Dynamic Effects in LHC Magnets

LHC-MTA, LHC-MMS, SL-PO
Presented by L. Bottura

Prepared for the VLHC Annual Meeting
Port Jefferson, NY, October 16-18, 2000

Overview

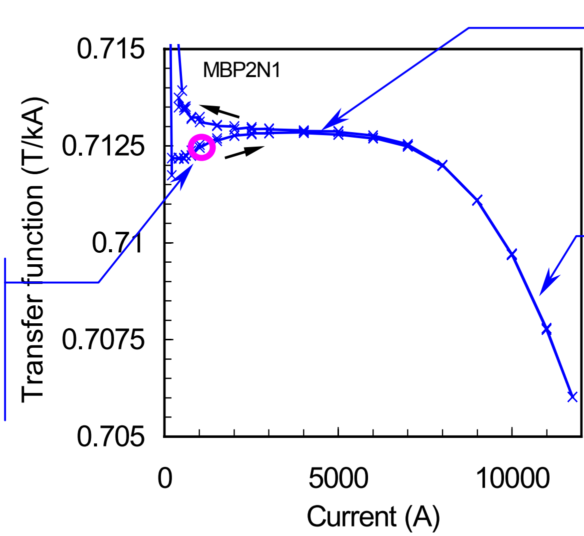
- What are dynamic effects ?
- Why are they important ?
- What do we know about them ?
  - physics
  - phenomenology
- How will we deal with them at LHC ?
- Summary and ideas for the VLHC

Dynamic Effects

What are dynamic effects ?

Static Field Quality in LHC Magnets

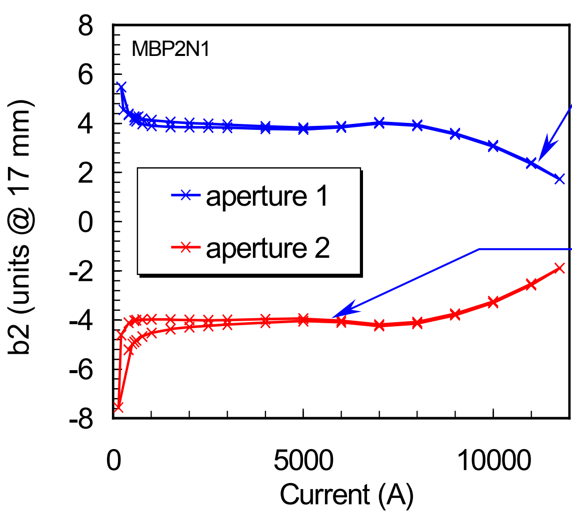
persistent currents
δT = -0.6 mT (0.1 %)



geometric (linear)
contribution
T = 0.713 T/kA

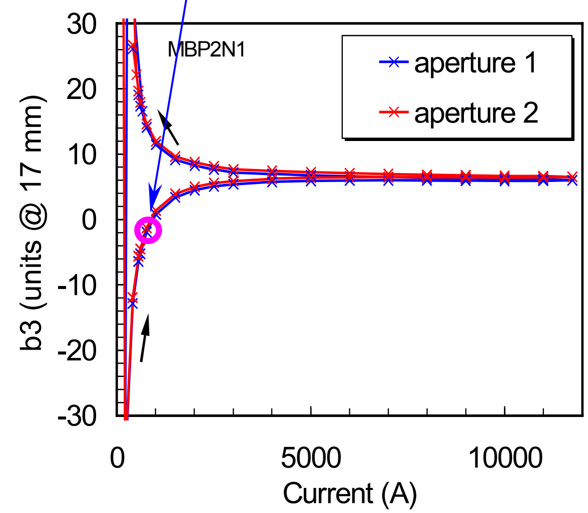
1 % iron
saturation

partial compensation
of persistent currents
at injection



iron
saturation

systematic b2
from two-in-
one geometry



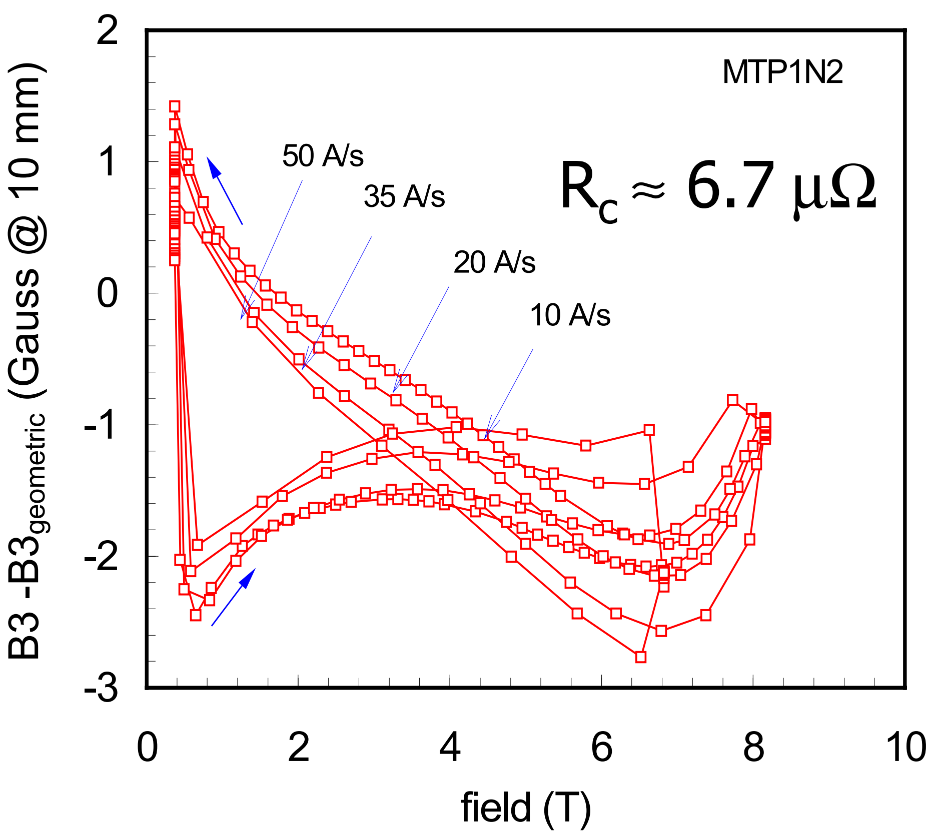
Ramp Rate Dependent Effects

- strands coupling currents
- eddy (coupling) currents in cables
- eddy currents in metallic components
  - beam screen
  - wedges
  - ...

Cable Coupling Currents - 1

- Systematic effects expected on allowed multipoles
  - B1, b3, b5, … in MB
  - B2, b6, b10, … in MQ

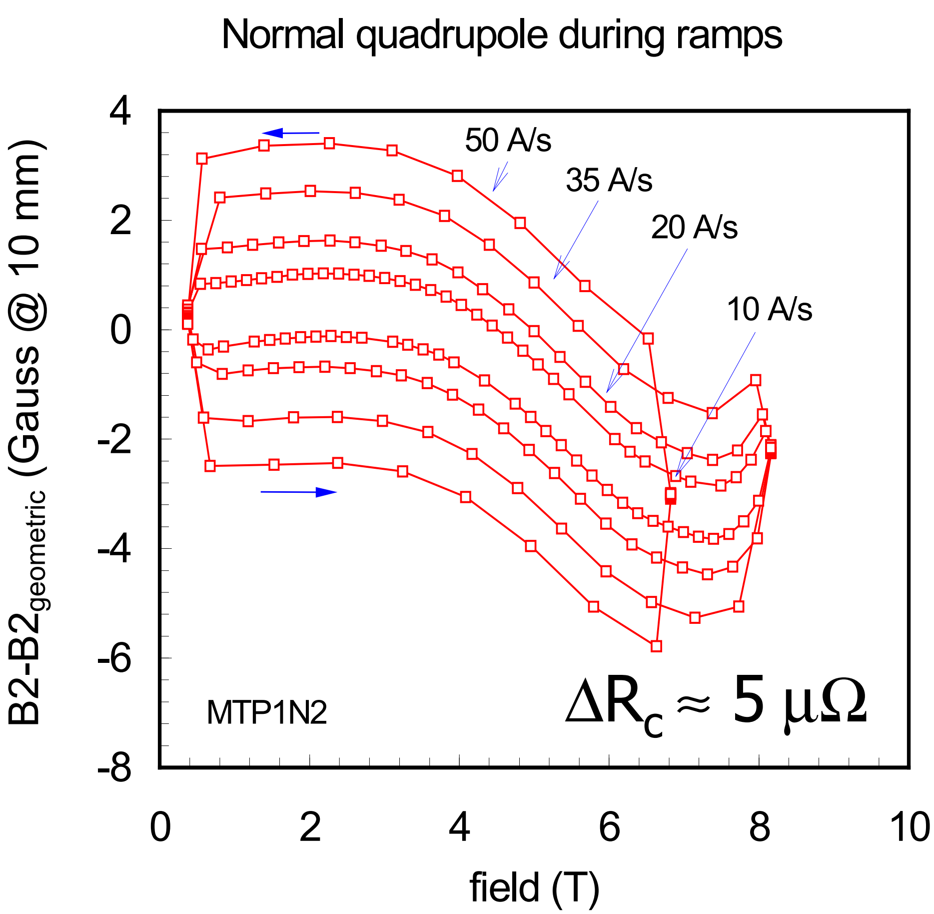
Normal sextupole during ramps



for the R_c value in MTP1N2 see:

R. Wolf, et al., IEEE Trans. Appl. Sup., 7 (2), 797, 1997

Cable Coupling Currents - 2



- Random, non-negligible effects expected on non-allowed multipoles
  - e.g. b2, a2 in MB

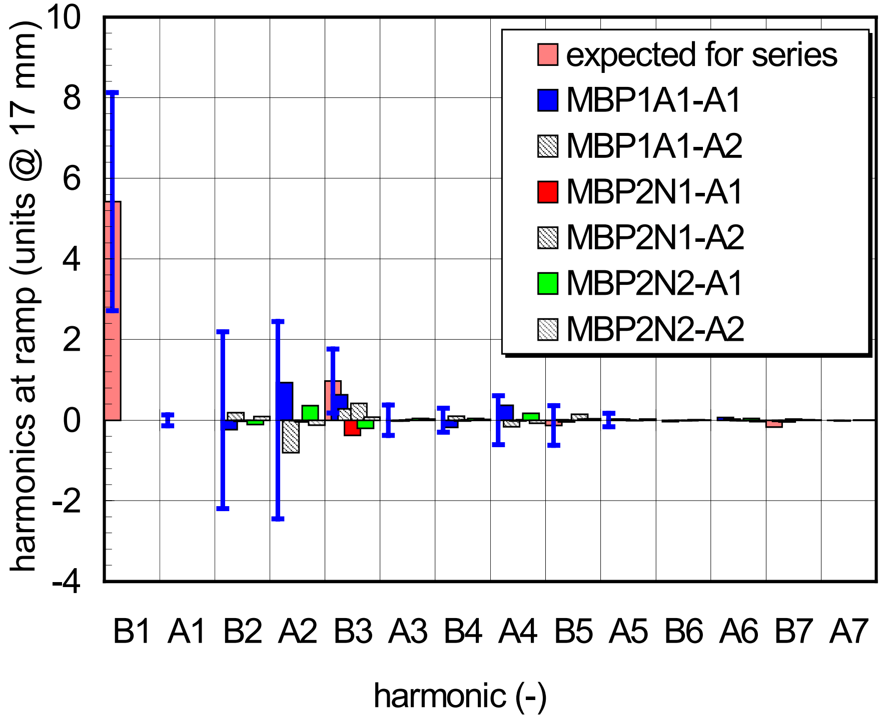
for the ΔR_c value in MTP1N2 see:

R. Wolf, et al., IEEE Trans. Appl. Sup., 7 (2), 797, 1997

Expected Ramp Rate Effects

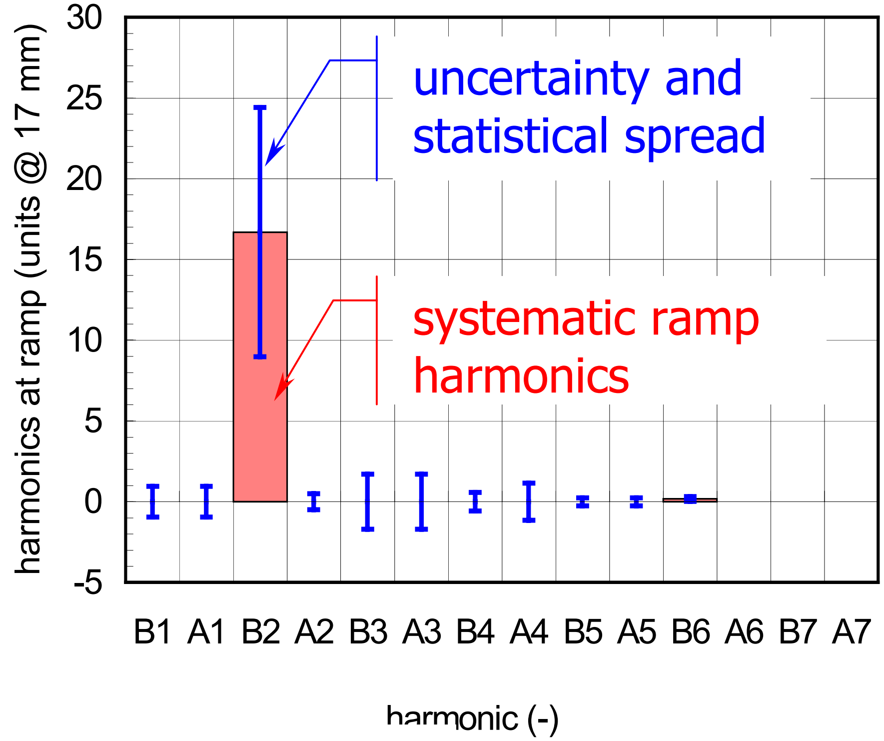
MB bending dipoles

Field Quality WG, MB-99-02



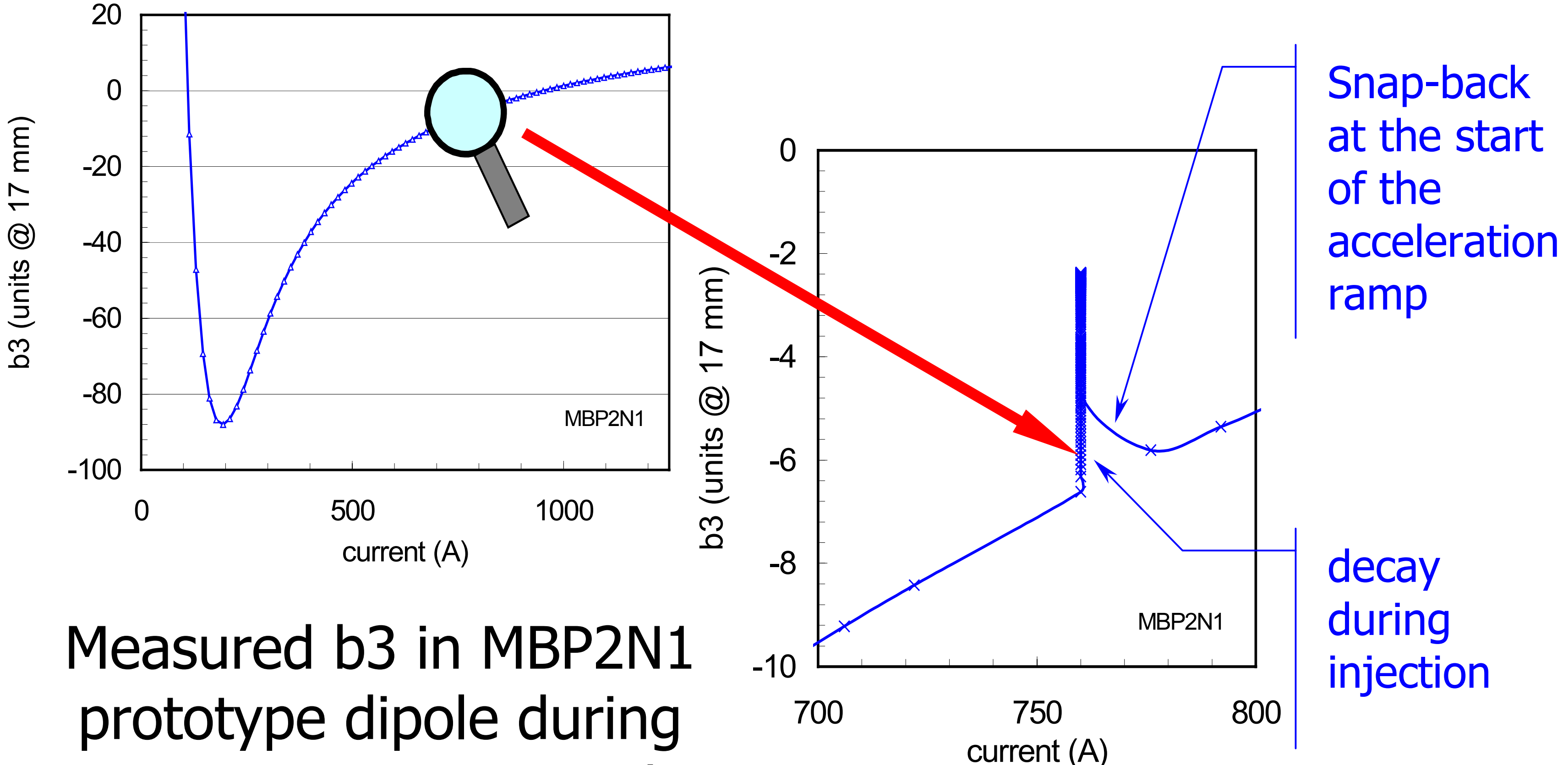
MQ quadrupoles

Field Quality WG, MQ-99-07



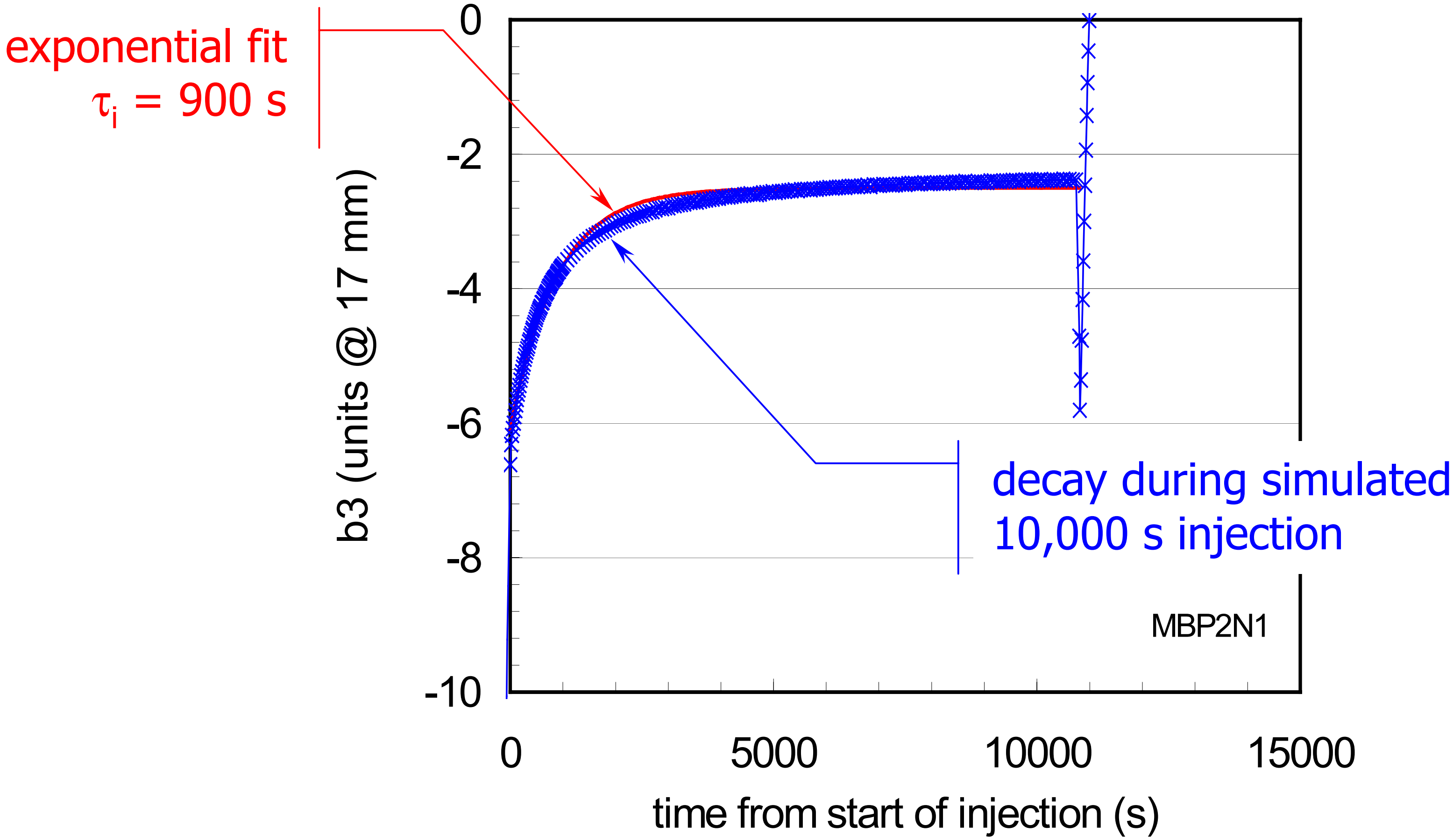
Rc=15 μΩ, 10 A/s at injection

Decay and Snap-back at Injection - 1

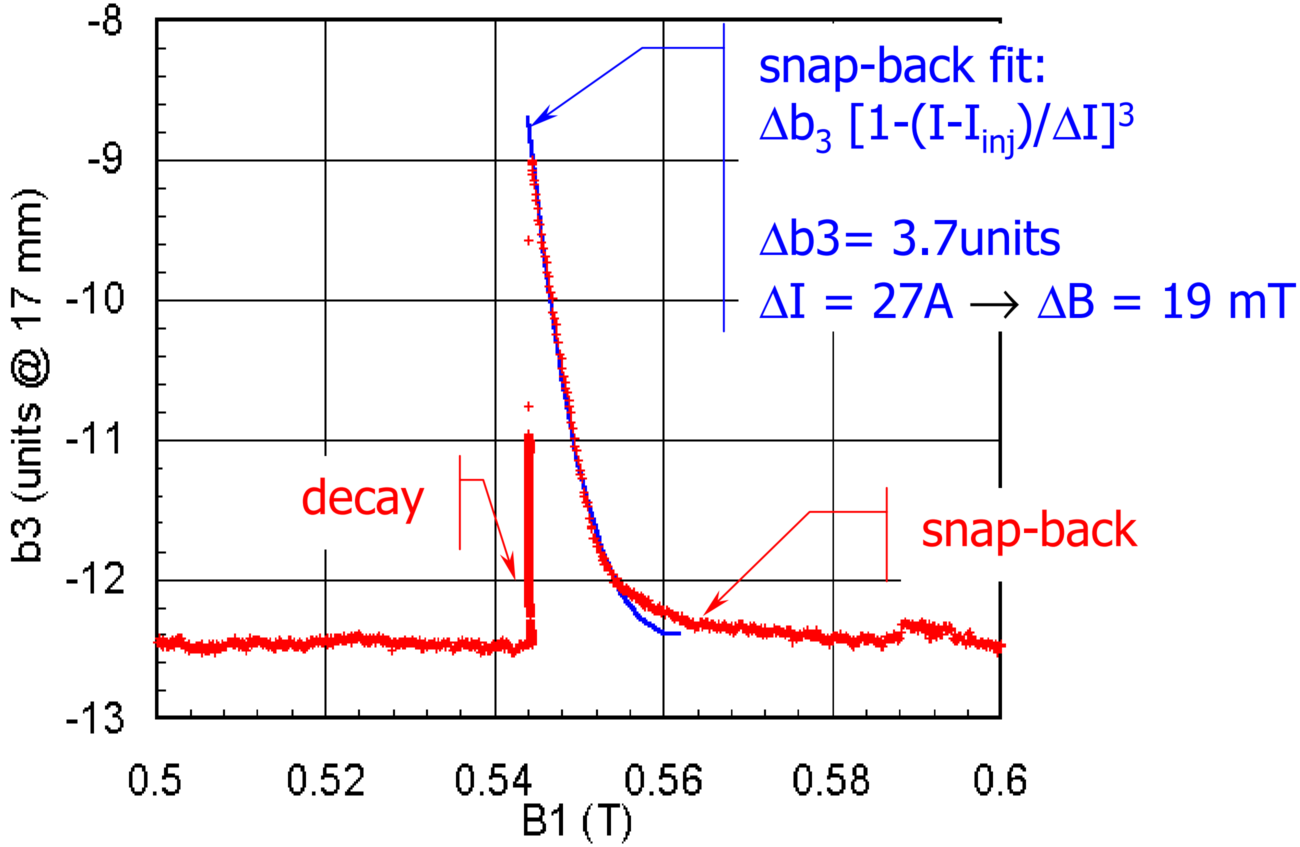


Measured b3 in MBP2N1 prototype dipole during ramp to injection and subsequent energy ramp

Decay and Snap-back at Injection - 2



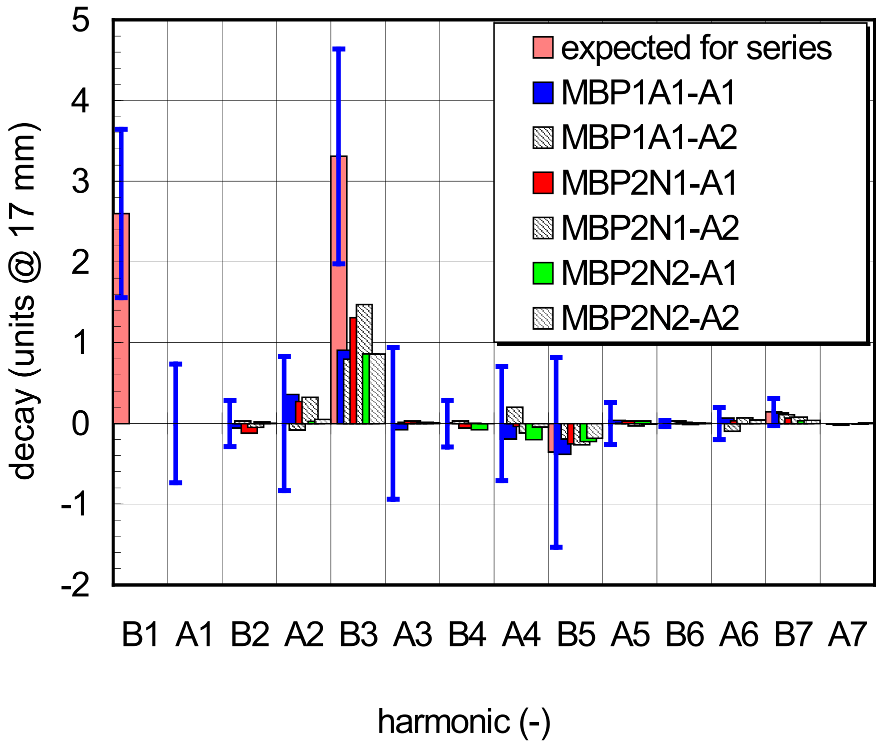
Decay and Snap-back at Injection - 3



Expected Decay and Snap-back

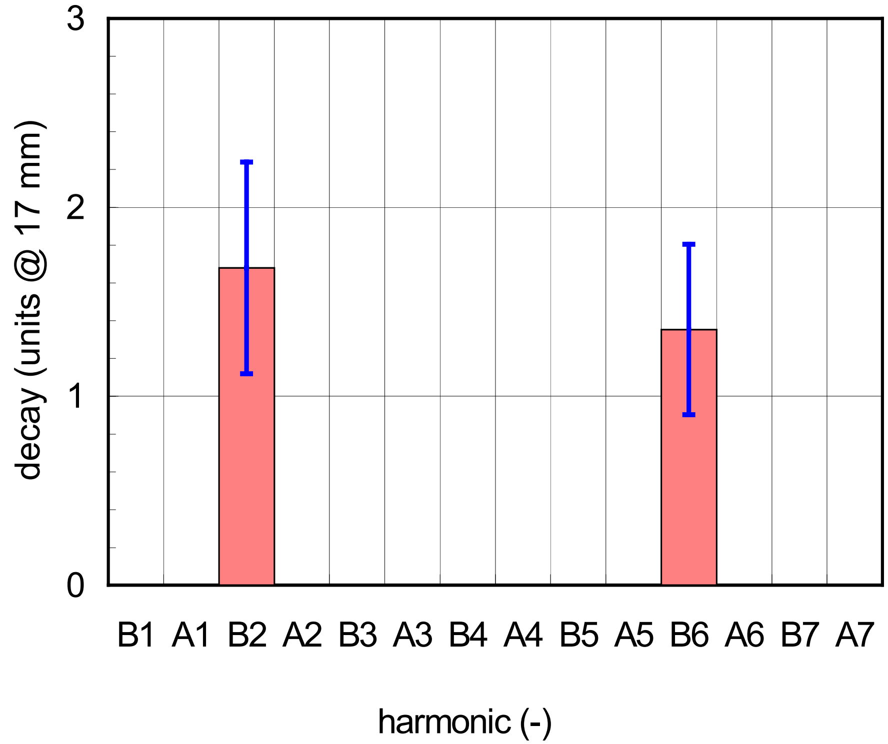
MB bending dipoles

Field Quality WG, MB-99-02



MQ quadrupoles

Field Quality WG, MQ-99-07



Dynamic Effects

Why are they important ?

Effect of an uncorrected ramp

- During uncorrected ramps (Rc=15 μΩ, 10 A/s)
  - $\Delta_{b1(MB)} = 5.4 \rightarrow \Delta Q = 0.054$ vs. 0.003
  - $\Delta_{b2(MQ)} = 17 \rightarrow \Delta Q = 54\ \Delta_{b2} 10^{-4} = 0.09$ vs. 0.003
  - $\Delta_{b3(MB)} = 1.0 \rightarrow \Delta\xi = 52\ \Delta_{b3} = 52$ vs. 1

(source: O. Bruening, SL-AP)

Effect of an uncorrected snap-back

- During uncorrected snap-back
  - $\Delta_{b1(MB)} = 2.6 \rightarrow \Delta Q = 0.026$ vs. 0.003
  - $\Delta_{b2(MQ)} = 1.7 \rightarrow \Delta Q = 54\ \Delta_{b2} 10^{-4} = 0.009$ vs. 0.003
  - $\Delta_{b3(MB)} = 3.3 \rightarrow \Delta\xi = 52\ \Delta_{b3} = 172$ vs. 1

(source: O. Bruening, SL-AP)

Dynamic Effects

What do we know about them ?

Physics of Coupling Currents

- Physical model for strand/cable coupling available
  A. Devred, T.Ogitsu, CERN 96-03, 1996
- Can be *controlled* at the strand/cable production level:
  - LHC target interstrand resistance $R_c > 20\ \mu\Omega \pm 5\ \mu\Omega$
  - obtained through controlled coating and accelerated oxidation
- *Reproducible* $\rightarrow$ measured on 100 % of magnets

Physics of Decay and SB - 1

- *Basic* understanding of physics principle available:
  - flux-creep (accounts for 10 % … 30 % of effect)
  - interaction between cable transport current re-distribution and filaments magnetization

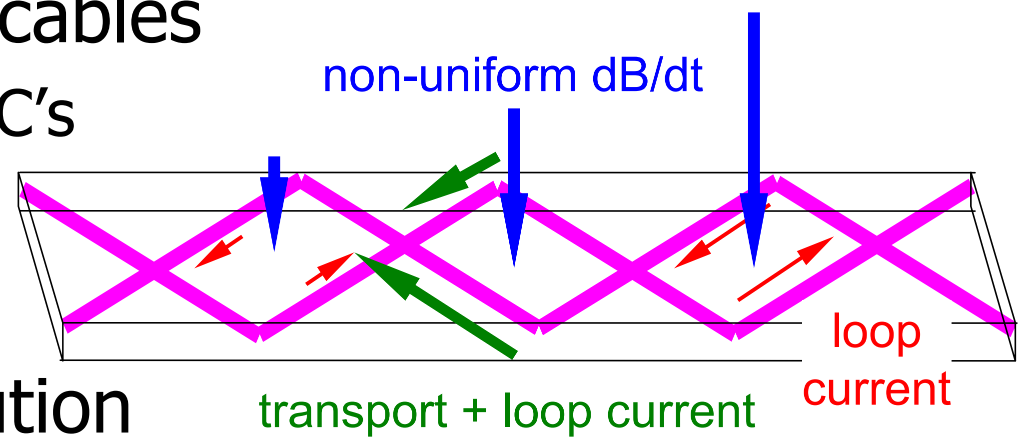
L. Bottura, et al., Field Errors Decay and "Snap-Back" in LHC Model Dipoles, IEEE Trans. Appl Sup., 7(2), 602, 1997

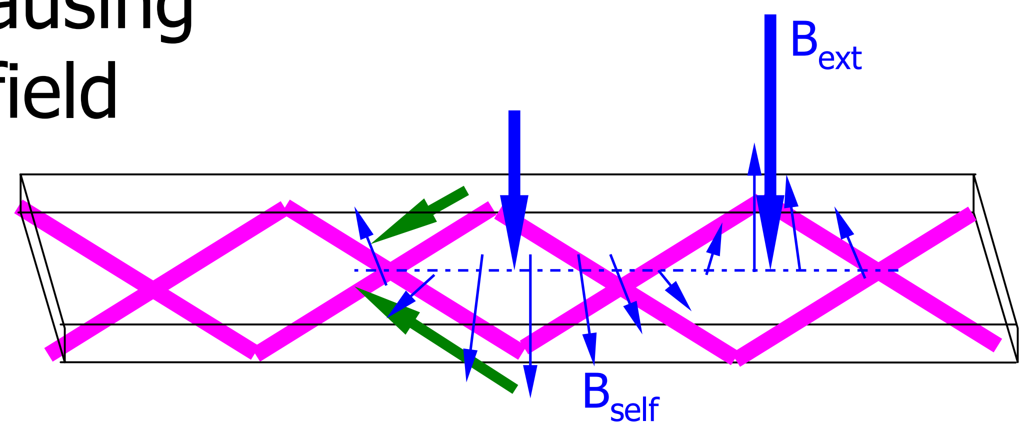
R. Wolf, *The Decay of the Field Integral in SC Accelerator Magnets Wound with Rutherford Cables*, Proc. of 15th Mag. Techn. Conf., Beijing, Oct. 20-24, 1997

- Cannot be *controlled* at production
- *Not reproducible* $\rightarrow$ measured on 110 % of magnets

Physics of Decay and SB - 2

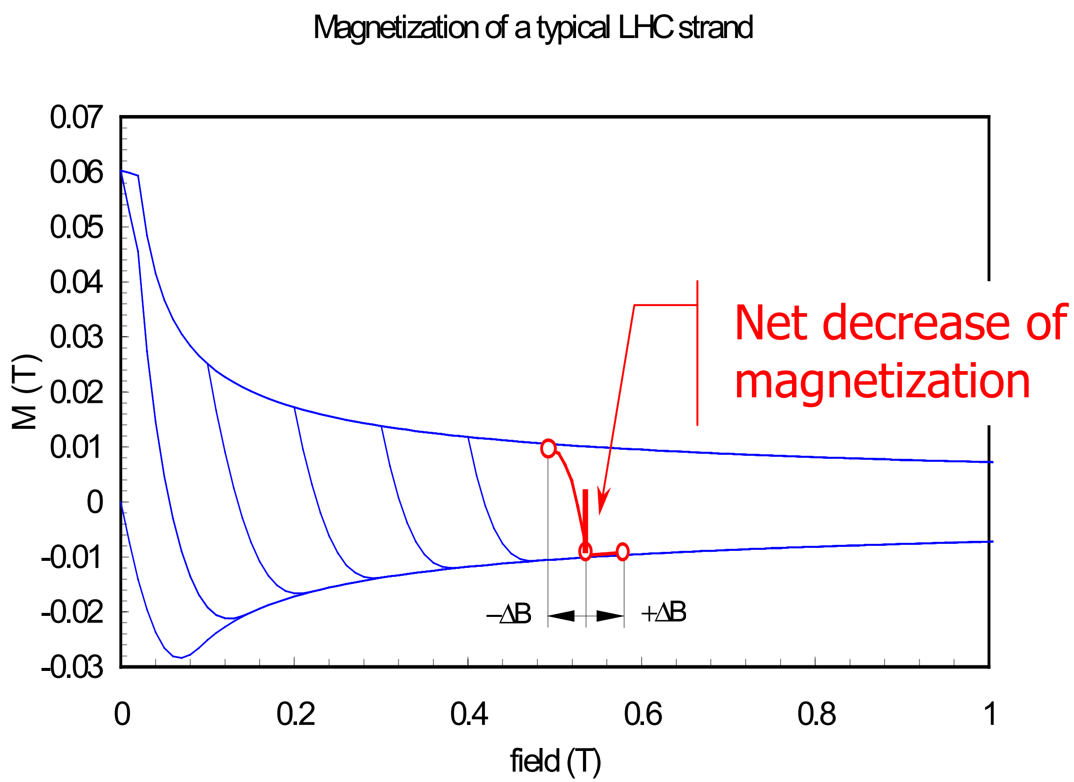
- The current distribution is <u>not uniform</u> in the cables
  - Supercurrents, BICC's
  - joints
  - …
- The current distribution <u>changes in time</u> , causing a variable rotating field





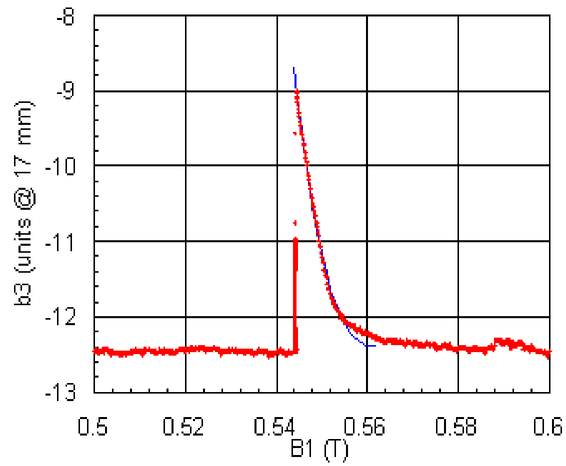
Physics of Decay and SB - 3

- The field change affects the magnetization M of the SC strand
- Average M drops ⇒ decay



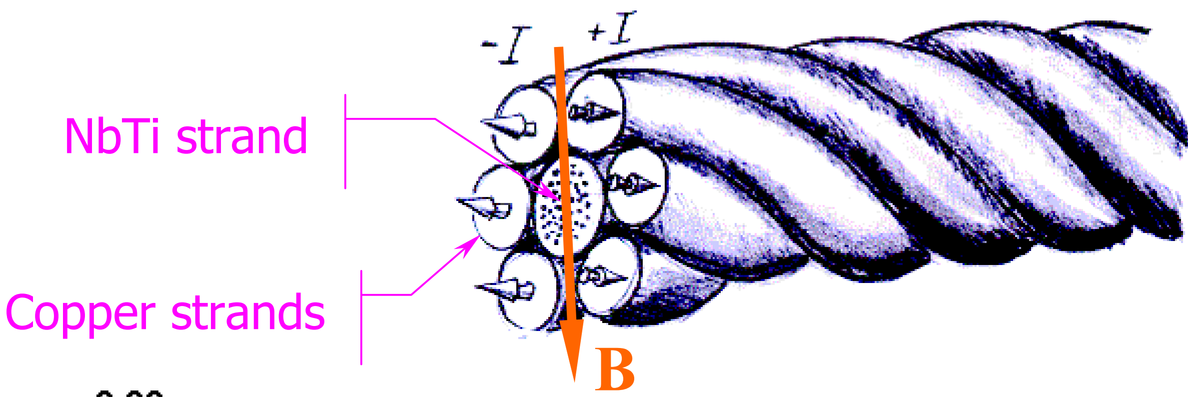
Physics of Decay and SB - 4

- The magnetization state is re-established as soon as the background field is increased
  ⇒ snap-back

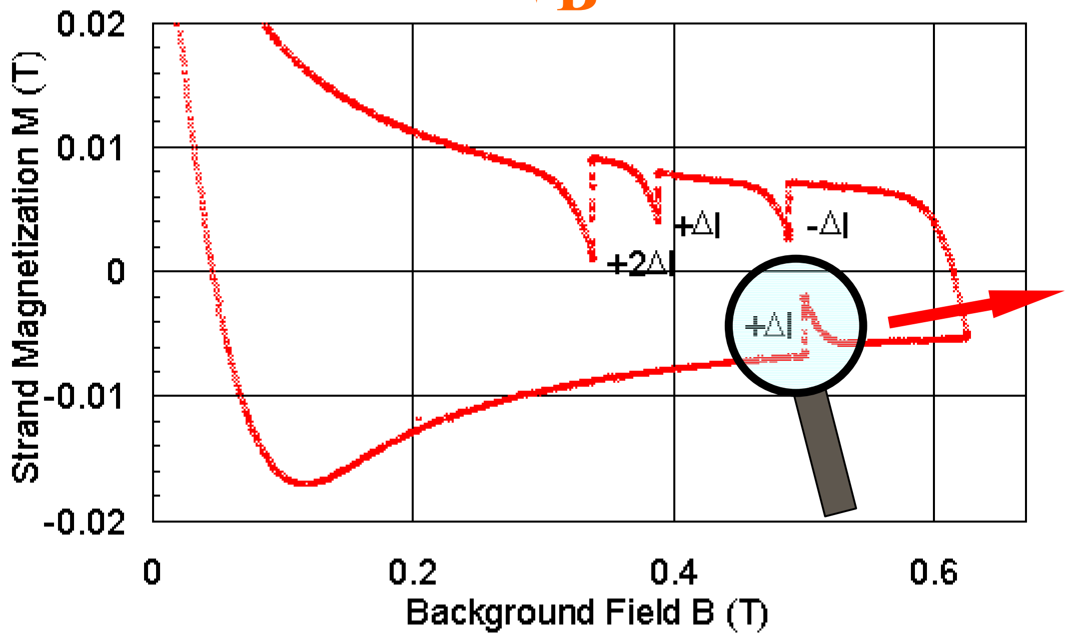


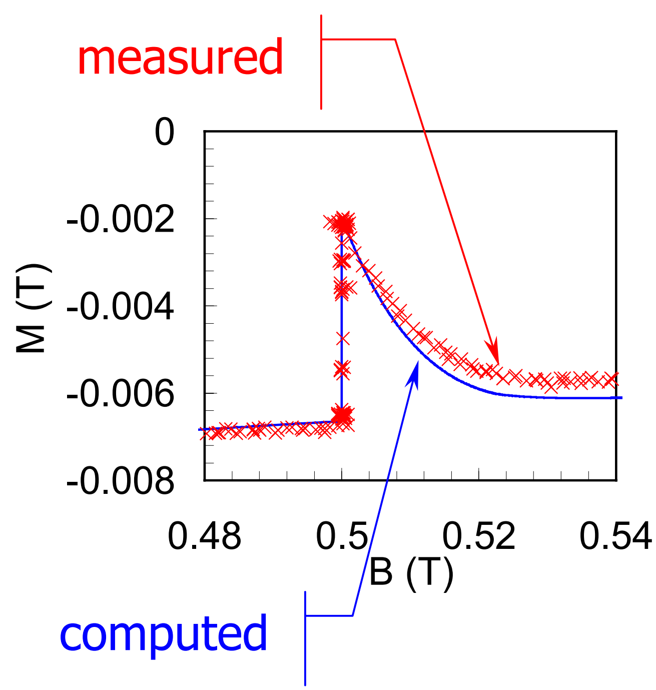
- The background field change necessary is of the same order of the internal field change in the cable
  - ≈ 100 A change in current imbalance
  - ≈ 10 mT average internal field change (vs. 5…20 mT measured)

Physics of Decay and SB - 5



Demonstration experiment at Twente University. Courtesy of M. Haverkamp

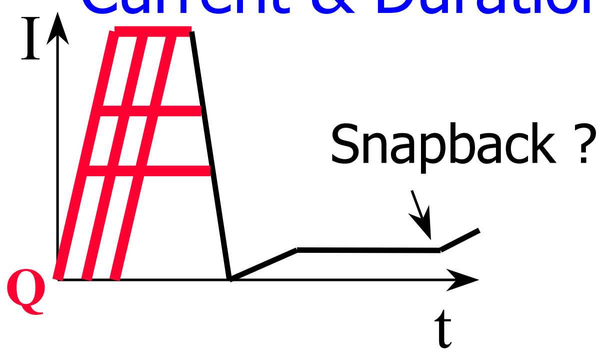




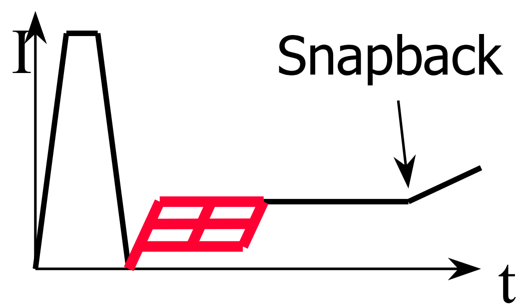
Measurements of Decay and SB - 1

- Parameters affecting decay and SB

Current & Duration



Pre Injection Duration & Current



and (many) others:

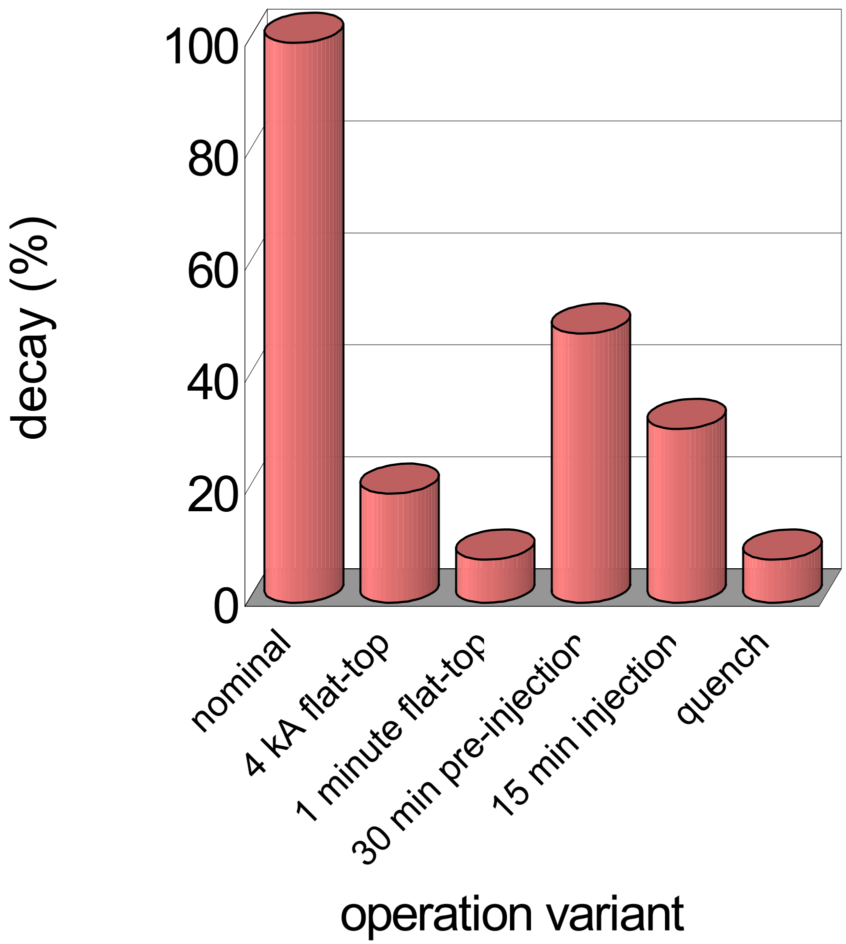
Number of pre-cycles

Quench

Ramping speed

…

Measurements of Decay and SB - 2



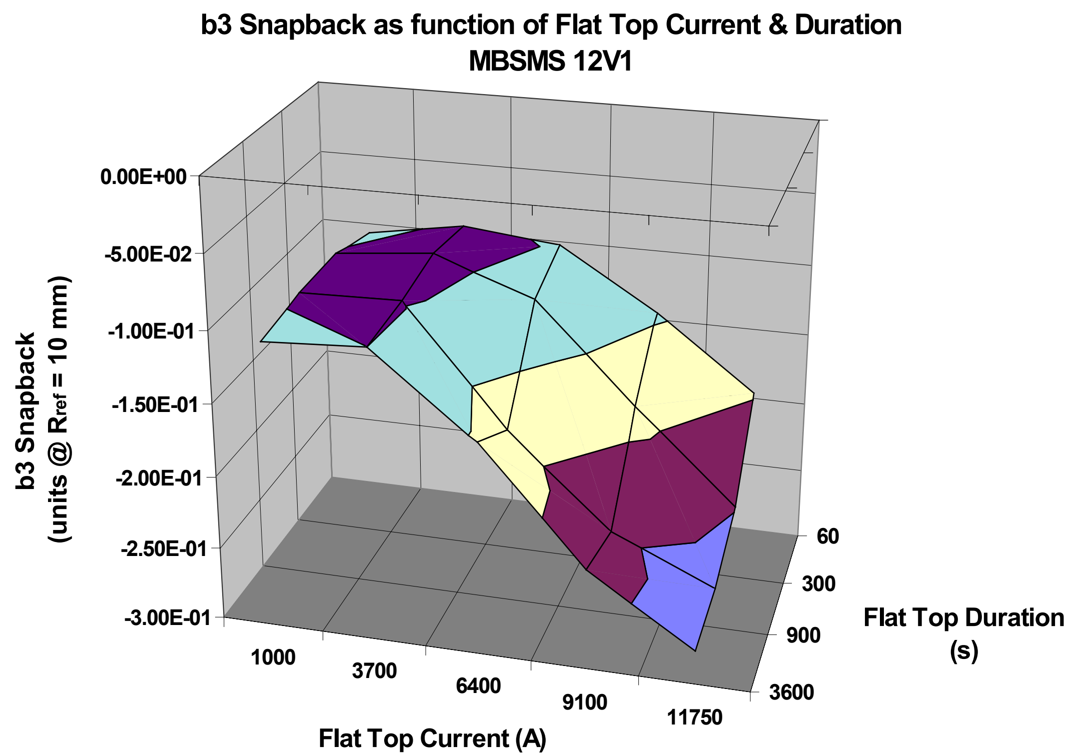
- Measured on a *small series* (≈10) of 1-m LHC model dipoles

- Large spread (1 order of magnitude) depending on the powering history and conditions

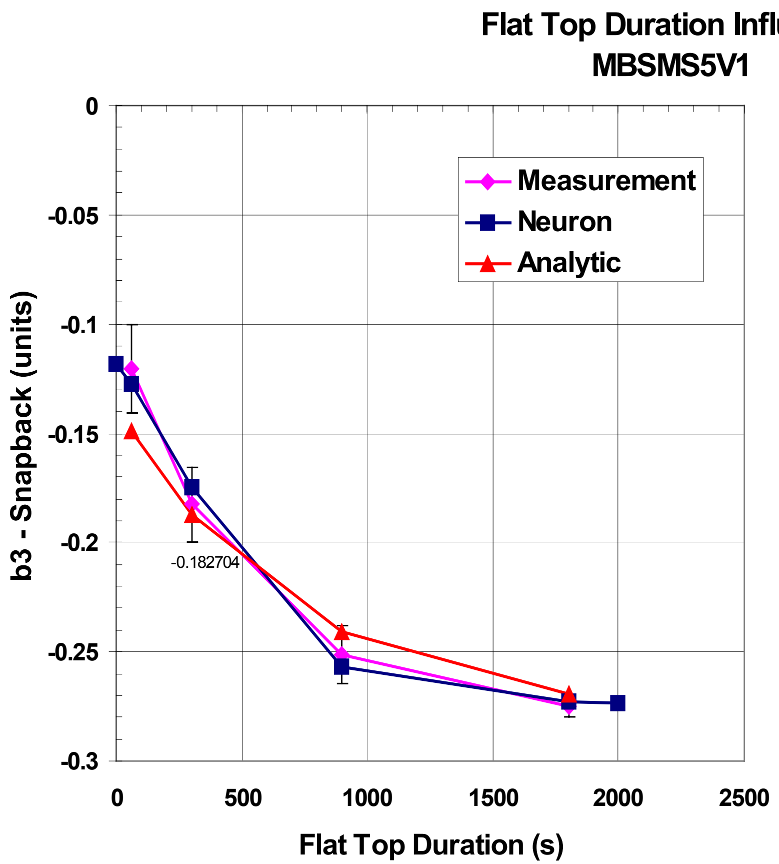
Measurements of Decay and SB - 3

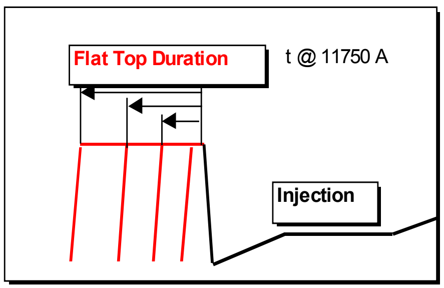
- Space of parameters:
  - pre-injection duration
  - injection duration
  - flat-top current
  - flat-top time
  - magnet temperature
  - ramp-rates
  - …

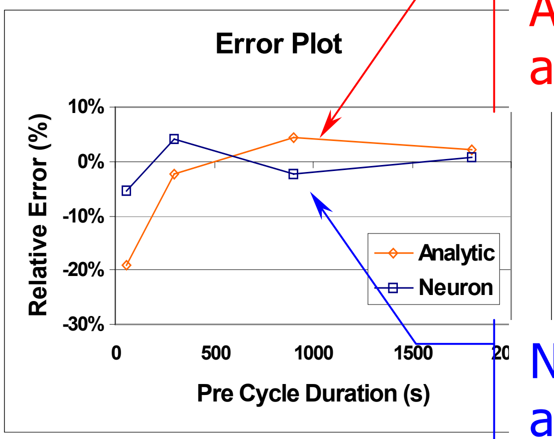
too large for series measurements



Modelling of Decay and SB







Analytical model accurate to 30 %

Neural network accurate to 5 %

Dynamic Effects

How will we deal with them ?

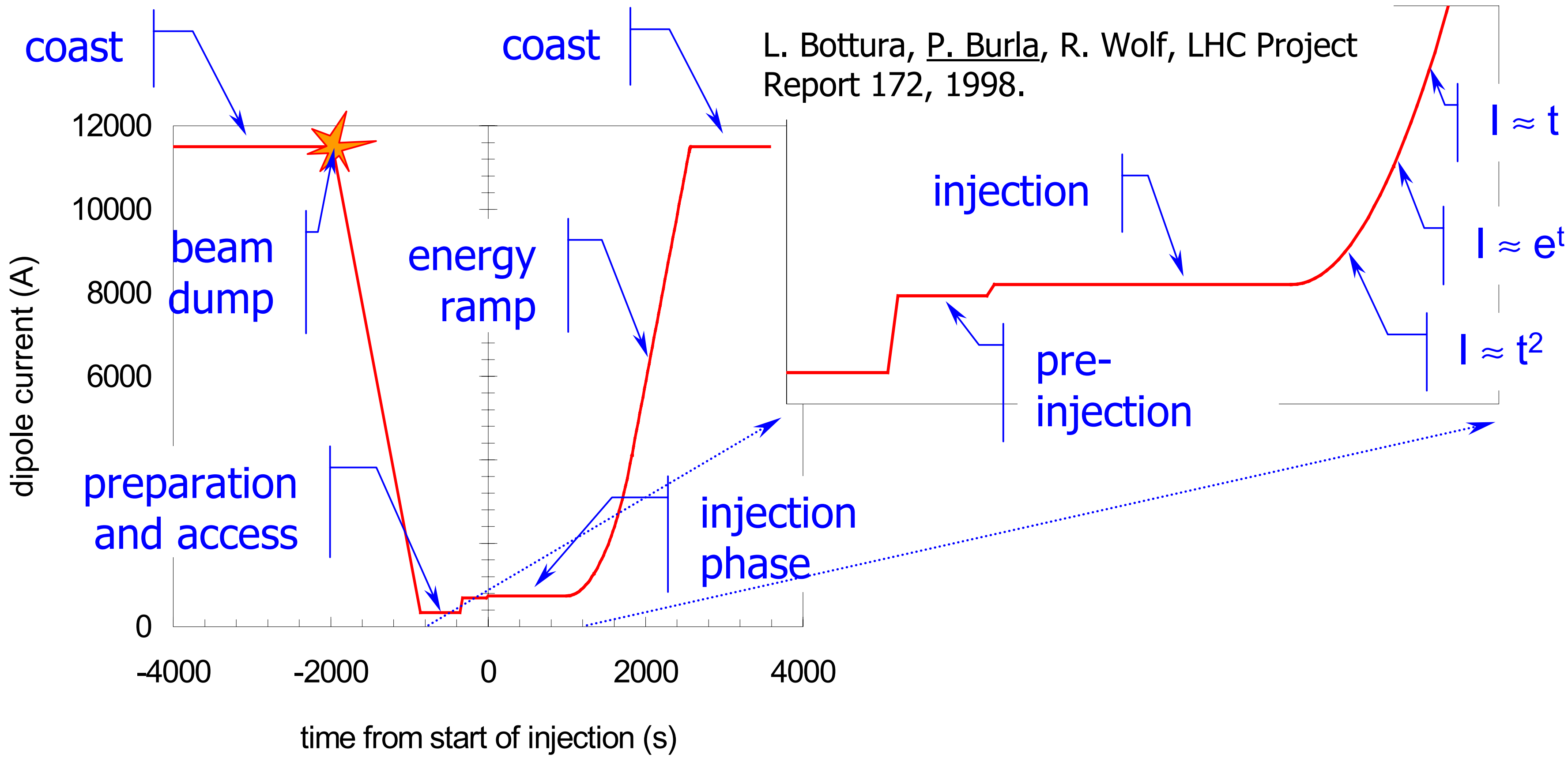
Control of Dynamic Effects

- Optimized ramp to minimize effects
- Cycling policy to guarantee reproducibility
- Feed-forward from the LHC magnetic reference
- Feed-forward from previous operating cycles
- Feed-back from on-line (BI) measurements

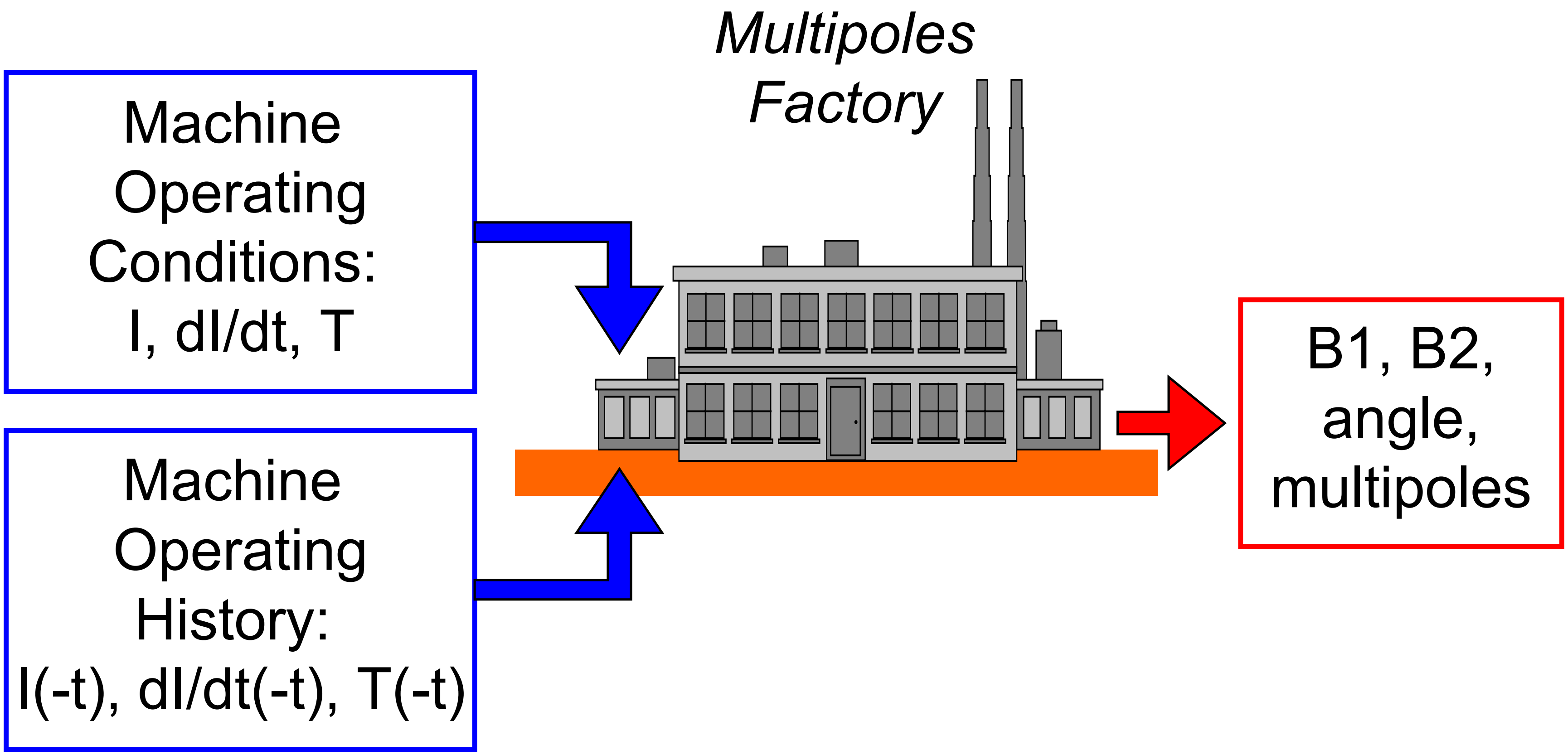
Optimized Ramp

A. Faus-Golfe, LHC Project Note 9, 1995.

L. Bottura, P. Burla, R. Wolf, LHC Project Report 172, 1998.



The LHC Magnetic Reference



Courtesy of Q. King

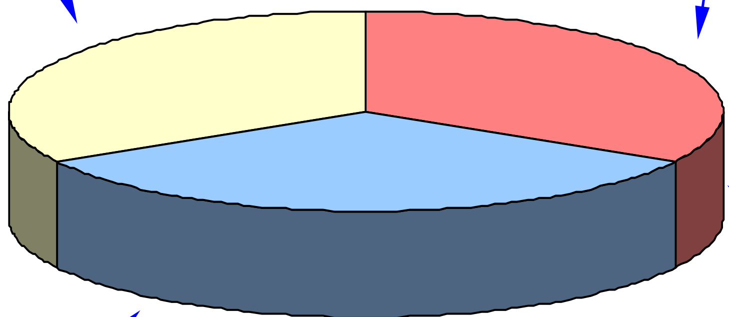
Inside the *Multipoles Factory*

dataBase tables from series measurements on 100 % of magnets

linear physical model of reproducible effects

non linear model of decay and snap back

dataBase tables from series measurements on 10 % of magnets



machine operating conditions: I, dI/dt, T

machine powering history: I(-t), dI/dt(-t), T(-t)

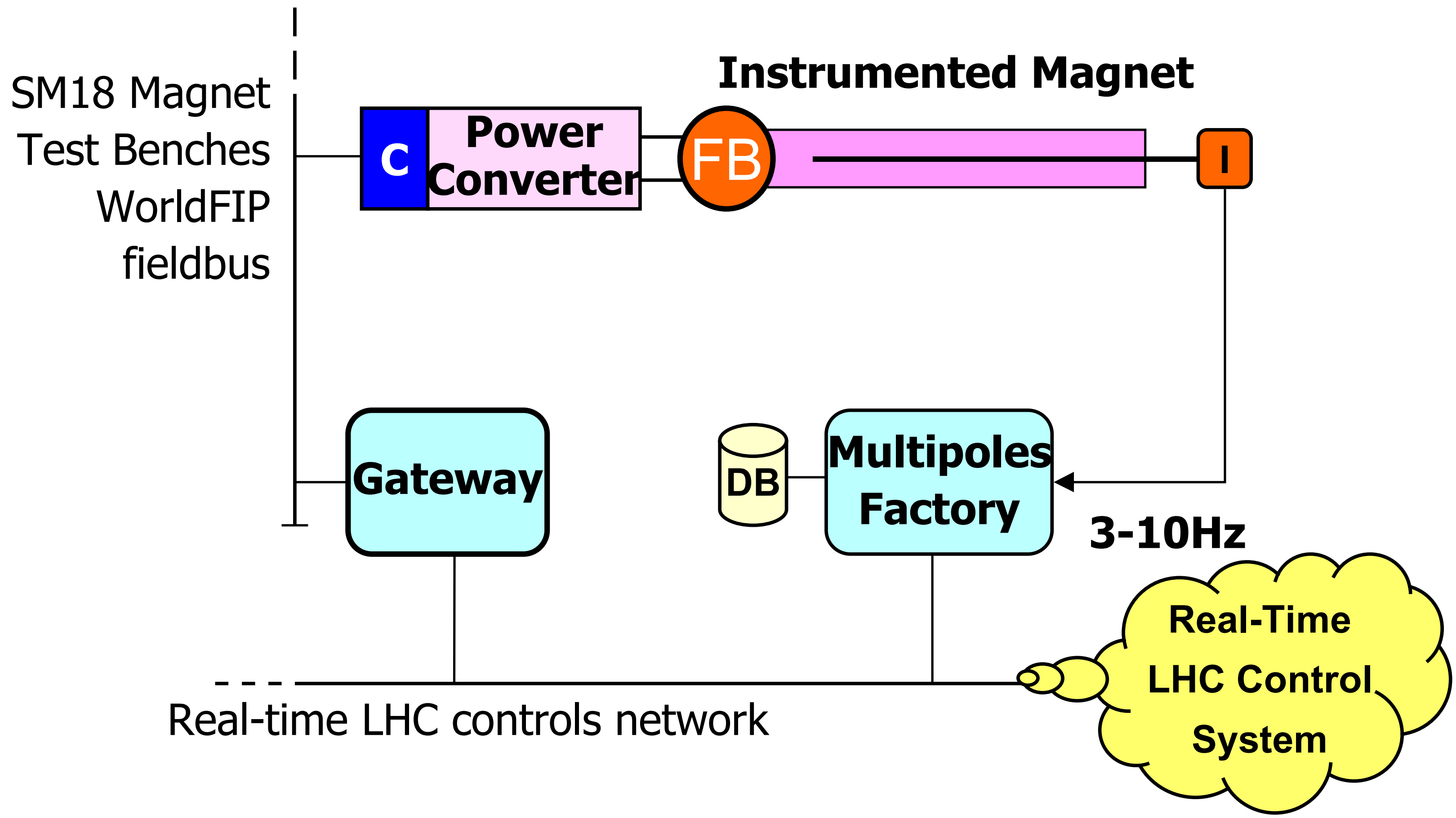
multipoles from reference magnets

non linear adjustment for actual powering conditions

multipoles from BI: tune (b2), chromaticity (b3)

B1, B2, angle, multipoles

Reference Magnets Control Interface



Courtesy of Q. King

Dynamic Effects

Summary and ideas for a VLHC

WGs, Workshops, Seminars !

- Working and study groups
  - Dynamic Effects Working Group (active 3 yrs, now dormant)
  - Interdivisional LHC Controls Project (active since early 2000)
  - Machine Commissioning Committee (planned)
- International Workshops and seminars
  - *Seminars on Dynamic Effects in Super-Conducting Magnets and their Impact on Machine Operation*, October 6th, 1995.
  - *LHC Workshop on Dynamic Effects and their Control*, February 5th to 7th, 1997.
  - *LHC Controls-Operation Forum*, December 1st-2nd, 1999.

vital to understanding, involvement and planning

Open Issues

- Reproducibility cycle-to-cycle ?
- Spread among octants ?
  - 5 cable and 3 magnet manufacturers
- Accuracy of predictive scalings ?
  - assume 80 % for the moment, 20 % residual error
- A *deterministic* model of decay and snap-back seems to be out of reach...

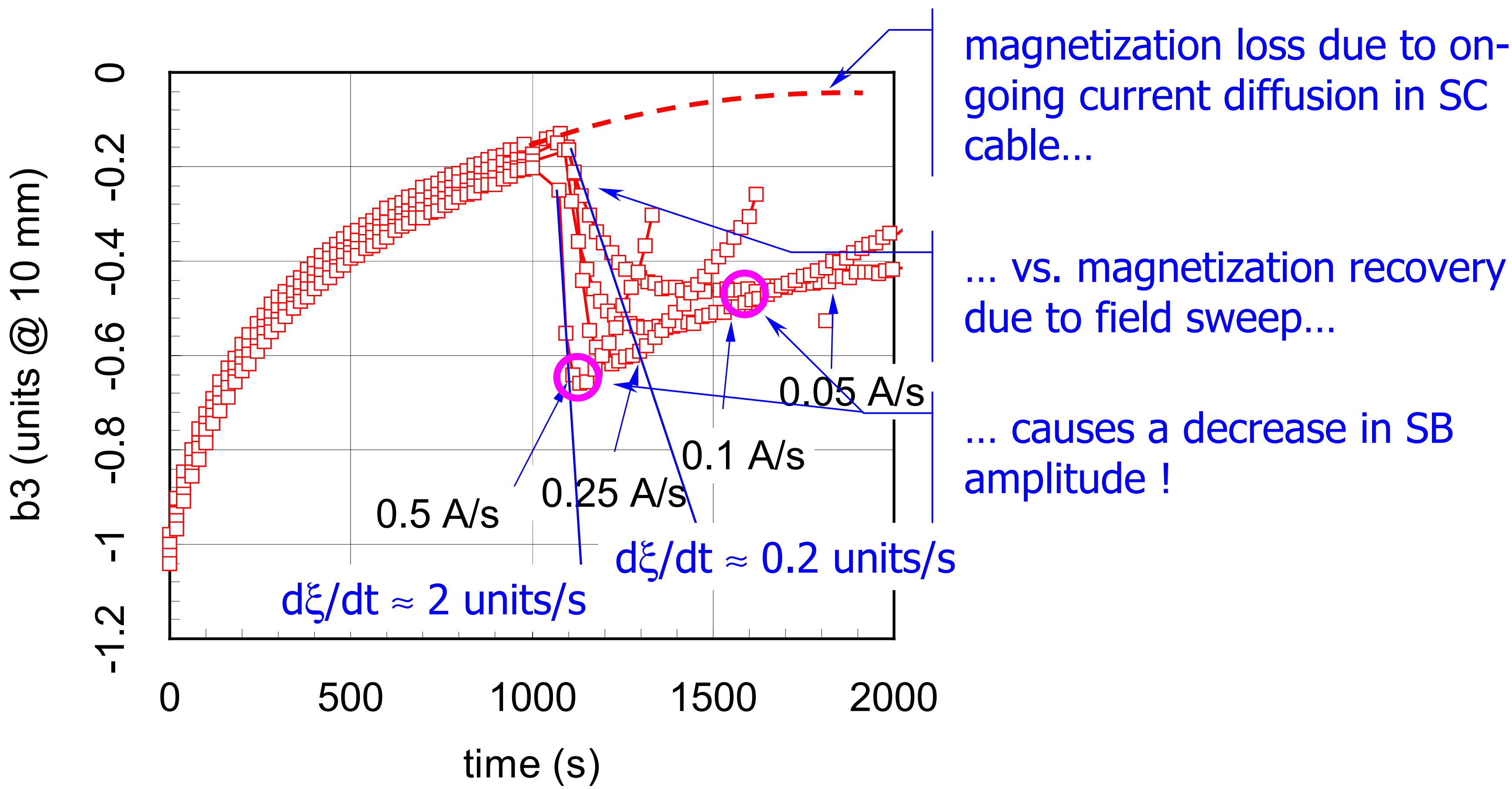
Perspective for LHC

- Treasured TeV and HERA experience
- Physics principle of decay and SB assessed, a working empirical scaling available
- 100 % cold measurements
- Involvement of machine control and operation teams for early integration
- *Sector test* (early 2004) can verify conceptual design of machine control

5 years to go before the first p is injected !

Ideas for VLHC - 1

- A slow ramp out of injection can help...



Ideas for VLHC - 2

- A *snapback-free* injection and acceleration start
  - continuous B1 ramp, injection on-the-fly
  - ΔB1 ≈ 15 mT