Field Quality of the LHC Dipole Magnets in Operating Conditions

Presented by L. Walckiers CERN/LHC-MTA

Contributors : L. Bottura, M. Buzio, S. Fartoukh, S. Russenschuck, S. Sanfilippo, W. Scandale, F. Schmidt, E. Todesco, R. Wolf

Goals of the Presentation

7 LHC Preseries Dipoles Measured @ 1.9 K

Field Quality Compared to Predictions [14 Apertures]

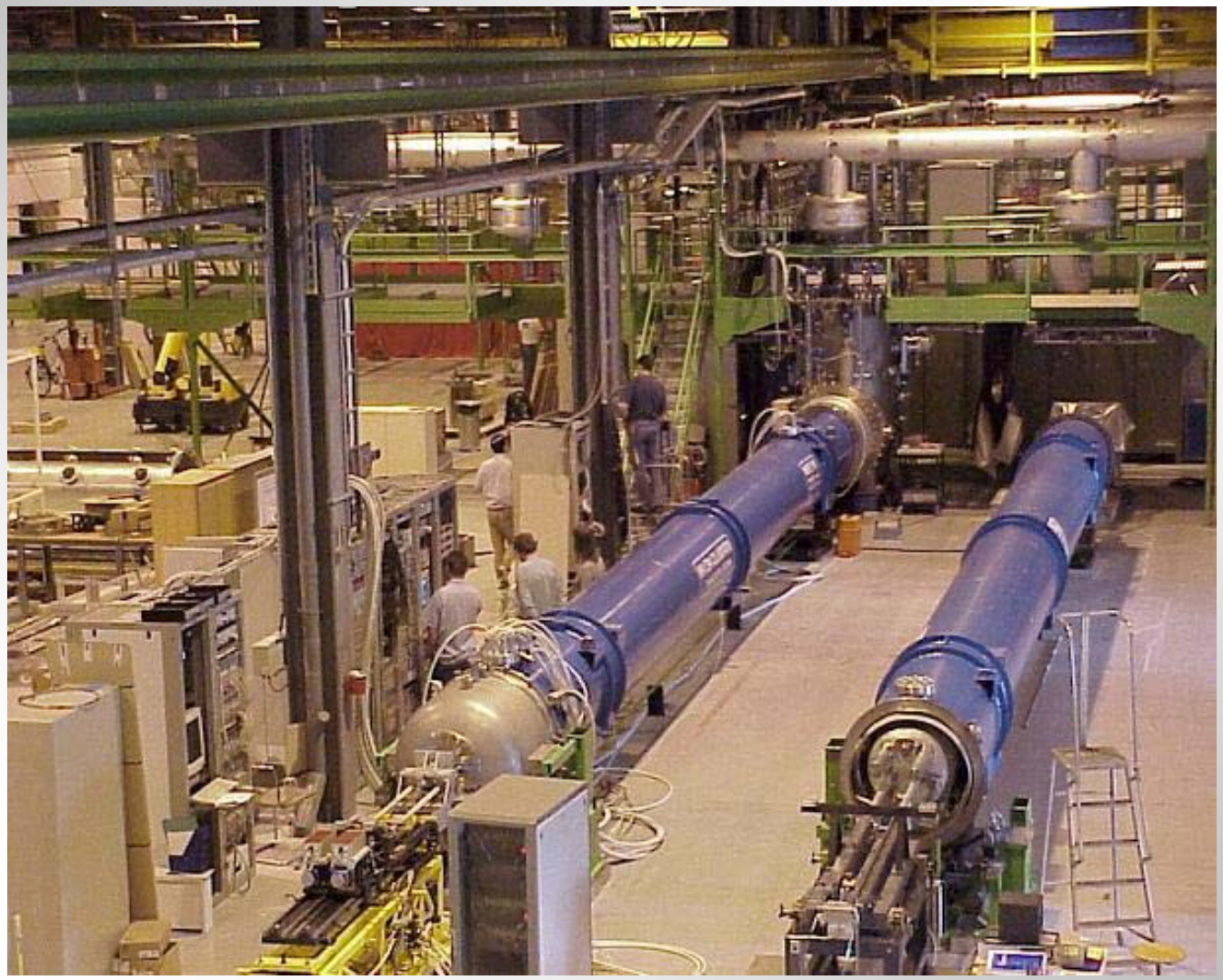
Computed

- **Iron Saturation**
- **Hysteresis & Persistent Current**
- **Ramp rate effects due to Interstrand Resistance**

Expected from Prototypes : Decay & Snap-Back

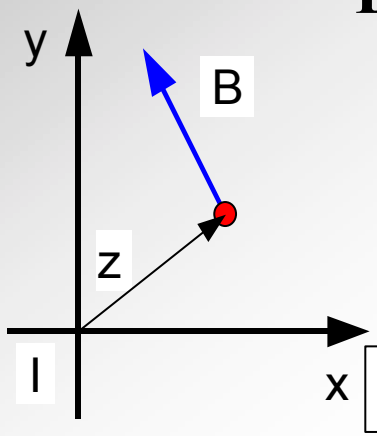
Compared with Beam Optics Requirements

The SM18 Test Station



Multipole field expansion in the complex plane.

- **2-D plane field in the current-free region of the magnet aperture**



$$\mathbf{B}_y + i\mathbf{B}_x = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}}\right)^{n-1} =$$

Skew

$$= \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R_{ref}}\right)^{n-1} =$$

Norma l

$$= |C_m| \sum_{n=1}^{\infty} \frac{(b_n + ia_n)}{10^4} \left(\frac{z}{R_{ref}}\right)^{n-1}$$

Relative to main field (units)

Reference radius (17 mm for LHC)

Dipole Strength and Direction

Spread of the strength (r.m.s.)

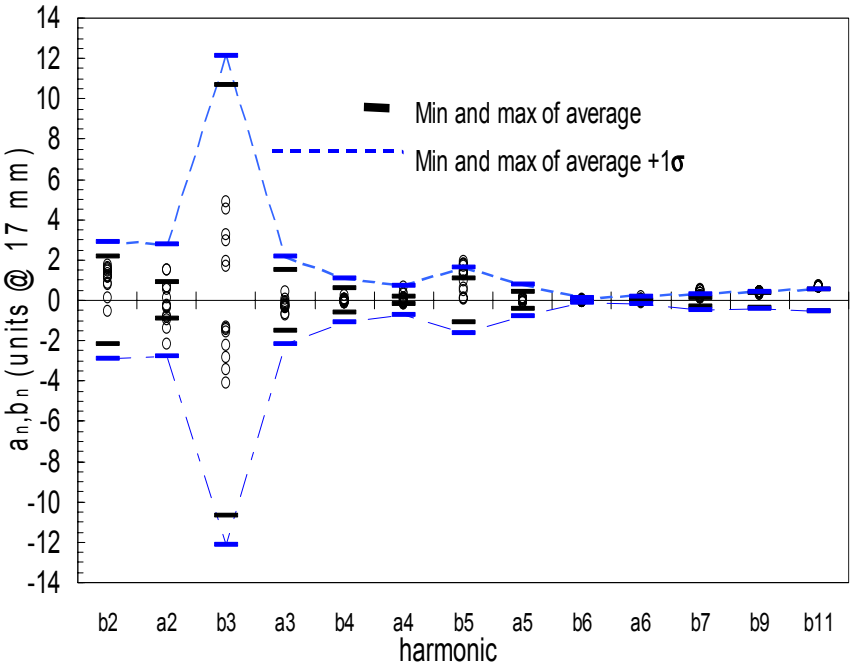
- 6.4 unit @ injection
- 5.5 unit @ collision
- 8 unit allowed

Field Direction

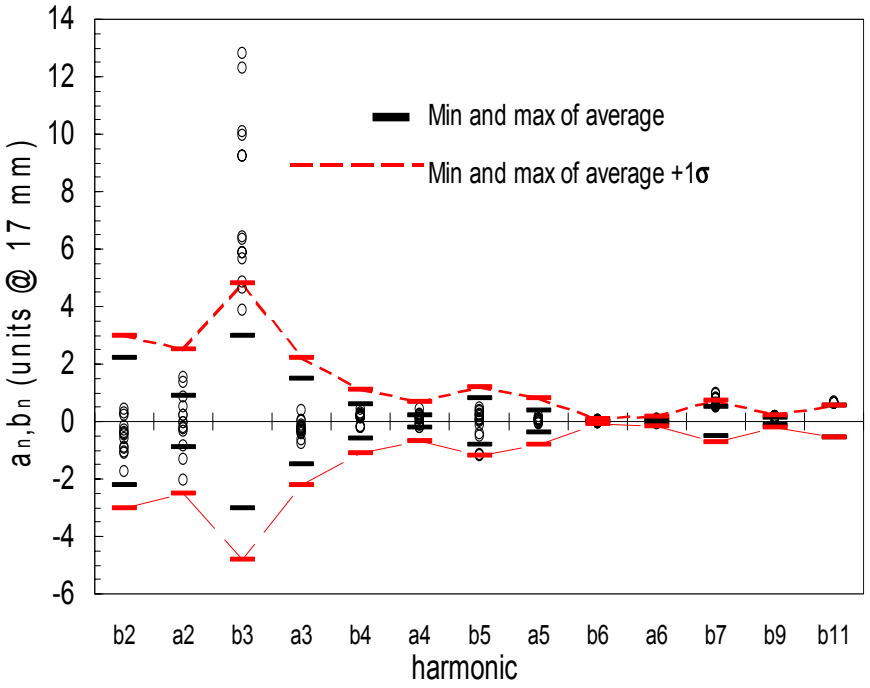
- Twist : 1.1 mrad meas. 3 mrad allowed
- Co-linearity : 0.5 mrad meas. 0.8 mrad allowed

Multipole Measured & Allowed

Injection



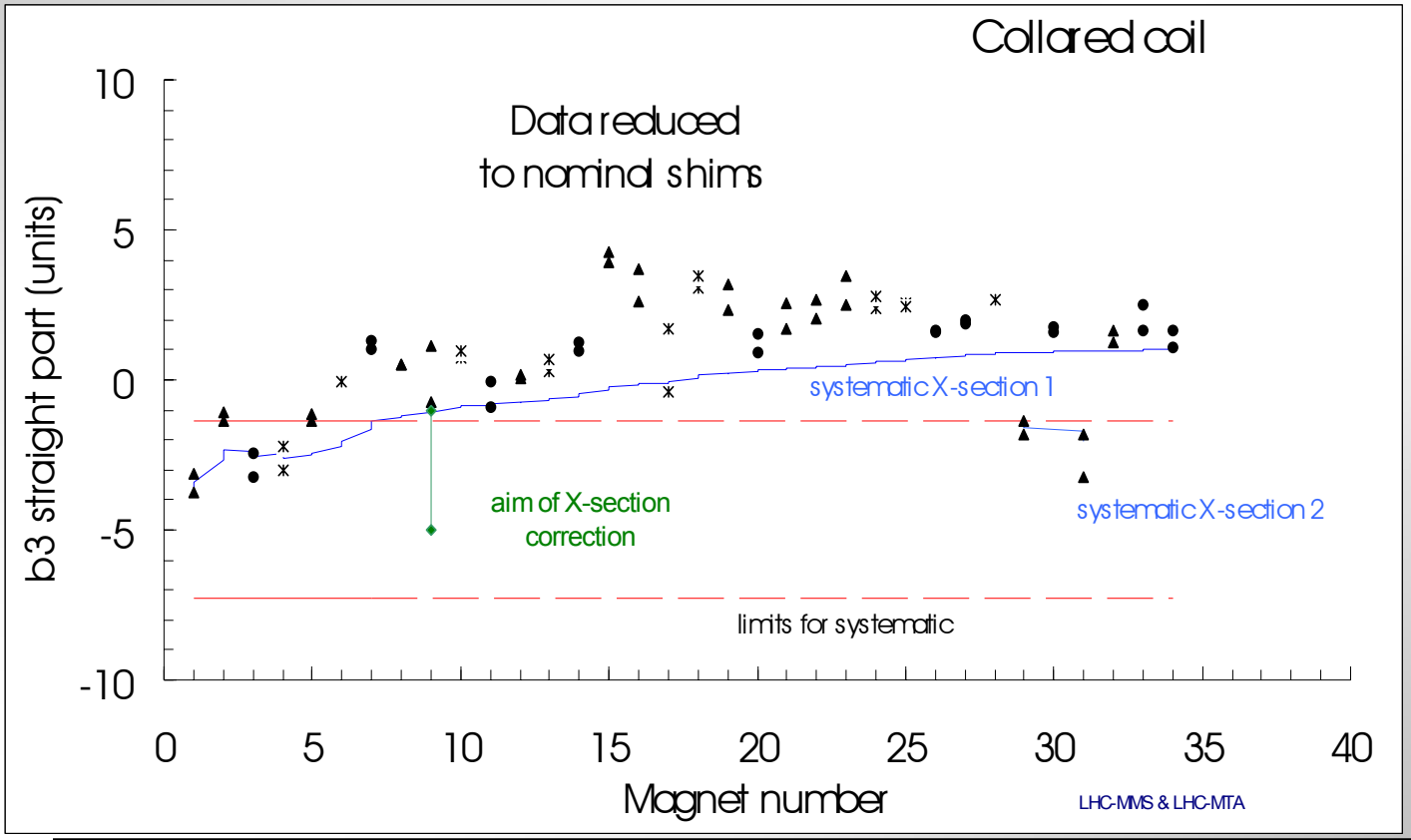
Collision



!! b_5 @ injection b_3 @ collision !!

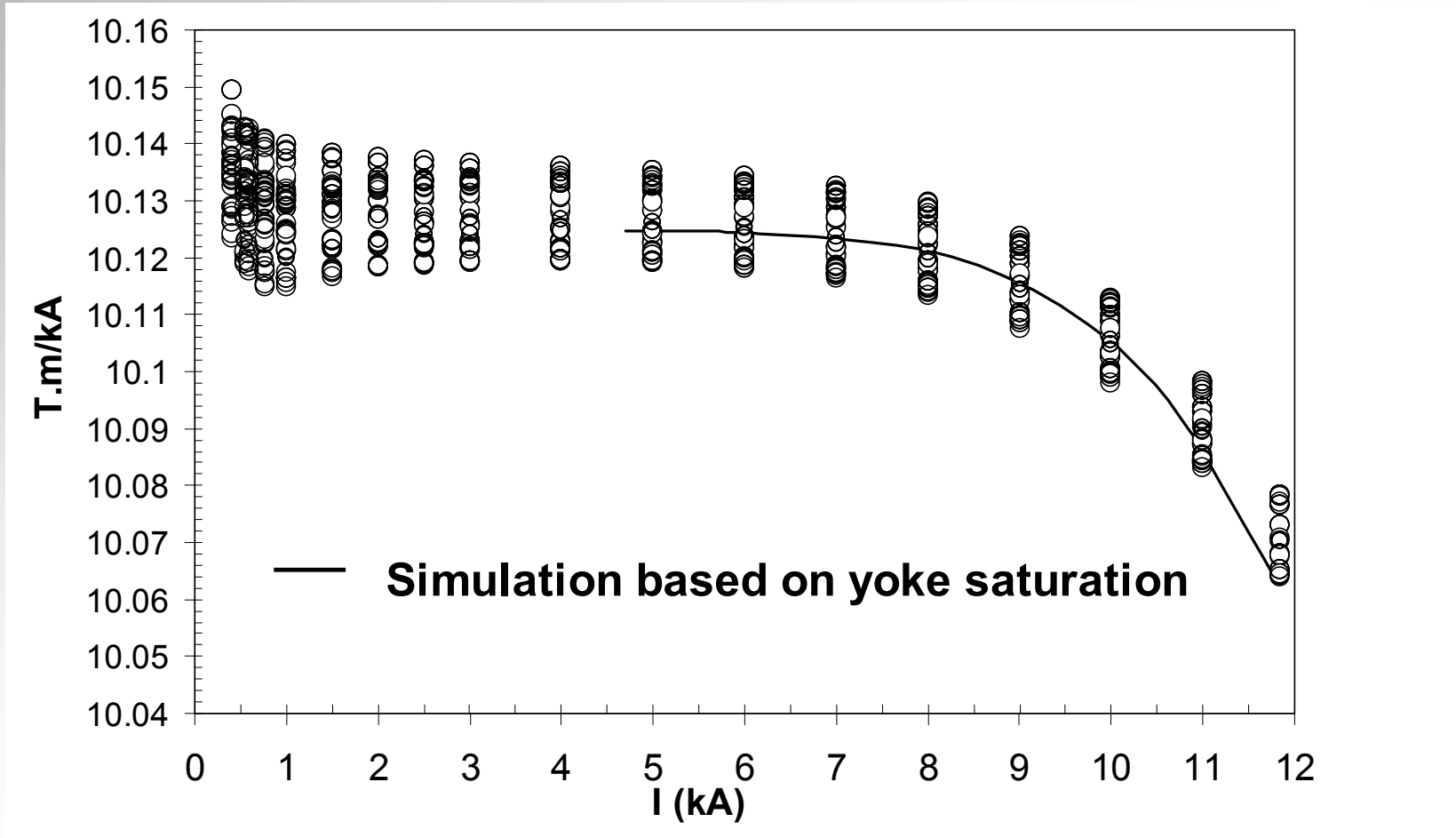
Change of cross-section: effect on b_3

- Control limits computed with correlations to measures at 1.9 K
- Correction worked as expected: we are inside the spec
- Drift (under investigation) observed from magnet 1 to 15



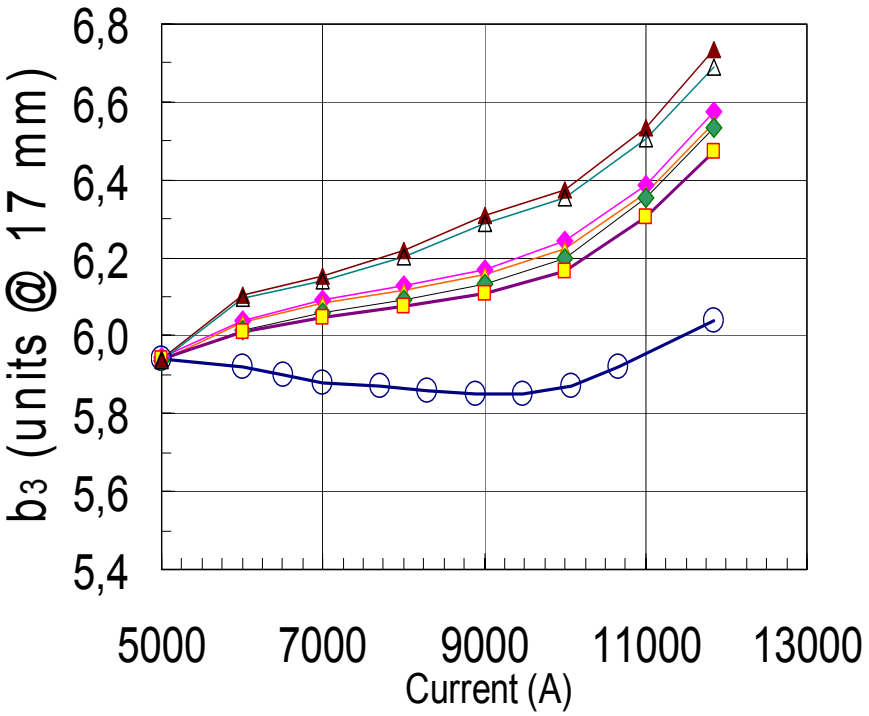
E. Todesco , Status Report on Field Quality in the Main LHC Dipoles, this conference

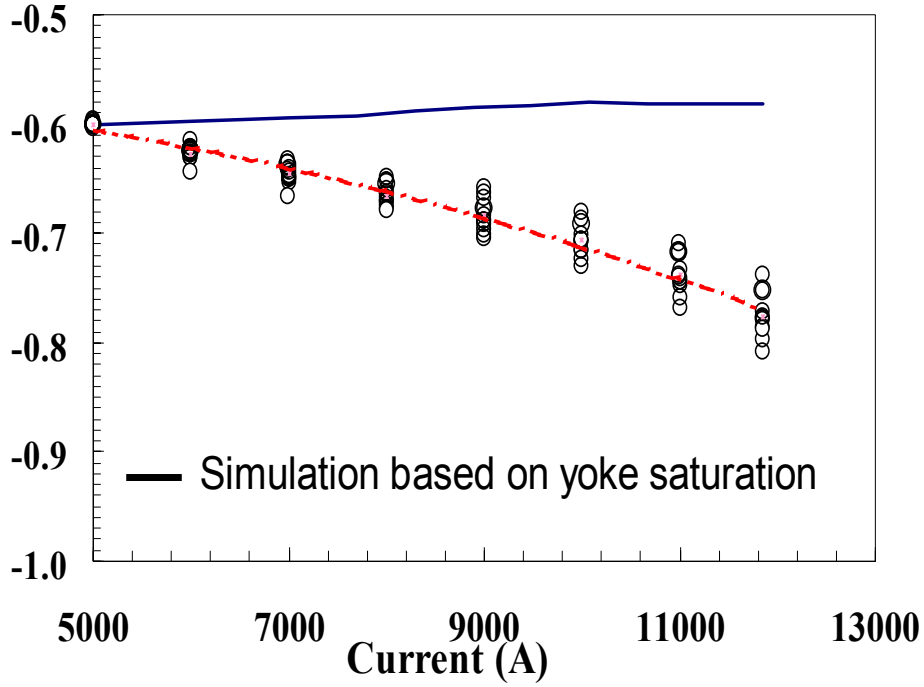
High Field Effect - Dipole



Small discrepancy between calculation & measurement

b_3 & b_5 *Saturation effect*

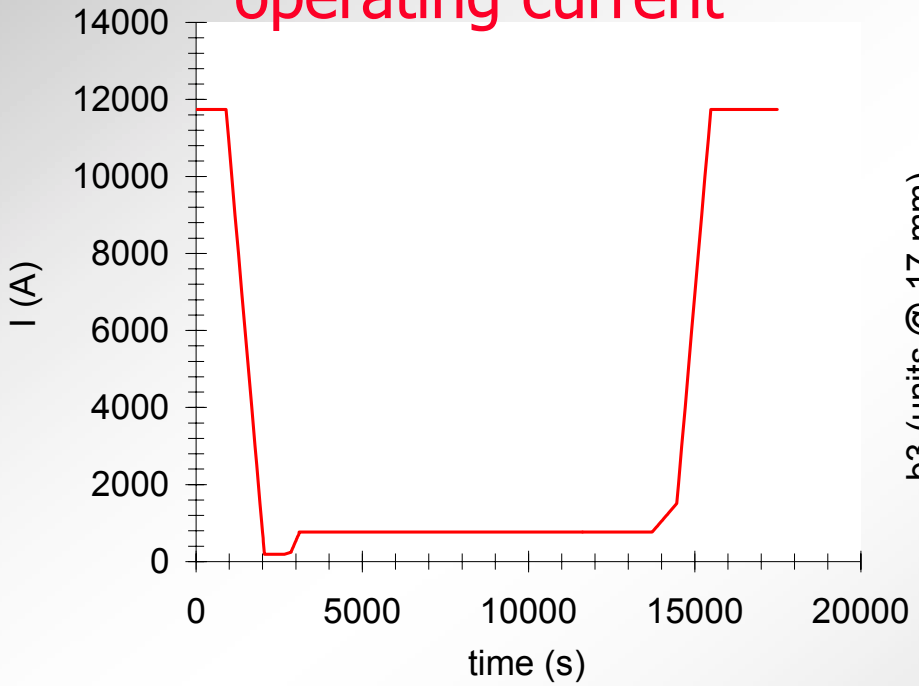


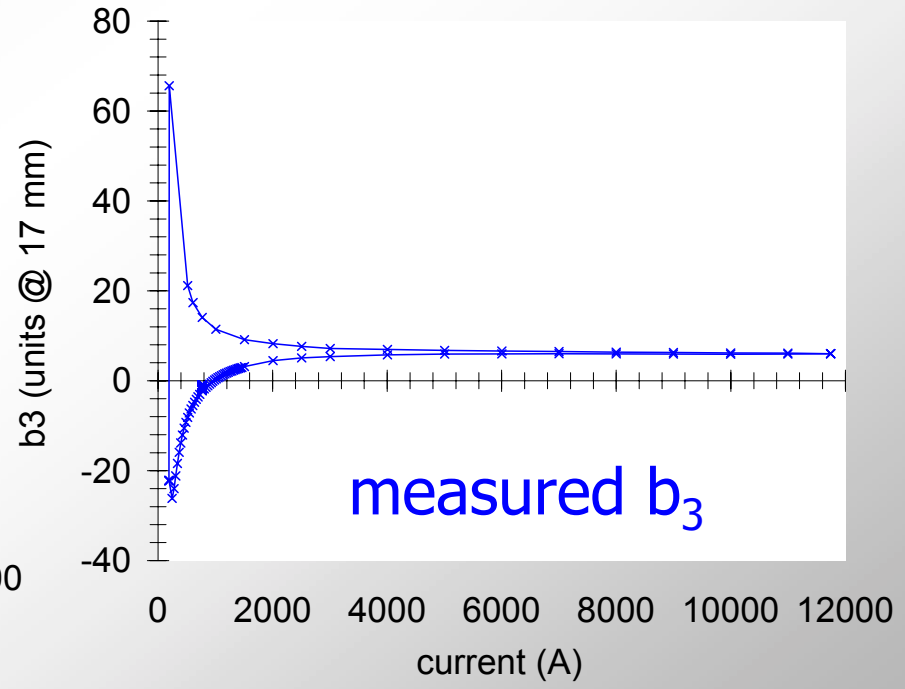


- Substantial deformation due to Lorentz Force

A typical LHC operation cycle

operating current





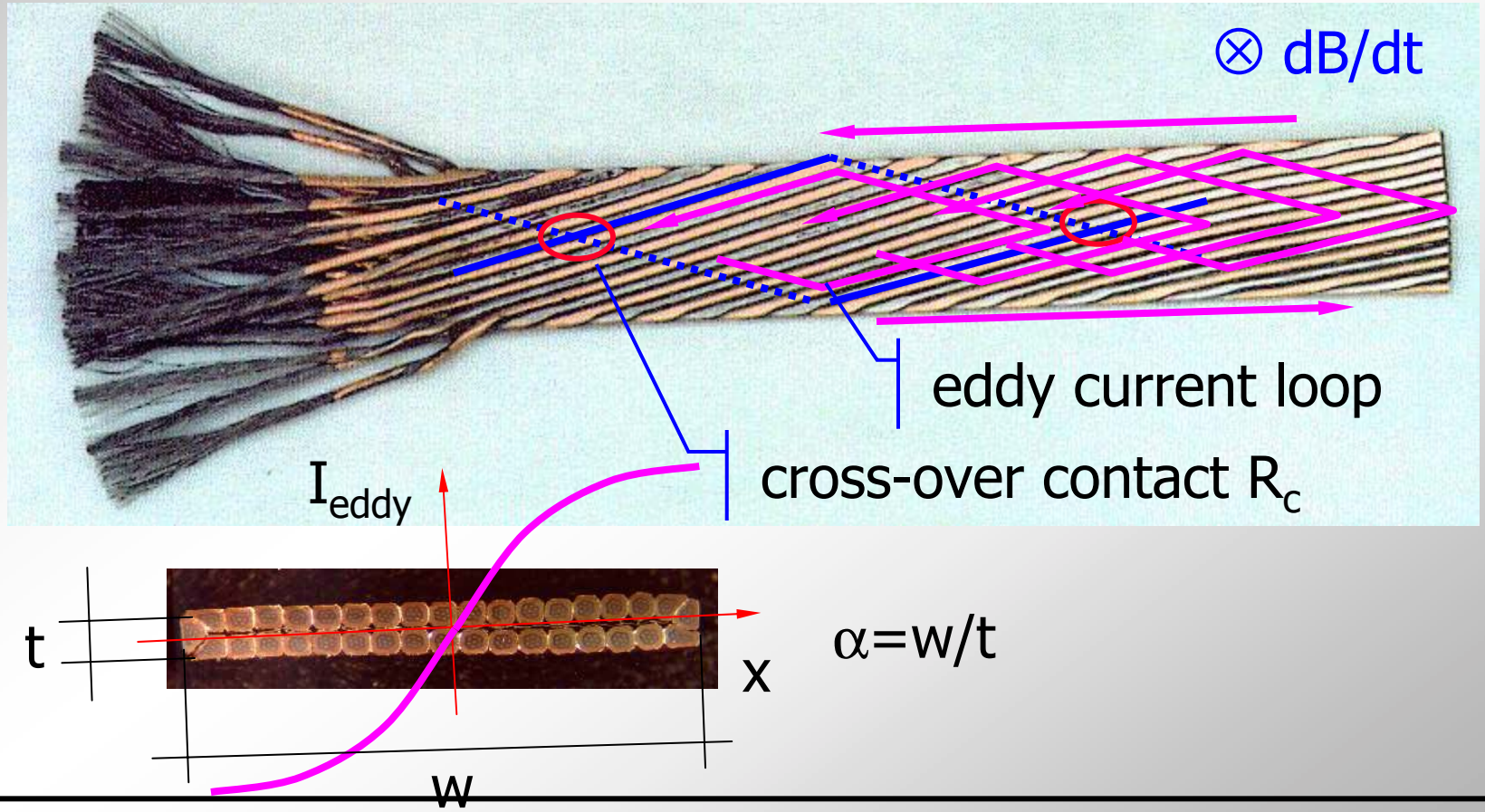
Magnetization @ Injection Field

Multipole	Measured		Calculated	
[Unit]	Average	Spread	Average	Spread
b_1	-2.19	1.78	-5.43	0.33
b_3	-7.31	0.31	-7.97	0.11
b_5	1.12	0.16	1.09	0.02
b_7	-0.39	0.027	0.43	0.007

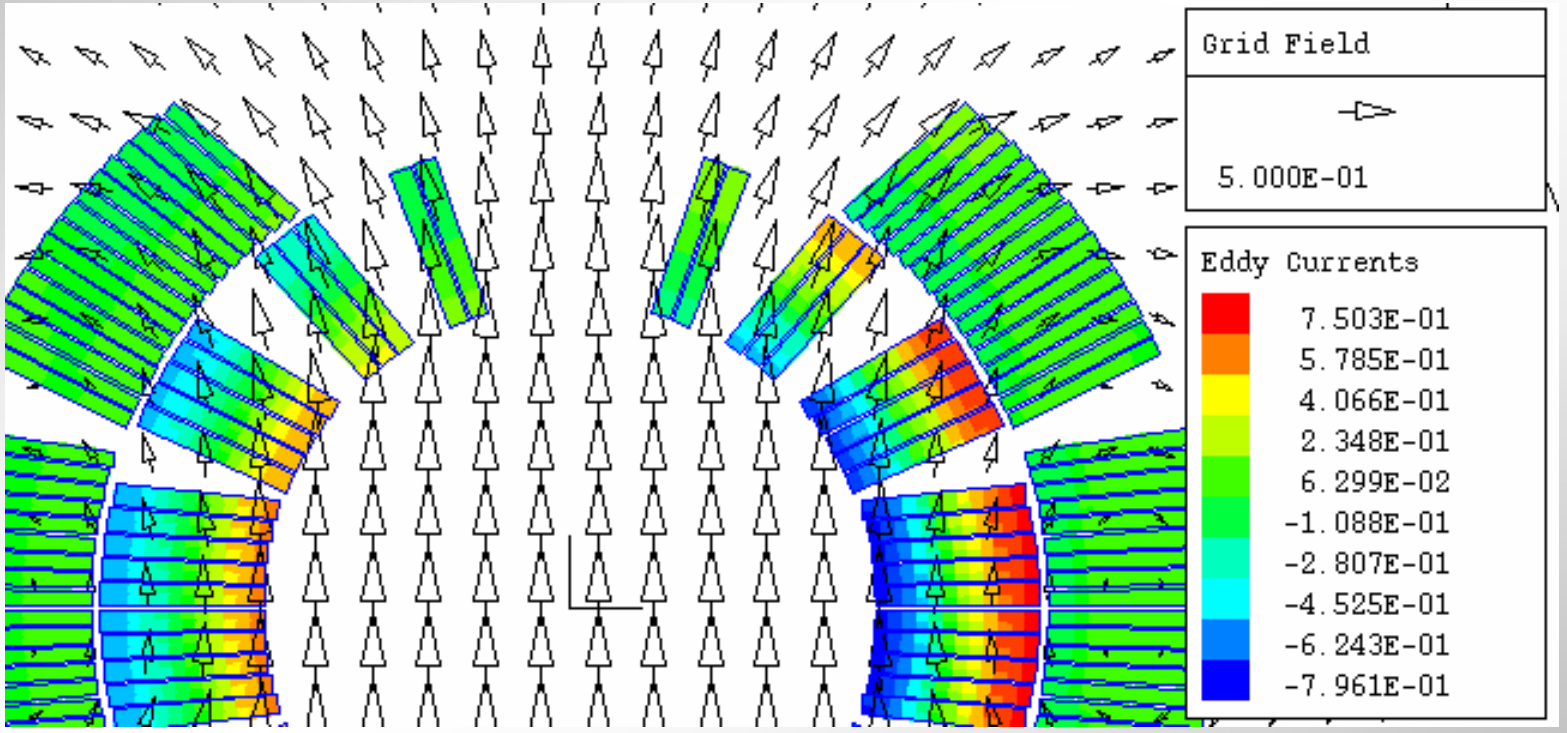
Discrepancy (high for small n) under investigation

Ramp Rate Effect

SC Rutherford cable in transverse field

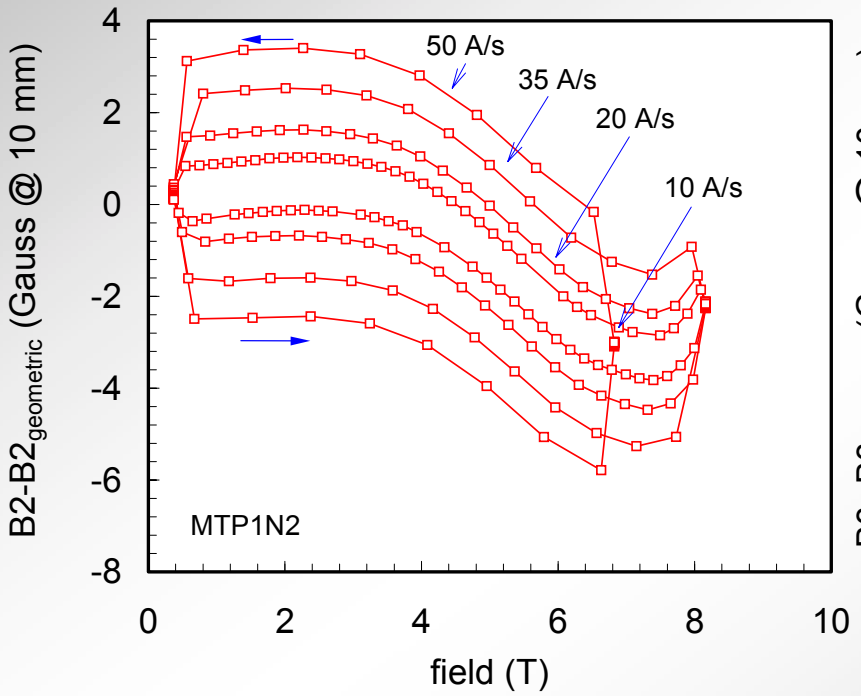


Eddy current in a LHC dipole Cross-section

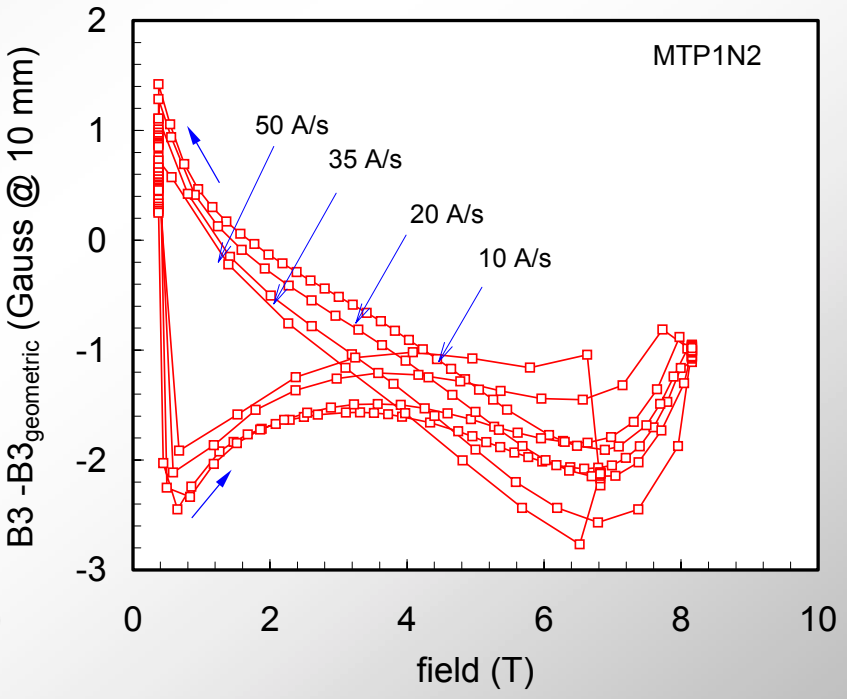


Ramp Rate Effect in Prototype Dipoles
Interstrand resistance < 10 μΩ

Normal quadrupole during ramps



Normal sextupole during ramps



Ramp Rate Effect in Preseries Dipoles

R&D to Control & Increase Interstrand Resistance

$R_{i.s.}$ Specified > 15 μΩ

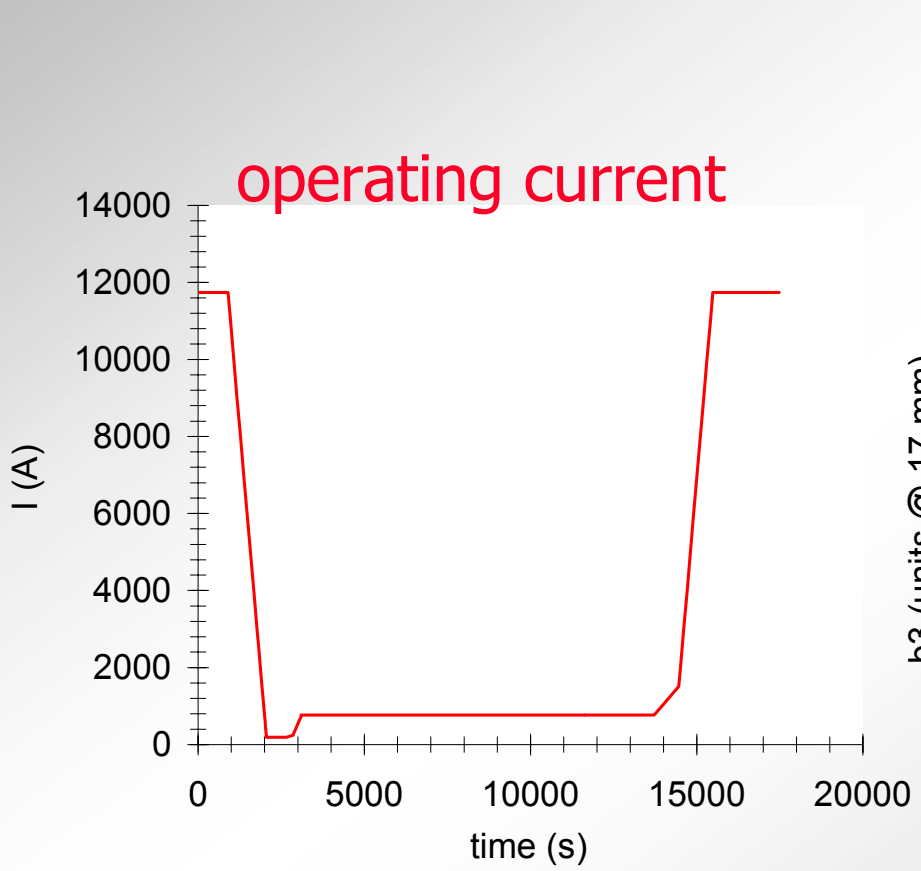
Measured $R_{i.s.}$: from 30 μΩ to more than 100 μΩ

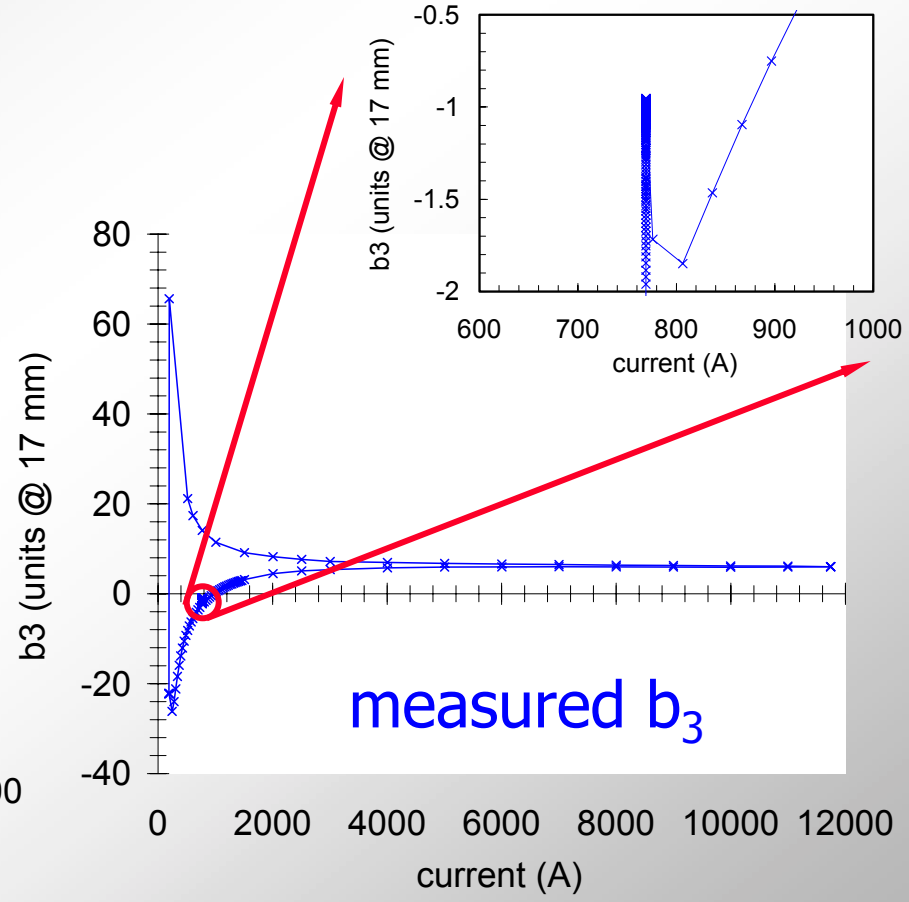
Multipole	Measured @ 10 A/s Injection Field	
[Unit]	**Average**	**Spread**
$\mathbf{b_3}$	0.05	0.13
$\mathbf{b_5}$	0.001	0.042

$\Delta\, b_3 = 0.02$ unit $\Rightarrow \Delta\, Q' = 1$ unit

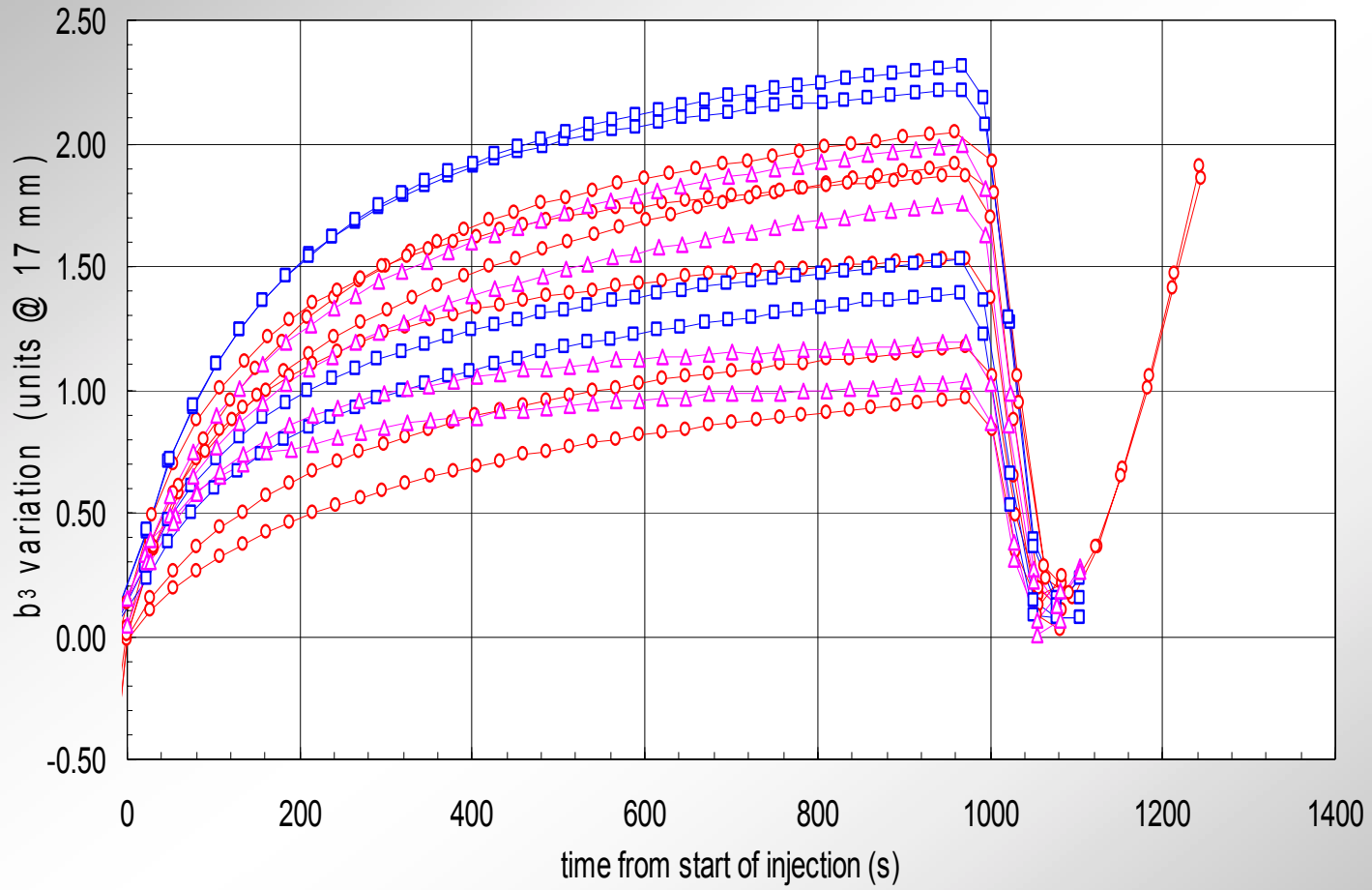
$\Delta\, b_5 = 0.2$ unit $\Rightarrow 1\ \sigma$ on D.A.

Decay during Injection
Snap-Back @ Acceleration Start





Decay & Snap-Back : Sextupole



$\Delta b_3 = 0.02$ unit creates $\Delta Q' = 1$ unit

Decay & Snap-Back

Multipole	Measured	
[Unit]	Average	Spread
b_3	1.6	0.47
b_5	-0.3	0.1

$\Delta b_3 = 0.02$ unit $\Rightarrow \Delta Q' = 1$ unit

$\Delta b_5 = 0.2$ unit $\Rightarrow 1\ \sigma$ on D.A.

Conclusions

- *Transfer function , Field Direction* — *O.K.*
- *High Field Effects depend on Iron Saturation + Lorentz Forces*
- *Multipoles* — *b3 , b5* — *improvement to verify @ 1.9 K*
- *Injection Field* = *Persistent Current* (+ ?)
- *Ramp Rate Effects* — *Clear Improvement since Prototypes*
- *Decay & Snap-Back* — *Delicate to control*