A ferrimagnetic resonance (FMR) marker for fast-ramped, non-uniform field

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1 – Introduction

Motivation and requirements for a new field marker

2 – Field Markers

Available technologies: peaking strips, NMR and FMR

3 – Calibration of FMR transducer

Performance as a high-reproducibility field marker

4 – Closure

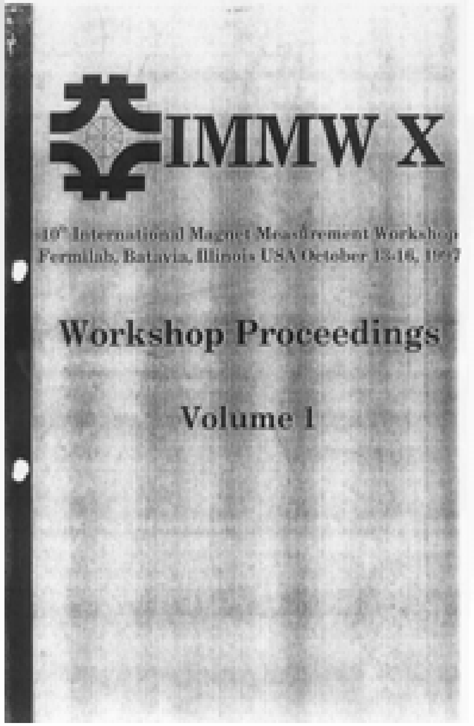
Summary and outlook

Introduction

FMR marker: a long history …

- A **Field Marker** is a device that provides a digital trigger pulse when the field reaches a given value
- The goal of this study: to find an alternative field marker for CERN Proton Synchroton (PS)
- A few IMMW talks on the subject, starting with the work of Fritz in 1997 on a Ferrimagnetic Resonance (FMR) probe (subject of an early patent application)
- Recent stimuli:

  - demands of higher performance field measurement from PS operation
  - B-train consolidation for the long-term
  - commercial availability of new high-Q single-crystal FMR filters

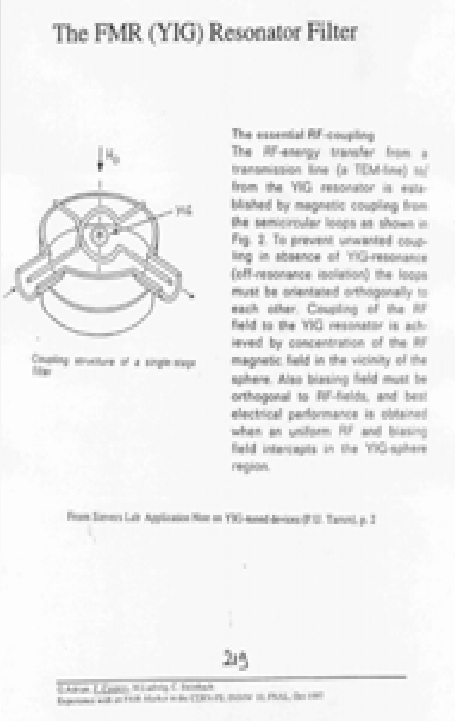


IMMW X

10th International Magnet Measurement Workshop
Fermilab, Batavia, Illinois USA October 13-16, 1997

Workshop Proceedings

Volume 1



The FMR (YIG) Resonator Filter

The essential RF-coupling
The RF-energy transfer from a transmission line (a TEM-line) to/from the YIG resonator is established by magnetic coupling from the semicircular loops as shown in Fig. 2. To prevent unwanted coupling in absence of YIG-resonance (off-resonance isolation) the loops must be orientated orthogonally to each other. Coupling of the RF field to the YIG resonator is achieved by concentration of the RF magnetic field in the vicinity of the sphere. Also biasing field must be orthogonal to RF-fields, and best electrical performance is obtained when an uniform RF and biasing field intercepts in the YIG-sphere region.

Coupling structure of a single-stage filter

213

Search for an industrial field marker inside the PS reference magnet

Didier CORNUET,

19-22 May 2003

A NMR Field Marker for
CERN PS Combined-Function Magnets

A Beaumont, M.Buzio

Contents

1. Introduction: B-train systems
2. Field markers
3. Passive gradient compensation
4. Test results
5. Conclusions & outlook

Background: "B-train" systems

- "**B-train**": **real-time measurement of local or integral field in a reference dipole**, used to infer $\int B d\ell$ over the whole machine

- **Users:** knowledge of the field is necessary for:
  - closed loop RF frequency control (mandatory !)
  - closed loop power supply control
  - beam diagnostics (e.g. beam current transformer)
  - qualitative feedback to operators

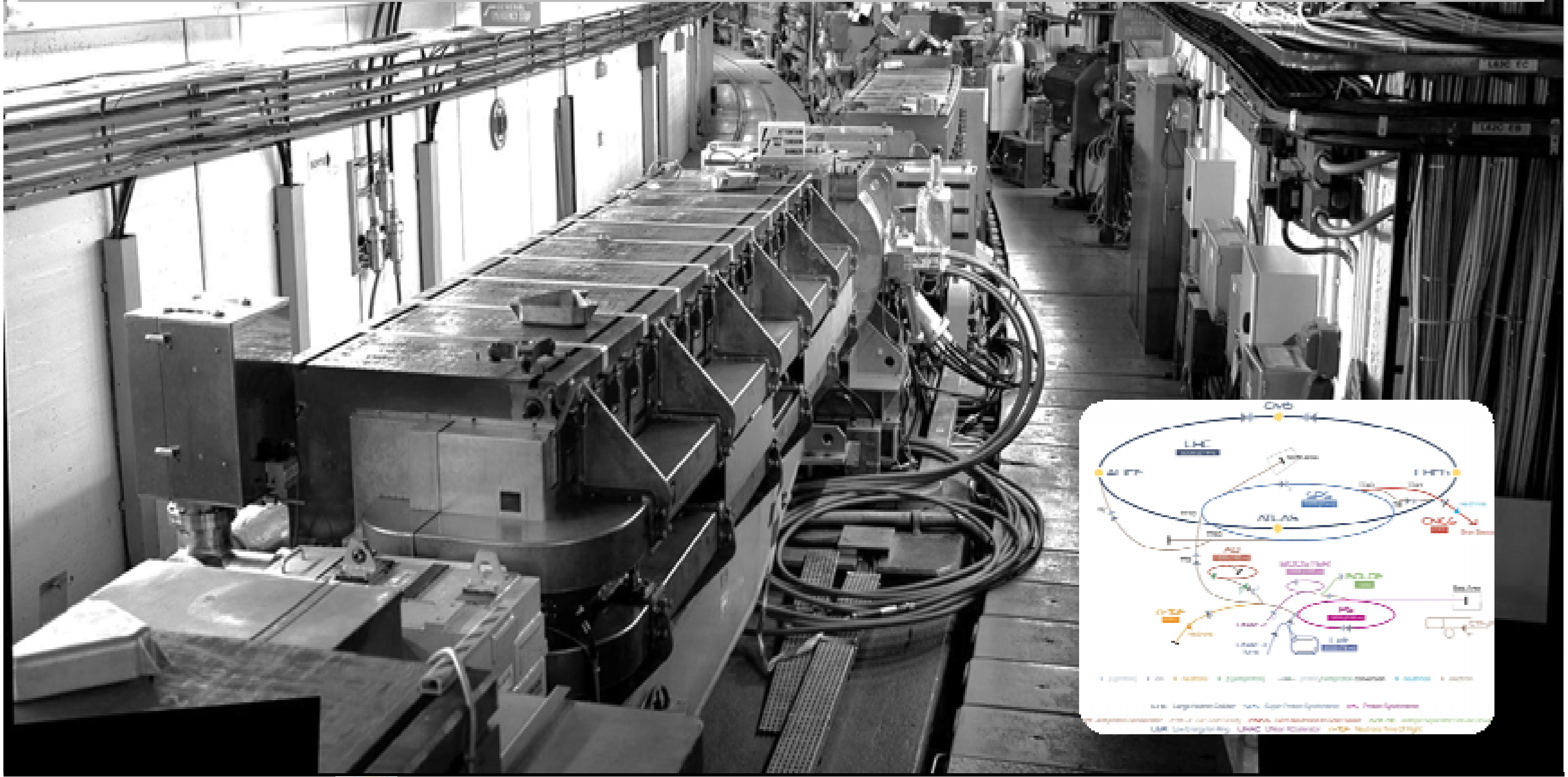
- **Motivation:** the field produced by a given current is not always predictable to the required accuracy (~10^{-4}) with a mathematical model ("synthetic" or "simulated" B-train), due to: **iron hysteresis, eddy currents, temperature effects, ageing, DCCT accuracy…**

- **Why a "train" ?** the field value is distributed on a dual digital serial channel, where one pulse represents a given increment/decrement (typically 10 μT)

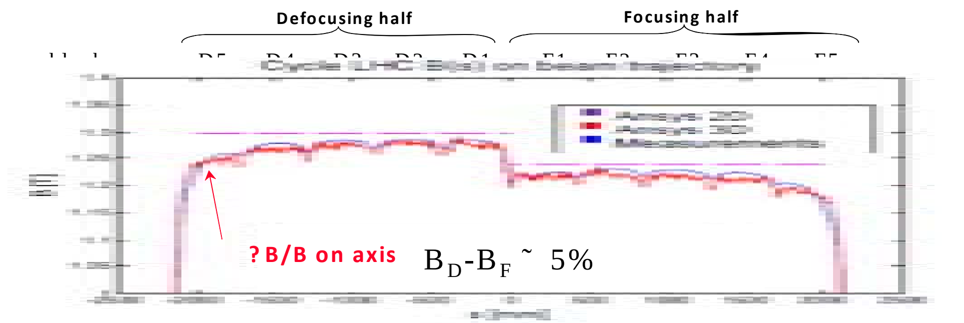
- **General method**:
  - a reference magnet in series with the ring is chosen
  - a **pick-up coil** provides the rate of change of the field: $V_{coil}=-A_{coil}\dot{B}$
  - a **field marker** provides the integration constant

CERN Proton Synchrotron: the most critical application

- LHC beams need tighter emittance control in the injectors
- Large Mean Radial beam Position (MRP) instabilities observed as a reproducible function of cycling
- Complex magnet very difficult to model and to control
- Ageing B-train components from the ‘70s, few spares

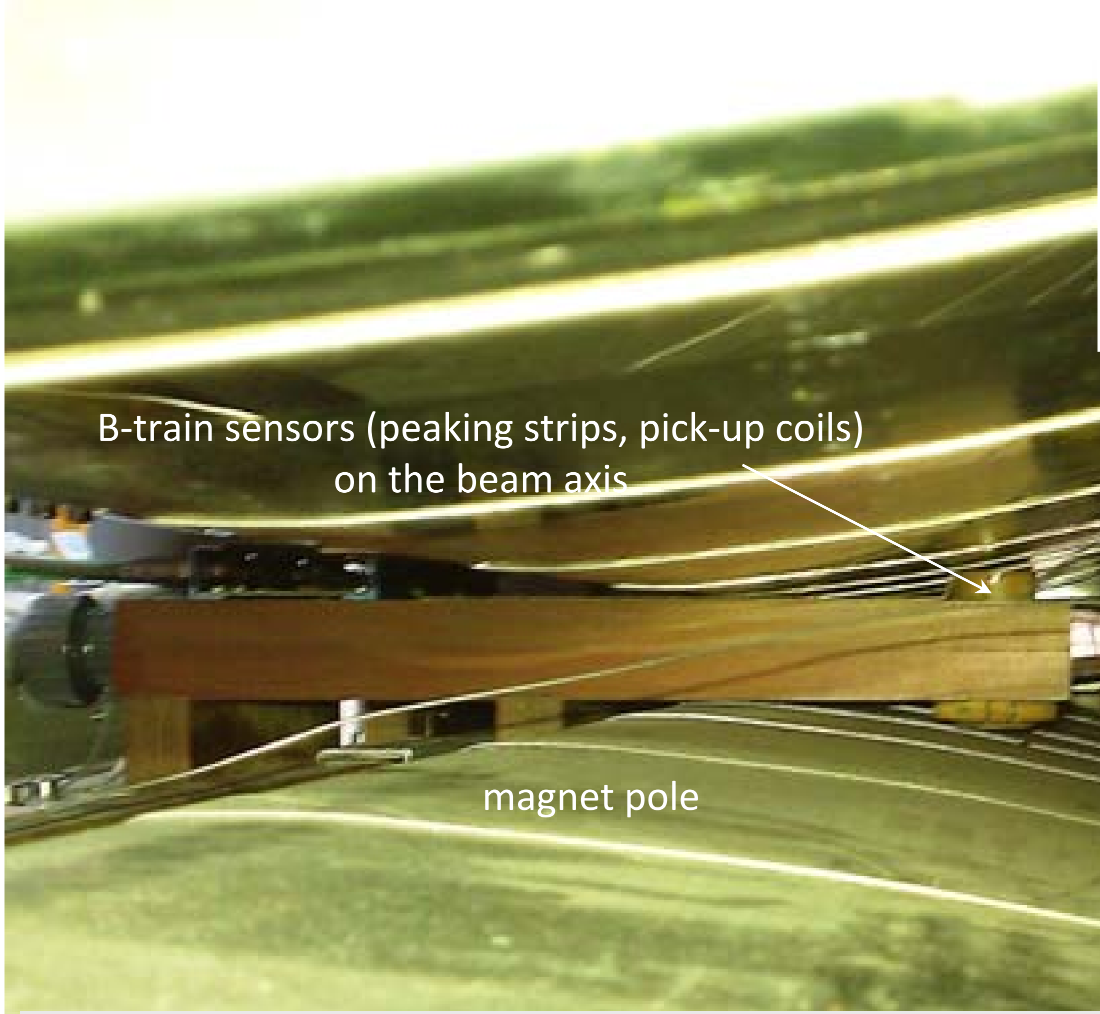


CERN PS: main combined-function magnets



? B/B on axis B_D-B_F ˜ 5%

A. Asklöv, "Magnetic measurement on the CERN proton synchrotron", 2005

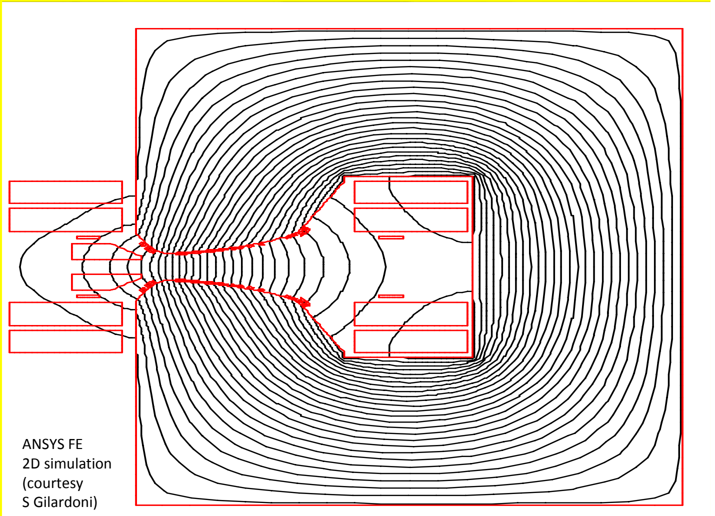


B-train sensors (peaking strips, pick-up coils) on the beam axis

magnet pole

- hyperbolic pole profile creates dipole + strong quadrupole
- focusing (F) in ½ of the magnet, defocusing (D) in the other ½
- 5 independent trimming coil sets control tune and chromaticity

very complex to model !

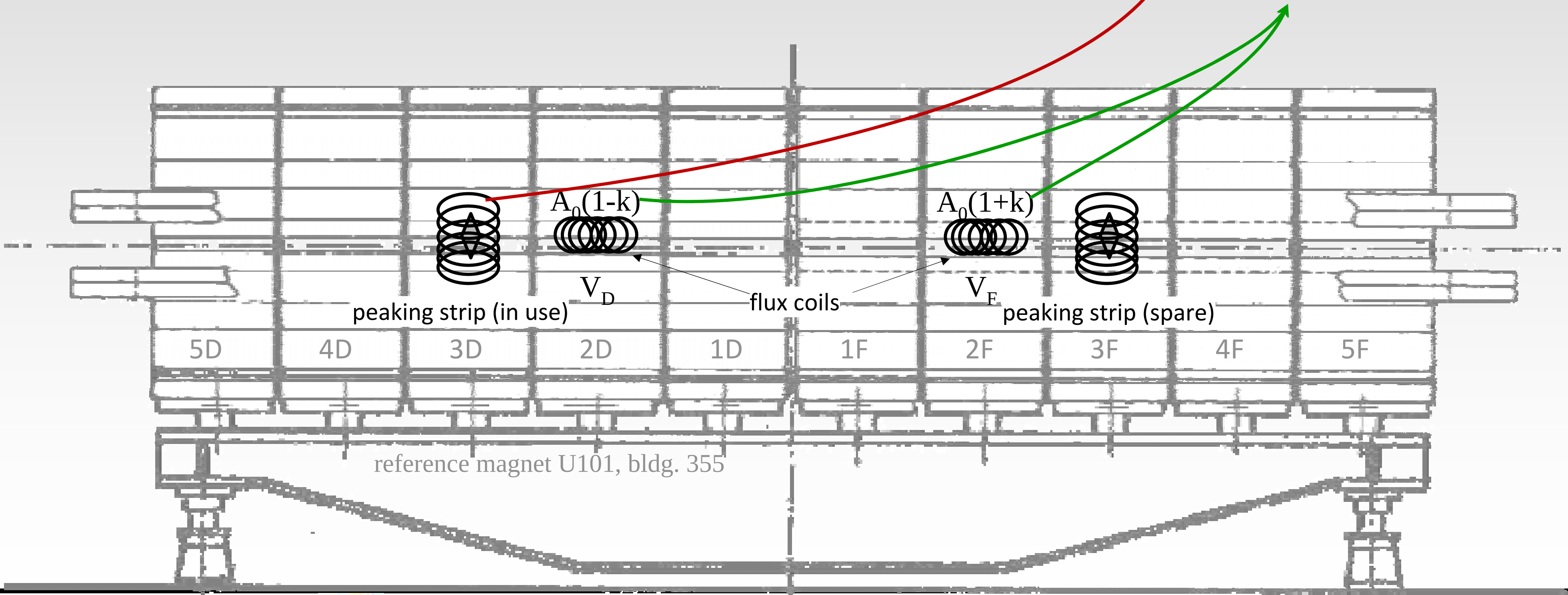


ANSYS FE 2D simulation (courtesy S Gilardoni)

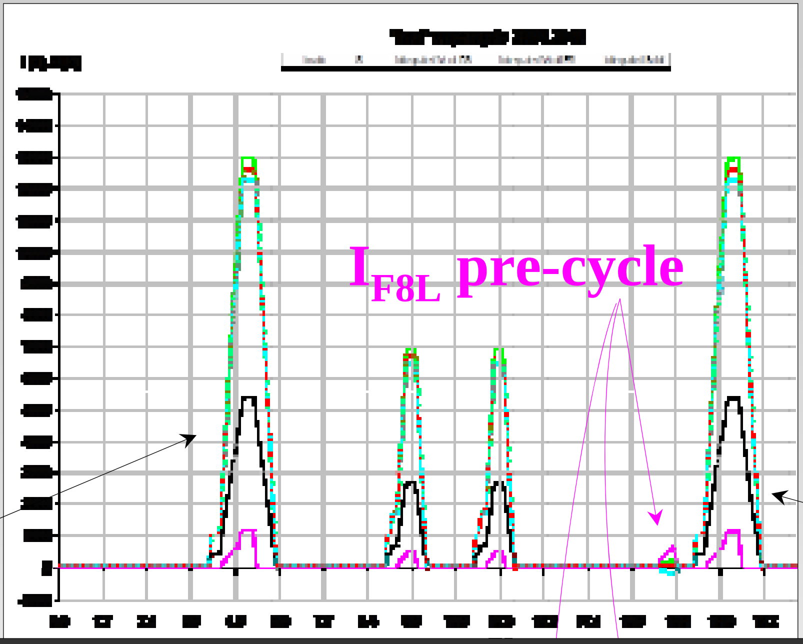
CERN PS B-train: current configuration

- B-train = **weighted average** of the local field in F/D halves
- Assumptions: $B_D(t_0)=B_F(t_0)=4.98$ mT, $k=0.091$
- Only one field marker in use (the second one is foreseen only for diagnostics)
- When these assumptions are not satisfied → B-train error → unstable beam
- Integrator is reset at the end of every magnet cycle

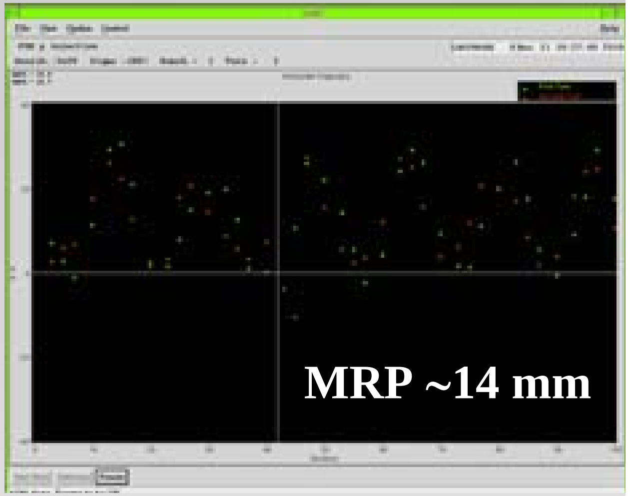
$$B_{avg} = \frac{1}{2}\left((1-k)B_D + (1+k)B_F\right) = 4.98\,mT + \frac{1}{2A_0}\int_{t_0}^{t}\underbrace{(V_D + V_F)}dt$$



CERN PS: power cycling-induced beam instabilities



“good” cycle

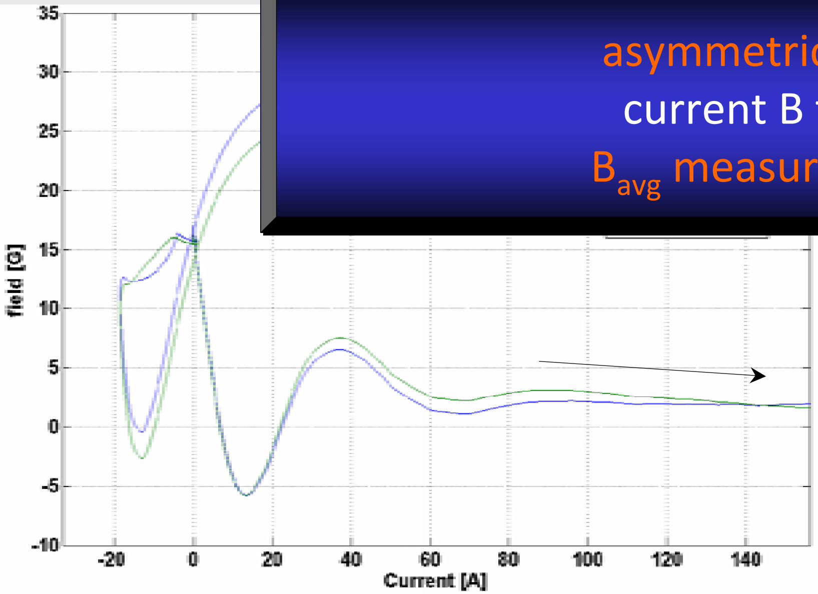


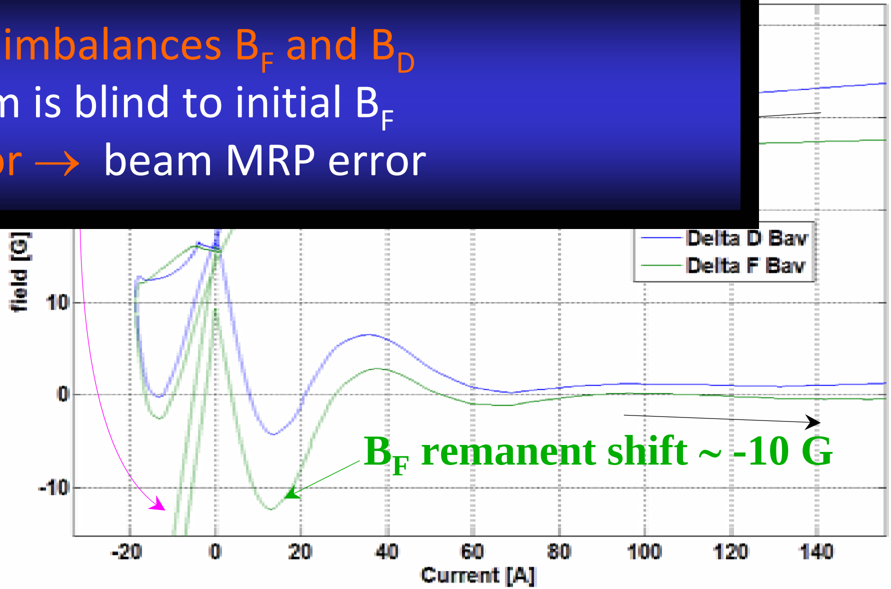
“bad” cycle

asymmetric powering imbalances B_F and B_D

current B train system is blind to initial B_F

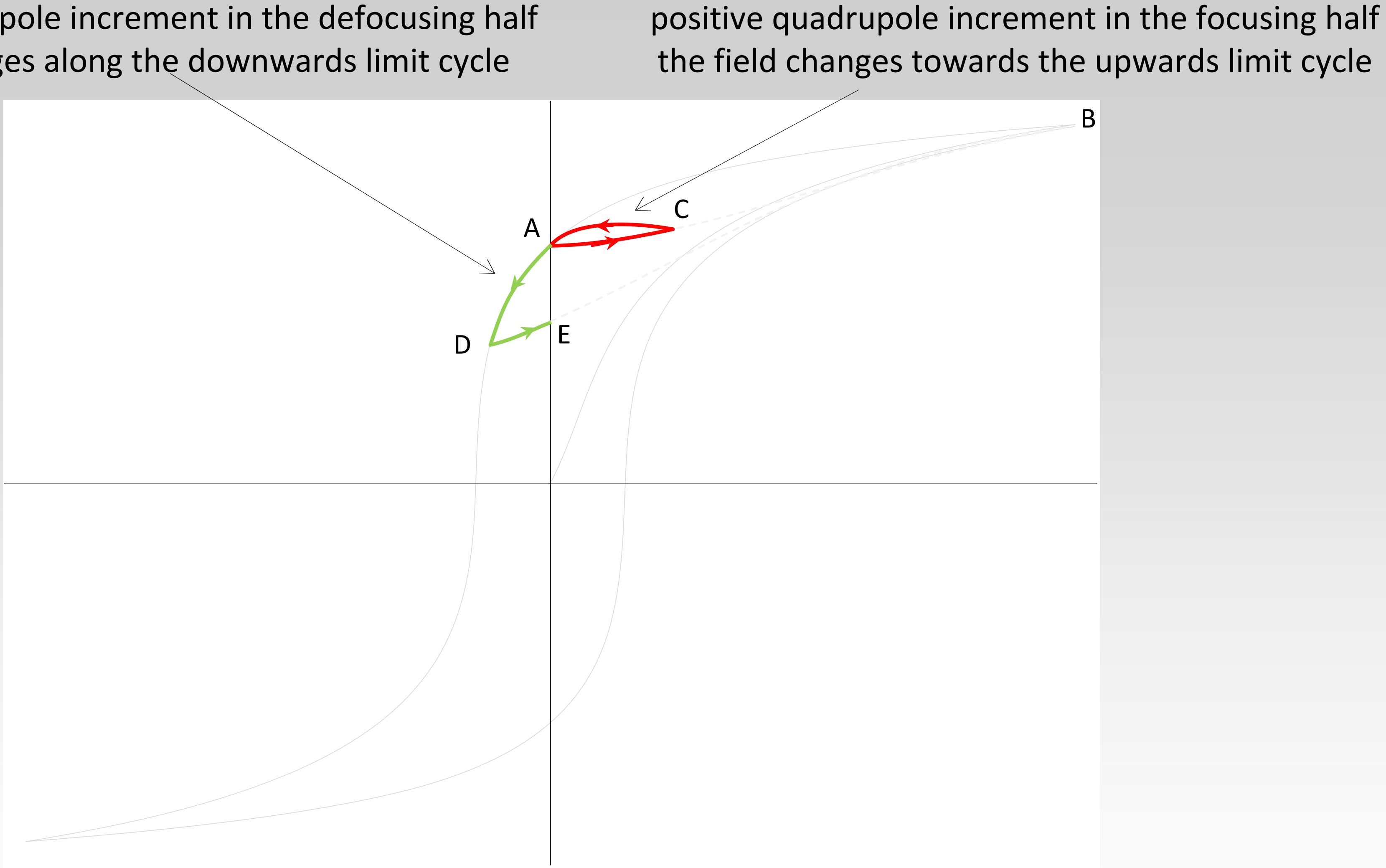
B_{avg} measurement error → beam MRP error





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

Field imbalance



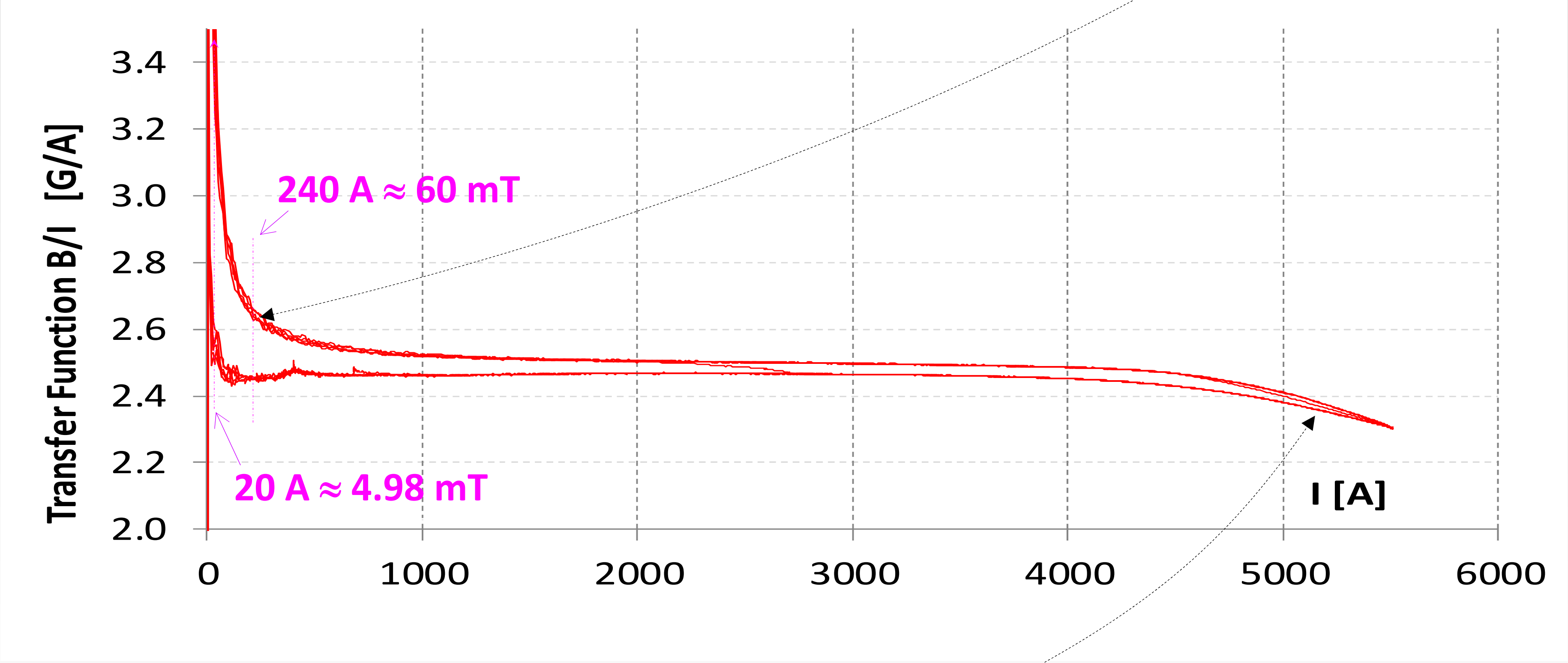
negative quadrupole increment in the defocusing half the field changes along the downwards limit cycle

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

CERN PS magnet: transfer function hysteresis

large fluctuations due to history-dependent residual field



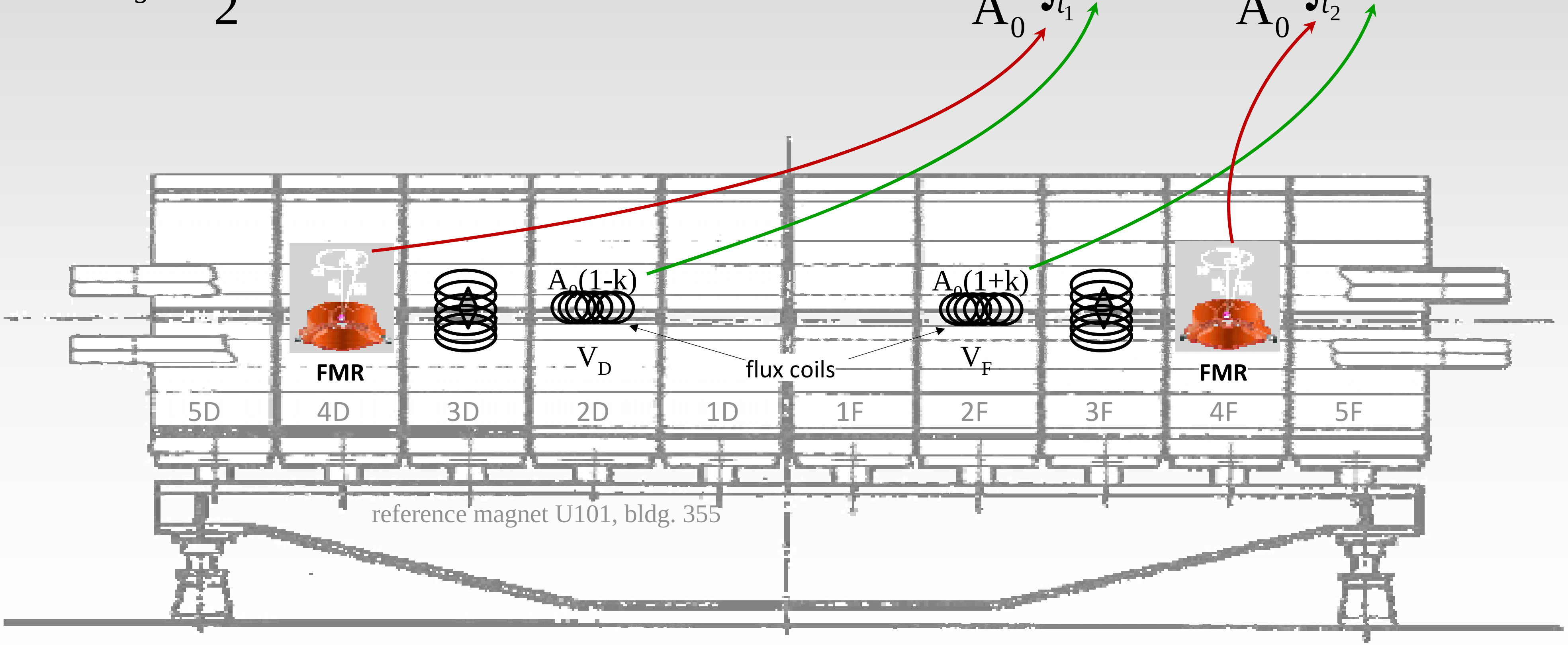
going into saturation erases the previous magnetic history

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

CERN PS B-train: upgraded configuration

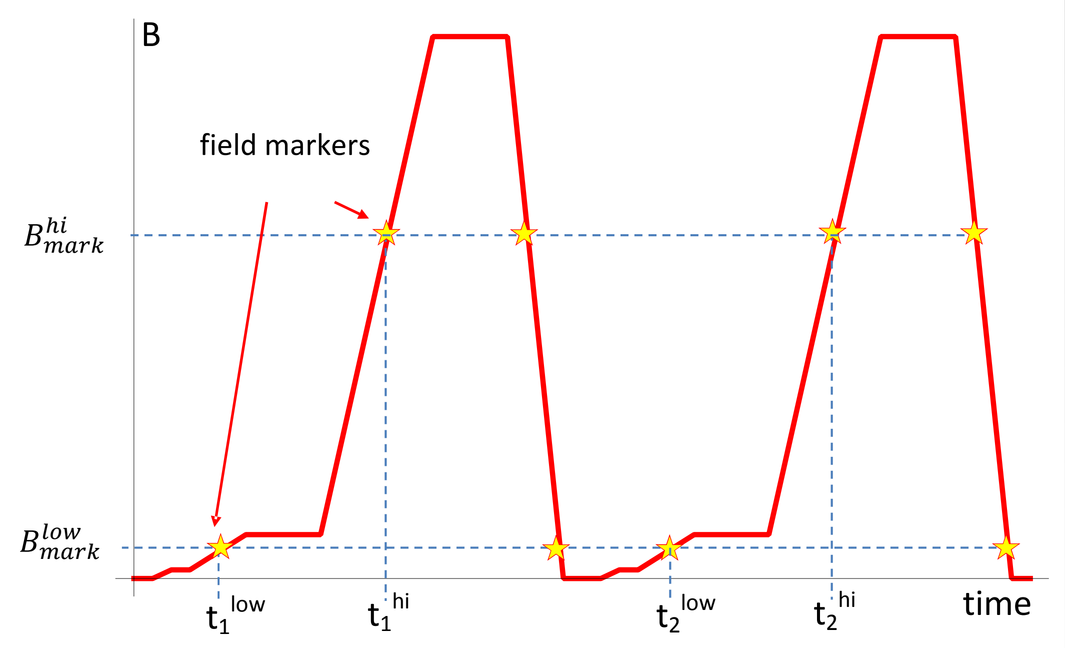
- Goal: remove constraints to operation and improve accuracy and reliability
- Independent high-field markers in F/D halves
- Higher initial level (field marker) to improve magnetic reproducibility
- Simpler synchronization with control system: broadcast continuously *B(t)* including on-the-fly corrections

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



Field marker specification

- Absolute accuracy: **100 μT**, short-term reproducibility: **5 μT**.
- Marked field between **60-80 mT** (below injection) for drift correction
  In addition, marking up to **1.2 T** is highly desirable for gain calibration
- Mark at up to about **3 T/s**



Integrator offset
updated every time the same marker level is reached

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

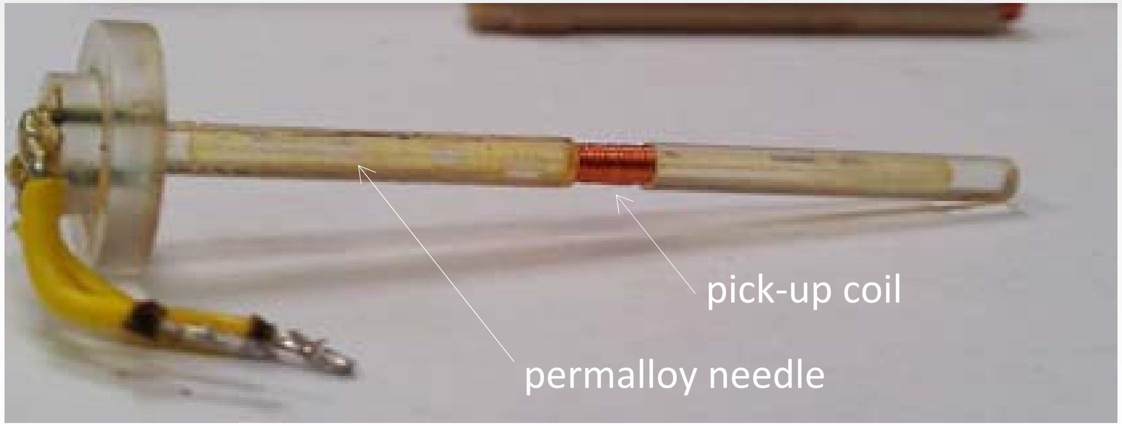
Integrator gain
updated every time a different marked level is reached

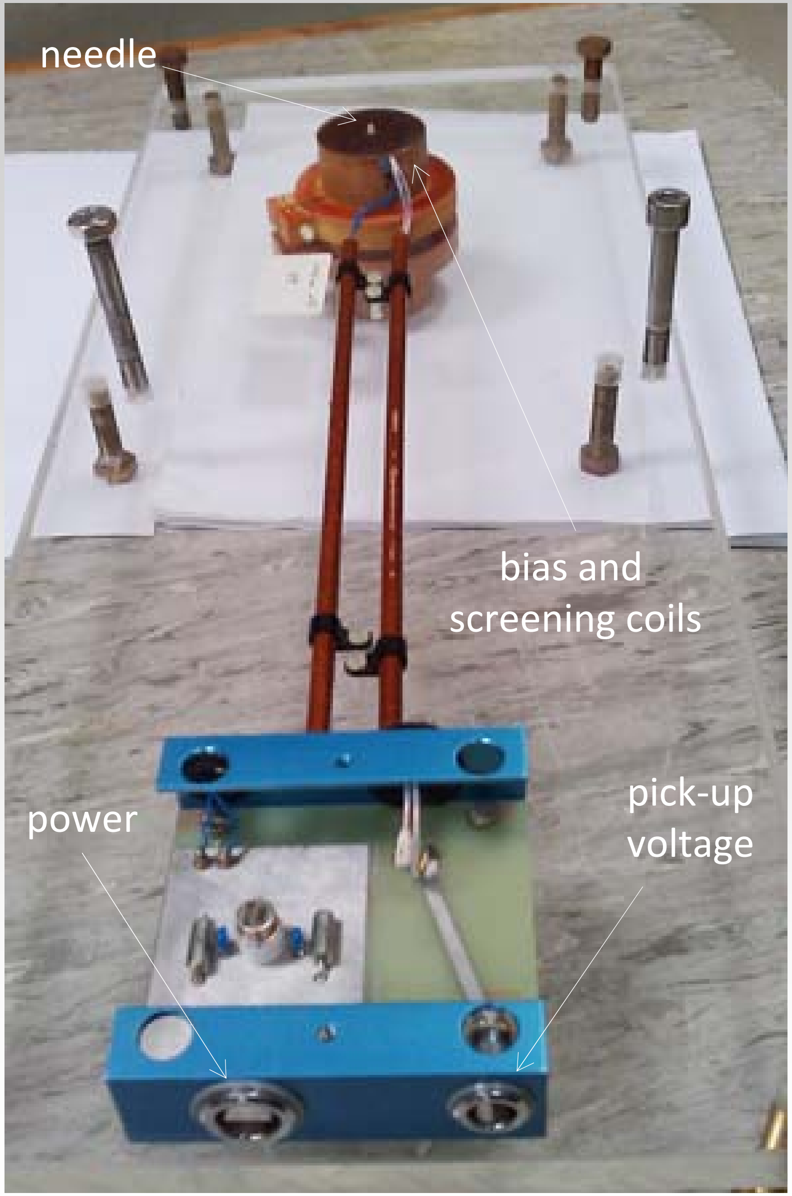
N different marker levels → up to 4 N corrections per cycle
Corrections smeared over a certain Δt to avoid sudden jumps

Field Markers

Existing field marker: peaking strips

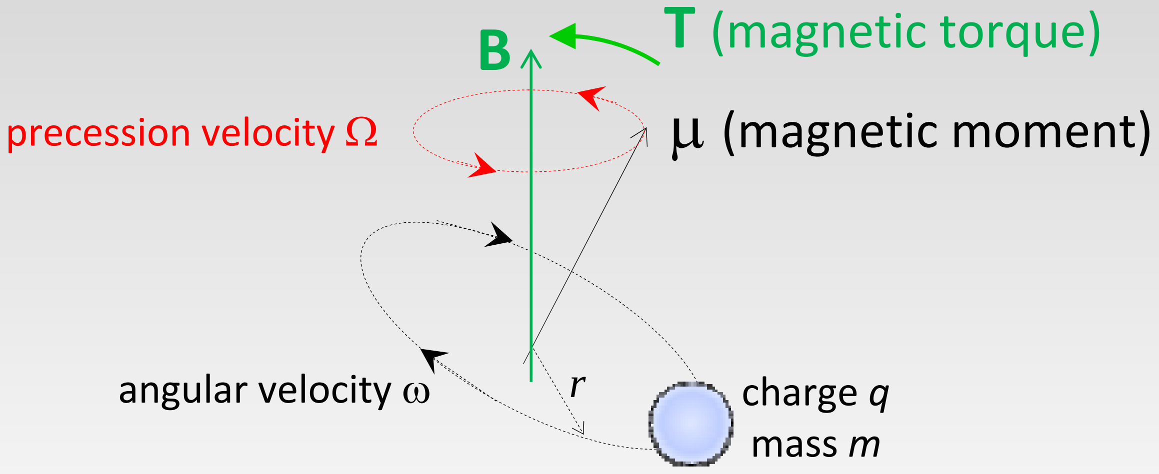
- Developed at CERN in 1956 specifically for combined-function PS magnets.
- Based on a pre-stressed bi-stable magnetic needle: magnetization flips over at a preset level and generates a pulse detected by a pick-up coil
- Two coils powered in series for bias and screening field, pulsed to avoid overheating
- 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 exceptionally stable (drift <50 µT in 20 year),
- Very few spares available (and making new ones is difficult)





Magnetic resonance

- Classical model of a rotating charge: magnetic moment μ proportional to angular momentum l
- External field → magnetic torque T → precession at angular velocity Ω
- Quantum description: essentially the same result holds for orbital and spin degrees of freedon, with the introduction of the Zeeman correction factor g
- Incident EM waves at frequency $\Omega/2\pi$ are absorbed and re-emitted with great efficiency (resonance)



$$\mu = IA = \frac{1}{2}q\omega r^2 = \underbrace{\frac{q}{2m}}_{\text{gyromagnetic ratio } \gamma} l$$

$$T = \mu B = \Omega l$$

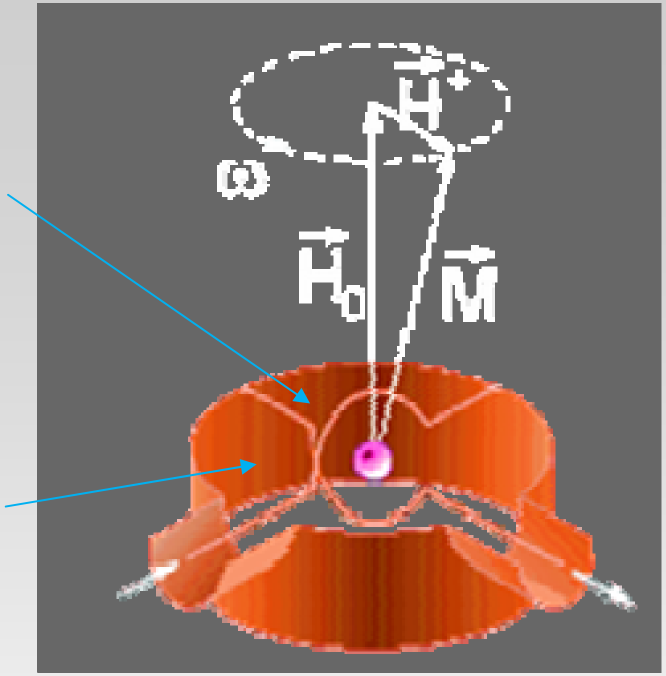
$$\gamma = \frac{q}{2m} = \frac{\mu}{l} = \frac{\Omega}{B} \quad rad\ s^{-1} T^{-1}$$

$$\gamma = g\frac{q}{4\pi m} = \begin{cases} \text{H}^+ \text{ (proton)} & 42.577 \\ \text{free electron} & 28\,015.737 \end{cases} \quad MHz\ T^{-1}$$

NMR (Nuclear Magnetic Resonance)
γ constant to better than 1 ppm

EPR/ESR (Electron Paramagnetic/Spin Resonance), FMR (FerriMagnetic Resonance)
actual value in materials depends on: chemical composition, microstructure, temperature …

FMR resonator



∅0.3 mm
YIG sphere

semi-circular
RF loops

RF in

RF out

- Yttrium 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 poly-crystalline YIG, installed in the PS since the '90s as a manually operated diagnostic tool
    low filter Q, but insensitive to temperature
  - new single-crystal YIG units. Higher Q ≈500-1000, critical alignment and T dependence
    tested in 2010/2011: one standard commercial + one customized unit

Calibration of the FMR transducer

FMR calibration test campaign

Aims:

- Derive a ***B(f)*** calibration table as a function of the operating conditions, mainly: ramp rate, temperature, field gradient relative to main dipole
- Metrological characterization of the sensor and the acquisition chain (bandwidth, noise, stability …)
- Familiarize our team with RF signal generation and treatment in a controlled environment before moving in the PS reference magnet (machine development time is very limited)

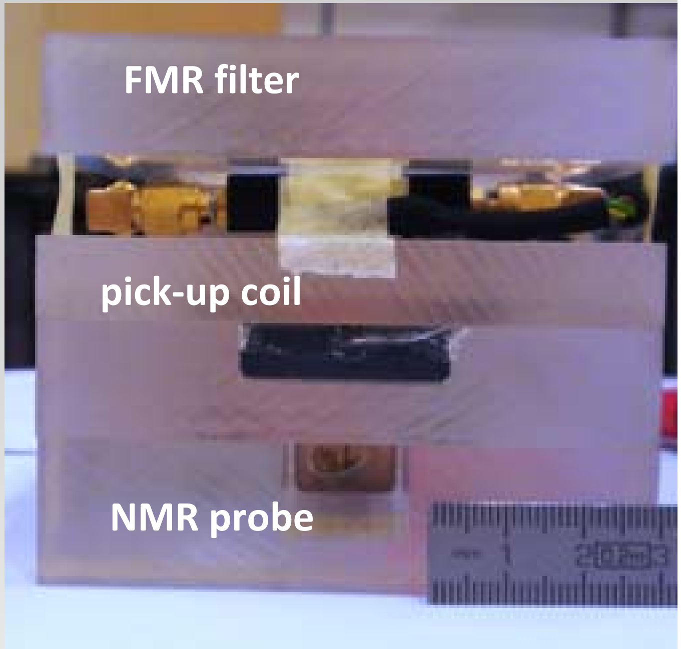
Method

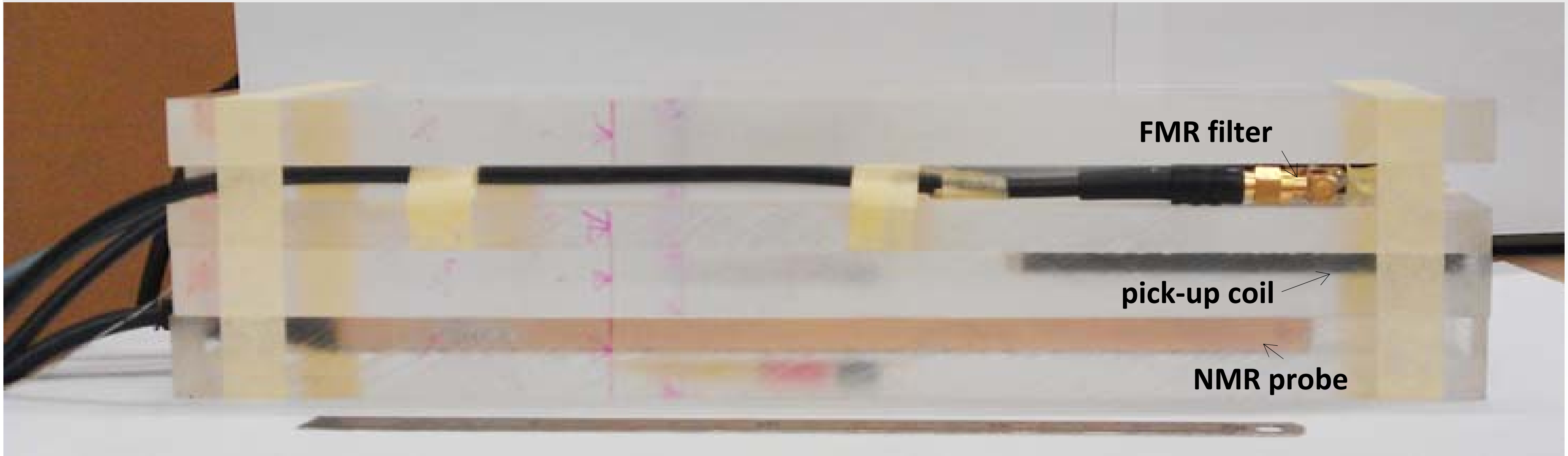
- Measurements inside an independent reference dipole (a quadrupole is also planned*)*
- Resonance curves measured with a **network analyzer** (filter only) and with an **ADC** (full transducer) to simulate the final working conditions in the PS B-train
- Reference measurement: NMR probe working in DC mode

FMR calibration setup

FMR calibration setup: main issues

- NMR and FMR placed as close as possible to minimize errors due to field inhomogeneity
- NMR and FMR average the field over a different volume: (NMR ~ 1000 mm^3, FMR 0.4 mm^3)
  → a detailed field map vs current B(x,y,z,I) is needed
- NMR and FMR cannot be powered simultaneously due to EM interference → delayed referencing
- Dynamic mode: an additional coil is needed to measure the time-varying reference component ("mini B-train")

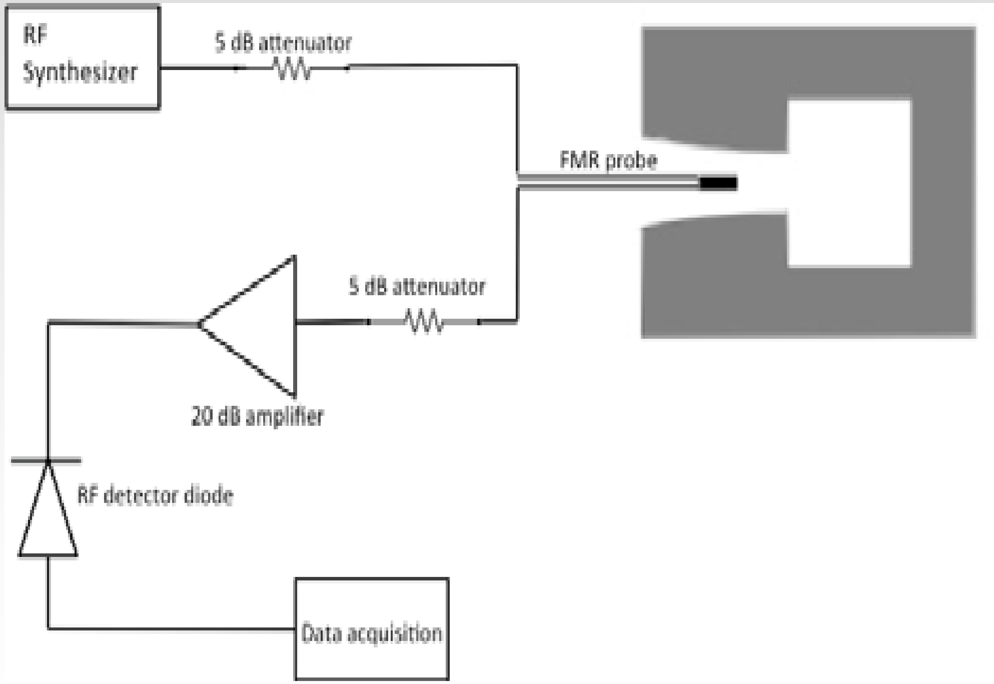




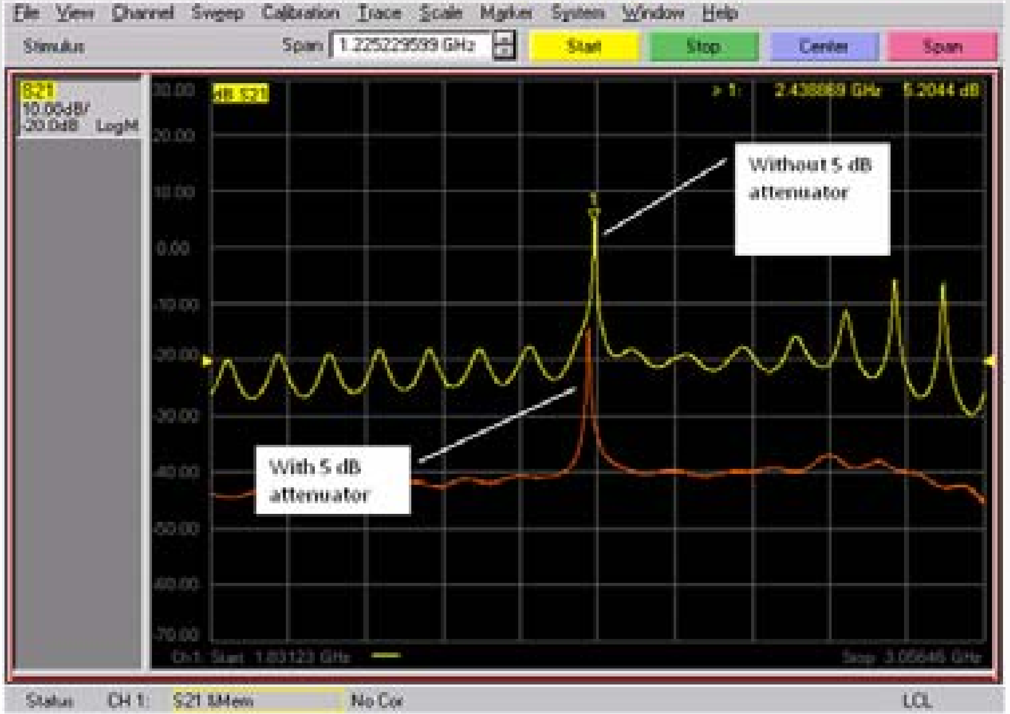
FMR transducer setup

Very simple acquisition electronics used to scale down frequency range from GHz to MHz range:

- **RF synthesizer** with 13 dB_m output (i.e. 13 mW – long term heating effects to be assessed)
- **RF detector diode** used to rectify the signal and give a smooth envelope (bandwidth=18 GHz)
- **Amplifier** needed to bring the signal in the linear range of the diode (bandwidth 0.1-9 GHz)
- Standard National Instruments **16-bit ADC** acquisition at **1 MHz**
- **Attenuator resistors** used to reduce reflections due to imperfect 50 Ω matching, causing spurious resonance peaks



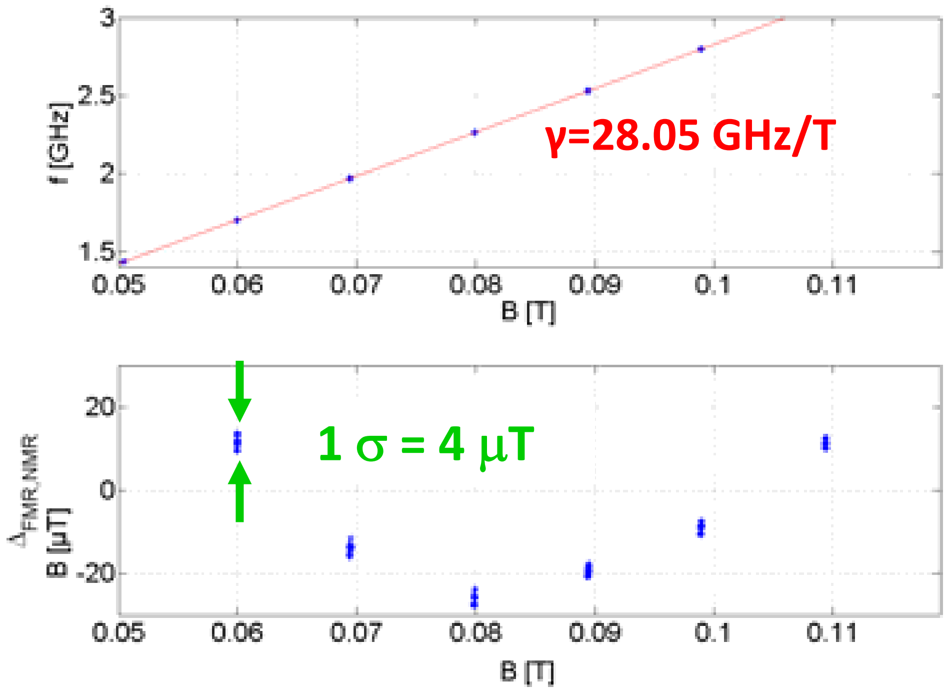
Electrical scheme of the transducer



Multiple reflections in the filter output

DC calibration

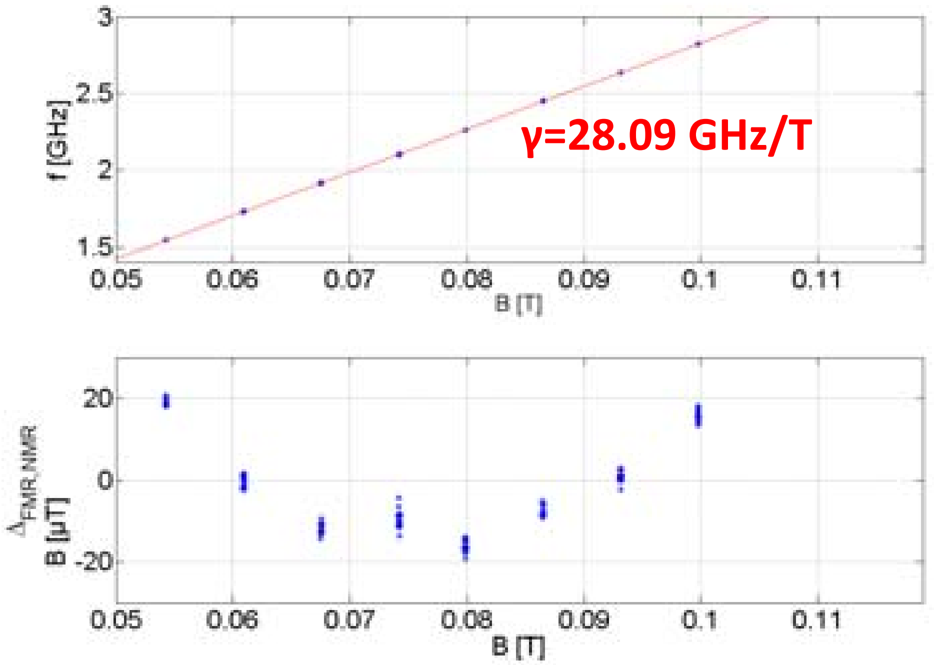
- Magnet pre-cycled 5 times (reproducibility 2 μT)
- DC measurement procedure: first take **NMR** reading, then sweep the **FMR** input frequency between 1.6 and 3.0 GHz (ie. from 50 to 110 mT) to find resonance
- Excellent **repeatability** better than **4 μT** across the range
- **Non-linearity error ±20 μT** after correction of field inhomogeneity
- The parabolic shape of this error confirms earlier measurements done in a different dipole



γ=28.05 GHz/T

1 σ = 4 μT

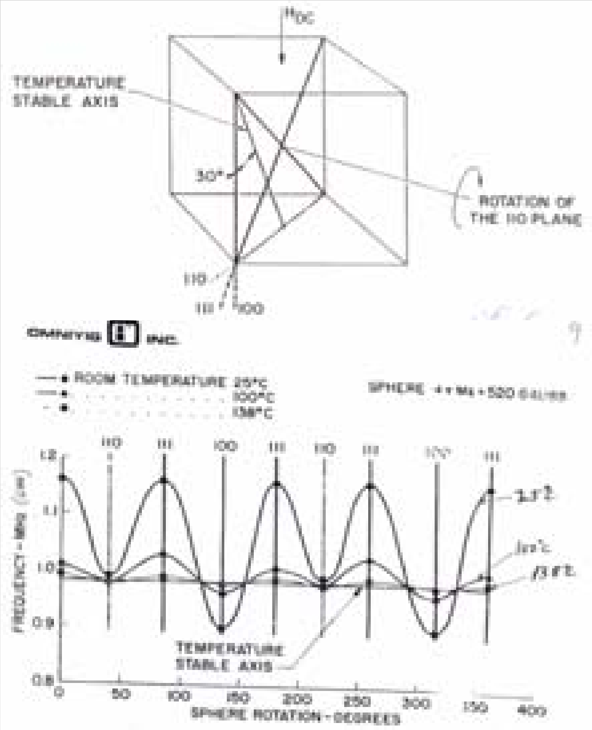
Sensor only (acquired with a network analyzer)



γ=28.09 GHz/T

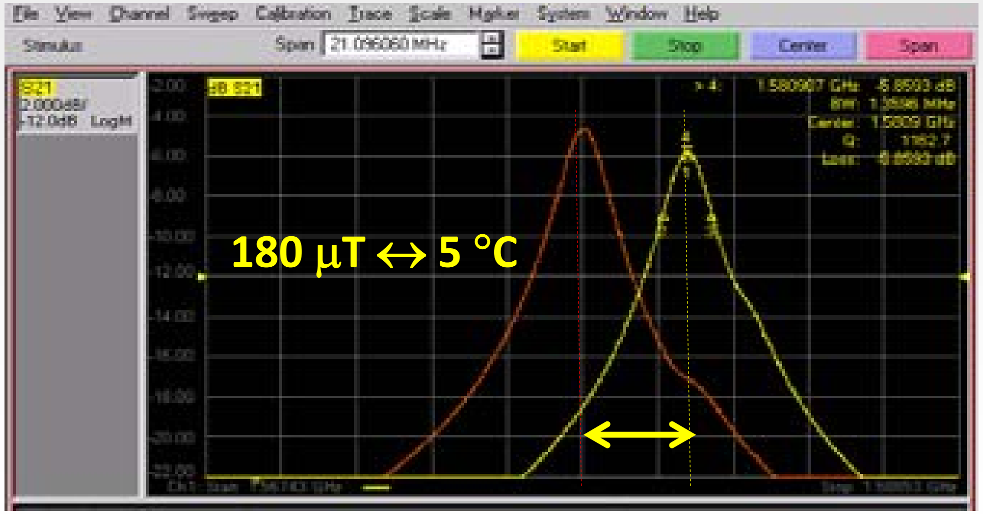
Full transducer (acquired with ADC)

Temperature effects

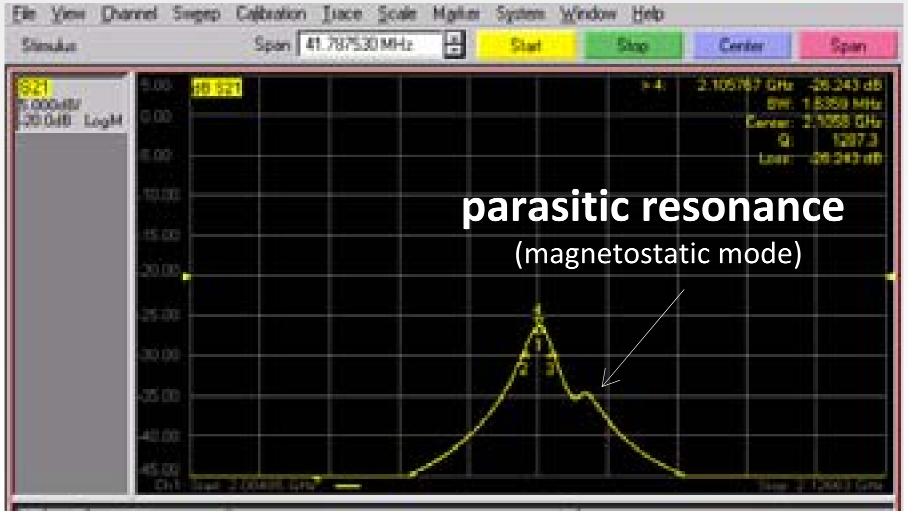


courtesy W. Capogeannis, OmniYig

- Alignment of the anisotropic YIG sphere along the appropriate crystallographic axis is crucial to minimize temperature effects
- Manufacturer can rotate the sphere so that temperature effects disappear at a given frequency.
- Standard units are actively stabilized with an electrical heater that was removed in order not to perturb the magnetic field
- The first filter tested (an unoptimized commercial unit) showed errors up to **36 µT/°C** and **parasitic resonance modes** that may affect automated peak detection electronics



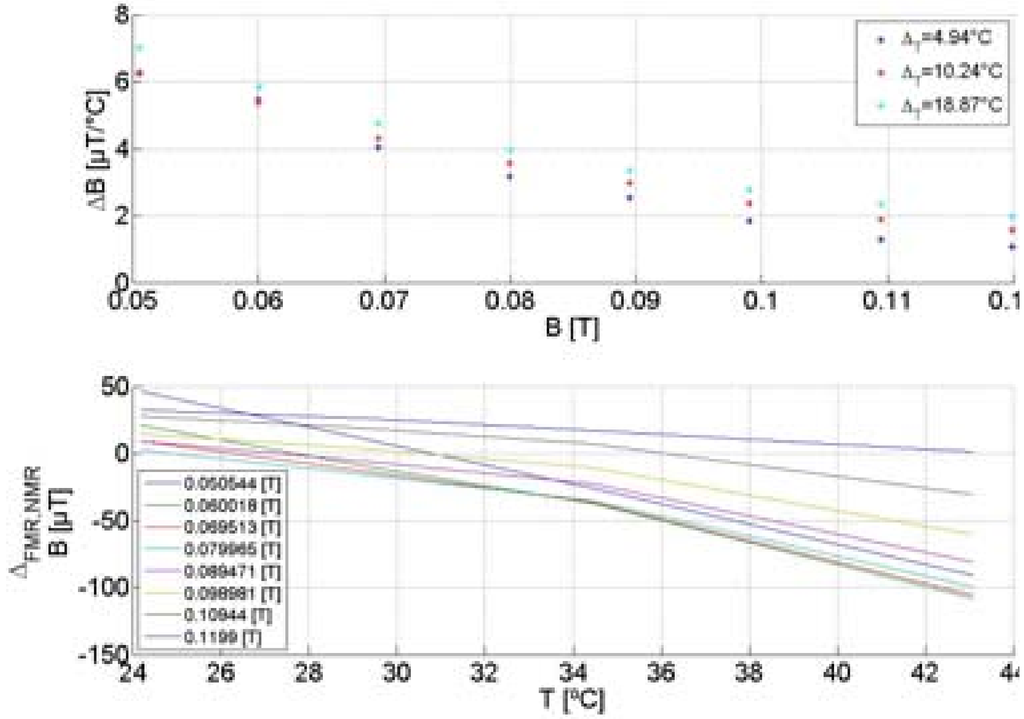
180 µT ↔ 5 °C



parasitic resonance
(magnetostatic mode)

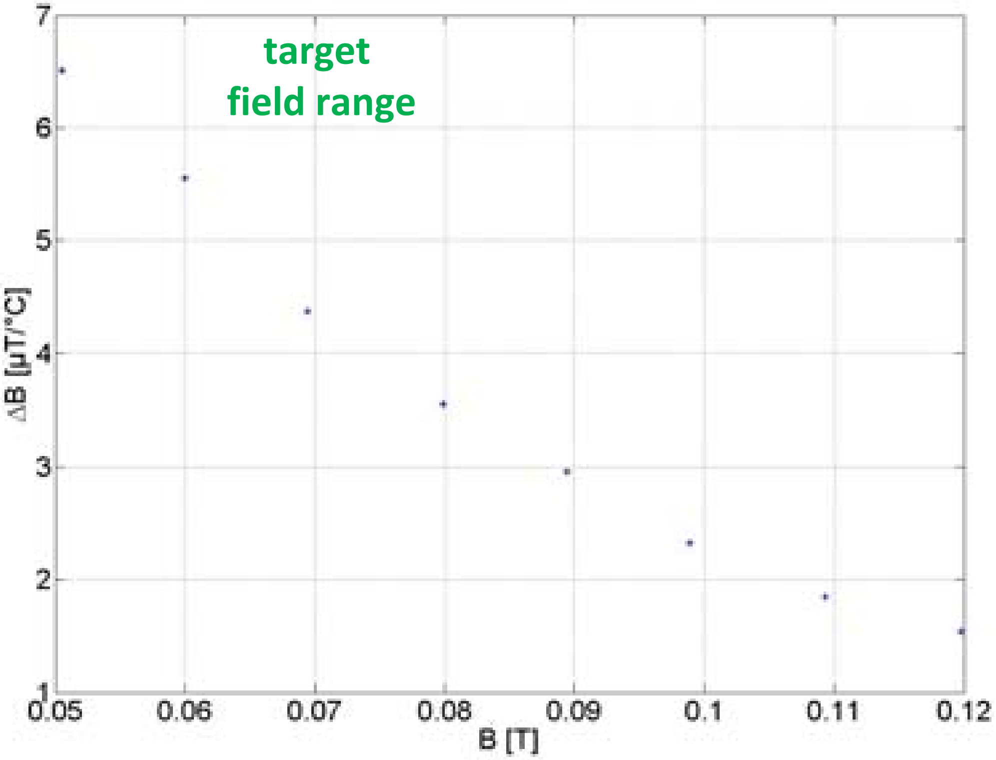
Temperature effects: optimized unit

- A single-crystal unit was optimized (i.e. aligned) by OmniYig for operation at 120 mT
- Temperature dependence measured over a 20°C range between 50 and 120 mT
- In the target field range the error is better than **5.5 µT/°C,** which in case of the fluctuations of ±2°C measured in the PS reference magnet gives about 2.2 µT error (fully acceptable)
- Options for further improvement: ask the manufacturer for optimization at the target working temperature (but: this might affect operation in a wider range); thermalization of the filter



field error vs. temperature at different field levels

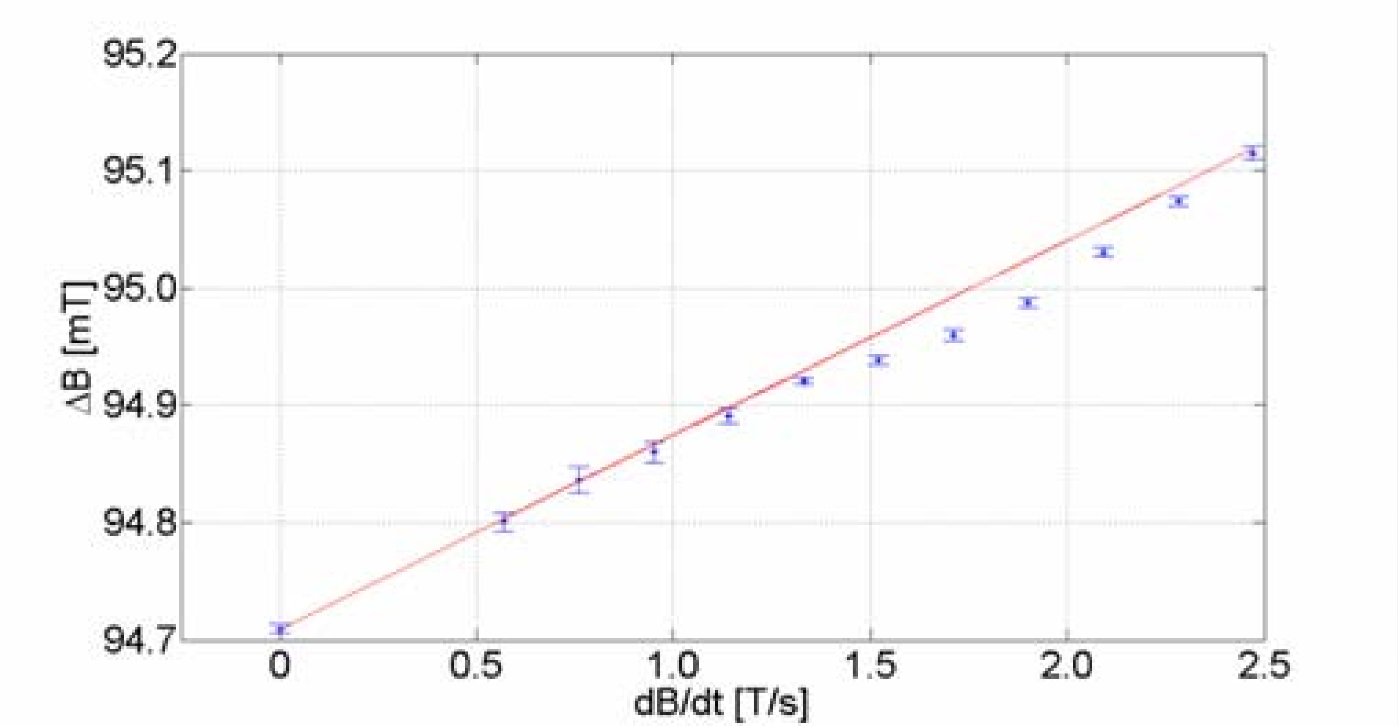
rate of field error/temperature at different field levels



target field range

AC calibration

ramp-rate dependence of standard commercial filter



standard commercial unit: Al casing

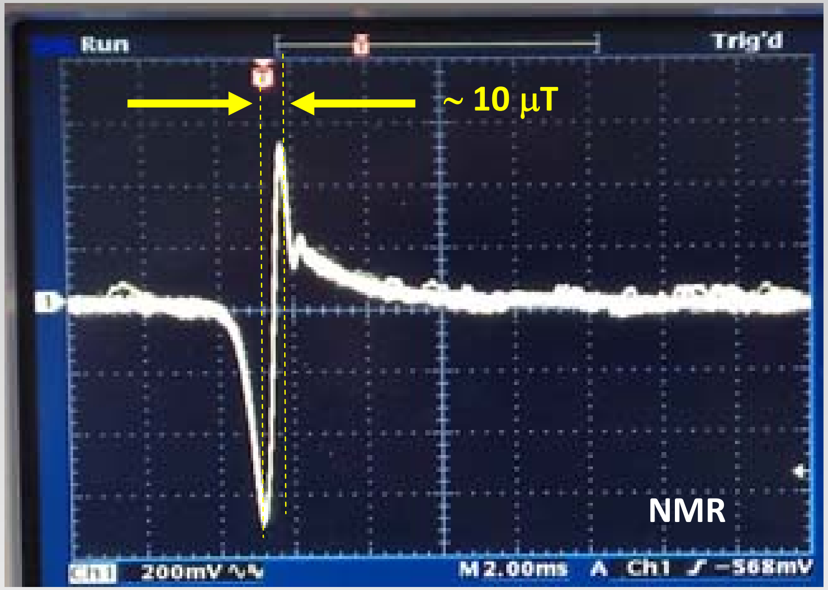
custom unit: Noryl + 8 µm Al + 8 µm Cu + gold flash

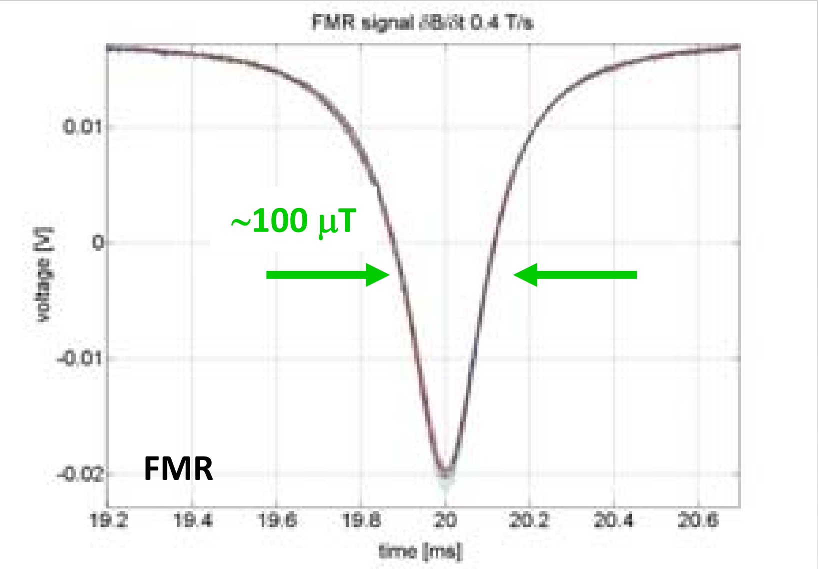
- During a field ramp unacceptable errors of the order of **$1.3 \cdot 10^{-3}$ per T/s,** i.e. **200 µT @ 700 A, 2.3 T/s** are observed (compatible with eddy currents in the original Al casing)
- A new customized Noryl casing with a conductive layer of only 16 mm, currently being tested, shows no measurable ramp rate dependence.

Closure

NMR vs FMR

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





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

Summary and outlook

- A field marker based on a FMR resonator has been demonstrated as capable of providing a **±4 μT repeatability between 60 and 80 mT**, as required for CERN PS
- Compatibility with high field strength, gradient and rate will provide much **improved operation flexibility** to the PS
- Improved B-train accuracy will be guaranteed by cycling the magnet with lower dynamics and more frequent automated calibration of integrator gain and offset
- A test campaign in parallel with the existing system is presently foreseen to assess long-term reproducibility
- Using the FMR in teslameter (absolute) mode requires better understanding of the 40 μT non-linearity in the response, as well as the sensitivity upon the relative orientation between field and YIG sphere

Thanks for you attention

Acknowledgment

•Many thanks to W. Capogeannis of OmniYig® Inc. for the customization of the YIG filter

•Many thanks to P. Sommer and J. Tinembart of Metrolab® for useful discussions about magnetic resonance methods

•Thanks to D. Cote, O. Dunkel, P. Galbraith, D. Giloteaux and L. Walckiers of CERN for their technical and scientific contribution

Any questions ?