





# How precisely can we control our magnets? Experience and impact on the expected control of machine parameters (tune and chromaticity)

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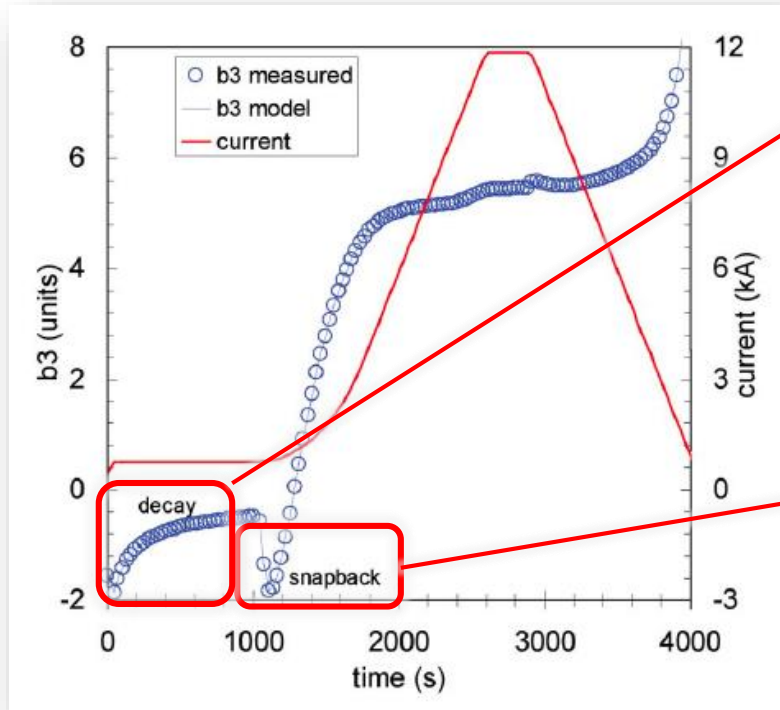
Thanks to: M.Lamont, M. Schaumann, E.Todesco, J.Wenninger

# Outline

- The FiDeL model and its implementation
- Tune: injection and snapback
- Q': injection, snapback, ramp and squeeze
- b3 to Q' “conversion”

# The FiDeL model

FiDeL dynamic component has been studied and modeled based on a massive set of magnetic measurements



## Decay

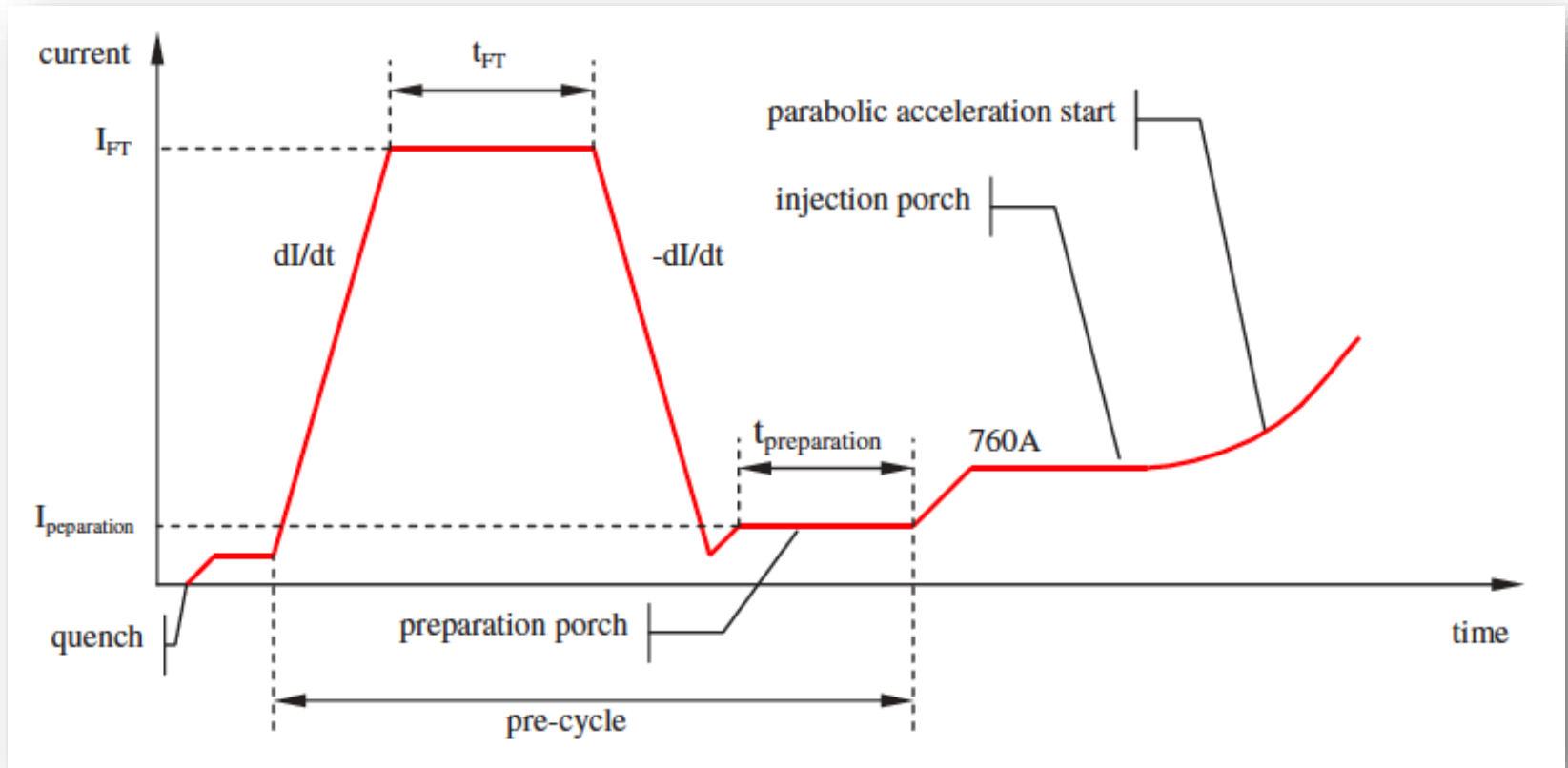
“The decay of harmonics at constant current is driven by current redistribution on superconducting cables, which results in a net decrease of the average dc magnetization of the cables and of its contribution to the total field”

## Snap back

rapid reestablishment of magnetization after decay. The field bounces back to its pre-decay level once the current in the magnet starts to ramp up

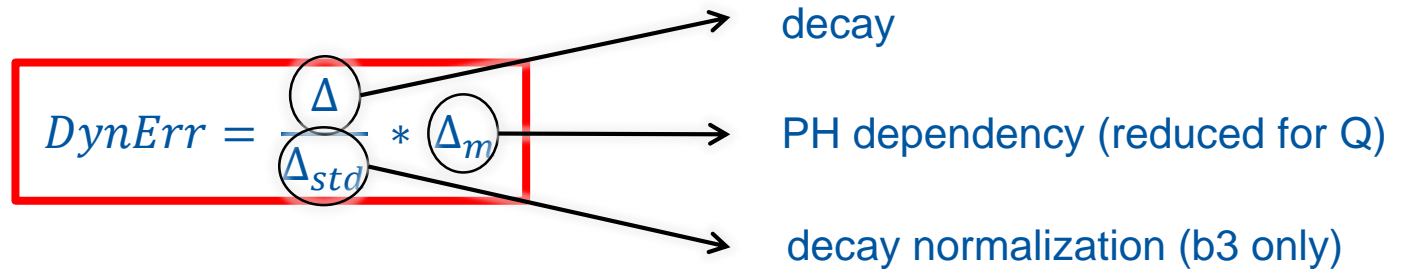
N. J Sammut et al., Phys.  
Rev. ST Accel. Beams 9

# The powering history dependency



The magnitude of the decay depends on the powering history, both on the waveform of the powering cycle as well as waiting times, and has memory of previous powering cycles, thus making this effect non-reproducible from cycle to cycle.

# The FIDEL model implementation



$$\Delta = dec_d * (1 - e^{\frac{-t}{dec_\tau}}) + (1 - dec_d) * (1 - e^{\frac{-t}{(9 * dec_\tau)}})$$

$$\Delta_{std} = dec_d * (1 - e^{\frac{T_{inj}}{dec_\tau}}) + (1 - dec_d) * (1 - e^{\frac{T_{inj}}{(9 * dec_\tau)}})$$

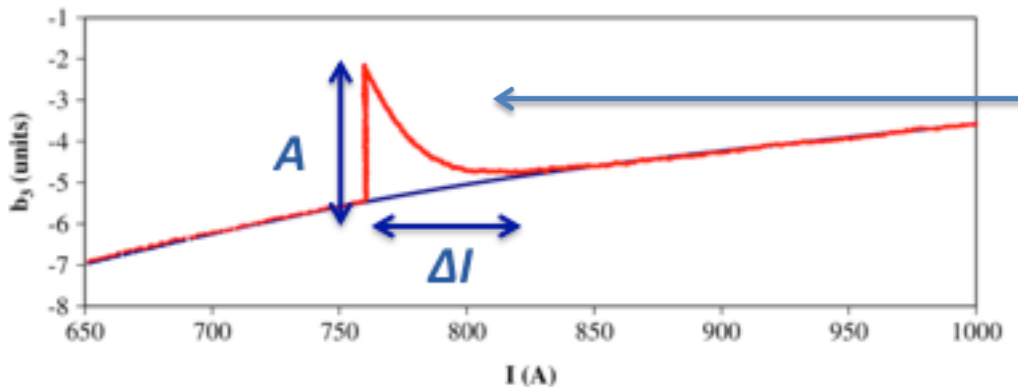
$$\Delta_m = dec_{delta} * \frac{(E_0 - E_1 * e^{\frac{-I_{FT}}{(\tau_e * \frac{dl}{dt})}})}{(E_0 - E_1 * e^{\frac{-I_{FTnom}}{(\tau_e * \frac{dl}{dt})}})} * \frac{(T_0 - T_1 * e^{\frac{-t_{FT}}{(\tau_t * \frac{dl}{dt})}})}{(T_0 - T_1 * e^{\frac{-t_{FTnom}}{\tau_t}})} * \frac{(P_0 - P_1 * e^{\frac{-t_{pre}}{(\tau_p * \frac{dl}{dt})}})}{(P_0 - P_1 * e^{\frac{-t_{preNom}}{\tau_p}})}$$

$dec_{tau}, dec_d, dec_{delta}$   
 fitting parameters

$I_{FT}, t_{FT}, t_{PRE}$   
 Powering History (PH)

$I_{FTnom}, t_{FTnom}, t_{PREnom}, T_{inj}$   
 PH normalization factors

# The snapback

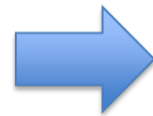


Measurements show that the **snap-back** to the hysteresis curve in the first part of the ramp follows an **exponential law in current**. As the current at the start of ramp is parabolic, the snapback is **Gaussian in time**

The amplitude  $A$  depends on length of injection plateau & powering history

$$\Delta I \propto A$$

$$I(t) \propto t^2$$

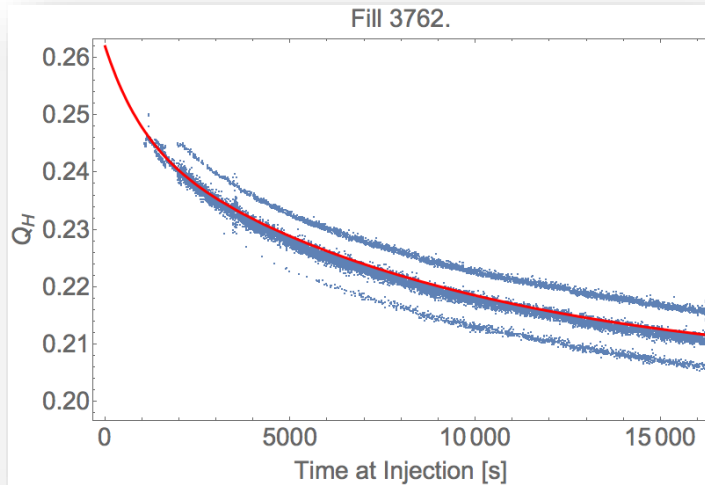


$$Q(t) = A \exp\left[-\frac{t^2}{A\tau}\right]$$

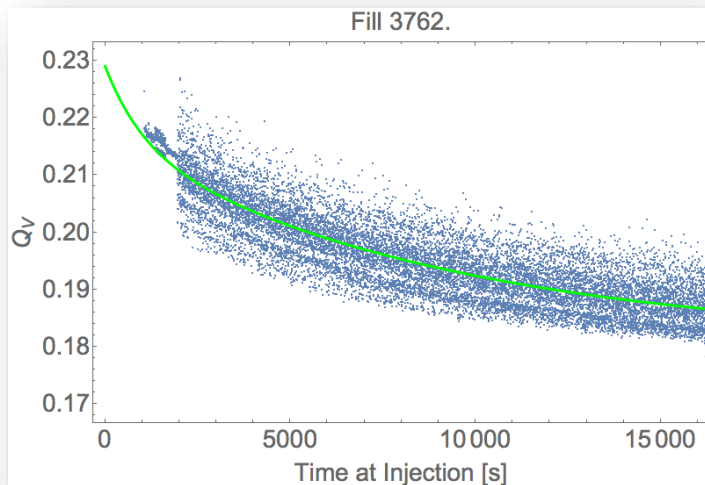
$$b_3(t) = b_3 e^{-\frac{(I(t) - I_{inj})}{\frac{b_3}{SBK_G}}}$$

N. J. Sammut et al., *Mathematical formulation to predict the harmonics of the superconducting Large Hadron Collider Magnets. II. Dynamic field changes and scaling laws*. **PRSTAB 10, 082802 (2007)**

# Tune injection decay



Example of bare tune decay at injection with corresponding exponential fit



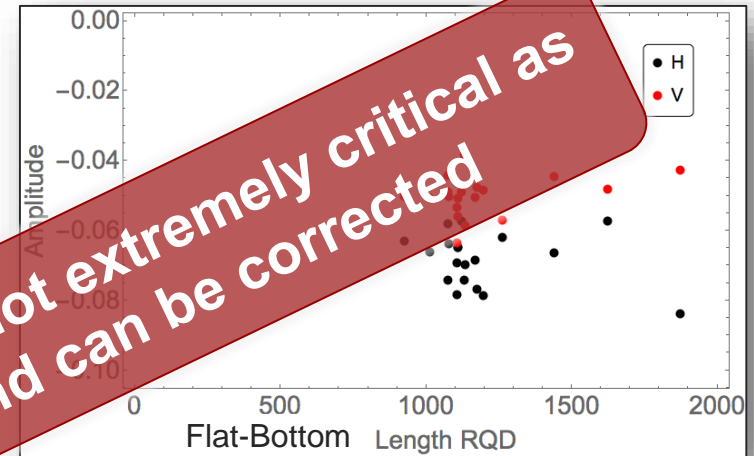
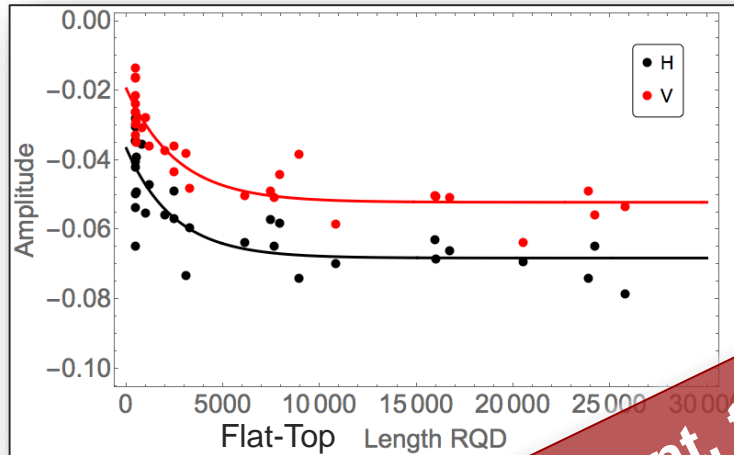
Synchrotron Sidebands (?)  
(Those lines decay with the tune already in the raw data. 50Hz lines have slightly smaller spacing but stay at constant frequency)

Courtesy of  
M.Schaumann



# Tune injection decay – PH dependency

To exclude dependence on preparation time, select only cycles with  $t_{pre} < 800s$



**Control is important, though not extremely critical as tune is always visible and can be corrected**

Although there is a **reproducibility** in the data (especially for pre-cycles), a **dependency of the decay amplitude with Flat-top time ( $t_{FT}$ )** is visible

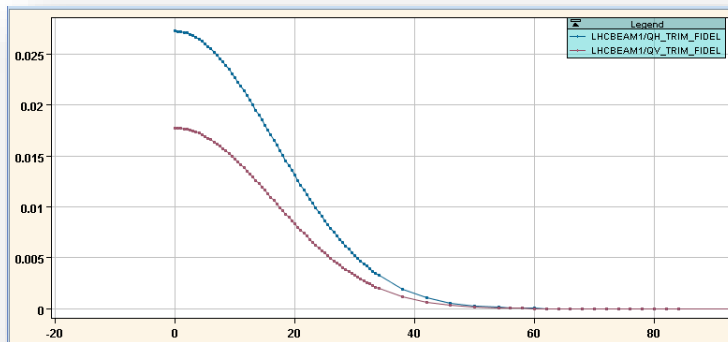
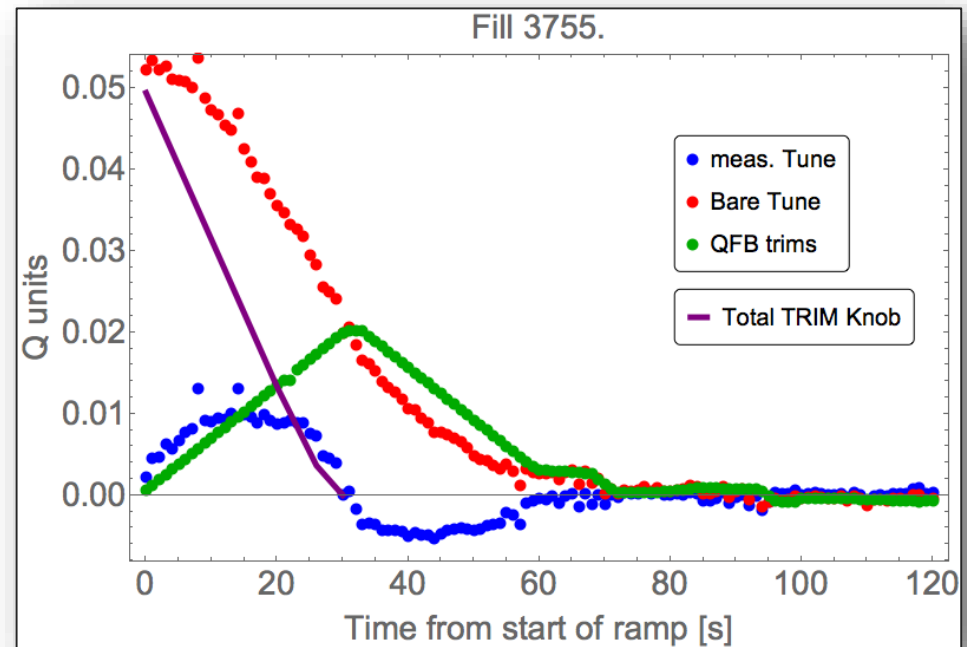
**No pattern of dependency of decay amplitude on preparation time ( $t_{pre}$ )**

A dependency of decay amplitude on  $t_{FT}$  has been implemented in the online correction system in 2015

Courtesy of M.Schaumann

# Tune snapback

If the correction incorporation is not good enough, it can be difficult for the QFB to keep the tunes constant and **large tune excursions** can occur at the beginning of the ramp with the risk of control loss

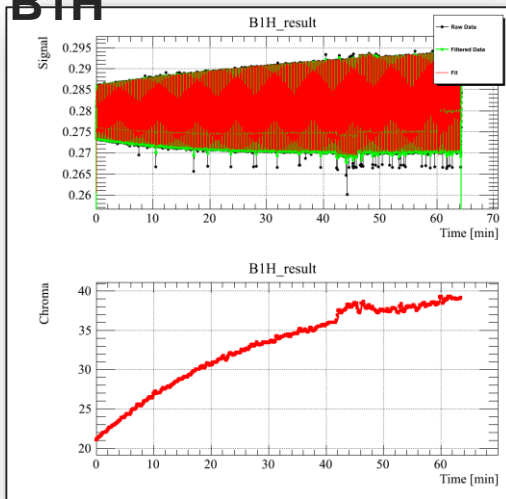


Example of snapback-like incorporation for Q implemented in Run2 to limit the load on the QFB

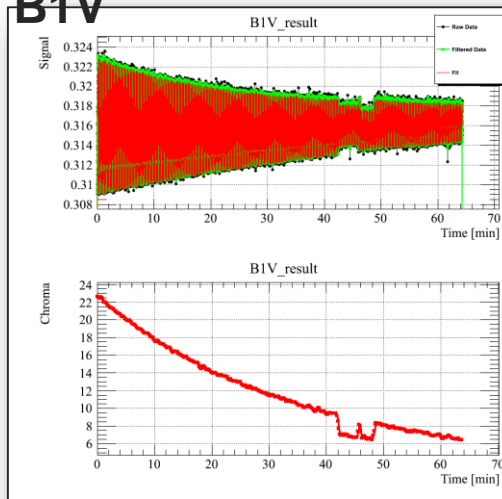
Courtesy of  
M.Schaumann

# b3 injection decay

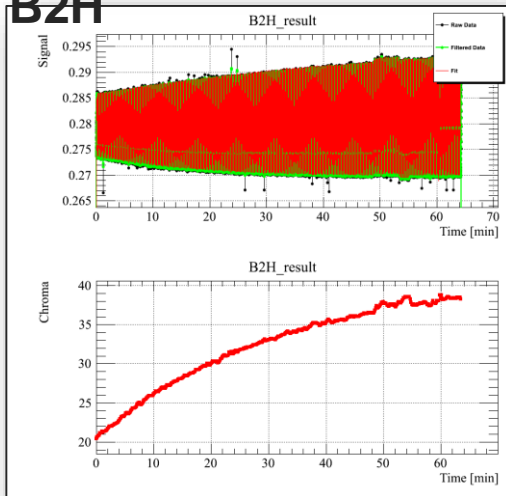
**B1H**



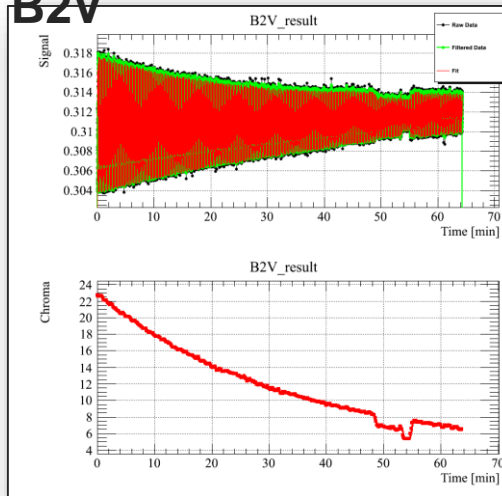
**B1V**



**B2H**



**B2V**



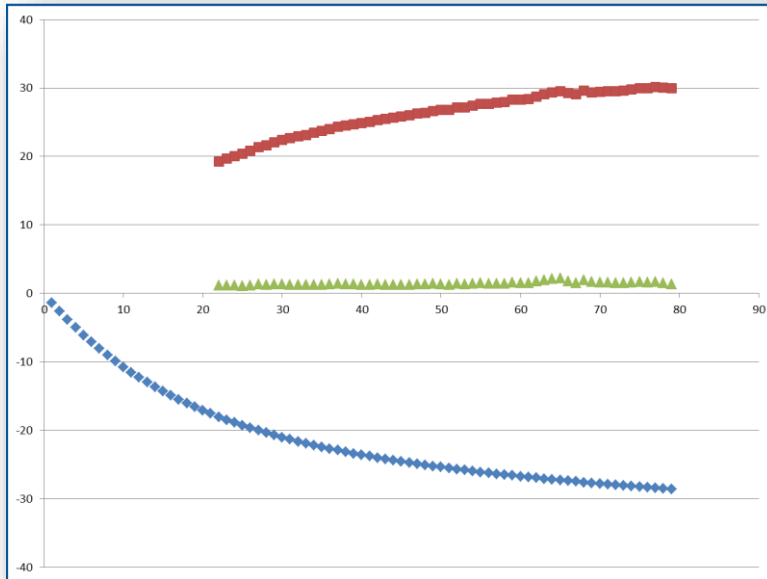
**About 0.46 b3 units (~20 Q' units) decay in 1 hour**

- Operationally difficult to inject in the very first part of the injection plateau
- Good fit, but few units will always “leak” into lattice sextupole correction

**As expected, decay amplitude is about 40% larger than at 4 TeV**

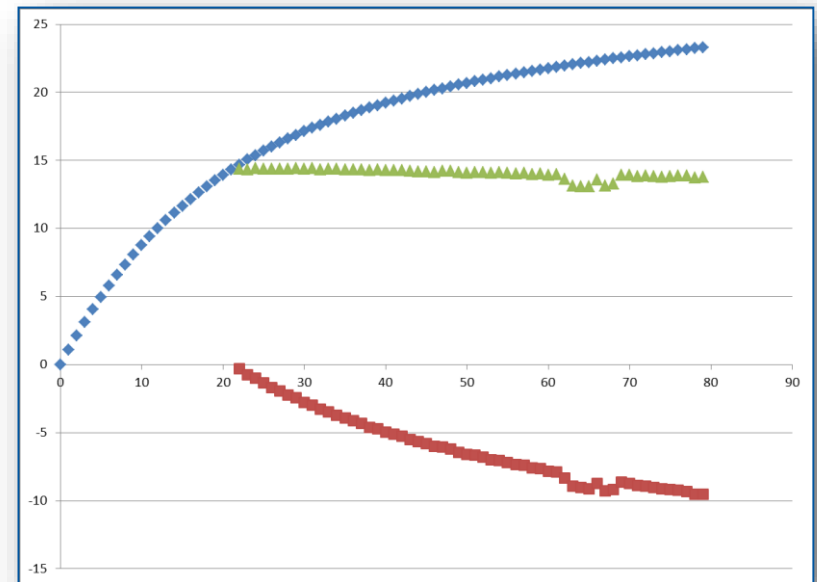
# b3 injection decay compensation

## Horizontal



- Measured Q'
- ◆ Decay compensation
- ▲ Corrected Q'

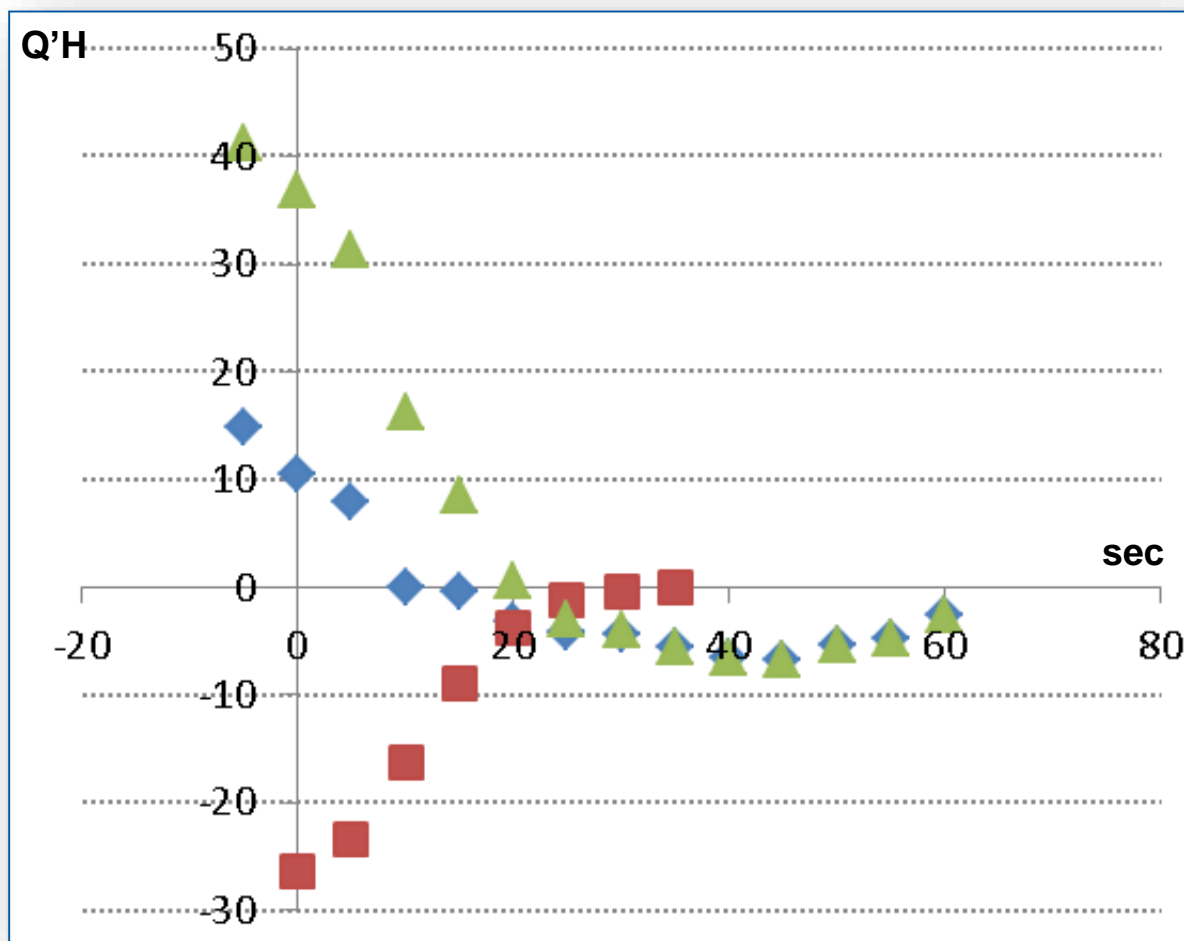
## Vertical



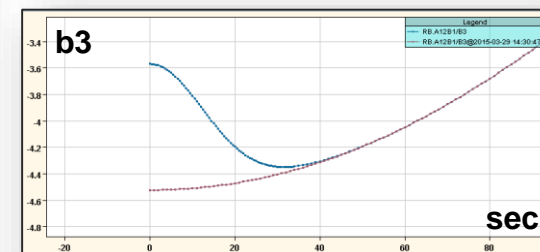
The present compensation of b3 injection decay makes Q' flat (in within  $\pm 0.5$  units)

**The precision of the correction over several fill depends on the quality of the powering history dependency model**

# Snapback - Horizontal

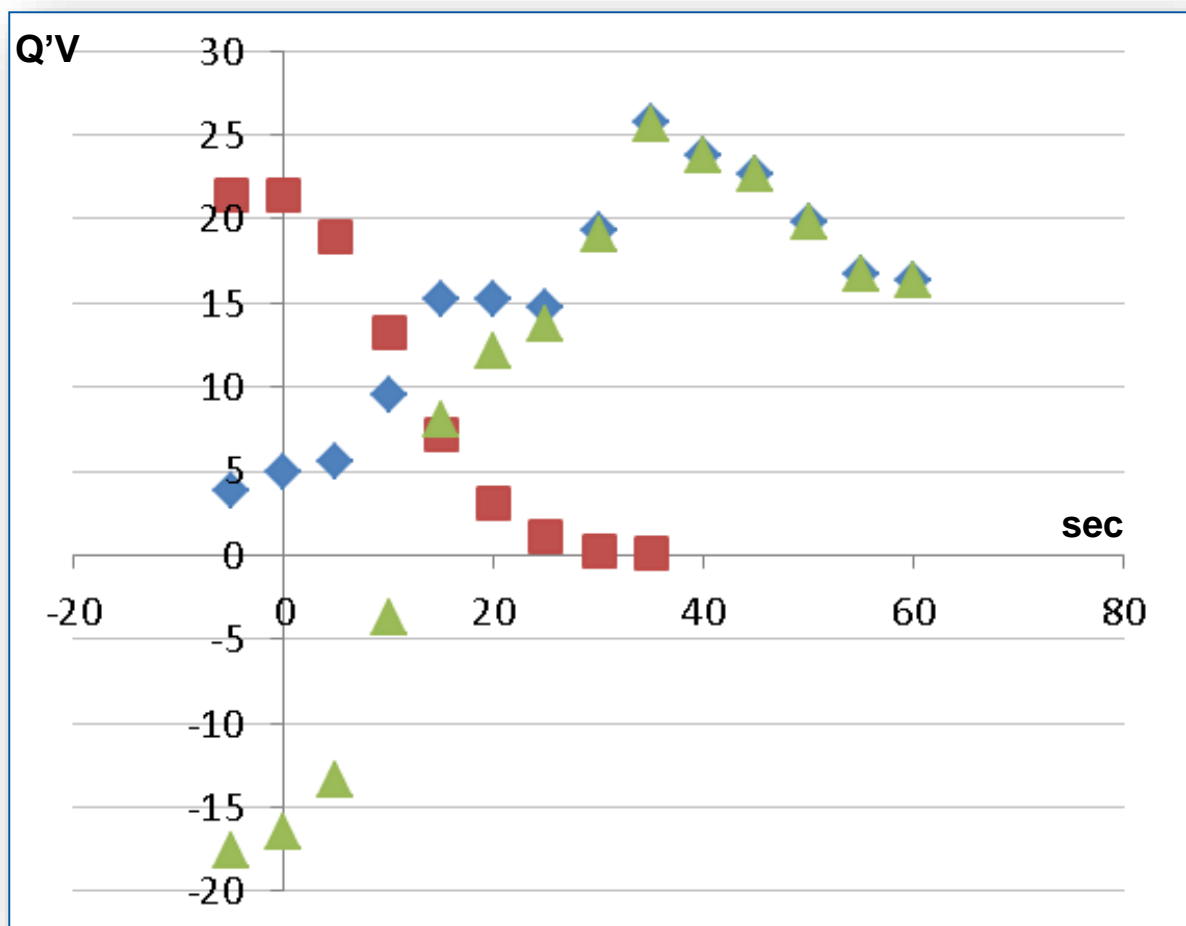


- $Q'$  corrections
- ◆ Measured  $Q'$
- ▲ Natural  $Q'$

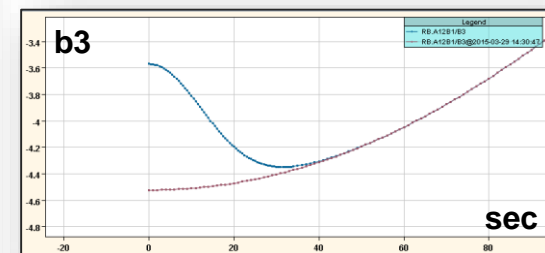


$b3$  correction is fully incorporated in ~30 sec (depending on the intensity)... **consistent with measurements!**

# Snapback - Vertical

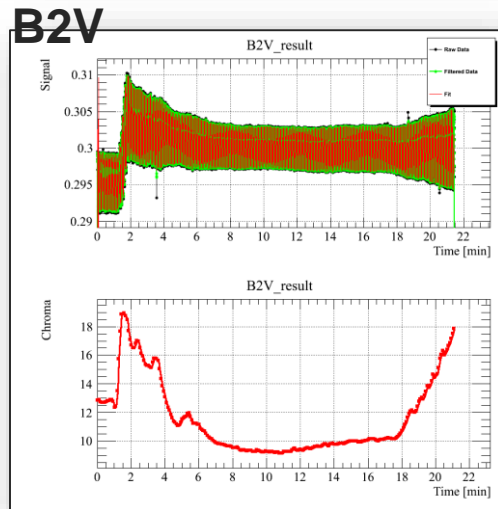
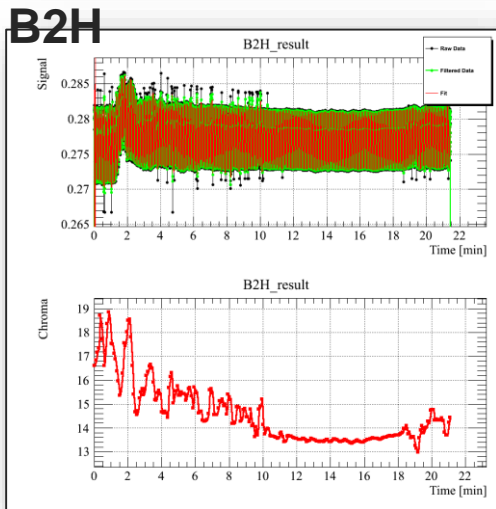
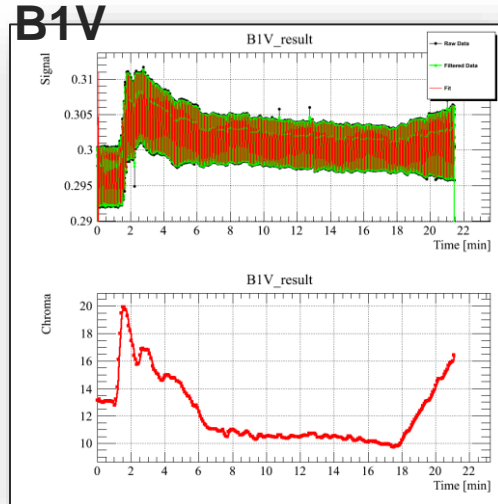
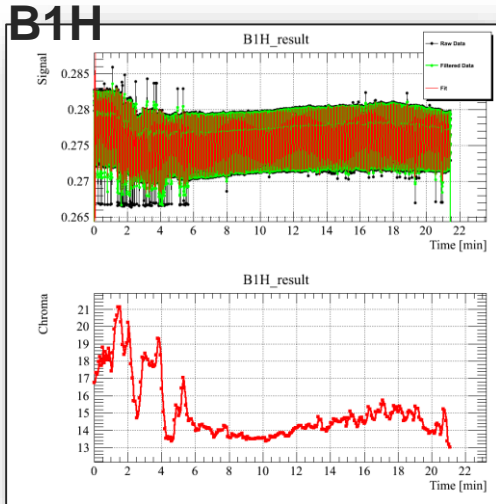


- Q' corrections
- ◆ Measured Q'
- ▲ Natural Q'



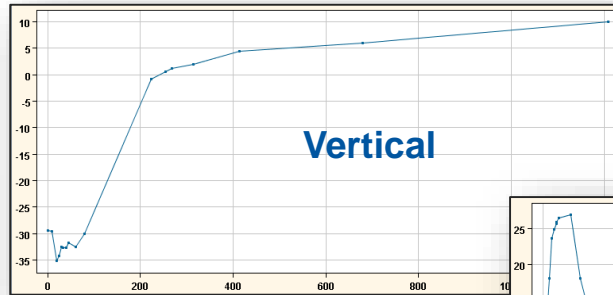
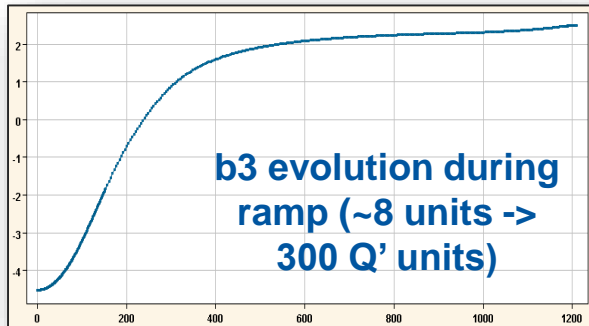
b3 correction is fully incorporated in ~30 sec (depending on the intensity)...**consistent with measurements!**

# Ramp

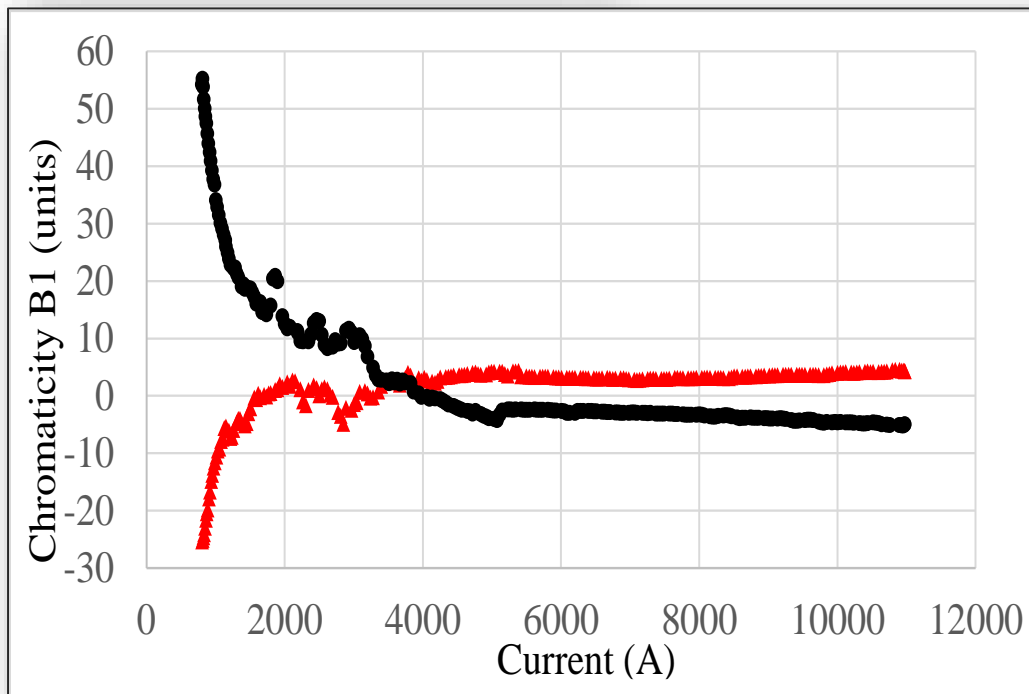
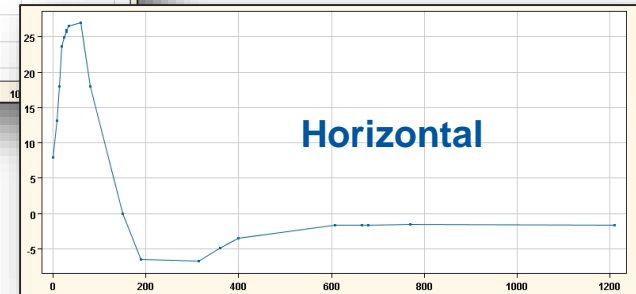


- Q' along the ramp is **well controlled** ( $\pm 2$  units)
- **Small imperfection** in the persistent currents model  $< 3$  kA, but still very good control considering the 8 units swing (300 Q' units) of b3
- No visible effect from the missing RCS (compensation split on the other 7 circuits)

# Ramp



Typical sextupole correction



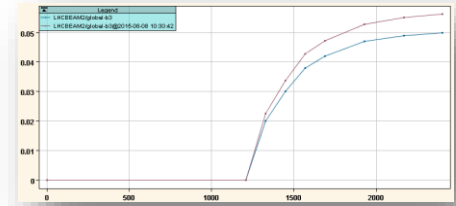
Bare Q' along the ramp  
(lattice sext corrections removed):

- Precision of the model above 3 kA is  $\pm 5$  Q' units
- $\sim 1$  unit of uncorrected b3 below 3 kA
- In addition, about 15 Q' units error (positive in both planes)...on  $\sim 300$  Q' swing

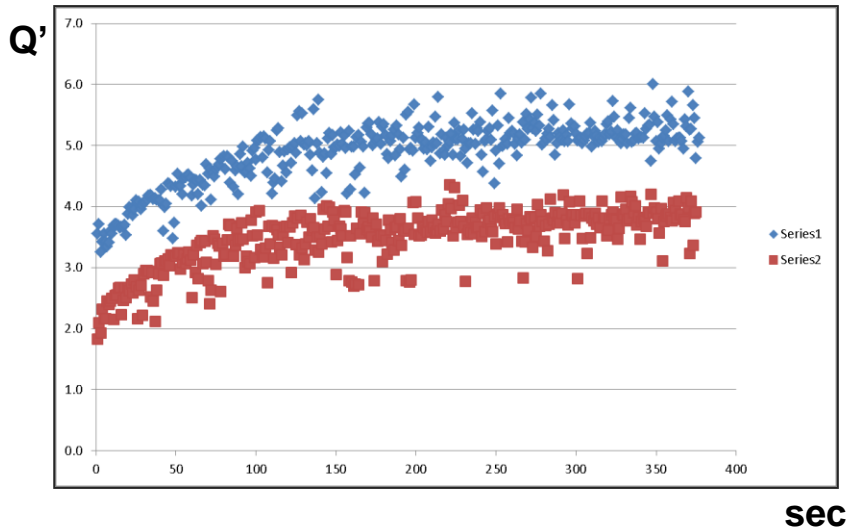


# Decay @flat-top

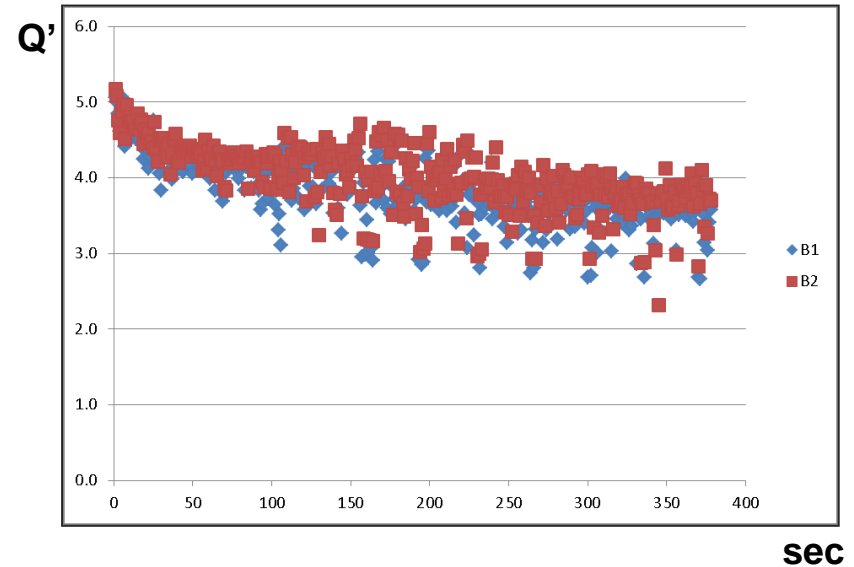
b3 compensation knob



Horizontal



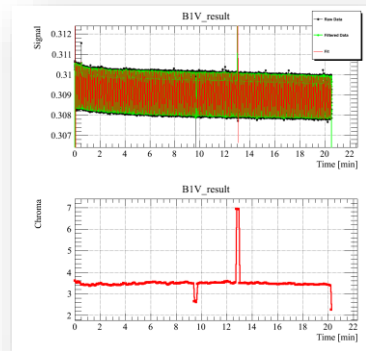
Vertical



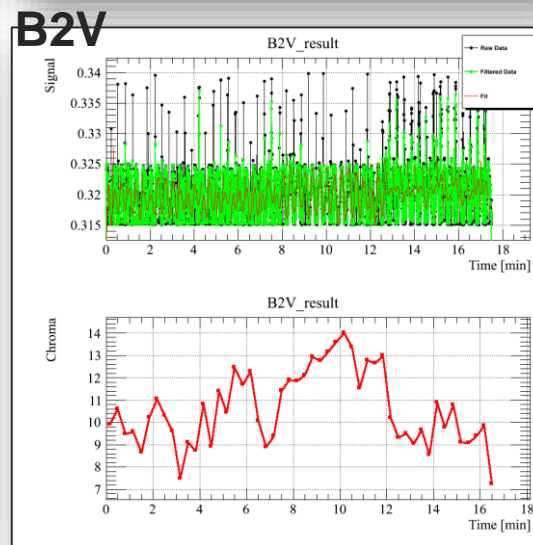
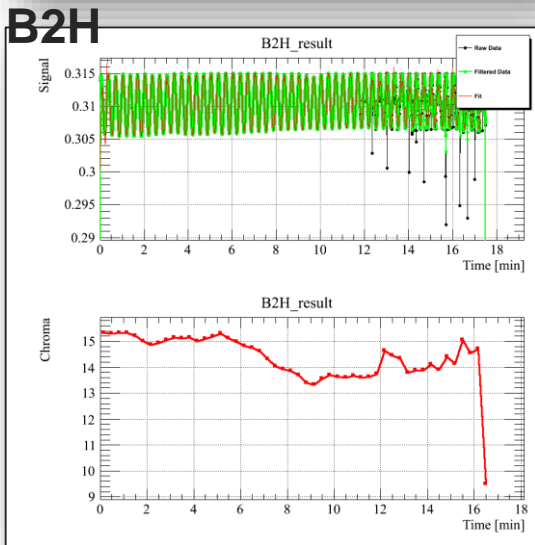
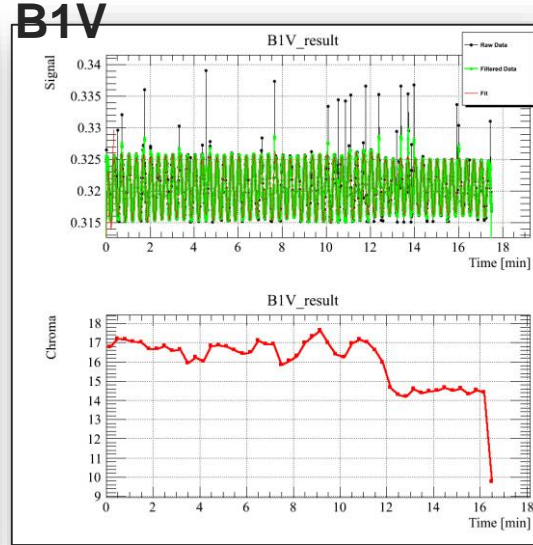
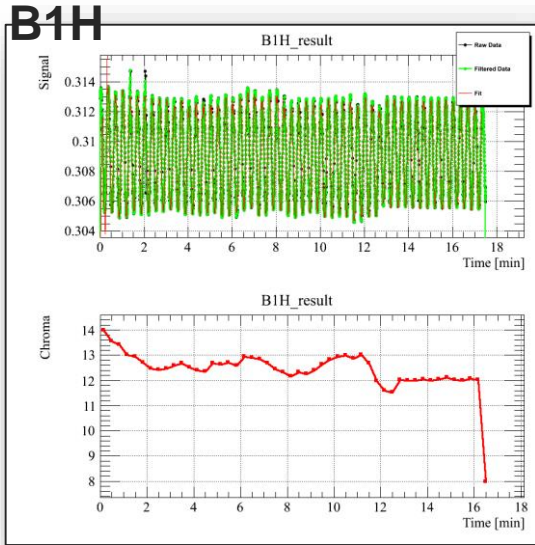
Q' decay  
 ~2 units in H → ~0.05 b3 units  
 ~1.5 units in V

Expected to be negligible  
 is indeed very small!

Example of Q' measurements at flattop after compensation



# Squeeze

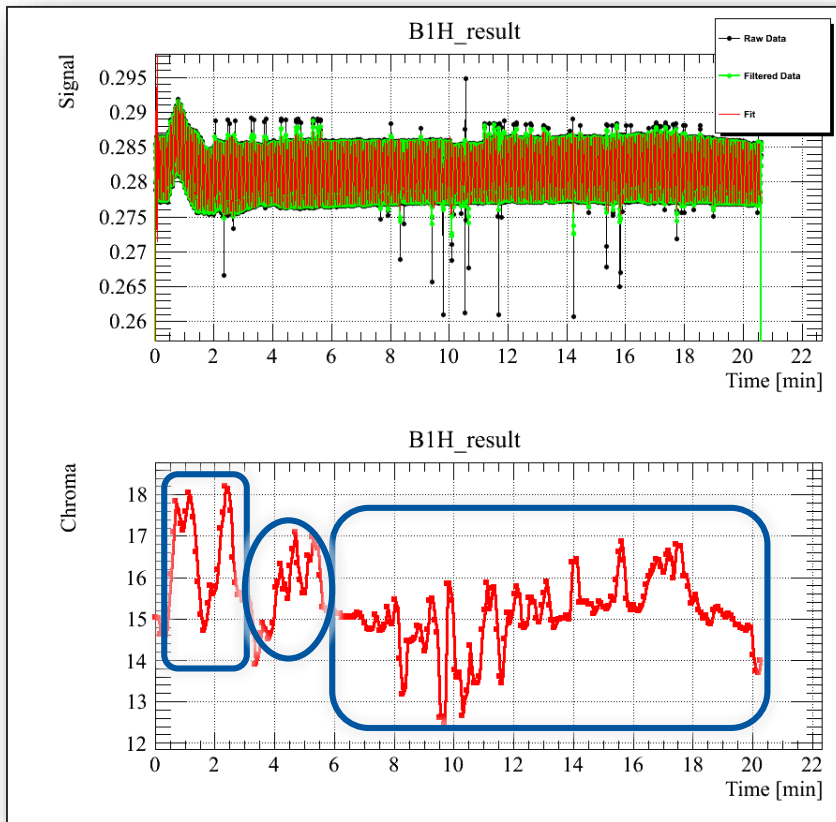


- Q' stable in within  $\pm 2$  units
- Noisy signal (V especially) => measurements not fully reliable
- Some feed-forward could be done (fine tuning)

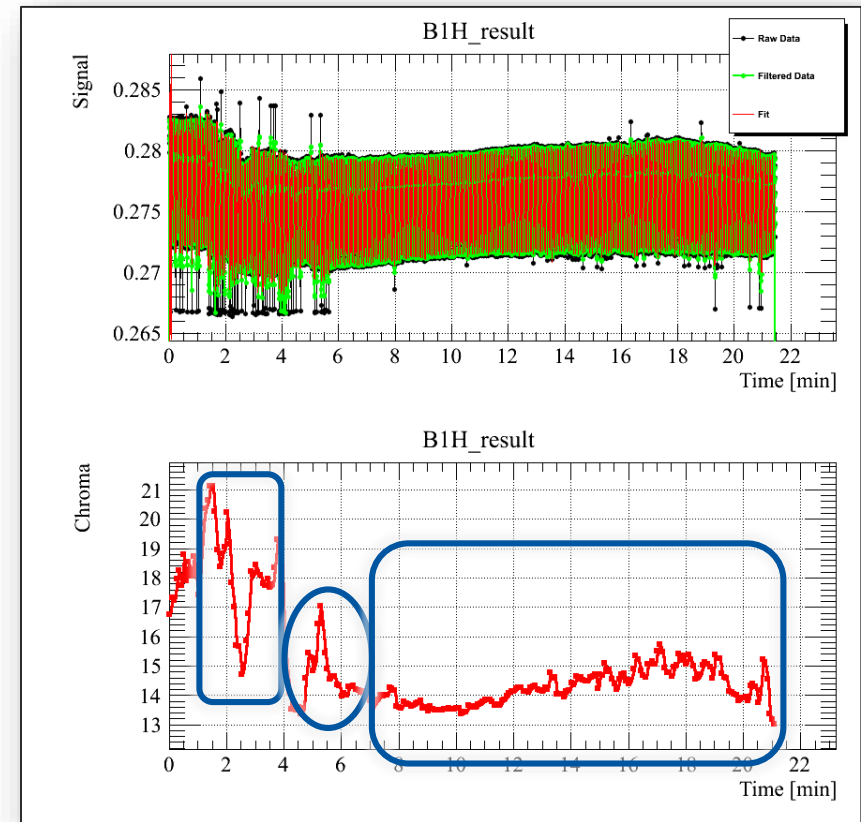
# Reproducibility – B1 Horizontal

In Fill 4534 we enter the ramp with  $\sim 2 Q'$  units more

## Fill 4307 on Sept 5<sup>th</sup>



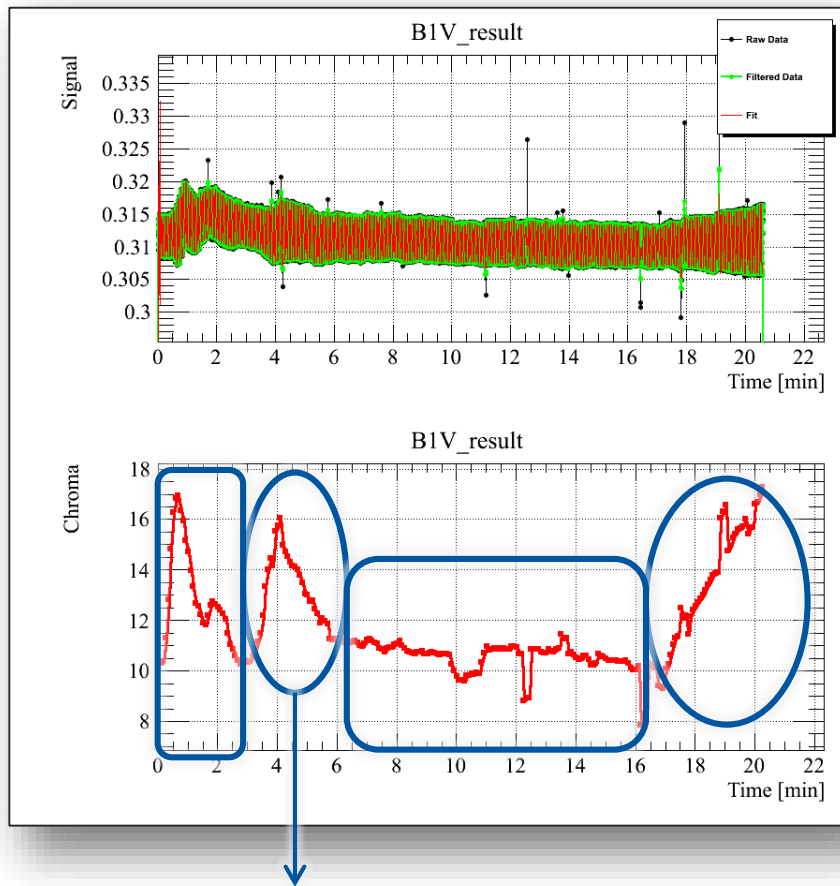
## Fill 4534 on Oct 25<sup>th</sup>



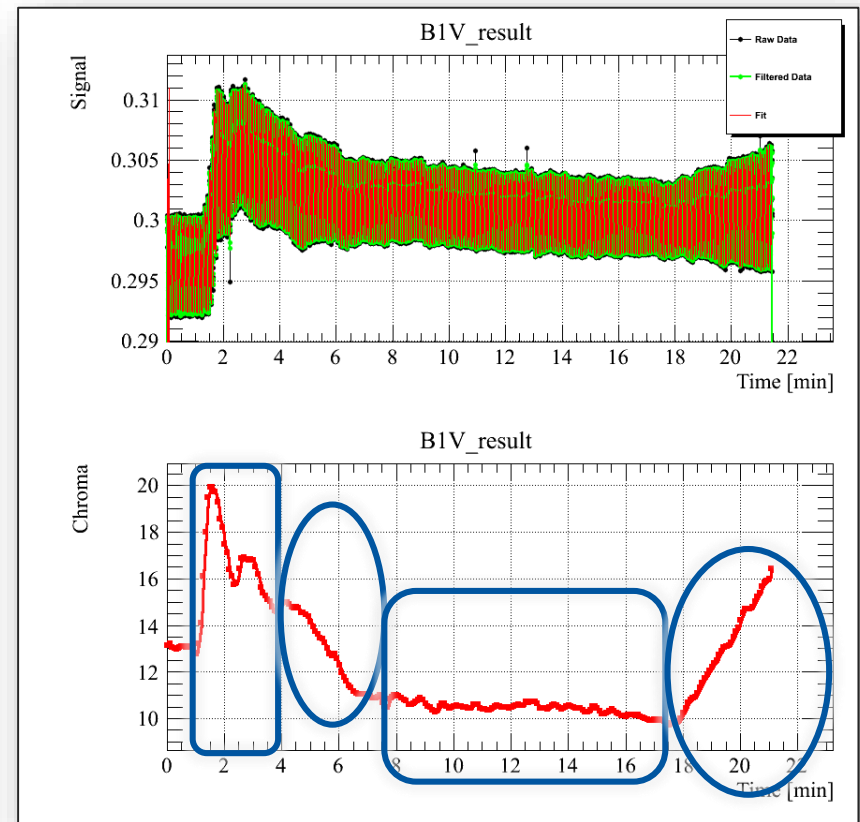
# Reproducibility – B1 Vertical

In Fill 4534 we enter the ramp with  $\sim 2 Q'$  units more

Fill 4307 on Sept 5<sup>th</sup>

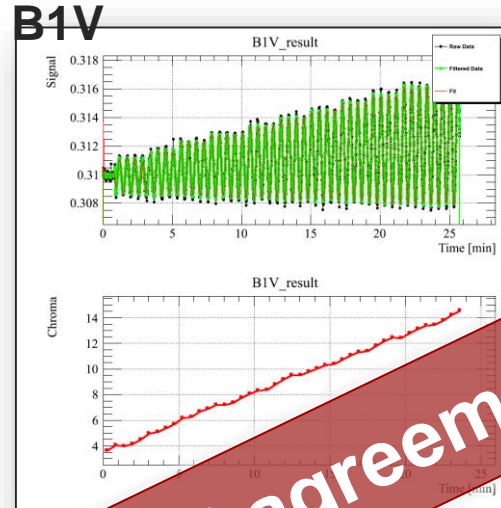
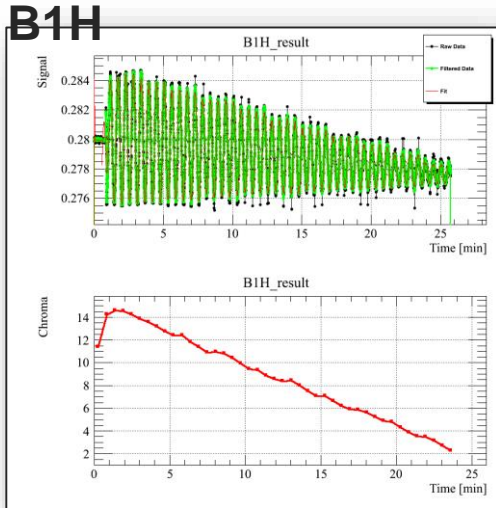


Fill 4534 on Oct 25<sup>th</sup>



Fed-forwarded peak

# b3 to Q' measurement

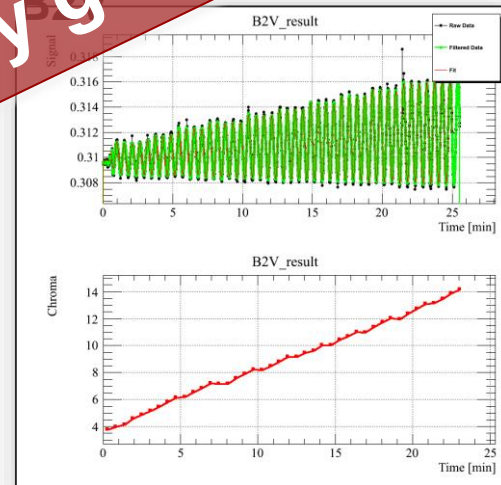
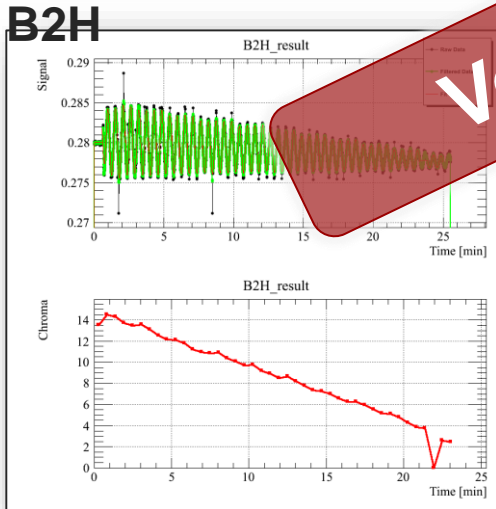


**Run1 assumption:**

- 1 b3 unit =
- 43 Q' units in H
- -35 Q' units in V

0.03 b3 units swing in 10 steps

**Very good agreement**



**New measurements**

1 b3 unit =

**B1**

- H ~ 42.6 Q' unit
- V ~ -35.3 Q' unit

**B2**

- H ~ 42 Q' unit
- V ~ -35 Q' unit

# Conclusions

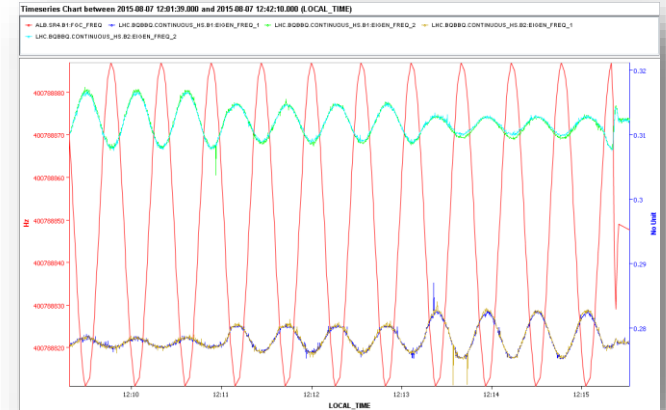
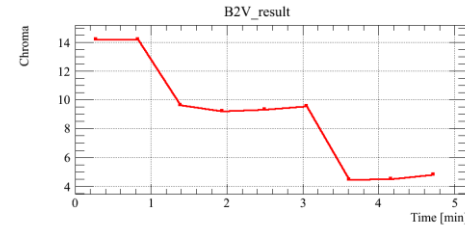
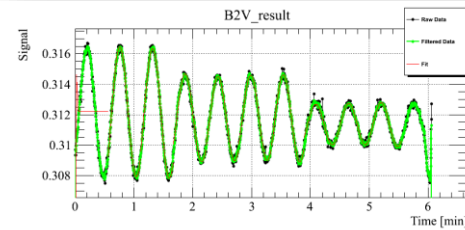
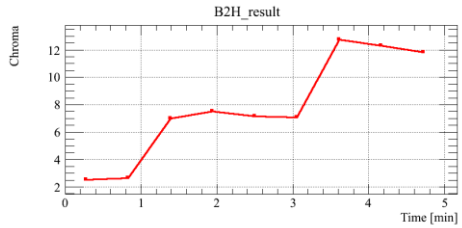
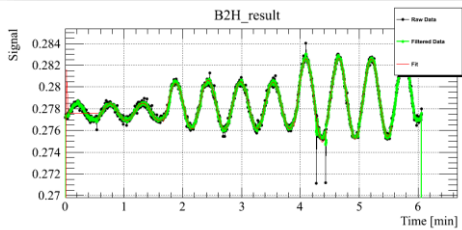
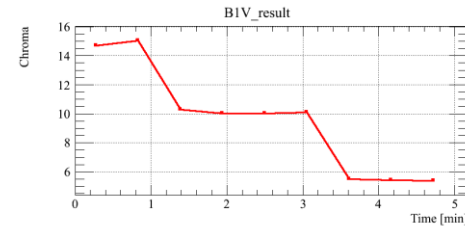
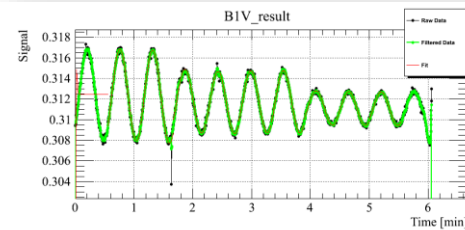
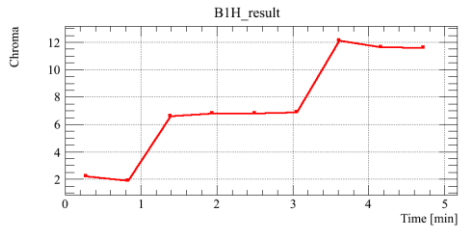
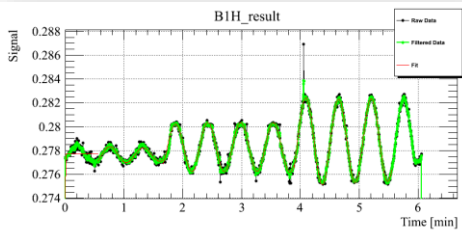
## ➤ **Tune**

- Tunes at injection are under control, although decay isn't fully reproducible
- Once the ramp starts the tunes are controlled by the QFB

## ➤ **Chromaticity** (measured with pilot)

- b3 injection decay is correctly compensated for operational purpose (it would be a plus to verify the powering history dependency)
- Good control and reproducibility during squeeze, ramp and snapback ( $\pm 2$  units)
- Small imperfection in the persistent current model below 3kA

# Q' knob check



## Knob measurements 2 steps of 5 units

### B1

- H -> 2 to 12
- V -> 15 to 5

### B2

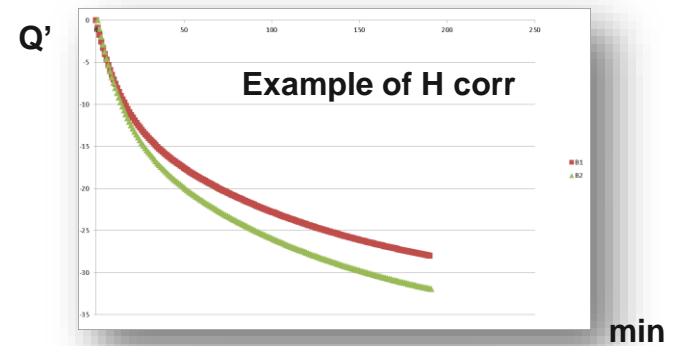
- H -> 2.2 to 12.2
- V -> 14 to 4

# OP without RCS.A78B2

## INJECTION

- b3 decay

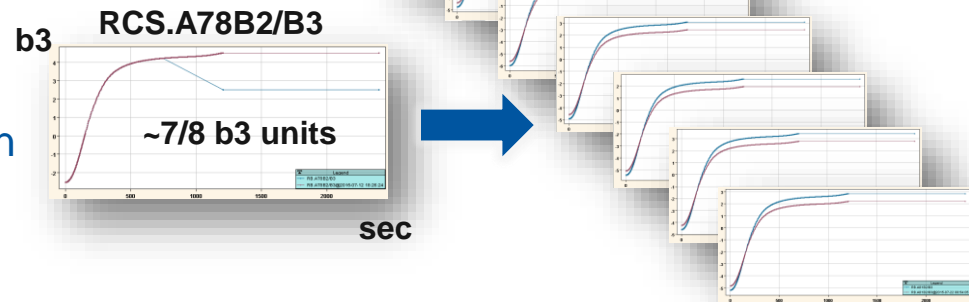
B2 compensation is calculated as for B1 then multiplied to a  $8/7=1.14$  factor



## RAMP

- Snapback
- b3 variation (momentum change)

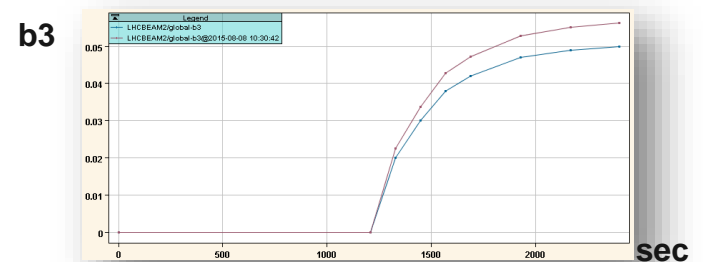
The RCS.A78B2/B3 function has been equally distributed on the other circuits



## FLATTOP

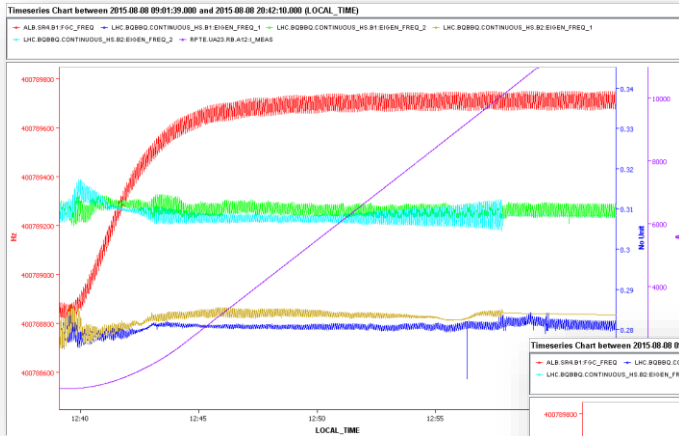
- b3 decay

The B2 global\_b3 knob has been multiplied by a  $8/7=1.14$  factor (effect of about 0.2 Q' units)



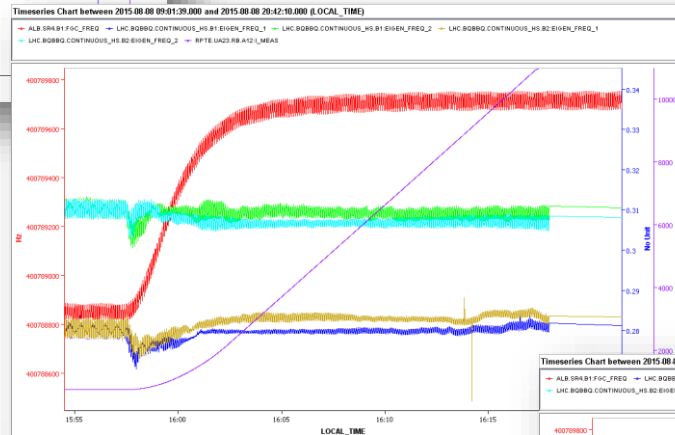


# Ramping w/o RCS.A78B2



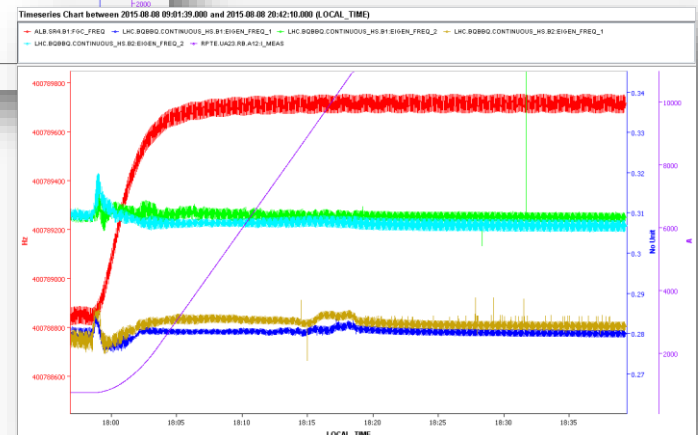
## First ramp:

At about 800 sec the B2Q'V starts growing and B2Q'H goes down then passes negative...B2 is dumped around 1080 sec after the ramp start



## Second ramp:

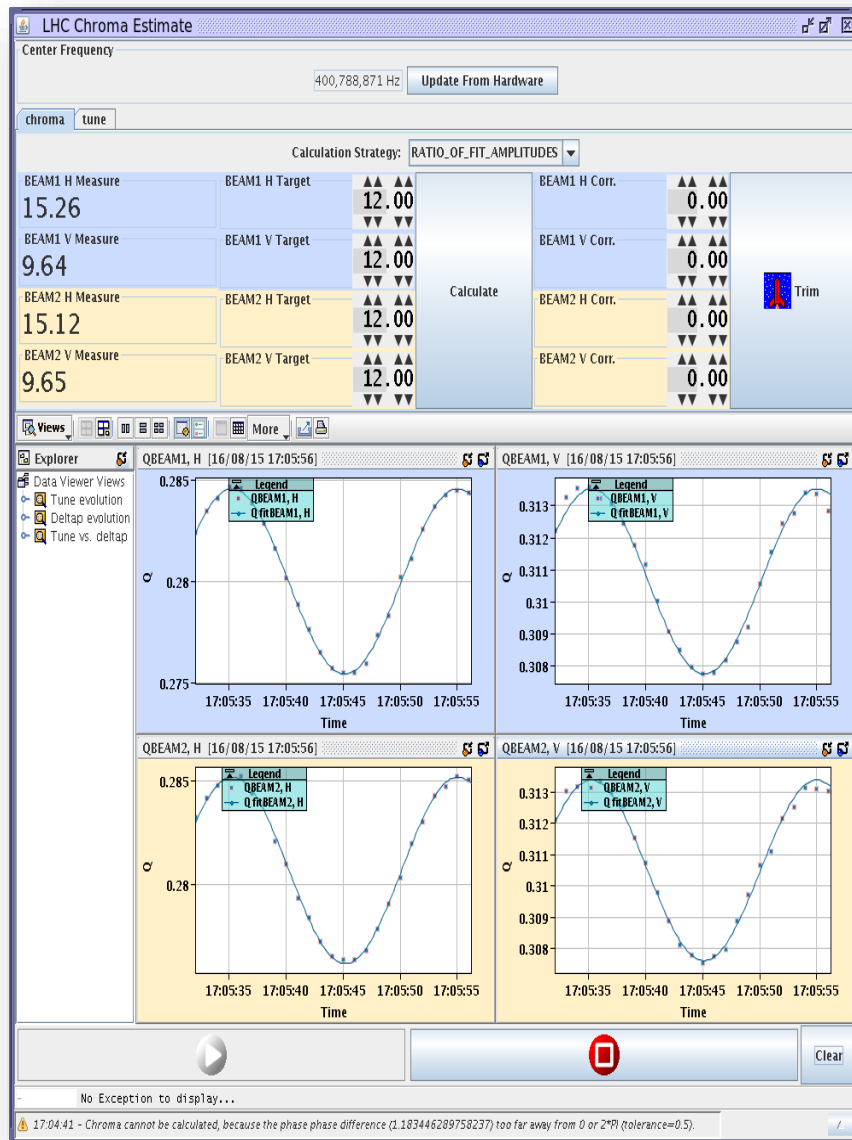
Both beams survive the ramp, but are dumped about 30 sec after flattop is reached (electrical glitch caught by FMCM RD1.LR5)



## Third ramp:

Both beams survive!  
Q' (re-)measured along the ramp (small corrections implemented) and at flattop

# Online Q'



- Worked very reliably for several fills
- Next improvement steps:
  - Q' trace (e.g. to observe evolution during ramp)
  - Feed Forward
  - Error Estimation

K.Fuchsberger