Overview of Magnet Test Activities at CERN

M. Buzio on behalf of the Test & Measurement team

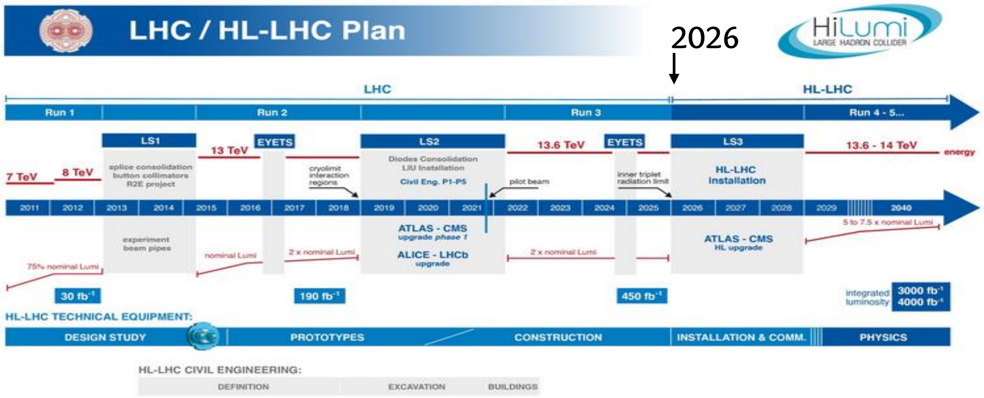
Contents

Part I
Team, Projects, Infrastructure

The Team

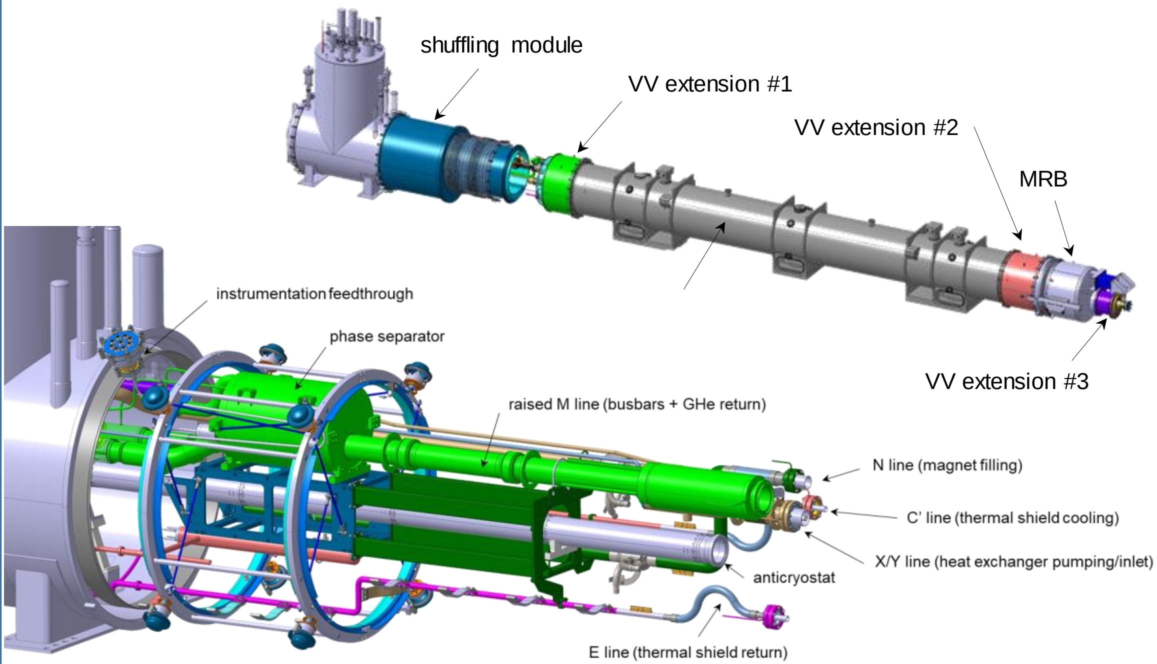
- SM18 (superconducting test station) and magnetic measurement teams merged in 2020
- Now 45 strong (20 staff, 17 students, 8 associates and industrial support)
- Slowed-down but not stopped by Covid 19 !

High-Luminosity LHC



https://espace.cern.ch/HiLumi

currently under test: MQXFB Q2 P3, D2 prototype



Carpenter test logbook

- Oracle DB interface via OpenShift, developed in PHP on Laravel framework
- Used for all cryomagnet tests in SM18 for safety, QA and result visualization

Testplan Logbook for MQXFBP2 in A1

Testplan General Information

Magnet owner:	Susana IZQUIERDO BERMUDEZ
Test engineer:	Franco Julio MANGIAROTTI
Test operator:	Gaelle NINET

Testplan Activities/Events Information

Cooldown #1

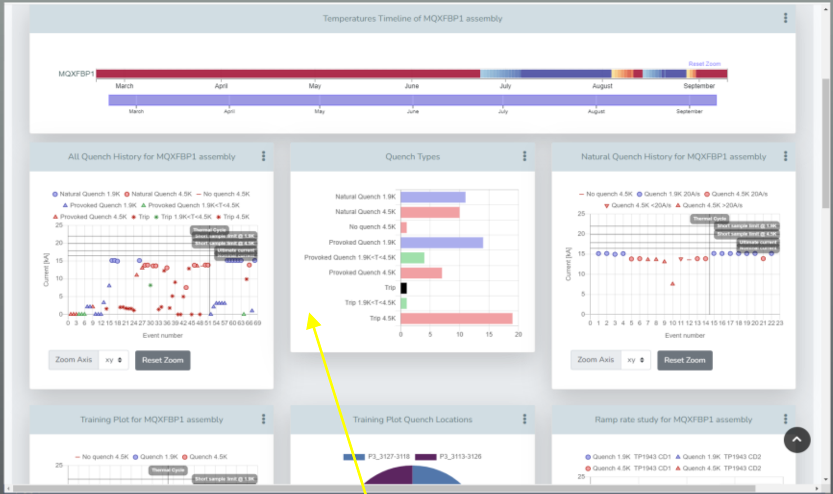
04/01/2021 11:05:52	**Cryo magnet reception (MTF)** SMA18 -- *Bertrand Jacques MOUCHES* Accepted -- *Bertrand Jacques MOUCHES*
06/01/2021 11:06:28	**Equipment installation** AC. alignement .isolation des lignes M2 M3 X et N. -- *Bertrand Jacques MOUCHES*
12/01/2021 10:00:18	**Continuity** Lien : G:\Workspaces\m\matest\Test results and reports\1.HORIZONTAL\Quadrupole Individually powered\Q2 - MQXF\QXF_PROTO2\3.TESTS Nom du fichier : Continuite_MQXFBP2 -- *Raphael BOUVIER* Accepted -- *Raphael BOUVIER*
13/01/2021 11:11:21	**Equipment installation** AC, MRB, Soufflet, Rallonge, Ligne Y. Il y avait des problemes sur connecter boite IFS et connection fibre -- *Franco Julio MANGIAROTTI* Accepted -- *Franco Julio MANGIAROTTI*
14/01/2021 16:53:52	**Installation on bench** -- *Bertrand Jacques MOUCHES* Accepted -- *Bertrand Jacques MOUCHES*
20/01/2021 10:15:14	**Electrical insulation test** MQXF002 Warm Initial not connected @292K @A1 by Vincent/Raphael. File name: MQXF002 Warm Initial not connected.xml -- *Vincent DESBIOLLES* Accepted -- *Vincent DESBIOLLES*
20/01/2021 14:39:08	**AC or NOAC registration** Only one aperture, new anticryostat. -- *Vincent DESBIOLLES* Accepted -- *Vincent DESBIOLLES*
20/01/2021 14:41:07	**MTF AC or NOAC registration** Only one aperture, new anticryostat. -- *Vincent DESBIOLLES* Accepted -- *Vincent DESBIOLLES*
20/01/2021 14:41:47	**Check IFS** IFS boxes has been reversed and then modified in order to give spaces for connectors. -- *Vincent DESBIOLLES* Accepted -- *Vincent DESBIOLLES*
20/01/2021 16:12:18	**Electrical insulation test MANUAL** Only manual tests have been done before connection (see results of the HV test). -- *Vincent DESBIOLLES* Accepted -- *Vincent DESBIOLLES*
20/01/2021 16:16:30	**Magnet alignment in bench** -- *Vincent DESBIOLLES* Accepted -- *Vincent DESBIOLLES*
21/01/2021 08:55:38	**Electric connection** -- *Raphael BOUVIER* Accepted -- *Raphael BOUVIER*
21/01/2021 11:16:12	**Manual clamp vtap measurement** -- *Raphael BOUVIER* Accepted -- *Raphael BOUVIER*
21/01/2021 15:30:03	**Hydraulic connection** -- *Raphael BOUVIER* Accepted -- *Raphael BOUVIER*
22/01/2021 16:00:19	**Config potaim cards** -- *Raphael BOUVIER* Accepted -- *Raphael BOUVIER*
25/01/2021 11:00:23	**Connect anticryostat** -- *Raphael BOUVIER* Accepted -- *Raphael BOUVIER*
26/01/2021 10:00:59	**Event on Data acquisition** Nous avons un problème avec l'éditeur de fichier LF DAQ gen3. Il nous est impossible de modifier les templates afin de pouvoir mettre les deux nouvelles courbes de calibrations des sondes de températures Cernox associées à ce quadripole QXF. Hubert investigue sur ce problème. Cela ne nous gêne pas pour l'instant mais nous ne pouvons pas lancer le cooldown Cryo tant que le problème persiste. -- *Raphael BOUVIER*

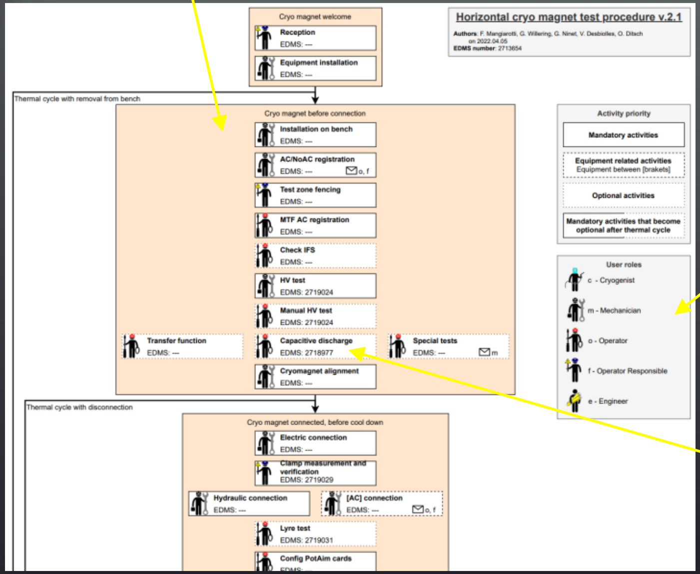
10 Mar 2022 10:36:33 1/15 Logbook for MQXFBP2 in A1

Current test status and responsible engineers clearly marked

Status, date/time and operator in charge of each step appear in the test chronology

Levels and sequence of tests conform to fixed templates





Standardized stats and plots include timeline of temperature, current etc.

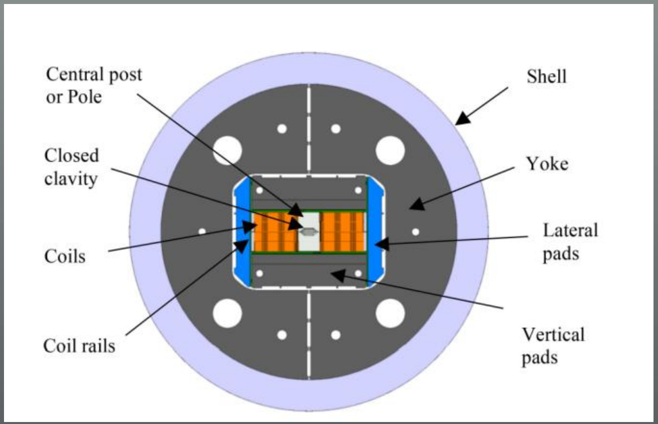
Different user roles for each step

Each step linked to formally approved procedure documents and checklists

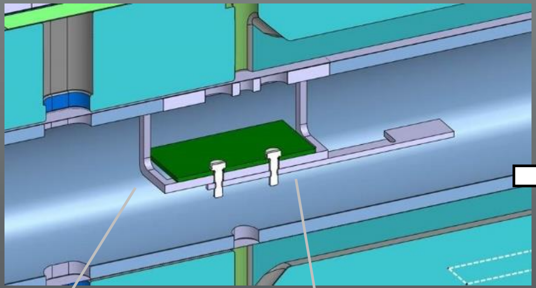
Credit: F. Mangiarotti

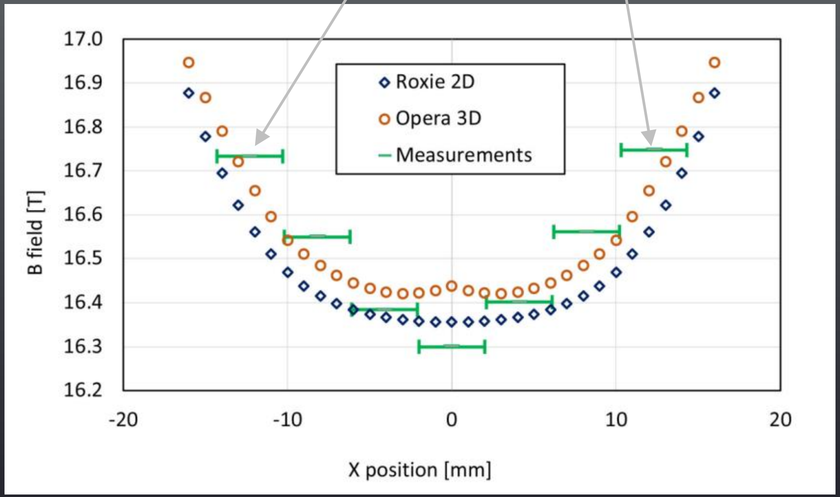
High Field Magnets for the Future Circular Collider

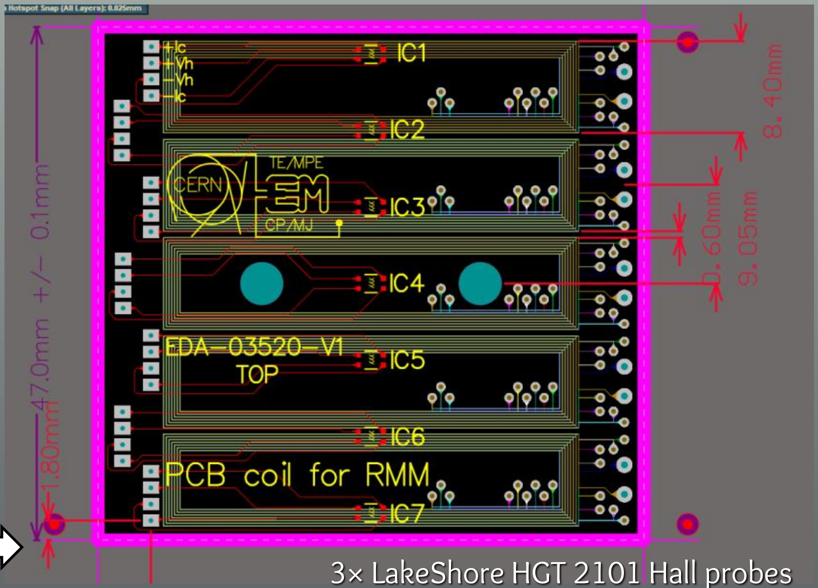
- Enhanced Nb_3Sn racetrack model coil eRMS
- 16.5 T peak field @ 13.8 kA, 1.9 K



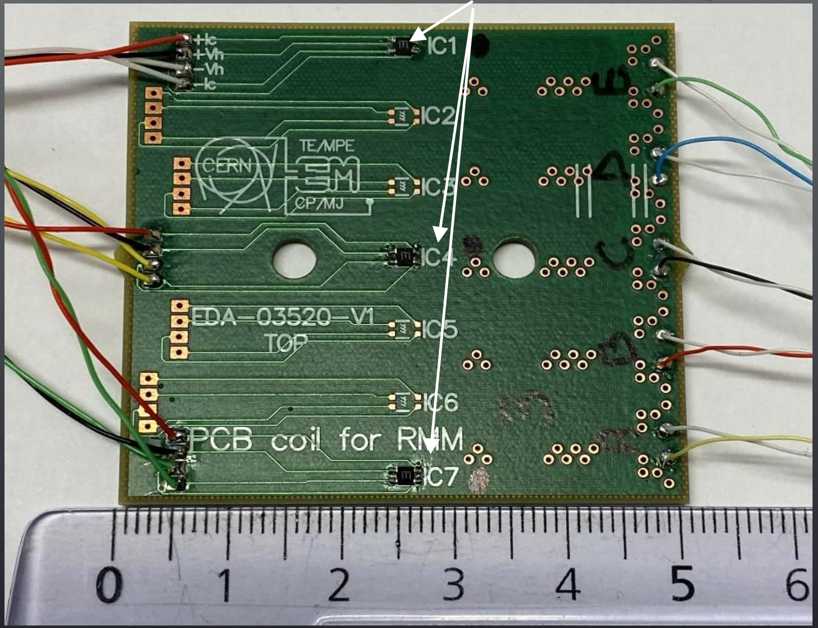
5×transversal coil array PCB
in the middle of the gap







3× LakeShore HGT 2101 Hall probes



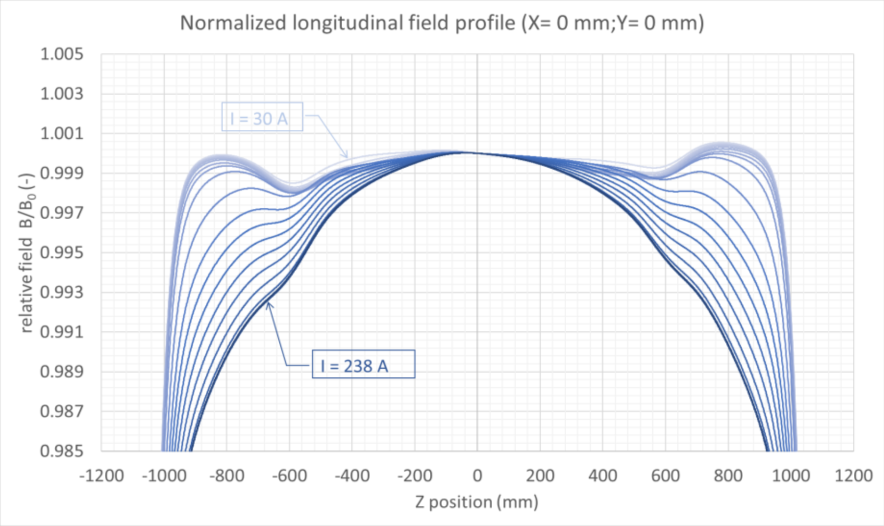
J C Perez, C. Petrone *et al*, "Construction and Test of the Enhanced Racetrack Model Coil", IEEE Trans. on Appl. Supercond. Vol 32 n. 6, Sep 2022

GSI/FAIR - SuperFRS

- 26 multiplets (ASG, 170 magnets), ∅192 mm warm bore, tested with rotating coil scanner/SSW
- 24 bending dipoles (Elytt), super-ferric with supercritical He cooling, 380 × 180 mm^2 warm bore, tested with translating fluxmeter/SSW
- 3 reconfigurable benches ready in b. 181
- Test campaign now ramping up …

First short multiples being tested with SSW

First main bending dipole being tested with translating fluxmeter

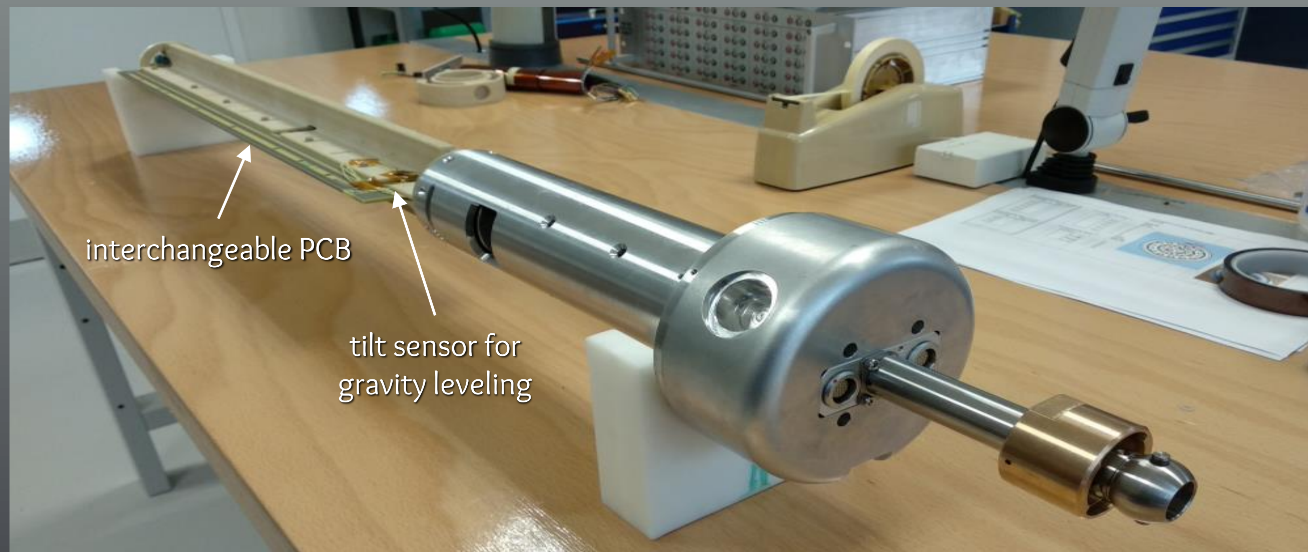


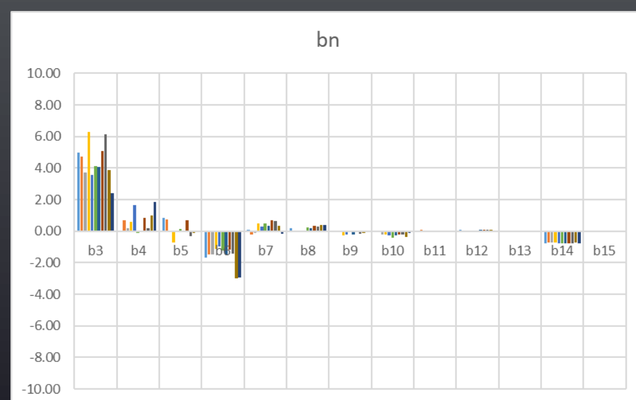
Credit: P. Kosek

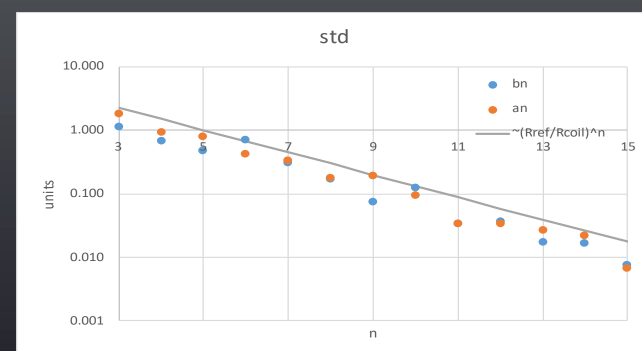
Part II
Instrumentation Highlights

Warm rotating coil scanner

- 600 mm long, interchangeable PCB design for bores ∅ 90 to 150 mm
- Measurement of warm HL-LHC MQXFB magnets @ 10 A, 4.4 mT @ 50 mm
- 3 units at CERN + 1 deployed to CIEMAT







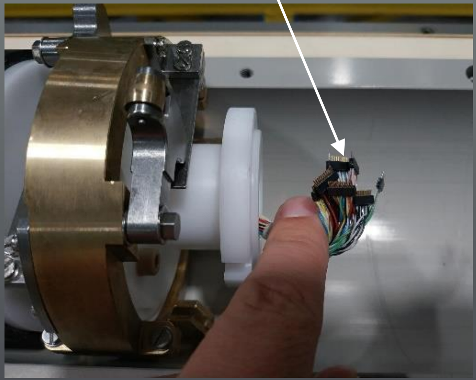
Credit: P. Rogacki, L. Fiscarelli

Long rotating coil shafts

- 4 × Ø109 mm, ~8 m long shafts being procured for HL-LHC magnets
- Prototype unit w/ PCB coil array sandwiched between high-precision C-fiber half-shells
- Good results, but price hikes and supply problems …

Double C-fiber half-shells for torsional and flexural stiffness
1.4 m long
~50 μm tolerance

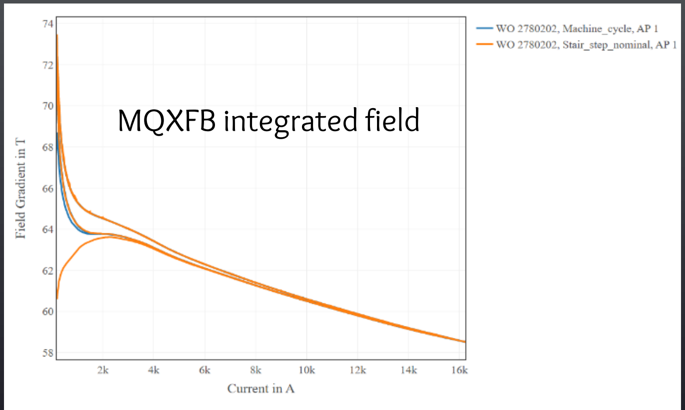
6 micro-connections per segment

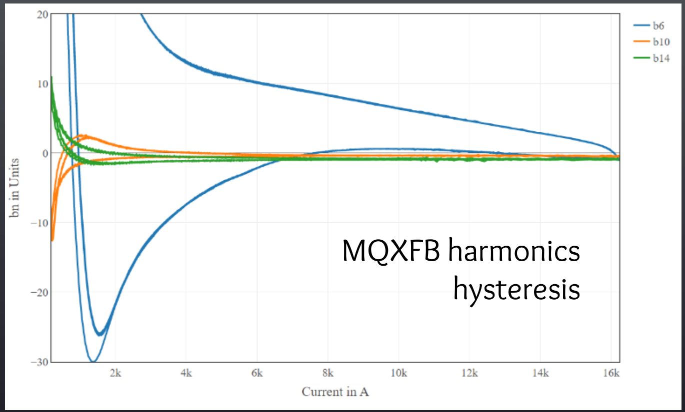


50-channel
Mobile Rotation Unit

Shaft prolongation
(no coils)

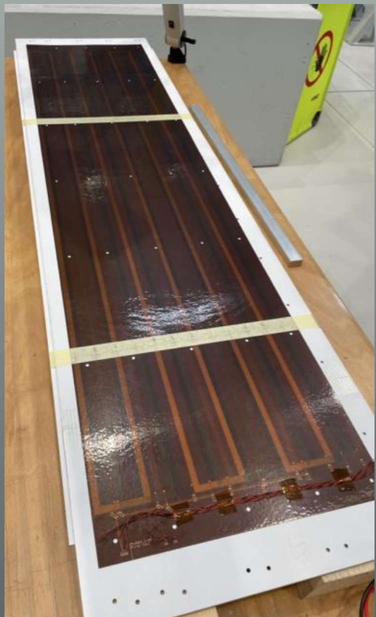
Sliding tracks



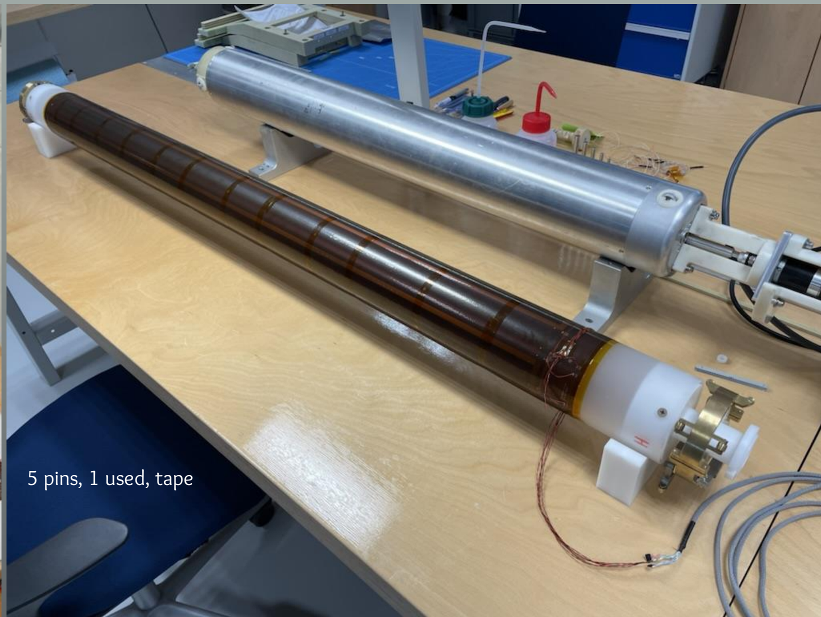


Credit: R. Beltron, O. Dunkel, G. Deferne, L. Fiscarelli

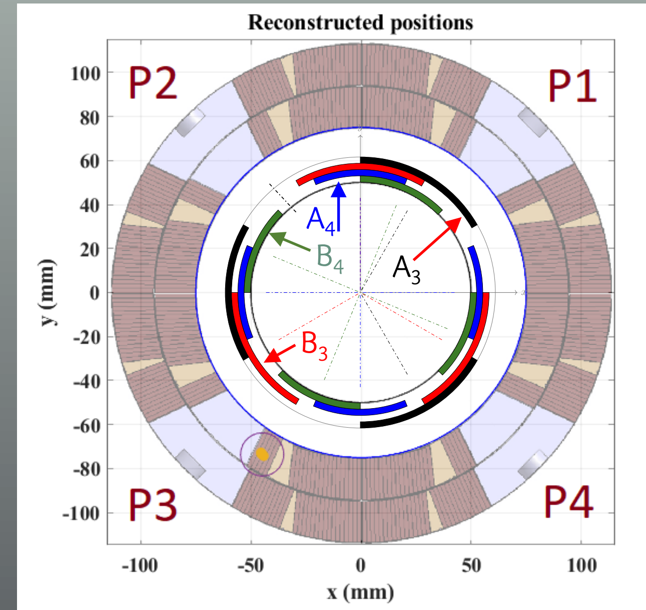
Ø110 mm Quench Antenna



2 × double-layer flexi PCB glued together,
4 × 16-turn tangential coils per layer



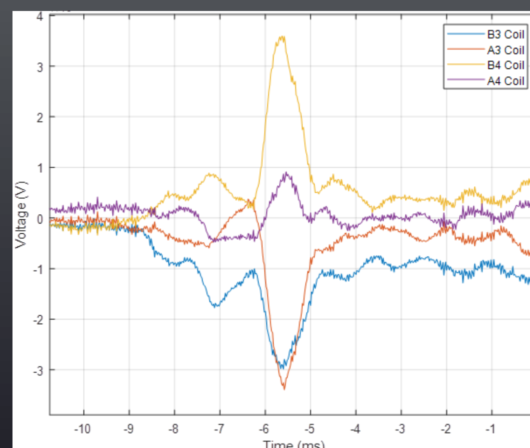
Ø100 mm, 0.6 long antenna segment

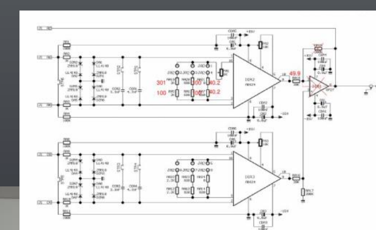


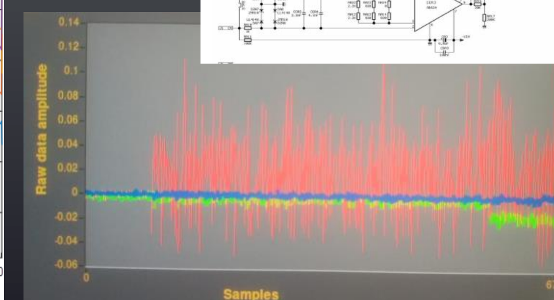
Quench reconstruction resolution:
- tangential: 5°
- radial: 5 mm

- 12-segment quench antenna designed to improve quench localization in critical MQXF quads
- New design: rolled-up flexi PCB
- On-board analog bucking → B_3, A_3, B_4, A_4 outputs
- Extremely easy to assemble/disassemble

- Bypass of analog-bucking op-amp on existing amplifier cards (G=100 to 500)
- Z_{in} adapted to compensate the capacitive load of long coax cables
- 10× S/N improvement !





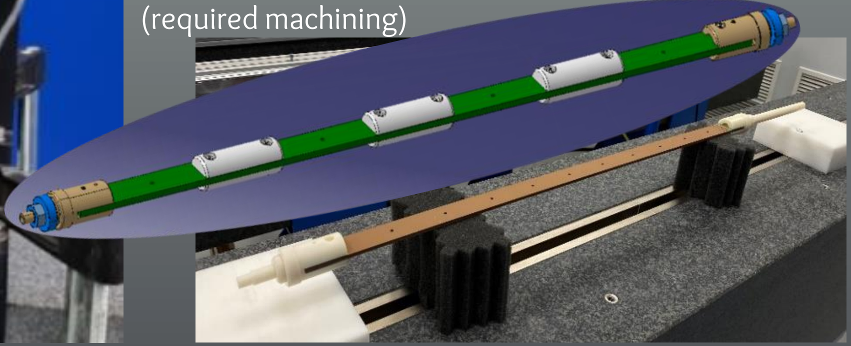


Credit: J. Kaeske, P. Rogacki, V. Di Capua, R. Beltron, L. Fiscarelli

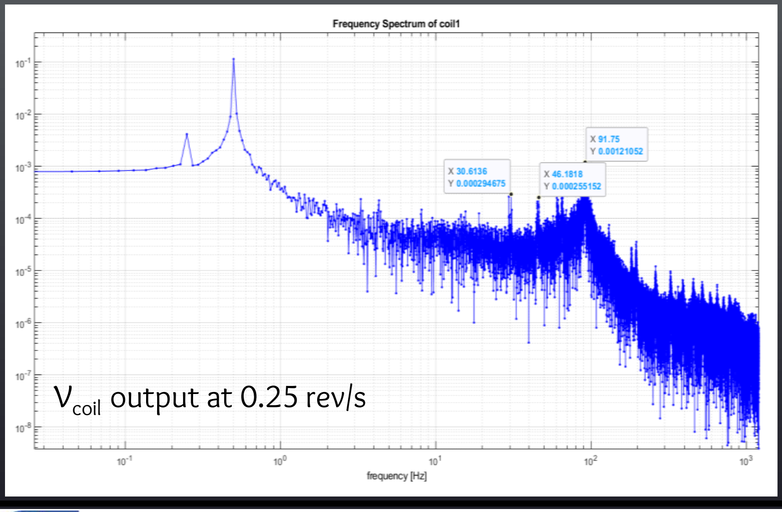
Small-diameter rotating coils for INFN-LNF's EuPRAXIA

Ceramic ball bearings | Low-cost Ø26 mm C-fiber tube (20 µm RMS tolerance) | Maxon DC motor

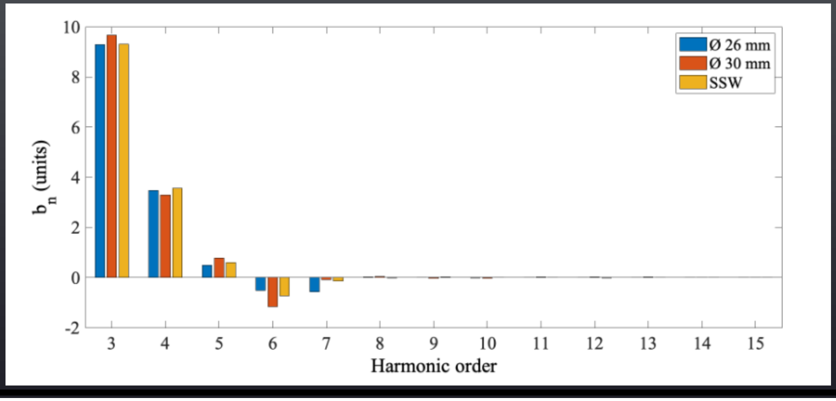
Accura 25® 3D-printed parts with 0.2 mm tolerance (required machining)



5×256-turn, 32-layer radial PCB coils inserted and pinned in the C-fiber tube



Harmonic torsional vibrations @ 4, 8, 15, 30 Hz visible in the outermost coil signal (< 1%)

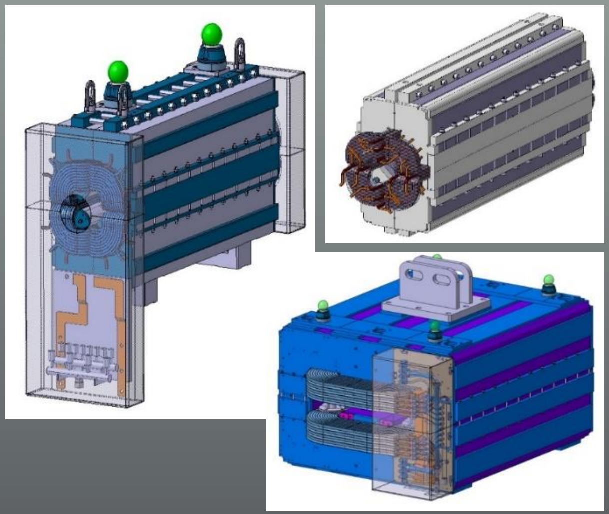


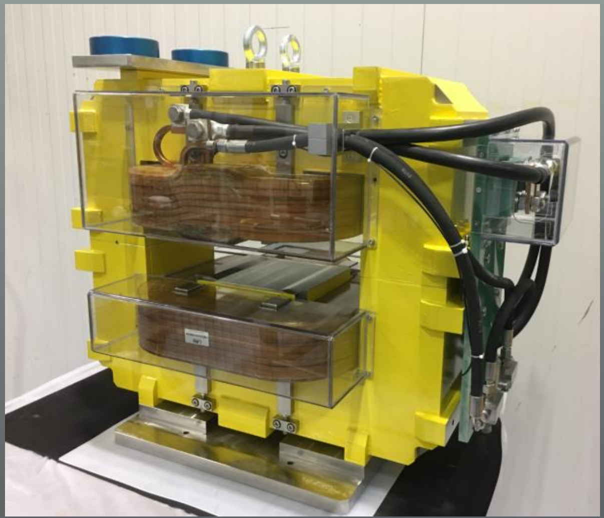
<0.5 units RMS @ 10 mm low-order differences w.r.t. other instruments

Credit: A. Lauria, M. Pentella

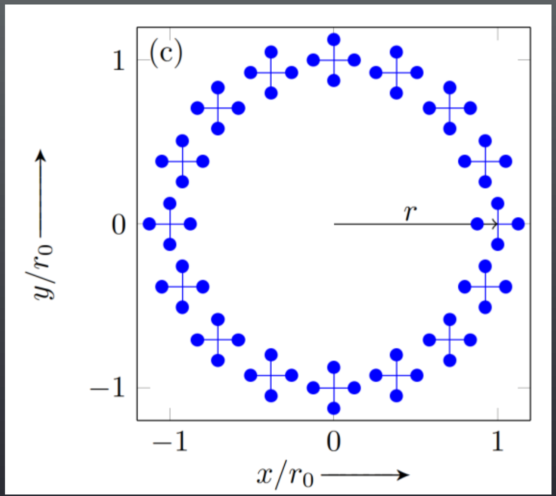
Rotating DC mode SSW

- 58 new/refurbished magnets for fixed-target East Area measured over ~one year
- Extensive use of SSW for integral harmonics

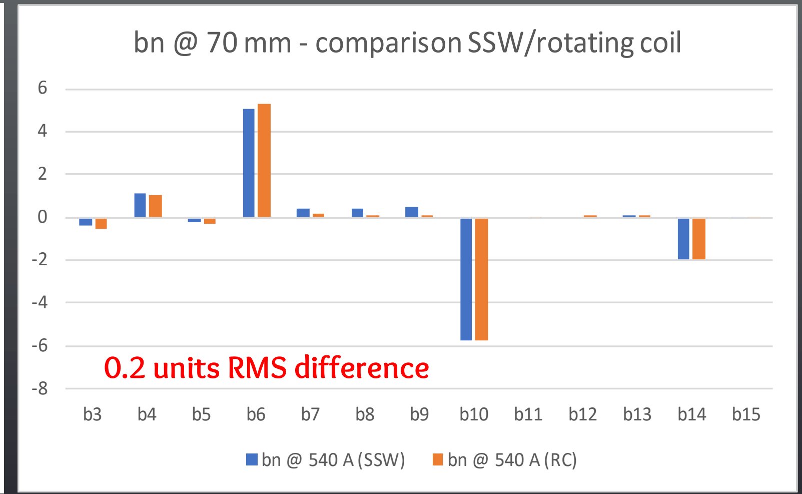




Ø70 mm quad used for cross-validation



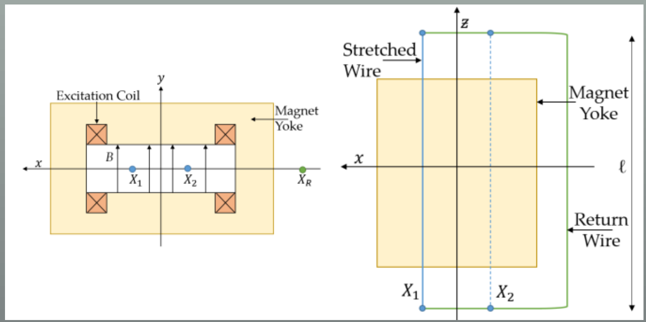
up to 128 × 3 mm × 3 mm
standard DC SSW measurements



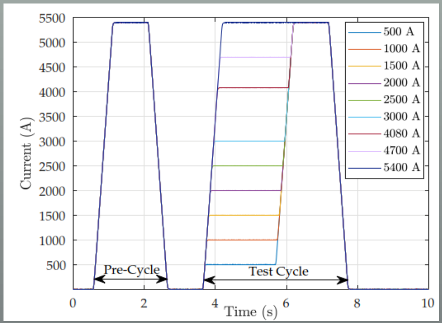
Harmonics fitted to actual flux spanned

Credit: R. Chritin, C. Petrone, P. Rogacki

Pulsed excitation mode SSW



Pulsed-mode flux integration in PS Booster main dipoles

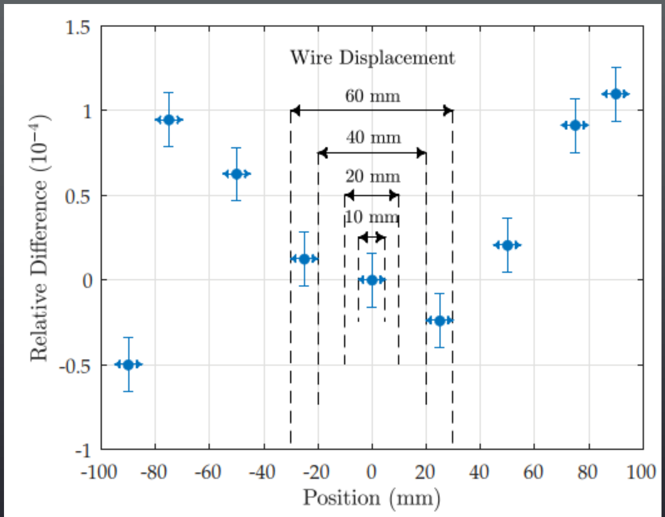


50-ppm excitation current reproducibility

$$\Delta\Phi_D(X, I_0, I) = \Phi(X, I) - \Phi(X, I_0) = \int_{-\frac{\ell}{2}}^{+\frac{\ell}{2}} \int_{X_R}^{X} [B_y(x, z, I) - B_y(x, z, I_0)]\, dx\, dz = \int_{t_0}^{t} V_c(\tau)\, d\tau$$

Create a 1-turn virtual coil by subtracting measurements at different wire positions

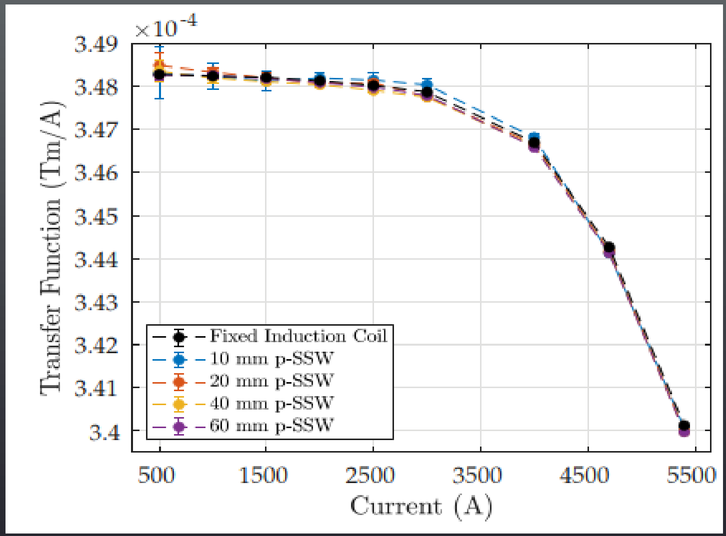
$$\Phi_{Coil}(X_1, X_2, I) = \Delta\Phi_S(X_1, X_2, I_0) + \Delta\Phi_D(X_1, I_0, I) - \Delta\Phi_D(X_2, I_0, I)$$



Standard static SSW measurement added in to recover initial level at I_0

200 ppm RMS difference vs. fixed integral coil

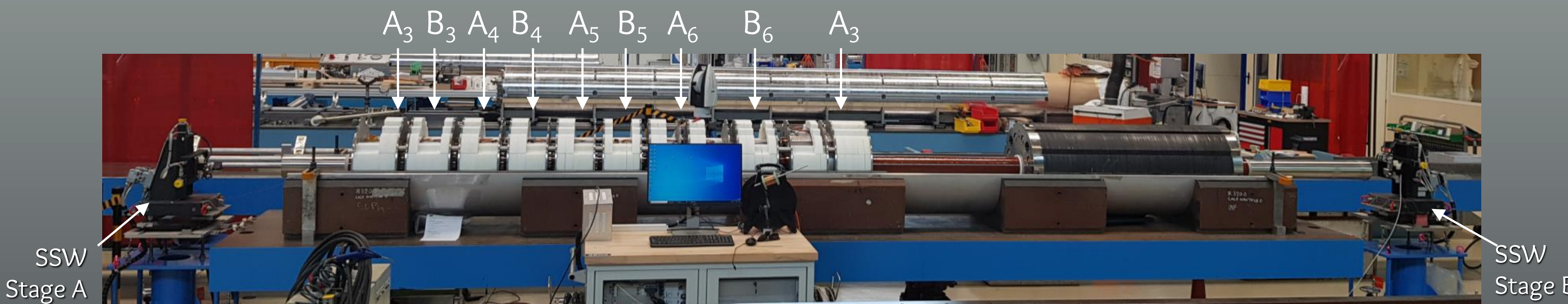
Wire offset X_2-X_1: trade-off between higher S/N and effect of B_3

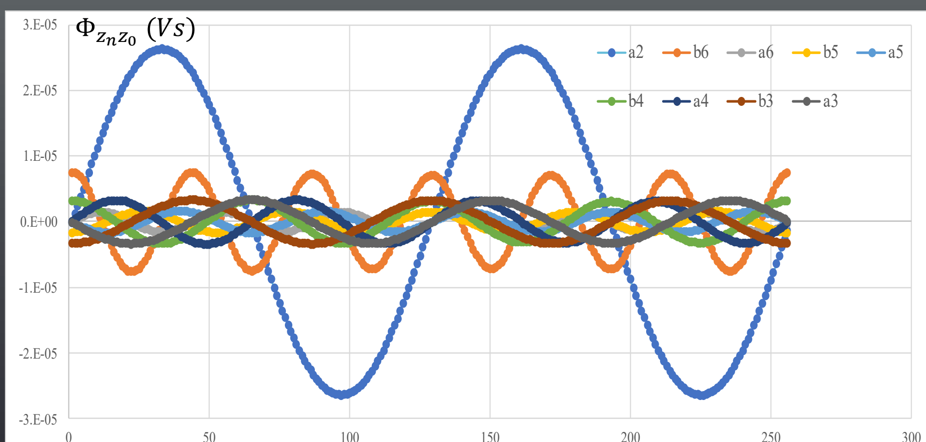


C Petrone, J Vella Wallbank *et. al*, "*Implementation of the SSW system in pulsed mode*", to be submitted to Sensors

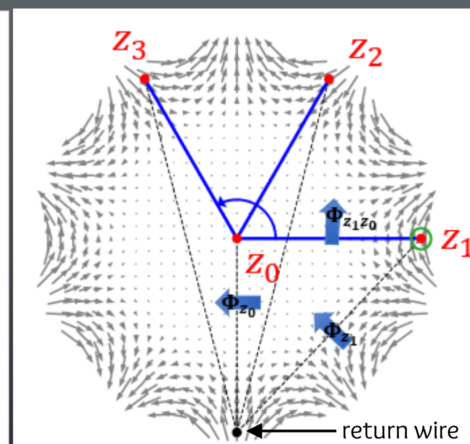
AC excitation mode SSW

- Goal: warm check of axis/field direction in HL-LHC corrector package MXBXFA
- Stepwise circular wire movement to mimic a radial search coil: $\Phi_{z_n z_0} = \Phi_{z_n} - \Phi_{z_0}$
- Analytical sag correction vs. longitudinal position
- Higher harmonics not precise enough → only measured when cold

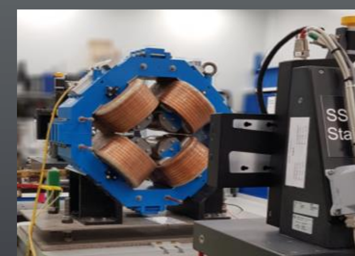




Magnets excited sequentially @ 19 Hz
(compromise sensitivity/eddy current effects/available voltage)



N=1 central + 256 tangential
6-second acquisitions
(oversampling)



Measurement	$\Delta x \pm 3\sigma$ in μm
DC at 112 A	-39.6±12.87
DC at -112 A	-2.53±27.94
DC averaged	-20.84±30.76
AC at 18 A, 7 Hz	-19.65±5.96

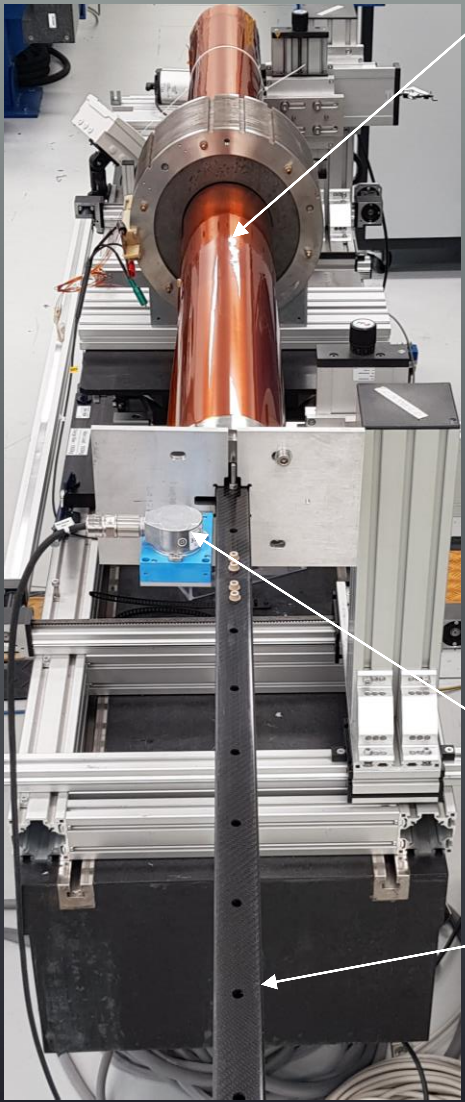
$\alpha_{roll} \pm 3\sigma$ in mrad
0.086±0.079
-0.133±0.089
-0.109±0.119
-0.125±0.289

Validated vs. DC-SSW on NC quad

Credit: E. Dalane, C. Petrone

Transversal Translating Fluxmeter

- Used for warm measurement of HL-LHC correctors
- Flux measurement taken on-the-fly



C-fiber guiding tube

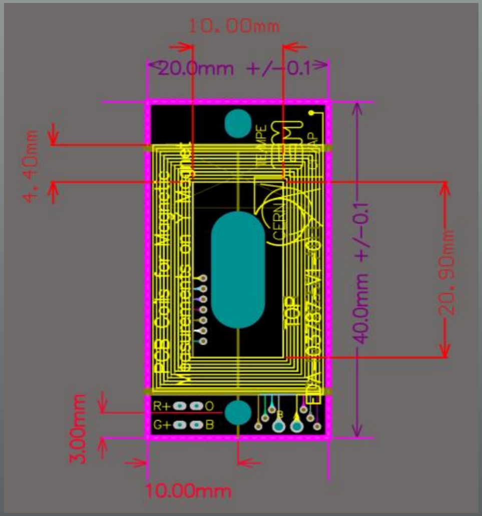
Sick® PFG08
wire draw encoder
(14 µm resolution,
300 µm reproducibility)

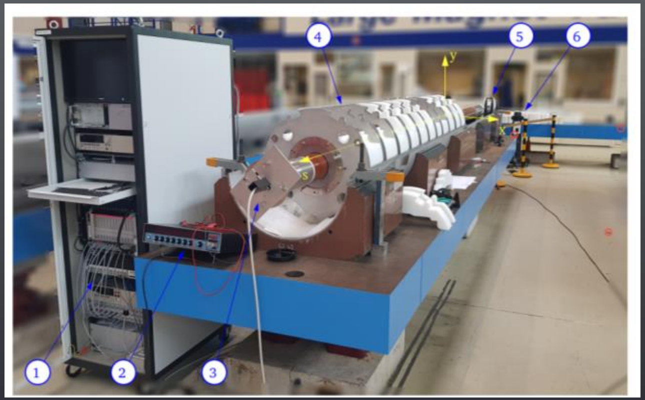
C-fiber moving rod
and guiding tube
(square !)

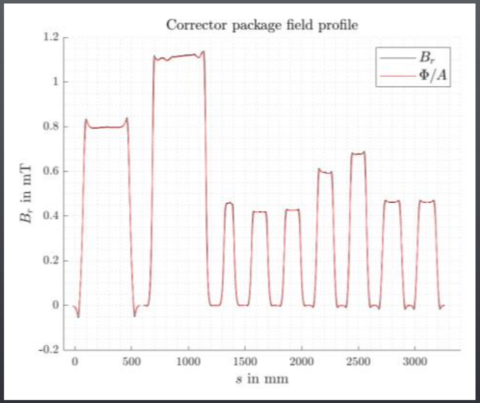
12×30° 160-turn,
16-layer PCB coils

One additional coil shifted by 15° /30 mm
to improve pitch/yaw misalignment

Prototype Accura 25®
3D-printed head







Longitudinal field profile of individual correctors in HL-LHC CP
(deconvolved with coil sensitivity kernel)
Localization accuracy << target 1 mm

Credit: E. Dalane, C. Petrone

Axial Translating Fluxmeter

- Goal: Quick in-situ measurement of field map/magnetic axis of 20 solenoids in the upcoming Antiproton Decelerator electron cooler
- SSW not possible (clearances, magnet cross-talk)
- Based on translating disc-shaped 8-layer PCB coil array

C Petrone et al., "Induction-coil measurement system for normal and superconducting solenoids", IEEE Trans. on Appl. Supercond. Vol 32, n. 6 Sept 2022

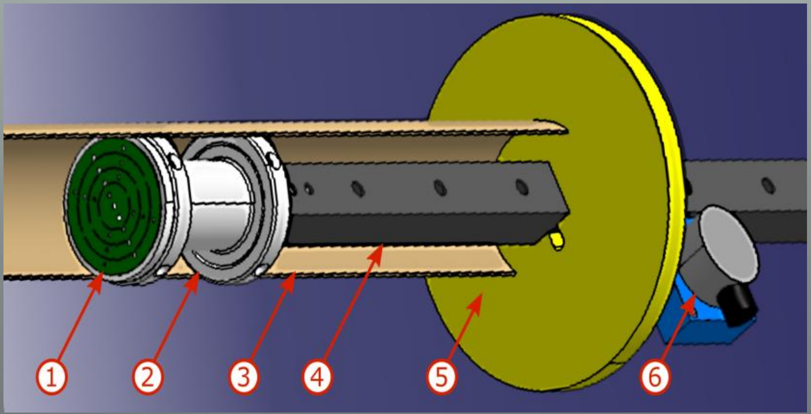
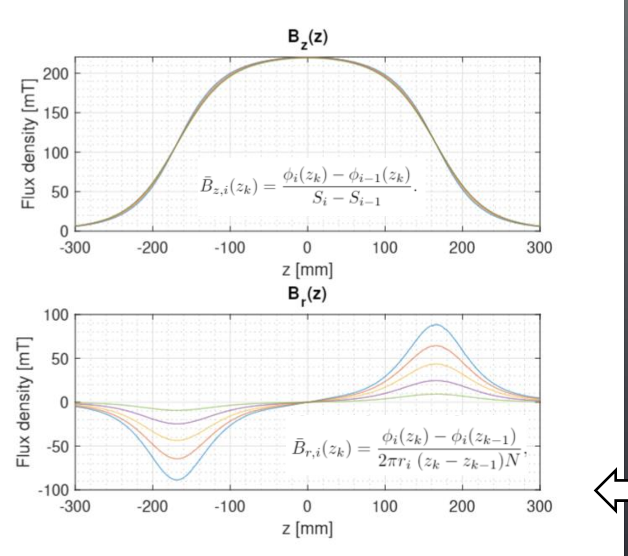
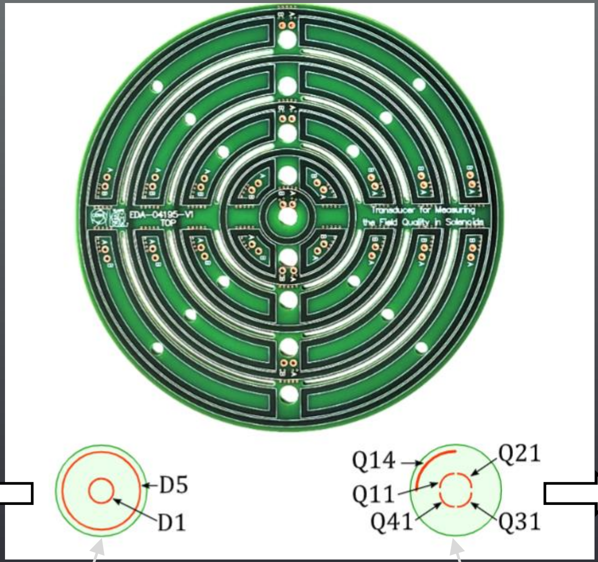


Fig. 3. Measurement system layout: (1) PCB coils, (2) Teflon PCB support and sledge, (3) guidance tube, (4) supporting arm, (5) anti-cryostat fixing plate, (6) linear encoder head.

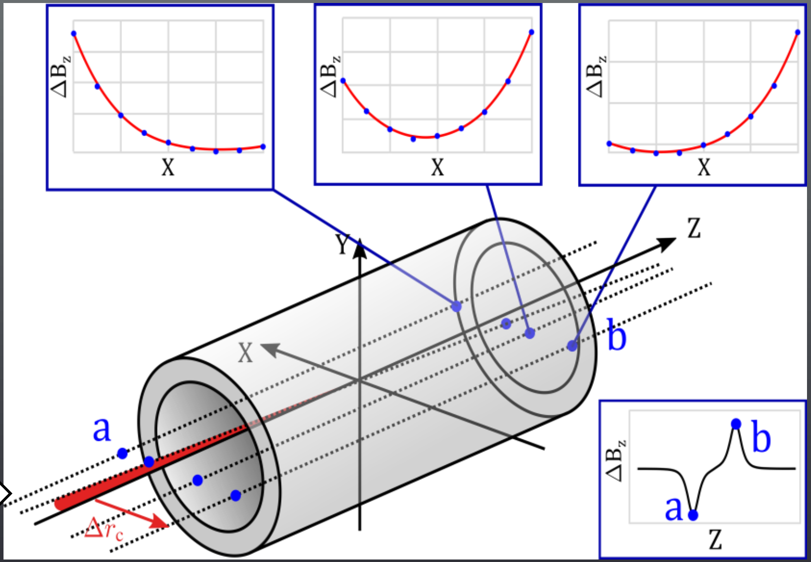


10 ppm field resolution



4×360° + 1 central, 6-turn concentric coils for axial and radial field profile

4×4×90°, 6-turn coils for magnetic axis localization



Axis defined by centers @ both end gradient peak planes

100 µm axis resolution with one pass

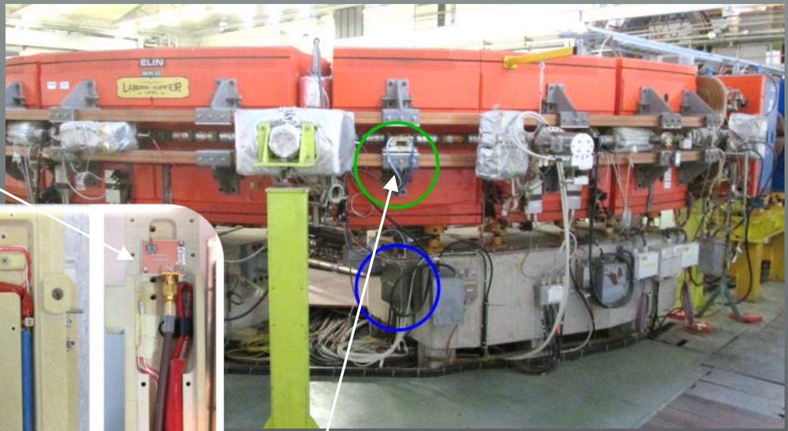
50 µm by repeating 9 passes w/ 5 mm offset

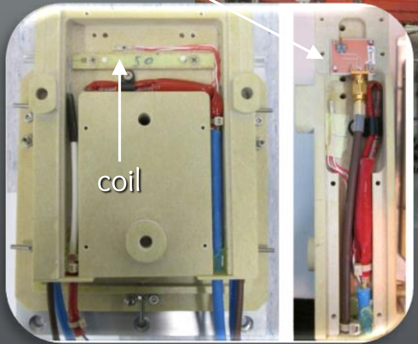
Real-time measurement systems

- 6 B-train measurement systems now operational in all normal-conducting CERN rings
- 250 kHz data rate, 30 μs latency, 2 μT resolution, ~100 μT absolute accuracy
- Complex, many challenges, simplified systems for smaller scale applications under study

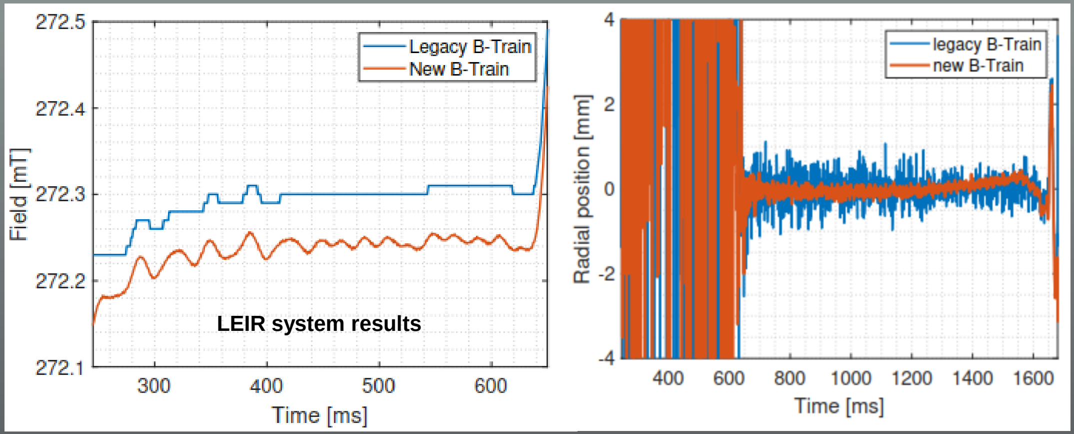
LEIR main bending dipole

FMR marker





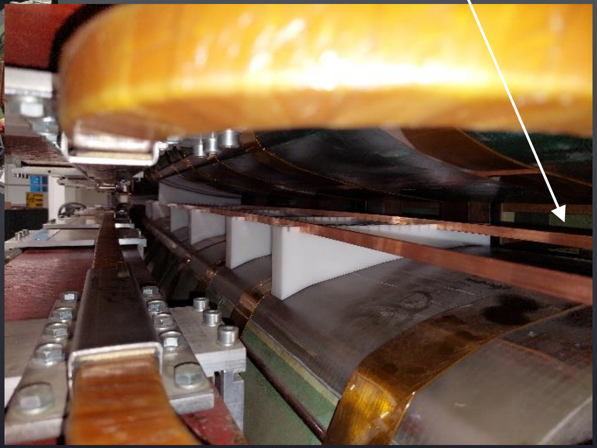
Sensors in the fringe field region



ISOLDE spectrometer challenges: only fringe region accessible, no spare, no validated FE model

Integral coil proposal for PS system (U17 unit under test in b. 867)

Simplest solution under test so far …



Credit: A. Beaumont, V. DI Capua, M. Pentella

Integrator drift cancellation with data fusion

- Problem: indefinitely long integration of fixed-coil output
- Kalman filtering for optimal estimation of the field in the presence of model (voltage offset V_0) + measurement noise
- Combining coil/Hall probe → <u>three orders of magnitude</u> improvement

Field = hidden state — Coil voltage = input variable

State-space model

$$x_k = B_k = B_{k-1} + \frac{1}{A_c}\frac{(v_k + v_{k-1})}{2}T_s$$

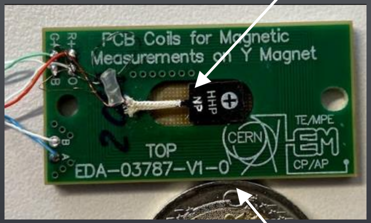
Case I: measurement = Hall probe

$$z_k = B_{H,k} = B_k + q_k$$

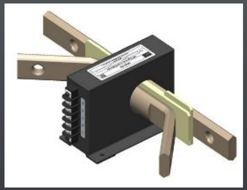
Case II: measurement = excitation current

$$z_k = \frac{I_k}{g} + q_k$$

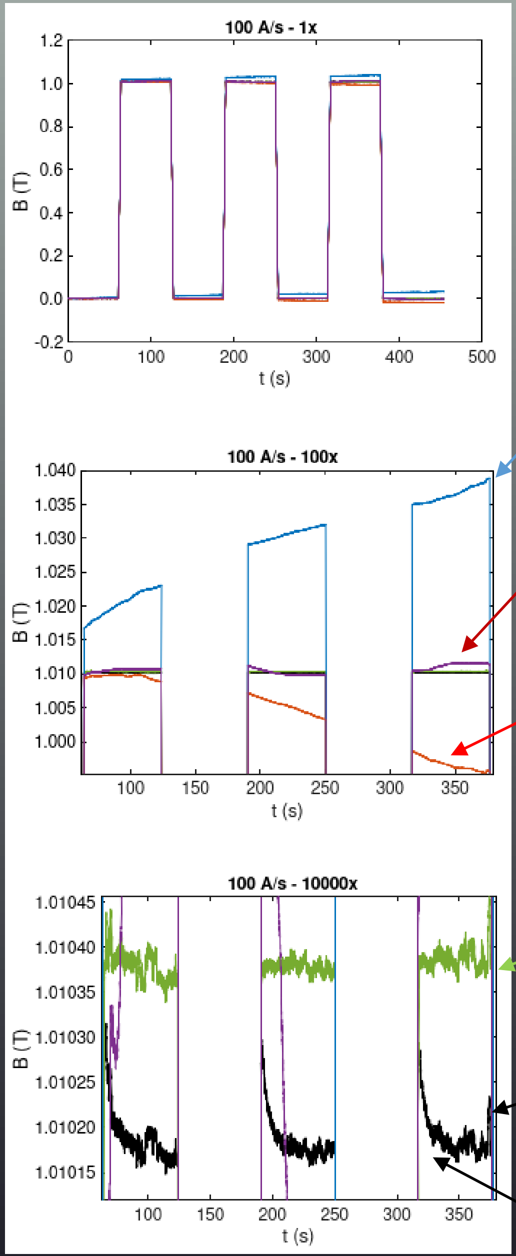
Arepoc HHP-NP 2067 Hall Probe



594 cm^2 160-turn 16-layer PCB coil



DCCT



Uncorrected drift 60 ppm/s

V_0 updated on plateaus 3 ppm/s

V_0 estimated 0—50 s 53 ppm/s

Kalman + exc. current 0.08 ppm/s

Kalman + Hall probe 0.03 ppm/s

Actual eddy current decay transient

V. Di Capua, M. Pentella *et al.*, *"Drift-free integration in magnetic measurements achieved by data fusion", Sensors 2022, 22, 182*

Thanks for your attention

… don't miss these other presentations from CERN:

- Improving the performance of a three-axes Hall probe mapper system (Melvin Liebsch)
- "Hysteresis Modeling in Iron-Dominated Magnets Based on a Multi-Layered NARX Neural Network Approach" (Vincenzo Di Capua)

- "A Static-Sample Magnetometer for Characterizing Weak Magnetic Materials"(Mariano Pentella)
- "Encoderless harmonic coil measurements" (Piotr Rogacki)