Measurement of LHC Superconducting Dipole and Quadrupole Magnets in Ramp Rate Conditions

G.Deferne, CERN

Aknowledgements:
M. Di Castro, S. Sanfilippo, L.Bottura, CERN

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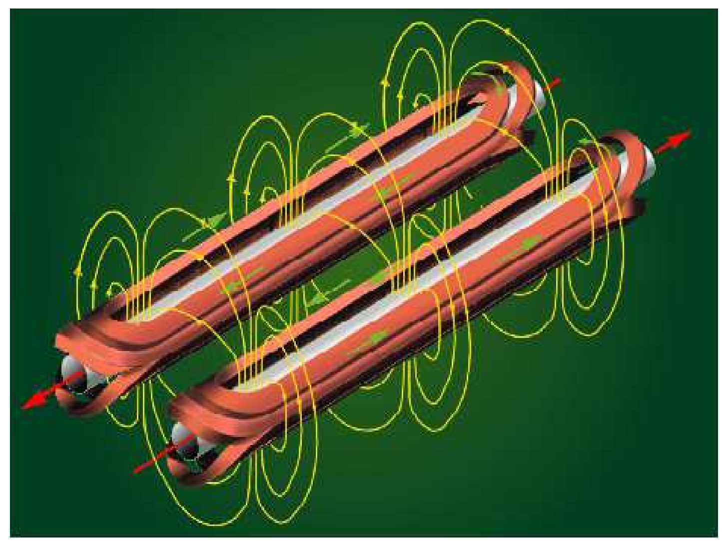


Motivations

- Rutherford type cables generate coupling currents during current ramps that affect reproducibility.

- Beam dynamic requirements:
  - Ratio b_2/b_1 has to be kept constant during the ramp from injection (0.54 T) to nominal (8.33 T) field. Tolerance is tight : $\delta b_2/b_1 \sim 2\ 10^{-5}$.

- Main field and harmonics distortion induced by ramp rate affect important beam dynamics parameters (tune, chromaticity). For example for LHC dipoles ramping at 10 A/s with $R_c \sim 15\ \mu\Omega$, the modelization gives:

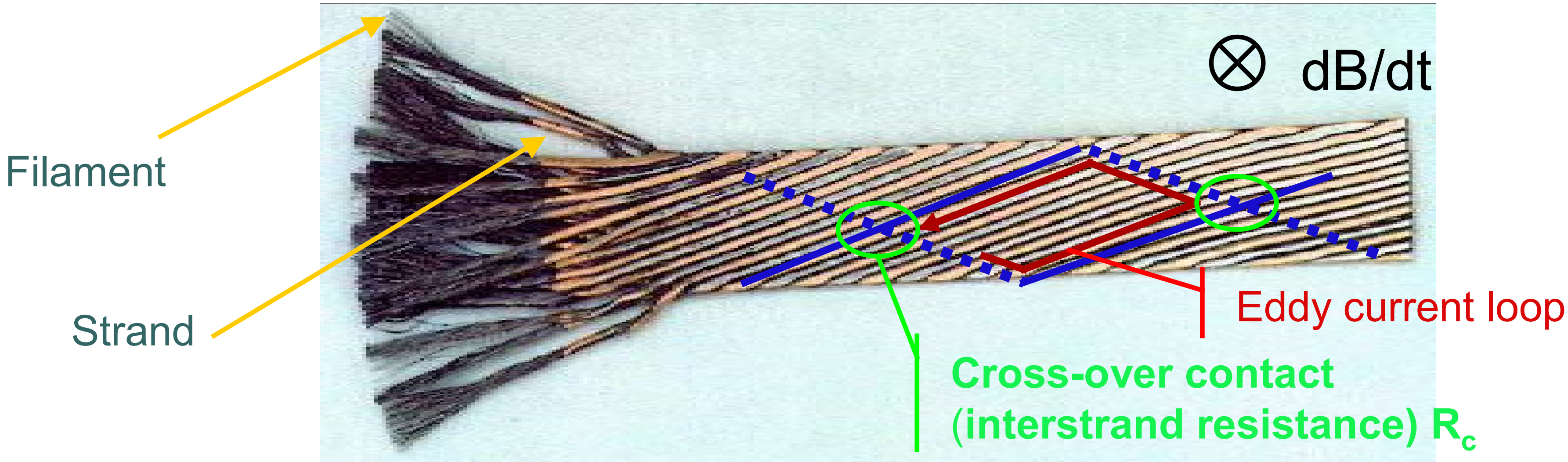
  - $\Delta b_1 = 5.4 \times 10^{-4} \rightarrow \Delta Q = 0.054$ vs. 0.003 allowed
  - $\Delta b_3 = 1.0 \times 10^{-4} \rightarrow \Delta \xi = 52$ vs. 1 allowed

➔ **B must be corrected!**

- Measurements in operating conditions and feedback to manufacturers during magnet production were needed.

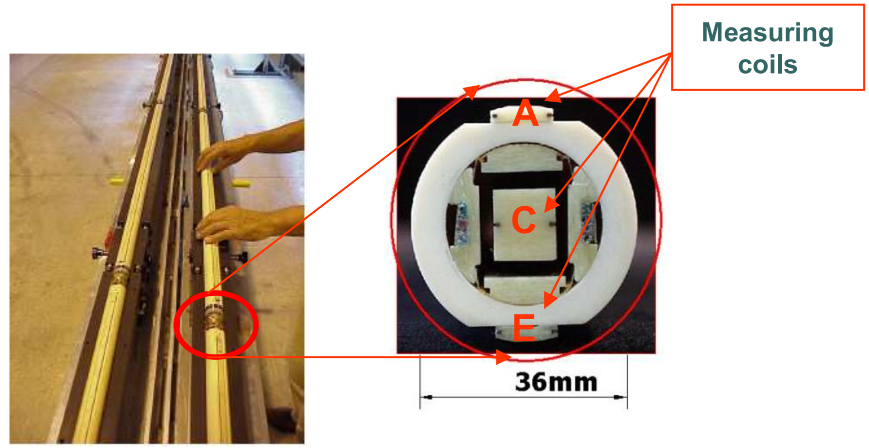
Coupling currents origin

- SC Rutherford cable in transverse field



- The eddy currents loops generate a magnetic field that adds ("*field advance*") to the background field inside the aperture, proportional to: dB/dt and $1/R_c$
- Current ramps induce field distortions for all harmonics Δb^{rr}_n, Δa^{rr}_n
- Minimum specified **Rc** value for the machine **~ 15 μΩ** which gives (estimation):
  - → b_1=6 units
  - → b_2=15 units
  - → multipoles errors ~ 0.1-1 units

Measurement techniques (1)



- Stationary coils shafts for field advance (FA) measurements
- Rotating shafts for multipoles measurement

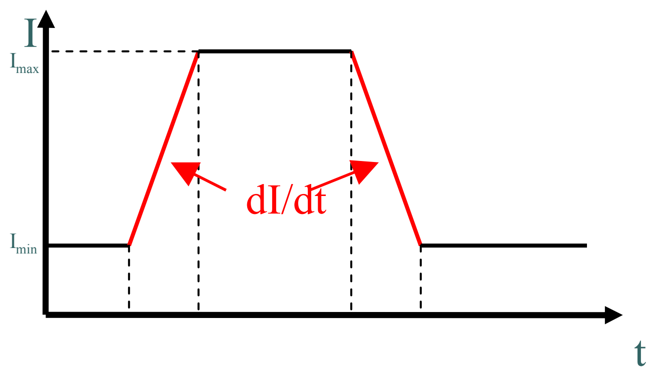
  - Dipole shafts:
    - 13 sectors of 3 coils with 36 turns each available
    - Magnetic coil area: **0.351** [m^2/coil] +/- 0,001 [m^2]

  - Quadrupole shafts:
    - 6 sectors of 5 coils with 64 turns each
    - Magnetic area: **0.381** [m^2/coil] +/- 0.001 [m^2]

Measurement techniques (2)

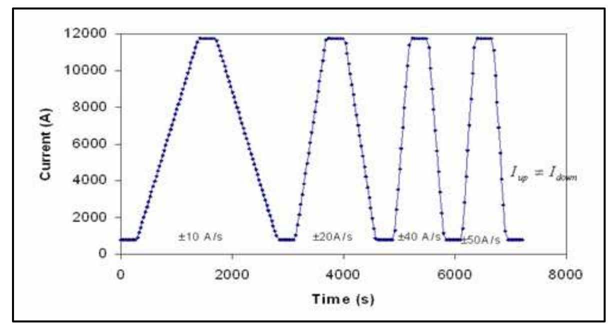
<u>Ramp effect on B_1, B_2 (Field Advance)</u>:

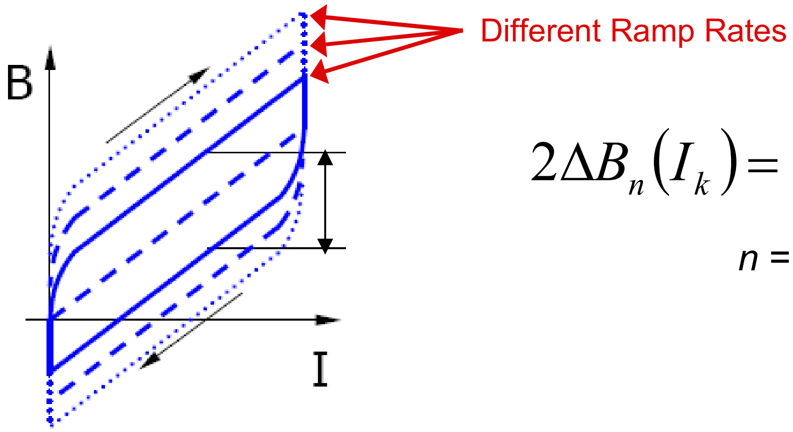
Fixed coils measurements



<u>Ramp effect on multipoles</u>:

Rotating coils measurements





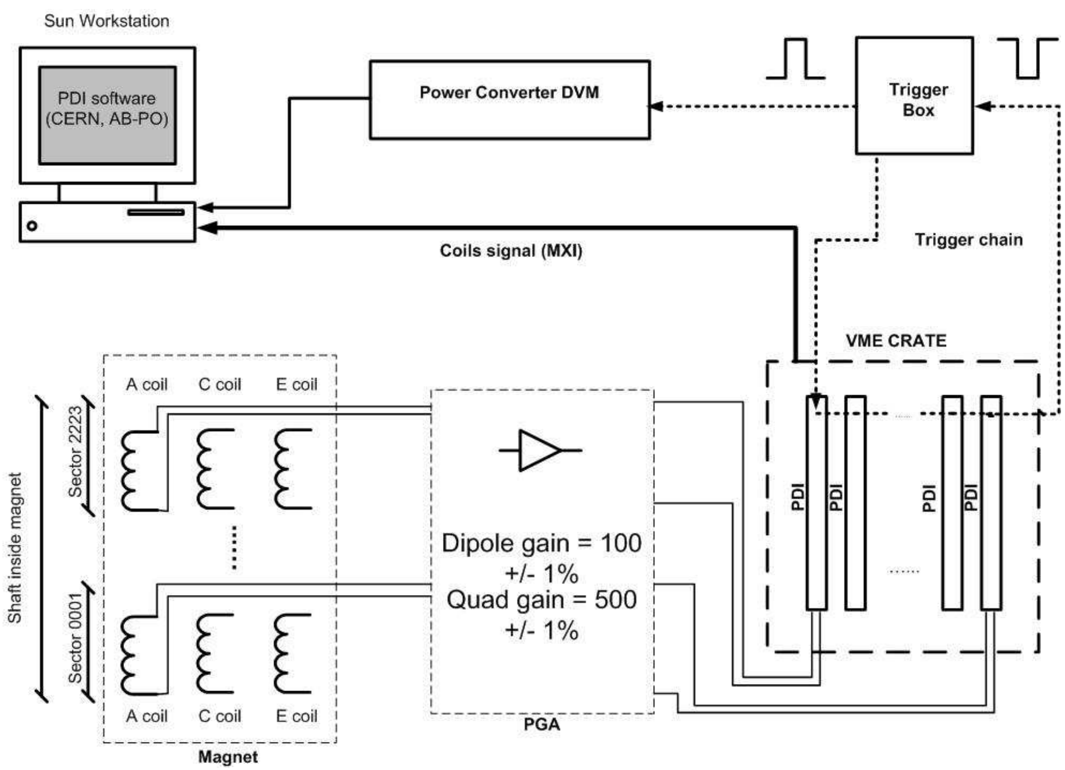
$$2\Delta B_n(I_k) = \left(B_n^{up}(I_k) - B_n^{down}(I_k)\right)$$

n = 1 and 2

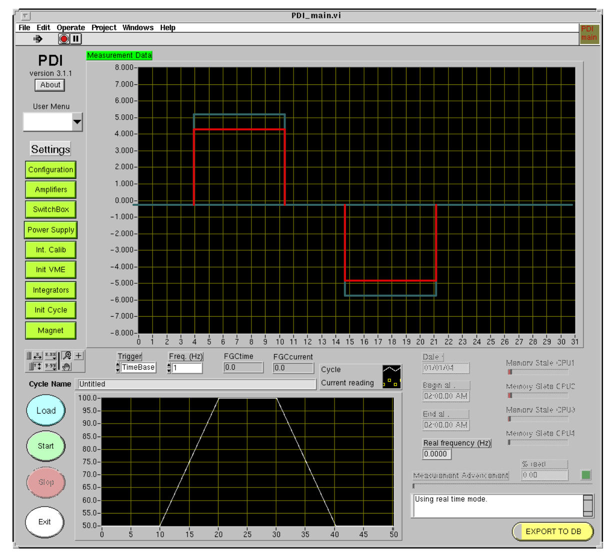
☺ Both techniques use mostly existing magnetic measurement equipment!

Field advance (1): measurement equipment

- **Stationary coils** in dB/dI, one coil per shaft sector
- Signal amplification through PGA
- CERN VME Precision Digital Integrator using internal 1 Hz or external **time based** trigger (0.1, 0.2, 1, 2 or 5Hz available)
- DCCT current reading synchronized with the PDI's



- Measurements are driven by the CERN "***PDI***" LabView Software running on a SunBlade 150

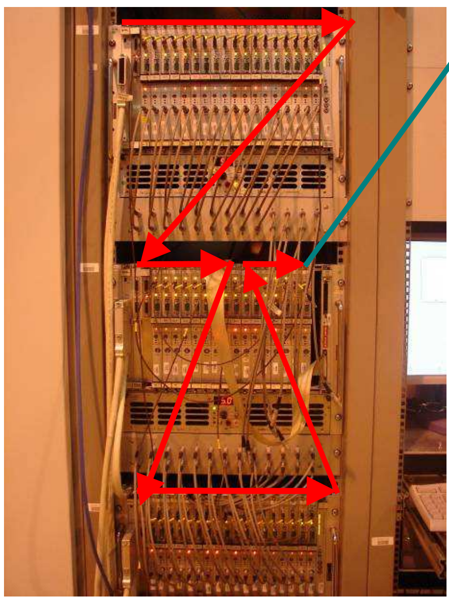


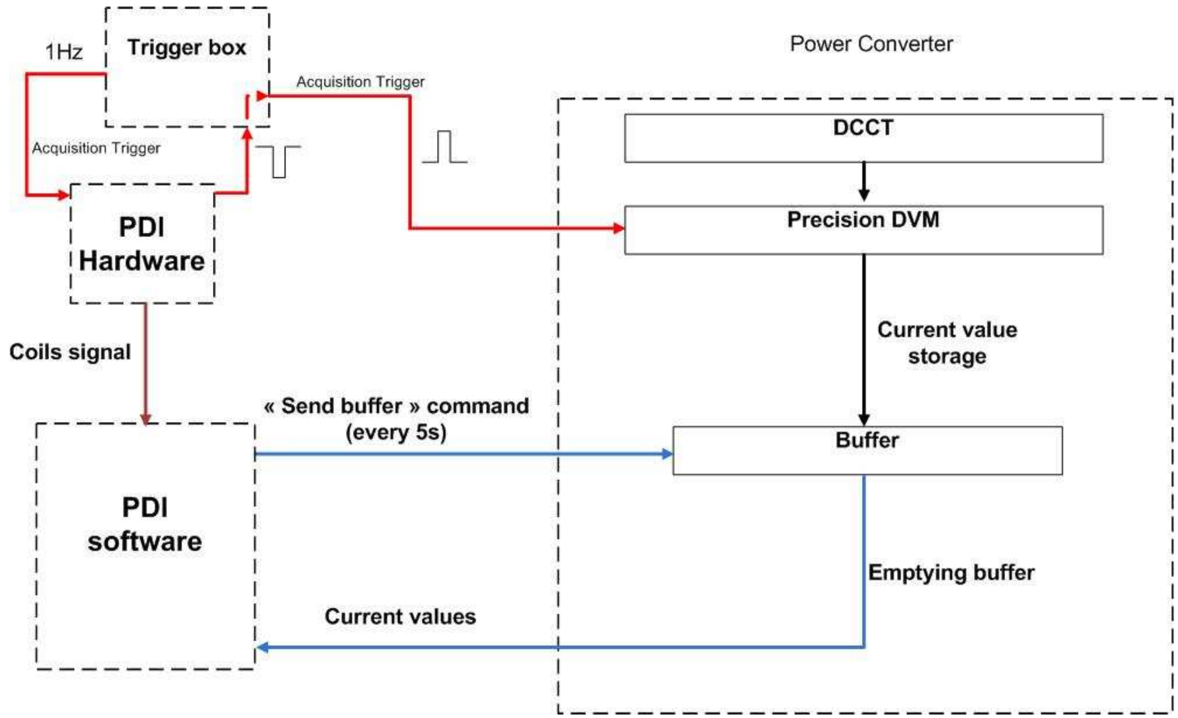
Field Advance (2): coil voltage vs current reading

- Synchronization between voltage integration and current reading is an essential parameter of the FA measurements
  - current/signal delay specification for field advance meas.: 1 [ms]
  - Trigger delay from first to last integrator <10 [µs]
  - Over all delay of the trigger chain better than 100[µs]

Trigger chain distributed to both apertures

Trigger sent to DVM for current reading





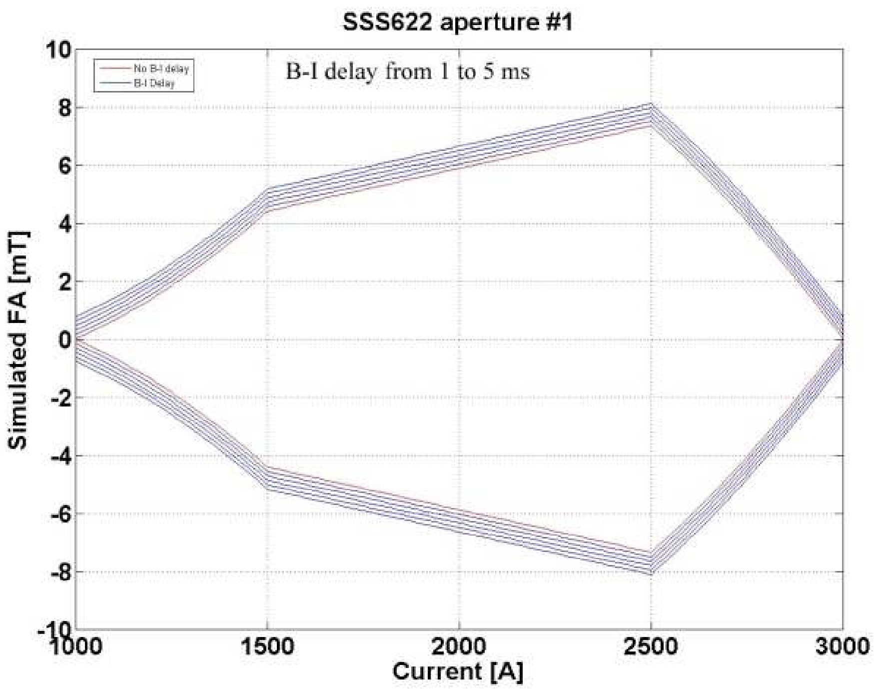
Field Advance (3): effects of trigger delay and sampling rate

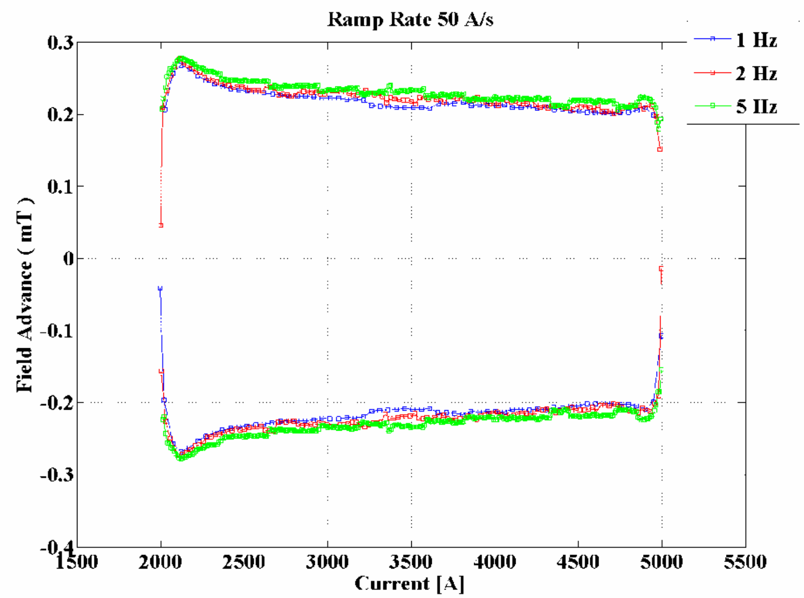
• Simulated additional delay in current reading:

1 [ms] ≈ 0.2 [mT]

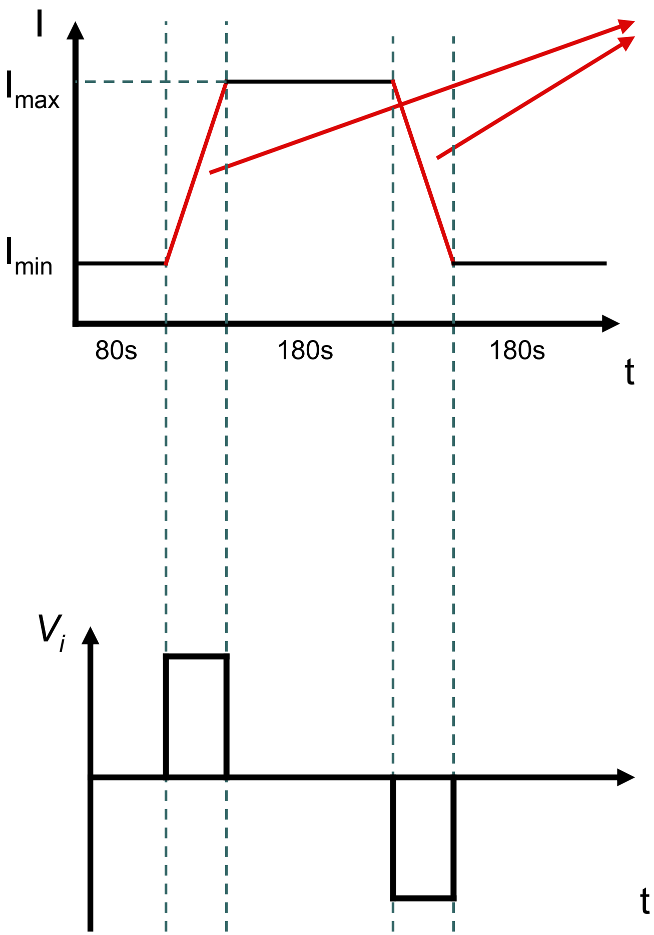
FA measurements at different sampling rate

$\Delta B_{(1\text{-}5Hz)} < 0.5$ [mT]





Field Advance (4): Data Processing



dI/dt → For each coil of the shaft:

$$V_i = \frac{V_{measured}}{G_{PGA}}$$

G_{PGA} = 100 for dipoles

G_{PGA} = 500 for quads

- Voltage offset (1.5-2 μV, mainly due to PGA), constant and stable during the whole measurement is removed from signal

→ $$\varphi_i = -\int V_i dt$$

→ $$B_i = \frac{\varphi_i}{A_i}$$

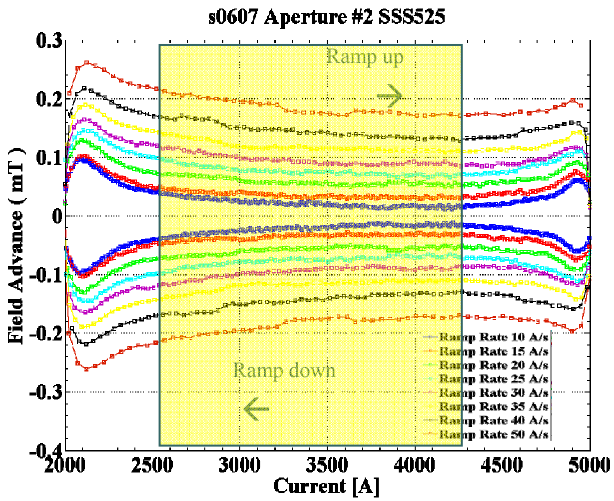
Where A_i the area of the coil

Half field hysteresis:

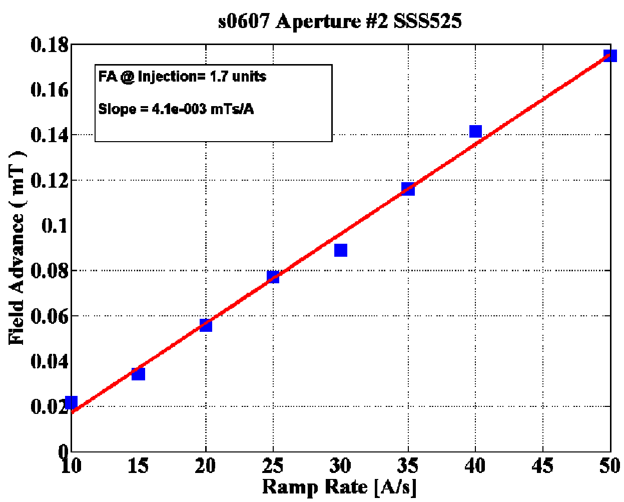
$$\Delta B_n(I_k) = \frac{1}{2}\left(B_n^{up}(I_k) - B_n^{down}(I_k)\right)$$

where I_k is the instant current during ramp up B^{up} (I_k) and ramp down B^{down} (I_k)

Field Advance (5): Data Processing (example of quadrupole)



- The field is measured at different ramp rate to distinguish the ramp rate effect from the steady-state contribution
- ΔB is averaged between 2500A-4500A (« flat zone »)
- ΔB is plotted as a function of the ramp rate



Dependance of ΔB on the ramp rate:

$$\longrightarrow \quad \Delta B = \Delta B^{(0)} + S\frac{dI}{dt}$$

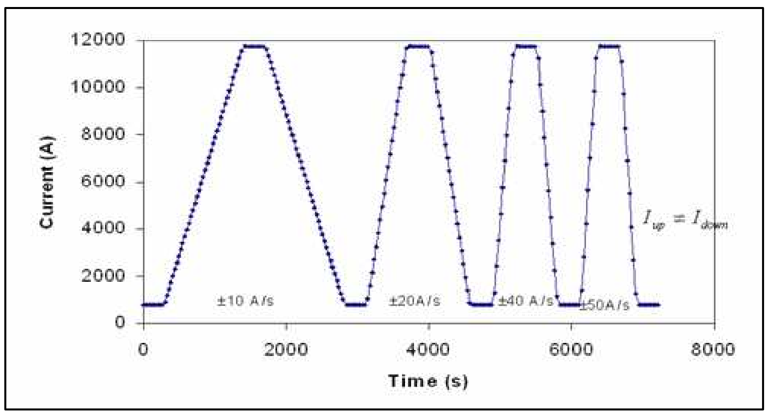
where - $\Delta B^{(0)}$ is an offset due to the demagnetization

- the slope S (in mTs/A) reflects mostly the interstrand coupling current due to the R_c

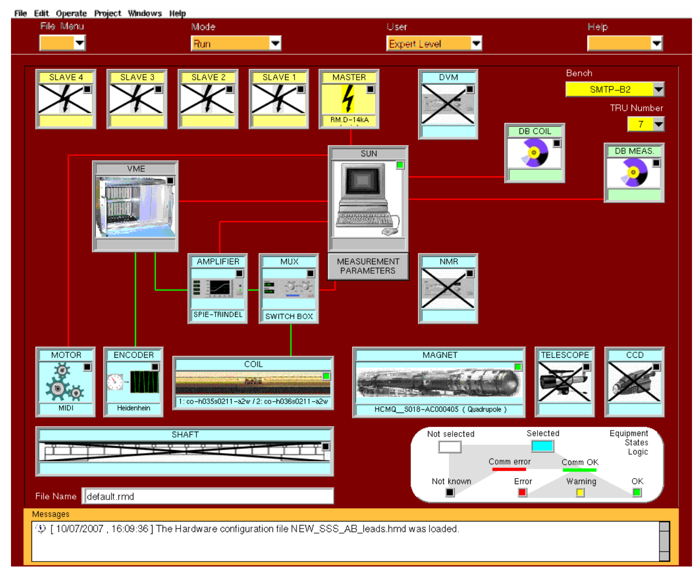
Ramp Rate Effect on Multipoles (1): equipment

- **Rotating coils** in dB/dt, giving absolute and compensated signals
- Signal amplification through PGA
- PDI using trigger from angular encoder
- DVM current reading triggered by the MMP application

• Measurements are performed during current ramps, up and down

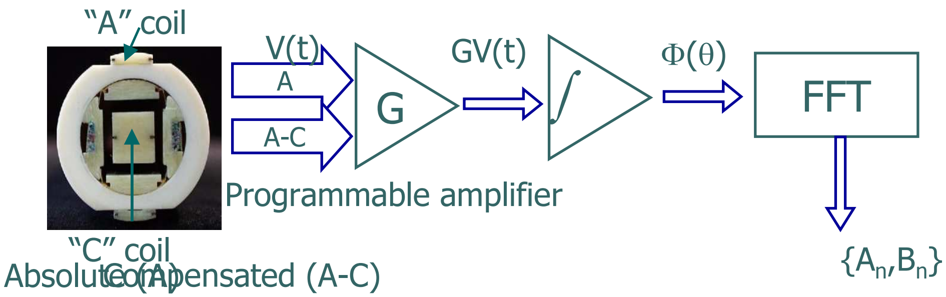


- Measurements are driven by the CERN standard "***MMP***" LabView 5.1 Software on a SunBlade 150



MMP software main configuration panel

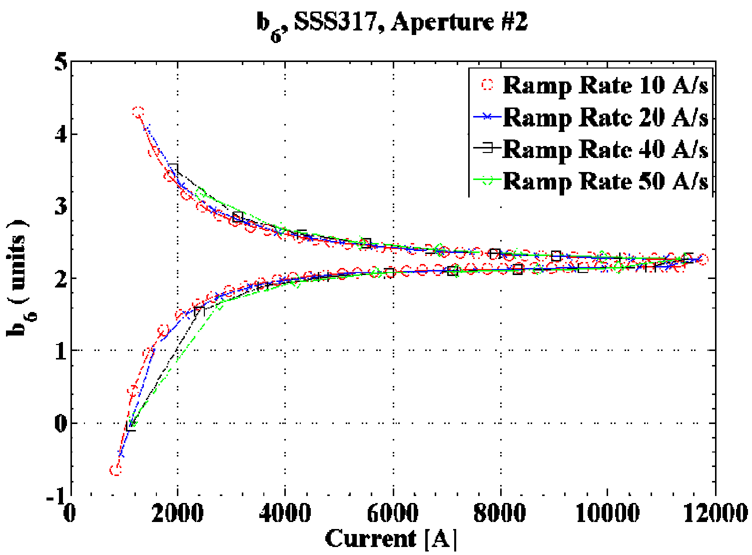
Ramp Rate Effect on Multipoles (2): processing



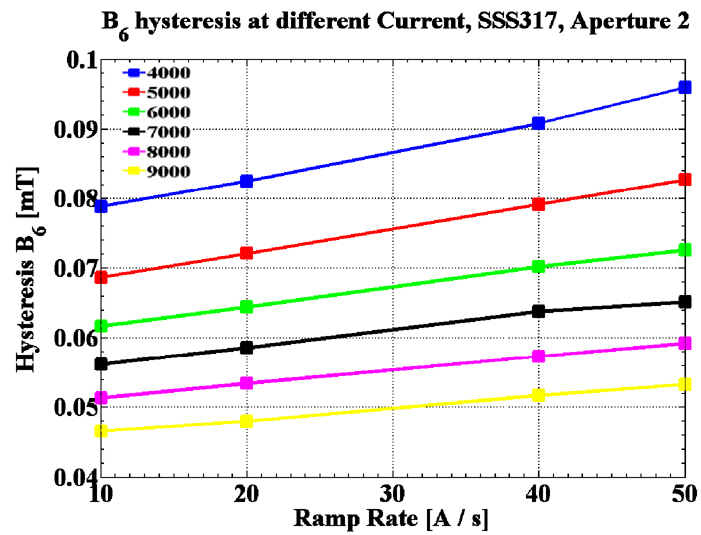
- The analysis is done for each normal and skew harmonic
- The difference between each multipoles field measured during ramp up and down is computed for a given current I_k (at a given ramp rate):

$$\Delta B_n(I_k) = \frac{1}{2}\left(B_n^{up}(I_k) - B_n^{down}(I_k)\right)$$

- The data is then treated the same way than for field advance.

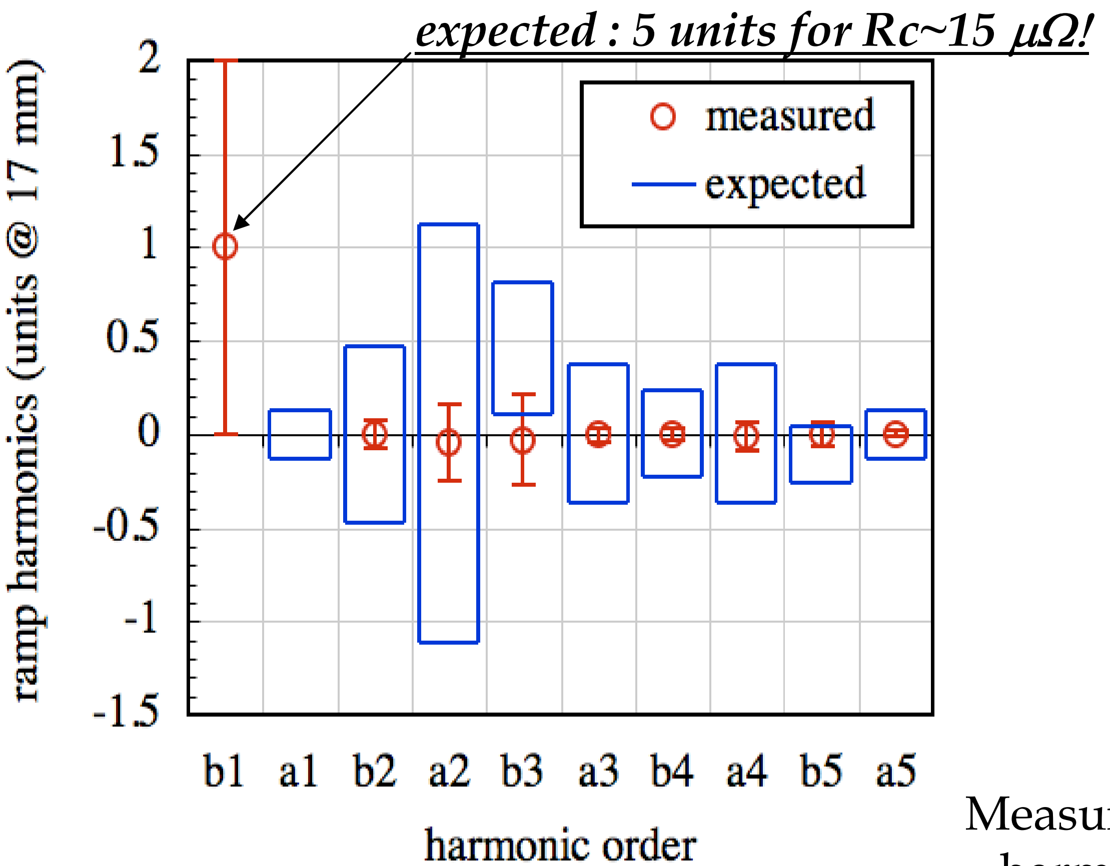


Example of b_6=f(I) at different ramp rates



Example of B_6=f(dI/dt) at different currents

Results (1): Ramp rate effect on dipoles



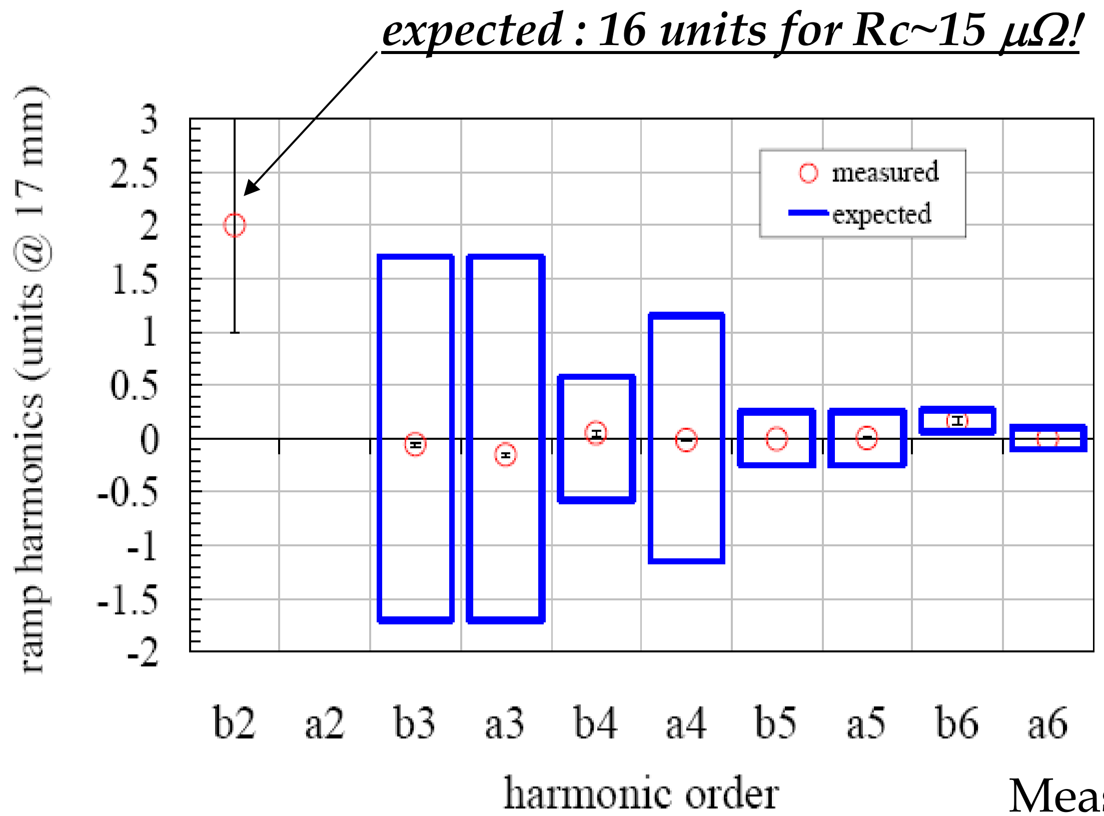
	average (units)	sigma (units)
b1	1.00	1.00
a1		
b2	0.00	0.08
a2	-0.04	0.20
b3	-0.03	0.24
a3	-0.01	0.03
b4	0.00	0.03
a4	-0.01	0.08
b5	0.00	0.06
a5	0.00	0.01

Measured vs. expected ramp induced harmonics referred to injection field (0.54 T) and nominal ramp-rate (10 A/s).

statistic on 64 MB (for multipoles) and 8 MB for main field

Small effect, below 0.1 unit, 1 unit for b_1
*Results consistent with R_c well above **50** $\mu\Omega$.*

Results (2): Ramp rate effect on quadrupoles



statistic on 8 MQ (for both multipoles and main field)

	average (units)	sigma (units)
b2	2.00	1.00
a2		
b3	-0.05	0.02
a3	-0.15	0.02
b4	0.05	0.03
a4	-0.01	0.01
b5	0.00	0.00
a5	0.00	0.01
b6	0.16	0.04
a6	0.00	0.00
b7	0.00	0.00
a7	0.00	0.00

Measured vs. expected ramp induced harmonics referred to injection field (0.54 T) and nominal ramp-rate (10 A/s).

Small effect, below 0.2 unit for multipoles, 2 units for b2. Results consistent with R_c between ***100-150*** *μΩ.*

Conclusion

- **Effective technique to measure ramp rate induced field errors on main field and multipoles**
  - Error on both dipoles and quadrupoles: max. 1 [unit]
  - 3 hours lasting measurements per magnet
  - Automatic data processing
- **Ramp rate effects on field quality**
  - Can be neglected for multipoles and b_1, 2 units for b_2
  - Results consistent with $R_c \approx$ 50 [$\mu\Omega$] for dipoles, $\approx$ 100-150 [$\mu\Omega$] for quadrupoles.
  - Order of magnitude of R_c confirmed using AC loss measurements on dipoles and quadrupoles

References

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