Run 3 configuration for protons and validation steps

S. Fartoukh, M. Barnes, H. Bartosik, X. Buffat, C. Bracco, R. Bruce, F. Cerutti, I. Efthymiopoulos, A. Huschauer, G. Iadarola, S. Kostoglou, L. Mether, N. Mounet, T. Persson, G. Sterbini, H. Timko, Y. Papaphilippou, S. Redaelli, G. Rumolo, B. Salvant, R. Tomas, J. Wenninger, etc.,

LHC Run III configuration WG

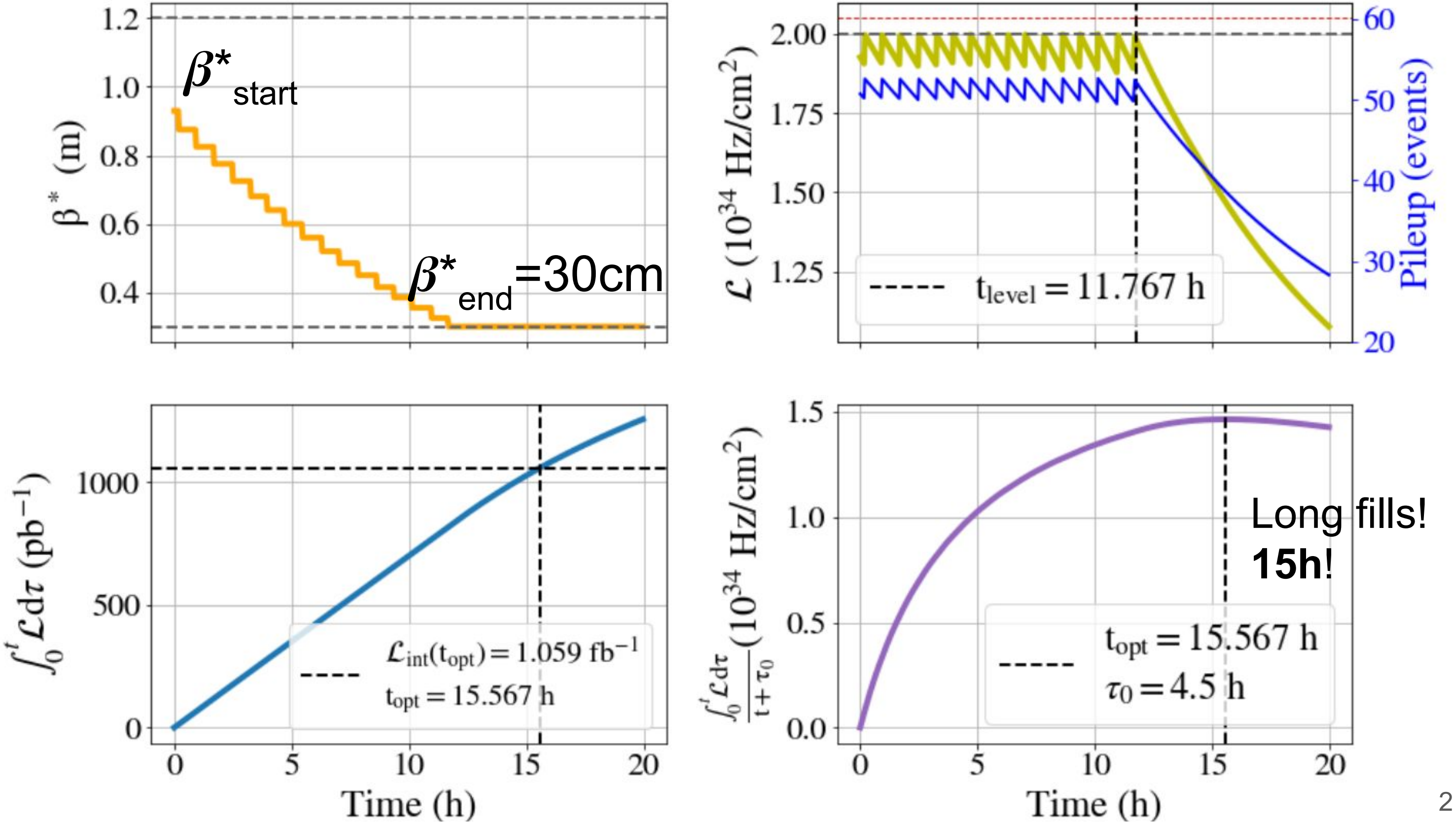
LHC Run 3 configuration report: CERN-ACC-2021-0007

Run 3 physics fill, an illustration

Steps of 5% in lumi

β^* levelling

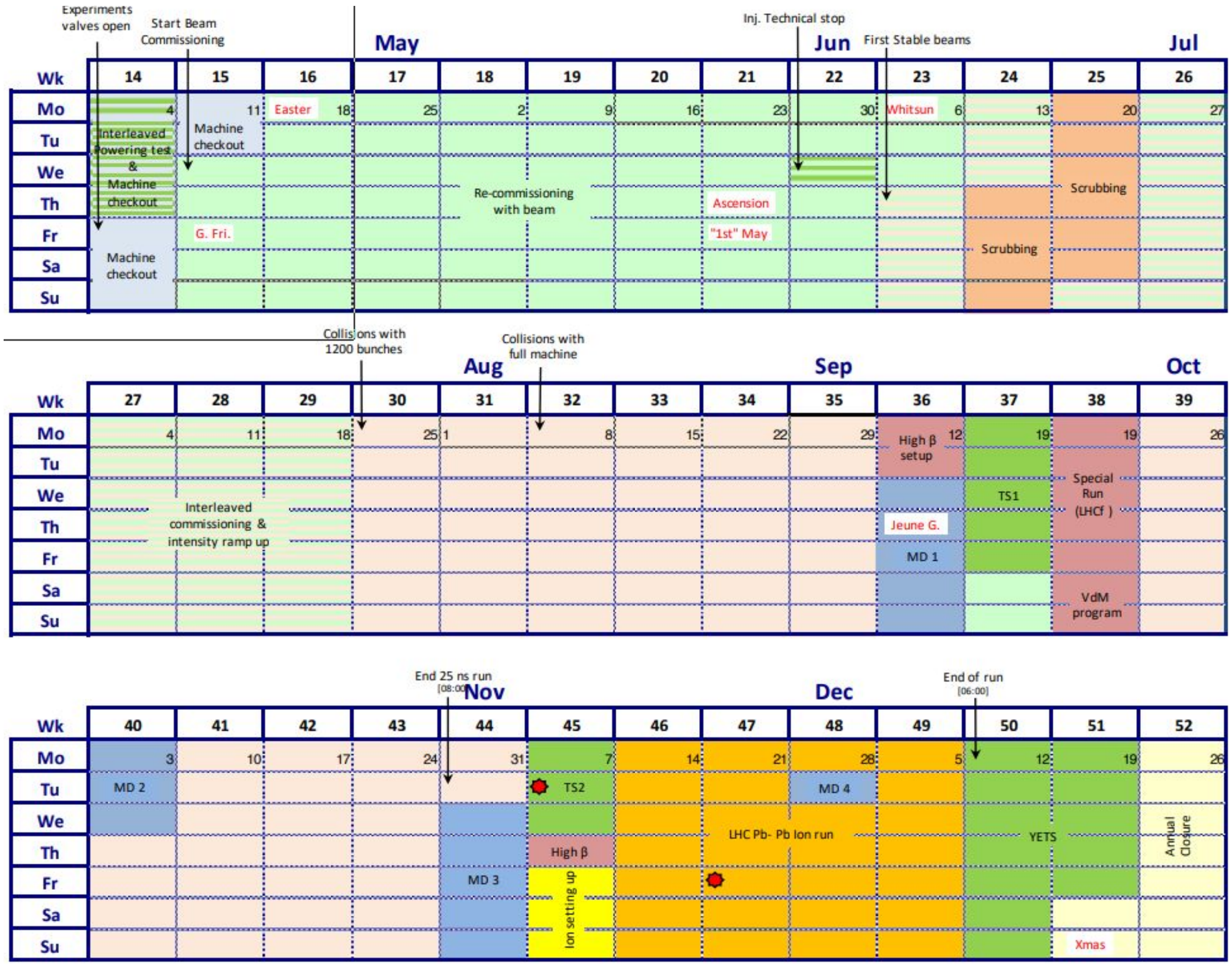
This particular case:
1.8×10^{11} ppb
emit= 2.5 μm
2748 bunches
σ_z= 9 cm
Xsing=160 μrad



See Rende’s talk yesterday

2022

phase	days
Commissioning	56
Int. ramp-up	36
Physics p	76
MD	14
Physics ion	27
Special runs	10

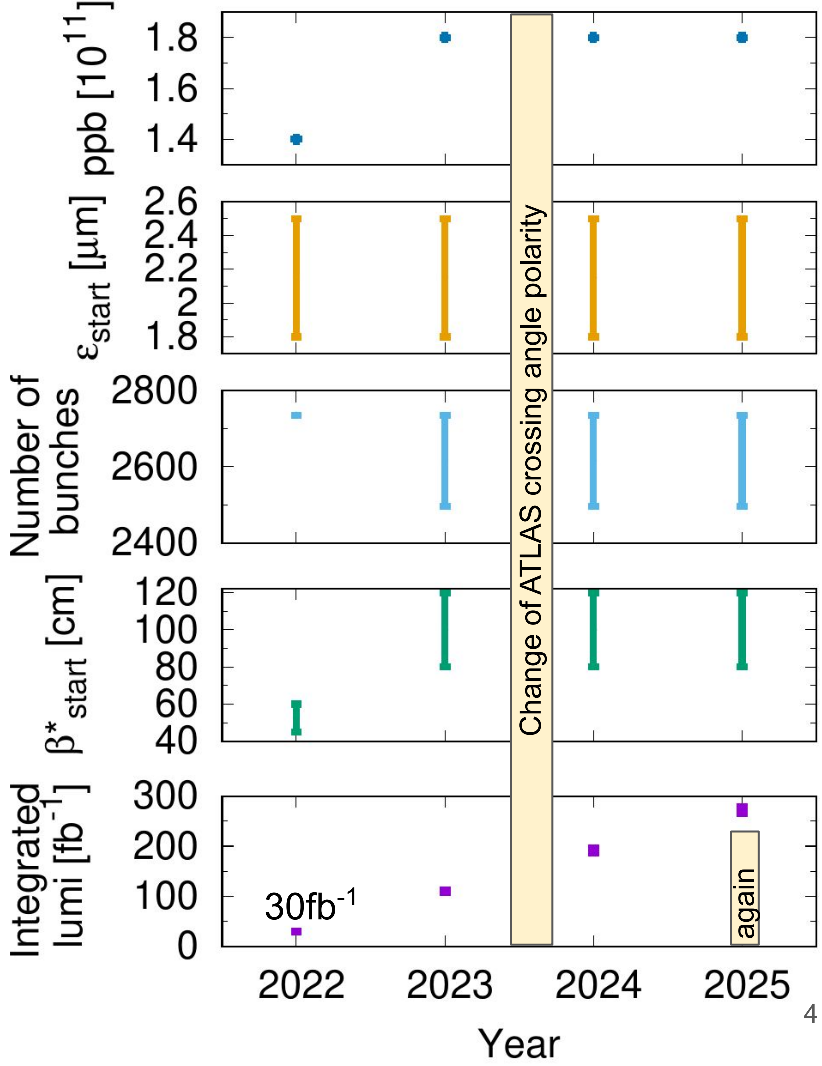


Assuming 110 days of p physics at 25% efficiency for 2022.

Run 3 at a glance

Assuming:
110 days of physics in 2022 and 130 in 23-25
turn-around-time of 4.5 hours,
max. bunch intensity 1.8×10^{11} ppb,
25% efficiency in 2022,
50% in 2023-2025,
large uncertainties in emittance (ε_{start}) at start of physics and in number of bunches
→Large uncertainties on β^*_{start} but,

Integrated luminosity uncertainty remains below 3% (for intensity uncertainties see later)



See previous talk by Brian

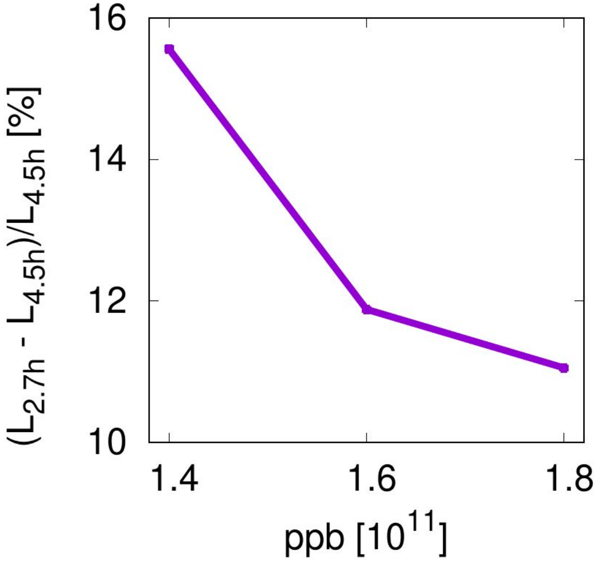
Run 3 proton targets and baseline predictions

Detector	Target [fb^{-1}]	Run 3 baseline [fb^{-1}]	Run 3 + 1 year [fb^{-1}]		Leveled luminosity [$10^{34}cm^{-2}s^{-1}$]
ATLAS & CMS	**160**	190	270		2
LHCb	**25**	20	28		0.15 - 0.2
ALICE	**0.2**	0.13	0.18		0.0013

Various solutions for LHCb and ALICE: Increasing efficiency, reducing turn-around time (next slide), extra year, increasing number of days in physics (145?), etc.

Turn-around-time breakdown in 2023/24

There is a large potential gain in performance by reducing the turn-around time from 4.5h to 2.7h:



Exploring improvements of TaT in F. Velotti, IEFC21.
In general, best turn-around time cure is reducing faults!

Process	Time [min]
Ramp-down	40
Preinjection set-up	15
Set-up with beam	15
Injection	35
Prepare ramp	5
Ramp & Squeeze	25
Flat-top	5
Mini-squeeze	4
IP8 xsing rotation	5
Q change	5 (conservative)
Adjust/collide	10 (conservative)
Total	**164 (2.7 hours)**

See talks by Yann and Marco yesterday and Helga's talk earlier today.

Intensity limitations

	Temp. raise wrt MKI-8C [%]
MKI.B5R8.B2	101
MKI.C5R8.B2	100 (the one to be replaced)
MKI.D5L2.B1	92

MKI-8C limits bunch intensity to 1.45×10^{11} p (@ $\sigma_z\approx9$ cm) in 2022. Replaced in YETS 22-23.

Other MKI modules limit bunch length to $\sigma_z\approx10$ cm (@ 1.8×10^{11} ppb) in **DC mode** for 2023/24, aiming operation at $\sigma_z\approx9$ cm with monitoring.

Dump could limit bunch intensity to 1.4×10^{11} p Ref: Decision by mid 2022.

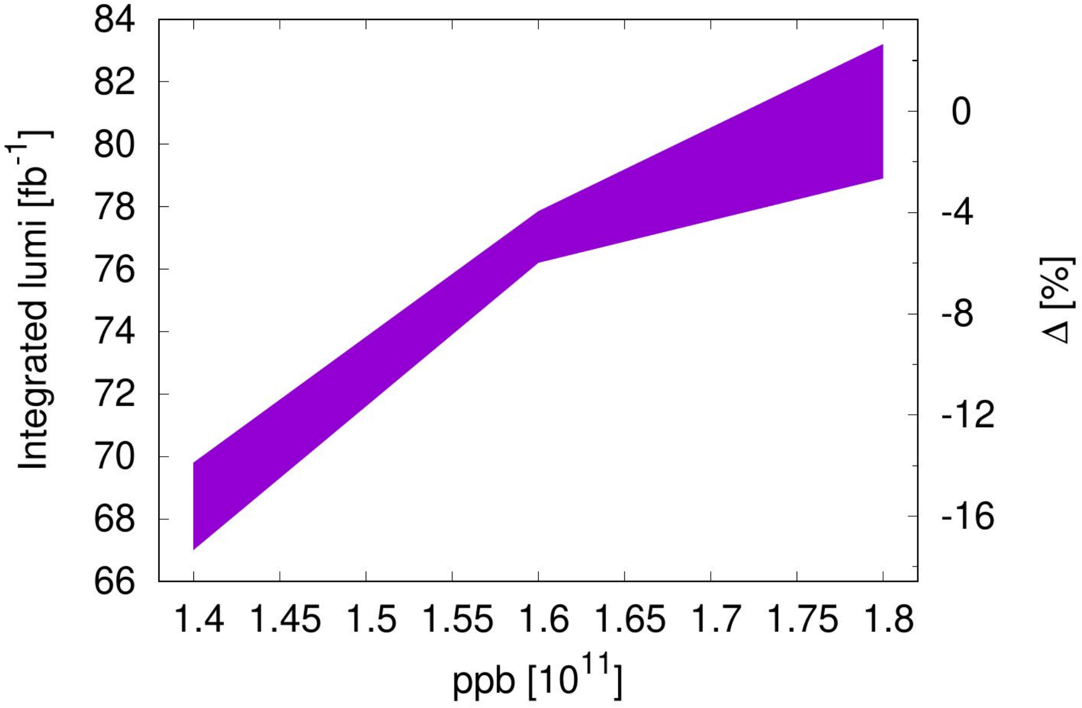
TCDS designed for 1.7×10^{11} ppb but likely OK at 1.8×10^{11} ppb (checks foreseen).

E-cloud It will be critical to measure SEY in 2022 and test highest possible bunch intensity in 2022 at injection.

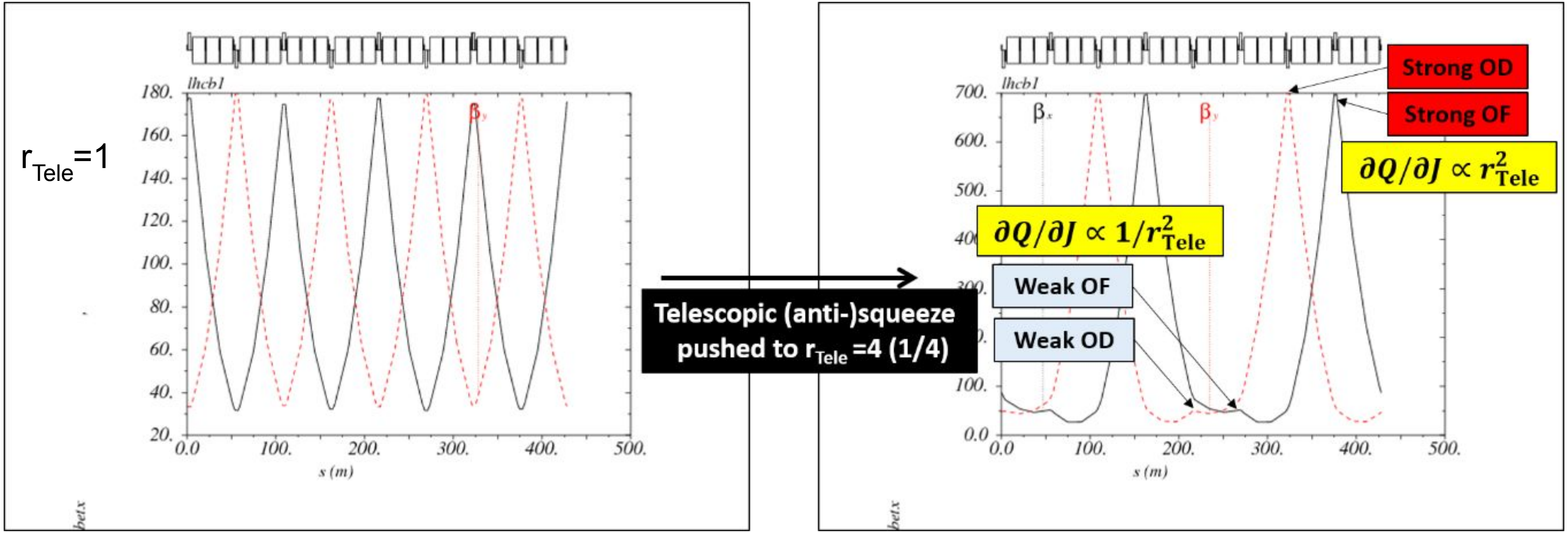
RF, **TCDQ** and **Collimation** should not limit intensity in Run 3 (up to 1.8×10^{11} ppb).

Yearly performance versus bunch intensity (130 days, 50% efficiency and 4.5h turn-around time)

Taking emittance uncertainty (1.8-2.5 μm) at all ppb and bunch number uncertainty (2484-2736) only at 1.8×10^{11} ppb.



Antitelescope (r_{Tele}<1) to be used in 2023 in the ramp



This allows for stronger Landau damping and to keep constant lattice elements between IP and Roman pots in physics. **2023 optics to be tested in 2022 MDs**

See Jan’s presentation on Thursday

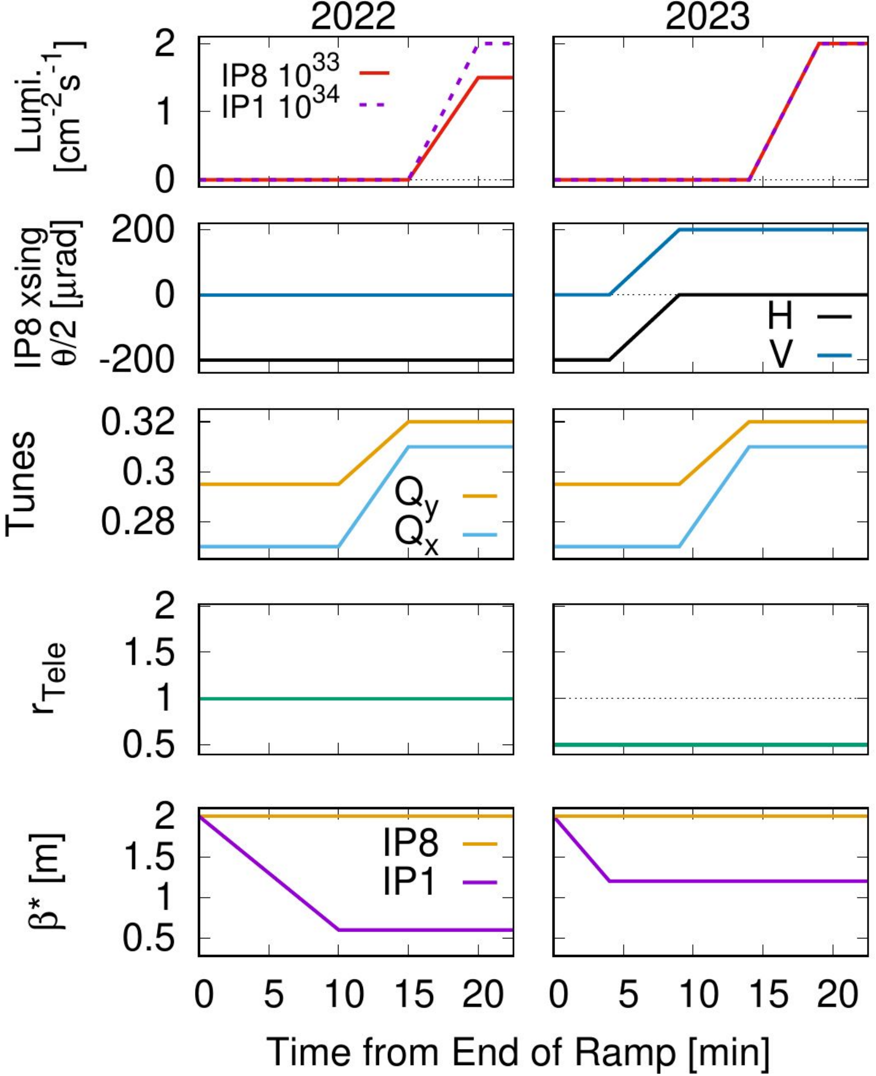
Processes from End of Ramp, 2022 Vs. 2023

IP8 crossing angle rotation only in 2023 (MDs needed in 2022)

Tune change just before collisions (this assumes good IR corrections in 2022)

Telescopic factor used towards the end of the ramp in 2023

If ε_{start}>1.8 μm or ppb < 1.8×10^{11} or σ_z>9 cm, β^*_{start} and r_{Tele} could be changed.

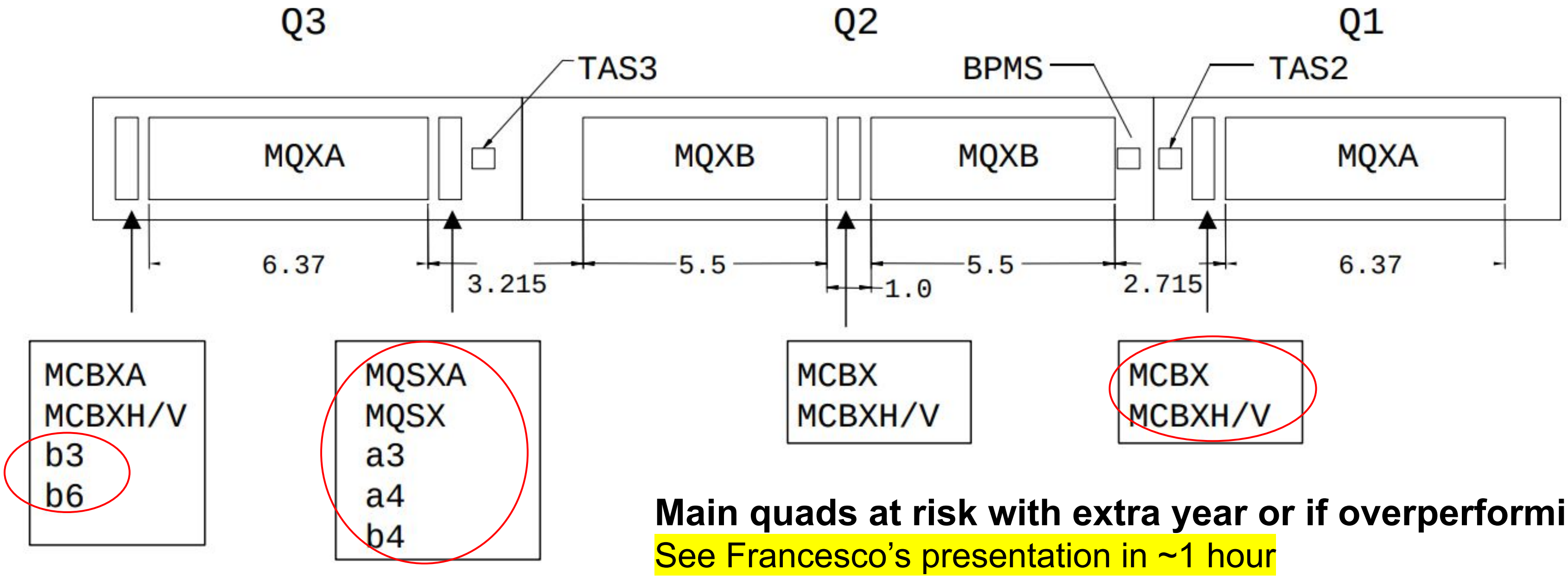


[OBJ]

LMC #419:

ATLAS and CMS Configuration for Run 3 (p-p runs), S. Fartoukh and S. Kostoglou

Radiation Estimate to the Triplet and IT Correctors, F. Cerutti



Main quads at risk with extra year or if overperforming?

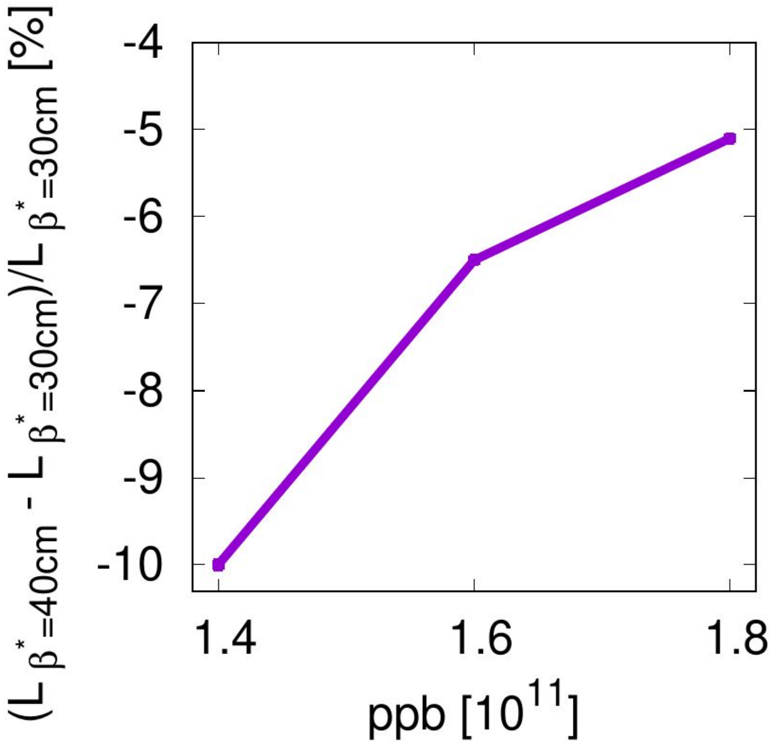
See Francesco's presentation in ~1 hour

Radiation might damage IR1&5: MCBX.1, MQSX and Non-linear corrs (sextupoles$^{\text{only IR1}}$, octupoles and dodecapoles)

MCBX (a1/b1): one can live with 2 MCBX's out of 3 per IP side, provided good alignment for Q1→**K-mod. & ballistic optics**

MQSX should be replaceable by tilts in the triplet →**Test planned in 2022**

Non-lin. corrs not used in 2016 with β^*=40cm: Max lumi loss shown on plot. ⟶
Need to use **LOF/D** for correction and **correct coupling and optics** for xsing angle changes (studies will be needed).



See Tobias' presentation on Thursday

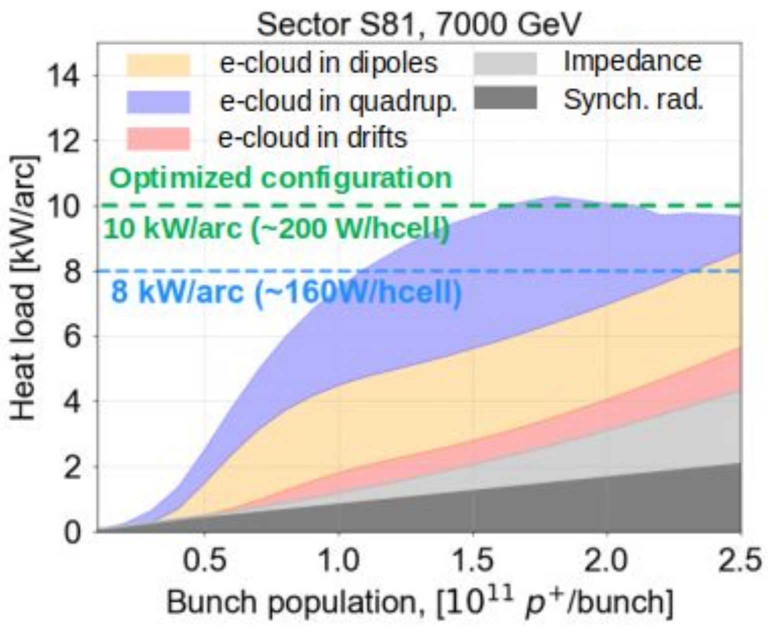
Heat-load

See Lotta's presentation on Thursday

Really at the limit!

Back-up: 8b4e mixed with 48b trains to reduce heat-load by 25%:

#collis.	IP1&5	IP2	IP8
48b	2736	2250	2376
Mixed	2484	1949	2132



E=7 TeV

48b trains

σ_z=9 cm

Approximately, at 6.8 TeV and σ_z=10.5 cm estimated heat load could be lower by about 5%

Impedance and octupole current

See Nicolas' presentation this afternoon

Impedance will require dedicated measurements in 2021, e.g. collimator impedance versus dose. LOF/D Amps needed at 6.8 TeV, 1.8×10^{11} ppb:

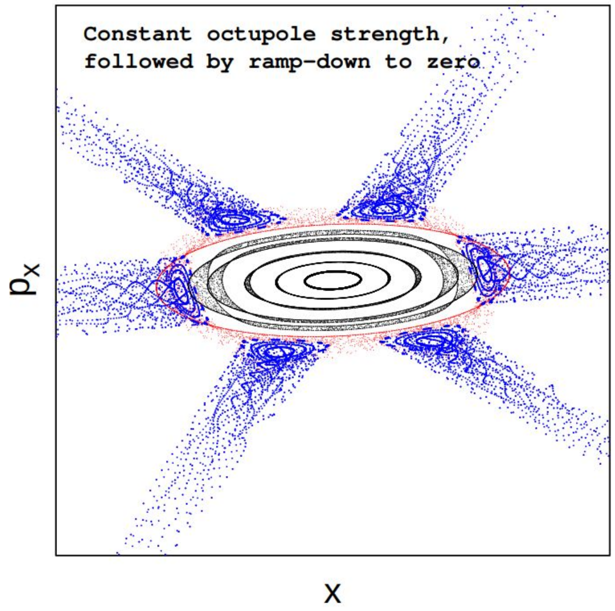
	r_{Tele}=1	r_{Tele}=0.5	r_{Tele}=1 & σ_z=10.5 cm
ε=1.8 μm	516	401	458
ε=2.5 μm	372	289	329

To further reduce octupole current, special IR7 optics developed by R. Bruce could be tested in 2022 MDs or collimators could be moved in physics (MD?) or longer bunch, σ_z=10.5 cm, can also reduce octs. by 10-20% as shown. (RF MD needed for $\sigma_z\approx$10 cm)

Uncertainties on emittance

Emittance growth in the ramp should be thoroughly studied in 2022. One known mechanism found by E. Maclean in simulations and experiments is island trapping with chromaticity (**start in commissioning!**).

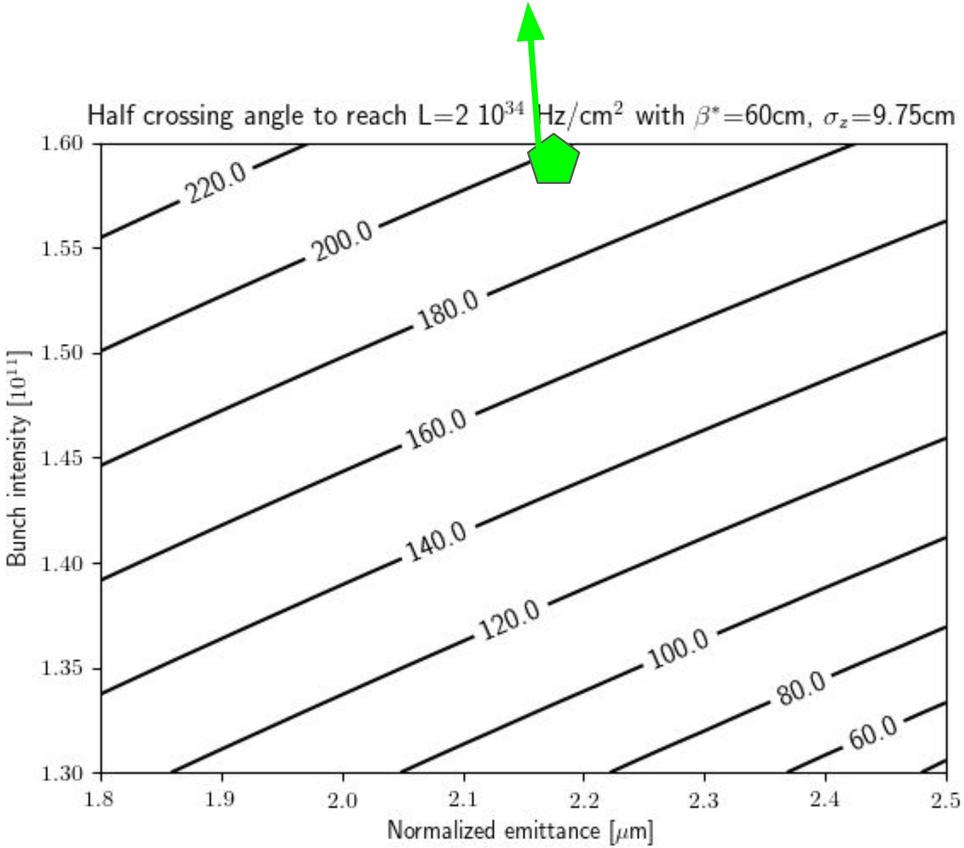
Further progress on luminosity model in 2022 will be crucial for possible optimizations, specially regarding emittance growth in physics and bunch-by-bunch fluctuations.



See next presentation by Ilias

E.g.: 1.6×10^{11} ppb, ε_{start}=2.2 μm, $\theta/2$=200 μrad, σ=9.7cm

2022 optics flexibility



The 2022 optics can easily accommodate bunch intensities up to 1.6 $\times10^{11}$ ppb by increasing emit, crossing angle or bunch length.

Benefits of larger emit: HO beam-beam and instabilities

See Sofia's talk in the afternoon

Benefits of larger xsing: HO beam-beam.

Benefits of longer bunch: HO, instabilites and MKI heating

→**Beam-beam and RF MDs in 2022**

Summary and outlook I

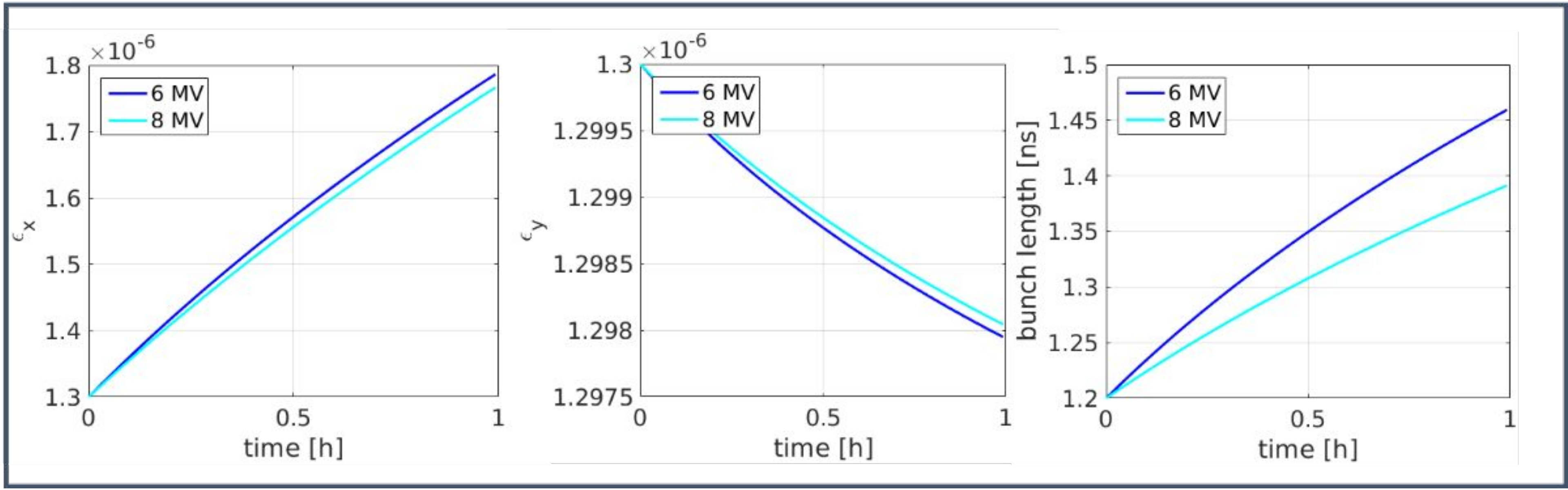
- There is a very robust plan to fully exploit LIU beams in the LHC!
- The main concerns *in order* are: dump ppb limitation, SEY, energy deposition, MKI heating, HO beam-beam, impedance and bunch-by-bunch fluctuations.
- Emittance growth in the LHC is not a big concern for performance but for machine configuration
- Yet, even in the worst case scenarios goals should be at reach probably by maximizing efficiency, reducing turn-around time, increasing days in physics, running the extra year, etc.
- Towards the end of 2022, after the successful MDs and forecasting the 2023 beam conditions we could freeze the only machine parameters that are a bit free: β^*_{start} , r_{Tele} and crossing angle at flat-top.

Summary of optics parameters

Optics Parameters	2022	2023/2024
ATLAS and CMS		
β^* [m] at the start of collision	0.60	1.20
β^* [m] at the end of levelling	0.30	0.30
Pre-squeezed β^* [m]	0.60	0.60
Telescopic index variations in SB	$1.0 \rightarrow 2.0$	$0.5 \rightarrow 2.0$
Half-crossing angle [μrad] (start of collision)	160	160
Half-crossing angle [μrad] (start of β^*-levelling)	145	135
Half-crossing angle [μrad] (end of β^*-levelling)	160	160
Alice		
β^* [m]	10.0	10.0
Half-crossing angle [μrad]	200 (V)	200 (V)
LHCb		
β^* [m]	2.0	2.0
Half-crossing angle [μrad]	200 (H)	200 (V)

Back-up slides

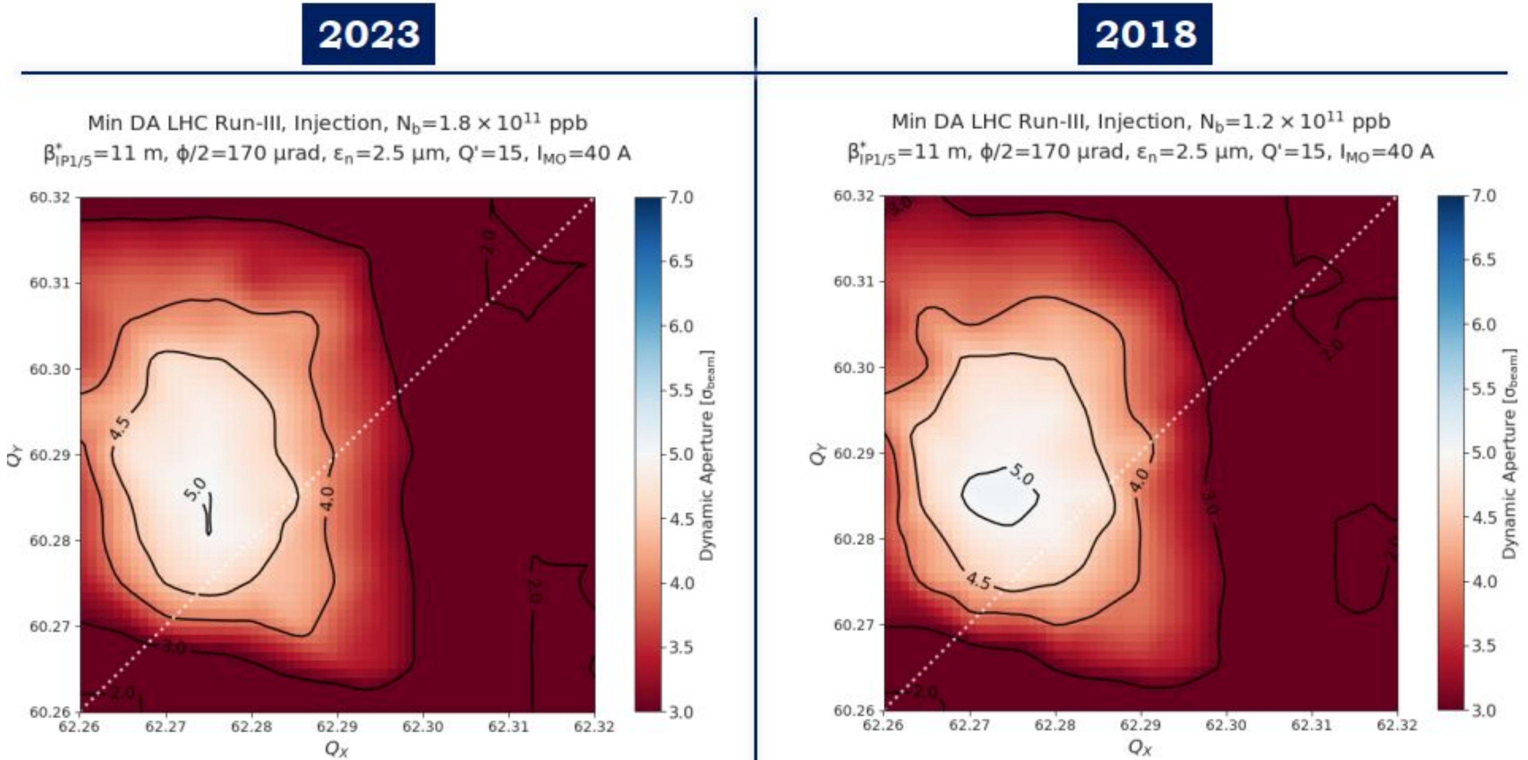
Emittance growth at injection (S. Papadopoulou)



Two possible scenarios at start of stable beam, assuming an emittance growth budget of 10% or 50% in the ramp: 1.8 μm & 2.5 μm

DA at injection with 1.8×10^{11} ppb: similar to 2018

Tune Scan @ I_{MO} = 40 A

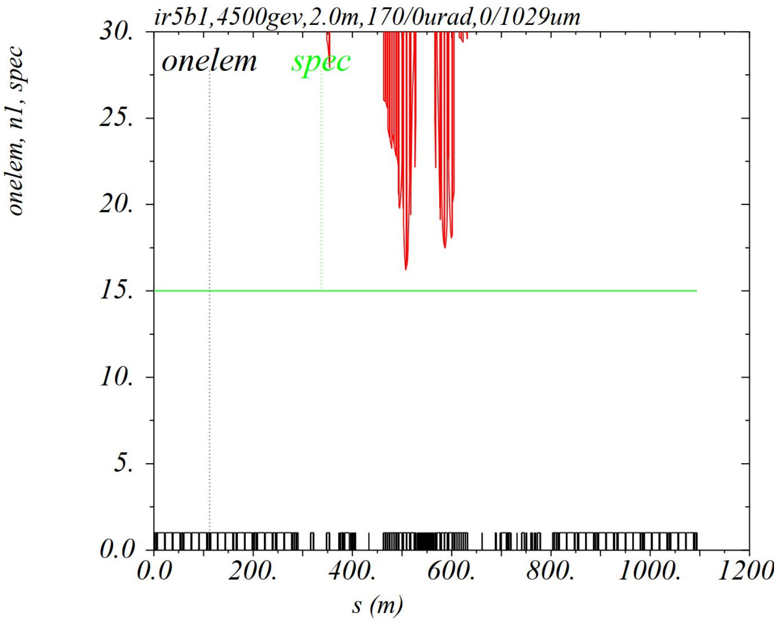


Ramp in 2023/34

A pre-squeezed β^* of at most 2 m before deploying the anti-telescope (match-ability of appropriate L/R phases of IR1 & IR5 only possible at small β^*)

A minimum allowed aperture of 15 σ in the ramp to avoid new commissioning steps for the ramp

16 σ in IR1/5 (IT)



The anti-telescope (@ $\beta^* = 2$ m) shall be deployed at E ≥ 4.5 TeV, limiting the tele-index reach to about r_{Tele} ~ 0.5 EoR (@6.5 TeV)

450 GeV: Run 2 injection optics
(BCMS preferred with 2748 bunches)

2022 (Run2-like) ← **Several optics synergies** → **2023/2024**

2022 (Run2-like)

Ramp: standard ramp & squeeze β^*= 2.0 m & r_{Tele} = 1.0 EoR
- β^*= 2 m @ IP1/5/8 reached at 4.5 TeV
- Then ramp continued at constant optics

Squeeze: β^*= 60 cm & r_{Tele} = 1.0 EoS

$$[\beta^*_{\mathrm{PreSq.}} = 2.0\ \mathrm{m}\,, r_{\mathrm{Tele}} = 1.0] \rightarrow [0.60\ \mathrm{m}\,, 1.0] \xrightarrow{\text{yields}} \beta^* = \beta^*_{PreSq.}\,/\,r_{Tele} = 2.0\ \mathrm{m} \rightarrow 0.60\ \mathrm{m}$$

[LHCb rotation assessed in MD] (H→ V ext. crossing @ β^*= 2.0 m at IP8)

Q-change (after the squeeze)

Adjust (β^*[m]= 0.6/10/0.6/2 at IP1/2/5/8 - X/2 = 160 μrad in IR1/5, 200 μrad in IR2/8)

Telescopic β^* levelling at IP1/5 β^*= 60 cm → 0.30 m (2 m @ IP8)
- First period of X-angle anti-levelling at cst β^* (to reach the BBLR limit of 145 μrad @ 60 cm)
- $[\beta^*_{\mathrm{PreSq.}} = 0.60\ \mathrm{m}\,, r_{\mathrm{Tele}} = 1.0] \rightarrow [0.60\ \mathrm{m}\,, 2.0] \xrightarrow{\text{yields}} \beta^* = \beta^*_{PreSq.}\,/\,r_{Tele} = 60\ \mathrm{cm} \rightarrow 30\ \mathrm{cm}$

2023/2024

Ramp combined with telesqueeze: β^*= 2.0 m & r_{Tele} = 0.5 EoR
- β^*= 2.0 m @ IP1/5/8 reached at 4.5 TeV
- Then telescopic gymnastics at constant β^*

$$[\beta^*_{\mathrm{PreSq.}} = 2.0\ \mathrm{m}\,, r_{\mathrm{Tele}} = 1.0] \rightarrow [1.2\ \mathrm{m}\,, 0.6] \rightarrow [1.0\ \mathrm{m}\,, 0.5] \xrightarrow{\text{yields}} \beta^* = 2.0 \rightarrow 2.0 \rightarrow 2.0\ \mathrm{m}$$

Mini-squeeze in IR1/5 (4 min) β^*= 1.2 m & r_{Tele} = 0.5 EoS

$$[\beta^*_{\mathrm{PreSq.}} = 1.0\ \mathrm{m}\,, r_{\mathrm{Tele}} = 0.5] \rightarrow [0.60\ \mathrm{m}\,, 0.5] \xrightarrow{\text{yields}} \beta^* = \beta^*_{PreSq.}\,/\,r_{Tele} = 2.0 \rightarrow 1.2\ \mathrm{m}$$

LHCb rotation (H→ V ext. crossing @ β^*= 2.0 m at IP8)

Q-change (after the squeeze)

Adjust (β^*[m]= 1.2/10.0/1.2/2.0 at IP1/2/5/8 - X/2 = 160 μrad in IR1/5, 200 μrad in IR2/8)

Telescopic β^* levelling at IP1/5 β^*= 1.2 m → 0.30 m (2 m @ IP8)
- First period of X-angle anti-levelling at constant β^* (to reach the BBLR limit of 135 μrad @ 1.2 m)
- $[\beta^*_{\mathrm{PreSq.}} = 0.60\ \mathrm{m}\,, r_{\mathrm{Tele}} = 0.5] \rightarrow [0.60\ \mathrm{m}\,, 2.0] \xrightarrow{\text{yields}} \beta^* = \beta^*_{PreSq.}\,/\,r_{Tele} = 1.2\ \mathrm{m} \rightarrow 30\ \mathrm{cm}$

Standard Vs BCMS in 2022

PS variant	# bunches at SPS extraction	Intensity / bunch at SPS extraction [10^{11} p]	ε_x [mm mrad]	ε_y [mm mrad]
LHCPROBE	1b	0.1	0.7	0.7
LHCINDIV	1b	0.1-1	1.5-2.2	1.0-1.6
LHC25#48b (2BP)	**5x48b = 240b**	**1.3 / 1.4**	**1.5 / 1.6**	**1.8 / 2.0**
LHC25#72b (3BP)	4x72b = 288b	1.3 / 1.4	1.5 / 1.6	1.8 / 2.0
LHC25#48b_BCMS (3BP)	**5x48b = 240b**	**1.3 / 1.4**	**1.3 / 1.4**	**1.3 / 1.4**

From Alex presentation + adding IBS + LHC growth, rough emittance at FT:

Standard 2.3 µm   and   BCMS 1.9 µm.

BCMS Integrated lumi is 3% larger than Standard.