Magnetic measurements @ CERN

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Outlook

Magnetic measurements on SC magnets

- Role in magnet development
- Challenges
- Techniques
- Our systems
- New development for HL-LHC
- Conclusions

SC magnet development

Development phase	Type of device under test	Required magnetic measurements
Validation of technologies	Racetrack coils	Selected magnetic figures (absolute field, magnetization…)
Demonstration of design	Short models	Geometric, saturation, persistent currents, induced currents, decays and snapback, cold/warm, other studies
Assessment of final design	Full-length prototypes	Geometric, saturation, persistent currents, induced currents, decays and snapback, alignment, other studies
Series production	Final magnets	Small set of representative tests, magnet to magnet reproducibility, QC

Challenges

- Wide range of field levels
  - Field quality at ambient temperature (~1 μT)
  - Transfer function at cryogenic temperature (~10 T)
- Wide range of measurement volume
  - No aperture in racetrack coils
  - 0.1 m x 10 m for some full length magnets
- “warm” and “cold”
  - Ambient temperature for collared coils and cold masses at the production facility
  - 4.3 - 1.9 K for racetrack coils and short models without anti-cryostat
  - Cold mass at cryogenic temperature but sensors at ambient temperature with anti-cryostat
- DC conditions, dynamic conditions, and fast transients
  - Static characterization (ambient temperature, geometric, persistent currents, saturation)
  - Effect of induced currents (ramps at different rates)
  - Decay-snapback (machine simulation cycles)

MM techniques

Different sensors and techniques can be used

- Hall probes
- NMR probes
- Static and rotating coils
- Stretched wire
- …

We can classify them in terms of

- Measured volume
- Measured properties (main field, homogeneity, axis…)
- Bandwidth
- Working temperature
- Accuracy

MM techniques

	Volume	TF	Homogeneity	Angle	Axis	Bandwidth	Temperature	Accuracy
Hall probes	~ mm^3	local	-	-	-	~kHz	ambient cryogenic	$<10^{-3}$
NMR probes	~ cm^3	local	-	-	-	<1 Hz	ambient	$<10^{-6}$
Static coils	10 mm^2 0.1 to 1 m	local integral	-	-	-	~kHz	ambient cryogenic	$<10^{-3}$
Rotating coils	∅ > 30 mm L = 0.1 to 1 m	local integral	multipoles	if calibrated	if rotation axis is known	<10 Hz	ambient cryogenic	10^{-4} on main field 10^{-6} on multipoles < 0.1 mm on axis
AC mole	∅ > 30 mm L = 0.1 m	-	-	-	local	-	ambient	<0.1 mm
SSW	∅ > 30 mm L = 0.5 to 15 m	integral	-	integral	integral	DC	ambient	< 10^{-4} on main field < 0.05 mm on axis < 0.1 mrad on angle

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Hall probes: small size, cryogenic → Racetrack coils

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NMR probes: best absolute accuracy → Calibration

MM techniques

	Volume	TF	Homogeneity	Angle	Axis	Bandwidth	Temperature	Accuracy
Hall probes	~ mm^3	local	-	-	-	~ kHz	ambient cryogenic	$<10^{-3}$
NMR probes	~ cm^3	local	-	-	-	<1 Hz	ambient	$<10^{-6}$
Static coils	10 mm^2 0.1 to 1 m	local integral	-	-	-	~ kHz	ambient cryogenic	$<10^{-3}$
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Static coils: bandwidth, cryogenic → Quench antennas

MM techniques

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Rotating coils: “what else?”→ Models, prototypes, and series magnets

MM techniques

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AC mole: local axis → studies on prototypes

MM techniques

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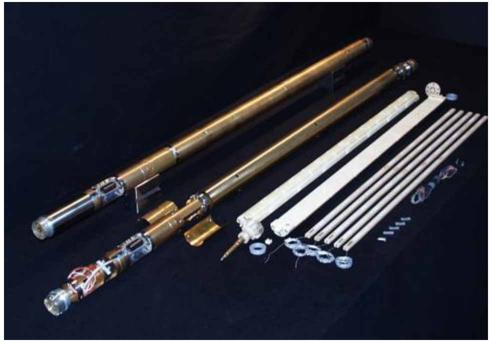
SSW: best accuracy for integral TF, angle, and axis → series magnets

Our systems

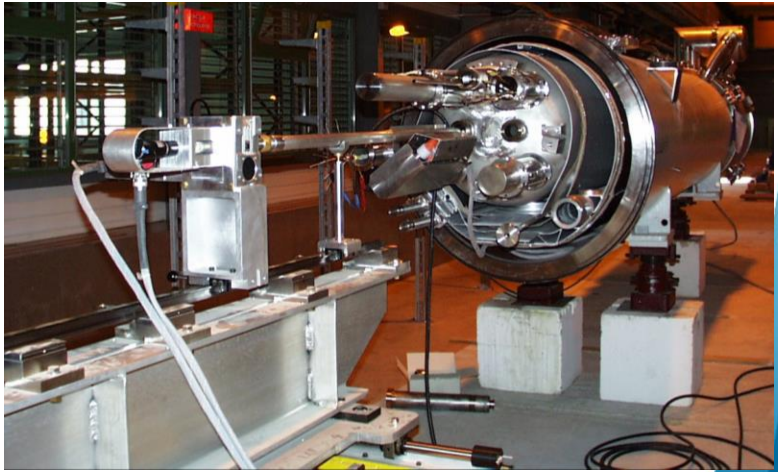
- Legacy systems (> 10 years)
  - DIMM and QIMM
  - AC mole
  - Single Stretched Wire (SSW)
- Recently developed systems (last years)
  - FAst Measurement Equipment family (FAME)
  - New SSW
- Ongoing development (next years)
  - PCB coils and carbon fiber shafts
  - Hall probes for racetrack coils

Legacy systems



QIMM and DIMM (rotating coils)

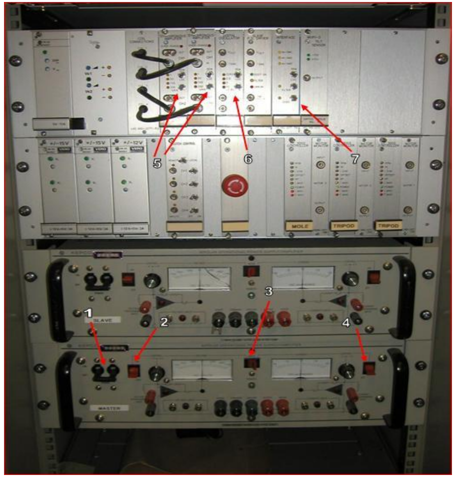
- Compatible with standard LHC cold-bore
  - Suitable for LHC spares and 11-T
- Mechanics and electronics are “oldish” but still ok
- Old software and computer
  - Critical components for future use
- QIMM upgrade
  - Upgrading the system aiming at compatibility with FFMM
- DIMM is not strictly required
  - No series production of large number of magnets similar to LHC dipoles

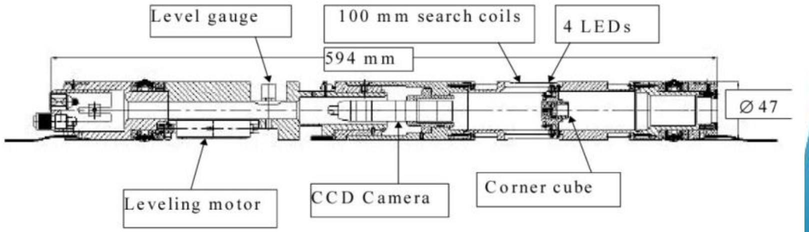


Legacy systems

AC mole (coils in AC mode)

- Compatible with standard LHC cold-bore
  - Suitable for LHC spares and 11-T
- Mechanics and electronics are “oldish”
  - New acquisition cards can be used
- Old software and computer
  - Critical components for future use
- Upgrade
  - Basic magnetic measurement and analysis already implemented to be compatible with FFMM. Manual procedure
  - Measurement of cold-bore tube position (CCD) not yet available

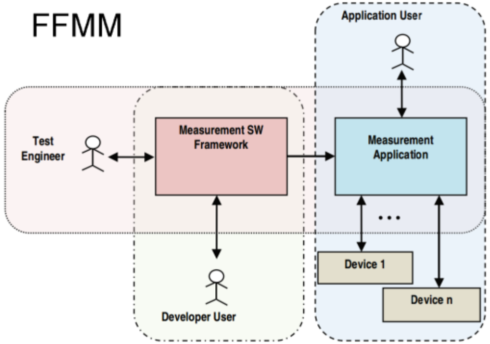




FAst Measurement Equipment (FAME)

Flexible framework for Magnetic Measurements (FFMM)

- Library with drivers for common instruments used for MM (such as integrators, acquisition cards, motors, encoder interfaces, DMM's…)
- Measurement procedure condensed in a short "script"
- Run-time generation of GUI for input parameters and data visualization
- Integrated post-processing with Matlab



Fast Digital Integrator (FDI)

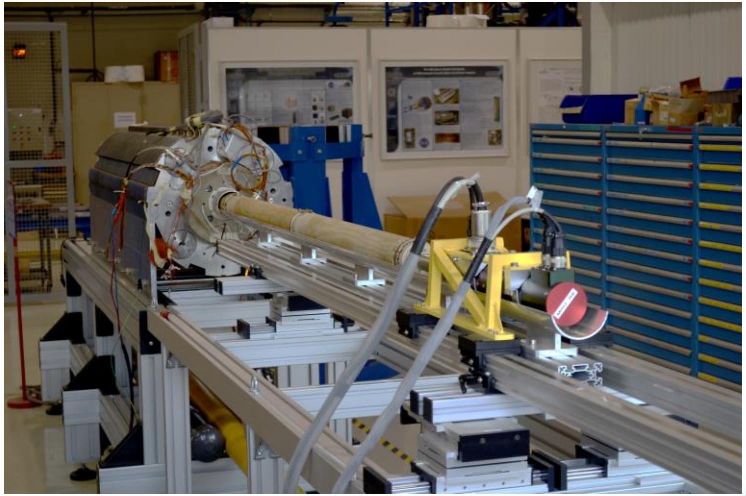
- Input range from ~ µV (SC magnet at "warm") to 30 V (super-segments at "cold")
- Fast triggering up to 10 kHz (rotating coils at 10 turns/s)

Micro rotating unit (MRU)

- Angular encoder with 4096 steps
- Slip rings with >50 signals (long multi-segment shafts)
- DC motor + reduction for providing high torque (shaft without ball bearings)

FAME for ambient temperature in 927

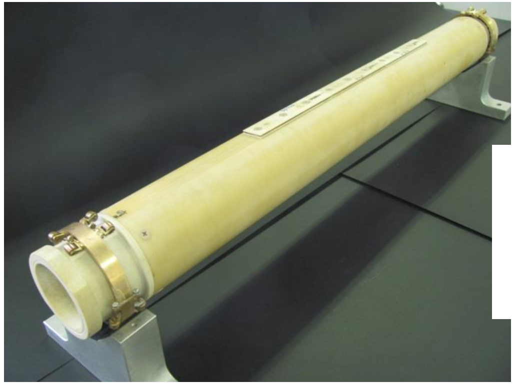
- Standard 19-inch rack including PXI crate, motor controller, patch panel
- PXI PC-blade running Windows7 and FFMM
- 2 independent integrator channels (ABS, CMP)
- One MRU mounted on a sliding bench with 3-m span
- FuG low voltage power supply (40 V, 20 A) and DCCT Hitec MACC-plus
- Set rotating heads
  - 3 x 130 mm or 1200 mm rotating coil heads
  - Measurement radii 22, 30, and 45 mm
  - CCR targets for referring magnetic axis wrt external points

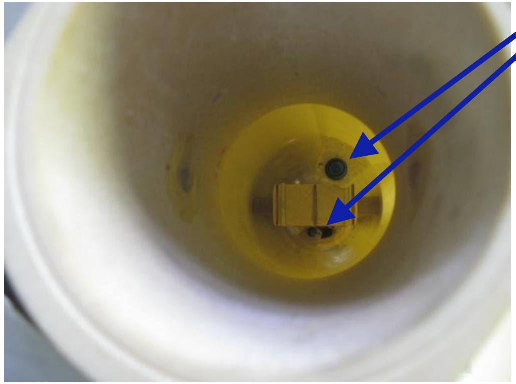


MM at ambient temp. on short models for HL-LHC.

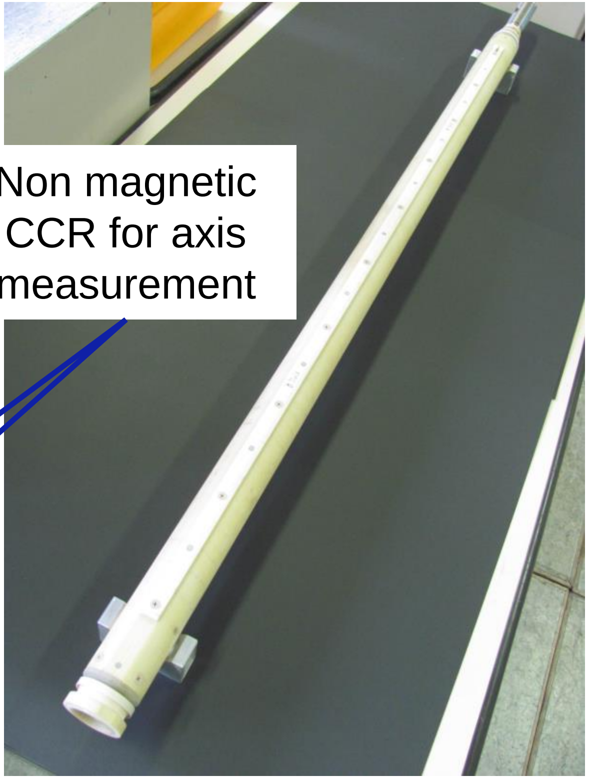
HiLumi HL-LHC PROJECT EuCARD²

FAME for ambient temperature in 927



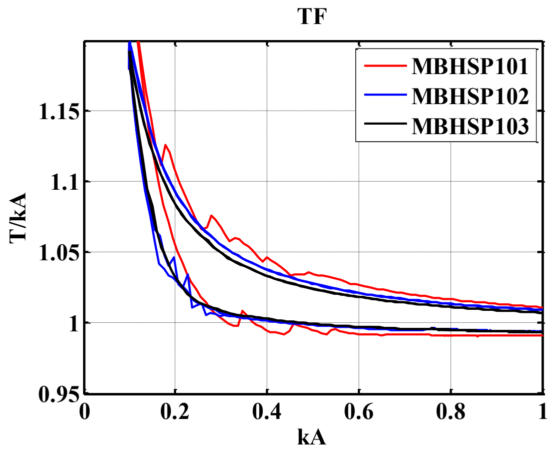


Non magnetic CCR for axis measurement

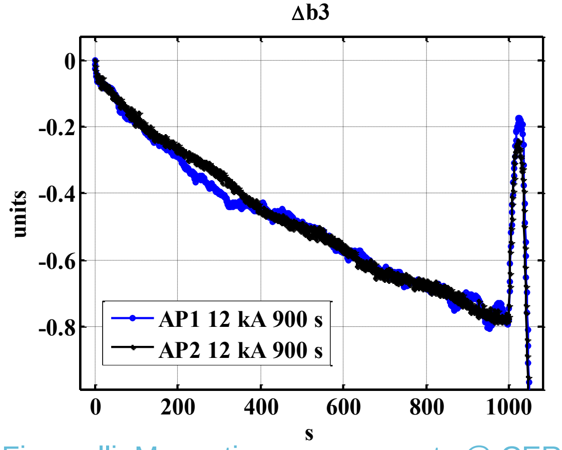


FAME for vertical benches

- Standard 19-inch rack including PXI crate, motor controller, patch panel
- PXI PC-blade running Windows7 and FFFM
- 12 independent integrator channels for parallel acquisition of signals from two multi-segment rotating-shafts
- Two MRU's with max rotation speed 8 turn/s (4 turn/s tested)
- GPS timing card for synchronization
- Multi-segment shafts without ball-bearings rotating in the helium bath

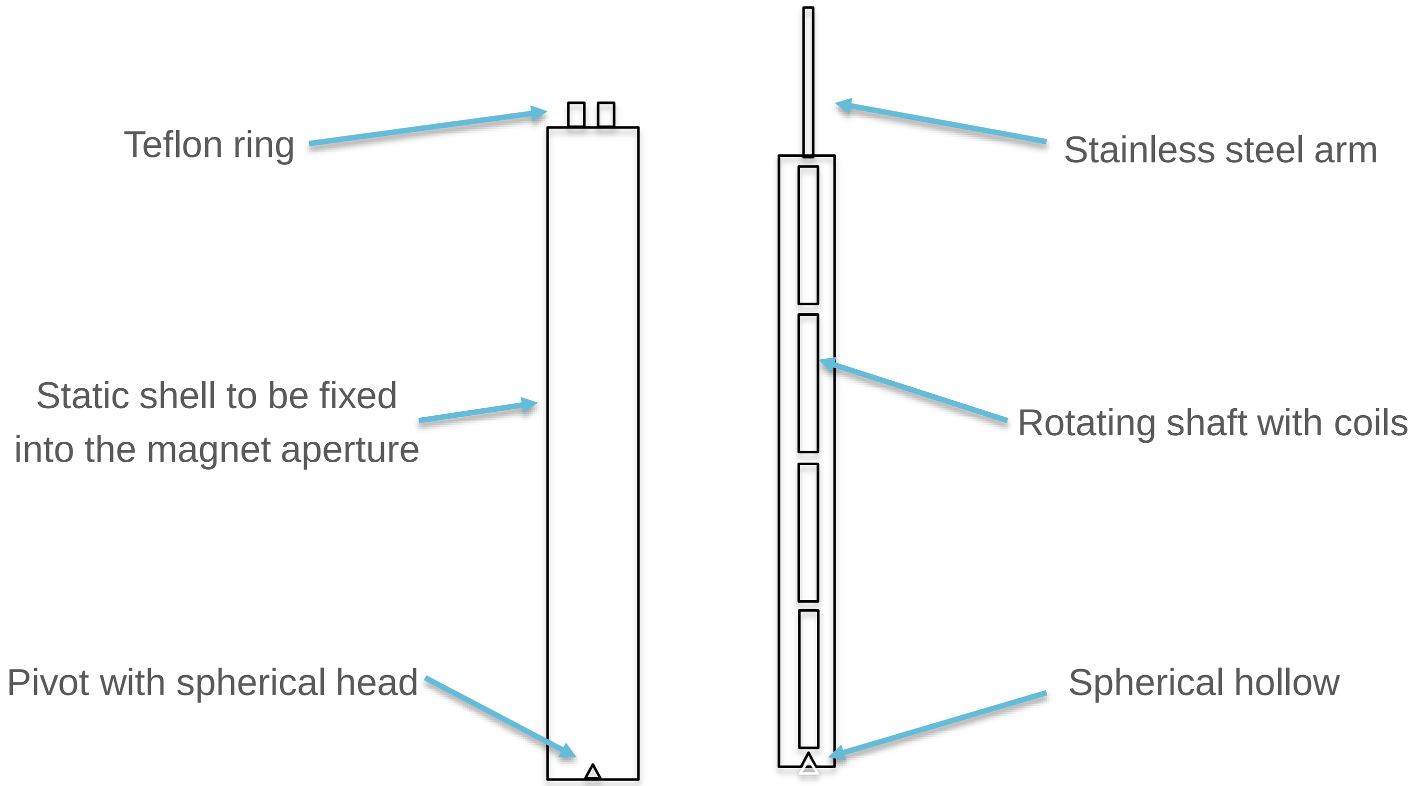


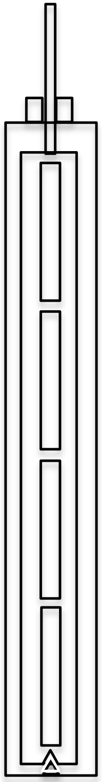
radius (mm)	length (mm)	segments	compensation
22	3680	3	D,Q
22	1319	5	D,Q
22	2120	7	D
45	1330	5	D,Q
45	2114	5	D,Q

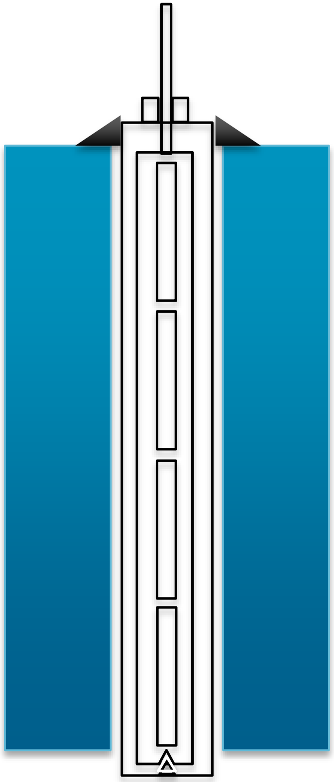


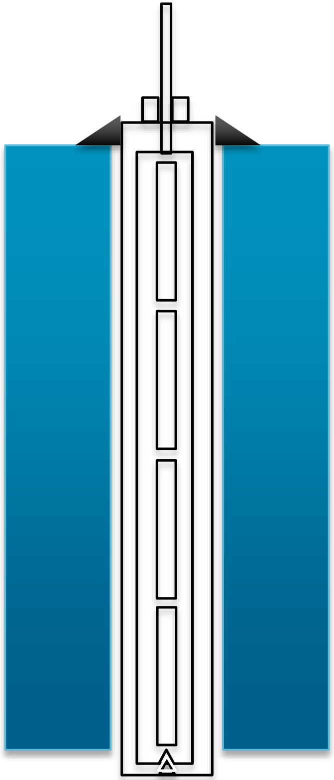
Rotating shaft in the helium bath

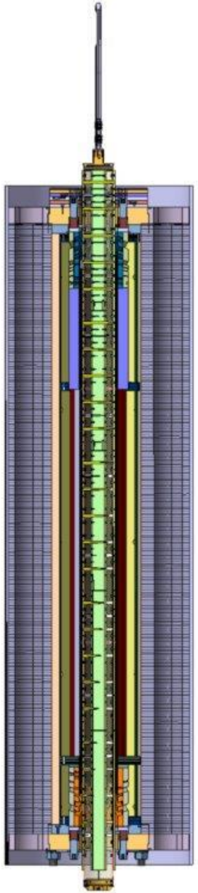
Mechanics at “cold” must be kept as simple as possible


Teflon ring
Static shell to be fixed into the magnet aperture
Pivot with spherical head
Stainless steel arm
Rotating shaft with coils
Spherical hollow









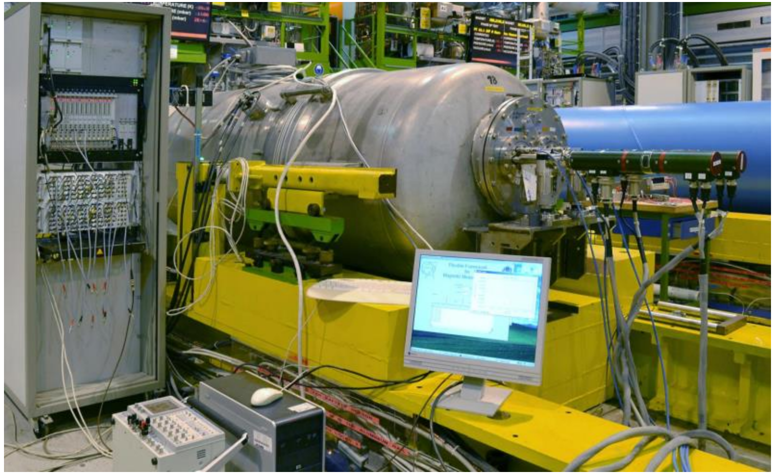
Anti-cryostat for vertical stations?

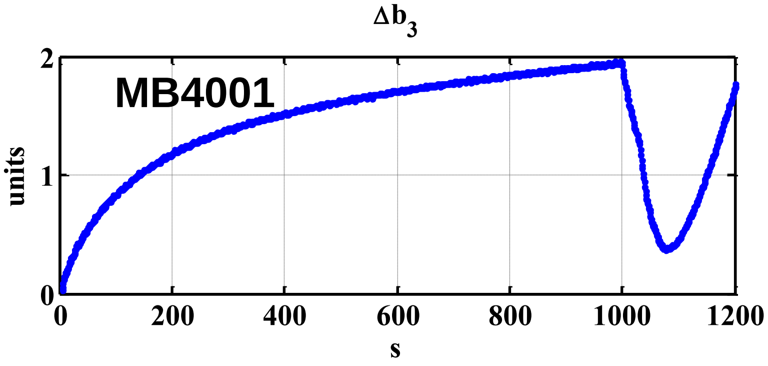
	Shaft in the He bath		With anti-cryostat	
Devices to be tailored to the magnet	Shaft for diameter and length	-	Shaft for diameter and length (?) Warm bore tube	- -
Space for shaft	All available space	+	Some space used for warm tube, problem in small diameter apertures	-
Heat load	No load	+	Should be taken into account	-
For double-aperture magnets	Additional shaft	-	Additional shaft (?) Additional warm bore tube	- -
Calibration	Correction for TF Ok for multipoles	-	Ok	+
In case of major fault of shaft	Thermal cycle is required	- -	Shaft can be replaced	+ +

Conclusion: differences but not clear advantages from one solution
It depends on the experience of the lab

FAME for horizontal benches

- Standard 19-inch rack including PXI crate, motor controller, patch panel
- PXI PC-blade running Windows7 and FFFM
- 12 independent integrator channels for parallel acquisition of signals from two multi-segment rotating-shafts
- Two MRU's with max rotation speed 8 turn/s (5 turn/s tested)
- GPS timing card for synchronization
- Multi-segment ceramic shafts for MB, MQ, D1 with anti-cryostat
- Adaptation to DS11 dipole proto ongoing

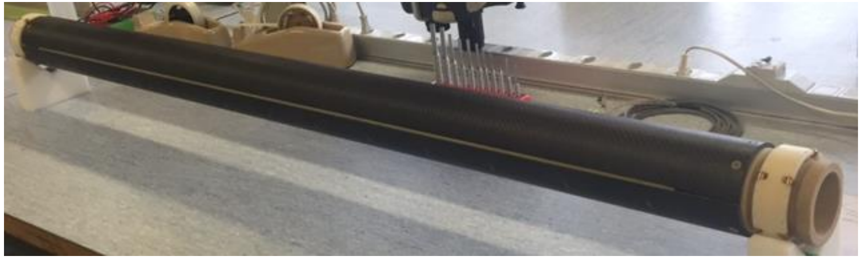




Prototype of new rotating-coil shaft

Carbon fiber shell

- Total weight 4 kg
- Standard fiberglass 7.2 kg



PCB

- 5 radial coils
- 90-mm width
- 1.3-m length

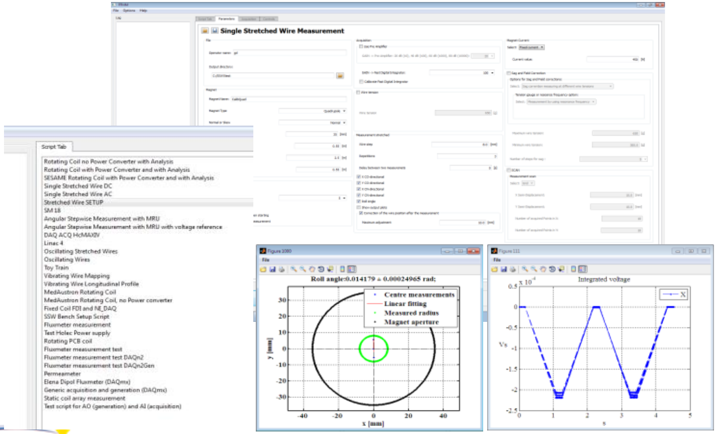
- Tilt angle <0.35 mrad
- Dipole bucking ~800
- Quadrupole bucking ~600

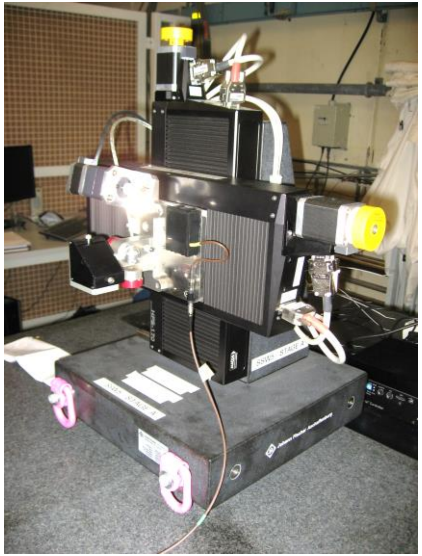
surface (m2) :	1.44749	1.44720	1.44738	1.44722	1.44731
ecart (%0)	‰ 0.0	-0.2	-0.1	-0.2	-0.1
radius(mm)	40.075	20.031	0.000	-20.031	-40.075

It is the "first brick" for a long multi-segment shaft for full length HL-LHC magnets (MQXF)

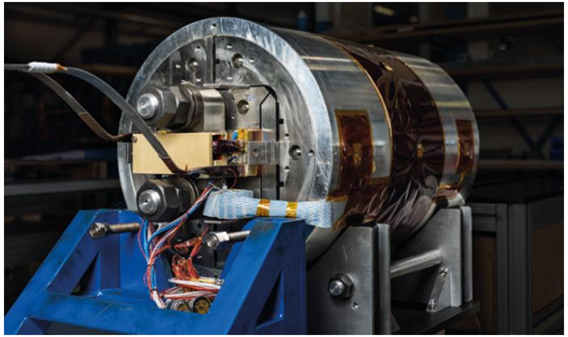
New SSW

- X-Y tables with 155-mm span
- Fast Digital Integrator
- FFMM software with user-friendly GUI
- Sensors and electronics for vibrating wire mode



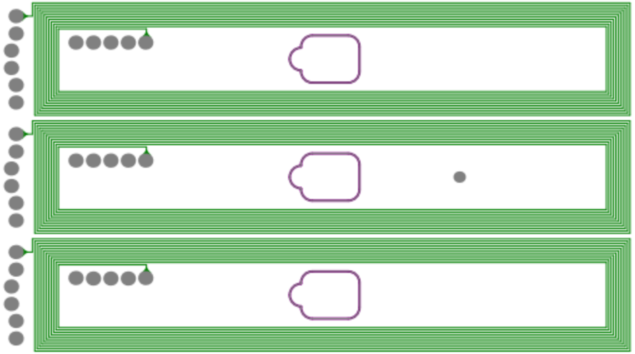


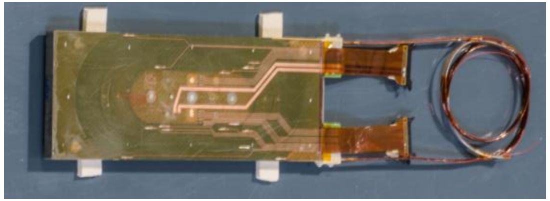
Racetrack coils



Fixed Coils in PCB

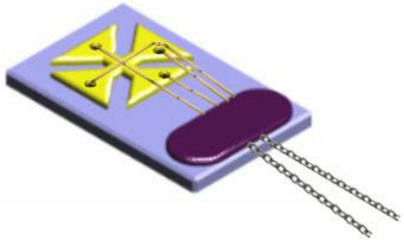
- Dedicated design
- Precise positioning of windings
- Standard in-house production process





Hall sensors

- Available on the market
- Large range: 0 - 30 T
- Temperature depended
- Non linear - Calibration is needed



5 x 4 x 1 mm

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MM system operated in other laboratories

- In principle it is possible but we should not underestimate the effort
- It requires an integration study insert-magnet-shaft
- Lead time for procurement of components
  - 6 months for a shaft
- Training of operators (at CERN ?, in loco ?)
- In some cases, all this for a single magnet ?

Conclusions

- SC magnets are challenging for magnet designers
- … for test-station people as well

- Many magnet families are being developed for HL-LHC
- Many people from different laboratories are involved

- We have the technologies and the know-how for fulfilling the requirements
- … we will have no time to get bored

Thank you