Working group on heavy ions at FCC-hh

Machine parameters and performance

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Material from Michaela Schaumann and John Jowett

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Pre-accelerator chain

Michaela

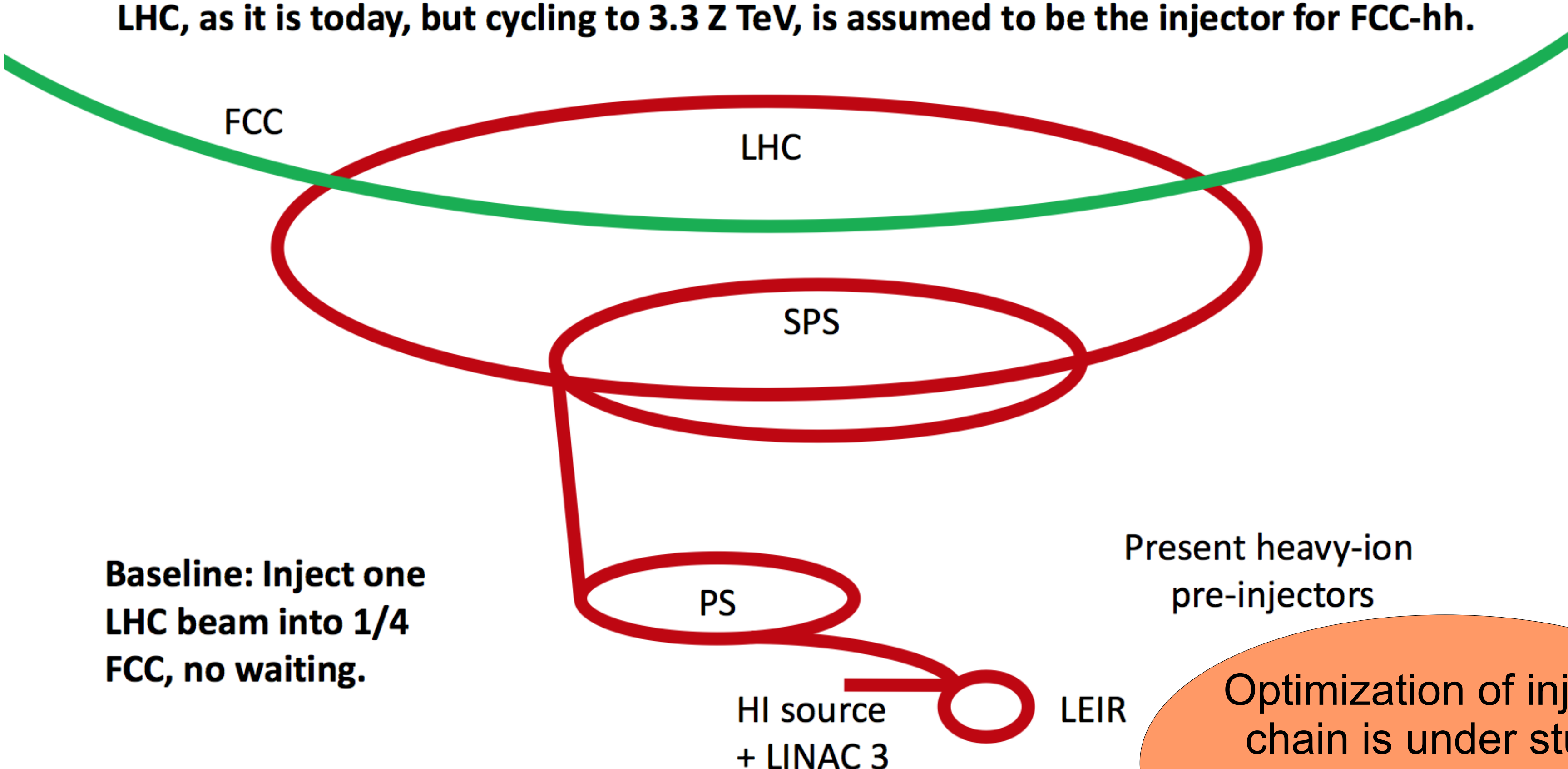
Heavy Ion Pre-Accelerator Chain

The requirements and performance of the pre-accelerator chain for FCC are under studied.

R&D

Straw-man assumption to estimate (conservative) beam parameters and luminosity:

LHC, as it is today, but cycling to 3.3 Z TeV, is assumed to be the injector for FCC-hh.



Baseline: Inject one LHC beam into 1/4 FCC, no waiting.

Optimization of injector chain is under study: HIGH POTENTIAL for lumi improvement

General FCC-hh parameters

Michaela Andrea

Based on a working p-p collider exists.

	Units	Injection	Collision
Circumference	[km]	100	100
Main dipole strength	[T]	1.0	16
Bending radius	[m]	10424	10424
Proton equivalent energy	[TeV]	3.3	50
Lead ion energy	[TeV]	270	4100
Lead ion energy/nucleon	[TeV]	1.3	19.7
C.M. energy $\sqrt{s}$	[TeV]	2.6	39.4

Centre-of-mass energy per nucleon-nucleon collision:

$$\sqrt{s_{NN}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \sqrt{s_{pp}} \Rightarrow \begin{array}{l} \sqrt{s_{PbPb}} = 39\ TeV \\ \sqrt{s_{pPb}} = 63\ TeV \end{array} \text{ for } \sqrt{s_{pp}} = 100\ TeV$$

Pb beam parameters

Michaela

Average beam parameters from 2013 are assumed as
VERY conservative baseline for FCC-hh!
→ Improvements are already under study for HL-LHC!

	LHC Design	LHC 2011	LHC 2013	FCC-hh
Beam Energy [Z TeV]	7	3.5	4	50
β-function at the IP [m]	0.5	1.0	0.8	1.1
No. Ions per bunch [10^8]	0.7	1.20 ± 0.25	1.40 ± 0.27	1.4
Transv. normalised emittance [μm. rad]	1.5	1.7 ± 0.2	~1.5	1.5
RMS Beam Size at IP [μm]	15.9	33.9	26.6	8.8
RMS bunch length [cm]	7.94	9.8 ± 0.7	9.8 ± 0.1	8
Number of bunches	592	358	358	432
Peak Luminosity [$10^{27} cm^{-2} s^{-1}$]	1	0.5 (Pb-Pb)	110 (p-Pb)	?

Potential limitations

Ultraperipheral electromagnetic interactions dominate the total cross-section during heavy-ion collisions and cause the initial intensity to decay rapidly.
Most important interactions:

Bound-Free Pair Production (BFPP)

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + \mathrm{e}^{+}$$

Electromagnetic Dissociation (EMD)

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + \mathrm{n}$$

Main contribution to fast Pb-Pb burn-off:

$$\begin{aligned}\sigma_{tot} &= \sigma_{BFPP} + \sigma_{EMD} + \sigma_{hadron} \\ &= 354\,\mathrm{b} + 235\,\mathrm{b} + 8\,\mathrm{b} = 597\,\mathrm{b}\end{aligned}$$

… and background!!

High intensity secondary beams

Because of the bound-free pair production (BFPP), high intensity beams emerge from the interaction points.

Dramatic increase at the FCC:

Beam Power: $P = \sigma_c \mathcal{L} \gamma m_{\text{ion}} c^2$

→ peak $P_{BFPP} \approx 1.7kW$

nominal LHC: *P* ≈ 26W

→ already expected to cause operational problems and long-term damage

Countermeasures (e.g., DS collimators) have to be considered in initial lattice & hardware design

More considerations on luminosity

Emittance: a new regime

- Intra-Beam Scattering (IBS)

  multiple small-angle Coulomb scattering within a charged particle beam → emittance growth
- (Synchrotron) radiation damping

  synchrotron radiation → emittance shrinking

Fast emittance decrease at the beginning of the fill, until IBS becomes strong enough to counteract the radiation damping

Artificial blowing against emittance and bunch length reduction will influence the luminosity

- **Beam-beam tune shift** close to the limit for Pb in p-Pb collisions
- In p-Pb: N(p) ≈ 100 N(Pb)

  very fast **Pb beam burn-off** (at ~constant n. of protons)

Accelerator parameters

	Unit	LHC Design	FCC Collision	FCC Collision
Luminosity				
Operation mode	-	Pb-Pb	Pb-Pb	p-Pb
β-function at the IP	[m]	0.5	1.1	
Initial RMS beam size at IP	[μm]	15.9	8.8	
Initial luminosity	[Hz/mb]	1	2.6	213
Peak luminosity	[Hz/mb]	1	7.3	1192
Integrated luminosity per fill	[μb^{-1}]	<15	57.8	21068
Integrated luminosity per run	[nb^{-1}]	-	8.3	1784
Initial bb tune shift per IP	[10^{-4}]	1.8	3.7	3.7
Total cross-section	[b]	515	597	2
Peak BFPP beam power	[W]	26	1705	0
Initial beam current lifetime	[h]	<11.2 (2 exp.)	10.9	39.3
Luminosity lifetime ($\mathcal{L}_0/e$)	[h]	<5.6 (2 exp.)	6.2	14.0

M. Schaumann, http://journals.aps.org/prstab/abstract/10.1103/PhysRevSTAB.18.091002

Luminosity numbers

First (conservative) estimates of luminosity (in comparison with LHC): >8 larger L_{int} per month of running

	LHC Run 2 [1]	LHC after LS2 [1]	FHC [2]
Pb–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	(2-3×)10^{27}	5×10^{27}	13×10^{27}
Pb–Pb L_{int} / month (nb^{-1})	0.8(1)	1(1.5)	>8
p–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	(2-3×)10^{29}	t.b.d.	3.5×10^{30}
p–Pb L_{int} (nb^{-1})	80	t.b.d.	>1800

A. Dainese at ECT*

Could aim for programme of 100/nb (LHC x10)

Smaller Z ions?

- New ions source & injectors □ possibly higher N_b are available.
  - ➢ No studies on improved heavy ion injectors done yet!
- Contribution of ultra-peripheral electromagnetic processes to the total cross-section would be reduced:
  - ○ $\sigma_{\mathrm{BFPP}} \propto Z^7$
  - ○ $\sigma_{\mathrm{EMD}} \propto Z^4$
  - ➢ Increased luminosity lifetime, more particles available for hadronic interactions.
  - ➢ Reduced secondary beam power emerging from collision point.
- Radiation damping rate does not change much for Z>60:
  - ○ $\alpha_{\mathrm{rad}} \propto Z^5/A^4$

Physics interest? Not discussed so far
Need a second ion source!

What to write in the document – opt A

- Beam energy (pp 100 TeV, Pb-Pb 39 TeV, p-Pb 63 TeV)
- Pre-accelerator chain (text only)
- Accelerator parameters (table)
- Luminosity numbers (table) ← reference for physics chapters
- One sentence about experiment/detectors (PID, low p_T)

So: text, 1-2 tables, no figures

What to write in the document – opt B

- 2-3 pages about the machine and the heavy-ion beams (John Jowett, Michaela Schaumann)
- Beam energy (pp 100 TeV, Pb-Pb 39 TeV, p-Pb 63 TeV)
- Pre-accelerator chain (text only)
- Accelerator parameters (table)
- Luminosity numbers (table) ← reference for physics chapters
- One sentence about experiment/detectors (PID, low p_T)

So: text, 1-2 tables, figures?