Effect of rectangular coil windings on magnetic field measurement using rotating coils system

Laurent Deniau, CERN-LHC/MTA

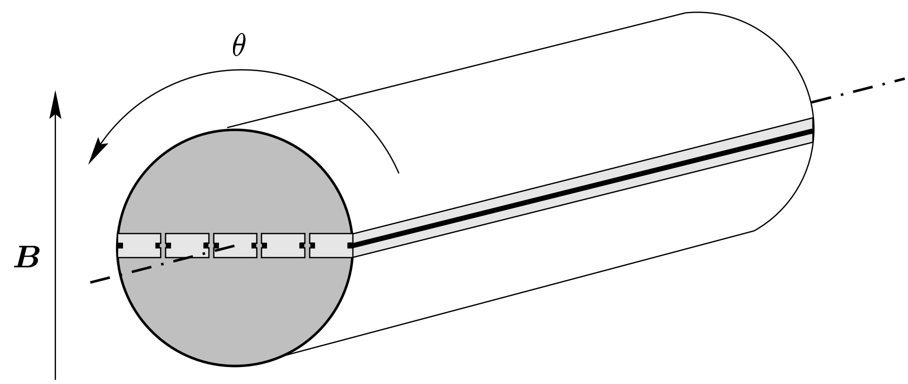
September 1999

Laurent.Deniau@cern.ch

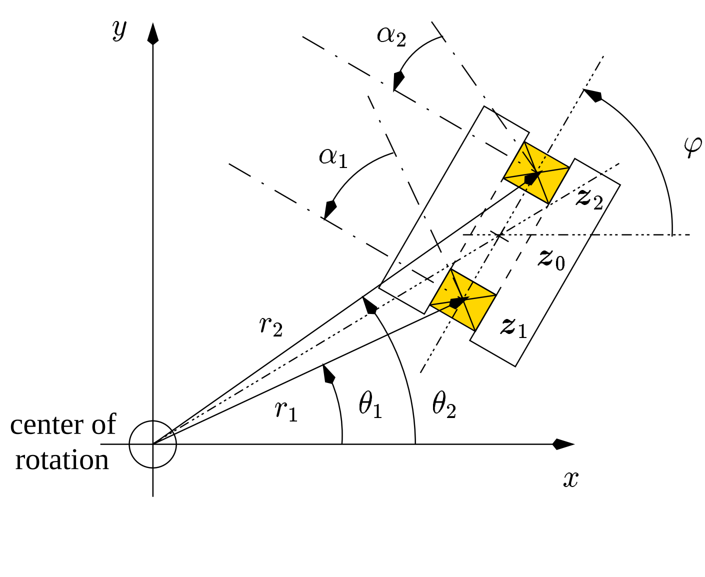
LHC - MTA

Field measurement with rotating coils system

Rotating shaft



Coil in the shaft (cross-section)



Filamentary approximation

Filamentary coil flux

$$\psi(t,\theta(t)) = N_t L \,\mathrm{Re}\left[\sum_{n=1}^{\infty} \frac{\boldsymbol{C}_n(t)}{n R_{ref}^{n-1}} (\boldsymbol{z}_2^n - \boldsymbol{z}_1^n)\, e^{i\,n\theta(t)}\right]$$

where $\boldsymbol{C}_n(t)$ are the field harmonics (MEASURED)

$\theta(t)$	is the coil angular position (KNOWN)
R_{ref}	is the reference radius (FIXED, 17mm for LHC)
L	coil length (UNKNOWN)
N_t	number of turn of the coil winding (KNOWN)
$\boldsymbol{z}_1$	cross-section position of the internal filament (UNKNOWN)
$\boldsymbol{z}_2$	cross-section position of the external filament (UNKNOWN)

Coil geometric factors

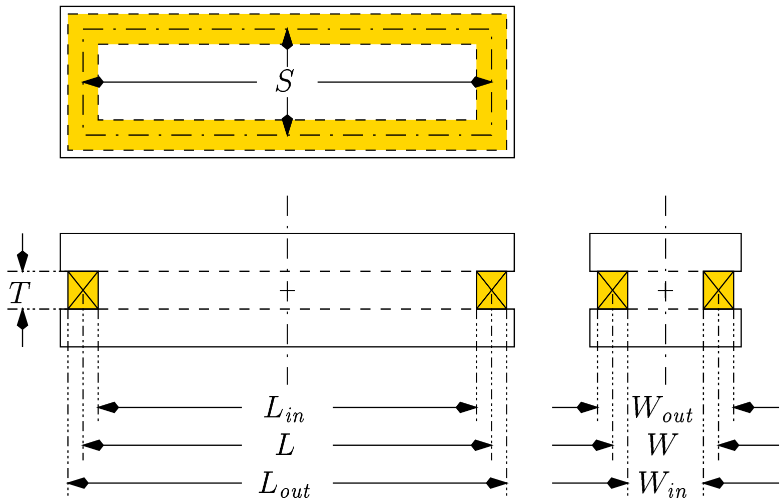
$$\boxed{\boldsymbol{\chi}_n = \boldsymbol{z}_2^n - \boldsymbol{z}_1^n}$$

Coil sensitivity factors

$$\boxed{\boldsymbol{\kappa}_n = \frac{N_t L}{n}\,\boldsymbol{\chi}_n}$$

Getting sensitivity factors (part I)

Dimensions of the coil (known)



☞ The MAGNETIC SURFA CE S of the coil measured at 10^{-4}m^2 in a reference dipole.

☞ The INNER LENGTH L_{in} of the coil known at 10^{-4}m from drawings.

☞ The INNER WIDTH W_{in} of the coil known at 10^{-4}m from drawings.

☞ The THICKNESS T of the groov e known at 10^{-4}m from drawings.

☞ The NUMBER OF TURNS N_t of the coil winding.

Position of the coil inside the head (known)

☞ The RADIUS r_0 from the center of rotation to the magnetic center $\boldsymbol{z}_0 = r_0\, e^{i\,\theta_0}$ of the coil known at 10^{-4}m.

☞ The RELATIVE P ARALLELISM φ_p of the coil with respect to the other coils known at 10^{-4}rad.

What we don't know !

☞ The COIL LENGTH L.

☞ The COIL WIDTH W.

☞ The COIL AXIAL TILT φ.

☞ The FILAMENTS POSITIONS $\boldsymbol{z}_1$ and $\boldsymbol{z}_2$ (deduced from $\boldsymbol{z}_0$, W and φ).

Getting sensitivity factors (part II)

Assumptions

- ☞ Coil winding thickness being constant everywhere $L - L_{in} = W - W_{in}$.
- ☞ Axial tilt equal to the relative parallelism $\varphi = \varphi_p$.

Deductions

- ☞ $\boxed{L \text{ and } W}$

$$\begin{cases} L - L_{in} = W - W_{in} \\ S = N_t L W \end{cases} \Longrightarrow \begin{cases} L = \dfrac{1}{2}\left[L_{in} - W_{in} + \sqrt{(L_{in} - W_{in})^2 + \dfrac{4S}{N_t}}\right] \\ W = \dfrac{1}{2}\left[W_{in} - L_{in} + \sqrt{(W_{in} - L_{in})^2 + \dfrac{4S}{N_t}}\right] \end{cases}$$

- ☞ $\boxed{\boldsymbol{z}_1 \text{ and } \boldsymbol{z}_2}$

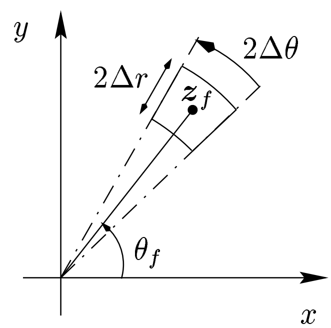
$$\begin{aligned} \boldsymbol{z}_0 &= r_0\, e^{i\,\theta_0}, \quad \Delta\boldsymbol{z}_0 = \frac{W}{2}\, e^{i\,\varphi} \\ \boldsymbol{z}_1 &= r_1\, e^{i\,\theta_1} = \boldsymbol{z}_0 - \Delta\boldsymbol{z}_0 \\ \boldsymbol{z}_2 &= r_2\, e^{i\,\theta_2} = \boldsymbol{z}_0 + \Delta\boldsymbol{z}_0 \end{aligned}$$

- ☞ $\boxed{\Delta\boldsymbol{z}}$ (winding half size, needed later)

$$\Delta\boldsymbol{z} = \frac{W - W_{in}}{2} + i\,\frac{T}{2}$$

We can now compute the sensitivity factors !

Rectangular coil winding
Sector approximation



Sector surface

$$S = \int_{\text{sect}} d\boldsymbol{z} = \int_{r_f-\Delta r}^{r_f+\Delta r} \left(\int_{\theta_f-\Delta\theta}^{\theta_f+\Delta\theta} r d\theta \right) dr = 4\, r_f \Delta r \Delta\theta$$

Sector center of mass

$$\begin{aligned} \boldsymbol{z}_g &= \frac{1}{S} \int_{\text{sect}} \boldsymbol{z}\, d\boldsymbol{z} = \frac{1}{S} \int_{r_f-\Delta r}^{r_f+\Delta r} \left(\int_{\theta_f-\Delta\theta}^{\theta_f+\Delta\theta} \boldsymbol{z}\, r d\theta \right) dr \\ &= \boldsymbol{z}_f \, \frac{2\sin(\Delta\theta)}{3\Delta\theta} \, \frac{(1+\xi)^3 - (1-\xi)^3}{\xi} \end{aligned}$$

where $\xi = \frac{\Delta r}{r_f}$.

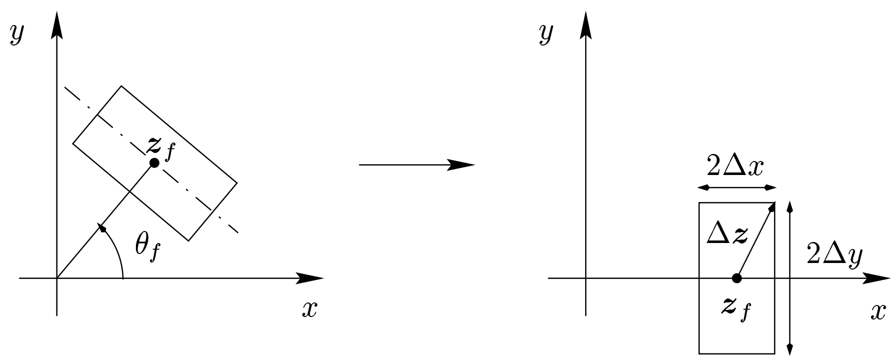
Sector vs Filamentary approximation

$$\begin{aligned} \boldsymbol{z}_s^n =< \boldsymbol{z}_f^n >_{\text{sect}} &= \frac{1}{S} \int_{\text{sect}} \boldsymbol{z}^n \, d\boldsymbol{z} \\ &= \frac{1}{S} \int_{r_f-\Delta r}^{r_f+\Delta r} \left(\int_{\theta_f-\Delta\theta}^{\theta_f+\Delta\theta} (r\, e^{i\,\theta})^n \, r d\theta \right) dr \\ &= \boldsymbol{z}_f^n \, \frac{\sin(n\Delta\theta)}{2n(n+2)\Delta\theta} \, \frac{(1+\xi)^{n+2} - (1-\xi)^{n+2}}{\xi} \end{aligned}$$

$$\boxed{\boldsymbol{z}_s^n = \,,_s\, \boldsymbol{z}_g^n}$$

where $,_s = \dfrac{3^n \Delta\theta^{n-1}}{2n(n+2)} \, \dfrac{\sin(n\Delta\theta)}{\sin(\Delta\theta)^n} \, \dfrac{(1+\xi)^{n+2} - (1-\xi)^{n+2}}{\xi\,(3+\xi^2)^n}$

Rectangular coil winding
Rectangular approximation



Pa rameters

$$\begin{cases} z_f & = r_f\, e^{i\,\theta_f} \\ \Delta z & = \Delta x + i\,\Delta y \\ S & = 4\Delta x \Delta y = -i\,[(\Delta z)^2 - (\Delta z^*)^2] \end{cases}$$

Rectangular vs Filamentary approximation

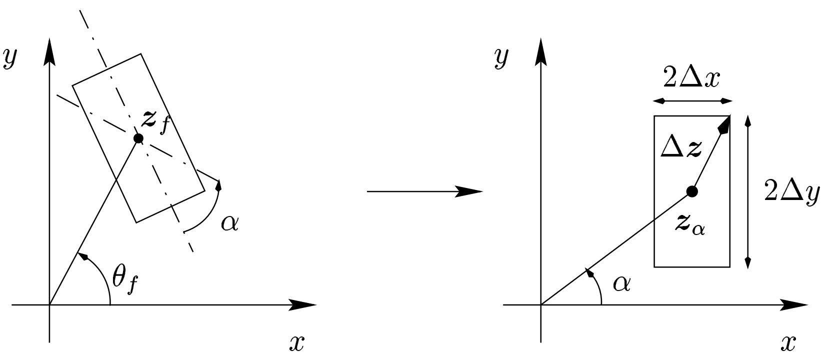
$$\begin{aligned} z_r^n =< z_f^n >_{\mathrm{rect}_\theta} &= \frac{1}{S}\int_{\mathrm{rect}_\theta} z^n\, dz \\ &= \frac{e^{i\,n\theta_f}}{S}\int_{-\Delta y}^{\Delta y}\left(\int_{r_f-\Delta x}^{r_f+\Delta x}(x+i\,y)^n\,dx\right)\,dy \\ &= z_f^n\,\frac{r_f^2}{i\,S(n+1)(n+2)}\times \\ &\quad \left[(1+\frac{\Delta z}{r_f})^{n+2} + (1-\frac{\Delta z}{r_f})^{n+2} - (1+\frac{\Delta z^*}{r_f})^{n+2} - (1-\frac{\Delta z^*}{r_f})^{n+2}\right] \end{aligned}$$

$$\boxed{z_r^n = \,,_r\, z_f^n}$$

where $,_r = \dfrac{(1+\xi)^{n+2} + (1-\xi)^{n+2} - (1+\xi^*)^{n+2} - (1-\xi^*)^{n+2}}{(n+1)(n+2)(\xi^2 - \xi^{*2})}$

and with $\xi = \dfrac{\Delta z}{r_f}$ and $\xi^* = \dfrac{\Delta z^*}{r_f}$

Rectangular coil winding
Rectangular with tilt approximation



Pa rameters

$$\begin{cases} \boldsymbol{z}_f &= \boldsymbol{z}_\alpha\, e^{i\,(\theta_f-\alpha)} \\ \boldsymbol{z}_\alpha &= x_\alpha + i\,y_\alpha \\ \Delta\boldsymbol{z} &= \Delta x + i\,\Delta y \\ S &= 4\Delta x\Delta y = -i\,[(\Delta\boldsymbol{z})^2 - (\Delta\boldsymbol{z}^*)^2] \end{cases}$$

Rectangular with tilt vs Filamentary approximation

$$\begin{aligned} \boldsymbol{z}_r^n =< \boldsymbol{z}_f^n >_{\mathrm{rect}_{\theta,\alpha}} &= \frac{1}{S}\int_{\mathrm{rect}_{\theta,\alpha}} \boldsymbol{z}^n\, d\boldsymbol{z} \\ &= \frac{e^{i\,n(\theta_f-\alpha)}}{S}\int_{y_\alpha-\Delta y}^{y_\alpha+\Delta y}\left(\int_{x_\alpha-\Delta x}^{x_\alpha+\Delta x}(x+i\,y)^n\,dx\right)\,dy \\ &= \boldsymbol{z}_f^n\,\frac{\boldsymbol{z}_\alpha^2}{i\,S(n+1)(n+2)} \\ &\quad \left[(1+\frac{\Delta\boldsymbol{z}}{\boldsymbol{z}_\alpha})^{n+2} + (1-\frac{\Delta\boldsymbol{z}}{\boldsymbol{z}_\alpha})^{n+2} - (1+\frac{\Delta\boldsymbol{z}^*}{\boldsymbol{z}_\alpha})^{n+2} - (1-\frac{\Delta\boldsymbol{z}^*}{\boldsymbol{z}_\alpha})^{n+2}\right] \end{aligned}$$

$$\boxed{\boldsymbol{z}_r^n = \,,\,_r(\alpha)\,\boldsymbol{z}_f^n}$$

where $,\,_r(\alpha) = \dfrac{(1+\xi)^{n+2} + (1-\xi)^{n+2} - (1+\xi^*)^{n+2} - (1-\xi^*)^{n+2}}{(n+1)(n+2)(\xi^2-\xi^{*2})}$

and with $\xi = \dfrac{\Delta\boldsymbol{z}}{\boldsymbol{z}_\alpha}$ and $\xi^* = \dfrac{\Delta\boldsymbol{z}^*}{\boldsymbol{z}_\alpha}$

Remarks on Γ_s, Γ_r and $\Gamma_r(\alpha)$

- ☞ Γ_s depends only on the radius r_f and on the winding sizes Δr and $\Delta\theta$ which all remain constant once the coil is built and glued in tothe head sector. Especially, Γ_s does not depend on θ_f, which is essential for being able to compute the geometric factors $\boldsymbol{\chi}_n$ independently from the coil position !

- ☞ Γ_r depends only on the radius r_f and on the winding size $\Delta \boldsymbol{z}$. Therefore, the abov e remark about the θ_f independence of Γ_s is still v alidfor Γ_r.

- ☞ $\Gamma_r(\alpha)$ is v erysimilar to Γ_r, but with the new parameter α. Taking $\alpha = 0$ gives us $\boldsymbol{z}_\alpha = r_f$ and bring us back to the expression of Γ_r.

Behaviour of correction factors

(2nd and 4th order development of Γ_r and $\Gamma_r(\alpha)$)

- From the Mac-Laurin development of $(1+\xi)^n$ we have:

$$(1+\xi)^n = 1 + n\xi + \frac{n(n-1)}{2!}\xi^2 + \frac{n(n-1)(n-2)}{3!}\xi^3 + \ldots$$

$$[(1+\xi)^n + (1-\xi)^n] - [(1+\xi^*)^n + (1-\xi^*)^n] = \\ n(n-1)(\xi^2 - \xi^{*2})\left[1 + \frac{(n-2)(n-3)}{12}(\xi^2 + \xi^{*2})\right] + \ldots$$

which converges in our case because $|\xi| \leq 1$ and $|\xi^*| \leq 1$ are always true.

- Using these results, we can easily get the firsts order of developments of the rectangular correction factors:

$$\Gamma^{(2)} = \Gamma^{(3)} = 1$$

$$\Gamma^{(4)} = \Gamma^{(5)} = 1 + \frac{n(n-1)}{12}(\xi^2 + \xi^{*2})$$

Dipole sensibility of Γ_r and $\Gamma_r(\alpha)$

- The sensibility of the coil to the dipole field component for rectangular approximation is obtain from the expression of Γ_r by taking $n = 1$:

$$\Gamma_r\Big|_{n=1} = \frac{(1+\xi)^3 + (1-\xi)^3 - (1+\xi^*)^3 - (1-\xi^*)^3}{6(\xi^2 - \xi^{*2})} = 1$$

- As we can see, the correction factor Γ_r is not sensible to the dipole component of the field and we have:

$$\boxed{\boldsymbol{z}_r = \boldsymbol{z}_f}$$

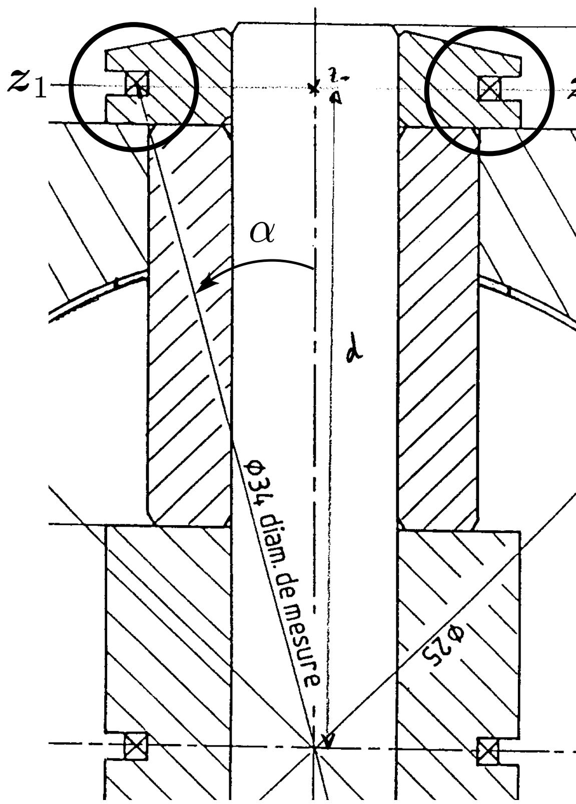
- It is interesting to note that we also have $\Gamma_s\Big|_{n=1} = 1$ because we have expressed $\boldsymbol{z}_s^n$ versus $\boldsymbol{z}_g^n$ instead of $\boldsymbol{z}_f^n$.

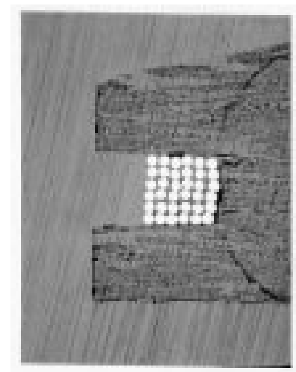
- For quadrupole and the sextupole, we can be easily retrieved the sensibility of Γ_r by using its 4th development:

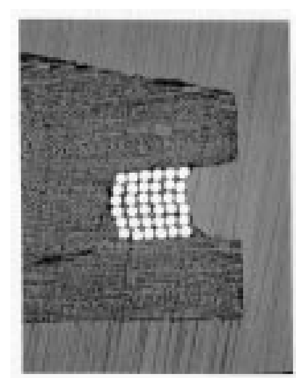
$$\Gamma_r\Big|_{n=2} = 1 + \frac{\xi^2 + \xi^{*2}}{6} \qquad ; \qquad \Gamma_r\Big|_{n=3} = 1 + \frac{\xi^2 + \xi^{*2}}{2}$$

Application to tangential coils

☞ From the figure below we can see the angle α being equal to the half of the opening angle of the tangential coil. For the LHC 15m dipole measurement system, the rotating coil has been designed in order to be *blind* to the harmonic 12.5, giving $2\alpha = 2\pi/12.5 = 28.8$ degres.



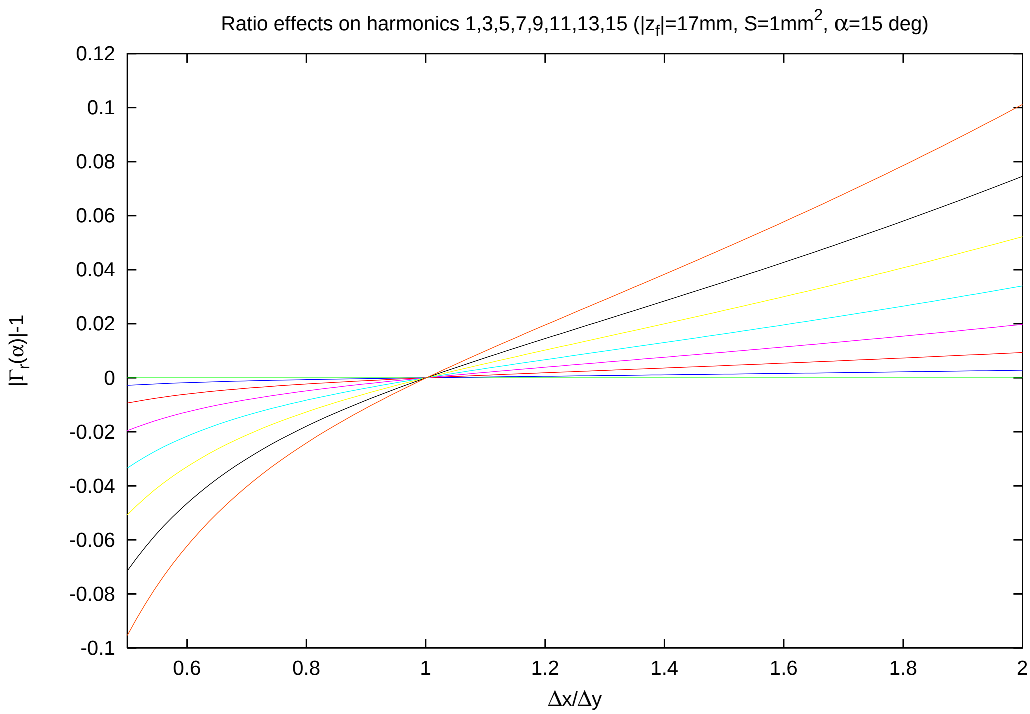


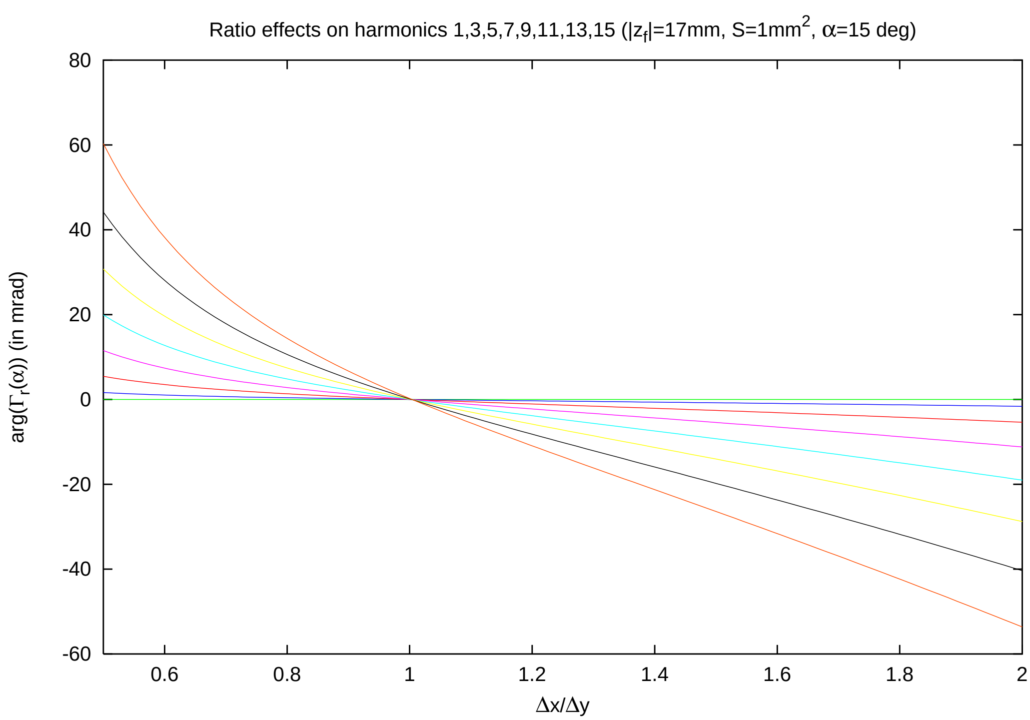


Winding	Turns	Width	Thickness	Surface	Ratio W/T
z_1	36	0.585mm	0.544mm	0.318mm^2	1.076
z_2	36	0.608mm	0.548mm	0.333mm^2	1.110

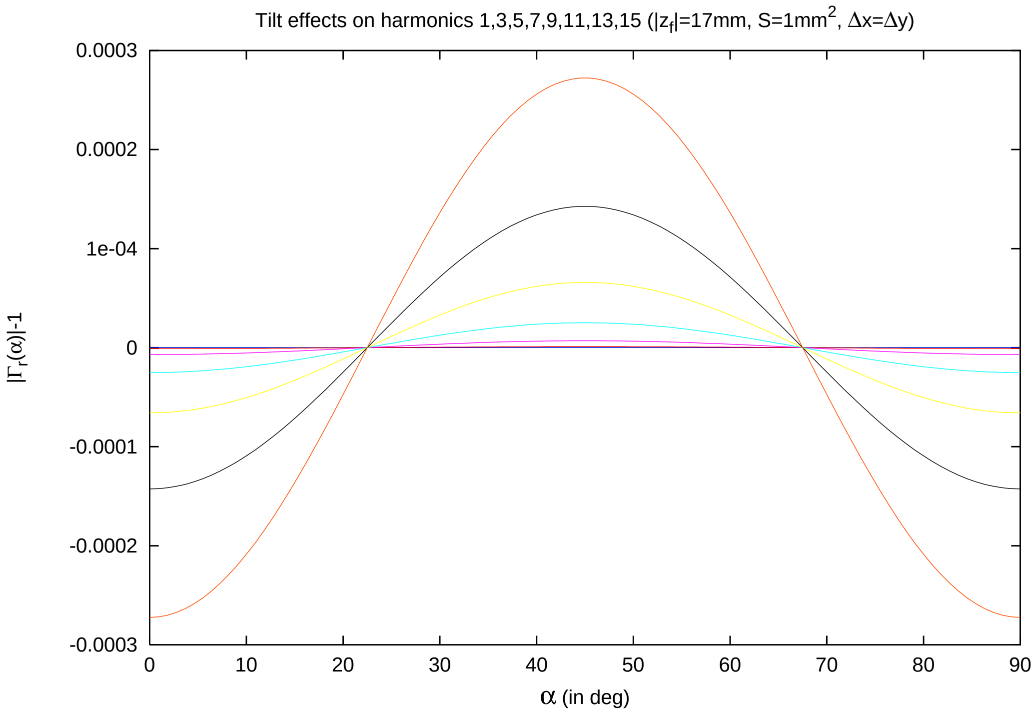
☞ The table above gives the sizes of the windings as well as their surfaces and their sizes ratios measured on the microscope photos shown in the figure above. The winding is made of 36 turns of a single filament with a diameter of 80μm, and wound in an approximate rectangle following the groove's shape.

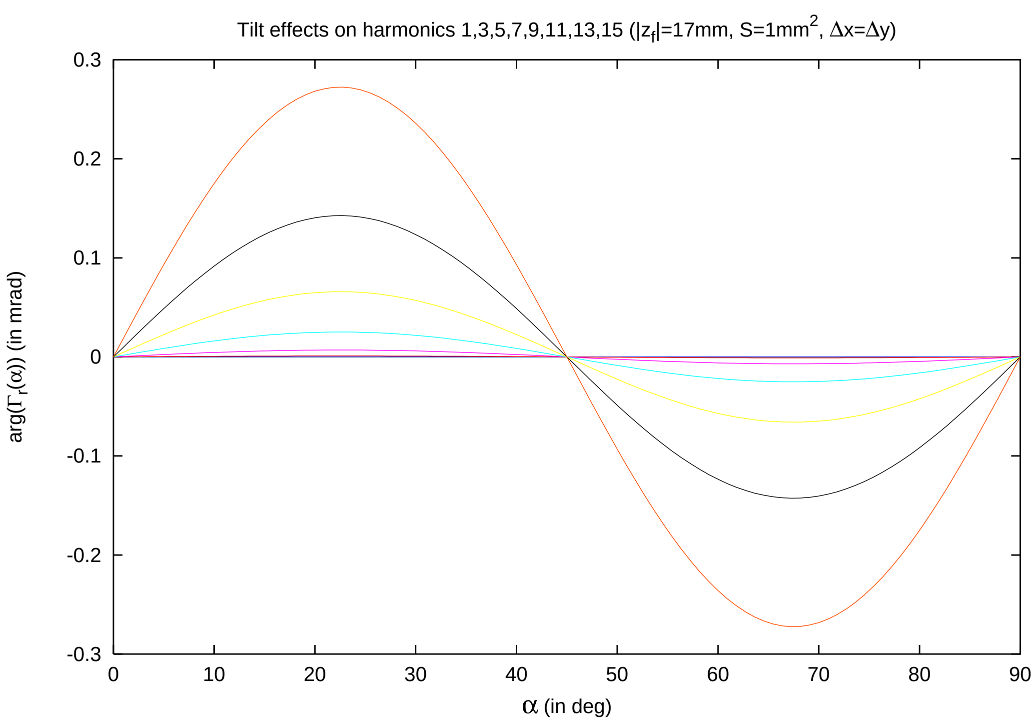
Effect of ratio $\Delta x/\Delta y$





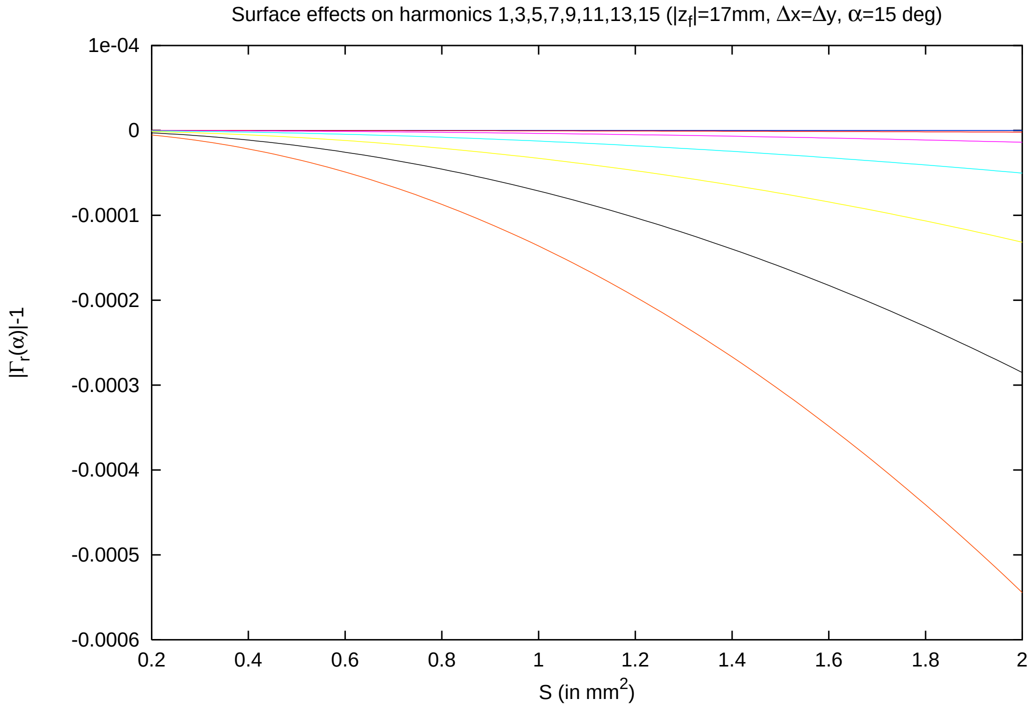
Effect of tilt α

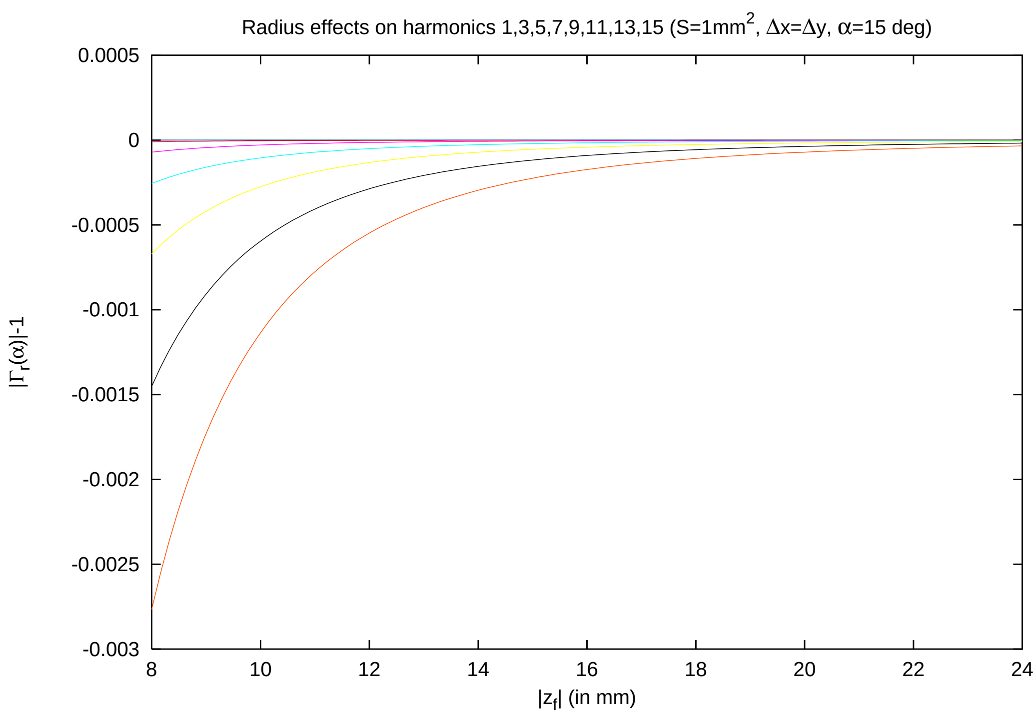




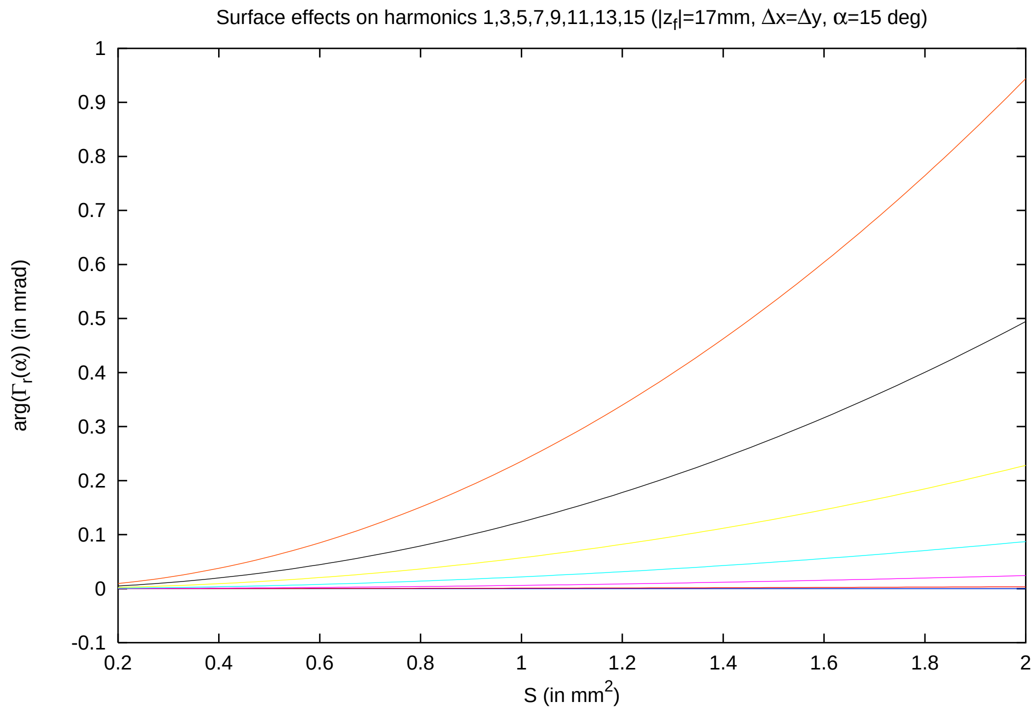
OPTIONAL SLIDES

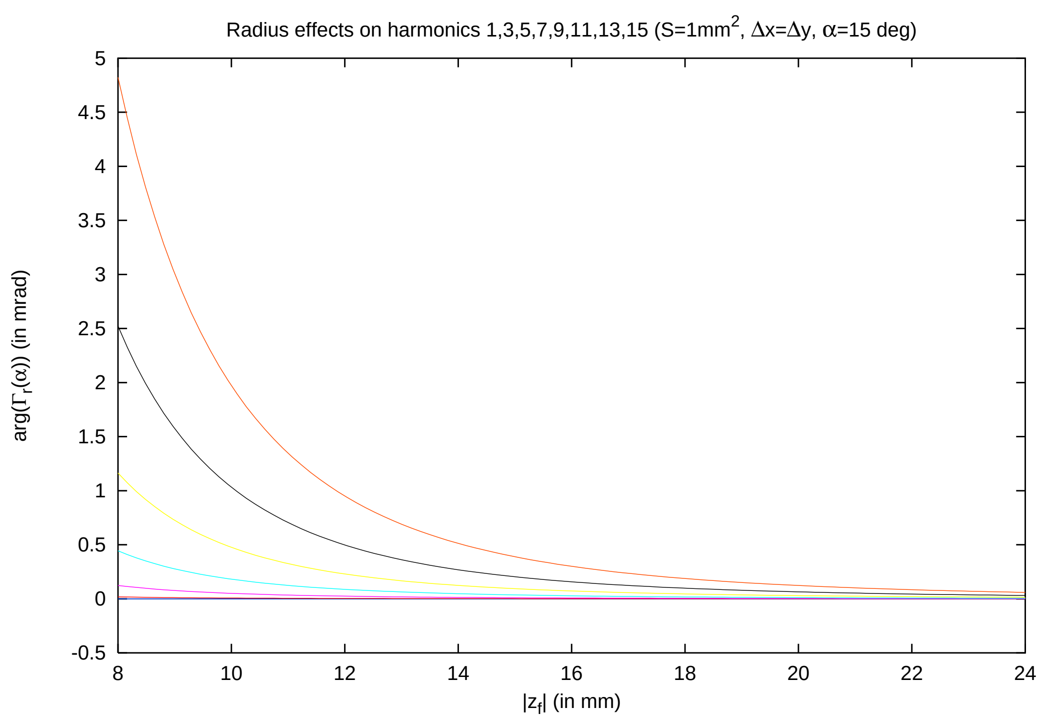
Effect of surface S





Effect of radius $|z_f|$

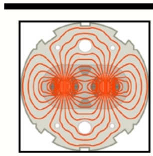


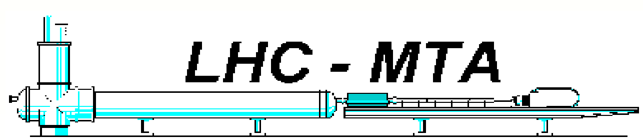


Measurements for the acceptance tests of the LHC superconducting magnets

11th International Magnetic Measurement Workshop
Brookhaven National Laboratory
September 21-24, 1999

Louis Walckiers
CERN , LHC-MTA





LHC Magnets

≈ 1200 Dipole cold masses

- MB — $L_{eff.}$ = 14.3 m
  8.3 T nominal , 0.54 T @ injection , $I_{nom} \approx 11.8$ kA
  twin aperture, cold bore 50 mm , coil aperture 56 mm
- End correctors — MCS (sextupole) MCDO (decapole-octupole)

≈ 400 MQ + 100 MQM or MQY Short Straight Section

- Overall length from 8 to 12 m , Quadr. length from 2.4 to 4.8 m
- More than 60 types of SSS according to correctors
  MSCB , MO , MS , MQT , MCB

MQR, MQX for interaction region (BNL, FNAL, KEK)

Quality Control during Magnet's Fabrication

Interaction with Fabrication process – Magnets at Room temperature

MB in Industry **(LHC-MMS)**

- Field Quality , geometry of coils and structures
- Alignment of end correctors, control of sagitta
- Field direction

MQ & MQM in Industry **(Saclay + LHC-MMS)**

Corrector Magnets

- Check mainly axis reference points and field direction
- In Industry with Cern equipment or at Cern

Reception Tests at Cern

Cold masses in warm or cold condition

Goals

- Alignment between correctors and main magnet after cryostating
- Stability of alignment with temperature, support, …
- Optimisation of magnet's geometry

  Systematic harmonics must be minimum at injection field
- Control of the reproducibility of the field quality

  Uncertainties or bias of averages are feared (b_3, a_3, b_4, a_4, b_5)
- Field quality for all accelerator's conditions (steering of the correctors chains)

  Persistent current & coupling current in superconducting cable,

  saturation effects,

  cross talk in nested windings, due to twin structure or between end fields.

MB Centring

Goals ***MCD's (and MCS's) to align within 0.3 mm***

- Verify sagitta and corrector alignment after cryostating
- Predict steering of the currents in the corrector schemes

Tool : Mole (Fraunhofer IPT, D)

- One pass measurement of field quality, direction, axis

Challenge ***Thermal gradient curves light beam***

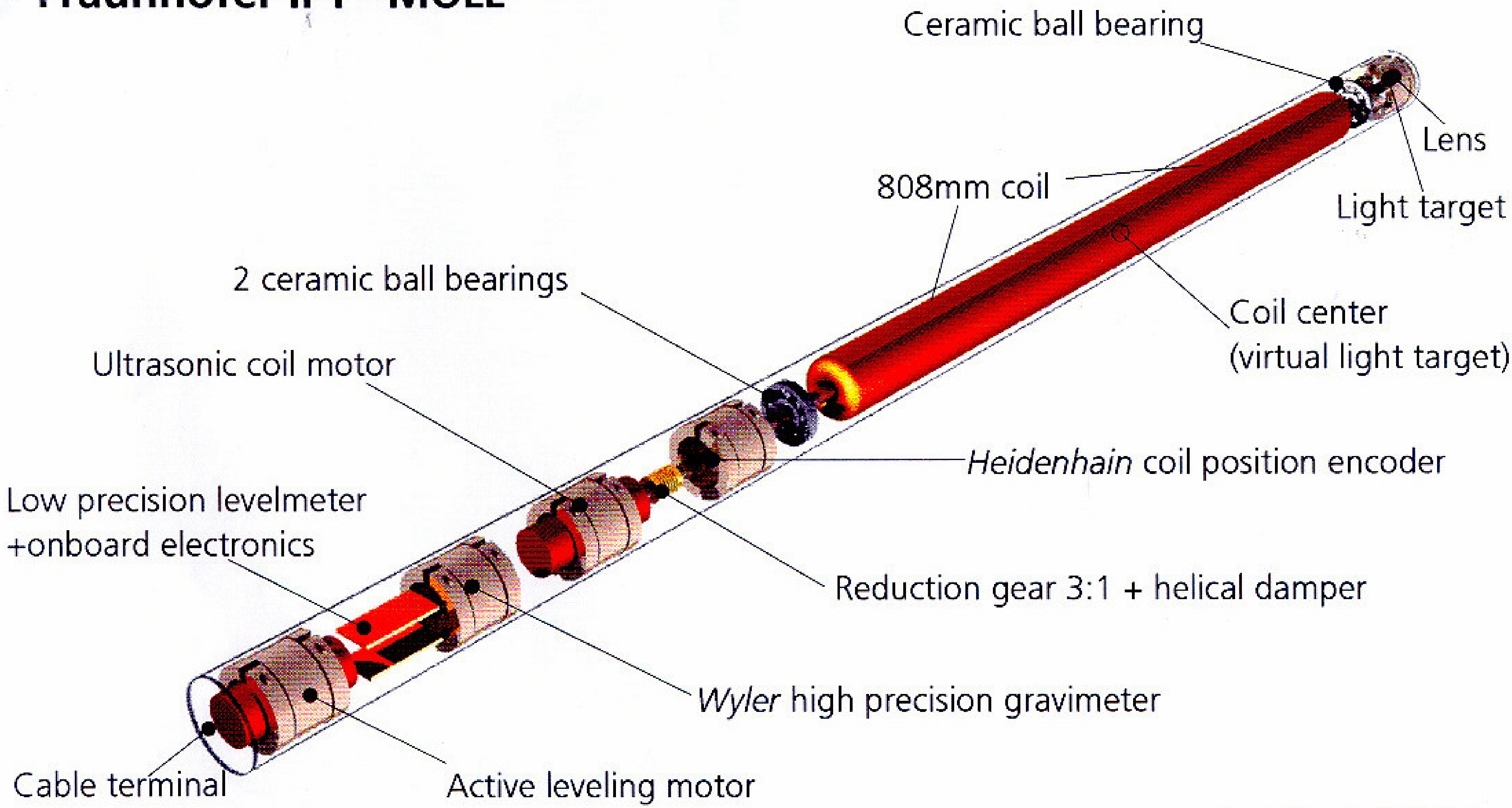
- Low power needed at room temperature (1 A ≈ 0.7 mT , b5 ≈ 1 Unit @ 17 mm)

QCD (Quadrupole Configured Dipole, ugly quadrupole)

Modulation of current during rotation of measuring coil

(reproducible enough for 2 pass measurement)

Fraunhofer IPT "MOLE"



Artist view, 1997

Fraunhofer Institut Produktionstechnologie

CERN

MB Field Quality

Challenge from magnets

- Transposition pitch effects
- Time dependent effects, dynamic effects
- Predict steering of the currents in the corrector schemes

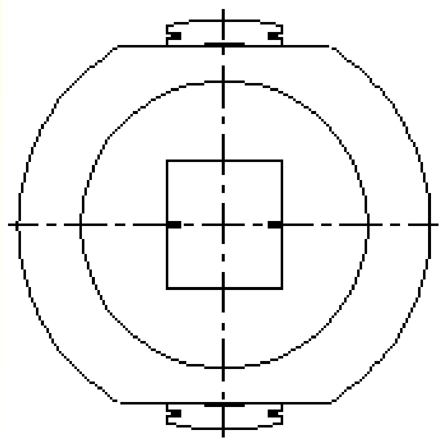
Tool : 15 m shaft for integral measurements

- tangential coil and mid-plane coil of same surface

  3rd coil symmetric

  no preamplifier for compensation

  $\sin(12.5*2\pi/\text{Ap.}) = 0$
- 12 + 1 length, 1.25 m long, gap of 110 mm
- used as well as "quench antenna"



15 m long shaft

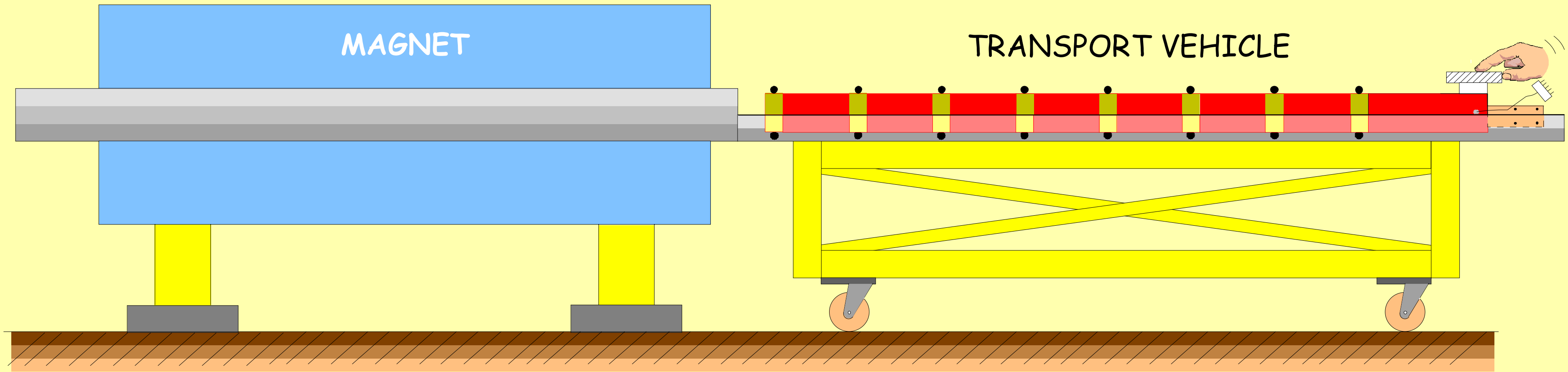
Challenges

- Field direction within 0.5 mrad
- Low torsion during rotation
- Integrated strength within 5.10^{-4}
- 39 coils to connect
- Interchangeable 1.25 m long modules

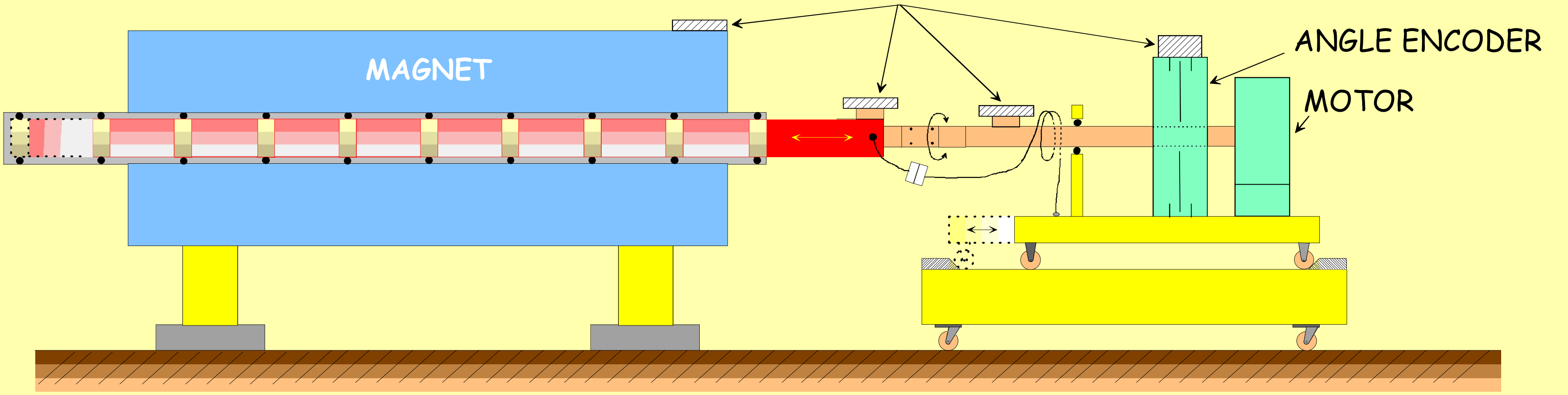
Tools

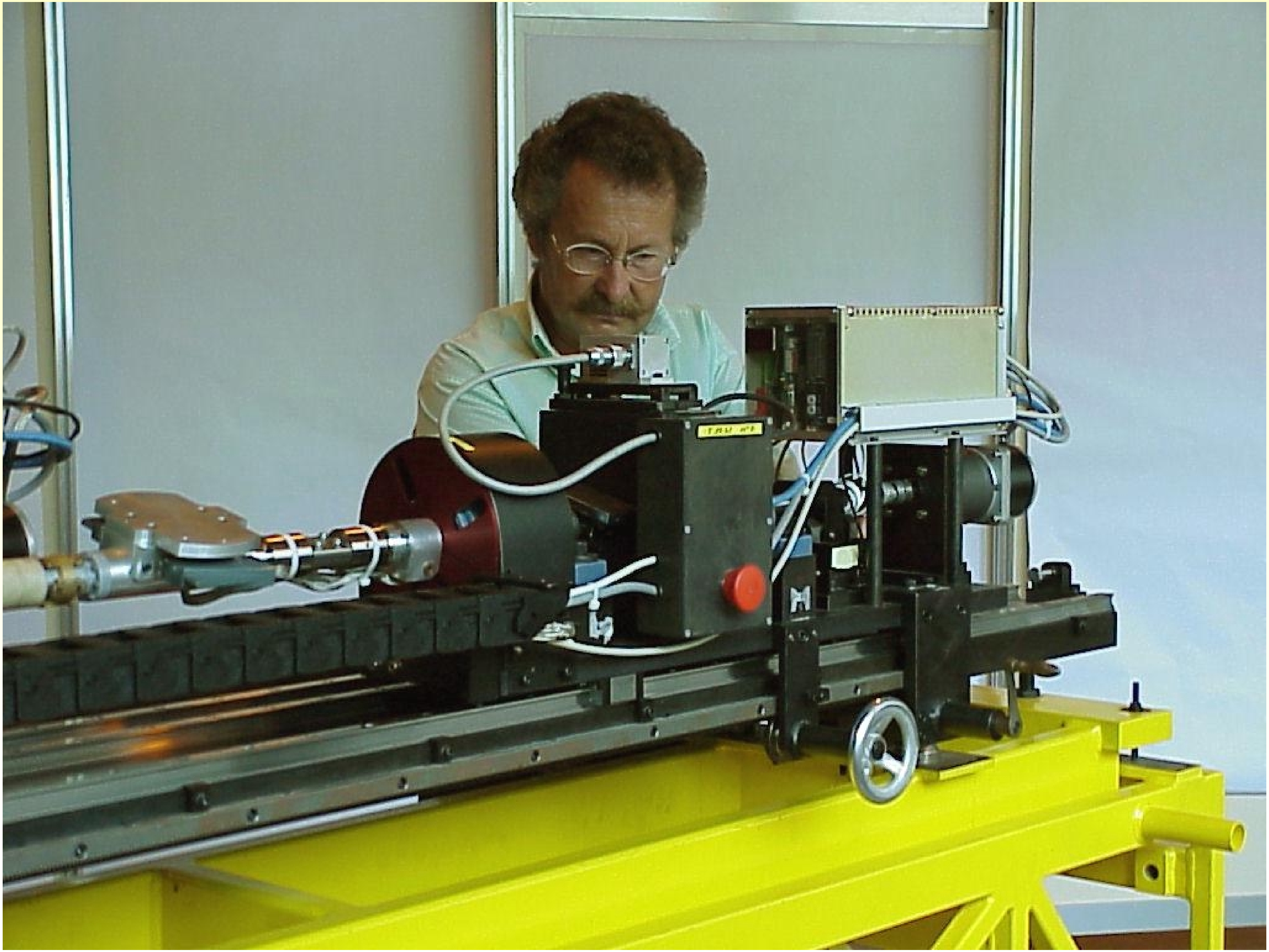
- High precision rotating unit (Britte, Be)
- Ceramic pipes, ceramic ball bearings, miniature connectors,
- Calibration bench

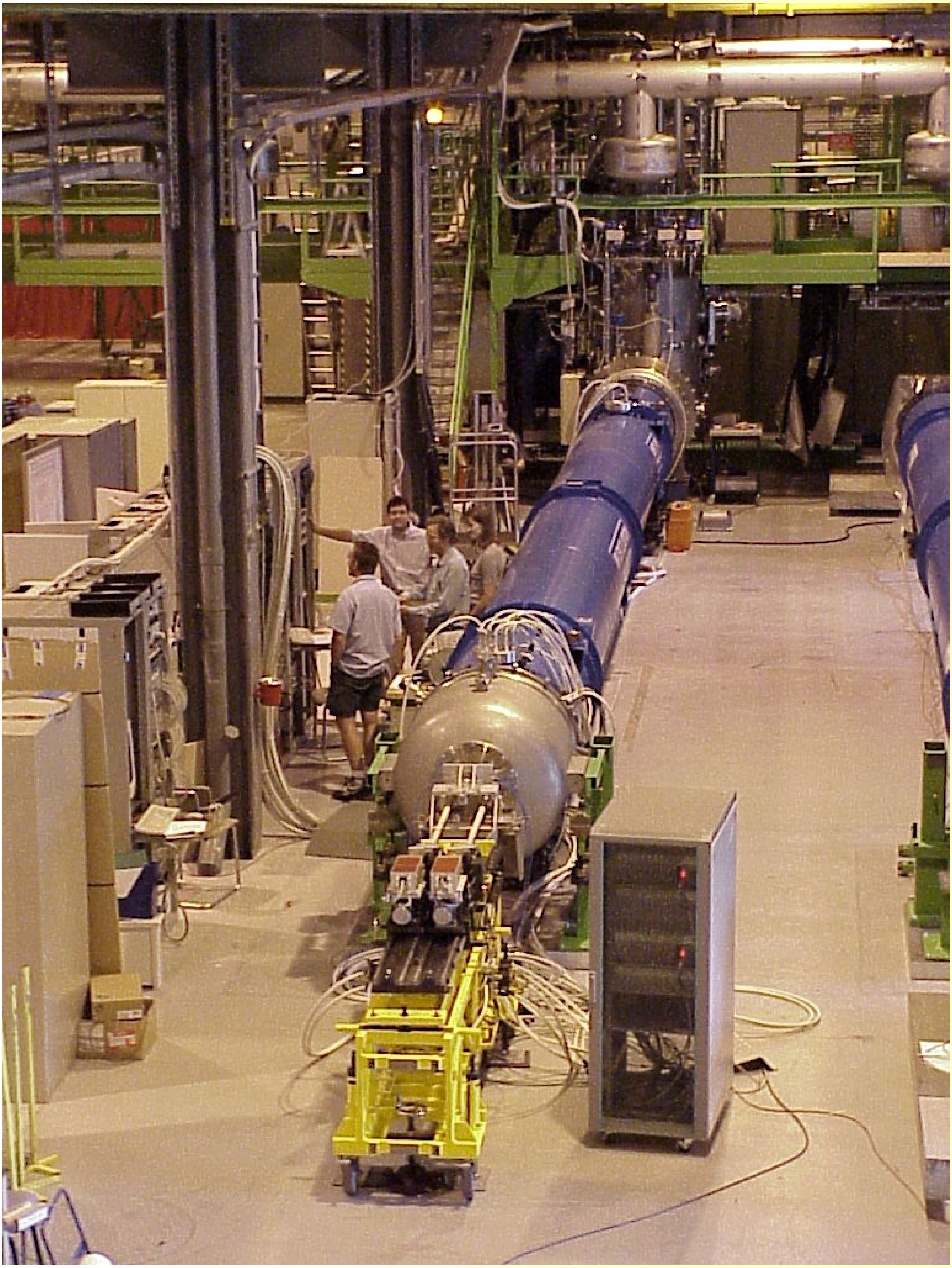
INSTALLATION INTO DIPOLE

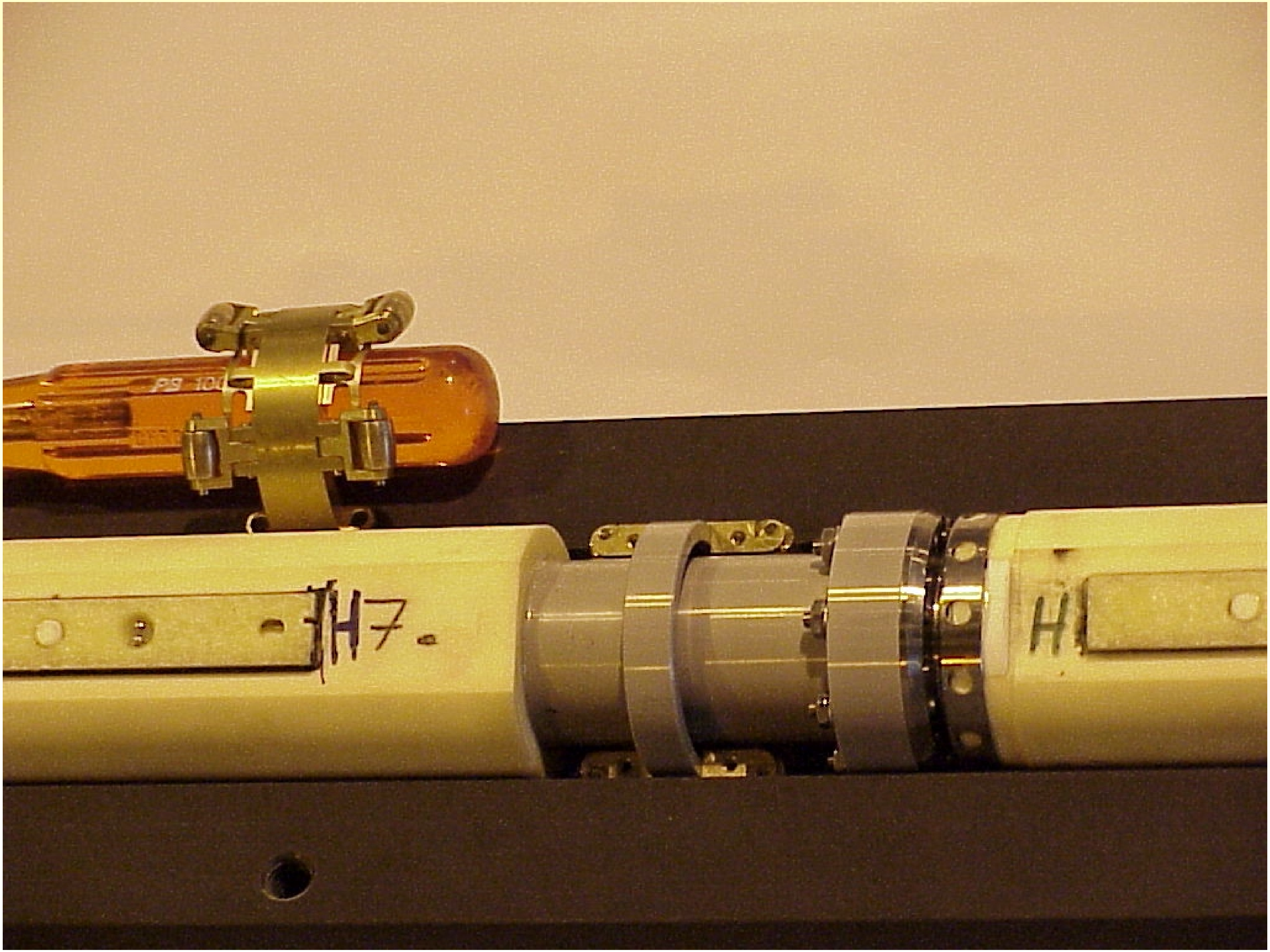


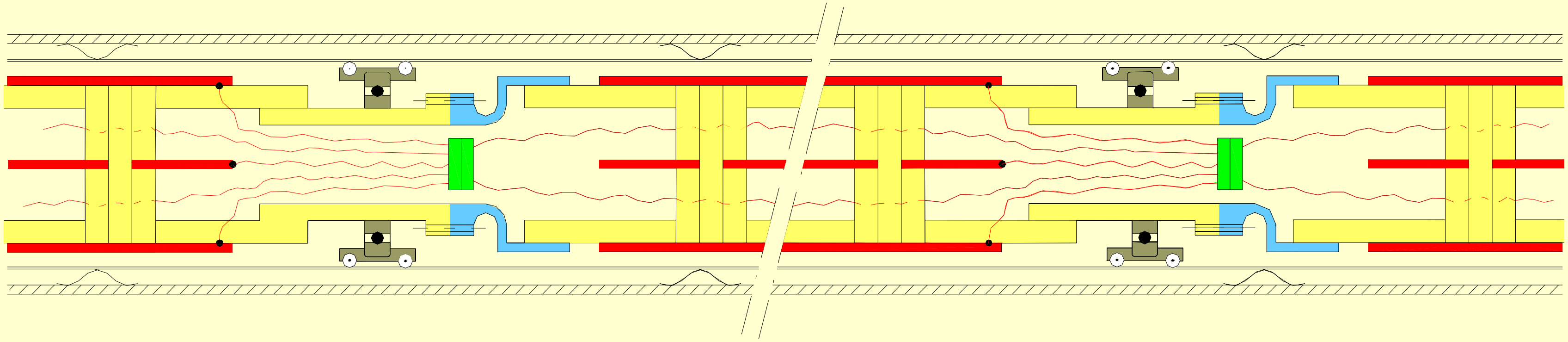
MAGNETIC FIELD MEASUREMENT



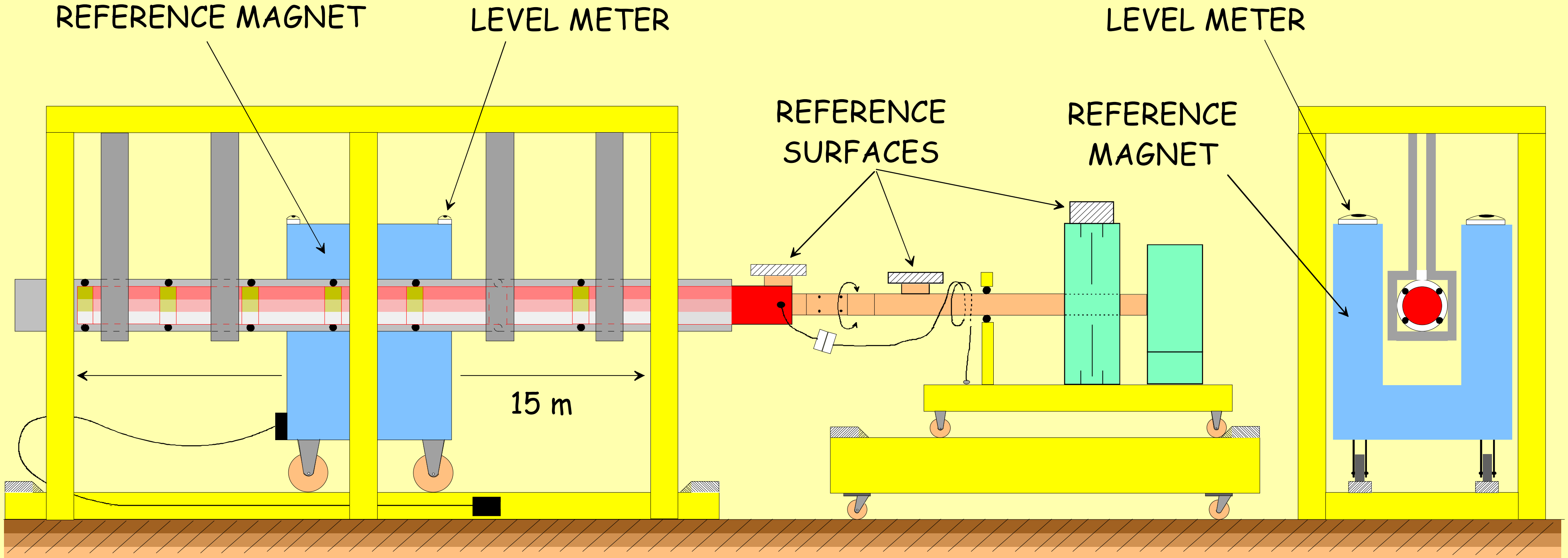





H7.
H



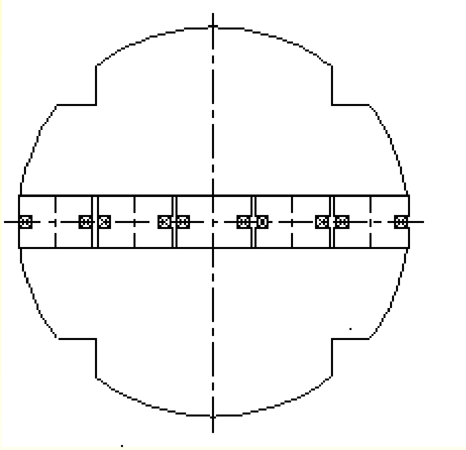
CALIBRATION BENCH



MQ Centring & Field Quality

Goals

- Position MQ axis inside cryostat, in cold condition
- Centring of correctors



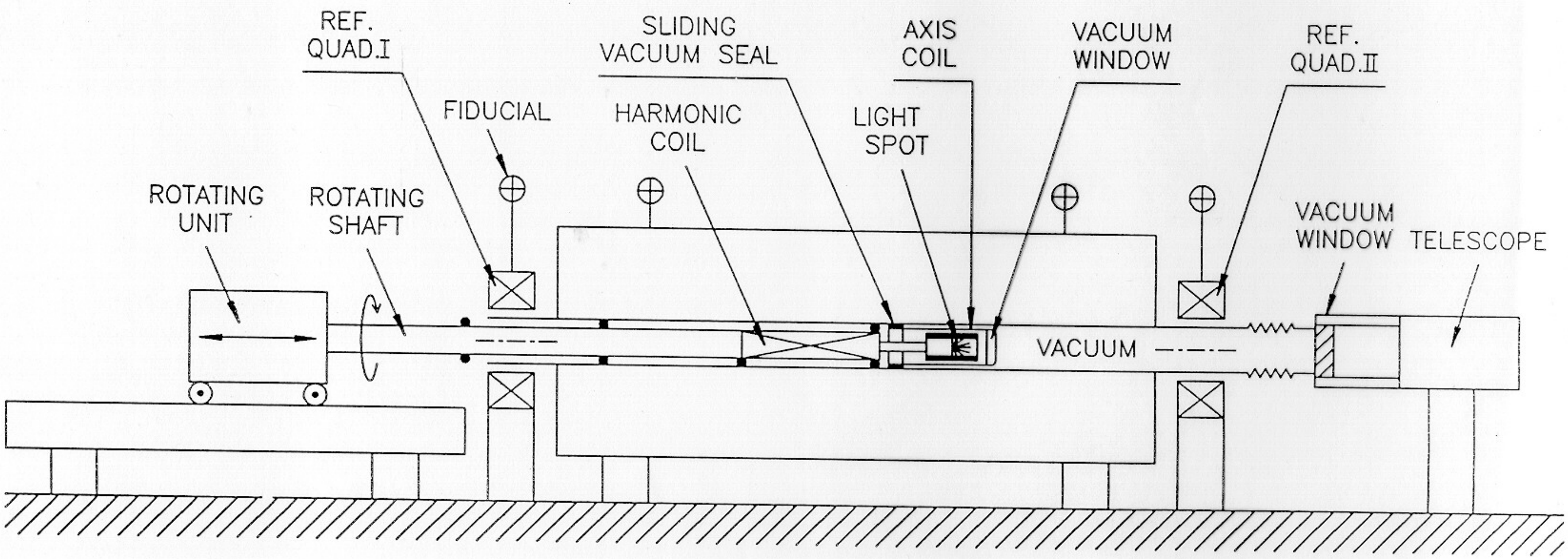
Challenge

- Thermal gradient in warm finger (several mm deflection in air)
- One pass mandatory due to warm finger's stability

Tool : 10 m long bench (Chaconsa, SP)

- 0.75 m long coil for field quality
- front end short coil with light source
- light beam under vacuum

QUADRUPOLE TEST STATION



MB Centring (2)

Goal

- Establish warm/cold correlation on reduced number of magnets

Challenge

- Thermal gradient in warm finger (several mm deflection in air)
- One pass mandatory due to warm finger's stability

Tool :

- Cold Mole under vacuum in development for MB & MQ (Fraunhofer IPT, D)
  (no axial motor ?)
- Stretched wire system (FNAL)

Time dependent & current ramp

Goals

- Predict field advance $\propto$ dI/dt
- Specify ripple and overshoot for the power converters
- Control of chromaticity during snap-back : $\Delta b_3 < 0.01$ U

  time resolution ≈, 100 ms if smoothed start of acceleration (6 ms if 10 As^{-1})

Tools

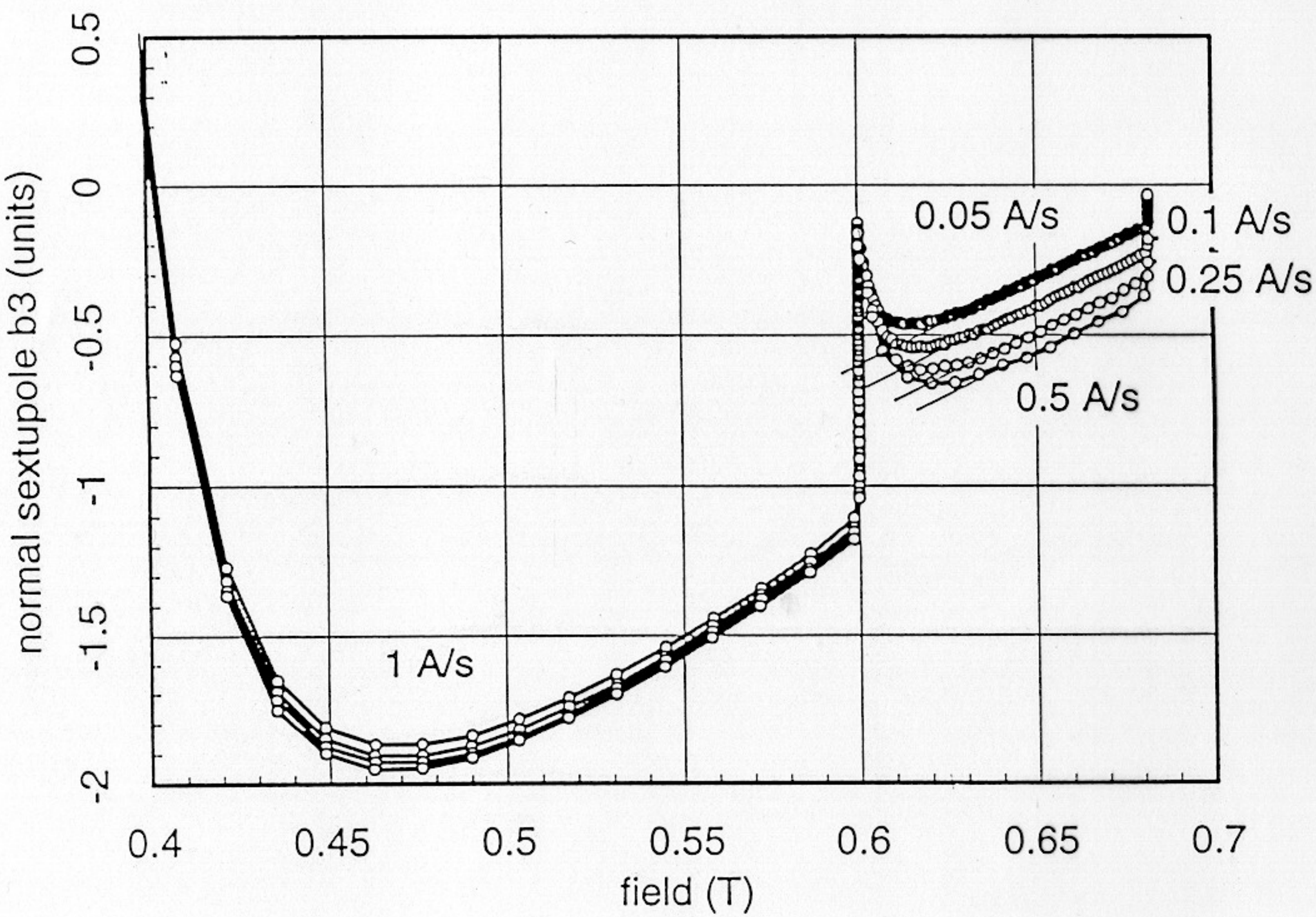
- Rotating coils with compensation of main harmonics

  Average on forward & backward (time resolution ≈ 10 s)

  $b_{3,persistent}$ ≈ constant with current
- 3 Hall plates head (cf. MT16)
- Fixed coil

  integrating voltmeters (Keithley-2001)

❐ Snap-back dependence on energy ramp speed (cont'd)



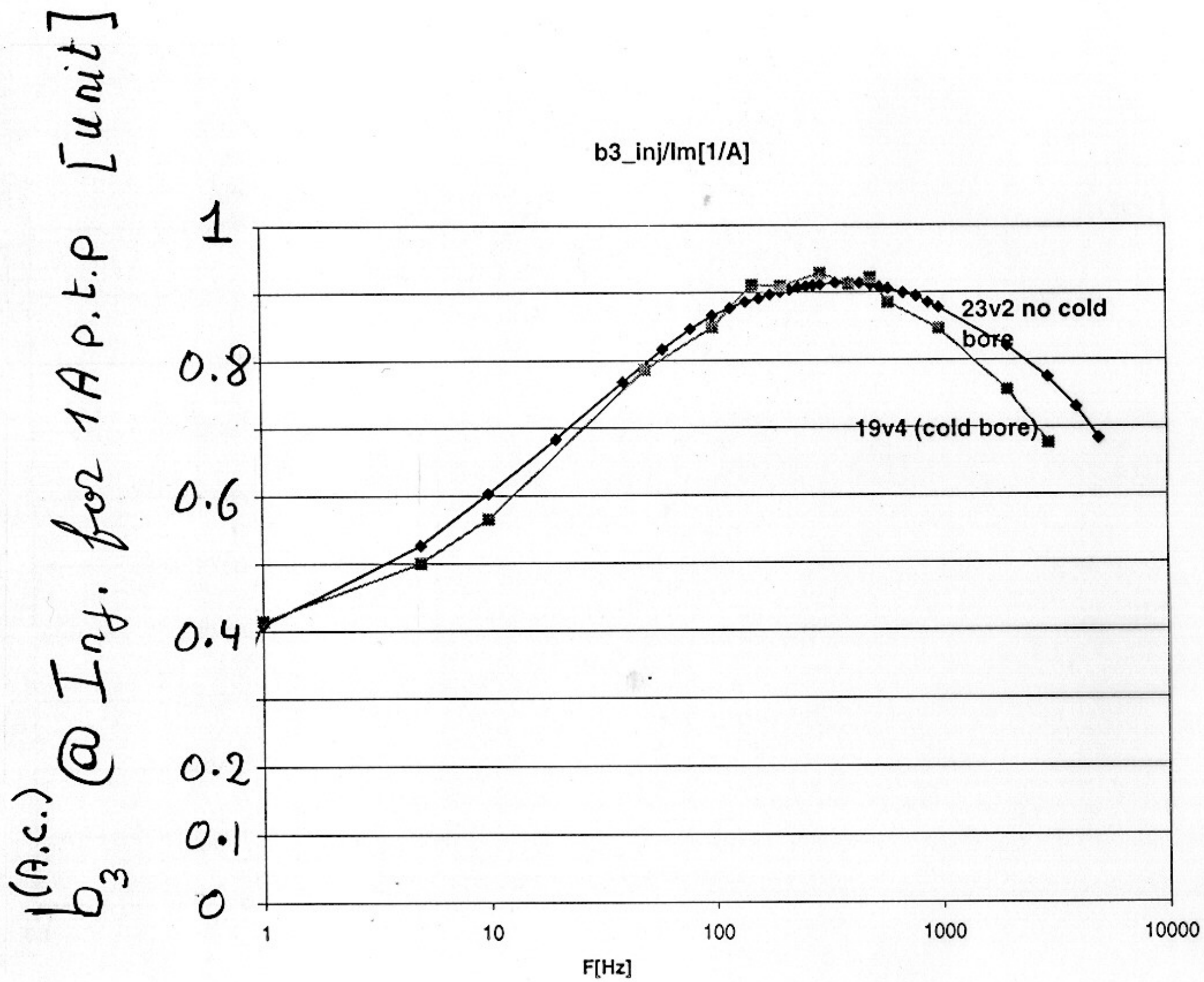


Figure 7. The sextupole component of AC field normalized by the DC field at injection / current passing the magnet ratio.

Acquisition, Data management

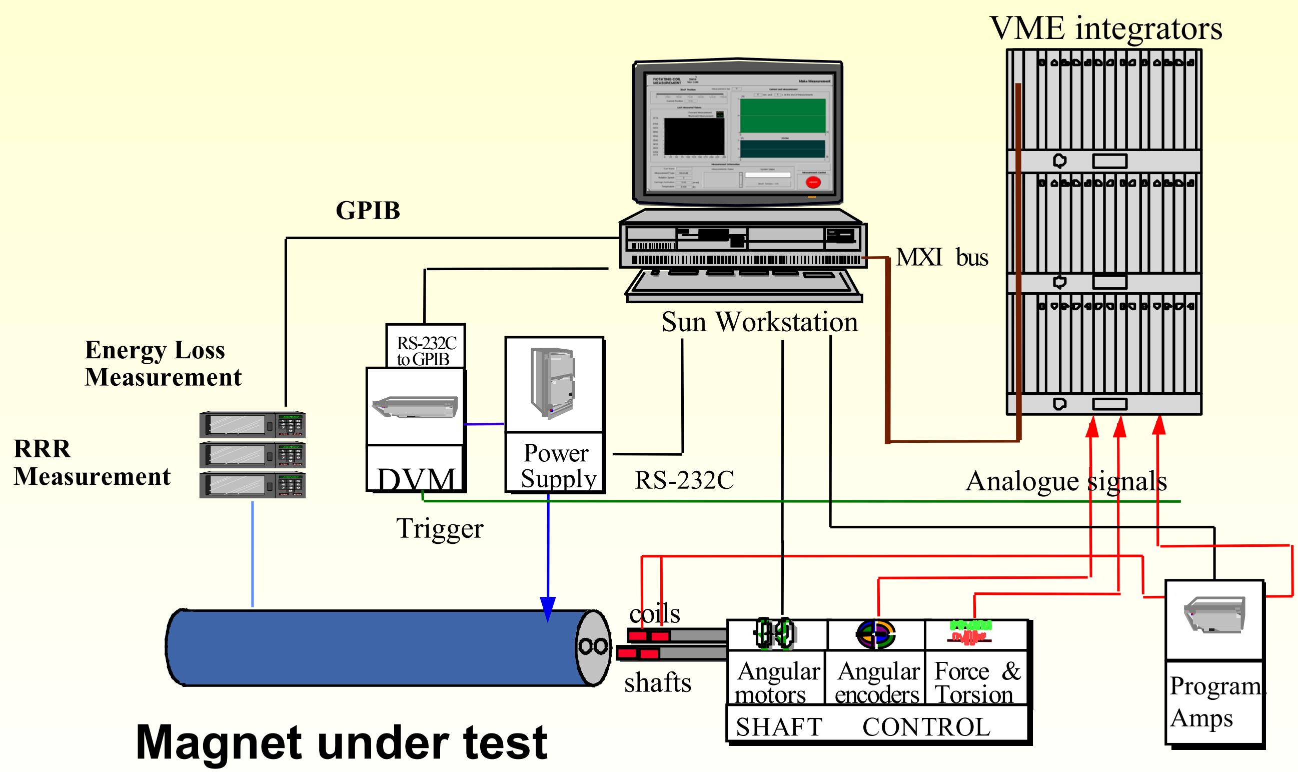
Challenge ***Cold tests of all cold masses*** ***Time / magnet < 16 hours***

- Automatisation
- Possibility of tracing back errors
- Round the clock work training operators , find simple check points

Tools

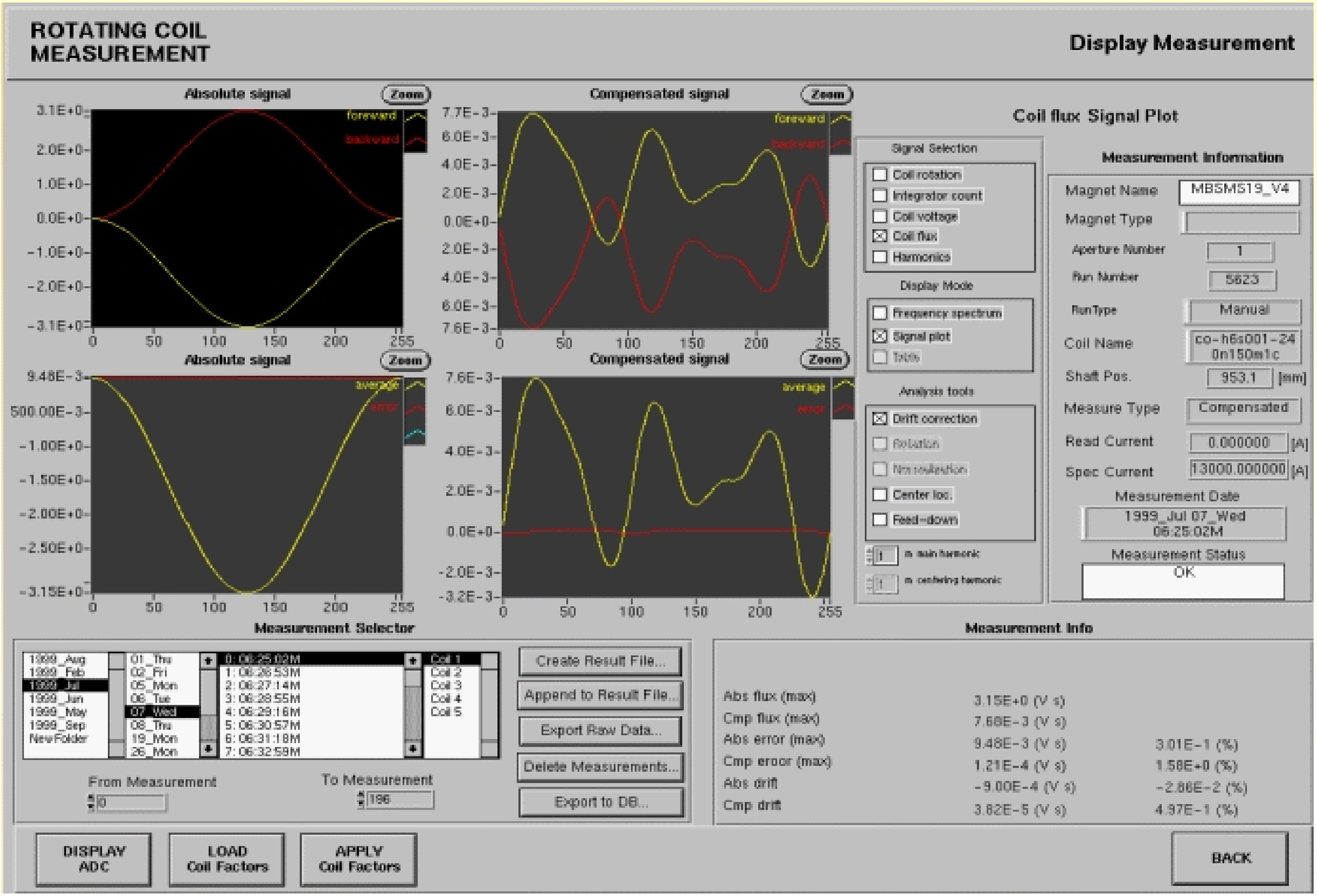
- 52 integrators / bench , MPX for warm/cold conditions & Quench antenna
- Labview , Sun , RT database (LHC-IAS)
- Full off-line treatment from raw data
- Centralised library for software, equipment & calibration

The Rotating Coil Magnetic Measurement System



The rotating coil magnetic measurement system has been extended with the Energy Loss and RRR measurements

A Typical Magnetic Measurement Screen

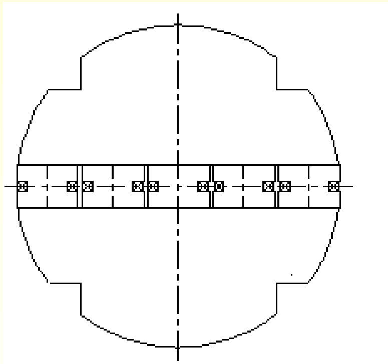


Corrector Magnets

L_{eff} from 0.06 m to 1.1 m , > 7000 magnets

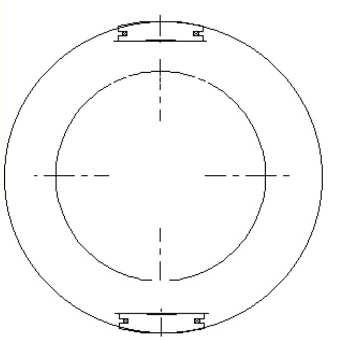
Goals

- Verify reference points with respect to magnetic axis
- Magnet's integrity : Nturns, interturns shorts, polarity of connections
- Width of hysteresis loop (mainly for nested magnets)



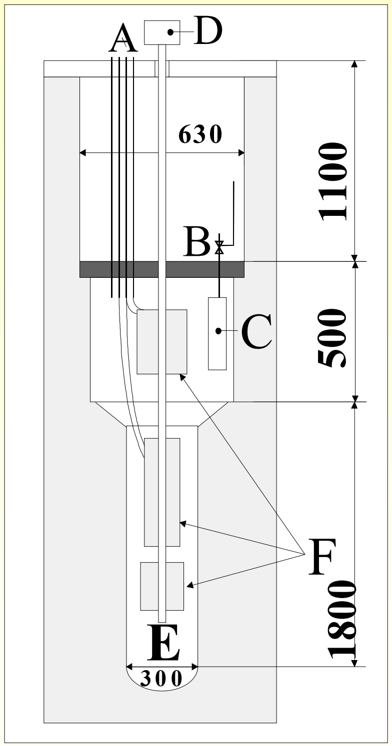
Tool ***Reference benches at Cern***

- Cold measurements of 2 % to 10 % of the magnets
- Warm bench(es) to position reference points



Tool ***Simplified bench for industrial use***

- Single coil
- Self-calibrating for axis and field direction



A : 2kA gas cooled current leads

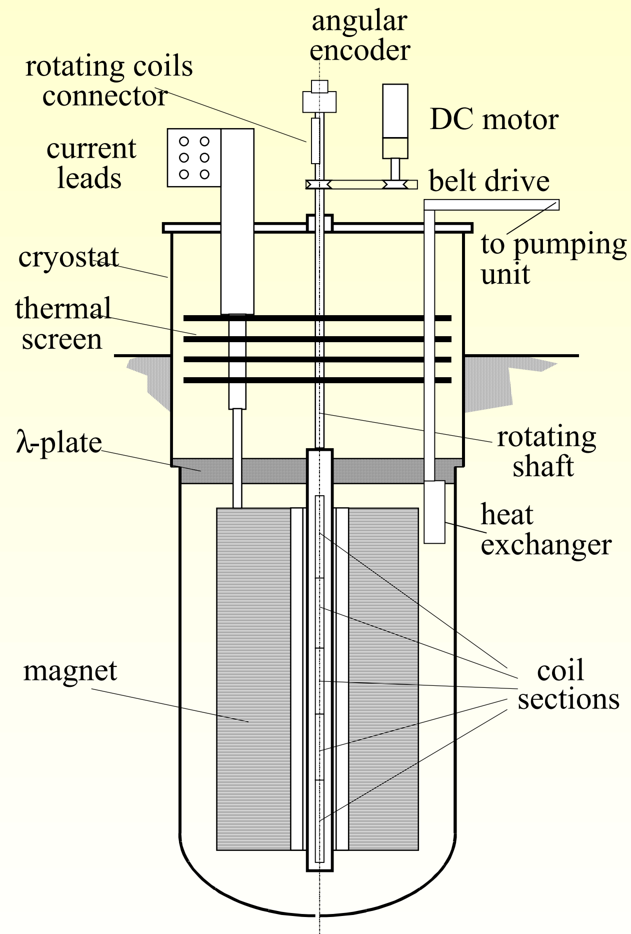
B : Joule - Thomson valve

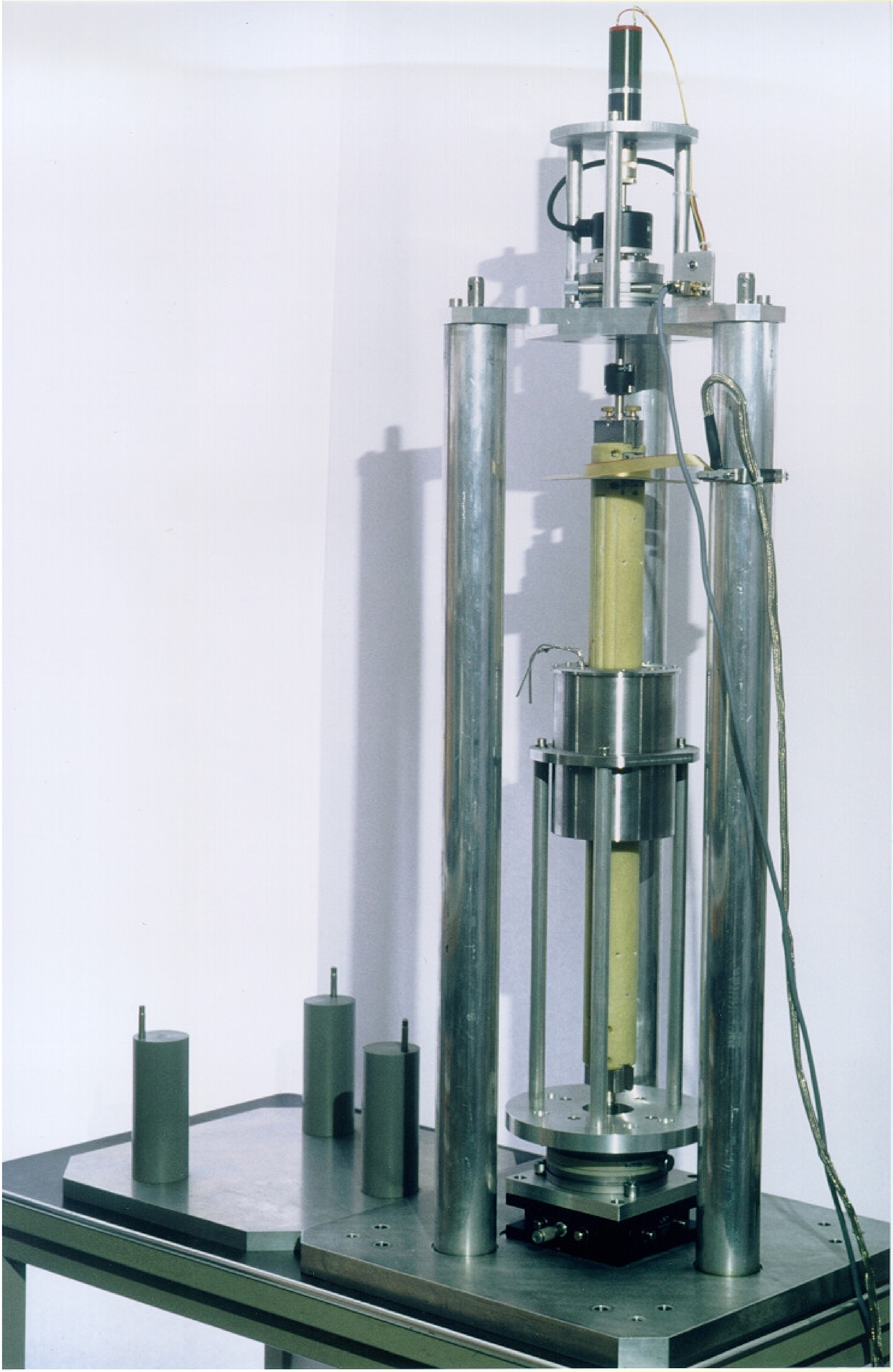
C : Heat exchanger

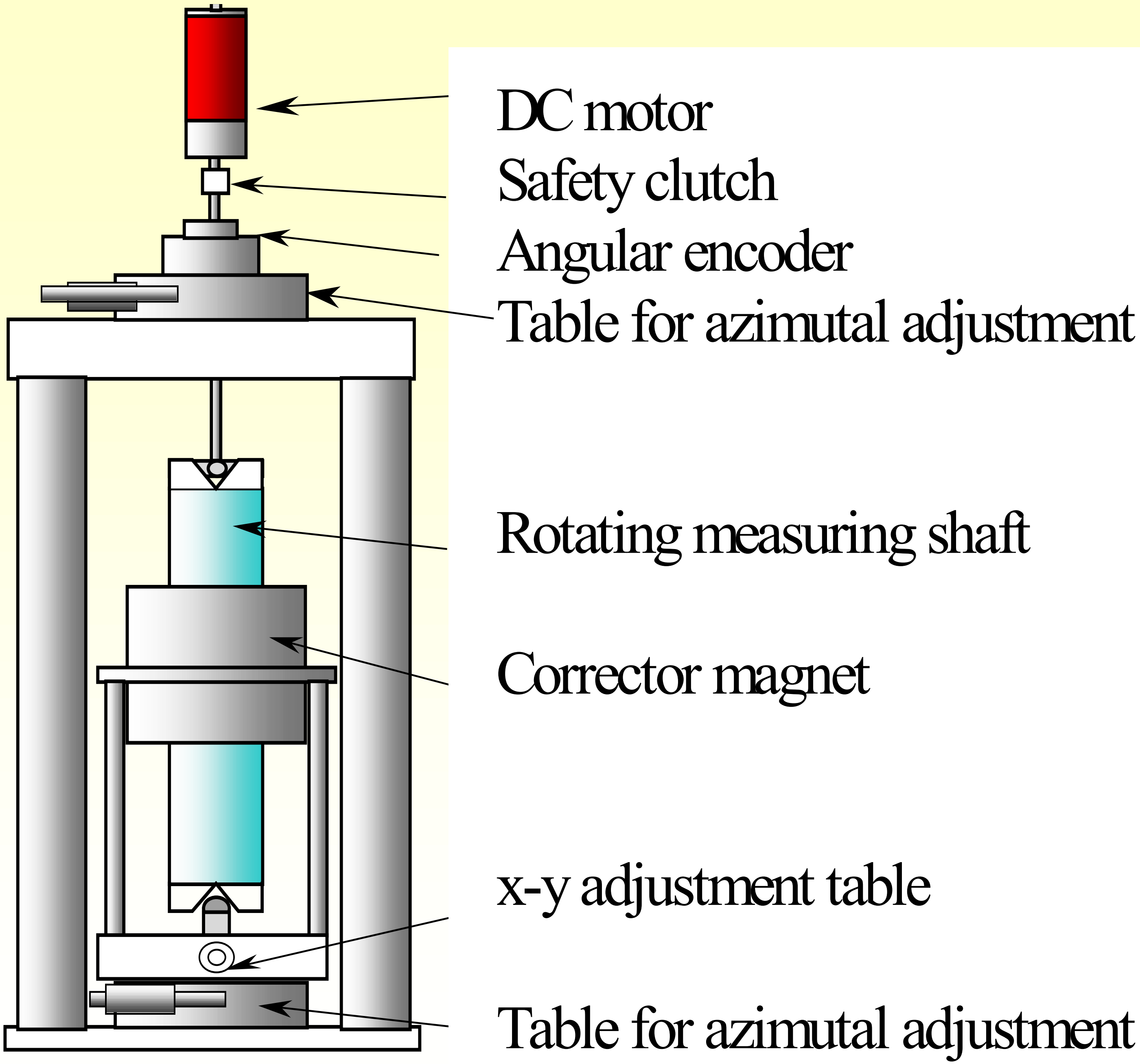
D : Encoder and motor for the magnetic measurements

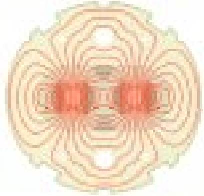
E : Magnetic measurement shaft

F : Corrector magnets






DC motor
Safety clutch
Angular encoder
Table for azimutal adjustment
Rotating measuring shaft
Corrector magnet
x-y adjustment table
Table for azimutal adjustment



Field Quality Measurements, FNAL HGQ Model Magnets

P. Schlabach

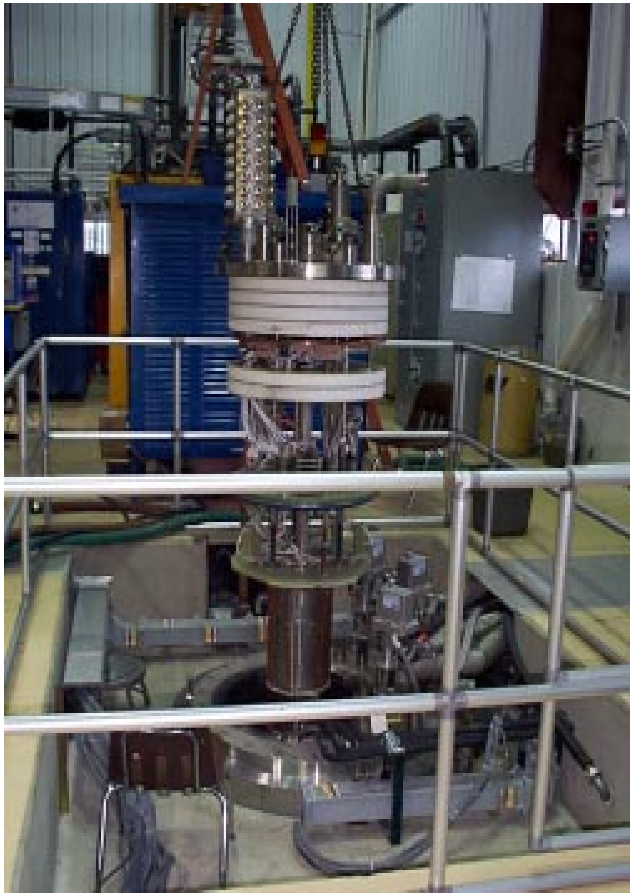
22 Sept. 1999

Outline

- apparatus
- field measurements
- anomalies
- studies of the ability to modify the design field with tuning shims

Measurements

- warm measurements during fabrication
  - axial scans (±10 A)
    - collared coil
    - completed cold mass
- measurements in vertical dewar
  - axial scan warm (±10 A)
  - full set of cold measurements



Measurement Systems

- Using Vintage SSC measurement system(s)
  - designed for 5 coil windings
  - FE1 mole for warm measurement
    - probe pulled through magnet aperture
    - no angular information
  - B&W system for VMTF measurement
    - probe signals, current read by 6 HP3458 DVMs simultaneously triggered by angular encoder
    - velocity feedback to stabilize rotation
    - probe driven into warm bore for measurement
    - z position control not integrated into measurement system
    - continuous measurement (0.3 Hz); 50% duty cycle (dead during read of HP 3458 DVM)

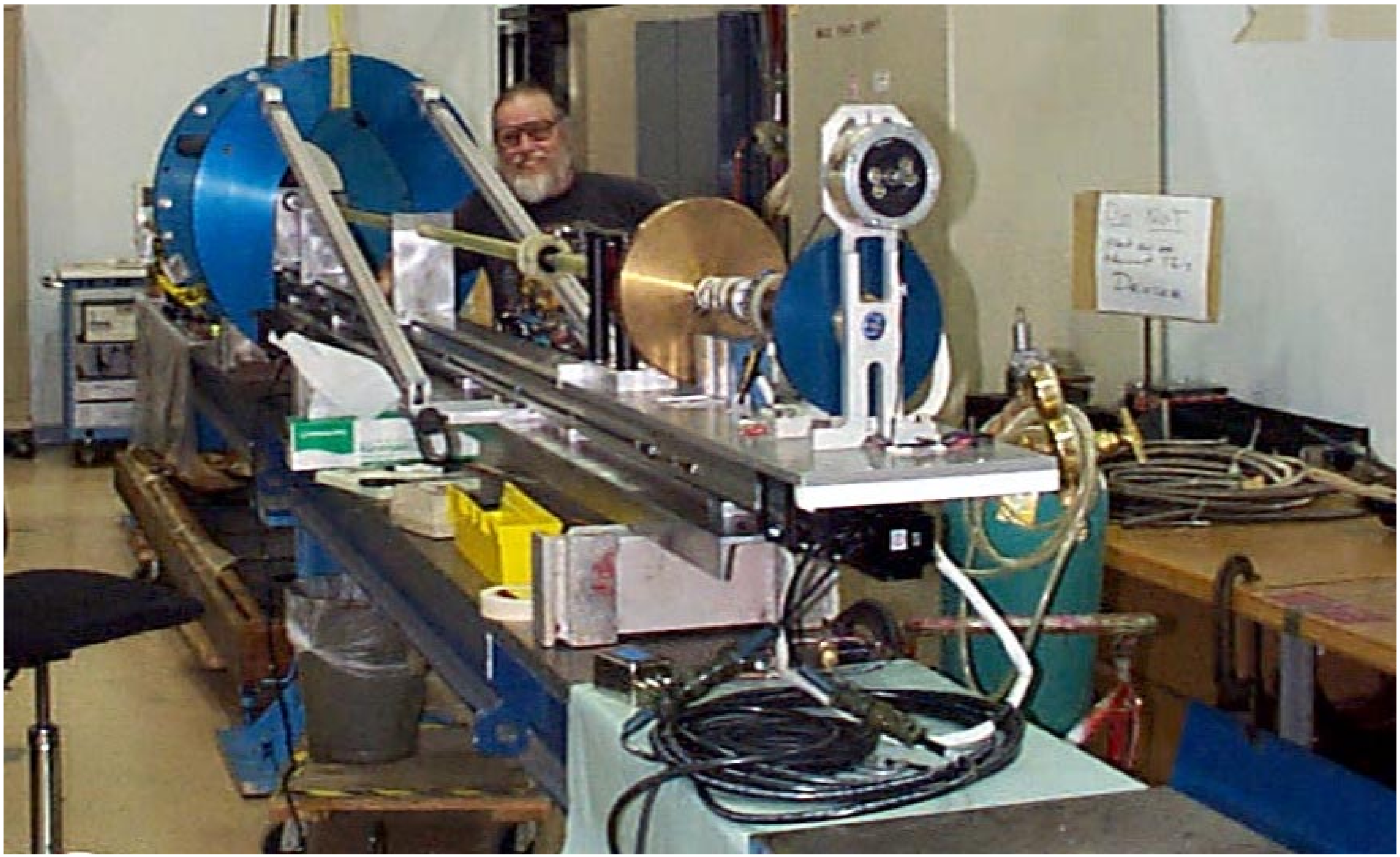
View of VMTF Measurement System

the Magnet Test Facility

fermilab

the Magnet Test Facility

fermilab



Probes

- all have similar design
  - tangential winding for harmonics
  - 2 dipole/2 quadrupole windings
    - used for bucking
    - measurement of the main field
    - probe centered using feed down of quadrupole to dipole
    - warm measurements utilize pre-amplifiers (G=128)
- 4 probes have been used

Measurement Probe(s)

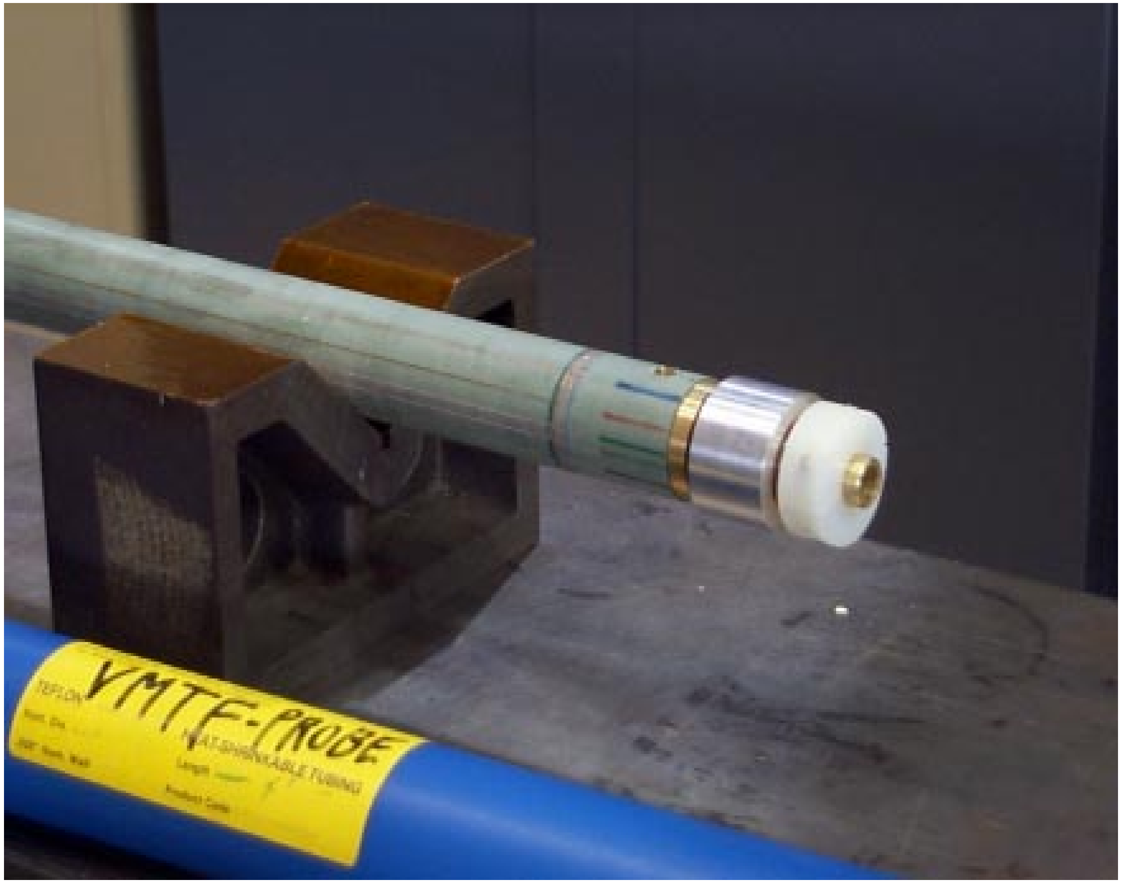
- FE1 mole for warm measurement
  - 1 m length, 2.5 cm OD
  - SSC legacy
  - wound on ceramic body
  - self-contained system: motor, encoder built into "shaft"

Measurement Probe(s)

- SSC legacy probe
  - 0.25 m length, 2.5 cm OD
  - came with SSC system
  - wound on ceramic body
  - glued to driveshaft
  - used for HGQ01

Probes, continued

- new cold measurement probe
  - optimized for HGQ bore
  - 0.82 m long; 4.1 cm OD
  - wound on G10 shaft
  - “thermometer” integrated into probe
  - substantially larger signal size
  - used for HGQ02 and magnets since



Probes, continued

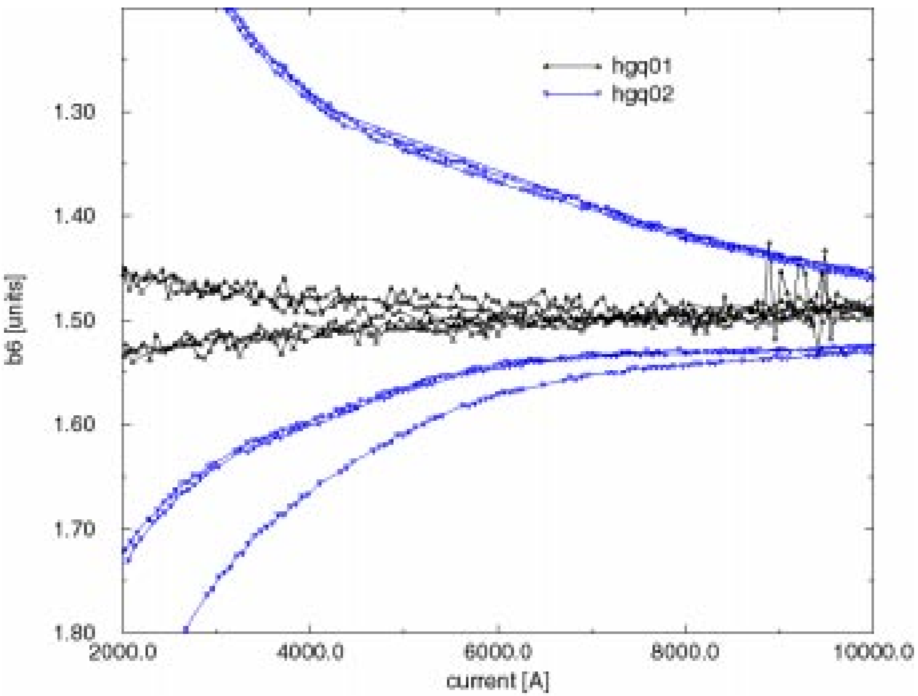
- short probe for longitudinal scans
  - 0.04 m length, 2.5 cm OD
  - wound on ceramic probe body
  - another probe from SSC days
  - drive shaft linkage was broken
  - removed linkage (broke 1 winding)
  - probe mounted in the end of a G10 tube which has the same coupling and centering bearings as our standard probe
    - removable for service
    - in particular we had to determine probe windings experimentally (two pass process)
  - small signal so we use pre-amplifiers that are used for warm measurements

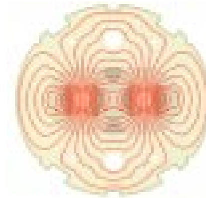
Improvements

- Improvements related to ease of use have been made
  - measurement rig can be installed or removed in 20 minutes or so
  - one person operation
- Improvements in measuring apparatus have been made
  - longer, larger radius probe improves signal-noise
  - better centering bearings
  - larger radius, multi-sectioned driveshaft separated by flexible couplings

Improvements

- Improvements in apparatus have lead to better field measurements
  - –my judgement is that this is mostly due to the increase in signal size





Measured Field Harmonics Summary

As Measured Harmonics						
	HGQ01	**HGQ02**	**HGQ03**	**HGQ05**	**HGQ06**	**HGQ07**
b3	0.36	-0.70	1.04	0.72	0.25	0.18
a3	0.27	0.55	-0.30	0.12	-0.27	0.41
b4	0.26	0.18	0.14	0.00	0.09	0.01
a4	2.00	0.53	0.32	0.19	-0.31	-0.50
b5	-0.29	0.09	-0.34	-0.04	-0.11	-0.04
a5	0.02	-0.17	0.26	0.05	-0.07	-0.24
b6	-3.91	-1.54	-1.02	-0.30	-0.05	-0.45
a6	-0.02	0.03	0.07	-0.03	-0.05	-0.10
b7	-0.08	-0.01	-0.06	0.01	-0.03	0.02
a7	-0.05	0.00	-0.03	0.01	0.00	0.08
b8	0.06	0.01	0.00	0.00	0.00	0.00
a8	0.02	0.02	0.03	0.00	0.00	0.01
b9	0.04	0.00	0.00	0.00	0.00	-0.01
a9	0.01	-0.01	0.01	0.00	0.00	0.01
b10	-0.10	-0.10	-0.04	0.01	0.00	-0.02
a10	0.02	0.00	-0.01	0.00	0.00	0.00

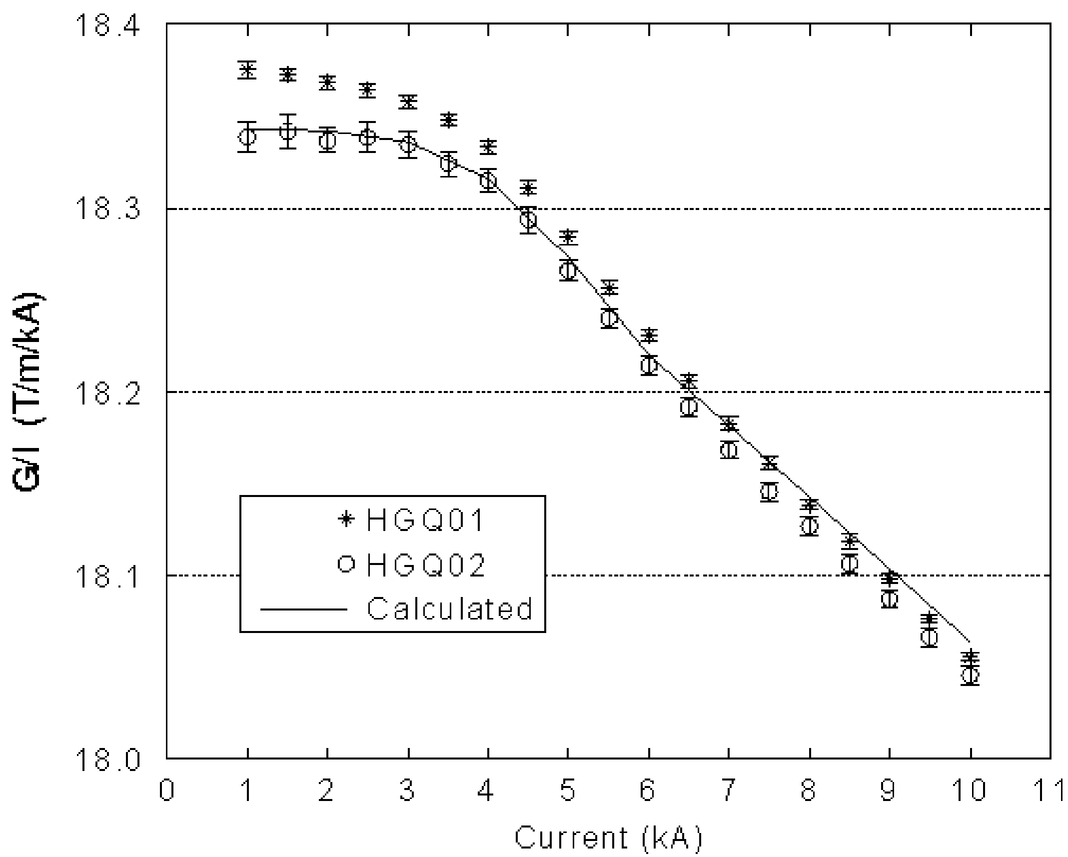
- Harmonics measured at magnet center
- Steady improvement in field quality
  - improvements in coil fabrication procedure have produced coils closer to design values

Predicted Field Based on As-Built Cross-Section

	HGQ01	HGQ02	HGQ03	HGQ05
a4	1.27	0.94		
b6	-4.24	-2.86	-1.39	-0.08
a8	0.02	0		
b10	-0.14	-0.09	-0.04	0.01

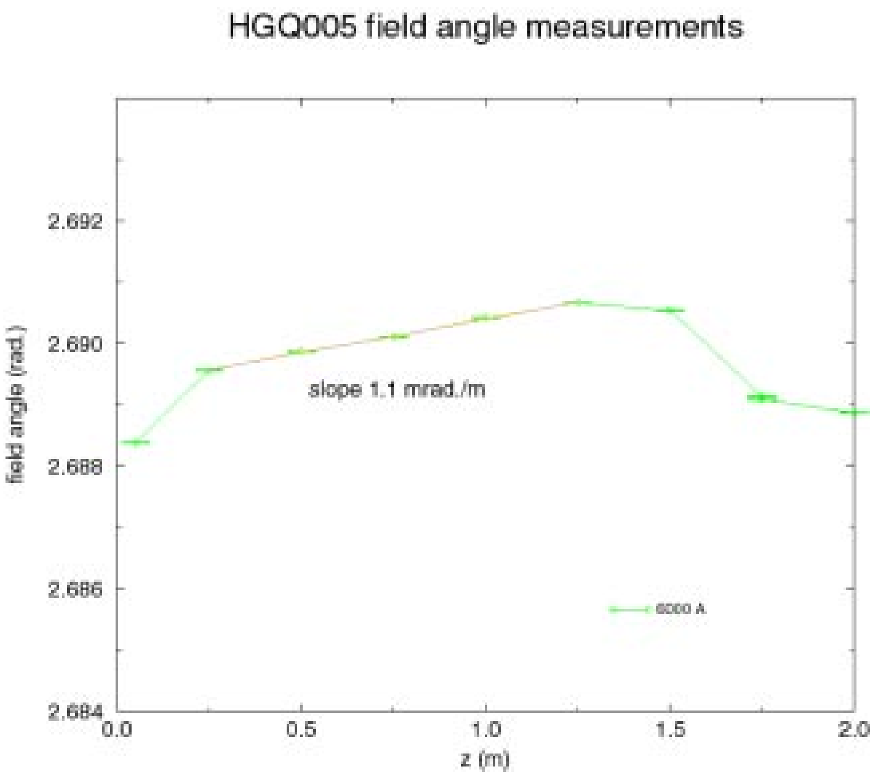
- adjustments made to
  - curing cavity size
  - curing pressure
  - cable insulation scheme
  - bare cable size
- coil shim thickness reduced by a factor of 2 from each magnet to the next
- more uniform coil size and modulus

Transfer Function



- Transfer function
  - G/I=18.35 T/m/kA at low currents
  - Iron saturation effect reduces transfer function by 2% at nominal current
- Variations seen from one test cycle to the next
  - HGQ01-05 (5-40 units)
  - HGQ06 < 1 unit

Field Angle, Magnet Twist



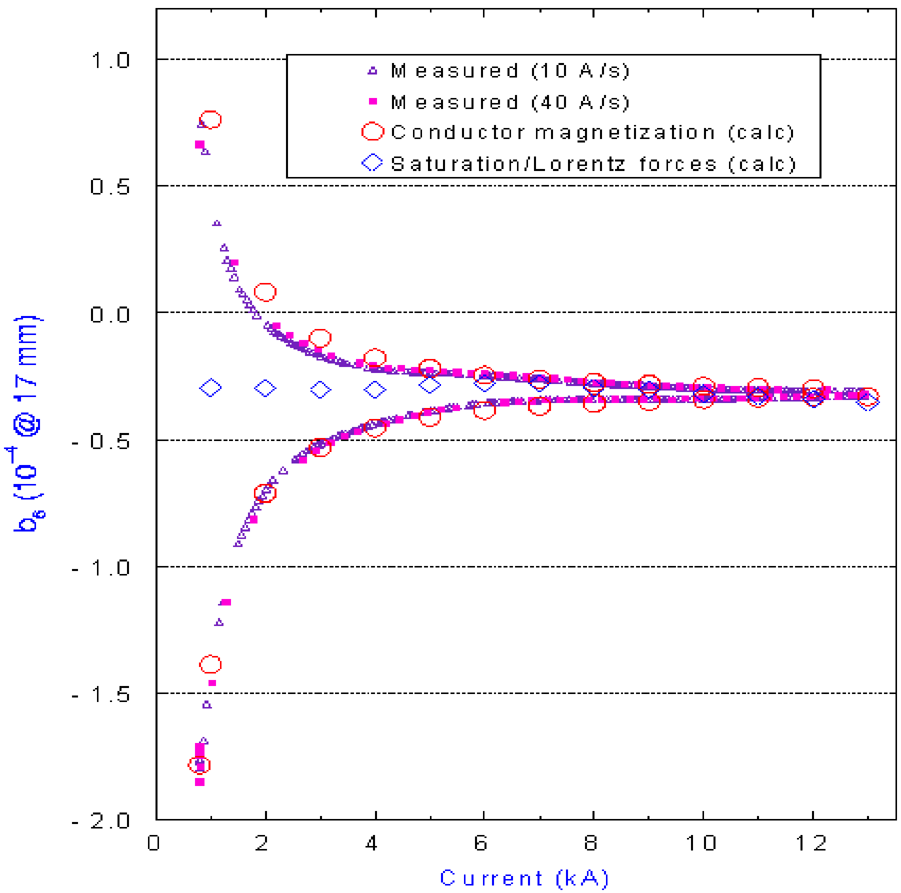
Field angle

Magnet twist (mrad/m):

	mech. meas.	magn. meas.
HGQ01	6	7
HGQ02	0.6	<1
HGQ03	1.0	1
HGQ05	0.9	1.1

- Good agreement between magnetic and mechanical measurements
- Magnets 6 & 7 have less twist
  - < 0.3 mrad/m target

Field Harmonics

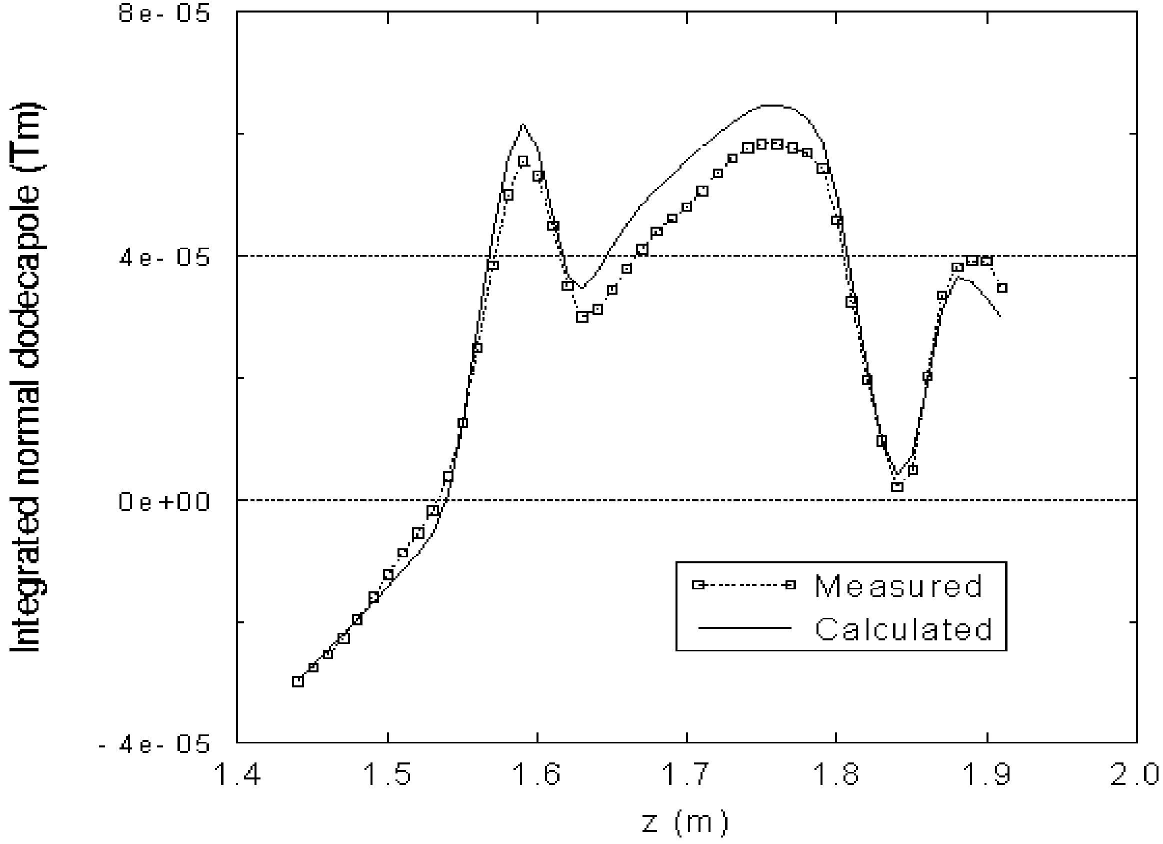


- Iron saturation and Lorentz force effects on b_6 at high currents are small

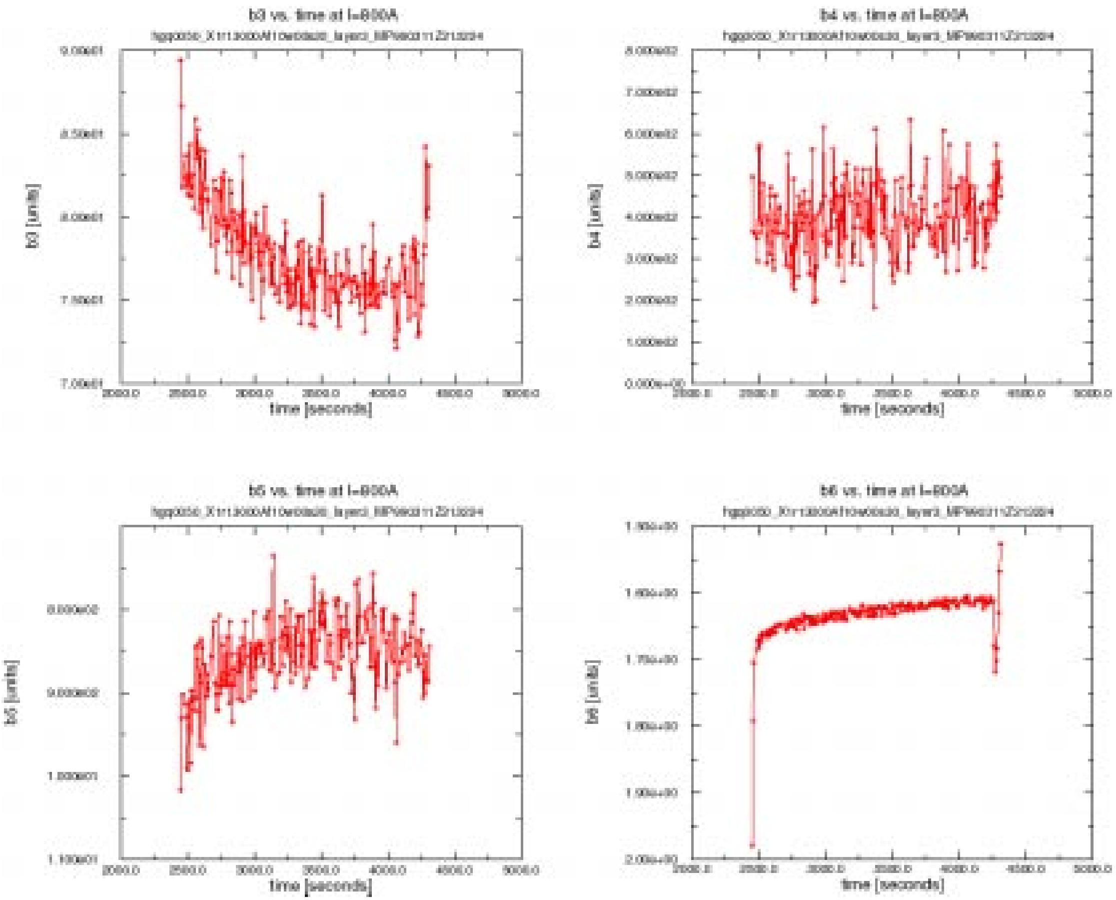
Coil magnetization effect on b_6 at low currents is in good agreement with calculations

- There is no noticeable effect of coil magnetization, iron saturation and Lorentz force on b_{10}

End Field Measurement



Injection Field



Summary of Field Measurements of 7 HGQ Models

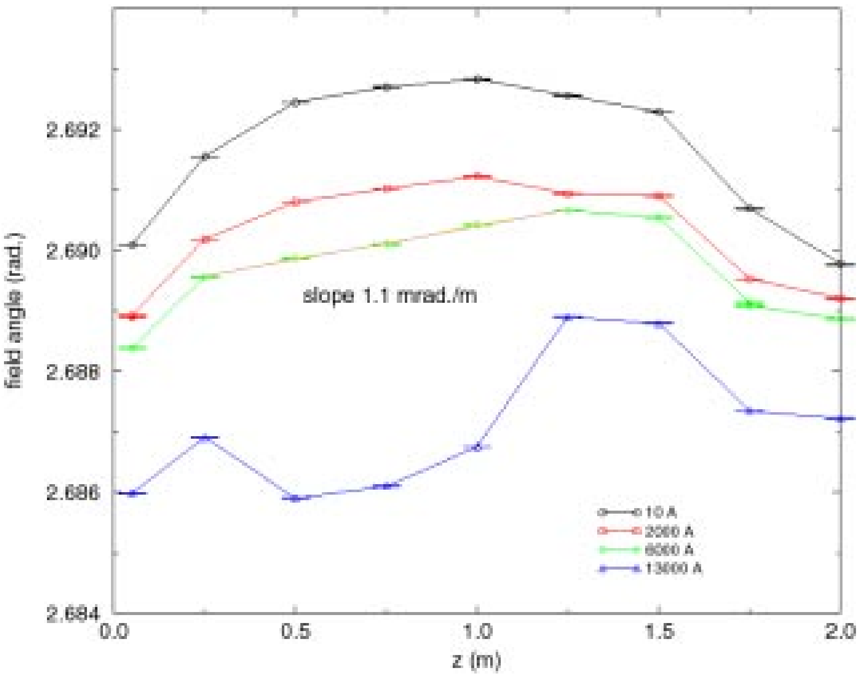
- Good agreement between measured and calculated field effects
- Field quality of model magnets has steadily improved
- Last few magnets have had acceptable field quality
  - large eddy current effect in the last two models

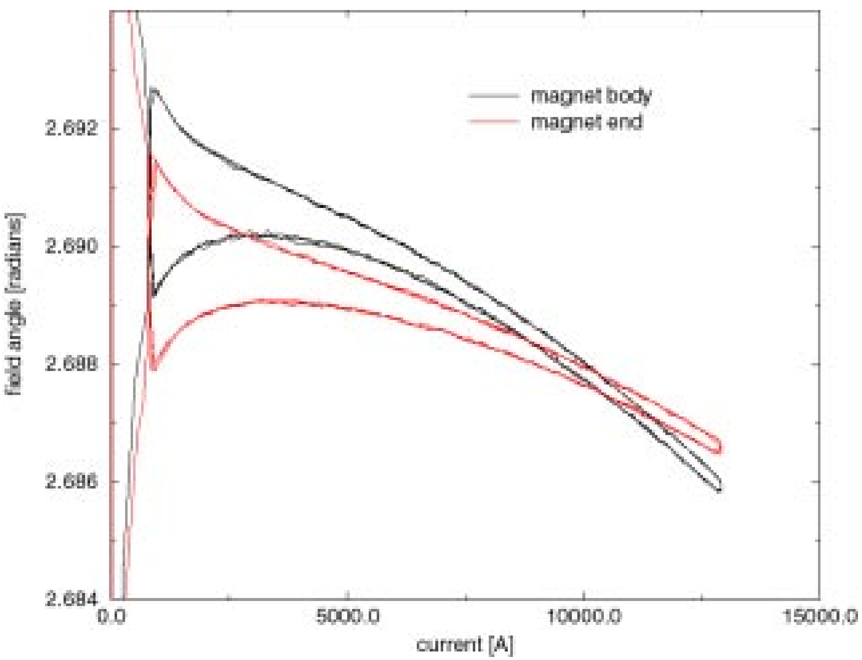
Summary of Field Measurements of 7 HGQ Models

Comparison to Targets								
	Ref Table 2.0		**All Corrected**		**IGQ01-03 Correcte**		**IGQ05-07 Measure**	
	Uncert	**Random**	**Mean**	**RMS**	**Mean**	**RMS**	**Mean**	**RMS**
b3	0.30	0.80	**0.31**	0.59	0.23	**0.88**	**0.38**	0.29
a3	0.30	0.80	0.13	0.35	0.17	0.43	0.09	0.34
b4	0.20	0.80	0.11	0.10	0.19	0.06	0.03	0.05
a4	0.20	0.80	0.00	0.49	**0.21**	0.58	**-0.21**	0.36
b5	0.20	0.30	-0.12	0.16	-0.18	0.24	-0.06	0.04
a5	0.20	0.30	-0.03	0.18	0.04	0.22	-0.09	0.15
b6	0.60	0.60	0.20	**0.64**	**0.67**	0.56	-0.27	0.20
a6	0.05	0.10	-0.02	0.06	0.03	0.04	**-0.06**	0.04
b7	0.05	0.06	-0.03	0.04	-0.05	0.04	0.00	0.03
a7	0.04	0.06	0.00	0.04	-0.03	0.03	0.03	0.04
b8	0.03	0.05	0.01	0.02	0.02	0.03	0.00	0.00
a8	0.03	0.04	0.01	0.01	0.02	0.02	0.00	0.01
b9	0.02	0.03	0.01	0.02	0.01	0.02	0.00	0.01
a9	0.02	0.02	0.00	0.01	0.00	0.01	0.00	0.01
b10	0.02	0.03	0.00	0.02	0.01	0.03	0.00	0.01
a10	0.02	0.03	0.00	0.01	0.00	0.02	0.00	0.00

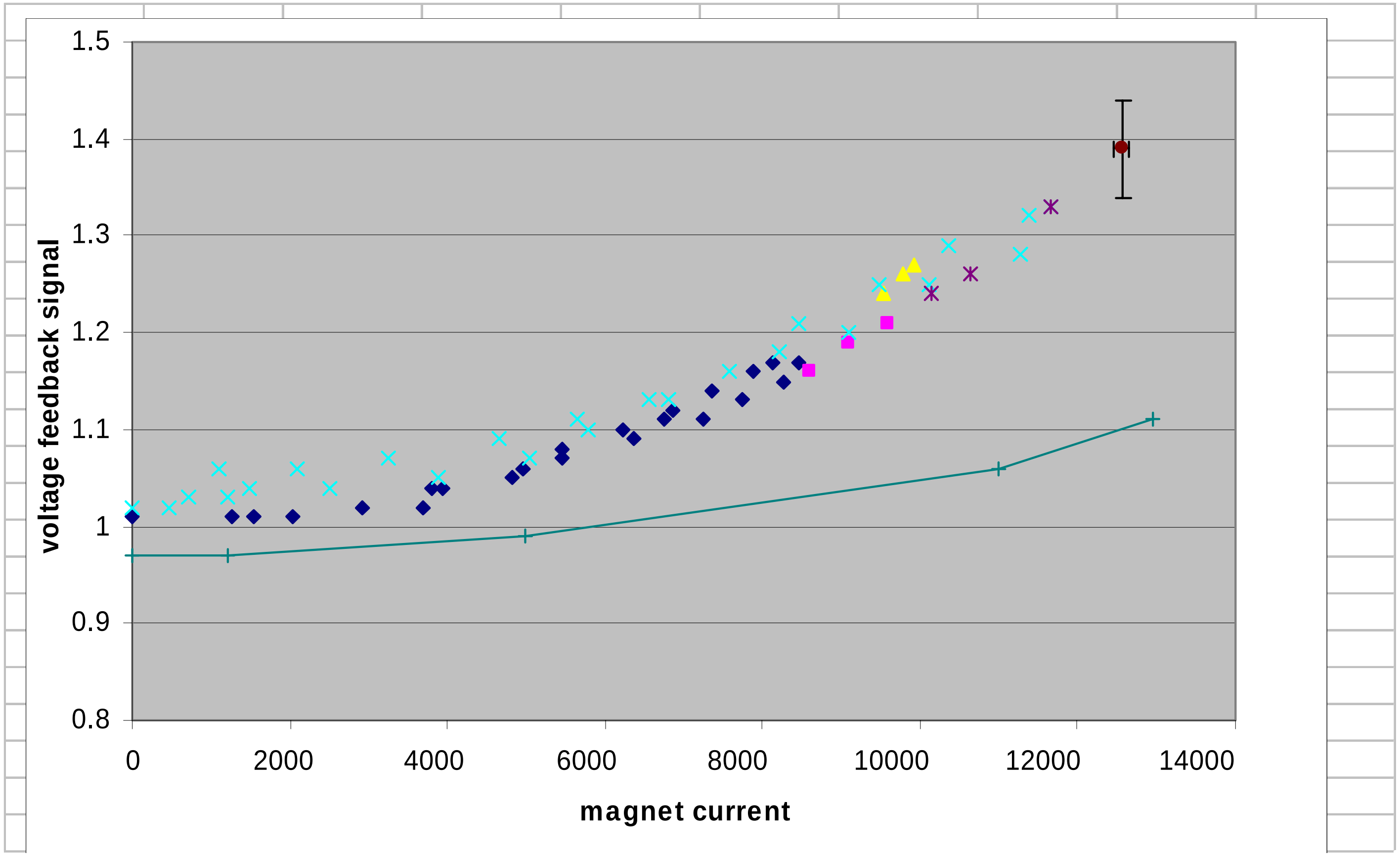
Field Angle, Magnet Twist, Revisited

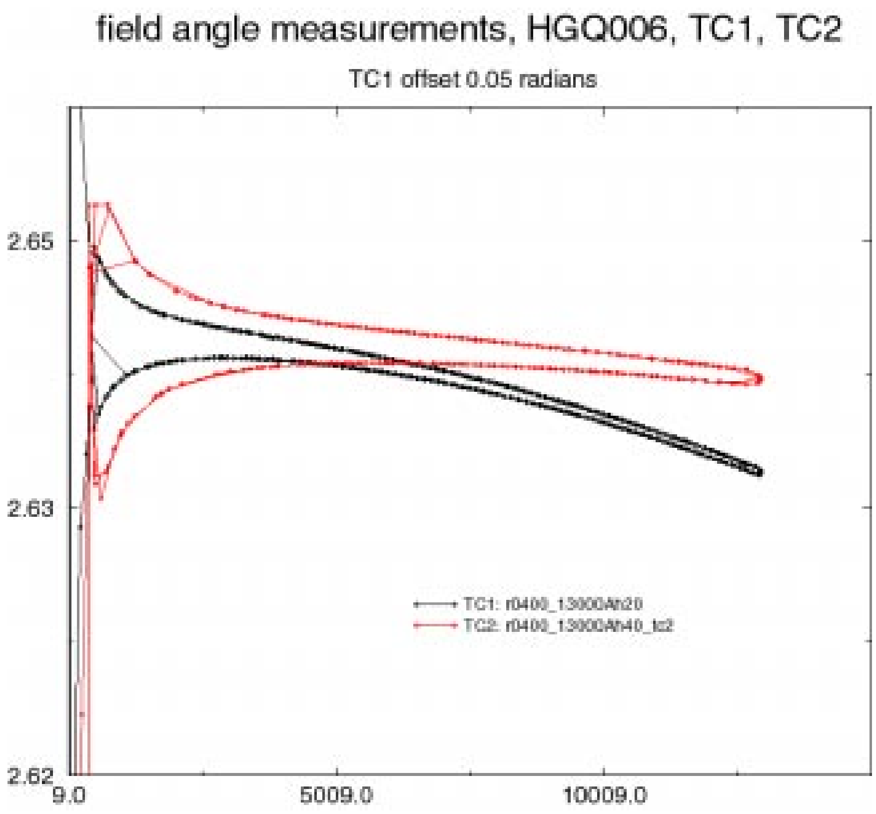
HGQ005 field angle measurements





Field Angle, Magnet Twist, Revisited

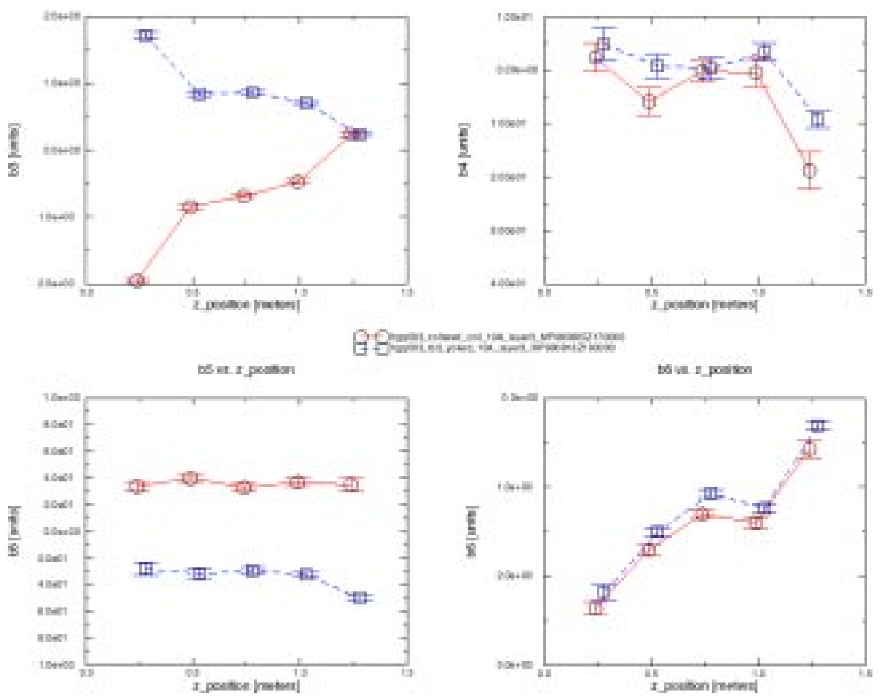




- During measurements of HGQ06 we switched from brass end plugs (test cycle 1) to stainless (test cycle 2)
- Explanation:
  - –Eddy currents induced in metallic end plugs
  - –Azimuthal force induced which opposes probe motion, trying to slow probe
  - –Velocity stabilization acts to maintain speed
  - –Driveshaft twists

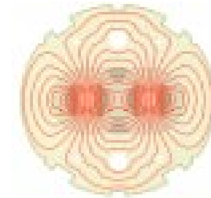
Warm Measurements

- •Pattern seen typical (2 of 1st 3 magnets)
  - –Odd harmonics reversed between collared coil and yoke measurements
  - –One or the other matched VMTF harmonics, but which matched was random
- •Improved apparatus to control angle of mole as it was pulled through the bore for 4th magnet
  - –slotted support tube and scribed line on probe body -- one end of probe is always visible
- •Same result



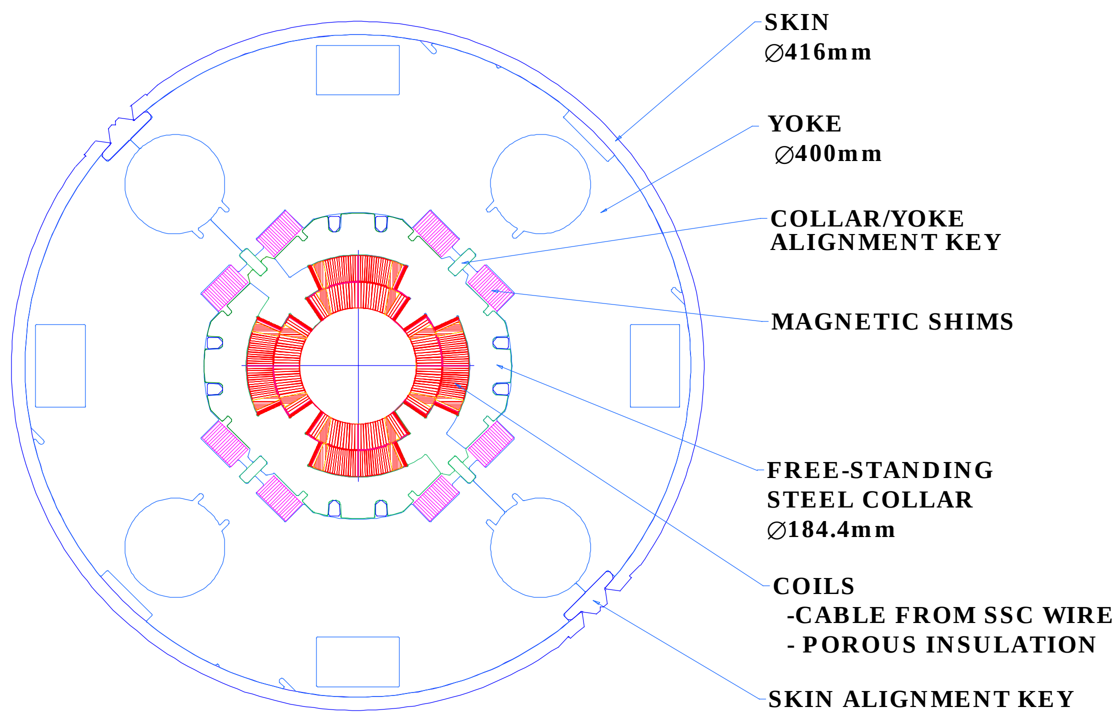
Warm Measurements, continued

Then and only then did I think to ask the techs if they always mounted the magnet oriented in the same way...



Warm Measurements, Studies Field Tuning Using Shims

- magnet cross section contains 20 mm holes for insertion of field tuning shims
- nominal design has each half filled by iron half by non-magnetic material
- changing the thickness of magnetic relative to non-magnetic material "tunes" the field
- the various shim positions tune different harmonic components



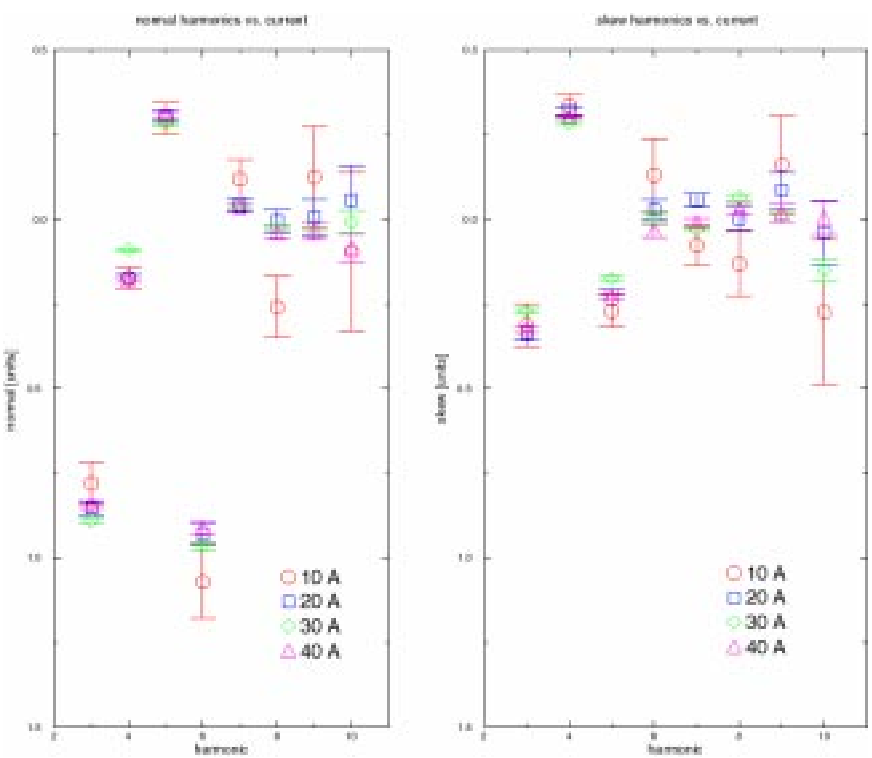
Tuning Shims: measured, predicted field changes

- after completion of cold testing, HGQ03 was used to test our ability to tune the field
- a shim pattern was selected which would tune skew octupole (a_4) leaving other harmonics unchanged
- required shims of 4.1, 15.9 mm nominal thickness
- expected changes:
  - a_4 -2.9 units
  - other harmonics “unchanged”
- measured changes:
  - a_4 -3.1 units
  - small changes in sextupole

Measured Field Changes

n	normal	skew
3	0.34±0.01	-0.19±0.01
4	0.05±0.01	-3.13±0.01
5	0.01±0.01	0.01±0.01
6	0.04±0.02	0.02±0.02

Tuning Shim, Warm Measurements



- Measurement accuracy at 10 A marginal
- Were we to implement this during production, we'd have had to understand the signal amplitude issues more carefully
- To improve accuracy for these important studies we measured with 47 A current in the magnet
  - This was a magnet we didn't care about
  - Probe support tube was warm to the touch, but not hot

Change in Field with Shim Thickness

- two sets of shims allow us to calculate Δb_n (Δa_n)/ Δf
  - f is the thickness of the magnetic part of the shim

	calculated		measured	
n	**$\Delta b_n/\Delta f$**	**$\Delta a_n/\Delta f$**	**$\Delta b_n/\Delta f$**	**$\Delta a_n/\Delta f$**
3	**0.51**	**0.00**	**0.48**	**0.00**
4	**0.14**	**-0.08**	**0.10**	**-0.07**
5	**0.01**	**-0.03**	**0.01**	**-0.02**

Summary of Studies of Tuning Shims

- We have targeted a tuned field and achieved it with 0.2-0.3 units accuracy based on calculations of the field change as a function of shim thickness
  - In practice, better accuracy would be achieved as we would use the measured field change as a function of shim thickness and use these functions to choose shim sizes
  - Accuracy set by the accuracy of magnetic measurements which in turn is a function of how much current we can safely put through the magnet
- We have what we need (including the measured change in field as a function of shim thickness) to use tuning shims except for the correlation between field of collared coil measured warm and field of cold cryostated magnet

Summary of Field Harmonics of the 4 Models

- Measurement equipment performing OK
  - there have been a few surprises along the way
  - test bed for production measurement systems
- Field quality in last few magnets adequate for a production magnet
- Model magnet ensemble field quality adequate, after correcting for production defects which we can
- MQX field quality adequate without resorting to tuning shims