Measurements of Dynamic Effects in FNAL 11 T Nb3Sn Dipole Models

August 28, 2017

G. Velev, T. Strauss, E. Barzi, G. Chlachidze,
J. Di Marco, F. Nobrega, I. Novitski, S. Stoynev,
D. Turrioni, A.V. Zlobin

Outline

- Motivation
- Short History
- Fast field change needs new measurement technologies: ADC/DSP DAQ systems and Printed Circuit Board (PCB) probes
- Dynamic effects in FNAL 11 T Nb_3Sn models
  - Main field;
  - Sextupole field component;
- Summary

Harmonics: $$B_y + iB_x = B_i 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_o} \right)^{n-1}$$ and r_0 = 17 mm

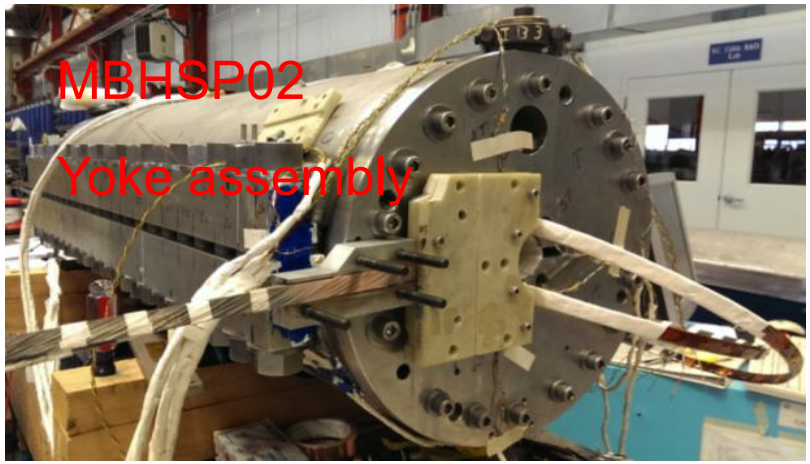
Motivation

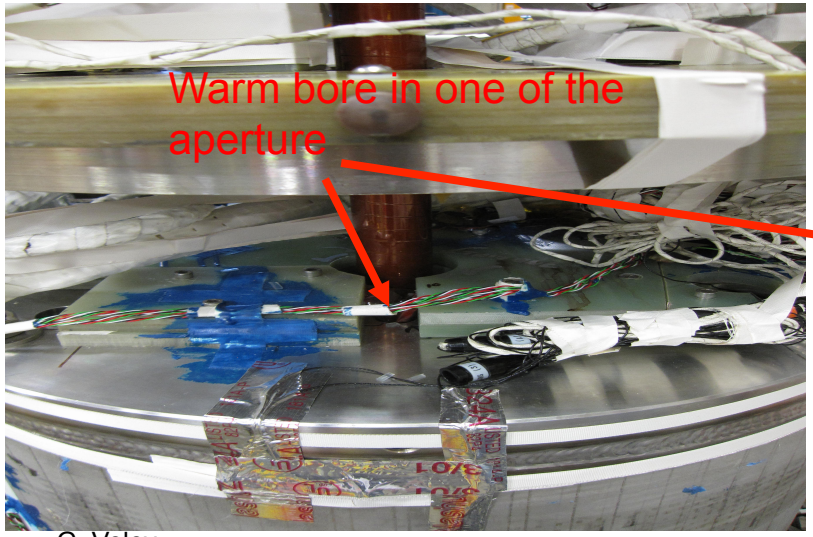
- Since 2001, Fermilab started a R&D program on Nb_3Sn magnets. At the Fermilab Test Facility, we performed a systematic measurements on models for: VHLC and LHC 11 T dipoles, LARP IR quadrupole upgrade.
- The results of this R&D program: Nb_3Sn magnets are a part of the HL-LHC upgrade: 11T dipoles, IR quadrupoles.
  - Recent results MBHSP/MBHDP published in:

    S. Izquierdo Bermudez, L. Bottura, L. Fiscarelli, E. Todesco, "Decay and Snapback in Nb3Sn Dipole Magnets", IEEE Trans. Appl. Supercond., vol. 27, no. 4, 2017, Art. no. 4002306 ,

    on MBHSP/MBHDP show discrepancy with the NbTi expectations
- 15-17 T Nb_3Sn magnets are planned for FCC – the goal is to learn as much as we can.

MTF – MBH 11 T model test





Five 11 T dipoles, four analyzed

MBHSP01,

MBHSP02,

MBHSP03,

MBHSP04,

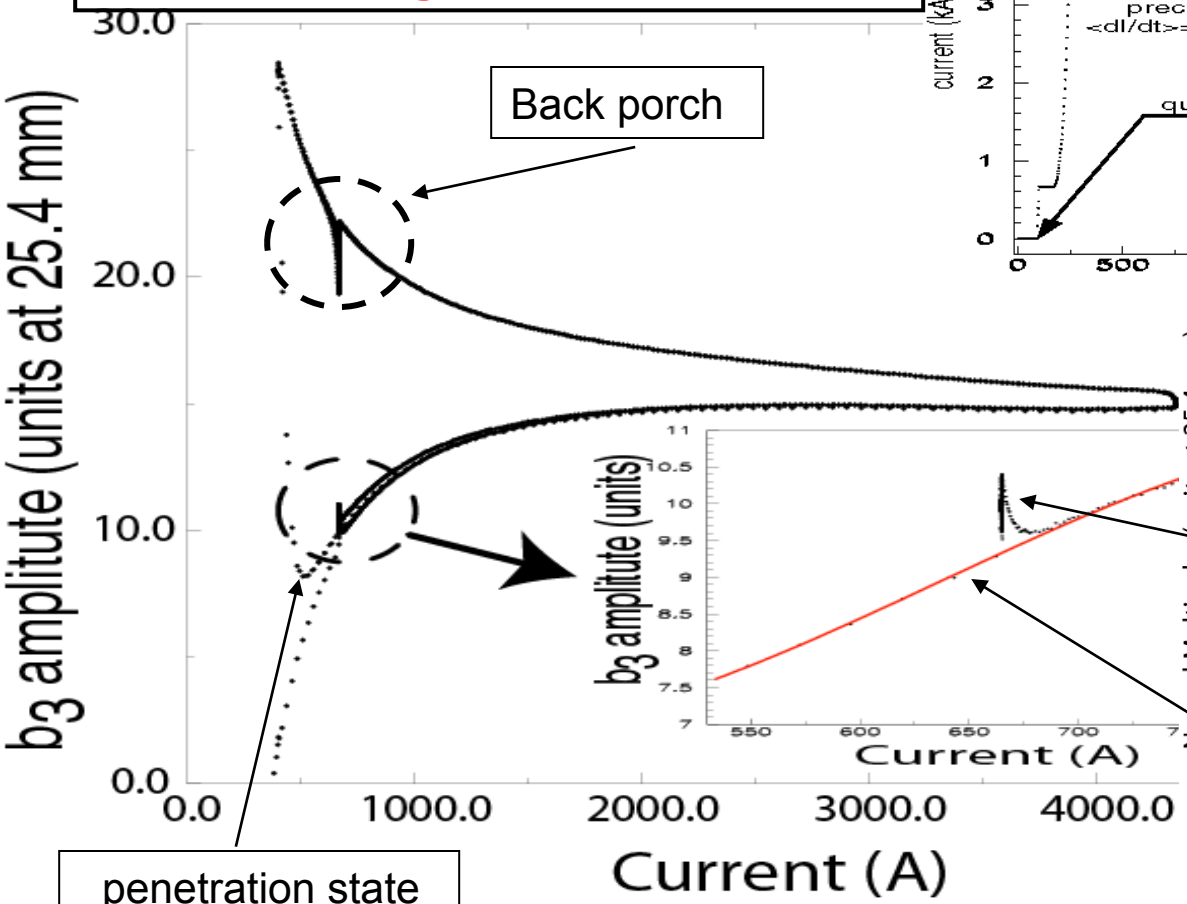
MBHDP01

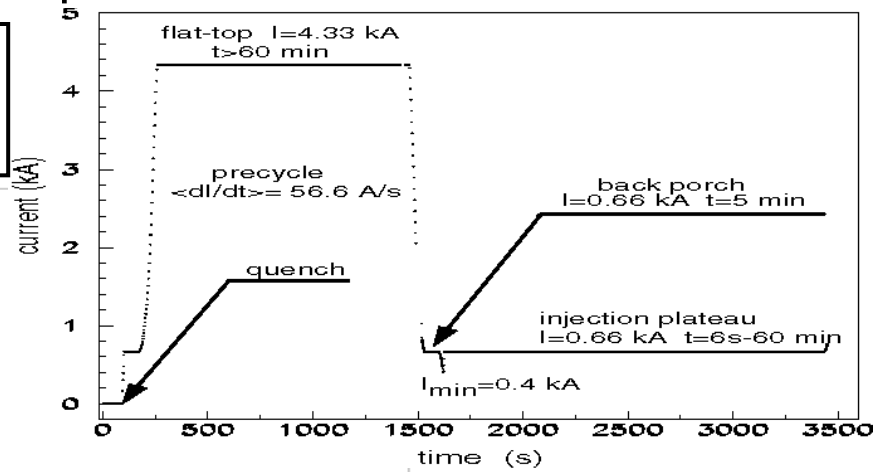
Short history

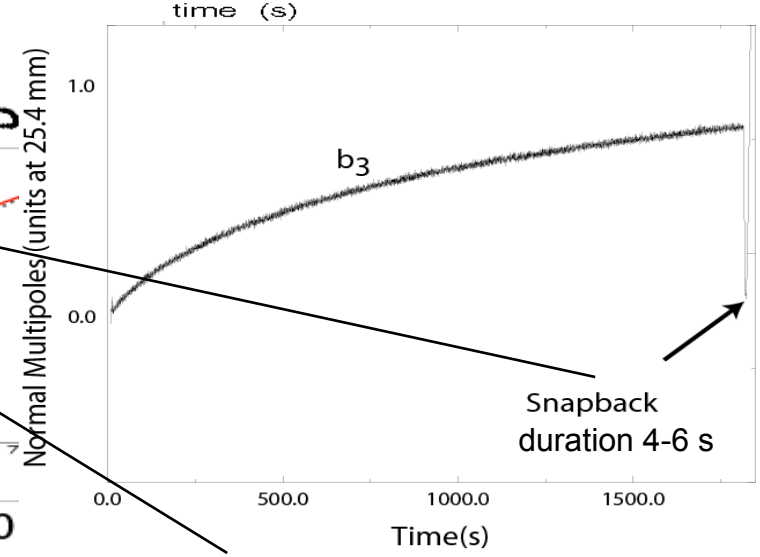
- Dynamic effects were discovered at early operation of the Tevatron observing a large chromaticity growth during the beam injection
- A detailed stand-alone measurement program was executed targeting the dynamic effects for Tevatron, HERA and LHC
- The measurements were done on NbTi dipoles - a lot of data exist
- If we have to summarize in one slide ….

Introduction to Decay and Snapback – based on NbTi data

Effects discovered during early commissioning of the Tevatron



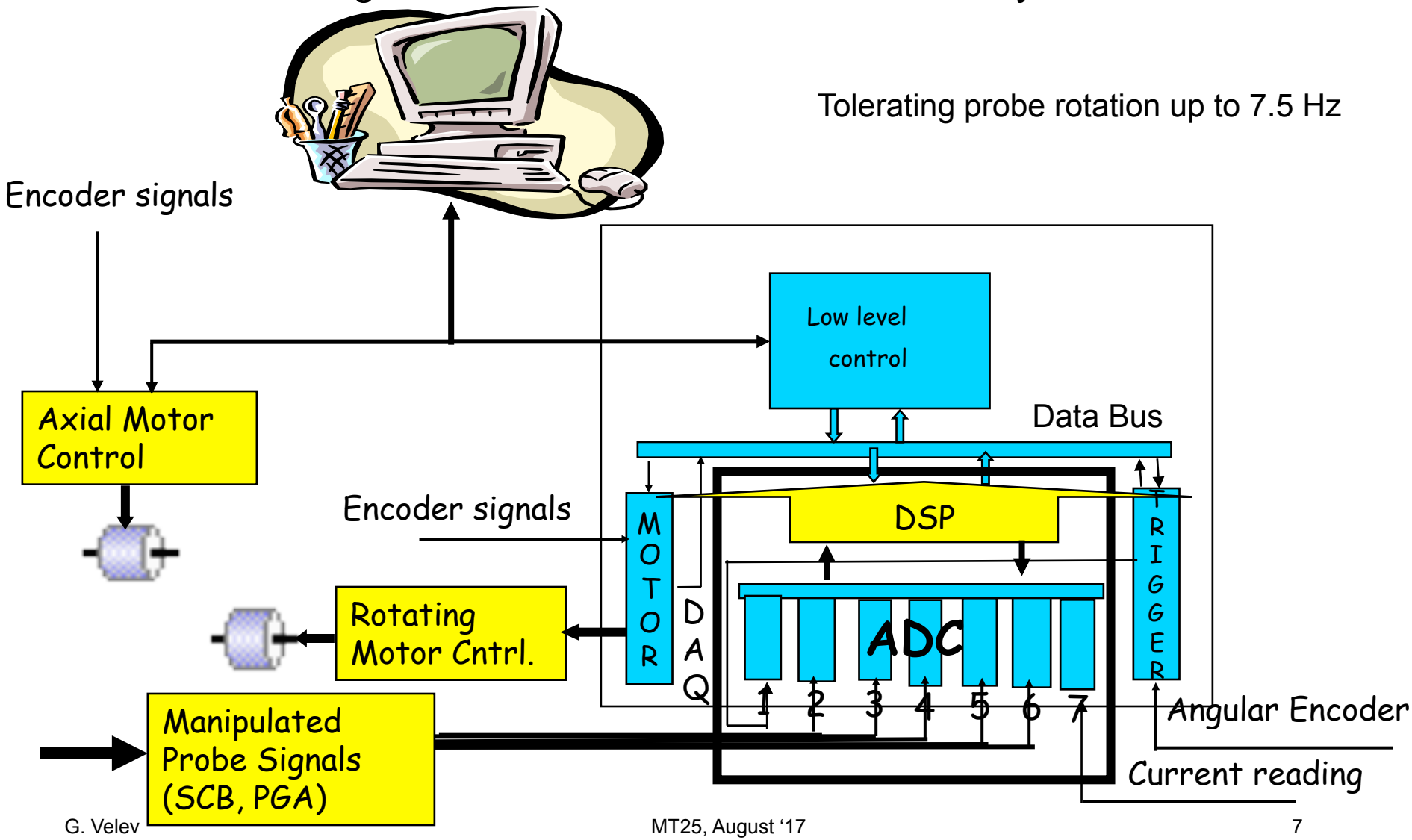




$$b_3^{hyst} = a + b \cdot I + c \cdot I^2$$

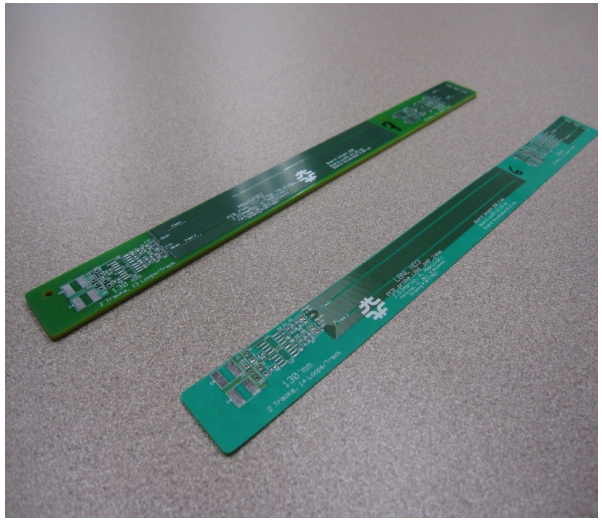
Diagram of the real time measurement system

Tolerating probe rotation up to 7.5 Hz

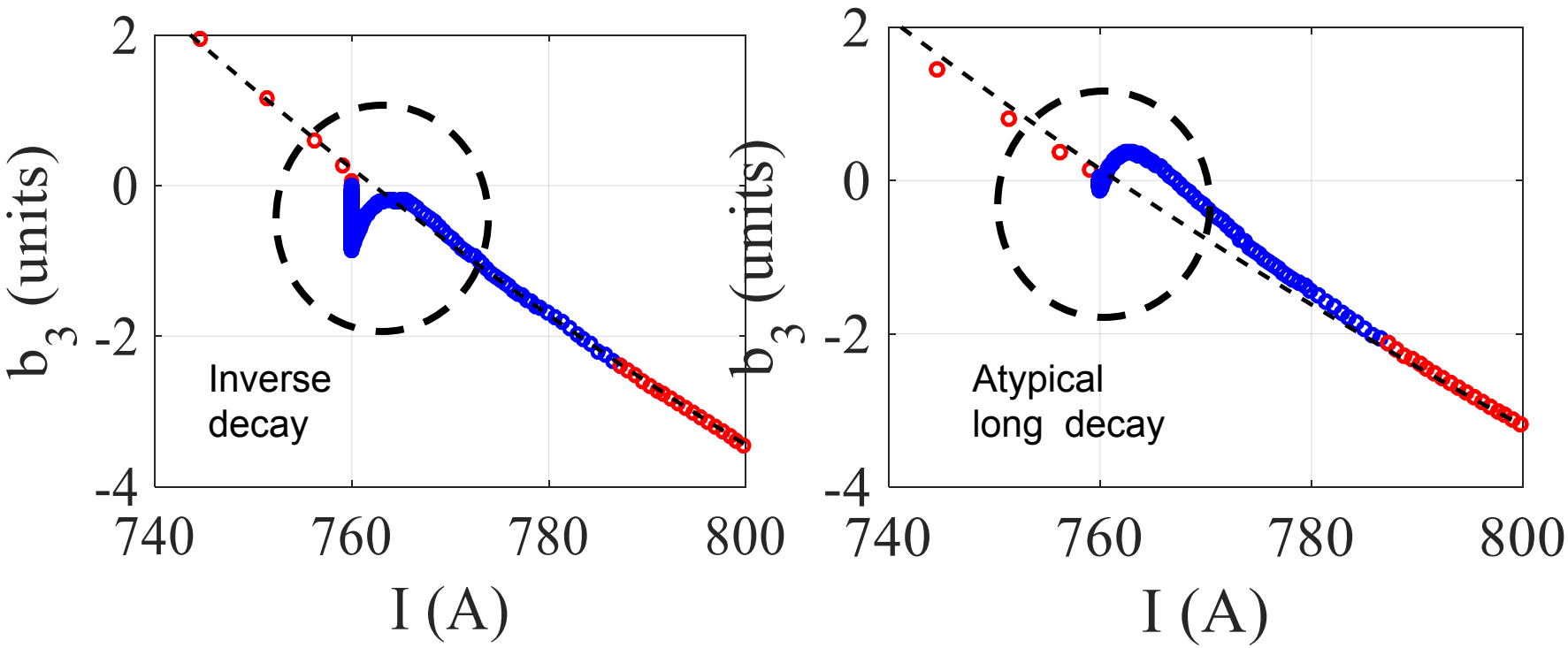


Magnetic measurement probes

- Printed Circuit Board (PCB) probe
- UnBucked (UB) and DipoleBucked (DB) windings
  - 16-Layer, 13 turns/layer/track with outer trace at 14mm radius
  - Probe has two different length circuits
    - 130mm (close to twist pitch)
    - 26mm (1/5) for fine structure measurements



MBHSP/MBHDP CERN Nb_3Sn model measurements



- Recent results from MBHSP/MBHDP published in:
  - S. Izquierdo Bermudez, L. Bottura, L. Fiscarelli, E. Todesco, "Decay and Snapback in Nb3Sn Dipole Magnets", IEEE Trans. Appl. Supercond., vol. 27, no. 4, 2017, Art. no. 4002306 .
- Similar decay in the main dipole field comparing to NbTi
- Inverse decay in the normal sextupole - not observed in NbTi

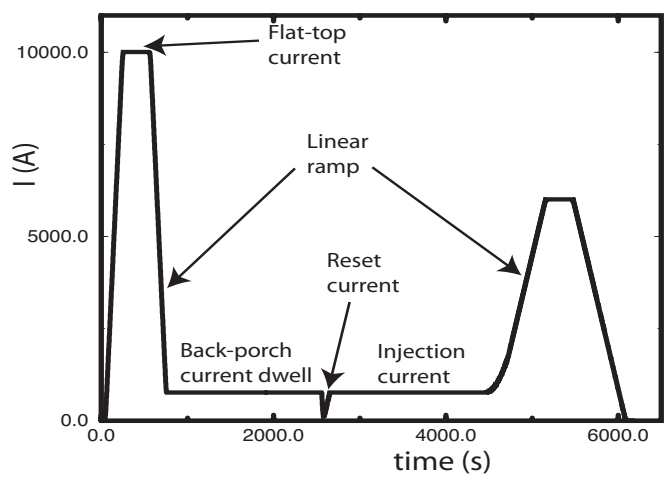
Main Field decay

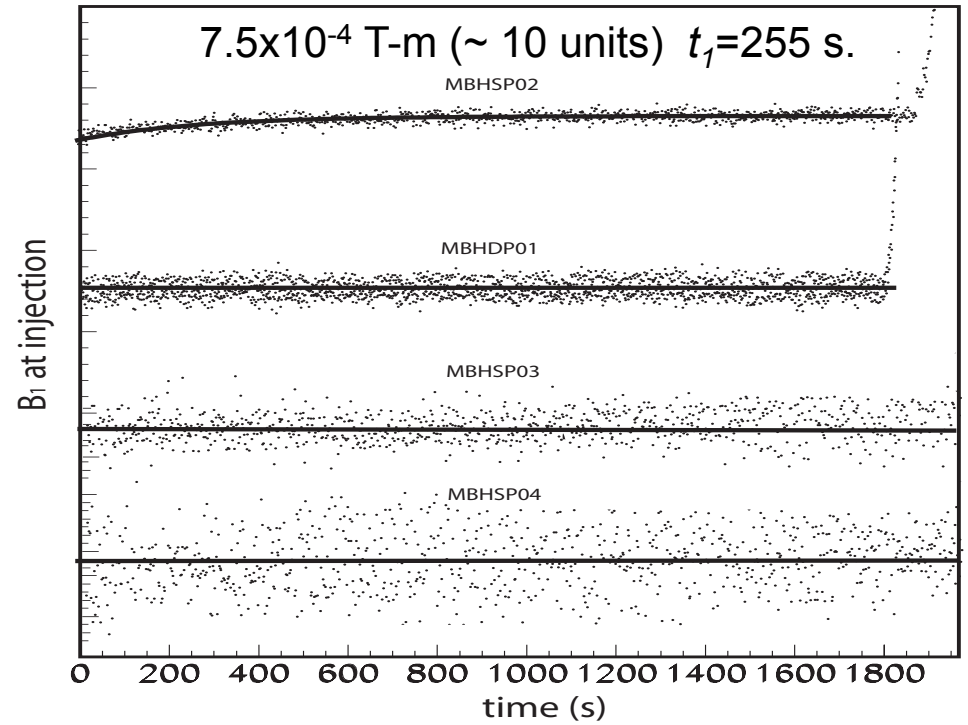
TABLE I
MAGNETS AND CURRENT PROFILE PARAMETERS

Magnet	I_{inj} (A)	Reset current (A)	Back-porch dwell (min)
MBHSP02	760	100	0
MBHSP03	760	100	0
MBHSP04	760	100	0
MBHDP01*	760	100	0
MBHDP01*	760	0	0
MBHDP01*	760	350	0
MBHDP01*	760	760	0
MBHDP01*	350	100	0
MBHDP01*	1170	100	0
MBHDP01*	1420	100	0
MBHDP01*	350	100	30
MBHDP01*	760	100	30

[a]MBHDP01 is a double aperture magnet

Back porch

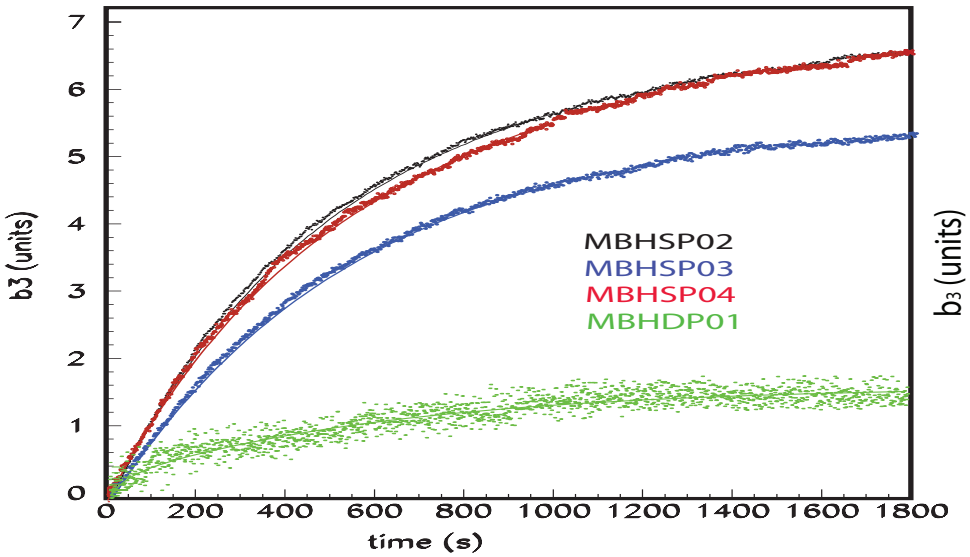


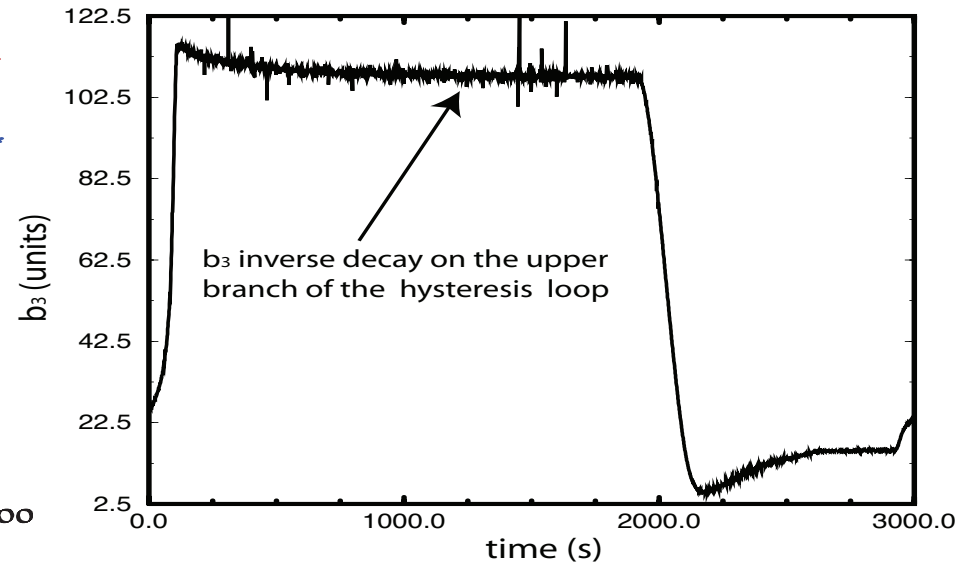


$$\Delta b_3^{dec} = b_{2,1} \cdot \left(1 - \exp\left(\frac{-t}{t_1}\right)\right) + b_{2,2} \cdot \left(1 - \exp\left(\frac{-t}{t_2}\right)\right).$$

Slow and fast mode

Norma sextupole decay (b_3)

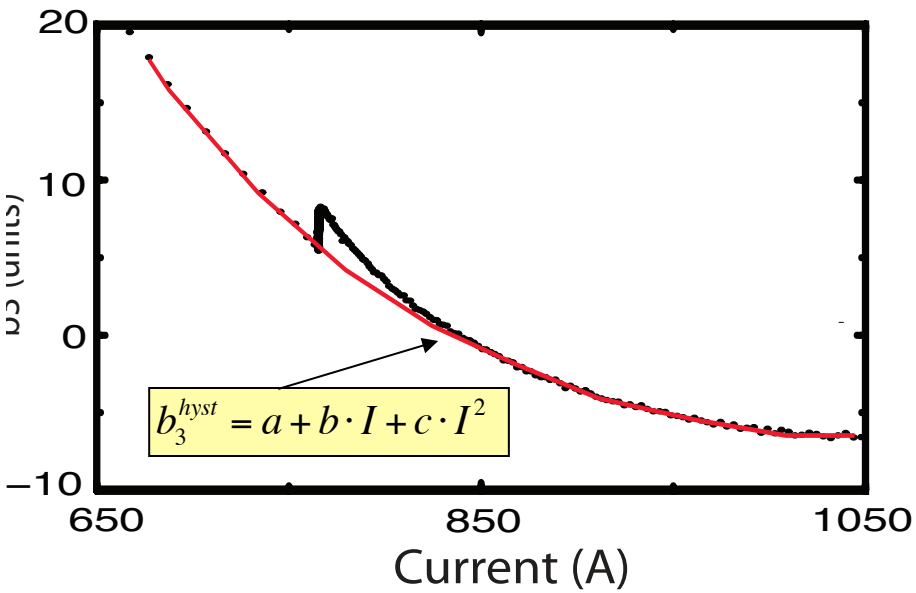


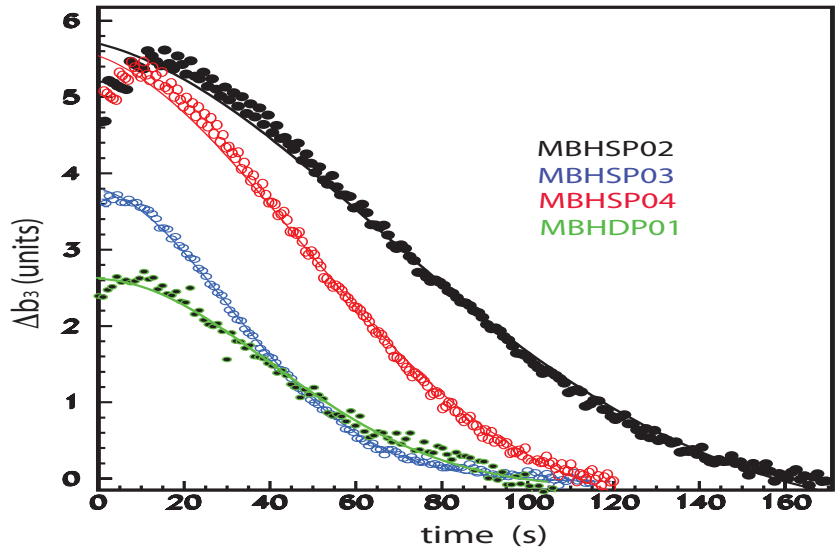


Magnet	I_{inj} (A)	$b_{3,1}$ (units)	t_1 (s)	$b_{3,2}$ (units)	t_2 (s)	b_3 (units)
MBHSP02	760	6.9	290	0	-	6.9
MBHSP03	760	5.1	302	0	-	5.1
MBHSP04	760	6.5	329	0	-	6.5
MBHDP01	760	2.5	1949	1.0	172	3.5
MBHDP01	350	0.7	630	0.6	32	1.3
MBHDP01	1170	1.7	400	0	-	1.7
MBHDP01	1470	1.6	630	0.3	36	1.8

- Normal sextupole at 760 A injection:
  - average amplitude: b_3=5.5 units, comparing to 1-2 units in NbTi
  - time constant: t_1= 718 s
- Inverse decay at the upper branch of the hysteresis curve, back porch at 760 A

Snapback in the normal sextupole





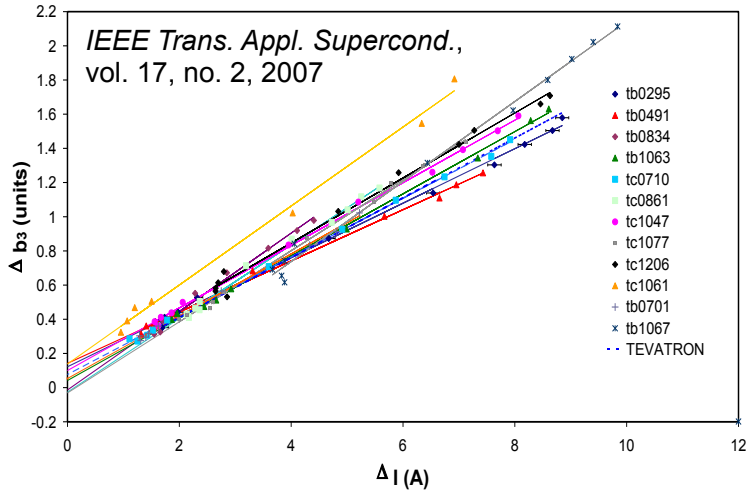
- In snapback parameterization:
  - Half Gaussian
  - $\Delta b_3^{sb}(0) \sim t^2 \sim \Delta I$

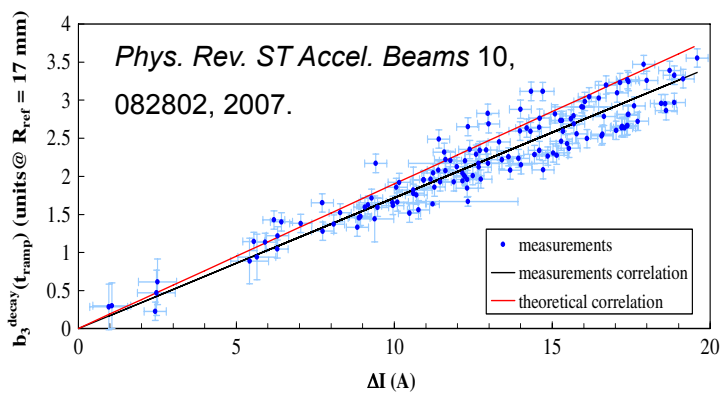
$$\Delta b_3^{sb}(t) = \Delta b_3^{dec}(t_{inj}^{end}) \cdot \exp\left(\frac{-t^2}{t_{sb}^2}\right)$$

Parabolic current ramp →

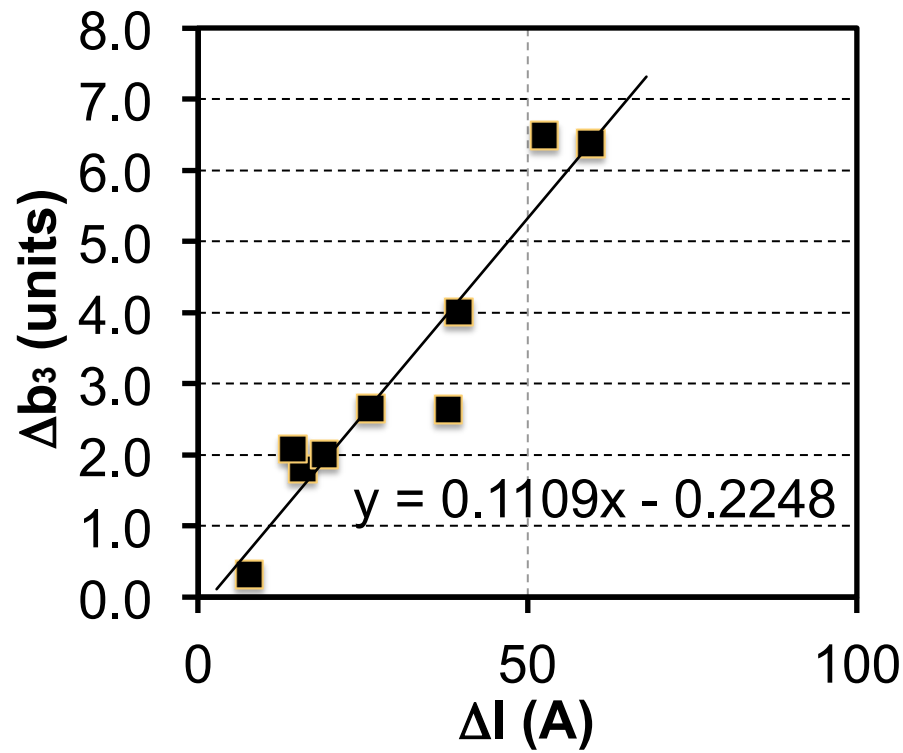
$$\Delta b_3^{sb}(t) = \Delta b_3^{dec}(t_{inj}^{end}) \cdot \exp\left(\frac{-(I(t) - I_{inj})}{\Delta I}\right)$$

"Scaling Law"





$$\Delta b_3^{sb}(0) = \Delta b_3^{dec}(t_{inj}^{end}) \sim \Delta I \sim t_{sb}^2$$



Scaling law: linear correlation between the decay/snapback amplitude and ΔI needed to return back b_3 to hysteresis curve

Important feature: predictability

Summary

- We presented a summary of the dynamic effects, including decay and snapback in the main dipole and sextupole fields for the Fermilab 11 T model magnets
- The results clearly show that decay and snapback follow the same trend as NbTi dipoles - comparison is done to the Tevatron and LHC main ring dipoles.
- A difference is observed in the amplitude of the decay in the normal sextupole, which found to be in average 5.5 units at injection, comparing to 1-2 in NbTi magnets.
- We found snapback time constants up to 10 times longer. This transfers to up to 80 A in ΔI.
- The ΔI is in order of magnitude larger than currents observed in the CERN MBH 11 T Nb_3Sn models
- In our 11 T dipoles measurements do not confirm the recent CERN MBH results about the inverse behavior in the normal sextupole
- Currently, new empirical models are introduced to describe the dynamic behavior of Nb_3Sn magnets. They are exploring partial magnetization of the filaments, flux jumps in Nb3Sn conductor and effects of the Wind&React processes
- To confirm these models more data from dedicated experiments are needed
  - next year, we will test of the 15 T dipole model as part of the US MDP program

Backup slides

Snapback parameterization

- In case:
  - Half Gaussian
  - $\Delta b_3^{sb}(0) \sim t^2$

$$\Delta b_3^{sb}(t) = \Delta b_3^{dec}(t_{inj}^{end}) \cdot \exp\left(\frac{-t^2}{t_{sb}^2}\right)$$

- Scaling law:

$$\Delta b_3^{sb}(0) = \Delta b_3^{dec}(t_{inj}^{end}) \sim \Delta I \sim t_{sb}^2$$