# Magnetic Measurements with the PS B-train
## Recent results and planned developments

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# Introduction

# What is a B-train ?

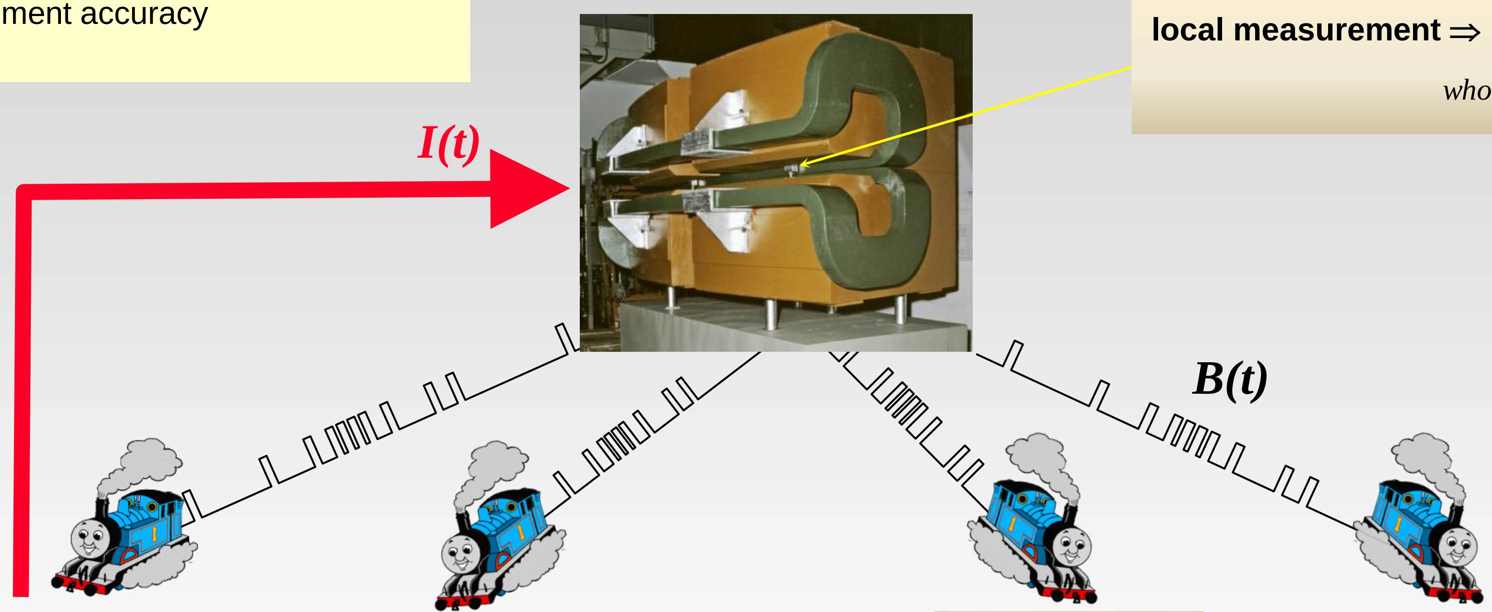
## real-time dipole field measurement for accelerator operation

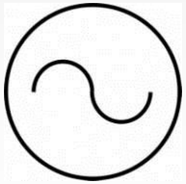
**sometimes B(t) ≠ f(I,dI/dt,I(τ≤t))**

- Hysteresis ("Pulse to Pulse Modulation")
- Temperature
- Eddy currents
- Ageing of iron yoke
- I(t) measurement accuracy
- Timing jitter

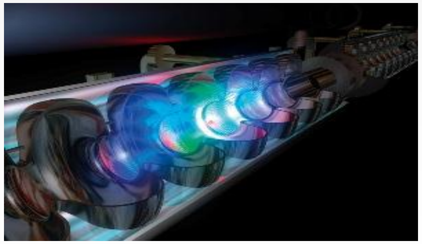
**reference dipole**
**(in the ring or external + series excitation)**

**local measurement** $\Rightarrow \oint_{whole\ ring} B\,d\ell$



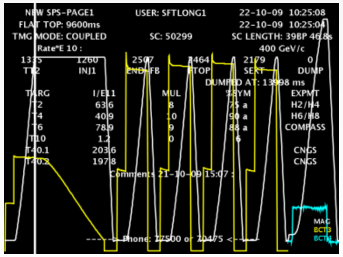


power supply control (B or dB/dt)



RF control (mandatory)

beam diagnostics
(beam current DCCT)



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FLAT TOP: 9600ms                           22-10-09  10:25:04
TMG MODE: COUPLED      SC: 50299      SC LENGTH: 39BP 46.8s
 Rate*E 10 :                                400 GeV/c
 1335      1260      2507      2464      2179      0
 TT2       INJ1      END-FB    FTOP      SEXT      DUMP
                               DUMPED AT: 13998 ms
 TARG      I/E11     MUL       %SYM      EXPMT
 T2        63.6      8         75 a      H2/H4
 T4        40.9      10        90 a      H6/H8
 T6        78.9      9         88 a      COMPASS
 T10       1.2       0         6
 T40.1     203.6                         CNGS
 T40.2     197.8                         CNGS
                Comments 21-10-09 15:07 :
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qualitative feedback to operation

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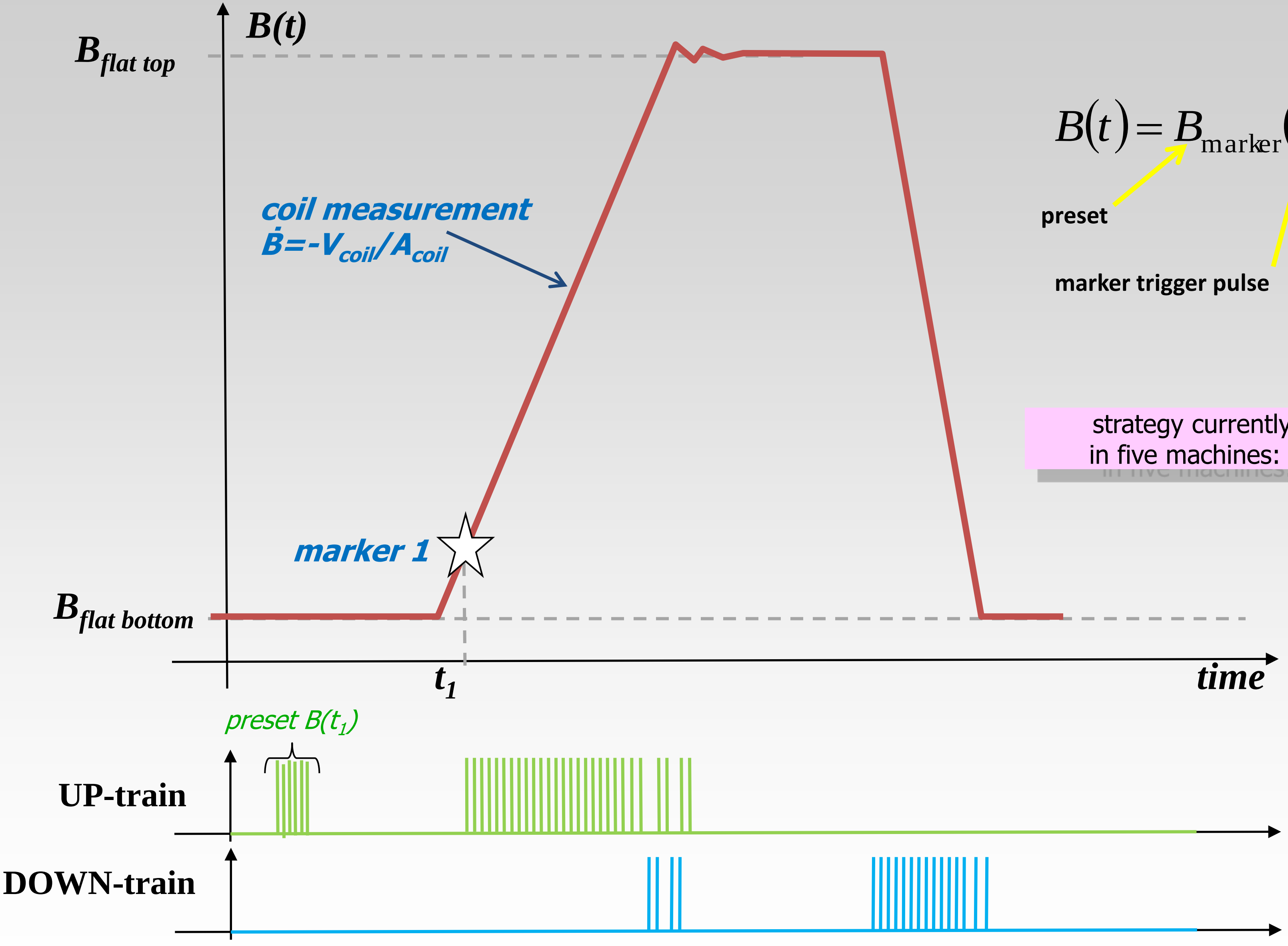
# B-train working principle – dynamic marker



$$B(t) = B_{\text{marker}}(t_1) + \int_{t_1}^{t} \dot{B}\,dt$$

**preset**

**marker trigger pulse**

strategy currently implemented at CERN
in five machines: PSB, PS, SPS, LEIR, AD

**"PS pulses"**
**(24 V, 1 μs)**
**0.02, 0.1, 1 or 10 G/pulse**
***digital tech from the '60s !***

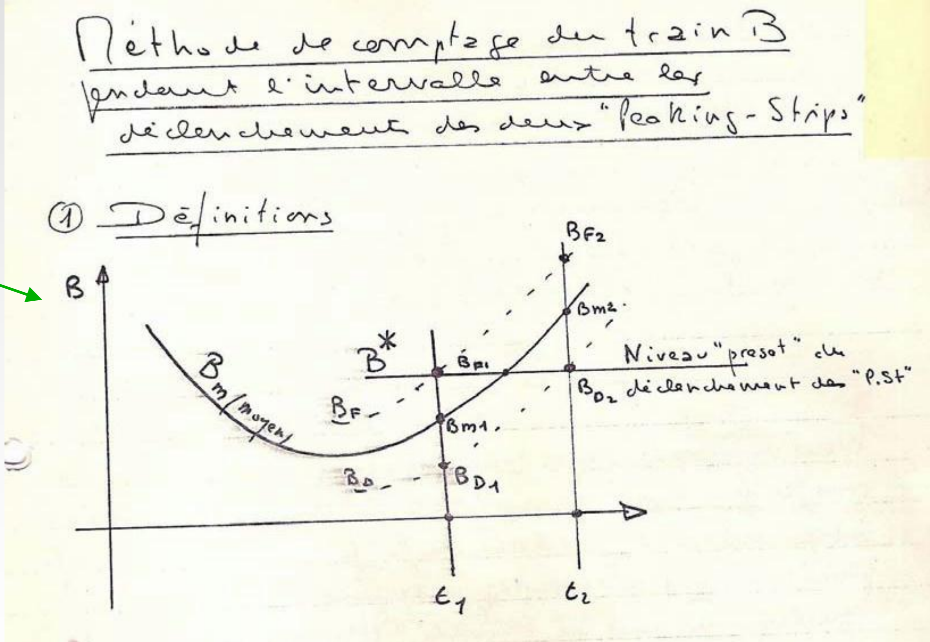
# Timeline of PS B-train systems

3 systems in the lifetime of PS:

- **Mark I (1960-1980)**
  - included in the original magnet design
  - only one side of U101 (block 4) equipped with peaking strips @ 50 G + flux coils
  - 3 channels @ 0.1, 1 and 10 G;
- **Mark II (1980-2000)**
  - motivation: adapt to multi-batch filling + new F8L
  - different F/D fields → sensors in both halves
  - new peaking strips designed for up to 400 G + new flux coils
  - extra logic to interpolate B(t) between triggers
- **Mark III (2000 – )**
  - motivation: improved precision and reliability
  - peaking strips @ 50 G (D only) + flux coils (D + F)
  - peaking strip F removed from B-train, after a few tests, in order to be compatible with the newly installed PSB/AD systems

Mark I

Mark II & III



Méthode de comptage du train B pendant l'intervalle entre les déclenchements des deux "Peaking-Strips"

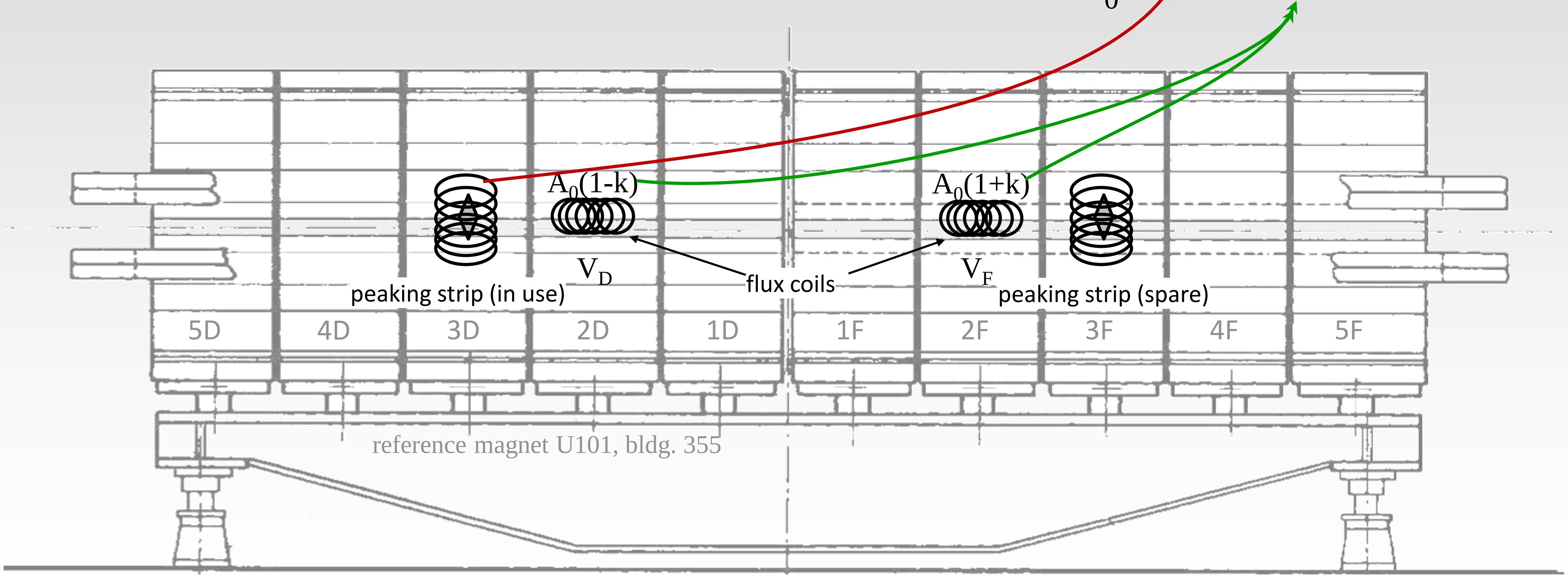
① Définitions

R. Gouiran, 1979

# CERN PS B-train: current configuration

- B-train = **weighted average** of the local field in F/D halves
- **In-built assumptions**: $B_D(t_0)=B_F(t_0)=4.98$ mT, $k=0.091^{\dagger}$
- Only one field marker in use (the second one is foreseen only for diagnostics)
- When these assumptions are not satisfied → **B-train error** → **beam may become unstable**
- Integrator is reset at the end of every magnet cycle (synch to control system timing)
- Integrator internal auto-calibration every 15 cycles *(not* synch to timing ….*)*

$$B_{avg}=\frac{1}{2}\left(\left(1-k\right)B_D+\left(1+k\right)B_F\right)=4.98\,m\mathrm{T}\;+\;\frac{1}{2\mathrm{A}_0}\int_{t_0}^{t}\underbrace{\left(\mathrm{V}_\mathrm{D}+\mathrm{V}_\mathrm{F}\right)}dt$$



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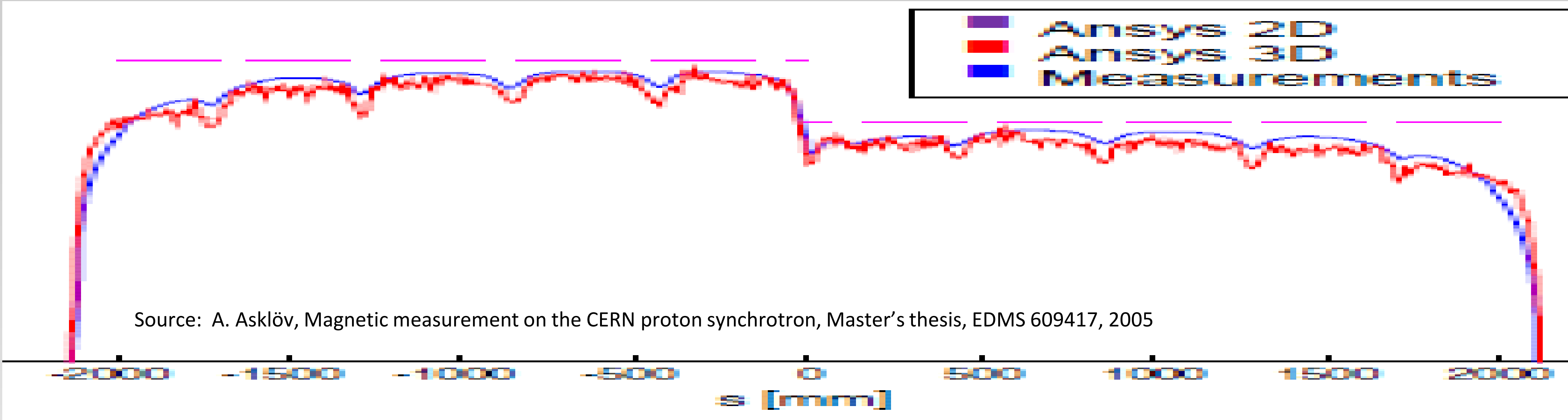
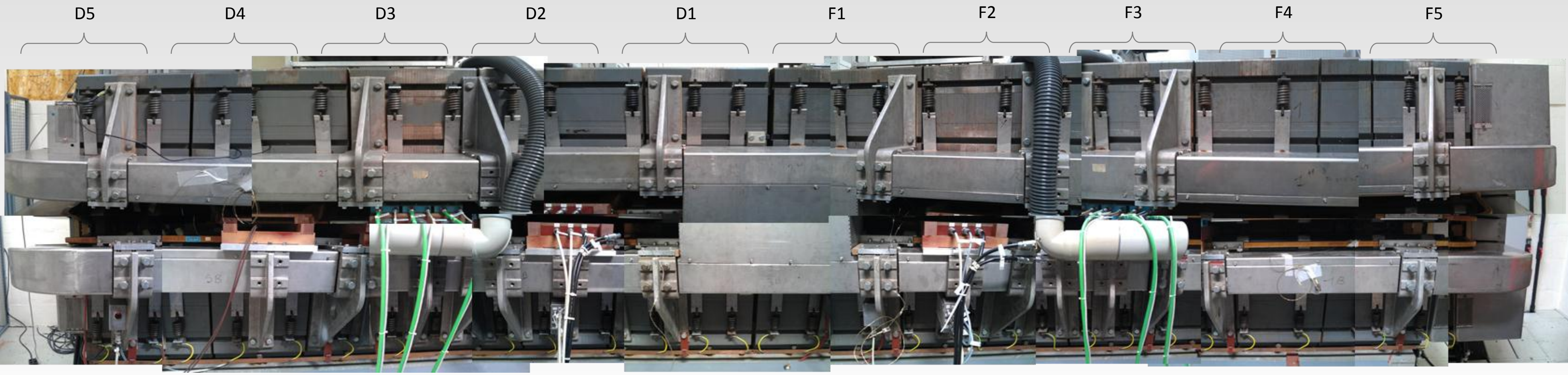
[†] *k* takes into account an oscillating dipole component generated by the PFW in 3-current mode. See: R. Gouiran, Enroulements polaires de l'aimant du CPS, Note Interne PS/SM 76-1

# Reference magnet U101



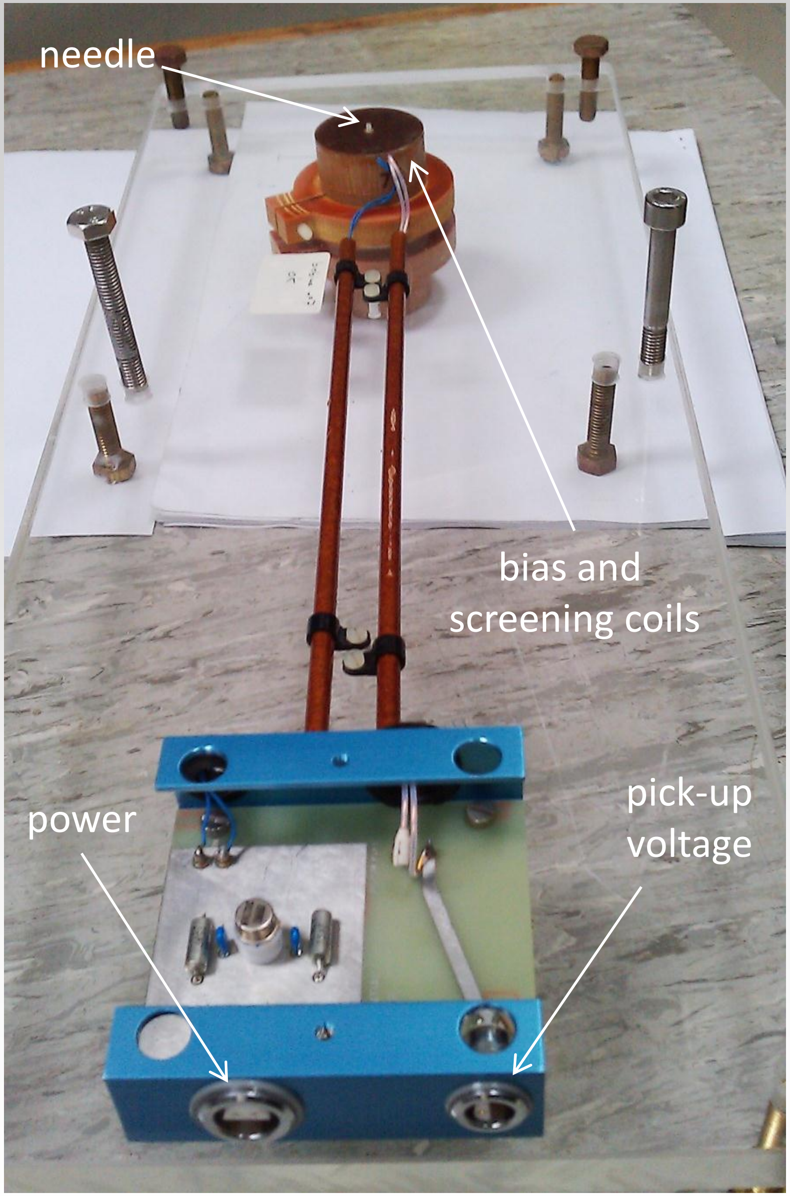
Source: A. Asklöv, Magnetic measurement on the CERN proton synchrotron, Master's thesis, EDMS 609417, 2005

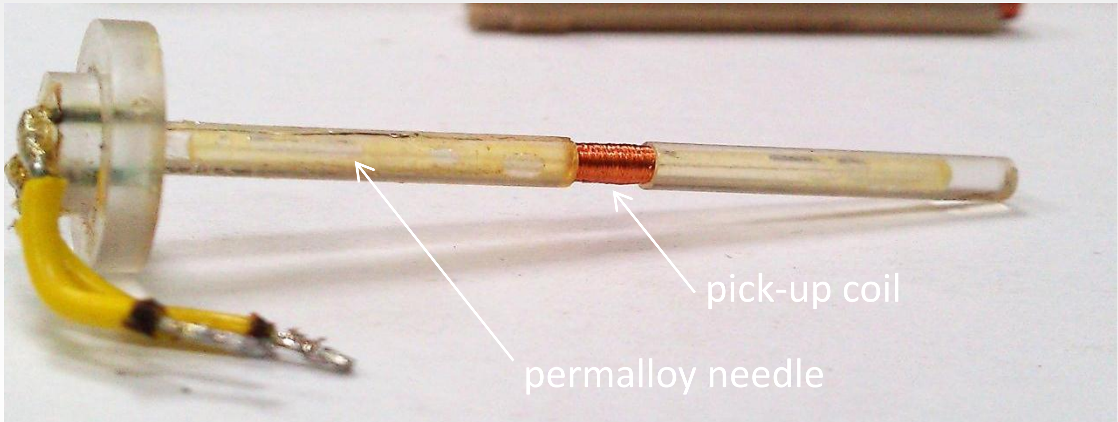


- Longitudinal field distribution varies with $I_{F8L}$, $I_{PFW}$, saturation
- Calibration vs. beam depends on sensor position
- Sensors may not work properly in end blocks (inhomogeneous/3D field)

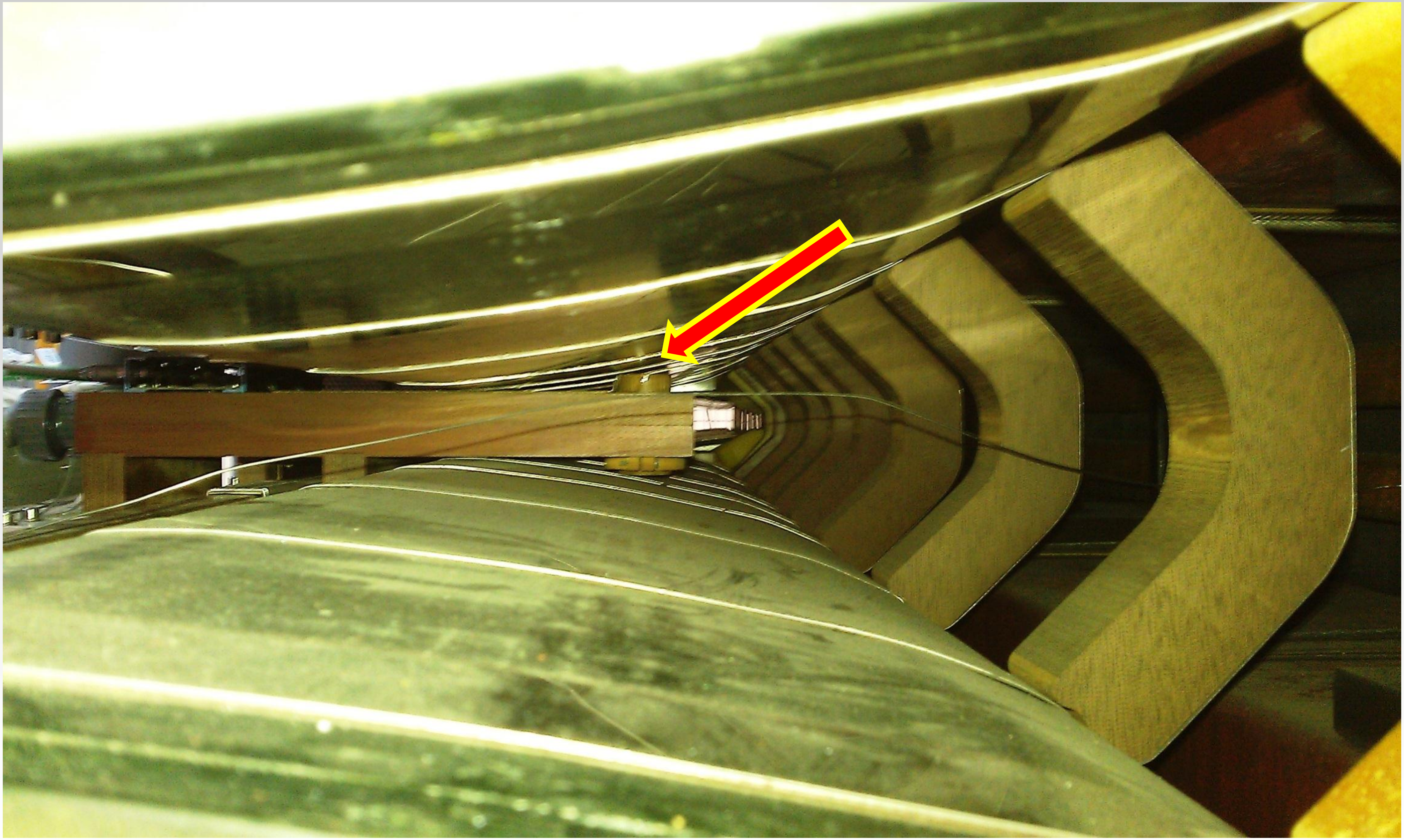
# Existing field marker: peaking strips

- Developed at CERN in 1956 specifically for combined-function PS magnets.
- Based on a pre-stressed bi-stable magnetic needle: magnetization flips over at a preset level and generates a pulse detected by a pick-up coil
- Two coils powered in series for bias and screening field, pulsed to avoid overheating
- Main constraints: bias coil heating at high field (> 5 mT); does not work at too high or too low dB/dt
- Experience shows that this sensor is very stable (drift <50 μT in 20 years),
- Very few spares available, all different from each other (making new ones is difficult)

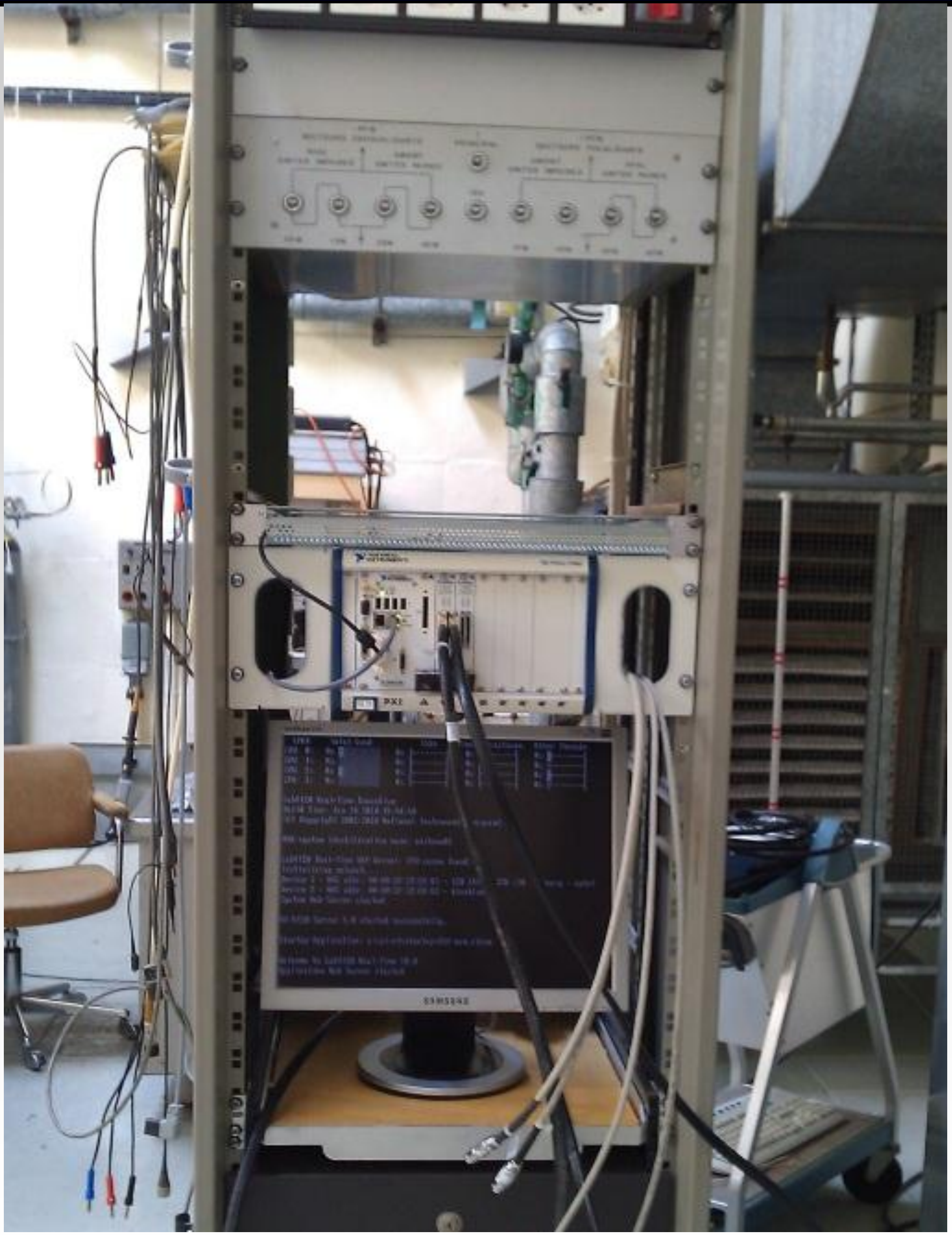




# Peaking strips in side U101



# Diagnostic off-line “spy” system (2010)

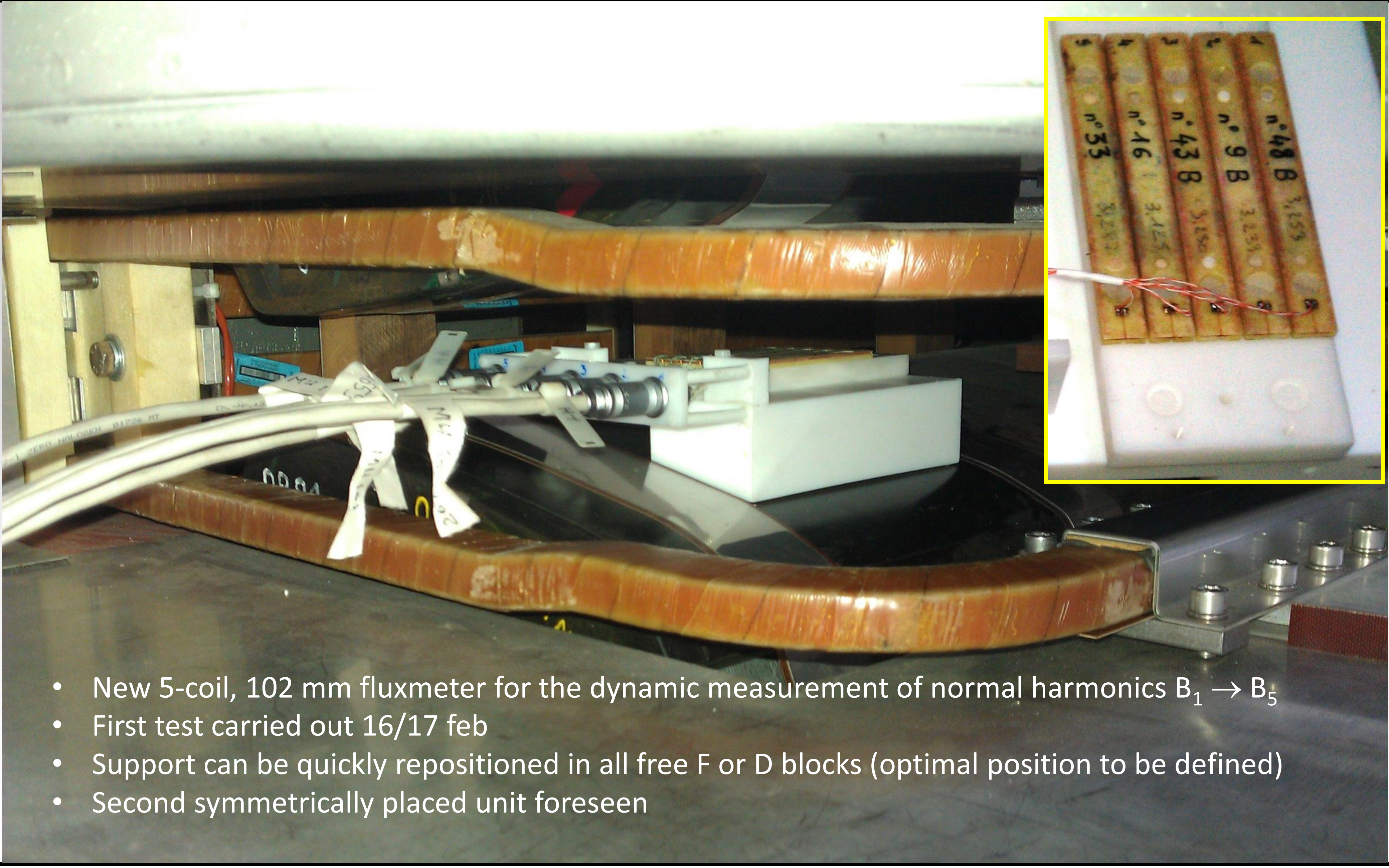


- Based on National Instruments hardware: PXIe chassis, RT controller, 2× 6366 DAQ cards (8×2 MHz parallel 16-bit channels + 32×10MHz digital I/O channels)
- Acquisition of all sensors and B-train signals
- Introduced in 2010 to track the magnetic state in F/D halves
- Used to check the consistency of sensor and B-train signals, timing and currents
- Testbed for the design of new sensors and acquisition algorithms

NB: high sample rate in the 200 kHz range is necessary for:

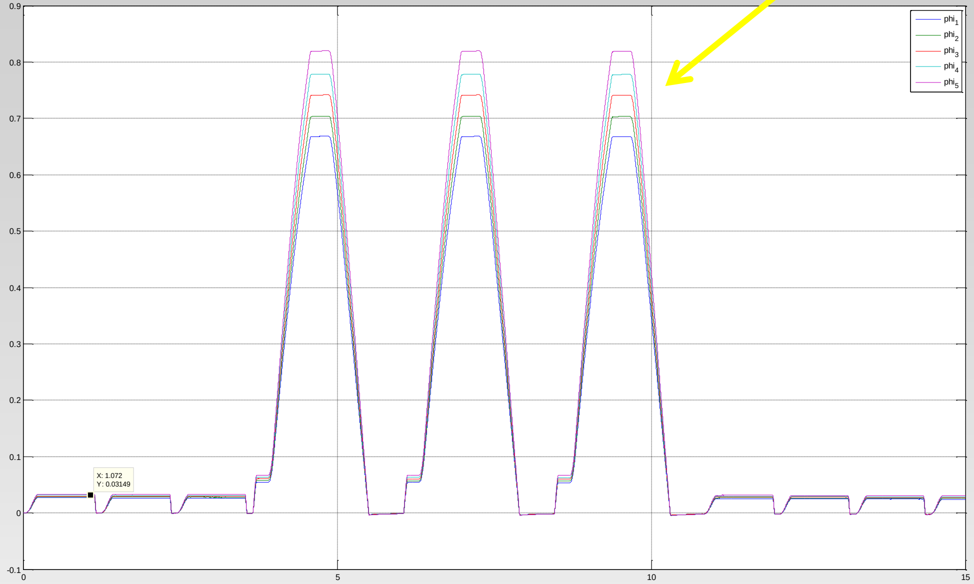
- accurate integration of flux coil output
- correlation of current/field to few 0.01 G

# Harmonic coil array (2012)



- New 5-coil, 102 mm fluxmeter for the dynamic measurement of normal harmonics $B_1 \rightarrow B_5$
- First test carried out 16/17 feb
- Support can be quickly repositioned in all free F or D blocks (optimal position to be defined)
- Second symmetrically placed unit foreseen

# Dynamic measurement of harmonics



5× measured integrated fluxes

wanted harmonics
(normal only)

$$\{\Phi_j(t)\} = [k_{jn}]\{B_n(t)\}$$

$$k_{jn} = \frac{A_j}{n w_j r_{ref}^{n-1}}\left[\left(r_j + \frac{w_j}{2}\right)^n - \left(r_j - \frac{w_j}{2}\right)^n\right]$$

weight matrix
(NB: problem intrinsically ill-conditioned
due to its polynomial-fitting nature)

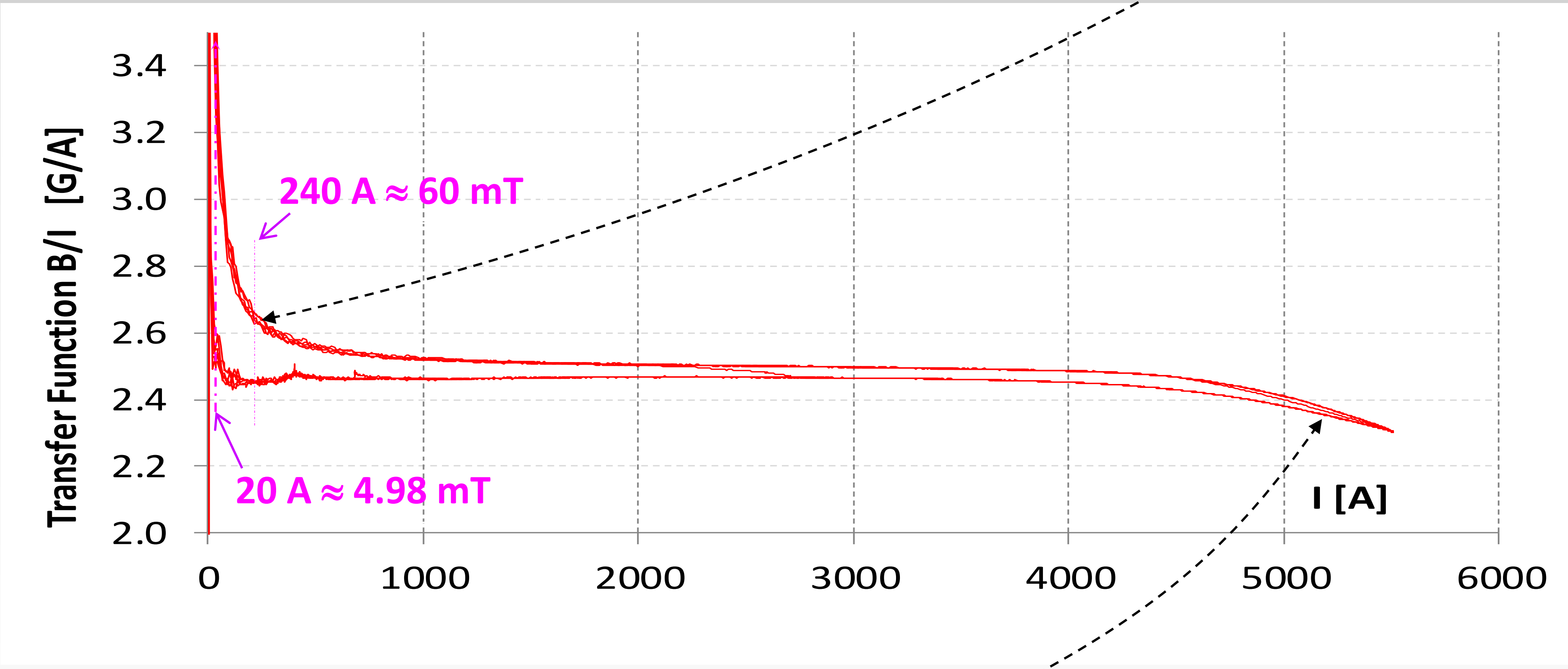
Open issues:

- integrator drift is very sensitive to calibration errors → only B1 and B2 OK for the moment (more accurate calibration in preparation)
- truncation error due to neglected n≥6 harmonics to be evaluated
- major improvements planned:
  - analog bucking of main components
  - circular array of tangential coils (well conditioned calibration + skew harmonics + possibility of rotation to measure accurately remanent harmonic components )

# Test results highlights

# Dipole transfer function

large fluctuations due to history-dependent residual field



going into saturation erases the previous magnetic history

**Pre-cycling at high field + higher minimum current → better field stability**

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# PS beam stability test – April 2010

PSB p injection

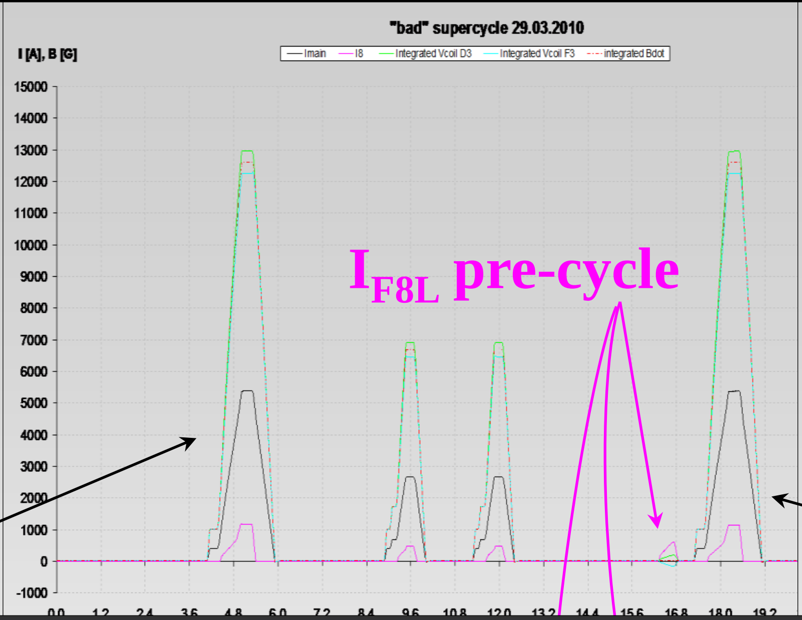
LHCPROBE 2 Mar 11 10:22:33 2010

Sensib.:2e09 Sigma =181% Bunch = 1 Turn = 1

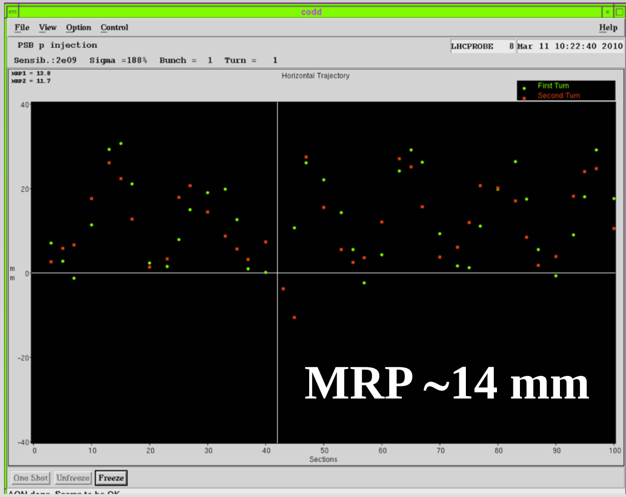
MRP1 = 4.1
MRP2 = 2.5

AQN done. Seems to be OK.

MRP ~4 mm



$I_{F8L}$ pre-cycle



PSB p injection

LHCPROBE 8 Mar 11 10:22:40 2010

Sensib.:2e09 Sigma =188% Bunch = 1 Turn = 1

MRP1 = 13.8
MRP2 = 11.7

MRP ~14 mm

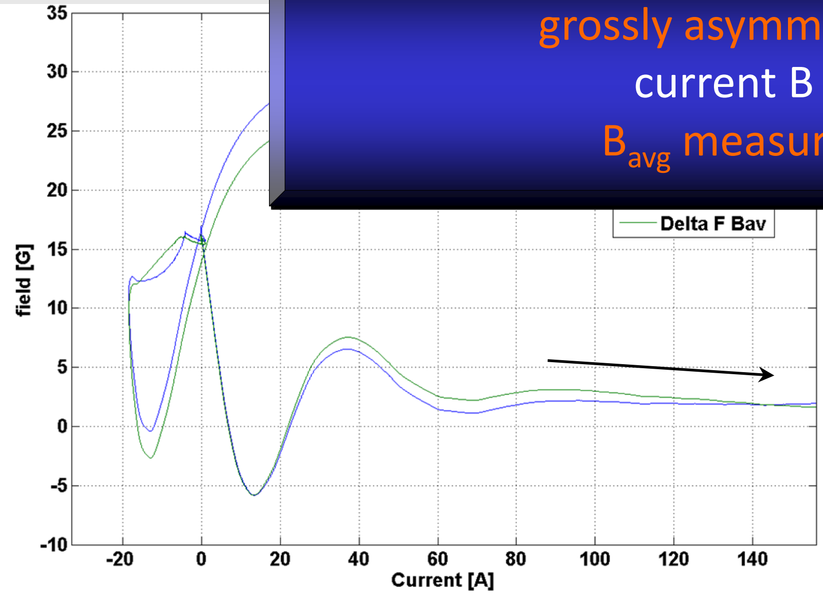
“good” cycle

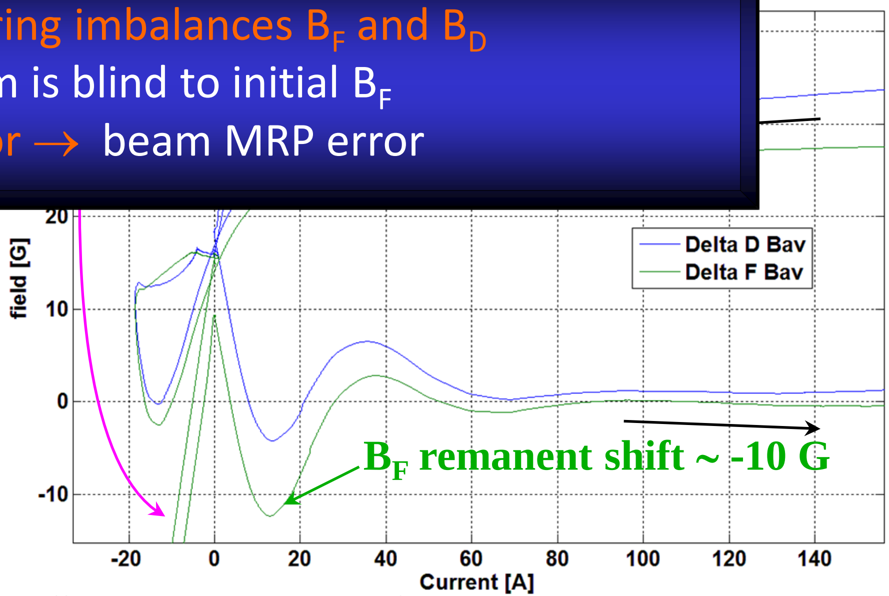
“bad” cycle

grossly asymmetric powering imbalances $B_F$ and $B_D$

current B train system is blind to initial $B_F$

$B_{avg}$ measurement error → beam MRP error

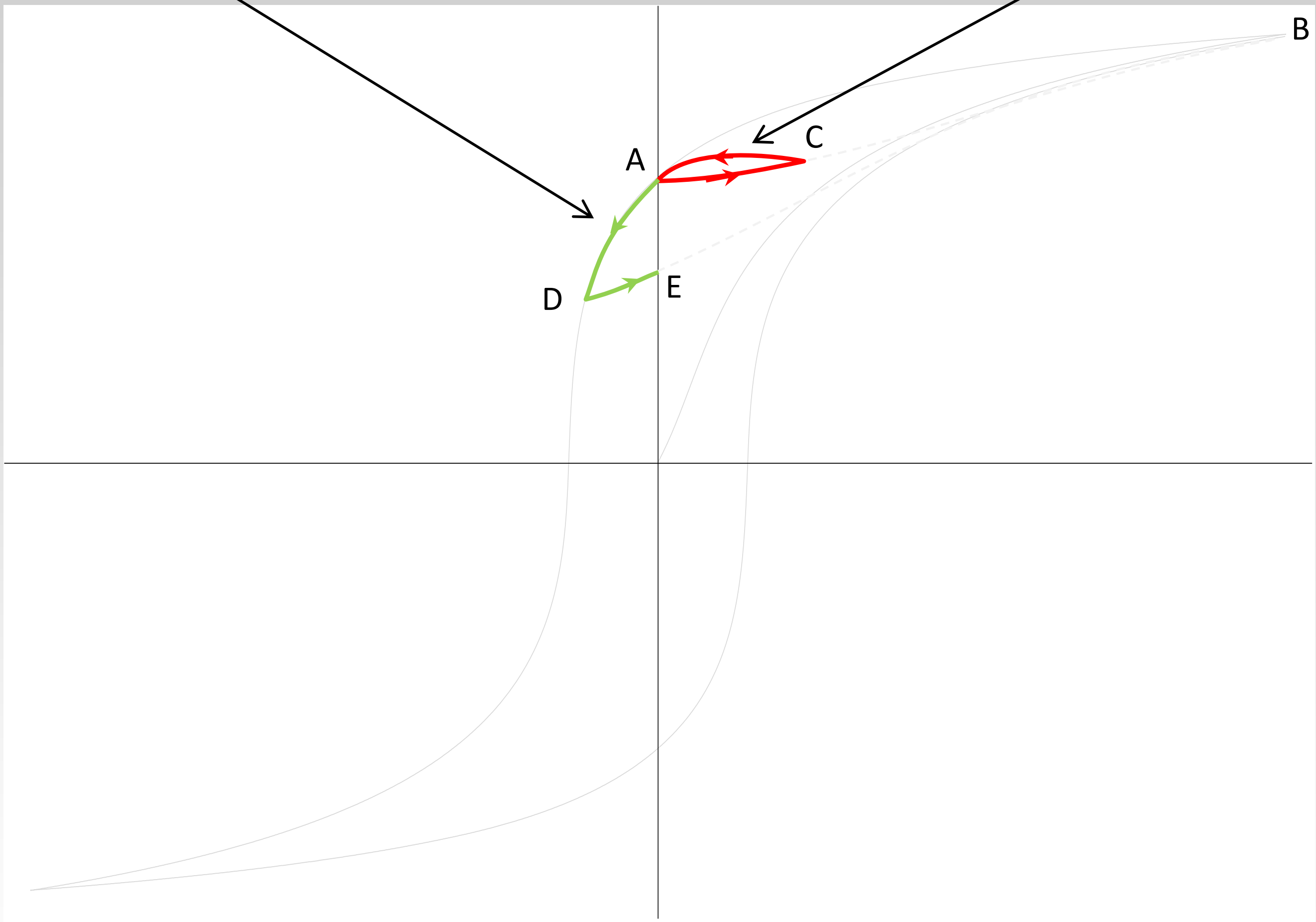




$B_F$ remanent shift ~ -10 G

Hysteresis curves $B_F(I)$ and $B_F(I)$ – Difference w.r.t. straight line fit

# Field imbalance

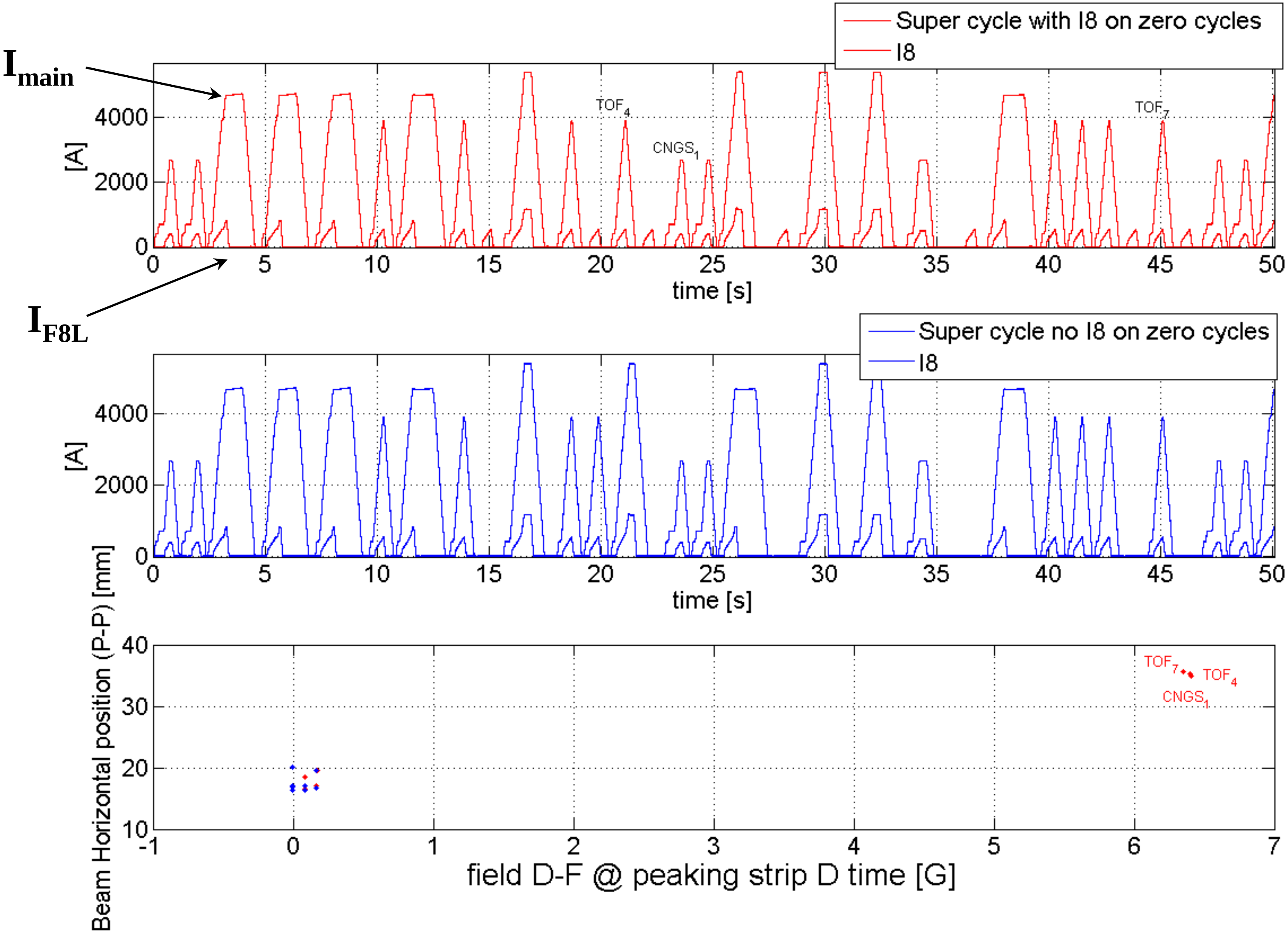


negative quadrupole increment in the defocusing half
the field changes along the downwards limit cycle

positive quadrupole increment in the focusing half
the field changes towards the upwards limit cycle

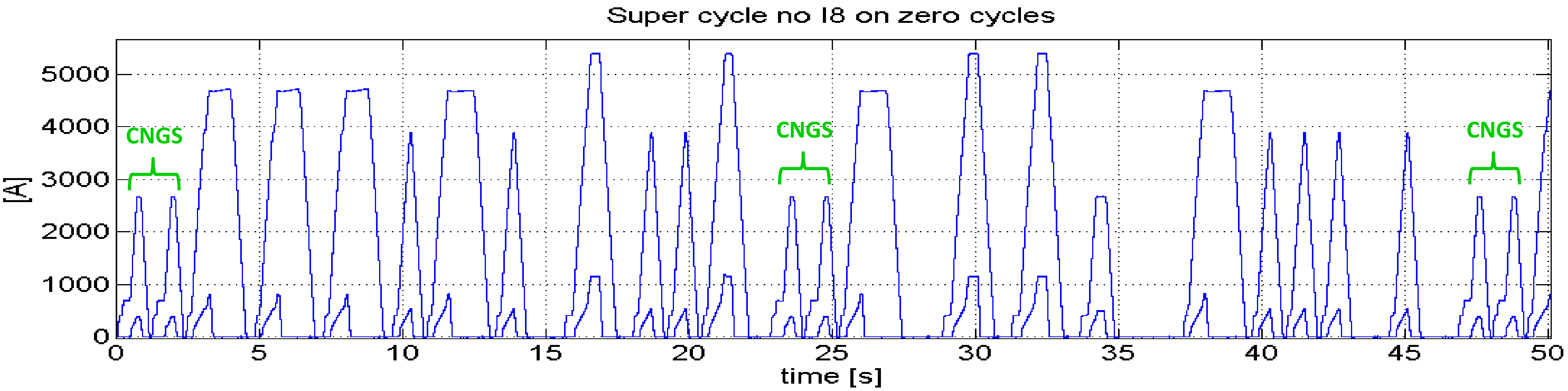
- dipole and quadrupole component are always proportional → tune trim circuit operation ($I_{F8L}$) at low field causes field imbalance in the two magnet halves
- Independent field marking in the two halves is necessary for correct $B(t)$ integration

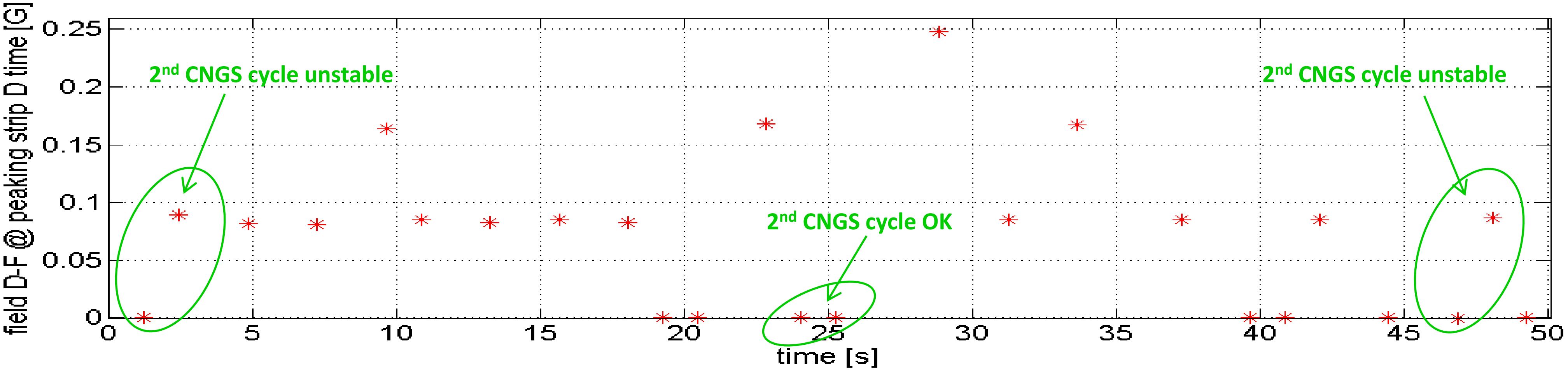
# PS beam stability test @ injection – June 2011



systematic correlation between initial field imbalance (→B-train error) and large RP error

# PS beam stability test @ injection – June 2011





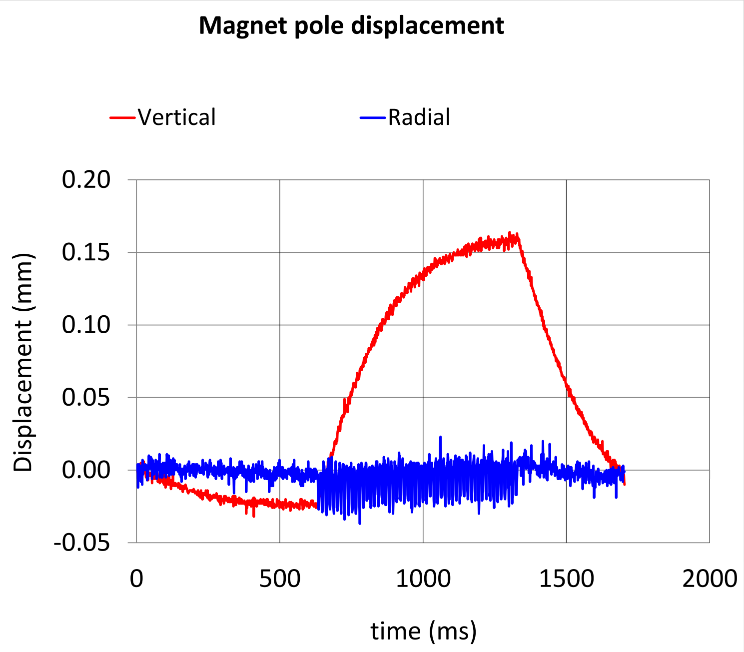
specific powering cycle sequences lead to reproducible MRP errors

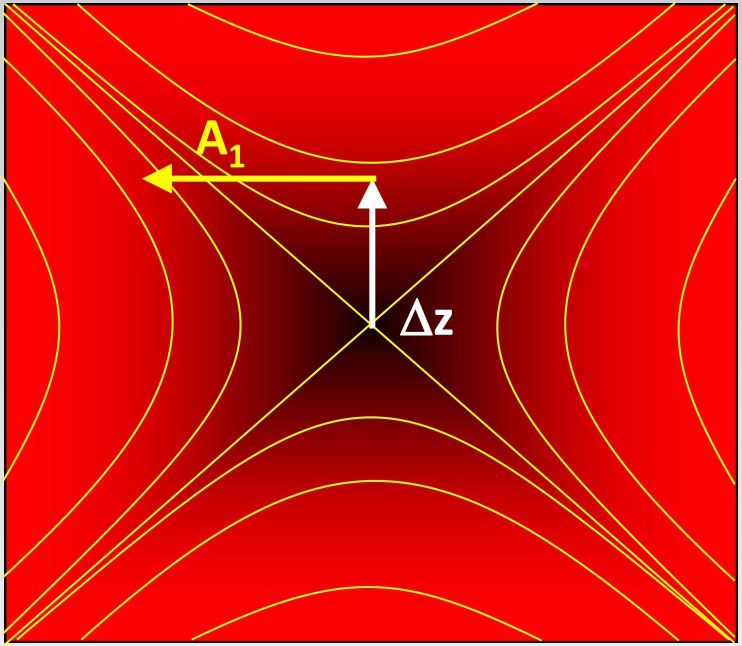
now we can observe correlation with reproducible magnetic errors

# Possible mechanical side-effects

Laser tracker measurements done on U17 to test stability of NMR marker support in 2008

# Possible mechanical side-effects





- Vertical displacement of bottom pole = 0.16 mm @ 5400 A (gap closes due due magnetic forces)
- All B-train sensors fixed to bottom pole
- Top/bottom asymmetry → possible vertical displacement of sensors w.r.t. to ideal axis
- Feed-down → skew spurious harmonics e.g. 0.1 mm → 5G
  (systematic effect as a function of main current)

# Bdot signal noise issues (2011)

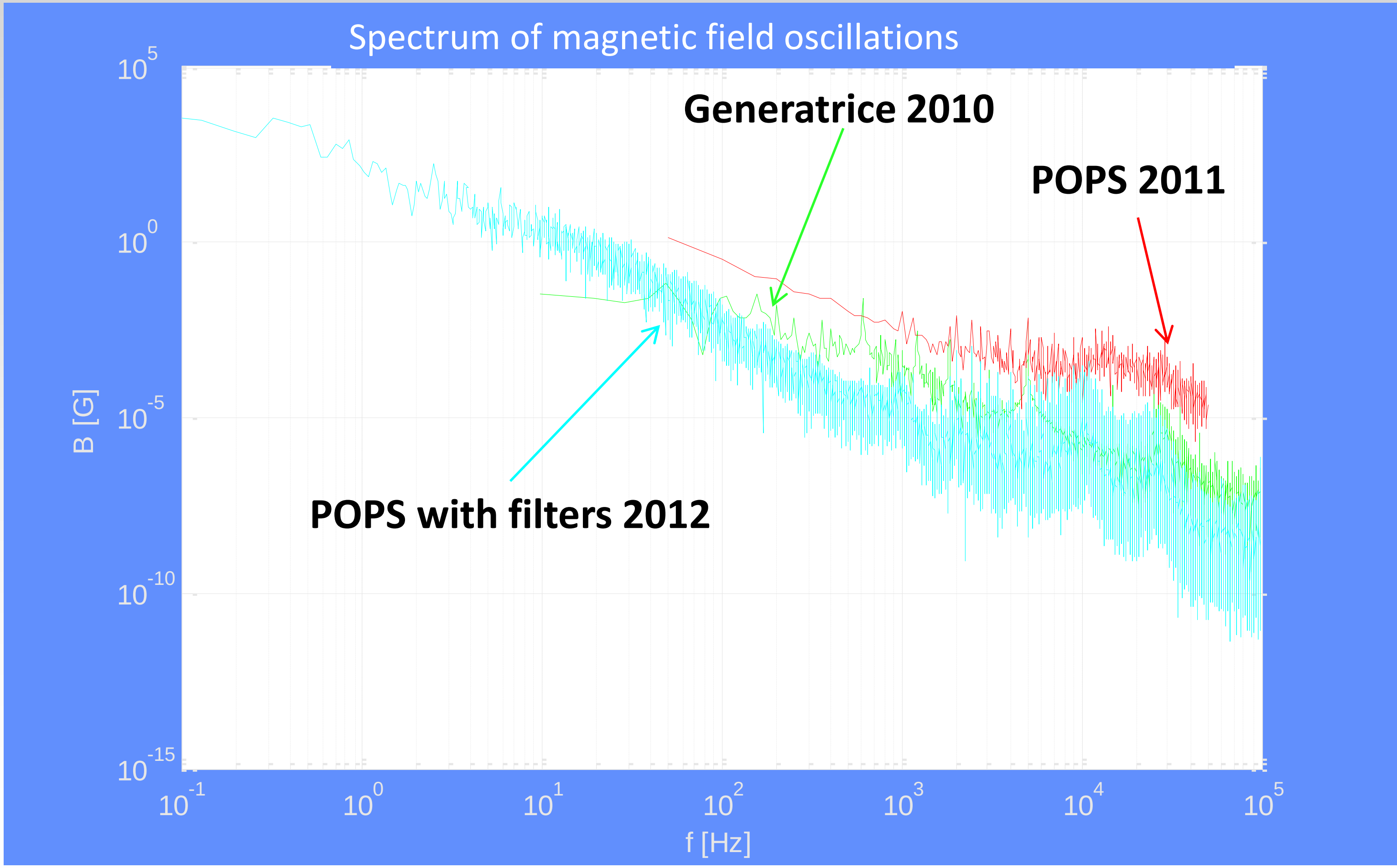
**Abnormally high noise on Bdot** reported by Ops in Feb 2011 (concern for RF).

- B(t) noise at *f* > 1 kHz found to be up to 40 dB higher in 2011 than 2010
- Observations consistent with actual (small) B fluctuations (see EDMS 1168725)
- Noise levels dropped back well below 2010 levels in 2012

Field spectrum inferred from flux coil measurements in U101:

(spurious resonances > $10^4$ Hz possible)

$$\frac{B}{V_{coil}} = \frac{1}{i2\pi f A_{coil}}$$

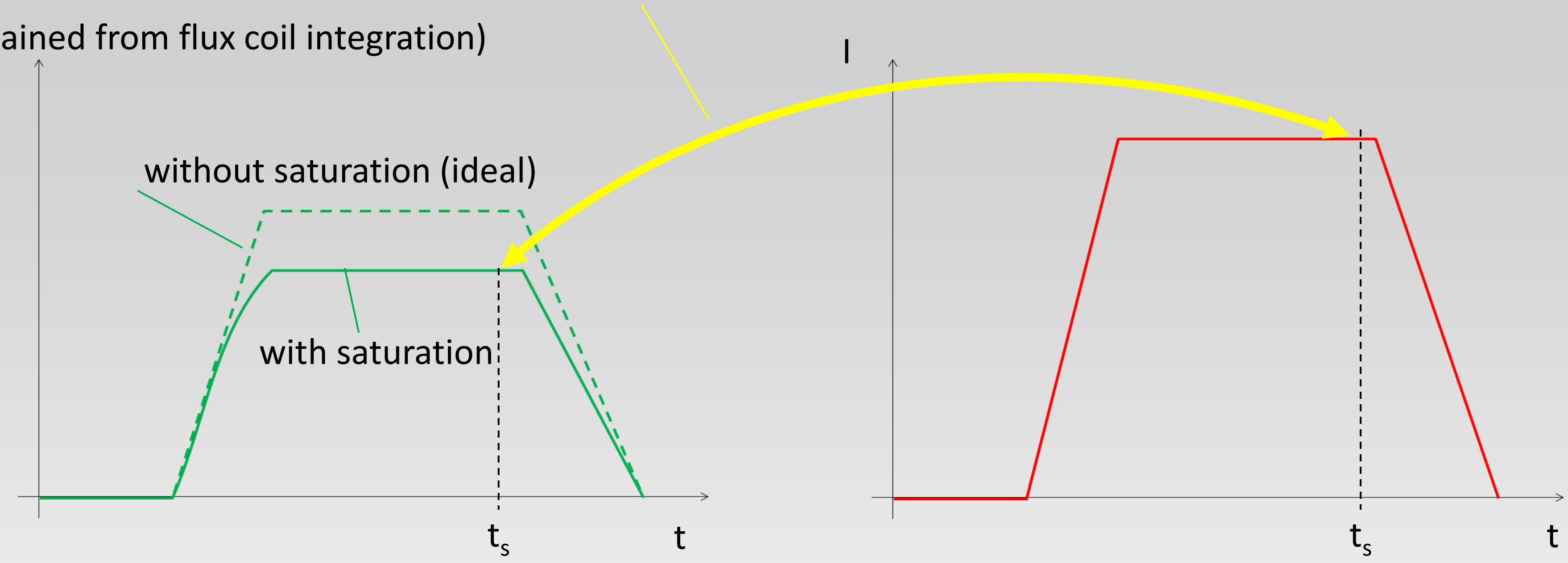


# Dynamic effects (eddy currents)

# Eddy current measurement method

Scale so that the curves coincide at the end of the flat-top

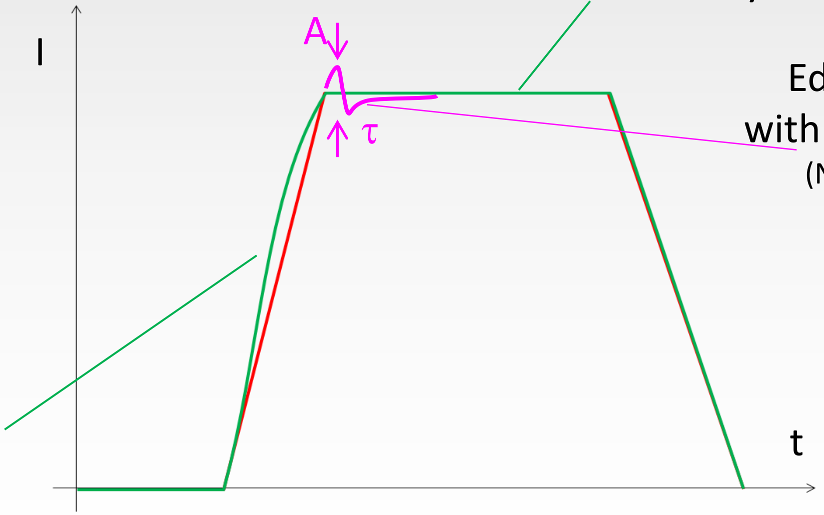
B (obtained from flux coil integration)



without saturation (ideal)

with saturation

No eddy currents → $I^* \equiv I$



Eddy currents show up as a transient with exponential decay at end of ramp-up

(NB: direction depends on current overshoot!)

equivalent current:

$$I^*(t) = \frac{I(t_s)}{B(t_s)} B(t)$$

relative field error

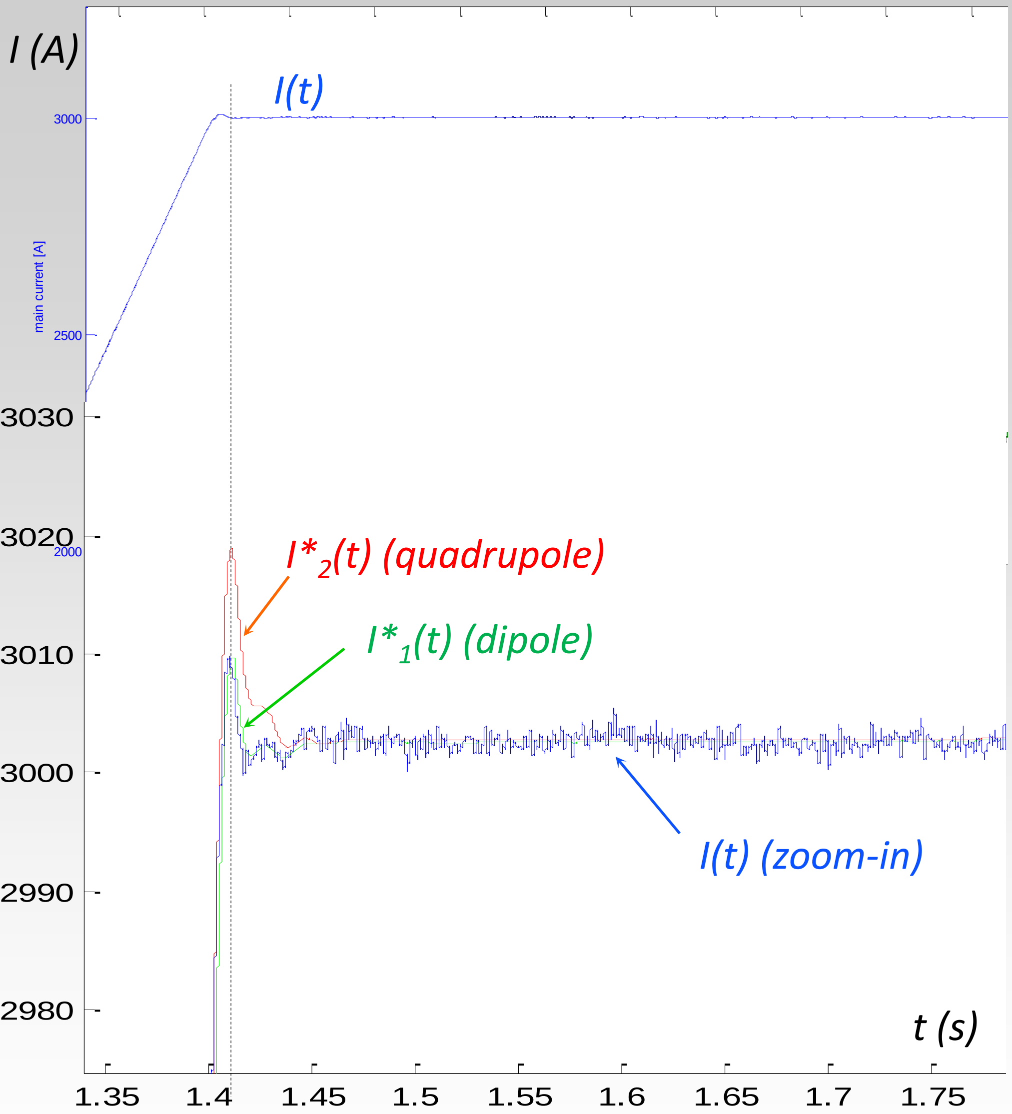
$$\varepsilon(t) = \frac{I^*(t)}{I(t)} - 1$$

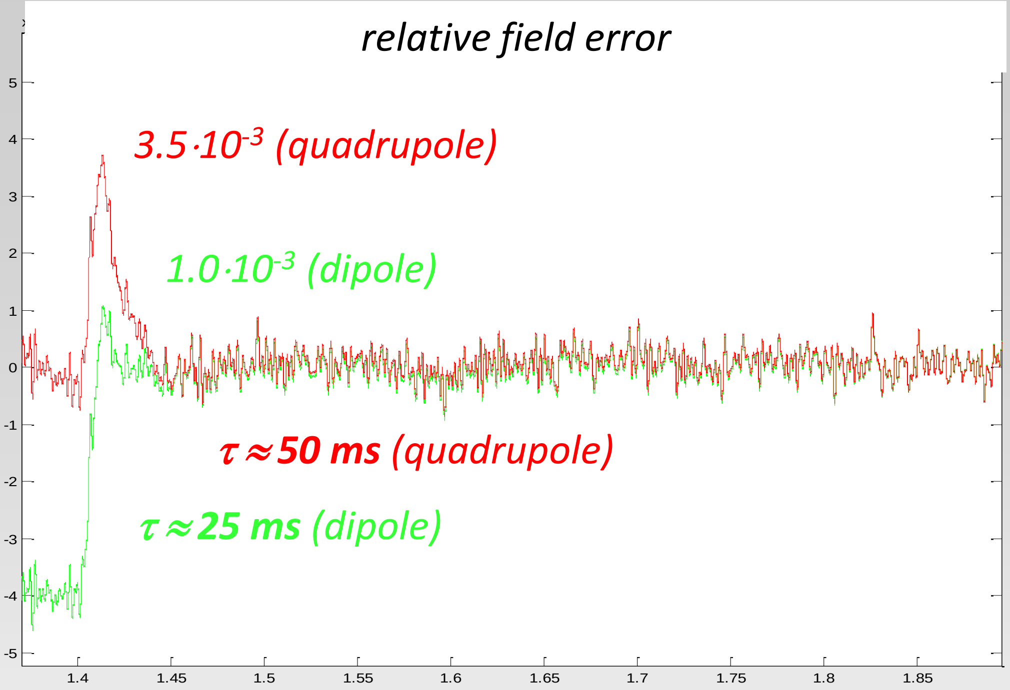
apparent field advance due to the scaling procedure

Ideal model:

- Transient amplitude $A \propto dB/dt$
- Decay time $\tau$ = constant

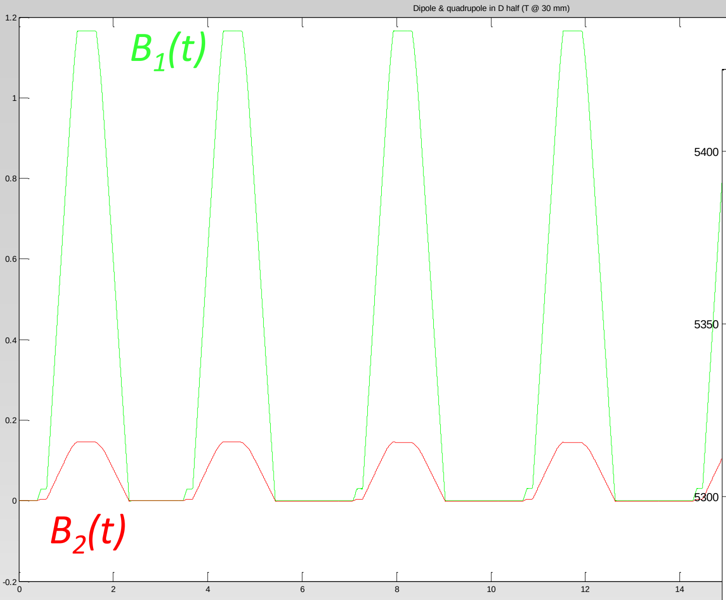
# Current-controlled plateau @ 3000 A, 9000 A/s

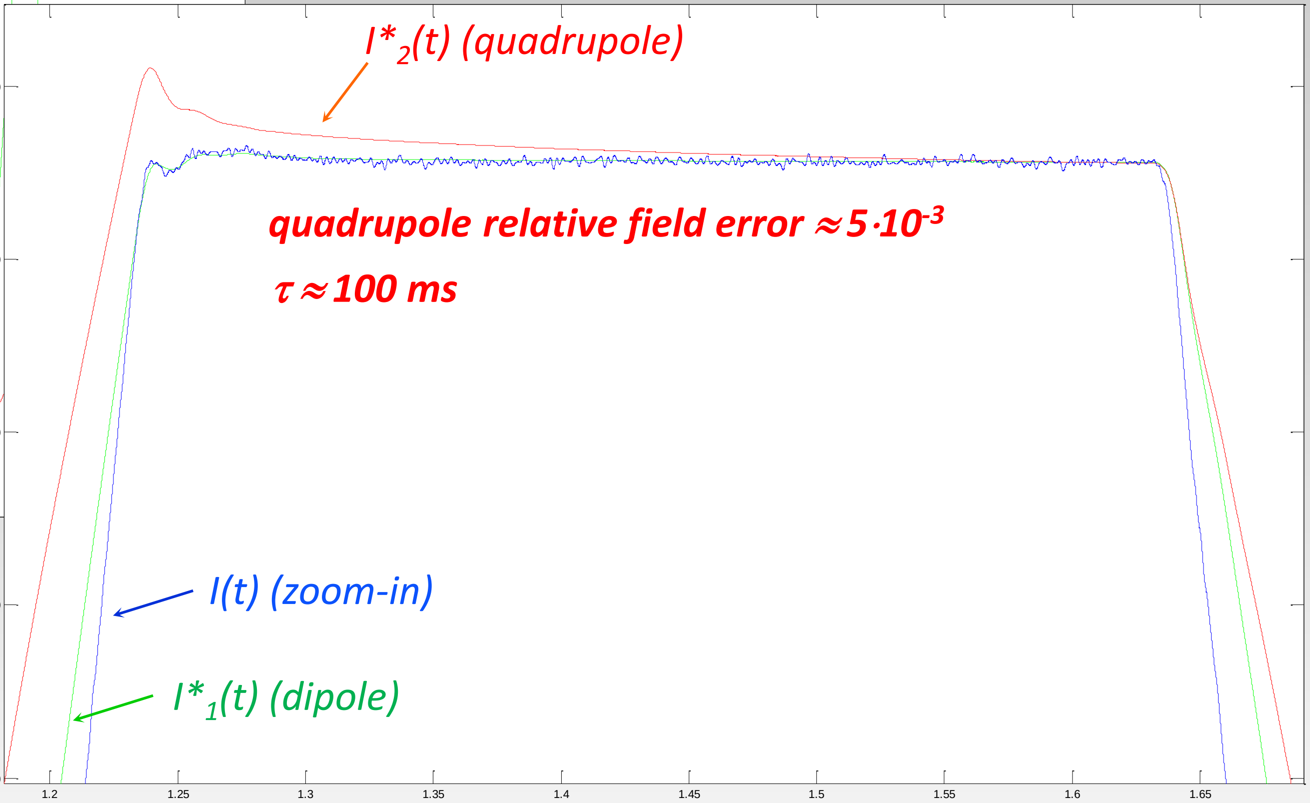




- At low field (linear range) eddy current effects are relatively small and fast
- Quadrupole effects significatively larger than on dipole

# Current-controlled plateau @ 5380 A, 8150 A/s





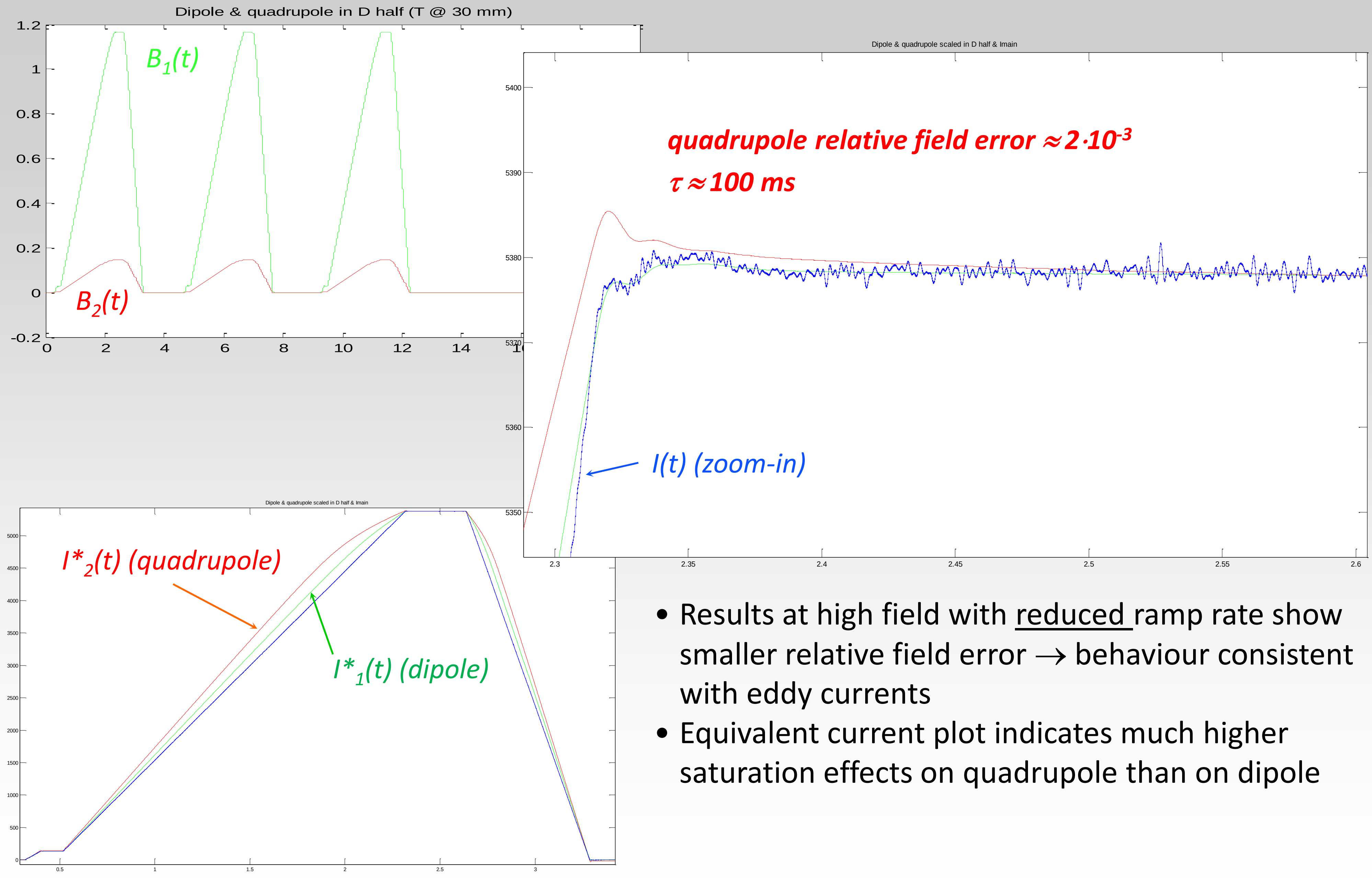
**quadrupole relative field error $\approx 5 \cdot 10^{-3}$**

**$\tau \approx$ 100 ms**

$$\nabla^2 B = \frac{\mu}{\rho}\frac{\partial B}{\partial t} \quad \rightarrow \quad \tau \propto \frac{\mu}{\rho}\ell^2$$

- Respect to intermediate field, the time constant and effect amplitude on the quadrupole are **~2 x**
- No appreciable change on the dipole
- Dimensional considerations based on magnetic field diffusion equations → time constant at high field expected to drop by 20% due to saturation (low $\mu$) only → dominant effect appears to be increase of magnetic circuit length due to flux leakage

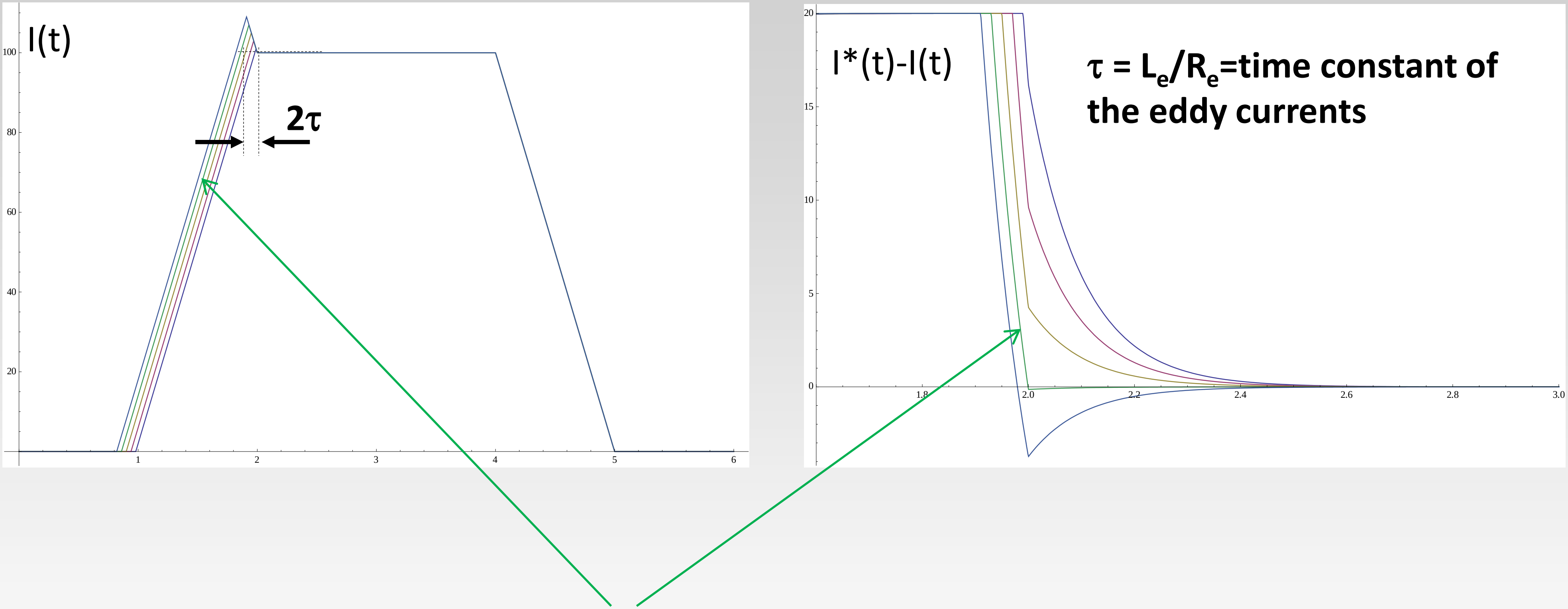
# Current-controlled plateau @ 5380 A, 3300 A/s



- Results at high field with reduced ramp rate show smaller relative field error → behaviour consistent with eddy currents
- Equivalent current plot indicates much higher saturation effects on quadrupole than on dipole

# Mitigation of eddy current effects

Compensation of eddy currents by controlled current overshoot:



**$\tau = L_e/R_e$=time constant of the eddy currents**

Ideally, a linear overshoot of length 2τ can cancel out completely eddy currents on the flat-top

*Can this be done with $I_{main}$ or $I_{F8L}$ ?*

# The new B-train system functional specifications

# Why a new B-train

Idea conceived in 2007 and green-lighted by IEFC in 2011.

Main goals evolved over time:

1. **Ensure long-term reliability**

   *concerns about spares: peaking strips (PS), old electronics (SPS)*

2. **Improve performance and flexibility as requested by users**

   *higher resolution 0.05 G, higher dB/dt for future machines*
   *remove operation constraints and downtime: <50 G flat-bottom due to peaking strips, constraints on cycle sequencing, recurrent timing and synch errors …*

3. **Correct/extend measurements to counter beam instability**

   *(e.g. instrument fully F half to cure injection instabilities observed in since 2010)*

Applies to PS in priority; progressively to be extended to SPS, AD and ELENA, PSB (upgraded) and LEIR

# B-train upgrade project: aim

- All technical solutions discussed in detail with users: operation/power converters/RF/beam diagnostics + control

- Progressive upgrade in parallel with existing system
  *(for cross-check and as a fallback solution )*

| **Phase** | **Objectives** | **Time frame** |
|---|---|---|
| **I – Component test** | • Test flux integration and correction algorithms<br>• Test individual electronic cards and components<br>• Compute offline *B(t)* and validate vs. beam behaviour | 2012 |
| **II – System test** | Minimal viability test: broadcast simplified *B(t)* to POPS and/or RF with beam | Nov-Dec 2012 |
| **Deployment** | Replace current system | LS1 |

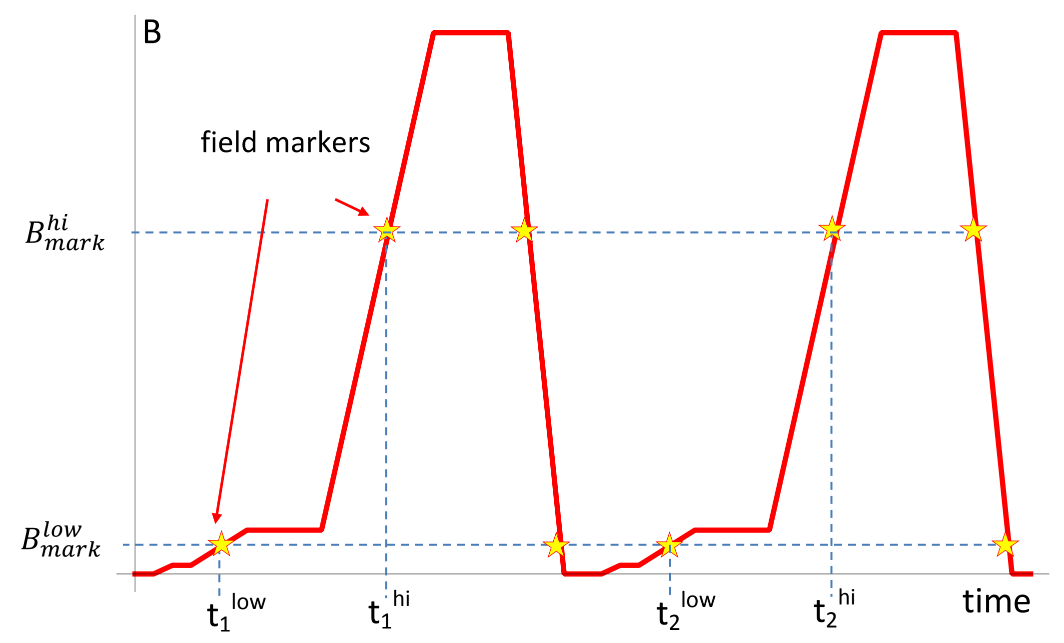
# Functional specifications – B(t) integration

**New concept: continuous digital distribution of *B(t)*** on a fast serial line to replace old pulse train

- Output stream continuously updated with current B(t) values
  → no need for complex triggering and reset logic; no $B_0$ initialization burst
- Adaptive auto-calibration of gain and offset using field markers on flat-top and flat-bottom
  → fully transparent correction of measurement error

**fast and robust transmission, no more timing conflicts**

**but: drift correction must be applied continuously on-the-fly**



ADC offset (→ integrator drift)
updated every time the same marker level is reached

$$B = B_0 + a\int_0^t (1+\varepsilon(t))(V(t)-V_0(t))dt$$

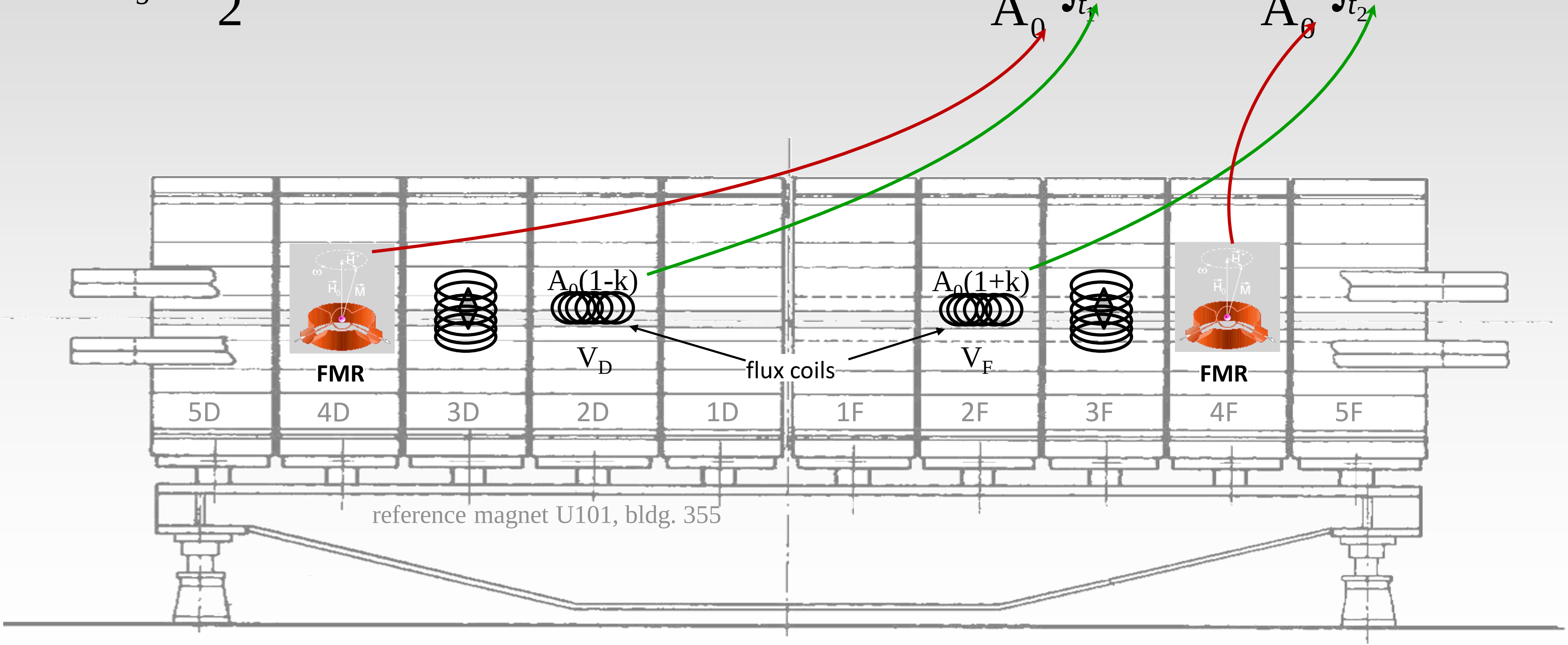
Integrator gain
updated every time a different marked level is reached

N different marker levels → up to 4 N corrections per cycle
Corrections smeared over a certain Δt to avoid sudden jumps

# Functional specifications: integration F and D halves

- Independent high-field markers and field integration in F/D halves
- No complicated marker interpolation required: $B_{avg}$ is constantly updated as t→∞
  marker triggers transparent internal correction in F/D haves independently
- **Higher ~600 G flat-bottom level** to improve magnetic reproducibility and allow the utilization of new FMR markers (NB: a stopgap solution using existing peaking strips was discussed and found to be technically as complex as switching over to FMR, minus all the advantages)

$$B_{avg} = \frac{1}{2}\left(\left(1-k\right)B_D + \left(1+k\right)B_F\right) = 60\,m\mathrm{T} \; + \; \frac{1}{\mathrm{A}_0}\int_{t_1}^{t} \mathrm{V}_\mathrm{D}\,dt + \frac{1}{\mathrm{A}_0}\int_{t_2}^{t} \mathrm{V}_\mathrm{F}\,dt$$



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# Component tests (2012)

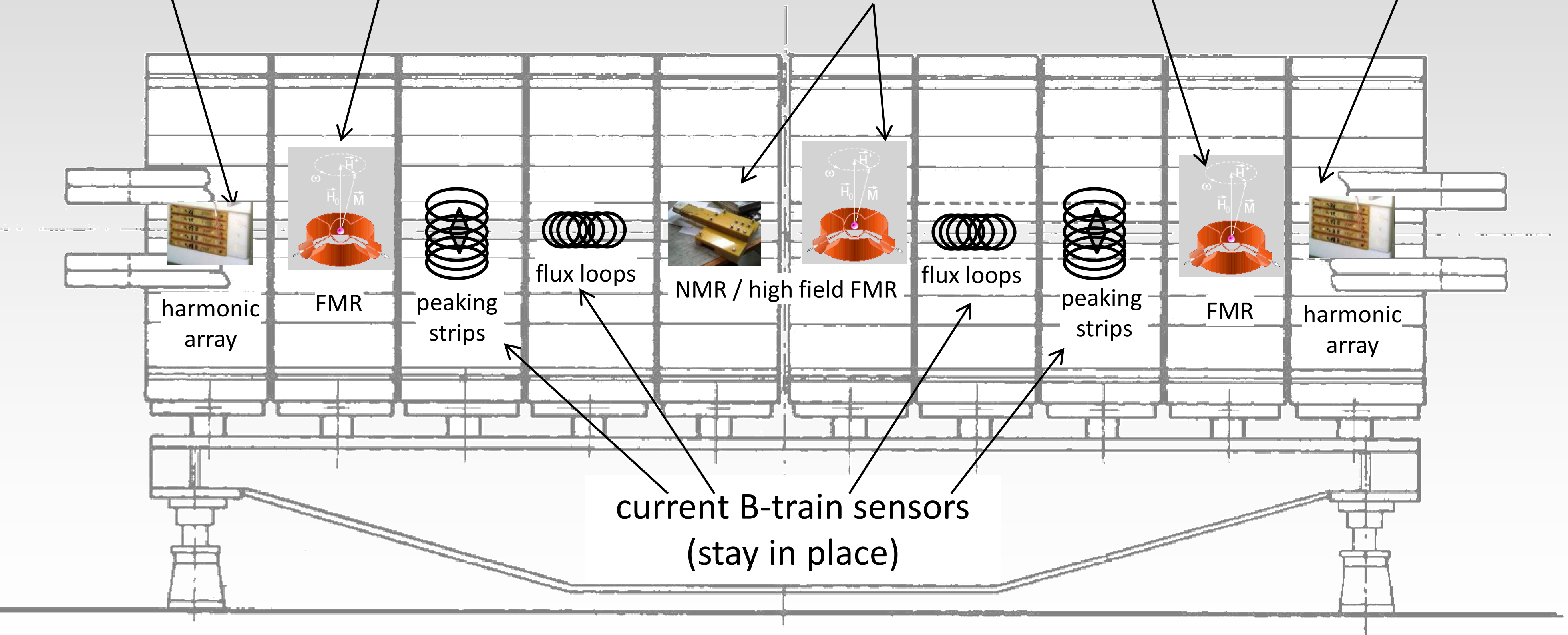
Prototype harmonic coil array *(in operation)*
- $B_n(I_k)$ relationships
- dynamic effects on multipoles
- provide multipoles to operation

Second harmonic coil array
(symmetric)

Prototype single-crystal FMR *(due in March)*
- stability vs. peaking strips/beam
- precision of trigger generation
- test 600 G flat-bottom mode

Final FMR (single or poly-crystal)
- symmetric placement
- generate full integral

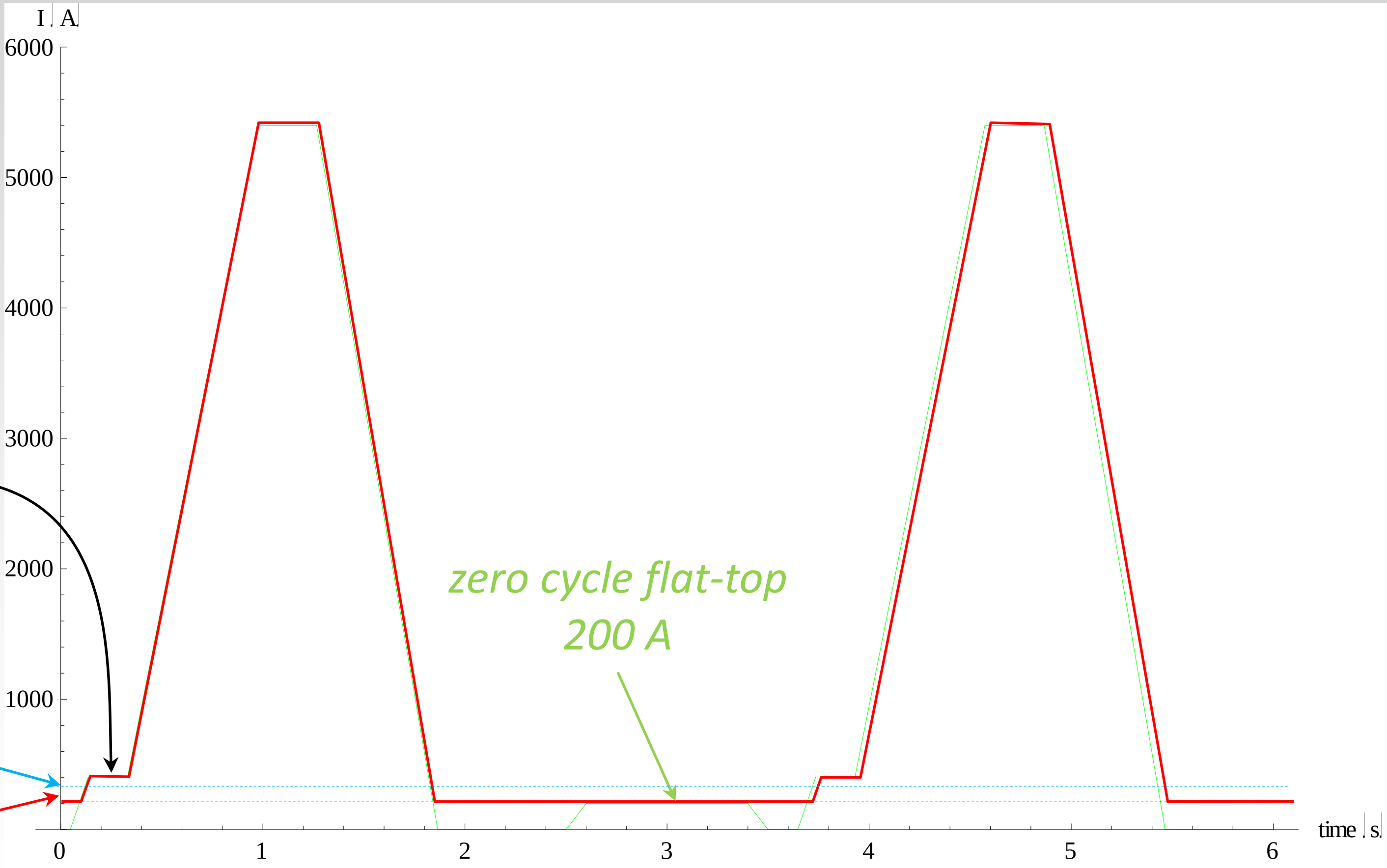
High field marker for
on-the-fly gain correction



current B-train sensors
(stay in place)

# Magnetic stability test: 500 G flat-bottom cycling mode

- descent below 50 G <u>no longer needed</u> when FMR replaces peaking strip
- **10× flat bottom=500 G** → better magnetic stability (should be tested shortly !)



*injection level*
*p 1013 G (404 A)*
*ions 687 G (275 A)*

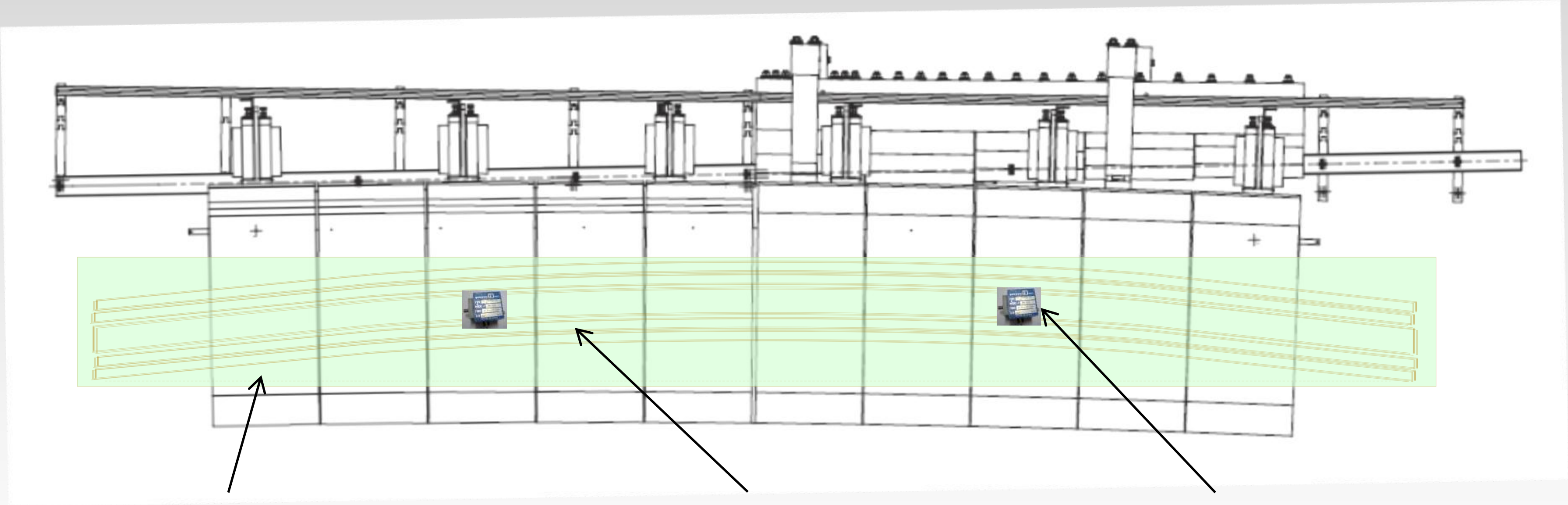
*zero cycle flat-top*
*200 A*

*low field marker*
*600 G (240 A)*

*flat bottom*
*500 G (200 A)*

# Integral fluxmeter

- near-ideal sensor: integral coil array for $\int B_n d\ell$
- removes one major uncertainty source i.e. extrapolation from local to integral measurement
  → future-proof against more surprises
- no design available to date, but unlikely to be mechanically compatible with existing sensors
  *can we dare to give it a try with beam before LS1 ?*



candidate technology:
MedAustron-style multi-PCB

Single-layer coils with <10 turns
sufficient for good signal levels

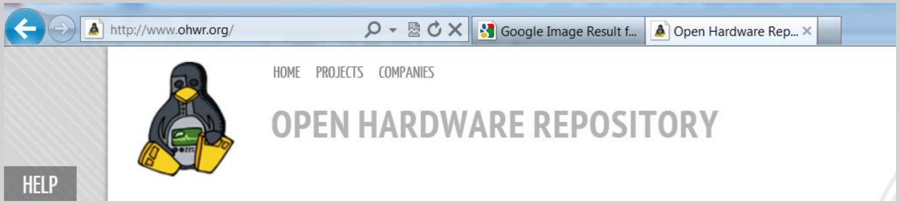
central coil is larger
to accommodate FMR markers

# The new B-train system

# hardware & software

# Hardware platform

**Standard CERN HW/SW platform**, mostly based on the Open Hardware concept strongly endorsed and fully supported by BE-CO in view of integration in the control infrastructure:



- **PICMG1.3** – (Open Modular Computing Specification) bus standard (industrial PC)
- **SPEC** (Simple PCIe FMC carrier) + **FMC** (FPGA mezzanine cards) for modular custom electronics, easily portable to other bus standards e.g. VME64x
- **Wishbone** serializer bridge FPGA core (used e.g. for DMA access)
- **White Rabbit** serial link
- **Scientific Linux** with C/C++, optional real-time kernel

# White Rabbit B(t) distribution

New CERN fieldbus standard = Ethernet + ns-accurate timing

- ☺ inexpensive, robust, extremely fast (Gbit/s) and accurate optical link
- ☺ Ethernet standard guarantees maintainability and interoperability with future control sy
- ☺ 64 byte standard data frames allow to pack in extra data for free (e.g. dB/dt)
- ☹ New electronic cards needed for compatibility with POPS (with support from BE/CO)
- ☹ The impact of switches on latency and jitter needs to be assessed

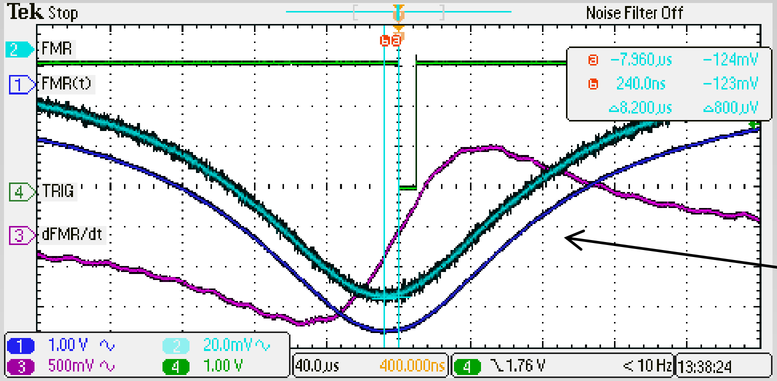
Proposed data format:

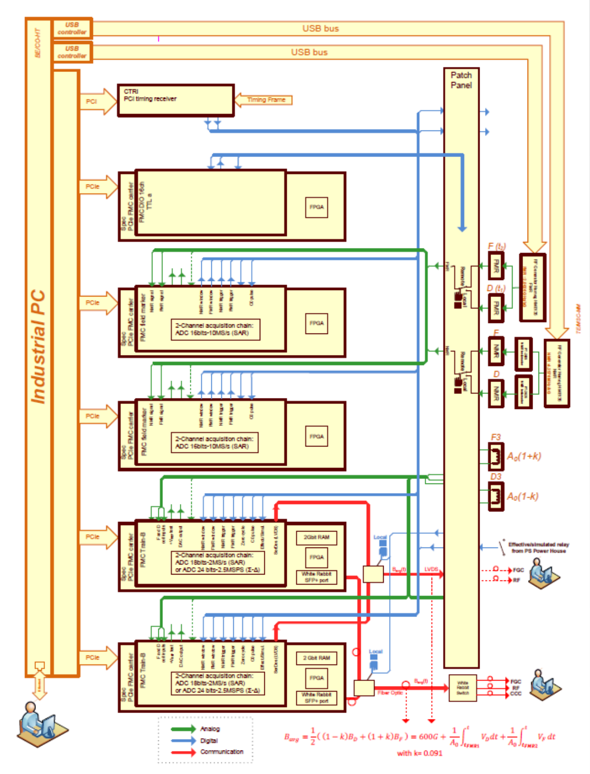
- **32-bit B(t) stream** → ppb-level resolution (e.g. 50 nT over a range of 20 T)
  PS only needs 4 ppm (0.05 G), however the extra range is useful for:
  - upcoming applications e.g. ELENA (very low field) will use same electronics and software
  - reducing quantization noise in the computed derivative
- **1 MHz frame rate** → max. 0.02 G differences between updates
  (even if the spectral content of the field is practically negligible above 10 kHz, high update rate comes at no cost and guarantees consistency for all users, which might be otherwise forced to use different interpolation methods)
- No UTC referencing (1 μs latency target, to be tested)

System based on industry standard BUT largely overspecified respect to actual needs
leaves headroom to scale down in case 1 MHz frame rate cannot be met in practical tests

NB: users wishing to maintain old system (i.e. Beam Current DCCT) will retrofit their HW with our help but under their responsibility

# New hardware: PCIe FCM cards





D.Oberson-D.Giloteaux (TE/MSC-MM) and BE/CO-HT 21/07/11

Overall system block diagram

Two cards designed and prototyped by MSC-MM (no commercial equivalent exists):

1. **FMR peak detection card**: based on 16-bit, 10 MHz ADC
   Function: produce a trigger corresponding to the FMR resonance peak via differentiation/threshold comparison. Compatible with NMR demodulated signal.
   Trigger validation (today done via error-prone synchronization with the timing system) could be accomplished downstream in software (e.g. by comparison with expected values B(I))

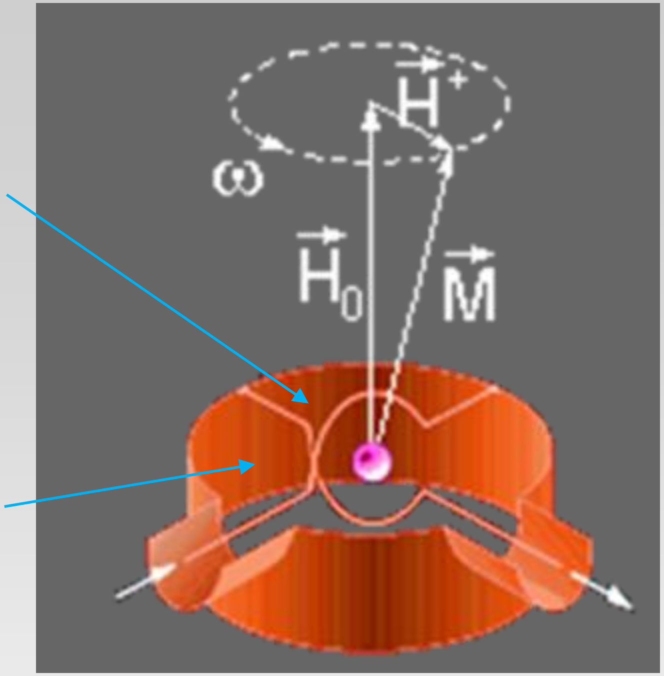
2. **Dual integrator card**: based on a 18-bit, 2 MHz ADC carries out the integration according to the model (page 3). Fully floating input for better CM rejection. Calibration coefficients are expected to be computed in software by the host controller (much less stringent timing needed, more flexibility to adapt software algorithms). General purpose ADC functions, card to be made available CERN-wide and beyond (OHCR community).

# FMR field marker

# FMR resonator

Ø0.3 mm
YIG sphere

semi-circular
RF loops



RF in

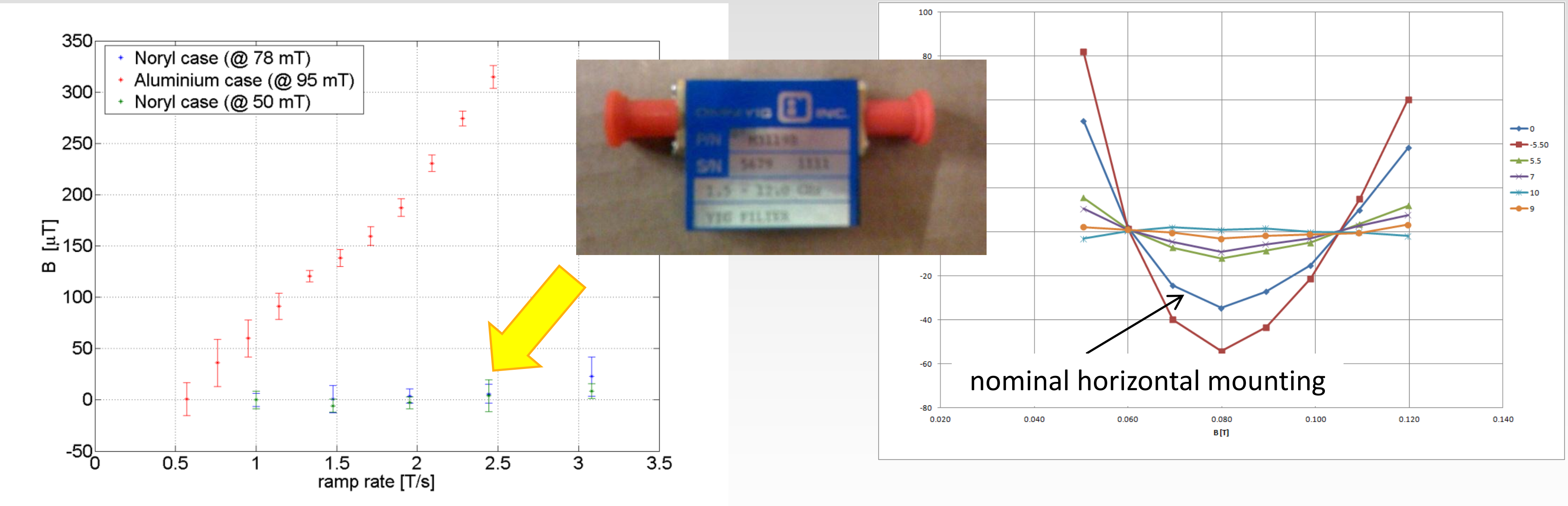
RF out

- Yittrium Iron Garnet (YIG) sphere coupling two orthogonal semi-circular RF loops
- Widespread commercial component used as bandpass RF filter
- Insensitive to field gradient due to small diameter
- Units tested at CERN:
  - old <u>poly-crystalline</u> YIG, installed in the PS since the '90s as a manually operated diagnostic tool low filter Q, but insensitive to temperature
  - new <u>single-crystal</u> YIG units. Higher Q ≈500-1000, critical alignment and T dependence tested in 2010/2011: one standard commercial + one customized unit
  - *new poly-crystalline unit: awaited May*

# Metrological characterization of FMR field marker

Calibration of a factory-optimized Noryl-case resonator in a reference dipole vs. NMR:

- DC reproducibility: **0.04 G** over the range 550 to 1200 G
- Ramp reproducibility: ~**0.1 G** @ 600 G, 2.4 T/s
- Temperature dependence: **0.04 G/°C** (±2°C in U101 → close to tolerance !)
- Roll angle dependence: **0.04 G/mrad** @ 600 G; non-linearity vs. B disappears at certain angles
  → very difficult to use in teslameter mode; strict mechanical tolerance in marker mode
- Resonance spread due to ∇B: still very good **Q≈1000** at ∇B/B=4.6 $m^{-1}$ (as in U101)

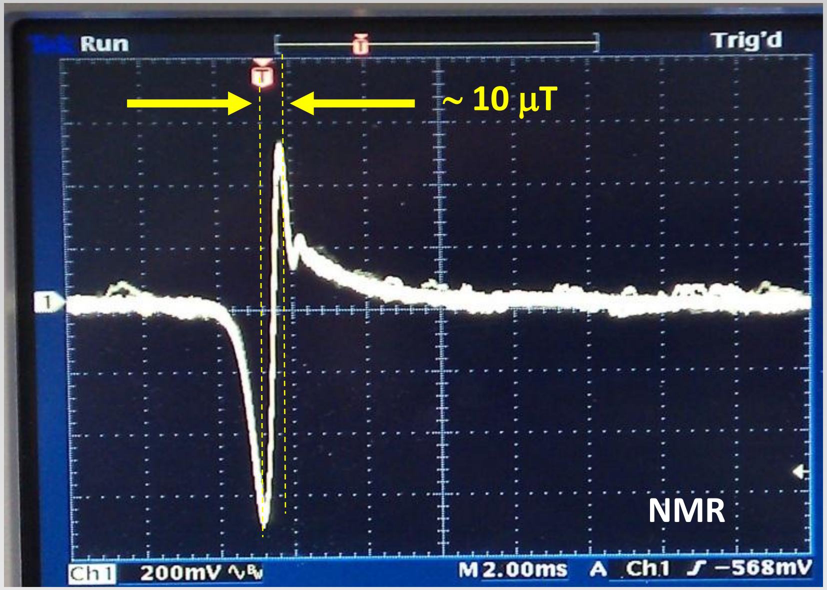


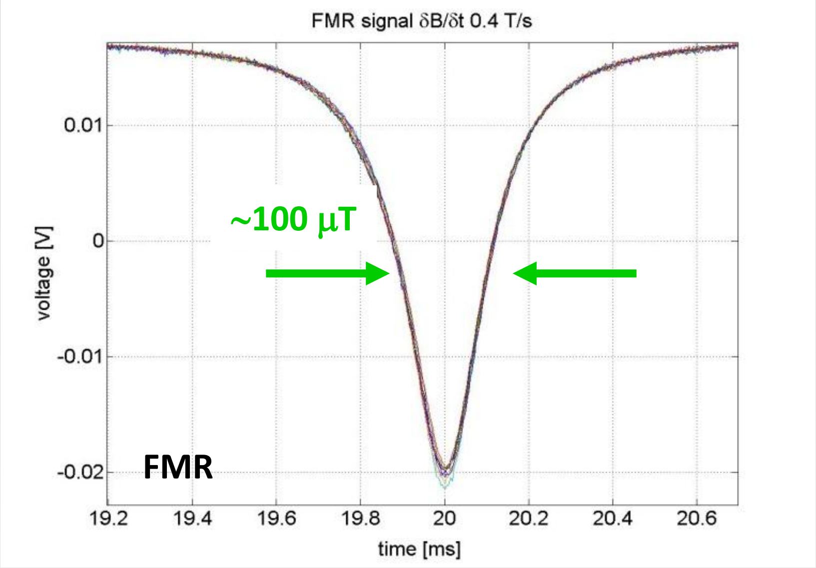
ramp-rate dependence ≤ reproducibility

non. linearity error vs. B, roll angle

# NMR vs FMR

Sensor output during a field ramp in "marker mode" (fixed frequency excitation)





| **Marker** | ☺ | ☹ |
|---|---|---|
| **NMR** | - absolute reference (metrological standard)<br>- commercially available instrument | - Requires ∇B compensation<br>- limited ramp rate: 20 to 50 mT/s<br>- B≥43 mT |
| **FMR**<br>single-crystal | - works up to several T/s<br>- simple direct acquisition of the resonance<br>- commercially available sensor<br>- larger dynamic range for a given sensor (current unit: 60-300 mT) | - B≥60 mT<br>- broader resonance peak<br>- needs complex calibration<br>- temperature-dependent (must be optimized for a target field) |

# Conclusions & outlook

# Summary

Diagnostic Spy System:

- The system can be used to explain beam observations in terms of the magnetic response of U101. Indication obtained: the tune drift on the flat top can be mitigated by controlling current overshoot
- Systematic correlations will continue to be investigated at the demand of Operation and Beam Physics teams. Other tests will proceed in parallel when possible (e.g. impact of eddy currents in the vacuum chambers).

Upgraded B-train:

- Prototypes of sensors and electronic components and are being built and shall be tested in the next months. When the existing B-train appears to be inconsistent with the beam, we shall provide a simulation of the upgraded B(t) to validate the measurement.

- Detailed schedule of tests and requests of MD for 2012 is in preparation. Online tests involving generation and distribution of *B(t)* with both proton and ion beams should be carried out to validate the design before the 2013 shutdown. An extended period in which the old and new B-train work in parallel is foreseen in 2014.