THE LHC NOMINAL CYCLE, PRE-CYCLE AND VARIATIONS IN 2015

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Abstract

For beam operation in 2015 a number of changes and improvements are foreseen for the machine cycle. The FIDEL data must be corrected and updated. The different cycle phases will become longer and may require re-optimization. Proposals are made to improve the overall quality of the settings, to collide faster and to remove orbit spikes in the squeeze. Some issues related the collide and squeeze are briefly addressed.

FIDEL

The core of the FIDEL transfer functions (TFs) are already present in the LSA DB. Within the DB the transfer functions and field errors of each magnet or magnet family are modeled by a number of parameters. A dedicated application is used to build the tables of field or field gradient as a function of circuit current as they are used in the LSA trim. With respect to 4 TeV saturation becomes significant at 6.5 and 7 TeV. But the saturation corrections were always part of the FIDEL model, therefore no surprises are expected. Some changes must be made to correct errors in some TFs (for example the MQY magnets) while other TFs must be extended, for example the for triplet. The MB and MQ TFs must be updated to take into account the 18 magnets that were exchanged, even if the expected changes may be negligibly small.

Decay and Snapback

The decay and snapback amplitudes at injection will increase proportionally to the flat top energy, i.e. roughly by 50%, see Table 1. It should be possible to keep the faster PELP at start of ramp (2011 and 2012 ramps), no significant problems are expected. The decay on the flat top is expected to scale $\propto 1/E$.

Table 1: Decay amplitudes (at ∞) for the injection plateau.

Parameter	4 TeV	6.5 TeV
Tune	-0.022	-0.035
b3	0.4	0.5–0.6

The decay at injection and flat top as well as the snapback at the start of the ramp must be remeasured. The measurements will then be used to fit the b2 and b3 component amplitudes and time constants. No changes to the software must be made besides adapting to the new LSA API. The FIDEL server will be reused for the injection plateau. A separate ramp beam process will again be used for the spools to correct the decay at the flat top.

Pre-cycle

No pre-cycle was generated so far for 6.5 TeV, some work is required on the code and some LSA DB tables must be updated. The expected changes:

- The pre-cycle length increases by $\approx$ 1000 s (dominated by MQs), see Fig. 1. The total pre-cycle duration will be around 4000 s.
- The ramp-down duration increases by $\approx$ 500 s to a total duration of around 2600 s.

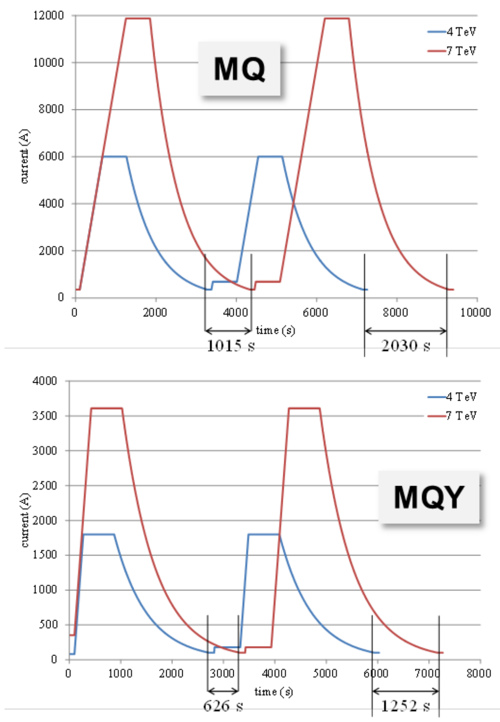

Figure 1: Pre-cycle functions for the MQ an MQY magnets that dominate the duration of the pre-cycle (courtesy N. Aquilina).

COLLISION CONFIGURATIONS

For 2015 we consider the following main collision configurations [1]:

- Low β^* in the range of 0.4 to 0.7 m.
- Medium β^* of 20 m (30-40 m for LHCb) for LHCf runs and vdM scans.
- High β^* of 90 m that will not be discussed here.

Both the medium and low β^* configurations must be prepared during the initial commissioning phase. The expected parameters for the configuration at injection, low and medium β^* are shown in Tables 2 to 4. The parameter θ corresponds to half the total external crossing angle. All numbers and plots presented refer to the classic optics used in 2012 (not the ATS-compatible optics). No significant difference is expected for the ATS-compatible optics. Up to a beam energy of 6.78 TeV there is no need to perform a pre-squeeze in IR2 and IR8 (triplet gradient limit). The injection optics can be scaled up. A combined ramp and squeeze is therefore not mandatory for 6.5 TeV.

Table 2: Injection configuration for 2015. In IR8 a parallel angle of 40 μrad must be added to the increased separation in the vertical plane.

IP	β^* (m)	θ (μrad)	Separation (mm)
1+5	11	± 170	± 2
2	10	± 170	± 2
8	10	– 170	± 3.5

Table 3: Low β^* configurations at 6.5 TeV.

IP	β^* (m)	θ (μrad)	Separation (mm)
1+5	0.65	± 170	± 0.55
1+5	0.4	± 155	± 0.55
2	10	± 120 (?)	± 0.55
8	10–3	– 250	± 0.55

Table 4: Medium β^* configuration at 6.5 TeV.

IP	β^* (m)	θ (μrad)	Separation (mm)
1+5	20	0	± 0.55
2	20	0 (?)	± 0.55
8	30–40	0 (?)	± 0.55

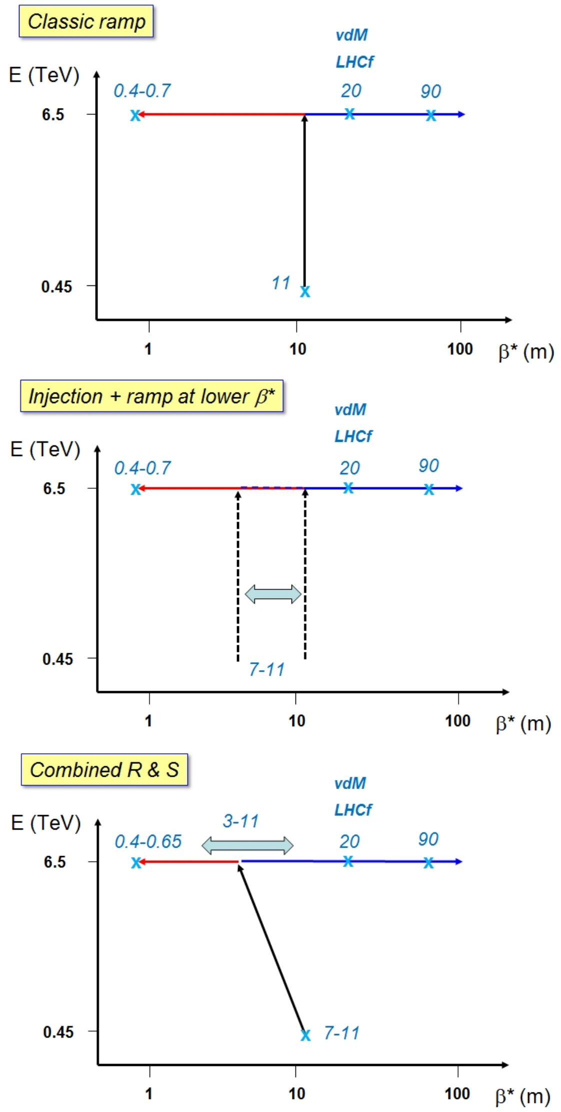

Figure 2: Three different possibilities for ramping and squeezing: classic 11 m injection and no optics change in the ramp (top), the same scenarios at lower injection β^* (middle) and finally the combined ramp and squeeze.

Combined Ramp and Squeeze

The duration of the ramp to 6.5 TeV will be 1200 seconds, which leaves of course ample time for potential optics changes. A combined ramp and squeeze beam process (R&S) may gain roughly 10 minutes during every LHC cycle with the reduced length of the squeeze, see Figure 2 for a comparison of different options for 2015. The design of the R&S and the generation of the settings are currently rather "clumsy" because the smoothing of the quadrupole gradients is not applied like in the squeeze, see Fig. 3. The distance between matched points (optics) must be tuned manually until the "kinks" in the functions become tolerable in terms of acceleration for the power converters. To operate seriously with R&S the smoothing that is performed for the squeeze design with parabolic segments must be extended to the ramp. One can probably use the same principle than for squeeze, and apply the energy ramping on top of it.

Proposal: proceed with standard ramp for the moment, but initiate development and testing of improved R&S software to be ready for future use.

Tunes

For the entire pre-LS1 period, the tune change from injection tunes (0.28/0.31) to collision tunes (0.31/0.32) was made at the start of the squeeze with the matching quadrupoles in IR1 and IR5. Proposal were made already during Run 1 to change the tunes at injection to collision tunes.

Options and possible evolution of the tunes in the cycles are indicated in Fig. 4. With the tune change decoupled from the squeeze, it is easier to evolve and change without impact

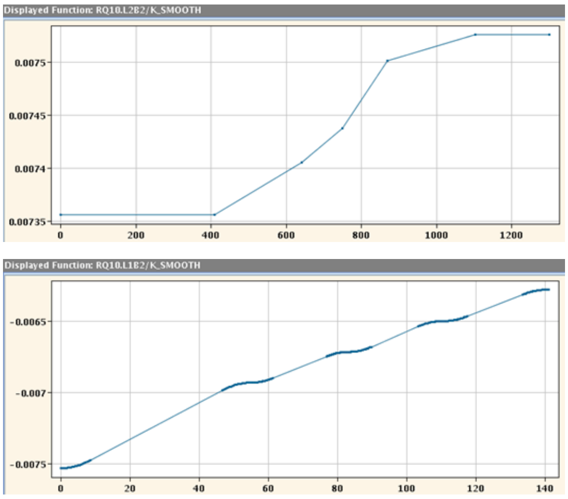

Figure 3: Evolution of the strength for the current ramp and squeeze (with kinks) and for the squeeze where the K's are smoothed (KSMOOTH functions).

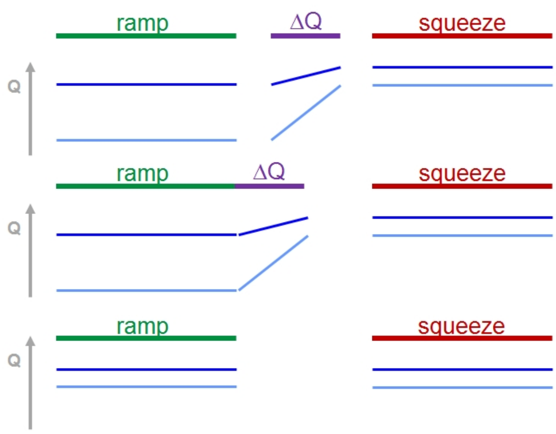

Figure 4: Possible scenarios for the evolution of the tune change between injection and collision tunes.

on the squeeze beam process. Furthermore the tune change should be made with the MQTs instead of the matching quadrupoles in 1+5: the change could be faster and it would lead to smaller orbit perturbations (strength change is more distributed). The induced beta-beating was simulated to be at the level of maximum 1%. This would be also ease switching from one tune working point to another: the tune is trimmed with the standard tune trim knob, and the optics id and name is updated (mainly for beam steering).

There are some practical reasons to use injection tunes instead of collision tunes at 450 GeV. They are mainly related to the tune signal quality and feedback performance. With collisions tunes the peak search windows are tighter and the peak search is more delicate, with a higher risk for the QFB to lock on wrong tune or switch off.

Proposal: start up with injection tunes at 450 GeV and review the choice at a later stage, decouple the tune change from squeeze, use the MQTs to apply tune change with respect to the collision tunes.

Squeeze

The lengths of the squeeze beam processes at 6.5 TeV for different values of β^* are given in Table 5 for the standard optics. Possible target β^* values are presented in Reference [2]. In all cases the tune change is not included and the initial β^* values are 10 and 11 m. The duration of the squeeze does not change much when the energy is changed from 4 to 6.5 TeV because the duration is determined by the circuits (Q4, Q5 and Q6) that ramp down and where the length is dominated by the decay time constant of the circuit.

Table 5: Squeeze durations at 6.5 TeV.

Type	Energy (TeV)	Target β^* (m)	Duration (s)
2012	4	0.6	906
Squeeze 1+5	6.5	0.6	955
Squeeze 1+5	6.5	0.4	1154
De-squeeze 1+5	6.5	19	453
De-squeeze 1+5	6.5	40	1138
De-squeeze 1+5	6.5	90	2415

BUMPS

There are larger bump shape (separation and crossing angle) changes during the squeeze in IR8 and IR2 than in IR1 and IR5, see Figures 5 and 6. This is due to the injection constraints where the bumps should be closed before the injection point and where the phase advance is constrained for the injection optics. In addition the matched points at the start of the squeeze were too coarsely selected for the IR2 an IR8 bumps: the squeeze was over-optimized with respect to tune and chromaticity without taking sufficiently into account the orbit effects.

Recommendation for the low β^* squeeze: one matched point should be added for IR8 between 10 m and 7.5 m, and another one between 7.5 m and 6 m to smoothen the evolution of the orbit and bumps.

For the ATS-compatible optics a complete analysis and optimization must be performed for tune, chromaticity and orbit once the squeeze becomes available.

Orbit Trim Incorporation

A probable origin of (some of) the orbit spikes near matched points observed in 2012 is the different smoothing methods for orbit correctors [3]. The correctors that were part of the separation and crossing bumps, as well as the MCBX, were incorporated between matched points using the parabolic rounding like for example all the quadrupoles (Fig. 3). All other correctors use a PLP method that did not follow the same shape, but allowed them to be trimmed at any point of the squeeze, even outside matched points. After LS1 all orbit correctors will be smoothed in the squeeze with

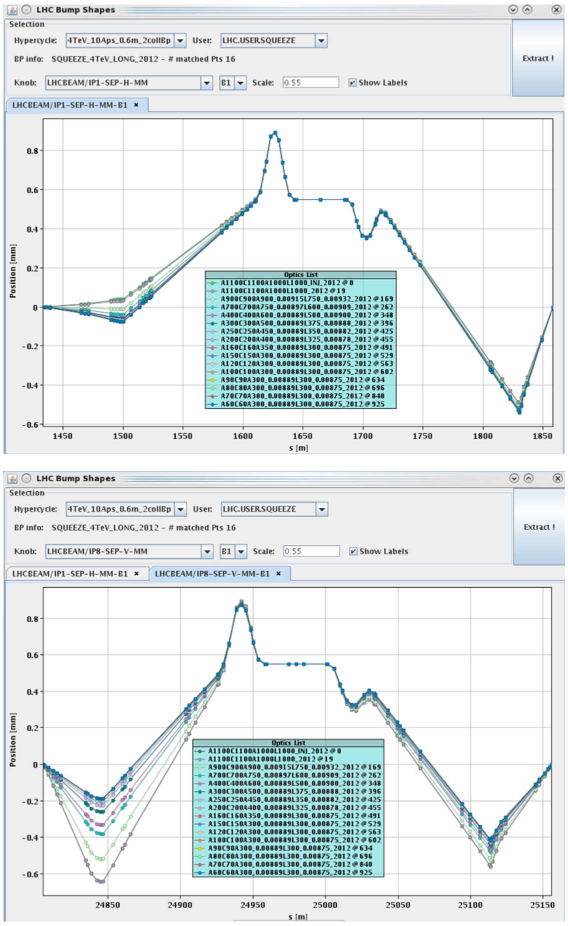

Figure 5: Evolution of the separation bump shapes during the 2012 squeeze in IR1 (top) and IR8 (bottom).

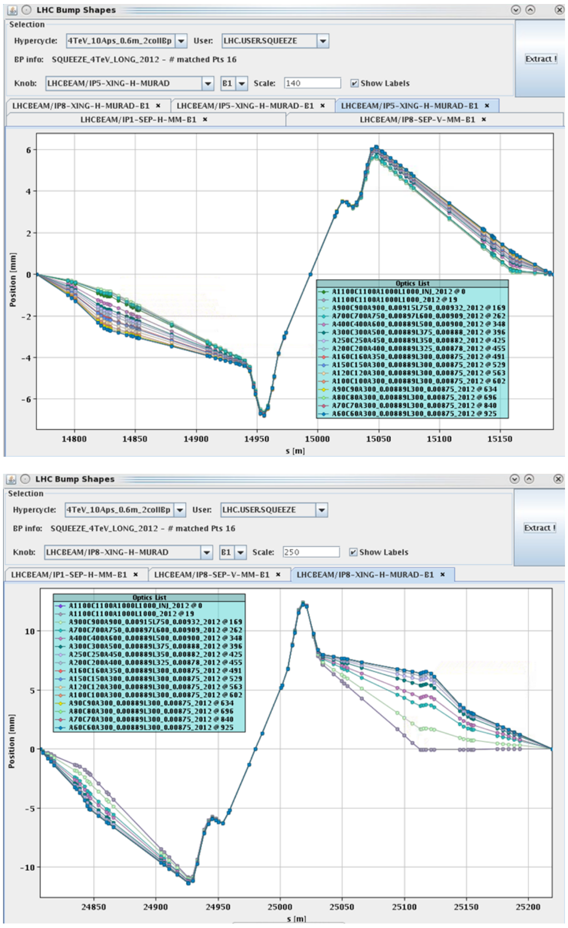

Figure 6: Evolution of the crossing bump shapes during the 2012 squeeze in IR5 (top) and IR8 (bottom).

parabolic rounding. The feed-forward of the real-time trims from the OFB will be applied as correction at the level of the KSMOOTH functions. This will hopefully remove the orbit spikes at the matched points.

COLLISION BEAM PROCESS

Since no problem was ever observed in the past during the IR1/5 separation bump collapse, one can continue to collapse IR1 and IR5 separation bumps together. Since the value of the separation knob is not a "static" part of the optics (it can be adjusted), the design of the collision beam process depends on its target value (and the required margin). For this reason the length of the parabolic sections at both ends and of the linear part are set manually. The required beam process length is adjusted by trial and error (and with time also some experience). Due to lack of diagnostics software, it was difficult so far to judge the efficiency of the collision beam process design. A new application that analyses all orbit corrections functions at the level of current I, ramp rate dI/dt and acceleration provides now diagnostics for the optimization of beam process parameters. An example for the analysis of the 2012 collision beam process is shown in Fig. 7: in that case it is apparent that the acceleration is very low, less than 0.1 A/s^2, while the maximum acceleration of the circuit is 0.2 A/s^2. The parabolic segments of the beam process were longer than necessary, slowing down the collapse in the critical part when the separation is close to zero.

With the new application it is easy to optimize the beam process. As an example a collision beam process was designed for 6.5 TeV and a β^* of 0.5 m, where the ramp rate in the linear part was pushed to 90% of the maximum rate of the orbit correctors at Q4 and Q5 (those limit the ramp in the linear part), while at the same time the acceleration of the RCBX that is limiting the parabolic segment is also pushed to 90% of its limit. Figure 8 gives the evolution of the separation for that beam process.

As an additional improvement the parabolic part could be shortened further if the kick strength that is currently using a single RCBX would be spread over 2 or 3 MCBX instead of just one magnet. Another gain may come from the powering tests where the acceleration rates will be pushed towards 0.5-1 A/s^2 design values.

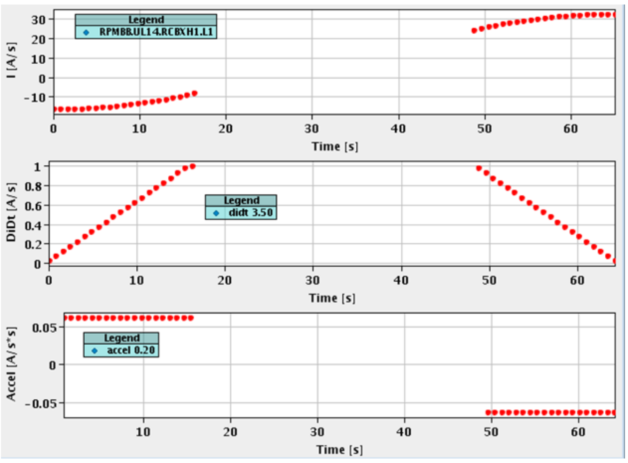

Figure 7: Evolution of the current I (top), the ramp rate dI/dt (middle) and acceleration (bottom) for the RCBXH1.L1 circuit during the 2012 collision beam process. The acceleration is only 0.06 A/s^2 for a limit of 0.2 A/s^2.

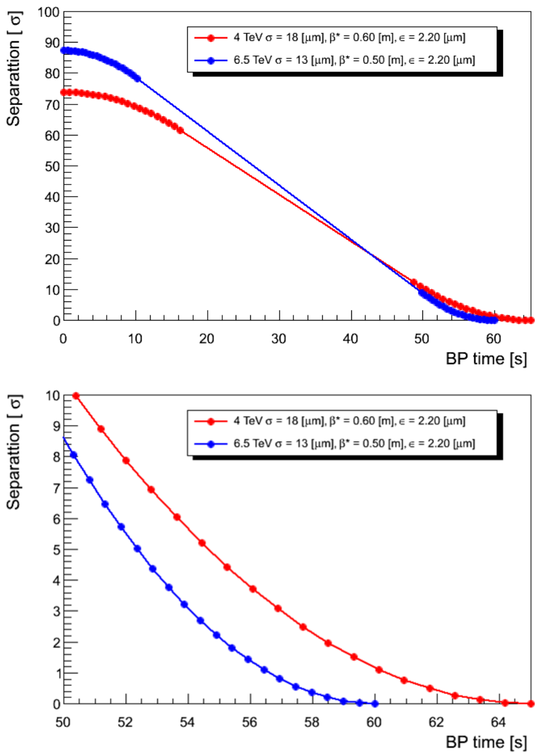

Figure 8: Evolution of the separation in IR1/5 for the optimized collision beam process at 6.5 TeV and the 4 TeV collision beam process used in 2012. The bottom figure is a zoom in the last part of the collapse. Despite the higher energy the 6.5 TeV beam process is shorter, and the collapse in the last parts where the beams approach each other is much faster.

ALICE

Due to the very low target luminosity of ALICE, see Fig. 9, offset leveling must be applied in IR2. The luminosity in ALICE is plotted as a function of the total separation of the two beams at 6.5 TeV for bunch populations of 1.2×10^{11}, β^* of 10 m and emittances of 2 μm and 3.5 μm. The corresponding beam sizes are 54 μm and 71 μm. A separation between 4 and 6 σ will be required, implying that the ALICE luminosity may become very sensitive to tails. It cannot be excluded that the luminosity will exhibits large fluctuations, in fact the luminosity may become an excellent tail diagnostics in the separation plane (i.e. horizontal).

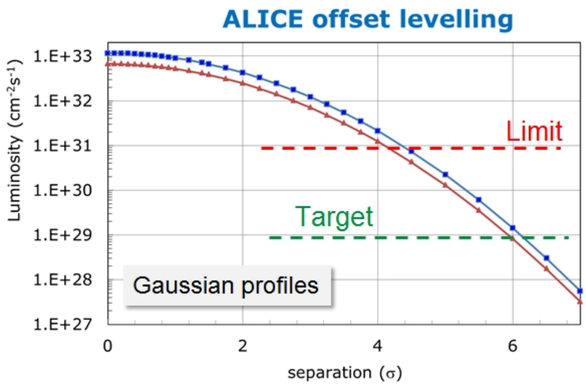

Figure 9: ALICE luminosity as a function of the total beam separation expressed in units of beam size.

Collide and Squeeze

In case the beam have to collide during the squeeze in IR1 an IR5 too ensure beam stability (C&S) [4], there are two options to handle the segment where the separation is collapsed. Either the beam collide at constant β^* and optics (Fig. 10 top) or the squeezes continues in parallel to collapsing the separation bumps (Fig. 10 bottom). For setup and regular (fill-by-fill) checks it must be possible to perform stops along the C&S at key points: before going into collision, at the first point where collisions are established, at the end of the squeeze and after colliding all IPs (yellow points in Fig. 10). In addition it must be possible to stop at intermediate points (pink points in Fig. 10) to establish collisions during commissioning and to re-establish collisions in case the beams no longer collide at a certain moment.

If the beam process is cut into 4 segments, the regular stops can be taken care of. The current implementation of the collimator interlock function does not allow intermediate stops due to the digital signatures associated with MCS. Either one has to split the squeeze into many short beam processes which makes the process rather clumsy, or one will have to revisit the collimator interlock function management (and / or MCS).

Another complexity of the C&S: head-on collisions will probably make life of the tune peak finder for the tune feedback even more difficult, unless non-colliding bunches are

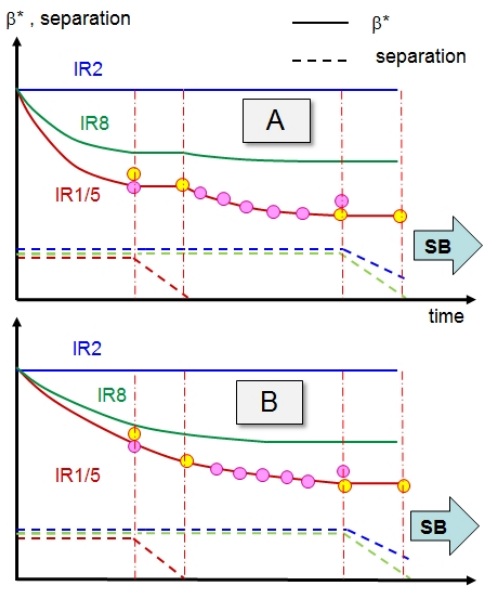

Figure 10: Possible design of a C&S where the squeeze is either stopped (top) or continued (bottom) while the separation is collapsed to bring the beams into collision. Stops points that are required for every fill are indicated in yellow, occasional stop points in pink (fixing the beam process, re-establish clean collisions).

maintained. As a feed-down effect it may also be more complicated to measure chromaticity since the quality depends directly on the tune measurements.

It is clear that an operational C&S requires more design work on the controls (MCS functions) side.

SOFTWARE

The settings generation and FIDEL software will receive some face-lifting. In order to easily switch configurations between pure squeeze, C&S, R&S etc, the setting copy tools must be improved to merge two beam processes, split one beam process into two, lengthen or shorten a beam process.

For the C&S work must be done for the collimator functions / MCS. To enhance the flexibility for switching β^* combinations, it is recommended to maintain corrections (optics, orbit) as local as possible in the future. During commissioning of the squeeze, orbit correctors in the arcs and in IRs that are not squeezed will be de-activated for the OFB and the manual steering. It is recommended to split beta-beating corrections in a similar way, at least as far as reasonably possible.

SUMMARY

First predictions for the length of pre-cycle and of standard beam processes within the operation cycle were presented. The cycle was analysed in view of past issues (orbit stability) and future improvements (C&S, R&S). Recommendations for changes and improvements were presented.

REFERENCES

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