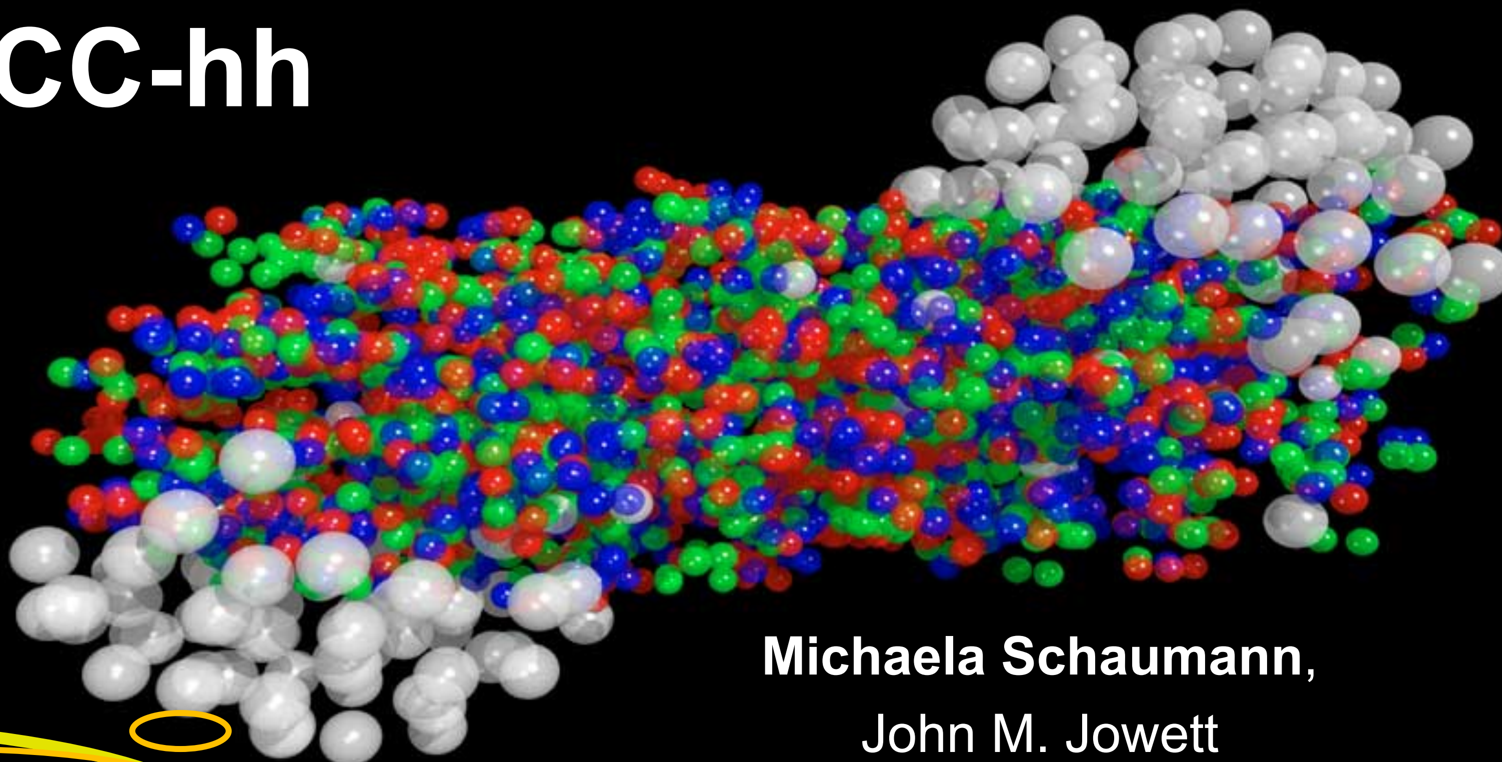
Heavy Ions at FCC-hh



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Introduction

- Heavy-ion collisions in FCC-hh have been considered **since the inception of the project.**
- **Luminosity projections have risen over the years** in line with the improved Pb-beams now being collided in the LHC.
- In close collaboration with the heavy-ion **physics** working group the **interest in Pb-Pb, p-Pb or lighter nuclei** collisions was evaluated.

Summary of heavy-ion physics cases: D. d'Enterria, Friday 11:15

- Summarized in detail in the CDR
  - Volume 3, chapter 12 (FCC-hh machine design)
  - Volume 1, chapter 29 (FCC-hh physics opportunities)

Main Differences to Proton Operation

- **Natural beam cooling** → fast synch. radiation damping
  - Pb damps ~2x faster than protons: $\tau_{\mathrm{rad}}\ (\mathrm{Pb}) \sim 0.5\ \mathrm{h}$
  - Damping can be fully exploited since far from beam-beam limits initially.
- **Strong IBS** once emittance has damped.
  - Limits emittance damping.
- Large cross-sections for **ultra-peripheral electromagnetic interactions**.
  - Powerful secondary beams emerging from the collision point
  - Fast luminosity burn-off
- More **complicated interactions with collimators**

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. Pb 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**

LHC experience

30% larger beam size than protons

more than 10x smaller as for protons

Choice of Species

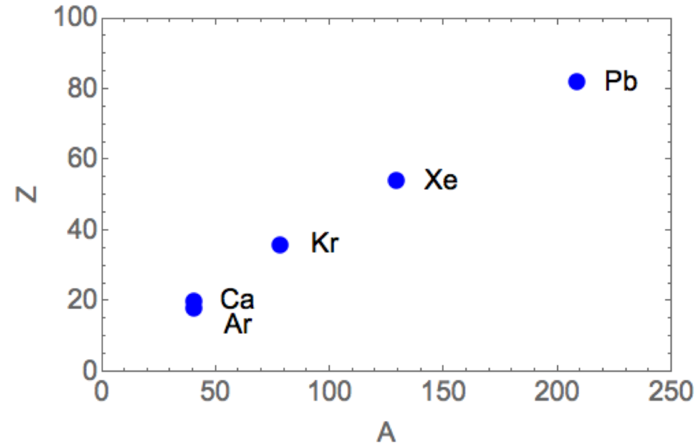
Baseline species Pb
with collision modes: Pb-Pb and p-Pb

Lighter ions are interesting, because of

- **Physics output**
- **Lower cross-section for ultra-peripheral el. mag. processes**:
  - → $\sigma_{BFPP} \sim Z^7$, $\sigma_{EMD} \sim Z^4$
  - → Reduced power in secondary beams emerging the IP
- Potential for significantly **higher nucleon-nucleon luminosity**
  - → Slower burn-off and longer fills, more ions left for usable luminosity
  - → Expect higher bunch charge in the injector chain

Considered species

$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$



Chosen from LHC injector experience & to cover a wide range of possibilities.

Optimal species choices for physics is a compromise between available luminosity and size of the QGP effects to be studied

Assumptions for Lighter Ions

Postulate simple form for bunch intensity dependence on species charge only:

$$N_b(Z,A) = N_b(82,208)\left(\frac{Z}{82}\right)^{-p}$$

$$\text{where} \quad p = \begin{cases} 1.9, & \text{fixed target experience} \\ 0.75, & \text{LHC: Xe run vs. best Pb} \end{cases}$$

Highly simplified scaling to project luminosity performance as a function of *p*.

p=1.5 seems reasonable.

Assume that other quantities, like geometric beam size, filling scheme, other loss rates, etc, are equal.

Same scaling used for LHC and HL-LHC predictions of lighter ions.

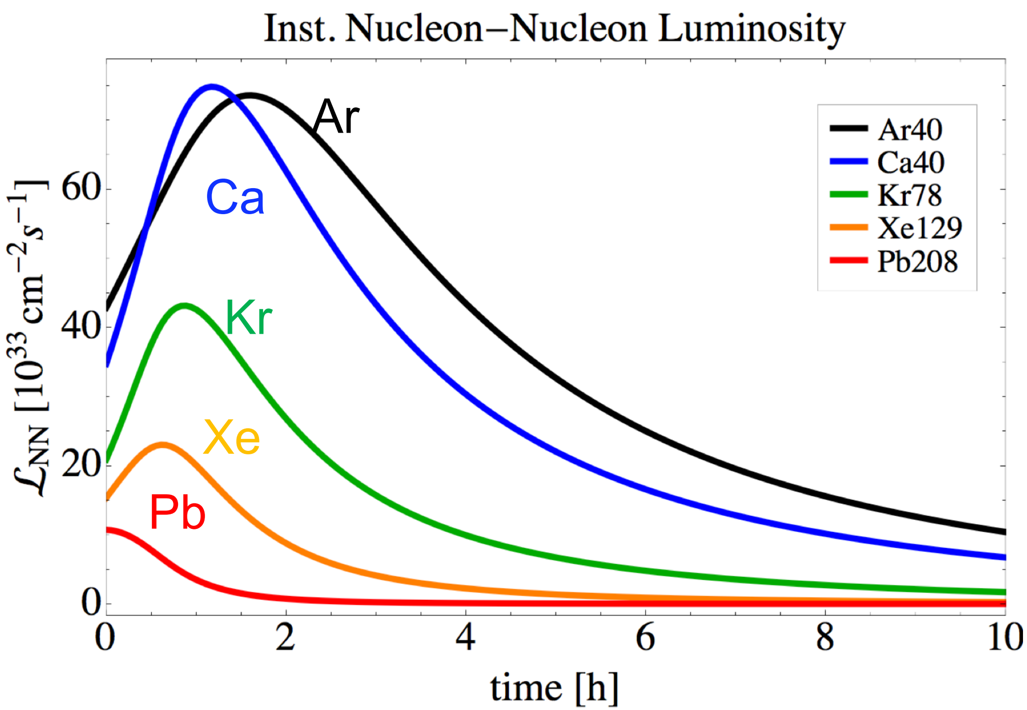
Nucleon-Nucleon Luminosity Evolution

$$\mathcal{L}_{NN} = A^2 \mathcal{L}_{AA}$$

Nucleon-nucleon luminosity (NN)

Mass number

Nucleus-Nucleus Luminosity (AA)



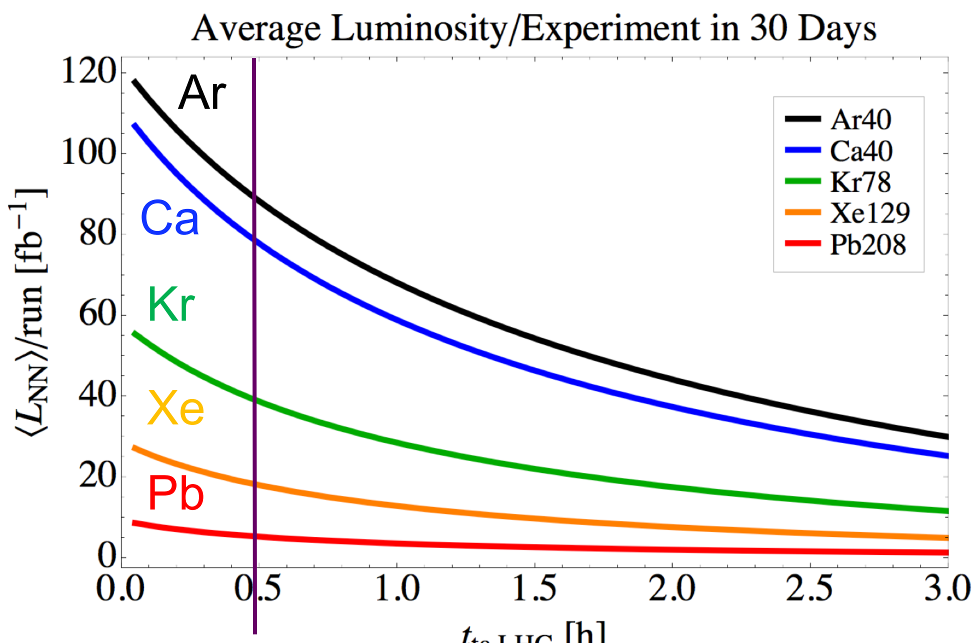
Assumptions:

- Ultimate Pb parameters
- Intensity scaling with p=1.5 for lighter species.
- 2 experiments

Spectacular boost w.r.t. Pb-Pb!

Increased luminosity lifetime, more particles available for hadronic interactions.

Nucleon-Nucleon Integrated Luminosity



Current LHC injectors estimate

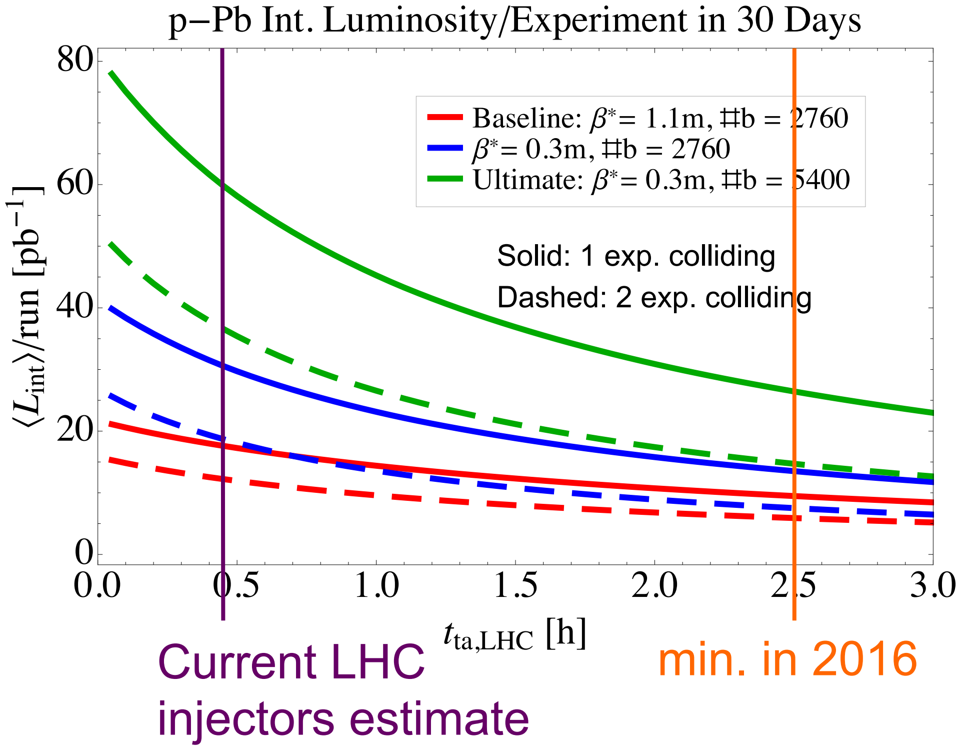
Assumptions:

- Ultimate Pb parameters
- Intensity scaling with p=1.5 for lighter species.
- 2 experiments

Table includes a **performance efficiency factor** of 50%

Isotope	$^{40}\mathbf{Ar}^{18+}$	$^{40}\mathbf{Ca}^{20+}$	$^{78}\mathbf{Kr}^{36+}$	$^{129}\mathbf{Xe}^{54+}$	$^{208}\mathbf{Pb}^{82+}$
Number of particles [10^8]	19.4	16.6	6.9	3.7	2.0
Integrated $\mathcal{L}_{AA}$ [nb^{-1}/run]	28381	25074	3286	560	62
Integrated $\mathcal{L}_{NN}$ [fb^{-1}/run]	45.4	40.1	20.0	9.3	2.7

p-Pb Integrated Luminosity per Run



Assumption:

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

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

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 nucleus-nucleus collisions

Ultra-peripheral electromagnetic interactions dominate the total cross-section in heavy nucleus-nucleus collisions.

Bound-Free Pair Production (BFPP)

$$^{A}X^{Z} + {}^{A}X^{Z} \rightarrow {}^{A}X^{Z} + {}^{A}X^{Z-1} + e^{+}$$

Electro-magnetic Dissociation (EMD)

$$^{A}X^{Z} + {}^{A}X^{Z} \rightarrow {}^{A}X^{Z} + {}^{A-1}X^{Z} + n$$

Change of charge-to-mass ratio

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

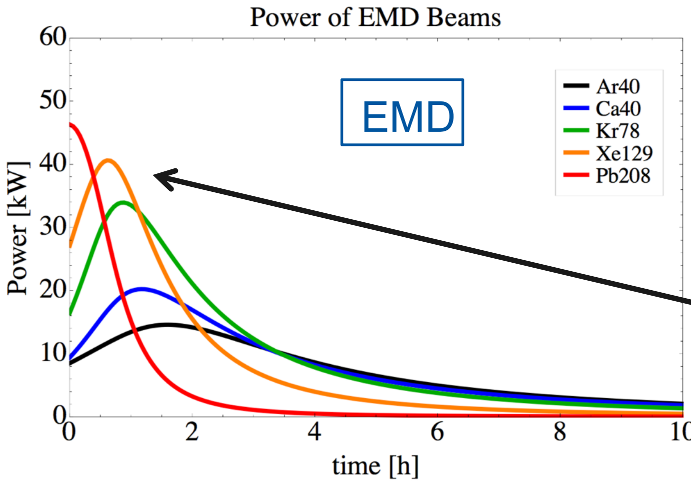
rigidity change:

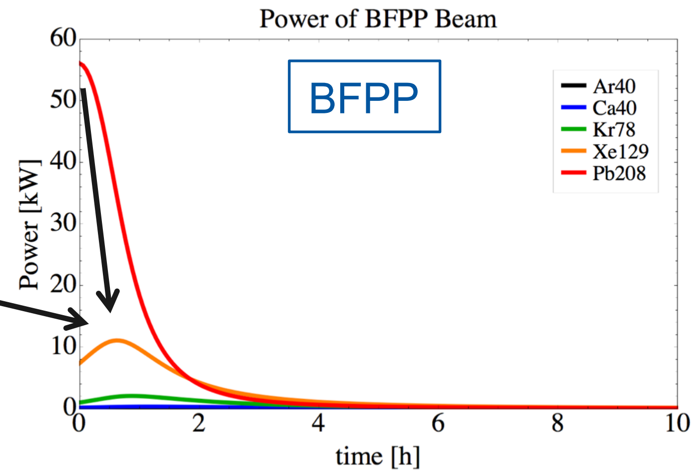
$$\delta = \frac{1 + \Delta m / m_{Pb}}{1 + \Delta Q / Q} - 1$$

Secondary Beam Power

Power carried by secondary beams: $P = \sigma_c L E$

BFPP Peak Power (Pb-Pb)
$P \approx$ **70 kW** (1 exp.)
56 kW (2 exp.)





Ultimate beam parameter for **2 experiments** in collisions

$$\sigma_{c,\mathrm{BFPP}} \propto Z^7$$
$$\sigma_{c,\mathrm{EMD}} \propto Z^4$$

Reduction of **cross-section for lower *Z*.**

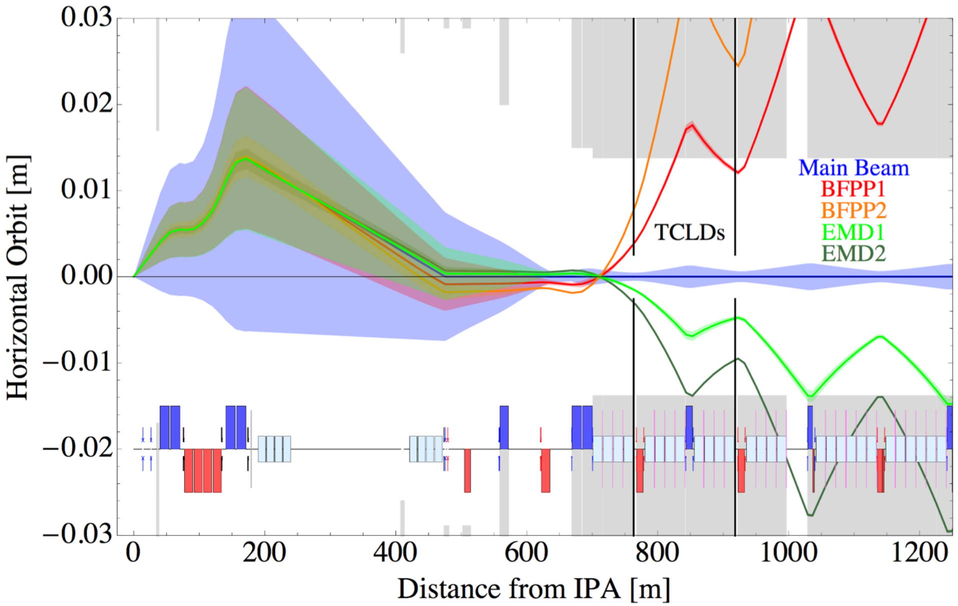
Isotope	$^{40}\mathbf{Ar}^{18+}$	$^{40}\mathbf{Ca}^{20+}$	$^{78}\mathbf{Kr}^{36+}$	$^{129}\mathbf{Xe}^{54+}$	$^{208}\mathbf{Pb}^{82+}$
$\sigma_{\mathrm{BFPP},tot}$ [b]	$\sim$0.02	0.042	$\sim$1	$\sim$18.5	344
$\sigma_{\mathrm{EMD},tot}$ [b]	2.2	2.7	16.6	67.9	284.2
$\sigma_{\mathrm{hadronic}}$ [b]	2.764	2.767	4.29	5.89	7.9
σ_{tot} [b]	5	5.5	22	92.3	636

Cross-sections calculated by Igor A. Pshenichnov et al. with RELDIS

⚠ *Power carried by EMD beams higher than BFPP already for Xe-Xe.*

Secondary Beam Trajectories (Pb-Pb)

High Power, continuous and very **localised** losses
Special collimators are required to absorb those beams and **enable** the FCC **to run with heavy ions.**



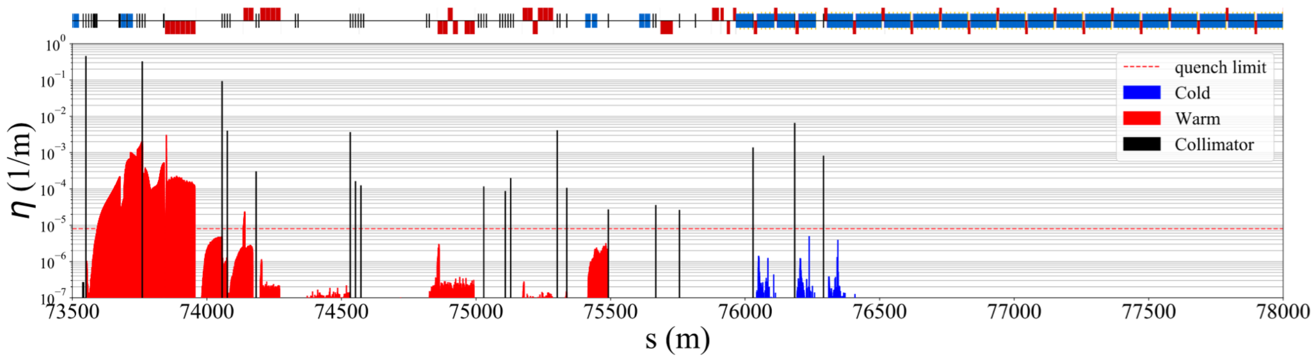
Dispersion Suppressor Collimator (TCLDs) positions for p-p can also **absorb secondary beams** from Pb-Pb collisions.

To be studied, if these collimators can absorb the deposited power and how showers develop into the cold area.

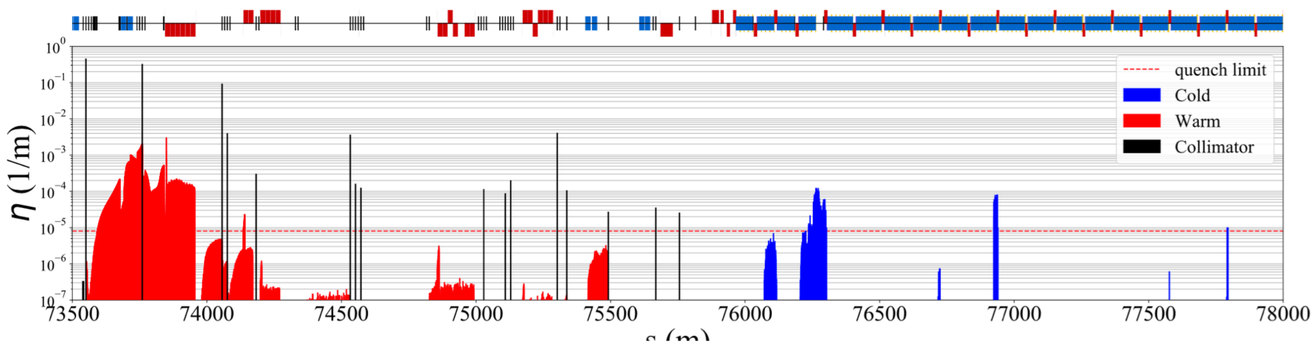
Collimation Cleaning Efficiency

Collimation cleaning efficiency has been studied for Pb-ions within nominal collimation system setup.

Discussed in detail by A. Abramov in the following talk.



With DS collimators (baseline)



Without DS collimators

Work of A. Abramov

Summary

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

Keep **close to p-p operation**

Luminosity performance:
- **Upgraded several times** since the inception of the study
- In line with beams currently collided in LHC.

Lighter ions
- operationally less challenging
- potential for higher performance compared to baseline Pb.

Detailed chapter included in CDR.

Ensure Feasibility

Fuller integration into FCC study
→ more people needed

Assumed existing LHC **injectors** - could **envisage upgrades**.

Enhanced collimation studies:
- Cleaning
- Secondary beams (BFPP)
- Luminosity debris in asymmetric collisions (p-Pb)

Clarification of **experimental conditions:**
- no. of experiments
- preferred ion species
- dedicated time

Thank you!

Parameter and Performance Table

Table 3: Parameter projections for alternative nuclei. Luminosity labelled with AA are nucleus-nucleus and NN are nucleon-nucleon values. All calculations assume the ultimate parameter scenario and two experiments in collisions.

Isotope	$^{40}\mathbf{Ar}^{18+}$	$^{40}\mathbf{Ca}^{20+}$	$^{78}\mathbf{Kr}^{36+}$	$^{129}\mathbf{Xe}^{54+}$	$^{208}\mathbf{Pb}^{82+}$
Number of particles [10^8]	19.4	16.6	6.9	3.7	2.0
$\sigma_{\mathrm{BFPP,tot}}$ [a] [b]	~0.02	0.042	~1	~18.5	344
$\sigma_{\mathrm{EMD,tot}}$ [a] [b]	2.2	2.7	16.6	67.9	284.2
$\sigma_{\mathrm{hadronic}}$ [a] [b]	2.764	2.767	4.29	5.89	7.9
σ_{tot} [a] [b]	5	5.5	22	92.3	636
Power carried by BFPP beams [kW]	0.1	0.3	2.0	11.0	56.0
Power carried by EMD beams [kW]	14.6	20.2	33.9	40.6	46.3
Optimum time in collisions [h]	4.5	3.75	3.0	2.25	1.25
Initial $\mathcal{L}_{\mathrm{AA}}$ [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	26.8	21.7	3.4	0.92	0.25
Initial $\mathcal{L}_{\mathrm{NN}}$ [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	42855	34713	20893	15353	10729
Peak $\mathcal{L}_{\mathrm{AA}}$ [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	46.0	46.8	7.1	1.4	0.25
Peak $\mathcal{L}_{\mathrm{NN}}$ [$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	73552	74805	43130	23017	10729
Integrated $\mathcal{L}_{\mathrm{AA}}$ [nb^{-1}/run]	28381	25074	3286	560	62
Integrated $\mathcal{L}_{\mathrm{NN}}$ [fb^{-1}/run]	45.4	40.1	20.0	9.3	2.7
Rate of hadronic interactions [MHz]	127.1	129.4	30.4	8.1	2.0
Events per bunch crossing	7.7	7.8	1.8	0.5	0.1

[a] Taken from Ref. [12]

References

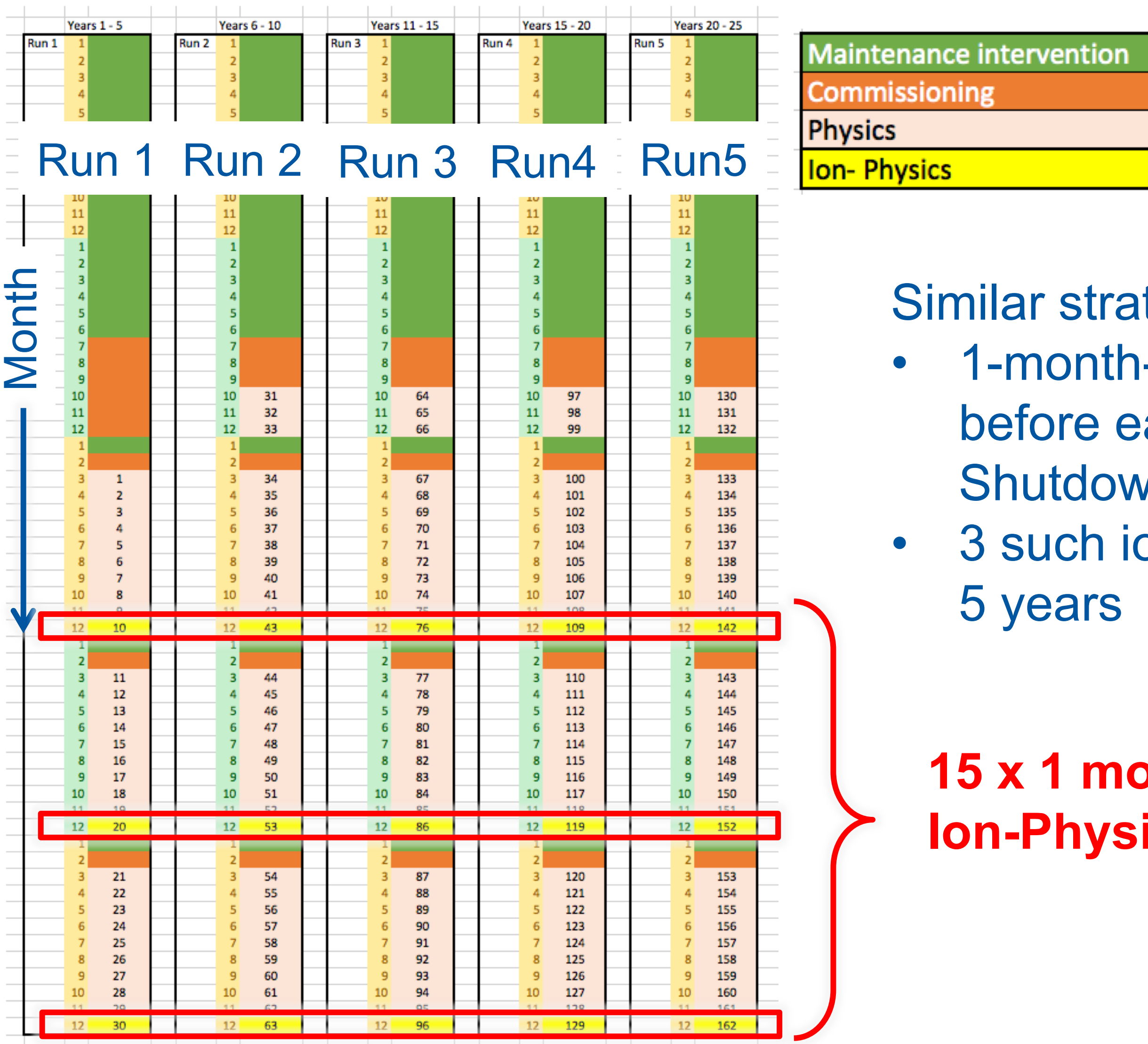
Presentations:

- 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/
- M. Schaumann et al., Heavy Ions at FCC-hh, FCC Week 2017 https://indico.cern.ch/event/556692/contributions/2484258/
- J. Jowett et al., FCC as a nucleus-nucleus collider, performance and status, FCC Week 2018 https://indico.cern.ch/event/656491/contributions/2939104/

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]
- FCC CDR, concise and full versions.

Tentative Run Schedule



Similar strategy as for LHC:

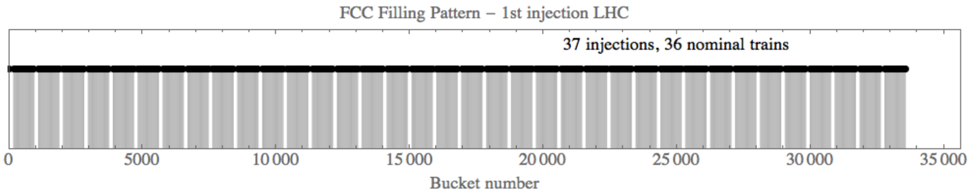
- 1-month-long Heavy-Ion runs before each Technical Stop or Shutdown
- 3 such ion runs per FCC-Run of 5 years

15 x 1 month Ion-Physics time

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**



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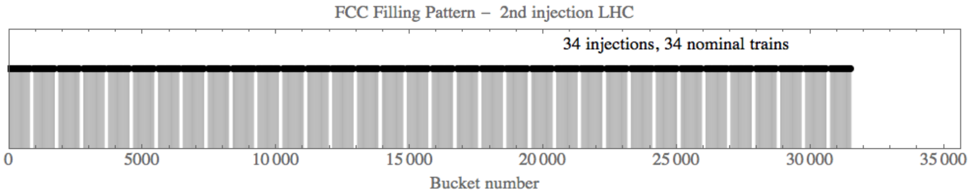
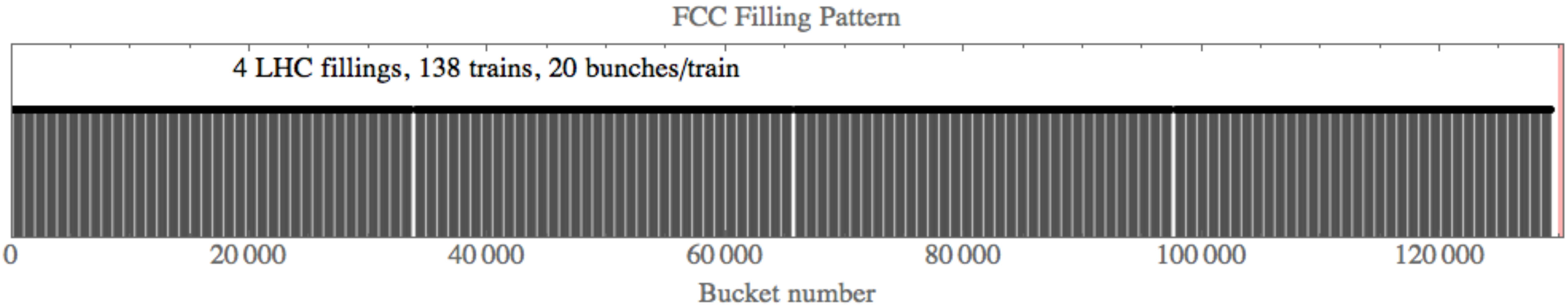
2nd, 3rd, 4th LHC transfer: **34 Trains**



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



Injection at 1.2 Z TeV

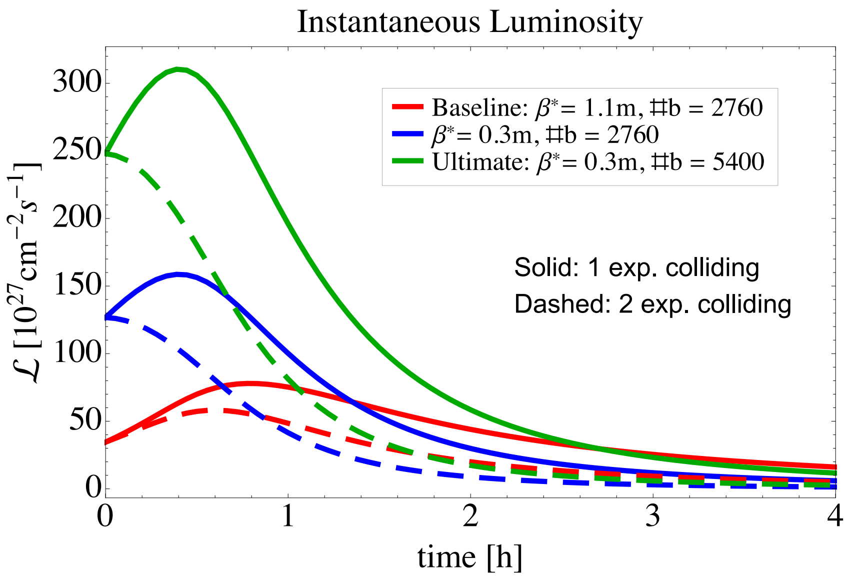
- **Ramping** of the superconducting magnets becomes a **significant fraction of the SPS cycle length**
  - ~2x 12sec ramp vs. 12-24sec filling

- **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 Luminosity Evolution



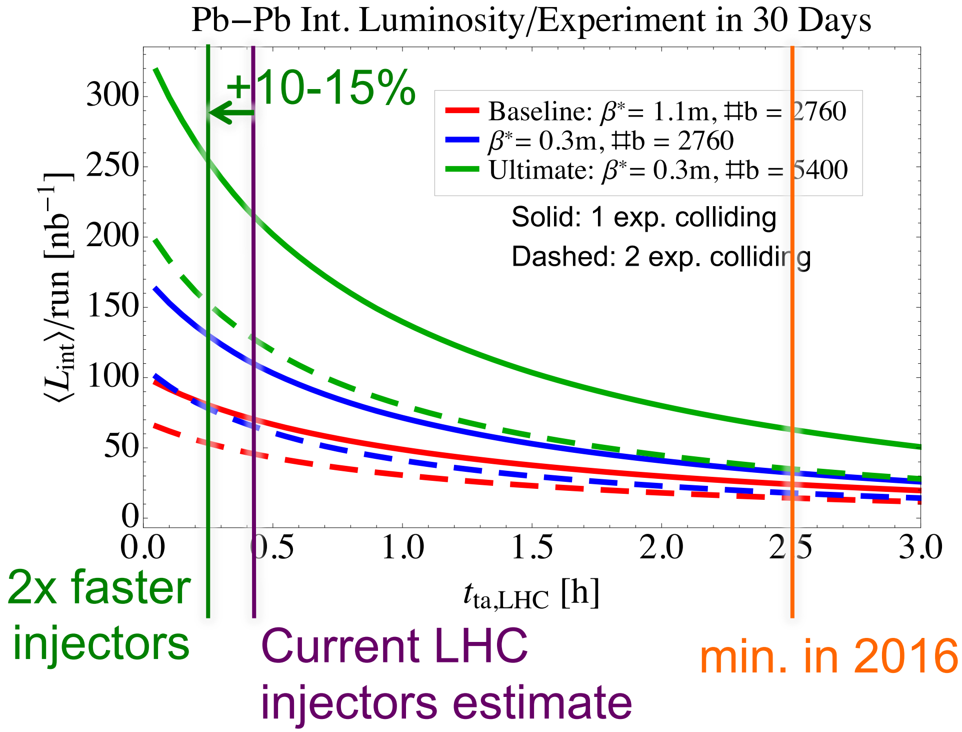
Scenarios:

- 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

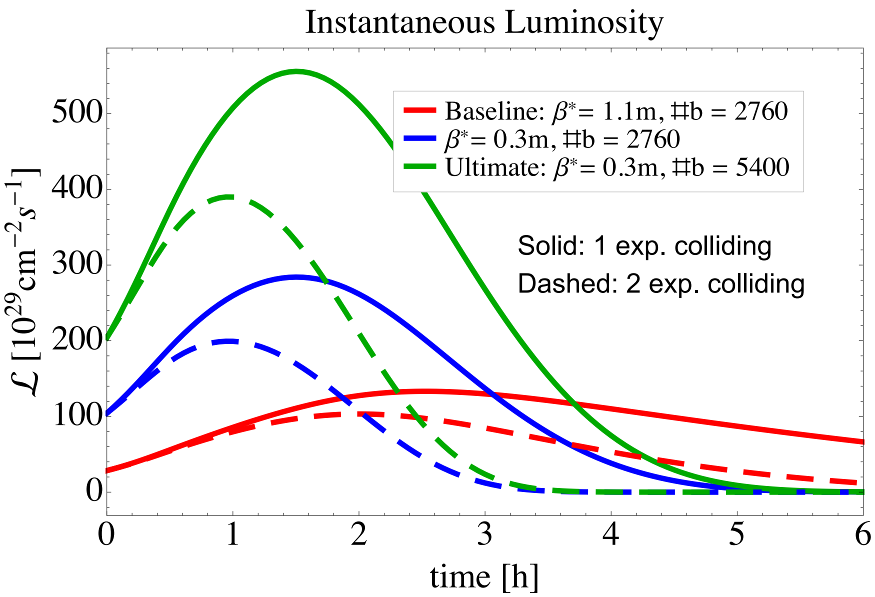
Neglects:

- **Down time** due to failures

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

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

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.