CERN
CH-1211 Geneva 23
Switzerland

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TELESCOPIC FLAT OPTICS WITH TRAINS

Abstract

The objective of the overall 2018 MD program on flat optics 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). After the success of the flat optics commissioning, triplet aperture measurements which took place, and first collisions established in MD1, this note contains a detailed description of the activities, together with the procedures to be followed up, which are foreseen in the two flat ATS shifts scheduled in MD2, namely: one shift with set-up beams (3E11 p/b) aiming at validating the cycle for an intensity ramp up, and the second one where a few BCMS trains should be injected for dedicated beam-beam studies, and complementary activities if time permits.

Prepared by:	*Checked by:*	*Approved by:*
S. Fartoukh **N. Karastathis** **A. Mereghetti** **A. Poyet** **M. Solfaroli** **G. Sterbini** **D. Valuch** **J. Wenninger** **...**		

Distribution list :

LHC Machine coordinator, Engineers in charge, LHC operators

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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 β^* 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 demonstrated this technique with round telescopic optics [3]).

2. HYPERCYCLE DESCRIPTION AND OVERALL OBJECTIVES

2.1 HYPERCYCLE & SETTINGS (INC. ADT, OCTUPOLES, COLLIMATOR)

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 is 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 hypercyle, as used in MD1 is described in details in [8], and summarised hereafter (including the latest modifications applied), in terms of the different beam processes (BP) and gymnastics involved:

- Nominal injection optics, and and quasi-nominal combined ramp and squeeze **RAMP_PELP-SQUEEZE-6.5TeV-ATS-1m-2018_V3_V1_TELE-ATSFlat** (a few OMC knob removed, QFB reference tune set to .275/.295).
- Exchange between the standard correction knobs for tune, coupling and chromaticity, with the corresponding so-called Tele-knobs, **TELE-ATS_knobs-2017_V1_ATSFlat**, including a small tune shift from (.275/.295) to (.28/.31).
- Additional tune change, **QCHANGE-6.5TeV-ATSFlat-2018_V1**, to reach the collision tune (.31/.32). In [8], this BP was foreseen to be played in the end of the tele-squeeze. As of the second shift of MD1, it is now inserted before the start of the squeeze, in order to further improve the horizontal MKD-TCT phase advances by up to 0.03 *360= 10.8 degrees (except for TCT5-B2 not impacted).
- Rotation of the crossing planes by -90 degrees in ATLAS and CMS, **BUMPS-INVERSION-2018_V1**, including at the beginning a small reduction of the crossing angle in IR1 and IR5, from 160 μrad to 150 μrad.

- Pre-squeeze from β^*=1 m down to 65 cm at IP1 and IP5, **SQUEEZE-6.5TeV-ATS-1m-65cm-2017_V1**, including a small reduction of the crossing angle from 150 μrad to 130 μrad in IR1 and IR5, and of the parallel separation from 0.55 mm down to 0.3 mm.
- Flat telescopic squeeze from β^*=65 cm down to 60/15 cm at IP1 and 15/60 cm at IP5, **SQUEEZE-6.5TeV-ATS-65cm-60_15cm-2017_V1**, played at constant IP knob value, and including the new OMC knobs derived in the first shift of MD1, and already probed with beams.
- Collapsing of the parallel separation bumps at all 4 IP's (w/o IP shift, neither at IP2 nor at IP5), **PHYSICS-6.5TeV-ATSFlat-2018_V1**, and including a small tune shift from (.31/.32) up to (.317/.323), as this working is expected to be better for the dynamic aperture for colliding beam with flat optics [9].

In view of the various optics gymnastics, inducing in particular substantial changes of the IR4 optics in the tele-squeeze, new ADT settings were generated [10]. It is however worth to be noted that, on purpose, the ADT phases were optimised for a working point of (.320/.325) as of the end of QCHANGE beam-process of above, which now means end of the ramp (after the hypercycle update emphasized above). This slight mismatch with the actual working point will hopefully not degrade the beam stability.

The octupole settings will be kpet nominal till the end of the pre-squeeze down to 65 cm (positive polarity, knob value set to -2.5 corresponding to 470 A at FT). During the tele-squeeze, the octupole current will be gradually ramped down (220 A in the end of the process), profitting from the increasing tele-index and subsequent boost of tune spread (factor of 2.76 at constant MO current at the end of the actual flat tele-squeeze).

The ramp will be played with nominal collimator settings in IR3/6/7 and nominal TCT settings, with the exception of the TCDQ and of the two TCSP jaws of Beam 2, tightened by 219 μm in the end of the ramp (linear trim applied between 6.0 and 6.5 TeV, which is within the BETS tolerances), as already approved by rMPP and applied in MD1. **Later on, brand new TCT function functions for IR1 and IR5 (centres and Nsigma), based on the results from MD1, will populate the various beam-processes at flat top energy [7]**, namely: the crossing bump rotation, the pre-squeeze and tele-squeeze, and the physics beam processes.

2.2 ALLOCATED BEAM TIME & OVERALL OBJECTIVES

Two shifts are foreseen for flat ATS optics related activities in block 2, the first one (6+2 h) scheduled towards the beginning, and the second (8+2 h) towards the end the block. Operating with setup beams ($<3\times10^{11}$ p/b) for the first shift, and hopefully with 3 BCMS trains for the second (see filling scheme in Fig. 1), the objectives and planned activities are the following (see later Tabs. 2 and 3 for more details):

1. **First shift** which will a priori consist in one single validation fill **with 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) and asynchronous dump test (with TCTs at 8.0/9.0 σ in the crossing/parallel sep. plane of IR1 and IR5). In collision, loss maps are foreseen both with a crossing angle of 130 μrad, and reduced down to 100 μrad (then back to 130 μrad for the asynchronous dump test), using the orchestration tool in expert mode (moving in particular the TCTH in IR1 and TCTV in IR5 to take into account the non-nominal crossing plane orientation). The outcome of this shift will hopefully the green light from rMPP for injecting unsafe beams in the second shift.

2. **Second shift with unsafe beams** for dedicated Beam-beam studies with trains. The main activities will cover (i) tune scans (going in the direction of reducing the tune split by increasing QH by step of 0.001, and keeping QV less than .325 in all cases), (ii) change of the octupole polarity in collision with the current pushed down to -570 A, (iii) an attempt for crossing angle reduction down to 120 μrad (or better), (iv) subsequent MO scan up and down in order to (re-)demonstrate the BBLR-MO mitigation with flat optics. With the evident synergies existing with the wire MD [11], the same online analysis tools will be used [12], focusing in particular on the pacman, intermediate and central bunches of the first train of 48 (Bunch#14, #26, #37, #49, #61 for each of the two beams), and, when applicable, correlating with the current recorded in the octupole circuits ROF.A12.B1 and ROF.A12.B2. The main objective is to obtain appropriate settings, in terms of tune, octupole and crossing angle for minimizing the effective cross-section of colliding beams with flat optics. If time permits, beyond the primary objectives of above, some attempt will be tried out in order to maximize the luminosity by acting on the skew quadrupole triplet corrector magnets MQSX (by step of a few 10^{-4} in K in a left/right anti-symmetric powering scheme, otherwise leading to linear coupling at a rate of $\Delta\kappa = 1.8\times10^{-3}$ per trim of 10^{-5} in one single MQSX). Dedicated beam stability studies with separate beams may also take place.

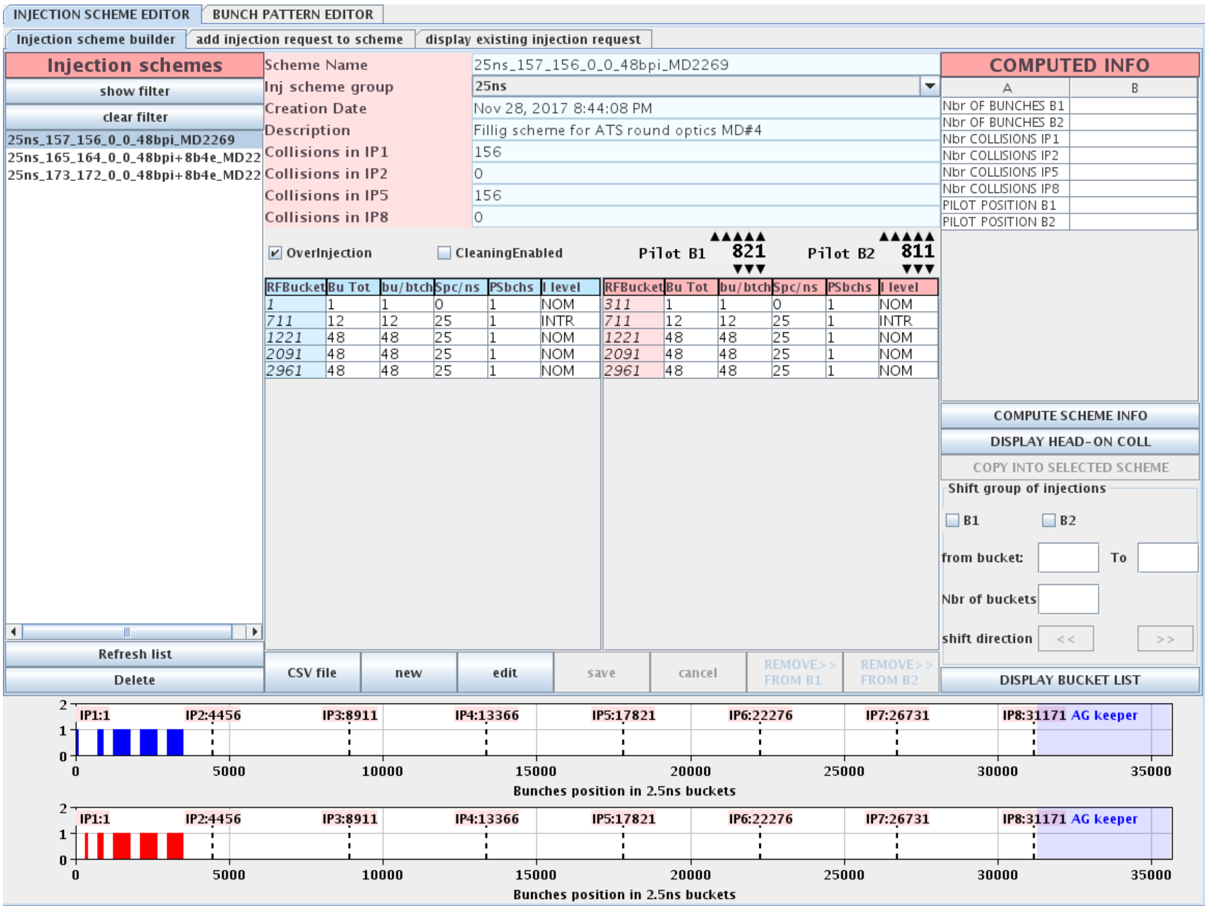
3. BEAM & MACHINE CONDITIONS

The beam and machine conditions, as previously described, are summarized in Tab. 1. The filling scheme foreseen for the second shift is shown in Fig. 1.

Table 1: 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]	Setup beams (3E11, under the form of 2 colliding nominal bunches+ 8-10 n.c. pilots) up to unsafe beams (2E13, under the form of 157 nominal bunches, see Fig. 1)
Number of bunches	Up to 157 nominal bunches
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 EoR at 1 m in IR1 and IR5 (see Section 2.1), and crossing angle scan in collision (see Tab. 2 & 3 for more details)
Interlocks [yes/no]	Some will be masked for the first shift with set-up beams, none for the second shift
Collimation change [yes/no]	**Yes : (i) TCDQ/TCSP tightening by 219 mm EoR for Beam2 and (ii) new TCT functions in preparation [7]** (see Section 2.1)
RF system change [yes/no]	No
Feedback changes [yes/no]	Yes (new phases [10] to cope with slighlty non-nominal tune evolution in the squeeze, but also and mainly for IR4 optics changes during the tele-squeeze, see Section 2.1)
Octupole changes [yes/no]	Yes (MO polarity kept positive, but current reduced during the tele-squeeze, see section 2.1). MO scan foreseen in collision for the second shift (see Tabs. 2 & 3 for more details)
What else will be changed ?	Tunes changed to 62.28/60.31, then to 62.31/60.32, in two consecutive BP's at the end of the ramp, then moved to 62.317/60.323 in the Physics BP (see section 2.1). Tune scan foreseen at the end of the squeeze and in collision for the second shift (see Tabs. 2 & 3 for more details)

Figure 1: Filling scheme for the second shift with trains: 157 bunches (1 INV+12b+3 BCMS), all colliding in IP1 and IP5, except the first INDIV for tune monitoring.



4. DETAILED STEPS TO BE TAKEN DURING THE MD

The sequence of activities during the first and second shift is detailed in Tabs. 2 and 3, respectively. Some contingency exists for a second fill in the first shift in case of unforeseen problems or sophistication needed in the procedure.

If time permits in the second shift, a second fill, with fresh beam injected, is already scheduled for the confirmation of the optimal settings (tune, MO, crossing angle) found in the first fill, and/or complementary studies (lumi optimization with MQSX), and, ultimately, instability studies with separated beams (not scheduled in Tab. 3, but with the same well-established procedure used in MD2269 [3]).

Table 2: Breakdown of activities in Shift1 with time estimate

Activity (and comments)	Time estimate [h]
Validation fill for loss maps, collision, and assynchronous dump tests at 60/15—15/60 **Single_7b_1_1_1_5ncPilots2cNom** (2 colliding nominal + 6-8 non-colliding probes) **New TCT functions loaded for IR1 and IR5, some interlocks masked for setup beams**	
- Setting up at injection with probes, and injection → 0.5 h - Nominal combined ramp & squeeze → 0.25h	4.5

- Setting up at flat top, Tele-knob exchange, Q-change and crossing bump rotation → 0.5h - **Loss Maps @ 1 m**→ 0.25 h - Pre-squeeze down to 65 cm, and setting up → 0.25 h - **Loss maps @ 65 cm** → 0.25 h - Telescopic squeeze down to 60/15—15/60 (130 μrad X-angle)→ 0.25 h - **Loss maps @ 60/15 cm (beam separated)**→ 0.25 h - **Find and optimize collisions at IP1/2/5/8** → 0. 5 h - **Loss maps in collision**→ 0.25 h - **Crossing angle reduction down to 100 μrad in IR1/5 and lumi re-optimisation** → 0.25 h - **Loss maps in collision @ 100 μrad** → 0.25 h - **Crossing angle back to 130 μrad in IR1/5 and lumi re-optimisation** → 0.25 h - **Scraping (<5E10), de-bunching, asynchronous dump (TCT @ 8.0/9.0 σ in X/II planes)** → 0.5h	
Total	**4.5**

Table 3: Breakdown of activities in Shift2 with time estimate

Activity (and comments)	Time estimate [h]
Dedicated studies with trains **25ns_157_156_0_0_48bpi_MD2269** (see Fig. 1) **New TCT functions loaded for IR1 and IR5, No interlocked masked**	
- Setting up at injection with probes and injection → 0.75 h - Nominal combined ramp & squeeze → 0.25h - Setting up at flat top, Tele-knob exchange, Q-change and crossing bump rotation → 0.5h - Pre-squeeze down to 65 cm, and setting up → 0.25 h - Telescopic squeeze down to 60/15—15/60 (130 μrad X-angle) → 0.25 h - **Tune scan (beams separated) by steps of 0.001**→ 0.5 h - **Collision and lumi optimisation with trains**→ 0. 5 h - **Tune scan (beams colliding) by steps of 0.001**→ 0.5 h - **MO polarity reversal, down to -570 A & Tune scan**→ 0.5 h - **X-angle reduction to 120 μrad (if life time good enough) & Tune scan** → 0.5 h - **MO scan from -570 A to +200 A (2/3 cycles in one go for each step)**→ 1.0 h	5.5
Dump & Ramp down	**1.0**
- Setting up at injection with probes and injection → 0.75 h - Nominal combined ramp & squeeze → 0.25h - Setting up at flat top, Tele-knob exchange, Q-change and crossing bump rotation → 0.25h - Pre-squeeze and Tele-squeeze → 0.25 h - **Collision and lumi optimisation with trains**→ 0. 25 h - MO, tune and X-angle settings optimised from previous fill → 0.25 h - **MQSX scan** (by small steps of a few 10^{-4} with left/right anti-symmetric powering) for lumi optimisation in IR1/5, and subsequent coupling fine-tuning (if needed) → 1.0 h - Programmed dump	3.0
Total	**9.5**

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