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LHC MD2148

TELESCOPIC FLAT OPTICS WITH PILOTS & 3E11

Abstract

This note summarises the key objectives of the first 2018 flat optics ATS MDs (MD 2148) which are scheduled to take place at the next MD block (2 shifts in MD1-2018). The target of the overall 2018 program is to demonstrate the feasibility of flat telescopic collision optics, as a possible option for operating the LHC in Run III, and as a back-up machine configuration for the HL-LHC (so-called HL-LHC Plan B with flat optics and wires for long-range beam-beam compensation). This note includes a description of the MD readiness, in terms of optics development and implementation in LSA, and contains the procedures to be followed up, which are two-fold for MD1, namely: (i) optics measurement and correction with probes in the first shift, then (ii) aperture measurement, loss maps and collision with setup beams (3E11 at most) for the second shift.

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History of Changes

Rev. No.	***Date***	***Pages***	***Description of Changes***
0.1	27-May-2018	All	First draft
0.2	30-May-217	All	Add aperture measurement at 65 cm in the first shift/second fill (as the IT aperture is still unexplored with the crossing bump rotated). IT Aperture estimated with 5% beta-beating instead of 10% [11]. New name for the Q-jump BP

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1. INTRODUCTION AND MOTIVATIONS

The Achromatic Telescopic Squeezing (ATS) scheme [1] offers new techniques to deliver unprecedentedly small beam spot size at the interraction points of the ATLAS and CMS experiments (β^*), while perfectly controlling the chromatic properties of the corresponding optics (linear and non-linear chromaticity, off–momentum beta-beating, spurious dispersion from X-angle). This scheme is a keystone of the HL-LHC project which heavily relies on a β^* as small as 10-15 cm at IP1 and IP5, while offering a wide number of other possibilities both for LHC and HL-LHC, in particular the feasibility of flat optics, with the same chromatic properties as above, while reaching even smaller β^* values in the plane perpendicular to the crossing plane (7.5-10 cm). Concerning the LHC, when reaching machine parameter sets (beta*, crossing angle, and bunch length) corresponding a Piwinsky angle in the viccinity of 1, the optimal performance of the machine is no longer obtained with round optics, i.e. with the same beta* in the two transverse planes. The same consideration applies to the HL-LHC, assuming strong limitations in the crab-cavities or no crab-cavity at all, in which case the only way to stick to the targeted performance is to rely on flat optics complemented with long-range beam-beam compensation techniques (so-called HL-LHC Plan B [2]). Flat optics however present a certain number of challenges related to optics and coupling correct-ability, different topology for the head-on beam-beam tune spread, and only partial compensation of the long-range beam-beam tune shift and tune spread between the two high-luminosity insertions. On the other hand, such configuration is in principle directly "testable" in the LHC, both the optics per say, and using the telescopic arc optics and Landau octupoles in order to mitigate the long-range beam-beam effect (see also MD2269 which demonstared this technique with round telescopic optics [3]).

2. OVERALL OBJECTIVE AND DESCRIPTION OF THE HYPERCYCLE

2.1 OVERALL OBJECTIVES

A huge effort for optics development [4] and implementation [5,6] was deployed at the end of 2017 in order to boostrap the activity, and enable first low-intensity tests with flat optics already in MD-block4 of last year. The same optics set will be used this year, but with slight modifications brought to the hypercycle, in particular recycling the nominal ramp (updated in 2018), and populating the beam processes with new dedicated TCT functions at flat top energy [7]. The corresponding hypercycle is described in the next sections, together with the different beam processes (BP) involved, described in terms optics, various gymnastics, and knob pre-setting strategy.

First of all, the overall template of the program for MD1 is introduced hereafter (and the detailed sequence of activities with time estimate reported in the end of this note). Two shifts of 10 h (+2h for ramp down) are foreseen for flat ATS optics related activities in block 1, the first one scheduled towards the beginning, and the second towards the end the block. Operating with probe beams ($<10^{10}$ p/b) for the first shift and with setup beams ($<3\times10^{11}$ p/b) for the second shift, the aim is two-fold:

1. **First shift (probes)** for OP mechanics demonstration and optics measurement and correction of flat optics with β^*=60 cm in the crossing plane (which is rotated vs. nominal configuration, see later), and β^*=15 cm in the parallel separation plane (V in ATLAS and H in CMS, see later). If time permits, a second fill with probes will be played, with the crossing angle kept ON over the full cycle, in order to (i) validate the triplet aperture at 65 cm (a situation still unexplored with the crossing bumps rotated), and (ii) prepare the second shift, in particular for the validation of the optics correction knobs, and to define pre-settings for the new TCT functions. In case of time limitation, this second fill will

take place at the beginning of the second shift (see below), and the second fill of the second shift (validation fill @ 3E11) will be postponed to MD2.

2. **Second shift:**
   a. **Setup fill (two nominal bunches + 6-8 probes)** for (i) TCT alignments (and possibly first loss maps) in the end of the ramp (after crossing bump rotation) at β^*=1 m (150 μrad), in the end of the pre-squeeze at β^*=65 cm (130 μrad), in the end of the squeeze at β^*=60/15 cm (130 μrad), and in collision, (ii) for establishing and optimizing the collisions at the 4 IPs, (iii) for aperture measurement in collision, and (iv) if times permits, for off-momentum loss maps before dump.
   b. **Validation fill (two nominal bunches + 8-10 probes)** for (i) loss maps with final TCT functions, after the crossing bump rotation at β^*=1 m, in the end of the pre-squeeze at β^*=65 cm, in the end of the squeeze and in collision, (ii) asynchronous dump test (with TCTs at 8.0 σ).

The global objective is to obtain the necessary results for approving an intensity ramp up as of MD block2, aiming at one nominal train of 72 (or 48) bunches per beam (with possibly some left over activities if time would be found to be too short to complete all the above activities in block1).

2.2 RAMP AND SQUEEZE

The nominal 2018 injection optics, and combined ramp and squeezed are re-used via a clone of the corresponding nominal beam process (**RAMP_PELP-SQUEEZE-6.5TeV-ATS-1m-2018_V3_V1_TELE-ATSFlat** [6]). The betatron tunes are 62.275/60.295, the collimators and machine protection devices have nominal settings, and the octupoles are ON in order to avoid any instabilities (even with probes). Some minor modifications have nonetheless been introduced in these clones, where only a subset of the available OMC knobs [8] which will be kept, namely: the knobs related to the global correction of the injection optics, which are vanishing at the end of the ramp (**B1_ATS_2016_injection_globcorr** and **B2_ATS_2016_injection_globcorr**), and some of the knobs related to the local correction of the inner triplet, for beta-beating (**2017_ATS_LocalCorrection**), coupling (**2017_ATS_Inj_LocalCoupling**), and octupolar imperfections (**2017_IRNL_b4**).

2.3 GYMNASTICS AT FLAT TOP

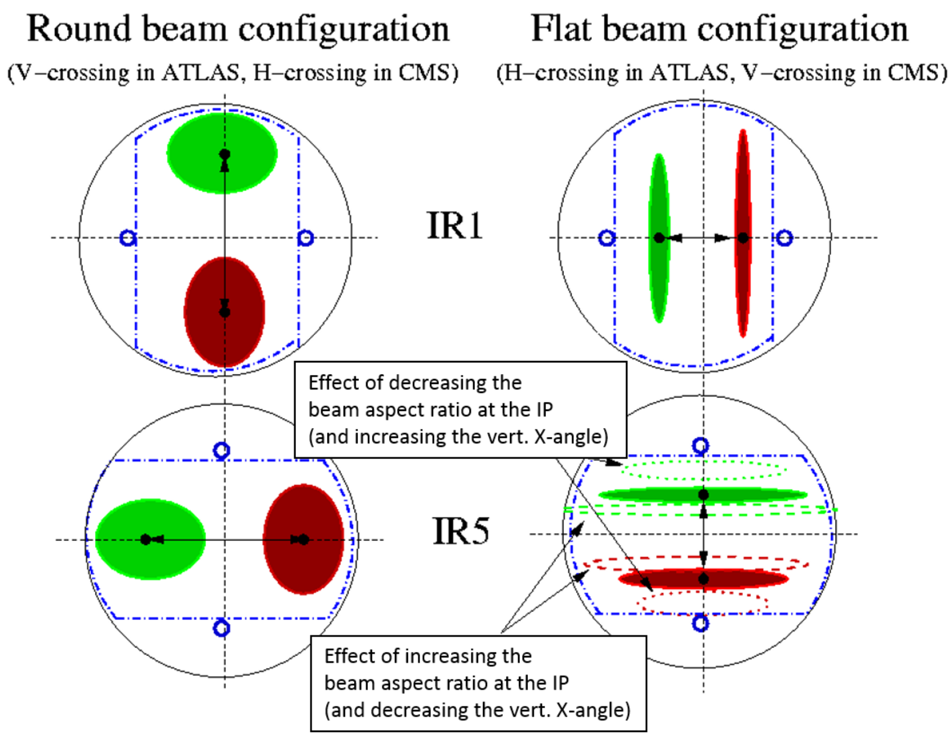
Arriving at flat-top energy (β^*=1 m at IP1 and IP5), the collimator are planned to be sent to coarse settings (see later), and the octupoles switched off, but only for the first fill(s) with probes, otherwise **this specific action will no longer be taken when the full cycle will have been validated with probe beams** (see later). Then the following two beam processes will be played in sequence:

(i) **TELE-ATS_knobs-2017_V1_ATSFlat** [5, 6], which exchanges the standard correction knobs with the so-called TELE knobs, for tune, coupling, and chromaticity, while shifting the betatron tunes from 62.275/60.295 (operational injection tunes) to 62.28/60.31 (design report injection tunes). The duration of this beam process is 210 seconds.

(ii) **BUMPS-INVERSION-2018_V1** [6], which reduces the crossing angle in IR1 and IR5 from 160 μrad (2018 end of ramp value) down to 150 μrad, and then rotates the crossing and parallel separation planes in ATLAS and CMS, at nearly constant radial crossing angle (150 μrad) and parallel separation (0.55 mm). The objective of this BP is to pass from the nominal V/H crossing configuration in IR1/5, to a H/V crossing configuration. During this process, the crossing planes in ATLAS and CMS are always kept perpendicular to each other, in order to maximize some long-range beam-beam self-compensation between IR1 and

IR5. More precisely, from the (presently positive) vertical crossing angle for beam1 in IR1, and (positive) horizontal crossing in IR5, these crossing angles become horizontal positive and vertical negative in IR1 and IR5, respectively. The above gymnastic is mandatory to liberate enough aperture for the squeeze in flat mode, when strongly reducing beta* in the plane corresponding to the flat of the beam-screen (see Fig. 1), while crossing in the plane corresponding to the largest β^* in the other plane. **For the shift with 3E11 p/beam, new TCT functions (Nsigma and center) are being prepared for this BP** [7]. The duration of this beam process is 280 seconds.

Figure 1: Maximising the triplet aperture for flat optics operation mode [9]



2.4 PRE-SQUEEZE

The nominal pre-squeeze sequence is re-used but truncated at β^*=65 cm (see Tab. 1): **SQUEEZE-6.5TeV-ATS-1m-65cm-2017_V1** [6].

The crossing bumps are still ON (and rotated) for this near to nominal beam process. The crossing angle is however reduced from 150 μrad down to 130 μrad in IR1 and IR5, and the parallel separation from 0.55 mm to 0.30 mm. In the end of this process, but only for the first fill(s) with probes, the crossing bumps will be switched off in the four experimental insertions; otherwise, **this specific action will not be taken later on. In particular, for the shift with 3E11 p/beam, new TCT functions taking into account the new crossing configuration in IR1 and IR5 are being prepared to populate this beam process** [7].

The OMC knob pre-setting strategy follows the one mentioned above for the clone of the nominal ramp & squeeze BP. The change in the tune, coupling and chromaticity knobs, as measured in nominal operation from 1 m to 65 cm, are directly reported to trim the corresponding tele-knobs. In particular the pre-squeeze beam process is planned to be played with the nominal injection tunes 62.28/60.31.

Table 1: Timing structure of the pre-squeeze from 1m to 65 cm [6]

Matched Pt	Time (s)	Parab. fr.	Optics Name	Beta* [cm] at IP1 &5	Energy (GeV)
1	0	0.00	R2017a_A100C100A10mL300	100.0	6500
2	53	0.19	R2017a_A80C80A10mL300	80.0	6500
3	110	0.18	R2017a_A65C65A10mL300	65.0	6500

2.5 TELE-SQUEZE

Using the ATS telescopic techniques, i.e. trimming only the IPQ circuits in IR8/2/4/6, this beam process reduces β^* by a factor of 4 in the parallel separation planes at IP1 and IP5, i.e. in the V plane for ATLAS and H plane for CMS (see Fig. 1), while β^* is kept (almost) constant in the crossing plane. For practical reasons, the first step of this beam process combines a pre-squeeze from 65 cm to 60 cm at IP1 and IP5, with a first segment of the telescopic-squeeze proper (in the sense of the IPQ circuit usage, only the ones in IR1/5 for the pre-squeeze, and the ones in IR8/2/4/6 for the tele-squeeze). This means that the final pre-squeezed β^* is actually 60 cm at IP1 and IP5 (a matched point which does not exist in the nominal pre-squeeze sequence). This also implies that this tele-squeeze leads to a flat telescopic optics with an H/V β^* of 60/15 cm at IP1 and 15/60 cm at IP5. This beam process is named **SQUEEZE-6.5TeV-ATS-65cm-60_15cm-2017_V1** [6]. Its timing structure is given in Tab. 2.

The IP knobs values will be kept constant defined by continuity from the previous BP, in particular set to 0 for the first fill(s) with probes. **For the shift with 3E11 p/beam, new TCT functions are being prepared to populate this BP** [7].

The OMC knob pre-setting strategy follows the one mentioned above for the clone of the nominal ramp & squeeze BP. In addition, two OMC knobs, calculated from the flat optics MD of last year, will be kept, namely **LHCBEAM/2017_Local_flat_ATS** (local triplet optics correction) and **LHCBEAM/2017_Coupling_Flat_ArcByArc_B1** (arc by arc coupling correction for B1). The tele-knob values are kept constant, defined by continuity from the previous beam process. In particular the telescopic will be played with the nominal injection tunes 62.28/60.31.

Table 2: Timing structure of the flat telescopic squeeze from 65 cm at IP1 and IP5 down to 60/15 cm at IP1 and 15/60 cm at IP5 [6]

Matched Pt	Time (s)	Parab. fr.	Optics Name	Beta* [cm] H/V at IP1--5
1	0	0.00	R2017a_A65C65A10mL300	65.0/65.0--65.0/65.0
2	109	0.38	R2017aT65_A60_51C51_60A10mL300	60.0/51.0--51.0/60.0
3	210	0.39	R2017aT65_A60_41C41_60A10mL300	60.0/41.0--41.0/60.0
4	306	0.40	R2017aT65_A60_31C31_60A10mL300	60.0/31.0--31.0/60.0
5	427	0.36	R2017aT65_A60_21C21_60A10mL300	60.0/21.0--21.0/60.0

2.6 Q-JUMP & PHYSICS BEAM PROCESSES

Two specific beam process are planned to be played the end of the squeeze.

(i) **QCHANGE-6.5TeV-ATSFlat-2018_V1** [6] to shift the working point onto the collision tunes (from .28/.31 to .31/.32), using the tune TELE knobs. The BP duration is 25 seconds.

(ii) **PHYSICS-6.5TeV-ATSFlat-2018_V1** [10] for collapsing the parallel separation bumps in the four experimental IPs, but w/o generating the vertical shift of IP2 (-2 mm) and IP5 (-1.8 mm) (as the latter will be very likely corrected in Run III). The BP duration is 25 seconds. **New TCT functions are being prepared to populate this BP** [7].

3. BEAM & MACHINE CONDITIONS

The beam and machine conditions, as previously described in details, are summarized in Tab. 3.

As previously mentioned, in order to safely commission the optics, specific coarse settings will be applied to the collimators in the end of the ramp, before the crossing bump rotation, but only for the first fill(s) with probes (see details hereafter and in Table 4); otherwise, dedicated new TCT functions, first preset using MADX expectations [7], then fine-tuned via beam-based measurements, will be loaded for the fills at higher intensity (second shift). Concerning the coarse collimator settings, based on the expected triplet aperture (as calculated using the LHC aperture tolerance budget given in [11]), the following strategy has been used in order to obtain the number given in the first column of Table 4:

- Single stage collimation (as usual), with same normalised settings for the TCPs in IR7 and the TCSPs in IR6 in the end of the tele-squeeze, corresponding to 8 σ for both devices, and to be compared to a triplet aperture of 8.9 σ without crossing bumps and limited in the parallel separation plane (note that the IT aperture is then only slightly reduced to 8.7 σ with the crossing bumps on, which is a feature of flat collision optics). Due to the variations of the β functions in IR6 during the tele-squeeze (see Fig. 2), the TCSP normalised settings needs to be adjusted to 8.9 σ / 7.6 σ for beam1 /beam2 in the end of the ramp (see Tab. 4).
- Specific TCT settings trimmed in mm at β^*=1 m, symmetric (as usual), the same for both beams, but different in the two IRs and the two transverse planes (i.e. 4 numbers in total). These settings are then kept constant all along the pre-squeeze and the tele-squeeze beam processes. As showed in the right part of Tab. 4, these coarse settings ensure in principle that, at any time during the commissionning with probes of the pre-squeeze (with the crossing bumps on), and of the tele-squeeze (with the crossing bumps switched off, a margin of about 1 σ exists between the TCSP and the TCTH's, and of 0.4-0.5 σ between TCPs and TCTs, and between TCTs and triplet, in the plane of smaller β^* (and more in the other plane).

Concerning, the crossing bump management strategy, the latter will be kept switched on till the end of the pre-squeeze (65 cm), as already demonstrated last year in the first and unique fill used for the 2017 flat optics MD. The latter will then be manually switched off in all IRs for the first fill(s) with probes. In all cases, a special fill with probes and the crossing bumps switched on all along is planned to validate the cycle, before going to setup beams.

In order to mitigate any coupling effects, the tunes will be adjusted to 62.28/60.31 after the tele-knob exchange beam process, and kept constant all along till the end of the flat tele-squeeze (although closest tune approach will be conducted at some occasions during the telescopic squeeze for precise global coupling correction).

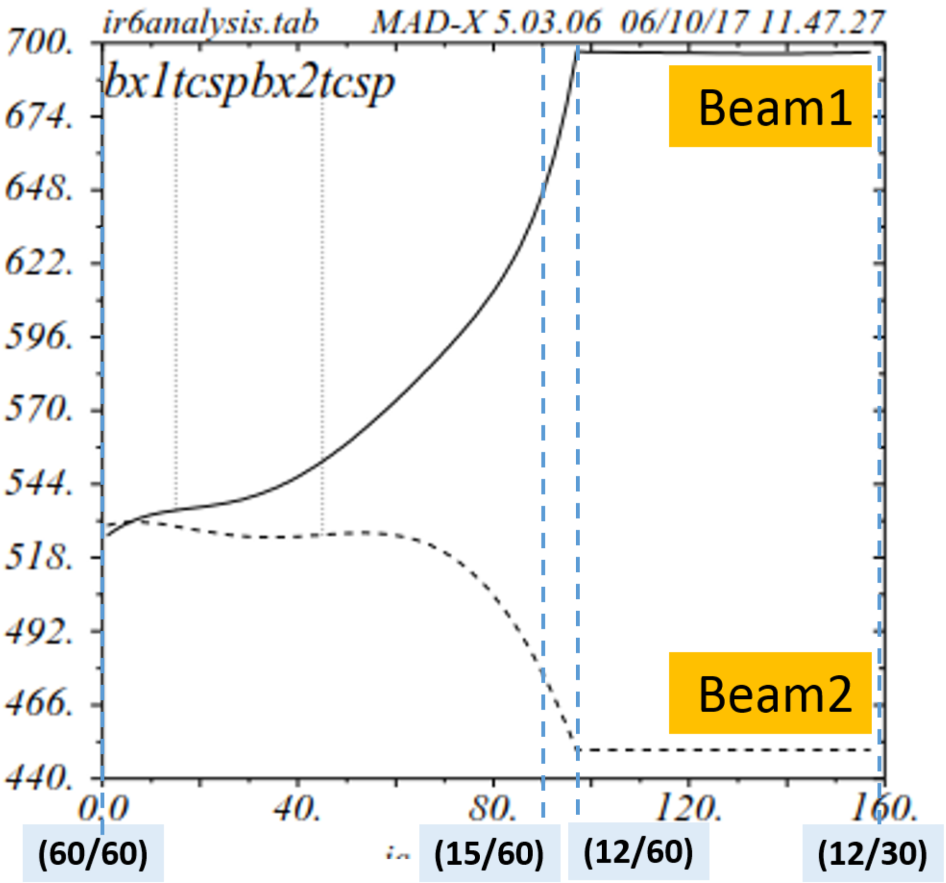
Table 3: Basic beam and machine parameters during the MD

Beams required [1, 2, 1&2]	1&2
Beam energy	Injection 450 GeV, ramp & squeeze, 6.5 TeV
Bunch intensity [#p, #ions]	Pilot bunch (5E9 → 1E10) up to 3E11 (2 colliding nominal+ 8-10 n.c. pilots)
Number of bunches	From 1 pilot up to 10-12 bunches per beam (2 nominal+ 8-10 pilots)
Transv. emittance [m rad]	As small as possible
Bunch length [ns @ 4s]	Not relevant
Optics change [yes/no]	Yes after β^* =65 cm
Orbit change [yes/no]	Yes: crossing plane rotation at 1 m in IR1 and IR5, then flat machine after 65 cm for the first fill(s) with probes. Later on, fills with the crossing bumps kept on will be played till reaching the 60/15-15/60 flat optics configuration.
Interlocks [yes/no]	Yes. Almost all masked for optics commissionning with pilots - LHC SIS & BIS: RQ-currents,TDI gaps up- and downstream, all collimators, BPM, BLM, RF, AC-dipole - SPS extraction BIS: CIB.SR2.INJ1/2.1/2 channels 8 & 10 (coll mov & BETS TDI/MSI)
Collimation change [yes/no]	**Yes : coarse settings sent at 1 m for the first fills with probes (see Tab. 4). Then new TCT functions operating@ 3E11 (in preparation [7])**
RF system change [yes/no]	No
Feedback changes [yes/no]	Yes (ADT off for the first fills with probes, then on when operating @ 3E11 (new settings as of 65 cm are in preparation [12])
Octupole changes [yes/no]	Yes (MO switched off at β^*=1 m for the first fills with probes)
What else will be changed ?	Tunes changed to 62.28/60.31 in the end of the ramp, then kept constant all along. A special BP is foreseen at the EoS in order to jump onto the collision tunes (62.31/60.32)

Table 4: Coarse collimator settings sent at β^*=1 m before the crossing bump rotation for the optics commissioning fill(s) with probes, and comparison with the triplet aperture at various steps during the pre-squeeze and tele-squeeze.

Collimator	Settings sent at β^*=1 m	Normalised Gap [σ] vs. IT aperture [σ] in IR1/5			
		β^*=1 m 150 μrad (0.55m)	β^*=65 cm 130 μrad (0.3 mm)	β^*=65 cm 0 μrad (0 mm)	β^*=60/15 cm 0 μrad (0 mm)
TCTH in IR1	+/- 8.1 mm	10.4 for b1 10.5 for b2 vs. 12.4 for IT	9.7 for b1 9.8 for b2 vs. 10.6 for IT	11.7 for b1 11.8 for b2 vs. 15.1 for IT	11.4 for b1 11.5 for b2 vs. 14.5 for IT
TCTV in IR1	+/- 9.6 mm	21.9 for b1 22.2 for b2 vs. 23.2 for IT	17.4 for b1 17.6 for b2 vs. 18.7 for IT	17.4 for b1 17.7 for b2 vs. 18.7 for IT	**8.4 for b1** **8.5 for b2** **vs. 9.1 for IT (D1)**
TCTH in IR5	+/- 12.0 mm	19.5 for b1 19.5 for b2 vs. 23.2 for IT	17.2 for b1 17.2 for b2 vs. 18.7 for IT	17.4 for b1 17.4 for b2 vs. 18.7 for IT	**8.5 for b1** **8.5 for b2** **vs. 9.2 for IT**
TCTV in IR5	+/- 6.5 mm	11.2 for b1 11.5 for b2 vs. 12.4 for IT	9.1 for b1 9.3 for b2 vs. 10.6 for IT	11.8 for b1 12.0 for b2 vs. 15.1 for IT	11.3 for b1 11.5 for b2 vs. 14.5 for IT
TCSP in IR6	8.9 σ for b1 7.6 σ for b2	8.9 for b1 7.6 for b2	8.9 for b1 7.6 for b2	8.9 for b1 7.6 for b2	8.0 for b1 8.0 for b2
TCPH/V in IR7	8.0 σ	8.0			
TCT in IR2/8	+/- 15 mm	Irrelevant			
TCDQ	15 mm	Irrelevant			
All others	+/-20 mm	Irrelevant			

Figure 2: Evolution of the horizontal beta functions at the TCSP during the telescopic squeeze



4. DETAILED STEPS TO BE TAKEN DURING THE MD

The sequence of activities during the first and second shift is detailed in Tabs. 5 and 6, respectively, leaving no contingency in case of unforeseen problems or sophistication needed in the procedure. Two fills are foreseen for each of the two shifts, the second fill, always slightly shorter, being a validation of the first one. In case of time limitation in the first shift, the second fill of Shift1 will be postponed to Shift2, and the second fill of Shift2 postponed to MD2.

It is worth noting that if rMPP would allow the first fill of shift1 to be played with already 2-3 probes instead of one unique pilot bunch per beam, the optics commissioning activities at 60/15 cm and the aperture measurement @ 65 cm could be combined in the same fill, which could help to build up some flexibility in the program.

Table 5: Breakdown of activities in Shift1 with time estimate

Activity (and comments)	Time estimate [h]
First fill: Optics commissioning @ 60/15—15/60 cm (with flat machine) 1 n.c. probe/beam (b1/2 e.g. in bucket 1/2001)	
- Setting up at injection → 0.25 h - Nominal combined ramp & squeeze → 0.25 h	1.5

- **Coarse collimator settings, octupole OFF** → 0.25 h - **Tele-knob exchange, crossing bump rotation and pre-squeeze to 65 cm** → 0.5 h - **Crossing OFF and setting up** → 0.25 h	
- **Telescopic squeeze by step down to 60/15—15/60** - Fast optics checks at the 5 intermediate steps (Q', coupling, YASP dispersion) → 0.5 h - Optics measurement and correction at 60/15—15/60, including W's, K-modulation, coupling correction and non-linear measurement → 5.0 h	5.5
Dump and Ramp down	1.0
Second fill (if time permits): IT aperture @ 65 cm and 60/15—15/60 optics reach (with crossing on) 2 probes/beam	
- Setting up at injection → 0.25 h - Nominal combined ramp & squeeze → 0.25 h - Coarse collimator setting, octupole OFF → 0.25 h - Tele-knob exchange and crossing bump rotation and pre-squeeze to 65 cm → 0.5 h - **IT aperture measurement** (10.6 σ expected in H/V for IR1/5, > 20 σ in V/H) → 1.5 h - **Telescopic squeeze down to 60/15—15/60 (crossing bumps still ON)** → 0.25 h - **Beam dump**	3.0
Total	**11.0**

Table 6: Breakdown of activities in Shift2 with time estimate

Activity (and comments)	Time estimate [h]
First fill: TCT alignment, collision, aperture measurement at 60/15—15/60 Single_7b_1_1_1_5ncPilots2cNom (2 colliding nominal + 6-8 non-colliding probes)	
- Setting up at injection with probes and injection → 0.5 h - Nominal combined ramp & squeeze → 0.25h - Setting up at flat top, Tele-knob exchange, crossing bump rotation → 0.5h - **TCT alignment @ 1 m→ 0.25 h** - Pre-squeeze down to 65 cm, and setting up → 0.25 h - **TCT alignment @ 65 cm** → 0.25 h - Telescopic squeeze down to 60/15—15/60 → 0.25 h - **TCT alignment @ 60/15 cm** → 0.25 h - **Find and optimize collisions at IP1/2/5/8** → 0.75 h - **TCT alignment in collision and first loss maps** → 0.25 h - **Intensity scraping down to 1-2 pilots /beam, and IT aperture measurement** (8.9 σ expected limited in V/H in IR1/5, ~10 σ in the other plane) → 2.0 h - If times permits, Off-momentum loss maps (one single sign) → 0.0 h	5.5
Dump and Ramp down	1.0
Second fill: Loss maps and asynchronous dump tests Single_7b_1_1_1_5ncPilots2cNom (2 colliding nominal + 8-10 non-colliding probes)	
- Setting up at injection with probes and injection → 0.5 h - Nominal combined ramp & squeeze → 0.25h - Setting up at flat top, Tele-knob exchange, and crossing bump rotation → 0.5h - **Loss maps @ 1 m** → 0.25 h	3.5

- Pre-squeeze down to 65 cm → 0.25 h - **Loss maps @ 65 cm** → 0.25 h - Telescopic squeeze down to 60/15—15/60 → 0.25 h - **Loss maps @ 60/15 (beams separated)** → 0.25 h - Find and optimize collisions at IP1/2/5/8 → 0.25 h - **Loss maps @ 60/15 (beams colliding)** → 0.25 h - **Scraping (<5E10), de-bunching, & asynchronous dump with TCT@ 8.0 σ** → 0.5h	
Total	**10.0**

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