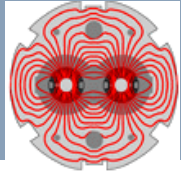
LHC RF capture transients and their adjustment

P. Baudrenghien, J. Wenninger

Energy matching at injection



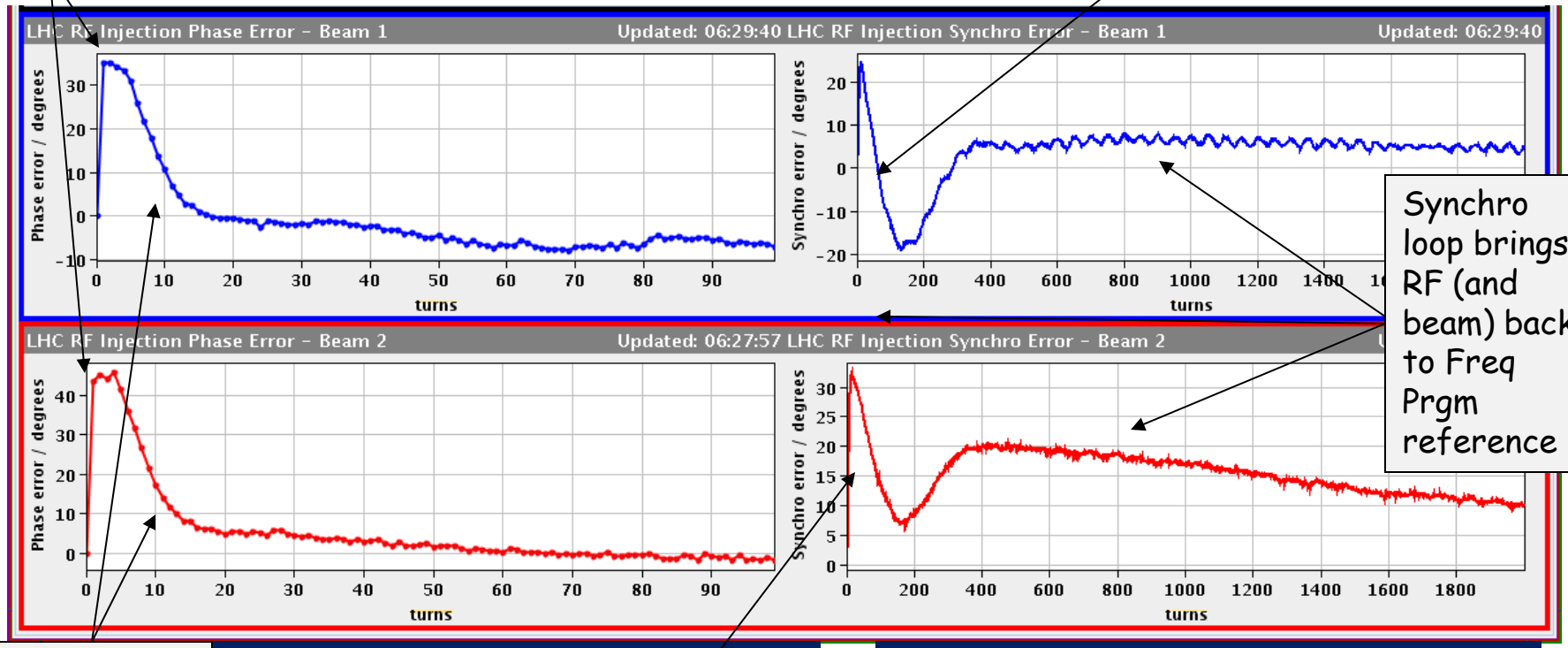
- This document describes the adjustment and boundary conditions for:
  - *The **RF injection phase**,*
  - *The **RF frequency**,*
  - *The **RF synchro error** (momentum matching SPS-LHC).*

LHC capture transients

Inj Phase Error 35 deg/45 deg

Phase loop is fast: "jumps" the RF on the beam at injection
Synchro loop is slow. No reaction in first 100 turns. Slope gives frequency (energy) error at injection

-30 deg in 60 turns -> -15 Hz @ 400 MHz
$\Delta p/p \sim 10^{-4}$



Synchro loop brings RF (and beam) back to Freq Prgm reference

Cavity field "jumps" on the beam in ~ 10 turns

Phase Loop Error: Beam PU-Cav Sum

Synchro Loop Error: VCXO-Freq Prgm

-15 deg in 80 turns -> -6 Hz @ 400 MHz

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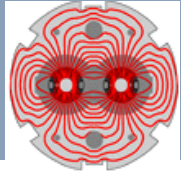
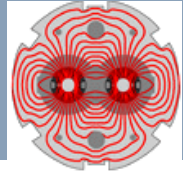
Capture ‘matching’



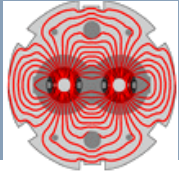
- The **RF phase loop** should be in phase with the incoming SPS beam. Large phase loop errors may lead to partial de-bunching (depending on the incoming bunch length…) or to the appearance of satellite bunches (at 2.5 ns).
- The **LHC RF frequency** should in principle be adjusted to ensure that radial position of the beams matches the reference orbit (that corresponds to a well centered orbit).
  - *Tides and long term circumference variations require adjustments of the RF frequency in a range of ±20 Hz.*
- The **LHC and SPS momenta should be matched**. If the momenta differ the synchro loop has to accelerate or decelerate the injected beam towards the LHC momentum (‘synchro loop error’). Large errors may lead to similar errors than injection phase errors.
  - *Matching is performed ideally side with the **horizontal orbit correctors**.*
  - *Or alternatively with the **RF frequency** if the errors are not too large.*

Ideal case



- The perfect situation:
  - *There is no **phase loop** error,*
  - *The **RF frequency** is set to have no radial orbit offset,*
  - *The momenta of LHC and SPS are perfectly matched and there is no **synchro loop error**.*

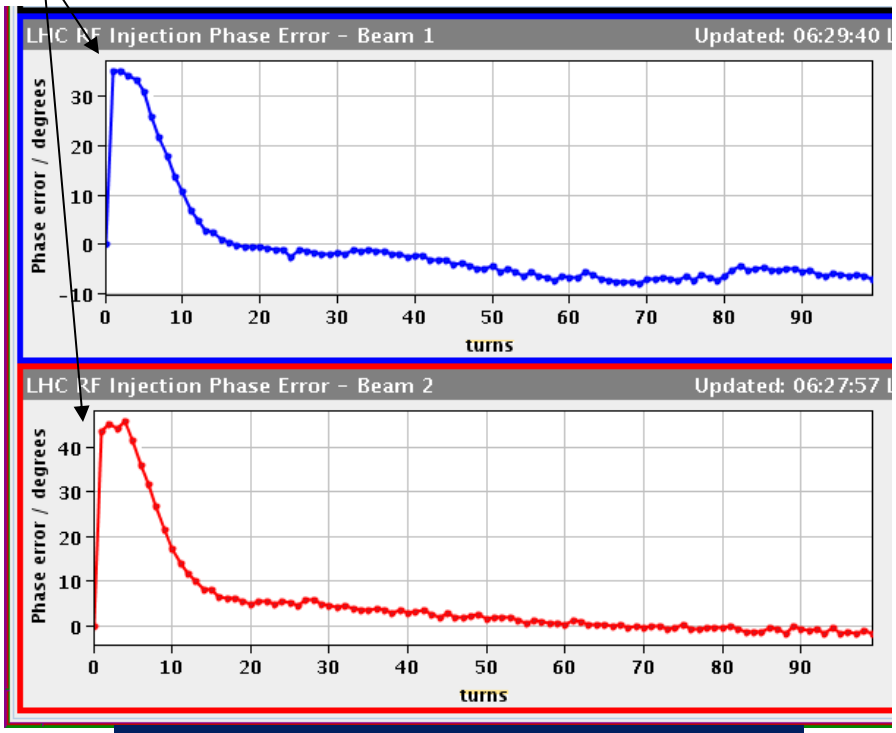
Compromise



- Since the energy matching with orbit correctors is more complicated, as an alternative it is possible to match the SPS and LHC energies with the LHC RF frequency.
- In that case one has to scarify the requirement of a radially centered orbit at injection. The orbit is offset to cancel (or reduce) the synchro error (another way to perform some form of energy matching for the closed orbit, but not the first turn).
  - *But then the closed orbit will not be centered → beam offsets in the off-momentum collimators.*
  - *During the ramp preparation, the RF trims should be taken out, or alternatively the radial FB will take care of the radial error.*
  - *If the synchro loop error exceeds XX degrees systematically in every fill, it is time to make a proper energy matching as described below.*

Step 1 – Injection phase error

Inj Phase Error 35 deg/45 deg



Phase Loop Error: Beam PU-Cav Sum

- Correction of the injection phase is done from a measurement on the first turn
- From the observation, we should correct the LSA setting by -35 degrees (B1) and -45 degrees (B2)
- The measurement averages over all bunches, that is the ones just injected and the circulating ones (if any). **It should be adjusted with the first pilot injection (no other circulating bunch) and checked/re-adjusted with the first batch injection (typically 12b in protons** – there will be a small unwanted contribution from the circulating pilot if we do not over inject)
- As filling proceeds, more bunches are circulating and the average reflects the injection transient less and less
- Adjustment of injection phase has no side-effect on other equipment. Should always be done

P. Baudrenghien

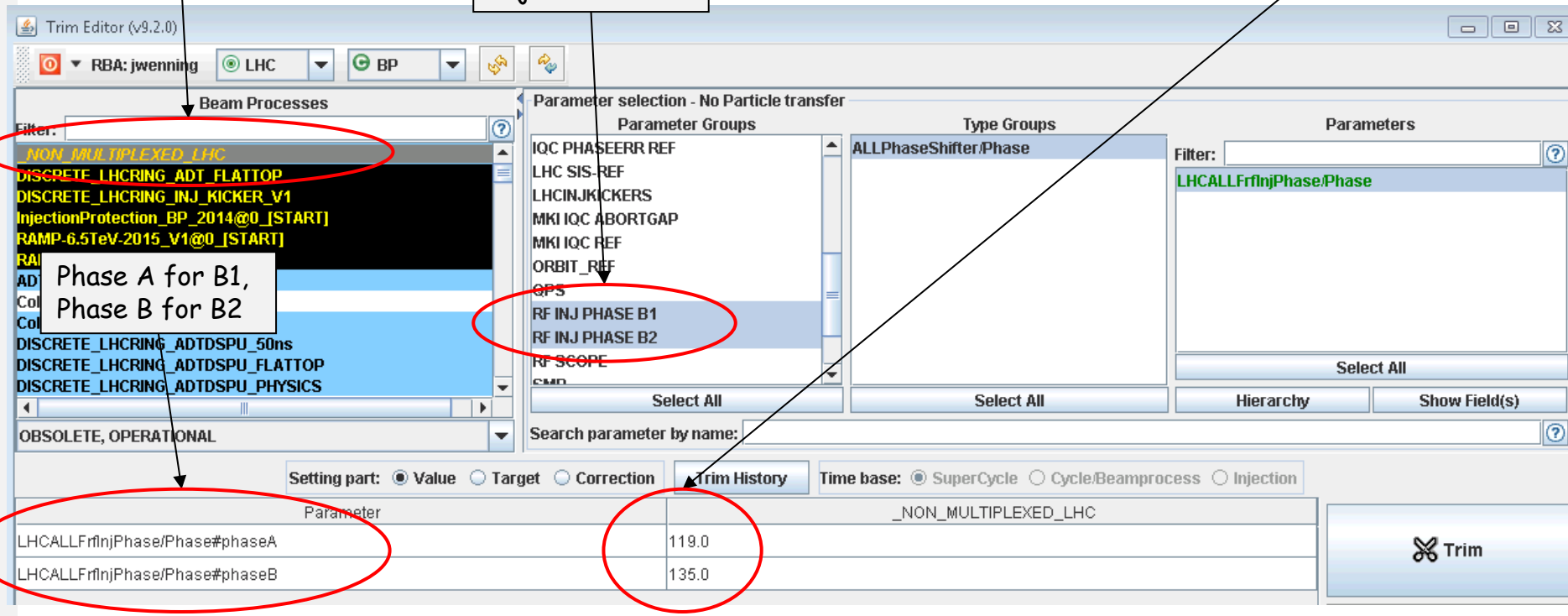
Step 1 – Injection phase error

- Correct the RF injection phase using TRIM on the non multiplexed LHC BP

NON_MULTIPLEXED

Injection Phase

If the measured phase error is **positive**, **increase** the LSA phase by the measured error (in degrees)



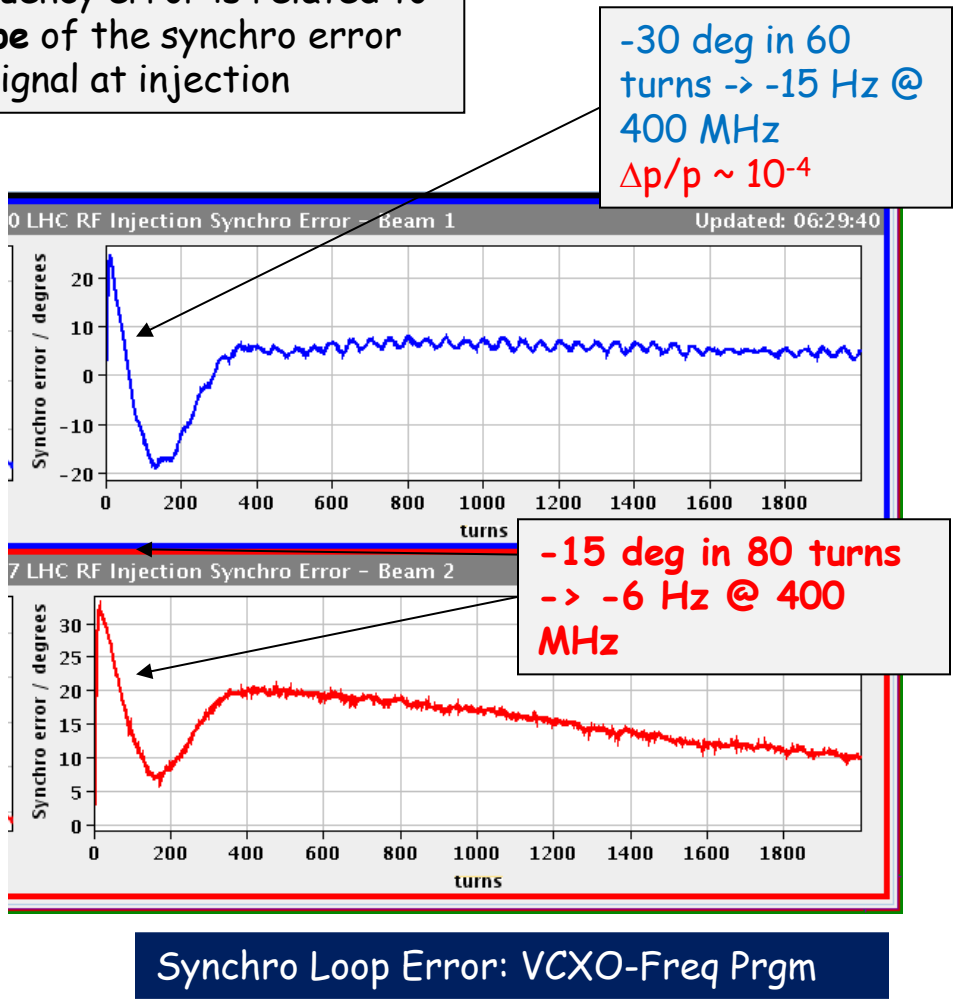
Step 2 - injection frequency / momentum

The frequency error is related to the **slope** of the synchro error signal at injection

- During the first ~50 turns after injection, the synchro error shows the phase slippage between the injected bunch(es) and the RF. The corresponding frequency error Δf can be deduced from the slope. Assume a phase slip $\Delta\phi$ (30 degrees) over N (60) turns, the frequency error is 15 Hz at 400 MHz

$$\Delta f = \frac{\Delta\varphi}{2\pi\, N\, T_{rev}}$$

- Caution: changing the injection frequency changes the orbit (after capture) and the SPS extraction momentum. It will require at least one SPS cycle for the rephasing to work



Synchro Loop Error: VCXO-Freq Prgm

P. Baudrenghien

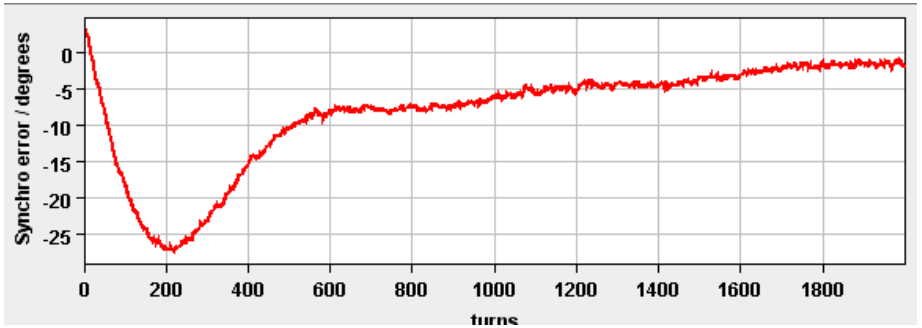
Adjustment example – 27th July 2010

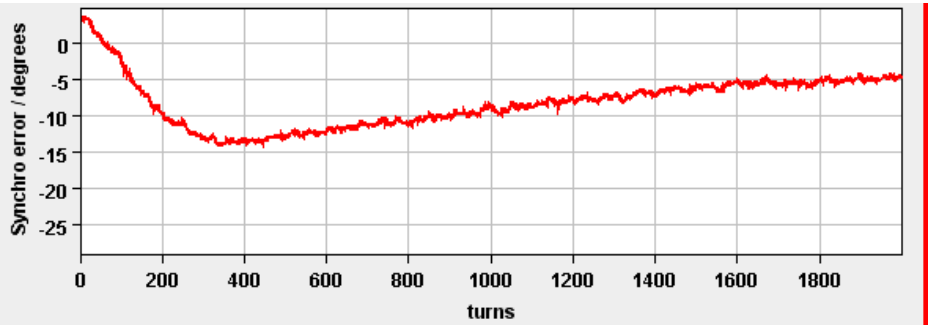
400.788863 MHz.
We measure a -20 degrees phase slip in 100 turns, or -6 Hz.
We add 10 Hz

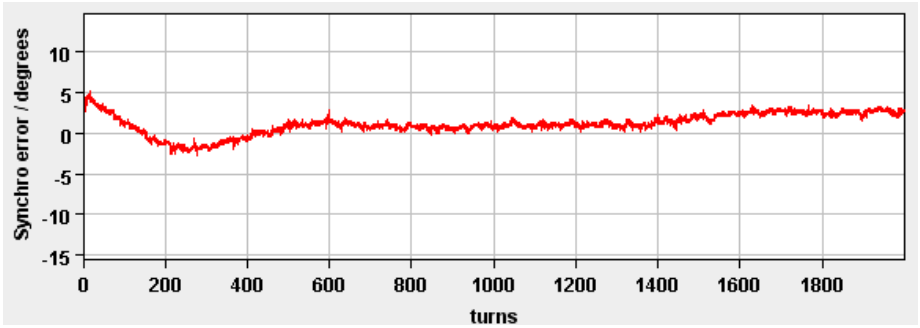
$$\Delta f = \frac{\Delta\varphi}{2\pi\ N\ T_{rev}}$$

400.788873 MHz.
We measure a -12 degrees phase slip in 200 turns, or -2 Hz.
We add 2 Hz

400.788875 MHz.
Good enough.
Frequency error below 1 Hz





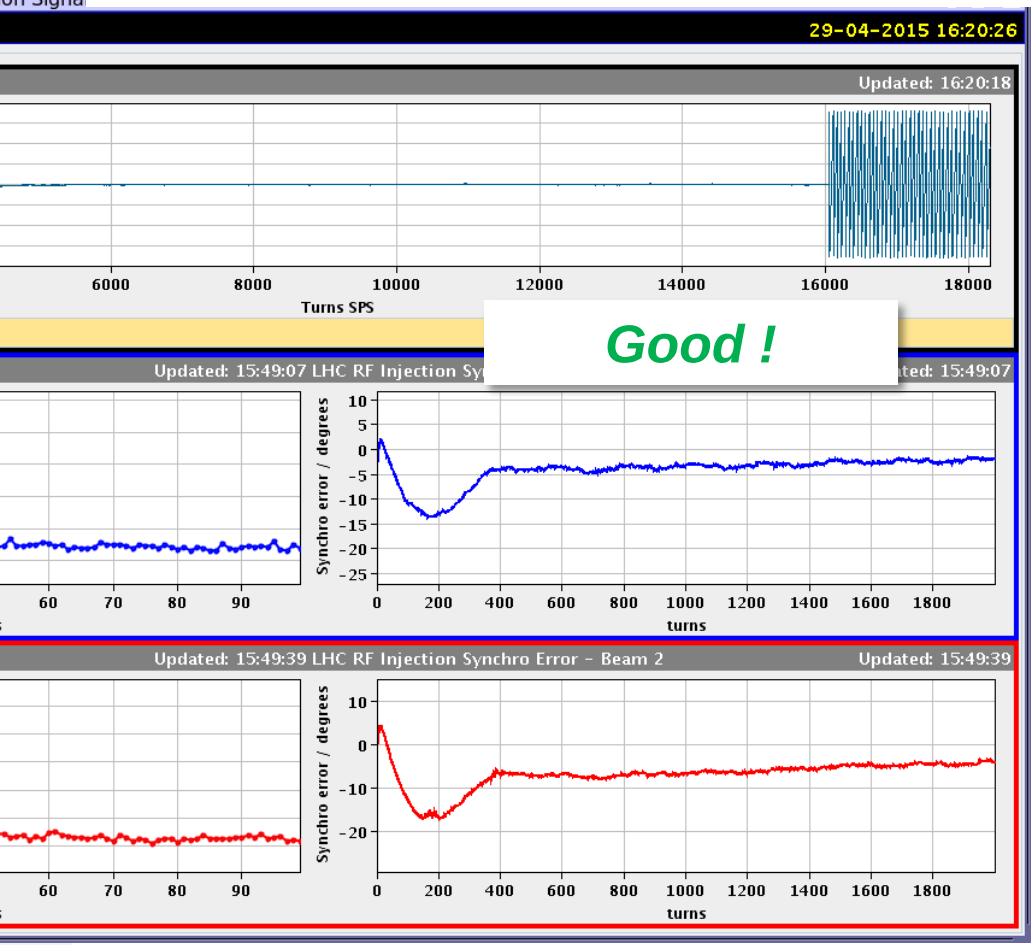


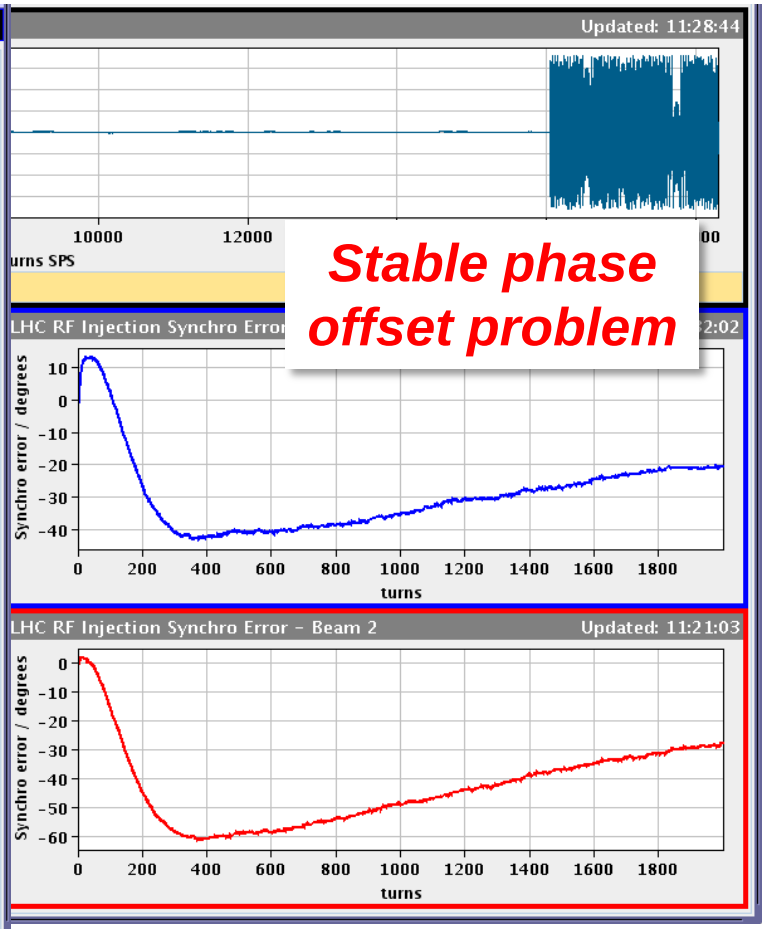
Synchro Loop Error: VCXO-Freq Prgm

- Note that the effect is always less than expected. This is explained by the change in revolution frequency caused by the change of momentum at SPS extraction, following the change of frequency, ≈10% correction.

Quality control

- The synchro loop error should show no or only a short transient (due to the momentum error of the injected beam) and then go back to 0.
- If the **synchro error drifts away** then there is a stable phase offset problem (electronics !) – call P. Baudrenghien et al. to fix the offset (first).





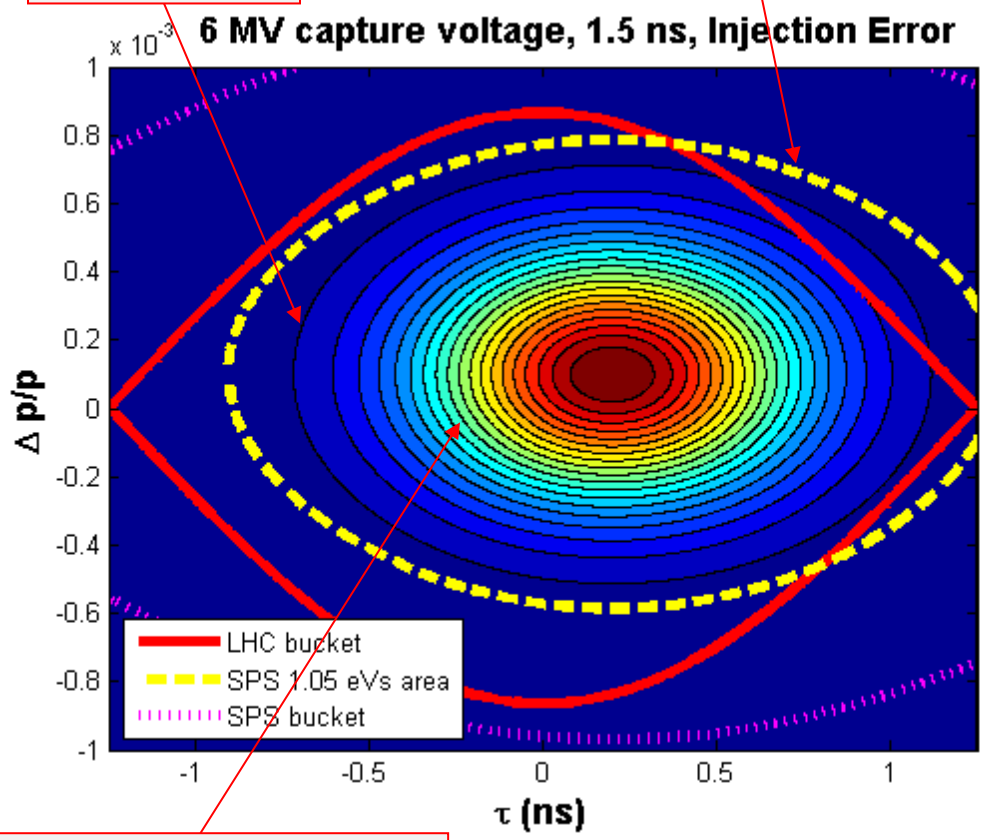
Capture losses

- Capture with 6 MV, in presence of 200 ps and **10^{-4} $\Delta p/p$ injection errors**

Losses:
2.47 % if the bunch distribution is Gaussian with infinite tails
0.6 % if the distribution is a Gaussian truncated by the 1.05 eVs contour

95% intensity contour

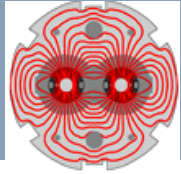
SPS scraping: contour at SPS extraction with same area as at the end of blow-up in the SPS ramp (1.05 eVs)



Contours correspond to steps of 5% in integrated intensity

Analysis by T. Mastoridis

Synchro loop and RF frequency

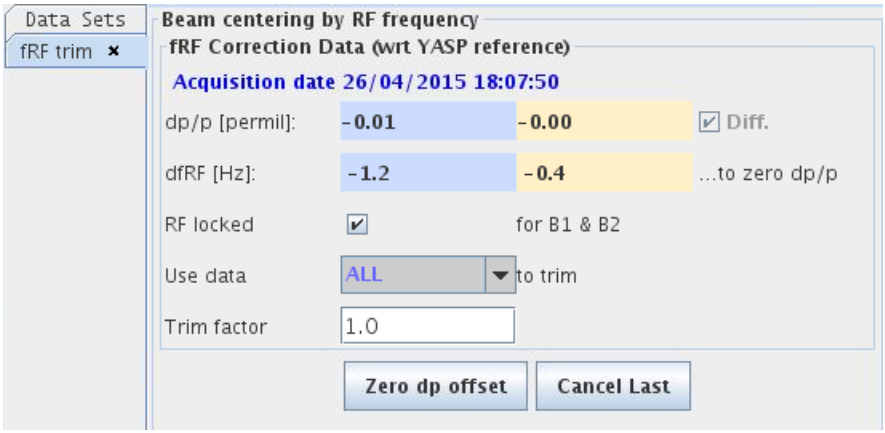


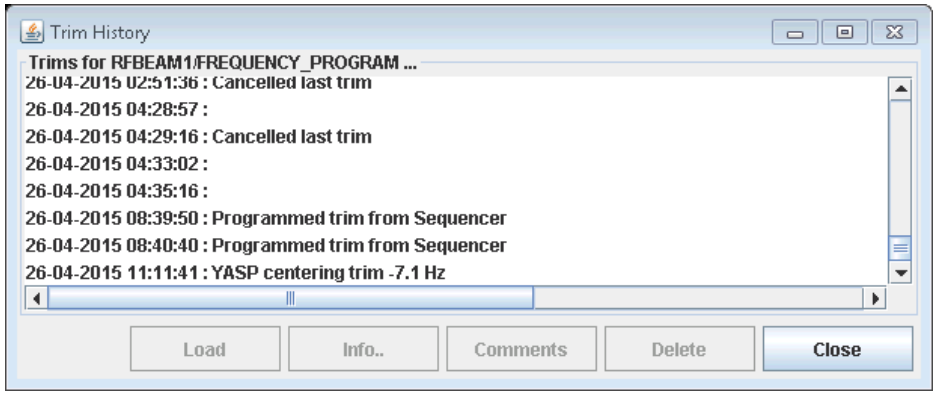
- Correction of the synchro loop error can be performed with the RF frequency up to an error of **XX** degrees.
- Beyond that value there is an increased risk of capture losses because more and more beam is injected outside the RF bucket.
- If the synchro loop error exceeds the limits regularly for all fills, it is time to apply the **energy matching procedure** that is described in the next slides.

E-matching Step 1 – RF frequency

- First center the beam radially wrt reference orbit.
- You can trim directly the RF frequency in the TRIM editor….
- …or you use YASP that will calculate the trim from the radial orbit offset.
  - menu ***Machine-Specials***, option ***Orbit centering / fRF***.

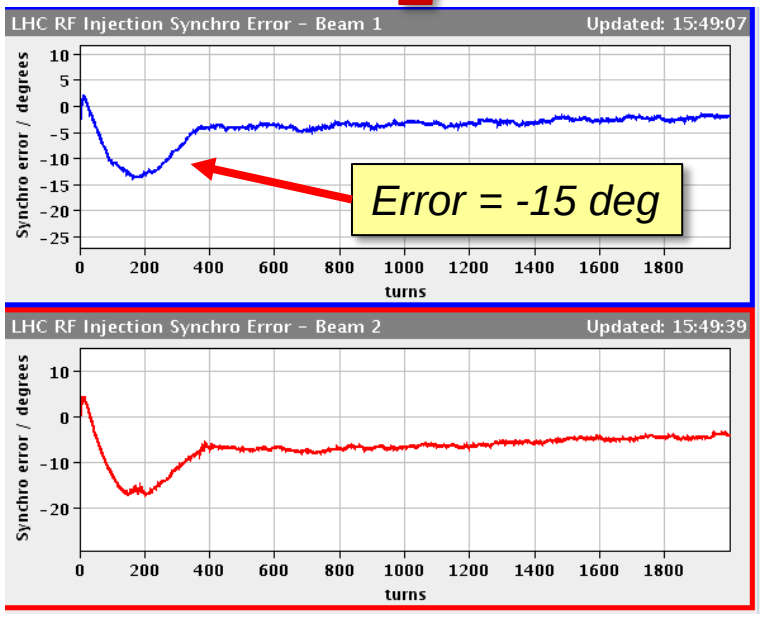
- Click on ***Zero dp offset*** to center the beam (it will trim f RF). The default settings should work well.
  - *You have the option of scaling the trim and of cancelling the last trim. The trims appear of course in the trim history of the RF frequency.*

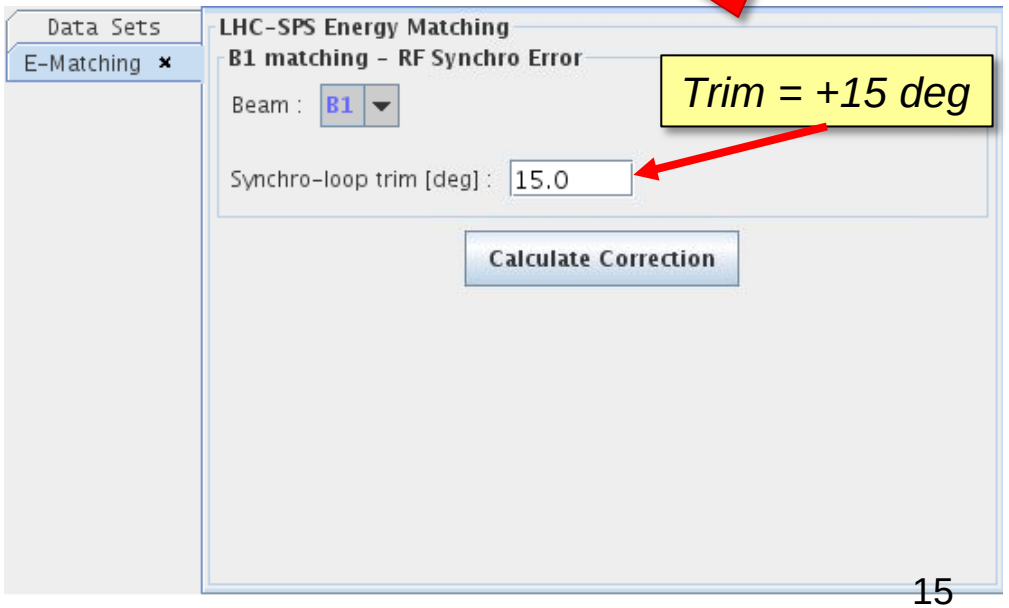




E-matching step 2 – Synchro loop error

- To correct the synchro loop error, we must match the **energy of SPS and LHC**. This can be done independently for each ring using the **mean deflection by the horizontal orbit correctors**.
- In YASP go to:
  - menu ***Machine-Specials***, option ***Energy matching/ synchro error***.
- Select the beam and enter the correction that must be applied to the synchro loop error.



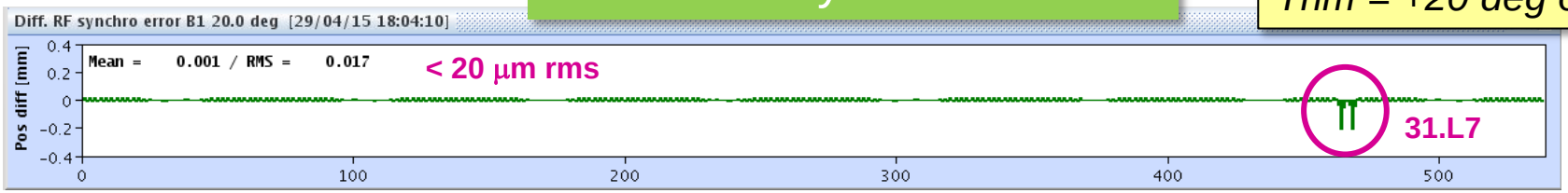


Synchro loop error - continued

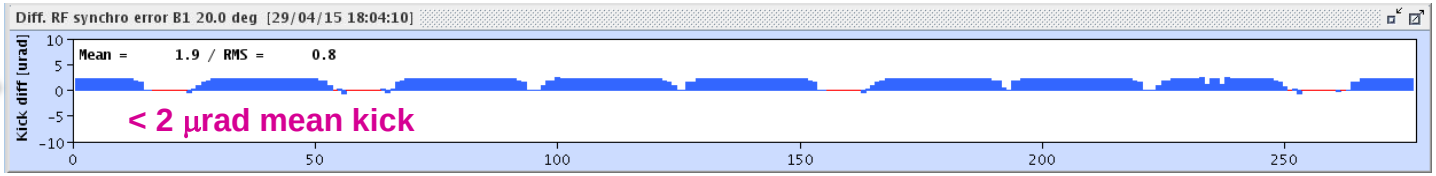
- The corrections induce very small (uncorrectable) orbit changes. On B1, due to a missing H cod in **cell 31 of sector 78**, an orbit bump will be introduced (or removed depending on sign, amplitude and initial orbit).
  - *This is '<u>normal</u>' !*

Note the very small scales !

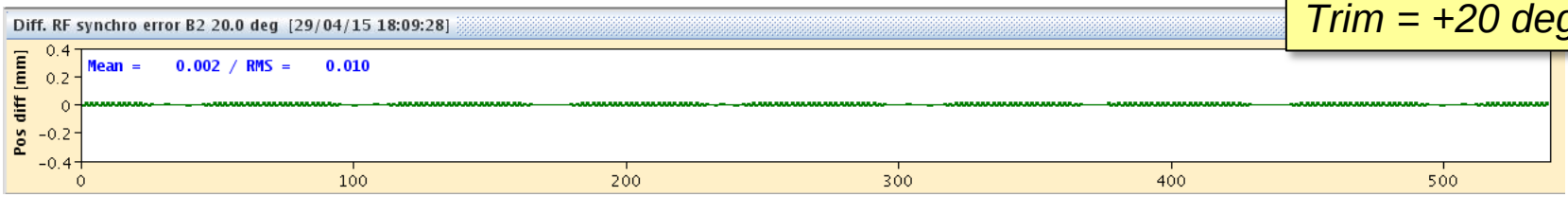
*Trim = +20 deg on **B1***



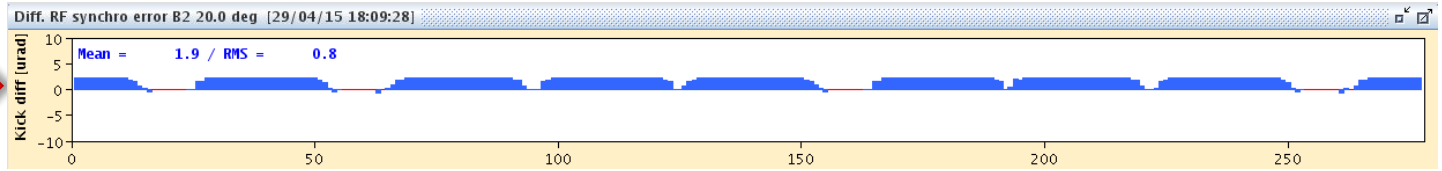
*Small mean shift of the **B1 H cods***



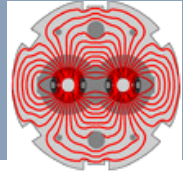
*Trim = +20 deg on **B2***



*Small mean shift of the **B2 H cods***

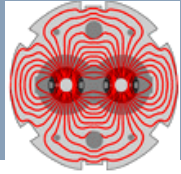


Parenthesis: side-effect of the trims



- The change in the horizontal correctors induces a change in energy.
  - *A trim of **+20 degrees** ⇔ **relative momentum change of -10^{-4}***
- As a side effect, such a trim will change the tunes through the natural chromaticity which is ≈ -100. This is the chromaticity you get when you switch off the lattice sextupoles.
  - *A trim of **+20 degrees** ⇒ **tune change of +0.01 in both planes.***
- As a consequence, when you rematch the energy / correct the synchro error:
  - *Be prepared for tune changes, positive trims can shift Qv into the third order resonance → correct in steps !*
  - *It is important to correctly **incorporate the trims** → see later.*

Synchro loop error - continued

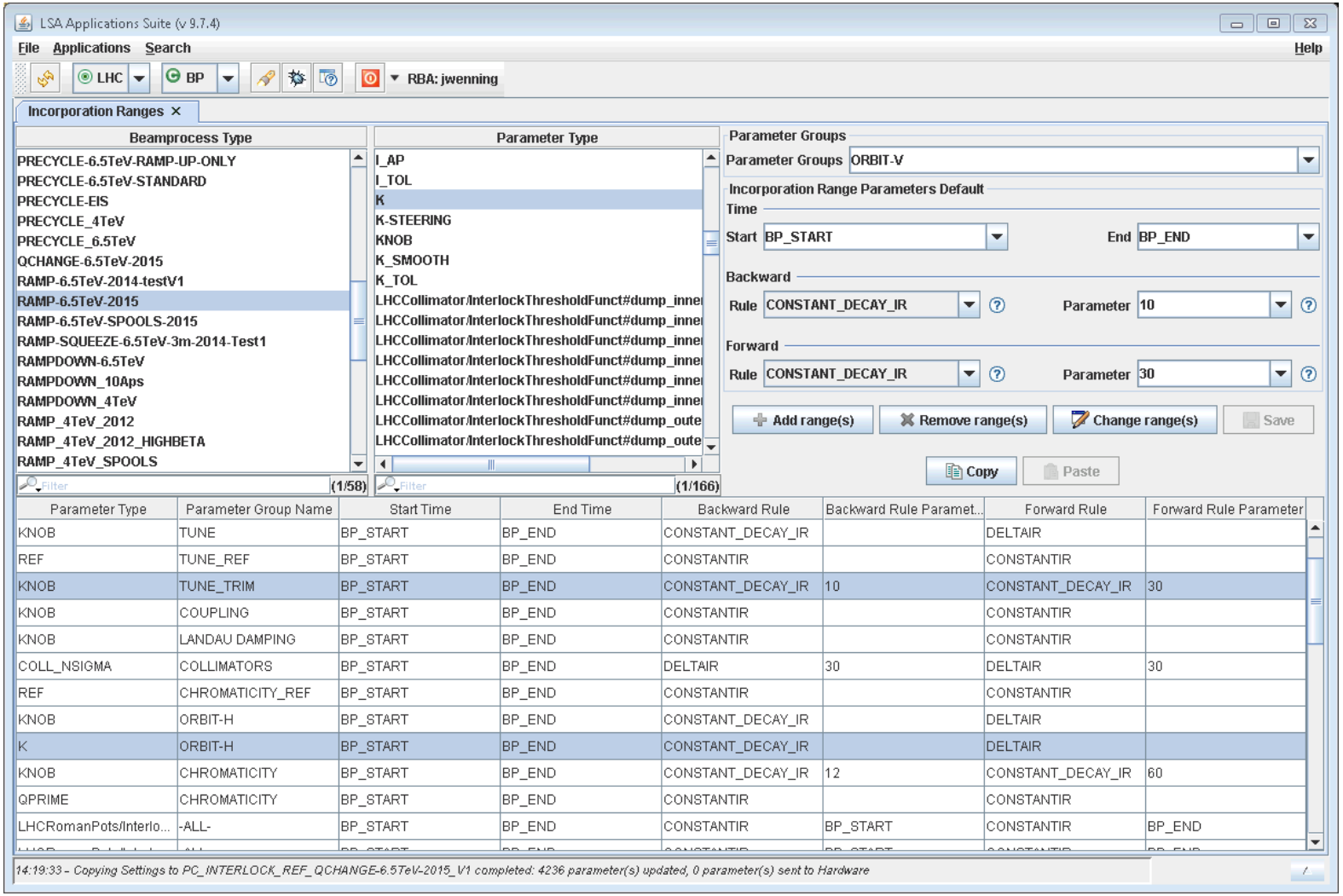


- When the correction is calculated for one of the beams, send the trim like any other correction.
- Dump and re-inject a fresh beam to check the correction.
- Correct the tunes.
- Iterate for both beams until you are satisfied / the synchro error is 0.

- The last step is now to **incorporate the trims into the ramp**. We have to make sure that the tune and energy matching orbit trims follow the same evolution in the ramp.
  - *We will take them out gradually in the very early part of the ramp.*

Momentum matching trim incorporation

- Open the **LSA Application Suite**, and in **Contexts** select **Incorporation ranges.**
- Select the ramp (RAMP-6.5TeV=2015).

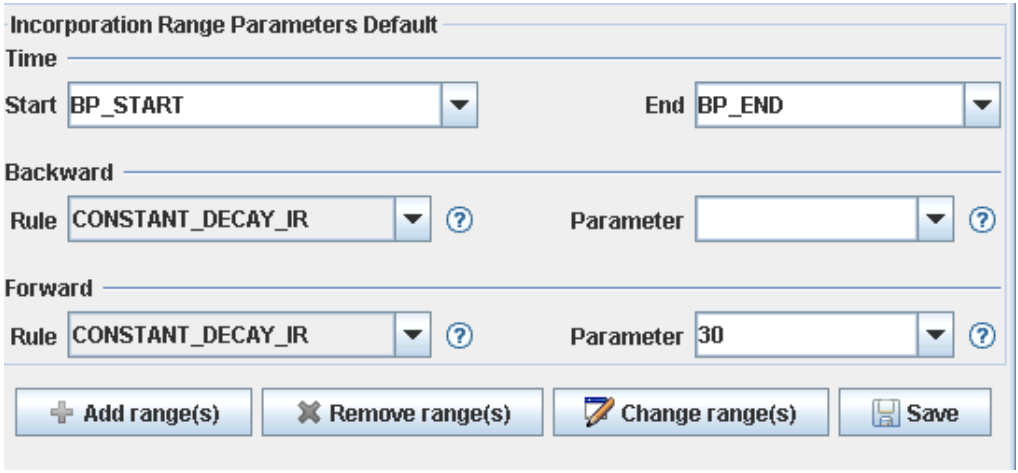


Momentum matching trim incorporation

- Default incorporation rules:

Parameter Type	Parameter Group N...	Start Time	End Time	Backward Rule	Backward Rule Par...	Forward Rule	Forward Rule Para
KNOB	TUNE_TRIM	BP_START	BP_END	CONSTANT_DECA...	10	CONSTANT_DECA...	30
K	ORBIT-H	BP_START	BP_END	CONSTANT_DECA...		DELTAIR	

- Change the **FORWARD** incorporation rules of **ORBIT-H** for **K** to match the one of the tunes.
  - *Select the line with **ORBIT-H** and **K**,*
  - *Change the **Forward** rule to **CONSTANT_DECAY_IR**,*
  - *Set **Parameter** to **30**,*
  - *Click on **Change range(s)**, the table should be updated,*
  - *Click on **Save**.*



Momentum matching trim incorporation

- Incorporate ORBIT-H and TUNE-TRIM.
- **Set back the ORBIT-H incorporation rule to its initial setting !**

Finished !!