HL-LHC optics studies and Machine development results

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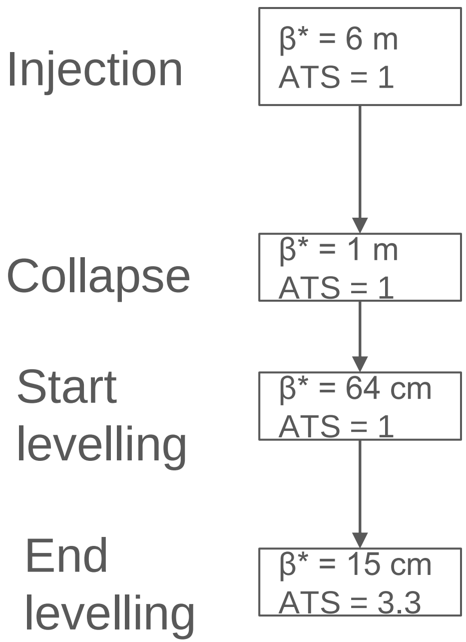
2024 HiLumi Annual meeting

Baseline optics cycle

As of LHC-PM-ED-0002 v.1.0

15 Weeks EYETS	Proton physics	Availability	min β*	CC	∫ L dt
	[days]		[cm]		[fb^{-1}]
2029	6	0.5	30	no	9.6
2030	136	0.5	25	yes	208
2031	154	0.5	20	yes	239
2032	152	0.5	20	yes	236
Run 5 avg	182	0.5	15	yes	280
Run 6 avg	184	0.5	15	yes	309

Design report



Solid baseline with a ramp up to nominal performance.
The focus now is addressing mitigation and performance optimization options motivated by:

- Shrinking schedule
- Feedback from hardware updates, improved understandings

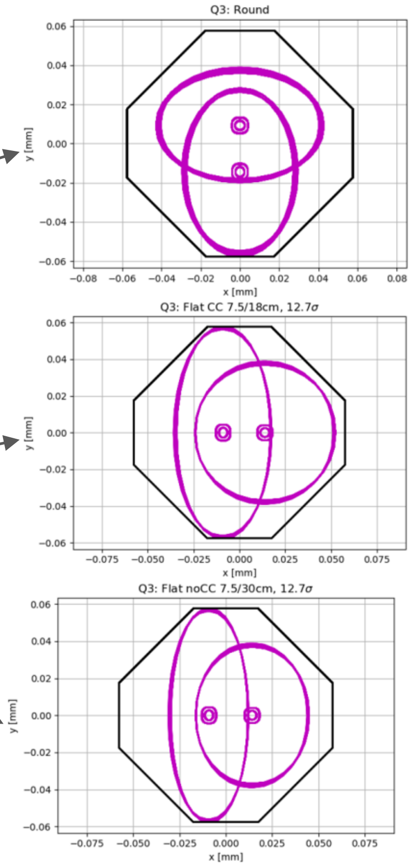
Flat optics opportunities

Flat optics: larger beta* in the crossing plane and lower beta* in the separation plane.

Flat optics at the end of the levelling increases virtual luminosity (for high pile-up, low ppb scenarios) for similar aperture in the triplets.

Flat optics throughout the cycle reduces emittance growth, impedance, failure induced losses from crab cavities.

Virtual lumi $2.2\ 10^{11}$ ppb	Round β*=15 cm	Flat β*=8 cm X-plane
CC On	$16.9\ 10^{34}\ cm^{-2}s^{-1}$ (250 μrad)	$20.6\ 10^{34}\ cm^{-2}s^{-1}$ (18 cm //-plane, 250 urad)
CC Off	$8.31\ 10^{34}\ cm^{-2}s^{-1}$ (250 μrad)	$16.5\ 10^{34}\ cm^{-2}s^{-1}$ (40 cm //-plane, 200 urad)



Flat optics are more sensitive than round to non-linear imperfections. Simulations have shown that flat with CC is viable at low chromaticity and negative octupoles is still viable.

Experience expected in 2025 will provide insights on these scenarios.

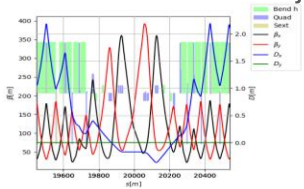
Impedance mitigation

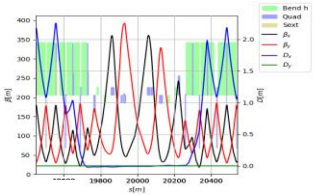
IR3 and IR7 (see Bjorn, Lorenzo slides)

Impedance is stabilized by Landau octupole and chromaticity at the cost of beam lifetime.

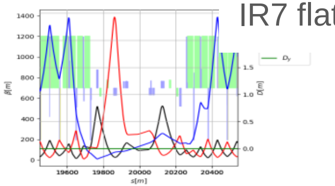
Studies ongoing to decrease impedance by new IR7 and IR3 optics (on top of potential gains by collimators gap), as well as increasing cleaning efficiencies.

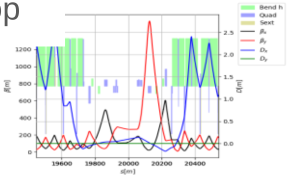
IR7 injection



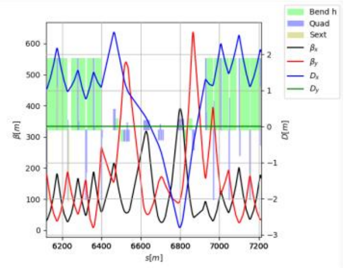


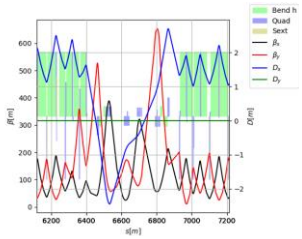
IR7 flat top





IR3 flat top





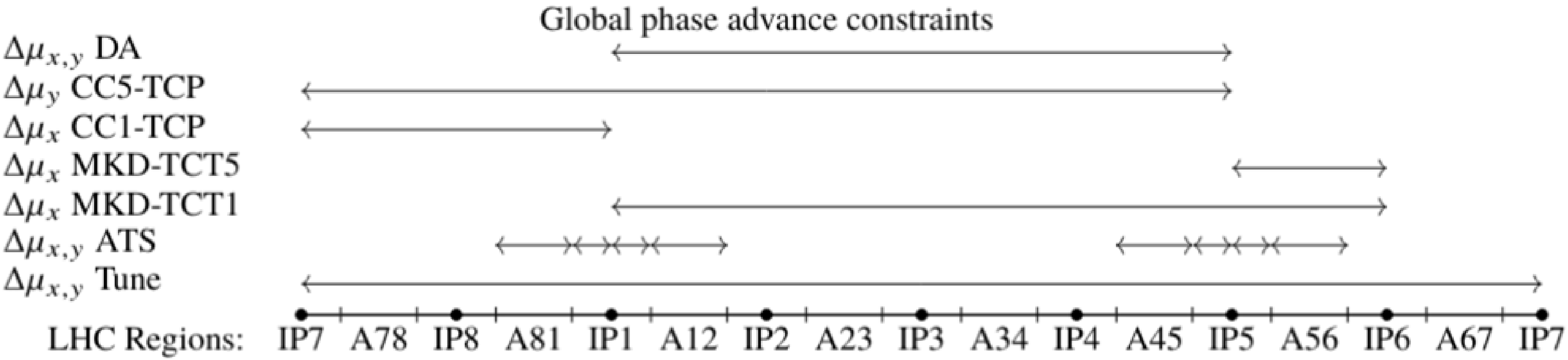
Flat optics

Large beta in the crossing plane enhance CC effect on luminosity, but also impedance and emittance growth. It is only needed at the end of levelling.

Flat optics mitigates this effect thanks to the smaller beta in the crossing plane.

β*	1.1 m high	1.1 m low	0.9/1.8 m low no ats	1.8/0.9 m with ats
Avg beta crab	680 m	466 m	327 m	280 m

Phase advance optimization



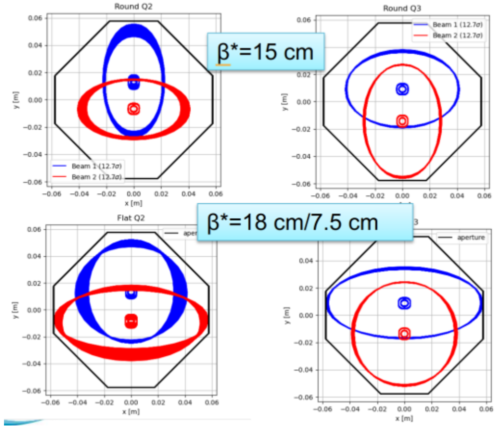
ATS blocks the phase in 4 arcs.
MKD-TCT phase is critical to the beta* reach.
CC-TCP phase is important for crab failure scenarios.
TCP-TCT important for background.
IP1-IP5 phase important for DA.

Efforts to find a global optimum for the different phases of the cycle that have different compromises. Work ongoing, iterative work.

Step in the cycle	β^* [cm]	Optimisation criteria
Injection	600	aperture in the arcs, octupole Resonance Driving Terms (RDT)
Flat top	200-50	β_{crab}, octupole RDT
Separation collapse	200-50	octupole RDT
Start of levelling	200-50	octupole RDT, $\Delta\mu_{x,\text{CC1-TCPH}}$, $\Delta\mu_{y,\text{CC5-TCPV}}$
End of levelling	20-7.5	aperture in the triplets, field quality, $\Delta\mu_{x,\text{MKD-TCT1,5}}$, $\Delta\mu_{x,\text{CC1-TCPH}}$, $\Delta\mu_{y,\text{CC5-TCPV}}$

β* reach and crossing planes

Flat and round have approximately the same beam size at the triplets.



β* reach depends on MKD-TCT phase advance and (new finding) TCL gaps. Crossing plane, triplet polarity, crabbing angle matters, IP1 or IP5!

1) MKD-TCT difficult to achieve when squeezing β^*_X in IP5. Vertical crossing angle (that is small β^*_x in P5) is the worst, well known, choice in this respect.

1) Present triplet polarity $\beta_X > \beta_Y$ at the TCL: large gaps needed (good for PPS2), -> small H radius in pass-through pipe -> large power deposited in D2 and TCLMB for vertical crossing.

Mitigations:

1) Exchange crab cavities for Run 5 (extend reach 5600 fb-1 lifetime)
2) Improve MKD-TCT also for V crossing in P5 (see next slides)
3) Explore RP optics (not for now)

IR4 Optics

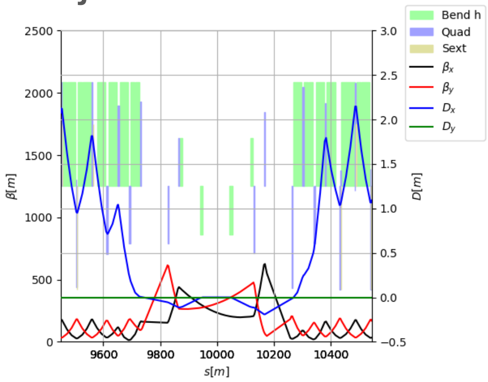
IR4 optics for HL was studied and optimized for BI around 2019.

At that time, it was decided not to use the aperture flexibility at high energy to increase beta* for the baseline.

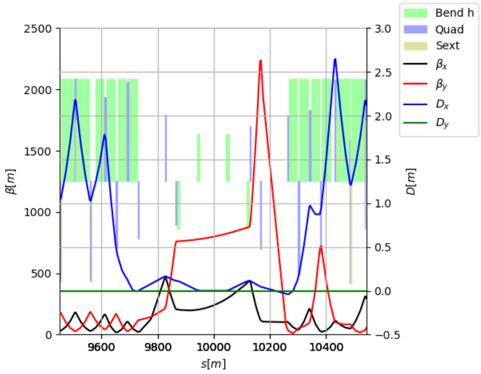
Still, the option is not excluded in general and the interest for BGI, coronograph, etc.. is very high.

For the MD studies, we proposed to try to increase the beta function during a segment in the squeeze.

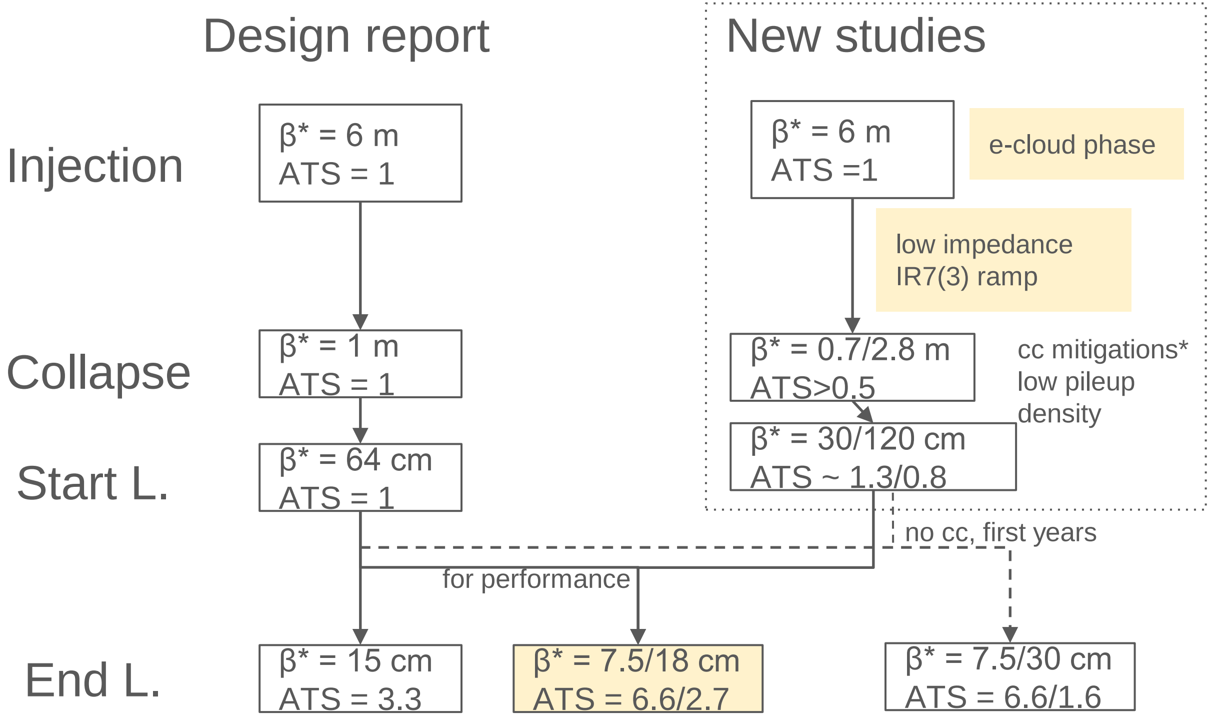
Inj. nominal



Proof of principle optics for machine studies



Nominal cycle vs new proposals for HL-LHC



Several decisions pending for new studies:

1. crossing plane VH better β* reach (MKD-TCT)
2. detailed β*, ATS steps

MD to focus on new studies and extremes cases.

* cc impedance, emittance growth, fast failure

Run 3 experience: OP and MD

HL-LHC baseline relies on an ATS factor of 3.3. A factor 4 was already tested in MD in 2012 [S. Fartoukh et al Phys. Rev. ST Accel. Beams 16, 111002 (2013)].

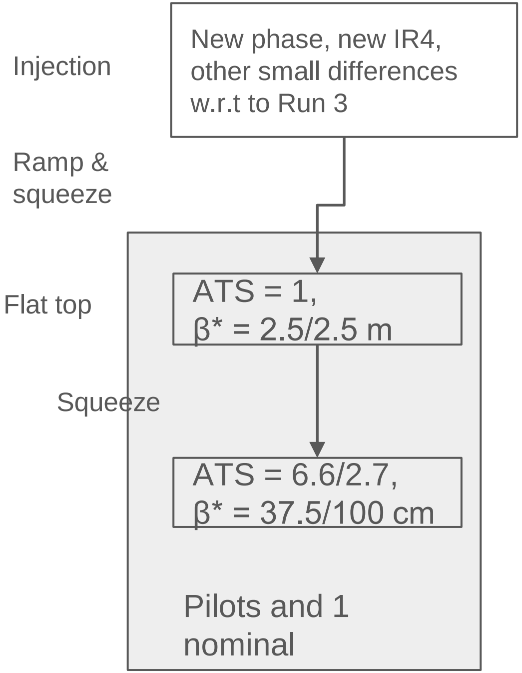
LHC Run 3 operates reliably with an ATS factor of 2. For 2025, the present assumption is to run with a flat optics with ATS factors 1/3.

MD Program in 2024:

Investigate the feasibility of new/advanced/extreme optics manipulations that could be used in the HL-LHC optics to enhance performance or mitigate unexpected issues.

1) ATS squeeze up to 6.6 factors (1.2 km beta in arc, but beta* = 1m/37.5 cm in IP1/5). Pushed optics for the arcs, never tested in the machine.
    a) Optics measurements and corrections.
    b) Aperture measurements in the arcs.
    c) On- / off-momentum loss maps with degraded off-momentum beta-beating.
    d) *Investigate the feasibility of a beta increase in IR4 during the squeeze at flat top.*
2) Test new K-smoothing algorithm for ramp & squeeze. It will improve future optics transitions during ramp, particularly needed for HL-LHC, as unnecessary acceleration/deceleration of the current will be removed.

HL-LHC MD cycle



Measure and correct orbit and optics,
Validate for $3\ 10^{11}$ total (1 or 2 bunches)
[Test aperture, ~~test DA with negative octupole polarity~~]

New IR7 and IR3 transition in the ramp.
Measure and correct orbit and optics,
Measure orbit stability at collimators.

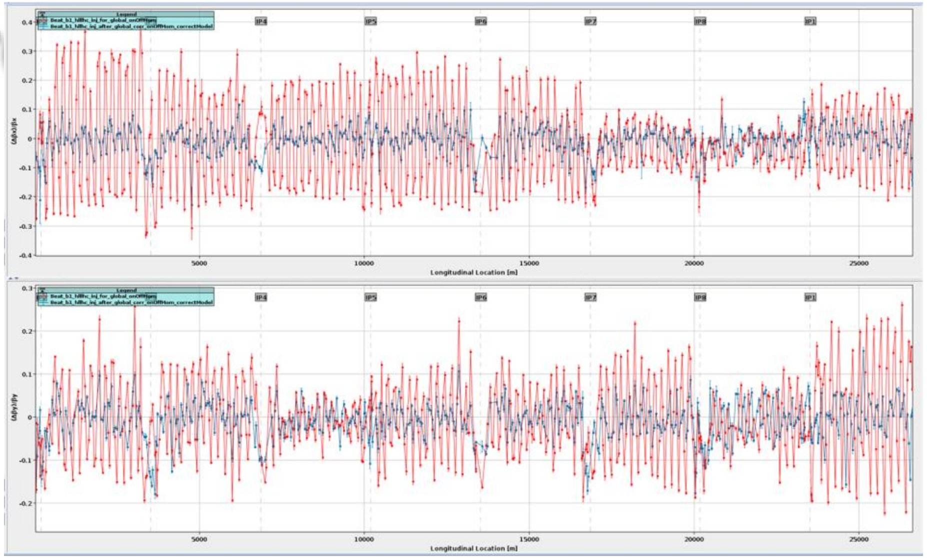
Experimental high beta in IR4 in beam 2 in part of the squeeze

Equivalent HL β*=7.5/20 cm
Measure and correct orbit and optics, measure orbit stability and aperture.
Collapse one nominal with a small crossing angle at some convenient stage.

Crossing planes V(IP1)H(IP5): to avoid TCDQ complication (to be solved by foreseen TCDQ/SMP control upgrade)

[First full cycle developed with xsuite in the machine!]

MD2 r

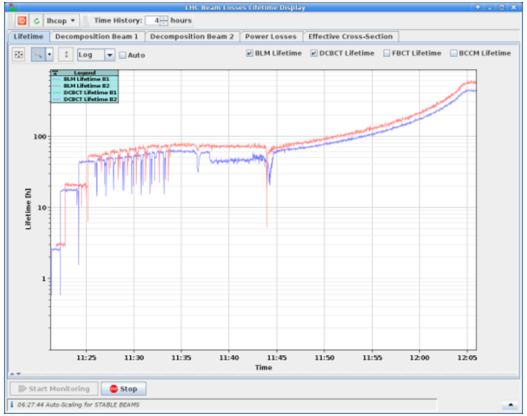


[Started June 6 14h to June 7 02h and restarted on Saturday 8 at 8h to 19h]

Injection:
Beam 1 was well corrected, while Beam 2 needed a second global correction.
Injection aperture within spec at injection in B1, B2. TCPs were aligned at FT with pilots.

Ramp:
Ramp was successful with good lifetime. No issues were observed during the ramp, such as spurious loss spikes in IR7. Loss maps ok!
At 1 TeV the beta-beating looks a bit high, going over the 20% mark.

Flat Top:
The corrections show good control of betas, below 10%.



MD3 results

Not very lucky: RF and AC dipole issues halved the allocated time.

Started on August 21 at 18h up to 6h.

Ramp:

New ramp successfully validate no issues!

Squeeze:

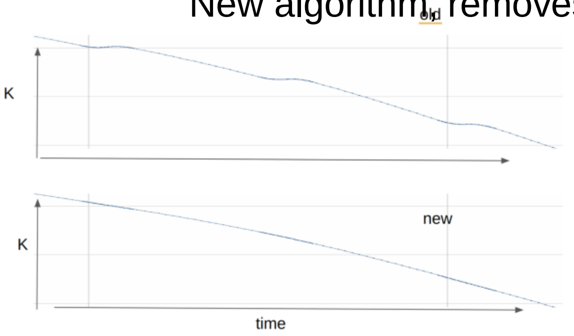
Record high ATS factor measured and achieved with beam.

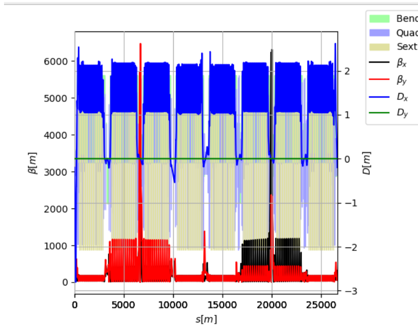
No specific issues with large βy in Point 4, AC dipole data acquired!

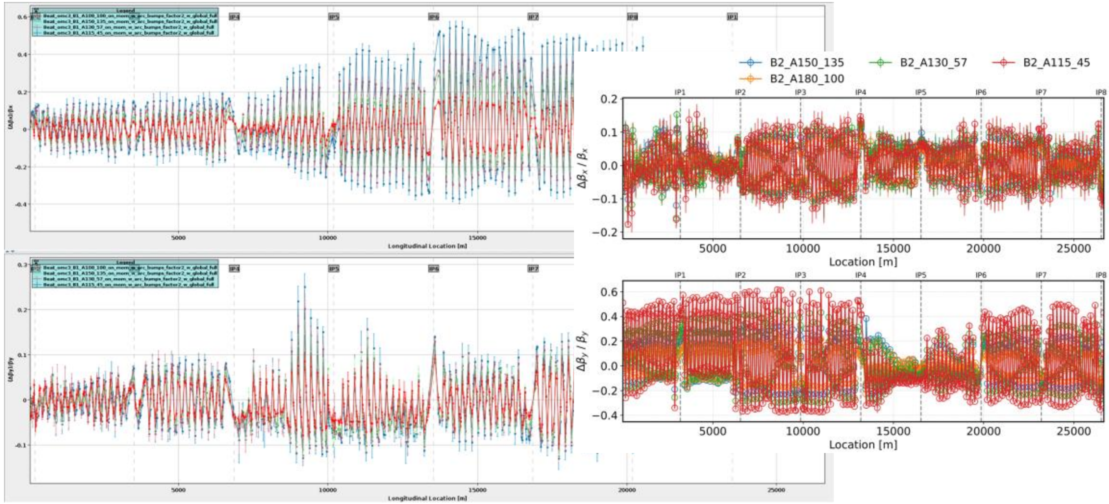
Challenging optics to correct expected, optics correction to be prepared to MD4.

Peak beating reached 55% in Beam 1 and 60% in Beam 2 at 1.15m/0.45m.

New algorithm removes the steps.







MD4 results

Started on Sep 29 at 0h up to 6h.

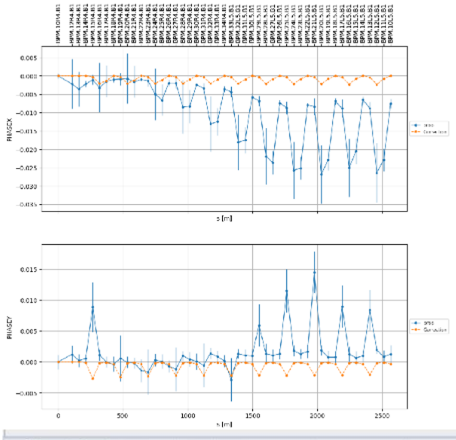
Squeeze:

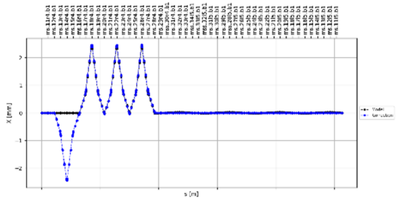
Step at 84 cm with ATS factor of 3 good corrections with beta-beating below 20%.

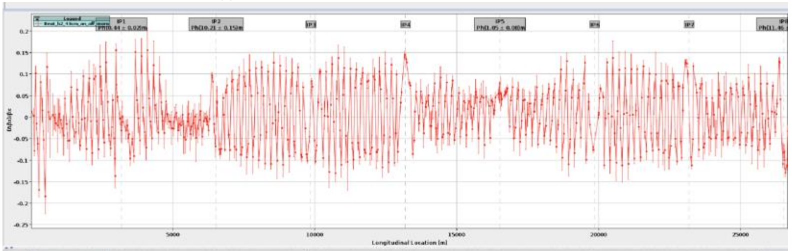
Step at 46 cm mostly successful in Beam 1 reaching slightly above 20% in a few points in the arcs, but Beam 2 still has close to 40% in arc45, while well corrected in all the other arcs.

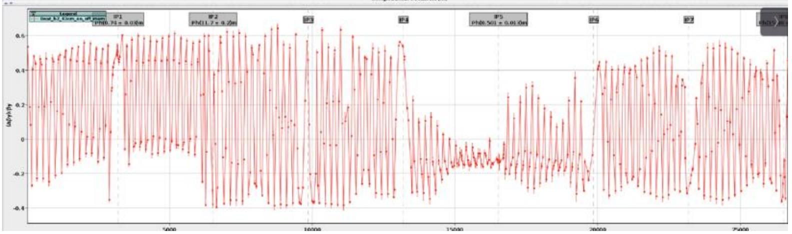
Last 2 steps prevented by a technical hiccup.

Loss maps at flat top ok, not conclusive for the squeeze.









Conclusion and next steps

HL-LHC optics baseline is solid and main ingredients well tested in the machine.

Current effort is on validating mitigation and performance improvements options with machine studies.

Next steps on studies:

2025: if not possible to introduce new IR7 and IR3 optics in the production cycle, build a new HL-like scenarios and test trains

2026: if successful, propose to add new optics in IR7, IR3 during the ramp.

Discussions on going on whether to start Run 4 with the TDR cycle or a new cycle integrating mitigations on the of balance of the

1. risk of introducing new features, which may reveal unexpected issues
2. cost of adding mitigations in the middle of Run 4.

Backup

TCL, TCT settings estimates

	MKD-TCT5	IP5			IP1		
		β*	TCTH(2)	TCL(2)	β*	TCTH(2)	TCL(2)
Round	30/31	15/15	10.9σ	14.2σ 21.3 mm	15/15	10.2σ	14.2σ 21.3 mm
Flat HV	40/45	9/18	12.3σ	12.3σ 23.8 mm	18/9	10.2σ(1)	15.5σ 21.3 mm
Flat HV	51/54	7.5/18	13.1σ	13.1σ 27.8 mm	18/7.5	10.2σ(1)	15.5σ 21.3 mm
Flat VH	27/25	18/7.5	11.7σ	15.5σ 21.3 mm	7.5/18	10.2σ	10.2σ 21.6 mm

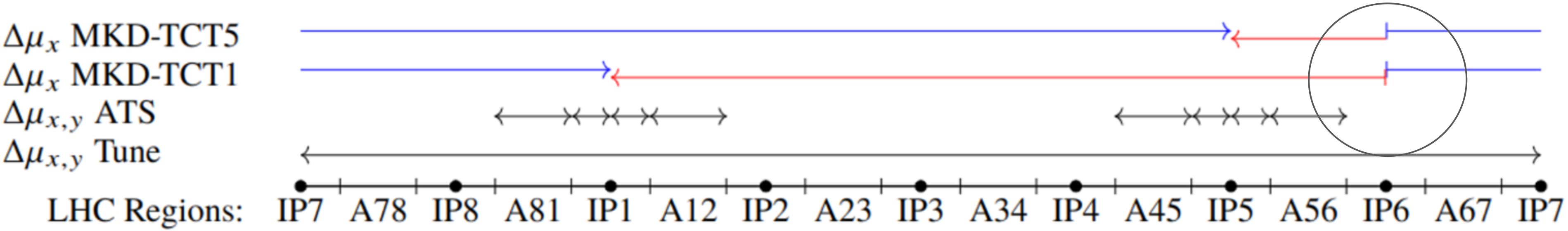
Assuming TCL can be as low as TCTs as they see the same MKD -TCT phase.

1) MKD-TCT is also responsible for limiting beta* reach due to power deposition in D2 and TCLMB
2) Reversing triplet polarity could help here! But, it requires a redesign of TCTPHX, TCLPX, reverse of MCBY orientation in Q4, demonstrate optics solutions in P1/5 for β* 0.5-30 m and crabbing angle >380 murad.
3) Switching crossing planes solves the problem should be the baseline for Run 5 and 6!
4) Exploring complications of improving MKD-TCT (next slide)

(1) achievable but not demonstrated yet, (2) tight collimator setting

MKD-TCT optimizations

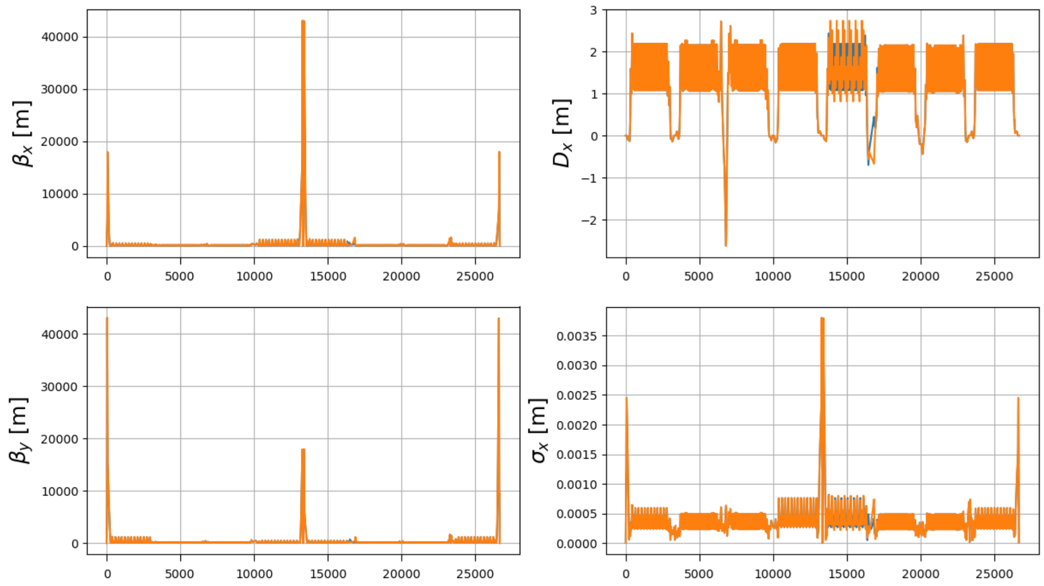
MKD-TCT are difficult in P5 because very few quadrupoles available (due to ATS) and many constraints



Horizontal matching more difficult because of the dispersion constraints. Options:

1) Relax dispersion matching -> dispersion beating in the arc 56 (next slide)
2) Relax ATS matching -> limit spurious dispersion correction and off-momentum beta-beating and Q' (next step)

Relaxing phase advance constraints



Courtesy G. Iadarola with Xsuite! Matching particularly tricky with many inequalities on arbitrary constraints, where MAD-X suffers. The matching algorithm based on MAD-X Jacobian method but further improved to limit diverging solutions.

MKD-TCT	B1	B2
Base	47(o) - 51(a)	49(o) - 53(a)
Opt	15(o) - 27(a)	33(o) - 37(a)

TCL	B1	B2
Base	12.8σ, 27 mm	13.1σ, 28 mm
Opt	10.8σ, 23 mm	11.7σ, 25 mm

Limited impact on beam size.

Well-behaved dispersion in the LSS6

Peculiar solution for the beta functions, could not find issues. Needs BETS upgrade!

Very interesting optics for the next MD program.

Next steps investigate change in arc phase.

Alignment and optics

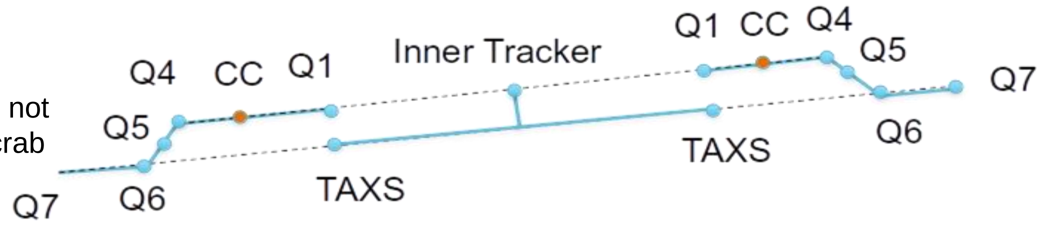
Operations are not guaranteed if the triplets magnetic fields are not aligned better than 0.5 mm relative to the line between IP and crab cavities.

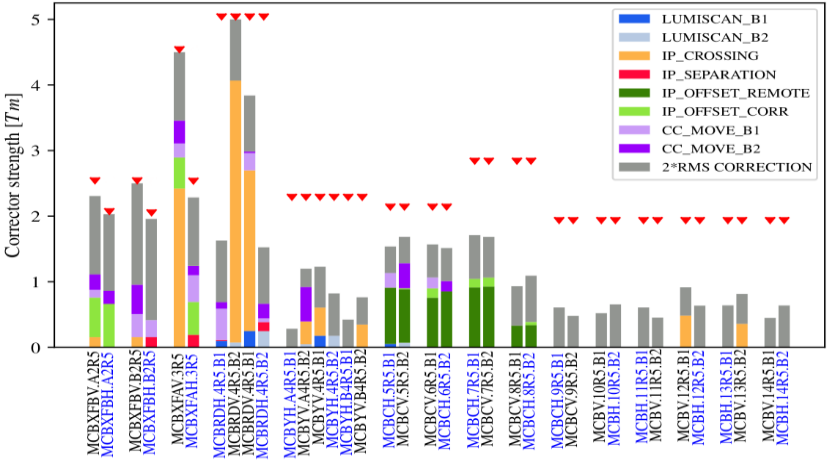
WP2 expects to:
- pre-align the triplets with the best knowledge of the magnetic axis
- refine the alignment after measurement with beams.

Present deformable RF bridges allow a large dynamic range, currently checks are ongoing to make sure that magnetic fields axis can be aligned.

Significant effort to have magnetic measurements (axis and multipole imperfections) and aperture on the same frame.
First results available and discussed at WGA.

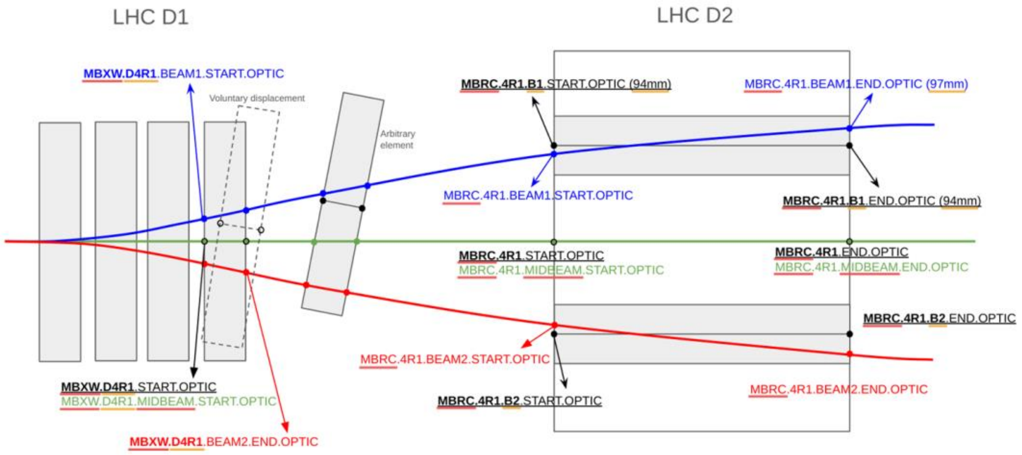
WP2-WP3-WP15-MAB exchange to define the best pre-alignment strategies.





E2A project: e

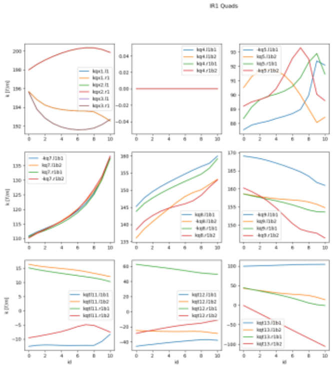
Effort of the ATS sector to streamline and automize steps of alignment process

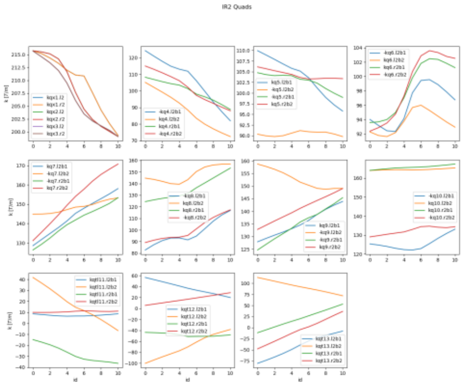


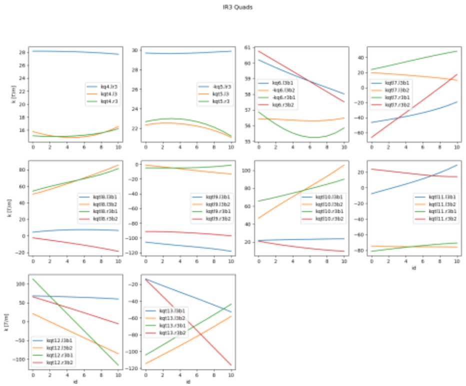
Key stones:

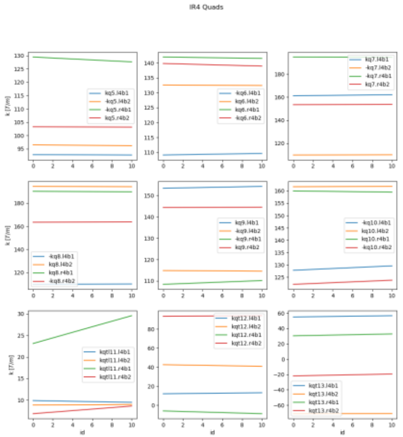
1. Better definitions of references.
2. Layout database as single source of truth.
3. Layout database to provide CCS references ("survey") for alignments

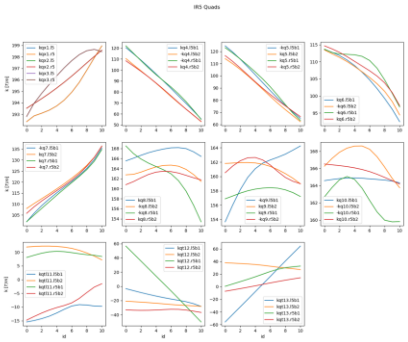
Ramp and squeeze function normalized gradient!

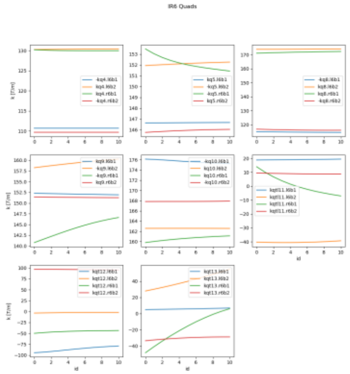


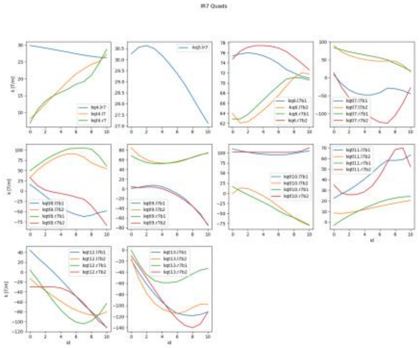


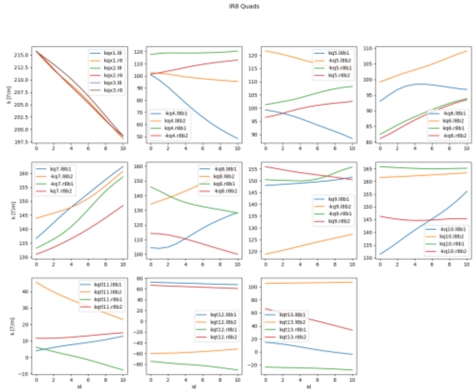












Aperture Round Flat

	TDR Round	New Round	Flat CC HV	Flat CC HV	Flat CC VH	Flat CC VH
β* Xing/Sep [cm]	15/15	15/15	18/9	18/7.5	18/7.5	18/8
Xing angle [μrad]	±295	±250	±240	±240	±240	±240
Crossing plane IP5	V (or H)	V (or H)	V	V	H	H
Aperture in Pt. 5	12.5	13.1	13.7	12.6	12.4	12.8
MKD-TCT [°] IP5 [B1/B2]	30/31	30/31	40/45	51/54	27/25	27/25
H Ap. Protected Ti./Re.	11.9/12.9	11.9/12.9	13.3/14.3	14.1/15.1	11.7/12.7	11.7/12.7
Ap. Margin [σ], Tight	0.6	1.2	0.4	-1.5	0.7	1.1
Ap. Margin [σ], Relaxed	-0.4	0.2	-0.6	-2.5	-0.3	0.1

LHC today in Point 5:
Aperture 9.4 σ (calculated tbc), 11.8 σ (measured),
TCT 10 σ, Protected aperture 11.7 σ,
Calculated Margin -2.3σ, Actual Margin 0.1 σ

Apertures: Round β*=15 cm, 500 μrad

	bare	bstol	align	beam	offset
TAXS	25.1	24.1	21.6	17.6	15.4
Q1	22.2	20.8	20.8	17.7	17.7
Q23	16.4	15.6	15.4	13.1	13.1
D1	17.4	16.5	16.3	13.9	13.9
D1 (ext)	17	16.1	15.9	13.5	13.5
TAXN	23.4	22.5	21.2	18	18
TCTPV	22.1	22.1	22.1	18.8	18.8
TCTXH	22.7	22.7	22.7	19.3	19.3
TCLPX	23.3	23.3	23.3	19.8	19.8
D2	24.9	24.9	23	19.3	19.3
D2 Corr.	25.7	25.7	24	20.1	20.1
CC (b.s)	27.8	27.8	25.9	21.8	21.8
Q4 Mask	25.9	25.9	23.6	19.3	19.3
Q4 Corr.	27.6	27.6	25.2	20.6	20.6
Q4	29	29	26.9	22.2	22.2
Q5 Mask	28.7	28.7	26.4	21.5	21.1
Q5 Corr.	31.4	29.8	27.4	22.3	22
Q5	31.8	30.2	27.9	22.7	22.4
Q6 Mask	36.5	36.5	34.1	27.9	26.7
Q6 Corr.	37.6	37.6	35.1	28.8	27.6
Q6	38	38	35.5	29.1	28.2

Apertures: Flat β*=7.5/30 cm, 490 μrad

	bare	bstol	align	beam	offset
TAXS	21.1	20.4	18.5	15.2	13.5
Q1	19.4	18.5	18.5	15.9	15.9
Q23	15.5	14.9	14.7	12.7	12.7
D1	15.8	15.1	14.9	12.9	12.9
D1 (ext)	15.5	14.8	14.6	12.6	12.6
TAXN	18.1	17.5	16.5	14.1	14.1
TCTPV	17	17	17	14.4	14.4
TCTXH	17.3	17.3	17.3	14.7	14.7
TCLPX	17.6	17.6	17.6	15	15
D2	18.9	18.2	17.1	14.5	14.5
D2 Corr.	21.3	20.5	19.3	16.4	16.4
CC (b.s)	20.6	19.7	18.3	15.4	15.4
Q4 Mask	19.2	18.3	16.7	13.6	13.6
Q4 Corr.	20.5	19.5	17.8	14.5	14.5
Q4	21.5	20.6	19.1	15.6	15.6
Q5 Mask	21.3	20.2	18.7	15.2	14.9
Q5 Corr.	22	20.9	19.4	15.8	15.6
Q5	22.3	21.1	19.5	15.8	15.6
Q6 Mask	25.9	25.9	24.2	19.7	18.9
Q6 Corr.	28.3	26.9	25.1	20.5	19.6
Q6	28.3	26.9	25.1	20.5	19.9

Aperture FlatCC: β*=7.5/18 cm, 480 μrad

	bare	bstol	align	beam	offset
TAXS	21	20.2	18.3	15.1	13.2
Q1	19.4	18.5	18.4	15.9	15.9
<u>Q23</u>	<u>15.5</u>	<u>14.9</u>	<u>14.7</u>	<u>12.7</u>	<u>12.7</u>
D1	15.8	15.1	14.9	12.9	12.9
<u>D1 (ext)</u>	<u>15.5</u>	<u>14.8</u>	<u>14.6</u>	<u>12.6</u>	<u>12.6</u>
TAXN	18.1	17.5	16.5	14.1	14.1
TCTPV	17	17	17	14.4	14.4
TCTXH	17.2	17.2	17.2	14.7	14.7
TCLPX	17.6	17.6	17.6	15	15
D2	18.9	18.2	17.1	14.5	14.5
D2 Corr.	21.3	20.5	19.3	16.4	16.4
CC (b.s)	20.6	19.7	18.3	15.4	15.4
Q4 Mask	19.2	18.3	16.7	13.6	13.6
Q4 Corr.	20.4	19.5	17.8	14.5	14.5
Q4	21.4	20.6	19.1	15.6	15.6
Q5 Mask	21.2	20.2	18.7	15.2	14.9
Q5 Corr.	22	20.9	19.4	15.8	15.6
Q5	22.3	21.1	19.5	15.8	15.6
Q6 Mask	25.8	25.8	24.1	19.7	18.9
Q6 Corr.	28.3	26.9	25.1	20.5	19.6
Q6	28.3	26.9	25.1	20.5	19.9

Protected aperture

Parameters	7 TeV	0.45 TeV
Min Ap. no TCT [σ]	19.4	12.6
Min H. Ap. with TCT [σ]	11.2-15.6	12.6
Min V. Ap. with TCT [σ]	11.2-12.2	12.6

Protected aperture depends on MKD-TCT phase advance at flat top in the horizontal plane.

$\Delta\mu_x$ MKD-TCT [°]	H. Ap. W [1] [σ@2.5μm]	H. Ap. CuCD [2] [σ@2.5μm]	H. Ap. W Relaxed [σ@2.5μm]
0-20	11.2	11.2	12.2
30	11.9	11.2	12.9
40	12.9	11.9	13.9
50	13.8	12.8	14.8
60	14.5	13.6	15.5
70	14.6	14.0	15.6
80-90	14.6	14.3	15.6

Collimator [σ@2.5μm]	2023 Injection	HL Injection	2023 end-of-level settings	HL end-of-level tight settings [1]	HL end-of-level relaxed settings [3]
TCP IR7	6.7	6.7	5.9	6.7	8.5
TCS IR7	7.9	7.9	7.7	9.1	10.1
TCDQ IR6	9.5	9.5	8.6	10.1	11.1
TCT	15.4	15.4	10.1	10.2-13.3*	11.2-14.6*
TCL	parking	parking	17	[21.3 mm]+	[21.3 mm]+
TCLA	11.8	11.8	11.8	13.7	13.7
Aperture	14.2 (meas)	12.6	11.2(meas)	11.2-14.3*	12.2-15.6*

* Collimation settings and protected aperture need to be validated with collimation simulations of specific optics.
+ Minimum setting in mm validated by radiation simulations (38W in D2)

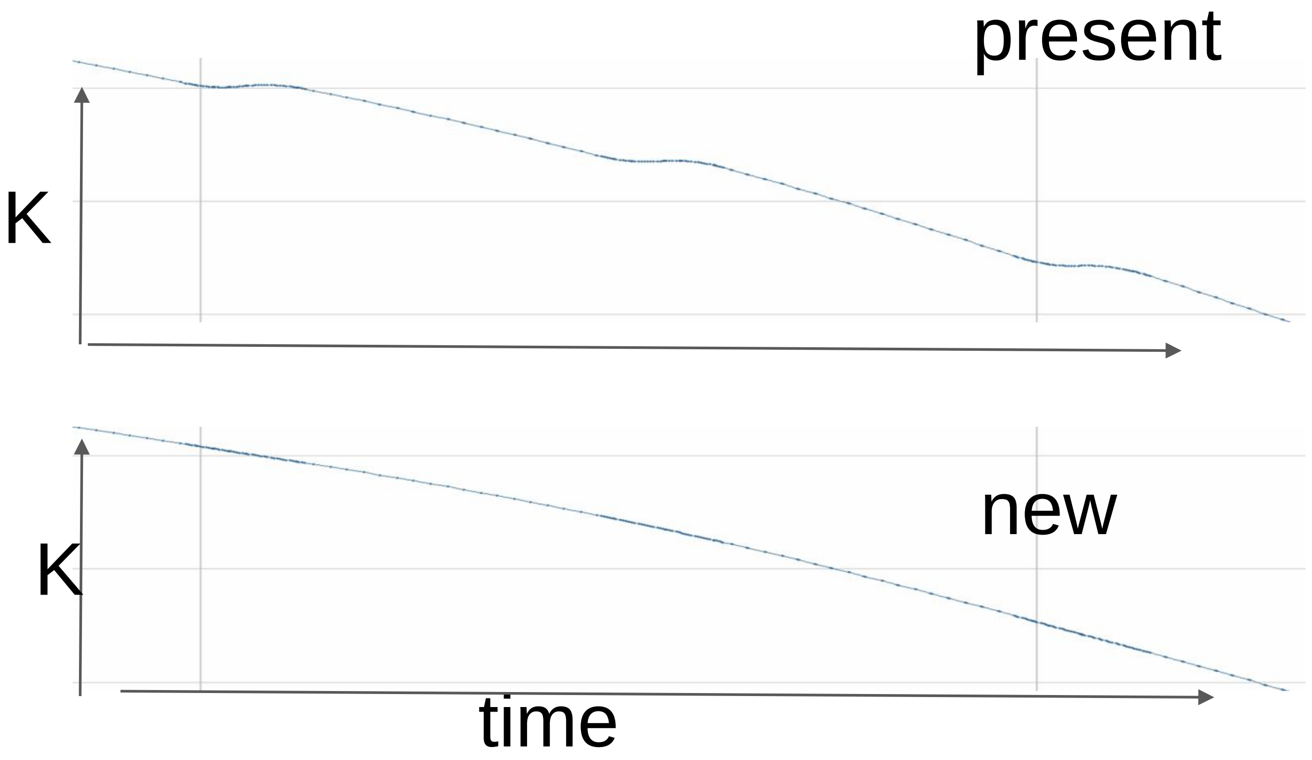
References:
[1] R. Bruce et al. CERN-ACC-2017-0051
[2] R. Bruce ColUSM 115
[3] R. Tomas et al. CERN-ACC-2022-0001

Ramp and squeeze

Discrete normalized fields (K) are smoothed by LSA before being converted in currents (I)
Present smoothing algorithm impose K'(t)=0 at matched points which introduces unnecessary I''(t) steps.

New algorithm, removes the steps.

Needed to fit HL-LHC optics ramp and squeeze.

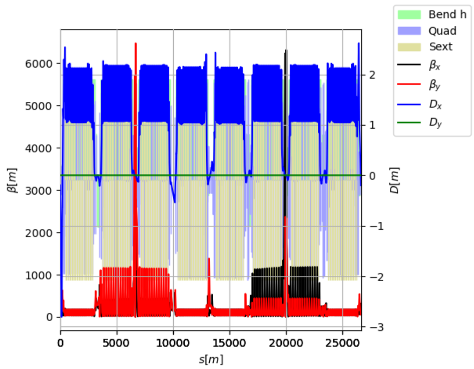


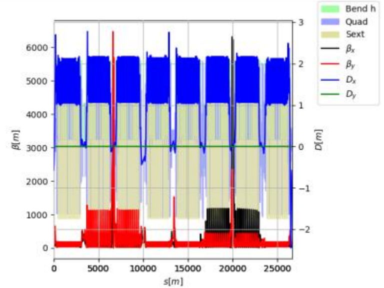
Squeeze at FT

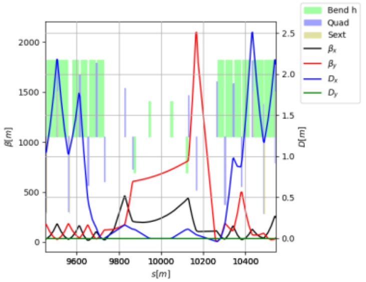
ATS squeeze up to factor 6.6 (but beta*=1m /37.5 cm) challenging for optics correction and aperture in the arcs.

1) Optics measurements and corrections:
    a) K-modulation (using DOROS) and on- / off-momentum AC dipole for complete set of corrections
    b) Check tune stability, at least ~20 AC dipole shots (~25min) necessary under static conditions. One of the critical aspects to be learned. To be re-done in 2025 with the dipole PC upgrade.
    c) Off-momentum AC data part of usual correction (as k-mod), now also critical for Dx,Dy

1) Aperture measurements at FT in the arcs, on- / off-momentum
2) Loss maps at FT on- / off- momentum
3) Investigate feasibility of a beta increase in LLS4 during the squeeze For this MD only B2 V in a few intermediate segments of



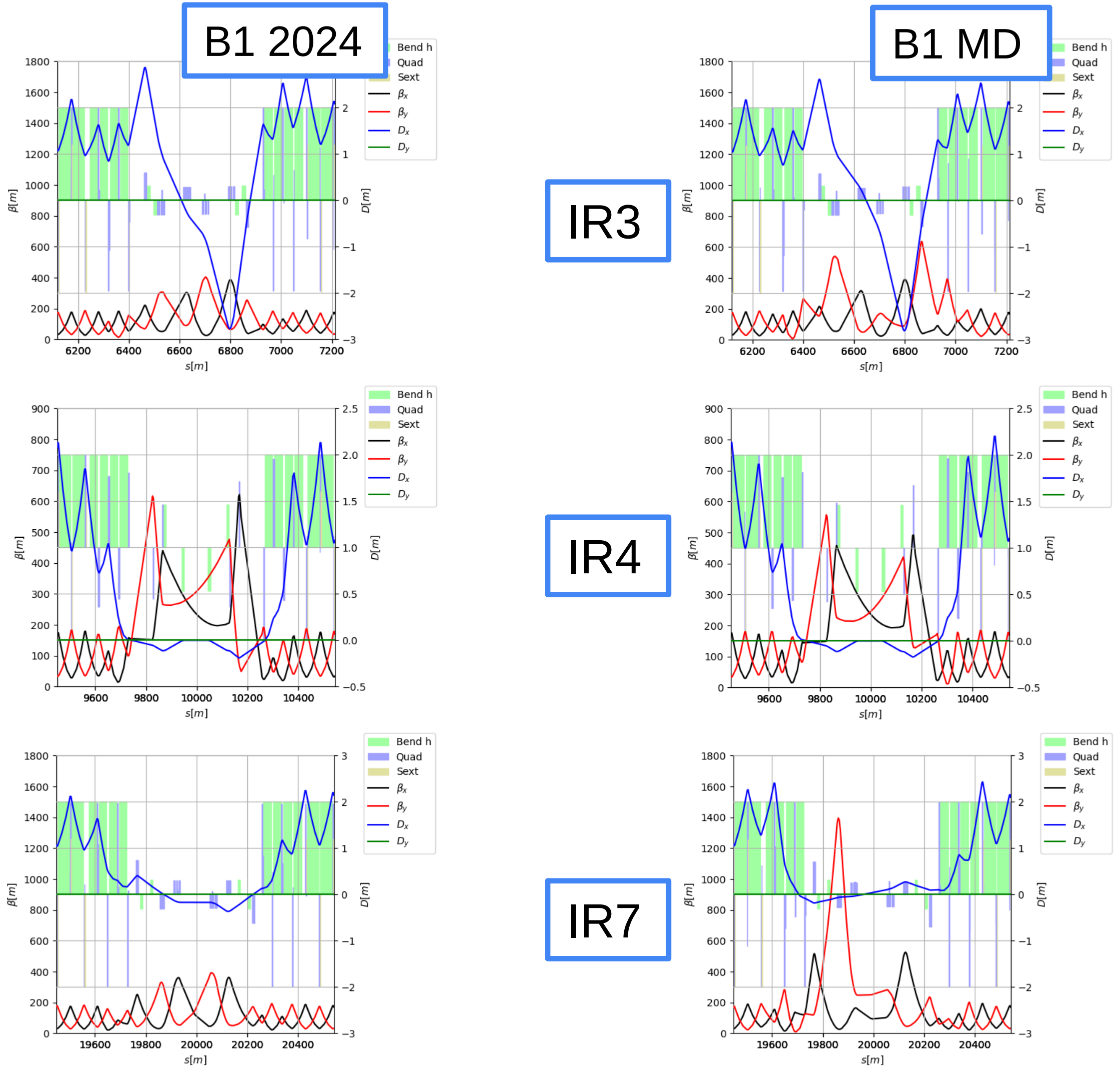




Optics changes

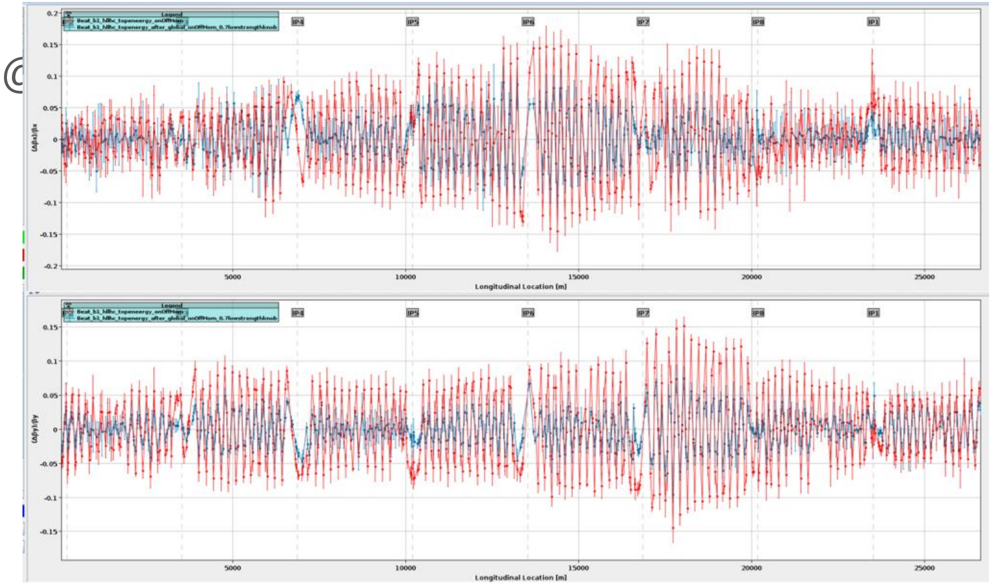
- **IR3** ramp+squeeze for impedance
- **IR4** new from injection to accomodate e-lens
- **IR7** ramp+squeeze for impedance+collimation performance
- **IR1 / IR5** with new ATS factors
- **IR8** kept at 10 m to simplify aperture meas.
- Phase advances around the ring

cycle for testing HL features without full implementation



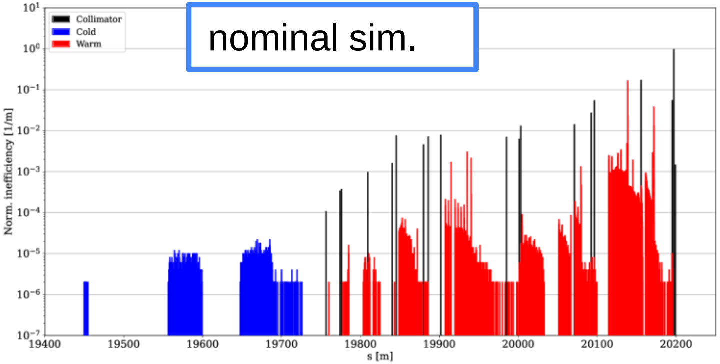
Optics measurements

- Optics successfully deployed, with global corrections at INJ, RAMP and FT
  - orbit: excellent (coll. center < 35 µm off from normal physics)
  - beta beat:
    - FT: < 10 %
    - RAMP: < 30 % @
    - INJ: < 15 %
  - dispersion: < 0.02

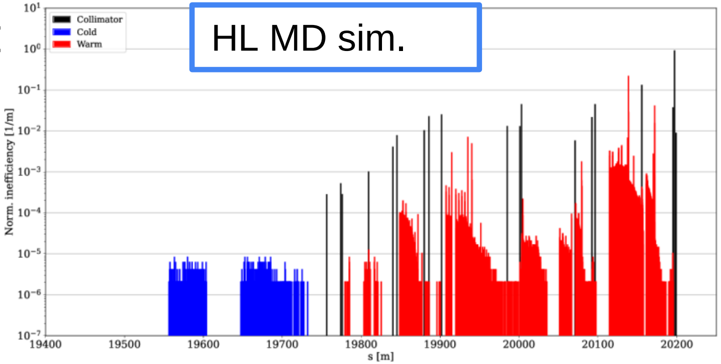


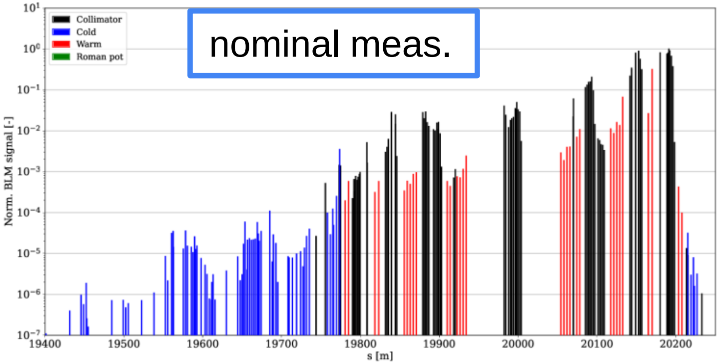
Collimation measurements

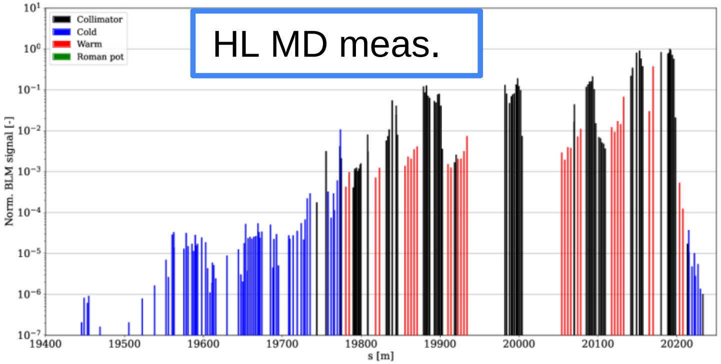
- Betatron loss maps during ramp
- Betatron + off-momentum loss maps at FT, with TCTs at FT settings and collision settings



61 % impr





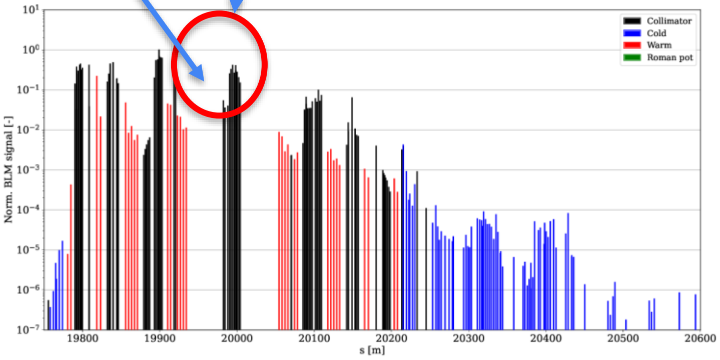


B1 hierarchy

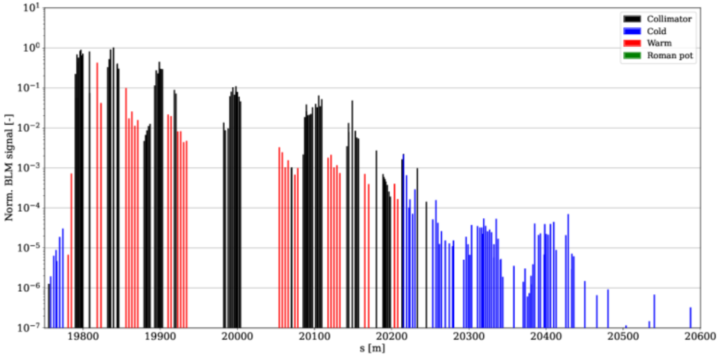
- First B1V measurements only small improvement (15 %) and hierarchy issue
- TCSG.B5L7.B1 at 120 %, moving jaws out solved hierarchy and

cleaning improved by 35 %

TCSG.B5L7



on estimate



Summary

- New optics successfully deployed and corrected
    - Beta beat at ramp needs further iteration – dedicated correction at 1 TeV?
- Collimation performance improved by 26 – 61 % in all planes
- No issue with loss spikes during combined ramp+squeeze with tight collimator settings
- Impedance improved in three out of four planes up to ~30 %
    - ADT obsbox data in B1H suspicious...

Next steps:

- Measure + correct new squeeze with beta in the arcs up to 1.2 km
- Test + validate optics measurements, techniques
- Global aperture measurement at end of squeeze
- Improve optics correction at injection and k-smooth algorithm during ramp
- Asynchronous beam dump
- Refine collimator alignment
- Redo B1H impedance and Octupole threshold
- Trains during ramp to ensure no losses

MD2 threading

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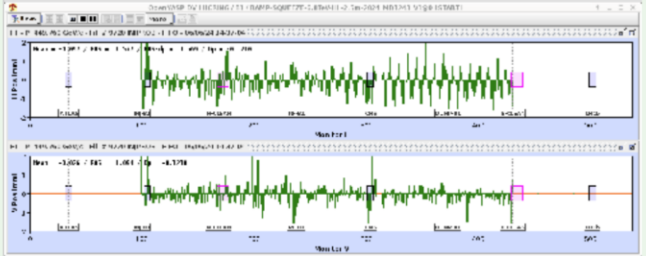
B1 to IP7



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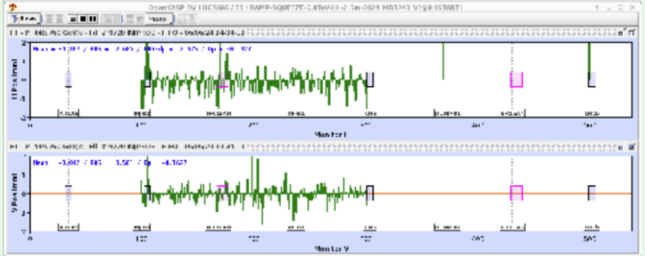
B1 to IP5



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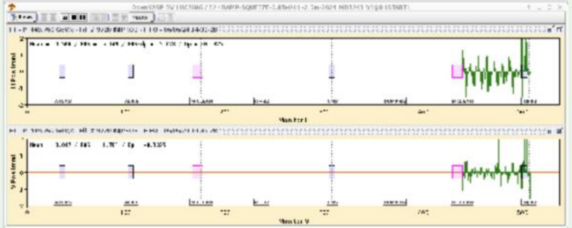
B2 to IP7



MD2 corrections