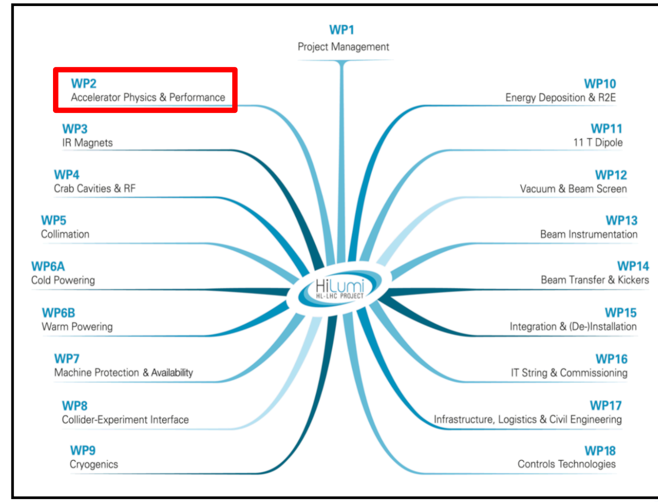
Run 4 operational scenario (p+) and status of optics v1.6

E. Métral and R. Tomás for WP2 (15+5 min talk)

Task leaders: R. Bruce, X. Buffat, R. De Maria, M. Giovannozzi, G. Iadarola and G. Sterbini

Scientific secretary: H. Bartosik

(who took over from N. Mounet => Many thanks for all the past work!)



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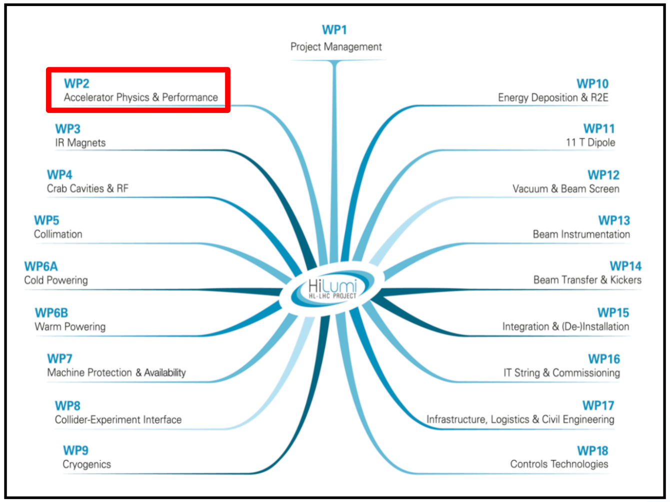

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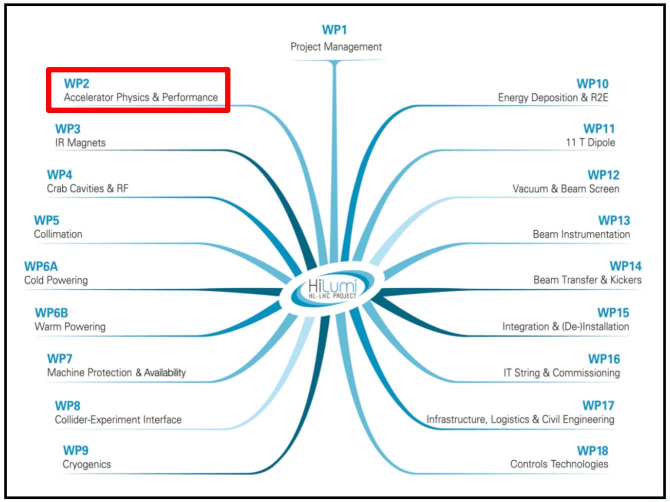

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Many thanks also to R. Calaga, S. Redaelli, E. Todesco and M. Zerlauth

Contents

- Introduction & main message
- Run 4 operational scenario
- Status of the optics v1.6
- Conclusions

Contents

Introduction

Introduction

3 main lessons from LHC

Introduction

3 main lessons from LHC

+

Environmental/energetic context

Introduction: 1st lesson from LHC

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Conclusion

- In a machine like the LHC, not only all the mechanisms have to be understood separately, but (ALL) the possible interplays between the different phenomena need to be analyzed in detail, including the
  - Beam-coupling impedance (driving and detuning)
  - Linear and nonlinear chromaticity
  - Transverse damper
  - Landau octupoles (and other intrinsic nonlinearities)
  - Space charge
  - Beam-beam: BBLR and BBHO
  - Electron cloud
  - Linear coupling strength
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  - Tune split between the two beams (bunch by bunch)
  - Transverse beam separation between the two beams
  - Noise
  - Etc.

E. Métral, Alex Chao Symposium, SLAC, CA, USA, 25/10/2019

Introduction: 1st lesson from LHC

HL-LHC will also include Crab Cavities (and associated challenges)

https://uspas.fnal.gov/about/prize-winners.shtml

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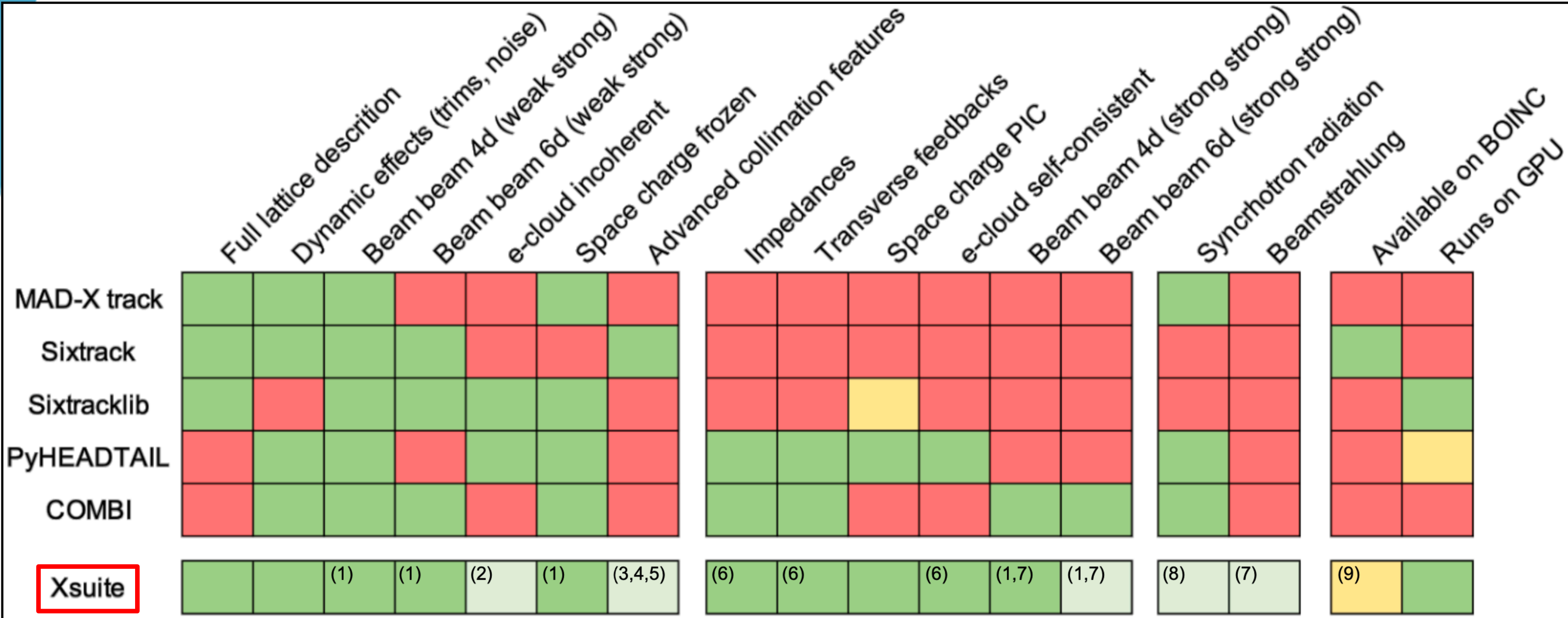
Computer modeling and heavy simulations needed

E. Métral, Alex Chao Symposium, SLAC, CA, USA, 25/10/2019

Introduction: 1st lesson from LHC



(1) Uses optimized implementation of Faddeeva function providing x10 speedup on GPU (M.Schwinzerl)
(2) To be ported from Sixrtacklib (straightforward)
(3) Electron lens implemented (P. Hermes)
(4) Geant4 interface working (A. Abramov)
(5) Porting K2 scattering and Fluka coupling is under development (F. Van Der Veken, P. Hermes)

(6) Through PyHEADTAIL interface (X. Buffat) Only CPU for now
(7) Under development (P. Kicsiny, X. Buffat)
(8) Under development (A. Latina)
(9) Under study

Courtesy of G. Iadarola (04/11/2021)

https://indico.cern.ch/event/1092908/contributions/4596241/attachments/2339369/3988004/024_Xsuite_GIM.pdf

Introduction: 2nd lesson from LHC

Introduction: 2nd lesson from LHC

Conclusion

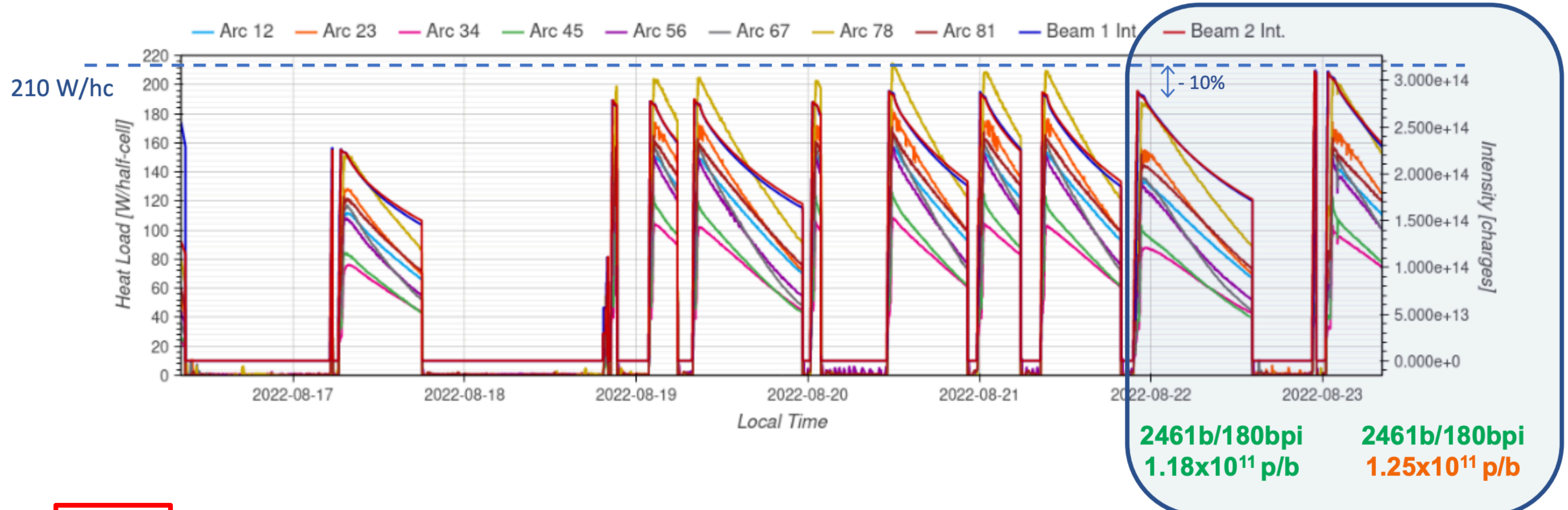
- **E-cloud (heat loads)** to be closely followed up as it is the largest threat => See talk from Giovanni Iadarola
  - 8b+4e is the back-up => Successfully used in 2017
  - But 8b+4e reduces performance by ~ 25%
    - Further optimization possible with beam-beam
    - Mixed filling scheme 25ns / 8b+4e
    - Another better scenario Xb+Ye possible? (Massimo Giovannozzi)

E. Métral, Madrid, 15/11/2017 25

Introduction: 2nd lesson from LHC

LHC operation

- Heat load in S78 keeps being the limit on total number of protons in LHC
  - Reached limit with 2413 bunches in trains of 48b (240 bpi, 1.19e11 p/b injected)
  - Moved to trains of 36b, gained 10% on S78 heat load, managed 2461b with 1.25e11 p/b



24.08.2022 G. Rumolo, CEI Section Meeting 7

Introduction: 2nd lesson from LHC

Electron cloud limits the number of bunches and bunch intensity + cryo cost!

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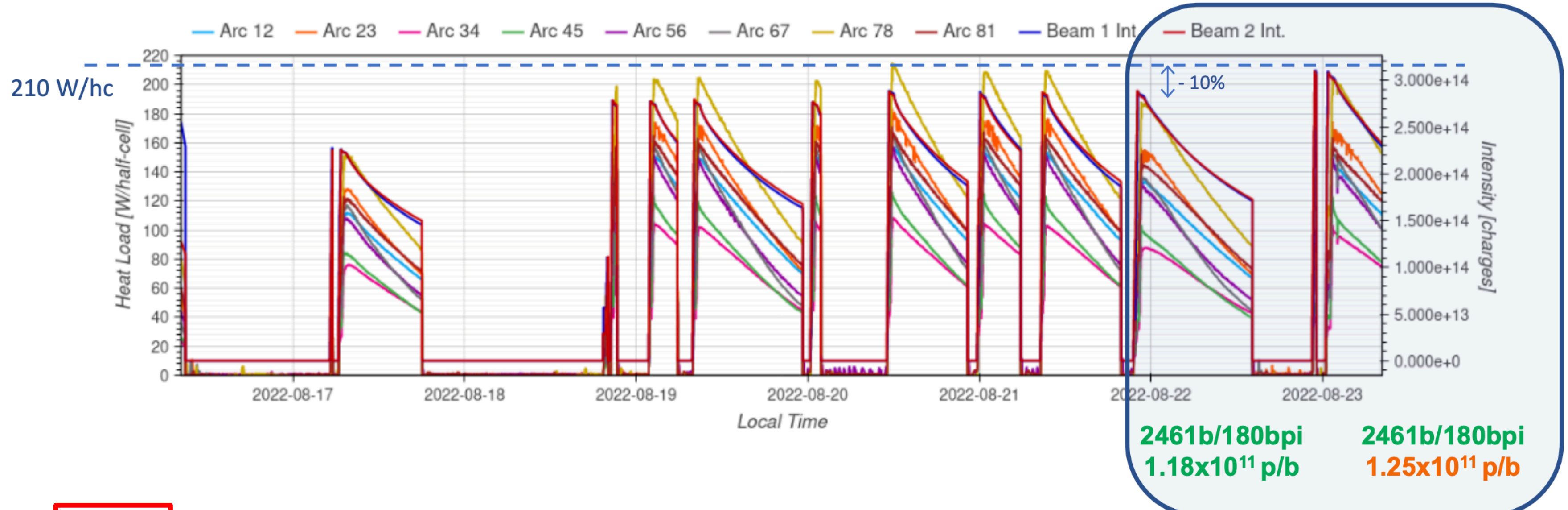

24.08.2022 G. Rumolo, CEI Section Meeting 7

See also **Konstantinos Paraschou (TH 09:00-09:20)**: LHC electron cloud studies

Introduction: 2nd lesson from LHC

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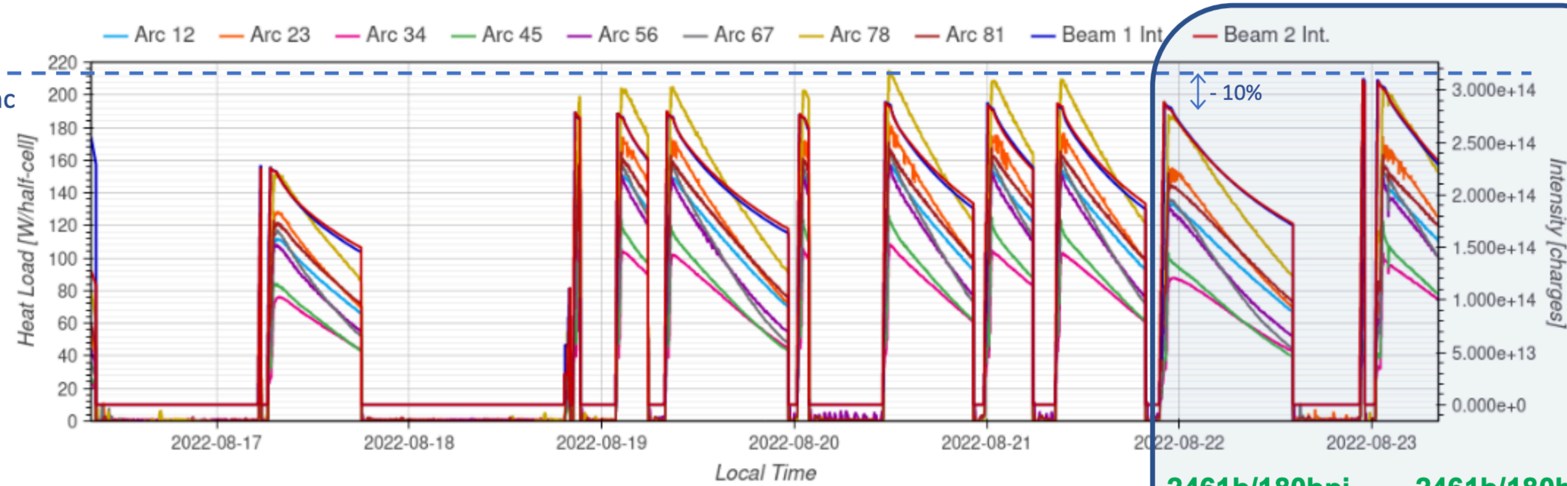


2461b/180bpi **1.18×10^{11} p/b**

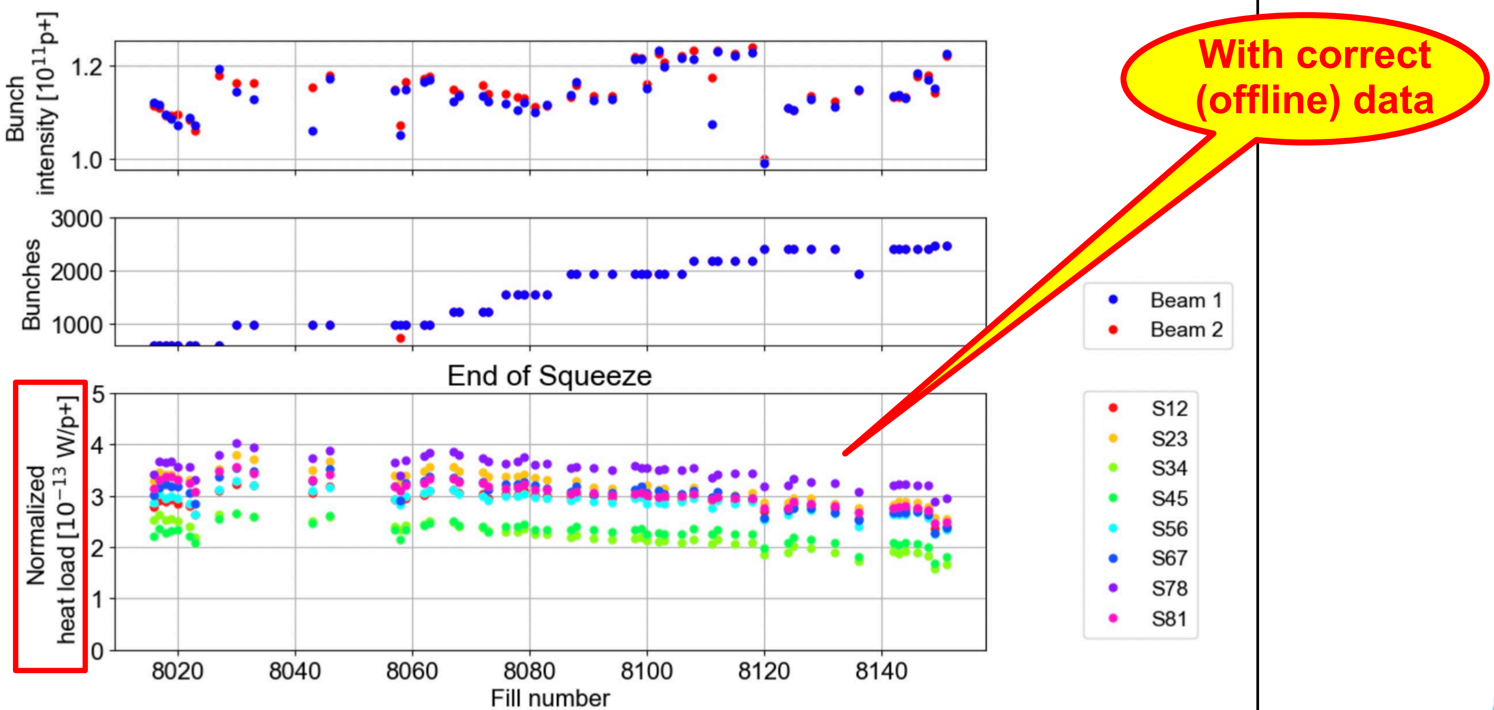
2461b/180bpi **1.25×10^{11} p/b**

24.08.2022 G. Rumolo, CEI Section Meeting 7

BE CAREFUL: difference between online (NXCALS) and offline computations (see B. Bradu, LMC 14/09/22: https://indico.cern.ch/event/1196469/contributions/5041007/attachments/2508323/4310659/2022_09_14_LMC_Update_CryoHeatLoads.pdf) => Correction done last week

Introduction: 2nd lesson from LHC

2022 Intensity ramp-up



- ~20% Reduction of heat load per proton is visible:
- Partially due to the optimization of beam configuration for max. intensity.
- Partially due to conditioning (scrubbing).

Intensity ramp-up is not finished.

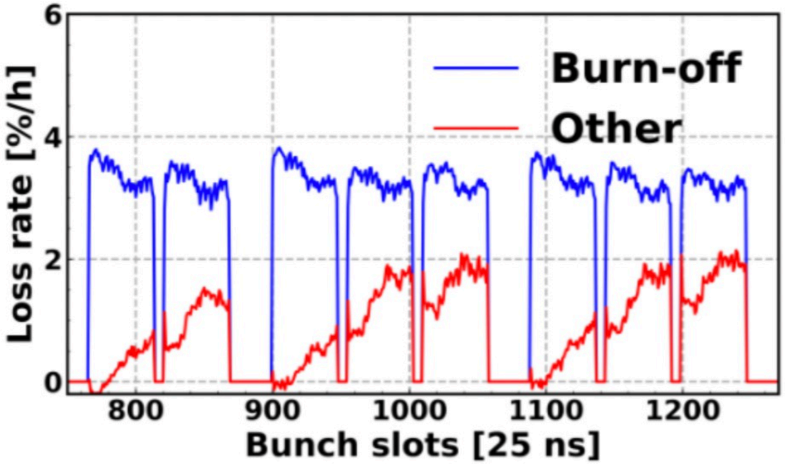
Conditioning is expected to continue well into 2023.

Courtesy of K. Paraschou

See also Konstantinos Paraschou (TH 09:00-09:20): LHC electron cloud studies

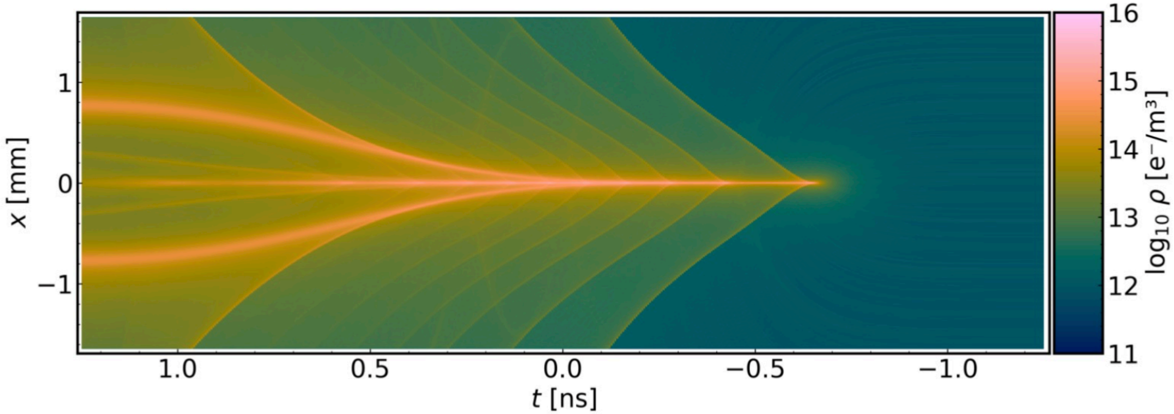
Introduction: 2nd lesson from LHC

Electrons accumulated in the beam chamber due to secondary electron emission (Electron Cloud) can introduce non-linearities in single-particle beam dynamics.



Bunch-by-bunch pattern of (slow) losses resembles e-cloud buildup.

PyECLOUD simulation:



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https://indico.cern.ch/event/1159642/contributions/4870271/attachments/2442748/4185062/20220512_ABP_incoherent.pdf

Introduction: 2nd lesson from LHC

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- Possible mitigation
  - **Surface treatment**: methods being investigate by dedicated Task Force

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- Possible mitigation
  - **Surface treatment**: methods being investigate by dedicated Task Force
  - **8b+4e**: ~ 25% performance loss => Could be partially mitigated by: **Flat Optics**, **MS10**, **2 CuCD collimators**, **BBLR wire compensation**

Introduction: 3rd lesson from LHC

Introduction: 3rd lesson from LHC

Conclusion

- Following LHC experience, $\boxed{\text{back-ups are important}}$
  - Brout-Englert-Higgs boson discovered in 2012 => With **50 ns beam**
  - Record peak luminosity in a collider (~ 2.2E34 $cm^{-2}s^{-1}$ > KEKB) in 2017 => With **8b+4e beam**

E. Métral, $\boxed{\text{Madrid, 15/11/2017}}$ 25

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E. Métral, Madrid, 15/11/2017 25

To push the performance in the future (with the environmental context, possible shorter runs, etc.), we need now to reinforce alternative scenarios

Introduction: Environmental/energetic context

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"The Electricity Fairy" (600 m^2) from Raoul Dufy, in Paris's Museum of Modern Art, for the 1937 International Exposition in Paris

Introduction: Environmental/energetic context

"La Jamais Contente" (The Never Contented) was the 1st road vehicle to go over 100 km/h (62 mph) on April 29, 1899. It was a Belgian electric vehicle. Soon after, the internal combustion engine supplanted the electric technology for the next century. Ecological considerations did not appear until much later…and we are now back to electric cars!

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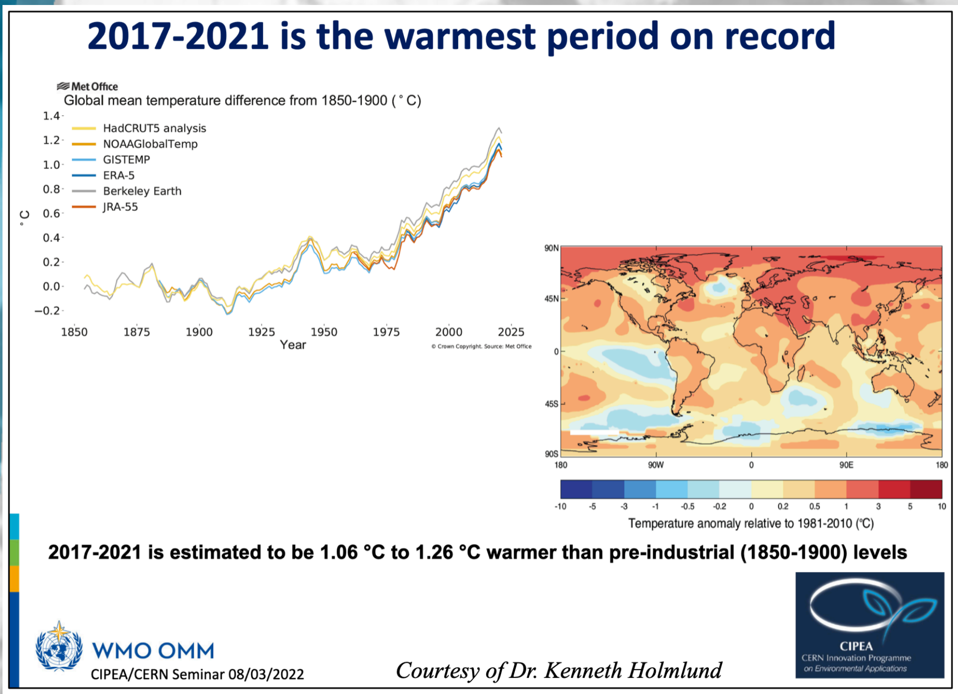

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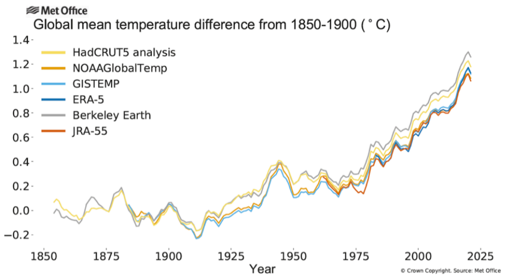
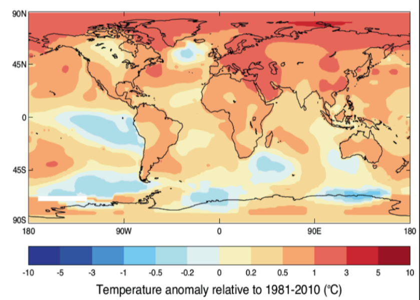
Introduction: Environmental/energetic context

2017-2021 is the warmest period on record





2017-2021 is estimated to be 1.06 °C to 1.26 °C warmer than pre-industrial (1850-1900) levels

WMO OMM
CIPEA/CERN Seminar 08/03/2022
Courtesy of Dr. Kenneth Holmlund
CIPEA CERN Innovation Programme on Environmental Applications

Why is it more than ever critical to talk about emission?

- Under the Paris Agreement, adopted by 196, countries agreed to limit warming to well below 2 °C (1.5 °C) above pre-industrial levels-> many evidences demonstrate that with current emission trajectory we are not meeting the goals (urgency of actions!)

PARIS 2015

COP26 in Glasgow in November 2021 ,

- Parties recognized that "{…} limiting global warming to 1.5 °C requires rapid, deep and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45 percent by 2030 relative to the 2010 level and to net-zero around mid-century, as well as deep reductions in other greenhouse gases {…}". Availability of authoritative and verifiable carbon monitoring data is critical to our ability to monitor progress toward this target.

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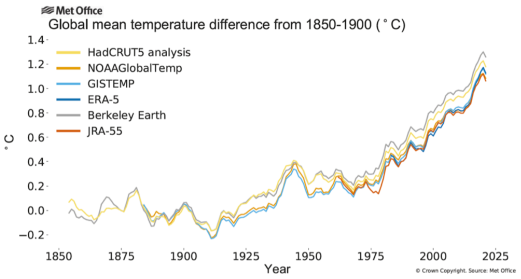

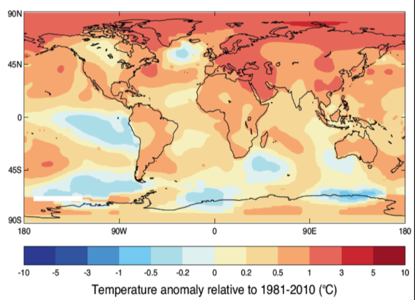

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Things will/should change in the coming years…

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- No HEL, TCP at 8.5 σ

Introduction & MAIN MESSAGE

Rogelio Tomás

e-cloud in arc78 limiting # of bunches to, e.g., 2200 ($L_{lev.} = 5\times10^{34}$cm^{-2}/s)

# of bunches	$\beta^*_{x,y}$ [cm]	L_{int} [fb^{-1}]	ppb$_{end}$ [10^{11}]	Pile-up	Fill length [h]	Hardware / comment
2748	20, 20	242	1.40-1.18	131	7.3	baseline Run 4
2200	20, 20	215 *-11%*	1.60-1.27	164	5.6	Lifetime!?

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2200	15, 15	226 -7%	1.43-1.17	164	6.1	+MS10

Introduction & MAIN MESSAGE

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# of bunches	$\beta^*_{x,y}$ [cm]	L_{int} [fb^{-1}]	ppb_{end} [10^{11}]	Pile-up	Fill length [h]	Hardware / comment
2748	20, 20	242	1.40-1.18	131	7.3	baseline Run 4
2200	20, 20	215	1.60-1.27	164	5.6	Lifetime!?
2200	15, 15	226	1.43-1.17	164	6.1	+MS10
2200	18, 9	234 *-3%*	1.30-1.09	164	6.6	+MS10

Introduction & MAIN MESSAGE

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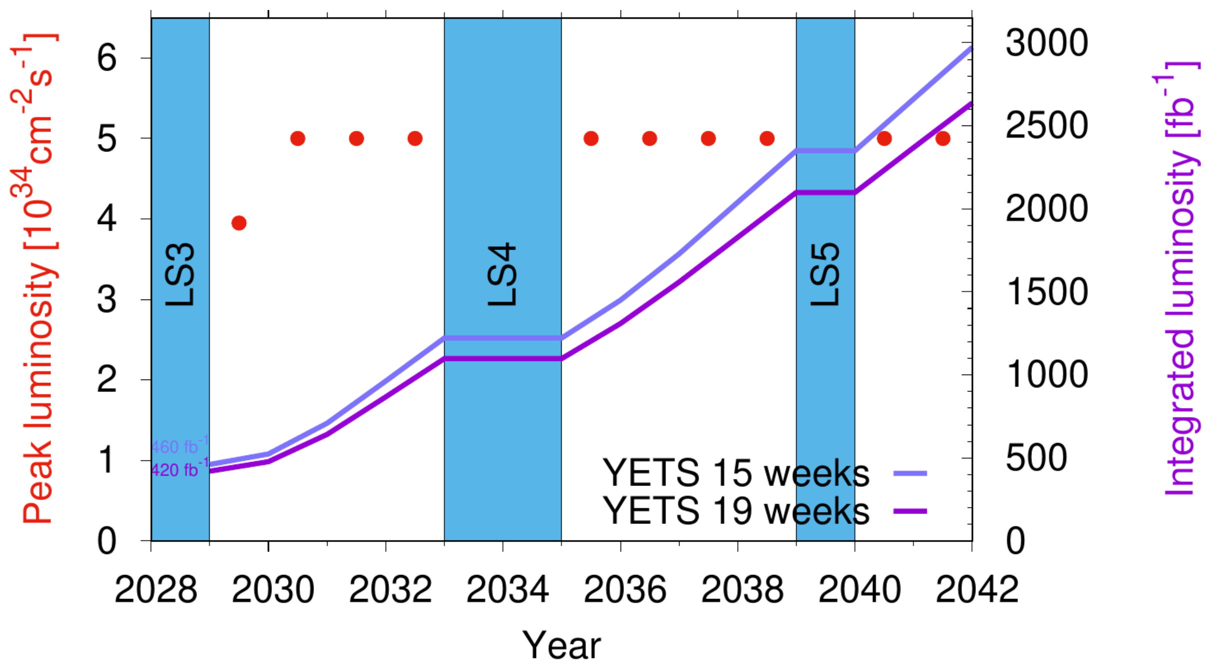
Ultimate scenario limited to $L_{lev.}$ **= 6.1×10^{34}cm^{-2}/s** brings little gain (at most 261 fb^{-1}). Need to support Heat Load Task Force work to prepare surface treatments techniques and optics alternatives: Flat, MS10, CuCD, wire.

New luminosity ramp-up approach?

Introduction & MAIN MESSAGE

Rogelio Tomás

Electricity cost/saving risk, e.g., extending all YETS to 19 weeks*



**There is an ongoing energy crisis in Europe and market prices are extremely volatile. It should be emphasised that projecting future energy prices over a 10-year timescale is necessarily speculative at this juncture, and that the measures outlined here should be regarded as exploratory at this stage.*

Courtesy of Mike Lamont

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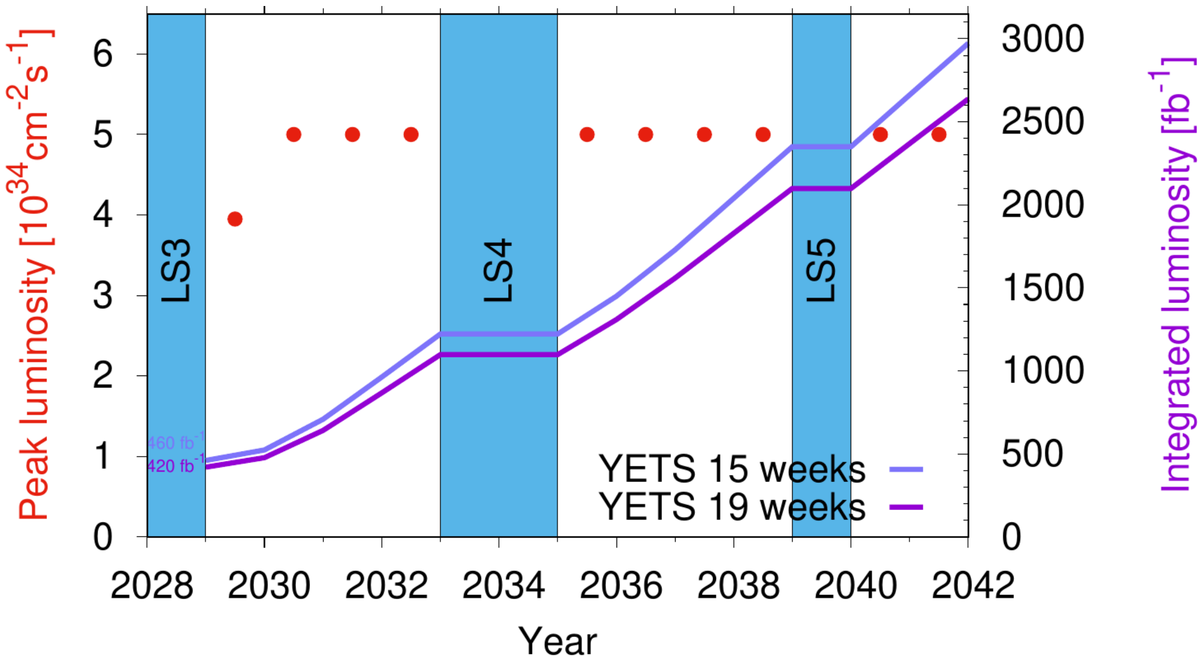

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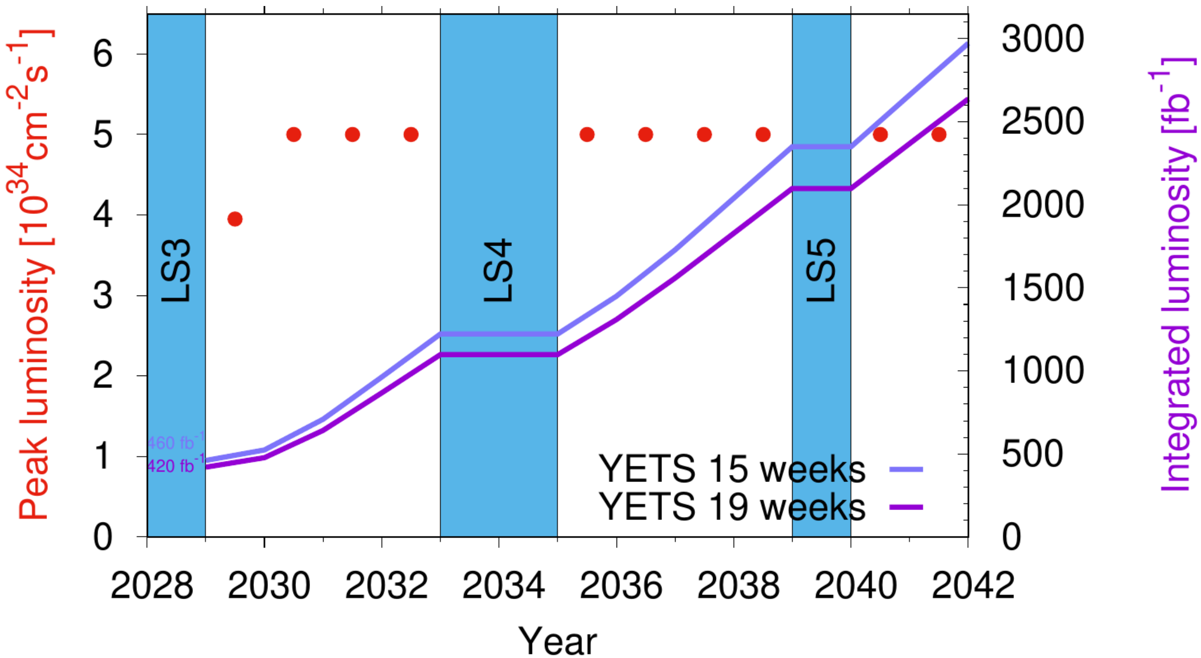
Restoring performance from a YETS extension would need alternative operational scenarios (Flat, etc.).



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Contents

- Introduction & main message
- Run 4 operational scenario
- Status of the optics v1.6
- Conclusions

Run 4 OP scenario

- 1st OP scenario in 2015 => http://cds.cern.ch/record/2016811/files/CERN-ACC-NOTE-2015-0009_2.pdf

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- 3rd OP scenario in 2022 => https://cds.cern.ch/record/2803611/files/CERN-ACC-2022-0001.pdf

CERN-ACC-2022-0001
rogelio.tomas@cern.ch

HL-LHC Run 4 proton operational scenario

G. Arduini, P. Baudrenghien, O. Brüning, R. Bruce, X. Buffat, R. Calaga, R. De Maria, J. Dilly, I. Efthymiopoulos, M. Giovannozzi, P.D. Hermes, G. Iadarola, S. Kostoglou, B. Lindström, E.H. Maclean, E. Métral, N. Mounet, Y. Papaphilippou, T.H.B. Persson, T. Pugnat, S. Redaelli, G. Sterbini, H. Timko, R. Tomás, F. Van der Veken, J. Wenninger, and M. Zerlauth,
CERN, Geneva, Switzerland.

CERN-ACC-2022-0001
29/06/2022

Abstract

Following new findings in beam dynamics and the latest HL-LHC project decisions, an operational scenario has been developed for the first HL-LHC run, Run 4. This new scenario is presented in this document along with the motivations for the proposed changes and performance estimates.

Geneva, Switzerland
June 29, 2022

Contents

Run 4 OP scenario

1st OP scenario

2nd OP scenario

Assumptions

Previous (2015) OP scenarios

- Parameters from SPS: 2.3E11 p/b within **2.0 μm**
- ATS optics: HLLHC**V1.1**
- New Mo+MoGr collimators in LSS7
- Level.: β* in 1&5 and // sep. in 2&8
- Few non-colliding bunches for experiments (background studies)
- Crab Cavities (CCs)
  - **Full compensation of Xing angle in 1&5**
  - **Continue impedance reduction**

Update (2017) OP scenarios

- Parameters from SPS: 2.3E11 p/b within **2.1 μm**
- ATS optics: HLLHC**V1.3**
- **+ 2 TCPs** in MoGr
- Level.: β* and **// sep. in 1&5 (< 1 σ)**
- Few non-colliding bunches for experiments (background studies)
- Crab Cavities (CCs)
  - **Number halved => Will not provide full compensation of Xing angle in 1&5**
  - **Impedance reduction done**
- **q-Gaussian** longitudinal distribution + increase of bunch length at high energy to avoid loss of longitudinal Landau damping => **RMS bunch length** (FWHM equivalent Gaussian) = **9 cm**
- **RF full detuning scheme** since acceleration
- **+ Others**

E. Métral, Madrid, 15/11/2017 5

Run 4 OP scenario

1st OP scenario

2nd OP scenario

Main results

Previous (2015) OP scenario

- Inject & Ramp with β* = 6 m
- ↘ **β* = 70/46 cm**
- **Collide & Squeeze**: ↘ β* = 15 cm
- Xing angles (constant since inj.)
  - ± 590 μrad in 1 (V)
  - + 590 μrad in 5 (H)
- Levelling
  - Nominal: 140 events/crossing
  - Ultimate: 210 events/crossing

Update (2017) OP scenario

- Inject with β* = 6 m
- **Ramp & Squeeze**: ↘ β* = **64 cm (TBC)**
- Nominal => Collide & Squeeze: ↘ β* = 15 cm
- Ultimate
  - Squeeze further: ↘ **β* = 41 cm**
  - Collide & Squeeze: ↘ β* = 15 cm
- Xing angles: injection (↘ in R&S and then constant for the moment)
  - **+ 590 (↘ to 500) μrad in 1 (H)**
  - **± 590 (↘ to ± 500) μrad in 5 (V)**
- Levelling
  - Nominal: 5E34 $cm^{-2}s^{-1}$
  - Ultimate: 7.5E34 $cm^{-2}s^{-1}$

E. Métral Madrid, 15/11/2017 6

Run 4 OP scenario

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  - ★ Cancellation of the installation of 11 T dipoles in LS2 => Run 4 will most likely happen without IR7 TCLDs and 11 T dipoles (earliest possible date of installation of these dipoles and the IR7 TCLDs seems to be LS4, due to manpower limitations)

Run 4 OP scenario

- Crab cavity (CC) noise. The expected CC phase and amplitude noise induce a transverse emittance growth larger than expected before
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- **Introduction of crystal collimation for ions**. These devices have to be compatible with proton operation in terms of impedance and e-cloud effects, although they are only used in operation with ions

Run 4 OP scenario

Table 1: Protons per bunch (ppb), virtual luminosity (calculated with $\beta^* = \beta^*_{\mathrm{end}}$), full crossing angle ($\theta$) and β^* targets in the HL-LHC luminosity ramp-up years. A normalised emittance, $\varepsilon_n = \varepsilon\gamma$ with $\gamma = E/m_p$, of $\varepsilon_n = 2.5\ \mu$m is assumed for all years. β^*_{start} and β^*_{end} correspond to the β-function at the start and at the end of the physics fill. β^*_{start} is defined to deliver 2.5×10^{34} cm^{-2}s^{-1} at the start of the fill to meet the requests from cryogenics. The Ultimate scenario is highlighted in yellow.

Year	ppb $[10^{11}]$	Virtual lumi. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Days in physics	θ [μrad]	β^*_{start} [cm]	β^*_{end} [cm]	HEL and CC	Max. PU
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2031	Long shutdown 4							
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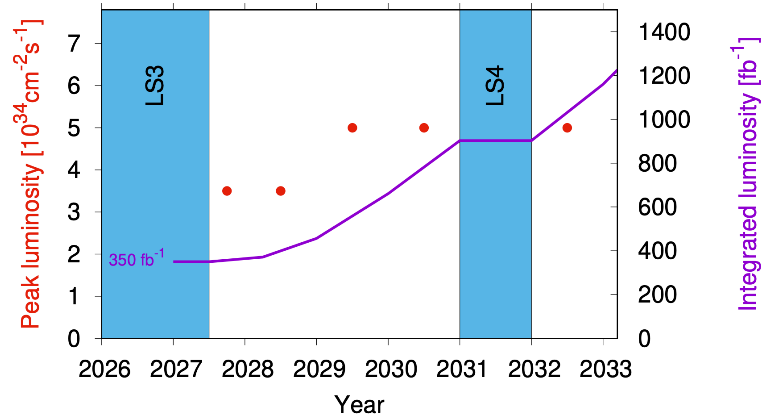

Figure 1: Peak and integrated luminosity during Run 4, assuming an integrated luminosity of 350 fb^{-1} by the end of Run 3.

Table 2: Breakdown of the minimum turn-around and physics fill times for Run 4.

Phase	Time duration [minutes]	Accumulated time [minutes]
Ramp-down	40	40
Pre-injection set-up	15	55
Set-up with beam	15	70
Nominal injection	30	100
Prepare ramp	5	105
Ramp & Squeeze	25	130
Flat-top	5	135
Collision adjustment	10	145
First luminosity plateau	10	155
Luminosity ramp up	10	165
Luminosity levelling	305	470
Luminosity decay	115	585

Run 4 OP scenario

Reminder that this Run 4 OP scenario (and schedule) is ALREADY OBSOLETE…

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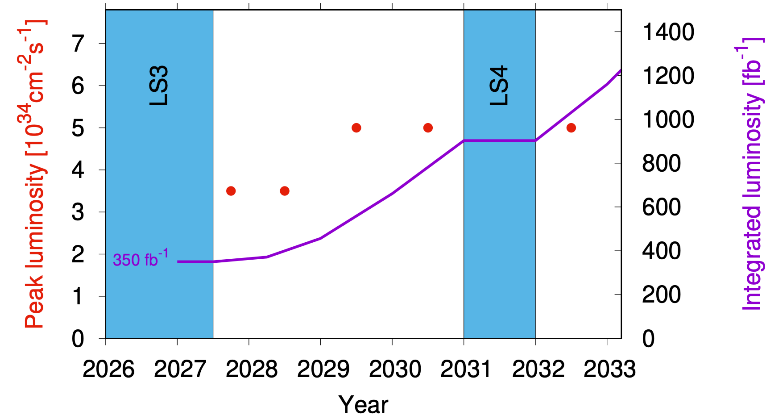

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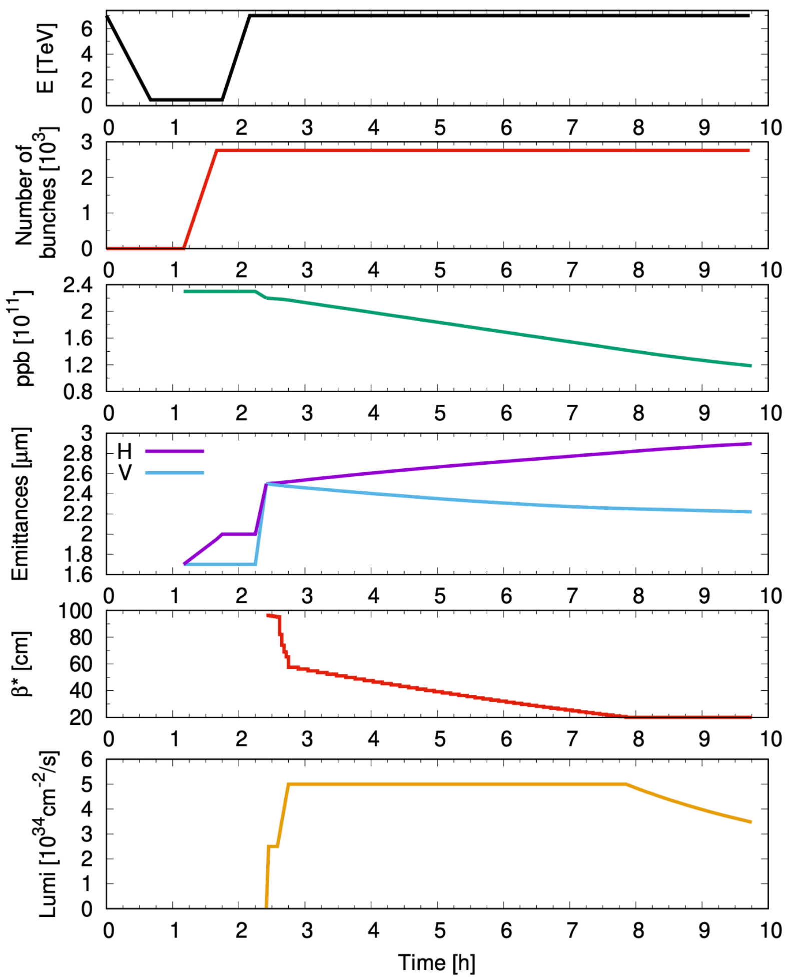

Figure 2: A schematic view of the Run 4 HL-LHC physics cycle showing magnetic cycle, number of bunches, protons per bunch (ppb), transverse emittances (BCMS case), and luminosity (top to bottom) versus time until the beam dump.

Run 4 OP scenario

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  - **New dates** for **Run 3** and **LS3**

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New baseline is to have it upgraded in LS3 and it is expected to be robust enough

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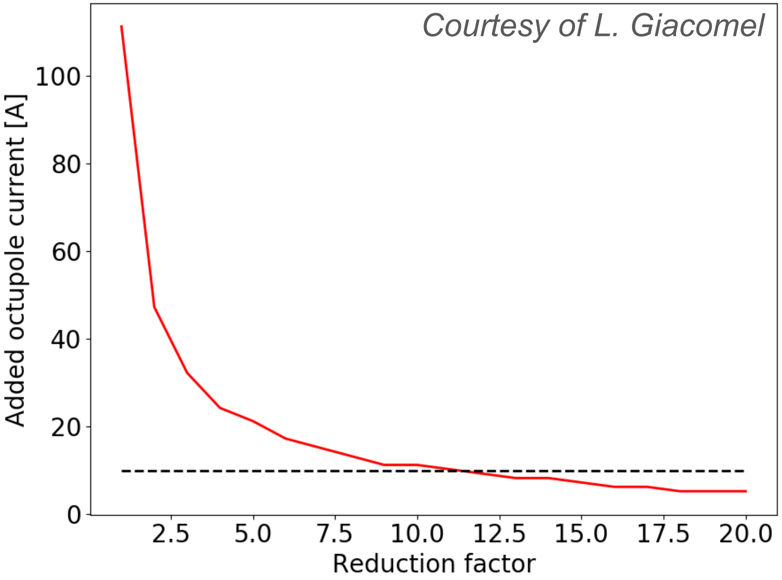

See also Lorenzo Giacomel (TH 09:40-10:00): Impedance measurements, LHC-MDs

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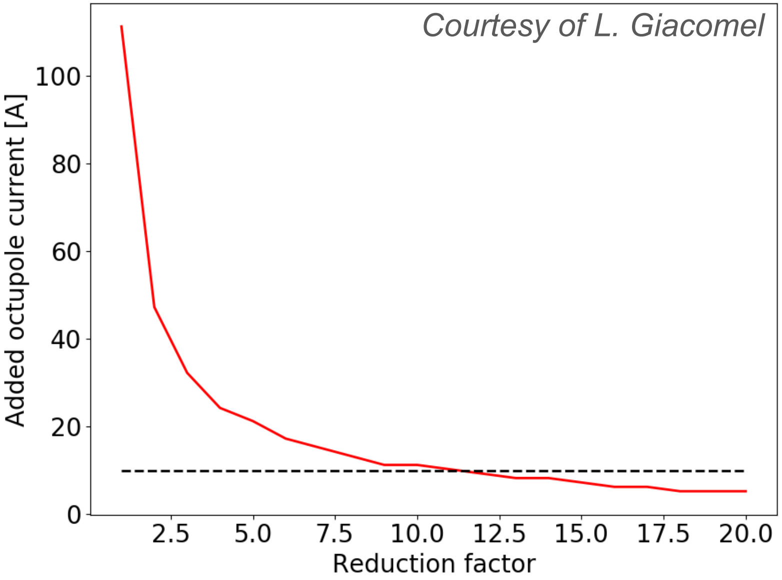

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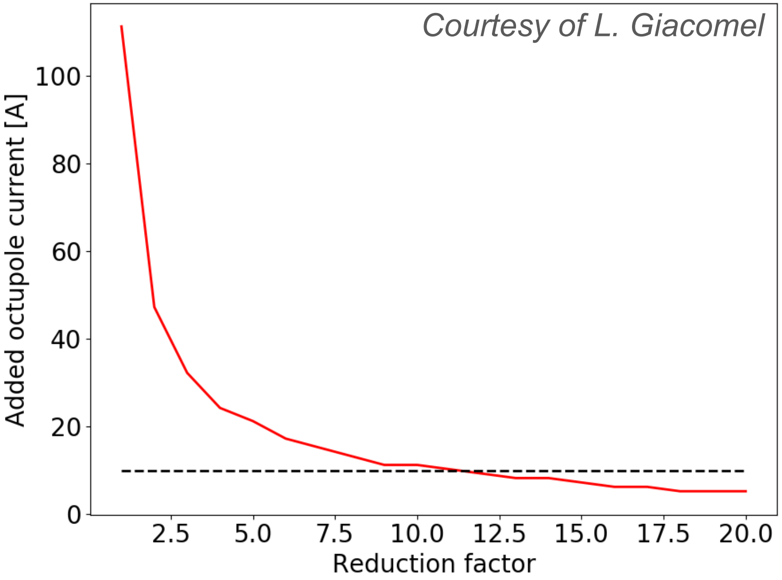
REMINDER for all people involved: see plot in Lorenzo's talk showing the LIMIT VALID FOR ANY RESONATOR-TYPE MODE!



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+ Ewen Hamish Maclean (WE 17:30-18:00): Status of DA with expected field quality
+ Ivan Karpov (TH 11:50-12:10): HL-LHC longitudinal stability

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CAVEAT: the LHC experience is still quite limited as we only got ~ 1.2×10^{11} p/b!

Contents

- Introduction & main message
- Run 4 operational scenario
- Status of the optics v1.6
- Conclusions

Status of optics v1.6

See also Riccardo De Maria (TU 14:00-14:20): Review of latest layout version and upcoming changes

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- **Layout changes v1.5 => v1.6**
  - Refined triplet magnetic length (~cm longer at constant integrate length) and position (thermal contraction)
  - Refined CP positions (better rounding)
  - Name change (BPM, CRABS ACFGA->ACFCA)
  - Change length TAXN (3.332 m => 3.310)
  - No MBH (11 T)
  - Change name and position of CRAB, APWL and BPTX (name only)
  - Changed position TCT/L.5/6, TCLMB/C
  - **MS10 is included in the optics files (because it is needed to study/optimise some OP scenarios) but it is not in the official drawings and DB (yet)**

See also Riccardo De Maria (TU 14:00-14:20): Review of latest layout version and upcoming changes

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- **Main messages**

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    - https://gitlab.cern.ch/acc-models/acc-models-lhc/-/tree/hl16
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  - **Next**: adapt the intermediate optics to the different OP scenarios => Several alternatives will be studied (β^* at the end of the ramp depends on the bunch intensity, the number of bunches, the CC impedance, etc.)

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- **Note: OP scenario for heavy-ion operation in Run 4 assumed to be the same as in Run 3 (see talk from R. Bruce and CERN-ACC-2020-0011: http://cds.cern.ch/record/2722753/files/CERN-ACC-2020-0011.pdf)**

Conclusions

TAKE-HOME MESSAGE

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The published Run 4 scenario (p+) is already old and we are already working on a new scenario assuming:

- MS10 (sextupoles in the dispersion suppressor)
- Flat Optics
- New bunch intensity / # of bunches (probably using hybrid 8b+4e) ramp-up pace following the experience from 2022 and 2023
- No HEL, TCP at 8.5 σ

Promising results from 1st DA studies with Flat Optics (see S. Kostoglou et al., https://indico.cern.ch/event/1197424/contributions/5035906/attachments/2507142/4308178/WP2_DA_flatoptics.pdf)

Many thanks for your attention!

WP2/WP13 HL-LHC Satellite Meeting, Uppsala 2022 - Long-Range Beam-Beam Wire
23 September 2022

Time	Contribution	Speaker	Location	Slot
	Welcome	Yannis Papaphilippou	New Consistorium room, Uppsala University	08:45 - 09:00
09:00	BBCW results during Run 3 operation	Philippe Belanger	New Consistorium room, Uppsala University	09:00 - 09:30
	BBCW collimation scenarios for Run 4	Roderik Bruce	New Consistorium room, Uppsala University	09:30 - 09:45
10:00	BBCW potentials for Run 4	Guido Sterbini	New Consistorium room, Uppsala University	09:45 - 10:15
	Coffee break		New Consistorium room, Uppsala University	10:15 - 10:45
11:00	Present BBWC mechanical design	Alessandro Bertarelli	New Consistorium room, Uppsala University	10:45 - 11:15
	Infrastructure/Integration/Schedule constraints	Adriana Rossi	New Consistorium room, Uppsala University	11:15 - 11:35
12:00	Impedance and RF heating	Benoit Salvant	New Consistorium room, Uppsala University	11:35 - 12:05
	Energy deposition studies	Marta Sabate Gilarte	New Consistorium room, Uppsala University	12:05 - 12:25
13:00	Lunch break		New Consistorium room, Uppsala University	12:25 - 13:30
	TRIUMF contribution to the BBLR Compensation Project	Oliver Kester	New Consistorium room, Uppsala University	13:30 - 14:00
14:00	Magnetic field modelling of the wire	Marco Marchetto	New Consistorium room, Uppsala University	14:00 - 14:30
	Discussion		New Consistorium room, Uppsala University	14:30 - 15:00
15:00				

https://indico.cern.ch/event/1168738/

REMINDER: PEOPLE ALSO HAVING A TALK LINKED TO WP2 ACTIVITIES

Roderik Bruce (MO 09:25-09:45): LHC Run3 operation plans
Riccardo De Maria (TU 14:00-14:20): Review of latest layout version and upcoming changes
Bjorn Hans Filip Lindstrom (TU 14:20-14:40): Collimator layout and performance
Ilias Efthymiopoulos (TU 15:20-15:50): Bunch-by-bunch variations in LHC 2022
Pascal Hermes (WE 14:40-15:00): Status and results of HL-LHC MDs for collimation
Bjorn Hans Filip Lindstrom (WE 15:00-15:20): New IR7 optics for improved cleaning and impedance
Ewen Hamish Maclean (WE 17:30-18:00): Status of DA with expected field quality
Natalia Triantafyllou (TH 08:40-09:00): Crab cavity emittance growth MDs
Konstantinos Paraschou (TH 09:00-09:20): LHC electron cloud studies
Lorenzo Giacomel (TH 09:40-10:00): Impedance measurements, LHC-MDs
Guido Sterbini (TH 10:30-10:50): Beam-beam & Noise studies
Ivan Karpov (TH 11:30-11:50): HL-LHC longitudinal stability
Ewen Hamish Maclean (TH 14:20-14:45): Optics measurements & outlook
+ Several people for WP2/WP13 Satellite Meeting on BBLR Wire on FR