A First Look
at Heavy Ion Operation of VHE-LHC

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Thanks to J.M. Jowett and R. Versteegen

16th December 2013

VHE-LHC kick-off for heavy ions, CERN

Outline

- General assumptions (Pre-accelerator chain, ring and beam parameters)

- Estimates for:
  - Circulating beam current and stored energy
  - Beam-beam tune shift
  - IBS
  - Radiation Damping
  - Radiated power, energy loss per turn, critical photon energy
  - Initial luminosity
  - Initial beam current lifetime
  - Luminosity and beam evolution with time
  - Luminosity lifetime
  - BFPP power

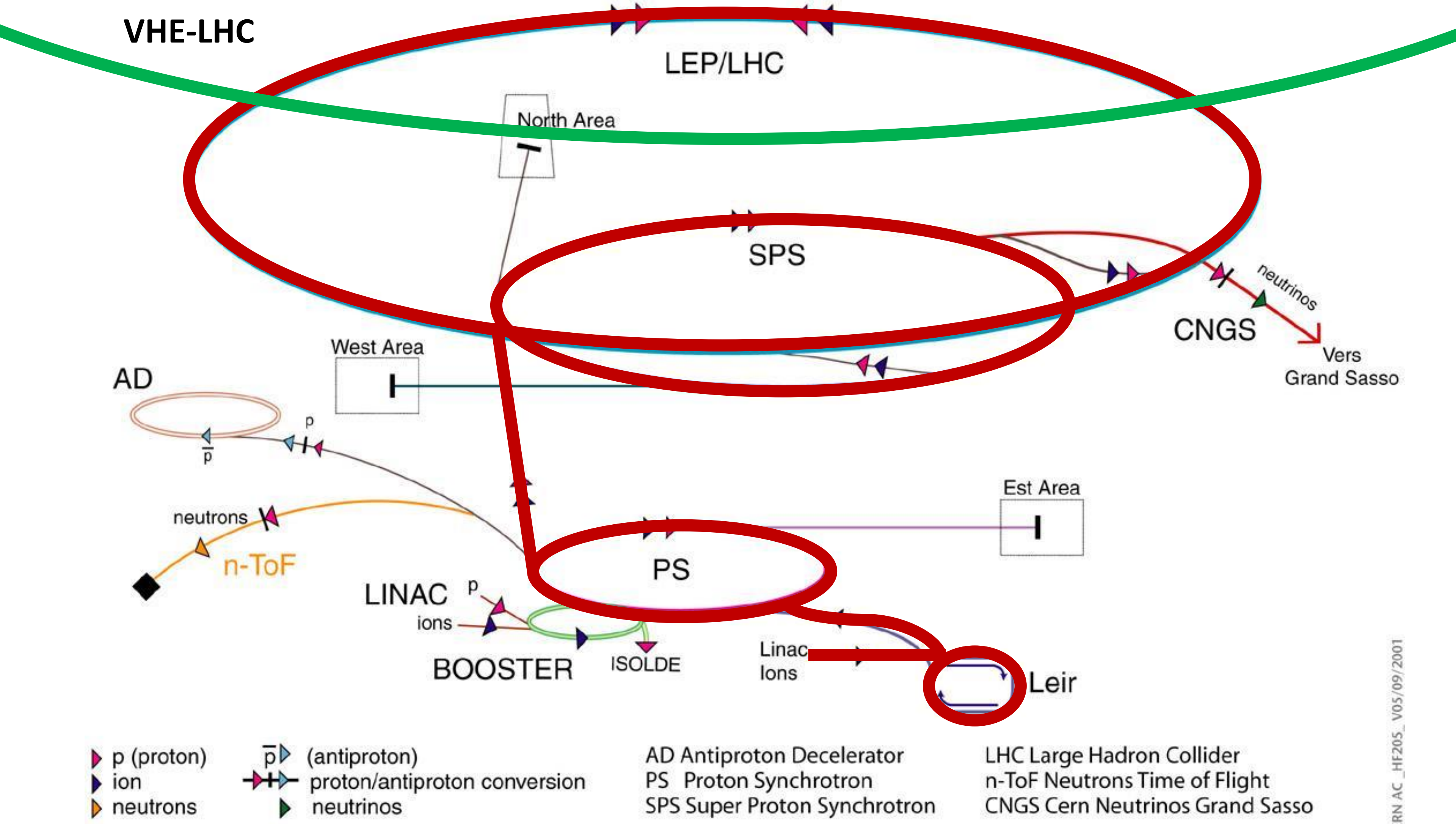
- Cycle optimisation
- Summary Table
- Conclusions

General VHE-LHC Parameters

	Units	Injection	Collision
Circumference	[km]	80	80
Main dipole strength	[T]	1.2	20
Bending radius	[m]	8339.1	8339.1
Proton equivalent energy	[TeV]	3	50
Lead ion energy	[TeV]	246	4100
Lead ion energy/nucleon	[TeV]	1.2	19.7
Relativistic γ-factor	-	1270.1	21168.2
C.M. energy $\sqrt{s}$	[TeV]	492	8200
Peak RF voltage	[MV]	11	22
RF frequency	[MHz]	400	400
Harmonic Number	-	106740	106740
β-function at IP	[m]	-	1.1
Geom. luminosity reduction factor *F*	-	-	1

Heavy Ion Pre-Accelerator Chain

LHC, as it is today, is assumed to be the last pre-accelerator before VHE-LHC.



Beam Parameter

In the following the bunch-by-bunch differences are neglected.
→ All bunches are assumed to be average.

	LHC Design	LHC 2011	LHC 2013	VHE-LHC
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 $[\mu m. \mathrm{rad}]$	1.5	1.7 ± 0.2	~ 1.5	~ 1.5
RMS Beam Size at IP $[\mu m]$	15.9	33.9	26.6	8.8
RMS bunch length $[\mathrm{cm}]$	7.94	9.8 ± 0.7	9.8 ± 0.1	10
Number of bunches	592	358	358	432
Peak Luminosity $[10^{27} \mathrm{cm}^{-2} \mathrm{s}^{-1}]$	1	0.4 ± 0.1	p-Pb	Pb-Pb

Longitudinal Beam Parameters

$$\begin{aligned} f_s &= \frac{\omega_0}{2\pi}\sqrt{\frac{|\eta| V_{RF} h Z e}{2\pi \beta_{rel} E}} \\ \sigma_p &= 2\pi \frac{f_s \sigma_s}{c|\eta|} \\ \epsilon_s &= 4\pi \sigma_p \sigma_s E/c \end{aligned}$$

f_s: synchrotron frequency
σ_s: bunch length
σ_p: relative momentum spread
ϵ_s: longitudinal emittance
E: beam energy
η: slip factor
$\omega_0/2\pi$: revolution frequency
V_{RF}: total RF voltage
h: harmonic number

at top energy

	Unit	LHC Design	VHE-LHC
Synchrotron frequency f_s	[Hz]	23.0	1.9
Momentum spread σ_p	$[10^{-4}]$	1.1	1.1
Longitudinal emittance ϵ_s	[eVs/charge]	2.5	23

S.Y.Lee, Accelerator Physics, 3rd edition

Circulating Beam Current and Stored Beam Energy

Circulating beam current: $$I_{beam} = N_b Q e f_0 k_b$$

Stored beam energy: $$W_{beam} = \gamma m_{ion} N_b k_b$$

γ: relativistic Lorentz factor
N_b: bunch intensity
k_b: number of bunches per beam

m_{ion}: particle's mass
Qe: particle's electric charge
f_0: revolution frequency

	Unit	LHC Design	VHE-LHC injection	VHE-LHC collision
I_{beam}	[mA]	6.12	2.98	2.98
W_{beam}	[MJ]	3.81	2.38	39.73

Beam-Beam Tune Shift

$$\xi_u = \frac{N_b r_0 \beta^*}{2\pi\gamma\sigma_u(\sigma_u+\sigma_v)}$$
$$u,v = x,y$$

Beam-beam tune shift per experiment

For round beams this simplifies to:

$$\xi = \frac{N_b r_0 \beta^*}{4\pi\gamma\sigma^2} = \frac{N_b r_0}{4\pi\epsilon_n}$$

r_0: classical particle radius
σ: beam size
ϵ_n: normalised emittance
β^*: β-functionat IP

	Unit	LHC Design Protons	LHC Design Ions	VHE-LHC
Beam-Beam Parameter per experiment	$[10^{-4}]$	37	1.8	3.7

The tune shift due to beam-beam interactions is negligible.

T. Pieloni, CERN-THESIS-2010-056

Intra-Beam Scattering

A. Piwinski Formalism for IBS **growth rates**:

$$\begin{aligned}
\alpha_{IBS,s} &= \left\langle \boxed{A} \frac{\sigma_h^2}{\sigma_p^2} f(a,b,q) \right\rangle \\
\alpha_{IBS,x} &= \left\langle \boxed{A} \left[f\left(\frac{1}{a}, \frac{b}{a}, \frac{q}{a}\right) + \frac{D_x^2 \sigma_h^2}{\sigma_{x\beta}^2} f(a,b,q) \right] \right\rangle \\
\alpha_{IBS,y} &= \left\langle \boxed{A} \left[f\left(\frac{1}{b}, \frac{a}{b}, \frac{q}{b}\right) + \frac{D_y^2 \sigma_h^2}{\sigma_{y\beta}^2} f(a,b,q) \right] \right\rangle
\end{aligned}$$

Lattice and beam sizes

Particle Type

$$A = \frac{\boxed{r_0^2}\, c \boxed{N_b}}{64\pi^2 \beta^3 \boxed{\gamma^4} \boxed{\epsilon_x \epsilon_y \sigma_s \sigma_p}}$$

Energy

Beam properties

The higher the energy the lower the IBS growth rates.

The higher the brightness of the bunch, the higher the IBS growth rates.

$$\frac{1}{\sigma_h^2} = \frac{1}{\sigma_p^2} + \frac{D_x^2}{\sigma_{x\beta}^2} + \frac{D_y^2}{\sigma_{y\beta}^2}$$

$$f(a,b,q) = 8\pi \int_0^1 \left\{ 2 \ln \left[\frac{q}{2} \left(\frac{1}{P} + \frac{1}{Q} \right) \right] - 0.577\ldots \right\} \frac{1-3u^2}{PQ} du$$

$$\left.\begin{aligned}
q &= \sigma_h \beta \sqrt{\frac{2d}{r_0}} \\
P^2 &= a^2 + (1-a^2)u^2 \\
Q^2 &= b^2 + (1-b^2)u^2
\end{aligned}\right\}
\quad
\begin{aligned}
a &= \frac{\sigma_h \beta_x}{\gamma \sigma_{x\beta}} \\
b &= \frac{\sigma_h \beta_y}{\gamma \sigma_{y\beta}}
\end{aligned}$$

Handbook of Accelerator Physics and Engineering, 1st Edition, 3rd Print, pp. 141

Smooth Lattice Approximation

A lattice design does not yet exist!
Approximations for smooth lattice functions are used where necessary.

Cell Length from aperture constraints

$$L_c = [1,2] L_{c,LHC}$$
$$\Rightarrow \bar{\beta} = [1,2] \bar{\beta}_{LHC}$$

Number of cells

$$C_{ring} \approx 3C_{LHC} \propto 3(L_c N_c)_{LHC}$$
$$\Rightarrow N_c = \left[3, \frac{3}{2}\right] N_{c,LHC}$$

Dispersion

$$D_x \propto \theta_c L_c$$
$$2\pi = \Sigma\theta_{c,i} = N_c \theta_c$$
$$\Rightarrow \theta_c = \frac{2\pi}{N_c}$$
$$\Rightarrow \bar{D}_x = \left[\frac{1}{3}, \frac{4}{3}\right] \bar{D}_{x,LHC} \quad C_{ring} \approx 3C_{LHC}$$
$$= \left[\frac{1}{4}, 1\right] \bar{D}_{x,LHC} \quad C_{ring} \approx 4C_{LHC}$$

Average LHC functions

β-function and tune:

$$Q \equiv \oint \frac{1}{2\pi\beta} ds \approx \frac{C_{ring}}{2\pi\beta}$$
$$\Rightarrow \bar{\beta} = \frac{C_{ring}}{2\pi Q}$$

Dispersion and momentum compaction factor:

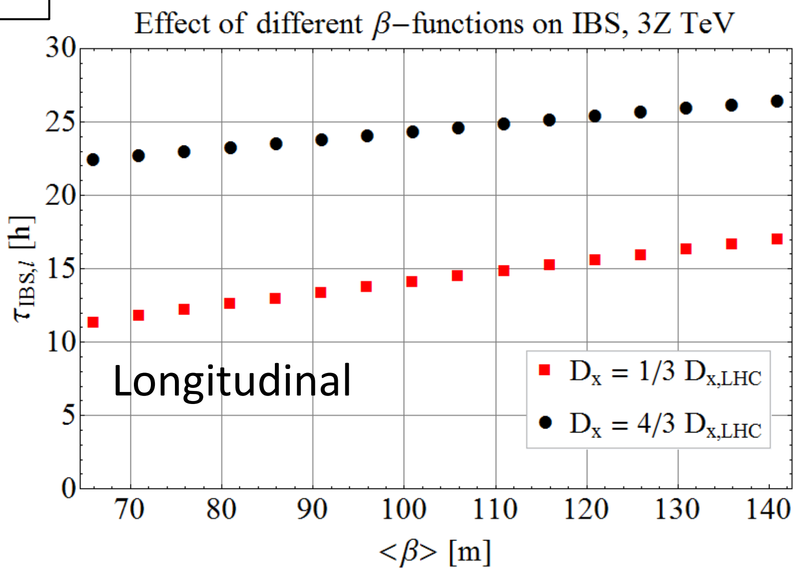
$$\alpha_c \equiv \frac{1}{\gamma_T^2} \equiv \frac{1}{C_{ring}} \oint \frac{D_x}{\rho_0} ds \approx \frac{2\pi D_x}{C_{ring}}$$
$$\Rightarrow \bar{D}_x = \frac{C_{ring}}{2\pi\gamma_T^2}$$

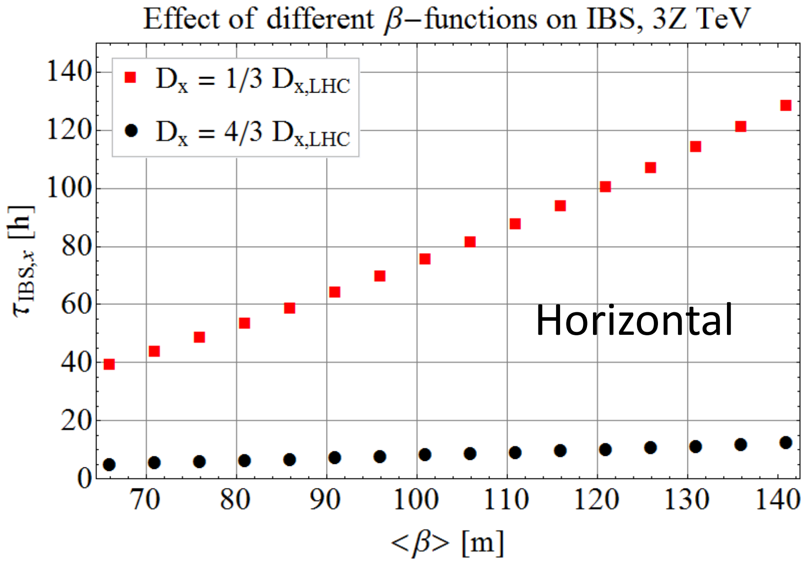
K. Wille, The physics of particle accelerators

Intra-Beam Scattering

3Z TeV

Evolution of IBS growth times with β-function and dispersion





Effect of IBS decreases with increasing β-function.
At collision energy, IBS is weak for initial beam parameters.

Damping Times	Unit	LHC Design	VHE-LHC injection	VHE-LHC collision
$1/\alpha_{\mathrm{IBS,s}}$	[h]	7.7	11.3	84.3
$1/\alpha_{\mathrm{IBS,x}}$	[h]	13	4.8	23.3
$1/\alpha_{\mathrm{IBS,y}}$	[h]	-75000	-11000	-9×10^6

Radiation Damping

Damping Rates

$$\begin{aligned}
\alpha_{rad,s} &= E^3 C_\alpha \frac{\mathcal{I}_2}{C_{ring}}(2+[\mathcal{I}_{4,x}+\mathcal{I}_{4,y}]/\mathcal{I}_2) \\
\alpha_{rad,x} &= E^3 C_\alpha \frac{\mathcal{I}_2}{C_{ring}}(1-\mathcal{I}_{4,x}/\mathcal{I}_2) \\
\alpha_{rad,y} &= E^3 C_\alpha \frac{\mathcal{I}_2}{C_{ring}}(1-\mathcal{I}_{4,y}/\mathcal{I}_2)
\end{aligned}$$

Energy Particle Type Ring

Handbook of Accelerator Physics and Engineering, 1st Edition, 3rd Print, pp. 210

$$C_\alpha = \frac{r_0 c}{3(mc^2)^3}$$

Constant depending on particle's mass and charge

Radiation Integrals

$$\begin{aligned}
\mathcal{I}_2[m^{-1}] &= \oint \left(\frac{1}{\rho_x^2}+\frac{1}{\rho_y^2}\right) ds \\
\mathcal{I}_{4,u}[m^{-1}] &= \oint \frac{D_u}{\rho_u^3}(1\pm 2\rho_0^2 k) ds
\end{aligned}$$

Isomagnetic ring with separated function magnets & $D_y = 0$

$$\begin{aligned}
\mathcal{I}_2 &\approx \frac{2\pi}{\rho_0} \\
\mathcal{I}_{4,x} &\approx 2\pi\frac{D_x}{\rho_0^2} \approx 0 \\
\mathcal{I}_{4,y} &\approx 0
\end{aligned}$$

Radiation Damping

$$
\begin{aligned}
\alpha_{rad,s} &= E^3 C_\alpha \frac{\mathcal{I}_2}{C_{ring}}\left(2+[\mathcal{I}_{4,x}+\mathcal{I}_{4,y}]/\mathcal{I}_2\right)\\
\alpha_{rad,x} &= E^3 C_\alpha \frac{\mathcal{I}_2}{C_{ring}}\left(1-\mathcal{I}_{4,x}/\mathcal{I}_2\right)\\
\alpha_{rad,y} &= E^3 C_\alpha \frac{\mathcal{I}_2}{C_{ring}}\left(1-\mathcal{I}_{4,y}/\mathcal{I}_2\right)
\end{aligned}
$$

Energy Particle Type Ring

Compare VHE-LHC to LHC

$$\frac{\alpha_{rad,VHE}}{\alpha_{rad,LHC}} = \frac{E^3_{VHE}/(\rho_{0,VHE}C_{VHE})}{E^3_{LHC}/(\rho_{0,LHC}C_{LHC})} \approx \frac{E^3_{VHE}/C^2_{VHE}}{E^3_{LHC}/C^2_{LHC}} \approx \frac{7^3}{3^2} \approx 38$$

$$
\begin{aligned}
\rho_0 &\propto C_{ring}\\
E_{VHE} &\approx 7E_{LHC}\\
C_{VHE} &\approx 3C_{LHC}
\end{aligned}
$$

Damping Times	Unit	LHC Design	VHE-LHC injection	VHE-LHC collision
$1/\alpha_{\mathrm{rad,s}}$	[h]	6.3	725	0.16
$1/\alpha_{\mathrm{rad,x}}$	[h]	12.6	1451	0.31
$1/\alpha_{\mathrm{rad,y}}$	[h]	12.6	1451	0.31

Energy Loss per Turn

Radiated power per ion: $$P_{rad,ion} = \frac{2r_0 m_{ion} c \beta_{rel}^4 \gamma^4}{3\rho_0^2}$$

Radiated power per beam: $$P_{rad,beam} = P_{rad,ion} N_b k_b$$

Energy loss per ion per turn: $$\Delta E_{rad,ion} = \frac{2\pi\rho_0}{c} P_{rad,ion}$$

Critical photon energy: $$E_{crit} = \frac{3c\gamma^3\hbar}{2\rho_0}$$

Damping Times	Unit	LHC Design	VHE-LHC injection	VHE-LHC collision
$P_{rad,ion}$	[W]	2.0×10^{-9}	1.5×10^{-11}	8.8×10^{-7}
$\Delta E_{rad,ion}$	[MeV]	1.12	0.01	969.1
$P_{rad,beam}$	[W]	83.9	0.7	53732
E_{crit}	[eV]	2.77	0.07	336.7

Handbook of Accelerator Physics and Engineering, 2nd Edition, pp. 215

Initial Luminosity

$$\mathcal{L} = \frac{N_{b1}N_{b2}f_0k_b}{2\pi\sqrt{\sigma_{x1}^2+\sigma_{x2}^2}\sqrt{\sigma_{y1}^2+\sigma_{y2}^2}}$$

$$= \frac{N_b^2 f_0 k_b}{4\pi\sigma_x\sigma_y} \longleftarrow \begin{array}{c} N_b = N_{b1} = N_{b2} \\ \sigma_{x1} = \sigma_{x2} \\ \sigma_{y1} = \sigma_{y2} \end{array}$$

Equal colliding bunches

$$= \frac{N_b^2 f_0 k_b \gamma}{4\pi\epsilon_n\beta^*} \longleftarrow \sigma^2 = \frac{\epsilon_n\beta^*}{\gamma}$$

Initial luminosity calculated form beam parameters coming from the injectors.

$L_{initial} \neq L_{peak}$ due to strong radiation damping!

	Unit	LHC Design Ions	VHE-LHC
No. of Bunches k_b	-	592	432
Bunch intensity N_b	[10^8 ions]	0.7	1.4
norm. Emittance ϵ_n	[µm]	1.5	1.5
Initial Luminosity	[$10^{-27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1.0	3.2

Initial Beam Current Lifetime

Lifetime due to burn-off only!

$$\frac{1}{\tau_N} = \frac{1}{N_{tot}}\frac{dN}{dt} = \frac{1}{N_{tot}}\sigma_{tot}\mathcal{L}_{initial}$$

$$\tau_N = \frac{N_b k_b}{\sigma_{tot}\mathcal{L}_{initial} n_{exp}}$$

Total cross-section at 50Z TeV:

H. Meier et al, Phys. Rev. A, vol. 63, 032713. 02/2011

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

N_{tot}: total beam intensity
σ_{tot}: total cross-section
$\mathcal{L}_{initial}$: initial Luminosity per experiment
n_{exp}: number of data taking experiments

	Unit	LHC Design (2 experiments)	VHE-LHC (1 experiment)	VHE-LHC (2 experiments)
τ_N	[h]	11.2	8.7	4.3

Luminosity Evolution

Luminosity evolution depends on the time dependency of the intensity and emittance:

$$\mathcal{L}(t) = A\frac{N_b^2(t)}{\epsilon_n(t)}$$

Intensity evolution:

$$\frac{dN}{dt} = -\sigma_{tot}\mathcal{L}(t) = -\sigma_{tot}A\frac{N_b^2(t)}{\epsilon_n(t)}$$

Case 1) consider only burn off:

$$\epsilon_n(t) = const.$$

$$\Rightarrow N_b(t) = \frac{N_{b0}}{AN_{b0}\sigma_{tot}t/\epsilon_{n0} + 1}$$

$$\Rightarrow \mathcal{L}(t) = \mathcal{L}_0\left(\frac{1}{AN_{b0}\sigma_{tot}t/\epsilon_{n0} + 1}\right)^2$$

Luminosity Evolution

Case 2) consider burn off and radiation damping:

IBS is weak at top energy and dominated by radiation damping, the emittance growth/damping time is approximated to be constant.

$$\tau_\epsilon = const.$$

System of two differential equations to be solved:

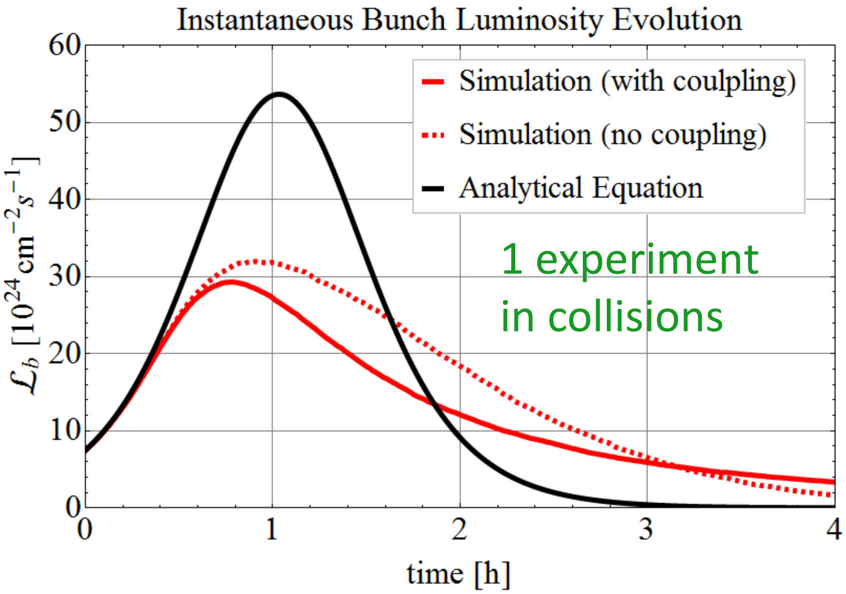
$$\frac{d\epsilon_n}{dt} = -\frac{\epsilon_n}{\tau_\epsilon} \qquad \frac{dN}{dt} = -\sigma_{tot} A \frac{N_b^2(t)}{\epsilon_n(t)}$$

$$\Rightarrow \epsilon_n(t) = \epsilon_{n0} \exp[-t/\tau_\epsilon]$$

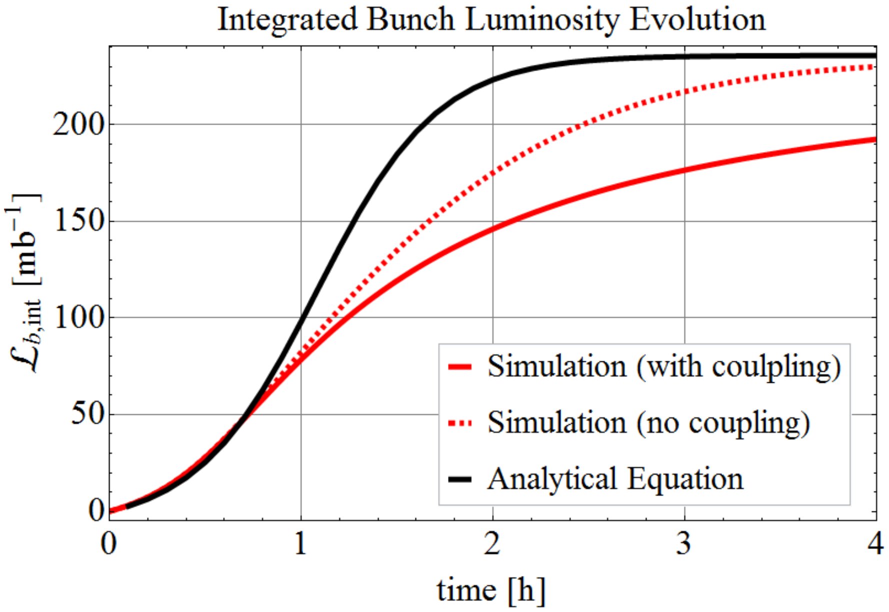
$$\Rightarrow N_b(t) = \frac{N_{b0}\epsilon_{n0}}{\epsilon_{n0} + AN_{b0}\sigma_{tot}\tau_\epsilon(\exp[t/\tau_\epsilon] - 1)}$$

$$\Rightarrow \mathcal{L}(t) = \mathcal{L}_0 \frac{\epsilon_{n0}^2 \exp[t/\tau_\epsilon]}{(\epsilon_{n0} + AN_{b0}\sigma_{tot}\tau_\epsilon(\exp[t/\tau_\epsilon] - 1))^2}$$

Luminosity Evolution


Instantaneous Bunch Luminosity Evolution

1 experiment in collisions


Integrated Bunch Luminosity Evolution

- Analytical calculation assumes $\tau_\epsilon = const.$
- In simulation IBS rate changes dynamically with beam parameters

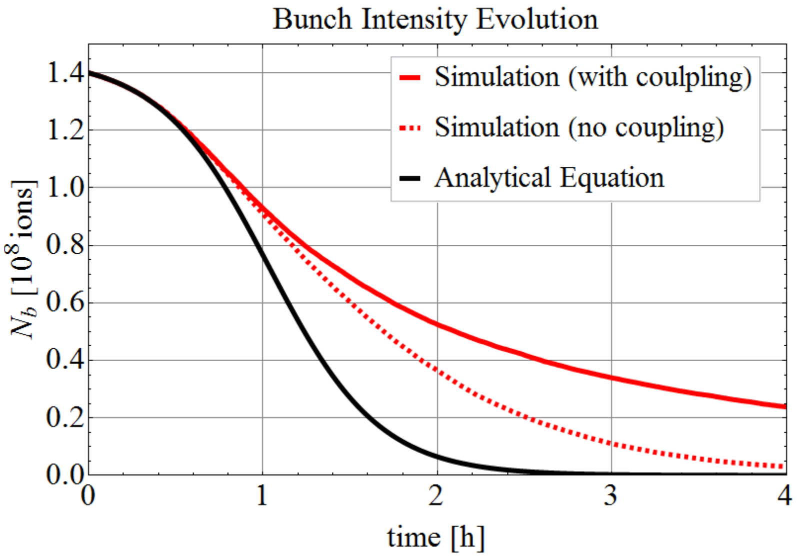
→ IBS increases as emittance decreases due to radiation damping.

→ IBS prevents emittance to decrease to unrealistically small values.

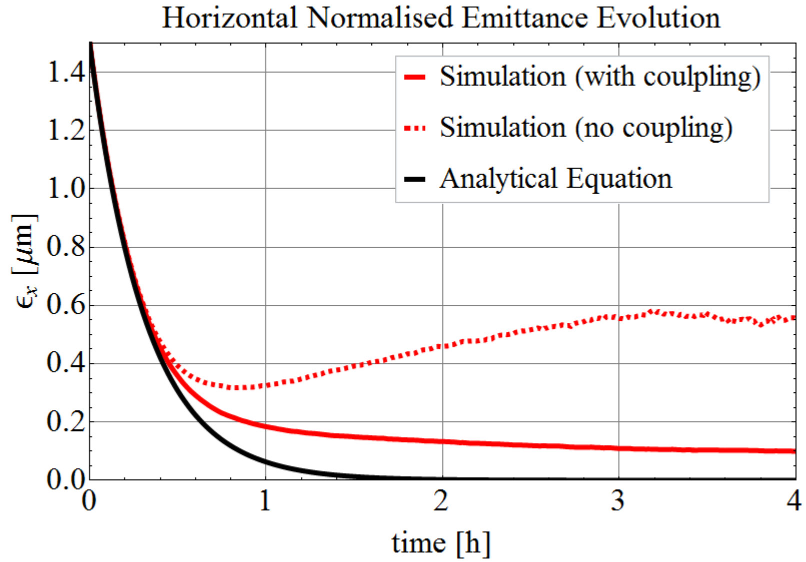
	Unit	per Bunch	whole Beam
$L_{initial}$	[Hz/mb]	0.0075	3.2
L_{peak}	[Hz/mb]	0.029	12.7
$L_{int,fill}$	$[\mu b^{-1}]$	0.2 (max=0.235)	83

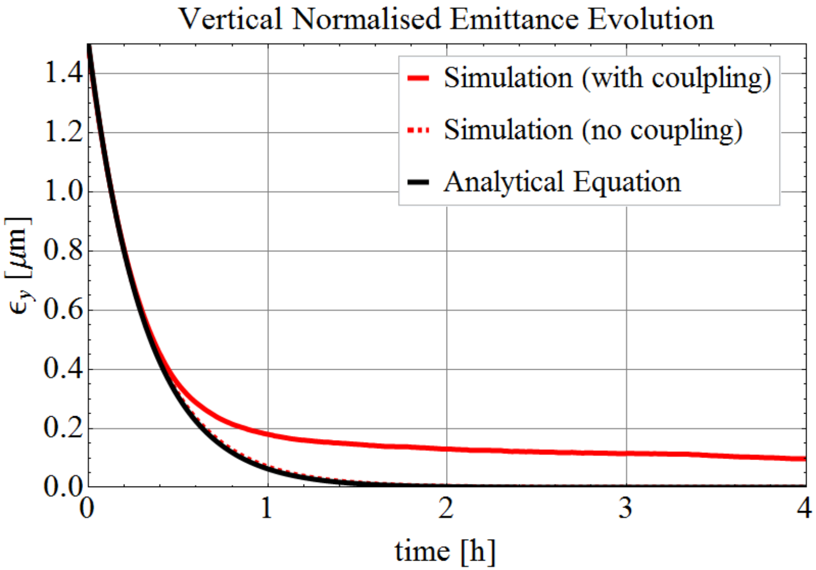
Very high L_{peak}!
Is detector able to take those rates?
Levelling required?

Beam Evolution



- Analytical calculation assumes $\tau_\epsilon = const.$
  → Emittances are damped to ~ 0, unrealistic!
- In simulation horizontal IBS counteracts radiation damping for small emittances:
  → Without coupling only in horizontal plane, vertical emittances ~ 0.
  → With coupling, horizontal IBS growth is transferred to vertical plane.
  → Equilibrium emittance in both planes.





Initial Luminosity Lifetime

Time at which the luminosity has decreased to 1/e of its initial value.

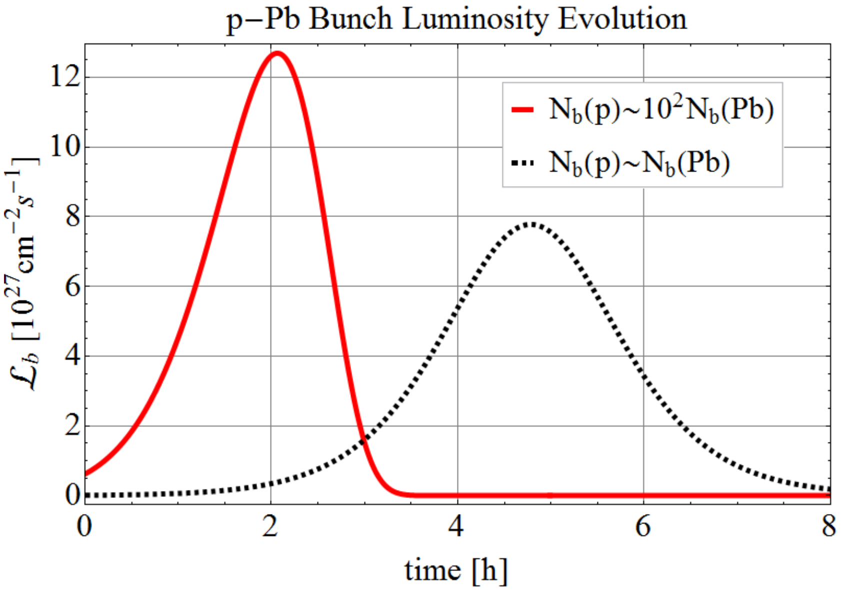
		Unit	LHC Design (2 exp.)	VHE-LHC (1 exp.)	VHE-LHC (1 exp. simulation)	VHE-LHC (2 exp.)
Case 1	τ_L (beam-beam only)	[h]	-	5.6	-	2.8
Case 2	τ_L (beam-beam, rad. damping, IBS)	[h]	< 5.6	2.4	3.7	2.0

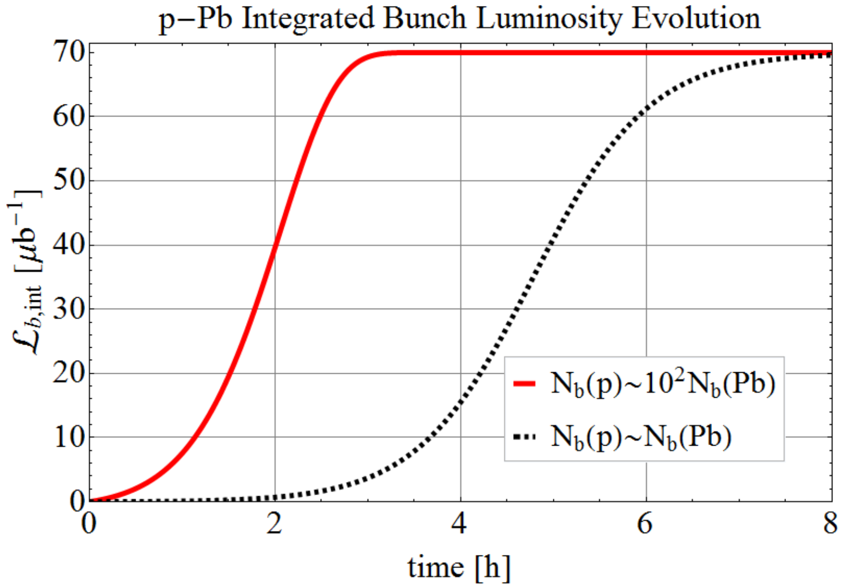
Things still to be studied:

- Bunch length damps 2x fast than transverse plane.
  → Longitudinal instabilities could become a problem.
  → Longitudinal blow-up might be necessary.
- For too small transverse emittances ($\epsilon = 0.1\mu m \rightarrow \sigma^* < 1\mu m$)
  → Orbit stability?
  → Finding collisions.
  → Transverse blow up might become necessary – method of levelling.

p-Pb Luminosity Evolution

Analytical calculation only! – Neglecting IBS





Equal geometric beam sizes for p and Pb

1) $N_b(\mathrm{p}) \approx 100\ N_b(Pb)$ = const.

→ Fast burn-off very fast: $\tau_L = 3.2h$

2) Slow down burn-off by decreasing p-intensity $N_b(\mathrm{p}) = N_b(Pb)$

→ $N_b(\mathrm{p}) \neq$ const

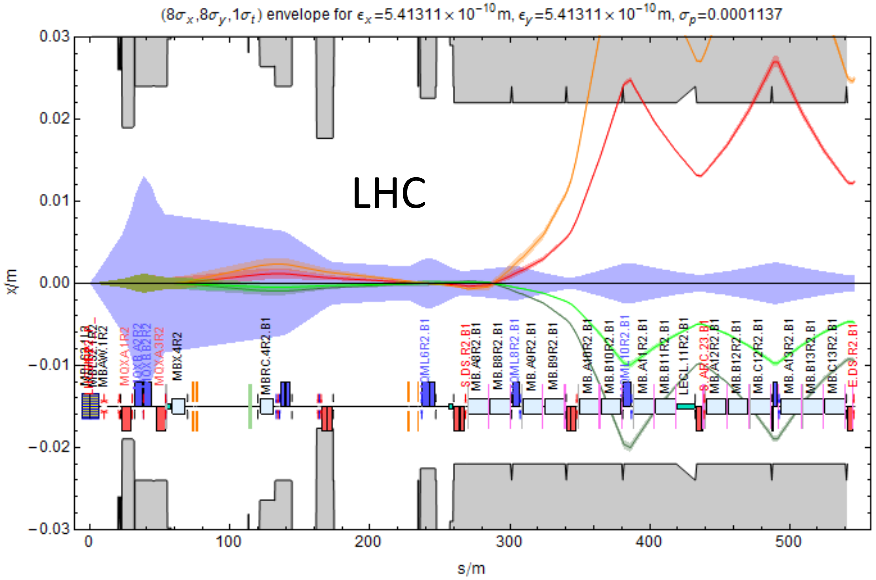
→ Luminosity lifetime $\tau_L \approx 10.6h$

Maximum integrated luminosity is achieved, when all Pb ions are converted into luminosity $\mathcal{L}_{int} = \frac{N_b k_b}{\sigma_{tot}}$

	Unit	per Bunch	whole Beam
$L_{initial}$	[Hz/mb]	0.007/0.6	3.2/267
L_{peak}	[Hz/mb]	8/13	3356/5477
$L_{int,fill}$	[μb^{-1}]	70	30240

BFPP Beam Power

LHC Pb beam right of IP2



EMD: Electromagnetic dissociation

$BFPP$: Bound-free pair production

Main: **208-Pb-82+**

BFPP1: **208-Pb-81+**

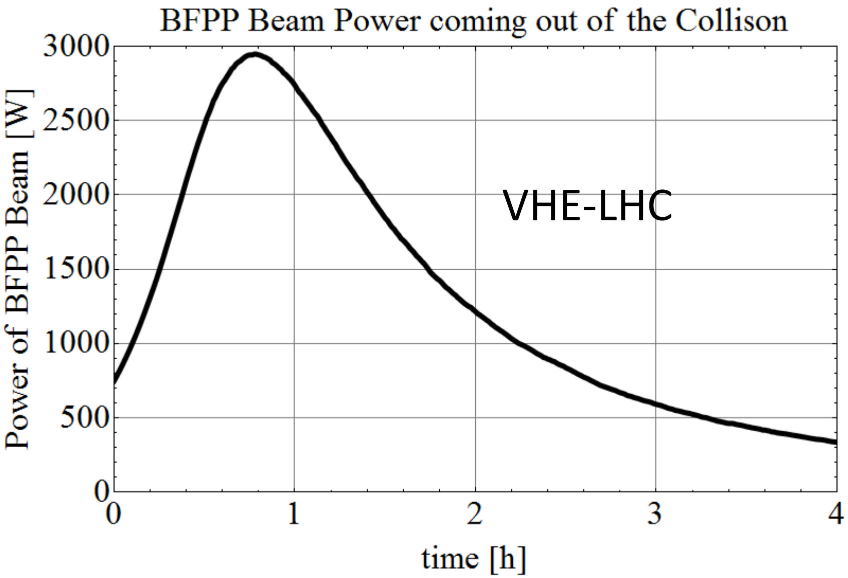
BFPP2: **208-Pb-80+**

EMD1: **207-Pb-82+**

EMD2: **206-Pb-82+**

The rigidity of each beam changed by

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

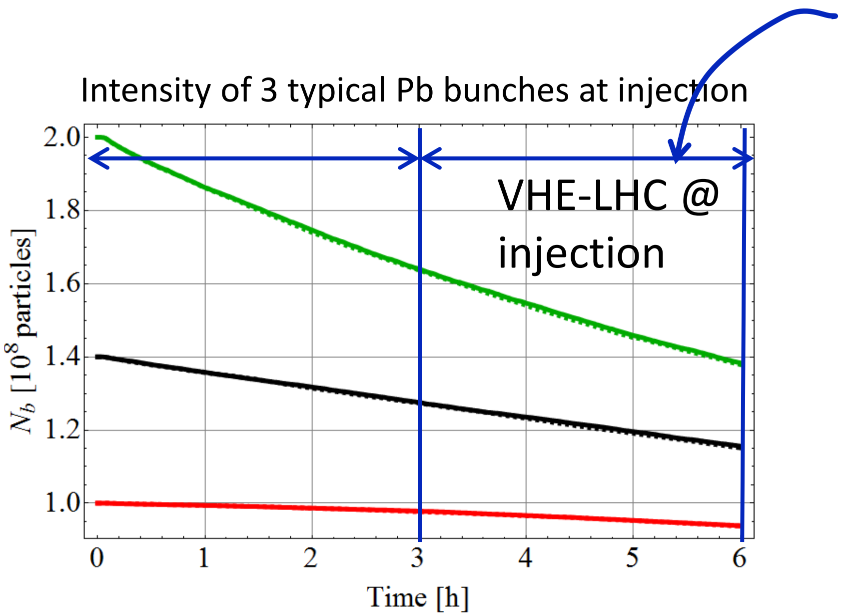


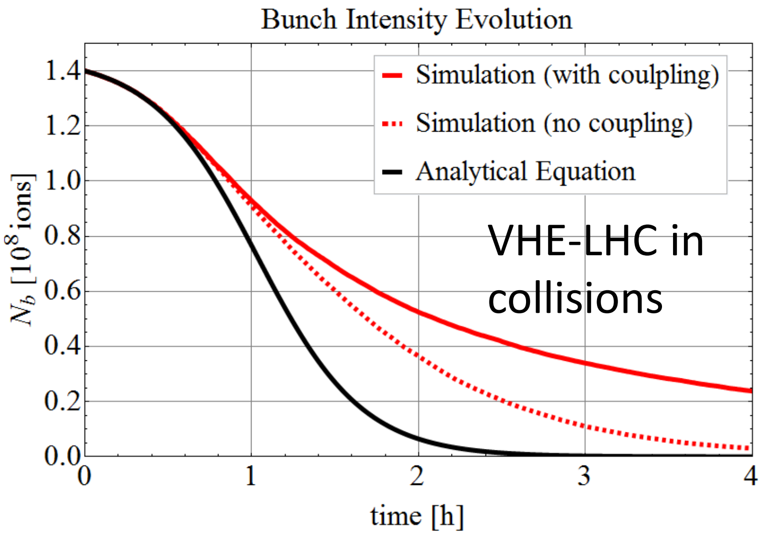
$$P_{BFPP} = \mathcal{L}\sigma_{BFPP}\gamma m_{ion}$$

$$\sigma_{BFPP} = 354\,\mathrm{b}$$

	VHE-LHC
initial P_{BFPP}	751 W
peak P_{BFPP}	2947 W

Cycle Optimisation





3h LHC turn around time
= time between 2 injections to VHE-LHC.

- 10% average intensity loss,
- 10% average emittance growth,

between two LHC shots at VHE-LHC injection plateau!

- Luminosity lifetime ~3h
  ≈ LHC turn around time.
- Optimal beam usage – only 15% of particles left after 4h of collisions.

→ Fill both beams of LHC and inject them into VHE-LHC.
→ Refill LHC during physics in VHE-LHC.
→ No waiting time for VHE-LHC due to cycling in LHC.

If 2 experiments are considered, they have to be placed at opposite positions in the ring to be provided with luminosity!

Summary Table (1)

	Unit	LHC Design	VHE-LHC Injection	VHE-LHC Collision	VHE-LHC Collision
Operation mode	-	Pb-Pb	Pb	Pb-Pb	p-Pb
Particle type	-	Pb	Pb	Pb	p
Beam Energy	[TeV]	574	246	4100	50
Relativistic γ-factor	-	2963	1270	21168	53290
Number of bunches	-	592	432	432	432
No. Ions per bunch	[10^8]	0.7	1.4	1.4	115/1.4
Transv. normalised emittance	[μm. rad]	1.5	1.5	1.5	3.75
RMS bunch length	[cm]	7.94	10	10	10
Synchrotron frequency	[Hz]	23.0	5.5	1.9	1.9
Longitudinal emittance (4σ)	[eVs/charge]	2.5	4	23	23
RMS energy spread	[10^{-4}]	1.1	3.3	1.1	1.1
Circulating beam current	[mA]	6.12	3.0	3.0	3.0/0.04
Stored beam energy	[MJ]	3.81	2.4	40	40/0.5
Longitudinal IBS emit. growth time	[h]	7.7	11.3	84.3	$1\times 10^4/1\times 10^6$
Horizontal IBS emit. growth time	[h]	13	4.8	23.3	$3\times 10^3/3\times 10^5$
Longitudinal emit. rad. damping time	[h]	6.3	725	0.16	0.32
Horizontal emit. rad. damping time	[h]	12.6	1451	0.31	0.63

Summary Table (2)

	Unit	LHC Design	VHE-LHC Injection	VHE-LHC Collision	VHE-LHC Collision
Operation mode	-	Pb-Pb	Pb	Pb-Pb	p-Pb
Power loss per ion	[W]	2.0×10^{-9}	1.5×10^{-11}	8.8×10^{-7}	5.4×10^{-9}
Energy loss per ion per turn	[MeV]	1.12	0.01	969.1	5.8
Synchrotron radiation power per ring	[W]	83.9	0.7	53732	26587/323
Critical photon energy	[eV]	2.77	0.07	336.7	5376
β-function at the IP	[m]	0.5	-	1.1	1.1
RMS beam size at IP	$[\mu m]$	15.9	-	8.8	8.8
Initial luminosity	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	-	3.2	267/3.2
Peak luminosity	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	-	12.7	5477/3356
Integrated luminosity per fill	$[\mu b^{-1}]$	<15	-	83	30240
Beam-beam tune shift	$[10^{-4}]$	1.8	-	3.7	3.7/0.045
Total cross-section	[b]	515	-	597	2
Peak BFPP beam power	[W]	26	-	2947	0
Initial beam current lifetime (1 exp.)	[h]	<11.2 (2 exp.)	-	8.7	24/2583
Initial luminosity lifetime	[h]	<5.6 (2 exp.)	-	3.7	3.2/10.6

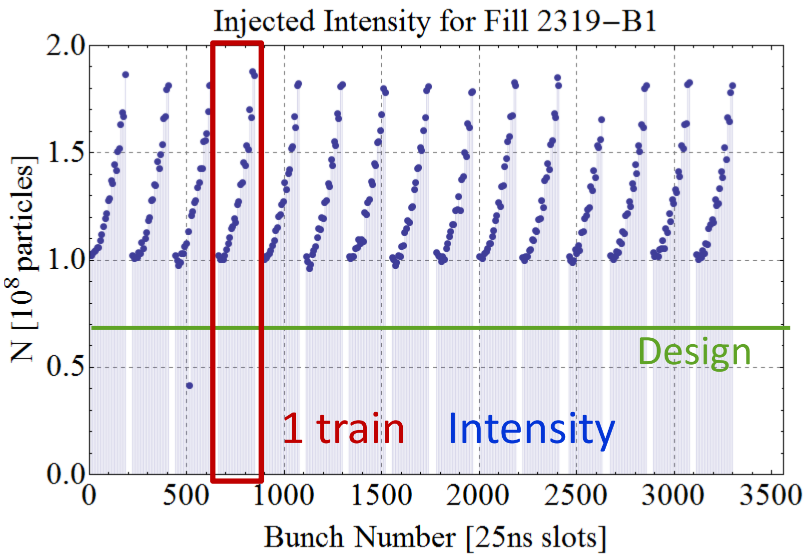
Conclusions

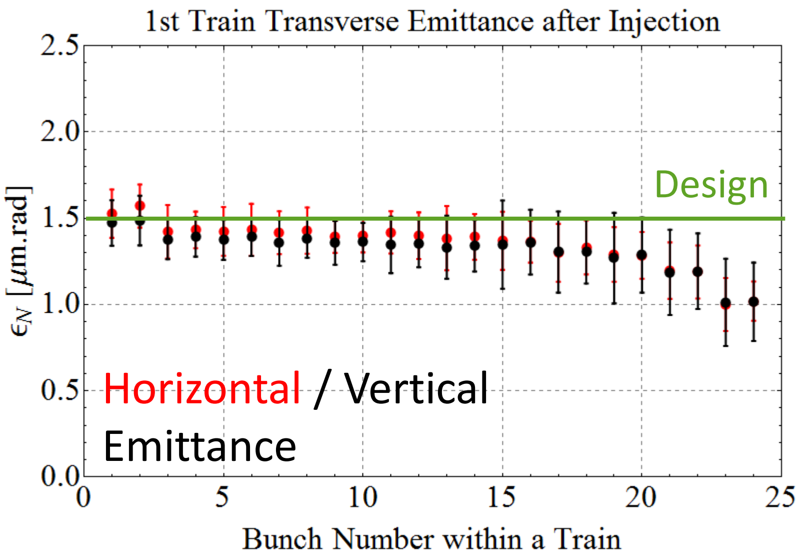
- VHE-LHC will enter a different regime of operation.
- Very strong radiation damping will lead to small emittances and thus effective intensity burn-off.
- The absolute integrated luminosity maximum per fill (convert all particles into luminosity) comes into reach.
- The peak luminosity can get very high ($\sim 12 \times$ nominal LHC) – levelling might have to be considered.
- Turn around time of the pre-injector LHC is about as long as the expected time in collisions per fill:
  → fill LHC in parallel to physics operation in VHE-LHC to maximise physics time.
- p-Pb: burn-off very fast - decrease the proton intensity compared to LHC operation, to lengthen the fill.

THANK YOU
FOR YOUR ATTENTION

Bunch-by-Bunch Differences after Injection in the LHC

E = 450 Z GeV



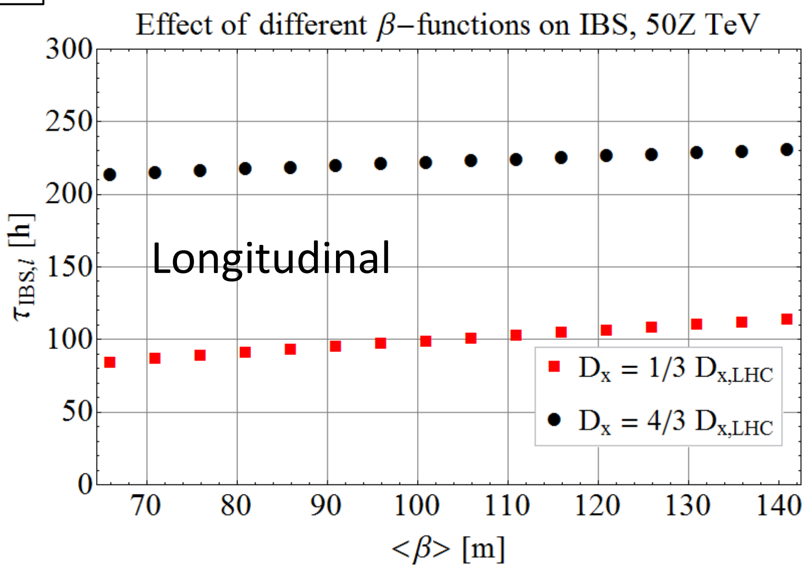


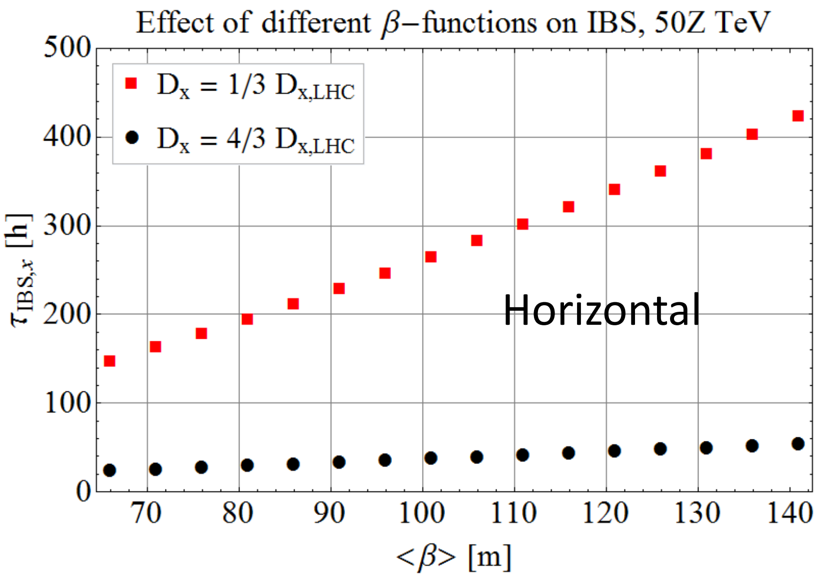
- Structure within a train (1st to last bunch):
  - increase: - intensity
    - bunch length
  - decrease: emittance.
- IBS, space charge, RF noise … at the injection plateau of the SPS:
  - while waiting for the 12 injections from the PS to construct a LHC train.
- First injections sit longer at low energy
  → strong IBS,
  → emittance growth and particle losses.

Intra-Beam Scattering

50Z TeV

Evolution of IBS growth times with β-function and dispersion





Effect of IBS decreases with increasing β-function.

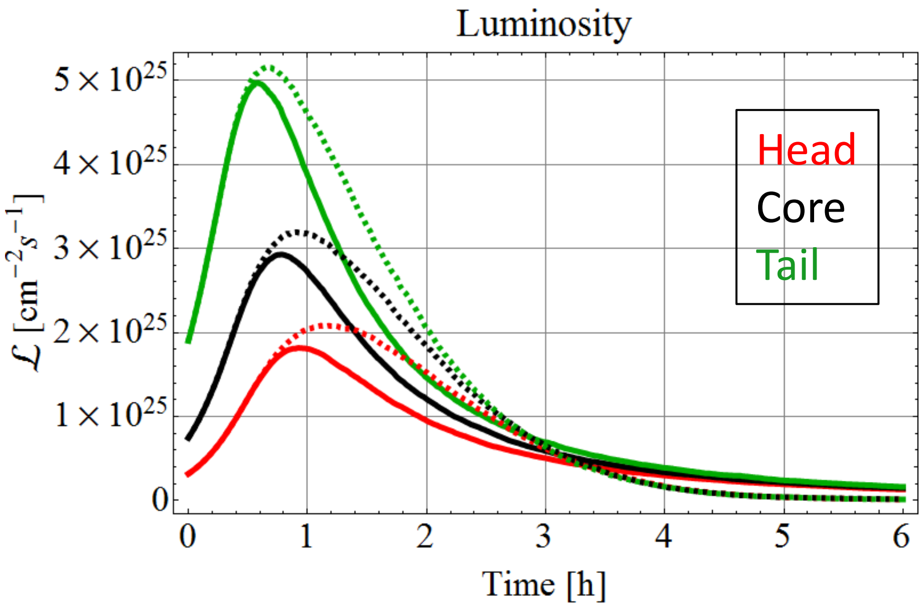
At collision energy, IBS growth almost negligible for initial beam parameters.

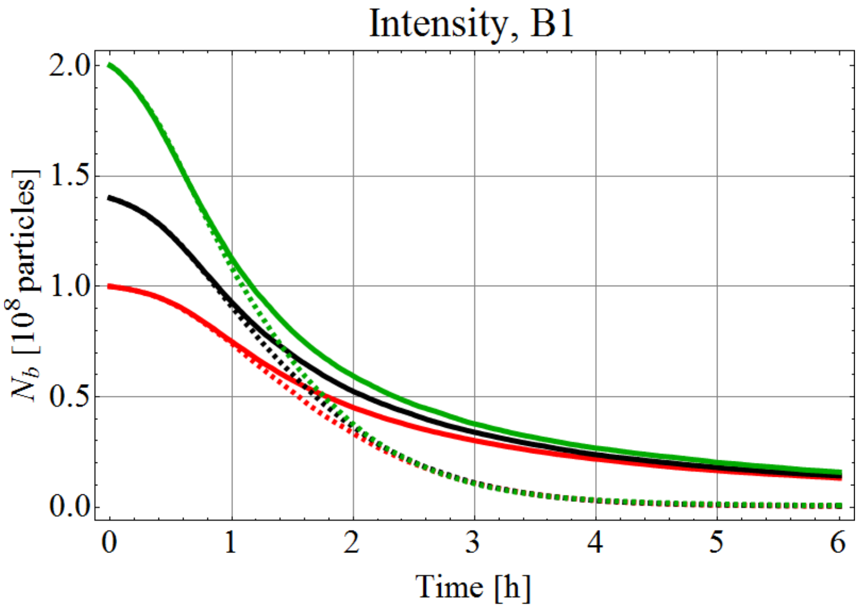
Damping Times	Unit	LHC Design	VHE-LHC injection	VHE-LHC collision
$1/\alpha_{\mathrm{IBS,s}}$	[h]	7.7	11.3	84.3
$1/\alpha_{\mathrm{IBS,x}}$	[h]	13	4.8	23.3
$1/\alpha_{\mathrm{IBS,y}}$	[h]	-75000	-11000	-9×10^6

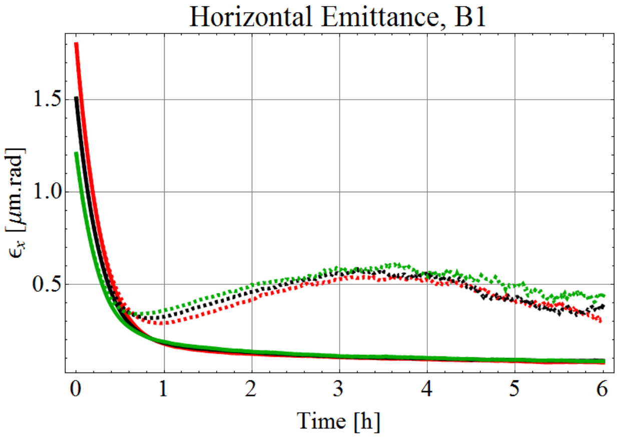
Beam Evolution Simulations

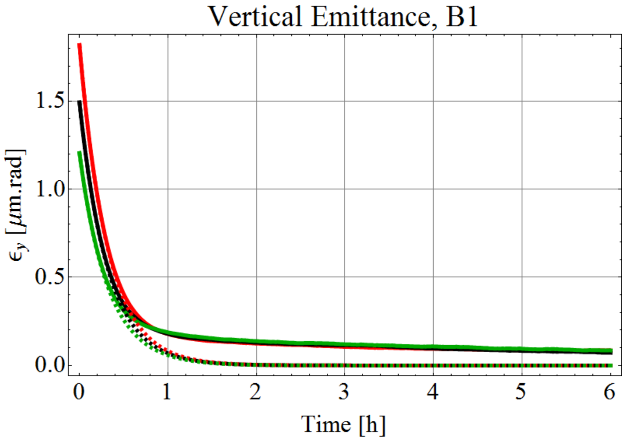
Evolution of 3 typical Pb-bunches in collisions.

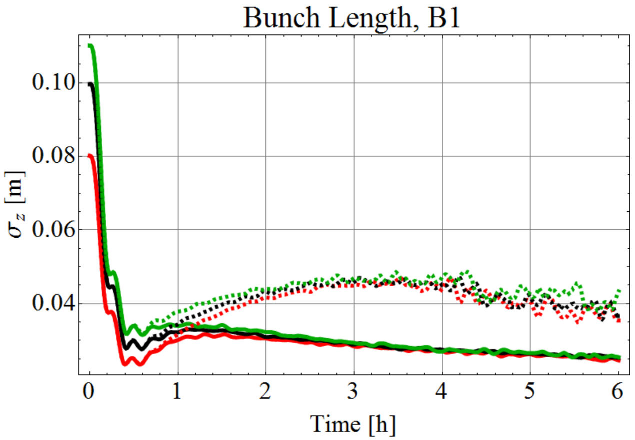
Dashed lines: without coupling
Solid lines: with coupling


Luminosity


Intensity, B1


Horizontal Emittance, B1


Vertical Emittance, B1


Bunch Length, B1