Optics and operational modes for the HL-LHC

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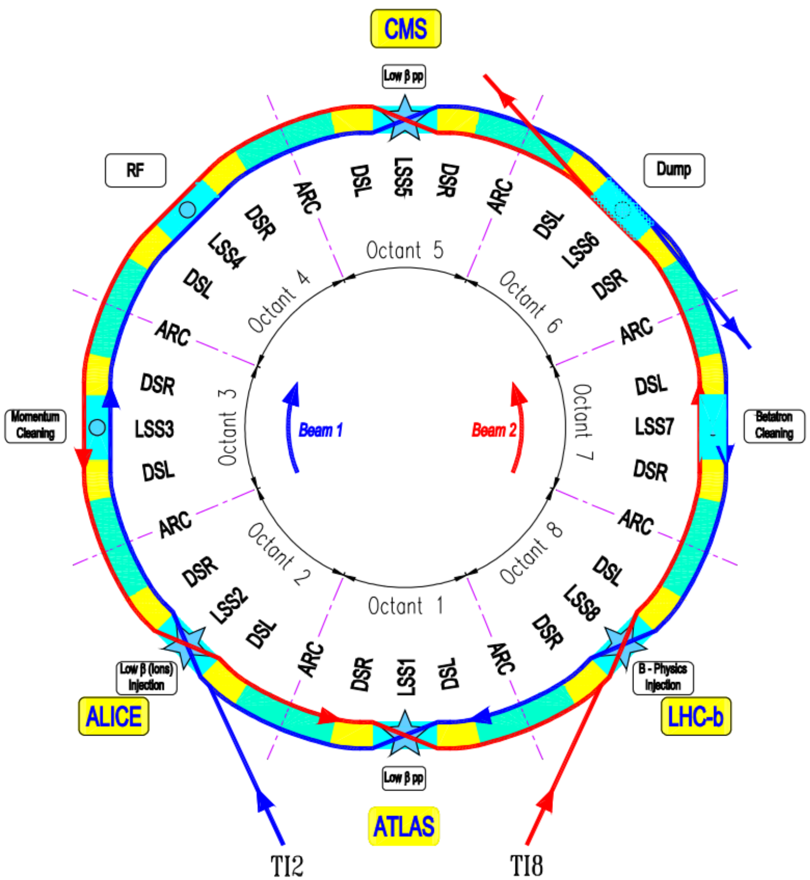
LHC layout



LHC: 8 Arcs, 8 Insertions.

Insertion Region (IR): contains individual powered quadrupoles for optics changes.
It comprises:

- Dispersion suppressor (DS): Q7-Q13 left/right
- Long Straight Section (LSS): Q1-Q7 left/right
  - Triplet in the LSS: Q1-Q3
  - Separation dipoles in LSS: D1-D2, D3-D4

IR6: has no Q7, Q6, Q3, Q2, Q1
IR4: has no Q4, Q3, Q2, Q1
IR3, IR7: special layout

One arc has:
1 MB family, 2 MQ family,
4 MQT (2 per beam): trim tune,
8 MS (4 per beam): control chromaticity,
4 MCS (2 per beam): correct coupling,
4 MSS (2 per beam): chromatic coupling,
4 M0 (2 per beam): Landau damping,
MCS, MCO, MCD: MB field quality correction.

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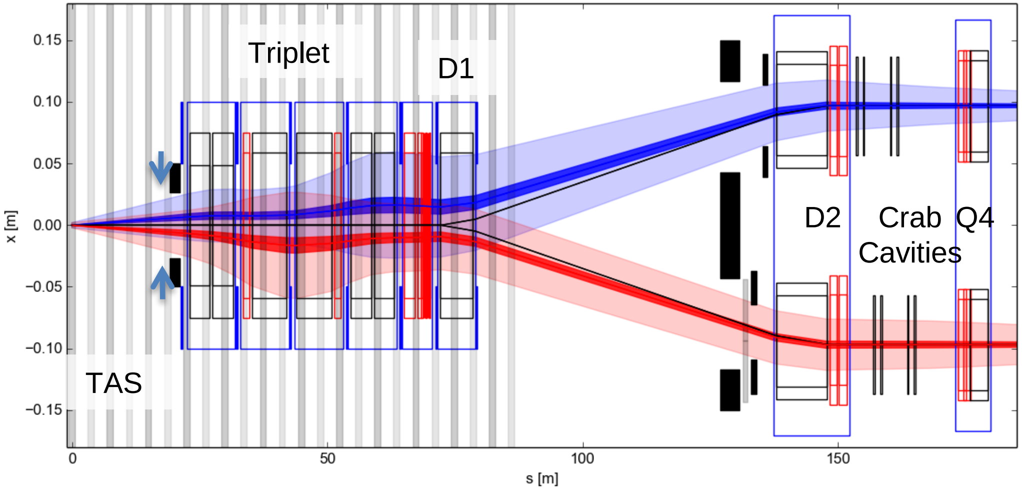
HL-LHC optics news

HL-LHCV1.0 in production for studies.

HL-LHCV1.1 latest development version.



Right side of IR1/IR5

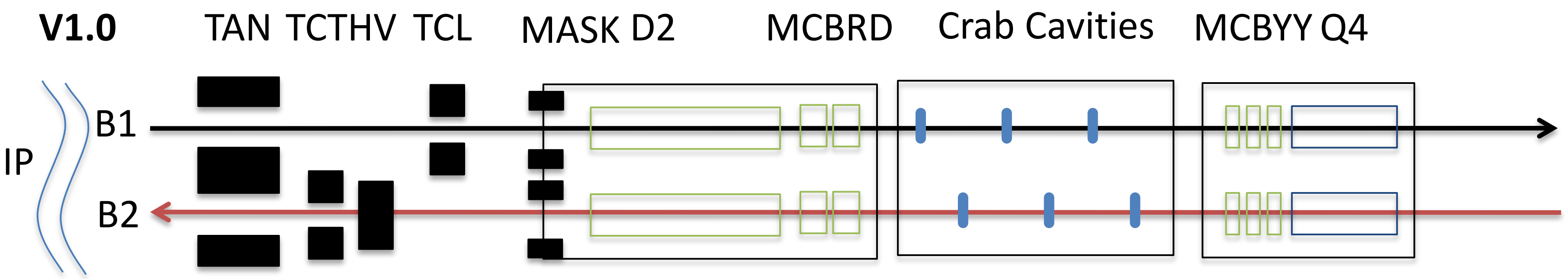
Changes in IR1/5

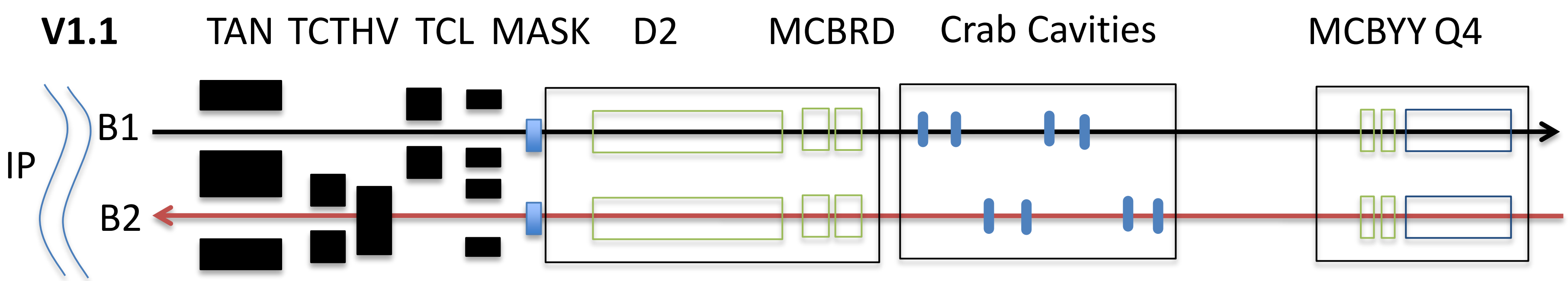
TAS aperture reduced .
Triplet, BPM, corrector layout update.
D1-D2 length reduction.
TAN new aperture and separation.
Displacement Q4 by 10m towards the arc
3 to 4 crab cavities per side per beam.
New MCBRD – MCBYY length and strength for crab cavity beam based alignment.
Additional masks and collimators
Q5: MQYL to MQY at 200 T/m.

Changes in IR6

Q5: MQYL to 2x MQY.

TAN-TCT-Mask: New base line





New TAN, Mask apertures due to optics and position changes.
Proposed octagonal beam screen for D2.
BB compensator tentatively in front of the TAN.
New position of Q4: 0.7MV reduction of total crab voltage, additional space for layout variants
TAN – D2 area with added valves and old functional position.

This area will continue to evolve
For more details see L. Esposito and P. Fessia talks.

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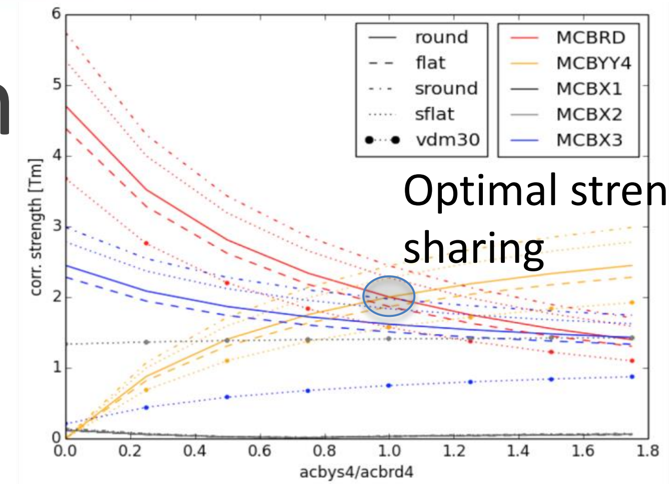
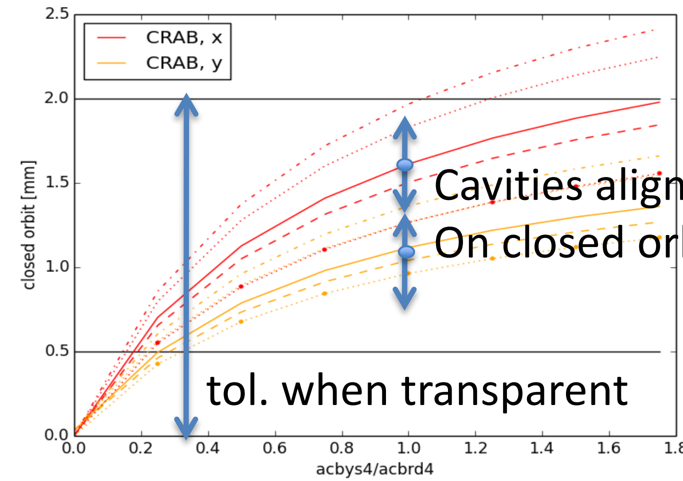
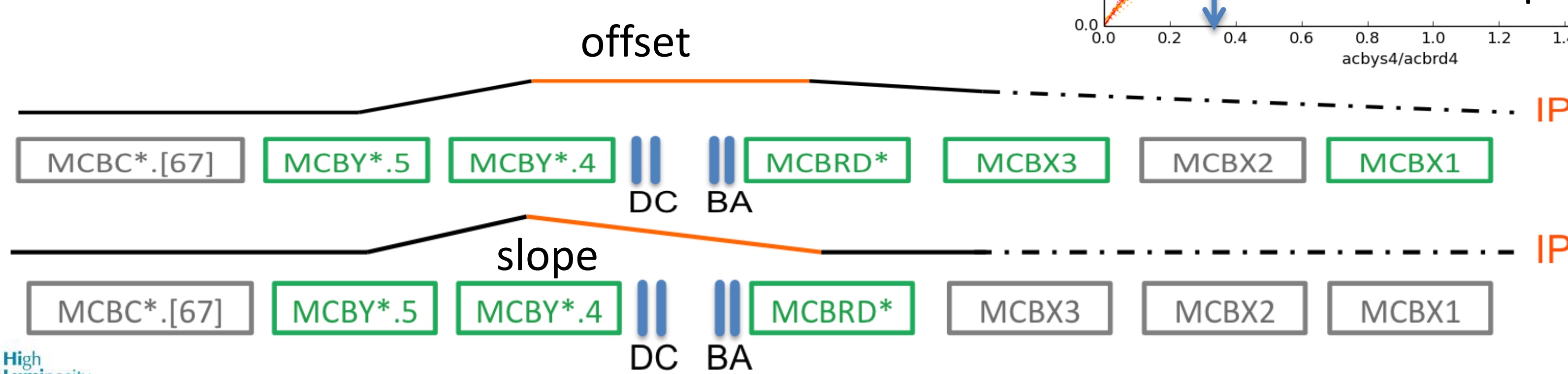
D2-Q4 Correctors 4.5 Tm

Provides:

- Crossing angle, separation, offset at the IP.
- Triplet misalignments and external orbit errors.
- Beam alignment for crab cavities on top of survey alignments to comply with 0.5 mm tolerance at high voltage.







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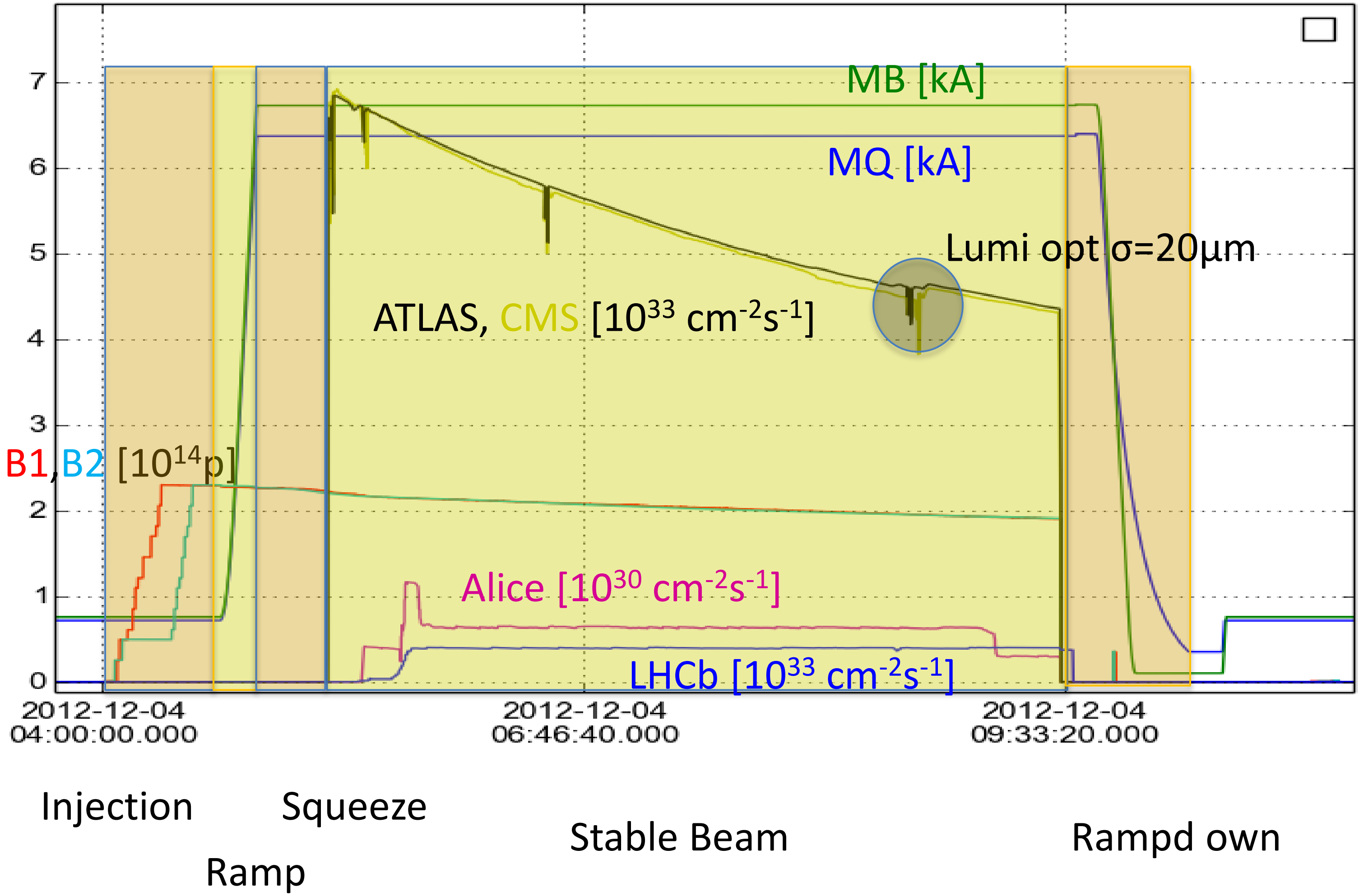
Typical LHC cycle



Turn-around time: assumed for HL-LHC 3h. During Run1: minimum 2h, average 5.5h. Ramp-down MQ and triplets dominating time spent.

Operational Cycles and optics

Different cycles are foreseen:

- Luminosity production for protons. Main options:
  - β^* in IP1/5: Round or Flat
  - leveling with: β^* or parallel separation or kissing in IP1/5[1]
- Van der Meer (VDM) scan (luminosity calibration).
- Luminosity production for ions.

All different cycles requires different optics and powering cycle of quadrupole, orbit corrector, sextupoles.

[1] S. Fartoukh, "Pile up management at the high-luminosity LHC and introduction to the crab-kissing concept", Phys. Rev. ST Accel. Beams 17, 111001.

High Luminosity LHC

Proton-Proton Luminosity

Leveling β* in IP1 and IP5:

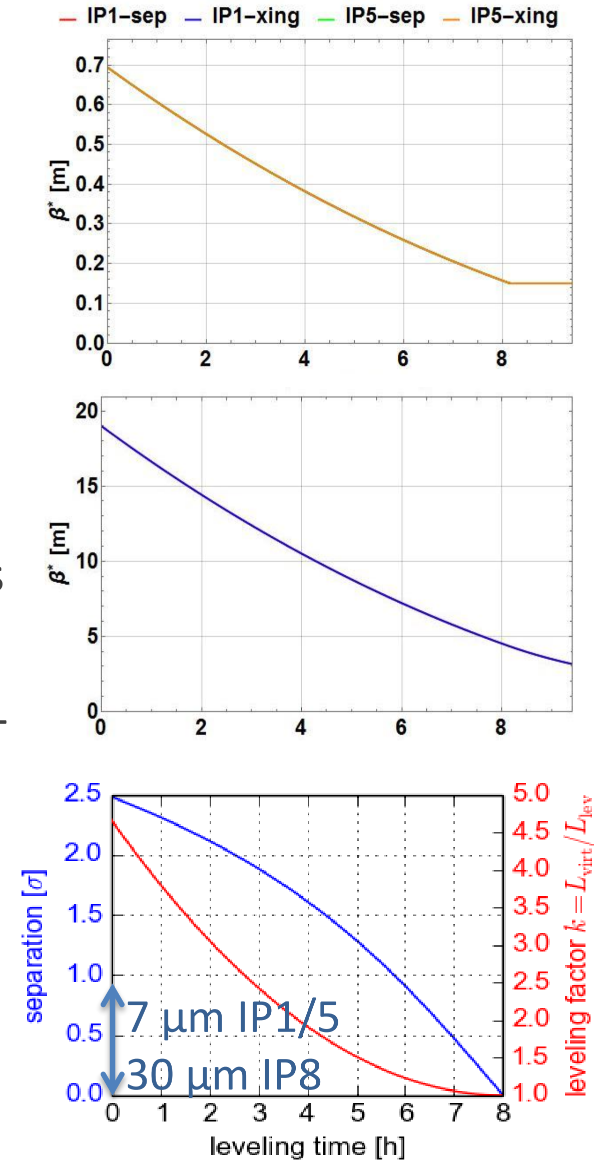
- collisions from β*=70 cm down to β*=15 cm:

Leveling in IP8:

- from β*=19 m up to β*=3 m
- or by separation from 2.7σ (80.5 μm) to 0σ

Challenges:

- Keep orbit stable for small β* and or when optics is changing.
- Separation enhance detrimental effects of beam-beam forces.
- BPM accuracy and orbit feedback at the IP.
- Magnetic model validation with beam, inclusior hysteresis effects.
- Power converter stability.



High Luminosity LHC

β*reach: optics

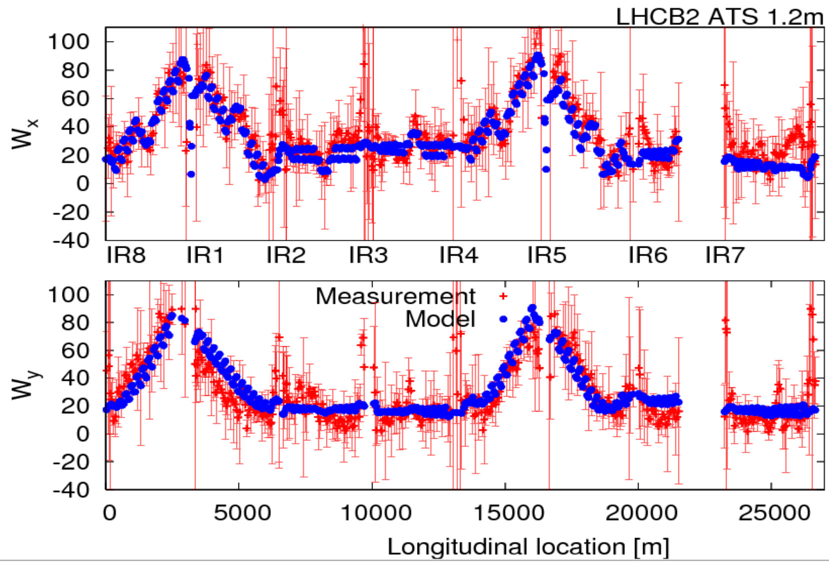
S. Fartoukh, Chamonix 2011, 2012 and reference therein

β* reach within IR1/IR5: 44 cm chromatically corrected.

ATS extend the reach to:

15cm or 30/7.5 cm and beyond

by changes in neighbor insertions



CERN-ATS-Note-2013-004 MD

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The 10 cm beta* ATS MD

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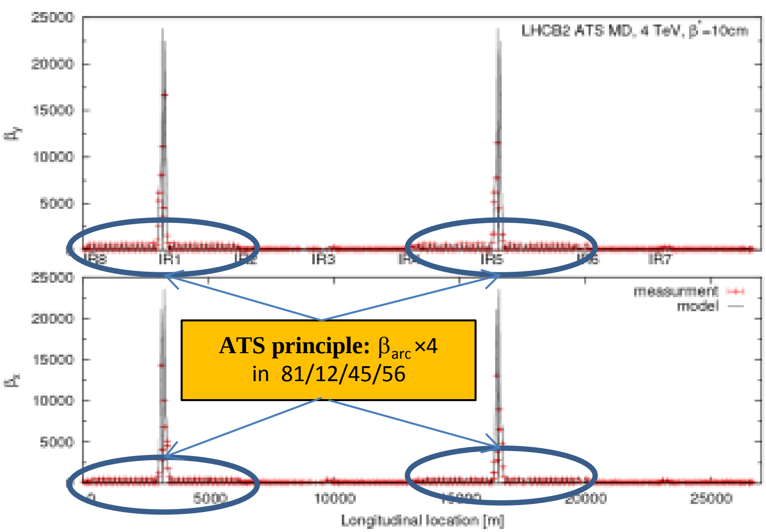
Keywords: LHC optics, Achromatic Telescopic Squeezing Scheme

Summary

This note reports on the results obtained during the last so-called ATS MD which took place in July 2012, and where a β^* of nearly 10 cm was reached at IP1 and IP5 using the Achromatic Telescopic Squeezing scheme.

1 Introduction

The Achromatic Telescopic Squeezing (ATS) scheme is a novel concept enabling the matching of ultra-low β^* while correcting the chromatic aberrations induced by the inner triplet [1, 2]. This scheme is essentially based on a two-stage telescopic squeeze. First a so-called pre-squeeze is



Leveling round beam

Since ATS is needed for β* below 44 cm in IP1/IP5, one can:

	IR1/5	IR2	IR8	IR4/IR6
Injection	6 m	10 m	10 m	Nominal
Ramp	6 m	10 m Triplet change	10 m Triplet change	No change
Squeeze	6 m to 65 cm	10 m	10 m to 19 m	No change
Level	65 cm to 44 cm	10 m	19 m to 12 m	No change
Level	no change, but 44 cm to 15 cm	10 m ATS 1x to 2.9x	12m to 3 m ATS 1x to 2.9x	Optics changes ATS 1x to 2.9x

Levelling in IP1/5 involving 40 quadrupoles per beam/ip.
β* in IP1 linked with the one In IP8. Ramp & Squeeze possible.
Other scenarios are possible.

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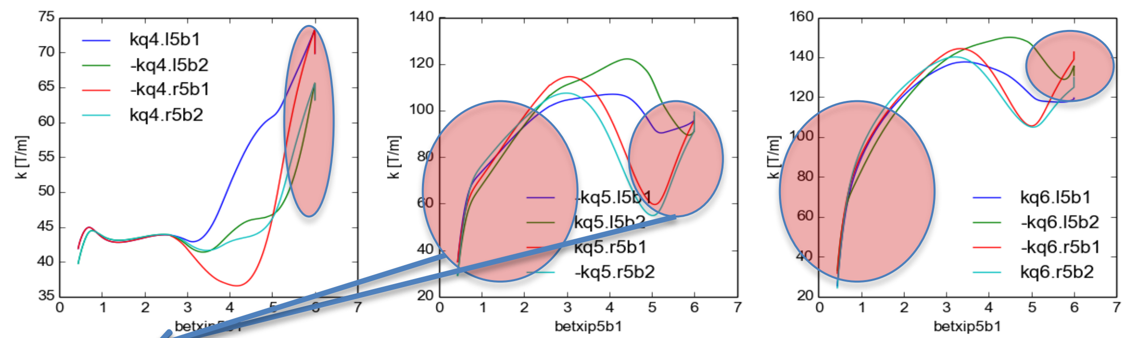
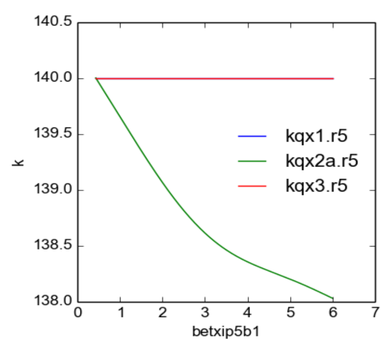
Squeeze in IR1/5 in HLLHCV1.0

- Longer transition from to β*= 6 injection tunes to 44 cm. ATS condition starts from 3 m.
- Further optimizations to smooth the transition are foreseen for HLLHCV1.1.

Time	β*	Slower
0 s	6 m	
68 (241) s	3 m	Q4/Q6
88 (313) s	1.9 m	Q6
150 (490) s	70 cm	Q6
270 (792) s	44 cm	Q6



Cured by
0-6kA,+-10V
Power converter



Triplet strength variation depends on the squeeze function, β*, β at the crab cavities. Flexibility need, see Miriam's talk.

270 s reached with bipolar converters in Q5 (otherwise to slow) and the small inductance of MQYY. [J-P Burnet, Q. King, M. Giovannozzi]

Analysis of the squeeze to be continued: QPS limit, rounding in/out, intermediate stops.

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IR8 Squeeze for ATS in IP1

IP8 collisions with max 4.5 evt/crossing or about 2 10^{33} $cm^{-2}s^{-1}$.

Transitions:

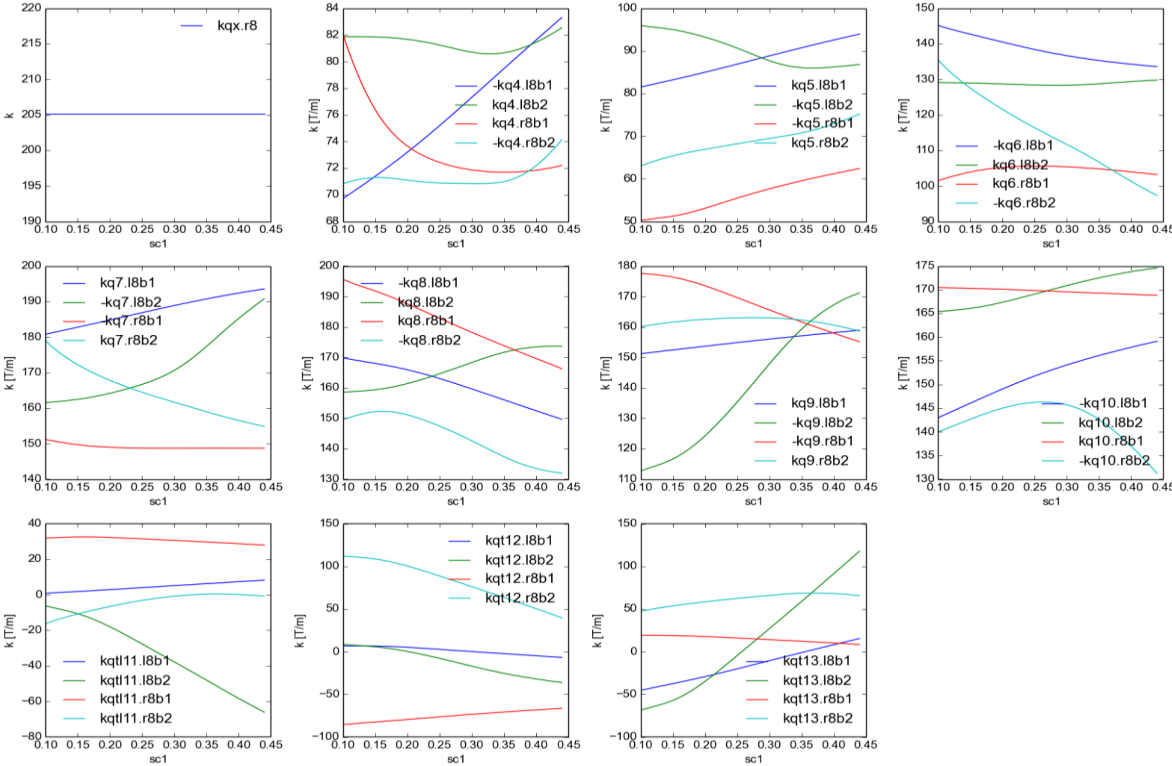
- Reduce triplet normalized strength, possibly during the ramp.
- Reach β* stage for leveling IP8 and/or ATS stage for leveling IP1:

A. 3 m for separation leveling

B. 19 m for β* leveling

- Level IP8 with β* and/or separation and in case IP1 with ATS.

Example ATS squeeze at β*=3m in IP8 for IP1 from β*=44 cm to β*=10 cm



Challenges:
Link between IP1 and IP8 β* (can be absorbed with separation)
Orbit stability.

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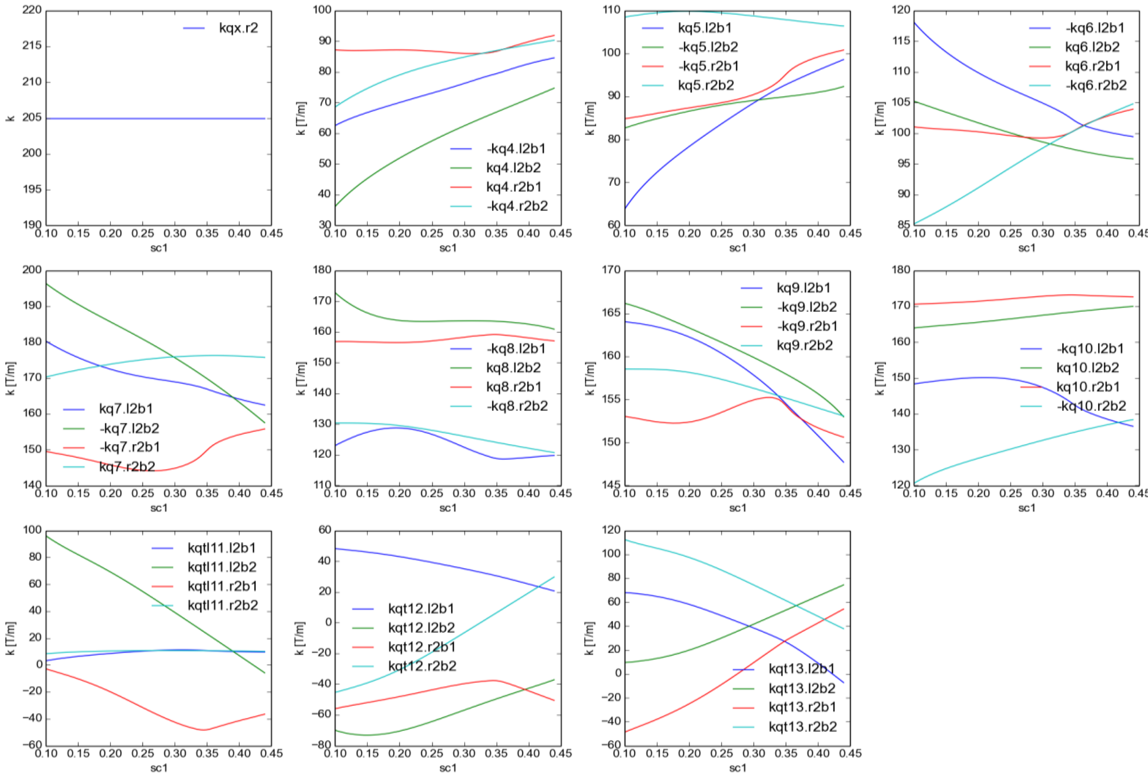
IR2 Squeeze for ATS in IP1

IP2 collisions with halo to keep luminosity below 2 10^{31} $cm^{-2}s^{-1}$ with large intensity.

Transitions:

- Optics transition during to reduce triplet normalized strength, possibly during the run.
- 10 m during collision.
- If IR2 levels β* in IP1 with ATS, ATS factor transition from 1x to 2.9x.

Example ATS squeeze at β*=10 m in IP2 for IP1 from β*=44 cm to β*=10 cm



Challenges:

Large separation very sensitive to orbit variations. Large β* desirable.

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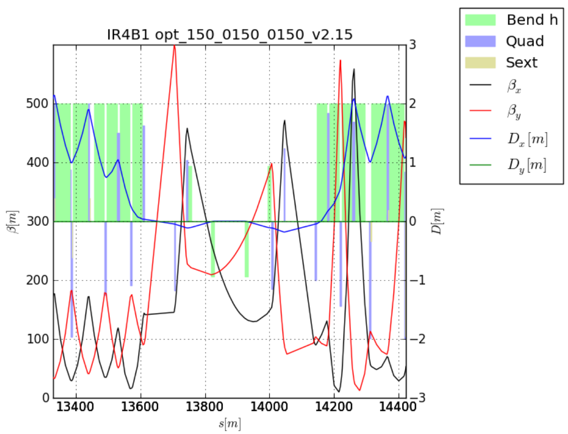
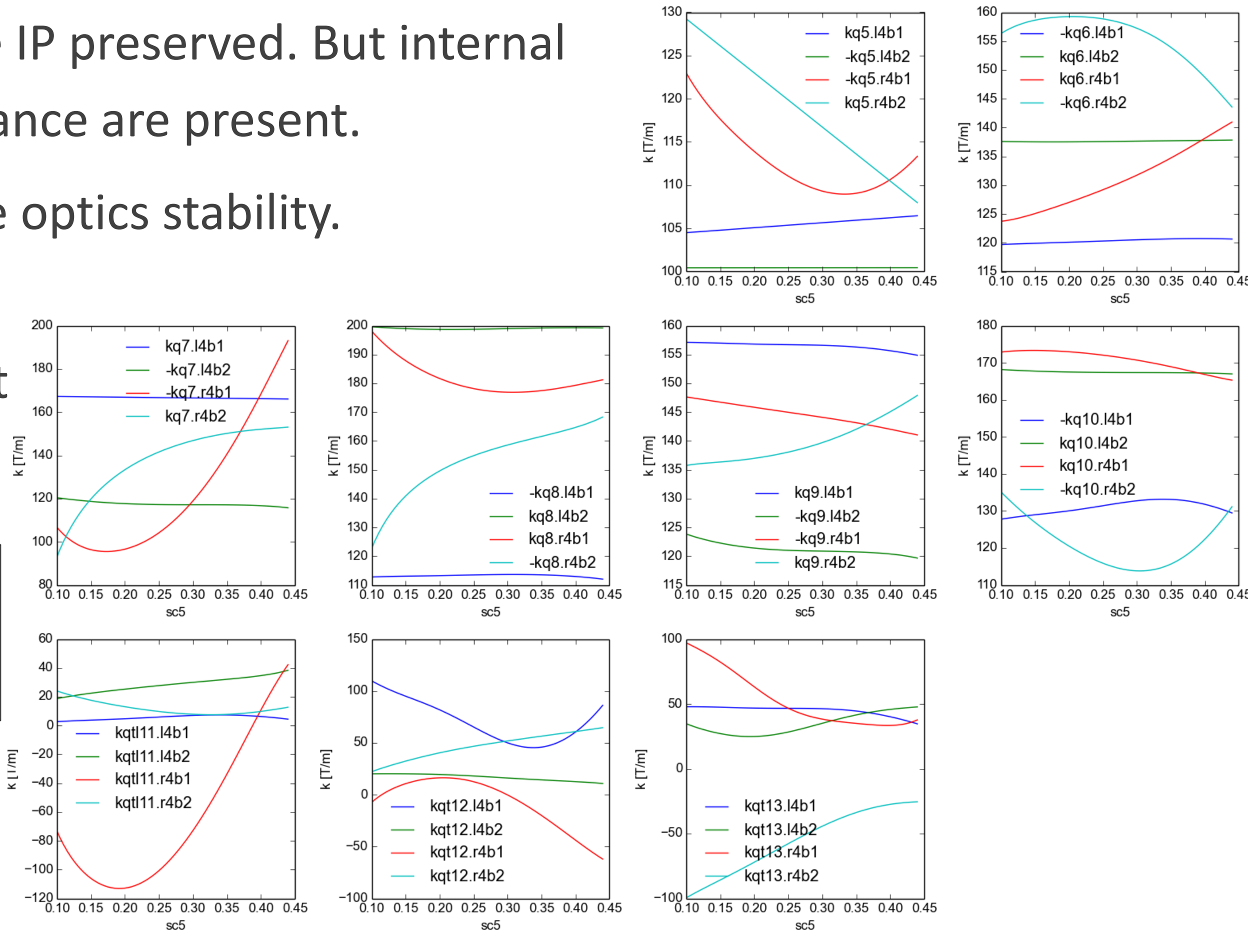
IR4 Squeeze ATS for IP5

- Twiss parameters at the IP preserved. But internal variations of phase advance are present.
- Instrumentation require optics stability.

- Magnet strengths do not present criticalities.





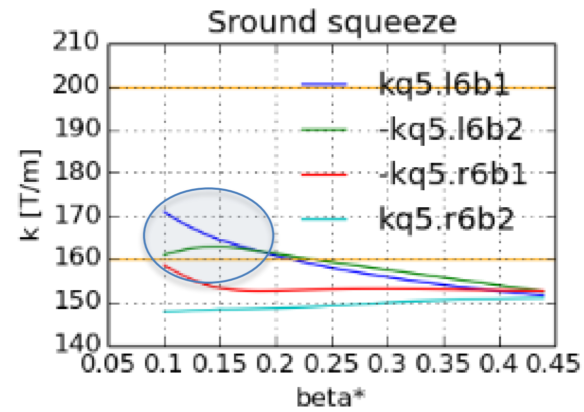
Example ATS squeeze for IP5 from β*=44 cm to β*=10 cm

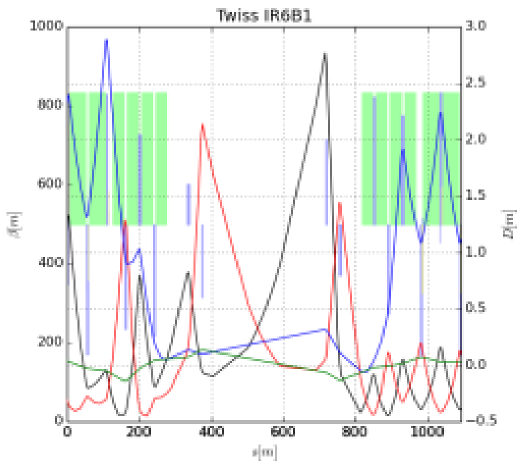
IR6 Squeeze ATS for IP5

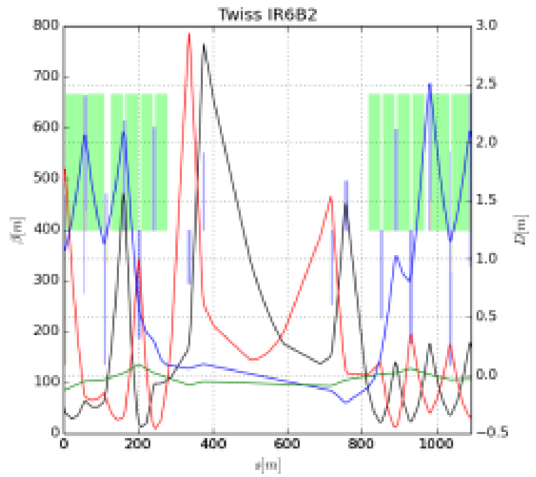
During squeeze:
- Phase advance MKD, Septum close to 90°.
- No change in Q4RB1,Q4LB2.
- Large or equal beam size at the dump.

But:
- Changes of β at collimators.
- Phase advance MKD, Septum not strictly constant.

Squeeze of Q5 pass MQY 160 T/m limit
Need stronger Q5: additional MQY

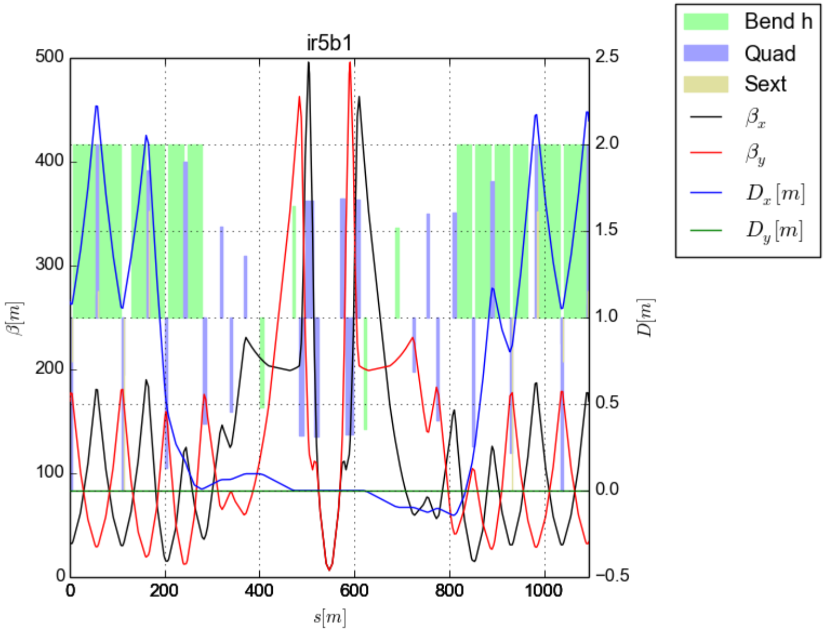






Injection

- Aperture maximized for large beams and injection oscillations.
- Lifetime must be maximized too (large DA, longer bunches for IBS, no e-cloud…) since it is long process.
- Quadrupole normalized strength must be in between 46.6% and 100%, rather than from 3% to 100% for flat top optics due to power converter stability at low current and transfer function accuracy.



	β* [m]	θ/2 [μrad]	d [mm]	
IP1/5	6	+-290	+-2	VH alternated crossing, 6 m limited by low current in few quadrupoles.
IP2	10	+-170	+-2	V crossing, injection constraints large triplets
IP8	10	-+250	-+3.5	H Crossing with angular offset at inj [1].

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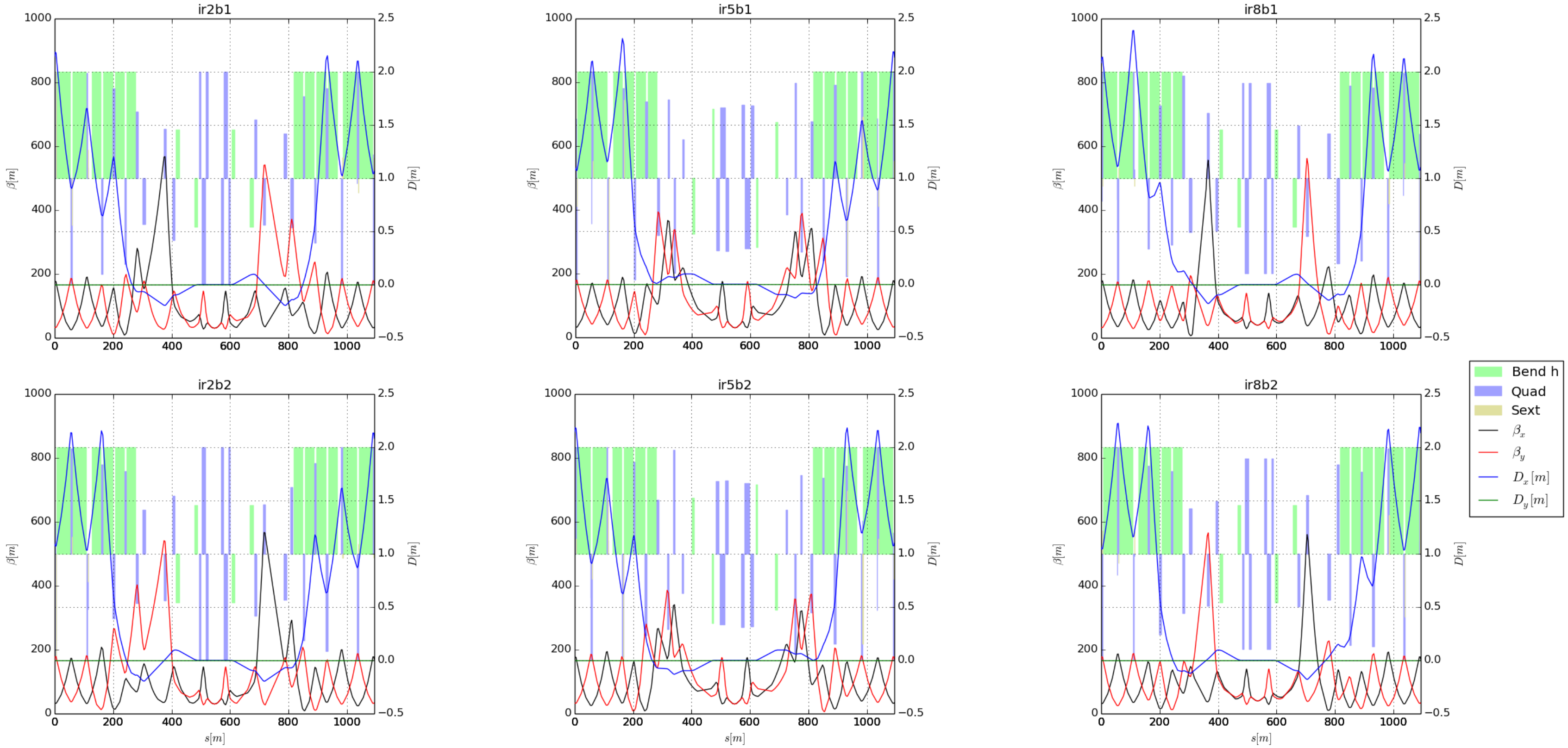
[1] S. Fartoukh, 167th LMC.

VDM optics

Collision energy, large β* (e.g. 30m).

Transitions from injection optics to be detailed with studies.



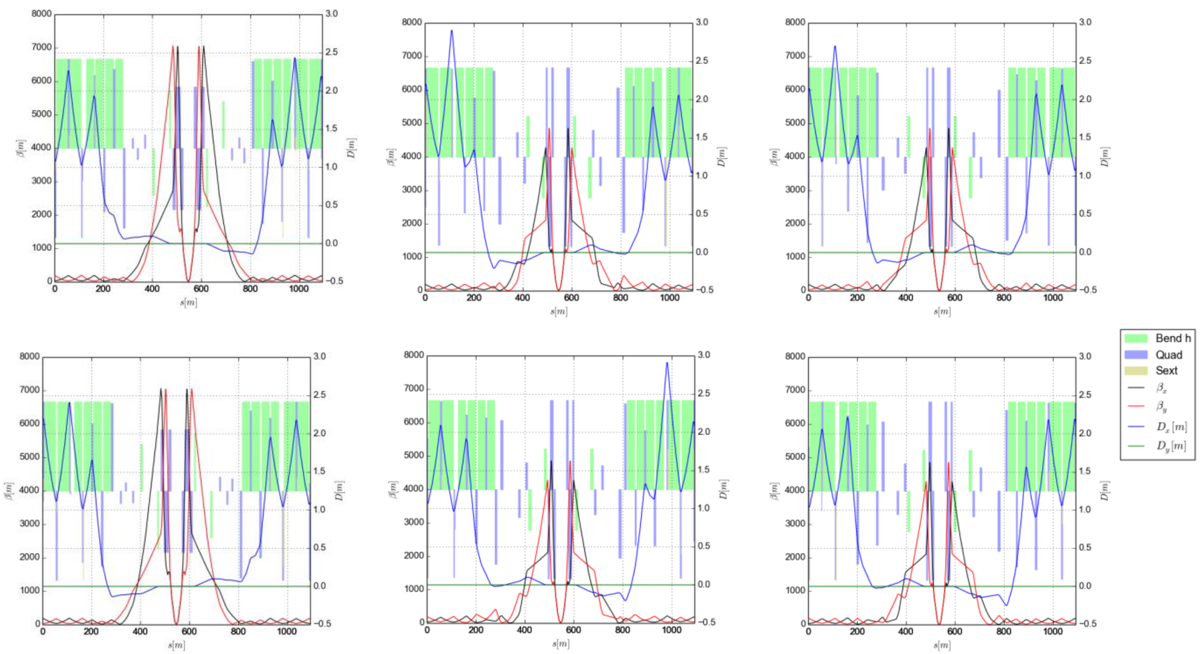
Ion optics

Request to reach low β* in all experiments, but no ATS needed.

	IR4/IR6	IR1/5	IR2	IR8
Injection	Nominal	6 m	10 m	10 m
Ramp	No change	6 m	10 m	10 m
Squeeze	No change	6 m to 44 cm	10 m to 50 cm	10 m to 50 cm

Triplet strength variation of IR2/Ir8 may happen during the ramp or during the squeeze.

Transitions:
IR1/5: same as protons
IR2: specific for ions
IR8: there might be some sharing depending on the scenario



Summary and outlook

- HL-LHC needs to run different types of cycles. For proton-proton different leveling scenarios leads to different optics transitions.
- Experiment conditions have been evolving, but are converging on requirements.
- Complete scenarios needs to be detailed and squeeze duration optimized in particular if several squeezes are combined.
- Reducing turn-around-time passes trough the optimization of optics transitions: strength functions, magnet inductance and resistance, power converter flexibility.
- Operational procedures are being investigated and input from Run 2 is certainly needed to build confidence on the chosen leveling mechanism.
- Leveling requires the best effort to control optics and orbit: magnet models, instrumentation and power converter stability.

Backup

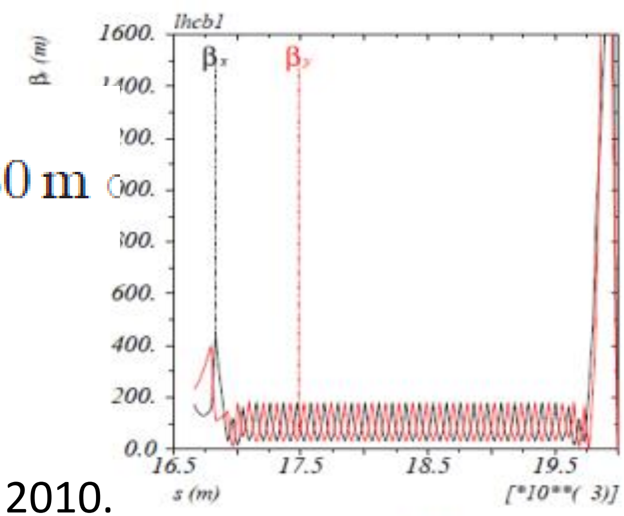
ATS scheme principles

- Blow-up β in the arc to reduce β* done by perturbing optics of IR8,2 for ATLAS and IR4,6 for CMS. IR6 optics not flexible enough -> doubled Q5.
- Specific phase advances are enforced to compensate chromatic aberrations of the triplet, however geometric aberrations are enhanced by the increase arc β.

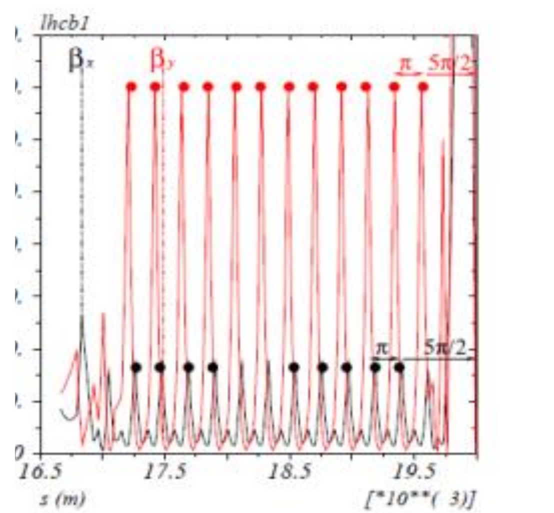
$$\hat{\beta}_{\text{arc}} \approx \frac{\beta^*_{\text{pre-squeeze}}}{\beta^*_{\text{col}}} \times 180\,\text{m}$$

ATS factor

S. Fartoukh, sLHC PR. 49 2010.



(b): Pre-squeeze, $\beta^{*IP1,IP5}_{x,y}$ =60 cm



n, $\beta^{*IP1}_{x/y}$ =7.5/30 cm and $\beta^{*IP5}_{x/y}$ =30/7.5 cm

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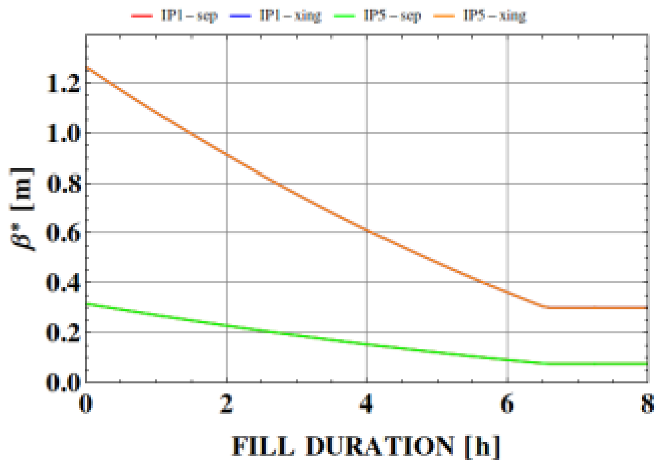
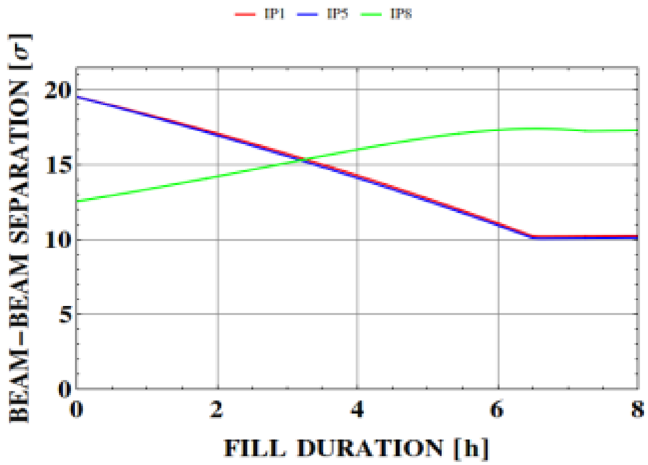
Leveling flat beam options

Flat β* and BBLR compensator allow to reduce the crossing angle from 590 µrad to 350 µrad and crab voltage from 11.7 MV to 7 MV in the crossing plane.





Similar option as for round leveling, but with different squeeze function for IR2/8/4/6 depending on the plane crossing in IR1/5.

More stringent orbit constraint and stability in the non-crossing plane as σ as low as 3.5 µm.

High Luminosity LHC

Leveling round beam

Since ATS is needed for β* below 44 cm in IP1/IP5, one can:

	IR1/5	IR2	IR8	IR4/IR6
Injection	6 m	10 m	10 m	Nominal
Ramp	6 m	10 m, Triplet change	10 m, Triplet change	No change
Squeeze	6 m to 65 cm	10 m	10 m to 19 m	No change
Level	65 cm to 44 cm	10 m	19 m to 12 m	No change
Level	no change, but 44 cm to 15 cm	10 m ATS 1x to 2.9x	12m to 3 m ATS 1x to 2.9x	Optics changes ATS 1x to 2.9x

Levelling in IP1/5 involving 40 quadrupoles per beam/ip.
β* in IP1 linked with the one In IP8. Ramp & Squeeze possible.

High Luminosity LHC

Leveling round beam (option B)

Since ATS is needed for β* below 44 cm in IP1/IP5, one can:

	IR1/5	IR2	IR8	IR4/IR6
Injection	6 m	10 m	10 m	Nominal
Ramp	6 m	10 m	10 m	No change
Squeeze	6 m to 1.9 m 70 cm at IP	10 m ATS 1x to 2.9x	10 m to 19 m ATS 1x to 2.9x	Optics changes ATS 1x to 2.9x
Level	1.9 m to 15 cm	10 m	19 m to 12 m	No change

No optics change in IR4/IR6 during levelling. 20 quadrupoles per beam/IP involved. β* in IP8 independent from β* in IP1. No need to speed-up second part of IR1/5 squeeze. Optionally ramp&squeeze: no need to speed-up first part of IR1/5 squeeze.

High Luminosity LHC

IR6 Optics and Squeeze

Basic needs taken into account: MKD – Septum phase advance , beam size at dumps.

However optics and squeeze are not fully validated (WP5, WP14):

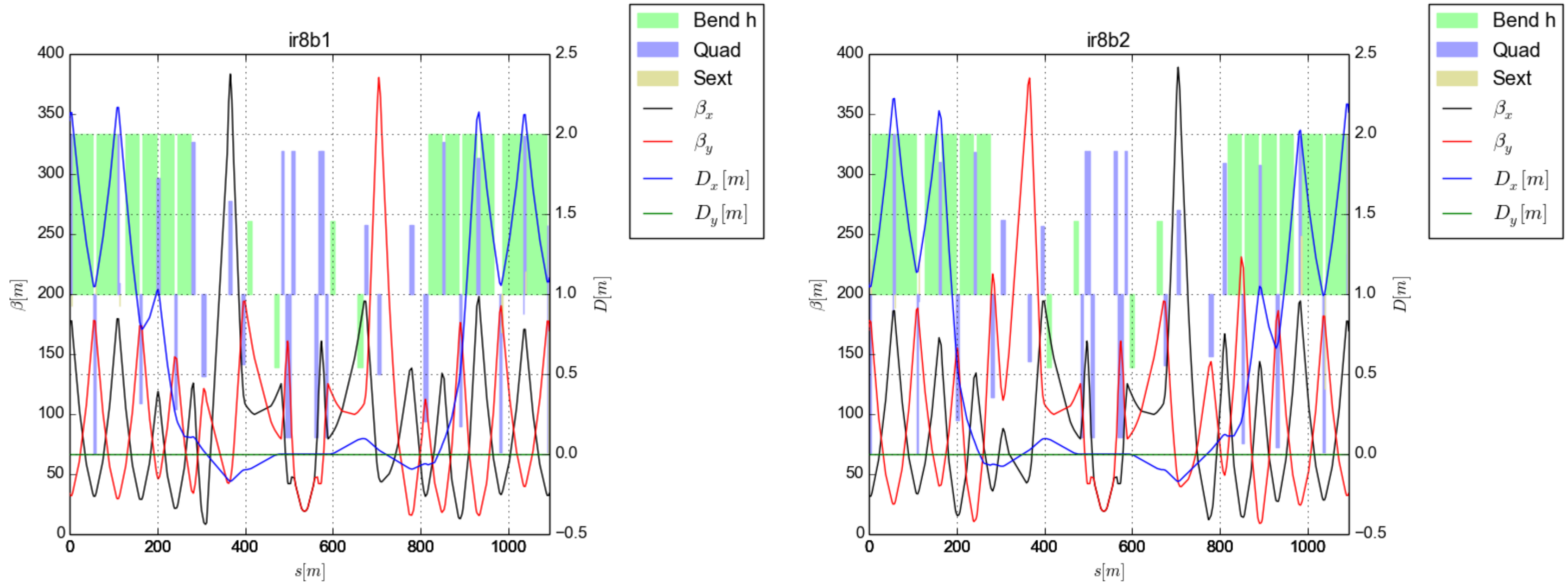
- phase advance between MKD and TCT are not optimal nor optimized and impact TCDQ – TCT retraction.
- Failure scenarios with ATS in the arc
- β-functions at TCDQ, TCDS, TDE do vary during the squeeze.
- Warnings issued for low β_y TCDQAR6.B1- TCDQAL6.B2 in sflathv and flat resp. large and large β_y in flathv, sflathv (Y. Uythoven 10/4/2014).

optics	β_x IP6	β_y IP6	μ_x tcsg → mkd_h5l6b1	β_x dump	β_y dump
inj b1	187.3	168.1	94.8	5012	3955
inj b2	187.7	178.4	94.8	5052	3698
round b1	324.3	188.2	90	8172	4463
round b2	248.8	176.7	90	6123	3698
flat b1	212.2	156.3	90	5067	4643
flat b1	217.6	238.5	90	5238	4286
flathv b1	298.1	236.3	90	7466	4446
flathv b2	272.8	205.9	90	6784	3717
sround b1	241.2	185	90	5900	3955
sround b2	252.5	167.2	90	6224	3725
sflat b1	236.9	190.6	90	5778	6771
sflat b2	248.7	237.1	90	6120	3728
sflathv b1	314	176.8	90	7895	3956
sflathv b2	277.7	216.9	90	6918	3722

KQ4.L6B1 and KQ4.R6B2 have nominal strength.

R. De Maria (CERN, Geneva) HLLHCV1.0 HL-LHC WP14, 2013/07/09 11 / 13

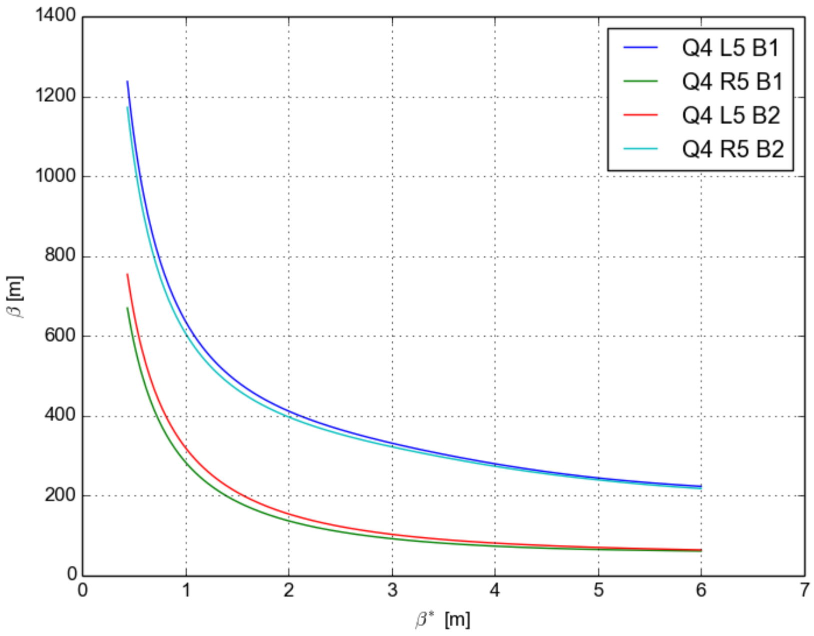
IR8 19m first attempt

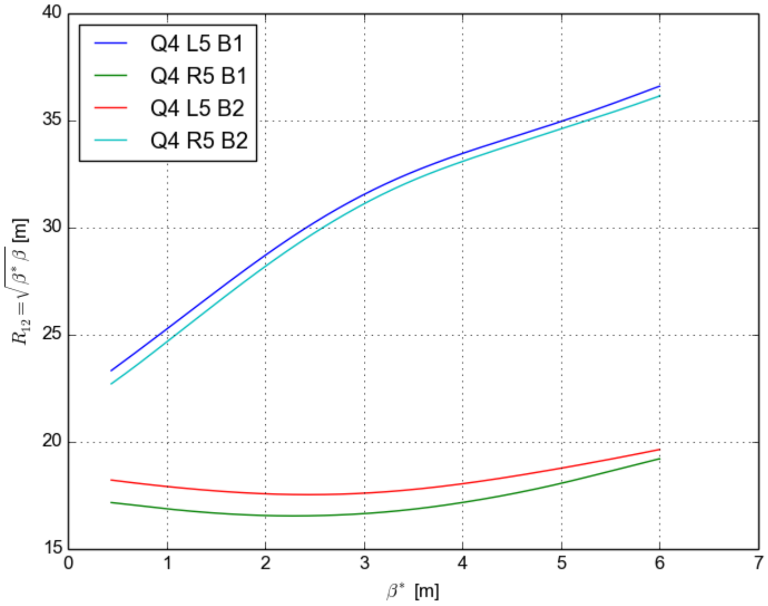


Triplet as low as 180 T/m.
MCBX123=-36 µrad (54%), ACB[CY]5=84% for 250 µrad crossing angle.

Beta at the crab cavity location (Q4)

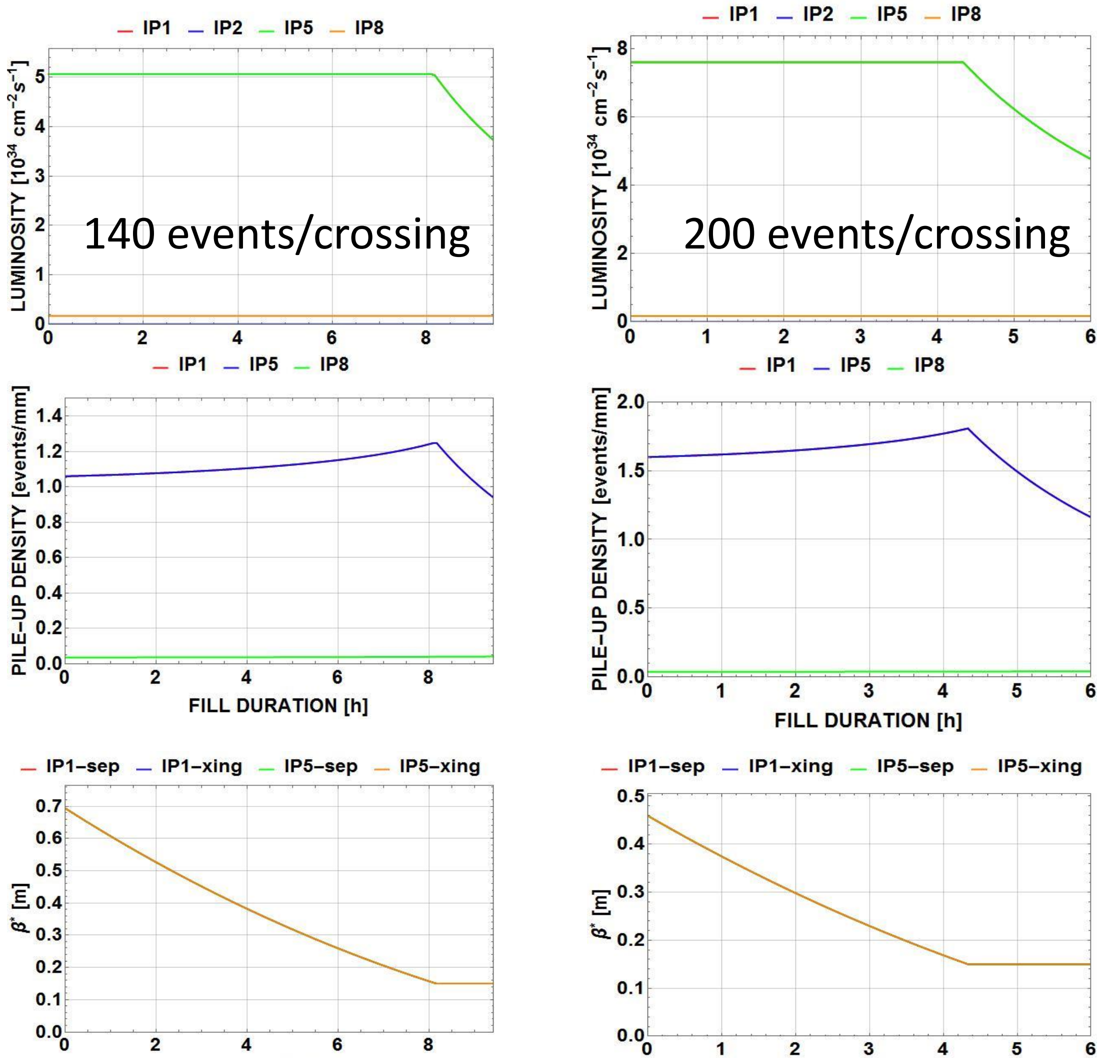
Variations during squeeze of IR1/IR5 of HLLHCV1.0.



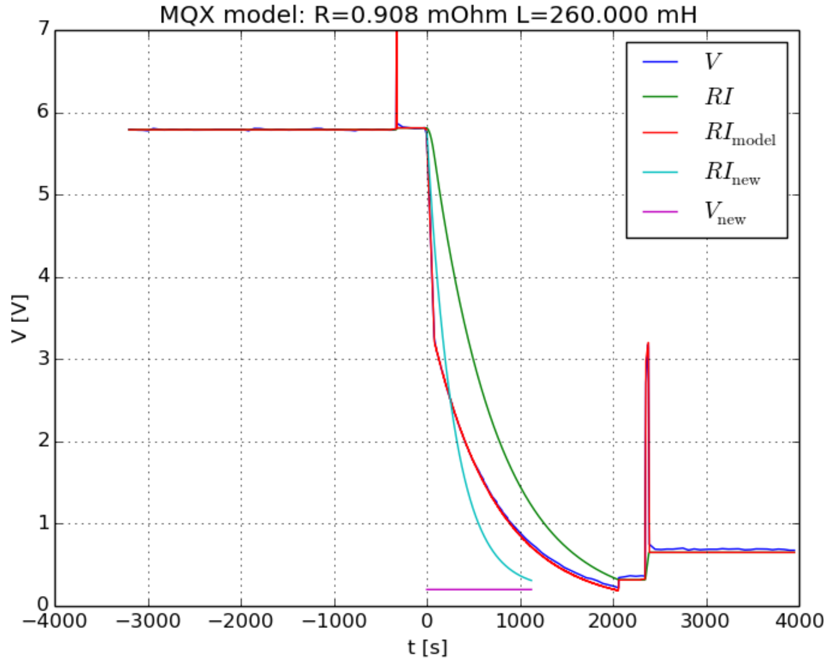


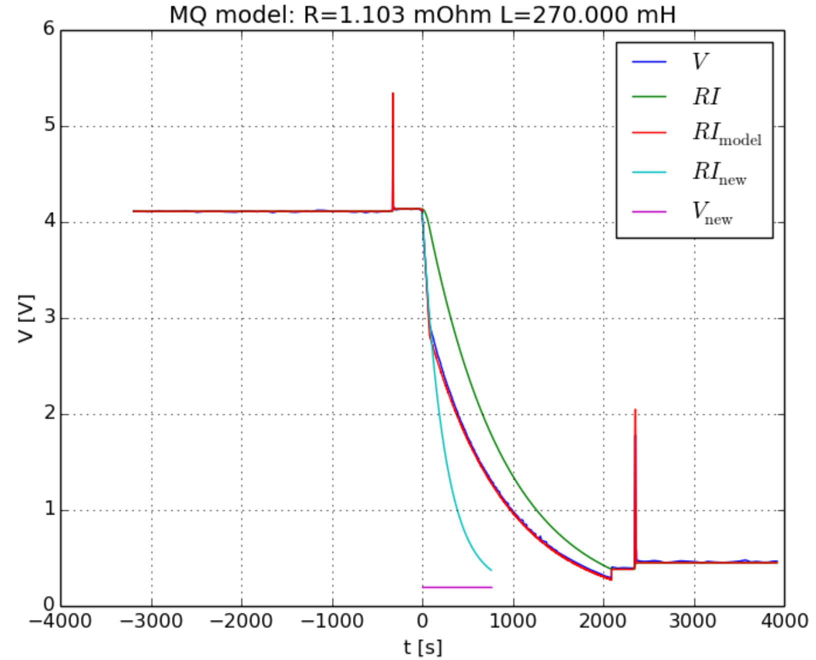
For HLLHCV1.1 monotic R12 will be attemped for low β*.

Comparison Leveling scenarios



MQ and Triplet ramp down at 4TeV





Are speed-up possible with uncontrolled discharge?

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