Recent advances in pulsed-mode measurements at CERN

M. Buzio, R. Chritin

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Overview

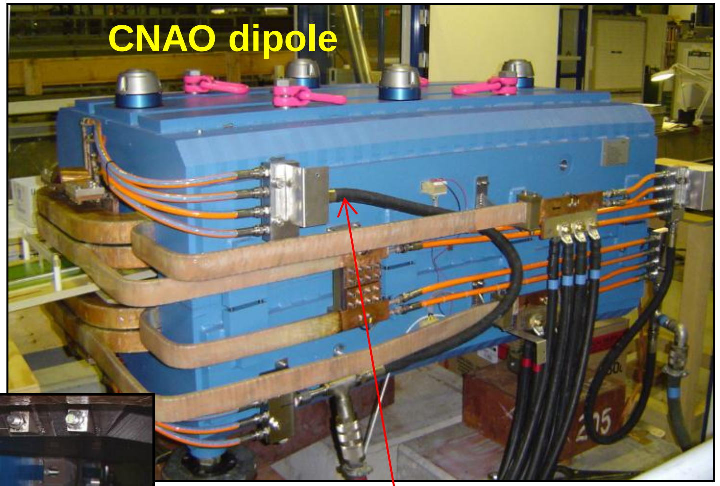
Pulsed-mode measurement with fixed coil:

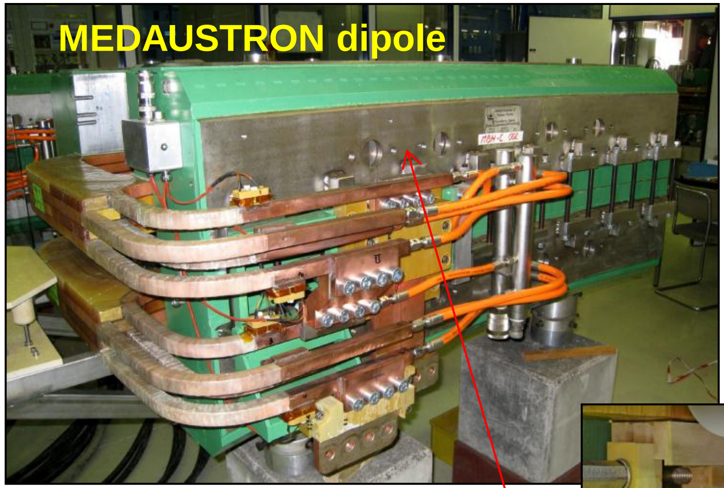
1) Eddy current studies of dipoles for a hadrontherapy synchrotron (MedAustron)

2) High frequency field fluctuations in the Proton Synchrotron's main magnets

3) Experimental determination of inductance in resistive magnet

Eddy current studies of dipoles for a hadrontherapy synchrotron (MedAustron)





Main magnets designs differences influencing Eddy currents

CNAO

Iron made (magnetic) tension bars

7 small blocks for shimming adjustment

No Rogowski profile for shims

MedAustron

Stainless steel (non magnetic) tension bars

5 large blocks for shimming adjustment

Rogowski profile for shims

Eddy current studies of dipoles for a hadrontherapy synchrotron (MedAustron) 2/3

Design options and benefits:

Stainless steel tension bars justification

→ A previous study on CNAO magnets did show a strong influence on Eddy current at magnet saturation

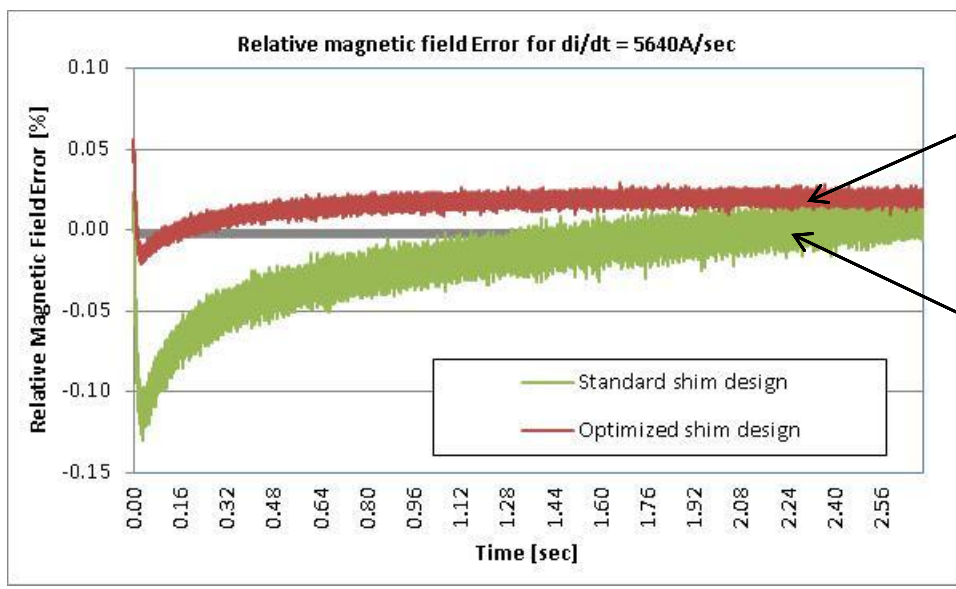
→ Eddy currents created in tension bars have a long decay time

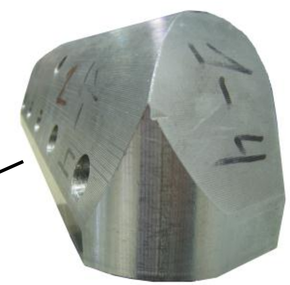
Shims with Rogowski profile interest

→ They limit the end field component on the Z axis, which create Eddy currents in shims

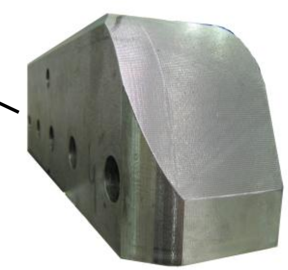
→ Eddy currents created in shims have a short decay time

Eddy currents effects amplitude variation of + 1.10^{-3} between the two types of shims





Optimized shim



Standard shim

Eddy current studies of dipoles for a hadrontherapy synchrotron (MedAustron) 3/3

Results comparison between the two types of dipoles for Eddy currents effects on the integrated field:

- **Amplitude** of Eddy currents effects :

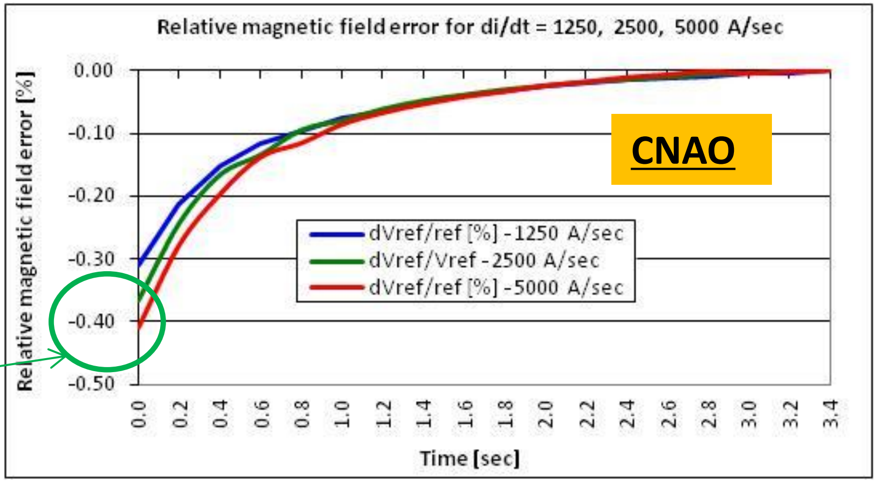
→ 16 times lower on MedAustron dipoles

CNAO = 0.4 %

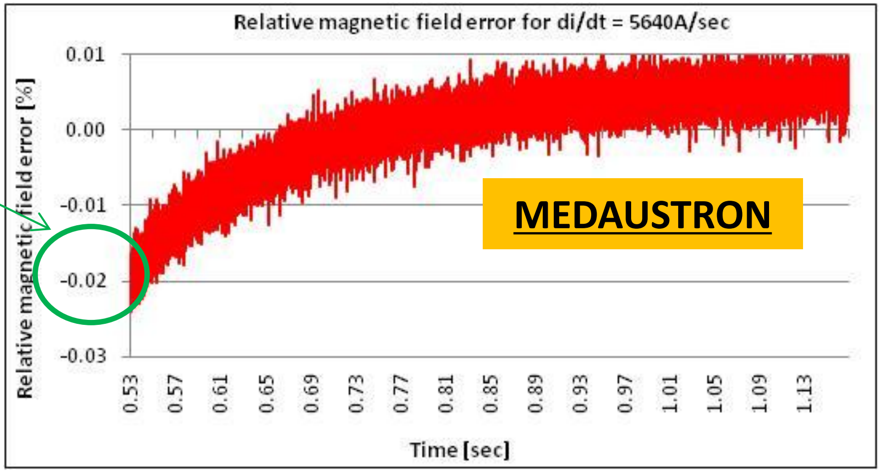
MedAustron = $2{,}5.10^{-4}$

- **Time constant** of Eddy currents effects :

→ ≈ 4 times lower on MedAustron dipoles



CNAO τ = 0.65 sec

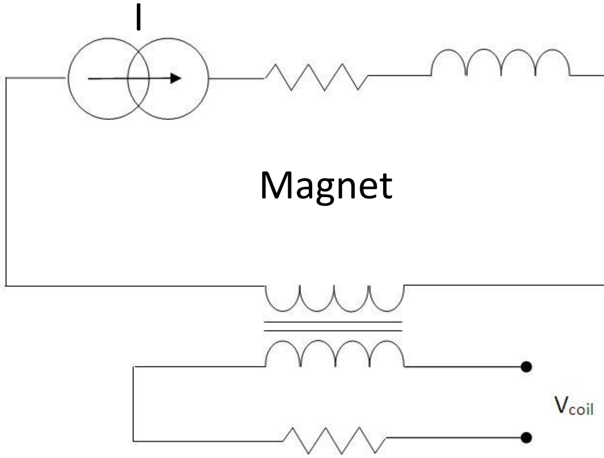


MedAustron τ = 0.15 sec

High frequency field fluctuations in the Proton Synchrotron's main magnets 1/3

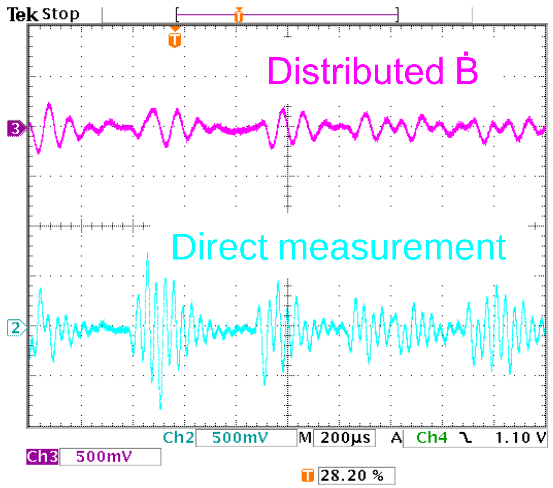
→ PS operation team reported high level of noise on the $\dot{B}$ signal of the real-time field measurement system (B-train) → stability of RF feedback, beam position

→ Measurement campaign done inside magnet gap with a fixed coil. Where does the observed noise come from ?

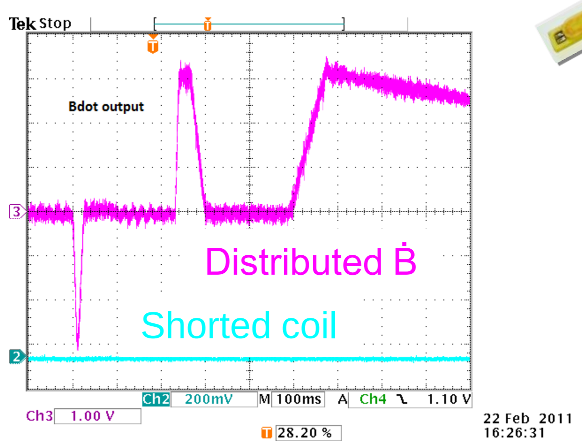


Electrical circuit: AC source, R, L inductive coupling to coil

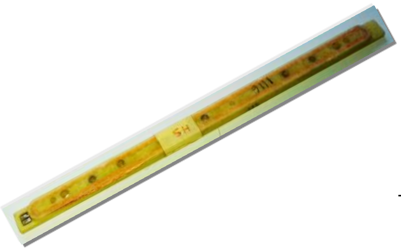
High frequency field fluctuations in the Proton Synchrotron's main magnets 2/3

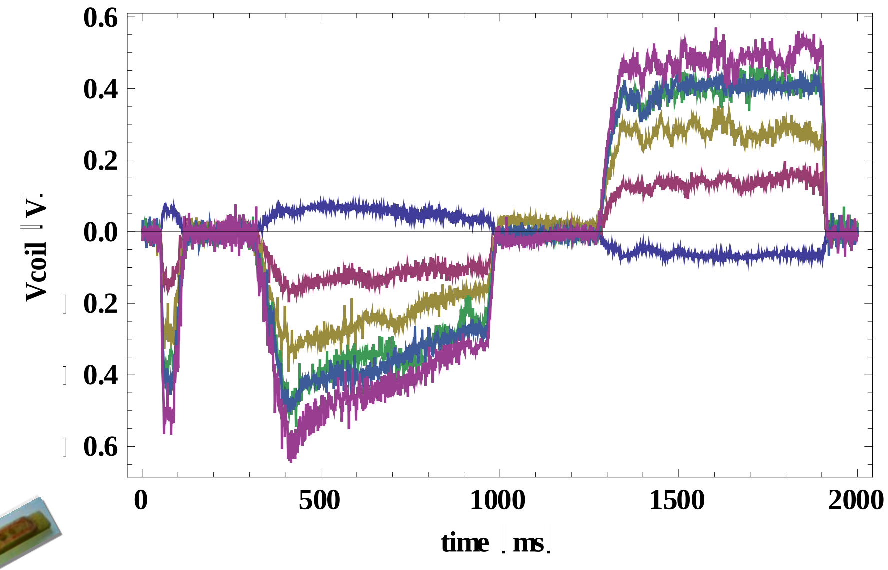


Measurement consistent with local 8 kHz LPF → noise not due to distribution

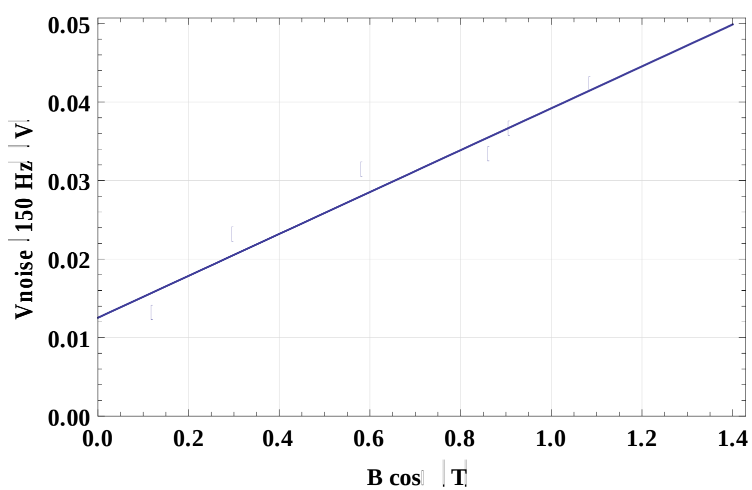


Noise drops in shorted coil
→ not due to acquisition system



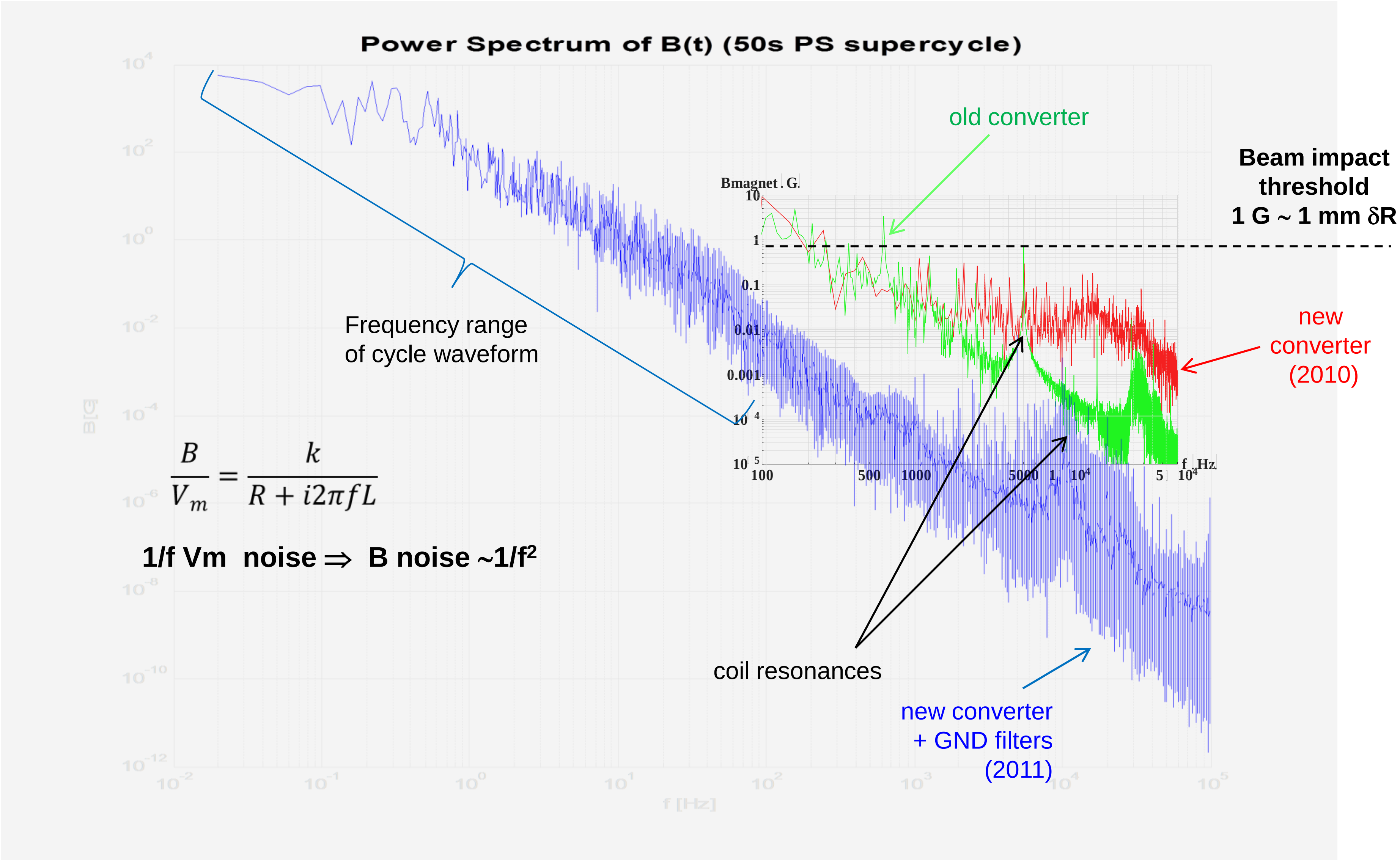


As the coil is turned from perpendicular to parallel to field, the noise varies linearly with the signal level
→ the noise mostly reflects actual magnetic field fluctuations



R Chritin, M. Buzio

Converter evolution and effects on the noise



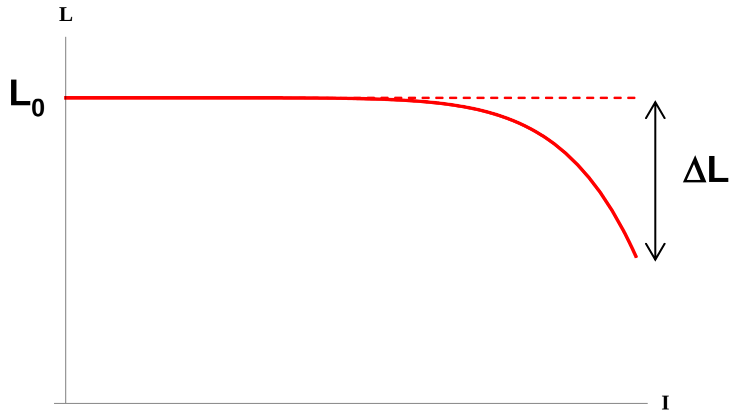
$$\frac{B}{V_m} = \frac{k}{R + i2\pi f L}$$

1/f Vm noise ⇒ B noise ~1/f²

Magnet inductance knowledge → essential for fast-cycled magnets

- Accurate knowledge of the load → **improve** the stability of the **current control** during operation
- Accelerator magnets behave electrically like **very large inductors**
- **Resistive magnet** → iron core **saturation** → **inductance non-linearity**

General qualitative behavior of magnet inductance *L* vs. excitation current *I*



- Main aim of this experimental determination: **establish L drop due to saturation at high current**
- Several definitions of inductance → all coincide in linear case , **all diverge at high field** (saturation)

Experimental determination of inductance in resistive magnet 2/6

Simplified electromagnetic model:

- Typical resistive magnet → excitation coil producing magnetic flux + iron yoke with relative permeability that channels the flux to an air gap.

Some of the flux leak out of the iron depending of field level and geometry

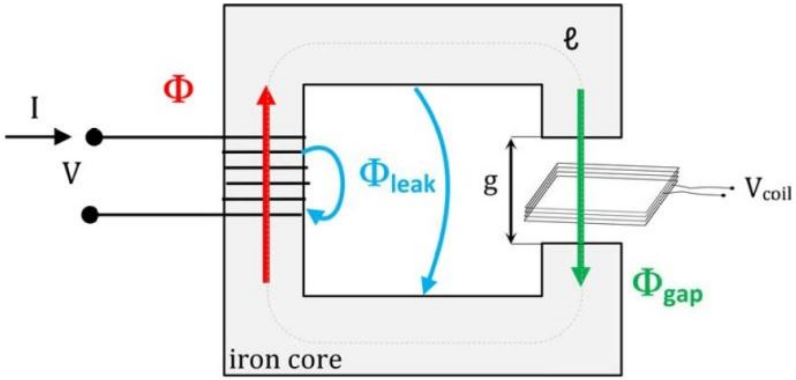


Fig. 2 – Schematic representation of a resistive dipole magnet

Field in the gap : $B = \frac{\mu_0 \mu_r N_t I}{l + \mu_r g}$

Inductance :

L *= Apparent inductance*

Ratio between excitation current and total flux crossing the coil.

$$L = \frac{\Phi}{I}$$

L$_d$ = Differential inductance (or incremental inductance)

Incremental ratio of flux to current or as the ratio of the inductive voltage to the current ramp rate .

$$L_d = \frac{d\Phi}{dI} = \frac{V - RI}{\frac{dI}{dt}}$$

L$_w$ = Energy equivalent inductance

Inductance related to the energy stored in the magnetic field. It can be evaluated form measurements of V and I.

$$L_w = \frac{2}{I^2}\int_0^t (V - RI) I dt$$

L$_g$ = Gap inductance

Inductance due to the energy in the air gap.

$$L_g = \frac{1}{\mu_0}\left(\frac{B}{I}\right)^2 g a l_m$$

g = air gap

a = air gap width

l_m = magnetic length

μ_o = vacuum perméabilité

Experimental determination of inductance in resistive magnet 3/6

Simulated L, L_d and L_w :

The link between the different definitions of inductance can be clarified by taking this simple expression for *L(I)* in closed form.

$$L(I) = L_0\left(1 - \left(\frac{I}{I^*}\right)^n\right)$$

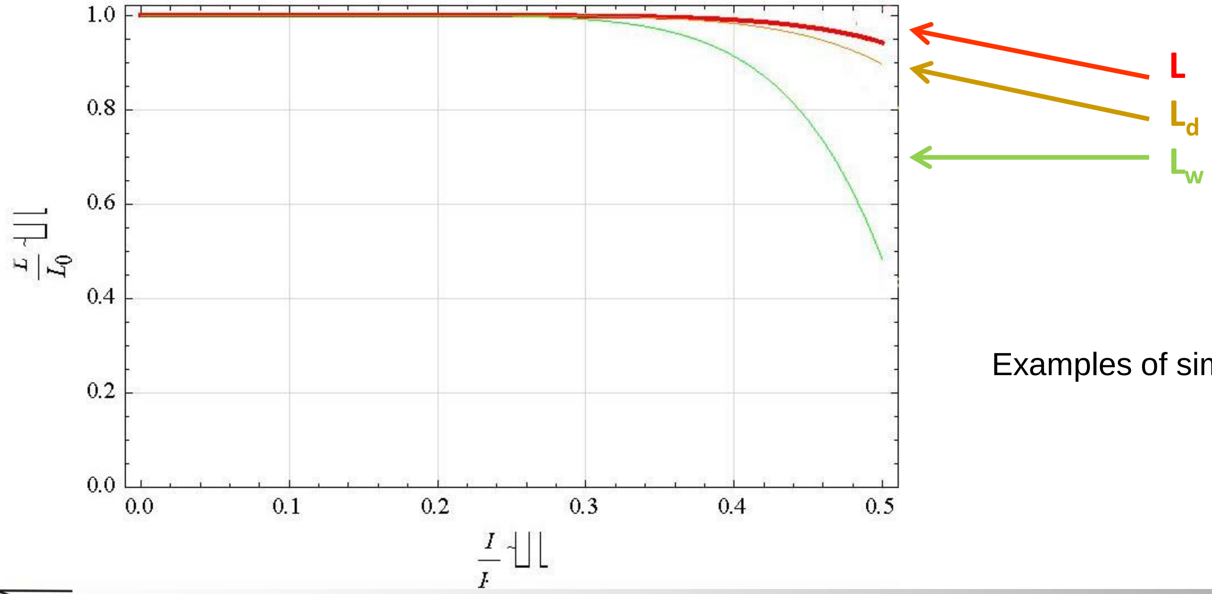
→ *if n* sufficiently high (which **describe magnets with delayed, but sharper saturation**) this expression fit experimental data reasonably well

By substitution of L(I) in the previous expression of L_d and L_w we can simulate the curves below and deduce that:

- Effects of saturation in $L_d(I)$ and $L_w(I)$ **are always proportional to the effect in *L(I)***, irrespective of the current.

- Drop of **energy equivalent** inductance L_w tends **to a limit magnitude** $\Delta L_w \rightarrow 2\Delta L$

- Drop of the **differential inductance** grows **unbounded**



Examples of simulated L(I), L_d(I) and L*w* (I) curves for n=10

Measurement procedure (on main SPS dipole type MBB):

- All the above defined versions of the inductance **can be derived from a continuous measurement of excitation current *I(t)* and voltage *V(t)*.** (Acquired with an ADC NI 16 bits USB 6216, 20 kHz sampling)

- Current was read on power supply DCCT, and voltage drop through connectors fixed onto the main current leads, in order to improve the accuracy of the resistance measurement.

- $V_{coil}(t)$ induced on an integral pick-up coil inserted into the magnet was measured in order to estimate the magnetic field energy in the gap.

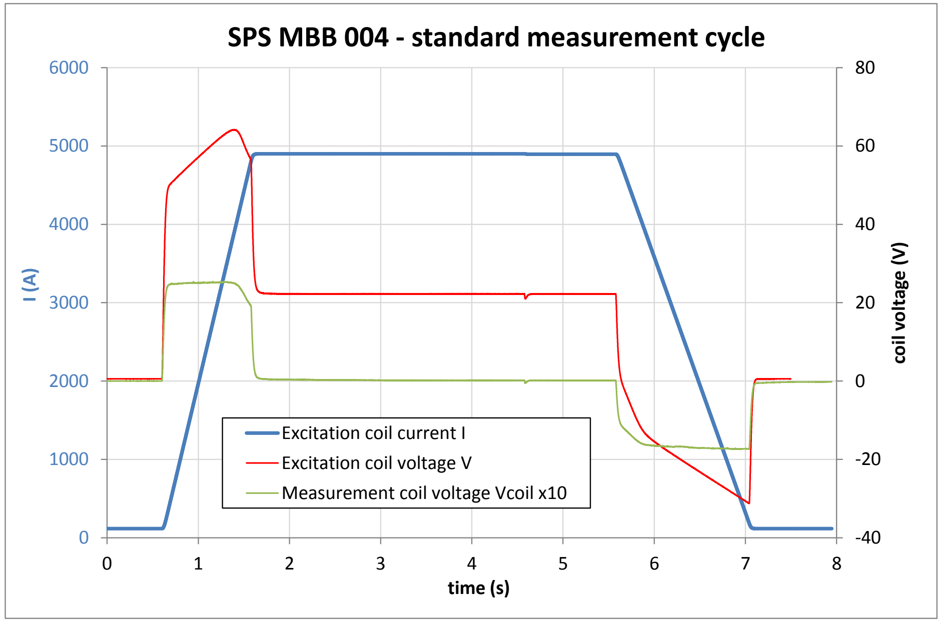
- Test done on standard measurement current cycle. (Saturation can be seen close to 4000 A).

- Coil resistance checked by taking the average of the V/I ratio on the flat-top (where both inductive voltages and eddy currents effects are negligible).

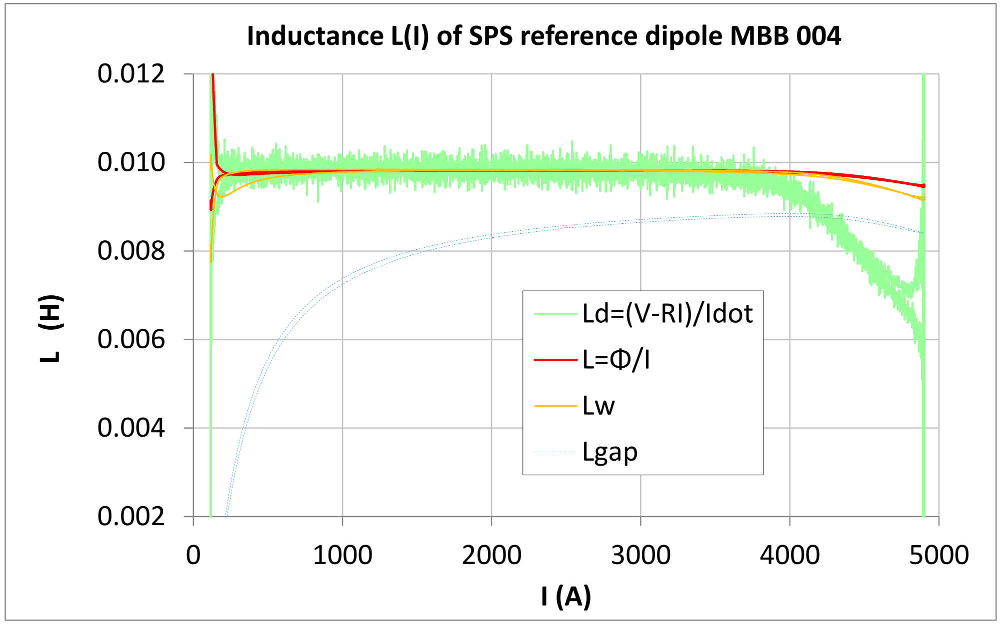
- Measurement done after cycling continuously the magnet in order to simulate the thermal conditions of the machine in operation.

Experimental determination of inductance in resistive magnet 5/6

Plotted results of the four versions of the inductance computed after measurements :



Signals measured at 20 kHz during a SPS reference MBB current cycle.
(Green curve (Vcoil) magnified by a factor 10)



Comparative plot of the apparent, differential, energy equivalent and gap inductances

The drop of the differential (L_d) and energy equivalent (L_w) inductance is respectively:

$$\frac{\Delta L_d}{L_0} \approx 39.4\%$$

$$\frac{\Delta L_w}{L_0} \approx 7.2\%$$

Experimental determination of inductance in resistive magnet 6/6

Conclusion:

- For MBB dipole a **magnetic field saturation** of just **3.4%** corresponds to a differential **inductance saturation** of almost **40%**.

- A large drop of the differential inductance at saturation is to be expected **even for magnets which limited saturation**.

- **Divergence** between differential and apparent inductance **grows larger for magnets which exhibit sharper saturation** at higher current

-In case such measurement is not possible **the drop of differential inductance may be predicted from the magnetic field behavior**, at the price of additional uncertainty due to the leaking flux fractions λ_{coil} and λ_{yoke}

- Measurement of the inductance curves can be done when necessary on the test bench in parallel with standard magnetic tests, adding little cost to the test program.