Potential Performance for p-p, Pb-Pb and p-Pb collisions in FCC-hh

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Outline

- General assumptions (lattice and beam parameters)
- Estimates for:
  - IBS and radiation damping
  - Luminosity and beam evolution
  - Beam-beam tune shift

  in p-p, Pb-Pb and p-Pb collisions.
- Conclusions

Smooth Lattice Approximation

Approximations for smooth lattice functions are used where necessary.

100km Circumference

Cell Length from aperture constraints

$$L_c = [1,2]\, L_{c,\mathrm{LHC}} \rightarrow 203\mathrm{m}$$

Assume FODO cell with $\mu = \frac{\pi}{2}$

$$\beta^{\pm} = \frac{L_c(1 \pm \sin\frac{\mu}{2})}{\sin\mu} \propto L_c$$

$$\langle D_x \rangle = \frac{L_c \theta_c}{4}\left(\frac{1}{\sin^2\frac{\mu}{2}} - \frac{1}{12}\right) \propto L_c^2$$

$$L_{Dipoles} = 2\pi\rho_0 = F_{Arc} L_{Arcs}$$

$$L_{Arcs} = N_c L_c = \frac{2\pi}{\theta_c} L_c$$

$$2\pi = \Sigma\theta_{c,i} = N_c \theta_c$$

$$\Rightarrow L_c \theta_c = F_{Arc} \frac{L_c^2}{\rho_0}$$

	Unit	LHC Design	FCC
Cell Length L_c	[m]	106.9	**203**
Arc Filling Factor F_{Arc}	-	0.79	0.79
Average β-function	[m]	[66, 71]	119
Average Dispersion (hor.)	[m]	1.4	1.5
Gamma Transition γ_T	-	55.7	103

Beam Parameters

Parameter	Symbol	Unit	Protons 25 ns	Protons 5 ns	Heavy-Ions Pb-Pb	Heavy-Ions p-Pb
No. of particles per bunch	N_b	$[10^{11}]$	1.0	0.2	0.0014	0.115
Normalised transv. emittance	ϵ_n	$[\mu m]$	2.2	0.44	1.5	3.75
RMS bunch length	σ_s	[m]	0.08	0.08	0.08	0.08
No. of bunches per beam	k_b	-	10600	53000	432	432
β-function at IP	β^*	[m]	1.1	1.1	1.1	1.1
Total cross section	$\sigma_{c,\mathrm{tot}}$	[mb]	153	153	597000	2000
No. of main IPs	-	-	2	2	1	1

Proton baseline parameters taken from
FCC-ACC-SPC-0001, Date 2014-02-11

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

Beam and Luminosity Evolution

During the beams are in collision the instantaneous value of the luminosity will change:

$$\mathcal{L}(t) = A\frac{N_b^2(t)}{\sqrt{\epsilon_x(t)\epsilon_y(t)}}$$

The beam evolution with time is obtained by solving a system of four differential equations:

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\sigma_{c,\mathrm{tot}}A\frac{N_b^2}{\sqrt{\epsilon_x\epsilon_y}}$$ Intensity

$$\frac{\mathrm{d}\epsilon_x}{\mathrm{d}t} = \epsilon_x(\alpha_{\mathrm{IBS},x} - \alpha_{\mathrm{rad},x})$$ Hor. Emittance

$$\frac{\mathrm{d}\epsilon_y}{\mathrm{d}t} = \epsilon_y(\alpha_{\mathrm{IBS},y} - \alpha_{\mathrm{rad},y})$$ Ver. Emittance

$$\frac{\mathrm{d}\sigma_s}{\mathrm{d}t} = \frac{1}{2}\sigma_s(\alpha_{\mathrm{IBS},s} - \alpha_{\mathrm{rad},s})$$ Bunch Length

with

$$A = f_{\mathrm{rev}}k_b/(4\pi\beta^*)$$

- f_{rev} : revolution freq.
- k_b : no. bunches/beam
- β^* : β-function at IP
- N_b : no. particles/bunch
- ϵ : geom. emittances
- σ_s : bunch length

- $\sigma_{c,\mathrm{tot}}$: total cross-section
- α_{IBS} : IBS growth rate
- α_{rad} : rad. damping rate

Analytical solution difficult, due to complicated dependency of α_{IBS} on $N_b, \epsilon_x, \epsilon_y, \sigma_s$.

Effects on the Emittance – a new regime

Intra-Beam Scattering (IBS)

Emittance Growth

Growth rate dynamically changing with **beam properties**:

$$\alpha_{IBS} \propto \frac{r_0^2}{\gamma^4} \boxed{\frac{N_b}{\epsilon_x \epsilon_y \sigma_s \sigma_p}}$$

IBS is weak for initial beam parameters, but increases with decreasing emittance .

Growth Times	Pb	p-p
$1/\alpha_{\mathrm{IBS,s}}$ [h]	29	265
$1/\alpha_{\mathrm{IBS,x}}$ [h]	30	32

(Synchrotron) Radiation Damping

Emittance Shrinkage

Damping rate is **constant** for a given energy:

$$\alpha_{rad} \propto \frac{E^3 C_\alpha}{\rho_0 C_{ring}}$$

$$\frac{\alpha_{\mathrm{rad,FCC}}}{\alpha_{\mathrm{rad,LHC}}} \approx \frac{E^3_{\mathrm{FCC}}/C^2_{\mathrm{FCC}}}{E^3_{\mathrm{LHC}}/C^2_{\mathrm{LHC}}} \approx \frac{7^3}{4^2} \approx 22$$

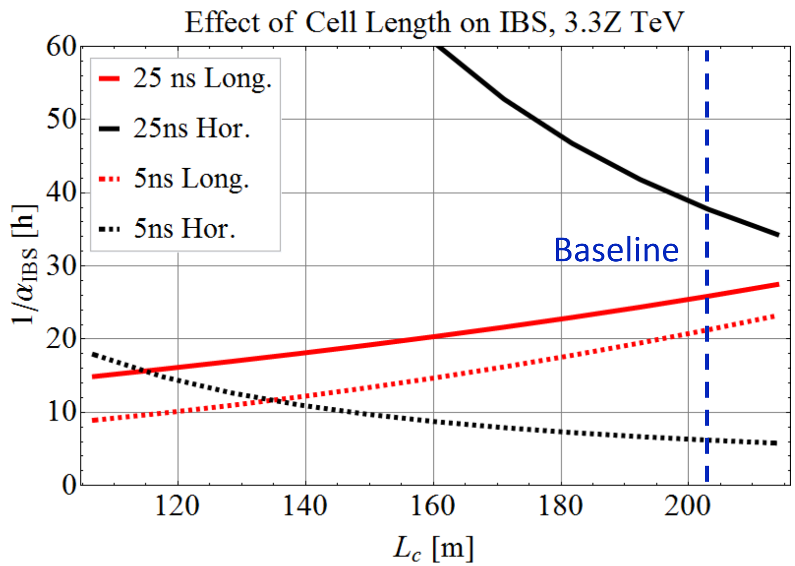
Damping Times	Pb	p-p
$1/\alpha_{\mathrm{rad,s}}$ [h]	0.24	0.5
$1/\alpha_{\mathrm{rad,x}}$ [h]	0.49	1.0

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

Proton-Proton Operation

p-p: Intra-Beam Scattering

Variation of IBS growth times for **initial beam conditions** with FODO cell length.



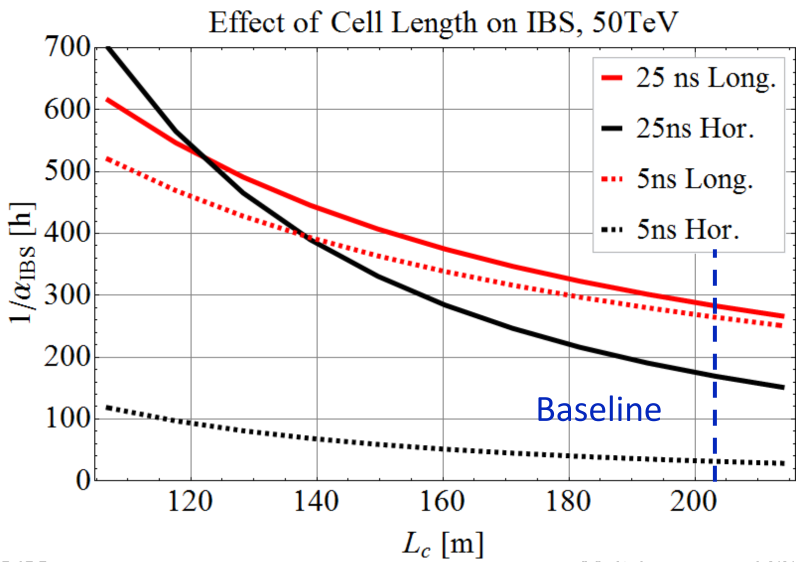
@ Injection:

- 25ns beam moderate growth times > 15h.
- 5ns beam more critical

→ rates for baseline lattice:

$1/\alpha_{\mathrm{IBS},s} = 21\mathrm{h}$

$1/\alpha_{\mathrm{IBS},x} = 6\mathrm{h}$

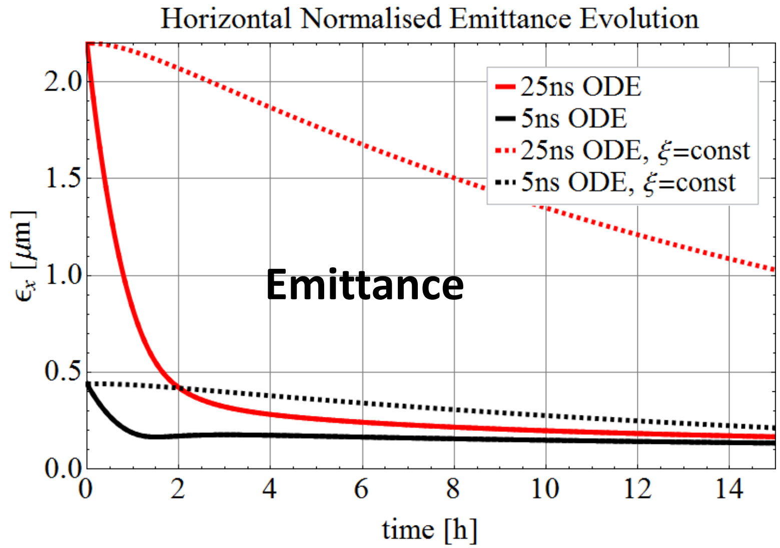


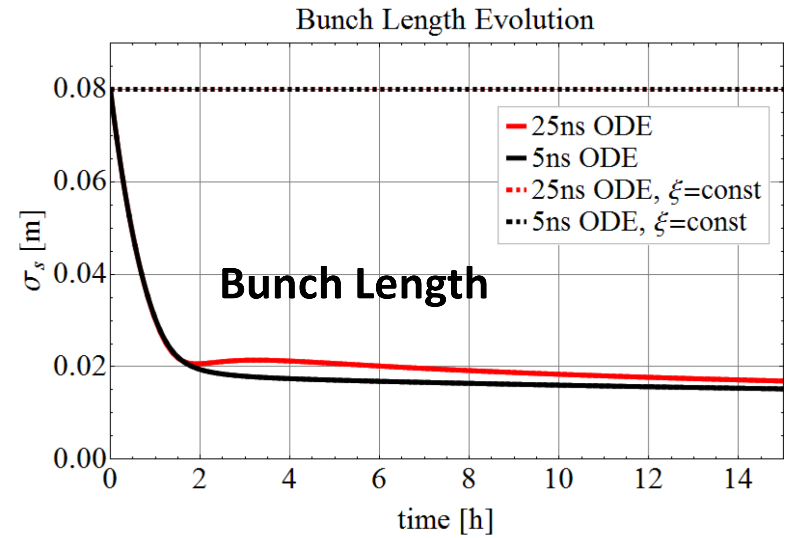
@ 50TeV:

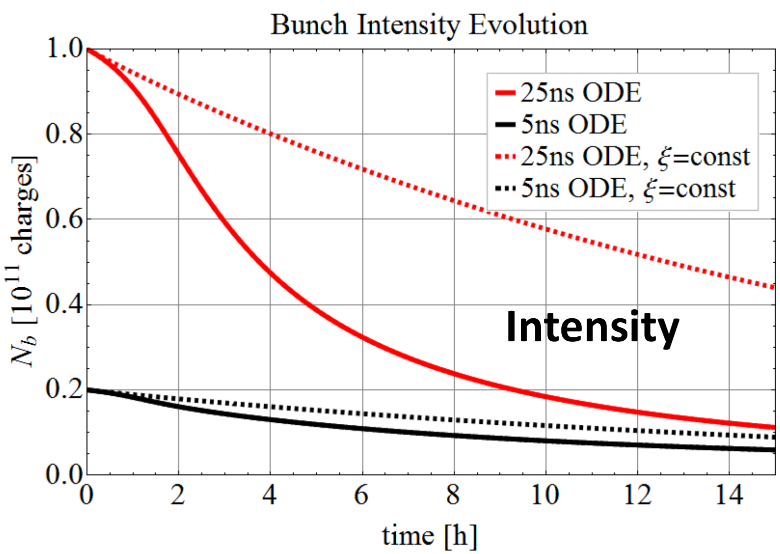
- negligible rates
- strongest effect for 5ns hor.

$1/\alpha_{\mathrm{IBS},x} = 31\mathrm{h}$

p-p: Beam Evolution







- *2 experiments are in collisions*
- *Full coupling = equal transv. emittances.*
- Solid lines: free beam evolution.
  → Balanced regime of IBS and rad. damping after ~2h.
- Dashed lines:
  → beam-beam tune-shift ξ=const.
  → modified ODE with artificial emittance blow-up:

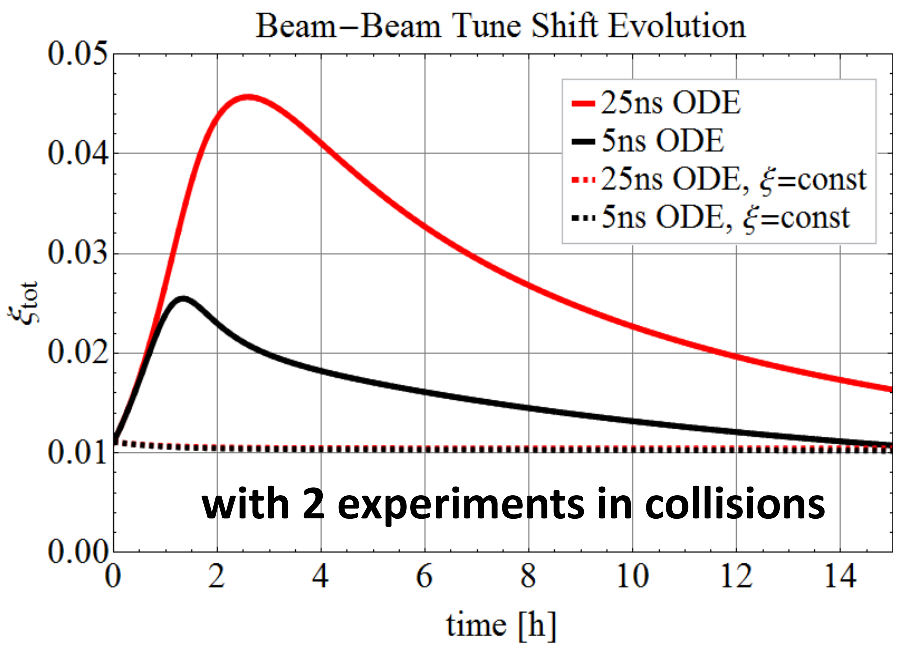
$$\frac{d\epsilon}{dt} = \alpha_{\mathrm{IBS},x}\,\epsilon - \alpha_{\mathrm{rad},x}\left(\epsilon - \frac{N_b}{N_{b0}}\epsilon_0\right)$$

$$\frac{d\sigma_s}{dt} = 0,$$

p-p: Beam-Beam Tune Shift

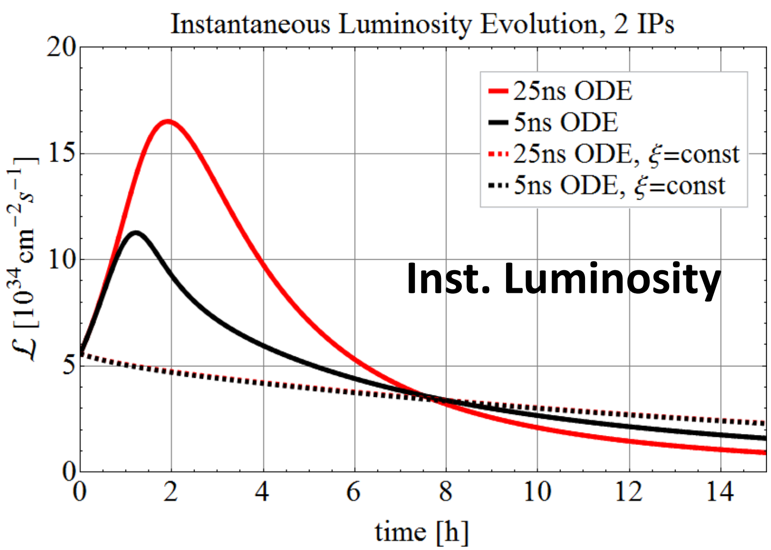
Beam-beam tune shift per experiment:

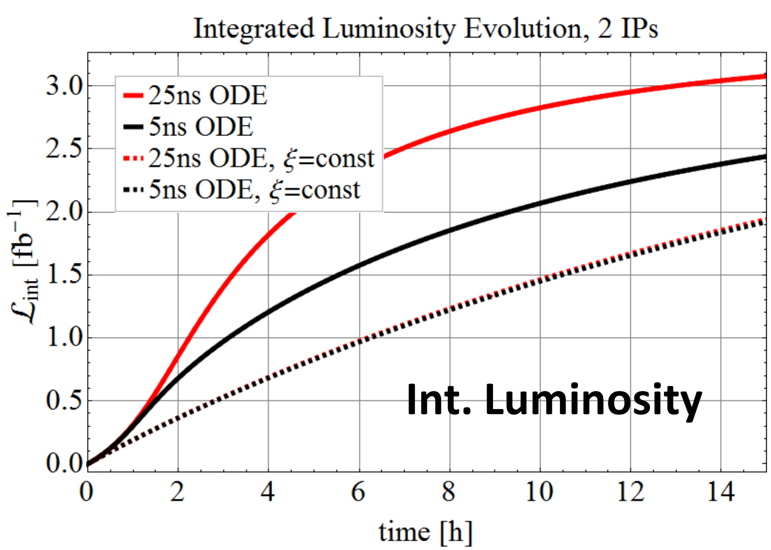
$$\xi = \frac{N_b r_0}{4\pi\epsilon_n}$$



- Total tune shift can go up to ~**5 times the expected limit** in case of 25ns beam.
- Peak for 5ns beam at $\xi = 2.5 \times$ limit
- **With artificial longitudinal and transverse blow-up ξ = const.= limit.**

p-p: Luminosity Evolution





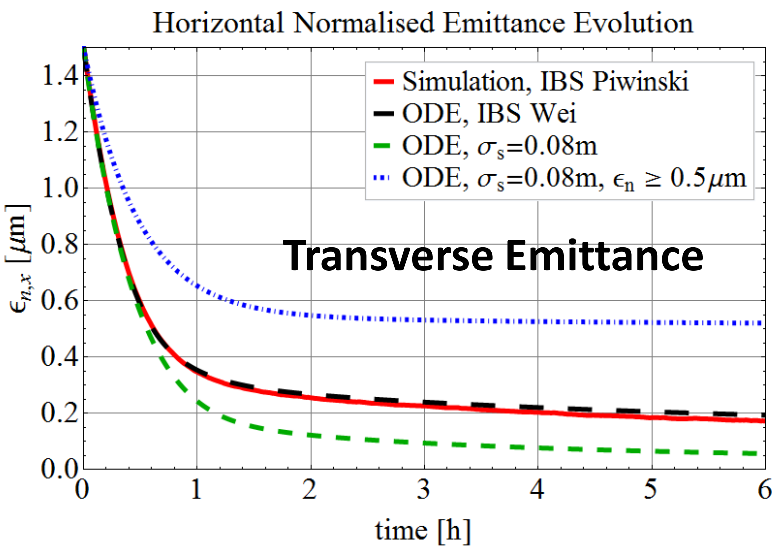
- Solid lines: free beam evolution
  → **Increasing luminosity** due to shrinking emittances!
- Dashed lines: beam-beam tune-shift ξ=const.
  → **Luminosity decrease** due to intensity burn-off:

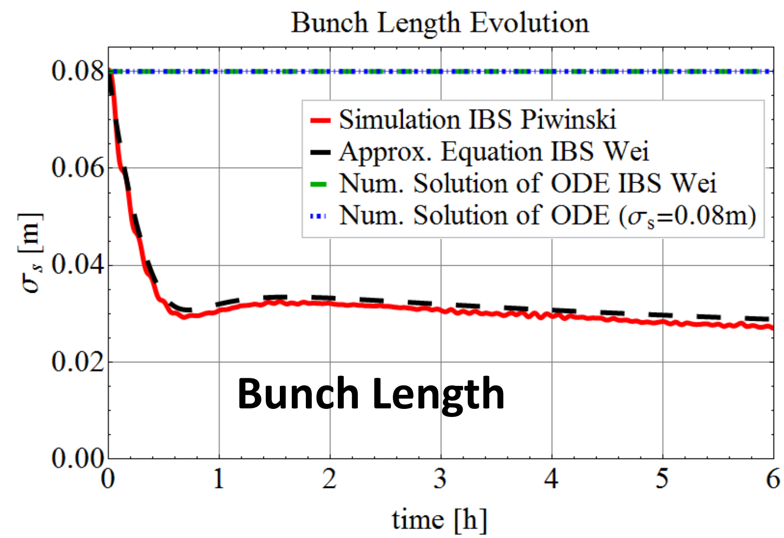
$$\mathcal{L} \propto \frac{N_b^2}{\epsilon} \propto N_b\, \xi$$

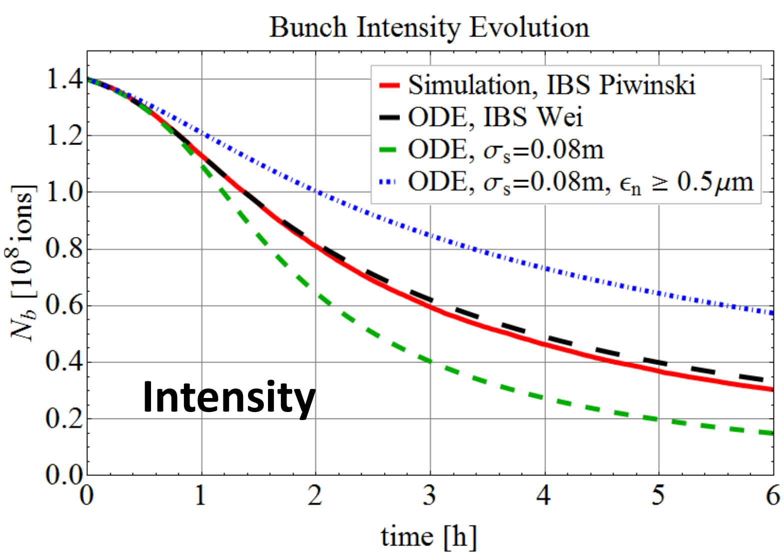
- If operation with max. ξ is possible the **integrated luminosity could be increased** by ~**30% (5ns) to 70% (25ns)** in a 12h fill.

Heavy-Ion Operation

Pb-Pb: Beam Evolution (1 Experiment)



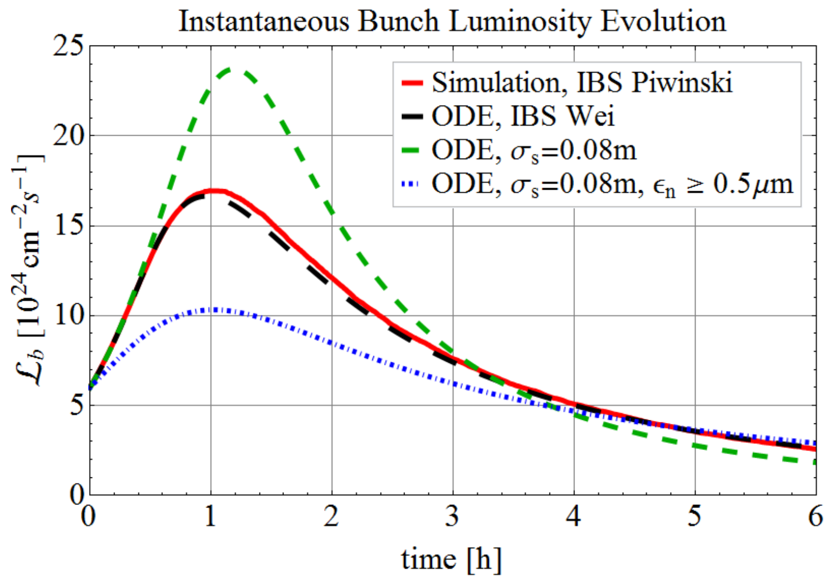




- **Red: tracking simulation** taking into account IBS, rad. damping, burn-off, …
- **Black:** numerical solution of the ODE system on slide 7, using J. Wei's analytical IBS formalism*.
  → emittances and bunch length become very small!
- **Green:** $d\sigma_s/dt = 0$: artificial longitudinal blow-up to σ_s = 8cm.
- **Blue:** artificial longitudinal and transverse blow-up to σ_s = 8cm and $\epsilon_n \geq 0.5\mu m$.

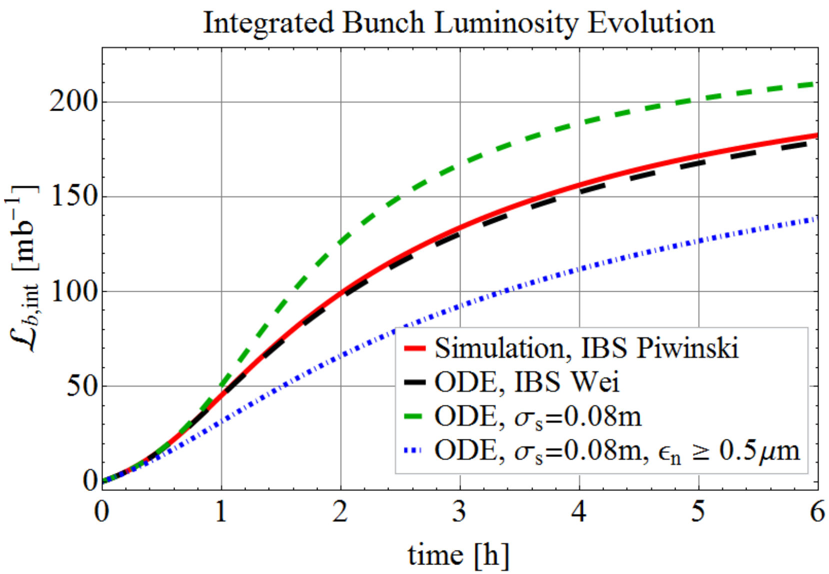
*J. Wei: *Evolution of Hadron Beams under Intrabeam Scattering*, Conf.Proc. C930517 (1993) 3651-3653, PAC 1993.

Pb-Pb: Luminosity Evolution (1 Experiment)



If the beam dimensions become too small and artificial blow-up has to be used, the luminosity will be affected:

- **Peak Enhancement for long. blow-up**, since long. and horizontal IBS are reduced, due to larger σ_s → smaller ϵ_n.
- **Reduced luminosity**, due to blown-up ϵ_n.

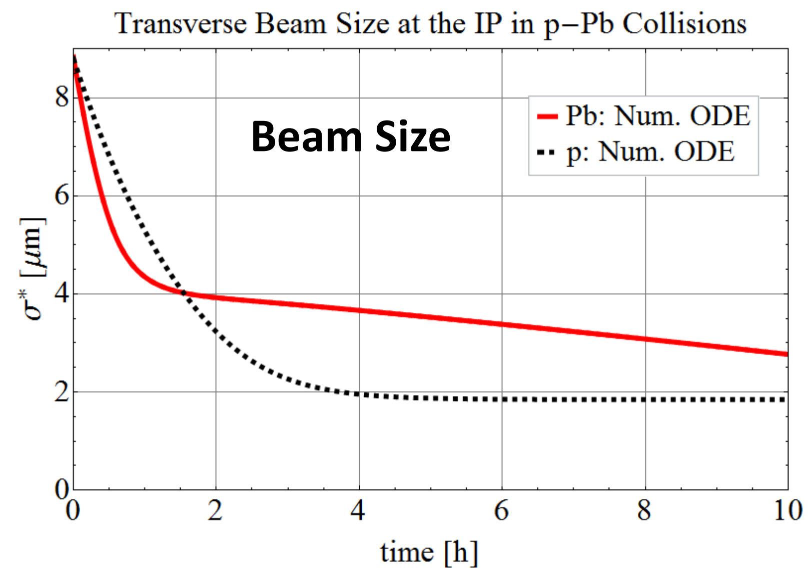


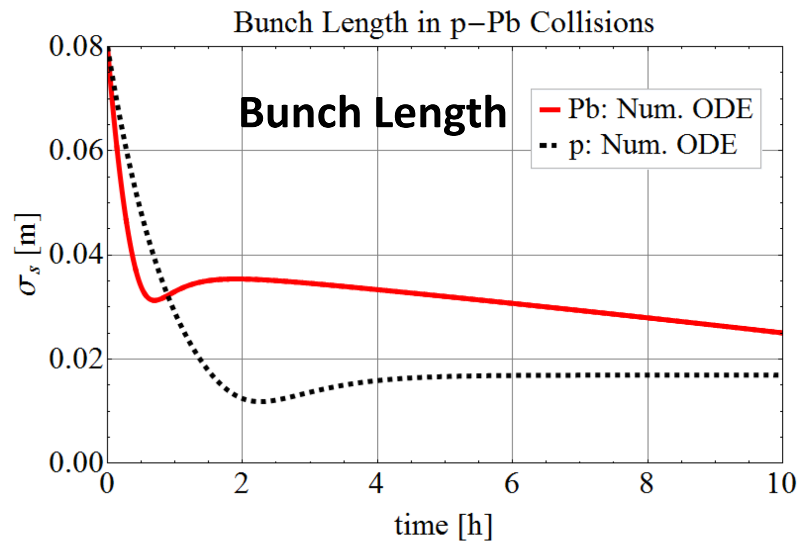
Summary for free beam evolution

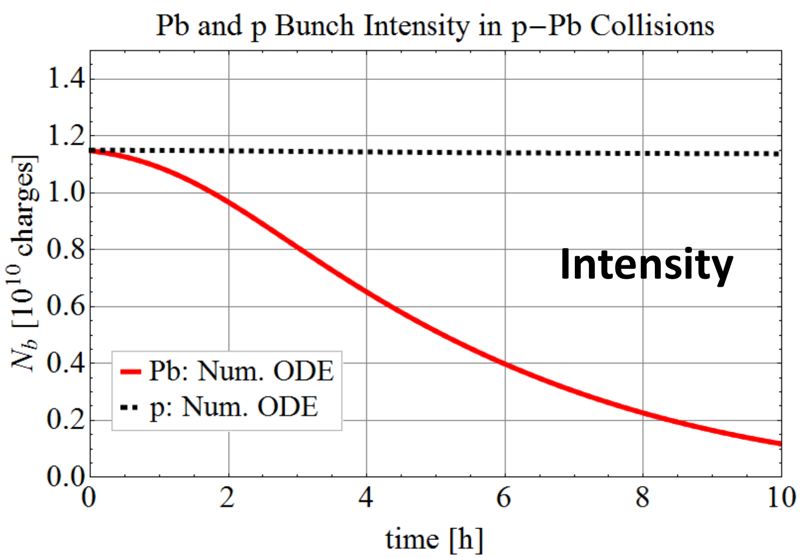
(no artificial blow-up)

	Unit	per Bunch	whole Beam
L_{initial}	[Hz/mb]	0.006	2.6
L_{peak}	[Hz/mb]	0.017	7.3
$L_{\mathrm{int,fill}}$	[μb^{-1}]	0.13	57.8

p-Pb: Beam Evolution (1 Experiment)



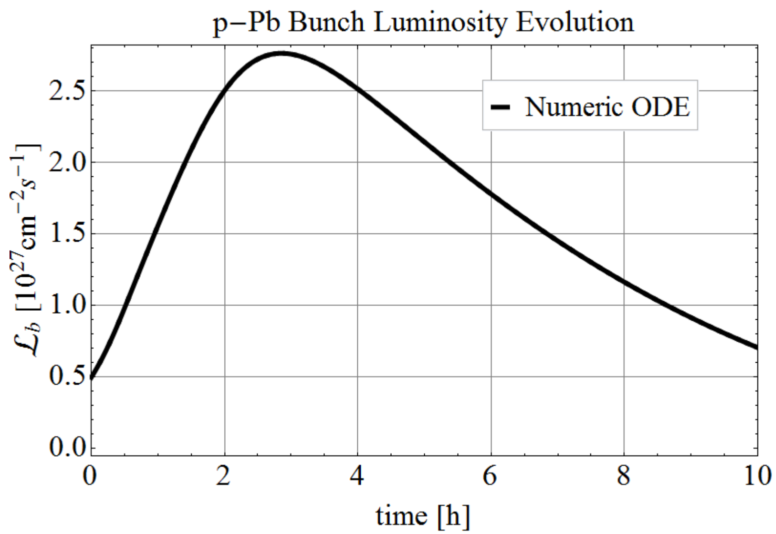




Initial conditions:

- Pb-beam as for Pb-Pb operation.
- Equal beam sizes, σ*, for p and Pb.
- Rad. damping $\propto Z^5/A^4 \approx 2$
  $\rightarrow 2\alpha_{rad}(p) \approx \alpha_{rad}(Pb)$
- IBS scales with $\propto (Z^2/A)^2 N_b$
- $N_b(\mathrm{p}) \approx 100\ N_b(Pb)$
  → Fast Pb burn-off, while
  $N_b(\mathrm{p}) \approx$ const.

p-Pb: Luminosity Evolution (1 Experiment)



Peak shifted to later times

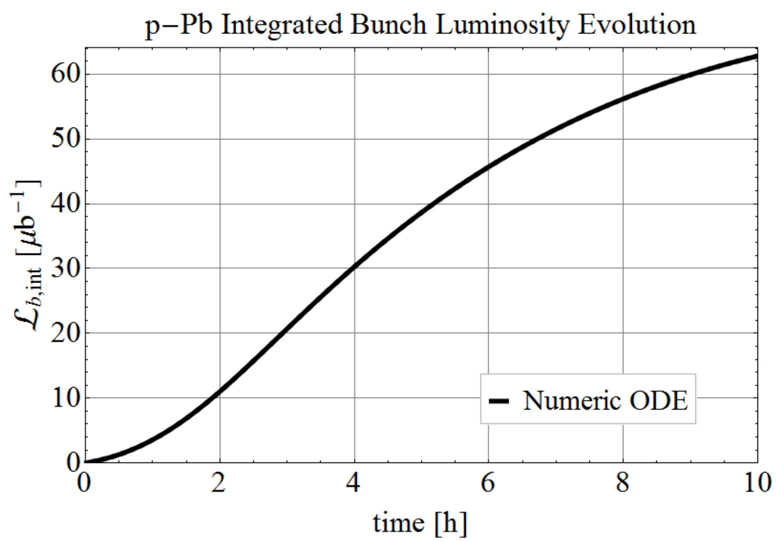
→ p shrinks slower than Pb

$$2\alpha_{rad}(p) \approx \alpha_{rad}(Pb)$$

Luminosity decays slower

→ N_b(p) ≈ const.

→ 1/e-Luminosity lifetime ≈ 14h.

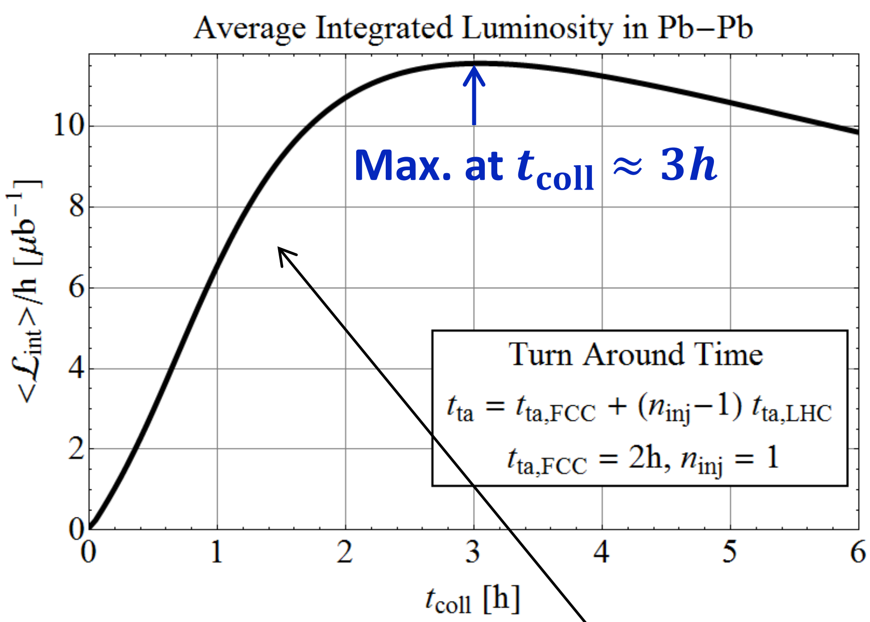


	Unit	per Bunch	whole Beam
L_{initial}	[Hz/mb]	0.5	213
L_{peak}	[Hz/mb]	2.8	1192
$L_{\text{int,fill}}$	[μb^{-1}]	48.7	21068

Average Luminosity

Average Luminosity per hour:

$$\langle \mathcal{L}_{\text{int}} \rangle = \frac{1}{t_{\text{coll}} + t_{\text{ta}}} \int_0^{t_{\text{coll}}} \mathcal{L}_{\text{inst}}(t) \text{d}t$$



t_{coll} = time in collisions → *to be optimised*

For free beam parameter evolution, red case in Pb-Pb

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

= turn-around time

= time dump → next collisions

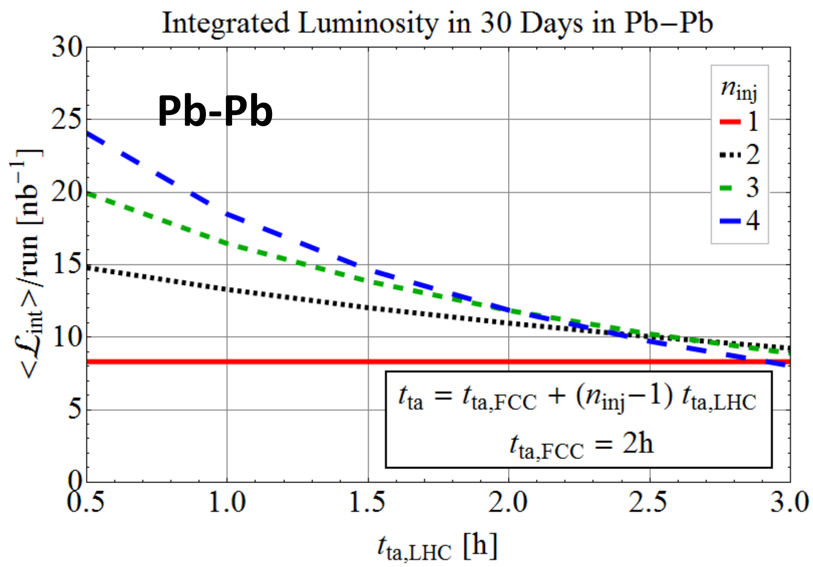
Assumption $t_{ta,FCC} = 2h$ (cycle time FCC, without injections)

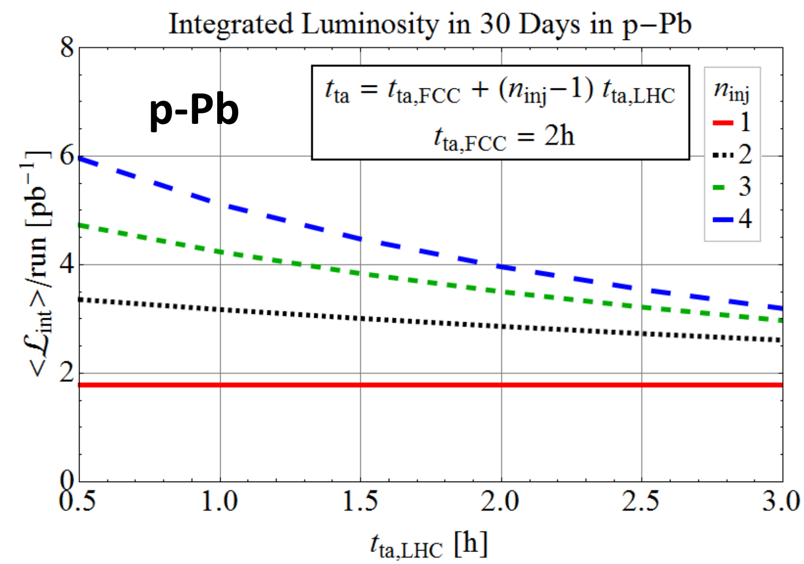
$n_{inj} = 1$ (no. injections from LHC)

Heavy-Ion Integrated Luminosity per Run

- **Consider more LHC injections**:
  → max. $\boldsymbol{n_{inj} = 4}$ (= FCC Length)
  → Dwell time at FCC inj. plateau
    → lengthen
    $$t_{\text{ta}} = t_{\text{ta,FCC}} + (n_{\text{inj}} - 1)t_{\text{ta,LHC}}$$
  → Particle losses (& emittance growth)
    → Loss rate of Pb at injection: $R_{\text{loss}} = 5\%$
    → Total beam intensity:
    $$N_{\text{beam}} = k_b N_b \sum_{i=1}^{n_{\text{inj}}} (1 - R_{\text{loss}} t_{\text{ta}} (i-1))$$

  → <$\mathcal{L}_{\text{int}}$> □ $(N_{beam}/k_b N_b)^2 \times$ <$\mathcal{L}_{\text{int}}$>





- **Optimised fill length ($\boldsymbol{n_{inj} = 1}$):**
  - Pb-Pb: 3h → <$\mathcal{L}_{\text{int}}$>/run ≈ 8nb^{-1}
  - p-Pb: 6.5h → <$\mathcal{L}_{\text{int}}$>/run ≈ 1700nb^{-1}
- **Uncertainty** on prediction significantly enhanced for $\boldsymbol{n_{inj} > 1}$
  → Early beam aborts and longer inj. times

Conclusions

Strong rad. damping: **small emittances and bunch length**

→ **Effective intensity burn-off**.
→ But high beam-beam tune shift in p-p ($5 \times limit$).
→ Artificial blow-up could be used as levelling method to keep **beam-beam tune shift below limit,** but **significant reduction of potential luminosity outcome**.
→ If operation with max. beam-beam tune shift is possible **int. luminosity +70%** with equal initial beam parameters.

Reduce turn around time!

→ Significant luminosity increase for heavy-ion operation

Potential performance of Pb-Pb and p-Pb presented at:

- Ions at the Future Hadron Collider, 16-17 Dec. 2013, CERN.
  → *https://indico.cern.ch/event/288576/timetable/#20131216*
- FCC Study Kickoff Meeting, 12-15 Feb. 2014, Geneva.
  → *https://indico.cern.ch/event/282344/timetable/#20140212*
- Ions at the Future Circular Collider, 22-23 Sep. 2014, CERN.
  → *https://indico.cern.ch/event/331669/timetable/#20140922*

Report covering Pb-Pb, p-Pb and p-p is in preparation…

THANK YOU
FOR YOUR ATTENTION

FCC-hh Storage Ring Parameters

	Unit	LHC Design	FCC Injection	FCC Collision
Geometry and Main Magnets				
Circumference	[km]	26.659	100	
Field of main bends	[T]	8.33	1.0	16
Bending radius	[m]	2803.95	10424	
Example Lattice				
Cell length	[m]	106.9	203	
Gamma transition γ_T		55.7	103	
RF System				
Revolution frequency	[kHz]	11.245	2.998	
RF frequency	[MHz]	400.8	400.8	
Harmonic number		35640	133692	
Total RF Voltage	[MV]	16	13	32
Synchrotron frequency	[Hz]	23.0	8.4	3.4
Bucket height $(\Delta E/E)$	$[10^{-4}]$	3.56	4.5	1.8
Bucket area	[eVs/charge]	8.0	4.7	28.6

Heavy-Ion Beam Parameter Summary

	Unit	LHC Design	FCC Injection	FCC Collision	FCC Collision
General Beam Parameters					
Operation mode	-	Pb-Pb	Pb	Pb-Pb	p-Pb
Beam energy	[TeV]	574	270	4100	50
Relativistic γ-factor		2963.5	1397	21168	53290
No. of bunches	-	592	432		
No. of particles per bunch	[10^8]	0.7	1.4		115
Transv. norm. emittance	[μm.rad]	1.5	1.5		3.75
RMS bunch length	[cm]	7.94	10.0	8.0	
RMS energy spread	[10^{-4}]	1.1	1.9	0.6	
Long. emittance (4σ)	[eVs/charge]	2.5	2.6	10.1	
Circulating beam current	[mA]	6.12	2.38		
Stored beam energy	[MJ]	3.8	2.6	39.8	
Intra Beam Scattering					
Long. IBS emit. growth time	[h]	7.7	6.2	29.2	4×10^3
Hor. IBS emit. growth time	[h]	13	10.0	30.0	4×10^3
Synchrotron Radiation					
Long. emit. rad. damping time	[h]	6.3	852	0.24	0.5
Hor. emit. rad. damping time	[h]	12.6	1704	0.49	1.0
Power loss per ion	[W]	2.0×10^{-9}	1.1×10^{-11}	5.7×10^{-7}	3.4×10^{-9}
Power loss per meter in main bends	[W/m]	0.005	1.0×10^{-5}	0.53	0.26
Energy loss per ion per turn	[MeV]	1.12	0.01	775.3	4.7
Synchrotron radiation power per ring	[W]	83.9	0.7	34389	17016
Critical photon energy	[eV]	2.77	0.08	269.3	4300.8

Heavy-Ion Luminosity Summary

	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

Intra-Beam Scattering

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

$$\alpha_{IBS,s} = \left\langle A \frac{\sigma_h^2}{\sigma_p^2} f(a,b,q) \right\rangle$$

$$\alpha_{IBS,x} = \left\langle A \left[f\left(\frac{1}{a}, \frac{b}{a}, \frac{q}{a}\right) + \frac{D_x^2 \sigma_h^2}{\sigma_{x\beta}^2} f(a,b,q) \right] \right\rangle$$

$$\alpha_{IBS,y} = \left\langle A \left[f\left(\frac{1}{b}, \frac{a}{b}, \frac{q}{b}\right) + \frac{D_y^2 \sigma_h^2}{\sigma_{y\beta}^2} f(a,b,q) \right] \right\rangle$$

Lattice and beam sizes

Particle Type

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

Energy

Beam properties

IBS strength changes dynamically with beam properties.

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

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

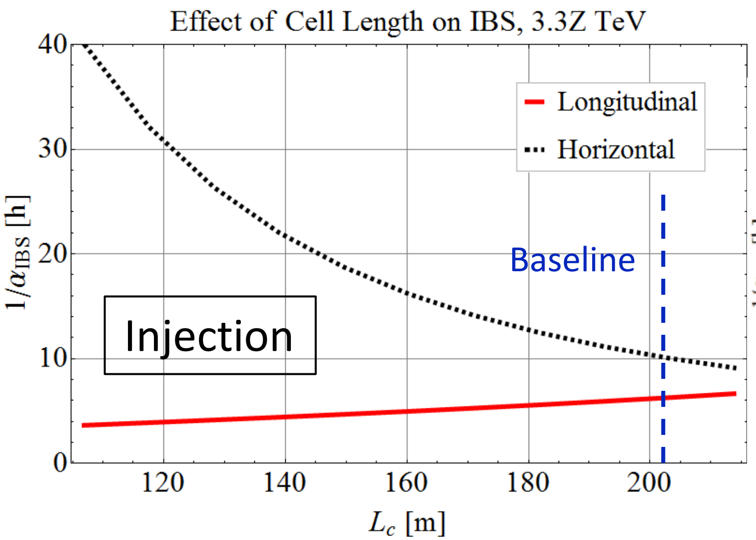
$$q = \sigma_h \beta \sqrt{\frac{2d}{r_0}}, \quad P^2 = a^2 + (1-a^2)u^2, \quad Q^2 = b^2 + (1-b^2)u^2$$

$$a = \frac{\sigma_h \beta_x}{\gamma \sigma_{x\beta}}, \quad b = \frac{\sigma_h \beta_y}{\gamma \sigma_{y\beta}}$$

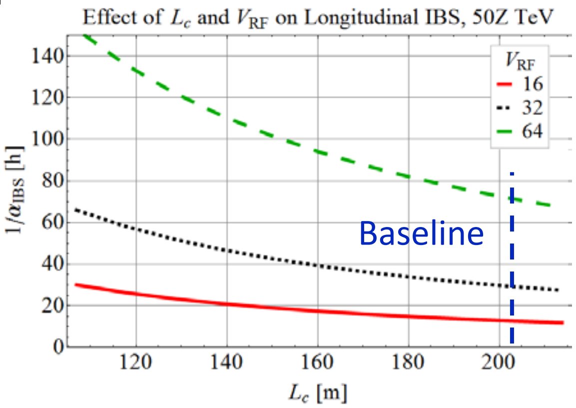
Handbook of Accelerator Physics and Engineering, 1st Edition, 3rd Print, pp. 141

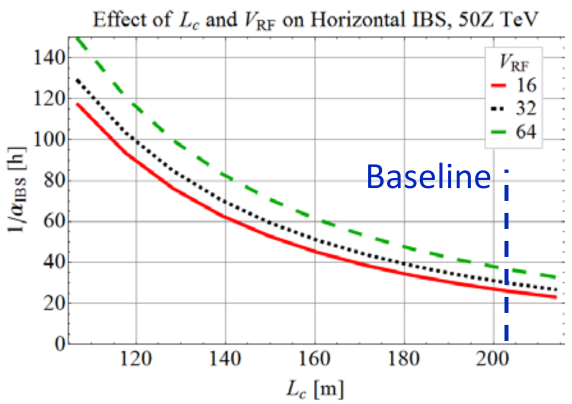
Pb: Intra-Beam Scattering

Variation of IBS growth times for **initial beam conditions** with FODO cell length.



Collision Energy





Effect of long. (hor.) IBS decreases (increases) with increasing cell length at injection energy.
At collision energy, IBS is weak for initial beam parameters.

Growth Times	Unit	LHC Design	FCC injection	FCC collision
$1/\alpha_{\mathrm{IBS,s}}$	[h]	7.7	10.0	30.3
$1/\alpha_{\mathrm{IBS,x}}$	[h]	13	6.2	29.2

Radiation Damping

Damping Rates

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

$$\alpha_{rad,x} = E^3 C_\alpha \frac{\mathcal{I}_2}{C_{ring}} \left(1 - \mathcal{I}_{4,x}/\mathcal{I}_2\right)$$

$$\alpha_{rad,y} = E^3 C_\alpha \frac{\mathcal{I}_2}{C_{ring}} \left(1 - \mathcal{I}_{4,y}/\mathcal{I}_2\right)$$

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

$$\mathcal{I}_2[m^{-1}] = \oint \left(\frac{1}{\rho_x^2} + \frac{1}{\rho_y^2}\right) ds$$

$$\mathcal{I}_{4,u}[m^{-1}] = \oint \frac{D_u}{\rho_u^3}(1 \pm 2\rho_0^2 k) ds$$

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

$$\mathcal{I}_2 \approx \frac{2\pi}{\rho_0}$$

$$\mathcal{I}_{4,x} \approx 2\pi \frac{D_x}{\rho_0^2} \approx 0$$

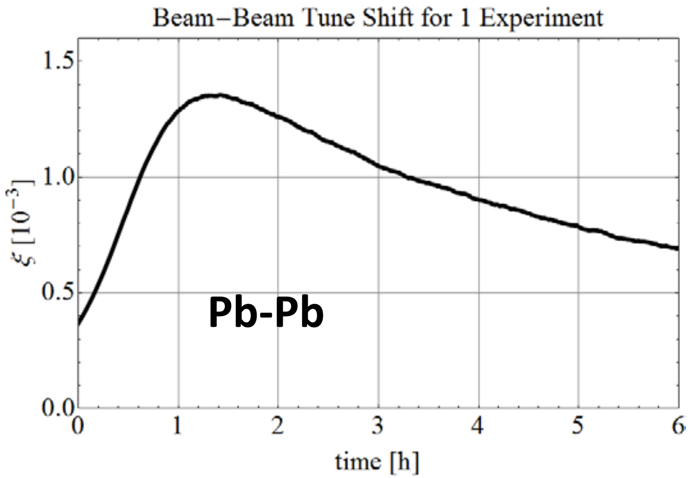
$$\mathcal{I}_{4,y} \approx 0$$

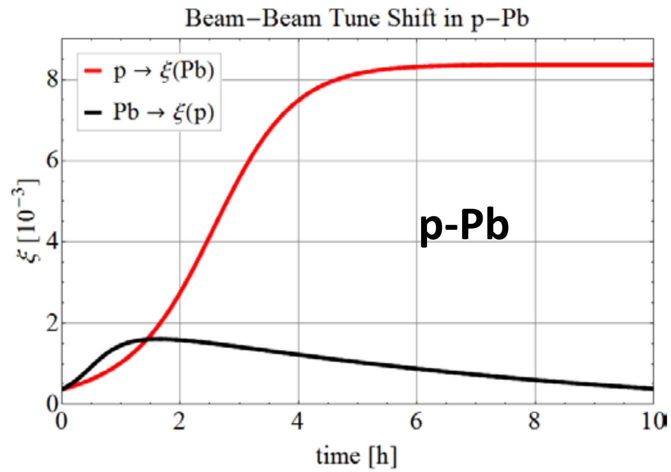
Heavy-Ion: Beam-Beam Tune Shift

Beam-beam tune shift per experiment:

- Beam *m* receives kick from Beam *n*
- *u,v =x, y*

$$\xi_{m,u} = \frac{N_{b,n} r_{p0} Z_m Z_n \beta^*}{2\pi A_m \gamma_m \sigma_{n,u}(\sigma_{n,u} + \sigma_{n,v})}$$





Beam-Beam Parameter per Experiment	Unit	LHC Design p-p	LHC Design Pb-Pb	FCC Pb-Pb	FCC p-Pb
Initial	$[10^{-3}]$	3.7	0.18	0.37	0.37
Peak	$[10^{-3}]$	3.7	0.18	1.4	8.3

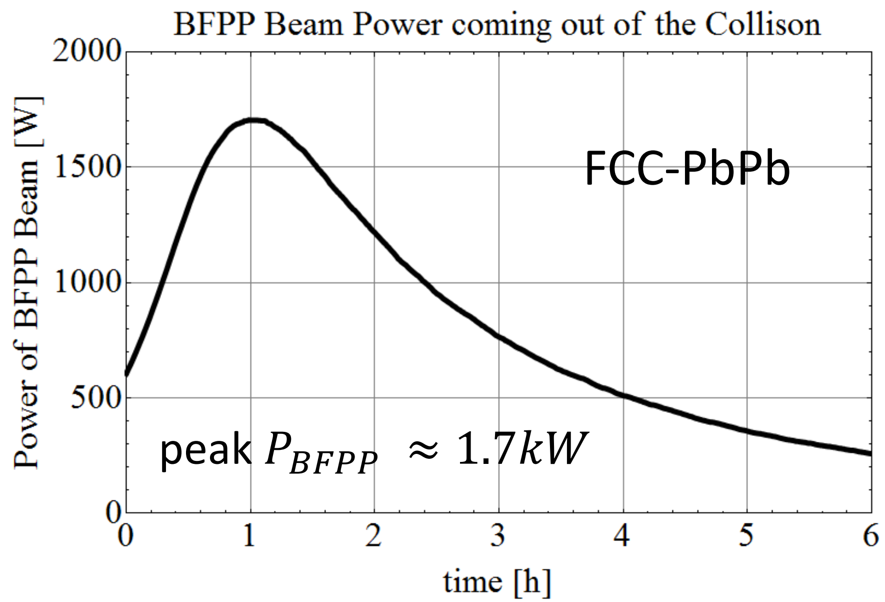
The tune shift due to beam-beam interactions remains well below assumed limit for Pb-Pb, but comes close to the limit for Pb in p-Pb collisions.

BFPP Beam Power

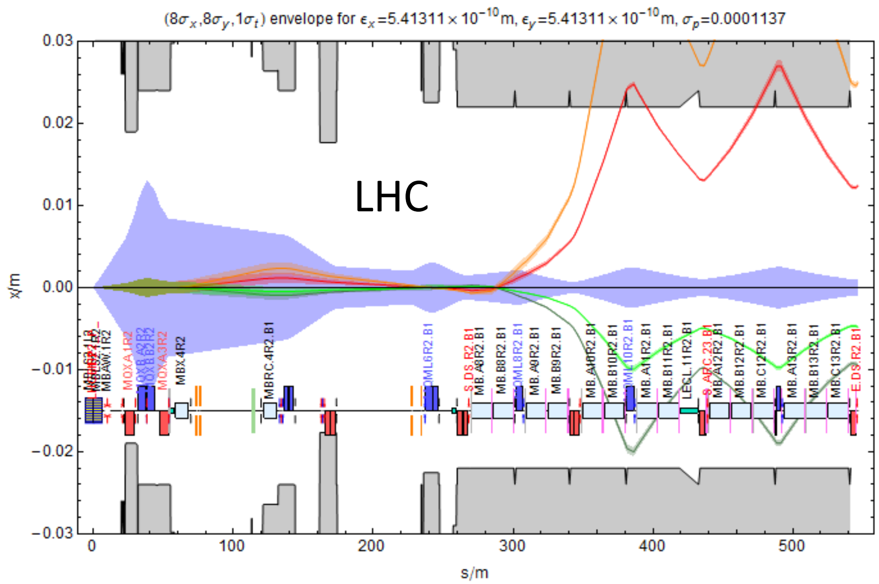
EMD: Electromagnetic dissociation
$BFPP$: Bound-free pair production

Main contribution to fast Pb-Pb burn-off:

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



Example: LHC Pb beam right of IP2



Main: 208-Pb-82+

BFPP1: 208-Pb-81+
BFPP2: 208-Pb-80+

EMD1: 207-Pb-82+
EMD2: 206-Pb-82+

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

Smaller Z Ions – Impact on Luminosity

- 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:
  - o $\sigma_{\mathrm{BFPP}} \propto Z^7$
  - o $\sigma_{\mathrm{EMD}} \propto Z^4$
  - ➢ 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:
  - o $\alpha_{\mathrm{rad}} \propto Z^5/A^4$