Magnetic measurements for accelerators @ CERN: an overview

L Bottura, N. Brooks[1], M Buzio, R Chritin, D Cornuet, G Deferne, JM Dutour, P Galbraith, D Giloteaux, J Garcia Perez, P Leclere, G Peiro, L Walckiers

1=University of Texas

Contents

Projects involving magnetic measurements:

1. Tests for the construction of the LHC
2. Tests for the operation of the LHC
3. Tests for CERN's accelerator chain (PS & SPS)
4. Tests for the upcoming Clic Test Facility CTF3
5. Tests for the upcoming Linac4

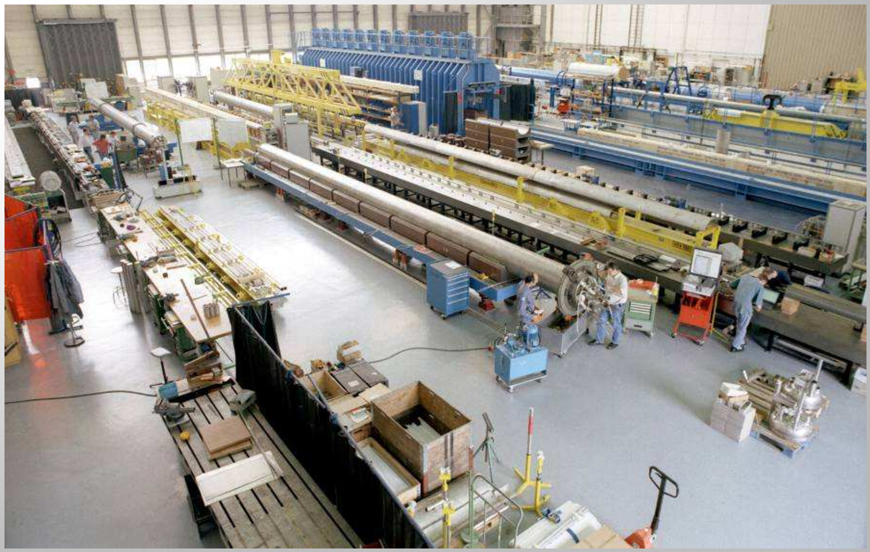
Tests for the construction of LHC

As the construction of the machine is nearly completed,
some activities related to the construction of the machine are still continuing …

- **Final series tests for the LHC**:
  - standard cryogenic tests of spare cryodipoles (MB) and quadrupoles (SSS)
  - warm re-test of repaired low-β quadrupoles
  - sporadic checks of magnet polarity/electrical integrity in the tunnel (esp. correctors)
  - special tests left pending from the series tests period: e.g. detailed characterization of warm quadrupoles (MQW), measurement of cold magnetic axis in SSS and MB, etc.

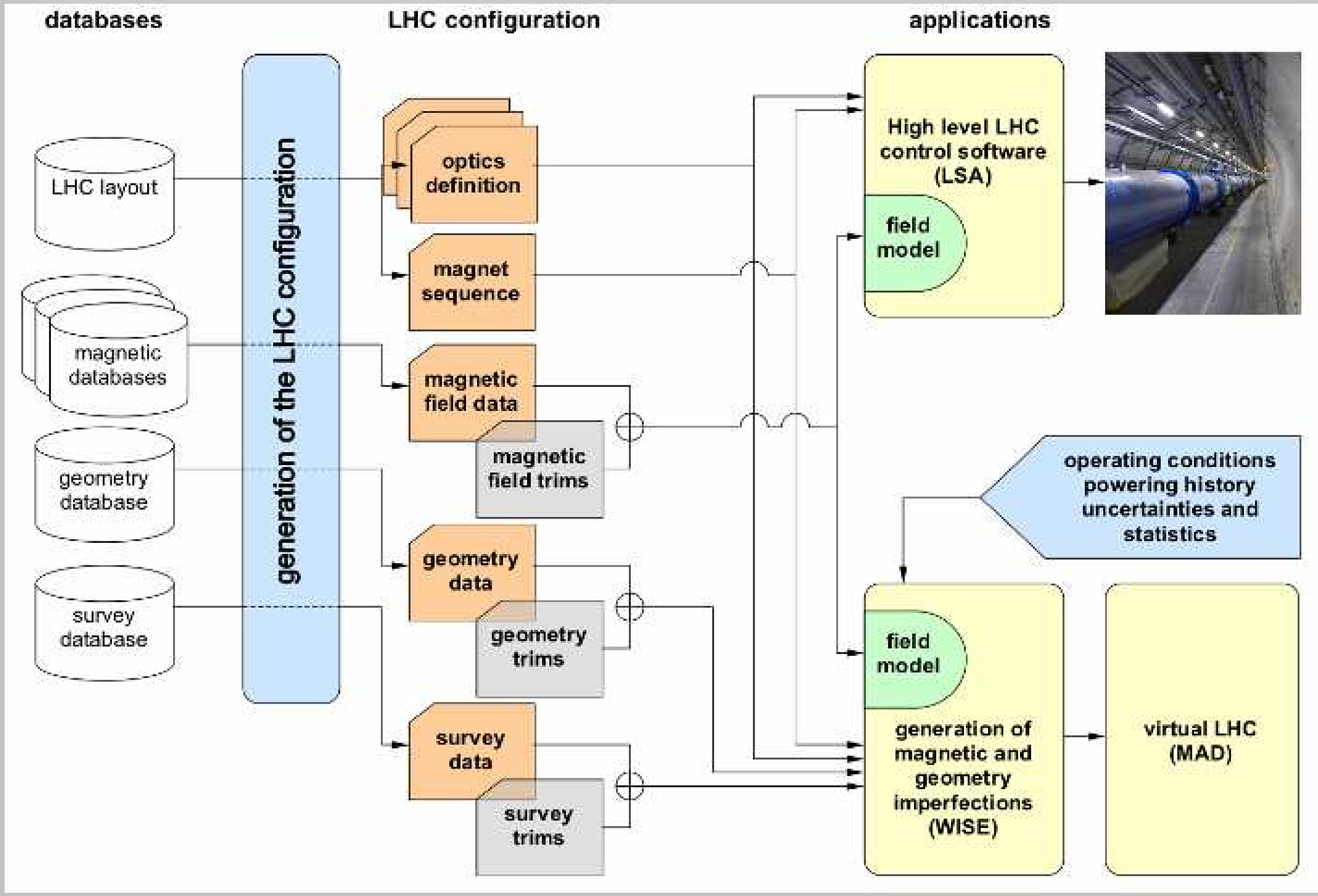
… and more are planned for the long term.

- **Preparation for future tests**:
  - CERN has repatriated the tools to build and repair all types of LHC magnets, in case any replacement will be needed during the lifetime of the machine (10-20 yrs ?)
  - we maintain the capability to perform (with some penalty) all standard tests with the same equipment and methods as was used during the series phase [that is, until we'll have something better …]



Tests for the operation of the LHC

Operation of the machine is based on a mathematical model (**FIDEL**: FIeld DEscription for the LHC) able to predict integrated strength and harmonics based on magnet current value and history.



see also: http://fidel.web.cern.ch/fidel/

Measurement campaigns related to FIDEL:

- **Accurate determination of model coefficients:**
  - field behavior is broken down in additive components: geometric, saturation, static SC effects (magnetization, ramp rate, field advance[1]), dynamic SC effects (decay, snap-back)
  - components are statistically related to cycle features, e.g.: pre-cycle level, duration and ramp rate; injection and flat-top duration; current shape at the beginning and end of a ramp, etc.
  - full exploration of the parameter space is combinatorially expensive and could not be carried out during the series tests" ⇒ more tests until end 2007.

- **Experimental testing of non-nominal machine cycles**:
  - modifications of the nominal cycle are expected during the commissioning phase; new modes of operation are foreseen throughout LHC's lifetime
  - we maintain the capability to test 1×MB + 1×SSS to validate and refine the FIDEL model accordingly (as a part of the FAME project[2])
  - "tracking tests" to verify the possibility of simultaneous measurements of multiple magnet types, fed in quasi-real-time with actual machine current, are being carried out now
  - **NB:** machine control is feed-forward only. The possibility to use magnetic measurements for real-time feed-back control is in theory possible but has been deemed unnecessary for now.

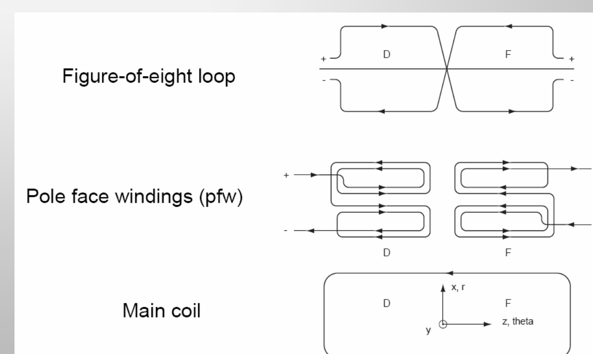
1=see G. Deferne's talk, this workshop; 2=see J.G. Perez's talk, this workshop

Tests for PS and SPS

Magnetic measurements of repaired resistive magnets for CERN's accelerator chain are now becoming more frequent as magnets get older and the park needs to be consolidated.
All magnets working in fast pulsed mode ⇒ "traditional" fluxmeter systems used.

- **Proton Synchrotron (PS) magnets**
  - main combined-function dipole/quadrupoles:
    - one extensive campaign carried out in 2001 to characterize new corrector coil circuits;
    - possibility of an additional campaign for the non-linear interaction of different circuits under discussion (*difficult* test: 30-ton, 6 m long magnet, 5 power circuits to test in combination, benefit of MM vs. beam measurements to be assessed)
  - sporadic tests of other magnets: e.g. elliptic gamma-jump quads, etc…

- combined function magnets (half-focusing, half-defocusing)
- pole-face and figure-of-eight windings to trim quadrupole and sextupole

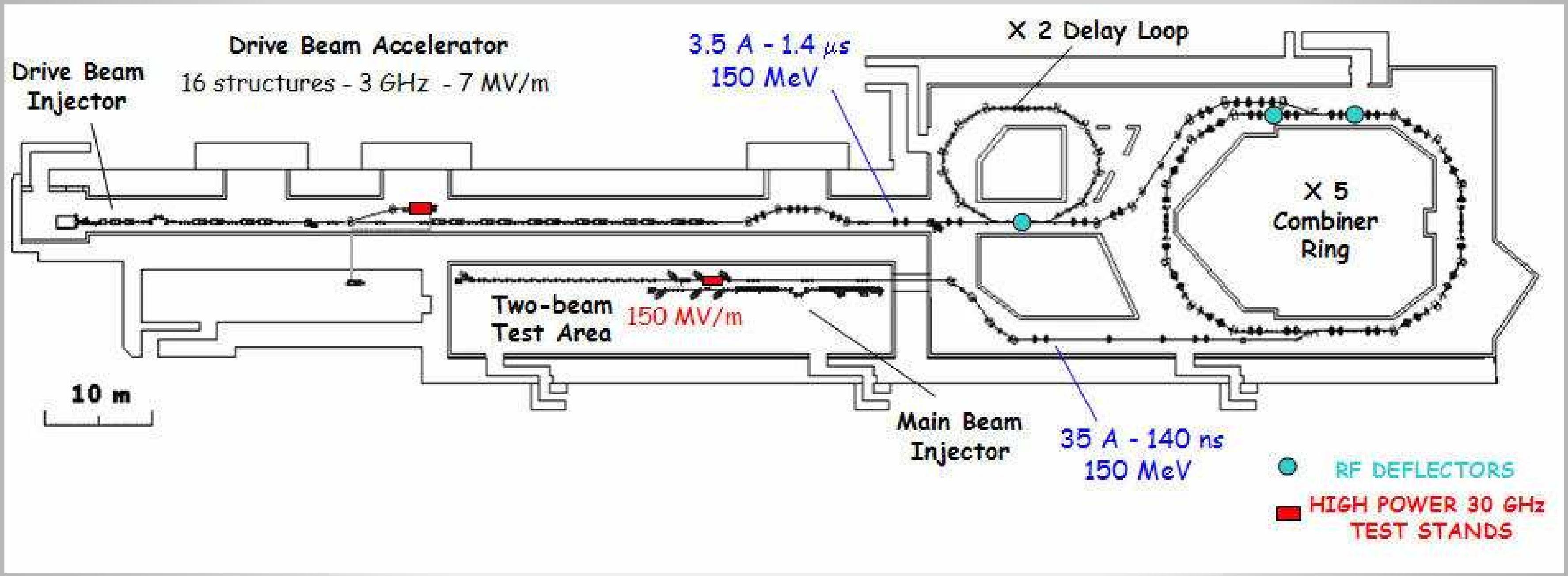


Tests for PS and SPS

- **Super Proton Synchrotron (SPS) magnets**
  - Increasing number of faults, due to:
    - decay of insulation
    - copper coils eroded internally by flowing cooling water.
  - Coils replaced at a rate of 5~6/year, magnets need to be measured and shimmed to match reference main dipole & quadrupole

Upcoming machine: CTF 3

CTF3 is a test facility for CLIC, aiming at demonstrating the drive beam concept and testing components at nominal power. CTF3 is now being built at CERN using ~300 new and (mostly) second-hand magnets, recuperated from machines throughout Europe.

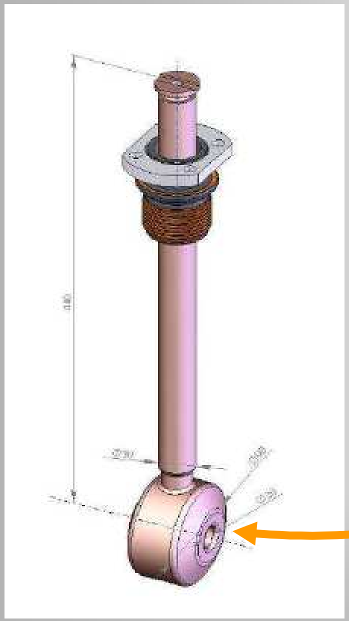


- **CTF3 magnets**
  - one-two magnets per type to be tested
  - ~10 magnets tested up to date, ~20 more expected until mid 2008 (dipoles, quads & sext.).
  - mostly standard tests (integrated strength, field homogeneity) using a flux meter
  - specs and methods yet to be fixed in some cases (e.g. trapezoidal-pole dipoles)

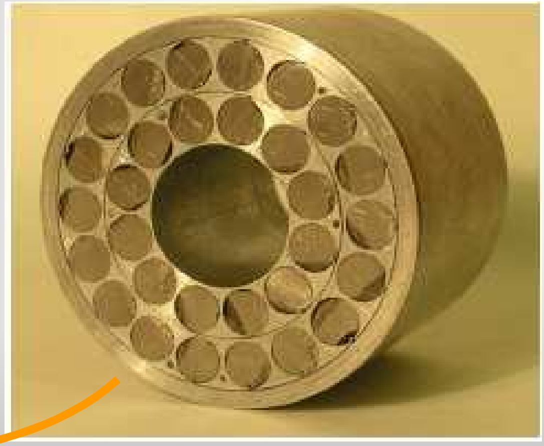
Upcoming machine: Linac4

The 160 MeV Linac4 is the recently approved upgrade to the LHC injector chain, designed to double the output intensity of the PS Booster thus allowing LHC to reach and surpass its nominal luminosity.

- **Linac4 magnets**
  - most magnets recycled from Linac2: only some quads to be remeasured
  - permanent quadrupoles: ~60 magnets to be fully tested (integral, harmonics, axis, field direction) to a high accuracy (0.05 mm axis budget) in 2008/2009.
    Under discussion: need to test after welding in the drift tube to verify any possible heat-induced degradation. Prototype tests started.
  - pulsed quadrupoles: ~60 magnets also coming in 2008/2009.



drift tube



prototype permanent magnet quad

Linac2-type pulsed quad

Ongoing/recent collaborations with external institutions:

1. CNAO – Centro Nazionale Adroterapia Oncologica
2. ASG – Ansaldo Superconduttori Genova
3. Academia
4. Other

External collaborations : aims & scope

As LHC-related magnetic test activity is drastically reduced, a small % of our Group's resources have been allocated to external collaborations.

Aims:
- foster scientific links and exchange with colleagues in HEP laboratories (as per CERN's mandate)
- transfer of technology to industrial partners (as per CERN's mandate)
- maintain and diversify the range of our own competencies

R&D partnership on specific hardware or software components (e.g. University of Florida, Università del Sannio)

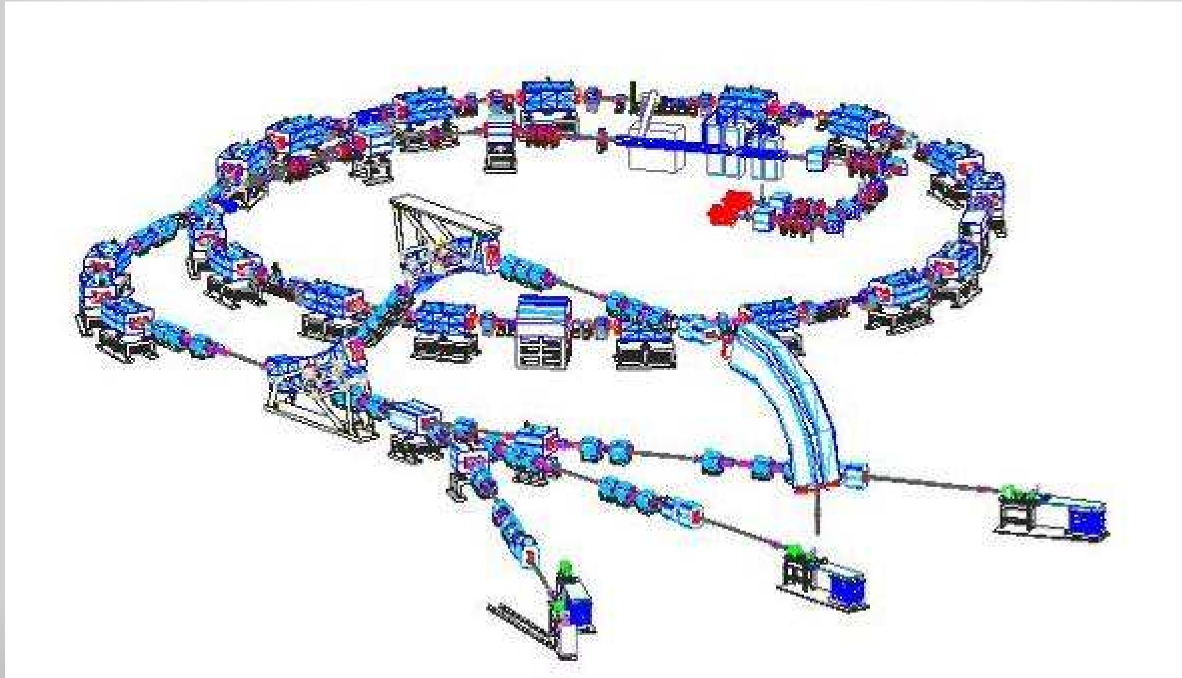
provide turn-key measurement instrument & software (e.g. QIMM mole for ASG)

plan & execute series tests for other accelerators, e.g. CNAO (FAIR ?)

Collaboration: CNAO

CNAO (National Center for Oncologic Hadrontheraphy) is a new medical accelerator being built at Pavia, Italy, expected to come online in 2008. Main features:

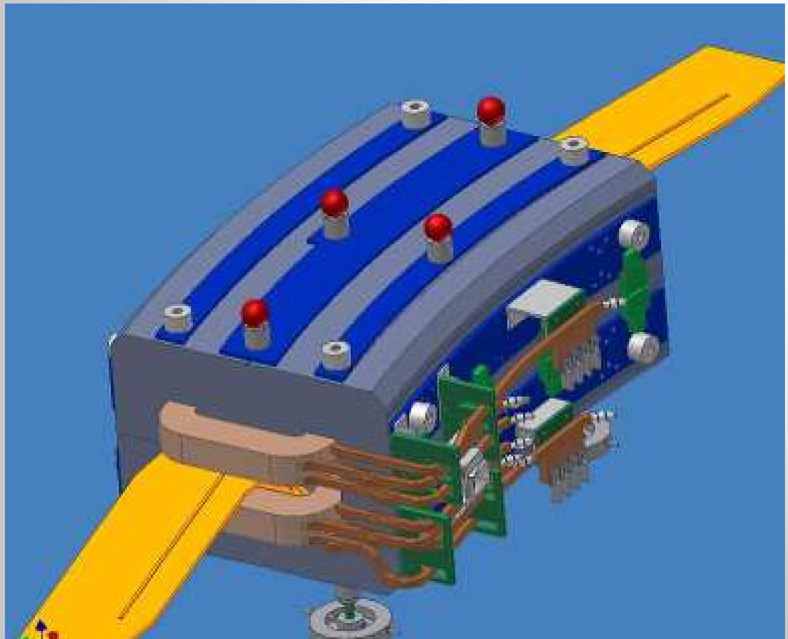
- 400 MeV/u C^{6+} beams with narrow Bragg peaks $\Rightarrow$ effective 3D voxel scanning of the tumour
- fast-pulsed (~2 s cycle time), almost continuously variable energy magnet cycling.
- strict tolerances on BdL and $\Delta B/B$ ($\pm 2 \cdot 10^{-4}$), very difficult to obtain dynamically
- field uniformity of dipoles to be measured along curved beam path



Courtesy of M. Pullia, CNAO

Collaboration: CNAO

- **CERN-CNAO agreement (2005 + addenda)**
  - — additional partner: LPSC Grenoble (M Baylac, E Froidefond)
  - — development of curved reference coil and 11-coil fluxmeter[1] for the synchrotron dipoles
  - — detailed characterization of two main dipole prototypes (including unforeseen dynamic fx)
  - — series test of 26 main dipoles (second unit being tested now: end foreseen Dec 2007)
  - — R&D for the full 3D mapping of a large aperture dipole
  - — R&D for the development of a B-train



Courtesy of M. Pullia, CNAO

B_{max} = 1.5 T
Gap height = 72 mm
Bending radius = 4.231 m
Bending angle = 22.5°
Magnetic length ~ 1.67 m

1=see R. Chritin's talk, this workshop

Collaboration: ASG (Ansaldo Superconduttori Genova)

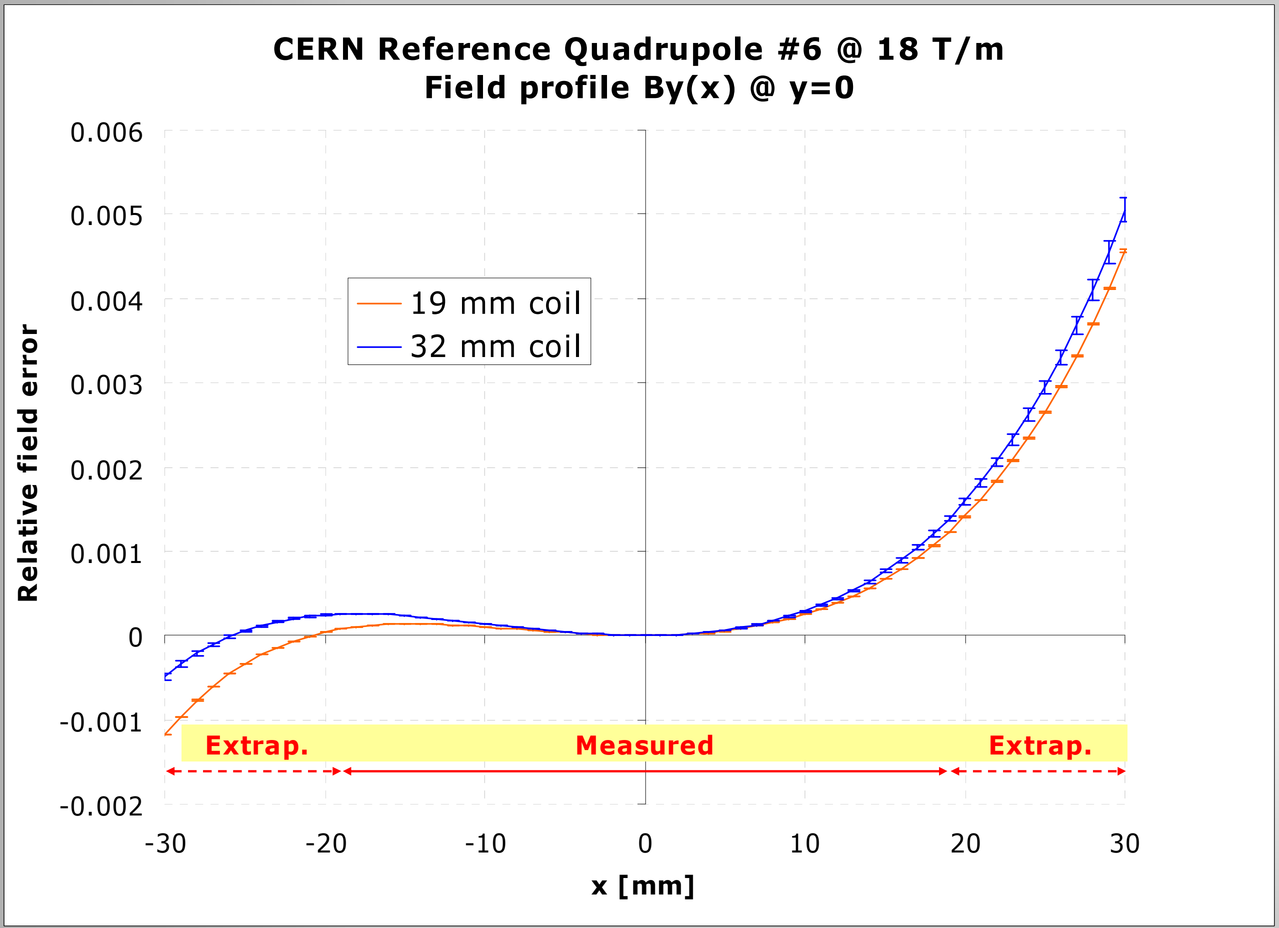
ASG is a major contractor for the CNAO project (main dipoles, dipole and quadrupole correctors for synchrotron and transfer lines). A Technology Transfer agreement was struck in parallel with CERN-CNAO collaboration to allow the firm to carry out some of the magnetic measurements.

- **CERN-ASG agreement**
  - joint development of one more curved fluxmeter coil for the transfer line dipoles (CERN provides a calibrated straight coil, materials and skilled manpower; ASG provides trainee manpower)
  - test of 3 transfer line dipoles at CERN with mixed CERN/ASG team (2 done, 1 yet to go)
  - supply of a turn-key quadrupole mole system, i.e. a QIMM (similar to the DIMM already used by Ansaldo for *in situ* series LHC dipole tests) modified with a R=32 mm coil.
  - Commissioning of the QIMM system at CERN, carried at the same time as technical training of ASG staff and characterization and shimming of 2 dipole and 2 quad corrector prototypes;
  - development of a simplified test protocol for the measurement of $\Delta B/B$ in magnets with aperture >> $\varnothing$ coil *[see following example results]*
  - remote follow up of series tests at ASG (support and consultancy within reason – system is contractually supplied "as is")

Very successful (… and even slightly profitable …) example of Technology Transfer; somewhat weird *menage à trois* with CNAO

Example of results: harmonics in large aperture by extrapolation at $r>r_{coil}$

Reference quadrupole measured in the same conditions with two moles having different coil ∅

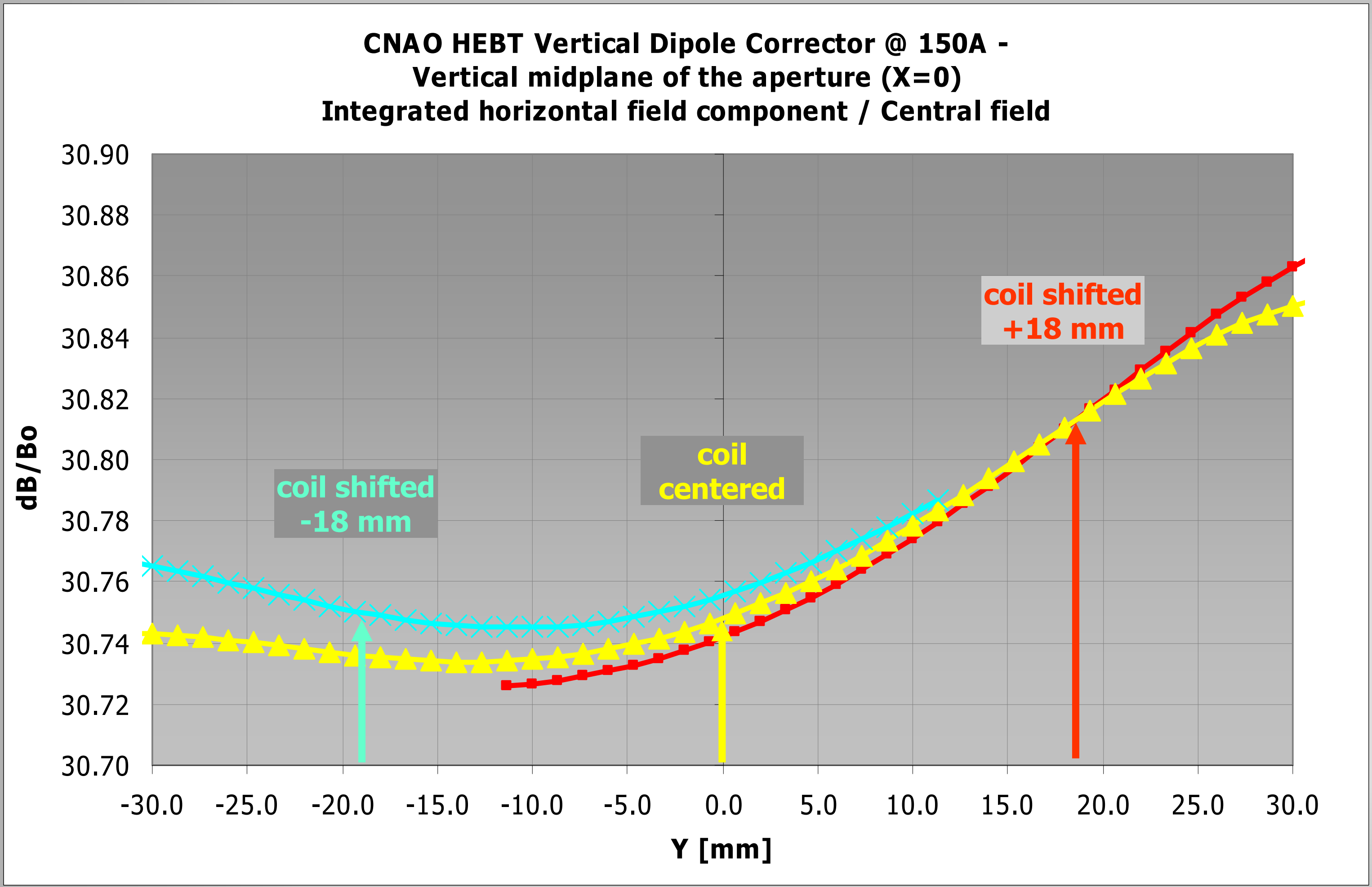


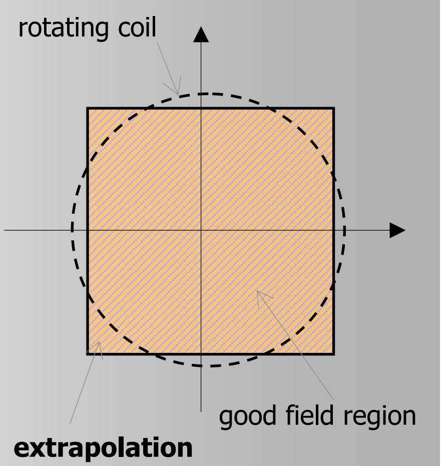
$$\varepsilon(z) = \frac{\Delta B}{B_{\max}} = \frac{r_{ref}}{\|C_2\| R_2} \sum_{n=3}^{15} C_n \frac{z^{n-1}}{r_{ref}^{n-1}}$$

Max. relative error in when extrapolating results @ R=19 mm
$\Delta B/B \approx 6 \cdot 10^{-4}$

Example of results: harmonics in large aperture by extrapolation at $r>r_{coil}$

Similar results obtained by comparing multiple measurements with the same coil (R=32)





Extrapolation within 60×60 “good field region” from center meas. only looks reasonable

Other collaborations

- **Academia**

  - Università del Sannio, Benevento, Italy: development of a Flexible software Framework for Magnetic Measurements[1]. The agreement involves one senior professors and several researchers, technical and doctoral students working on CERN site.
  - Florida A&M University: development of a fast rotating coil system for the FAME project. The agreement involves a researcher at CERN and several students in the US
  - Università di Bologna, Italy: informal collaboration with locally based researchers and students on topics related to the current distribution in superconducting cables

- **Other recent/ongoing collaborations**

  - PSI, Villigen, CH: cross-calibration of an NMR and an Hall probe in an LHC dipole at 3T
  - OSQAR (Optical Search for QED vacuum magnetic birefringence): effect of 9T magnetic field on the polarization of a laser beam reflected back and forth across an LHC dipole aperture

- **Future possibilities**

  - ESRF: collaboration on the magnetic measurements for the synchrotron update under discussion
  - ALBA (CELLS, Barcelona): rotating coil systems for synchrotron magnets, under discussion
  - FAIR (GSI): partnership on design and testing of pulsed SC magnets under discussion
  - R&D activities with European partners under the $6^{th}/7^{th}$ EU Framework Program (CARE network), starting with measurements of first model Nb_3Sn coils (NED)
  - desirable in the longer term: collaborations with ITER and experimental magnet community ?

1=see M. Buzio's talk, this workshop

Status and prospects for different instrumentation families:

1. Rotating coil systems
2. Traveling probes (moles)
3. Fluxmeters
4. Hall probe systems
5. Stretched wire systems
6. Material property instrumentation
7. B-trains

Rotating coil systems

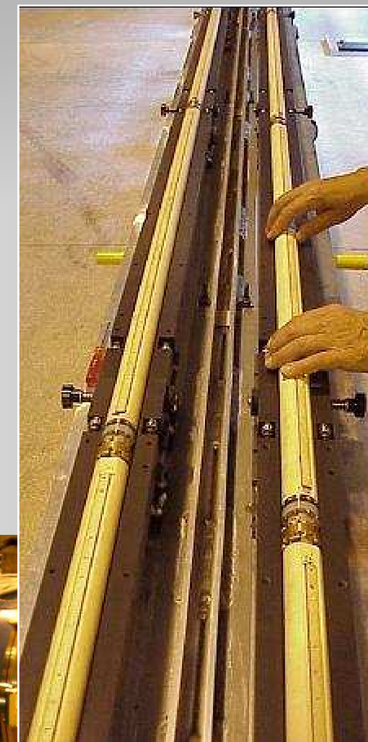
- **Long ceramic coil shaft systems**

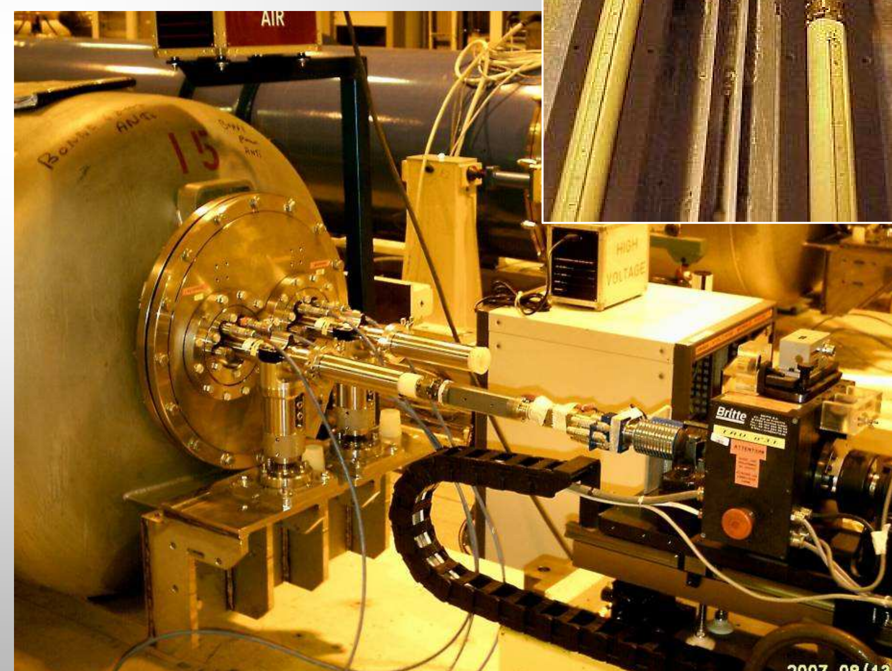
  — crucial to obtain integrated strength and harmonics on long cryomagnets + fault detection
  (local harmonics, quench localization) for FIDEL tests and future repairs

  — existing equipment (12×15 m dipole shafts, 4×9 m quad shafts, 6 TRU, 0.2 Hz in washing machine mode) to be gradually phased out (FAME project[1], currently being tested):

  - PDI integrators → Fast Digital Integrators (FDI)
  - Twin Rotating Units (TRU) → Mini Rotating Units (MRU)
  - Standard coil shafts → dedicated FIDEL shafts with super-sectors in series (fewer turns)

  — coil shaft upgrades for high field, high ramp rate SC magnets:
  ~10 Hz rotation with continuously updated flux interpolation to improve time resolution of measured harmonics; fewer turns, better mechanical balancing

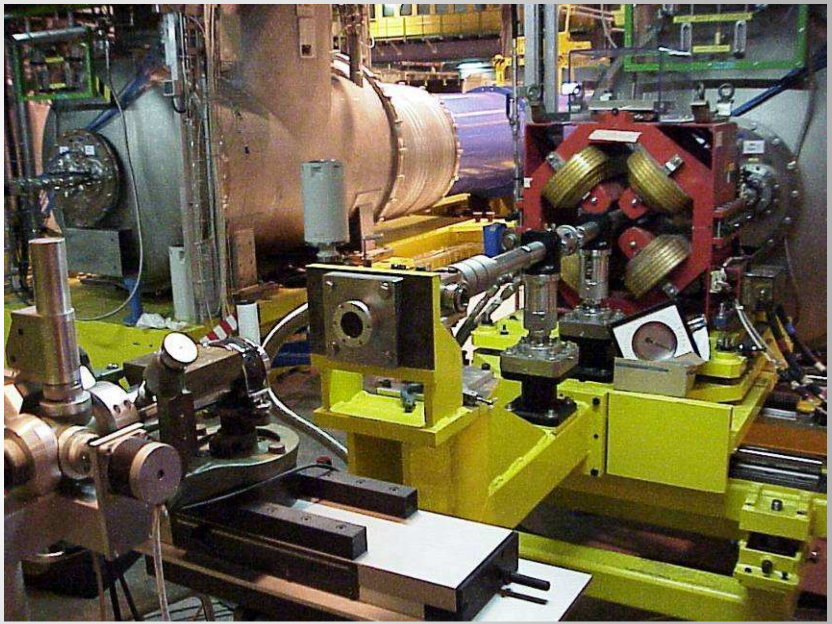




1=see J.G. Perez's talk, this workshop

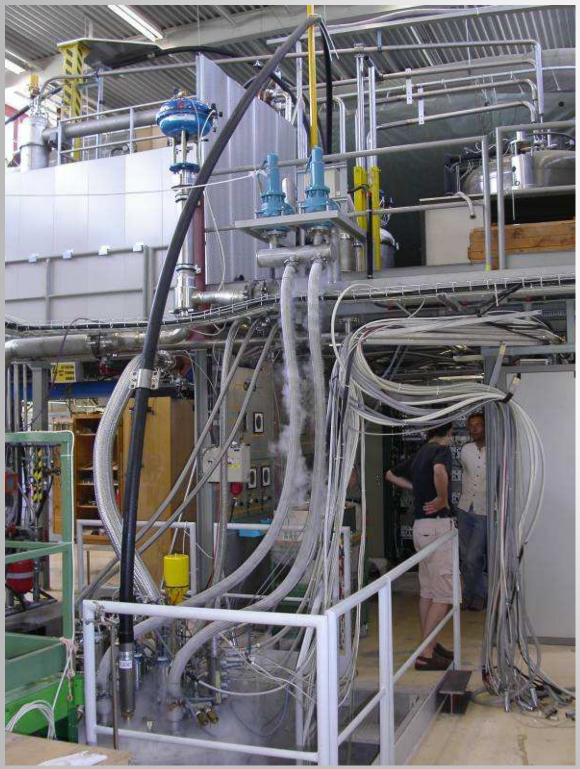
Rotating coil systems

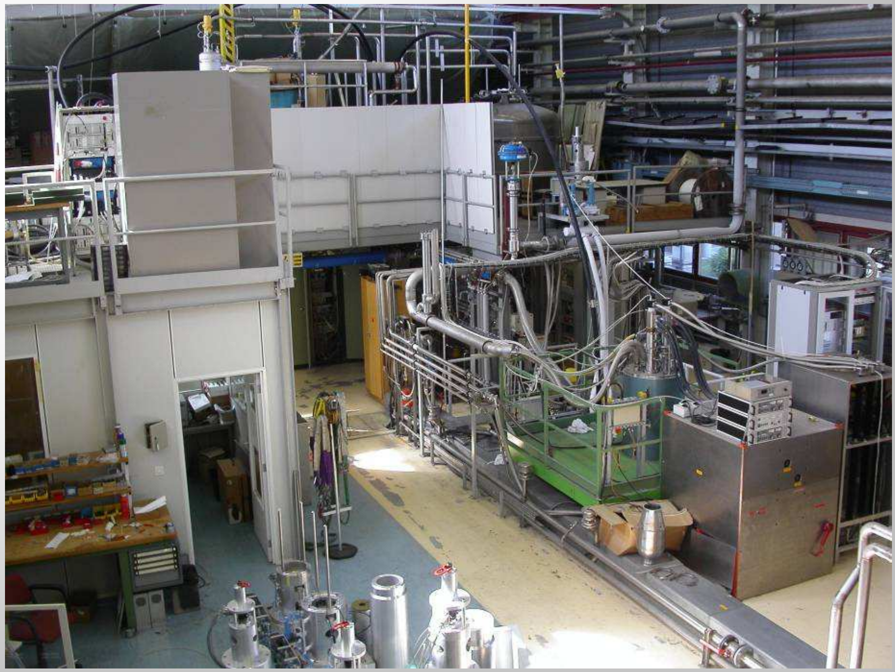
- **Scanning machines**
  - — Two Chaconsa units, designed for 10 m long cryomagnets, with one measurement head (harmonic coil or axis search coil with integrated LED + telescope system)
  - — Rather difficult to operate, depending on MMP, no real advantage over mole systems (except DC axis measurement with harmonic coil) ⇒ systems discontinued



Rotating coil systems

- **Cold rotating coil systems**
  - Three vertical rotating coil systems used extensively in Bloc4 (Prevessin) for LHC correctors
  - Cryostats being moved to SM18 laboratory in 2008 to share infrastructure/personnel
  - Systems may be adapted for future superconducting model magnets.





Travelling probes (moles)

- **Harmonic Moles**[1]
  - 750 mm, ∅19 mm coil, dipole- or quadrupole-compensated with tilt sensor and fully motorized longitudinal transport system
  - 12 dipole units (DIMM) + 6 quadrupole units (QIMM) used for LHC cryomagnet series tests in the industries and at CERN
  - a few units to be kept operational for future LHC cryomagnet testing + as a general-purpose instrument

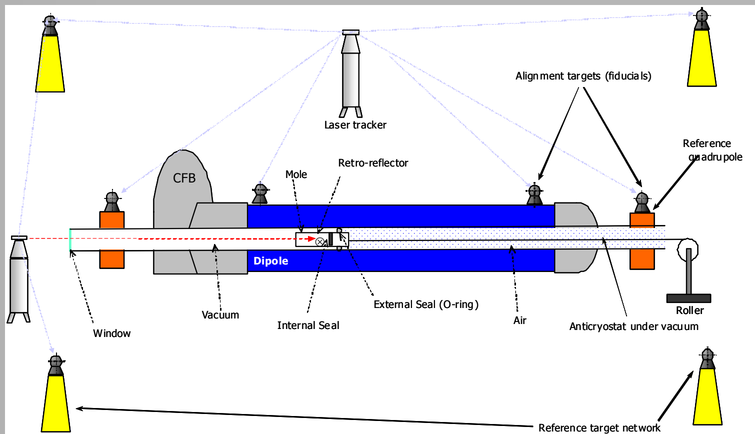
- **AC moles**[2]
  - 200 mm, 4× tangential coil with retro-reflector for accurate axis finding at low power, AC powering with synchronous detection, stepwise rotating mode for harmonics/field direction measurements
  - 6 warm units + 2 optimized for cold tests, at low field (∅40 mm, Ti body, non-magnetic tilt sensor, piezo motor)
  - 1-2 units to be kept operational for future LHC cryomagnet testing + as a general-purpose instrument

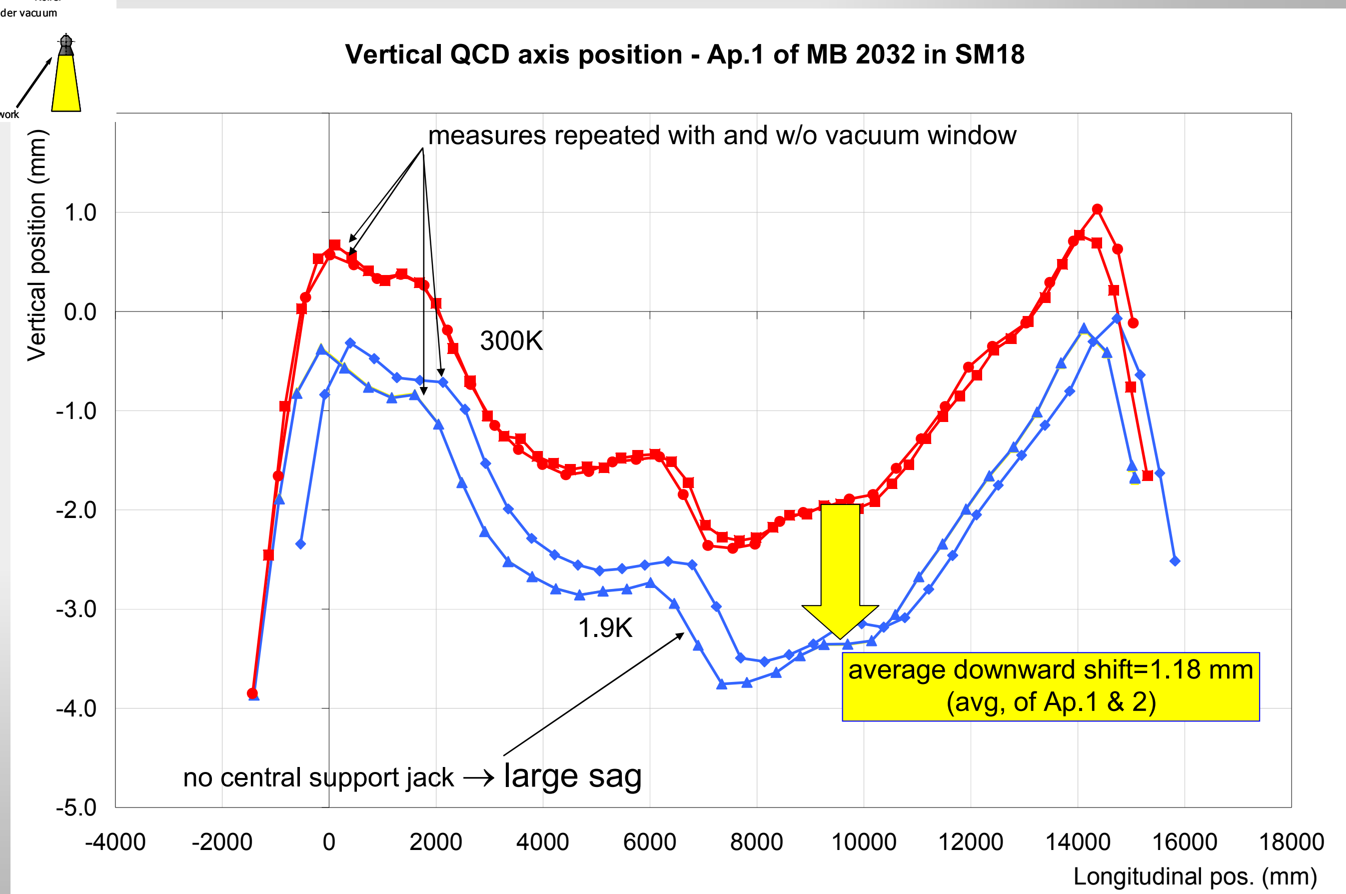
- **IPT Fraunhofer moles**[3]
  - 750 mm, ∅19 mm coil with LED source + telescope detection for axis finding
  - two warm units + one optimized for cold tests at high field (∅40 mm, Ti body, non-magnetic tilt sensor, piezo motor)
  - cumbersome operation & calibration + LabWindows software very difficult to debug, upgrade or maintain ⇒ system discontinued since 2003 [bitter lesson about externally source software !]

future integration of functionality in a "supermole": DC/AC modes, high field, harmonic coil, tilt sensor, axis tracking …

1=see J.G. Perez's talk, this workshop; 2= J.G.Perez, IMMW 14; 3=M. Buzio, IMMW XI

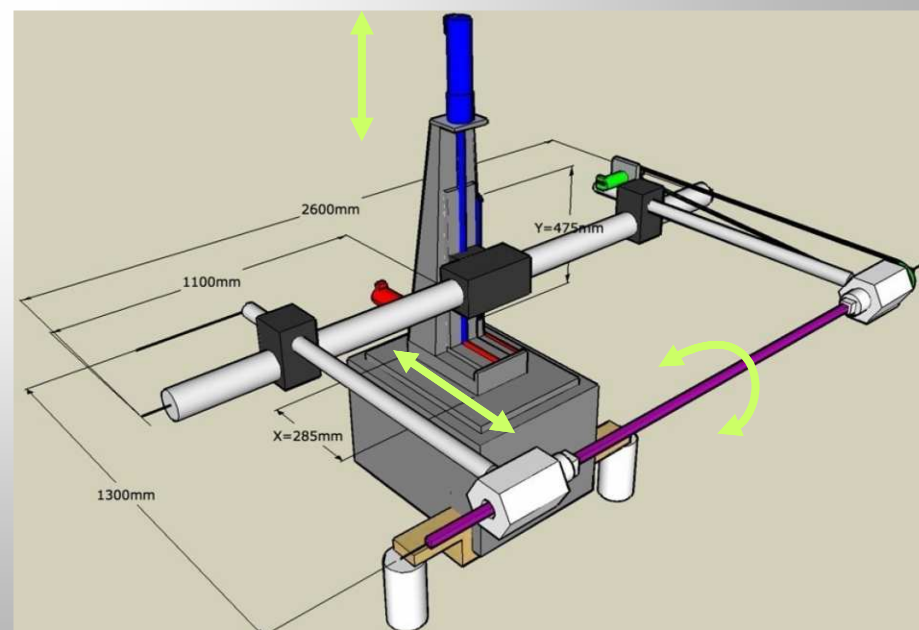
Example of results: cold magnetic axis of a dipole



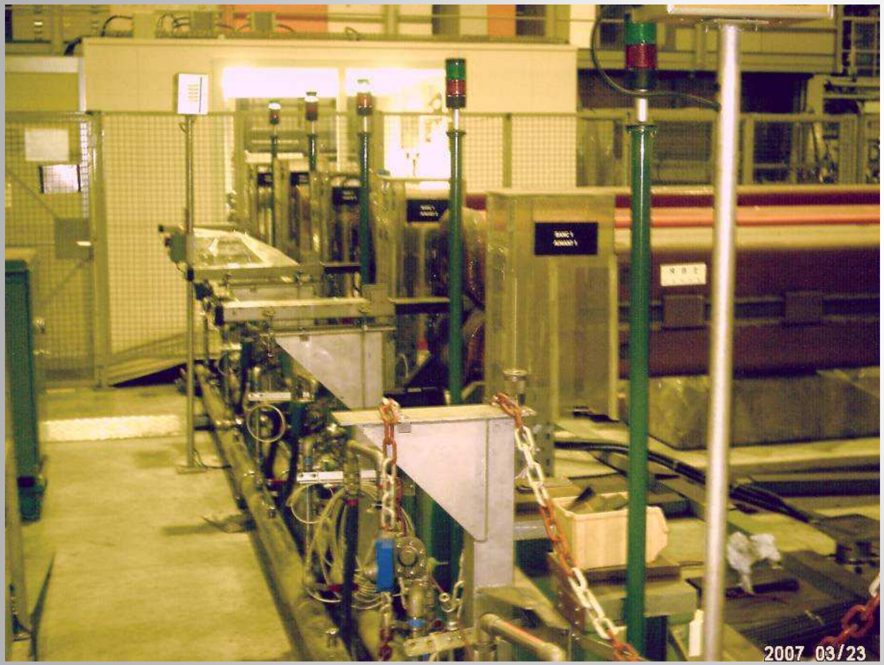


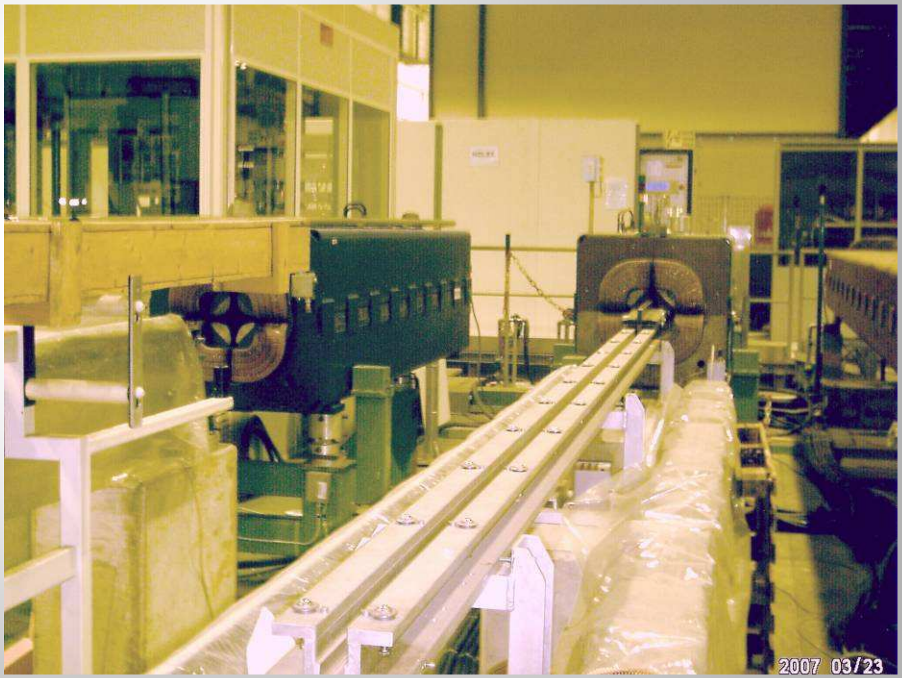
Fluxmeters

- **PS "Huron" Bench**
  - high-precision coil rotation and transversal displacement of coils from 30 mm to 2 m
  - truly polyvalent system: integrated flux can be measured with fixed or moving/rotating coil to obtain integrated field strength, harmonics, center, direction and uniformity
  - advantages over mole systems:
    - naked coil ⇒ no support tubes = easier installation, no magnetic material-induced artifacts, no eddy currents in pulsed mode; smaller ∅ possible
    - single-pass integral (up to coil length)
    - easy to measure directly field or gradient uniformity even in very large gaps
  - routinely used to measure small/medium size resistive magnets (e.g. for PS, CTF3, etc..)
  - recently refurbished; future developments include data treatment for harmonics in pulsed/DC mode



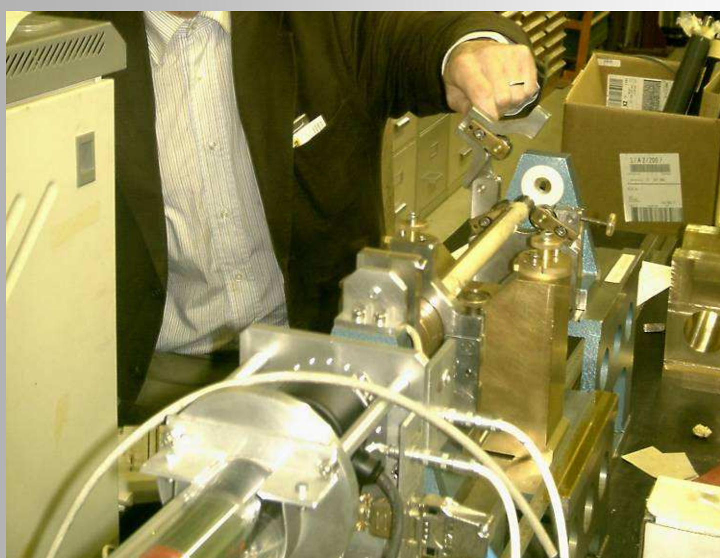
- **SPS Bench**
  - "historical" bench originally developed for series tests, now used for repaired magnets
  - adapted for 7-m long dipole and quadrupole coils

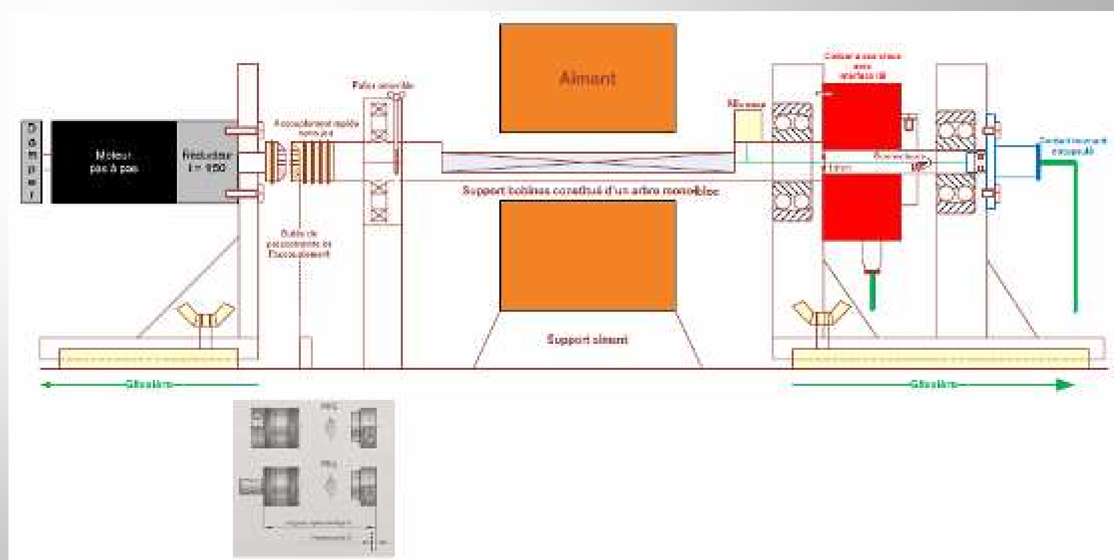




Fluxmeters

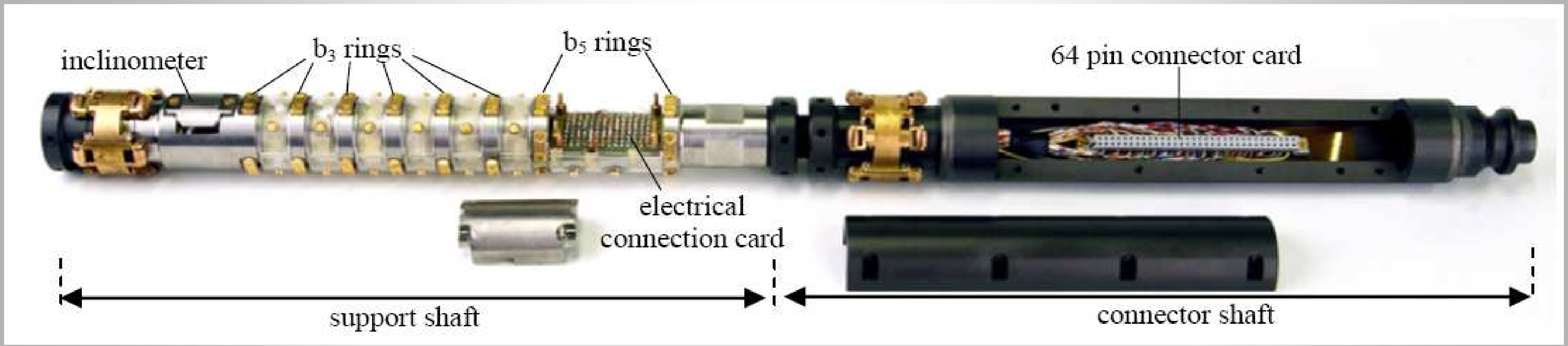
- **Linac4 bench**
  - 200 mm, ∅20 mm coil + high-precision mechanics for tests of permanent and pulsed Linac-type quads
  - R&D ongoing to refurbish with new motor/encoder/brake able to work in two distinct modes:
    - permanent magnets: standard rotating harmonic coil
    - pulsed magnets: stepwise harmonic measurement (possibly with mechanical stabilization of the coil during current pulses)





Hall probe systems

- **b3/b5 probe:** this probe, providing high-bandwidth (~1 kHz) local measurements of harmonic decay and snapback effects in SC magnets, is used sporadically to provide data for the FIDEL model. Pending performance assessment of the new, faster harmonic coil systems, no further developments are planned for now.

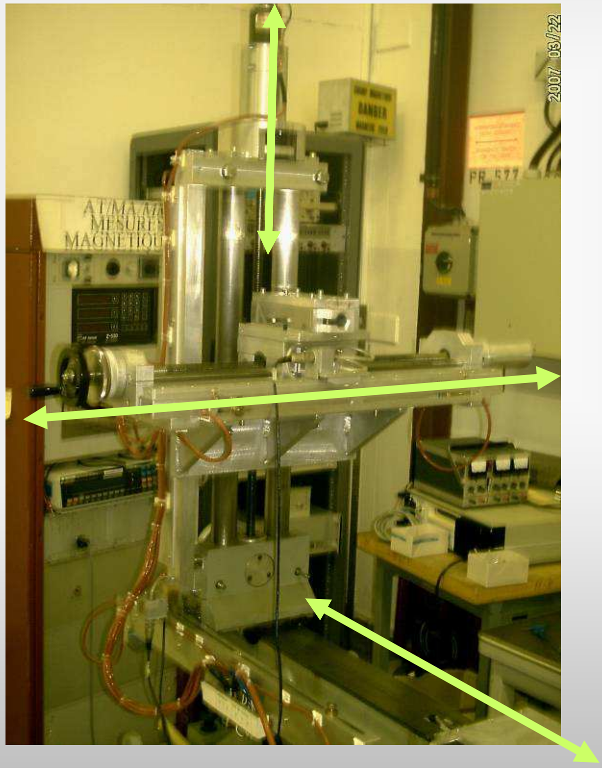


Hall probe systems

- **2D scanner**: this high-precision bench can map a region of 6.0×0.5 m with a Hall or NMR probe. Originally designed for mapping of C-shaped dipoles, possible future utilization is not clear at the moment.

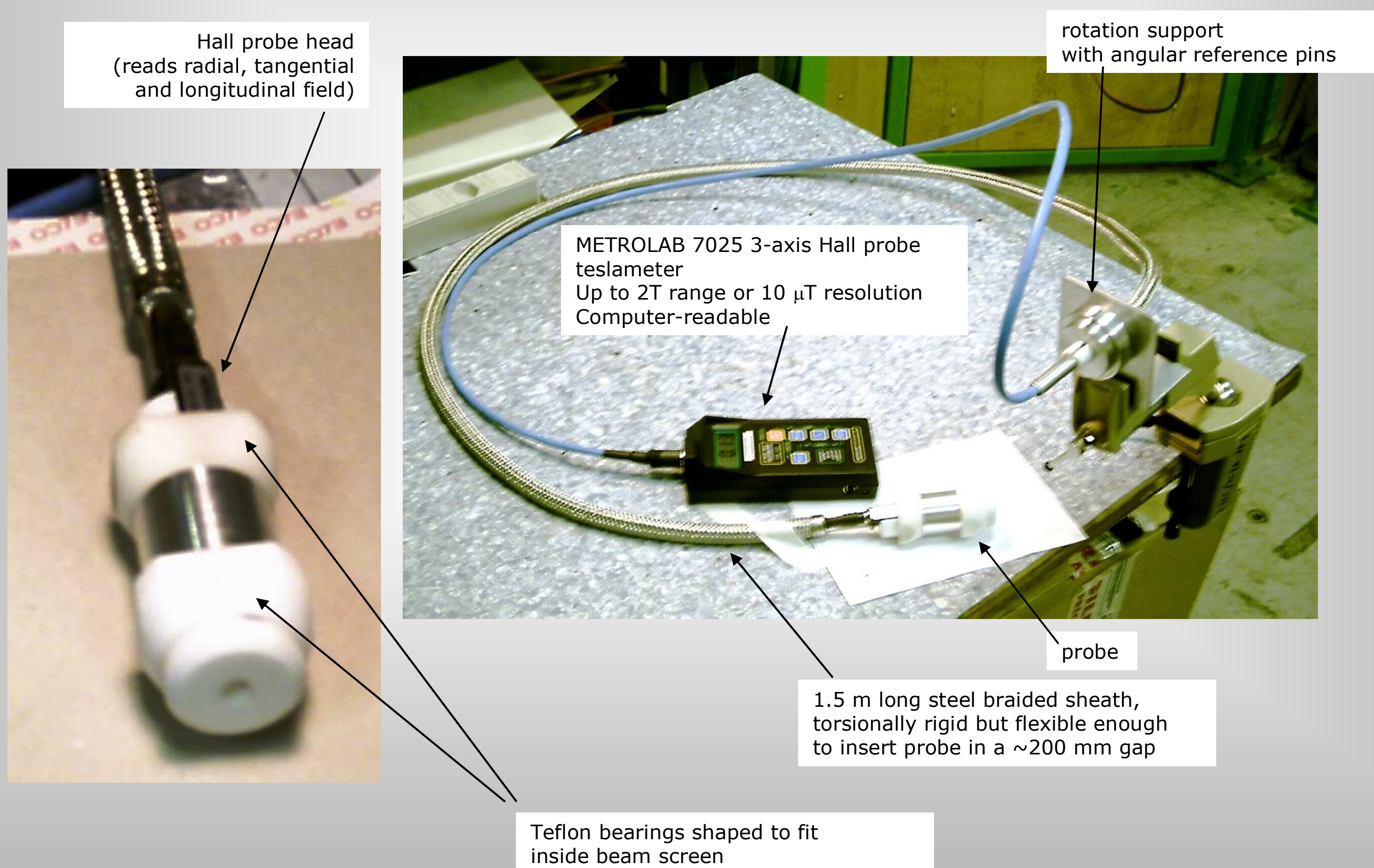
Hall probe systems

- **3D scanner:** this general-purpose machine provides scanning over a 0.5×0.5×0.5 m volume, and has been used recently to scan the fringe field of CNAO dipoles.
  Planned developments include improvement of the control software to automate scanning over complex-shaped regions

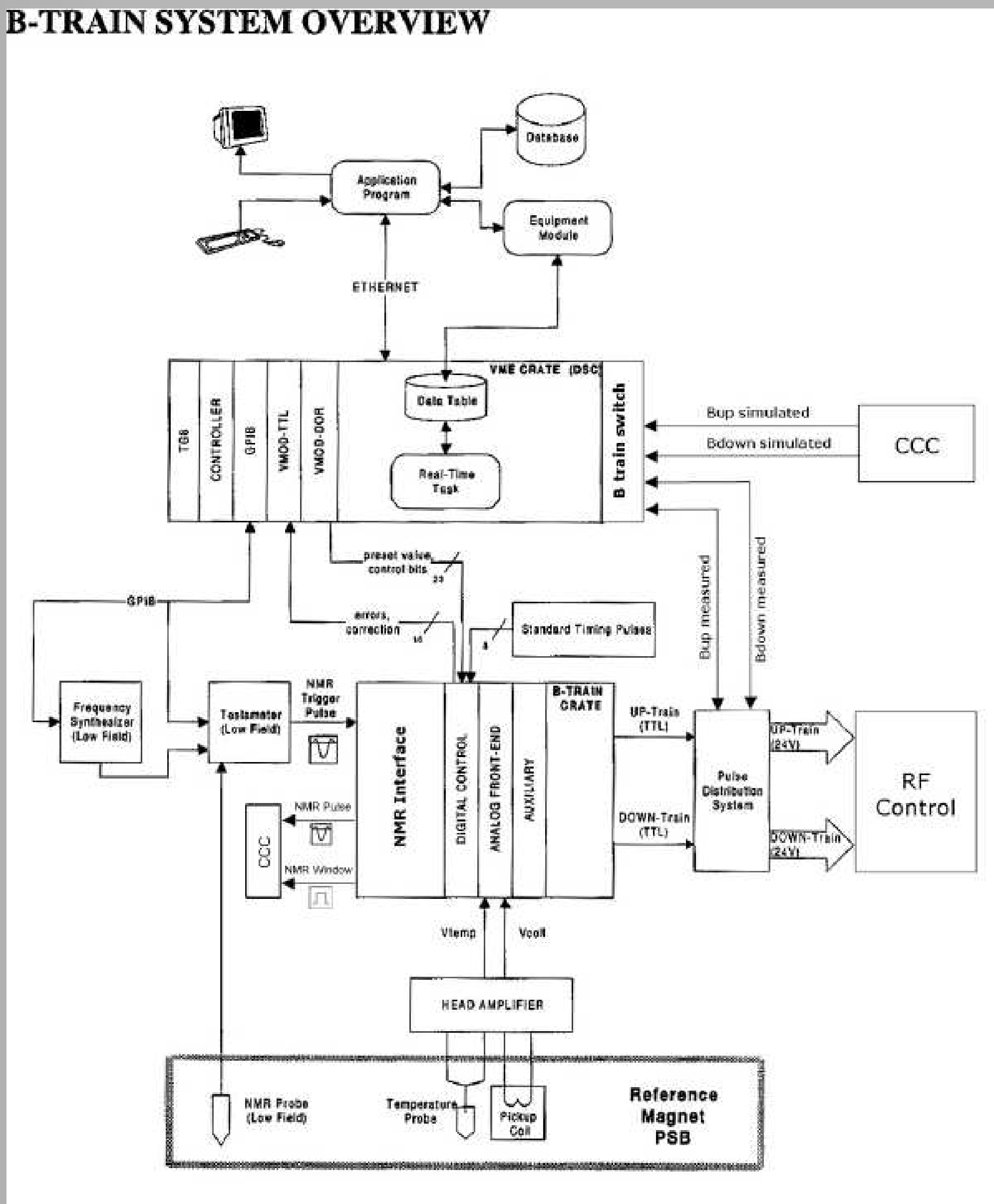


Hall probe systems

- **polarity checker:** based rotating Hall sensor, 5 units built of which 1-2 to be kept operational to check repaired magnets. One hand-operated version used to measure *in situ* when electrical connections are repaired in the tunnel (improvement with 360 deg electronic tilt sensor under way)



B-trains



Real-time measurement of BdL in a reference dipole in series with the machine ⇒ feedback to the RF control system for more accurate beam acceleration, despite field non-linearities and history-dependent effects

Basic principle of measurement:

- flux coil to get field increment during ramps (integrated or not according to the downstream control system being based on B or dB/dt)
- field is typically encoded digitally as a pair of TTL pulse trains, e.g. 1 pulse = ±0.1 Gauss
- if needed for accuracy, a field marker (NMR, peaking strips) read at every cycle to compensate for magnet, coil and integrator drifts
- redundant parallel chains and simulated trains often provided for safety

(for more info: see presentation by D. Cornuet at https://edms.cern.ch/file/844310/2/B_trains_AT_MTM_seminar.pdf)

B-trains

- **B-trains in operation at CERN:**

  - **PS:** (1960s) peaking strip+ (experimental) FMR markers
  - **SPS:** (1980s) no marker (preset), only relative mode (DB)
  - **Booster:** NMR marker
  - **AD:** no marker, measurement done directly in the machine
  - **LEIR:** no marker, measurement done directly in the machine

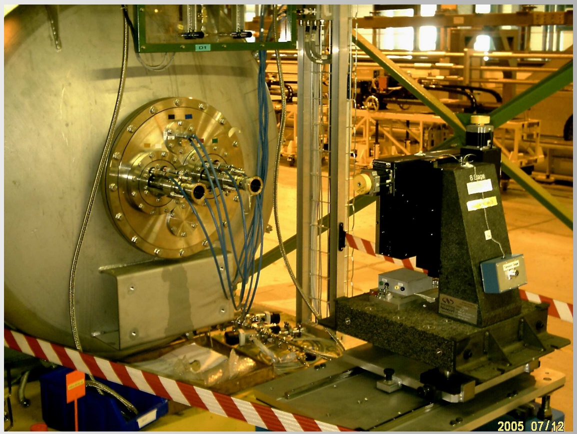
- **Related activities**

  - maintenance of the hardware of existing systems
  - in concert with end users, specification and development of upgrades, e.g.:
    - improved control-room diagnostics
    - remotely hot-switchable redundant systems
    - re-introduction of NMR field marker in the SPS
    - field markers for high field and/or dynamic conditions (e.g. settable/high field peaking strips working in gradient field of combined magnet)
  - in the long term: standardization of hardware in all CERN systems (instrumentation, electronics, integrators, timings etc..)
  - R&D for new systems: e.g. CNAO, ELENA …

(for more info: see presentation by D. Cornuet at IMMW 13: https://edms.cern.ch/file/402476/1/IMMW13_slides_Cornuet.pdf

Single stretched wire system

- **Status:**
  - Three systems built and remotely maintained by J DiMarco
  - SSW measurements have provided a reliable reference for series tests of BdL, GdL, field direction and axis of LHC cryomagnets
  - At least two systems to be kept in working order to ensure future measurements
  - *In addition*: one old system with short, vertical wire intended for CLIC-type magnets (at present out of working order)

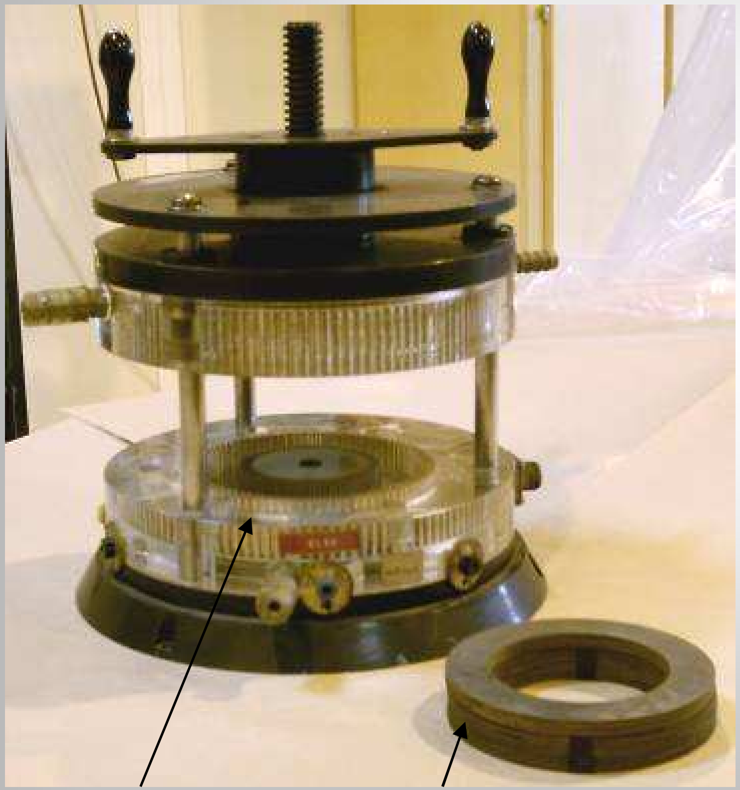


- **Prospects:**
  - Despite Joe's kind and continued assistance, we aim at becoming self-sufficient for what concerns this mission-critical instrument. Steps to be taken:
    1) porting of existing Solaris/C software under more easily manageable platform (FFMM and/or EMS ?)
    2) once driver issues can be solved in-house, we'll be in a position to maintain/upgrade HW & SW autonomously
    3) in the longer term: when a clear need will arise, it would be interesting to extended the functionality to new operation modes (pulsed or vibrating wire, etc…)

Material permeability instrumentation

The responsibility for testing of magnetic properties of materials will be shortly taken up by our Group.

- **Permeability test equipment:**
  - Commercial permeameter for thick sheet samples
  - CERN-built split-coil permeameter for toroidal samples
  - Cryogenic equipment for tests at 1.9 and 4.2 K (to be moved to SM18)

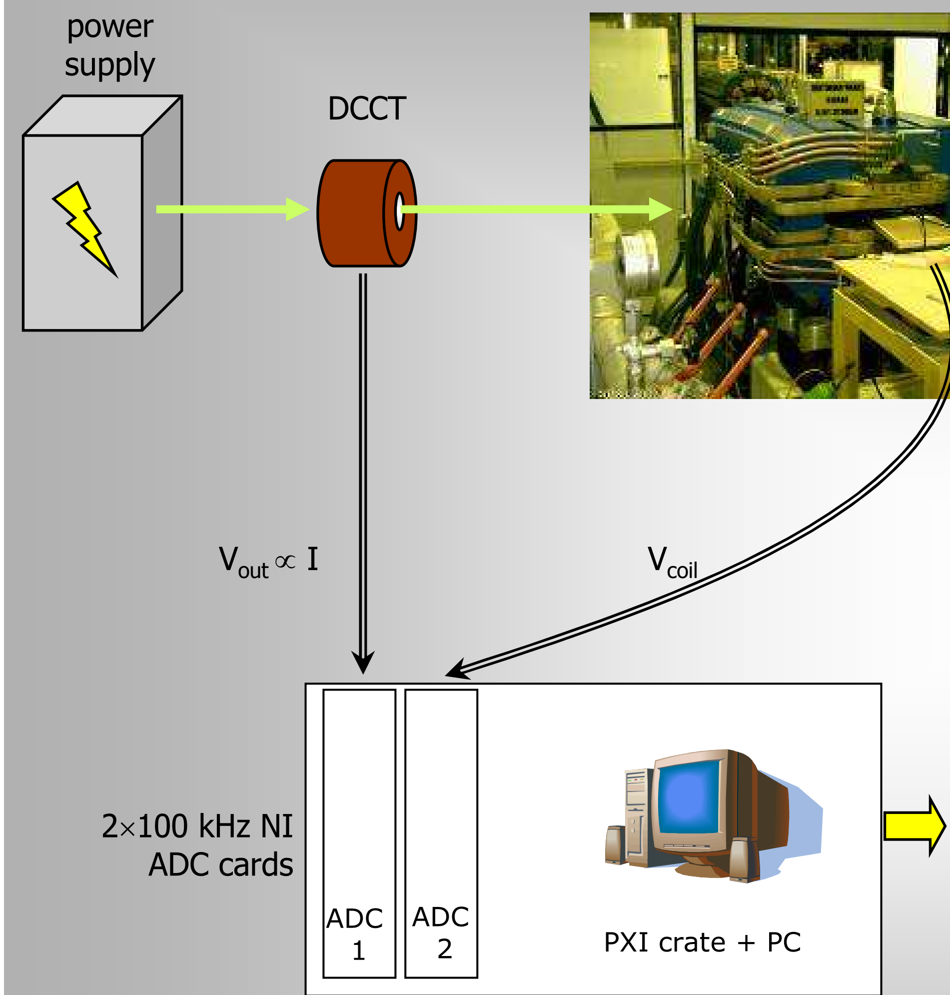


golden contacts

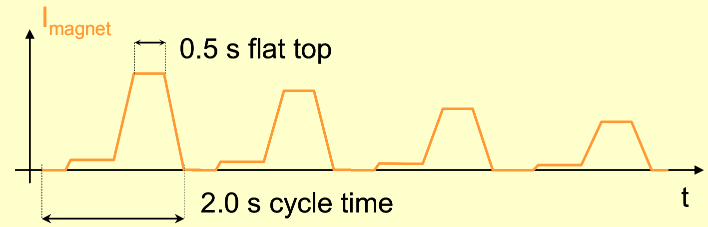
laminated sample

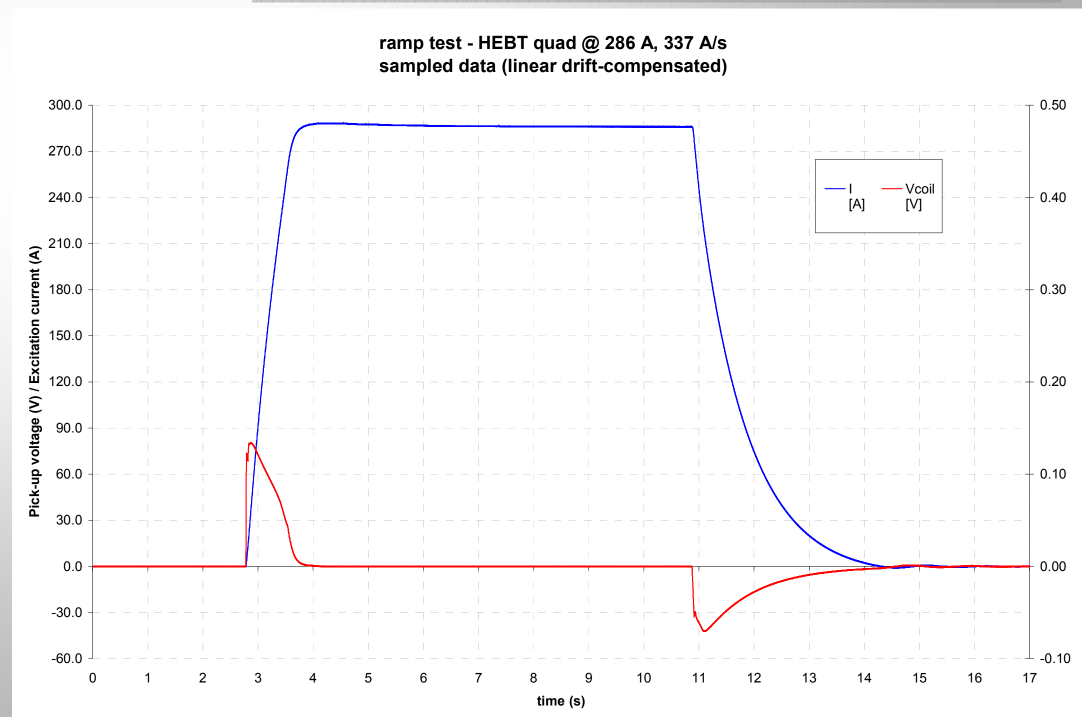
- split-coil permeameter
- originally developed by K. Henrichsen (1965)
- 3 split & interleaved toroidal coils
- 2×90-turn primary
- 1×90-turn secondary
- may be necessary in future to assess material properties for novel NbTi/Nb_3Sn magnets

Example of results: dynamic effects in CNAO magnets



problem: the field of CNAO magnets should stabilize rapidly within ~10^{-4} on flat tops,
⇒ compare B(t) vs. I(t)

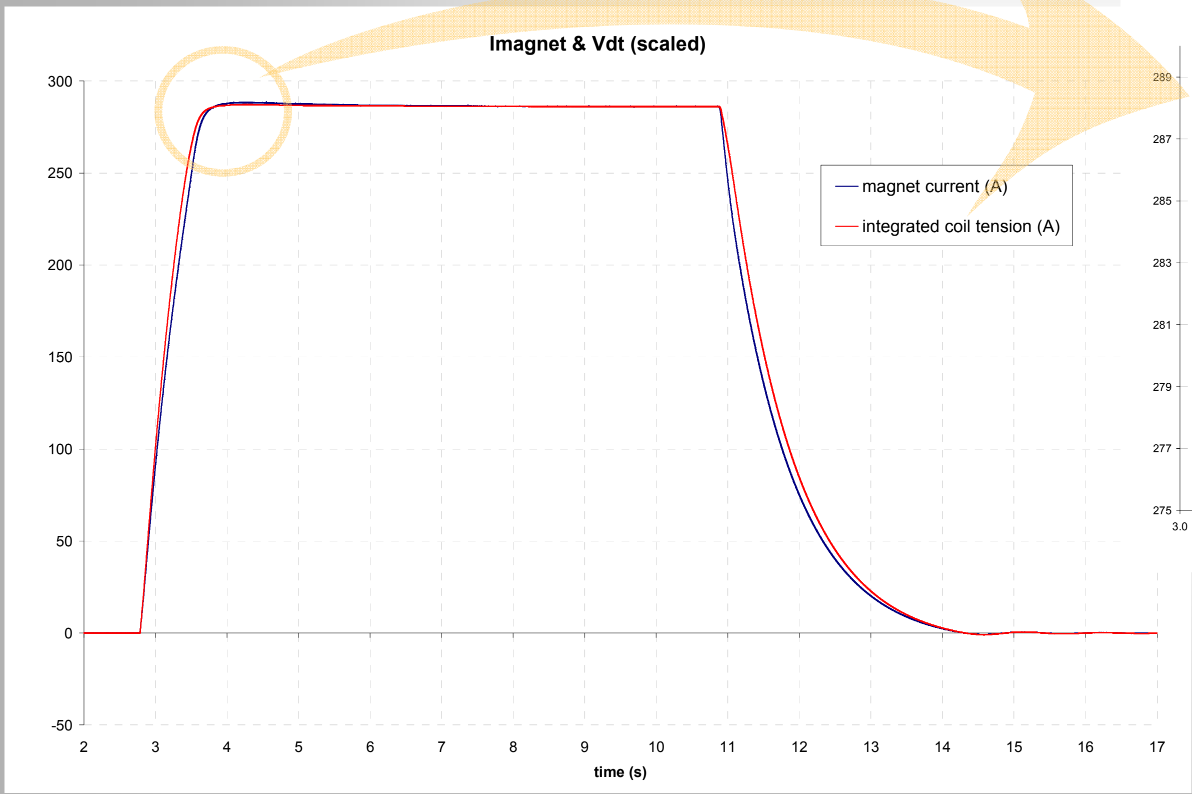


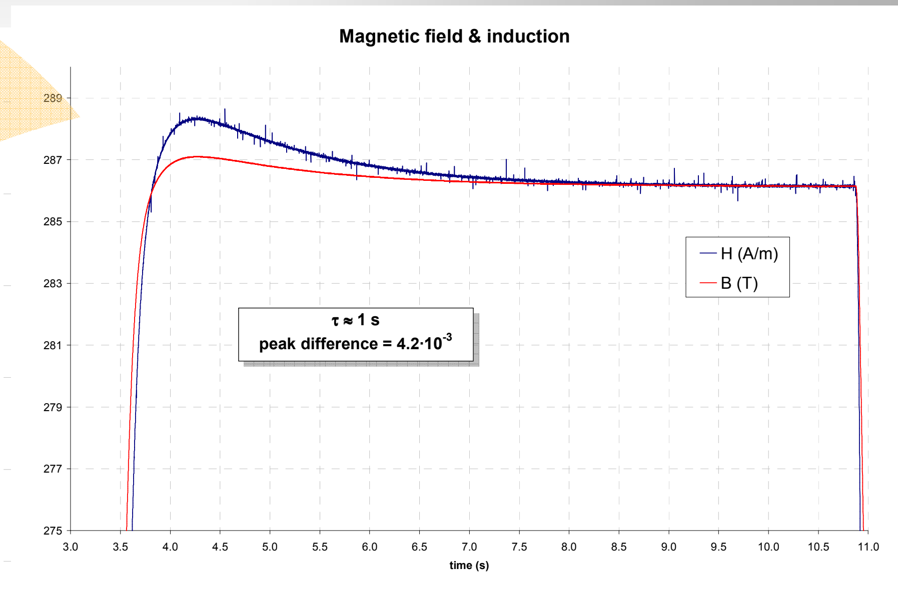


tests done on main dipoles [see R. Chritin's talk] and on dipole/quad correctors (illustated here)

Example of results: dynamic effects in CNAO magnets

- coil voltage is integrated and scaled to coincide with I_{magnet} at the end of the flat-top
- transient behavior is qualitatively similar in all cases: there is a delay during the ramp-up + several s relaxation at the end
- **Puzzling aspects**:
- naïve estimation gives τ_{eddy} < 5 ms
- delay and overshoot NOT proportional to ramp rate, BUT strongly dependent on field level

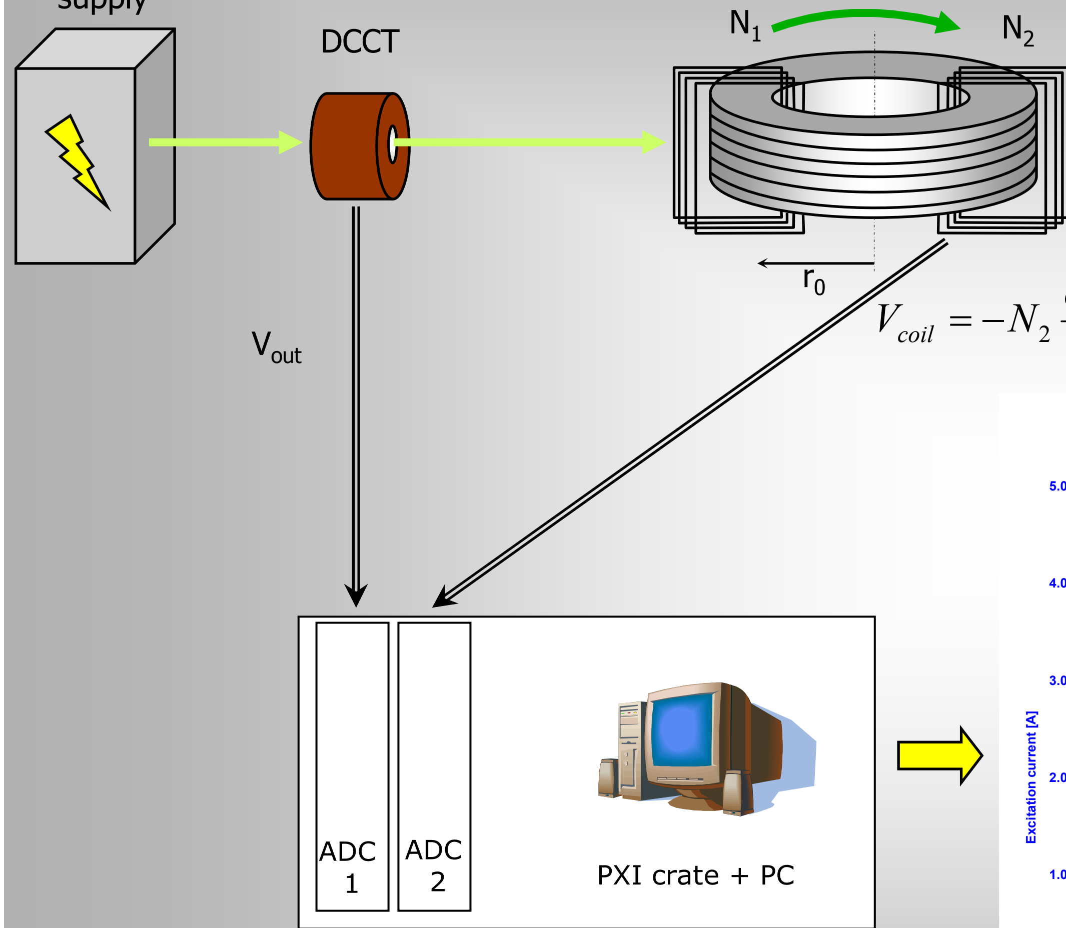


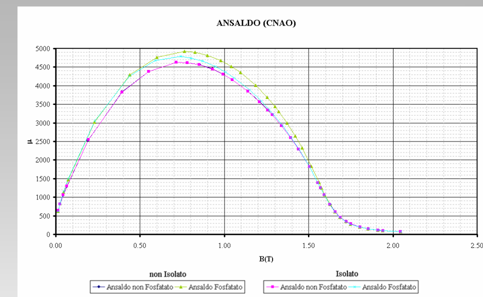


working hypothesis:
not eddy currents, but
material-dependent “magnetic friction” ?

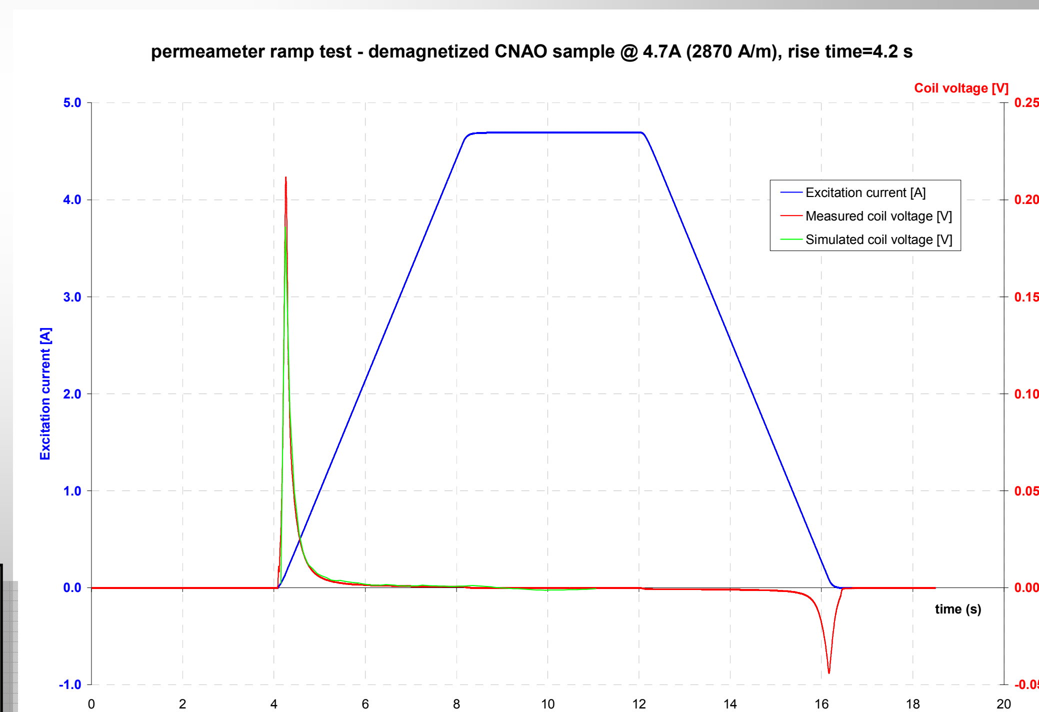
Dynamic ramp test in material sample: permeameter set-up

$$\Phi = BA = \mu_0 \mu_r(H) HA, \quad H = \frac{N_1 I}{2\pi r_0}$$





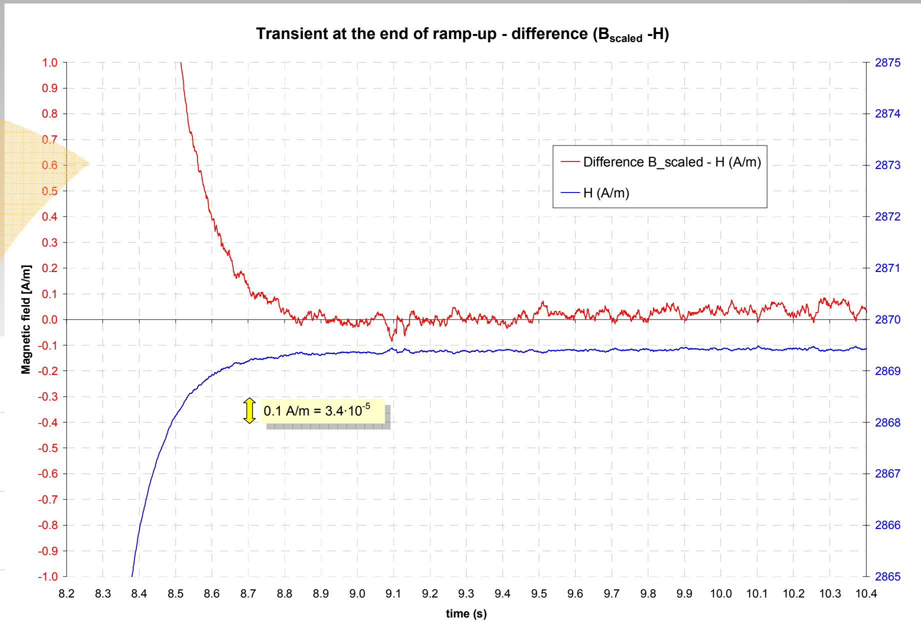
$$V_{coil} = -N_2 \frac{\partial \Phi}{\partial t} = -N_2 \frac{\partial \Phi}{\partial H}\frac{\partial H}{\partial t} = -\frac{\mu_0}{2\pi} N_1 N_2 \frac{A}{r_0}\left(\mu_r + \frac{N_1}{2\pi r_0} I \frac{\partial \mu_r}{\partial H}\right)\frac{\partial I}{\partial t}$$

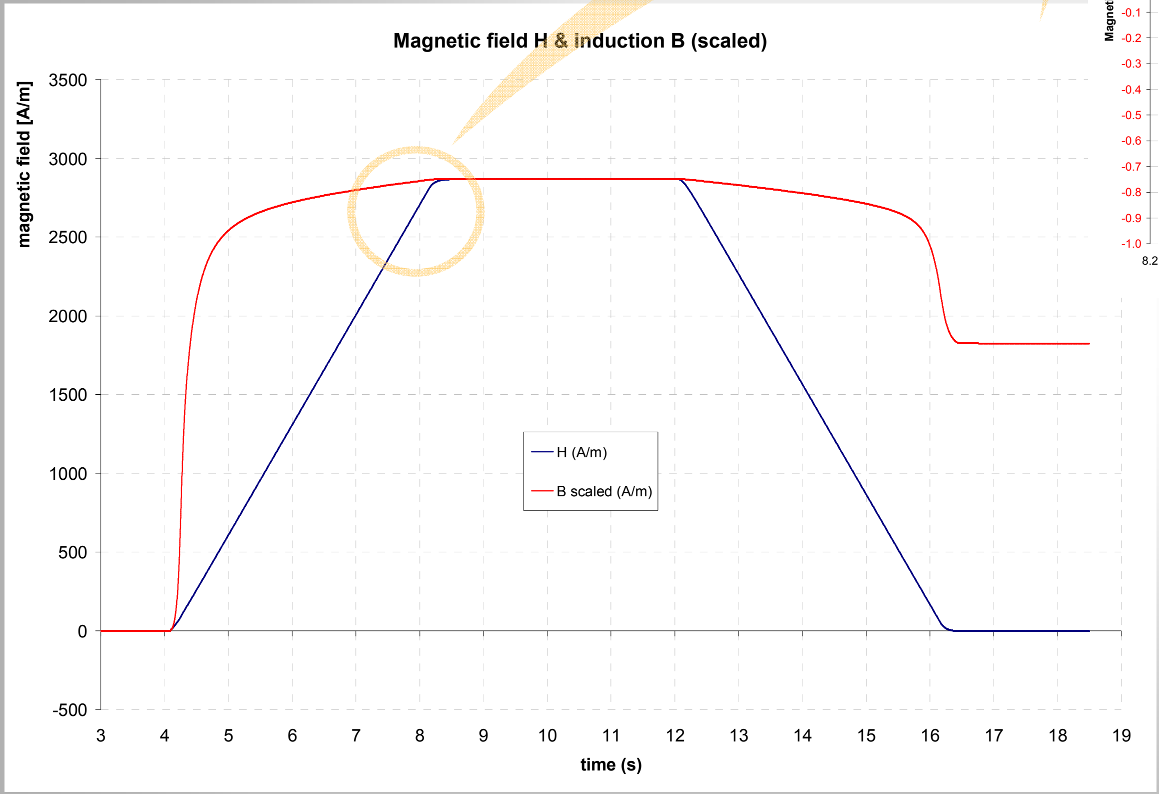


small toroidal laminated sample $\Rightarrow \tau_{eddy} << 1$ ms
any observed dynamic effects to be ascribed to magnetic friction

Dynamic ramp test in material sample: results

no eddy currents or magnetic friction effects in the material sample





observed effects in magnets must be due to eddy currents along non-obvious paths (possibly depending on material saturation, e.g. in the heads)

further studies ongoing:

- localization of transient effects
- tests at low field and ramp rates

Inventory of surplus items

End of series LHC tests + gradual hardware upgrade ⇒ stock of unused instruments

- **~300 × VME digital integrators:** 500 MhZ VFC-based, with selectable gain 1-500 and encoder interface, resolution ≈ 10^{-6} Vs, with ancillary electronics (CPU, MXI and ADC cards)
- **~12 × harmonic mole systems** … with dipole-compensated coils, telescope + LED source transversal tracking, 20 m motorized longitudinal transport system and full DAQ software/hardware. Two 50 mm ∅ units for measurements in warm magnets + one 40 mm ∅ unit (made of Ti + non-magnetic components) for measurements in high field.
- **2 × AC mole systems** with synchronous detection, fixed-coil/harmonic mode, retro-reflector optical target for high precision magnetic axis measurements in warm multipole magnets
- **3 × 15-m twin dipole coil shaft systems,** including rotating units, electronics and software for harmonic measurements in long superconducting magnets
- **2 × 10-m quadrupole harmonic coil scanner (Chaconsa),** with telescope + LED source transversal tracking for accurate measurements in cold and warm long superconducting magnets
- **vast assortment of calibrated search coils,** ~10^{-3} to ~10 m^2 surface, (most of them > 20 y old and therefore very stable)

Conclusions

Which directions to go for our Group at the end of the LHC series era ?

- **simplification:** needs disappear, personnel for maintenance and operation is cut down ⇒ we must consolidate our instrument park, eliminate redundant systems, integrate functionality in polyvalent hardware and software

- **performance:** we prepare to upgrade our systems to the foreseeable demands of the next generations of magnets:
  - high fields and ramp rates
  - both larger and smaller apertures than LHC
  - comparable accuracy

  starting with the basic components (fast integrators, unified software)

- **autonomy:** flexible and reliable software prototyping requires programmers and users to be very close ⇒ we should internalize software development to become more efficient

Farewell

Au revoir to our friend and colleague Didier Cornuet