required to damage shaft > 12 lb-in. (as per design calc.) - in practice we include intermediate couplers that will yield below this)




WIN
ICK-GRIP

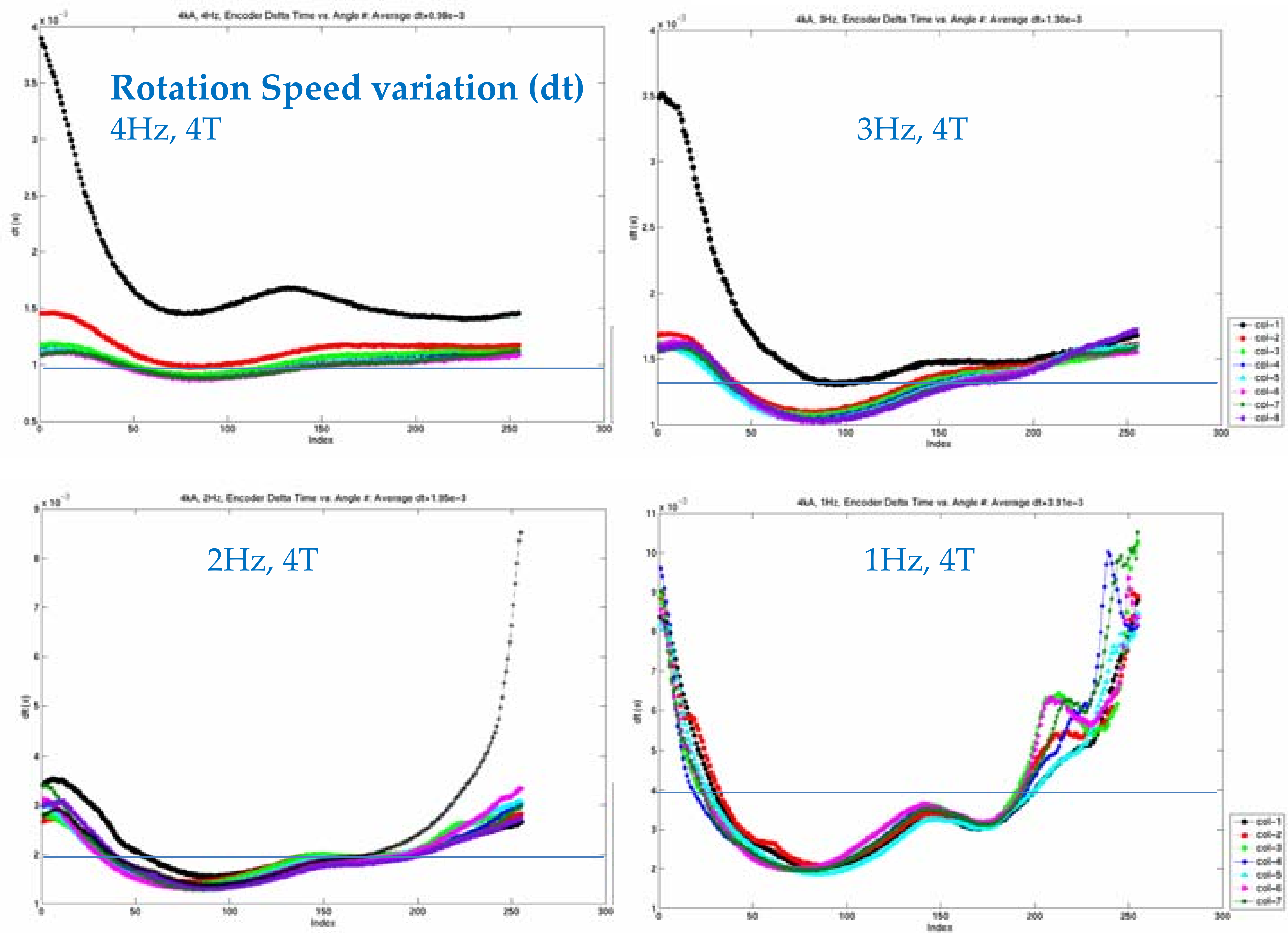


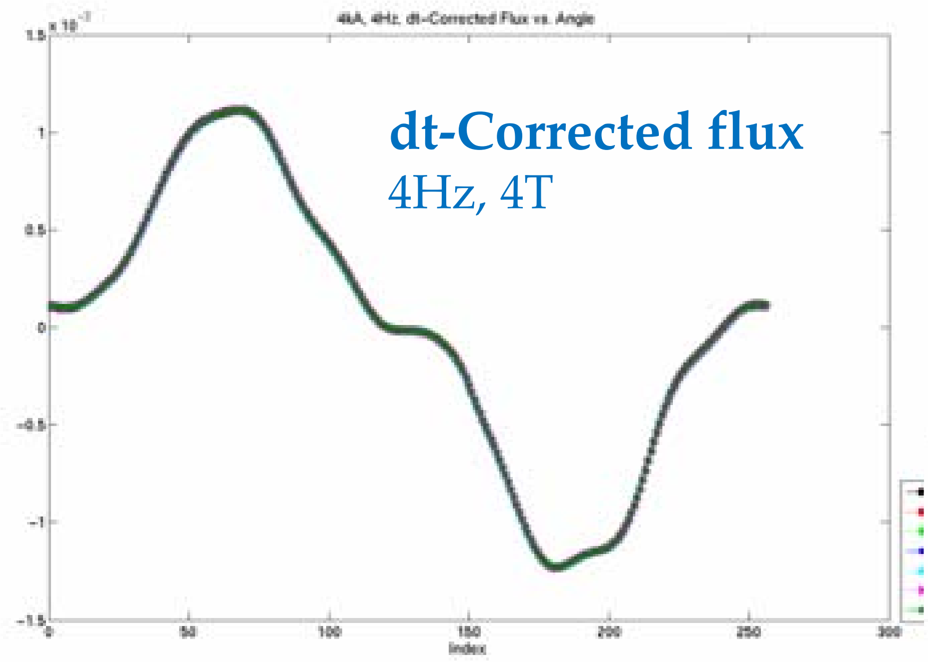
Motor/Flex-drive (cont.)

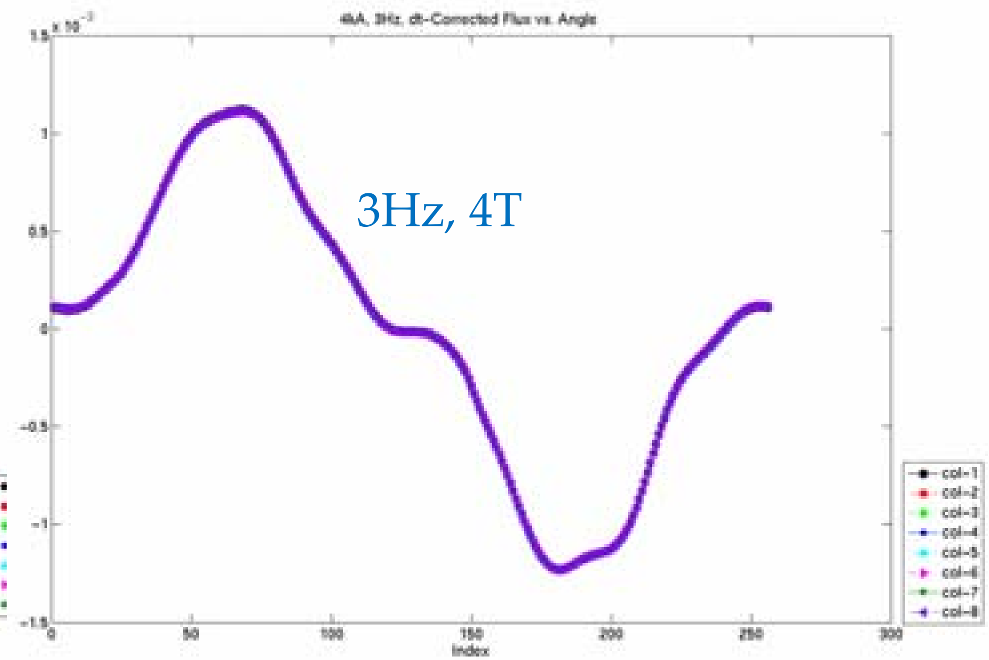
- Able to make measurements at **1, 2, 3, and 4Hz rotation rates** at fields between **0 and 4.7 Tesla**. (4Hz limitation from slip-ring specification).

- There can be considerable variation in angular velocity during rotations ➔ but these do not affect the measured flux…

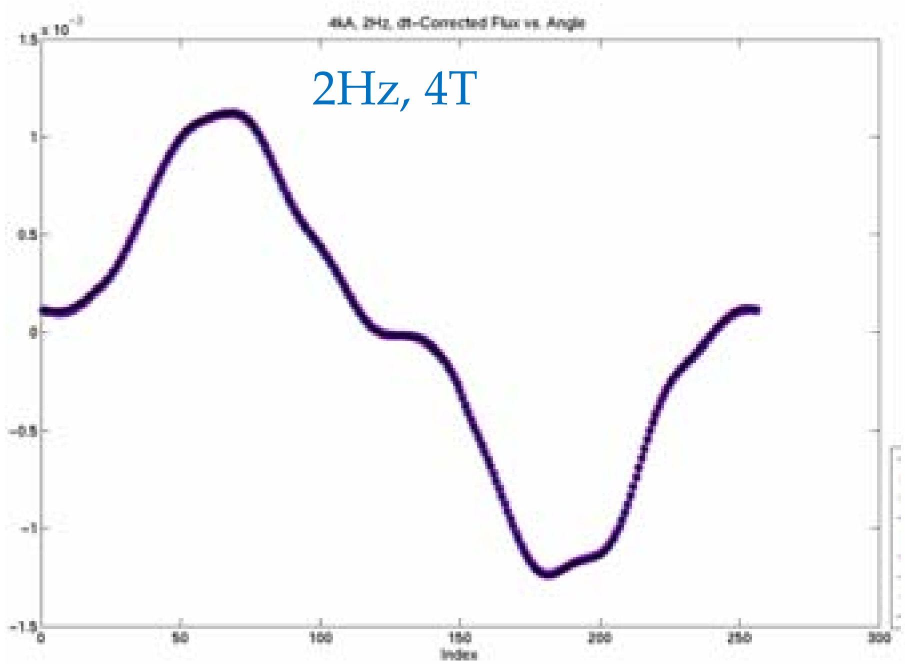
Rotation Speed variation (dt)

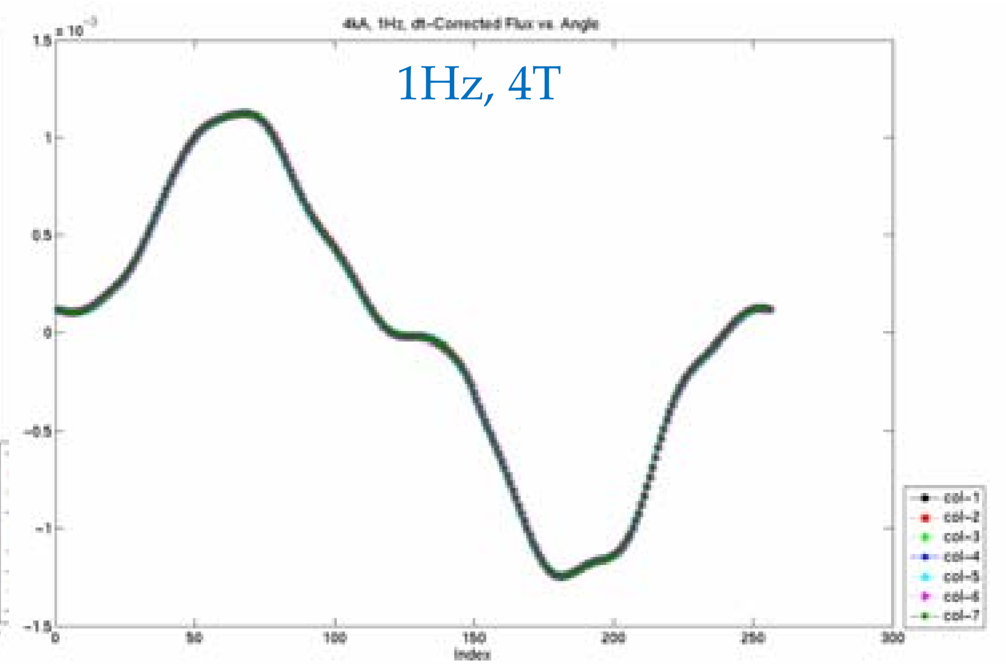




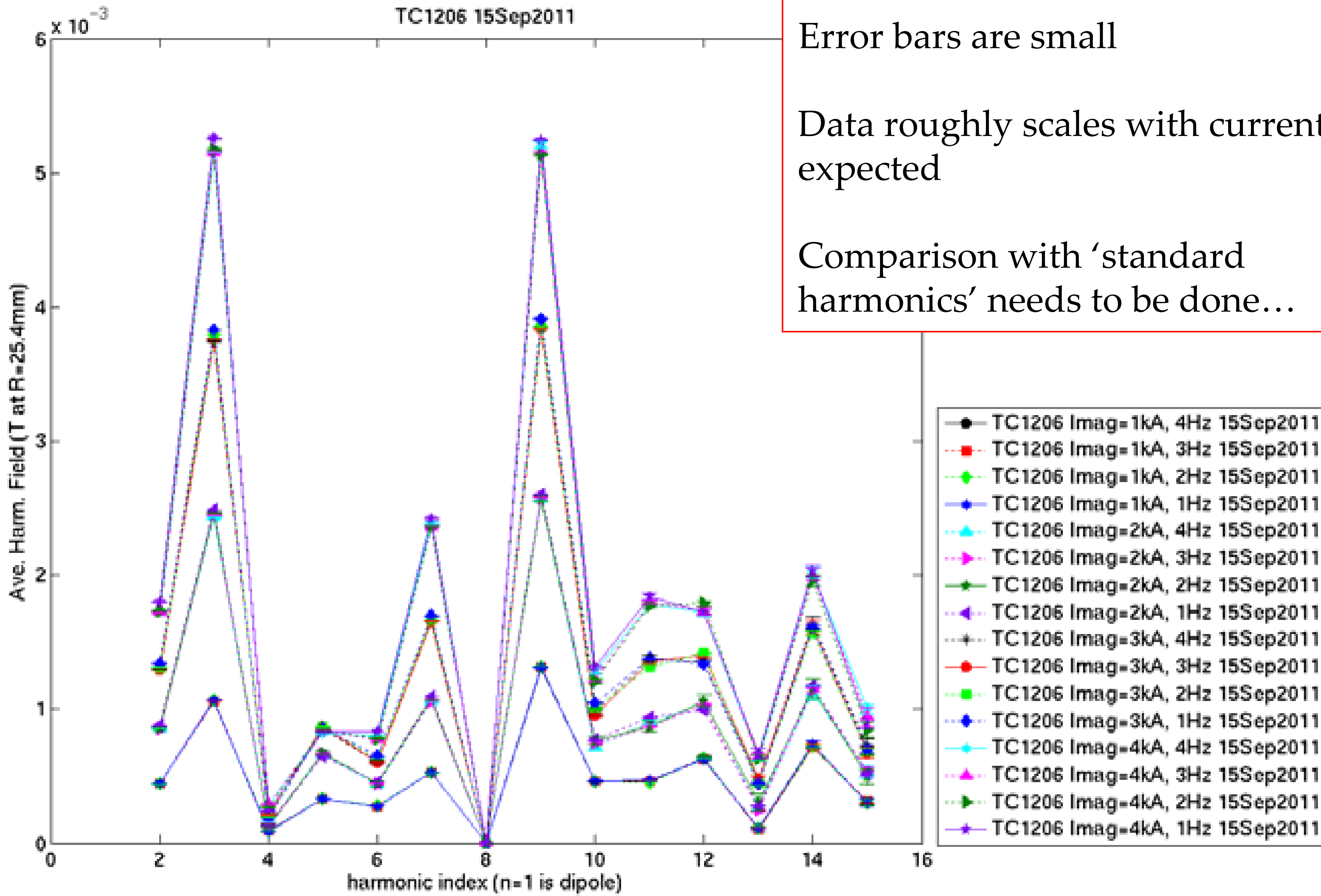


Bucking ratio ~650





High-Field Harmonics



At a given current, measurements with different rotation rate agree well.

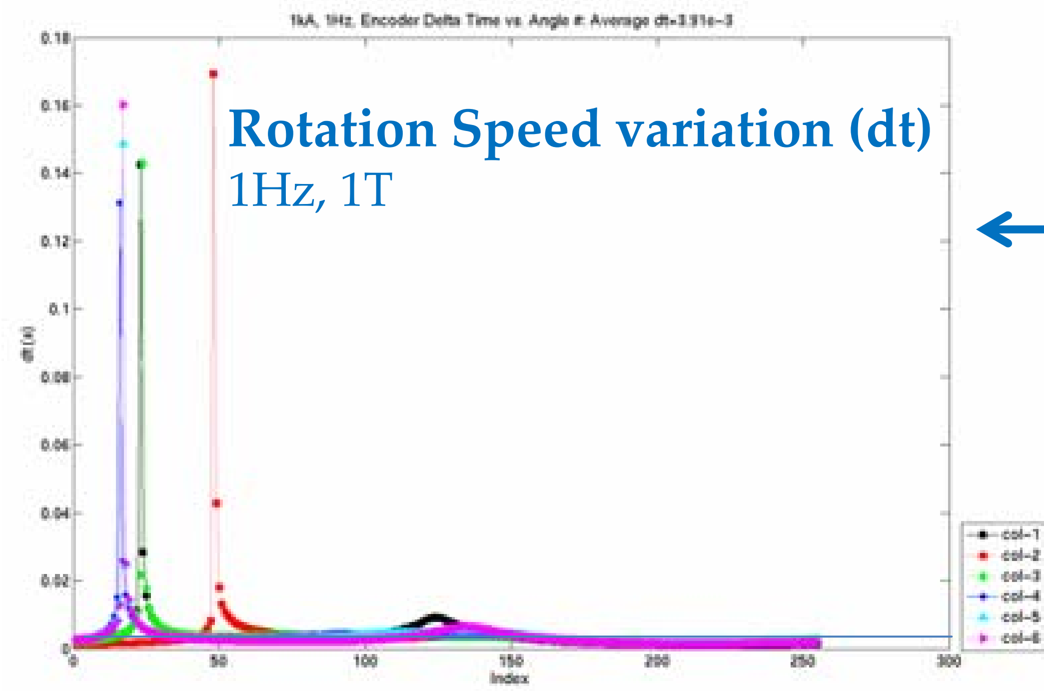
Error bars are small

Data roughly scales with current as expected

Comparison with 'standard harmonics' needs to be done…

Field effects on flex drive

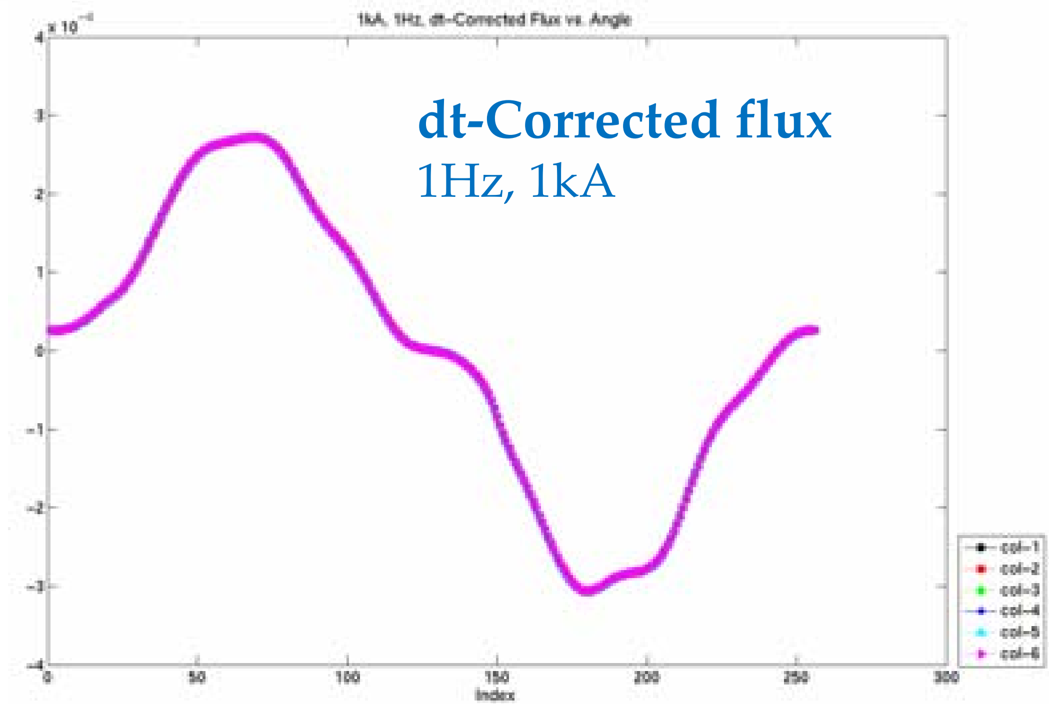
- **Observe signs of force effects at higher fields**. For example, for request of 10 rotations, at 4Hz rotation rate, get 1 less rotation at 4T than at 1T
- Consistent with magnitude of dB/dt needed to induce eddy current fields on stainless steel (316L) beam tubes ➔ 10-20 T/s
  (immw16 presentation)
- 1Hz rotation gets ***more*** uniform at high field



1Hz rotation much less smooth at 1kA than 4kA (dt max. is ~160ms when average is ~4ms).

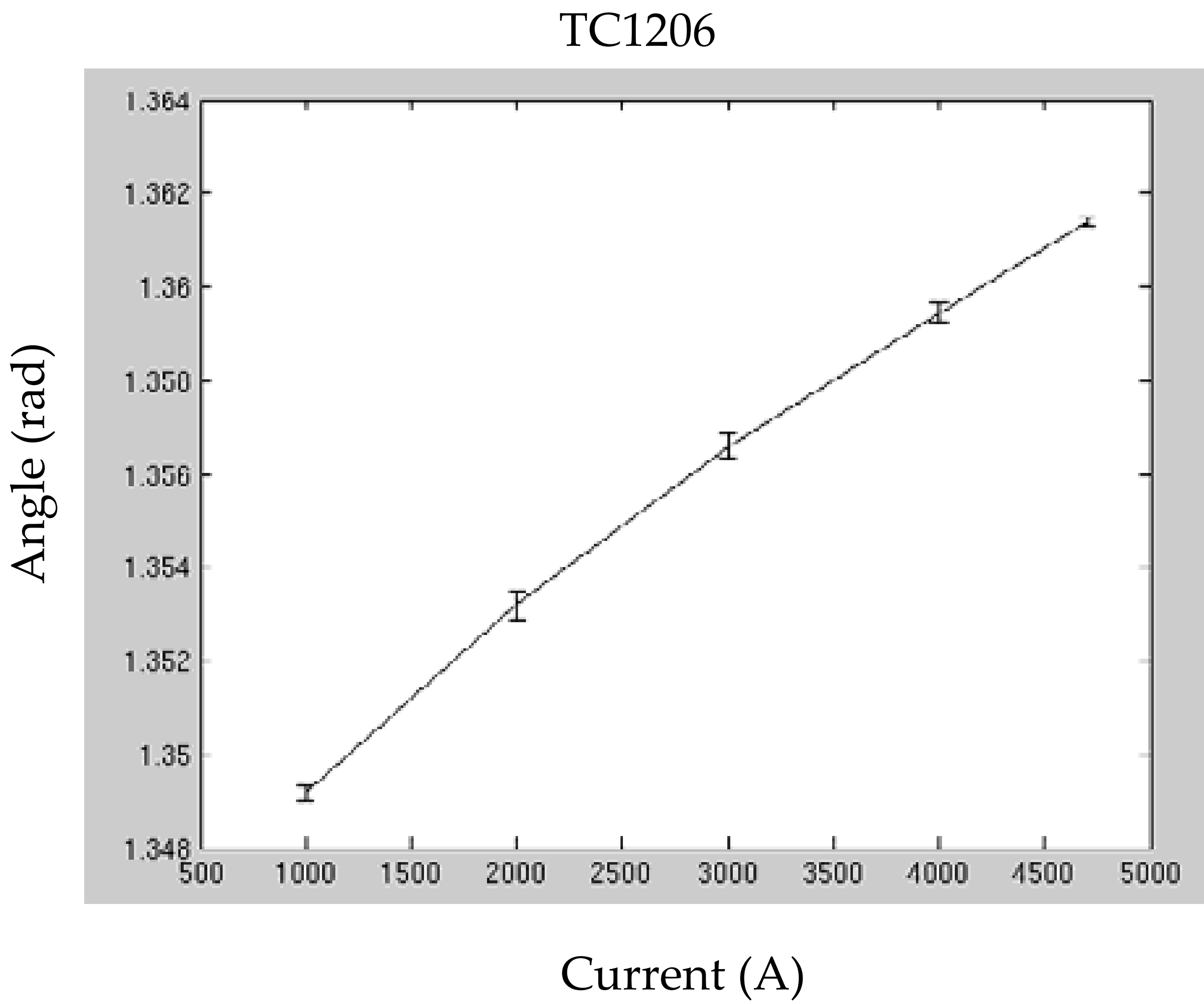
Probably magnetic resistance requires more 'wind-up' of flex shaft at higher fields → this may be at the same or greater level needed to overcome resistance forces in the mechanics, and so gets smoother…

(Note that flux after correction is still ok) →



Gravity sensor

- MEMS chip with XY accelerometers (ADXL203EB, 20x20mm)
- Performs well – minimal field effects to 4.7T
- Resolution is < 1mrad “DC”
- Also provides vibration information about probe.



Gravity sensor reports a change of about 13mrad in the probe angle during excitation from 1kA to 4700A.

Still determining if this is an instrumentation effect in response to the field, or an actual change

In Summary…

- Ferret system is up and running
- Seems capable of good measurements in low and high fields (high field comparison still in progress…)
- Adaptable to different size apertures
- Major components tested and seem to be adequate
- Flex shaft concept with correction for non-uniform motion works.
- Measurements performed at 4Hz rotation rate with 5m of 12.5m flex shaft exposed to 4T field.