Tune and Chromaticity: Decay and Snapback

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Acknowlegments to:
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Outline

- Introduction to the effect
- **Tune decay at injection**
- **Tune snapback at the start of the ramp**
- Summary of chromaticity studies

Origin of the Effect

During injection the superconducting magnets are at constant current.

➔ The **magnetic field multipoles drift** when the magnets are on a constant current plateau, due to current redistribution on superconducting cables.

➔ **Decay of tune and chromaticity.**

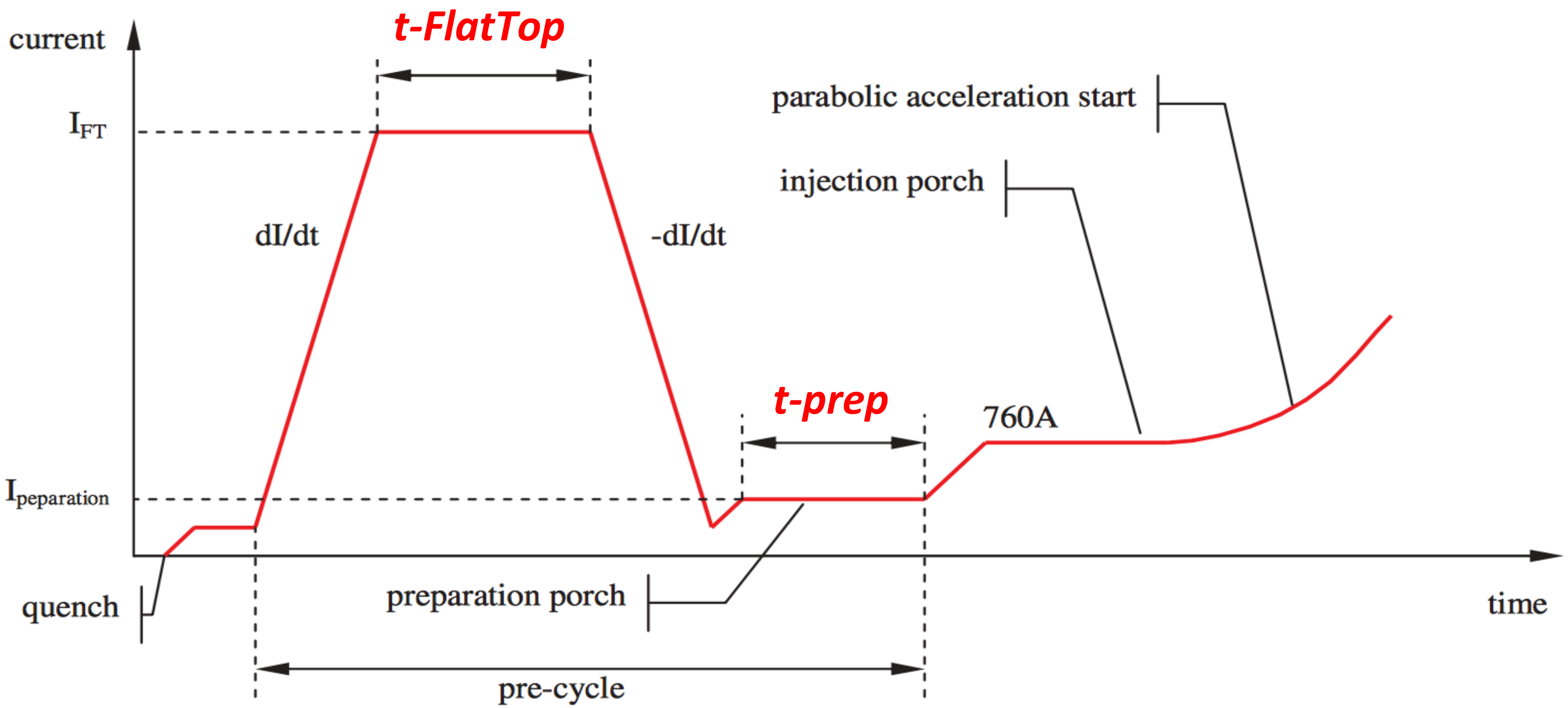
In the **first few seconds of the ramp**, when the magnetic field is increased, the original hysteresis state is restored:

➔ **snap-back**

This dynamic behavior of the magnetic fields has been studied and model with the ***Field Description of the LHC (FiDeL) model***.

Dependency on Powering History

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



Correction Methods

Several systems correct the chromaticity and tune to the reference:

- **Field description for the LHC (FIDEL):** feed-forward system to compensate for predictable field variations of the magnets.
- **Tune feed-back (QFB):** beam based correction.
  - *no continuous measurement of Q’, no feedback available.*
- **Manual trims,** applied when necessary for Q and at the beginning of the injection plateau for Q’.

Decay at Injection

- The FiDeL model requires beam based parameters, which are obtained by studying the **bare tune and chromaticity evolutions**.
- Bare evolutions are obtained by **removing ALL applied trims form the measurement.**
- Detailed equations of the FiDeL model are complicated (see back-up).
- Bare decay (w/o normalization & powering history) is sum of exponentials, with multiples of a single time constant:

$$Q(t) = v + c\left[d\left(1 - e^{-(t/\tau)}\right) + (1-d)\left(1 - e^{-(t/9\tau)}\right) + \ldots\right]$$

Initial value

Amplitude of decay

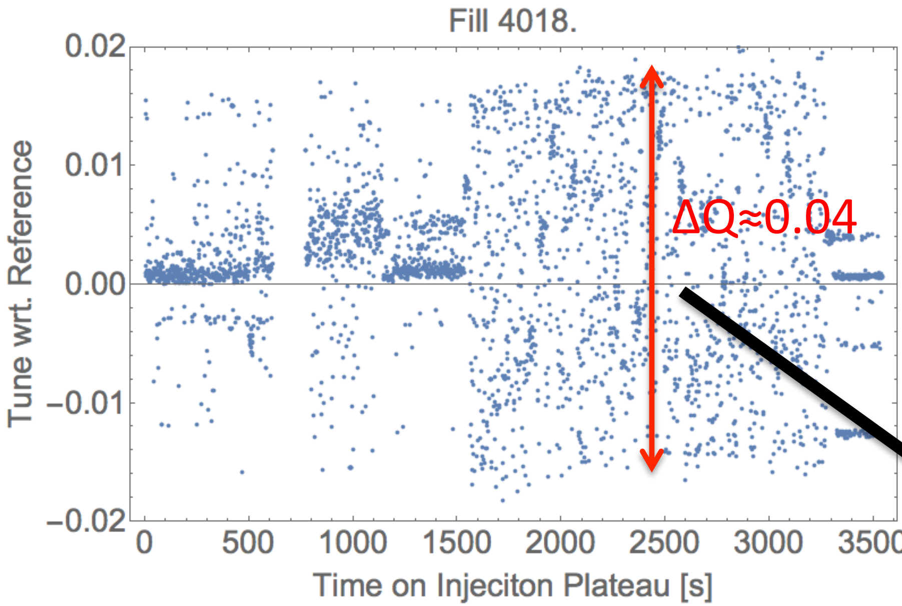
Mixing of slow & fast components

Time constant

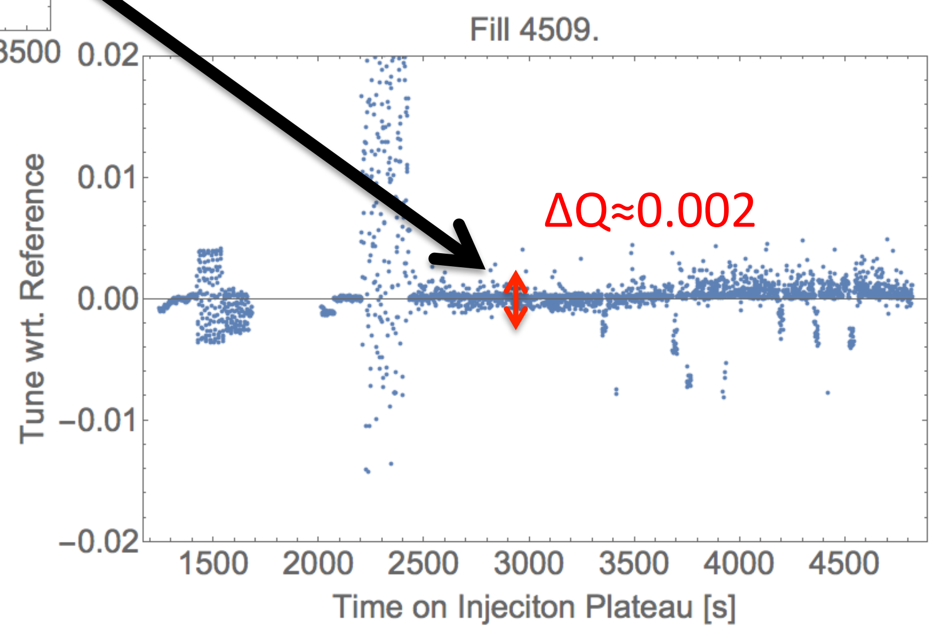
2 Fit parameters

For Q decay, these parameters are set to constant values based on previous studies.

Tune Measurement Quality



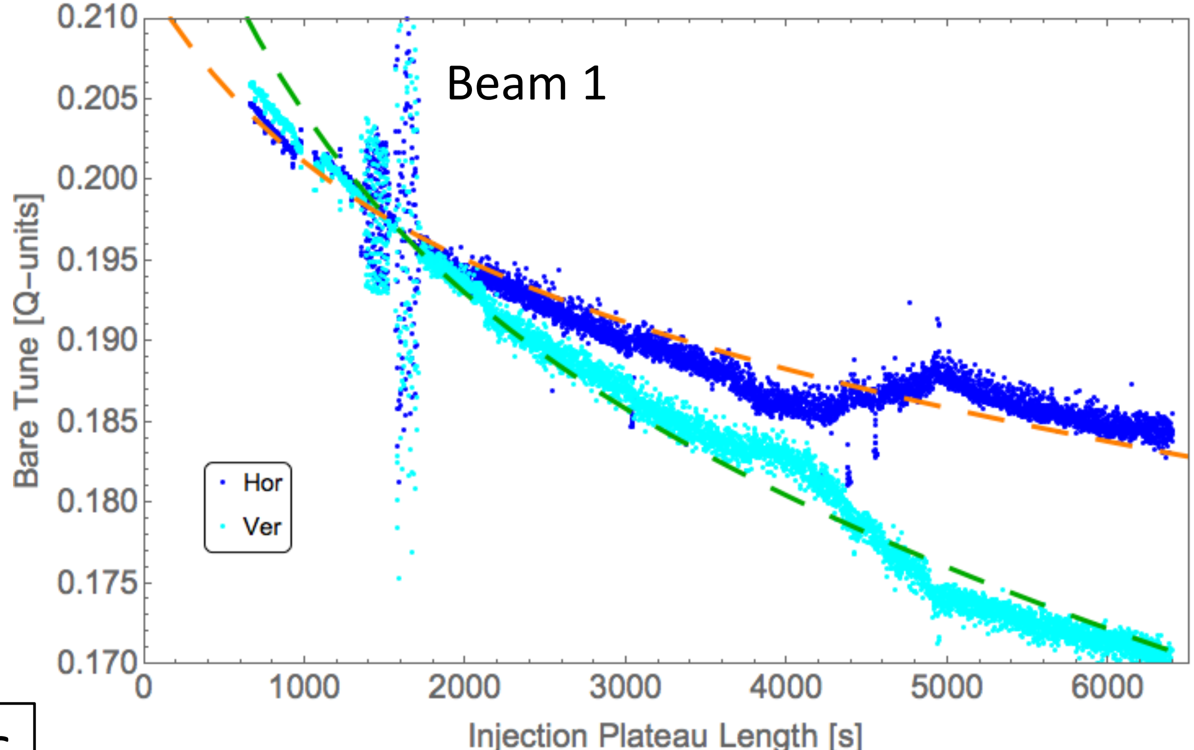
Improved filtering of tune signals implemented during MD1 block.



Removes 50Hz lines and gives better accuracy for high damper gain.

Tune Decay at Injection

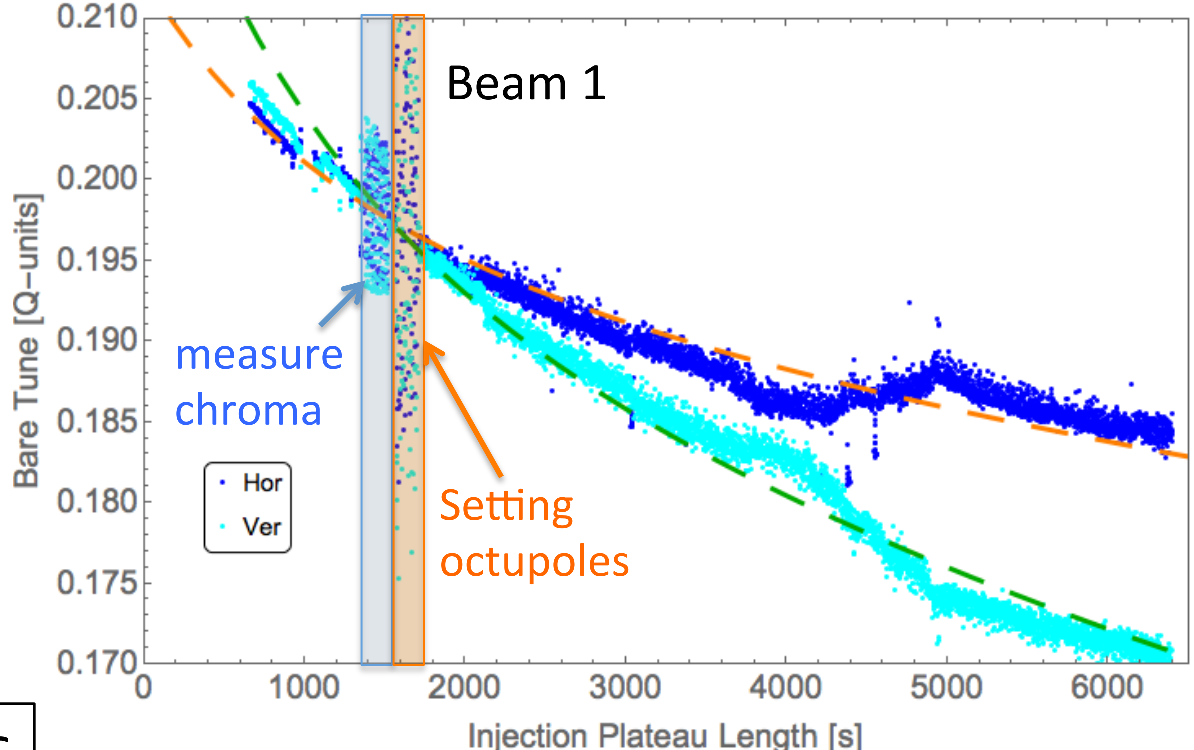
Example of bare tune decay at injection with corresponding exponential fits.



Fill 4526

Tune Decay at Injection

Example of bare tune decay at injection with corresponding exponential fits.



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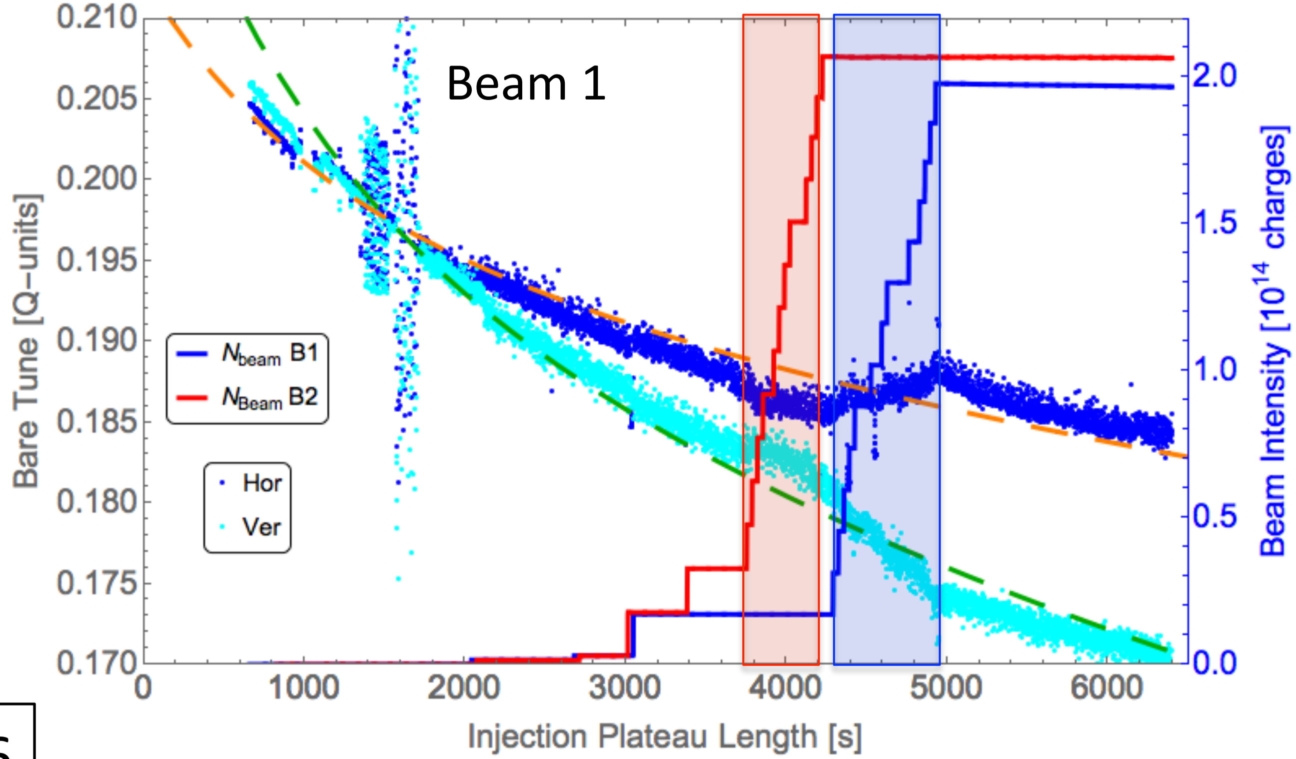
Tune Decay at Injection

Example of bare tune decay at injection with corresponding exponential fits.

Kink related to intensity increase



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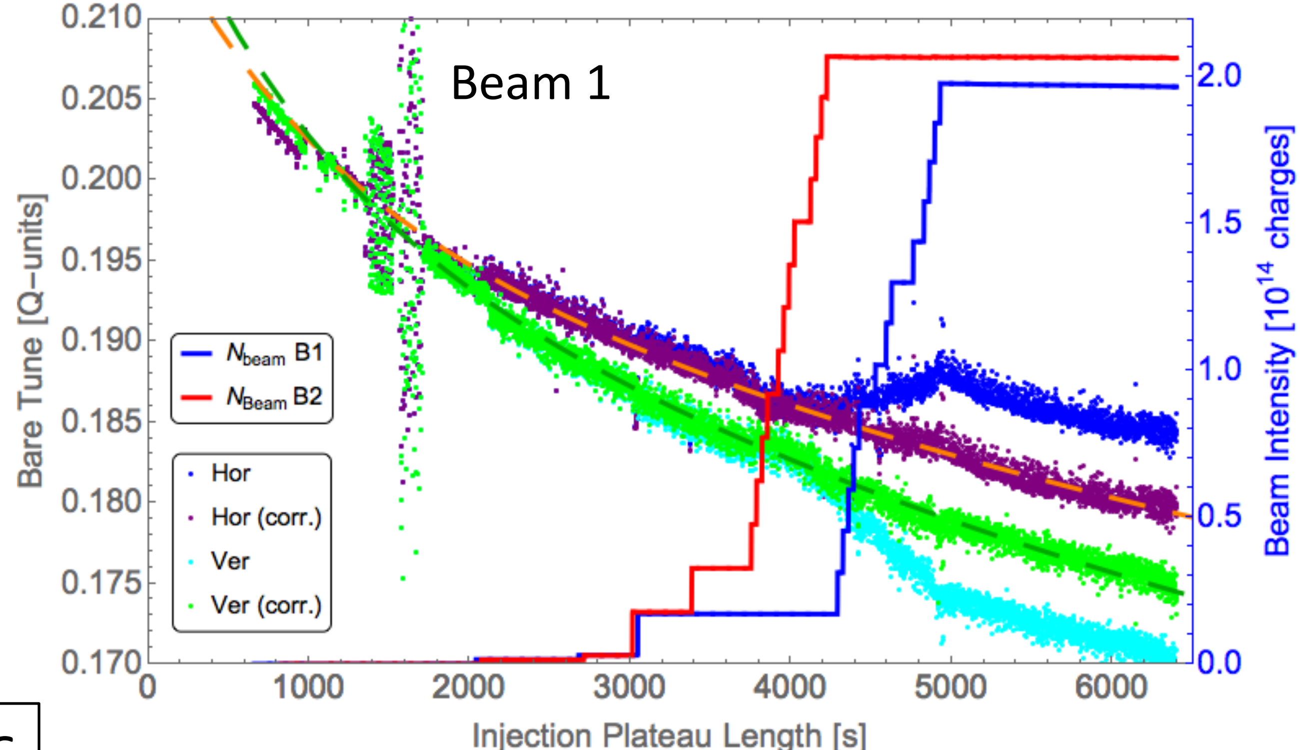
Tune Decay at Injection

Apply correction for **Laslett tune shift** proportional to intensity:

(tune shift due to image currents)

$$\Delta Q_{\mathrm{Laslett}} = -\frac{N_{\mathrm{b}} k_{\mathrm{b}} r_{\mathrm{p}} \beta_{\mathrm{av}}}{\pi \gamma} \left(\frac{\varepsilon_1}{h^2} + \frac{\varepsilon_2}{g^2} \right) \simeq \begin{cases} -1.7 \times 10^{-2} & \text{at 450 GeV,} \\ -1.1 \times 10^{-3} & \text{at 7 TeV,} \end{cases}$$



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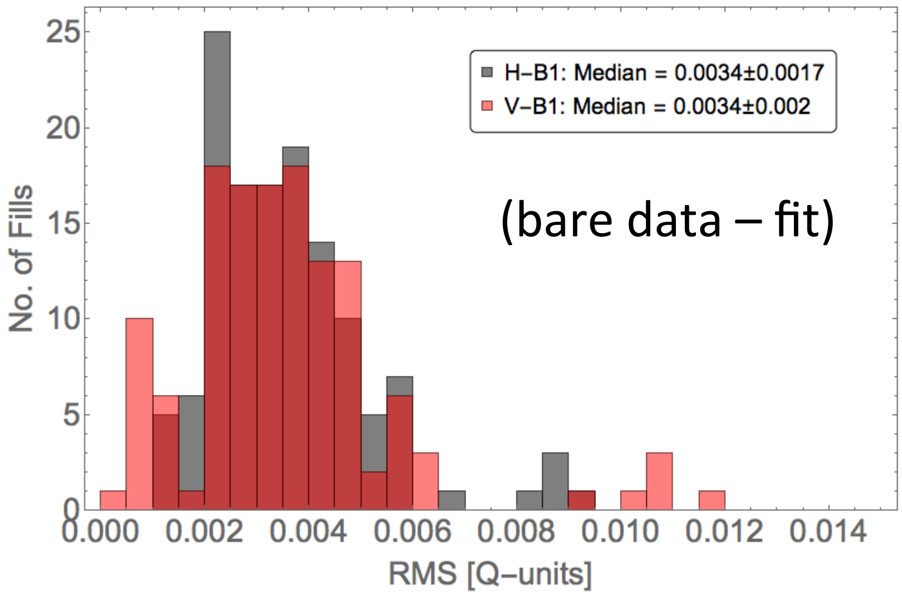
F. Ruggiero, *Single-Beam Collective Effects in the LHC*, Part. Accel. 1995, Vol. 50, pp 83-104.

Goodness of Fit

RMS of residuals

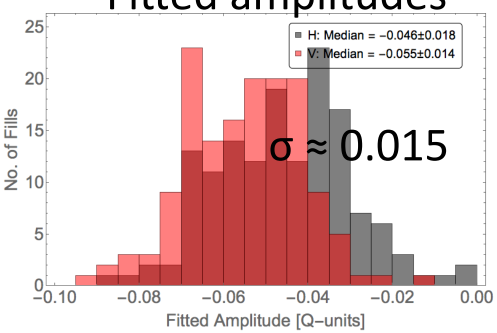


Average RMS over all fills is close to measurement accuracy.

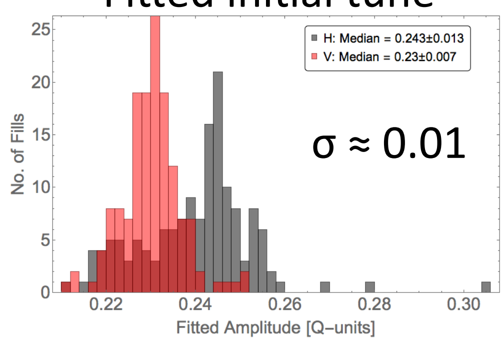
However, fit parameters show a large spread between fills.

Partially introduced by dependency on powering history.

Fitted amplitudes



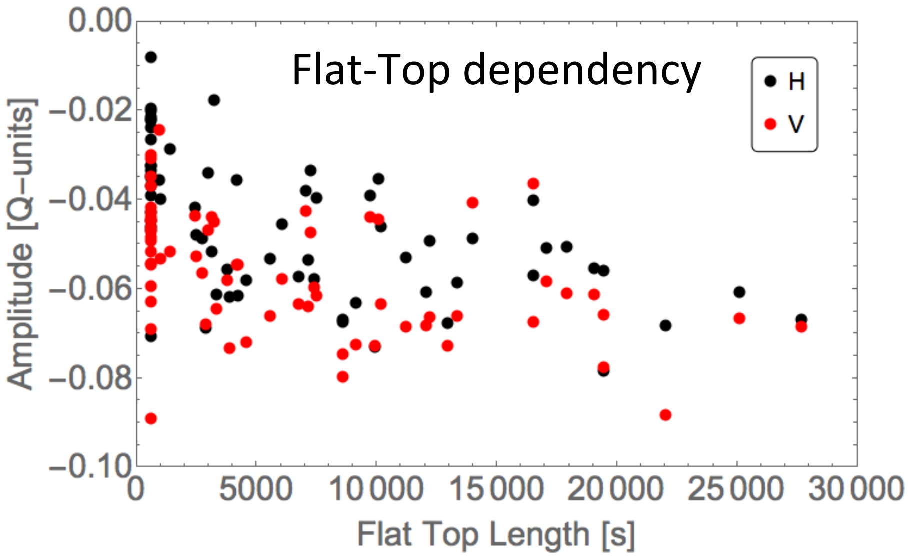
Fitted initial tune



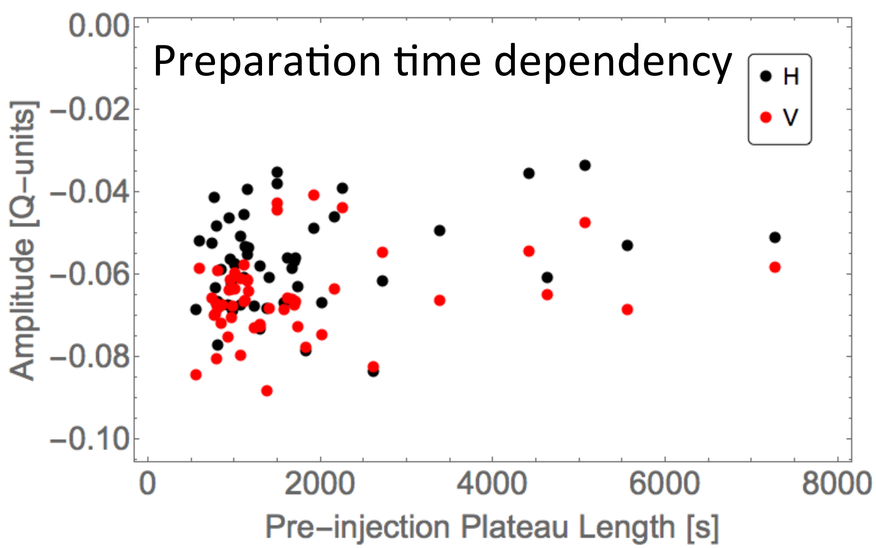
Could also be influenced by octupole and chromaticity settings, which were frequently changed during the run.

Powering History Dependence

Exclude dependence on preparation time: select only cycles **with *t-prep*>1000s**



Exclude dependence on flat top time: select only cycles **with *t-FlatTop*>4000s**

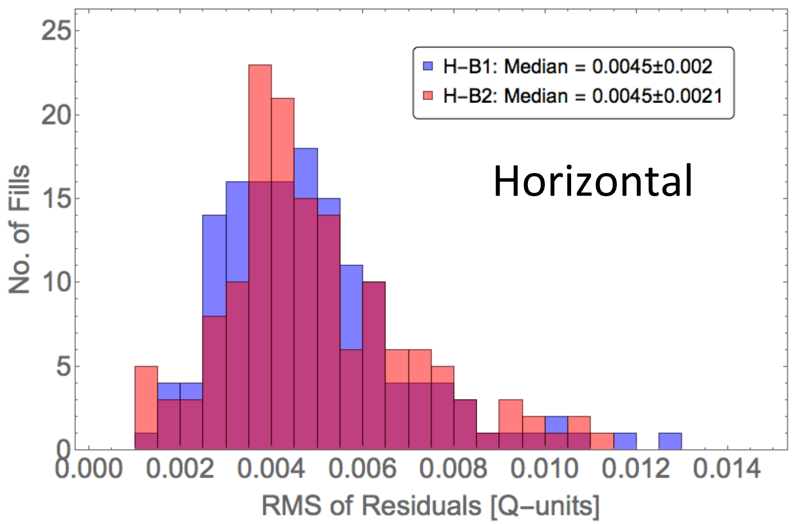


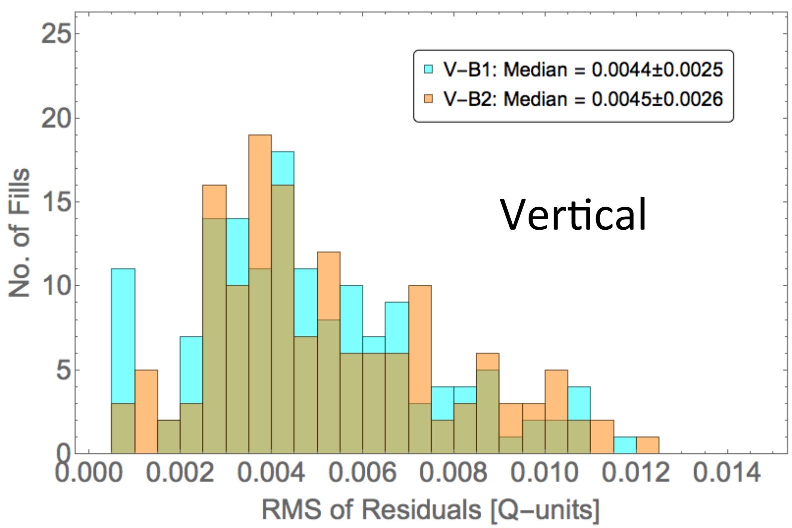
- Bad reproducibility between fills.
- But decay amplitude tends to decrease with flat top length.

A dependency of the decay amplitude on the time spent at flat top has been implemented in the online correction system in 2015.

Applied Correction

RMS of Residuals (data – reference)



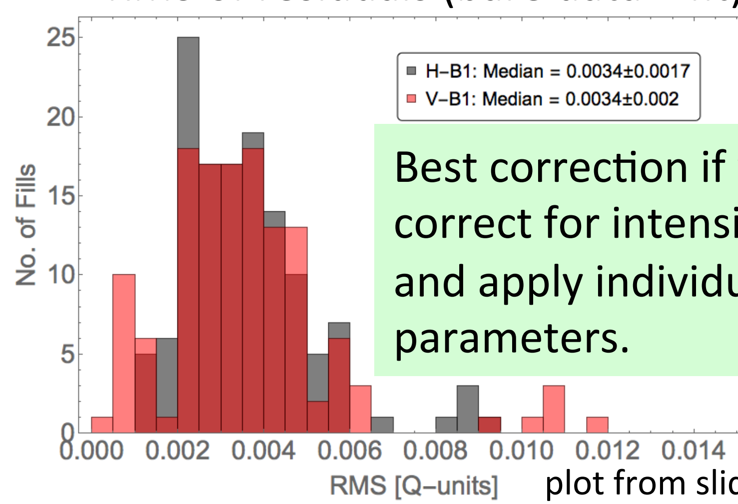


RMS of residuals of tune measurement with respect to reference.

➔ ~30% worse than best correction (individual fit).

➔ Applied correction uses average decay and powering history parameters.

RMS of residuals (bare data – fit)

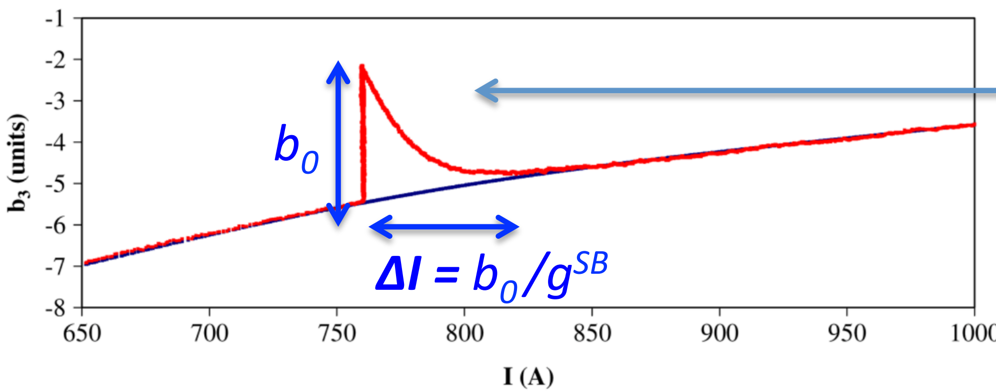


Best correction if we could correct for intensity effect and apply individual fit parameters.

plot from slide 11

Snap-back

Multipole component of magnetic field



Magnet current

Measurements show that the **snap-back** to hysteresis curve in first few seconds of the ramp follows an **exponential law**.

The amplitude b_0 depends on length of injection plateau & powering history.

$$b^{snap-back}(t) = b_0 \exp\left[\frac{(I_{Inj} - I(t))g^{SB}}{b_0}\right]$$

Tune at Start of Ramp

Example of amplitude dependent bare tune evolution as a function of magnet current during snap-back with corresponding exponential fits.

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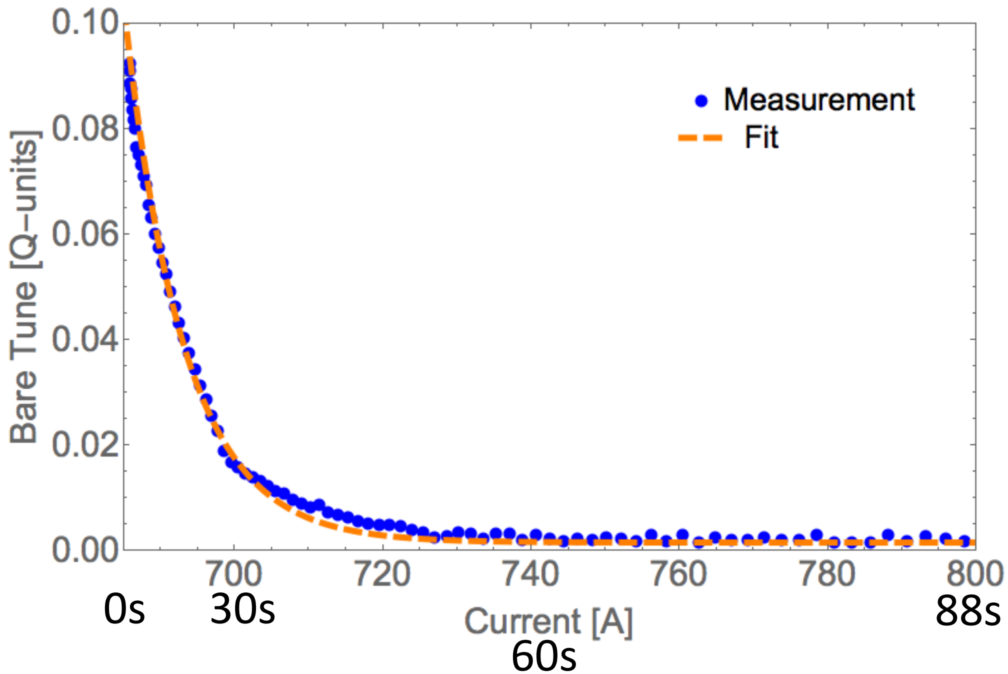
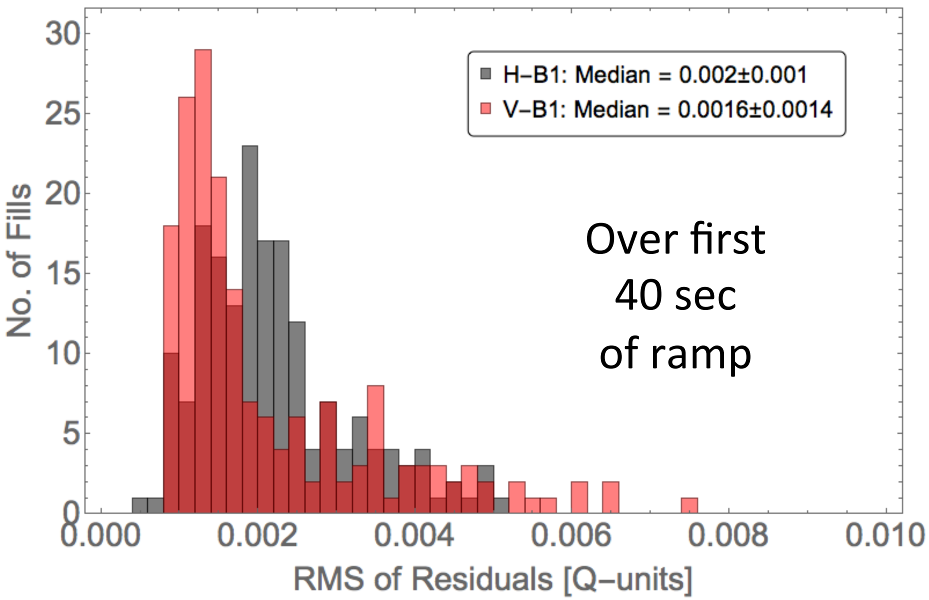


The snap-back lasts 30-60sec depending on the initial amplitude at the end of the injection plateau.

Goodness of Fit and Proposed Correction

RMS of residuals (bare data – fit)

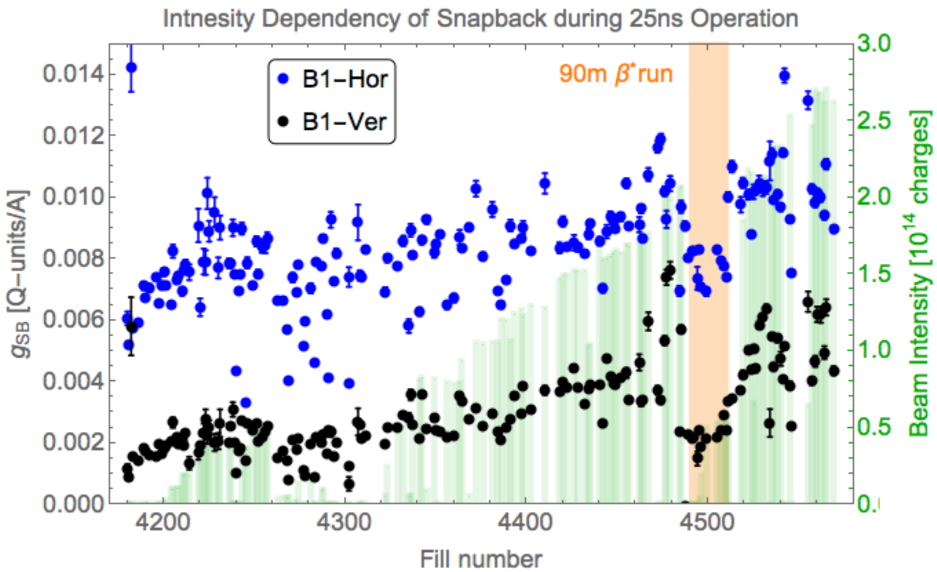


Data and model fit are in excellent agreement.

Tune measurement during the initial part of the ramp seems to be more precise than under stable conditions.

Again, large spread of fit parameters between fills is observed.

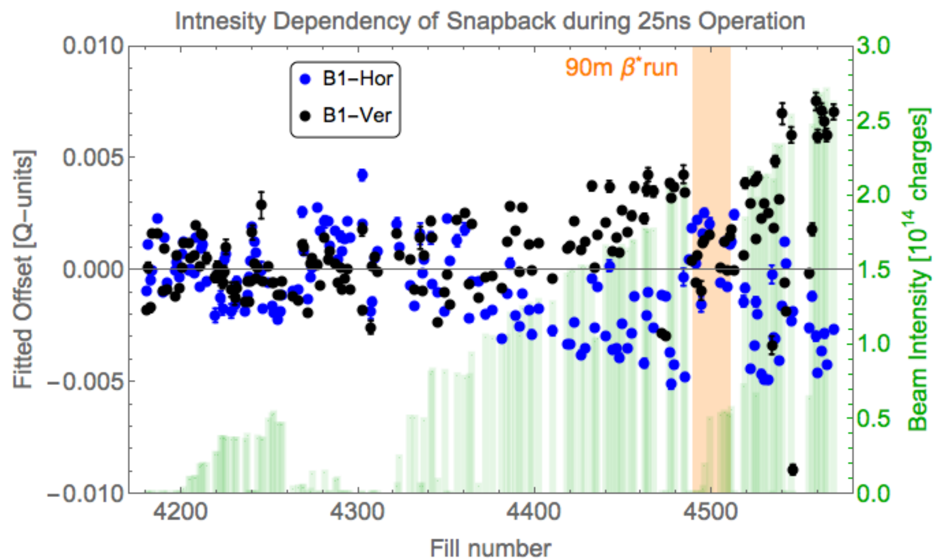
Dependency on Intensity



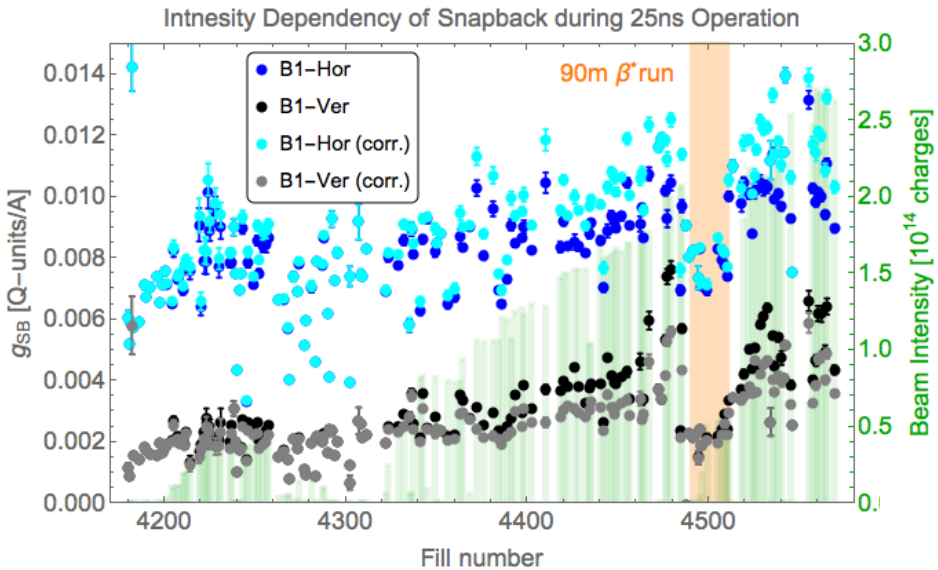
Fit parameters drift over the year.

A correlation with intensity is present.

- Time constant increases.
- Offset shows opposite slope in Hor. and Ver.

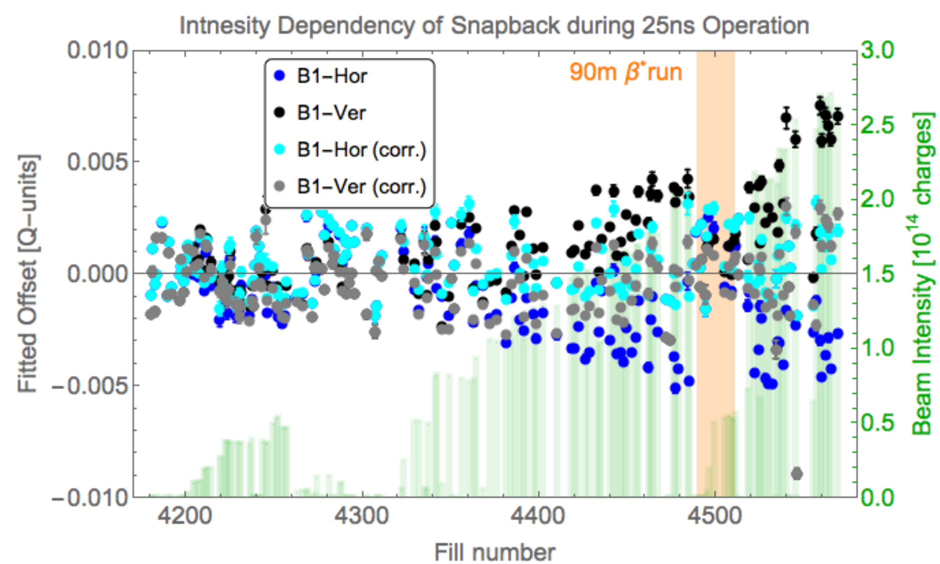


Dependency on Intensity



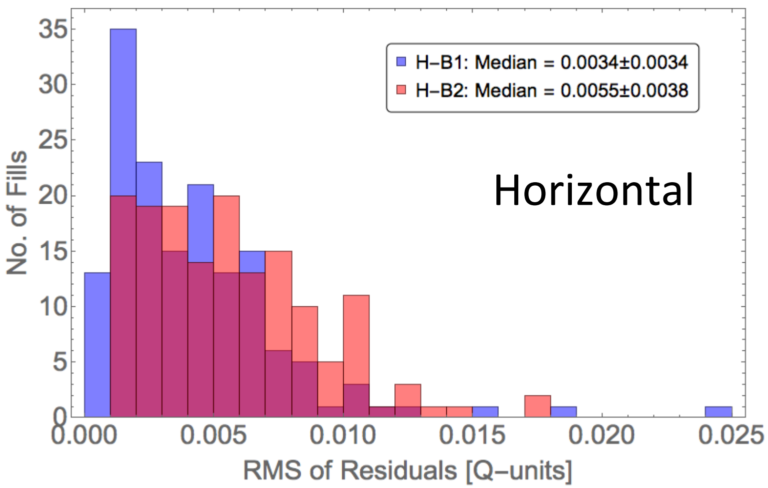
Correction of Laslett tune shift removes intensity dependency of fitted offset, but not of time constant.

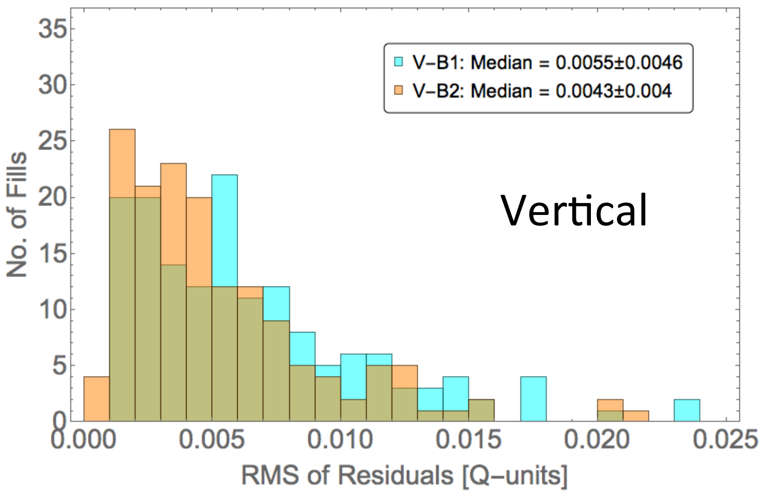
Source of time constant drift remains unknown, but seems to be related to intensity.



Applied Correction

RMS of Residuals (data – reference)

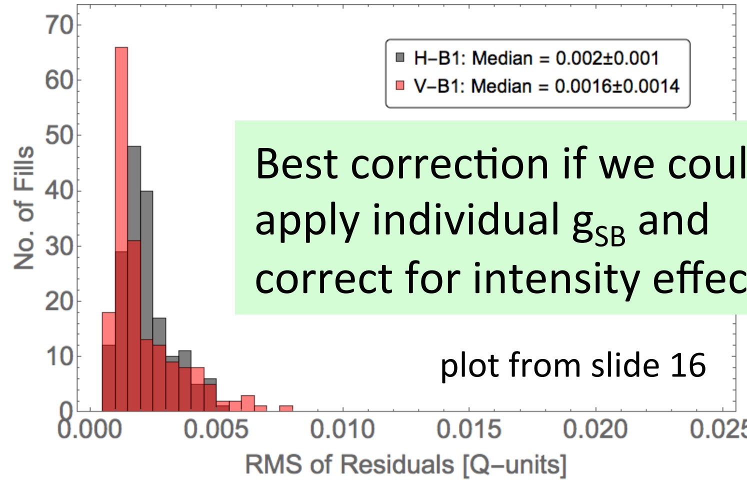




- The same g_{SB} is used for all fills.
- The initial amplitude is obtained from the trims applied during injection.
- No offset is fed-forward.

- **Drift of g_{SB} and intensity dependency degrade quality of correction.**

RMS of residuals (bare data – fit)

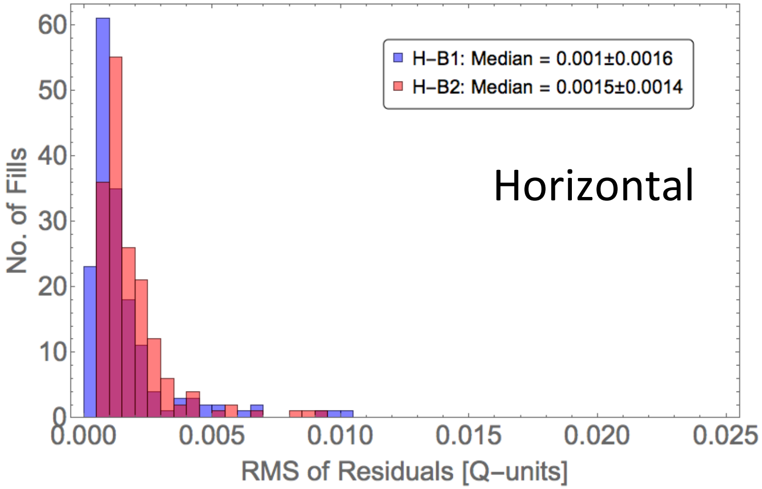


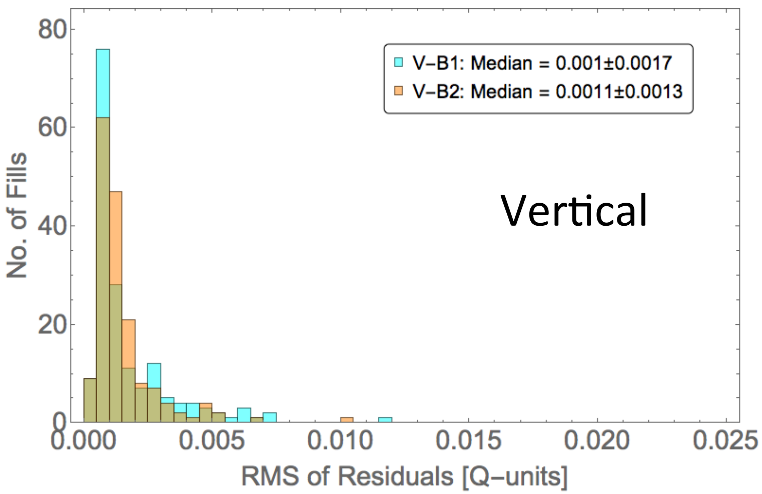
Best correction if we could apply individual g_{SB} and correct for intensity effect.

plot from slide 16

Applied Correction

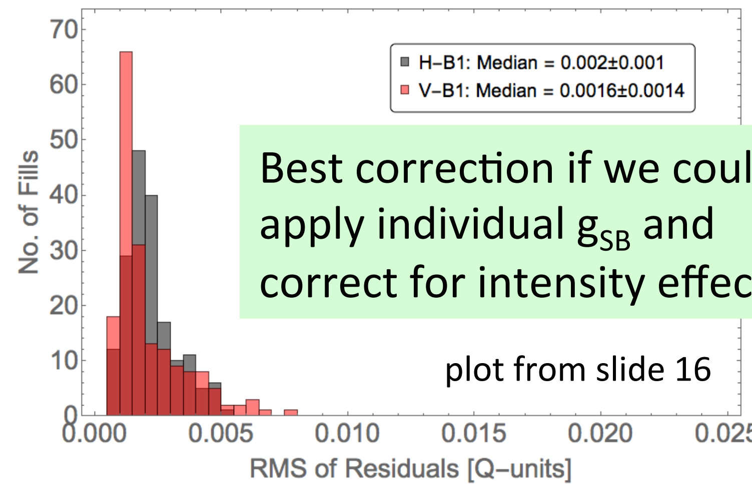
RMS of Residuals (data – reference)





With the QFB working the correction is close to the optimum.

RMS of residuals (bare data – fit)



Best correction if we could apply individual g_{SB} and correct for intensity effect.

Chromaticity

Dedicated measurements (with pilots) have to be performed to obtain the chromaticity.

- These have been done along the cycle only for very few fills this year.
- It would be good to investigate reproducibility with beam several times through the year.
  - ➢ Could be done parasitically e.g. during setup for loss maps etc.

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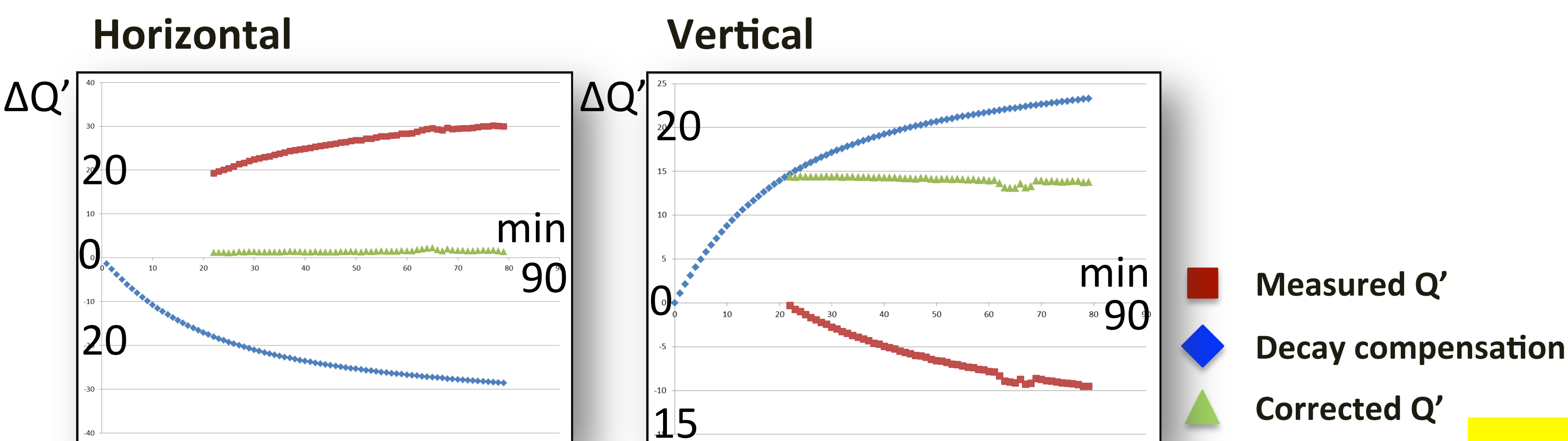
Chromaticity

The chromaticity is in general well controlled along the cycle to the required accuracy.

- Injection decay
  - ➢ The precision of the correction over several fill depends on the quality of the powering history dependency model.
  - ➢ Powering history dependency should be verified with more beam-based measurements.



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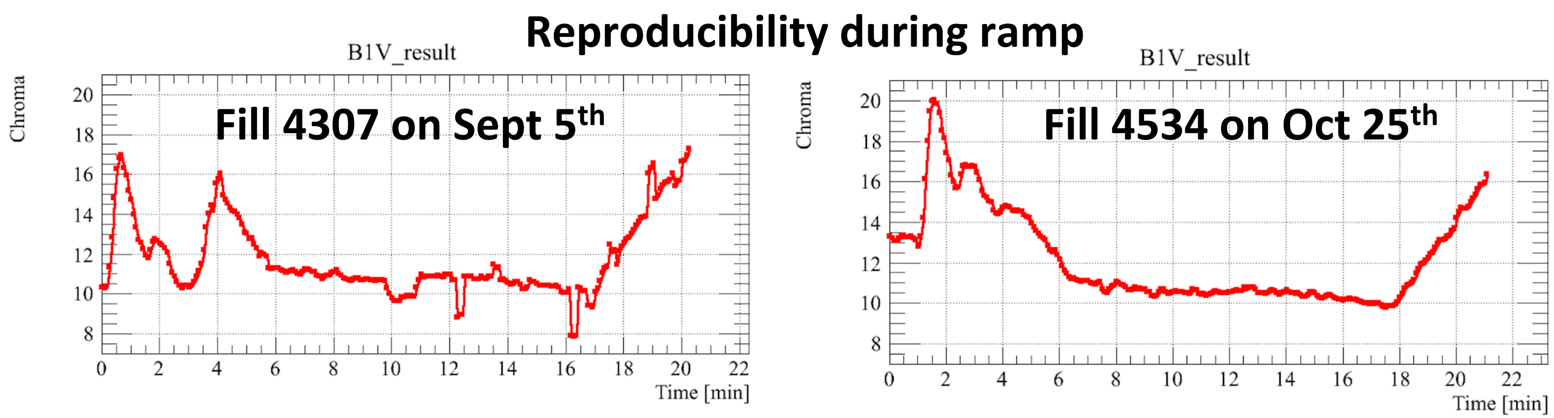
Chromaticity

The chromaticity is in general well controlled along the cycle to the required accuracy.

- Good control and reproducibility during squeeze, ramp and snapback (±2 units)
  - ➢ Small imperfection in the persistent current model below 3kA, but still very good controlled.
- Decay at flat top was expected to be negligible and is indeed observed to be ~2 units.



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Summary of Tune Analysis

Decay at Injection:

- **Tunes at injection are under control**, although the decay is not fully reproducible and influenced by beam intensity.

Snap-back:

- FiDeL trims are incorporated into the ramp according to the expected shape of the snap-back.
  - Manual trims are still linearly incorporated, but contain leakage of the FiDeL model.
- Increasing beam intensity degrades snap-back correction.
- Unexplained drift of time constant (with beam intensity).
- With the help of the QFB, the **snap-back is well controlled,** but it can not do the job alone.

With a better incorporation of the manual trims and **feed-forward of the Laslett tune shift**, the feed-forward corrections could be improved further.

Some References…

- 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).**

- N. Aquilina et al., *Tune variations in the Large Hadron Collider* (Mathematical description of the effects and observations in 2011/12)

- M. Juchno, Presentation at FIDEL meeting 02/06/2015

- F. Ruggiero, *Single-Beam Collective Effects in the LHC*, Part. Accel. 1995, Vol. 50, pp 83-104.

Back-up

The FIDEL model implementation

$$DynErr = \frac{\Delta}{\Delta_{std}} * \Delta_m$$

- Δ → decay
- Δ_m → PH dependency (reduced for Q)
- Δ_{std} → decay normalization (b3 only)

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

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

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

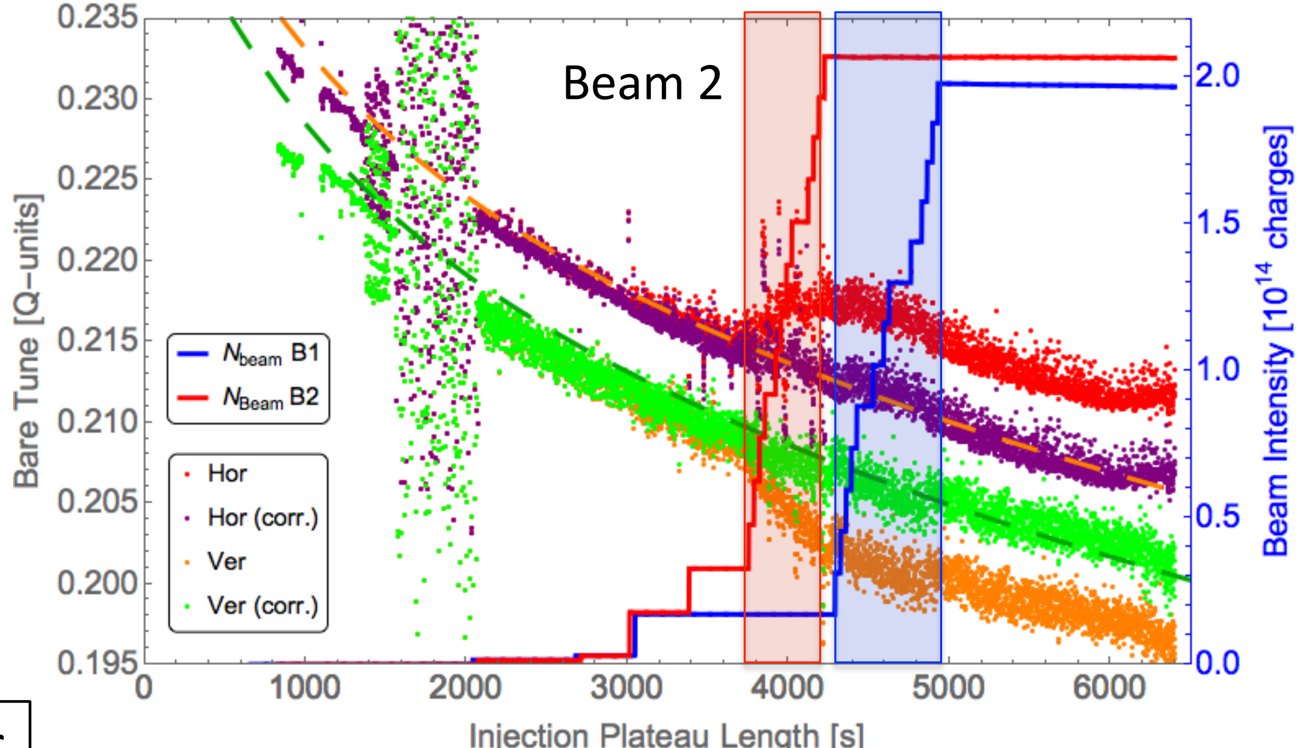
dec_{tau}, dec_d, dec_{delta}
fitting parameters

I_{FT}, t_{FT}, t_{PRE}
powering history

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

Tune Decay at Injection

Example of bare tune decay at injection with corresponding exponential fits.



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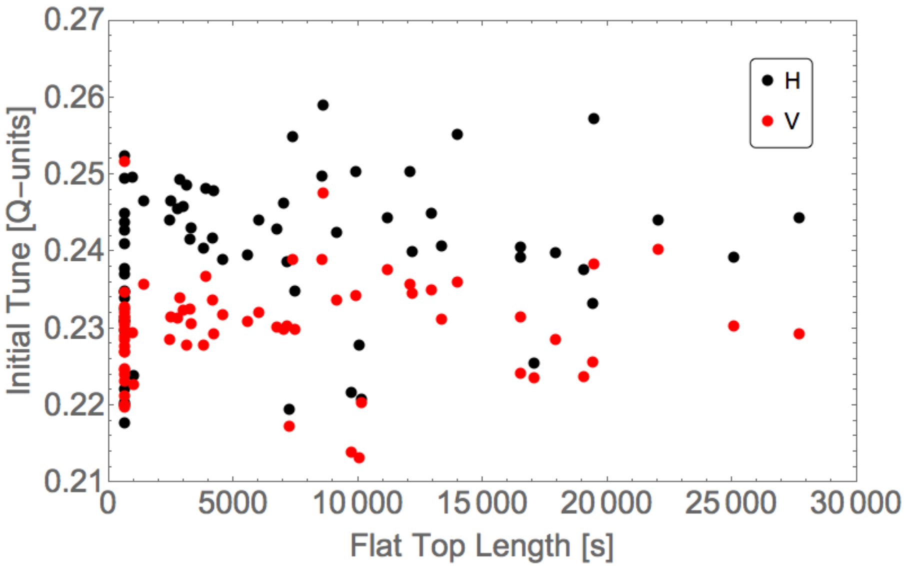
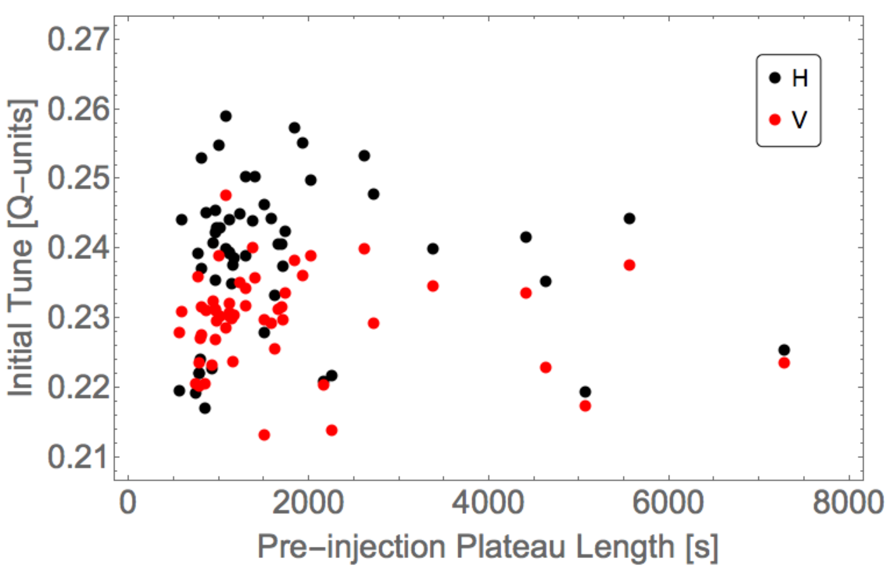
Powering History Dependence

Exclude dependence on preparation time:
select only cycles **with *t-prep*>1000s**



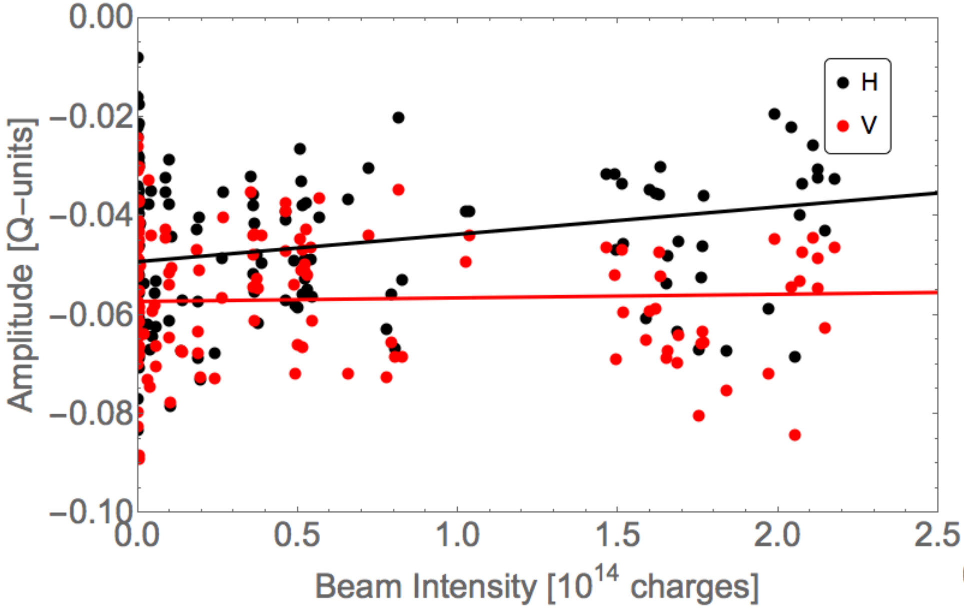
Exclude dependence on flat top time:
select only cycles **with *t-FlatTop*>4000s**



- Bad reproducibility between fills.
- No clear trend of initial tune to depend on powering history.

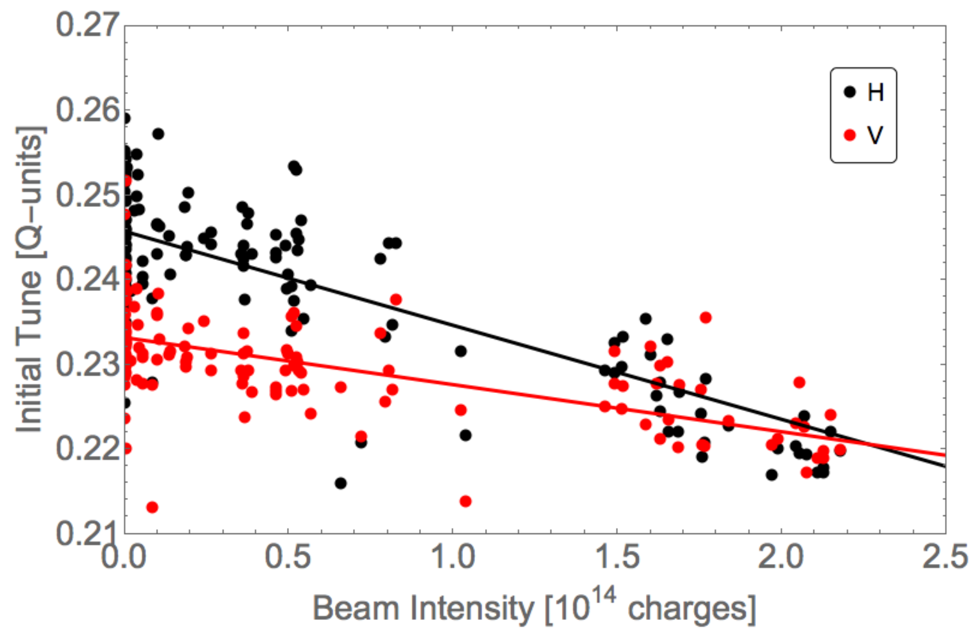
A dependency of the decay amplitude on the time spent at flat top has been implemented in the online correction system in 2015.

Tune Decay – Intensity Dependency

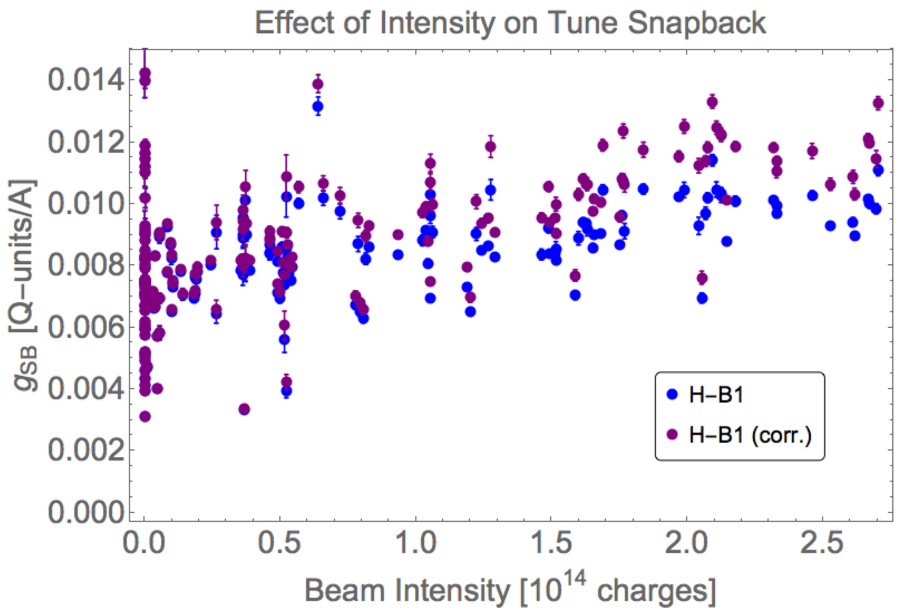


After correcting for the Laslett tune shift, some dependency of tune decay fit parameters on beam intensity remains.

The actual dependency could be on octupole and chromaticity settings rather then on the intensity itself. The conditions of these settings have frequently changed through the run.

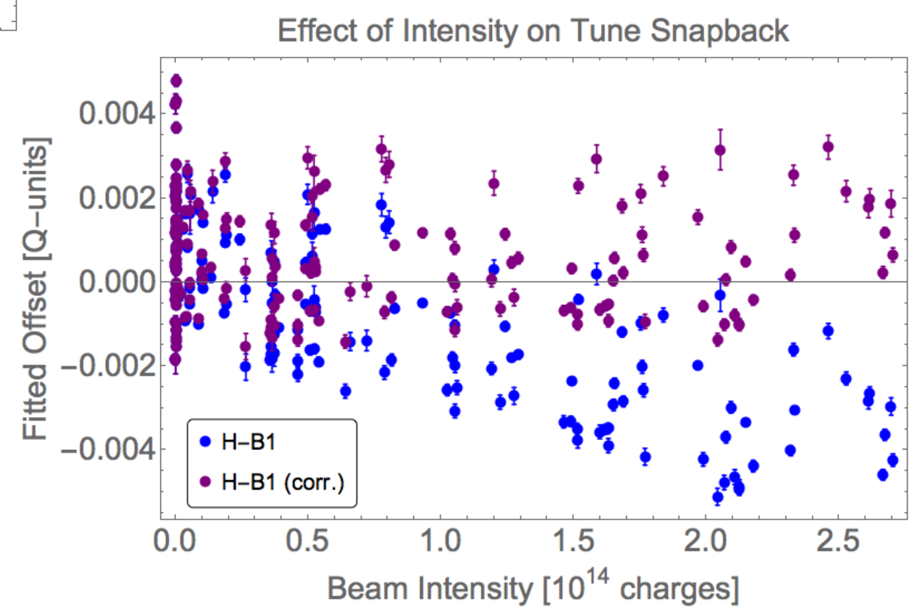


Snap-back: Intensity Dependency



Fit parameters vs. Beam Intensity

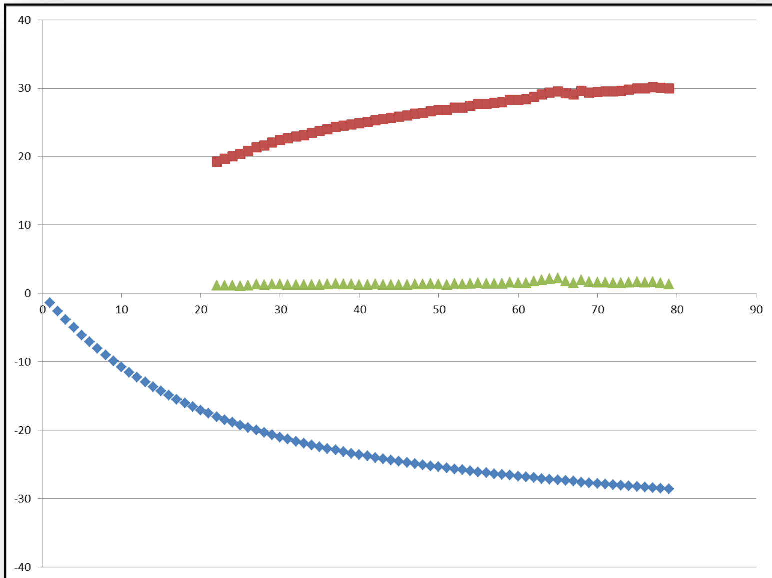
Purple points are corrected for Laslett tune shift.



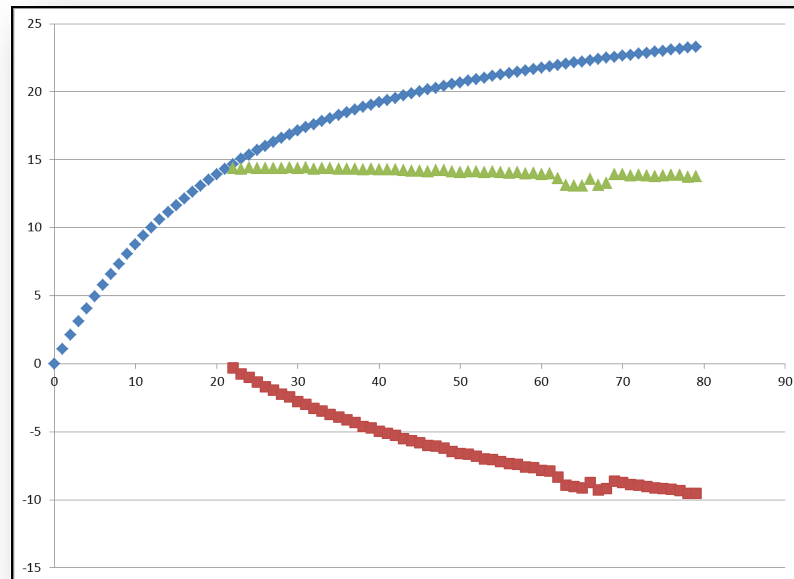
b3 injection decay compensation

Measured Q'
Decay compensation
Corrected Q'

Horizontal



Vertical



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

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

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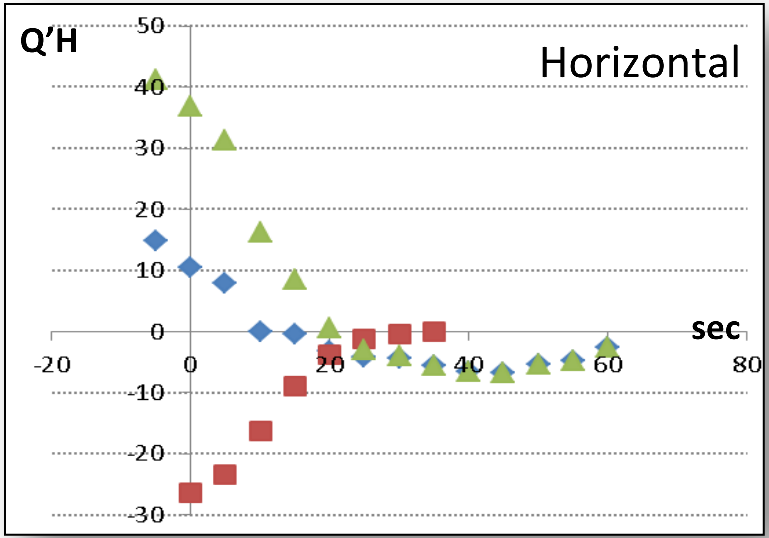
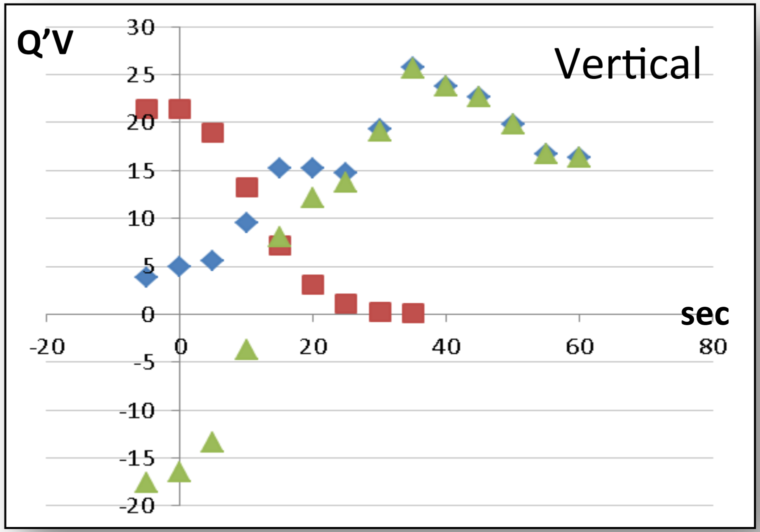
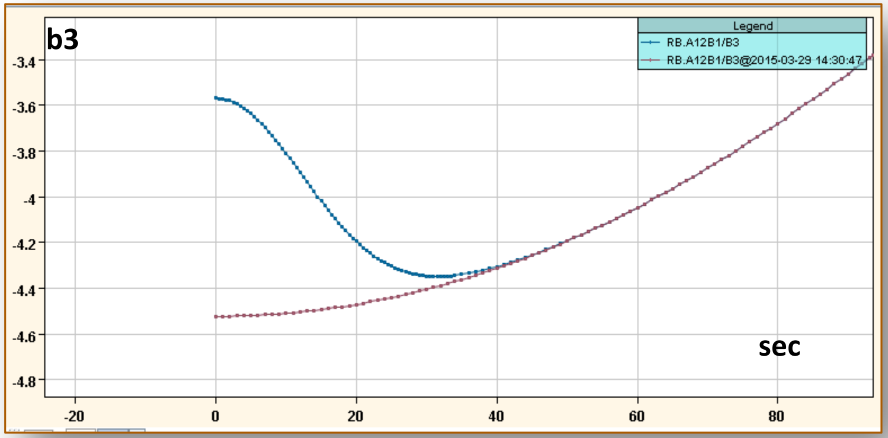
Chromaticity - Snapback



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





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