Luminosity leveling with crabs

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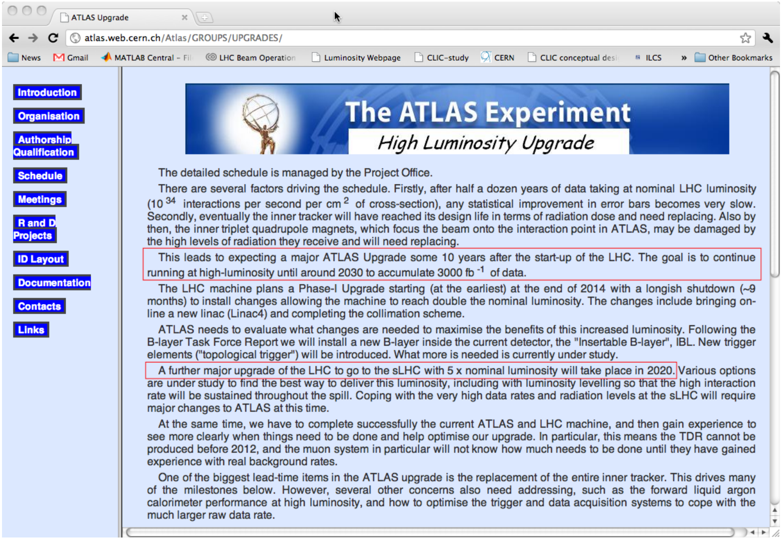
Thanks to Rama and Riccardo for the discussions

Outlook

- Introduction: the goals, crab Xing and the crab leveling.
- Adopted model: hypotheses, approximations, limits.
- Benchmarking of the model with LHC (an example).

- Different scenarios for HL-LHC with crabs.
- Conclusions

The goal...



ATLAS Upgrade

atlas.web.cern.ch/Atlas/GROUPS/UPGRADES/

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Introduction
Organisation
Authorship Qualification
Schedule
Meetings
R and D Projects
ID Layout
Documentation
Contacts
Links

The ATLAS Experiment
High Luminosity Upgrade

The detailed schedule is managed by the Project Office.

There are several factors driving the schedule. Firstly, after half a dozen years of data taking at nominal LHC luminosity (10^{34} interactions per second per cm^2 of cross-section), any statistical improvement in error bars becomes very slow. Secondly, eventually the inner tracker will have reached its design life in terms of radiation dose and need replacing. Also by then, the inner triplet quadrupole magnets, which focus the beam onto the interaction point in ATLAS, may be damaged by the high levels of radiation they receive and will need replacing.

This leads to expecting a major ATLAS Upgrade some 10 years after the start-up of the LHC. The goal is to continue running at high-luminosity until around 2030 to accumulate 3000 fb^{-1} of data.

The LHC machine plans a Phase-I Upgrade starting (at the earliest) at the end of 2014 with a longish shutdown (~9 months) to install changes allowing the machine to reach double the nominal luminosity. The changes include bringing on-line a new linac (Linac4) and completing the collimation scheme.

ATLAS needs to evaluate what changes are needed to maximise the benefits of this increased luminosity. Following the B-layer Task Force Report we will install a new B-layer inside the current detector, the "Insertable B-layer", IBL. New trigger elements ("topological trigger") will be introduced. What more is needed is currently under study.

A further major upgrade of the LHC to go to the sLHC with 5 x nominal luminosity will take place in 2020. Various options are under study to find the best way to deliver this luminosity, including with luminosity levelling so that the high interaction rate will be sustained throughout the spill. Coping with the very high data rates and radiation levels at the sLHC will require major changes to ATLAS at this time.

At the same time, we have to complete successfully the current ATLAS and LHC machine, and then gain experience to see more clearly when things need to be done and help optimise our upgrade. In particular, this means the TDR cannot be produced before 2012, and the muon system in particular will not know how much needs to be done until they have gained experience with real background rates.

One of the biggest lead-time items in the ATLAS upgrade is the replacement of the entire inner tracker. This drives many of the milestones below. However, several other concerns also need addressing, such as the forward liquid argon calorimeter performance at high luminosity, and how to optimise the trigger and data acquisition systems to cope with the much larger raw data rate.

TARGET: $\int \mathcal{L}dt \approx 300$ fb^{-1} year^{-1} AND pile-up $\lesssim 100$

Compute the $\int \mathcal{L}(t)dt$: the adopted model.

How to evaluate the performance? We need to

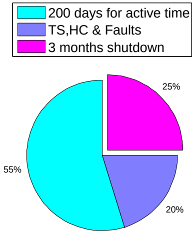
- chose/guess the parameters for reaching $\hat{\mathcal{L}}$ $(\beta^*, N_b, \epsilon_n \ldots)$,
- compute $\mathcal{L}(t)$ (dynamic model for proton burn-off, emittance growth,. . .),
- and integrate it in a realistic domain (machine availability, Turn-Around-Time,. . .).

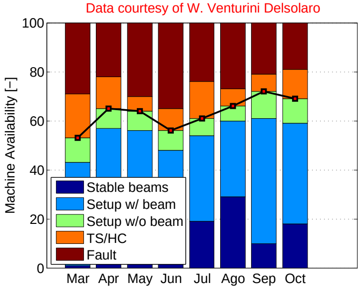
The 2010 LHC has given us a lot of information for HL-LHC.

$\int \mathcal{L}$ dt: the domain of integration.

Assumptions in simulations

- 200 days of machine availability ($\approx$ 70% on 9 months),
- 10 h of Turn-Around-Time (TAT),
- (3 months shut-down per year).





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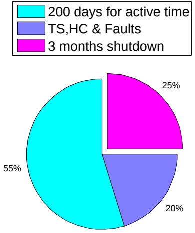

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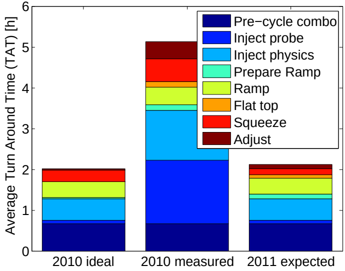
Observations in LHC

- $\approx$ 65% availability,
- 5 h of Turn-Around-Time .

Data courtesy of S. Redaelli



How we compute $\mathcal{L}(t)$

What the model does

- Solve a system of differential equations taking into account a simple model for intra-beam and rest-gas scattering.
- Take into consideration proton burn-off and allows feedback on the luminosity (e.g. leveling).

What the model does not

- Only fully matched beams (same N_b, ϵ_n) and rounds beams,
- No hourglass effect or Crab RF curvature ($<10\%$ effect on $\hat{\mathcal{L}}$ in our parameter space),
- No additional diffusion mechanism for the beam-beam interaction.
- ...

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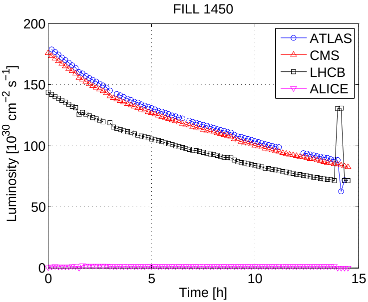
Let us benchmark the code with FILL 1450...

FILL 1450 (one of the last pp fill this year).

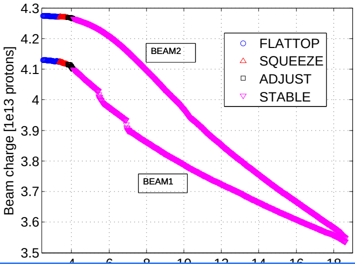
The effect of the crossing

Visible effect of the large crossing angle in LHCb: we can see the geometrical factor (≈ 0.8). Very good agreement with the expected one.



Different Current decay

When the beams are put in collision the beam lifetime is reduced. In real life the two beams have very different behavior.



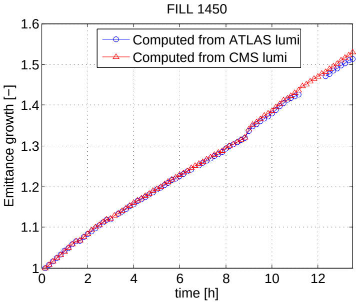
FILL 1450 (one of the last pp fill this year).

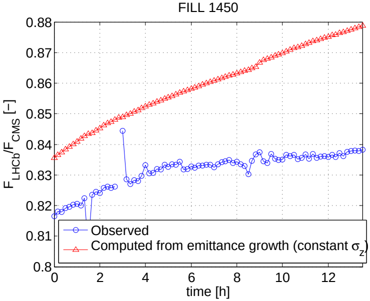
Emittance growth (round beam)

From $\mathcal{L}$ and $N_b = 1.14\text{e}11$ we can compute $\epsilon_n \approx 2.4\mu\text{m rad}$ and it is growing 4%/h.

What about σ_z?

From the F factor in LHCb it seems growing too since there is a mismatch with the emittance growth.





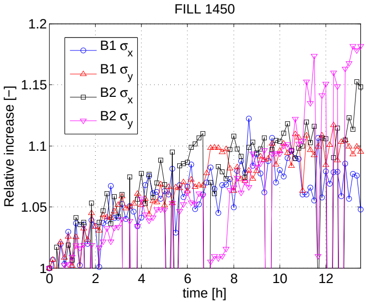
FILL 1450 (one of the last pp fill this year).

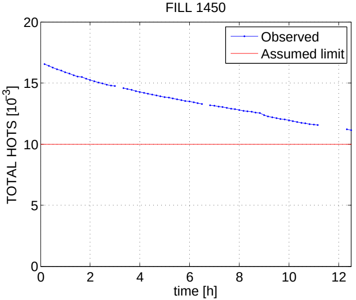
The measured σ

From the synchrotron light monitor a factor 2 is missing.

What about the total head on ΔQ?

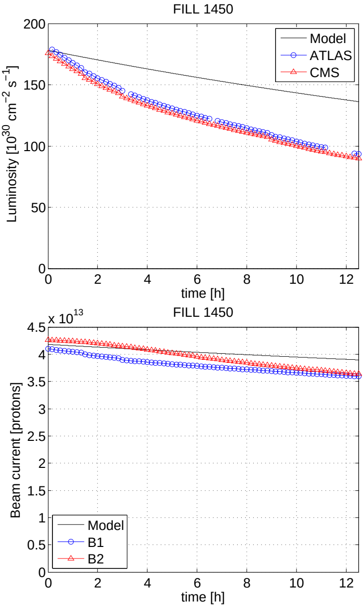
Almost 17e-3: That is significantly above the 10e-3 reference limit.





Benchmarking with FILL 1450

The model is not conservative. The luminosity decay computed is slower of the actual one: in fact the model underestimate the current decay rate and the emittance growth.



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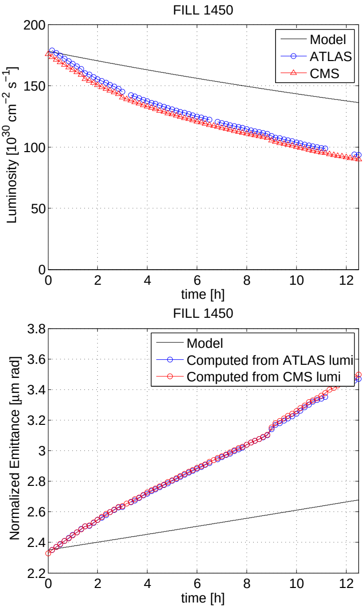
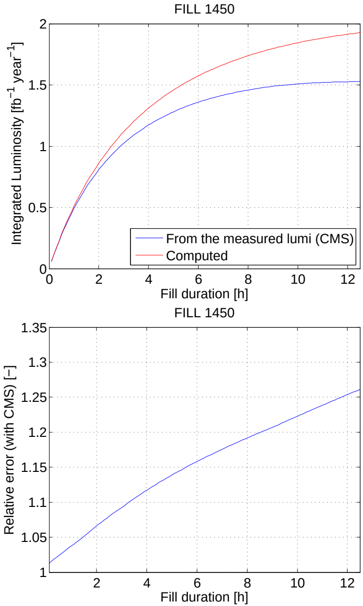


Benchmarking with FILL 1450

What about $\int \mathcal{L} dt$?

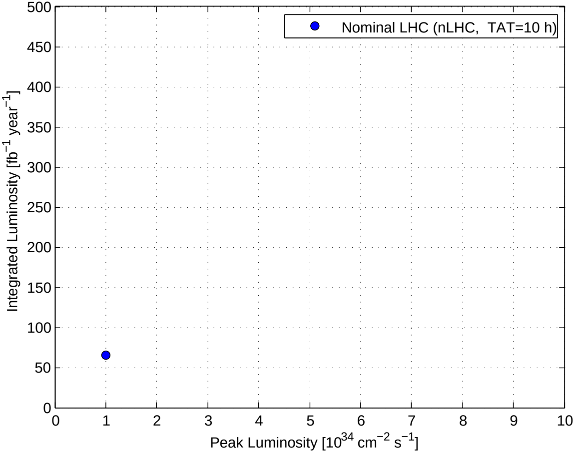
The error depends on the fill duration. For 12 h is $\approx$ 25%. But in the fill duration of the HL-LHC we expect an error $\approx$ 15%.



. . . interlude. . .

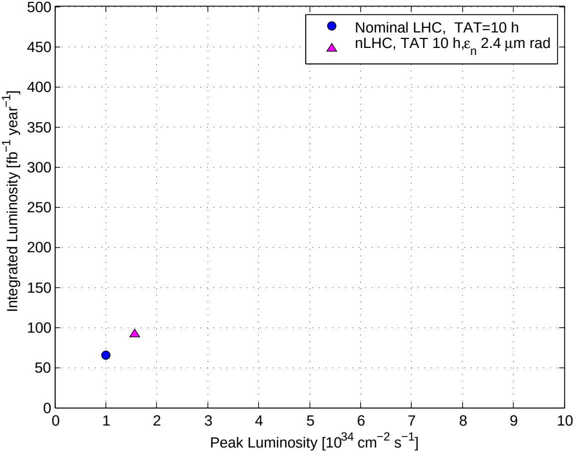
(if not differently stated I refer to the 25 ns beam)

A possible journey on the luminosity plane in LHC...



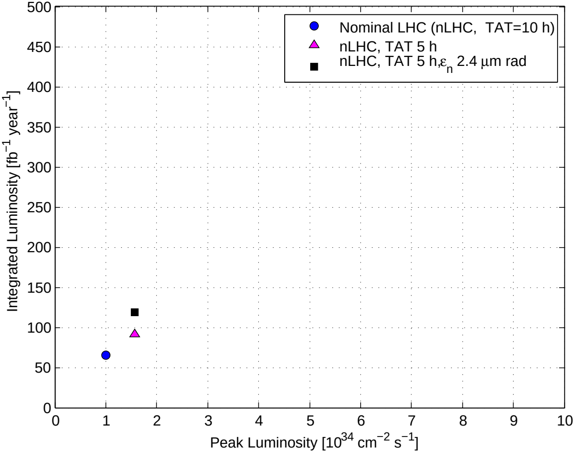
The starting point: ≈ 65 fb^{-1} per year.

A possible journey on the luminosity plane in LHC...



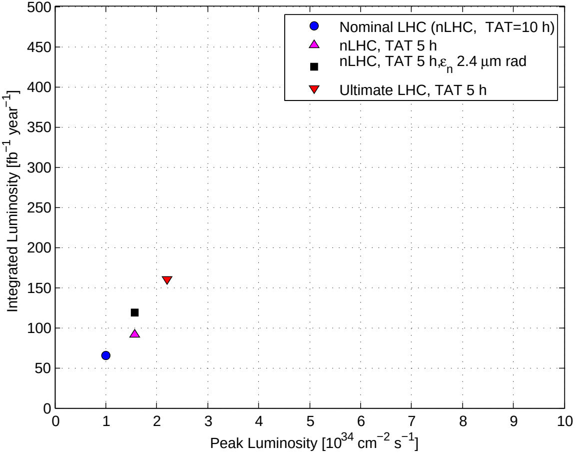
We can profit of the $\epsilon_n = 2.4\ \mu$m rad.

A possible journey on the luminosity plane in LHC...



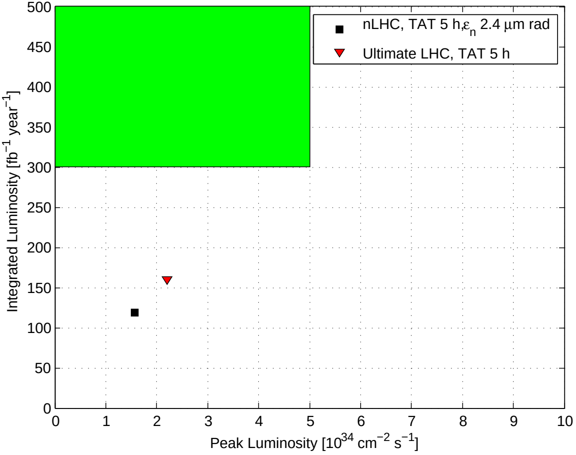
We can profit of the 5 h Turn-Around-Time.

A possible journey on the luminosity plane in LHC...



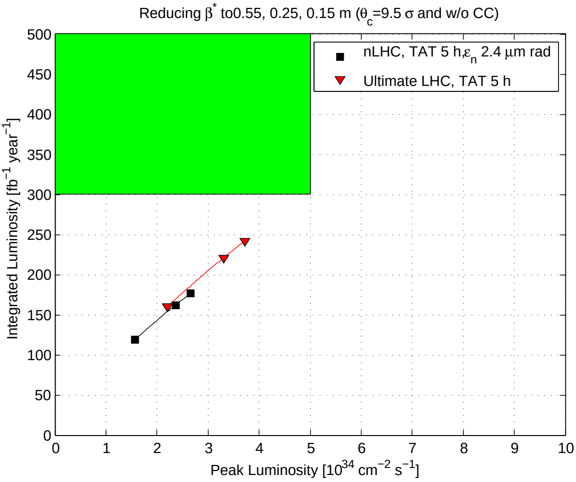
We can consider the ultimate N_b (1.7e11 at 3.75 μrad m).

A possible journey on the luminosity plane in LHC...



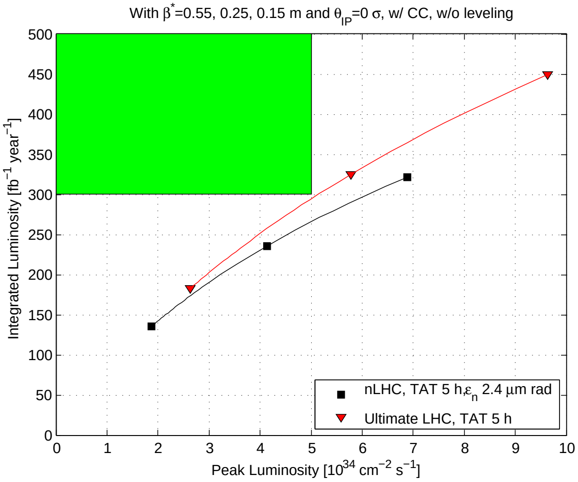
...half the way still to be done, half the way already gone...

...adding New Insertions...



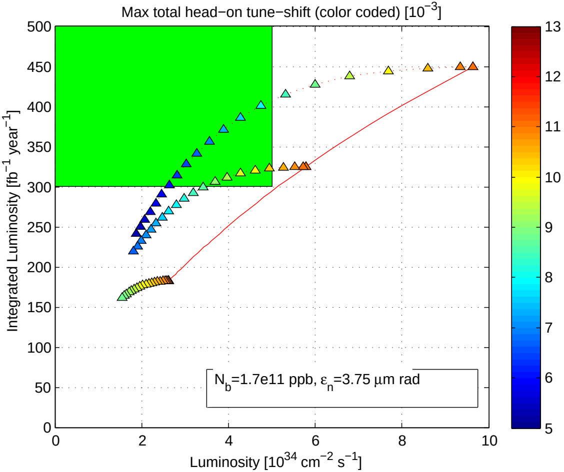
Reducing β^* helps but the 9.5σ beam separation reduces the gain.

...adding Crab Crossing...



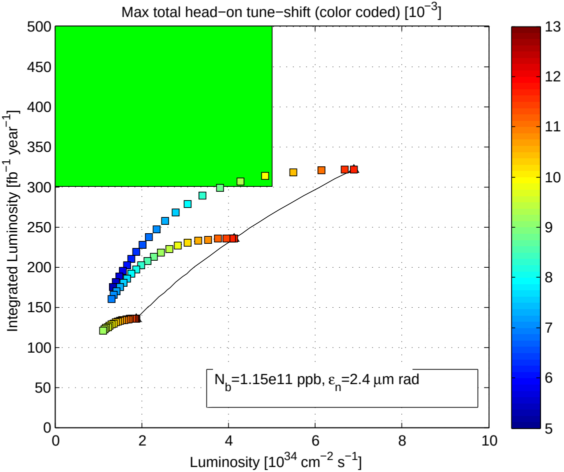
The Crab Crossing boosts the performance!

...adding Crab Leveling...



With Crab Leveling we can reduce $\hat{\mathcal{L}}$ and reach the target (w/ $\beta^* = 0.15$ or 0.25 m at very low head-on tune shift).

...adding Crab Leveling...



Similar approach with reduced N_b

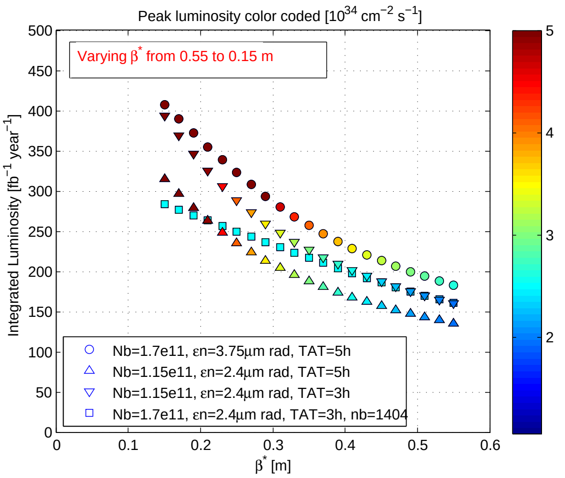
($\beta^* = 0.15$ and increased head-on tune shift).

Additional scenarios

Additional considerations...

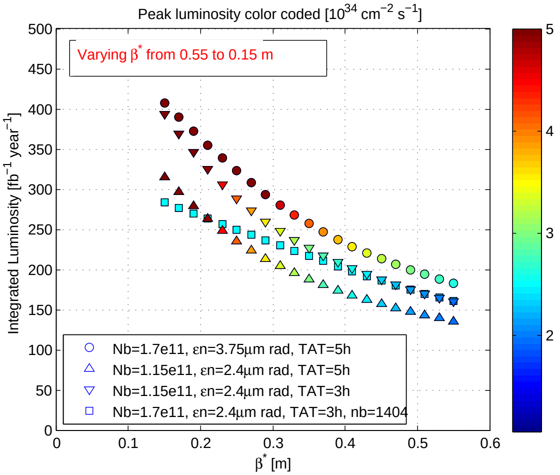
1. At which Turn-Around-Time the N_b=1.15e11 is equivalent to 1.7e11?
2. Can we reach the goal with 50 ns beam?
3. How does $\int \mathcal{L}dt$ scales with β^* at pile-up$<$ 100?

$\int \mathcal{L}dt$ vs β^* at pile-up $\lesssim 100$



1.15@2.4 + 3 h TAT ≈ 1.7@3.75 + 5 h TAT

$\int \mathcal{L}dt$ vs β^* at pile-up $\lesssim 100$



50 ns ($\approx$ 1.7@2.4 + 3 h TAT) almost reaches the target

Conclusions I

From 2010 run

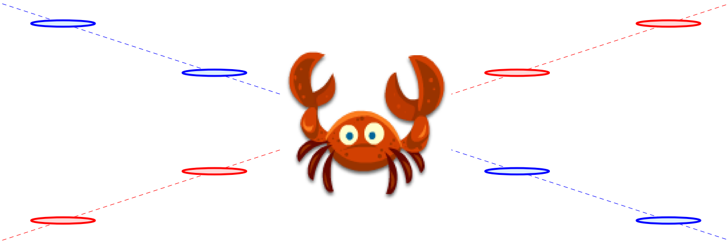
- $\approx$ 65% machine availability + 5 h of Turn-Around-Time,
- bunch 60% brighter than the nominal one,
- head-on ΔQ beyond the expected limit,
- geometrical reduction of $\mathcal{L}(t)$ observable in LHCb.

Conclusions II

$\int \mathcal{L} dt$ per year at pile-up ≈ 100

- Leveling appears essential for alleviating the detector pile-up.
- Crab Leveling $+ \beta^* = 0.15$ m can reach the target (7 TeV):
  - 320 fb^{-1}: 25 ns, with the observed bunch in LHC (5 h TAT)
  - 400 fb^{-1}: 25 ns, with the ultimate bunch (5 h TAT)
  - 280 fb^{-1}: 50 ns, N_b=1.7e11, $\epsilon_n = 2.4$ μrad m and 3 h TAT.

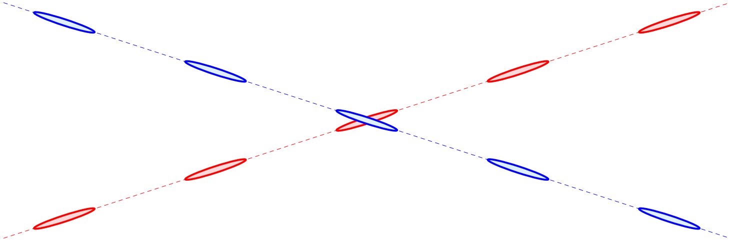
Happy crabbing!



Thank you!

BACKUP SLIDES

Crab CROSSING and crab LEVELING

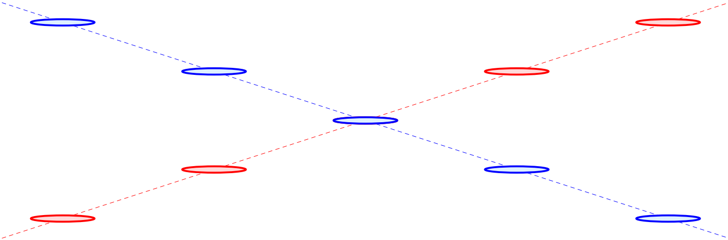


Crab CROSSING

We can have a better overlapping of the bunches at the IP AND a large beam separation at the parasitic encounters.

ing ☺

Crab CROSSING and crab LEVELING



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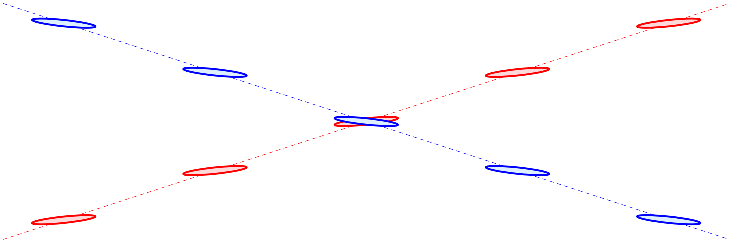
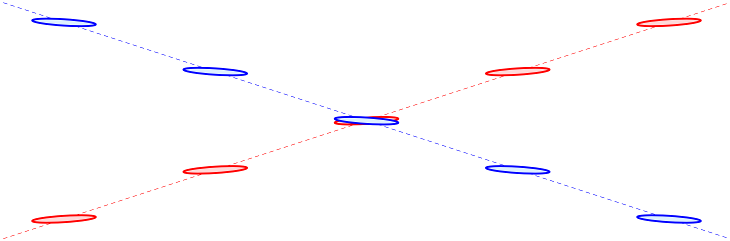


Crab LEVELING

We can use the CC RF voltage as a knob to keep constant the luminosity and to alleviate the beam-beam interaction at the IP.

Crab CROSSING and crab LEVELING



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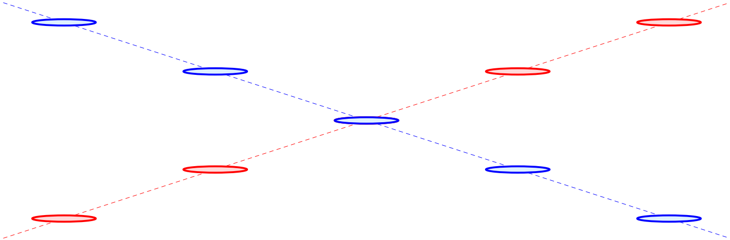

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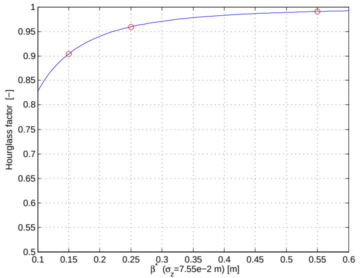
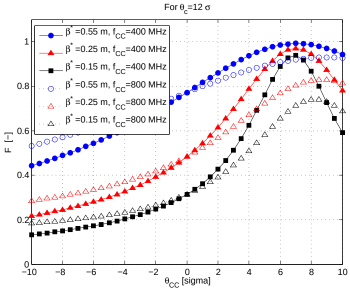
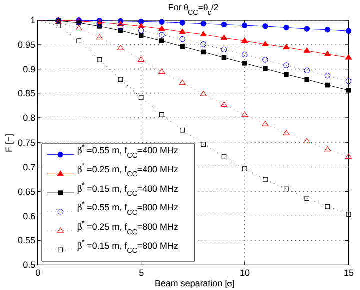
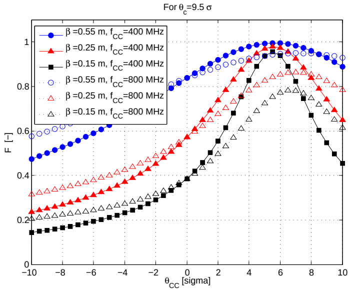
Hourglass Effect and RF Curvature Effect on F

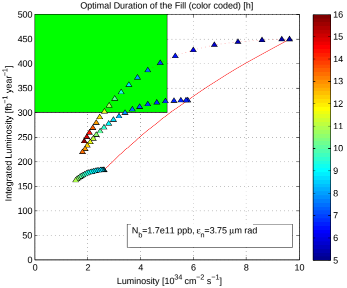


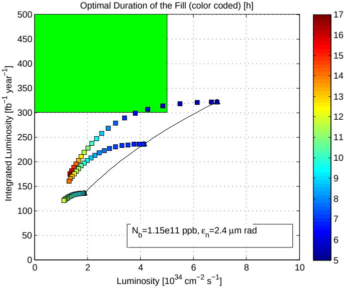


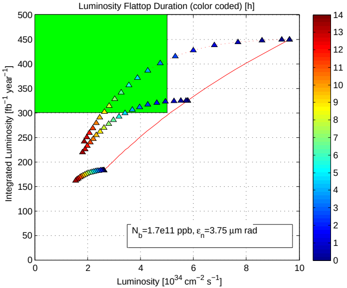


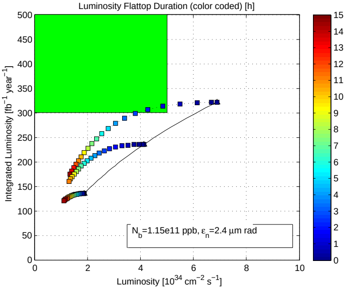


Luminosity leveling

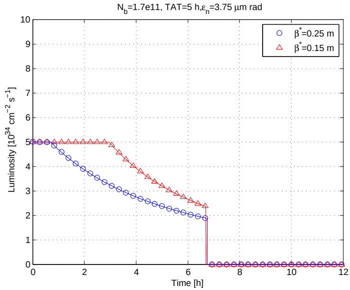


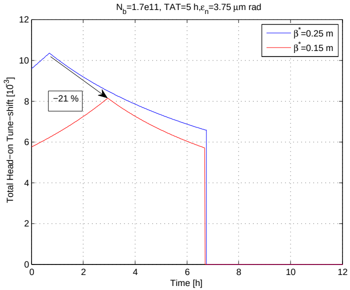


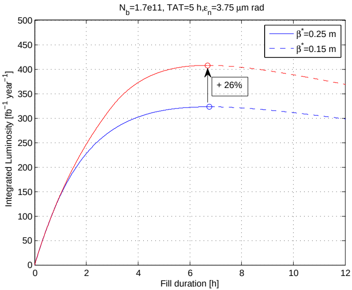


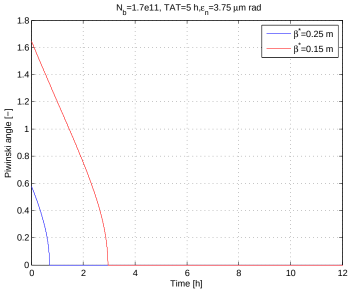


An example of luminosity leveling wrt time

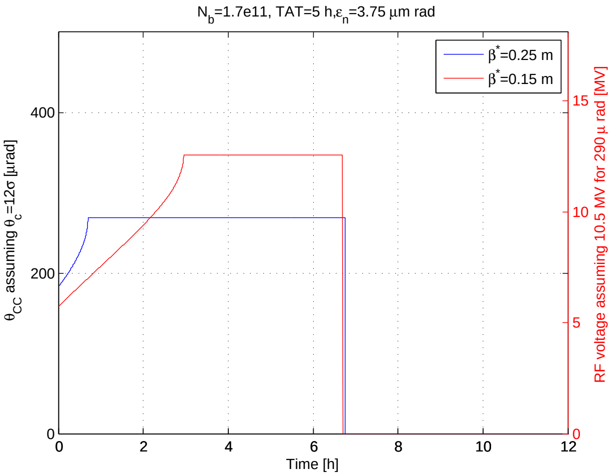




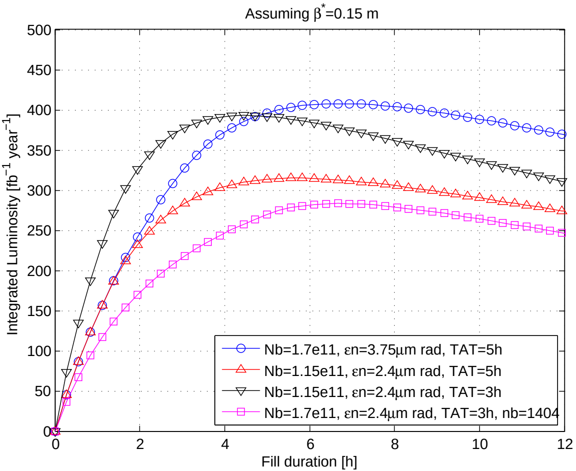




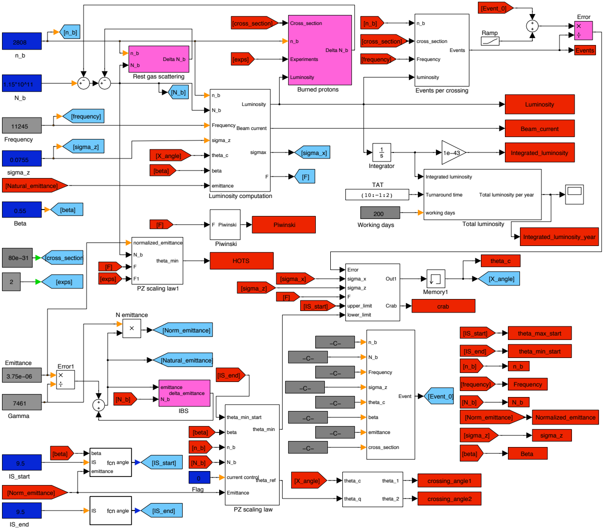
RF Voltage Required



$\int \mathcal{L}dt$ vs β^* at pile-up $\lesssim 100$



The Simulink^{TM} model programmed



4 scenarios on the luminosity plane