Heavy Ions at FCC-hh

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Introduction

- LHC works *extremely* well as nucleus-nucleus and proton-nucleus collider
  - Largest steps in collision energy in history of accelerators
  - Already far into “HL-LHC” performance regime
  - 3×(Pb-Pb) and 8×(p-Pb) design luminosity after 12 and 8 weeks total operation time (2010-2016)
  - High precision heavy-ion physics and unexpected discoveries
  - New beam physics limitations seen, solutions established

- FCC-hh can perform even better than LHC
  - Strong radiation damping can be fully exploited
  - LHC solutions can be extended to FCC-hh
  - Physics case being elaborated, includes QGP physics but also ultra-peripheral photon-photon collisions (Higgs, top, ...)

More details about physics cases: David d’Enterria, today 16:10

Outline

- General Assumptions
  - Beam parameters
  - Filling Pattern
  - Filling Time
  - Run Schedule
- Update on Performance Estimates: Pb-Pb & p-Pb
  - Luminosity and Beam Evolution
  - Secondary Beams
- Other Ion Species

- Further Studies
- Conclusions

General Parameters

	LHC achieved	HL-LHC baseline	FCC-hh baseline	FCC-hh ultimate
Circumference	26.66 km		**97.75 km**	
Beam Energy [Z TeV]	6.5	7	**50**	
β-function at the IP [m]	0.6	0.5	**1.1**	**0.3**
No. Ions per bunch [1e8]	2.2	1.8	**2.0**	
Transv. normalised emittance [μm.rad]	~1.5	1.65	**1.5**	
Bunch spacing [ns]	100	50	**100**	**50**
Number of bunches	518	1256	**2760**	**5400**
Stored energy/beam [MJ]	10	21	**362**	**709**
Stored energy/beam at Injection [MJ]	0.7	1.5	**24**	**47**

new layout

LHC experience

30% larger beam size as protons

more than 10x smaller as for protons

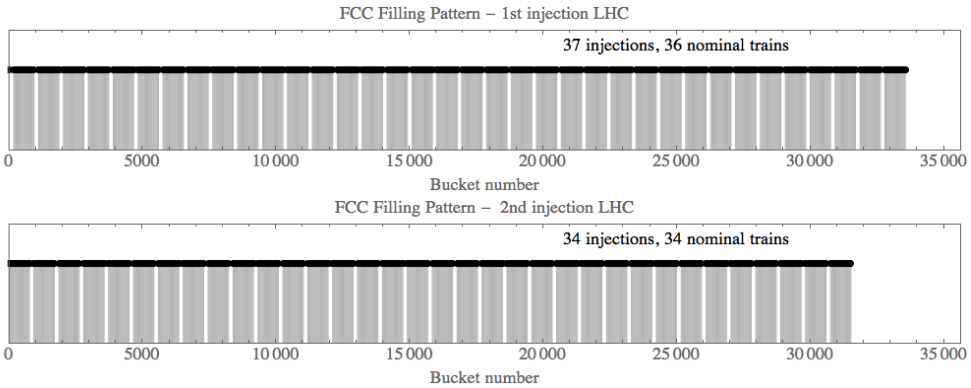
Filling Pattern (Baseline)

Trains of 5x4 Bunches = 20 Bunches/Train, ***spaced by 100ns***
(limited by LHC extr. kicker flat top length)

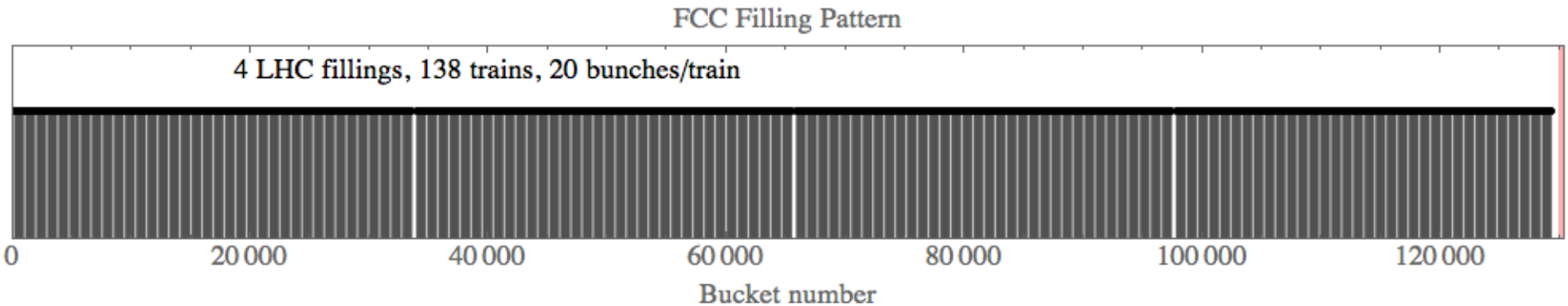
1st LHC transfer: 1 Pilot + **36 Trains**

+

2nd, 3rd, 4th LHC transfer: **34 Trains**



~ 690 bunches per LHC cycle → **2760 colliding bunches**



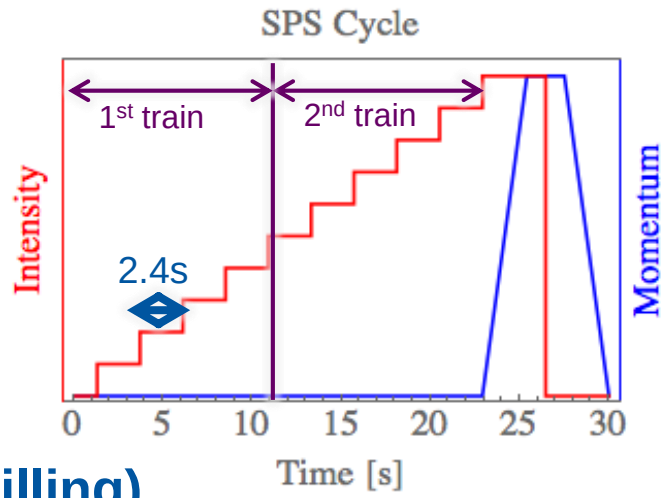
Filling Time (Current LHC Injectors)

with small upgrades

SPS cycle time per train = 32.4 s

Assuming:

- LEIR/PS cycle time = 2.4 s
- PS injections/train = 2x5
- Preparation time = 8.4 s

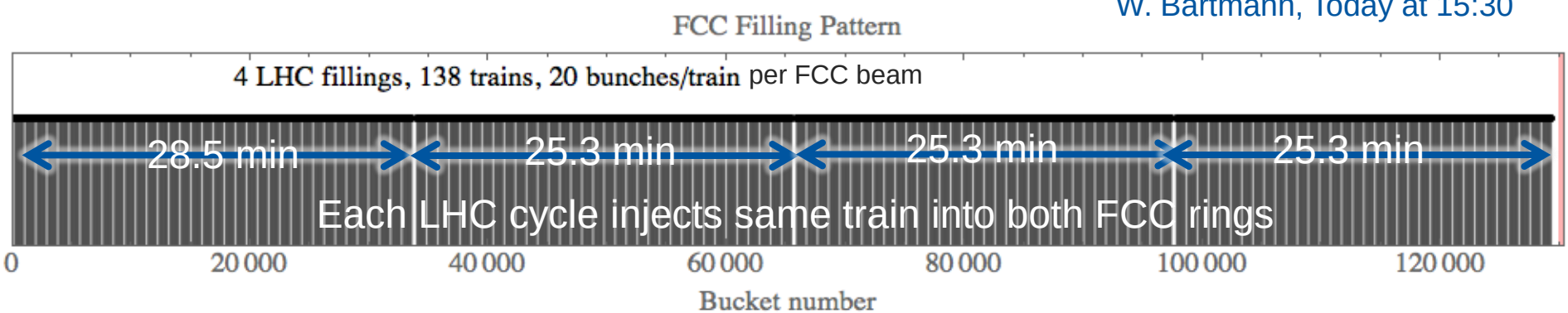


LHC preparation time = 7 min (+ 2 min 1st Filling)

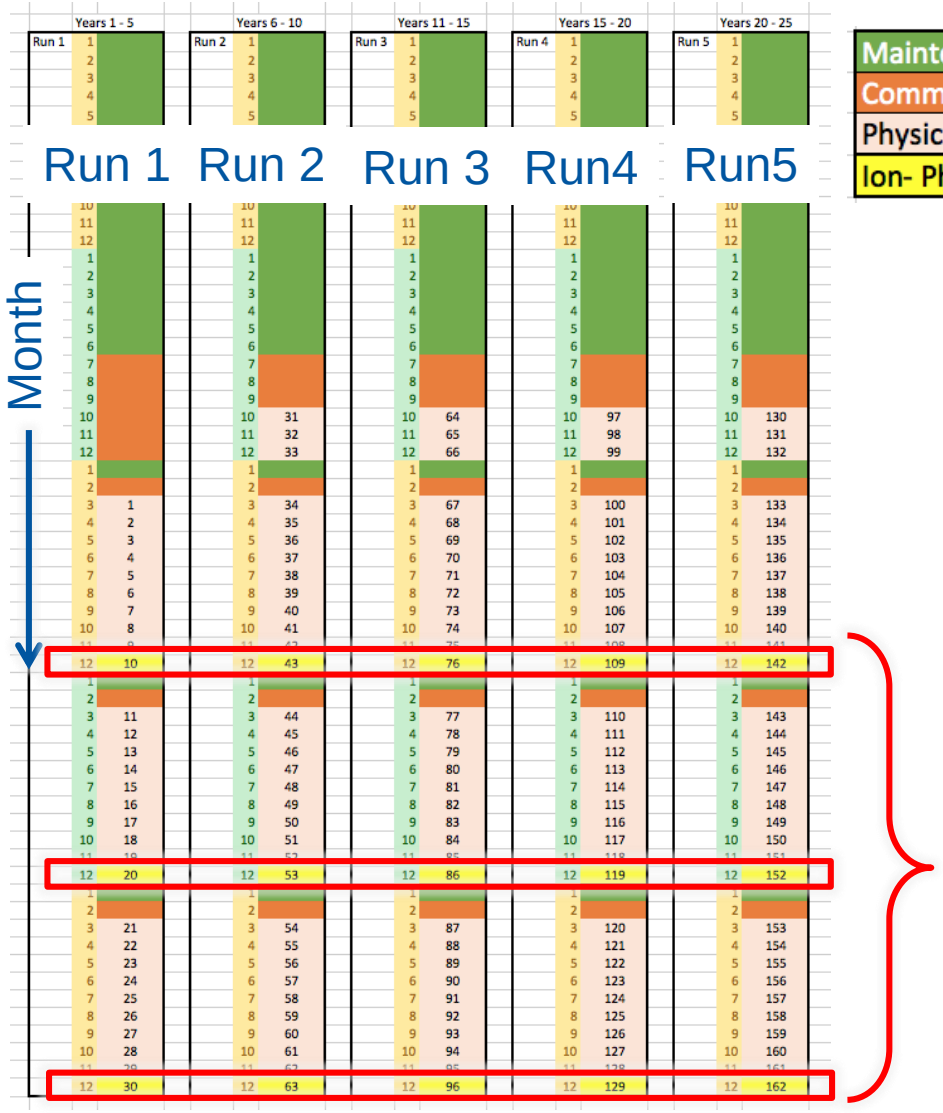
→ **FCC filling time (2 beams) = 105 min**

→ (8x more SPS-LHC transfers than in p-p)

Current estimate for p-p: 44 min
W. Bartmann, Today at 15:30



Tentative Run Schedule



Maintenance intervention
Commissioning
Physics
Ion- Physics

Similar strategy as for LHC:

- 1-month-long Heavy-Ion runs before each Technical Stop or Shutdown
- 3 such ion runs per FCC-Run of 5 years

15 x 1 month Ion-Physics time

See Talk by A. Niemi, Thu 1 Jun, 15:30

Beam Evolution Studies

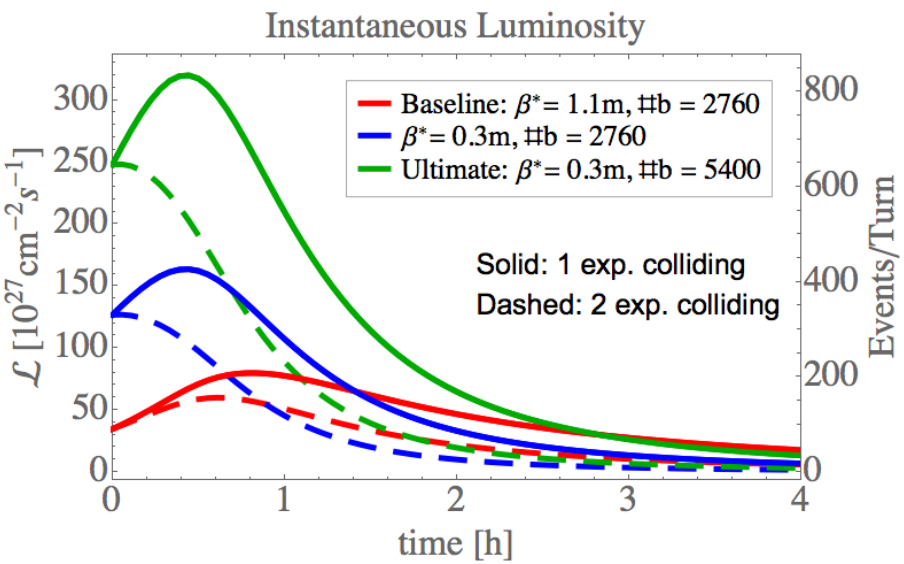
- Time evolution of beam parameters obtained from numerical solution of a **system of four coupled differential equations**
  - dN/dt, $d\varepsilon_{xy}/dt$, $d\sigma_s/dt$.
  - Includes luminosity burn-off, intra-beam scattering (IBS) and synchrotron radiation damping

- Pb damps ~2x faster than protons.
  - radiation damping times for Pb ~0.5h

- Initial IBS is weak, but damping is very fast.
  - → Fast emittance decrease at the beginning of the fill until IBS starts to counteract the damping.

Plots of beam evolution can be found in the Extra Slides.

Pb-Pb Luminosity Evolution



Scenarios:

- Baseline and Ultimate
- 1 (solid) and 2 (dashed) experiments in collisions in **main IPs**

The available total integrated luminosity is shared.

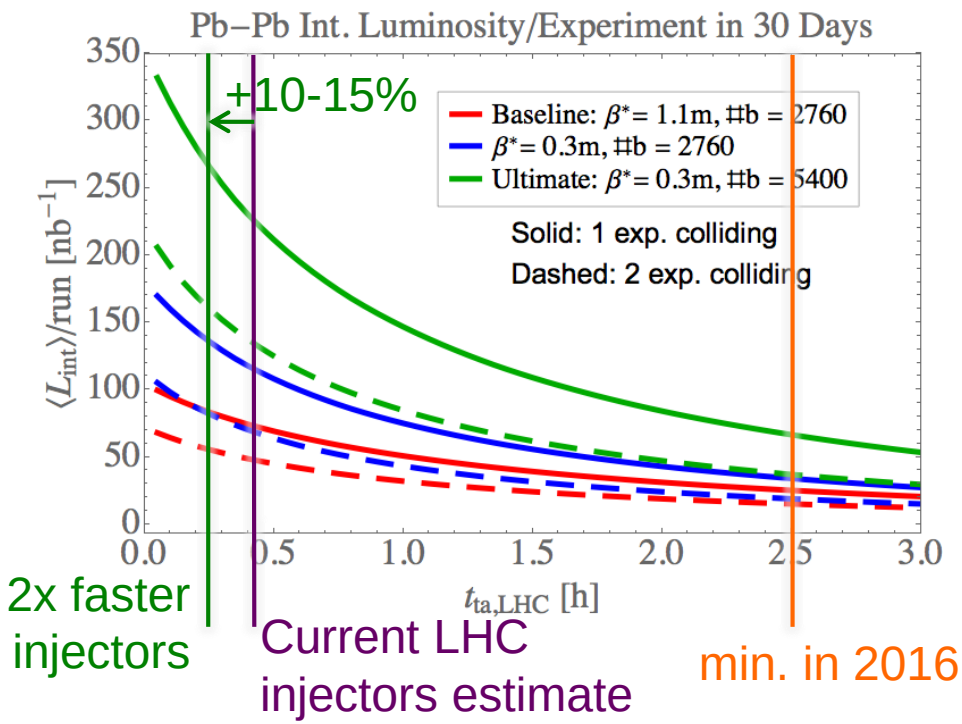
Case of a special heavy-ion experiment installed in secondary IP:

→ *larger β*, less colliding bunches*

→ Luminosity would be reduced

→ We do NOT consider this scenario at present.

Pb-Pb Integrated Luminosity per Run



Considers:

- **Particle losses on FCC injection plateau** of already circulating trains.
- **Optimum turn around**
- **Optimum time in collision** for each scenario

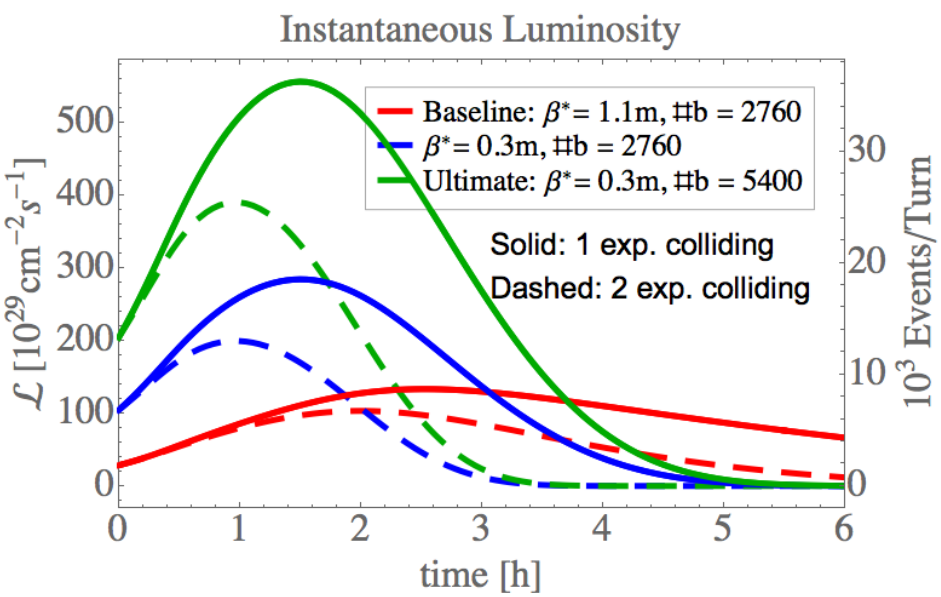
Neglects:

- **Down time** due to failures

Including a **performance efficiency factor** of 50%

	Baseline:	Ultimate:
1 exp. L_{int}/run:	**35nb^{-1}**	**110nb^{-1}**
2 exp. L_{int}/run:	**23nb^{-1}**	**65nb^{-1}**

p-Pb Luminosity Evolution



Same color code as for Pb-Pb

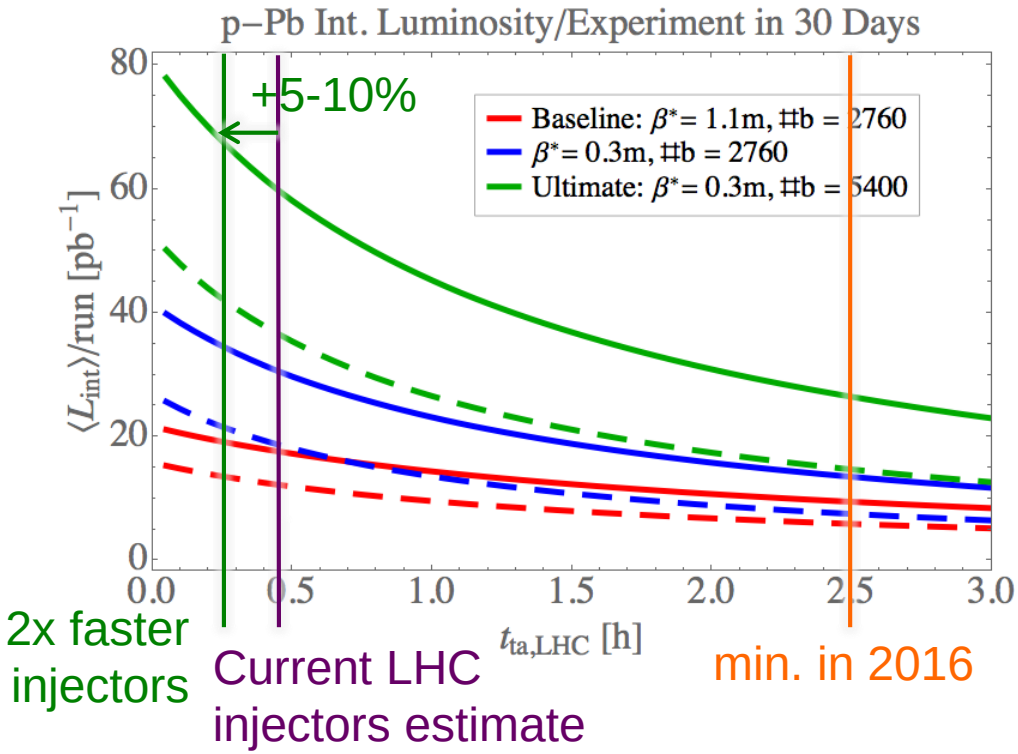
Assumed:

- same Pb-beam as in Pb-Pb
- p-beam with the same number of charges and geometrical emittance as Pb-beam.

Longer luminosity lifetime, because for 82-Pb charges only 1-p is burned-off.

Potential to increase p intensity as already done at LHC in 2016.

p-Pb Integrated Luminosity per Run



Including a **performance efficiency factor** of 50%

	Baseline:	Ultimate:
1 exp. L_{int}/run:	**8pb^{-1}**	**29pb^{-1}**
2 exp. L_{int}/run:	**6pb^{-1}**	**18pb^{-1}**

γ-γ and γ-A processes in Pb-Pb collisions

Ultra-peripheral electromagnetic interactions dominate the total cross-section during Pb-Pb collisions.

Bound-Free Pair Production

BFPP1: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{208}Pb^{81+} + e^{+}$,

$s = 354$ b, $d = 0.01235$

BFPP2: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{208}Pb^{80+} + 2e^{+}$,

$s \approx 10$ mb, $d = 0.02500$

Electro-magnetic Dissociation

EMD1: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{207}Pb^{82+} + n$,

$s = 200$ b, $d = -0.00485$

EMD2: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{206}Pb^{82+} + 2n$,

$s = 35$ b, $d = -0.00970$

Hadronic cross section is 8 b (so much less power in debris).

Each of these makes a secondary beam emerging from the IP.

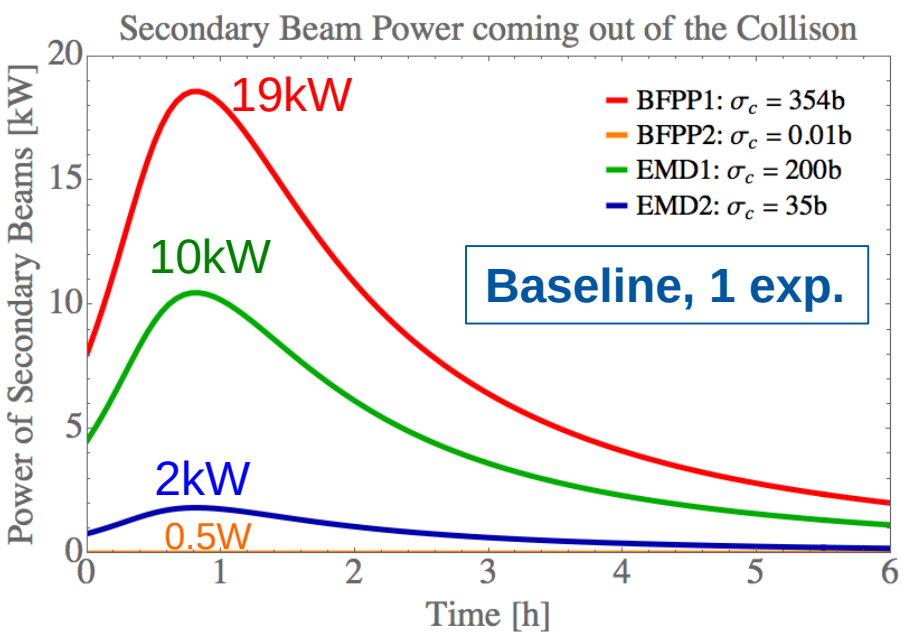
rigidity change:

$$\delta = \frac{1 + \Delta m / m_{Pb}}{1 + \Delta Q / Q} - 1$$

Secondary Beam Power

$P = \sigma_c L E \approx$ ***19kW*** (Baseline, 1 exp.)
75kW (Ultimate, 1 exp.)

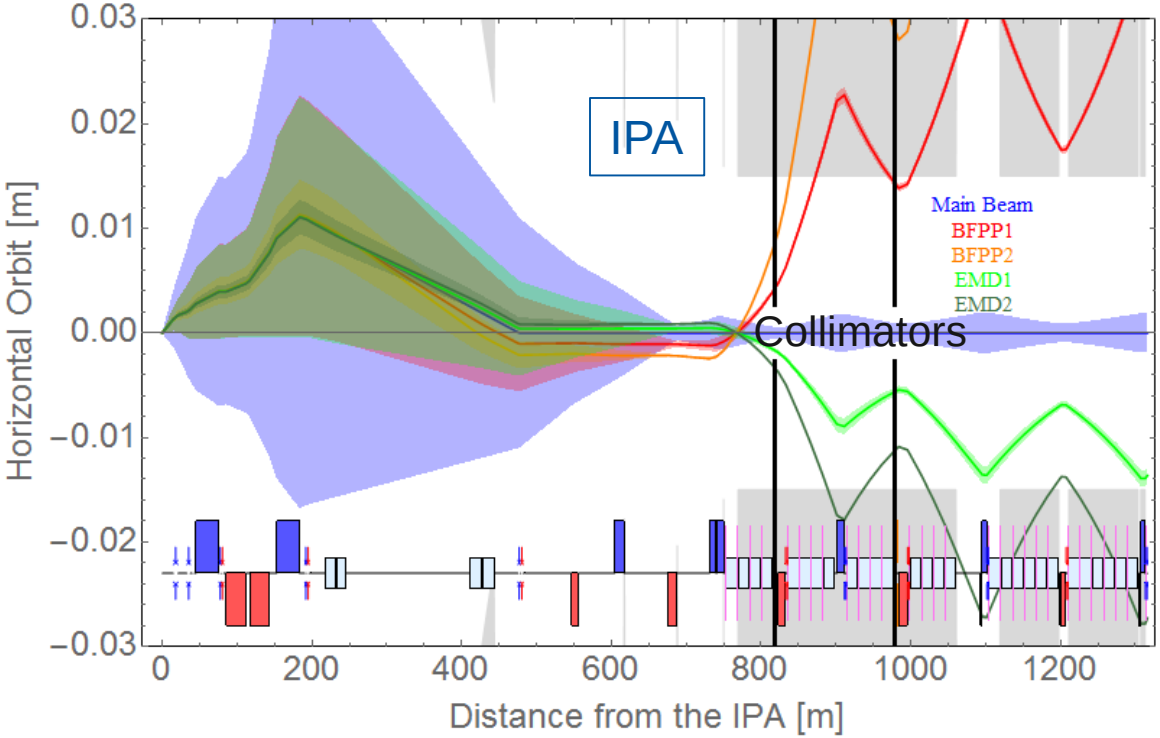
Continuous and very **localised** losses



nominal LHC: *P ≈ 26W*
→ mitigation methods are already required, long-term damage expected

Special collimators are required to absorb those beams and **enable** the FCC **to run with heavy ions.**

Secondary Beam Trajectories



Main IPs have different crossing.

Dispersion Suppressor Collimator positions for p-p can also **absorb secondary beams** from Pb-Pb collisions.

Very localized loss: 1σ beam size on collimator front plane ≥ **85/33µm** (beam size at IP = 4µm)

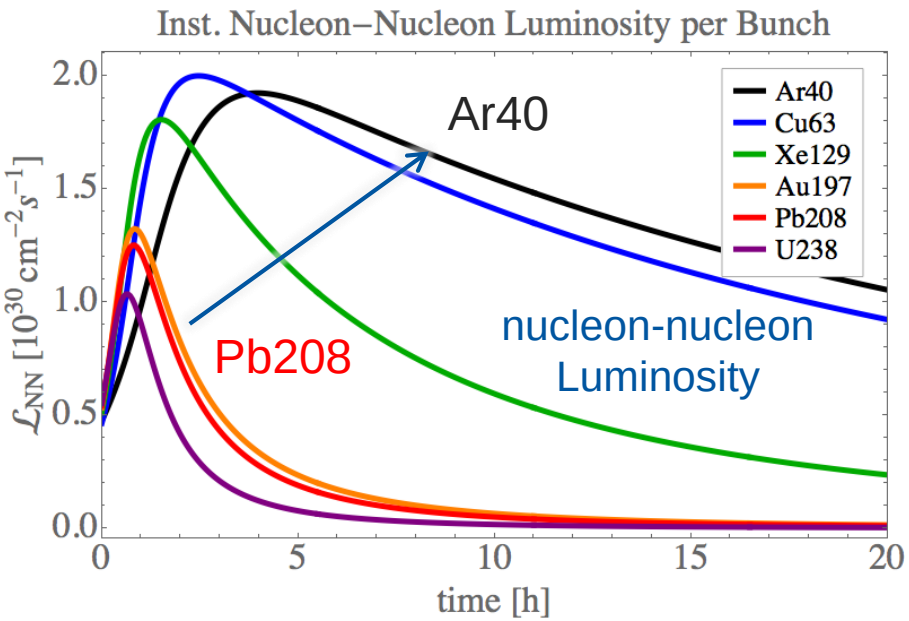
To be studied, if these collimators can absorb the deposited power

Other Ion Species

- Intensities form Injectors: possibly similar number of charges per bunch = more ions per bunch for lower Z

- Contribution of ultra-peripheral electromagnetic processes to the total cross-section would be reduced:
  - $\sigma_{BFPP} \sim Z^7$
  - $\sigma_{EMD} \sim Z^4$

Other Ion Species (Baseline)

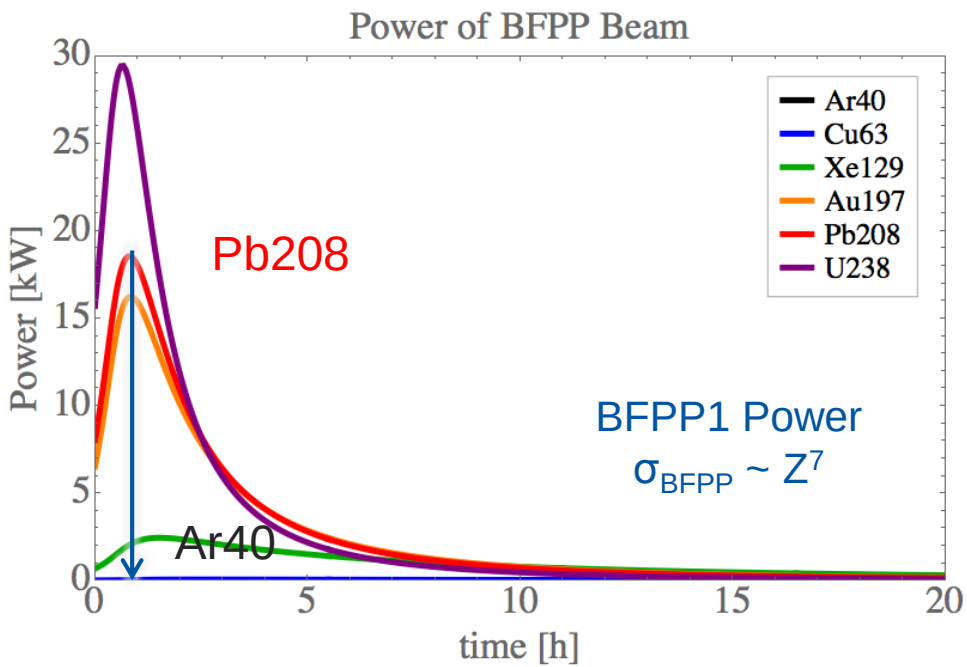


✧ **Increased luminosity lifetime**, more particles available for hadronic interactions.

$$N_{\text{hadronic}} = \sigma_h \int L\,dt \propto \frac{\sigma_h}{\sigma_h + \sigma_{\text{BFPP}} + \sigma_{\text{EMD}}} N_{tot} \propto Z^{-(6\text{--}8)}$$

Other Ion Species (Baseline)

✧ **Reduced secondary beam power** emerging from collision point.



Worth considering small Z reduction from Pb!

Outlook & Further Studies

- Heavy-ion beams to be included in the future evolution of the **injector chain**.
  - *Define beam parameters and requirements.*

- Heavy-ion **collimation** studies are crucial.
  - *DS collimators (few 10th kW secondary beams)*
  - *Beam Cleaning System*
  - *Collimator design, material, shower calculations, quench risk, cleaning efficiency, etc.*

- Decisions/Input from Experiments:
  - ***Dedicated time*** *for Heavy-ion operation*
  - *Number and requirements of* ***active experiments***
  - *Preferred* ***Ion species***

Conclusions

- **FCC-hh could be a very high performance heavy-ion collider.**

- **Complete review of all parameters** and estimates has been performed since FCC week 2015
  - *Baseline and ultimate scenarios have been studied*
  - *1 or 2 experiments in main IPs have been taken into account*

- Keep as **close** as possible **to p-p operation and design**.

- The most important studies to be done before the CDR concerns **collimation**.

Extra Slides

References

Presentations:

- M. Schaumann et al., *A first look at heavy ion operation of the FHC*, Ions at the Future Hadron Collider, 16-17 Dec. 2013, CERN.
  → *https://indico.cern.ch/event/288576/timetable/#20131216*
- M. Schaumann et al., *First look at performance for Pb-Pb and p-Pb collisions and required R&D,* FCC Study Kickoff Meeting, 12-15 Feb. 2014, Geneva.
  → *https://indico.cern.ch/event/282344/timetable/#20140212*
- M. Schaumann et al., *Potential Performance for nucleus-nucleus and proton-nucleus collisions in the FCC-hh*, Ions at the Future Hadron Collider, 22-23 Sep. 2014. (update to 100km)
  - → *https://indico.cern.ch/event/331669/timetable/#20140922*
- J.M. Jowett et al., *FCC-hh as a heavy-ion collider,* FCC week 2015.
  → *http://indico.cern.ch/event/340703/contributions/802113/*
- A. Dainese et al., *Heavy-ion physics studies for the Future Circular Collider*, FCC Week 2016.
  - → *https://indico.cern.ch/event/438866/contributions/1084977/*
- M. Schaumann et al., Current Status of the studies on Heavy Ions in the FCC-hh, FCC-hh General Design Meeting, 2 Mar. 2017, CERN.
  → *https://indico.cern.ch/event/617603/*

Documents:

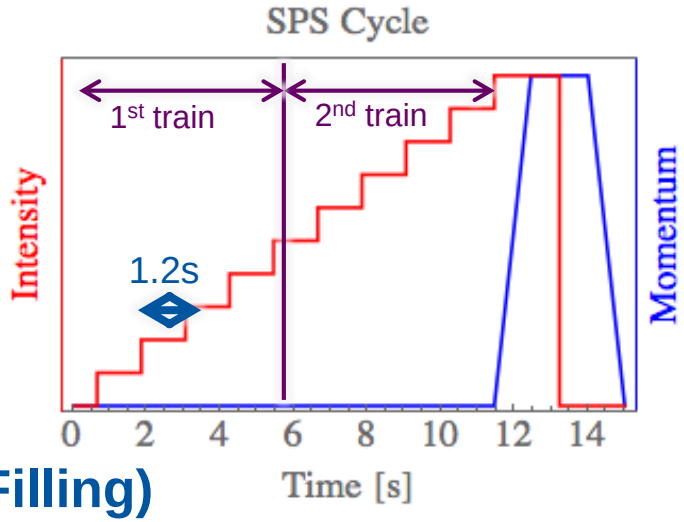
- M. Schaumann, *Heavy-ion performance of the LHC and future colliders,* PhD Thesis (Chapter 9), CERN-THESIS-2015-195
- M. Schaumann, *Potential performance for Pb-Pb, p-Pb and p-p collisions in a future circular collider*, Phys. Rev. ST Accel. Beams **18**, 091002 (2015).
- A. Dainese et al., *Heavy ions at the Future Circular Collider*, (update of LHC turnaround time and intensity) CERN-TH-2016-107, arXiv:1605.01389 [hep-ph]

Filling Time (2x Faster Injectors)

SPS cycle time per train = 16.2 s

Assuming:

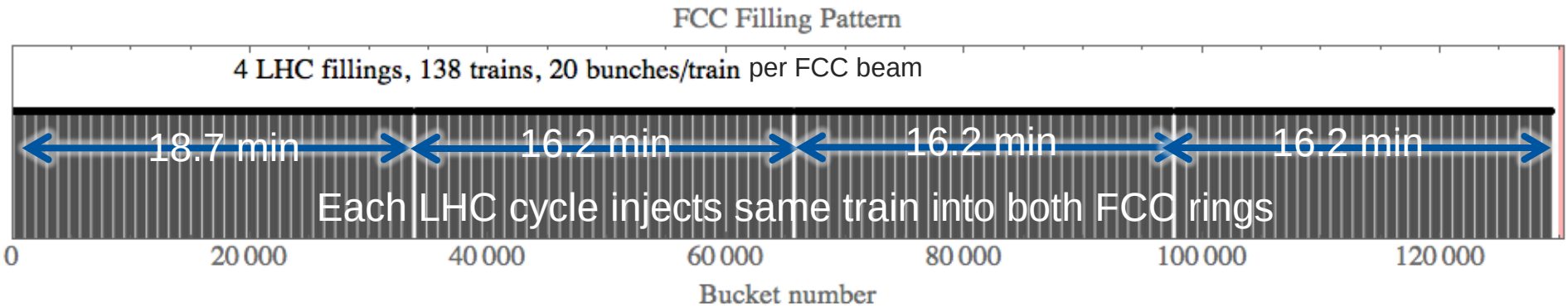
- LEIR/PS cycle time = **1.2 s**
- PS injections/train = 2x5
- Preparation time = **4.2 s**



LHC preparation time = 7 min (+ 2 min 1st Filling)

→ **FCC filling time (2 beams) = 67 min**

(8x more SPS-LHC transfers than in p-p)



Injection at 1.2 Z TeV

- **Ramping** of the superconducting magnets becomes a **significant fraction of the SPS cycle length**
  - ~2x 12sec ramp vs. 12-24sec filling

- **Filling FCC** with 2x138 trains into FCC takes **~1.5h-2h**
  - For heavy-ions one SPS cycle produces 2 train with 20 bunches

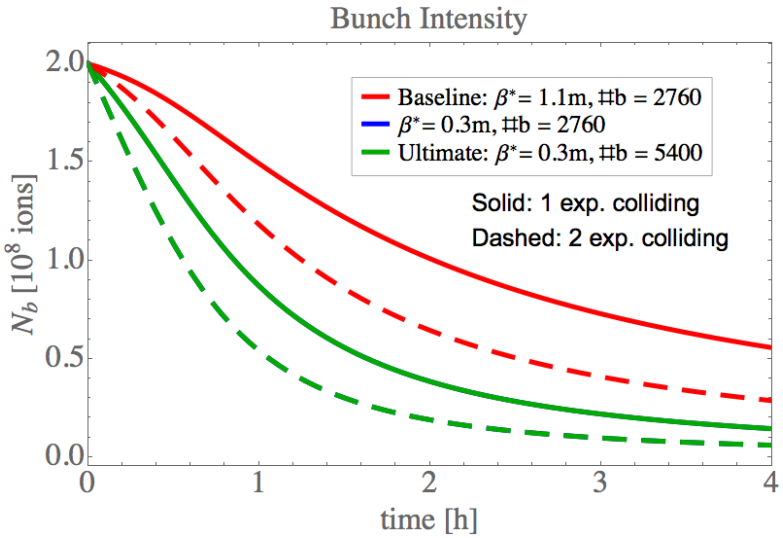
- Debunching losses from **IBS are enhanced** at lower energy.

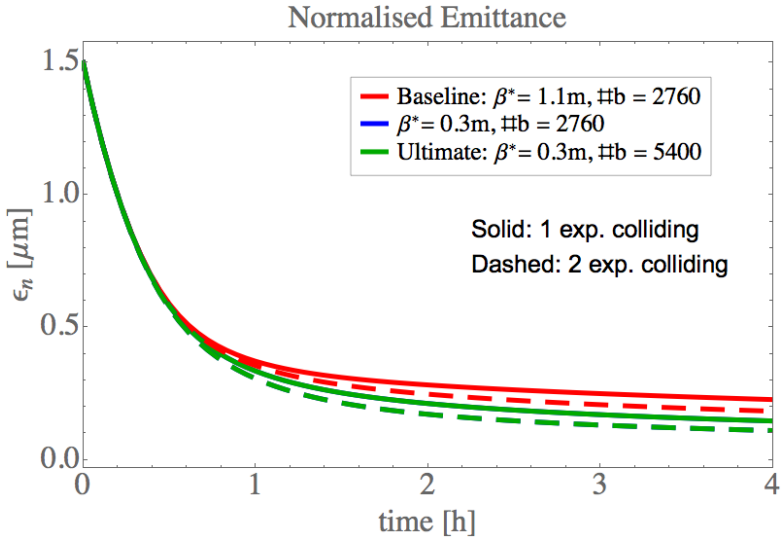
→ **Reduction of total intensity**

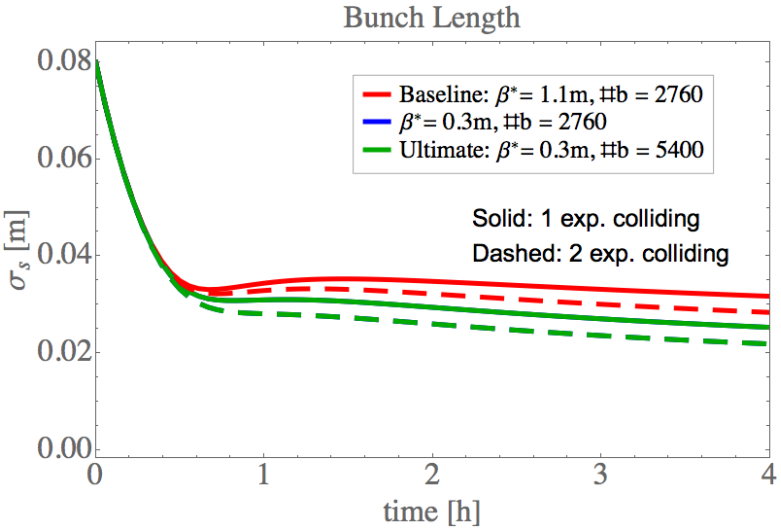
→ Generally **more losses** and a **longer dwell time**

→ Detailed studies needed.

Pb-Pb Free Beam Evolution, Diff. Cases

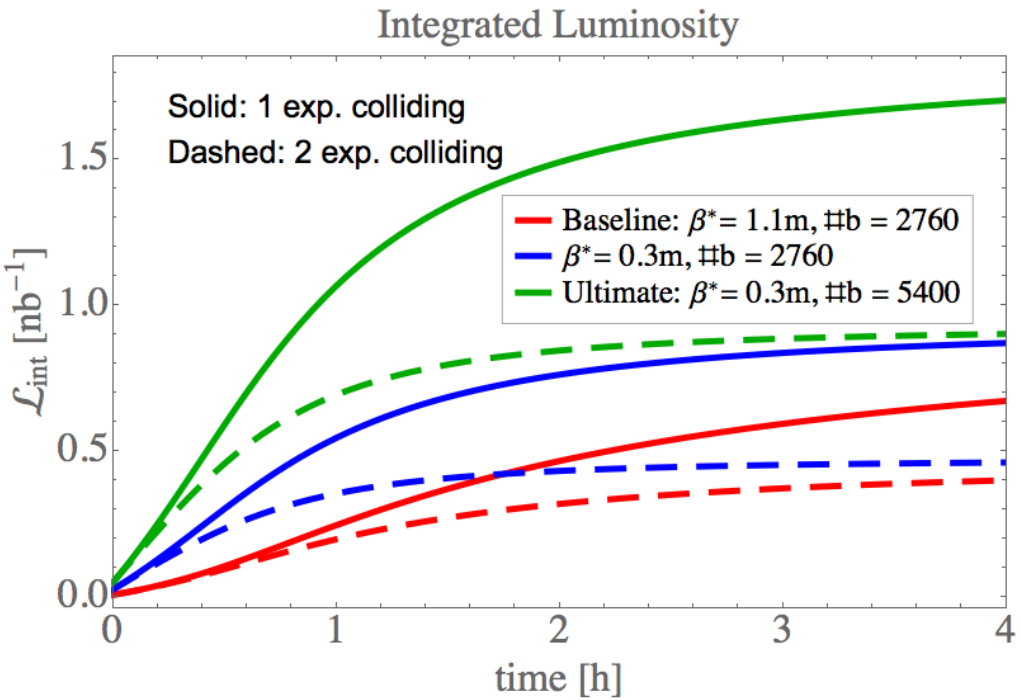






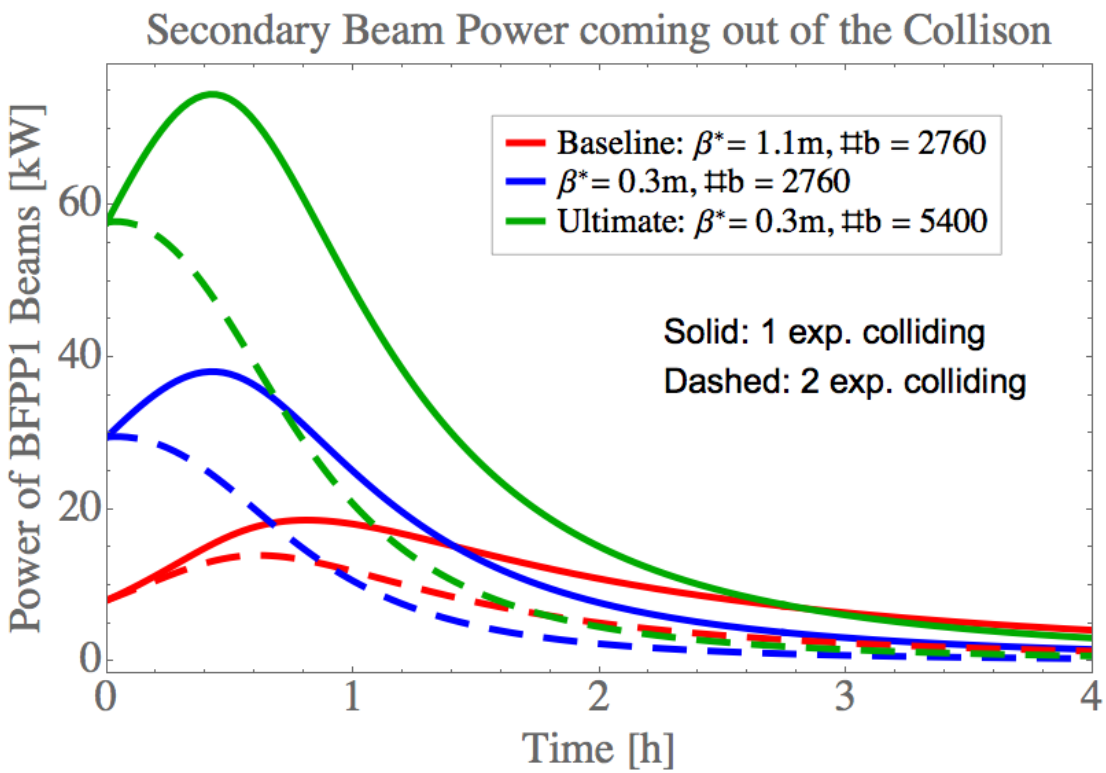
Single bunch evolution is shown, therefore the blue cases with β* = 0.3m and 2760 bunches is hidden behind the green.

Pb-Pb Integrated Luminosity per Fill

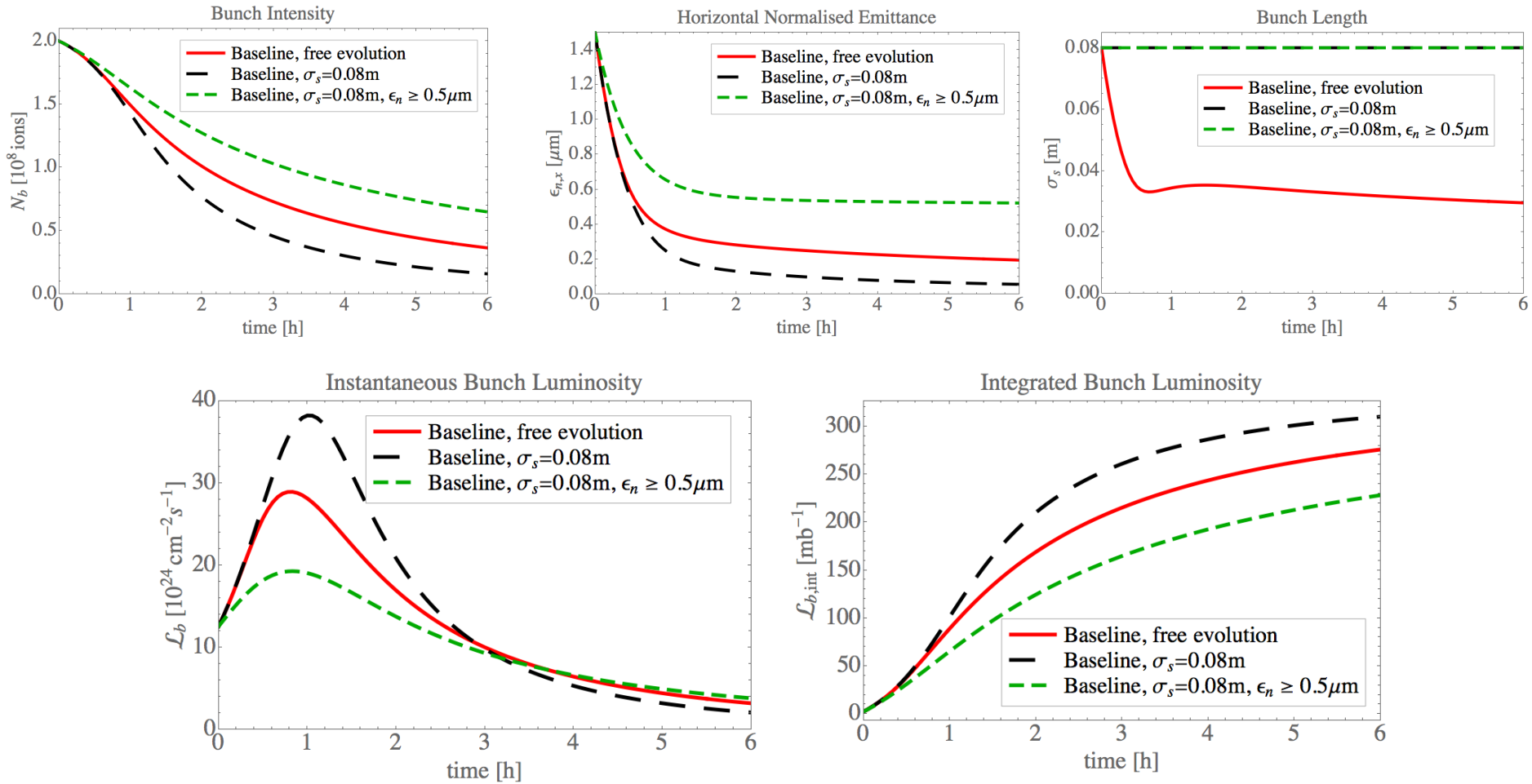


Available luminosity is shared between (equal) experiments

BFPP1 Power, Diff. Cases



Pb-Pb Beam and Luminosity Evolution, Baseline Scenario with Artificial Blow-up



Particle losses on FCC injection plateau

Consider 4 LHC injections:

→ Dwell time at FCC injection plateau

$$t_{\mathrm{ta}} = t_{\mathrm{ta,FCC}} + (n_{\mathrm{inj}} - 1) t_{\mathrm{ta,LHC}}$$

→ Particle losses (& emittance growth)

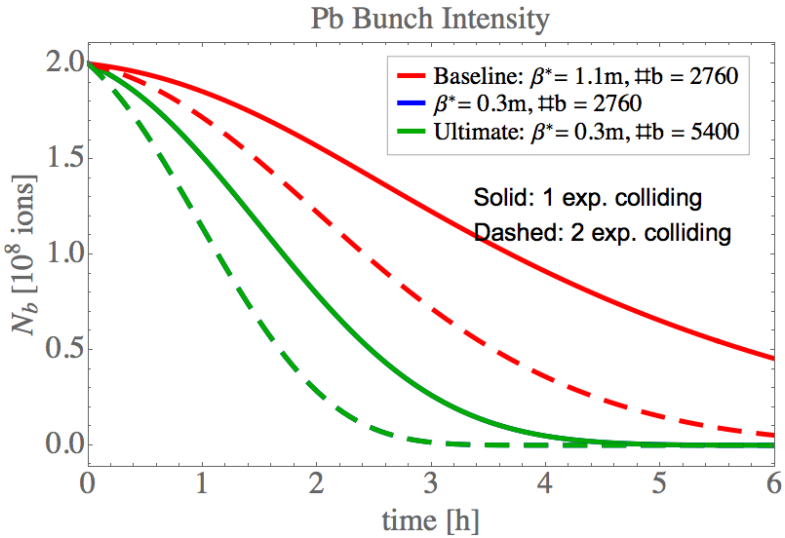
→ Loss rate of Pb at 3.3TeV in FCC (from tracking simulations):

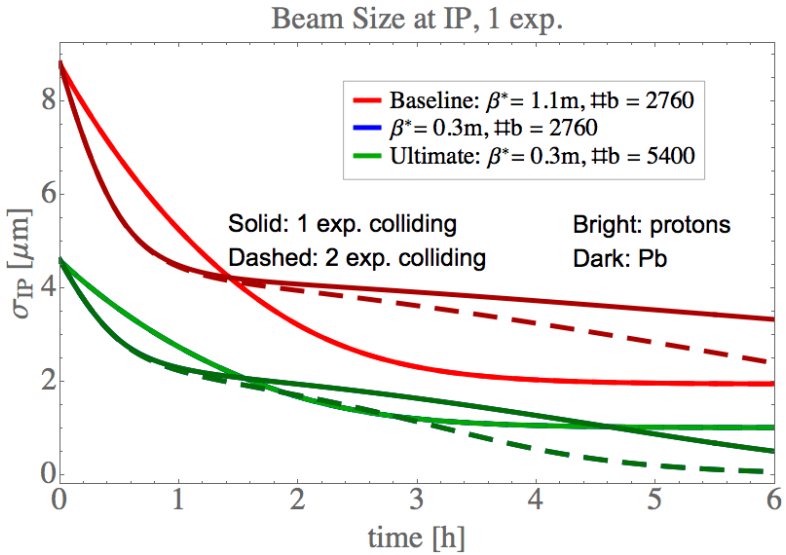
$$R_{\mathrm{loss}} = 5\%$$

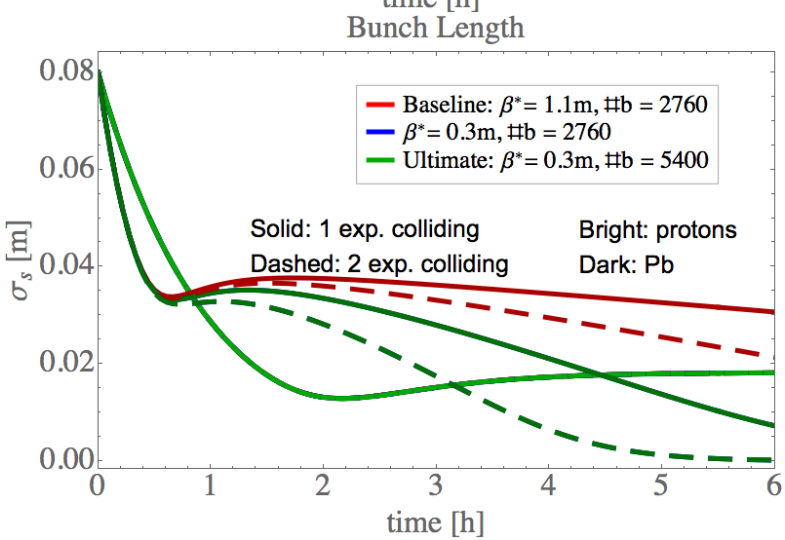
→ Total beam intensity:

$$N_{\mathrm{beam}} = k_b N_b \sum_{i=1}^{n_{\mathrm{inj}}} (1 - R_{\mathrm{loss}} t_{\mathrm{ta}} (i-1))$$

p-Pb Beam Evolution



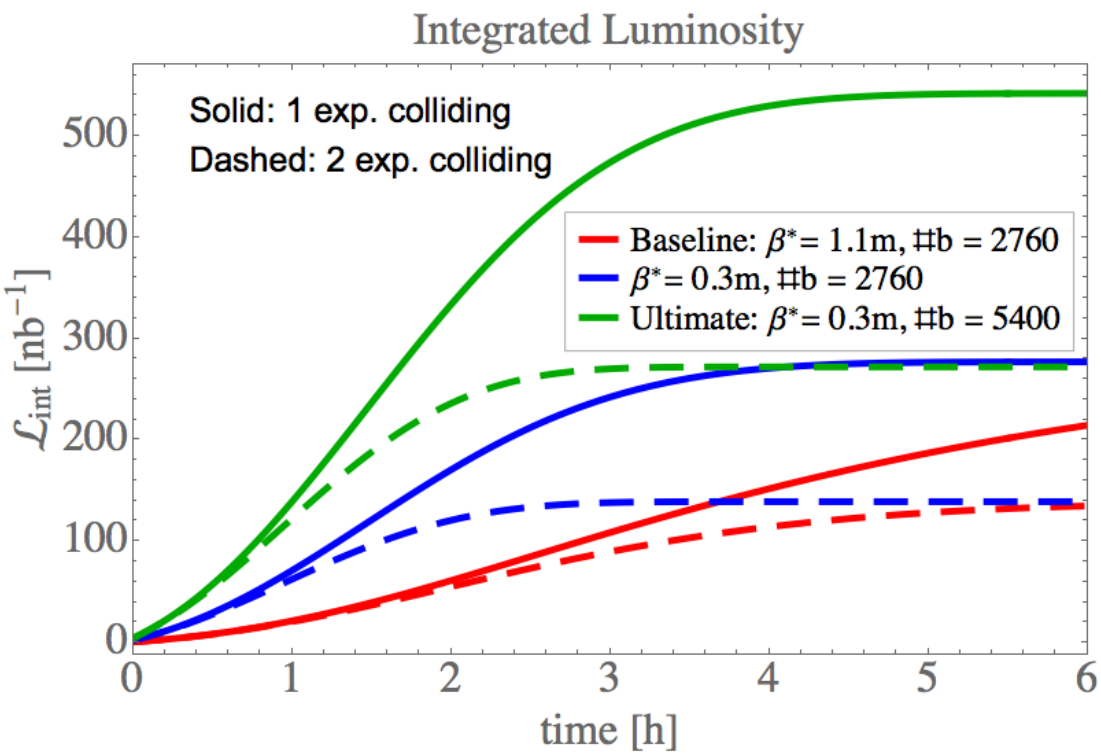




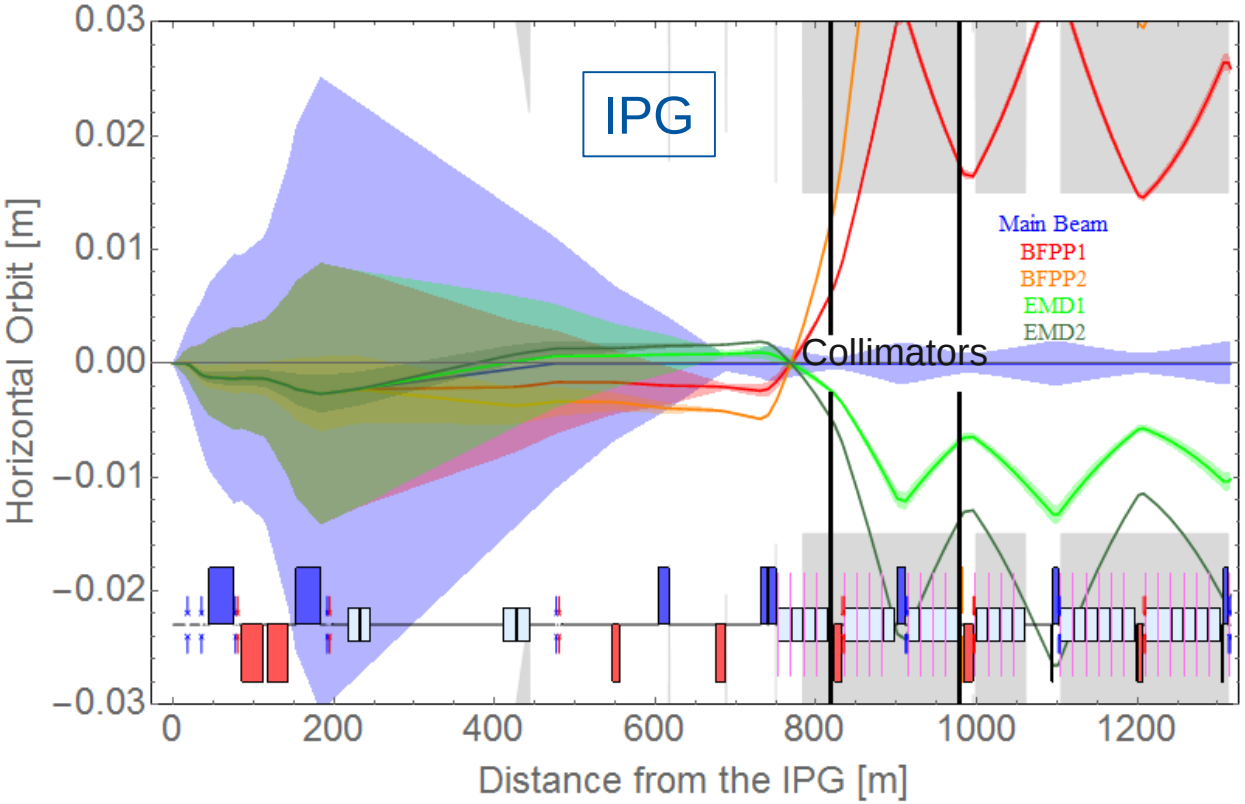
1 proton is lost for 82-Pb charges
→ Proton beam loses ~1% of its initial intensity, while the Pb intensity is completely burned-off

Radiation damping time for p = ½ Pb

p-Pb Integrated Luminosity per Fill



Secondary Beam Trajectories



Main IPs have different crossing, which influences trajectory of secondary beams and their capture in collimators.

Other Ion Species