



CLIC Luminosity Challenges at 380 GeV

CLIC Project Meeting

June 15, 2021

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Key Parameters



Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	\sqrt{s}	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	\mathcal{L}	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of \sqrt{s}	$\mathcal{L}_{0.01}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Charge per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x / σ_y	nm	149/2.9	$\sim 60/1.5$	$\sim 40/1$
Normalised emittance (end of linac)	ϵ_x / ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x / ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

Can re-write normal luminosity formula

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} \underbrace{N n_b f_r}_{\text{Beam current}} \frac{1}{\sigma_y}$$

↑ Luminosity spectrum
 ↑ Beam current
 ↑ Beam Quality (+bunch length)

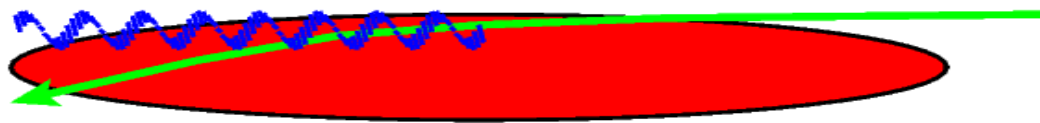
Need to ensure that we can achieve each parameter



Beam-beam Effect



$$\mathcal{L} \propto H_D \left(\frac{N}{\sigma_x} \right) N n_b f_r \frac{1}{\sigma_y}$$



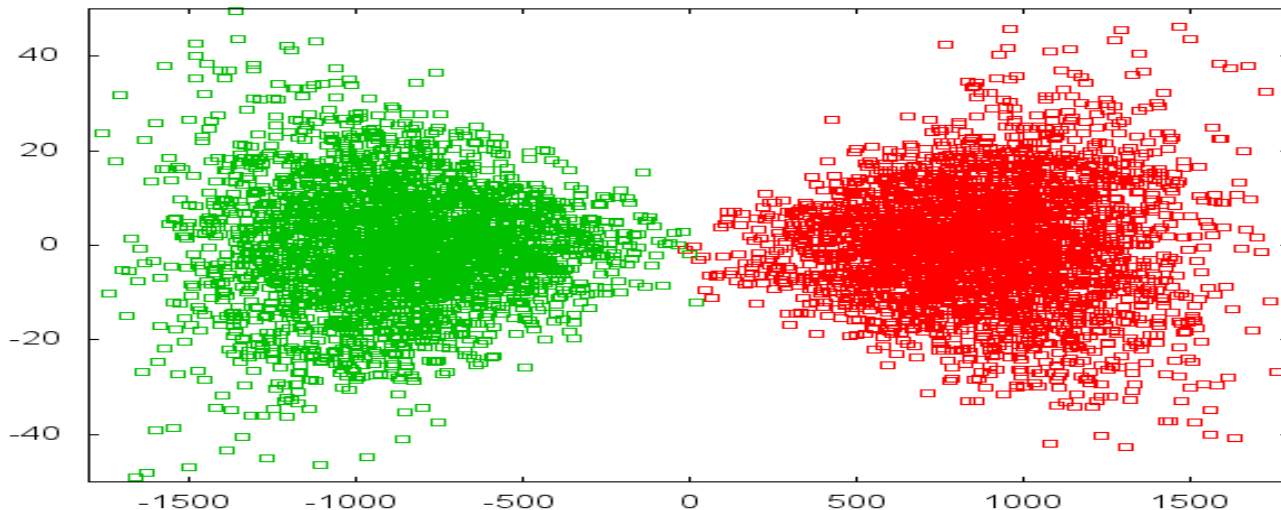
Dense beams to reach high luminosity
Beam focus each other

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

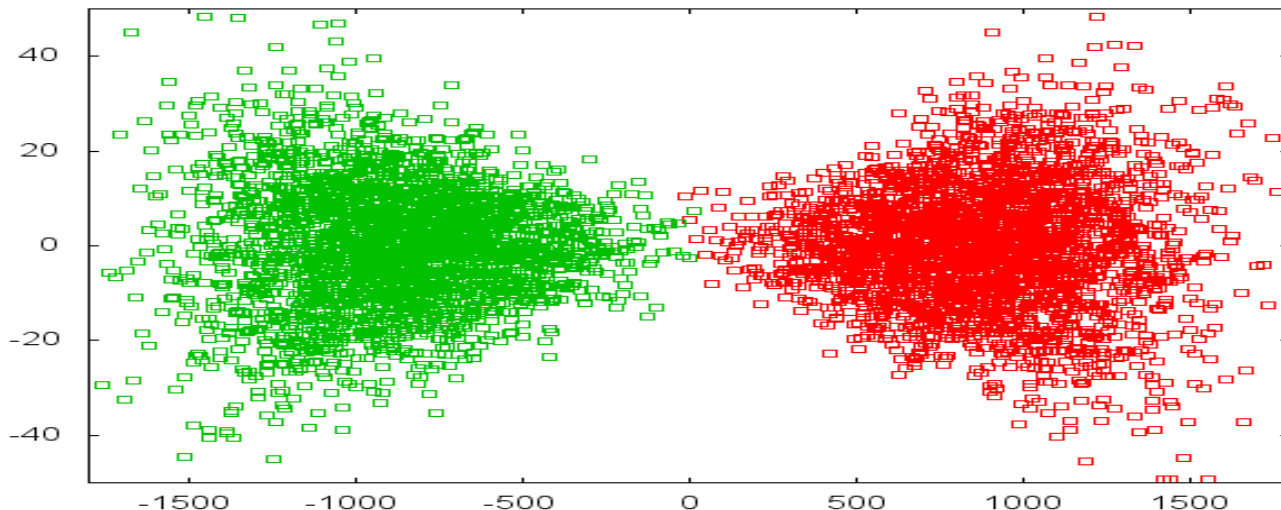
$$\sigma_x \gg \sigma_y \quad \sigma_x + \sigma_y \approx \sigma_x$$

Y direction [nm]

Beam-beam force off



Beam-beam force on



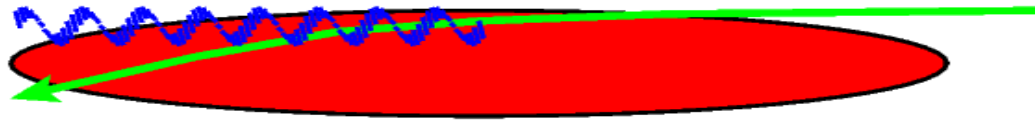
Z direction [μm]



Beam-beam Effect

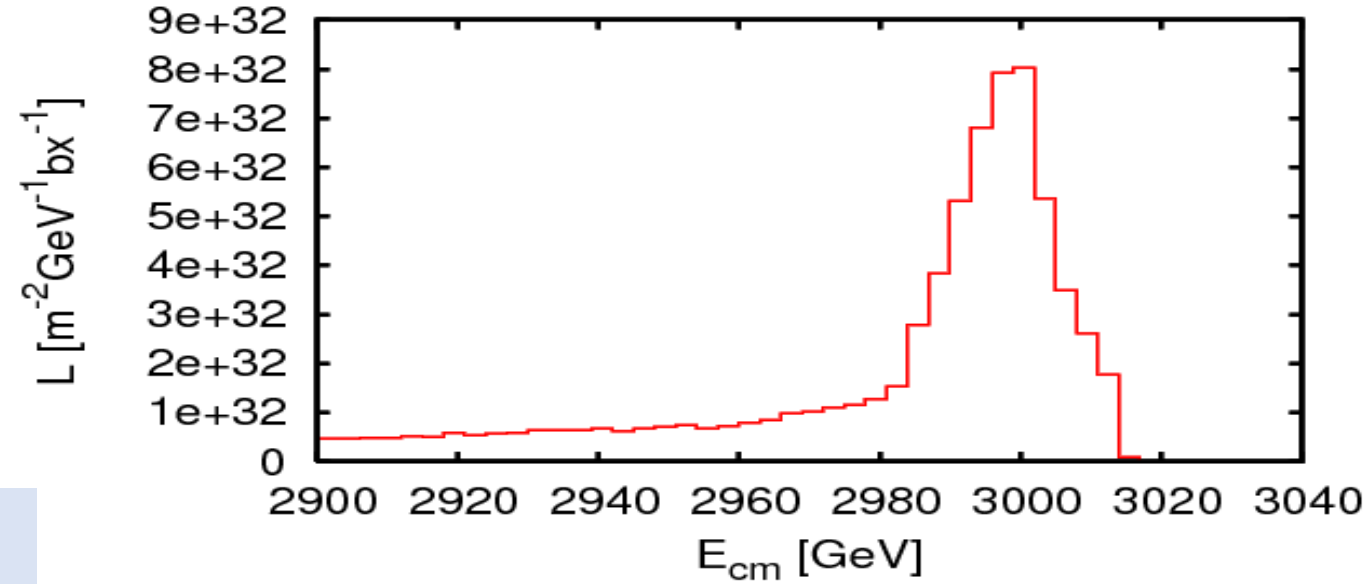


$$\mathcal{L} \propto H_D \left(\frac{N}{\sigma_x} \right) N n_b f_r \frac{1}{\sigma_y}$$



Emitt beamstrahlung

Develop luminosity spectrum

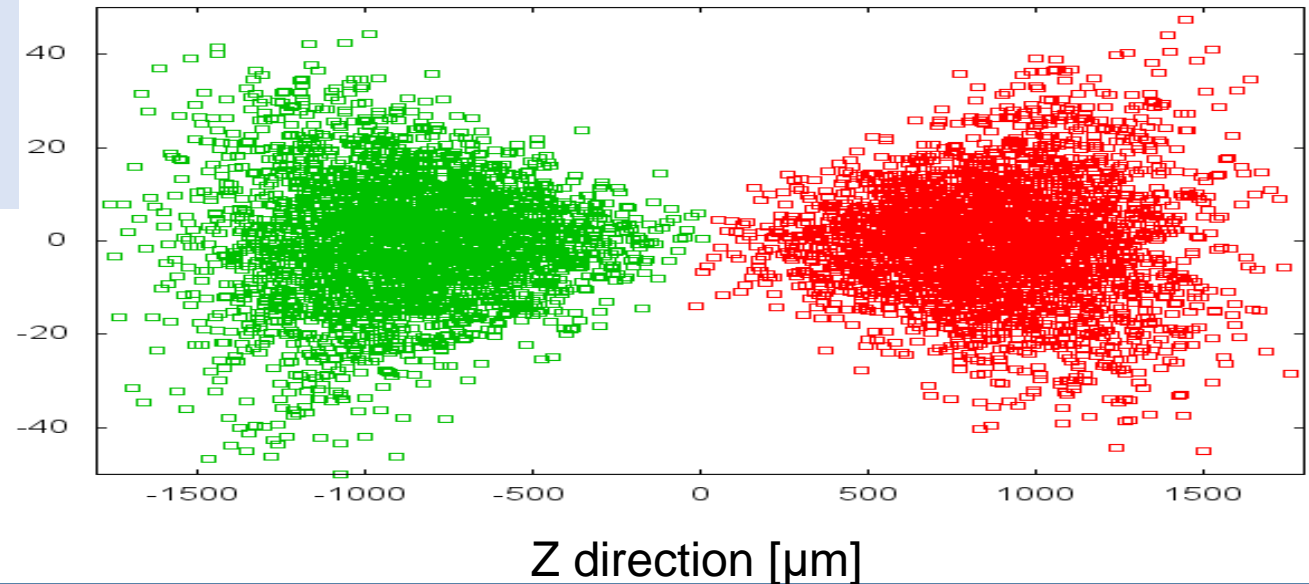


$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

Aim for O(1) at 380 GeV
yields 60% in peak and
fixes N/σ_x

$$n_\gamma \propto E_\gamma \propto \frac{1}{\sigma_x + \sigma_y}$$

$$\sigma_x \gg \sigma_y \quad \sigma_x + \sigma_y \approx \sigma_x$$



Can re-write normal luminosity formula

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

The limit for N is the beam stability in the main linac for n_b the RF pulse length

only f_r can be modified

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} \underbrace{N n_b f_r}_{\text{Beam current}} \frac{1}{\sigma_y}$$

Luminosity spectrum Beam current Beam Quality (+bunch length)

Look at beam quality first



Luminosity and Beam Quality



$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \left(\frac{1}{\sigma_y} \right) \sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Damping ring main source of horizontal emittance
But value is OK, as we will see

	$\Delta\epsilon_x$ [nm]		$\Delta\epsilon_y$ [nm]	
	Total contribution	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	700	5	0	0
End of RTML	150	1	2	2
End of main linac	50	0	5	5
Interaction point	50	0	5	5
sum	950	6	12	12

Imperfections are the main source of final vertical emittance

Require 90% likelihood to meet static emittance growth target in each area
We only have one machine

Average dynamic emittance growth should meet target
we integrate over many cases



Luminosity Scaling



No imperfections: $\sqrt{30/6} \times L_0 = L = 3.35 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Only static imperfections: $\sqrt{30/18} \times L_0 = L = 1.94 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

All but dynamic in BDS: $\sqrt{30/25} \times L_0 = L = 1.65 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

All imperfections: $\sqrt{30/30} \times L_0 = L = 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

	$\Delta\epsilon_x$ [nm]	$\Delta\epsilon_y$ [nm]		
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sum	950	6	12	12

Due to disruption the luminosity actually increases faster as the emittance decreases

But the sensitivity to dynamic imperfections increases also faster



Maximum Luminosity



No imperfections

Simple scaling

$$L = \sqrt{30/6} \times L_0 = 3.35 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Simulation

$$L = 4.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

	$\Delta\epsilon_x$ [nm]	$\Delta\epsilon_y$ [nm]		
	Total contribution	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	700	5	0	0
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Static Imperfections: Main Linac



Imperfection	With respect to	Value	$\Delta\epsilon_y$ [nm]		
			1-2-1	DFS	RF
Girder end point	Wire reference	12 μm	12.91	12.81	0.07
Girder end point	Articulation point	5 μm	1.31	1.30	0.02
Quadrupole roll	Longitudinal axis	100 μrad	0.05	0.05	0.05
BPM offset	Wire reference	14 μm	188.99	7.12	0.06
Cavity offset	Girder axis	14 μm	5.39	5.35	0.03
Cavity tilt	Girder axis	141 μrad	0.12	0.40	0.27
BPM resolution		0.1 μm	0.01	0.76	0.03
Wake monitor	Structure centre	3.5 μm	0.01	0.01	0.35
All			204.53	25.88	0.83

Stays well below goal (5 nm)
 90% likelihood to stay below 1.5 nm
 \Rightarrow have some margin in the design

average 0.9 nm
 \Rightarrow expect higher luminosity on average

Key contributors to emittance:

- Bookshelving
- Wake monitors

\Rightarrow verify them

Note:

Missing all imperfections by factor 2 would lead to 6 nm for 90% and 3.6 nm average
 Some but not huge margin

Could relax tolerance compared to 3 TeV, but do want to keep them for later upgrades



Expected Luminosity



Only static imperfections

From scaling

$$L = \text{sqrt}(30/18) \times L_0 = 1.94 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Simulation average

$$L = 3.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

Simulation 90%

$$L = 2.35 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

	$\Delta\epsilon_x$ [nm]	$\Delta\epsilon_y$ [nm]		
	Total contribution	Design limits	Static imperf.	Dynamic imperf.
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Achieve 20% more than scaled value

Margin for unaccounted effects, degraded performances, ...

But could use performance prediction as goal

- have to make sure all relevant effects are included

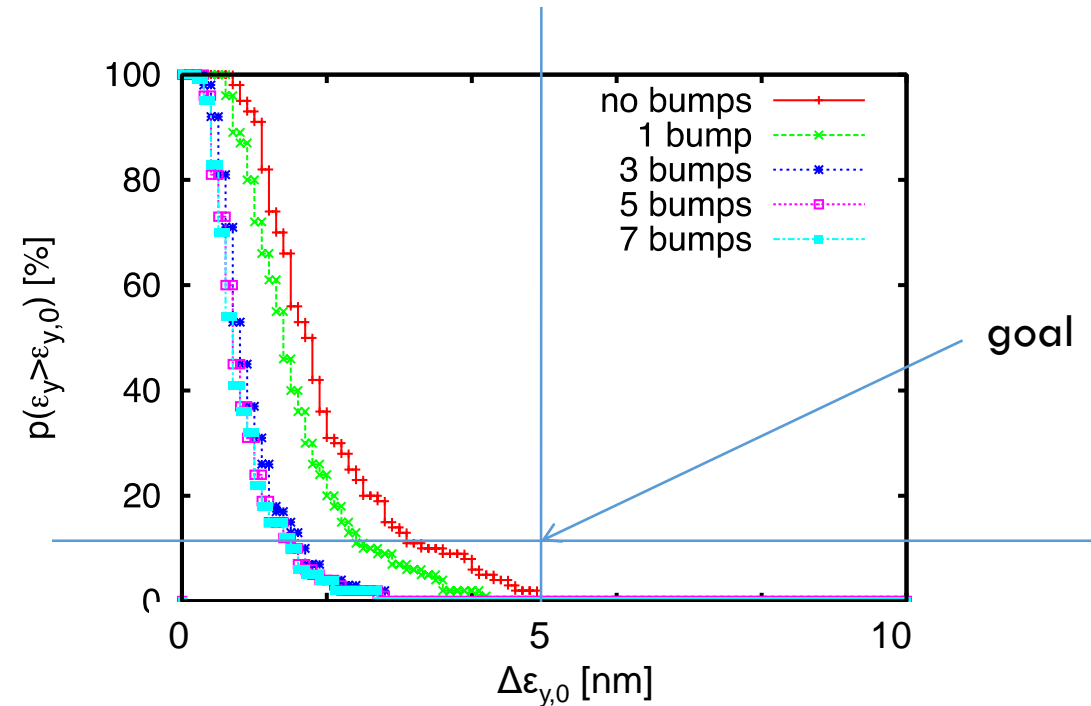
Can consider a number of improvements
were in part kept as reserve for more margin

Better alignment reduces emittance
Naïve model:
halving imperfections reduces emittance growth by
factor 4

Further improvement using tuning bumps (3 TeV
shown)
More complex tuning but might help

Also should consider additional tools

- e.g. high-bandwidth kicker to correct systematic offsets along bunch train

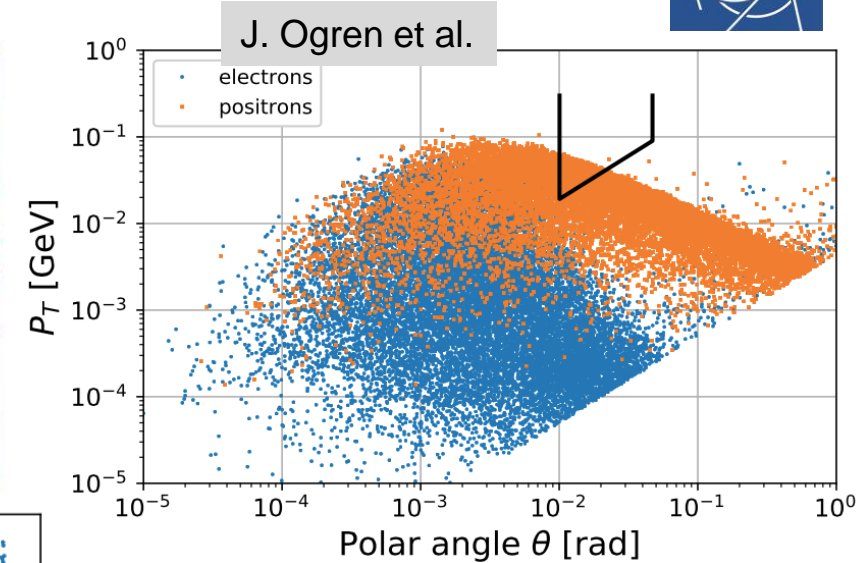
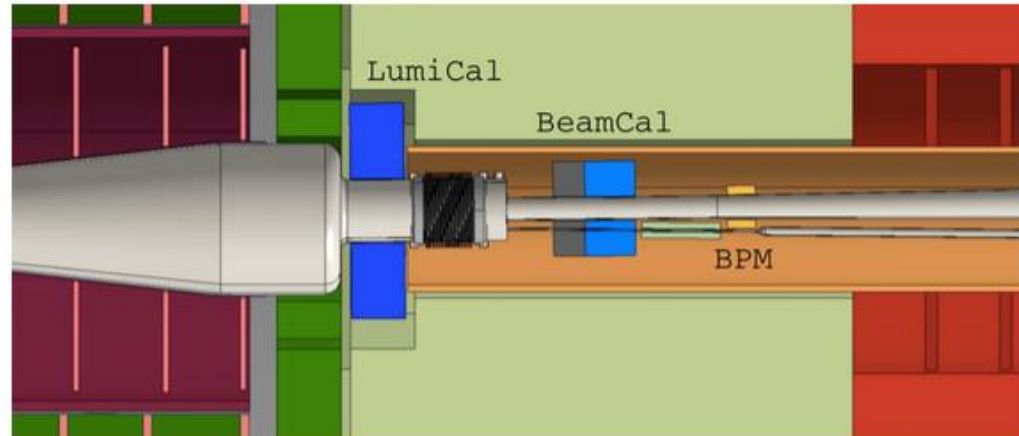


For highest luminosity pushing damping ring and RTML is important

And continued BDS effort

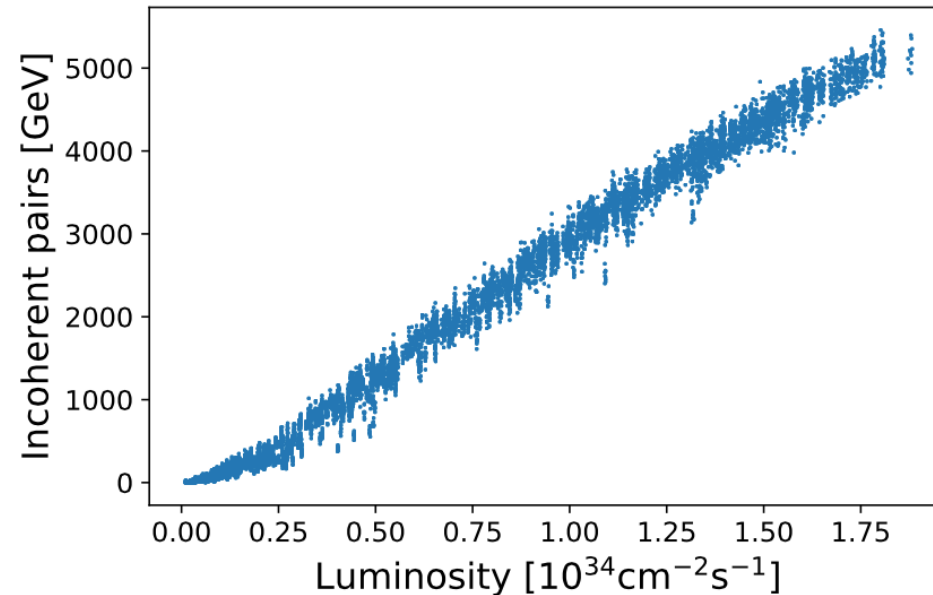
An essential worry:
Luminosity measurement
is slow:

- bremstrahlung is not visible in background



Other signals are not strictly
proportional to luminosity

- beamstrahlung depends on the know used
- pairs are proportional to luminosity but depend on other parameters as well
- but both can give directional information, e.g. which beam is larger



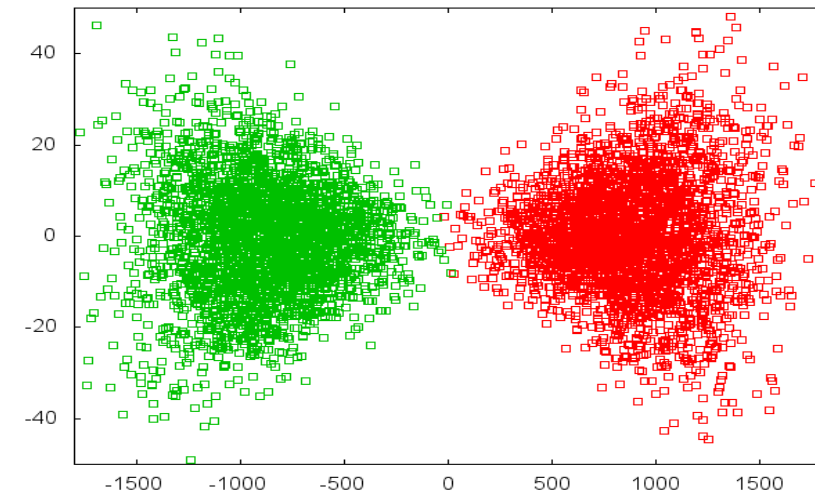
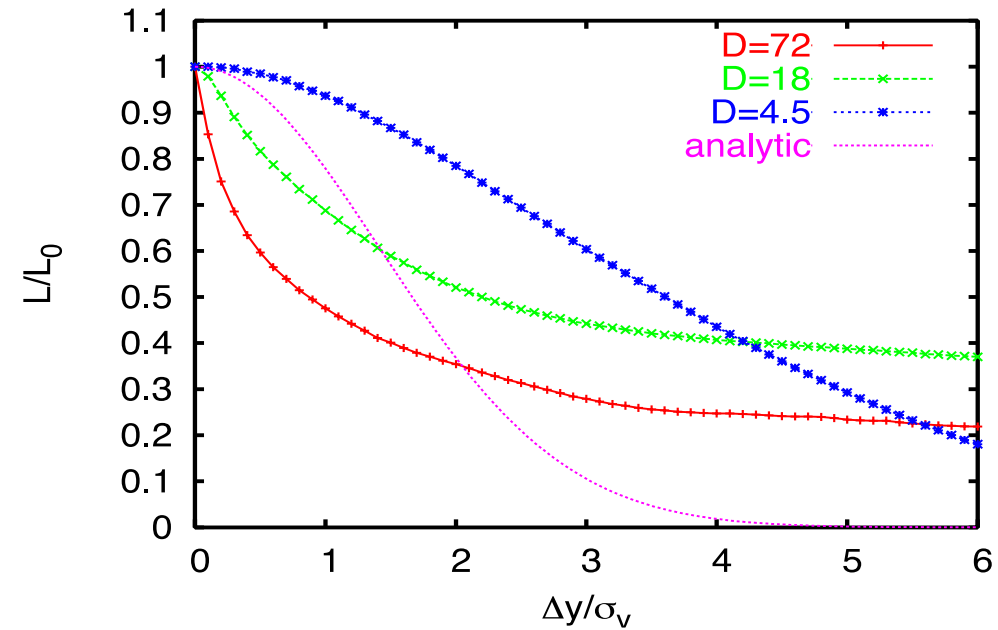
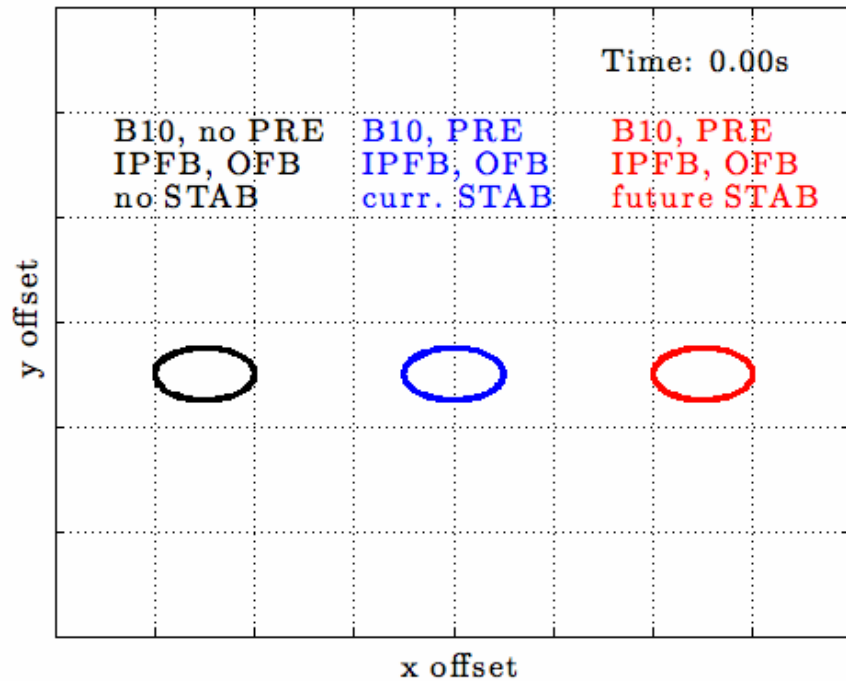
Detailed tuning studies using
these realistic signals reach the
luminosity target

- beamstrahlung for first phase
- switch to pairs as luminosity increases

Luminosity loss for rigid bunches with offset

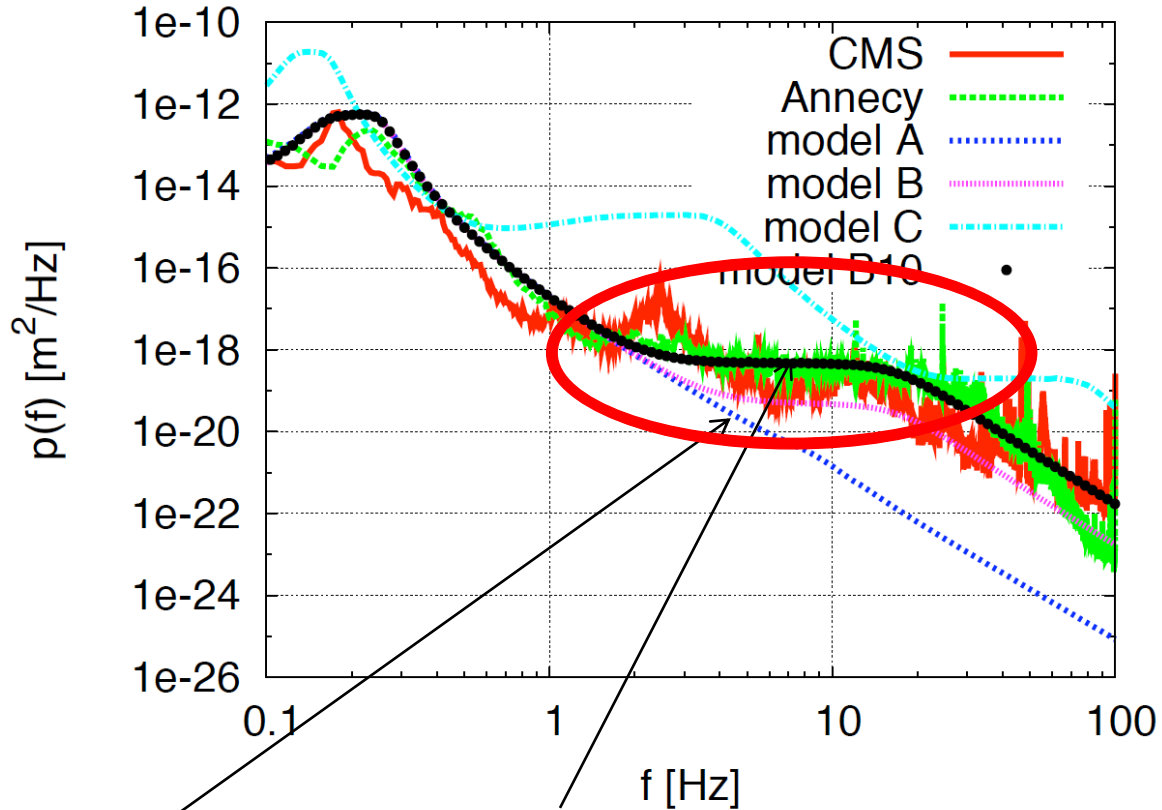
$$\frac{\mathcal{L}}{\mathcal{L}_0} = \exp\left(-\frac{\Delta y^2}{4\sigma_y^2}\right)$$

Actual loss depends strongly on disruption



Ground motion can impact beam trajectory

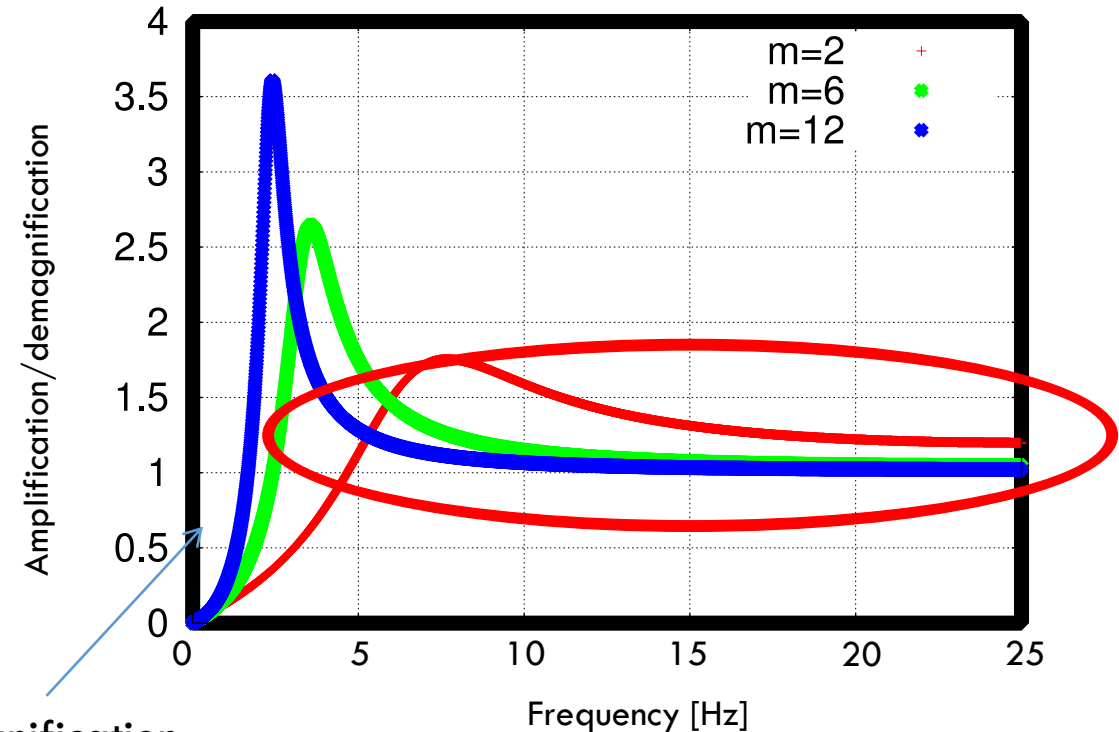
Beam-trajectory feedback corrects pulse-to-pulse (20 ms)
 ⇒ Cures low frequency ground motion
 ⇒ But not higher frequencies



LEP tunnel

Want to be able to cope with this
 (Model B10 similar to CMS hall)

Beam-trajectory feedback:
 Example transfer curve (recursive filter)



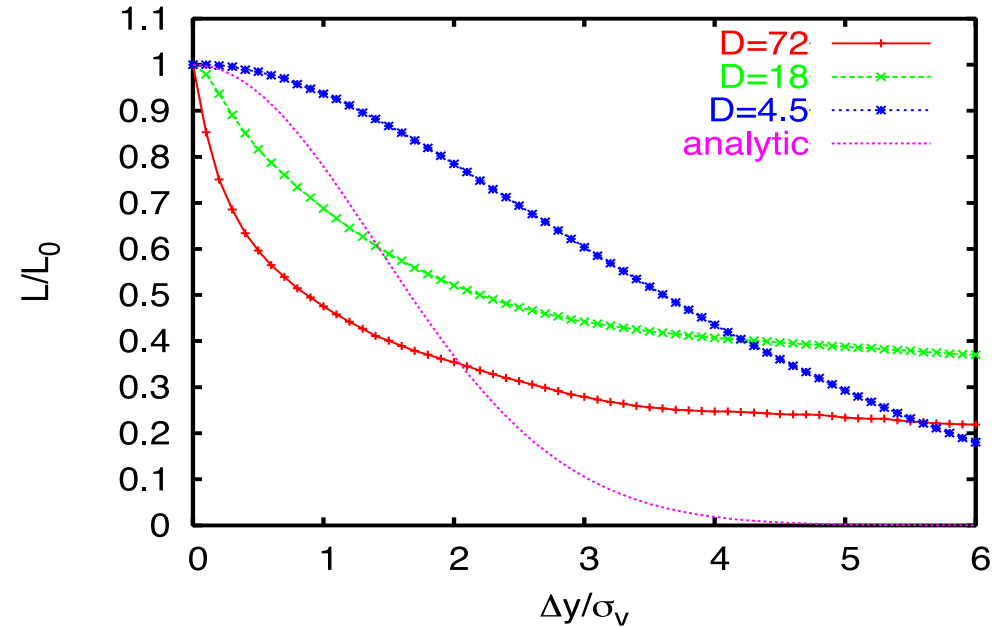
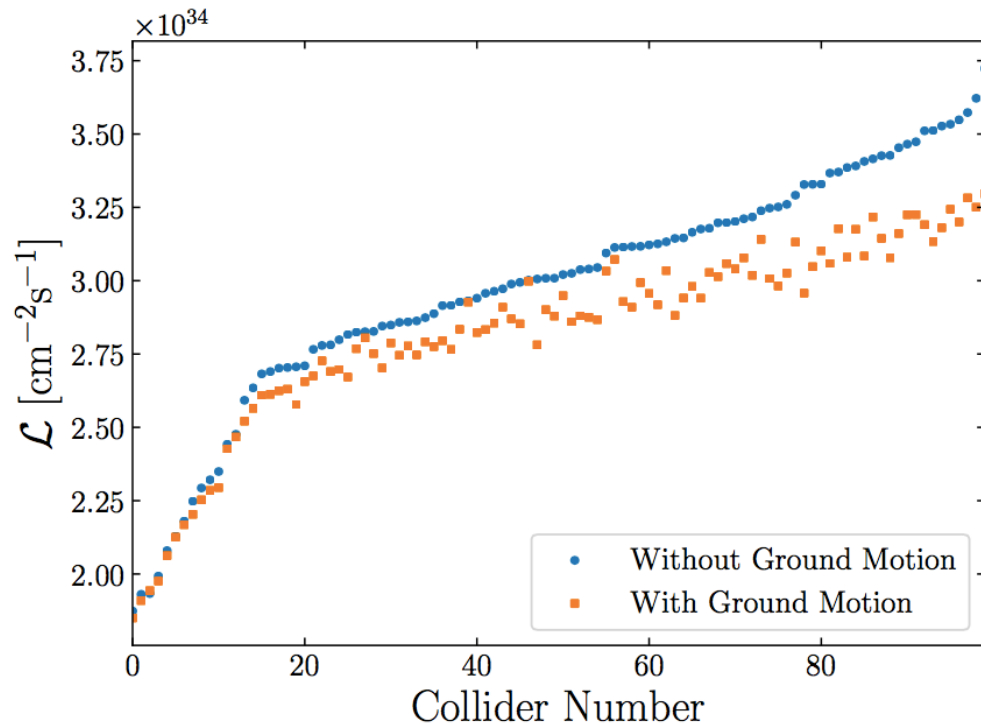
demagnification

Goal with all imperfections $L = 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Including static imperfections and ground motion representing a conservative estimate:

Simulation average $L = 2.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Simulation 90% $L = 2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$



Jitter tolerance is tighter for smaller beam

- more than proportional

Study of machines with ground motion and without shows

- better machines suffer more from ground motion
- need to check for other imperfections

Committing to lower budget means we have to make sure there are no unidentified contributions

Dynamic magnetic fields are produced by

- natural sources (e.g. sun activity)
- environmental sources (e.g. power lines, trains)
- and technical sources (e.g. the drive beam in the collider itself)

The largest field contributions are at 50 Hz

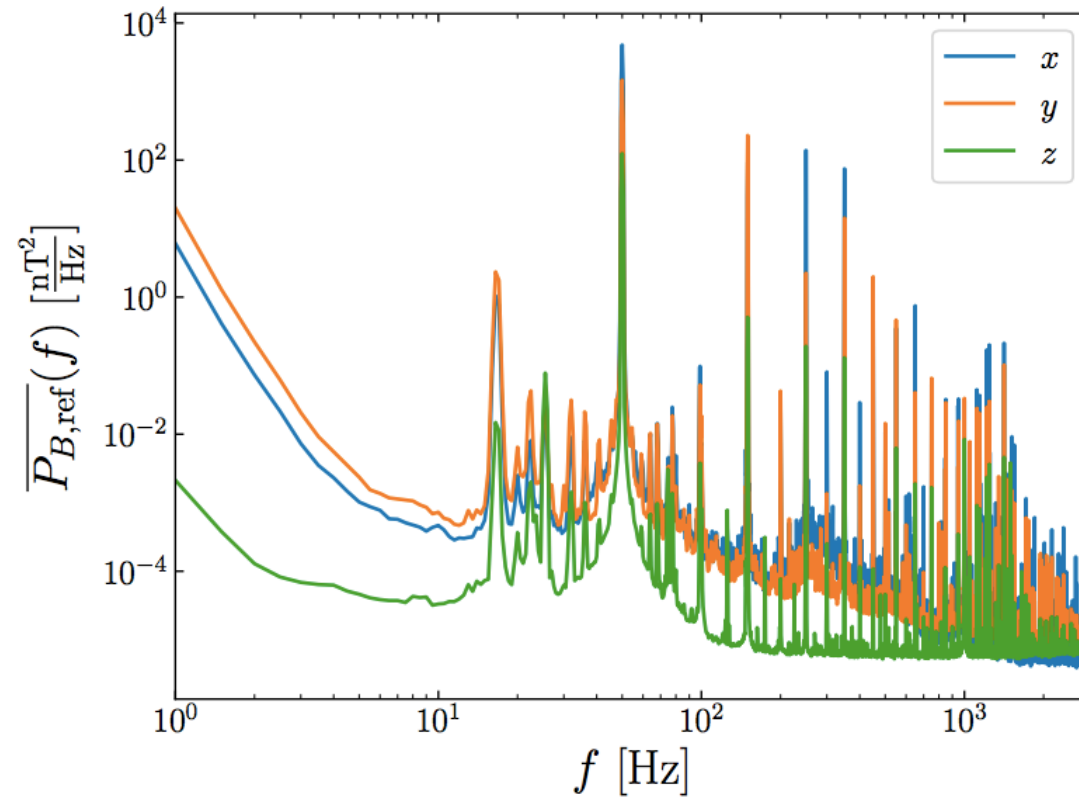
⇒ this is the reason to run at 50 Hz

⇒ grid perturbations appear (almost) static

Tightest tolerance in BDS and long transfer line:
O(0.1 nT) with no mitigation

Main linac is more relaxed

Measurements in LHC tunnel



Calculate integrated effective field

- corresponds to the field that has the same impact on luminosity

Conclusion

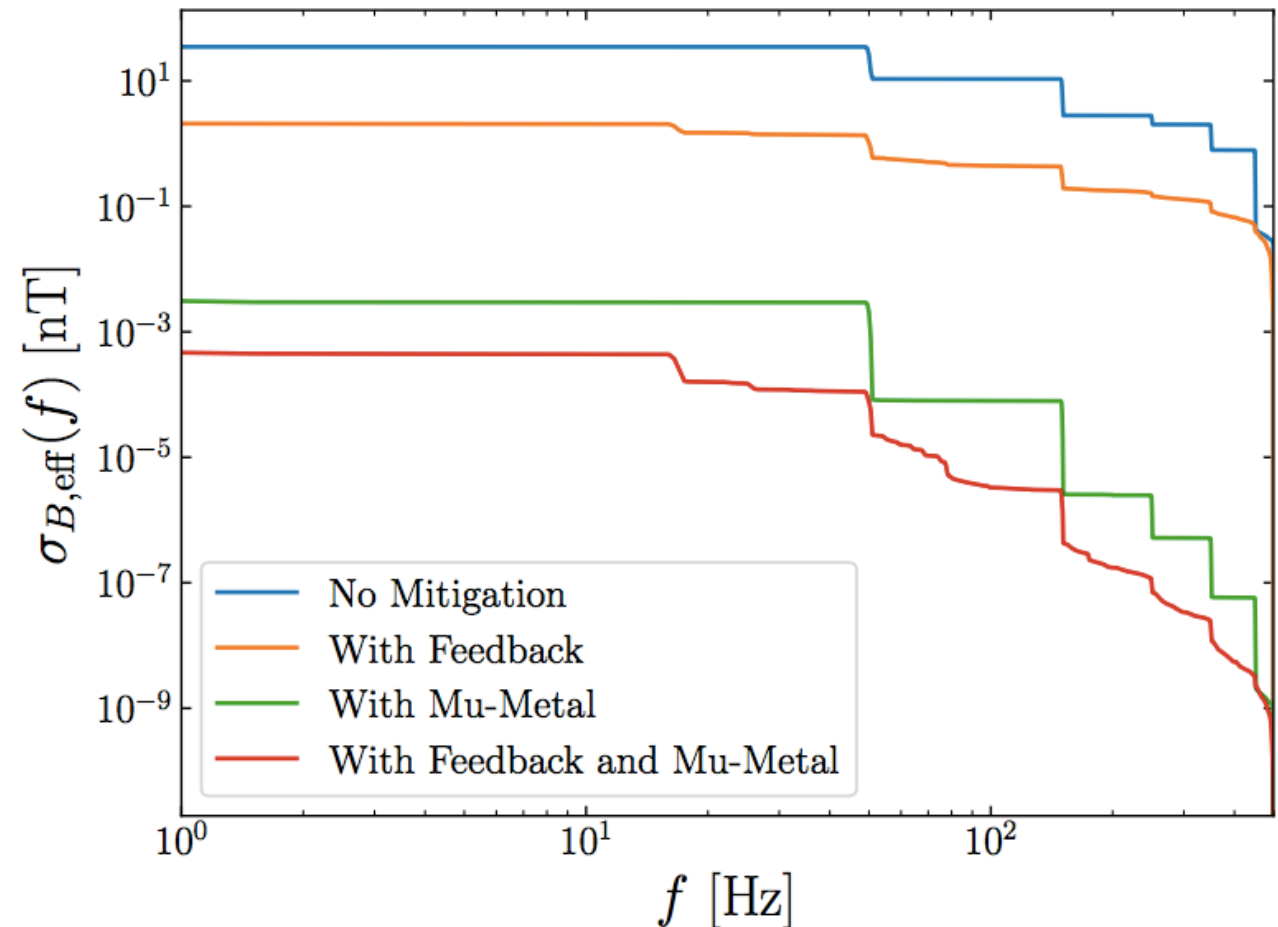
- feedback (and 50 Hz sampling) alone is a bit marginal
- mu-metal is sufficient
- the combination is best

Essentially no impact on luminosity if shielding is installed

Note: even in geomagnetic storm only 0.2% luminosity loss

Measurements in LHC tunnel and mitigation

C. Gohil et al.





Luminosity Expectation



Static imperfections, ground motion and stray fields

Goal	L	$= 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Simulation average	L	$= 2.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Simulation 90%	L	$= 2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

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	Total contribution	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	700	5	0	0
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Interaction point	50	0	5	5
sum	950	6	12	12

About 50% larger than goal

- Can we modify our goal to match the expectation?

Need to include all relevant imperfections

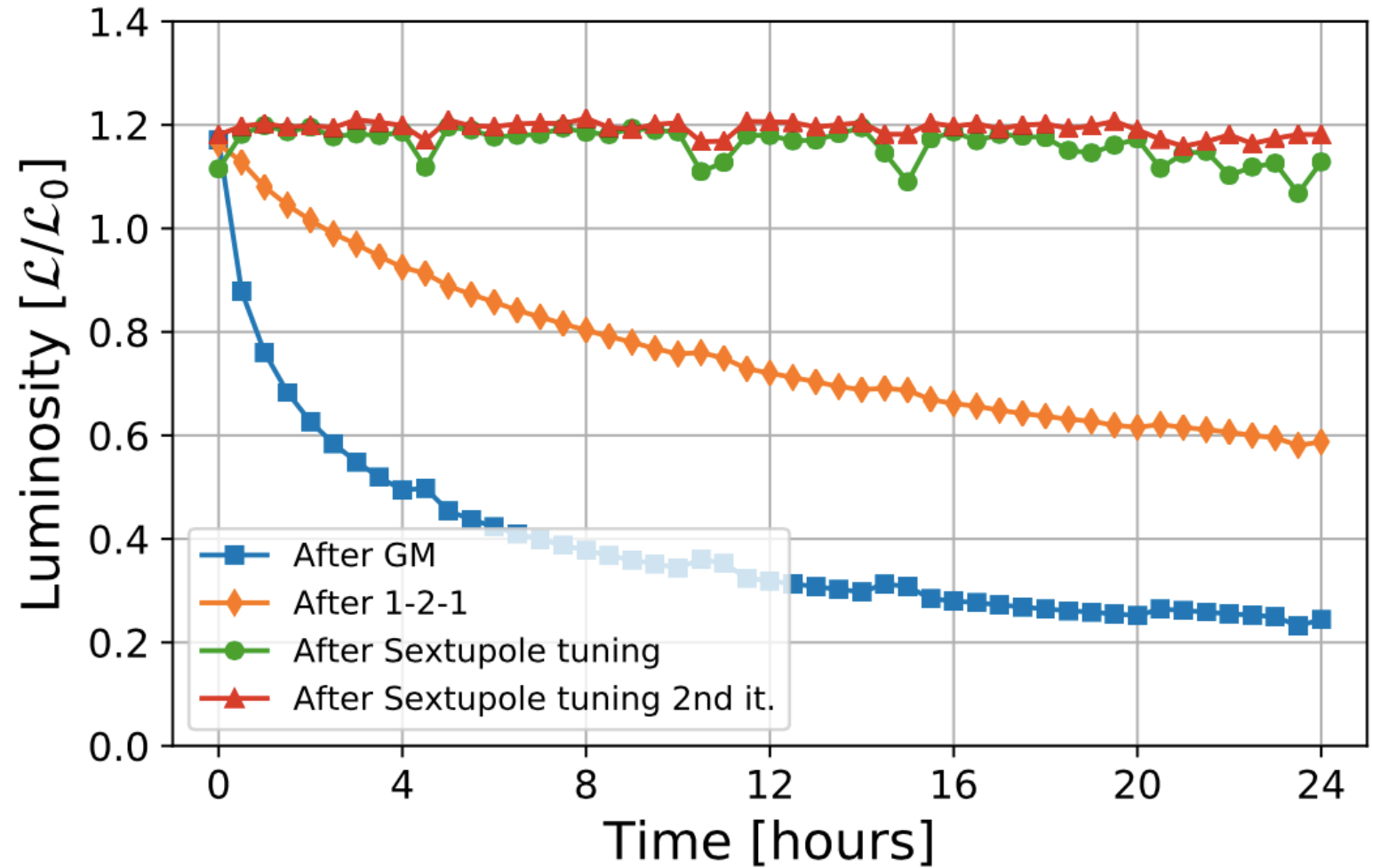
- other static effects
- other dynamic effects between corrections
- dynamic effects during operation

How bad is an interruption of the operation?

Using long-term ground motion model D (our conservative standard)

- Can recovers relatively quickly
- flat steering
 - sextupole know scans

Quite reassuring



Doubling the Beam Power

Estimate total power to increase from 170 to 220 MW (A. Grudiev)

Need to pulse all systems twice as often

Might need to damp two pulses in the damping ring in parallel

⇒ No real obstacle

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

↑ ↑ ↑
Luminosity spectrum Beam current Beam Quality (+bunch length)

For ground motion gain higher sampling rate

But 50 Hz pulse-to-pulse machine imperfections are a concern

⇒ magnetic stray field

Calculate integrated effective field

- corresponds to the field that has the same impact on luminosity

Conclusion

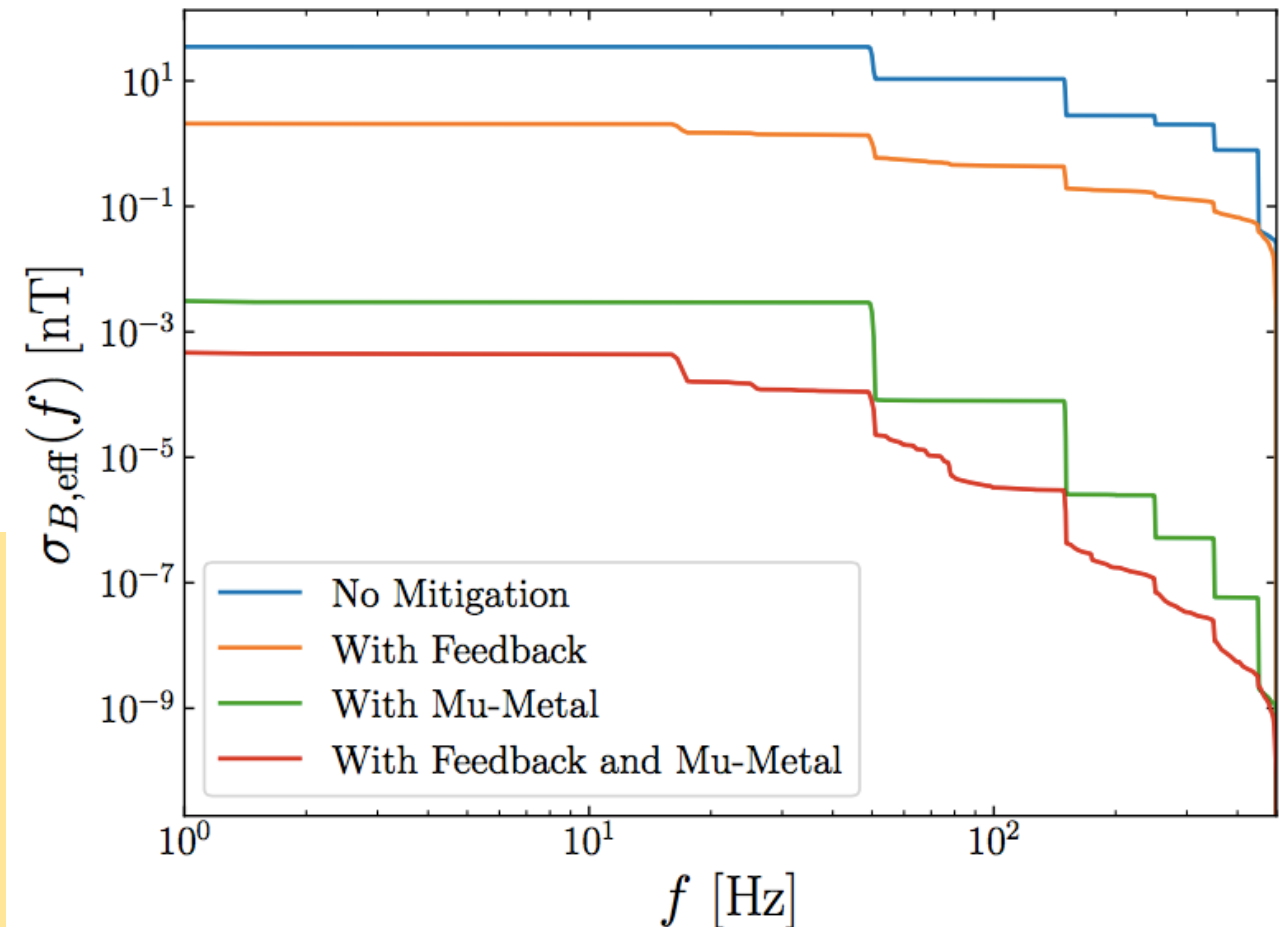
- feedback (and 50 Hz sampling) alone is a bit marginal
- mu-metal is sufficient
- the combination is best

For 100 Hz

- impact of 50 Hz is increased, not reduced
- But with mu-metal it remains sufficient

Should have two interleaved feedback loops
requires fast correctors

Measurements in LHC tunnel





Conclusion



- PIP performance predictions contain some margin
- But there are still some areas where robustness can be added
 - Accelerating structure wake monitors and bookshelving
 - BDS tuning
- Luminosity increase has several components
 - 100 Hz operation
 - Reduced safety margin
 - need a more detailed assessment to ensure prediction are reliable
 - Improved static imperfections
 - less bookshelving
 - better wake monitor
 - better BDS alignment and BPMs
 - Improved tuning
 - e.g. more bumps
 - Dealing with dynamic imperfections
 - reassessment of emittance budget
 - higher luminosity makes dynamic tolerances more stringent

Maybe a factor 3 to be gained in total





Horizontal Optimum



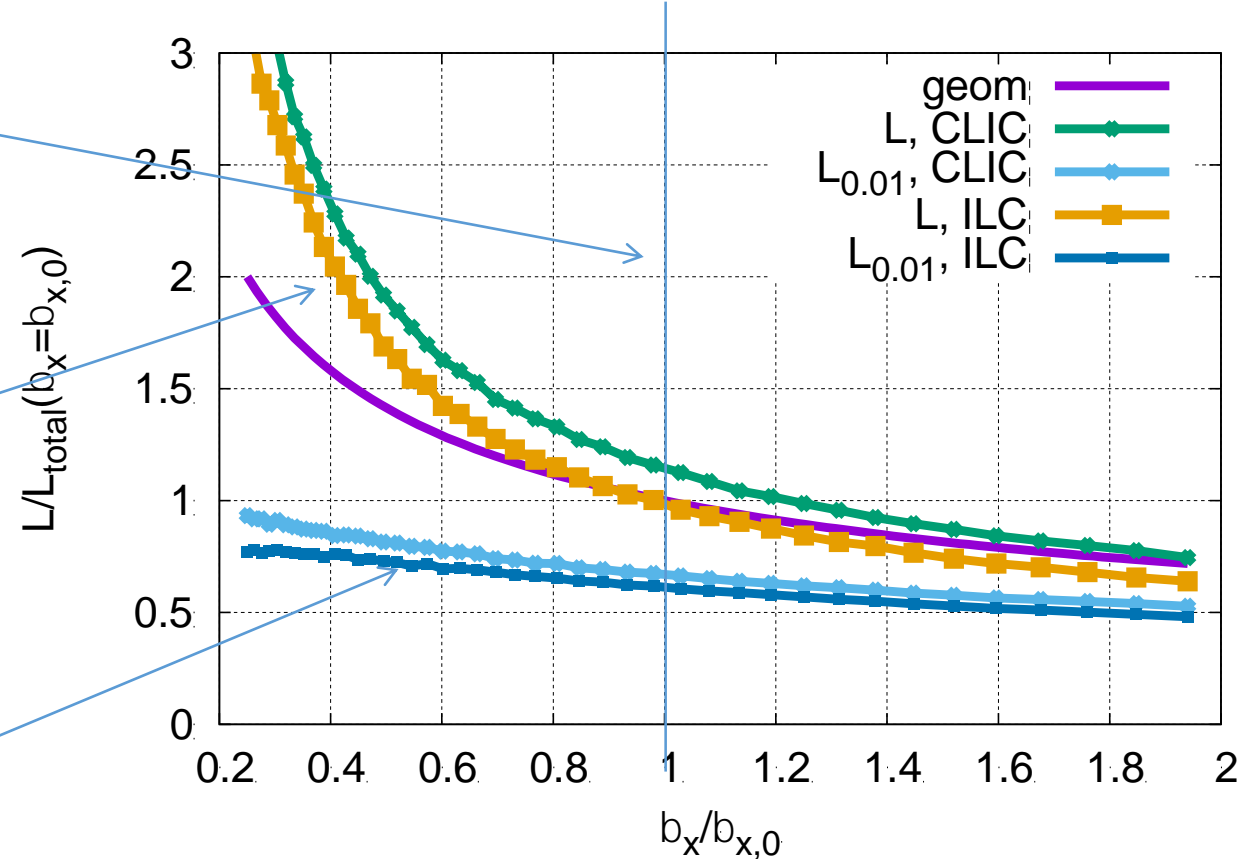
Design value $\beta_x = 8$ mm

Reaches $L_{0.01}/L=60\%$

The total luminosity L varies strongly with beta-function

But $L_{0.01}$ does not change so much

Hard to push beta-functions that low



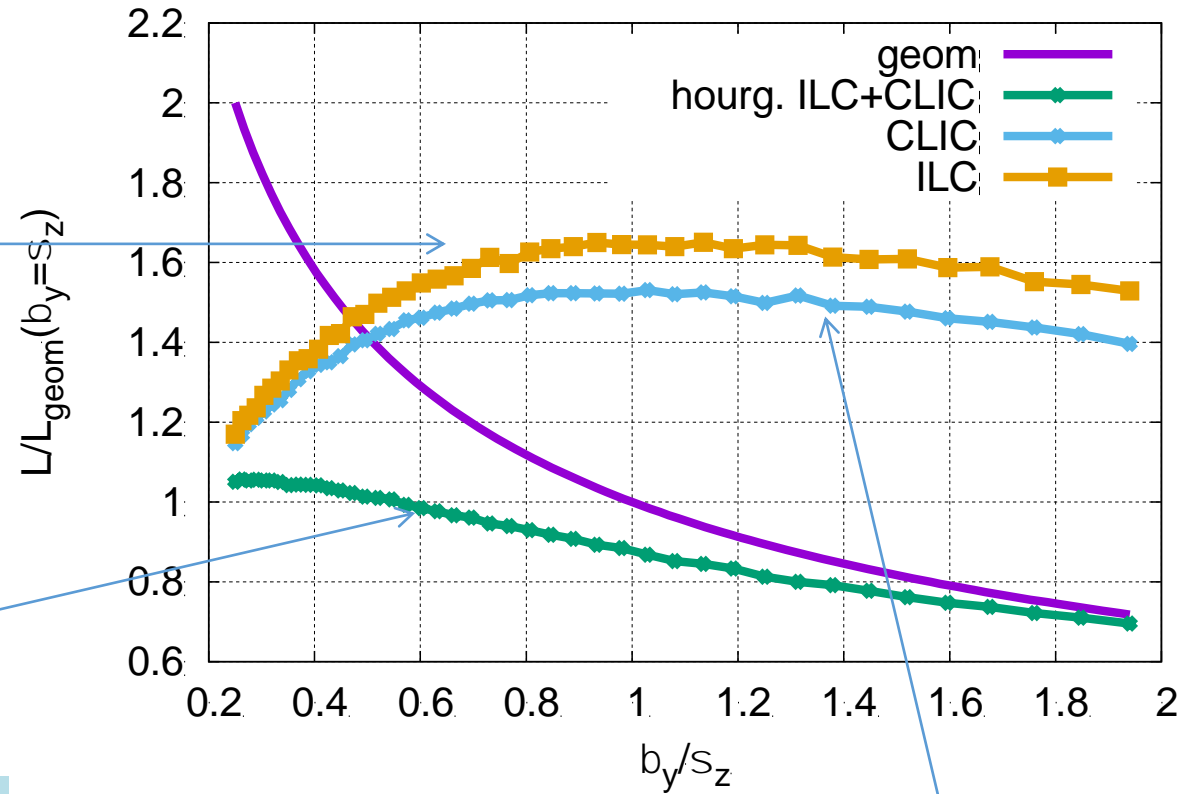
Use $L_{0.01}/L=60\%$ as criterion
Reasonable compromise for most physics studies

Smaller horizontal emittance has same effect as smaller beta-function
Cannot profit from smaller horizontal emittance
 N/σ_x is fixed

Including pinch effect

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

Geometric luminosity
No beam-beam forces



Somewhat above optimum beta-function because it is easier for the machine

Little to be gained by smaller beta-function but possible to exploit smaller emittance

CLIC choice 100 μm, reached by beam delivery system