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LHC MD2148

TELESCOPIC FLAT OPTICS WITH PILOTS

Abstract

This note summarises the key objectives of the fourth series of ATS MDs (MD 2148), which aims at demonstrating 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 MD procedure describes the present situation in terms of optics development and implementation in LSA, and will fix the goal of the first MD of this program, as foreseen in block 4 with probe beams only.

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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 15-20 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 completed 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 the on-going MD campaign MD2269 to test this functionality with round telescopic optics).

2. DESCRIPTION OF THE HYPERCYCLE

A huge effort for optics development [3] and implementation [4,5] was deployed over the last few weeks in order to boostrap this activity already in 2017, and enable first tests with probe beams already in block4. The corresponding recently built hypercyle [4] is described below, together with the different beam processes (BP) involved, described in terms optics, various gymnastics, and knob pre-setting strategy.

2.1 RAMP AND SQUEEZE

The nominal 2017 injection optics and combined ramp and squeezed are re-used via a clone of the corresponding nominal beam process [5] (**RAMP-SQUEEZE-6.5TeV-ATS-1m-2017_V3_V1_TELE-ATSFlat_MD4)**. The collimator and machine protection devices have nominal settings, and the octupole are kept on to avoid any instabilities (even with probes). Some minor modifications have nonetheless been introduced, with only a subset of the available OMC knobs [6] which are kept, namely: the knobs concerning the global correction of the injection optics, vanishing in 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**).

2.2 GYMNASTICS AT FLAT TOP

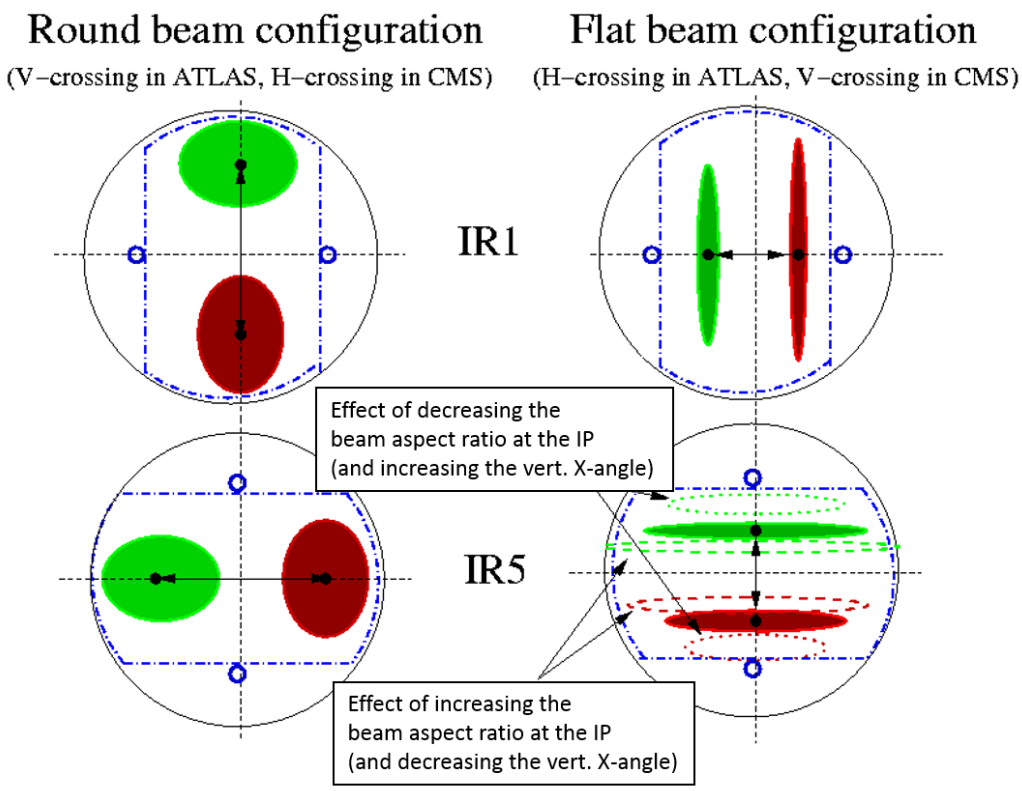
Arriving at flat top (β^*=1m at IP1 and IP5), the collimator are sent to coarse settings (see later), the octupoles are switched off and the following two beam processes are played in sequence:

(i) **TELE-ATS_knobs-2017_V1_ATSFlat** [5], a clone of the beam process **TELE-ATS_knobs-2017_V1,** which was developed for the round ATS MD (MD2269).

This BP exchanges the standard correction knob values with the so-called TELE knobs, for tune, coupling, and chromaticity, while shifting the betatron tunes from 62.27/60.295 (operational injection tunes) to 62.28/60.31 (design report injection tunes). The duration of this beam process is 210 seconds. It could be incorporated in the ramp at some point.

(ii) **BUMPS-INVERSION-2017_V1** [5], which 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), in order to pass from the nominal V/H crossing configuration in IR1/5, to an H/V 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 a (presently) positive vertical crossing angle for beam1 in IR1 and horizontal in IR5, these crossing angles become horizontal positive and vertical negative in IR1 and IR5, respectively. This 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. The duration of this beam process is 240 s. It could be incorporated in the ramp at some point.

Figure 1: Maximising the triplet aperture for flat optics operation mode [7]



2.3 PRE-SQUEEZE

The nominal pre-squeeze is re-used but truncated at β^*=65 cm (see Tab. 1): **SQUEEZE-6.5TeV-ATS-1m-65cm-2017_V1** [5]. 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 this BP is planned to be played with the nominal injection tunes 62.28/60.31. **Unless counter-indication by rMPP**, the crossing bumps are still kept on for this near to nominal beam process. In the end of this process, the crossing bumps will however be manually switched off in the four experimental insertions.

Table 1: Timing structure of the pre-squeeze from 1m to 65 cm [5]

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

2.4 THE TELE-SQUEZE "14-41"

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 keeping it constant in the crossing plane. For practical reasons, the first step of this BP is a pre-squeeze from 65 cm to 60 cm at IP1 and IP5, combined with a first segment of telescopic-squeeze (in the sense of the IPQ circuit usage, only IR1/5 for the first, and IR8/2/4/6 for the second). 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 the so-called telescope "14-41" brings to to a flat telescopic optics with an H/V β^* of 60/15 cm at IP1 and 15/60 cm at IP5. This BP is called **SQUEEZE-6.5TeV-ATS-65cm-60_15cm-2017_V1** [5]. Its timing structure is given in Tab. 2. The OMC knob pre-setting strategy follows the one mentioned above for the clone of the nominal ramp & squeeze BP. The tele-knob values are kept constant, defined by continuity from the previous beam process. In particular this BP is planned to be played with the nominal injection tunes 62.28/60.31. The IP knobs are defined and connected but set to zero, a least for the fill.

Table 2: Timing structure of the first flat telescopic squeeze from 65 cm at IP1 and IP5 down to 60/15 cm at IP1 and 15/60 cm at IP5 [5]

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
6	526	0.35	R2017aT65_A60_15C15_60A10mL300	60.0/15.0--15.0/60.0

2.5 THE TELE-SQUEZE "25-52"

A second telescopic squeeze follows, with in mind the HL-LHC Plan B [2]. The aim of this BP is to further squeeze β^* in the separation planes of IR1 and IR5 (reaching a

telescopic index of 5 in the vertical plane for the sectors s81/s12 and in the horizontal plane for the sector s45/s56), but also and mainly to gain a factor of 2 in β^* in the crossing planes of the two high-luminosity insertions. With the pre-squeezed optics matched to β^*=60 cm, this so-called "25-52" telescopic squeeze brings to a flat collision optics with an H/V β^* of 30/12 cm at IP1 and 12/30 cm at IP5. This BP is called **SQUEEZE-6.5TeV-ATS-60_15cm-30_12cm-2017_V1** [5]. Its timing structure is described in Tab. 3. The OMC knob pre-setting strategy follows the one mentioned above for the clone of the nominal ramp & squeeze BP. The tele-knob values are kept constant, defined by continuity from the previous beam process. In particular this BP is planned to be played with the nominal injection tunes 62.28/60.31. The IP knobs are defined and connected, but set to zero.

Table 3: Timing structure of the second flat telescopic squeeze from 60/15—15/60 at IP1—5 down to 30/12—12/30 [5]

Matched Pt	Time (s)	Parab. fr.	Optics Name	Beta* [cm] H/V at IP1--5
1	0	0.00	R2017aT65_A60_15C15_60A10mL300	60.0/15.0--15.0/60.0
2	74	0.39	R2017aT65_A60_12C12_60A10mL300	60.0/12.5--12.5/60.0
3	168	0.38	R2017aT65_A47_12C12_47A10mL300	47.0/12.0--12.0/47.0
4	260	0.36	R2017aT65_A36_12C12_36A10mL300	36.0/12.0--12.0/36.0
5	342	0.37	R2017aT65_A30_12C12_30A10mL300	30.0/12.0--12.0/30.0

3. OBJECTIVES FOR MD4 AND MACHINE CONDITIONS

3.1 OBJECTIVES

A shift of 8 h (+2h for recovery) is foreseen for flat ATS optics activities in block 4. The goal is to establish, measure and correct the 60/15-15/60 flat optics, which offers an interesting configuration for operating the LHC in Run III. If time permits, (i) the second telescopic squeeze will be played and the optics measured at 30/12-12/30 cm, and, ideally, (ii) a second fill with the crossing bump kept on all along will be played. This hypothetical second fill will however be dumped in the end of the first tele-squeeze (60/15-15/60).

3.2 BEAM & MACHINE CONDITIONS

Only pilot beam will be used (see Tab. 4). As previously mentioned, coarse setting will be applied to the collimators in the end of the ramp (see details hereafter and Tab. 5), and then the octupole switched off, before any other gymnastics takes place (i.e. before the knob exchange and crossing plane inversion BP's). The crossing bumps will (a priori) be kept on down to 65 cm (end of the pre-squeeze BP), then manually switched off. 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 (although closest tune approach will be conducted at some occasions during the telescopic squeeze for precise global coupling correction).

Based on the expected triplet aperture (as calculated using the LHC aperture tolerance budget given in [8]), the following strategy has been used in order to define the "coarse" collimator settings given in Tab. 4:

- Single stage collimation (as usual), with same normalised settings for the TCPs in IR7 and TCSPs in IR6, corresponding to 8 σ in the end of first telescope vs. a triplet aperture of 8.7 σ (8.5 σ) without (with) crossing bumps, and to 7.3 σ in the end of second telescope vs. a triplet aperture of 7.8 σ (6.6 σ) without (with)

crossing bumps. Due to the variations of the β functions in IR6 during this process (see Fig. 2), and the further reduced triplet aperture in the end of the second tele-squeeze, a small readjustment of the TCP and TCSP is requested in the end of the optics measurement activities at 60/15-15/60 cm (see Tab. 4).

- New TCT settings defined in mm at β^*=1 m, symmetric (as usual), same for both beams but different in the two IRs and the two planes (4 numbers in total), then kept constant all along the pre-squeeze and the two tele-squeeze beam processes. Right-after the crossing plane rotation, when the crossing bumps are still on at β^*=1m, the settings of the TCTH(V) critical jaws in IR1(5) correspond to a normalised opening of 10.4 (11.4) σ, still below the triplet aperture estimated to 12.0 σ in this configruation, and which is limited in the new crossing H (V) planes of IR1 (IR5). In this respect, the impact of the crossing plane rotation should not be overlooked, although done at the still modest β^* of 1 m. If the (rotated) crossing bumps are kept on during the pre-squeeze (as a priori foreseen down to 65 cm), the above values shrinks to 9.5 (8.8) σ, compared to 9.7 σ for the triplet aperture. Thhese settings also warrant that, at any time during the two tele-squeeze beam processes (with the crossing bumps switched off), a margin in the range of 0.3-0.5 σ exists between TCP/TCSP and TCT in the plane of smaller β^* for both IR1 and IR5 (more in the other plane), and that a margin of 0.2 σ is preserved between TCT and triplet (still in the plane of smaller β^*, more in the other plane).

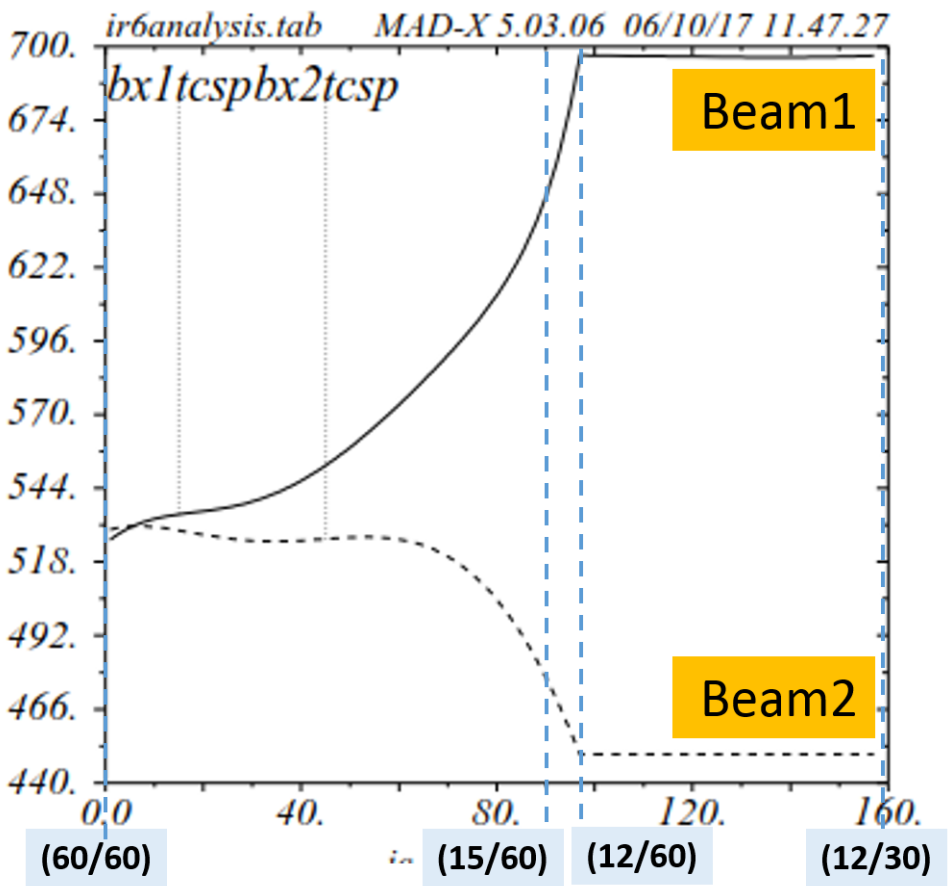
Table 4: Basic beam and machine parameters during the MD

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)
Number of bunches	1 pilot per beam
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 at least for the first fill. A possible second fill with the crossing bumps on will stop with not go beyond the 60/15-15/60 optics
Interlocks [yes/no]	Yes. Almost all masked - 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, further slighlty modified before starting the second telesopic squeeze (see Tab. 5)**
RF system change [yes/no]	No
Feedback changes [yes/no]	Yes (ADT off all along)
Octupole changes [yes/no]	Yes (MO off at β^*=1 m)
What else will be changed ?	Tunes changed to 62.28/60.31 in the end of the ramp, then kept constant all along

Table 5: Coarse collimator settings sent at β^*=1 m, followed by a small re-adjustment of the TCP's in IR7 and TCSP's in IR6 before starting the second telescopic.

Collimator	Settings sent at β^*=1 m (the IT aperture is 12.0 σ after the Xing rotation)	Normalised Gap [σ] for the 60/15—15/60 optics The IT aperture is **8.7 (8.5) σ** without (with) Xssing bumps, limited in the || plane (14.2 σ in the X-plane w/o X-angle)	Normalised Gap [σ] for the 30/12—12/30 optics The IT aperture is **7.8 (6.6) σ** without (with) Xssing bumps, limited in the || plane (10.0 σ in the X-plane w/o X-angle)
TCTH in IR1	+/- 8.1 mm	8.5 σ in the || plane (smaller β^*) 11.4 σ in the X-plane (larger β^*)	7.6 σ in the || plane (smaller β^*) 8.1 σ in the X-plane (larger β^*)
TCTV in IR1	+/- 9.7 mm		
TCTH in IR5	+/- 12.0 mm		
TCTV in IR5	+/- 6.5 mm		
TCT in IR2/8	+/- 15 mm		
TCPH/V in IR7	8.0 σ	8.0 σ <u>readjusted</u> to 7.3 σ	7.3 σ
TCSP in IR6	8.9 σ for b1 7.6 σ for b2	8.0 σ <u>readjusted</u> to 7.6 σ for b1 8.0 σ <u>readjusted</u> to 7.1 σ for b2	7.3 σ for b1 7.3 σ for b2
TCDQ	15 mm		
All others	+/-20 mm		

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 is described in Tab. 5, leaving no contingency in case of unforeseen problems or sophistication needed in the procedure.

Table 5: Breakdown of activities with timing estimate

Activity (and comments)	Time estimate [h]
First fill: objective 30/12-12/30 (with crossing off) Probes (b1/2 in bucket 1/2001)	
- Setting up at injection → 0.25 h **- Nominal combined ramp & squeeze** → 0.25 h **- Coarse collimator settings, octupole OFF** → 0.25 h **- Tele-knob exchange and crossing bump rotation** → 0.5 h **- Pre-squeeze down to 65 cm, crossing OFF and setting up** → 0.25 h	1.5
First telescopic squeeze by step down to 60/15—15/60 - Fast optics checks at the 5 intermediate steps (Q', coupling, YASP dispersion) → 0.75 h - Optics measurement at 60/31—31/60 (step 4), optionally first optics corr. → 0.5 (+1.0) h - Optics measurement and correction at 60/15—15/60, including W's and K-modulation with 2 or 3 different anti-symmetric trims applied to the MQSX → 3.0 h - Manual re-adjustment of TCP in IR7 and TCSP in IR6 (see Tab. 4) → 0.25 h	4.5 (+1.0)
Second telescopic squeeze by step, down to 30/12—12/30 - Fast optics checks at the 4 intermediate steps (Q', coupling, YASP dispersion) → 0.75 h - Optics measurement at 30/12—12/30 (W's optional) → 0.75 h - Beam dump	1.5 h
Ramp down	1.0
Second fill (if time permits): objective 60/15—15/60 (with crossing on) Probes (b1/2 in bucket 1/1)	
- 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** → 0.25 h **- Pre-squeeze down to 65 cm and telescopic squeeze by step down to 60/15—15/60** → 0.5 h **- Beam dump**	1.5
Total	10 (+1.0)

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