Magnetic measurement systems for future high performance magnets

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Contents

Introduction

- Magnetic measurement services at CERN centralized in two work units as of 2007:
  PH-DT1-MM: experimental magnets
  AT-MEI-MM: accelerator magnets (resistive, superconducting … everything BUT kickers)
- Accumulated equipment and knowledge from many groups and projects over 50 years
- Most instruments optimized for a specific magnet family (LHC, SPS, etc ..)
  adaptations possible but not always practical
- Large variety → some duplication of functionality, costly maintenance, HW and SW platforms not always consistent (LabView, Visual Basic, C …)
- Overall: an extensive array of instruments, devices and facilities that has served well its purpose for the existing machines

Present objectives

- Qualify new/repaired magnets for existing machines and upgrades
- Refine magnetic models for accelerator operation ("FIDEL")
- Extend capabilities and improve accuracy for LHC and future projects

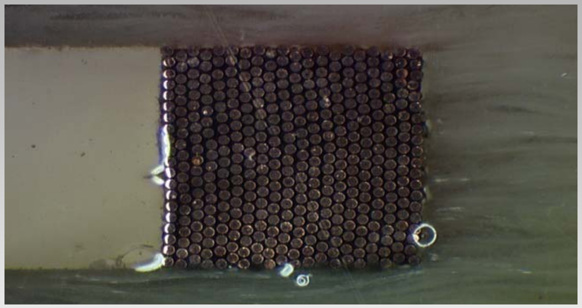
Current status – instrumentation

	System	magnet parameters					quantity					performance	
									axis		field	resolution	
		T	Field [T]	dB/dt [T/s]	L_{MAX} [m]	Gap/∅ [mm]	∫BdL ∫GdL	b_n a_n	magn	mech	dir.	time [s]	length [mm]
harmonic coil	15m shaft ("TRU")	W/C	0.01 - 10	0.007	15	40	✓	✓				10	1150
harmonic coil	Shafts for vertical cryostat ("bloc4")	W	0.05 - 10	0.007	3	50-70	✓	✓	✓			10	1000
harmonic coil	Industry dipole moles ("DIMM")	W	0.01 - 0.05	*steady-state*	*any (scan)*	50	✓	✓			✓	*steady-state*	200-750
harmonic coil	Industry quad moles ("QIMM")	W	0.01 - 0.05	*steady-state*	*any (scan)*	45-70	✓	✓			✓	*steady-state*	750
harmonic coil	AC mole	W/C	10^{-5}	*steady-state*	*any (scan)*	40-50		±	✓	✓	±	*steady-state*	100-200
harmonic coil	Linac 2 bench	W	0.001-1	*steady-state*	0.2	20-30	✓	✓	✓		✓	*steady-state*	*integral*
fixed coil	Fluxmeter + digital integrator	W	*n.a.*	$f(N_{TURNS}A_{COIL})$	2	≥ 20	✓	±				10^{-2}	*integral*
fixed coil	Fluxmeter + digital integrator (SPS)	W	*n.a.*	2	8	≥ 20						10^{-2}	*integral*
fixed coil	Fluxmeter + fast ADC	W	*n.a.*	$f(N_{TURNS}A_{COIL})$	2	≥ 20						10^{-5}	*integral*
fixed coil	PS ("Huron") bench	W	*n.a.*	1	1.5	≥ 20	✓		✓		✓	10^{-2}	30-1000
fixed coil	Linac 2 bench	W	*n.a.*	300	0.2	20-70	✓	✓	✓		✓	*n.a.*	*integral*
S.W.	Single Stretched Wire (FERMILAB)	W/C	0.01 - 10	*steady-state*	20	≥ 10	✓	±	✓		✓	*steady-state*	*integral*
S.W.	Double Stretched Wire	W/C	*n.a.*	$f(L_{MAGNET})$	20	≥ 10	✓					*steady-state*	*integral*
Hall	3-axis Hall probe scanner	W	30	*steady-state*	1.5	≥ 30	✓	✓				*steady-state*	2
Hall	B3-B5 Hall probe ring	C	10	0.007	*any (scan)*	40		✓				10^{-3}	2
Hall	Polarimeter (rotating Hall plate)	W	0.1	*steady-state*	*any (scan)*	50	±					*steady-state*	2

- Typical accuracies: B1 10^{-4}, B2 10^{-3}, harmonics (relative) 10^{-5}, magnetic axis wr.t. external fiducials 0.2 mm
- Instruments often customized for internal use and external collaborations eg CNAO, ASG, CELLS/ALBA, Saclay
- Main HW platform: VFC-based "Programmable Digital Integrator" PDI on VME bus

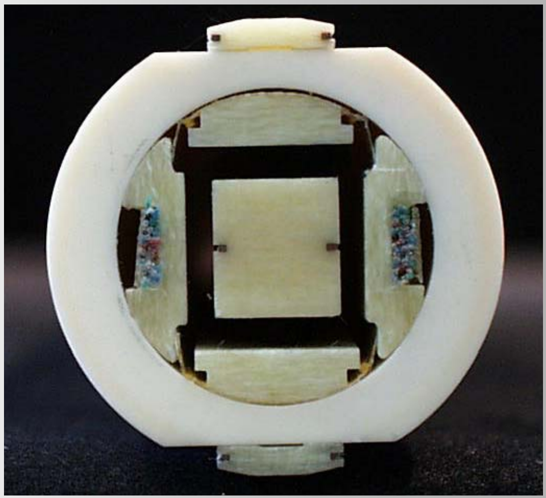
Current status – measurement coils

2.5 m curved fluxmeter array for CNAO dipoles



X-section of 20x20 multi-strand flat cable coil

Inset quadrupole-compensated coil for Linac4 PMQs



X-section of 15m long LHC ceramic coil shaft

- Large stock (~1000) of measurements coils and assemblies (20 mm≤∅≤70 mm, 2 mm≤L≤7 m)
- Specialized coil manufacturing and calibration facility: **2 mm to 2 m long**, up to **4000 turns** with mono-(machine wound) or multi-strand wire (manually wound), air or G10 core
- Coil arrays, dipole and quadrupole-compensated assemblies (bucking factor up to 6000 with matched sets) on ceramic or composite supports, straight or curved
- Specific expertise in design, micro-welding, precision machining, gluing and magnetic calibration

New demands

Magnet parameters

Linac 4	LHC Upgrade Phase I	LHC Upgrade Phase II	PS2
• Resistive • B_{peak} ~1 T • $\dot{B}$ ~700 T/s (EMQ) • τ_{CYCLE} 1.6~6.0 ms • $\varnothing_{CB}$ 20~70 mm	• NbTi • B_{peak} ~10 T • $\varnothing_{CB}$ 110~130 mm	• Nb_3Sn • B_{peak} 12~15 T • $\varnothing_{CB}$ 130~150 mm	• NbTi • B_{peak} ~1.8 T • $\dot{B}$ ~ 2 T/s • $\varnothing_{CB}$ ~70 mm

Measurement parameters

- **LHC** (or any SC magnet)**:** improve time resolution (0.1→5 Hz) and harmonic accuracy (0.1→0.02 units) for dynamic phenomena (snapback)
- **Fast-pulsed magnets:** improve time resolution for local/integral eddy current transients *(recently required for PS & CNAO)*
- **Linac 4:** measure magnetic axis in assembled DTL module (∅20 1500 mm bore)
- **LHC Upgrade:** same accuracy of strength/harmonics/axis than existing triplets (??)

Main issues

Higher B + higher dB/dt+ larger ∅ = **higher signal** = **better measurement**, *however …*

Harmonic/fixed coil systems

- Faster measurements and/or increased B, $\dot{B}$, ∅ ⇒ signals exceeding typical 10V range ⇒ use coils with reduced surface (turns), modulate rotation speed (better accuracy) and/or amplifier gain (more practical)
- Faster measurements ⇒ continuous rotation
- Existing PDI integrators cannot cope with high acquisition bandwidth
- Larger $\varnothing_{BORE}$ ⇒ keep $\varnothing_{COIL} \gtrsim \frac{2}{3}\varnothing_{BORE}$ to minimize harmonic extrapolation errors ⇒ design & build new coil support shafts
- Larger $\varnothing_{COIL}$ ⇒ massive ceramic shafts unsuitable ⇒ new mechanical design necessary (but: easier to machine, room to add optical targets for axis detection)
- Larger $\varnothing_{COIL}$ ⇒ calibration in existing reference magnets may be not possible ⇒ new reference magnets/calibration procedures/coil geometries

General problems

- Eddy current magnetic forces scale as $\mathbf{B\dot{B}}$ ⇒ effects on probe materials increased by 10^1~10^2
- High field reference magnets: needed for sensor calibration, material and system characterization (NB: existing Metrolab NMR teslameter maxes at 14 T, primary reference needed)

Undergoing Activities

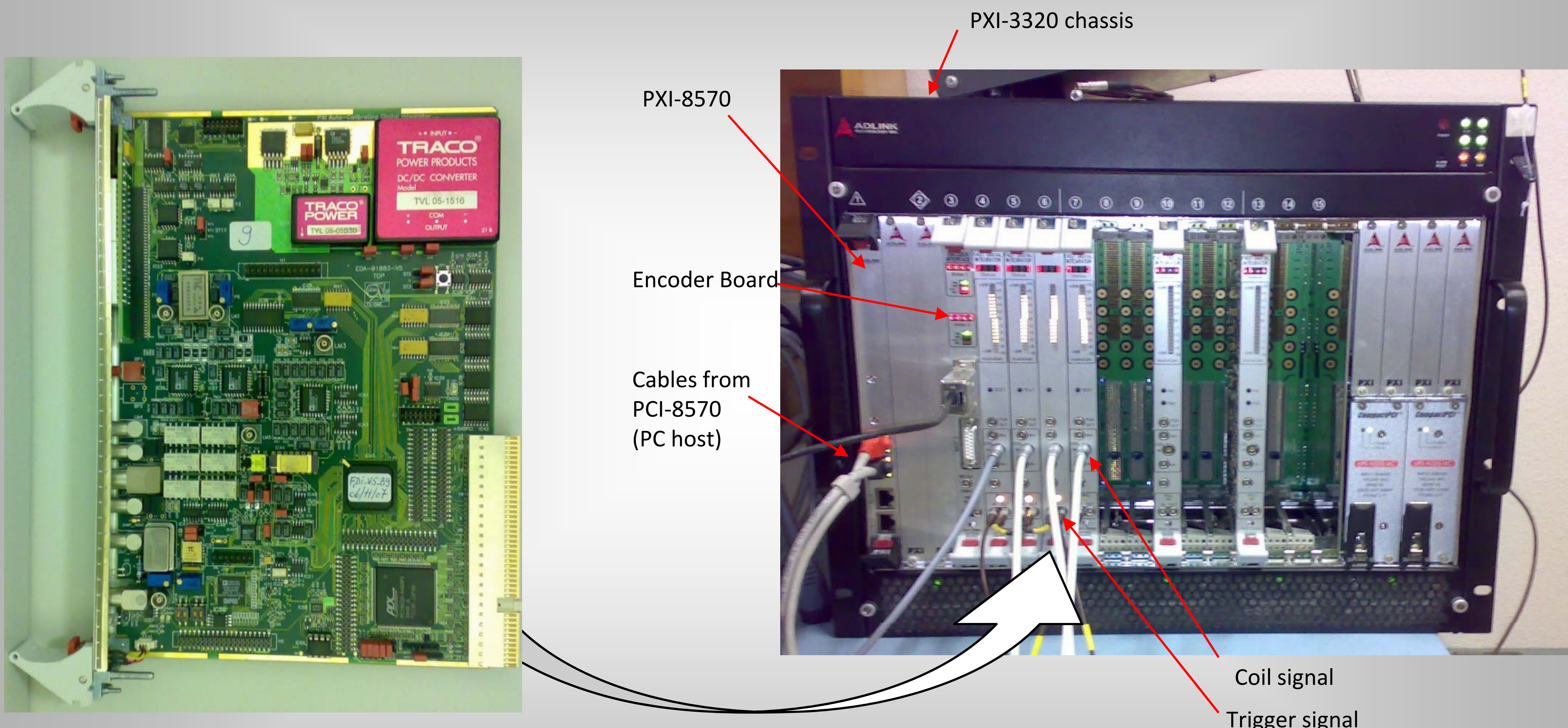
- Higher speed signal acquisition and integration → **Fast Digital Integrator (FDI)**
- Higher speed harmonic measurements → **FAst MEasurement system (FAME)**
- Obsolescent software → Flexible Framework for Magnetic Measurements (**FFMM**) (with UniSannio)
- Linac 4 → Existing **Linac 2 bench being upgraded** for permanent and fast-pulsed magnet (new mechanics, coils, integrators, power supplies, software)

Future Activities

- Large diameter bores → R&D for suitable coil shafts (geometry, materials, calibration etc..)
  - coil shaft for short models in vertical cryostat ("Bloc4" cold measurement system)
  - coil shaft for long cryoassemblies w/ anticryostat (SM18 test benches)
- General-purpose travelling probe family with tangential harmonic coils and optical target for axis detection ("supermole")
- R&D on components at high $B/\dot{B}$: inclinometers, piezo motors, encoders etc …
- Measurement and analysis techniques for strongly curved magnets

Fast Digital Integrator (FDI) – overview

- joint development since 2005 with Università del Sannio (Italy)
- PXI board integrating analog front-end, programmable amplifier, 18-bit ADC, DSP numerical processing
- software drivers for LabView + new in-house C++ class framework (FFMM)



aim: increase bandwidth and accuracy for fast fixed- and rotating-coil magnetic measurements

Set to replace existing base of VFC-based PDIs – workhorse of our future HW platform

Fast Digital Integrator (FDI) - characteristics

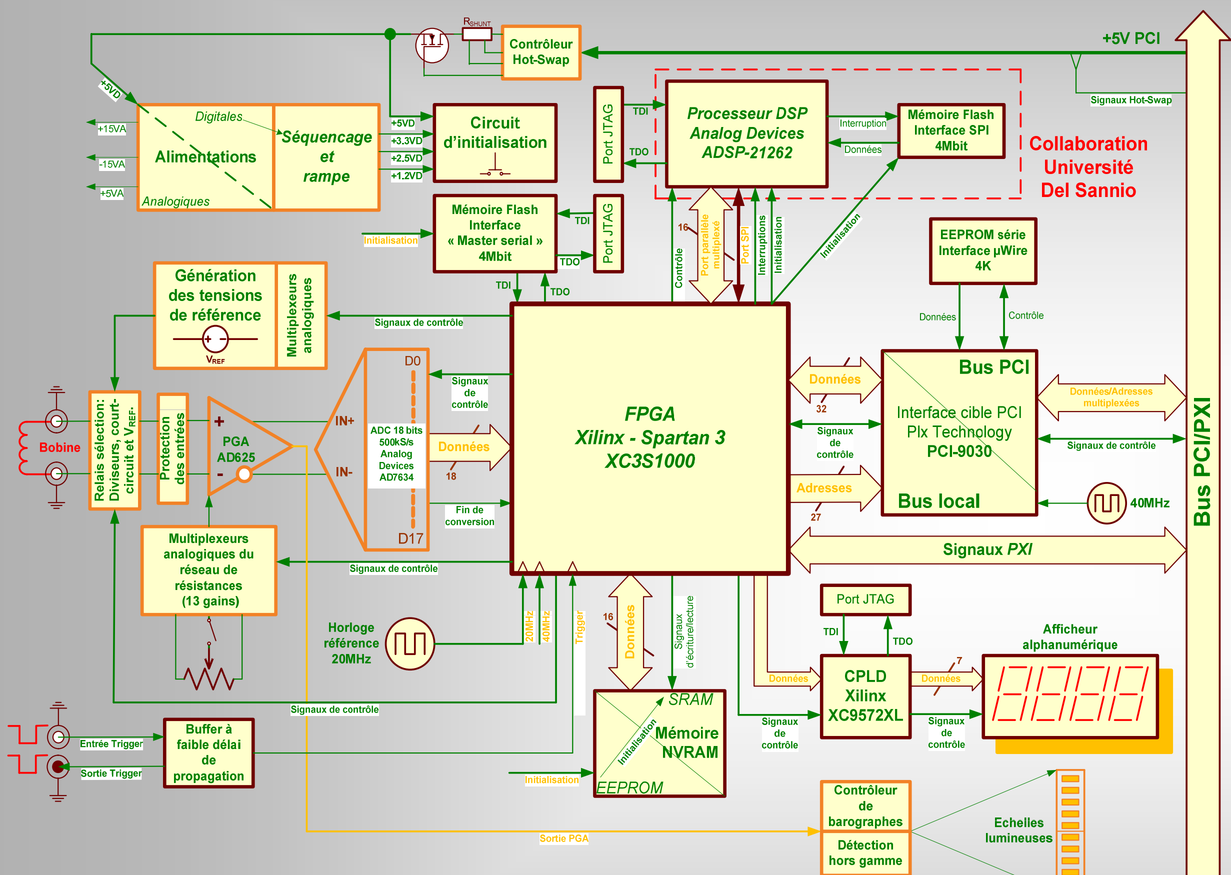


Schéma bloc de l'intégrateur numérique rapide

- overvoltage-protected, low-pass filtered analog front-end
- fast-switchable programmable gain levels from **0.1** to **100**
- auto-calibration of gain & offset with $V_{reference}$ generator
- 18-bit, 500 kHz ADC
- DSP allows multiple upgradeable integration/filtering/compression algorithms
- FPGA glues logically components
- industry-standard compact PCI interface
- real-time LED display of gain and signal level

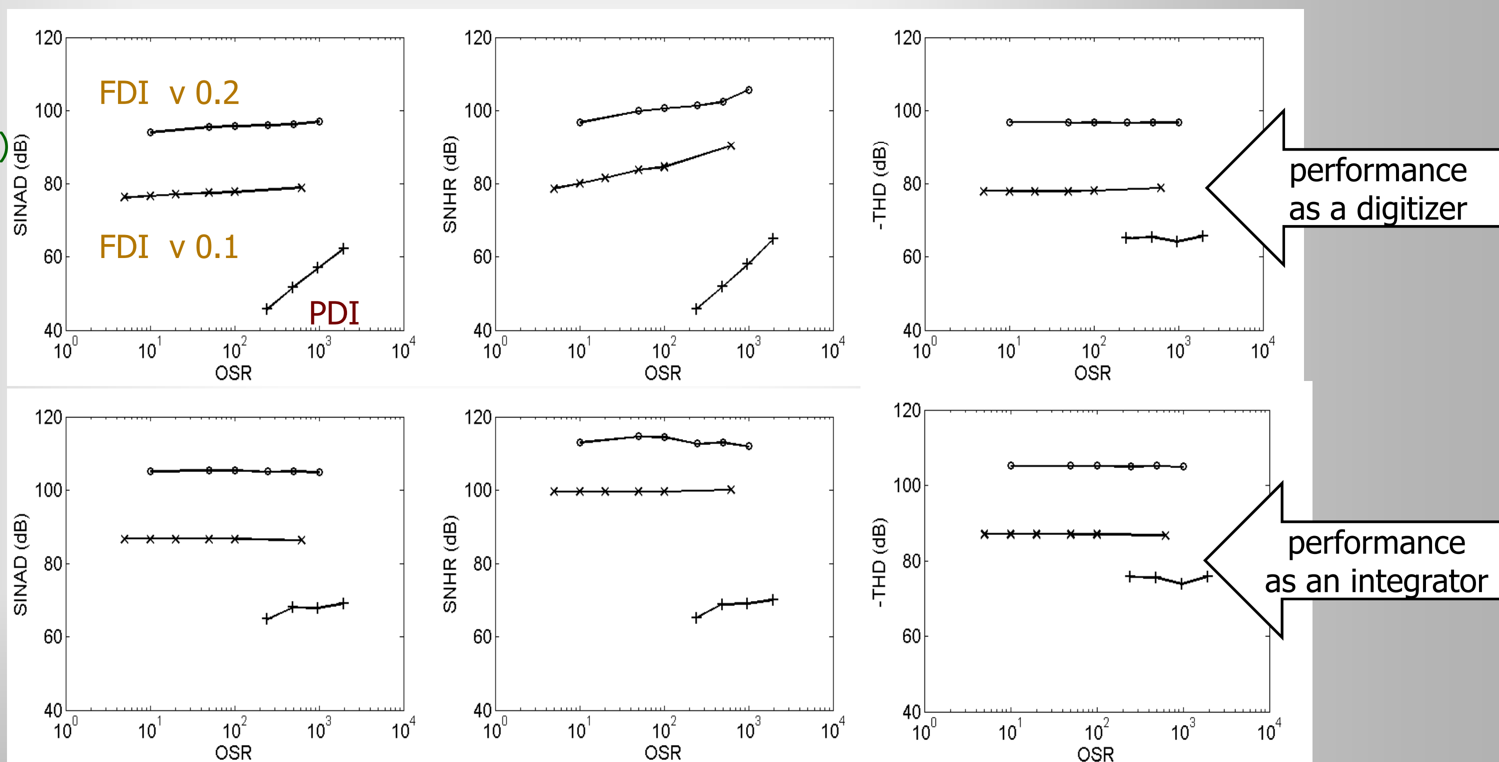
Main advantages in switching from PDIs to FDIs:

- Integrated board (filter+ampli+ADC) → higher noise rejection, streamlined implementation, more cost-effective
- Bandwidth up to **250 kS/s** (PDI: 1 kS/s)
- Signal-to-noise up to **110 dB** (PDI: 70 dB)
- Equivalent resolution: **0.5 nVs** (PDI: 50 nVs)

Signal-to-noise metrics:

SINAD
(Signal to Noise And Distortion Ratio)
SNHR
(Signal to Non Harmonic Ratio)
THD
(Total Harmonic Distortion)

test carried out with pure sine wave signal @ 10 Hz, 20 Vpp
trigger rate = up to 256/revolution



OSR = oversampling ratio = ADC sampling rate/encoder trigger rate (typical value: 2000)

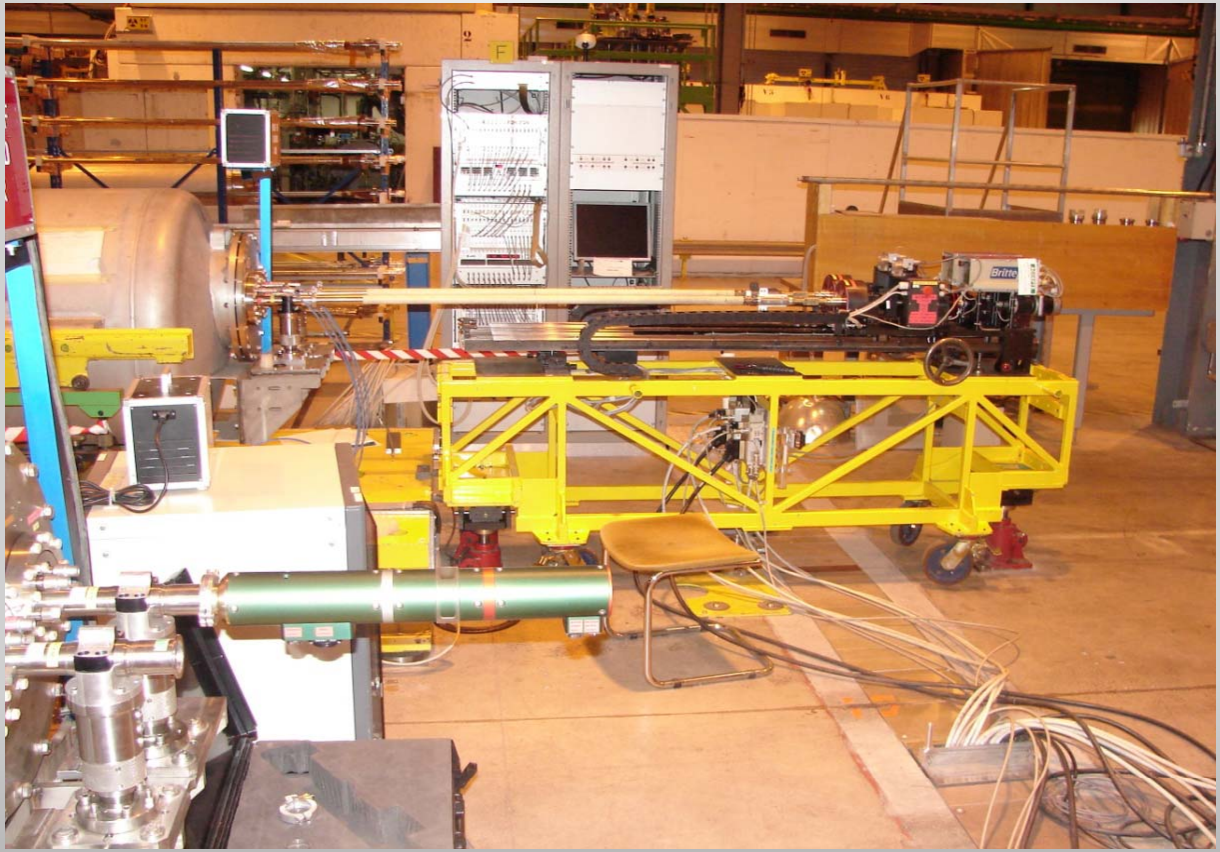
Fast Digital Integrator (FDI) - outlook

- **12** prototype cards in use, **40** in production (NB long lead times for components)
- firmware and drivers being updated to exploit full HW capabilities (software programmable trigger generation, ADC mode, elimination of card-to-PCI bus bottleneck)
- Possible future HW upgrades: stand-alone version with USB interface, increased buffer memory, 18-bit DAC for flexible self-calibration and programmable function generation;

commercialization accord with METROLAB in progress → lower volume/maintenance costs !

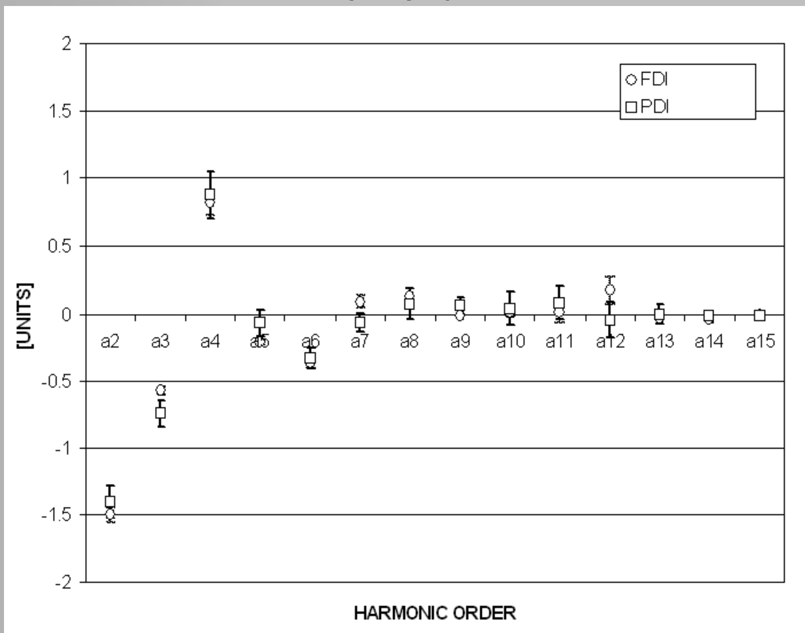
FAME (FAst Measurement system) - overview

- Continuous, high-speed (8 Hz) harmonic measurement system for main LHC dipoles and quadrupoles $\rightarrow$ improvement of magnetic model for accelerator control (FIDEL)
- High-accuracy, high bandwidth integrated and local field quality during snapback transients
- Upgraded ceramic coil shaft with 6-turns coils, better mass balancing, robust connectors
- Compact Mobile Rotating Unit (MRU) simplifies installation and maintenance, might be adapted to other rotating coil systems *(downside: longitudinal positioning requires Ti extension pieces)*

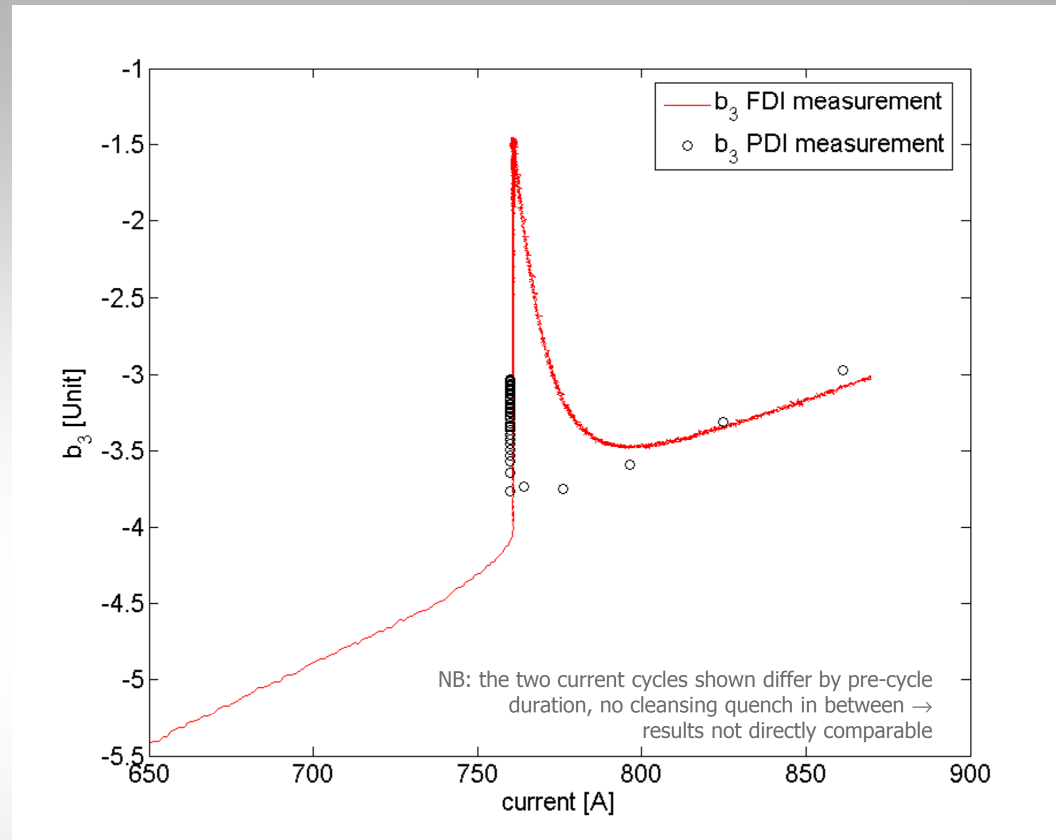


FAME – first results and outlook

Comparison of center harmonics in warm LHC dipole with FAME/FDI and old (PDI) system



Qualitative comparison of center b3 snapback curves in LHC dipole with FAME/FDI and PDI system



- <u>Validation and characterization test</u> campaign being carried out with two prototype MRU + dipole shafts in SM18 *(tests interrupted due to a cryogenic accident freezing the prototype shaft – now being repaired)*
- Results <u>coincide with older</u> system within measurement uncertainty (< 0.1 unit)
- <u>Coming next</u>: spare dipole + quadrupole system; integration in new control/analysis software framework; new analysis algorithms to improve accuracy and bandwidth (harmonic reconstruction in rapidly changing field, progressive update during coil rotation)

Timely input from our valued magnetic measurement clients !

Critical information:

- ∅ cold bore: some R&D required + long lead times for coil shafts (and anticryostats)
- twist pitch λ: in long shafts, gap and coil length must be integer multiples of λ

Also important to know:

- Maximum B and $\dot{B}$
- Geometrical parameters: good field region, magnet length, curvature radius for short dipoles, position of mechanical references/optical targets
- Desired accuracy for field strength, harmonics, direction and axis

… have you got a magnet to spare ?

high field/large aperture magnets to be kept stably as references for calibration and cross-checks, and as test beds for materials and technologies