Summary of the Session on *Dynamic Effects*

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15th International Magnet Measurement Workshop, Fermilab, August 21-24, 2007

Session Contents

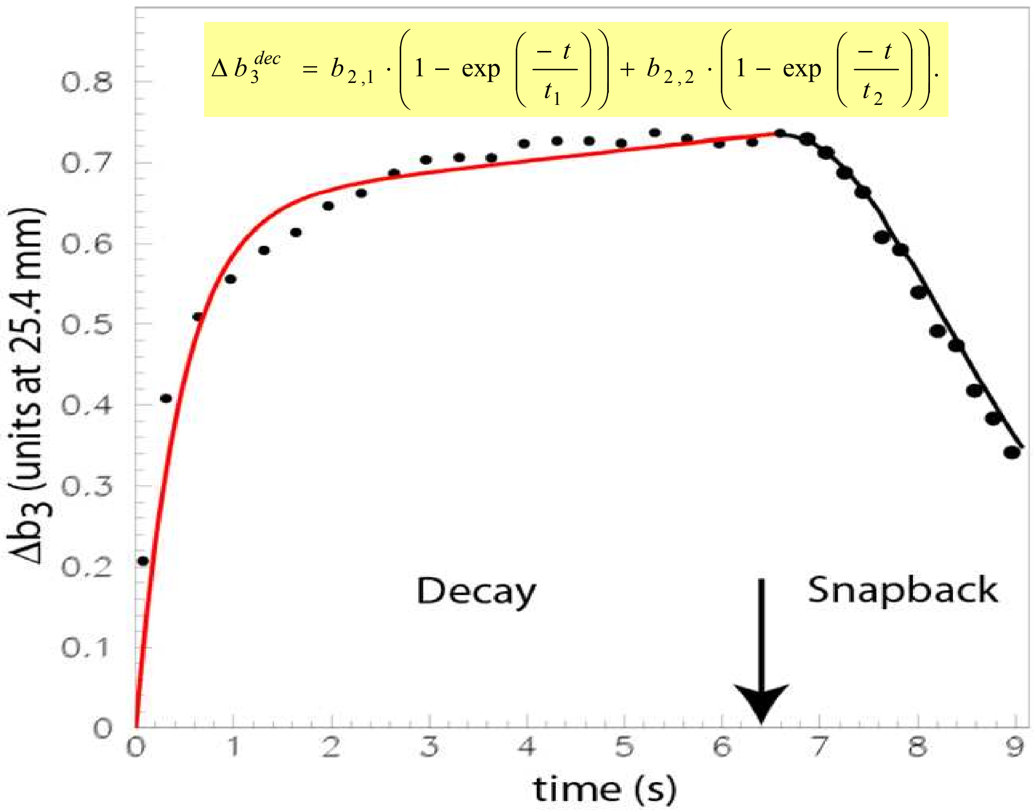
- Three Talks:
  - *Decay and Snapback Measurements for the Tevatron* (Gueorgui Velev, FNAL)
  - *Curved Fluxmeter for Static and Dynamic Characterization of Pulsed CNAO Magnets* (R. Chritin, CERN)
  - *Measurement of LHC Superconducting Dipole and Quadrupole Magnets in Ramp Rate Conditions* (Guy Deferne)
- Nature of content very similar to that in the session on Fast Ramp measurements.
- Techniques ranged from fast rotating coils to a fixed coil array, as well as "normal" rotating coils.

Tevatron Magnets: G. Velev

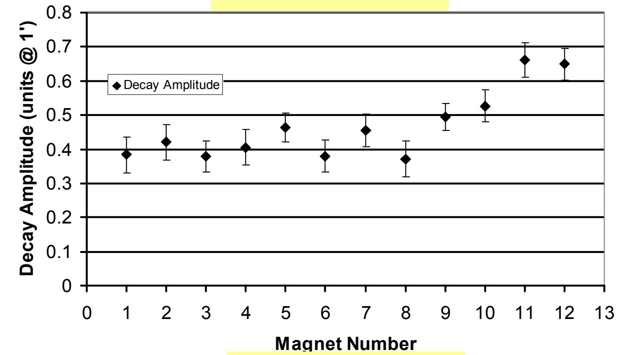
- Time decay and snapback measured in detail in 12 Tevatron magnets.
- Used fast rotating coils up to 6 Hz, but most work apparently done at 3 Hz.
- DSP and ADC based acquisition.
- Observation of two exponential time decay.
- Test of snapback scaling law.
- Main field decay behavior (hard to do!)
- Behavior of higher order harmonics.

Fast decay at beginning of injection

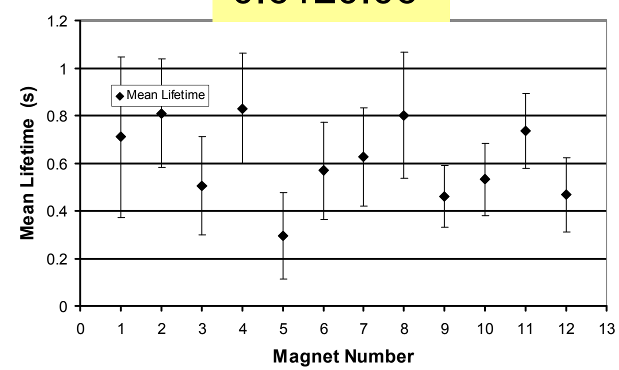
- The data 6 s injection
- The logarithmic function does not work



0.45±0.10



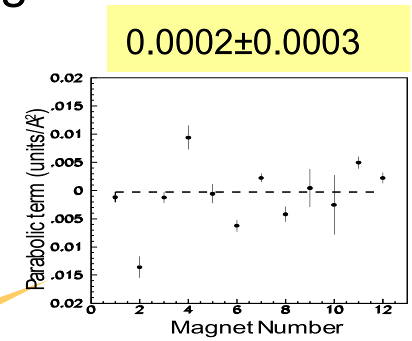
0.61±0.06

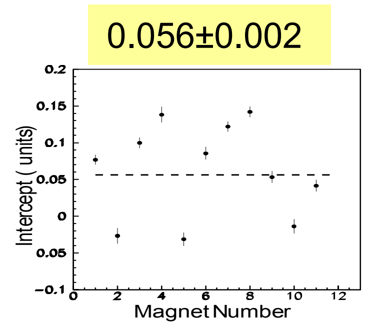


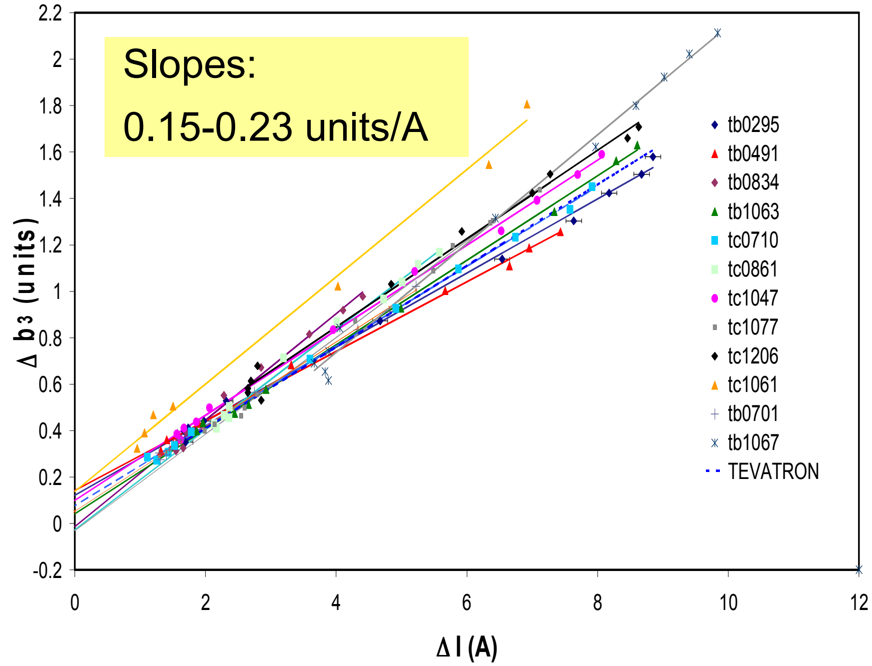
Remarkably small magnet to magnet variation in the decay parameters.
How about the second time constant?

Scaling Law

- Scaling law:
  - linear without intercept
  - all the magnets with same design should have the same correlation
- 12 Tevatron dipoles tested with the DSP system.
  - accurate linear dependence for every magnet is observed
  - slopes are close but inconsistent within the error values
  - for an ensemble the linear correlation should be preserved
- Feed-forward version is now implemented in the Tevatron



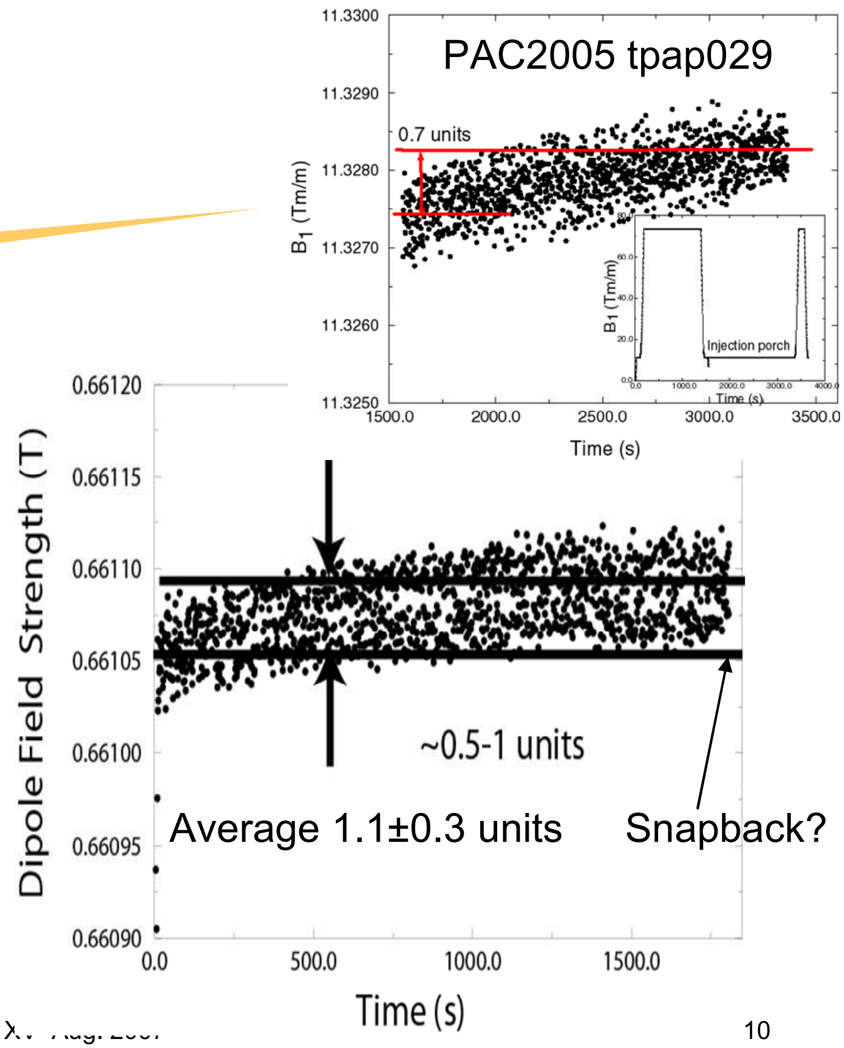




Decay in the main field

- Quadrupole main field – reported at PAC2005
- Observed: 0.7±0.1

- The decay amplitude is in the range of 0.5 to 1.6 units
- Attempts to find the following snapback-type effect were unsuccessful.
- Taking into account the average decay change in the main dipole field of 7.35x10-5 T and the current needed for this change, we estimated that the snapback should occur during a time interval of ~ 0.6 s.



Very difficult to measure decay, and particularly snapback, in the main field. Decay can be "guessed" due to long time periods. Snapback occurs fast!

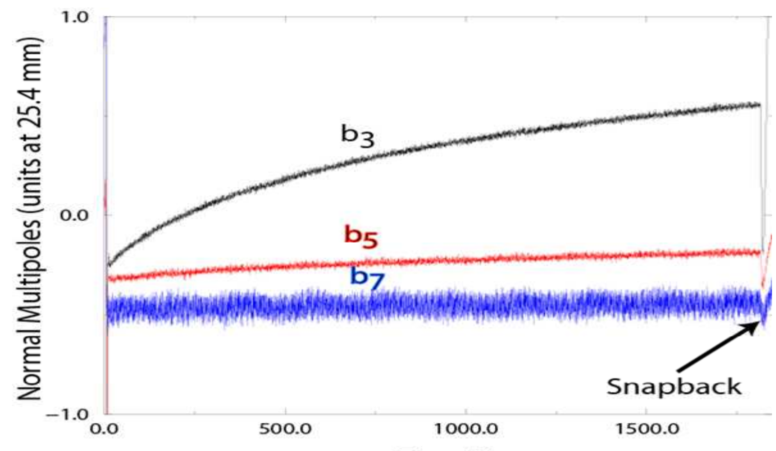
High order harmonics

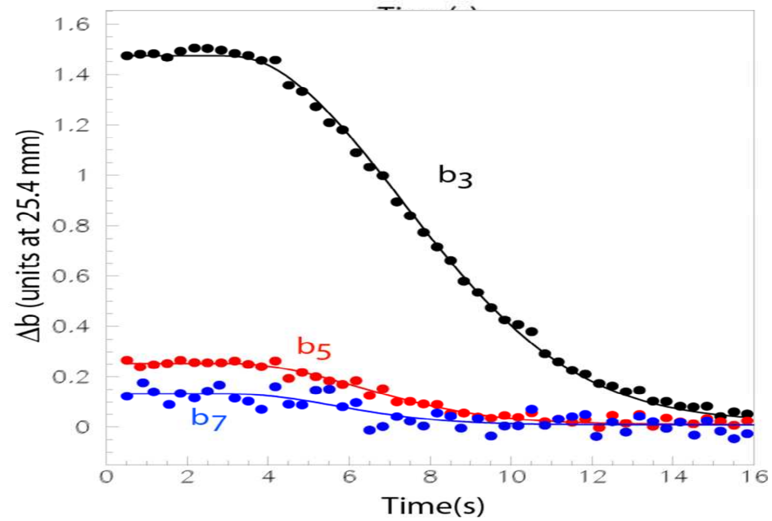
Why should the snapback times be different for different harmonics?

- Decay in decapole (b_5) and tetradecapole (b_7)
- Results are presented relatively to sextupole decay
- The same sextupole scaling law?

$$\Delta b_k^{sb} / \Delta b_3^{sb} = t_{sb,k}^2 / t_{sb,3}^2, k = 5,7$$

Dipole name	$\Delta b_5^{sb}/\Delta b_3^{sb}$ amplitude ratio	$\Delta b_7^{sb}/\Delta b_3^{sb}$ amplitude ratio	$t_{sb,5}/t_{sb,3}$ snapback time ratio	$t_{sb,7}/t_{sb,3}$ snapback time ratio
TB0295	0.11	0.07	0.53	0.94
TB0491	0.20	0.09	0.73	1.11
TB0701	0.22	0.05	0.92	0.43
TB0834	0.27	0.05	1.28	0.71
TB1063	0.14	0.05	0.63	0.35
TB1065	0.18	0.07	0.87	0.78
TC0710	0.17	0.09	0.76	0.63
TC0861	0.22	0.07	1.02	0.14
TC1047	0.22	0.05	0.95	0.67
TC1061	0.19	0.07	0.84	0.60
TC1077	0.19	0.07	0.83	0.73
TC1206	0.16	0.08	0.79	0.95
Average	0.19±0.04	0.07±0.2	0.85±0.19	0.67±0.27





Curved Fluxmeter for CNAO: R. Chritin

- Conventional, curved dipoles.
- Linear array of curved stationary coils.
- Ramp rates ~ 1.5 T/s.
- Field homogeneity desired $\pm 2\times10^{-4}$ over fairly large volume.
- Novel use of a reference coil to overcome difficulty with absolute calibration of curved coils.
- Shimming to improve field quality – need to use a special type of bolts.
- Eddy current control and "Memory effect".

CNAO

AT - MTM

CNAO measurements: 26 curved dipoles

Nominal maximum field [T]	1.4992
Bending radius [m]	4.231
Bending angle [deg]	22.5
Magnet gap height [mm]	72
Magnetic length (@ max.) [m]	1.6772
Overall length [m]	1.9046
Good field region [mm]	± 60 (hor); ± 28 (vert)
Field Quality [ΔB/Bnom]	$\pm 2 \cdot 10^{-4}$
Nominal Current [A]	2800
Maximum Current [A]	3000
I nominal / I injection ratio	17
Field stabilization time	500 ms

- Curved fluxmetre choice :

⇒ designed to measure integrated field and its uniformity along the bent beam path.

⇒ allows small difference between the measured integrated field and the integrated field on the real trajectories of the beam.

⇒ method based on bucked signals appears to be the most appropriate for the high homogeneity of the field requested.

R. Chritin
CERN - Geneva

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CNAO

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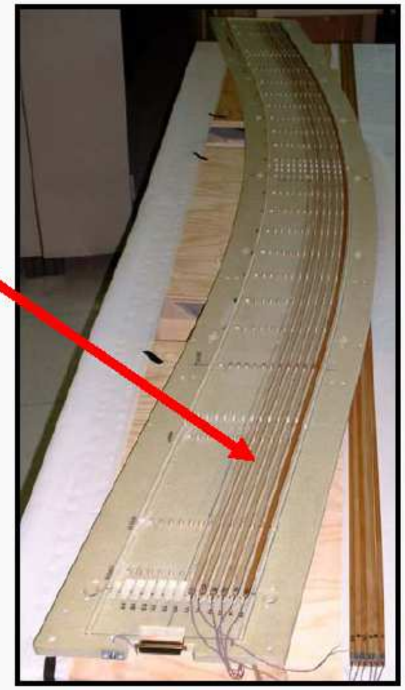
Fluxmeter making



Fluxmeter

- 11 curved coils (+ 1 spare) - Coils size = 6 x 8 x 2755 mm.
Mounted on a rigid support, and maintained by glass fiber pins (15 mm spacing).

- A cover protect the coils ⇒ the reference coil can slide on it without creating any vibration on the fluxmeter's coils.

- 14 Delrin wheels ⇒ to roll the fluxmeter longitudinally.

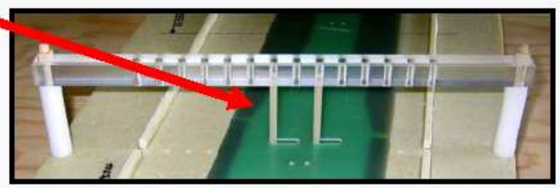
- Connections of the coils with twisted pair cables to a CANNON connector.

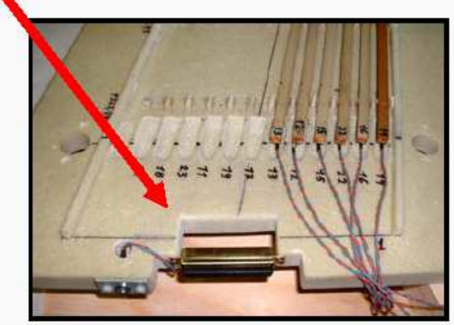
Reference coil

- Reference coil curved in the same way as the fluxmeter's coil.

- Stability guaranteed by its glass fibre support (116 mm width, 10 mm height).

- Precise positioning of the reference coil on each coil of the fluxmeter with a system based on vertical rods .





Relative accuracy of coils better than 10^{-4}

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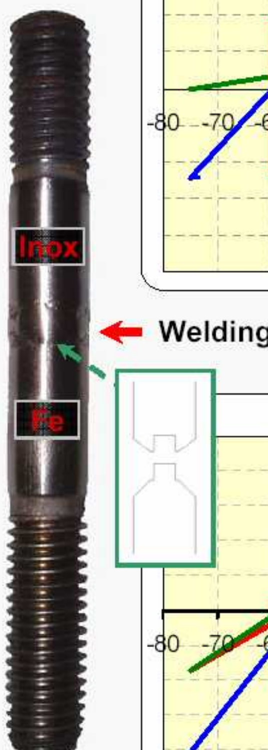
Bi-metal bolts effect on shimming

Bi-metal bolts:

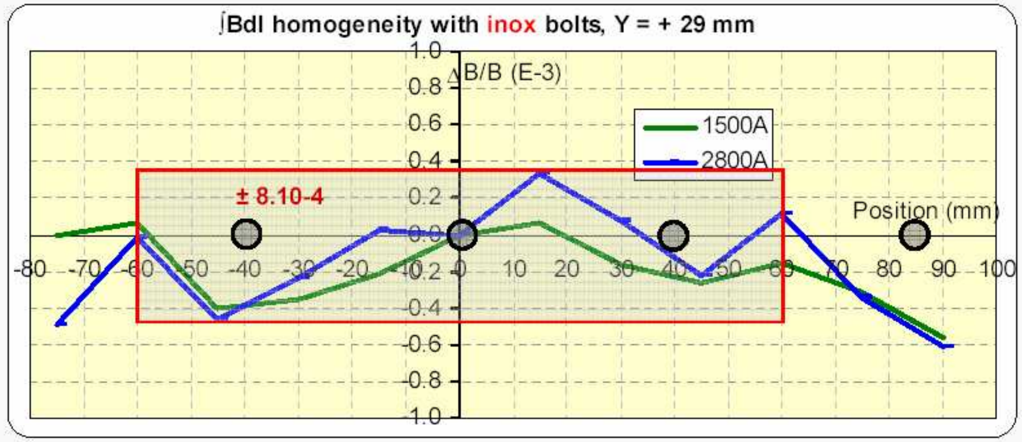


⇒ allow ± 10^{-4} field homogeneity adjustment (We couldn't obtain it only with shimming plates).

⇒ allow the magnet to fulfill the specifications for both I injection and I nominal.

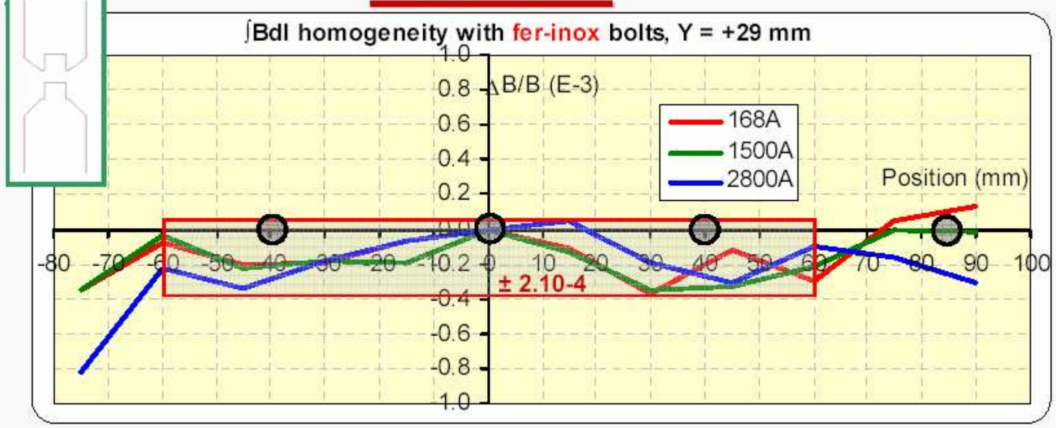
⇒ widen the good field area on the Y axis.

Inox bolts



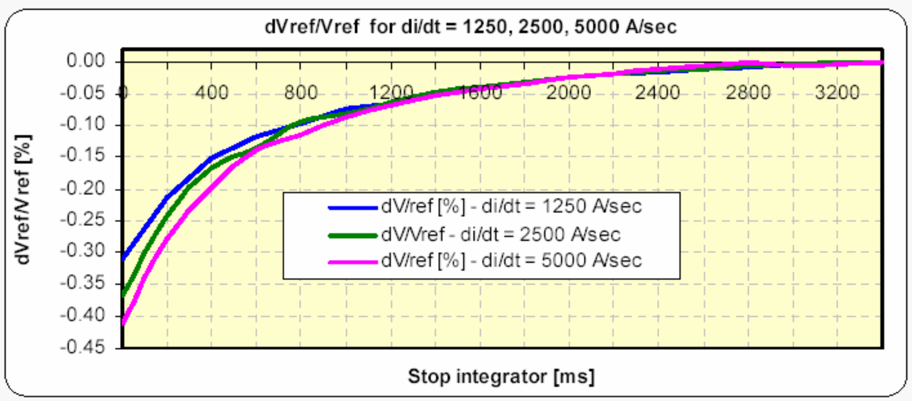
= Bolts position

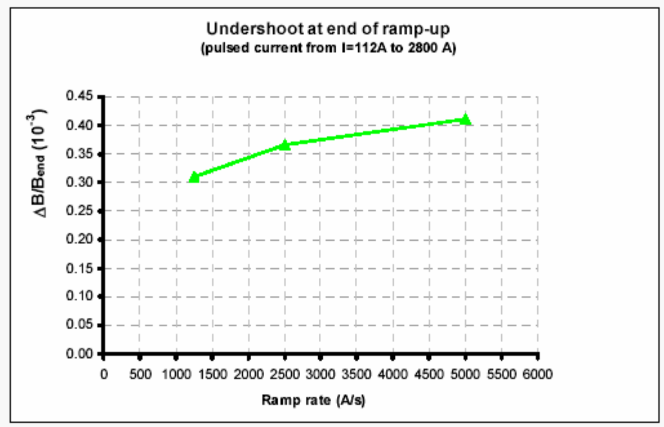
Fe-Inox bolts



Magnet dynamic behavior

- Strong Eddy current effects, field stabilized more than 2 seconds after the current flat-top start, with growing current.
- Even with phosphated metal sheets. (2nd prototype)
- Eddy current not proportional to di/dt (curves below) ⇒ CNAO magnet behaves like a short magnet.
- Needs at least 30 cycles to stabilize the remanent field ⇒ Problem due to the <u>only hot-rolled</u> yoke metal sheets ?
  (CNAO magnets are built using only hot-rolled metal sheets, without a following cold-rolled process as on other former magnets).

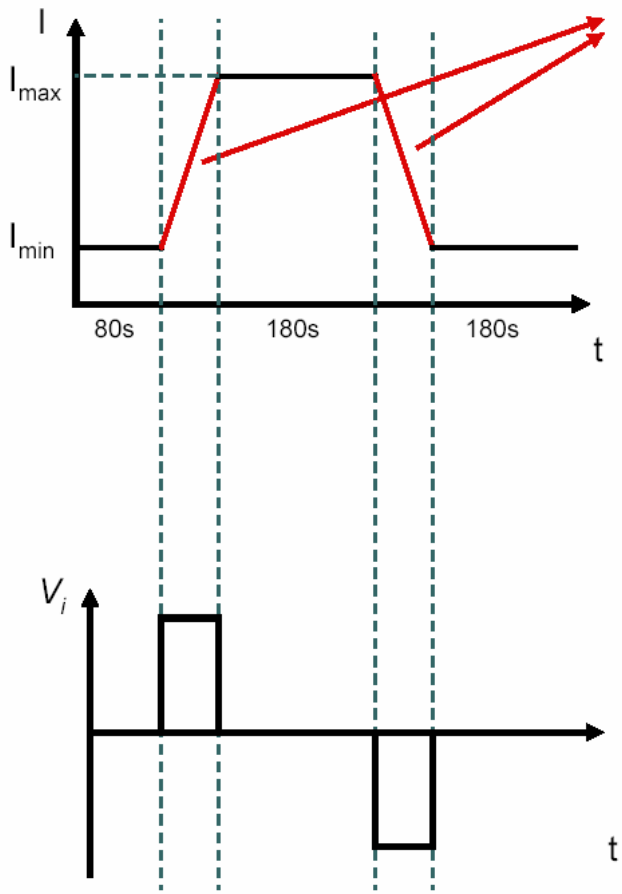




Ramp Rate Effects in LHC: G. Deferne

- Ramp rate effects *could* become a problem, particularly tune and chromaticity change during ramp, based on models.
- Used existing rotating coil equipment to carry out measurements.
- Main field (Field Advance) measured using the coils in stationary mode.
- Ramp rate induced harmonics measured in rotating mode. Use of bucked signal, as well as averaging of forward and backward rotation data, allows simple FFT to work.
- Ramp rate effects not as bad as the worst fears!

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

$$\rightarrow \quad \varphi_i = -\int V_i dt$$

$$\rightarrow \quad B_i = \frac{\varphi_i}{A_i}$$

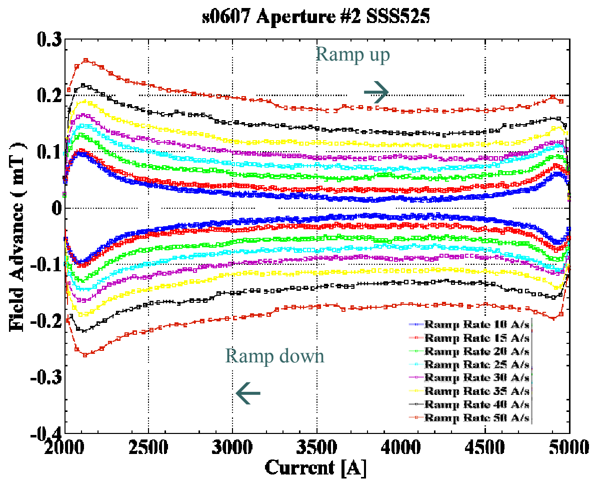
Where A_i the area of the coil

Half field hysteresis:

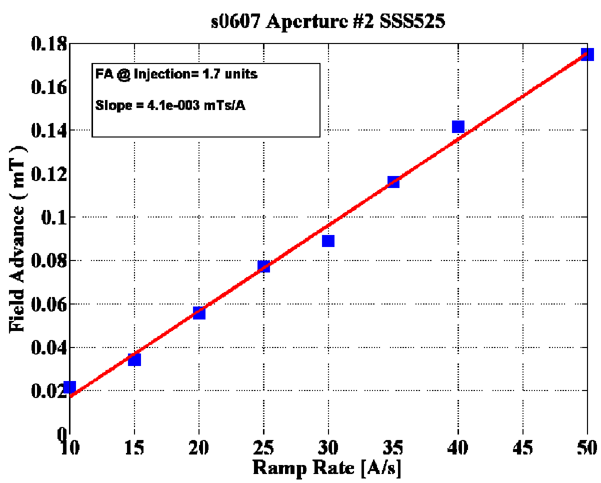
$$\Delta B_n(I_k) = \frac{1}{2}\left(B_n^{up}(I_k) - B_n^{down}(I_k)\right)$$

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

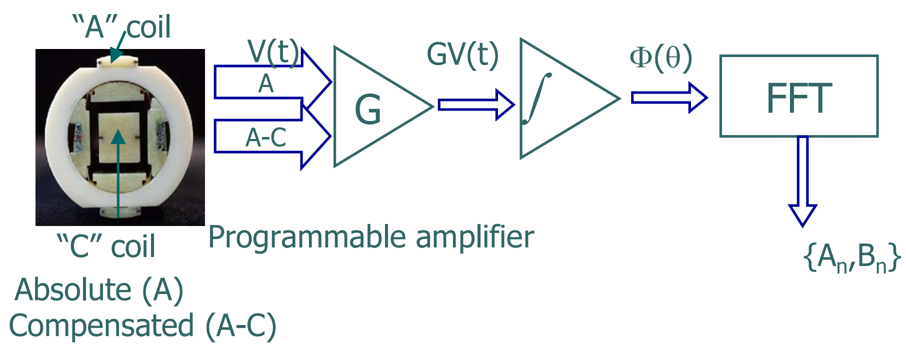


Dependance of ΔB on the ramp rate:

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

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

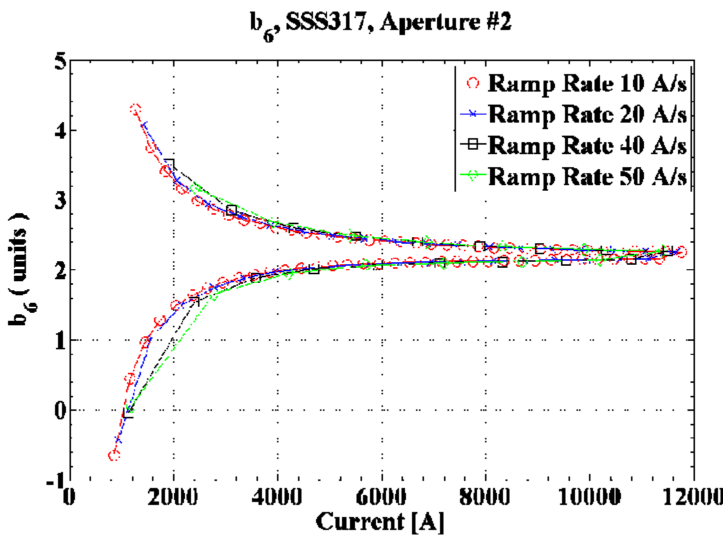
Ramp Rate Effect on Multipoles (2): processing



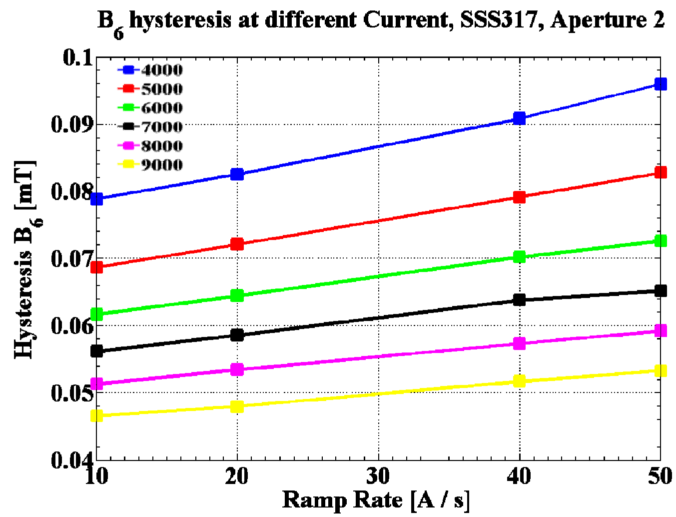
- The analysis is done for each normal and skew harmonic
- The difference between each multipoles field measured during ramp up and down is computed for a given current I_k (at a given ramp rate):

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

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

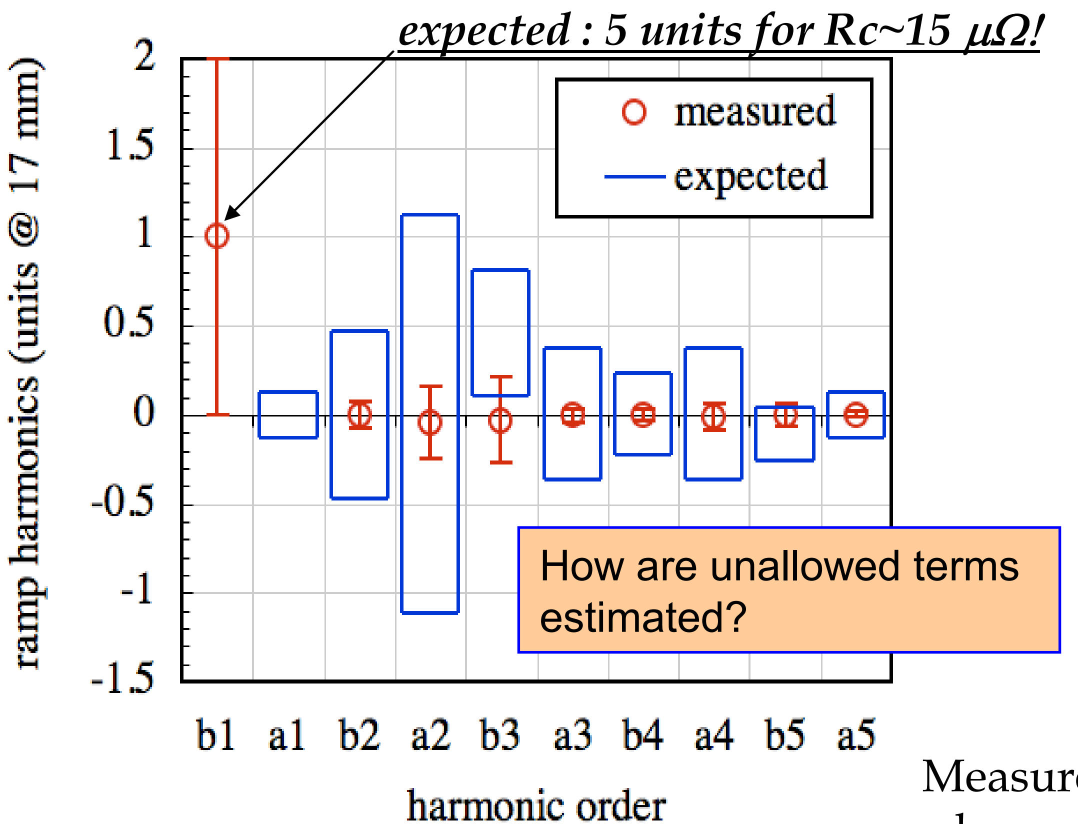


Example of b_6=f(I) at different ramp rates



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

Results (1): Ramp rate effect on dipoles



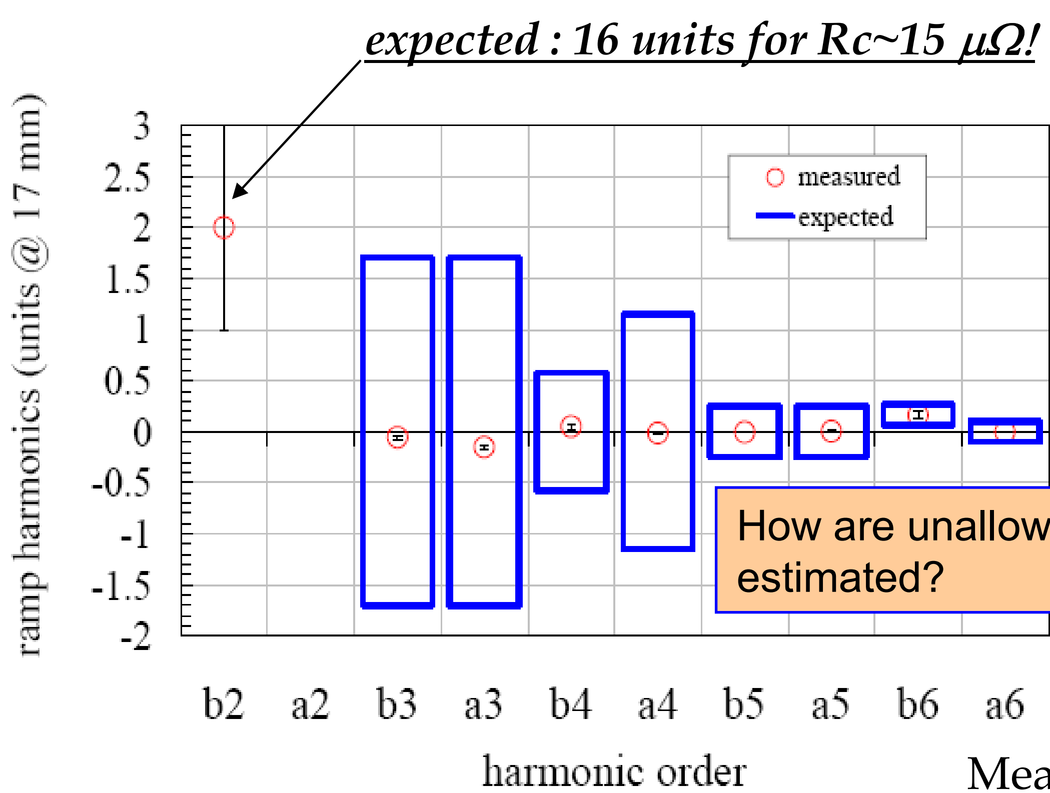
	average (units)	sigma (units)
b1	1.00	1.00
a1		
b2	0.00	0.08
a2	-0.04	0.20
b3	-0.03	0.24
a3	-0.01	0.03
b4	0.00	0.03
a4	-0.01	0.08
b5	0.00	0.06
a5	0.00	0.01

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*** *μΩ.*

Results (2): Ramp rate effect on quadrupoles



How are unallowed terms estimated?

	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

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

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.*

Summary

- Only three talks in the session, but a wealth of data in each one of them.
- Variety of techniques applied to a wide range of ramp rates and time scales.
- Measurements using fast rotating coils in Tevatron dipoles have led to improved algorithm for snapback correction during operation.
- Measurements using array of novel curved coils have helped to understand behavior of CNAO dipole and improve its field quality by shimming.
- Measurements in the LHC dipoles and quadrupoles have shown that the ramp rate effects are much smaller than what 15 $\mu\Omega$ cross over contact resistance would predict.