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Chromaticity decay due to superconducting dipoles on the injection plateau of the Large Hadron Collider

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Overview

- **Field description for the LHC (FiDeL)**
  - introduction and overview
  - the model
- **Behaviour of the machine - Analysis and Results**
  - decay model
  - powering history scaling law
- **Conclusions**

Field description for the LHC (FiDeL)

FiDeL - introduction

- On the FiDeL website, https://lhc-div-mms.web.cern.ch/lhc-div-mms/tests/MAG/Fidel/ one finds the following description:
  - "…refer to this set of equations together with the coefficients estimated from measurements as the *Field Description for the LHC (FiDeL)*…"
  - "…The aim is to provide the integral transfer function (integral field vs. current) in a form suitable for inversion (current vs. integral field) for each circuit in the LHC. In addition, for the main ring magnets FiDeL will provides a prediction of the field errors to be used to set the corrector circuits…"

FiDeL - overview

FiDeL model

provides the superconducting magnet integral field transfer function, such that the various powering circuits of the LHC supply the necessary currents

predicts field errors and sets the corrector circuits to compensate for errors

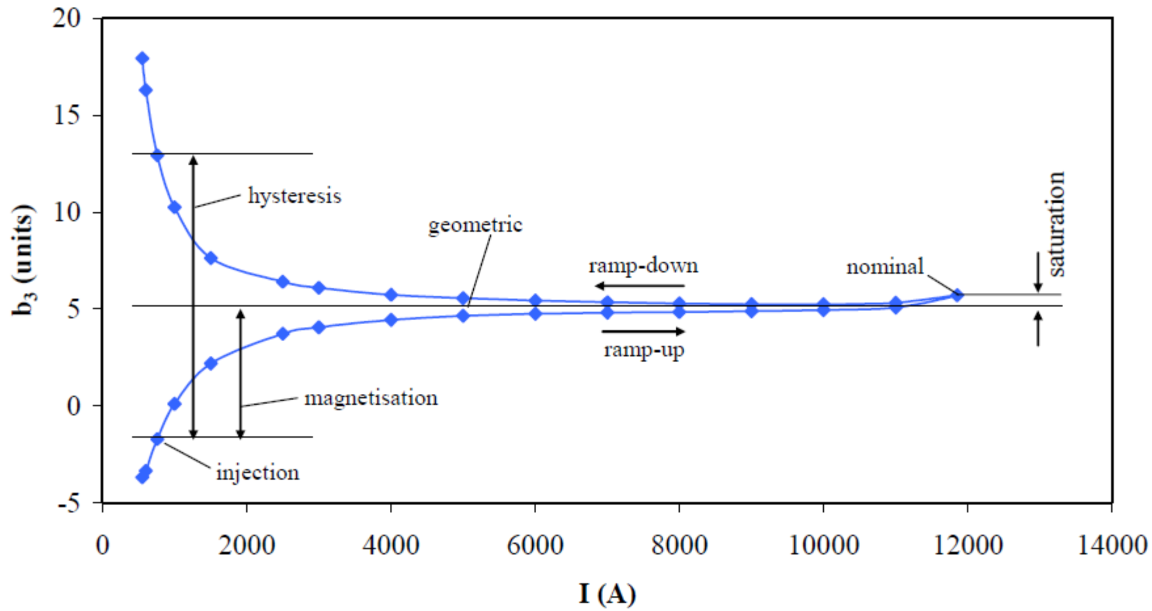
static components

geometric contribution

d.c. magnetisation contribution

saturation contribution

residual magnetisation contribution



FiDeL - overview

FiDeL model → provides the superconducting magnet integral field transfer function, such that the various powering circuits of the LHC supply the necessary currents

FiDeL model → predicts field errors and sets the corrector circuits to compensate for errors

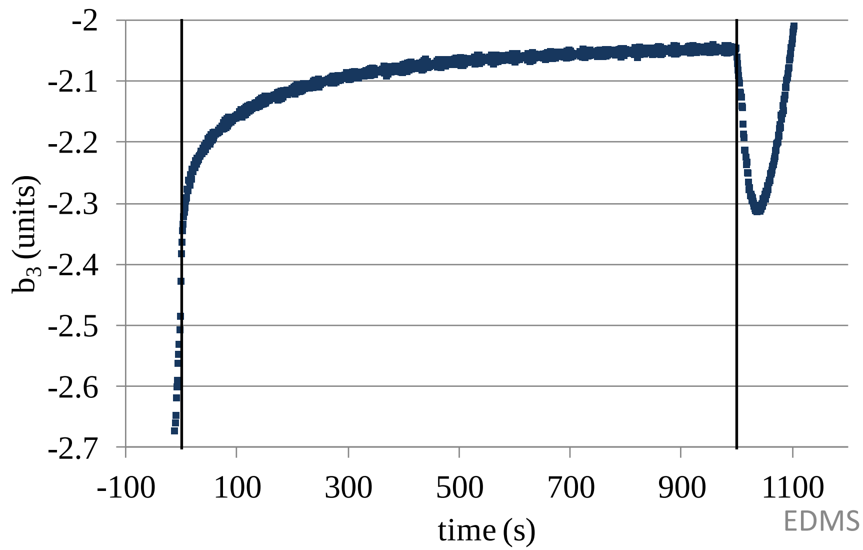
predicts field errors… → dynamic components

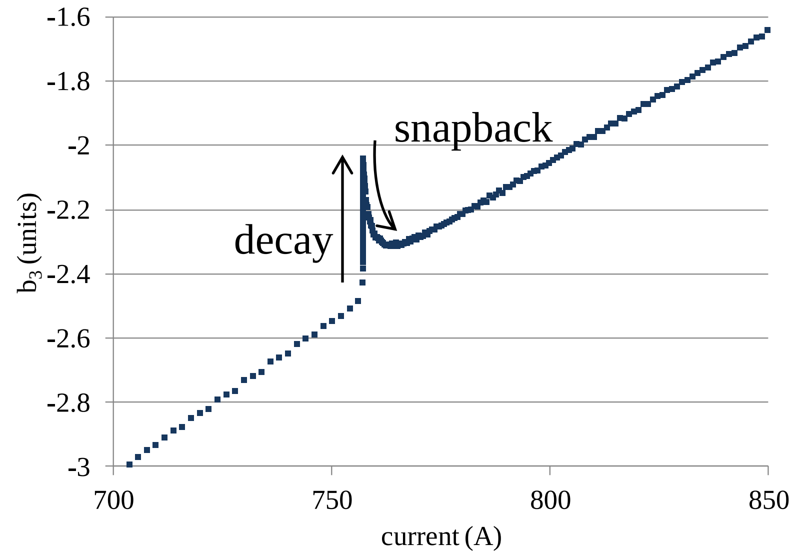
dynamic components → snapback

dynamic components → decay

$$b_n^{snapback}(I) = \Delta b_n e^{-\left(\frac{I - I_{inj}}{\Delta I_n}\right)}$$

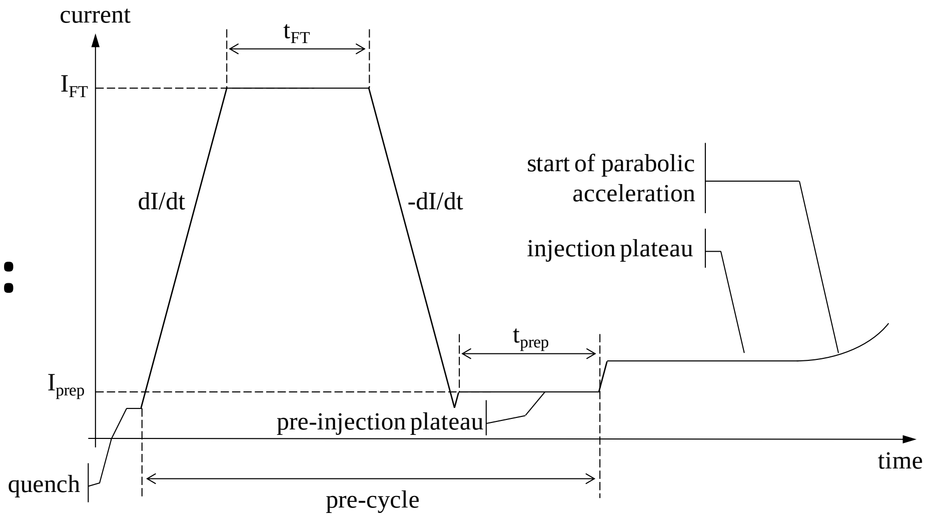
$$b_n = \delta_n^{std}\left(d\left(1 - e^{-t/\tau}\right) + (1-d)\left(1 - e^{-t/9\tau}\right)\right)$$



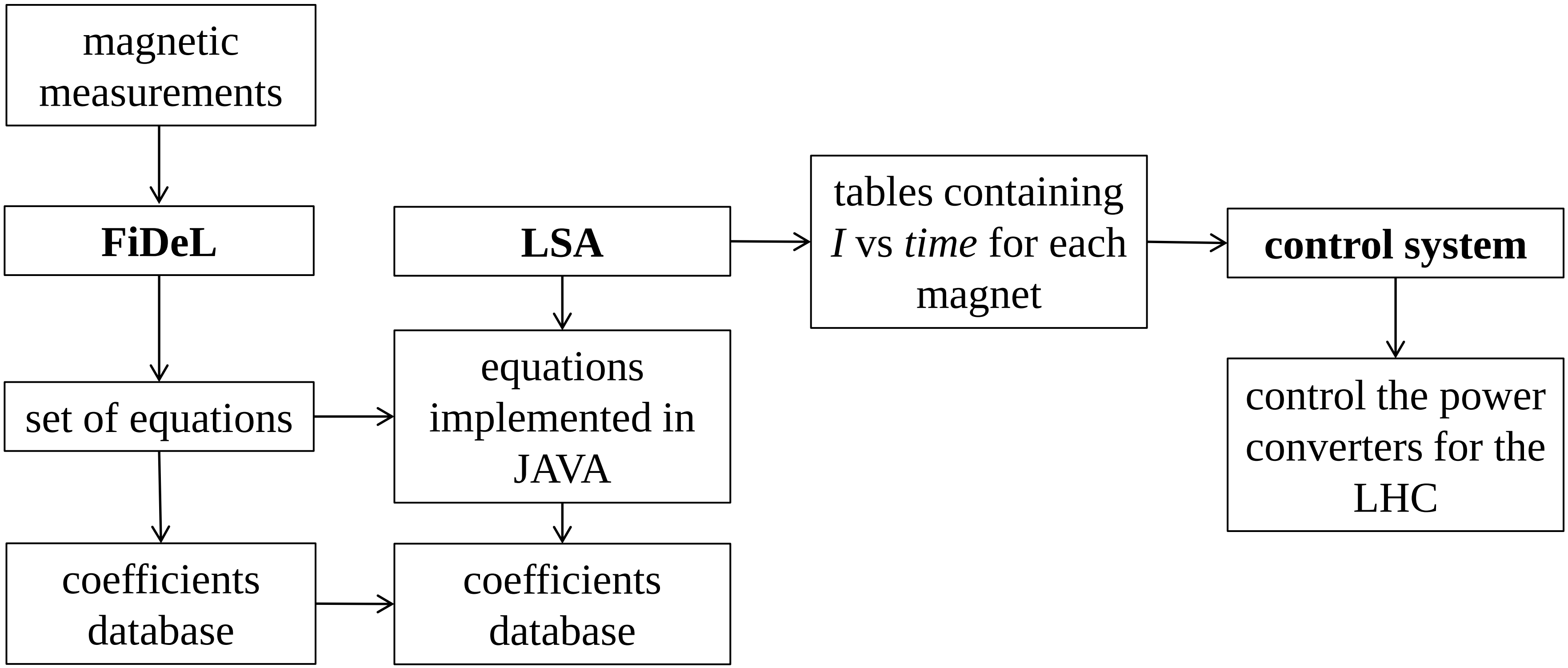


Powering history scaling law

- **Dynamic components are time and current dependent**
  - previous cycle affect their behaviour
- **Previous cycle can be:**
  - a pre-cycle
  - previous physics run
- **Decay amplitude is affected by:**
  - ramp rate (*dI/dt*)
  - flattop current (I_{FT})
  - flattop time (t_{FT})
  - preparation time (t_{prep})
- **A scaling factor need to be applied accordingly**



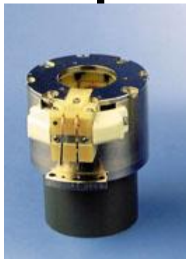
Implementation of FiDeL in the control system



- LSA (LHC Software Architecture) contains the FiDeL equations implemented in JAVA
- LSA generates the current tables for several beam processes
- These are used by the control system in the CCC to supply the necessary currents

Beam observables

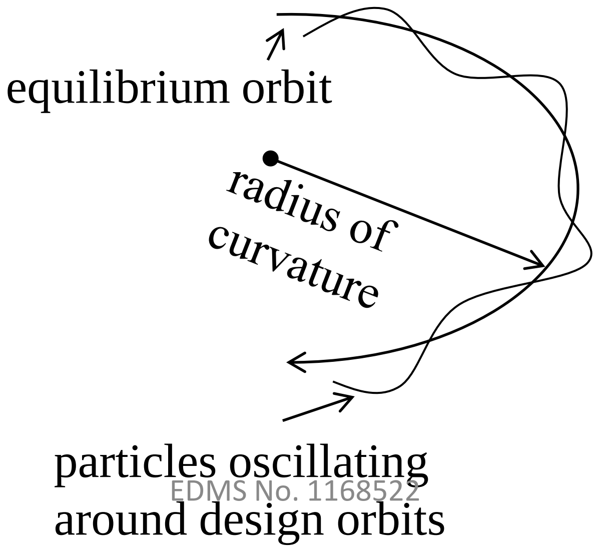
- **Orbit → b_1**
  - depends on the dipole
- **Tune → $b_2=B_2/B_1$**
  (B_2 = main field of the quadrupole, B_1 = main field of the dipole)
  - need to be controlled within 10^{-3} units
  - depends on the quadrupoles and the dipoles
  - global measurement



- **Chromaticity → b_3**
  - depends on the sextupole component (dipole, spool pieces)
  - global measurement
- **Beta-beating → $b_2=B_2/B_1$**
  (B_2 = main field of the quadrupole, B_1 = main field of the dipole)
  - depends on the quadrupoles
  - local measurement

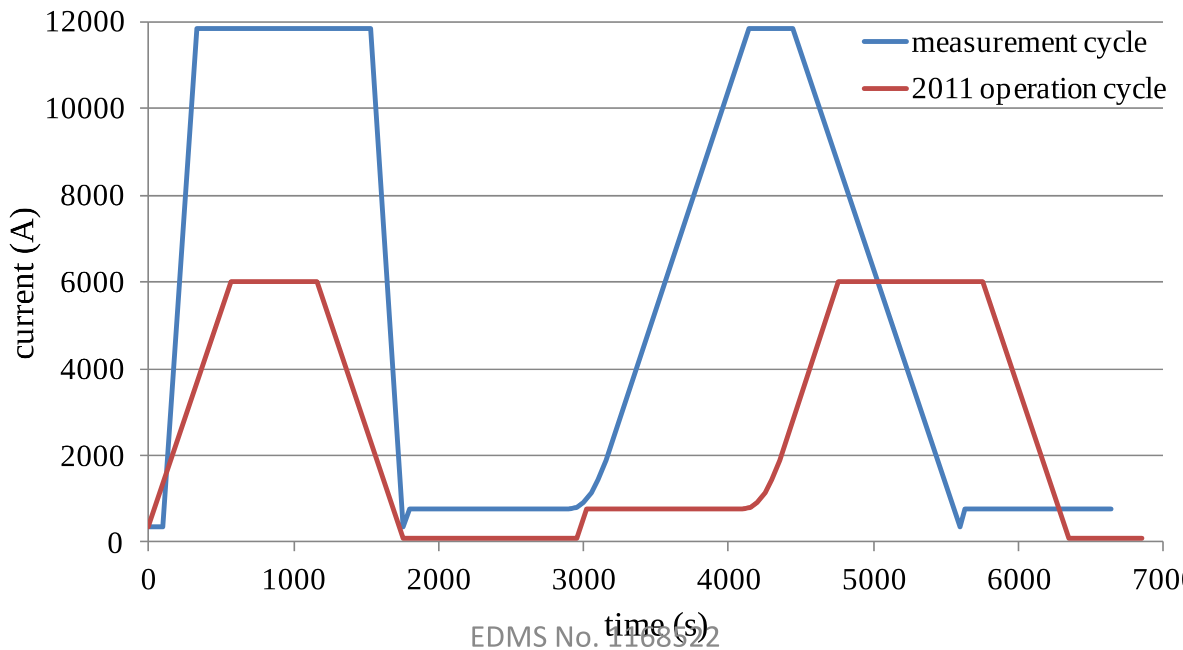
Tune and chromaticity in the LHC

- **Tune: number of oscillations the particle goes through as it travels one revolution around the machine**
  - Set to a particular value not to have resonance
  - Horizontal tune (at injection) = 64.28±0.005
  - Vertical tune (at injection) = 59.31±0.005
- **Chromaticity: variation of tune with relative momentum change**
  - inside a bucket, change in momentum of the particles is of the order of 10^{-3}
  - for a chromaticity of 10 units, the change in tune is of the order of 0.01
  - enough for the tune to jump from 64.28 to 64.29!!



Measurement cycles used during series production

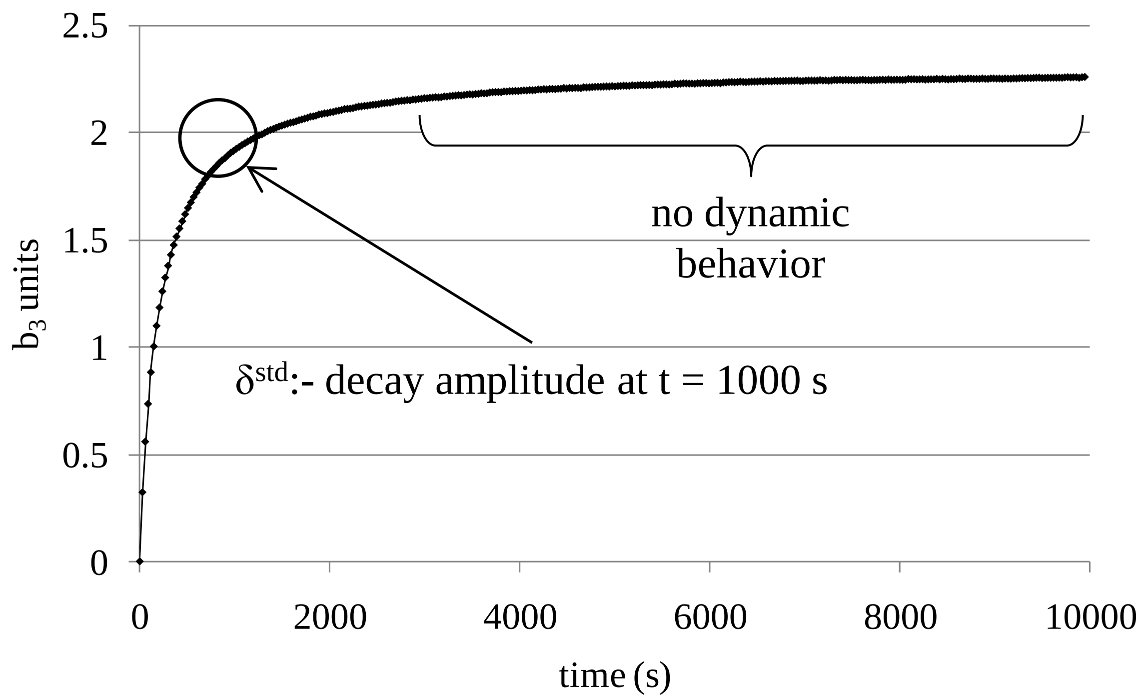
- **18% of the magnet population was measured at 1.9 K using the measurement cycle shown (blue)**
  - Pre-cycle ramp rate: 50 A/s, now 10 A/s
  - Flattop current: 12 kA, now 6 kA
  - Preparation time: 0 s, now 1200 s
- **On considering these differences, the decay amplitude was reduced by a factor of four**



Expected b_3 decay behaviour (based on magnetic measurements)

- 90% of the decay is over after the first 1000 s
- Static correction is enough
- δ_{std} is the decay amplitude at 1000 s

Parameter	Dimension	b_3
τ	(s)	189
d	(...)	0.66
δ^{std}	(units)	2.01 (0.5)*



b_3 behaviour during a 10000 s injection plateau as measured in MB3028

*decay amplitude reduced by a factor of four

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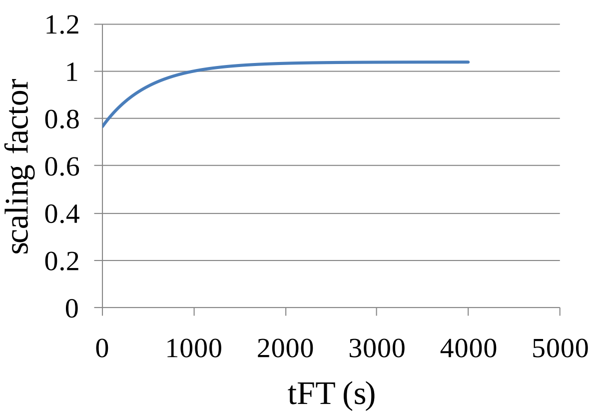
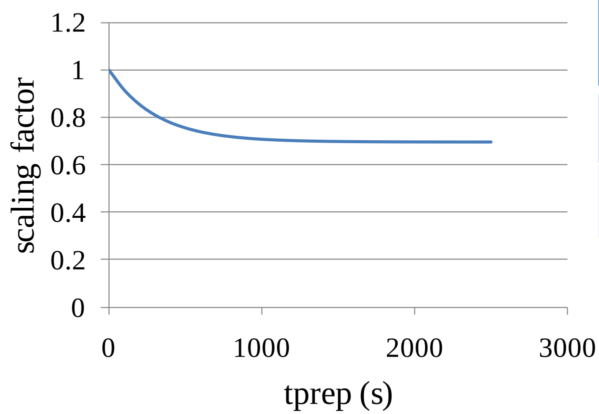
Expected powering history dependence (based on magnetic measurements)

$$\delta_n = \delta^{std}\left(\cancel{F_{dI/dt} \times F_{IFT}} \times F_{tFT} \times F_{tprep}\right)$$





Parameter	Dimension	b_3
τ_{tFT}	(s)	505
τ_{prep}	(s)	375

- Decay amplitude depends on the pre-cycle parameters: *dI/dt*, I_{FT}, t_{FT}, t_{prep}
- Powering history dependence time constant around 400-500 s
  - behaviour is asymptotic after 20 minutes
- Static correction is enough

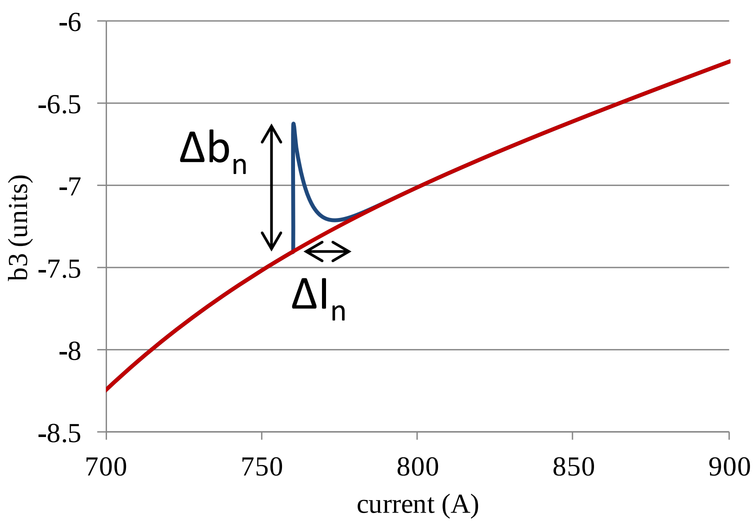
Expected snapback behaviour (based on magnetic measurements)

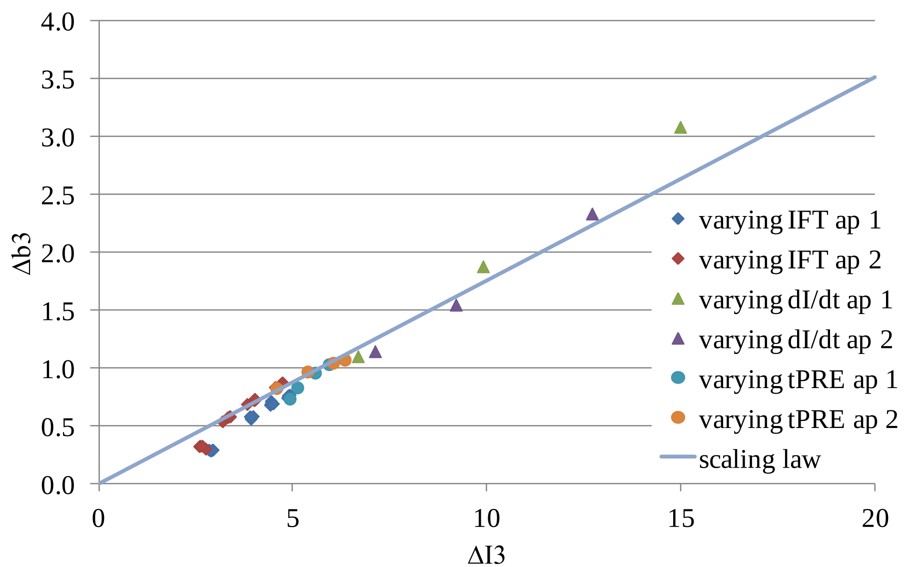
- Snapback follows an exponential decay
- There exists a linear correlation between the decay amplitude (Δb_n) at the end of injection and the time for snapback to occurs (ΔI_n)

$$b_n^{snapback} = b_n^{measured} - b_n^{baseline}$$

$$b_n^{snapback}(t) = \Delta b_n e^{-\frac{I(t)-I_{injection}}{\Delta I_n}}$$

$$\Delta b_n = g_n^{SB} . \Delta I_n$$

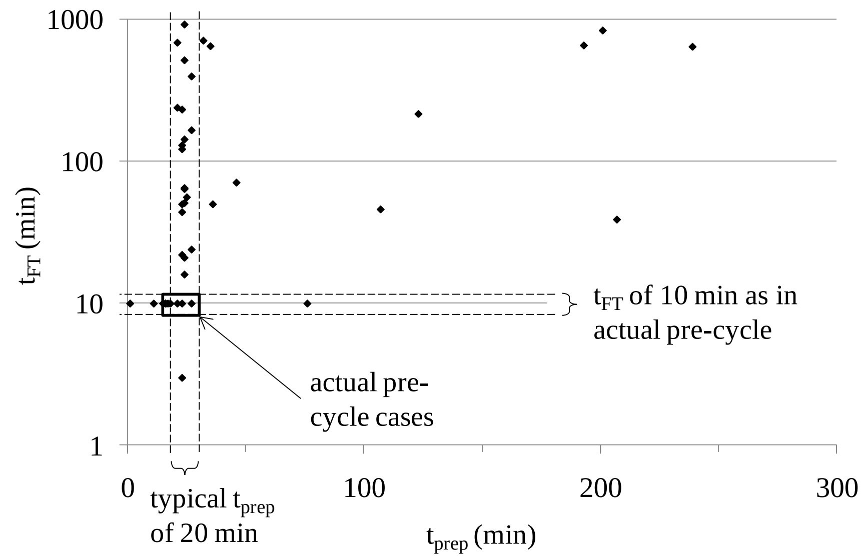


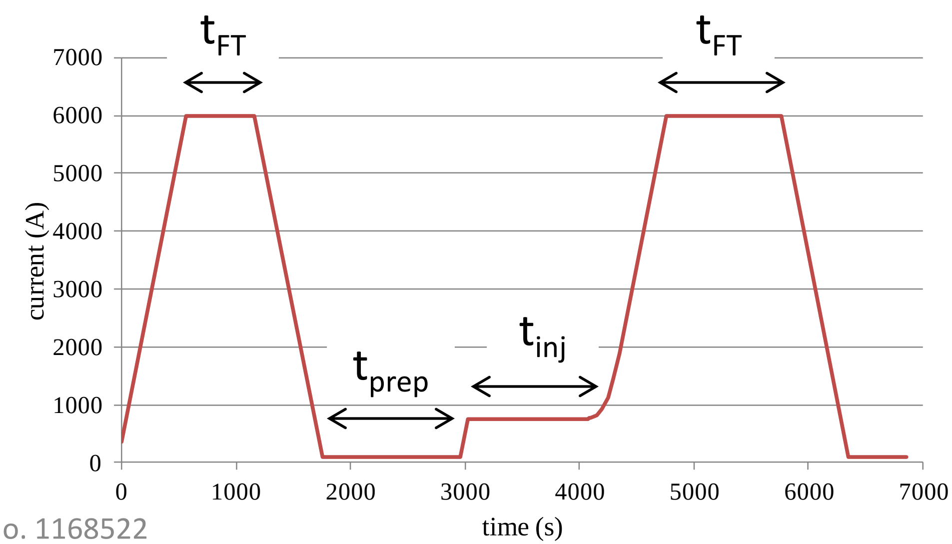


Behaviour of the machine - Analysis and Results

Typical operation of the machine

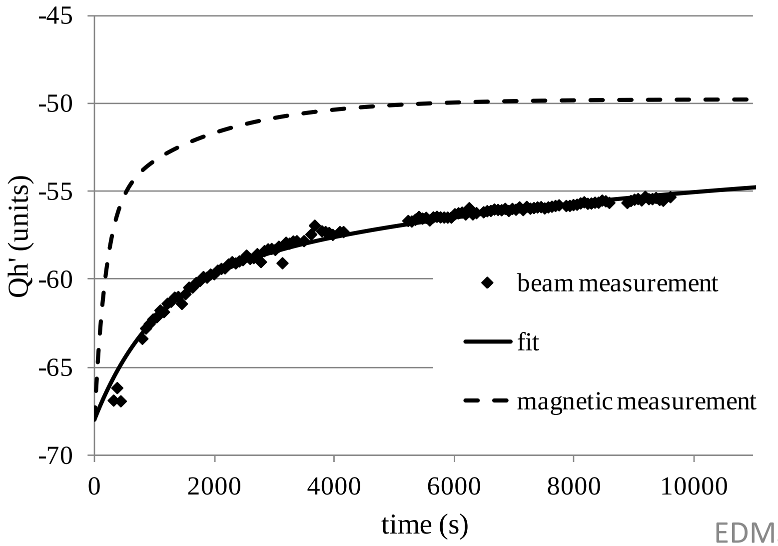
- **An actual pre-cycle is not always used in the LHC**
  - this put some variation in the operation of the machine from run to run
- **Preparation time (*t_{prep}*)**
  - pre-cycle case: 20 minutes
  - typically 20-25 minutes
  - longer if access to the machine is given
- **Injection time (*t_{inj}*)**
  - minimum injection time: 20 minutes
  - average injection time: 1-2 hours
- **Flattop time (*t_{FT}*)**
  - pre-cycle case: 10 minutes
  - minimum flattop time: 30 minutes
  - average flattop time: 5 hours
  - can be long as 15 hours

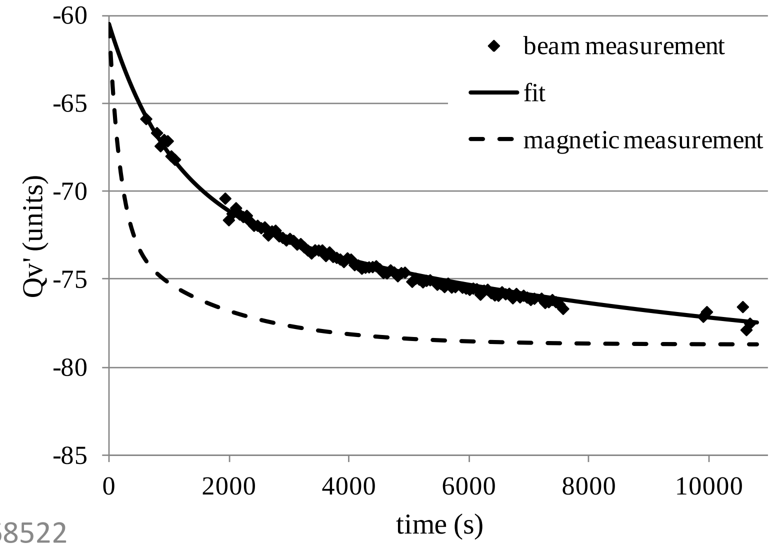




1^{st} observation: Decay behaviour in the machine

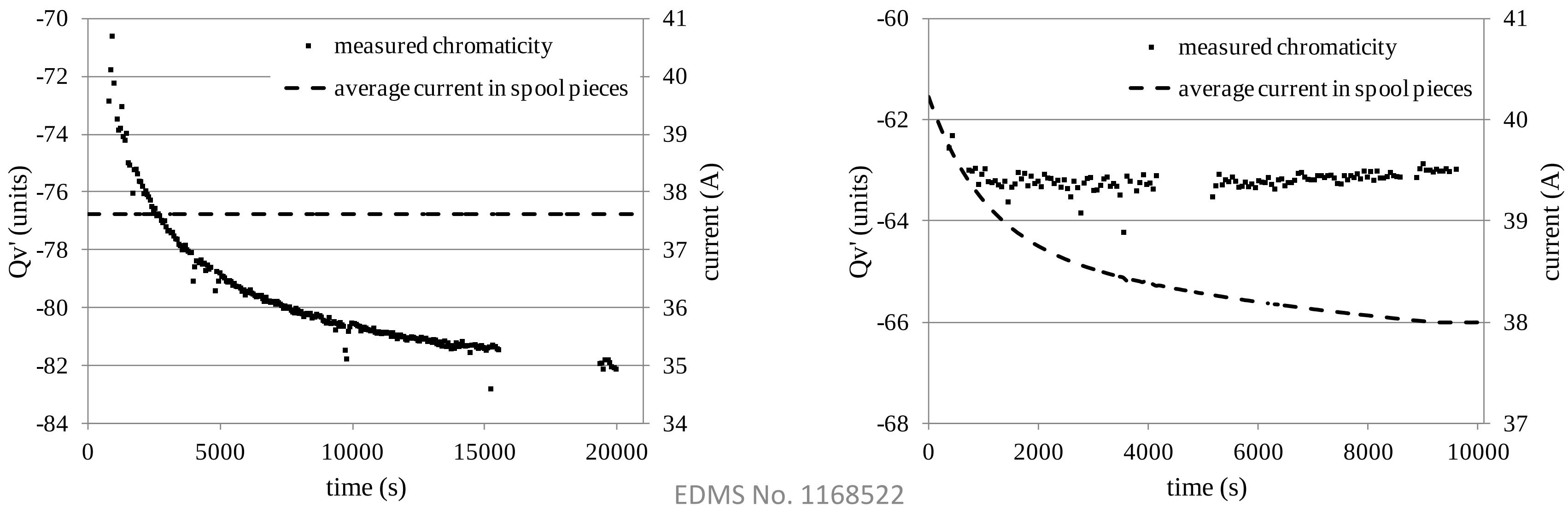
- Decay behaviour in the machine is slower than that observed during magnetic measurements
  - τ of 1000 s instead of 200 s
- After 30 minutes, decay is still dynamic
  - dynamic correction required





Updates to the decay model

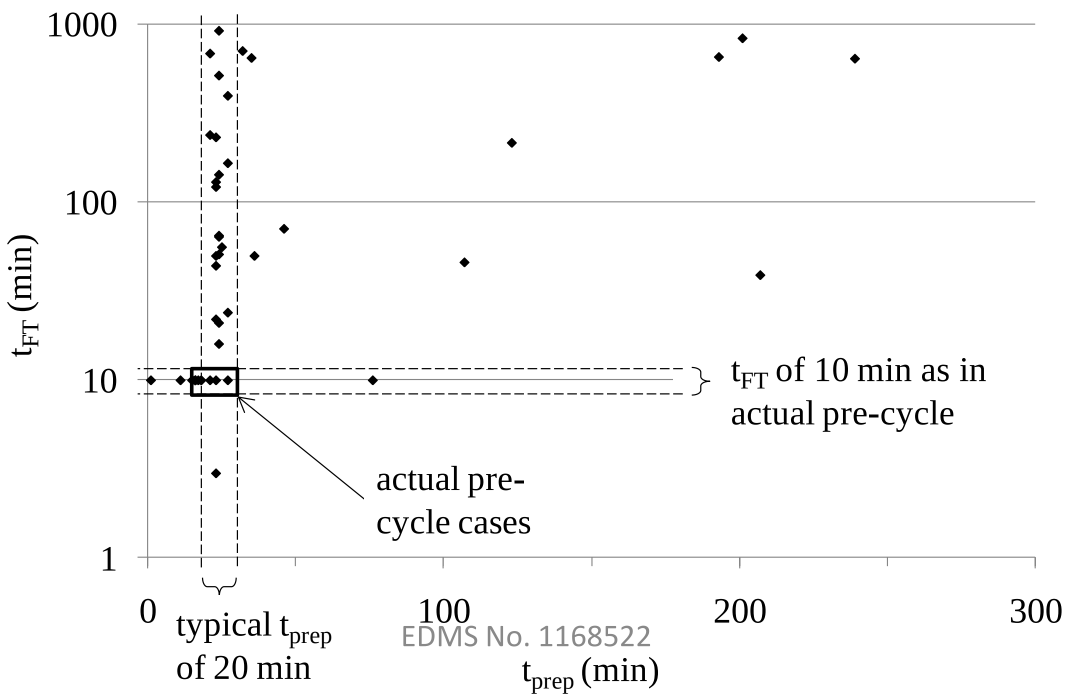
- **A static correction was being used**
  - asymptotic decay behaviour
- **This was not enough, and chromaticity decay was still observed during injection**
  - chromaticity decay of 12 units
- **A dynamic correction was implemented in the machine (in April 2011) based on beam based measurements**
  - chromaticity decay was corrected within 1-2 units



injection on 21/02/2011 EDMS No. 1168522 injection on 02/05/2011

2^{nd} observation: Powering history dependence in the machine

- Typical powering history parameters during May-June 2011
- Each point represents a chromaticity measurement performed during the LHC operation

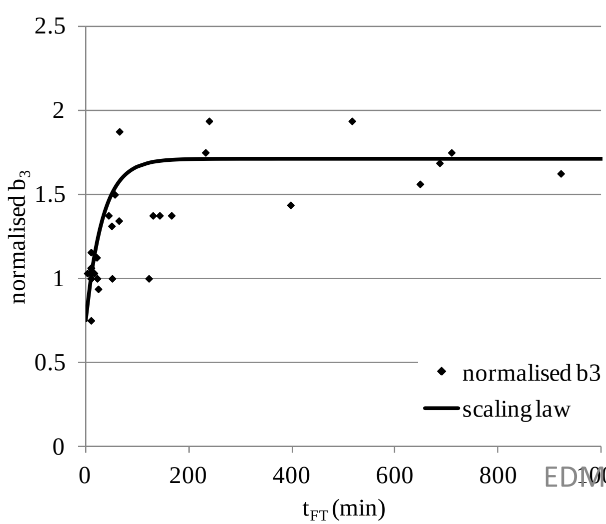


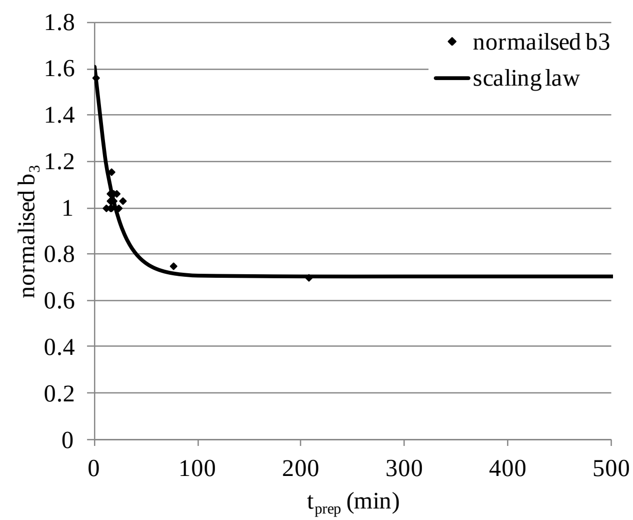
Update of the powering history scaling law

- **Powering history dependence is longer**
  - τ is factor of 3-4 larger
  - t_{FT}: asymptotic behaviour starts after 3 hours
  - t_{prep}: asymptotic behaviour starts after 1.5 hours
- **Powering history correction need to be dynamic**
  - needs to be computed for every run
  - implemented in the machine in May 2011

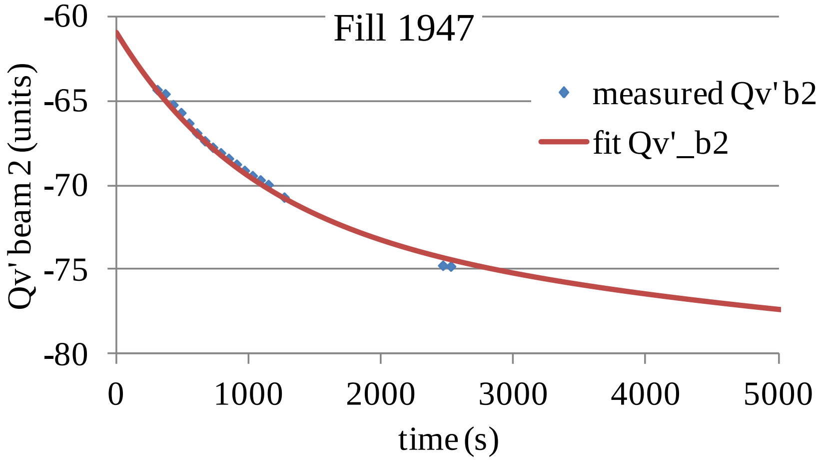
$$\delta_n = \delta^{std}\left(F_{tFT} \times F_{tprep}\right)$$

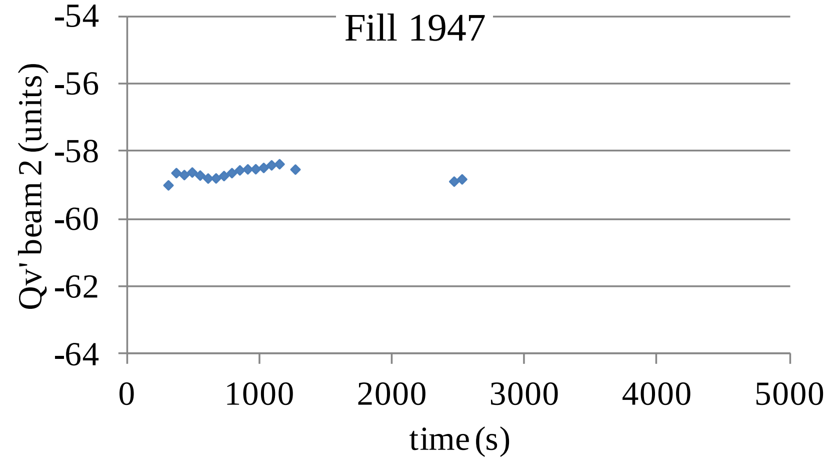
Parameter	Dimension	b_3 *(new)*	b_3 *(old)*
τ_{tFT}	(s)	2000	505
τ_{prep}	(s)	1100	375





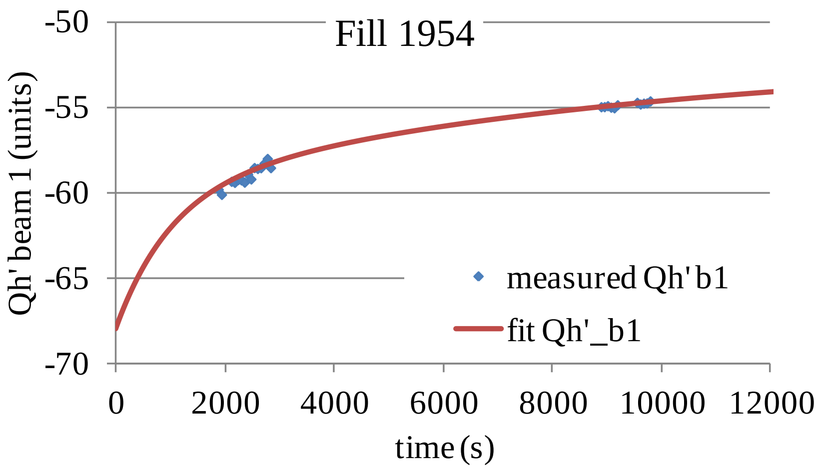
Behaviour of the machine after updating FiDeL

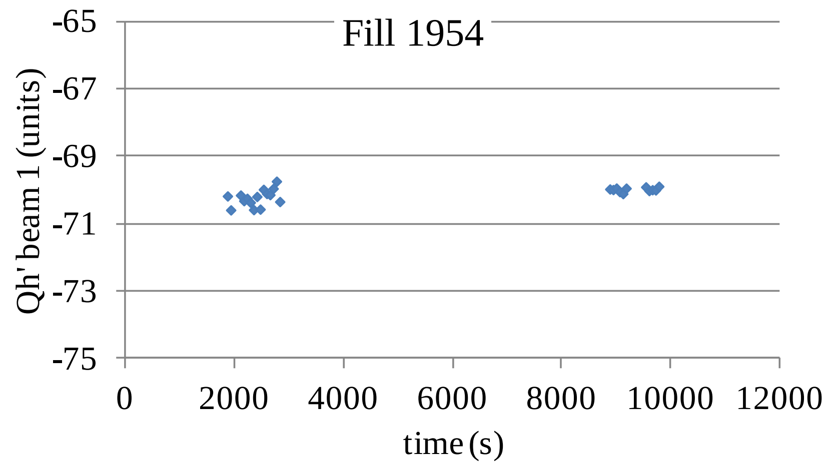




Fill 1947: t_{FT} = 228 minutes

t_{prep} = 25 minutes



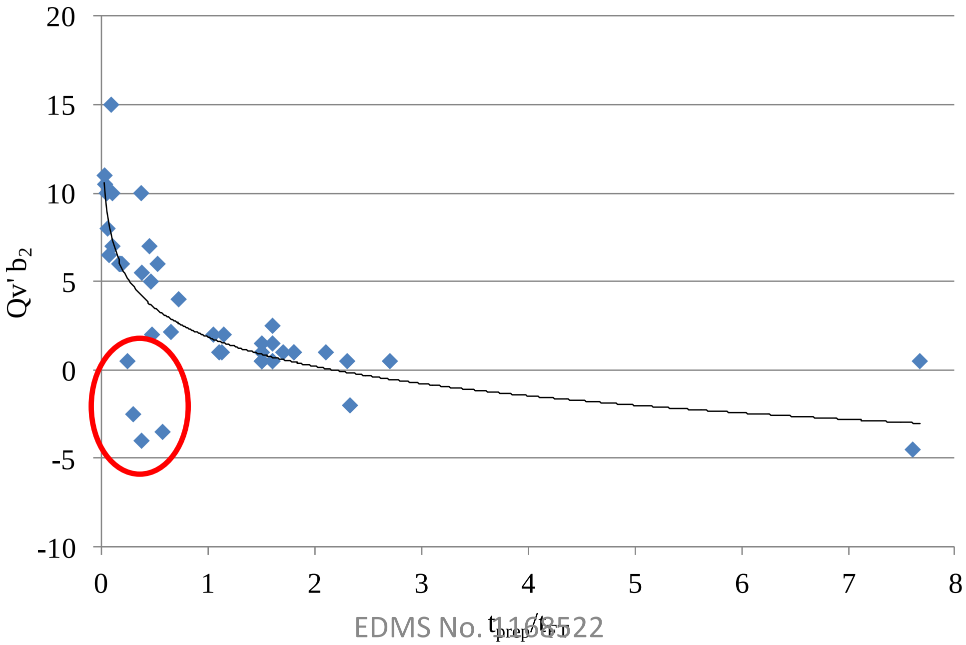


Fill 1954: t_{FT} = 10 minutes

t_{prep} = 20 minutes

Further considerations for the powering history scaling law

- The current powering history scaling law excludes any coupling between the pre-cycle parameters and their effect on the decay amplitude
- However, based on beam measurements, it was observed that there exists some relation between the decay amplitude and the ratio t_{prep}/t_{FT}
- The four outlier points refer to cases with long t_{prep} and t_{FT}
- Further measurements and analysis required



Thanks to L. Deniau

Conclusions

- The decay of b_3 is a source of chromaticity change that affects operation of the machine
  - first estimate carried out during production phase: 2 units (of b_3) of decay after 1000 s on the injection plateau
  - using LHC operation cycle (dI/dt = 10A/s and I_{FT} = 6 kA) this is reduced by a factor of 4, therefore 0.5 units of b_3 after 1000 s on the injection plateau
- Chromaticity measurements performed during routine operation of the machine show that
  - the decay amplitude is inline with what was found during production phase
  - the snapback behaviour is inline with what was found during production phase
  - the decay time constant is larger (1000 s instead of 200 s)
    - dynamic correction was required, implemented in April 2011
  - powering history dependence is longer than observed during production
    - powering history dependence model was implemented in the control system in May 2011
- With the present correction, chromaticity is stable within 1-2 units, equivalent to correcting the b_3 component within 0.05 units
- Still to understand why there is a different decay behaviour when comparing a single magnet to the accelerator as a whole