CLIC Luminosity Challenges at 380 GeV

CLIC Project Meeting

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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	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}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

Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

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

Luminosity spectrum

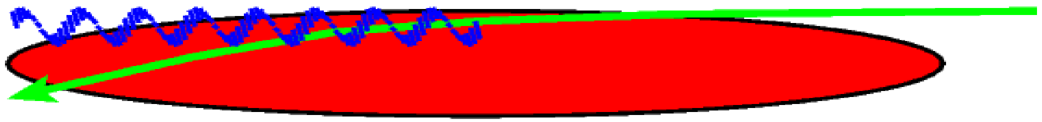
Beam current

Beam Quality (+bunch length)

Need to ensure that we can achieve each parameter

Beam-beam Effect

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

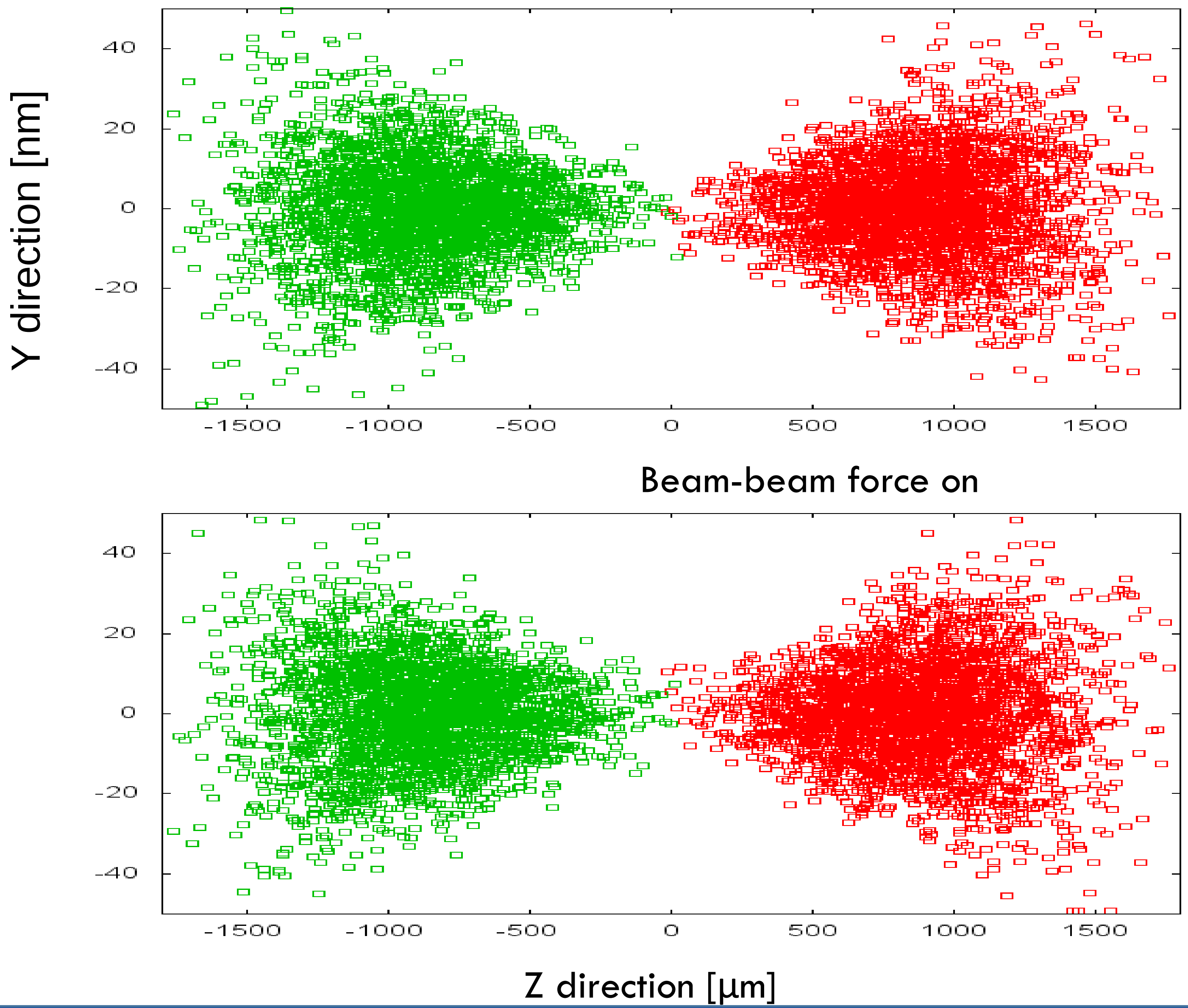


Dense beams to reach high luminosity

Beam focus each other

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

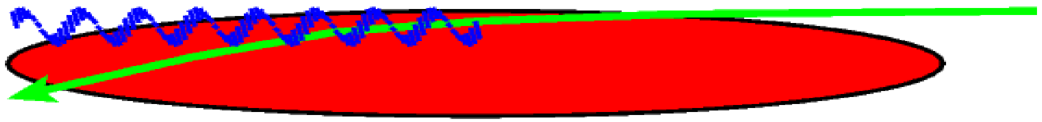
$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$


Beam-beam force off

Beam-beam force on

Beam-beam Effect

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



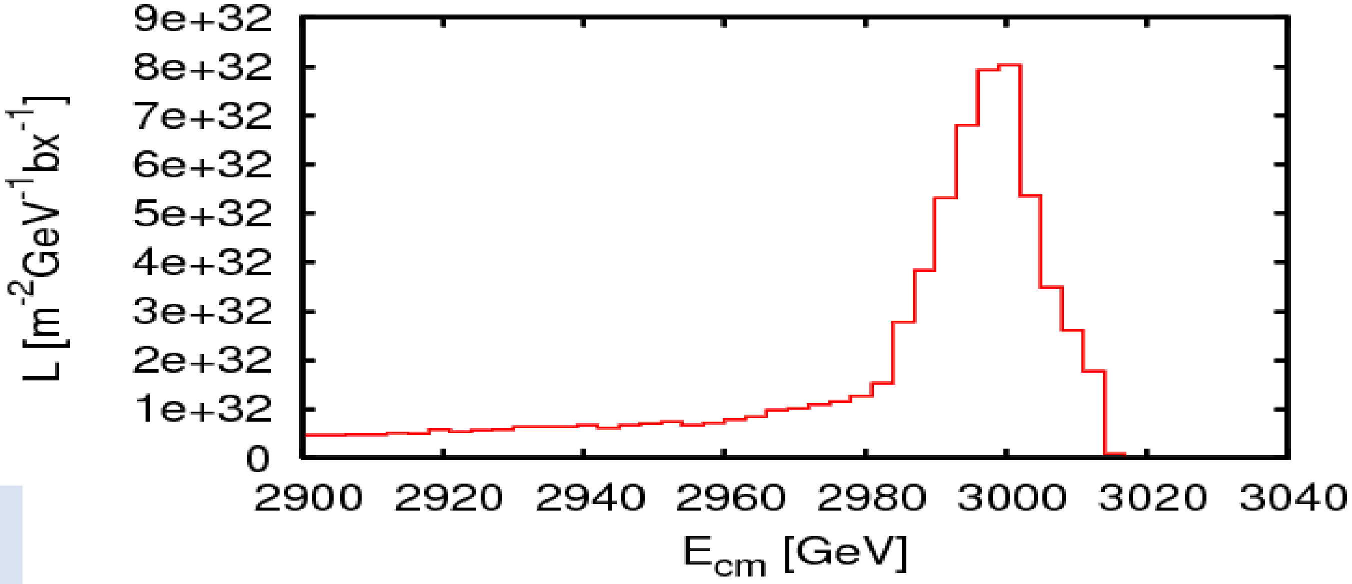
Emitt beamstrahlung
Develop luminosity spectrum

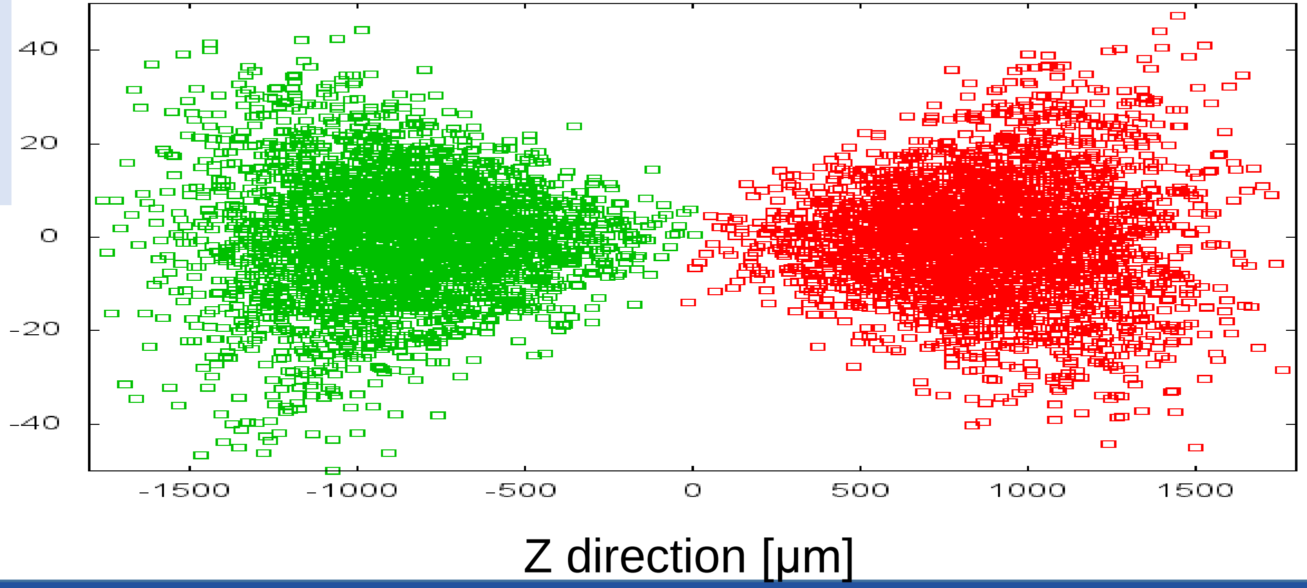
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

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

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

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$





Luminosity and Parameter Drivers

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

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

Beam current

Luminosity spectrum

Beam Quality (+bunch length)

Look at beam quality first

Luminosity and Beam Quality

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}} \qquad \sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

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) x L_0 = L = 3.35 x 10^{34} $cm^{-2}s^{-1}$

Only static imperfections: sqrt(30/18) x L_0 = L = 1.94 x 10^{34} $cm^{-2}s^{-1}$

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

All imperfections: sqrt(30/30) x L_0 = L = 1.5 x 10^{34} $cm^{-2}s^{-1}$

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

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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) x L_0 = 3.35 x 10^{34} $cm^{-2}s^{-1}$

Simulation L = 4.3 x 10^{34} $cm^{-2}s^{-1}$

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

	$\Delta\epsilon_x$ [nm]	$\Delta\epsilon_y$ [nm]		
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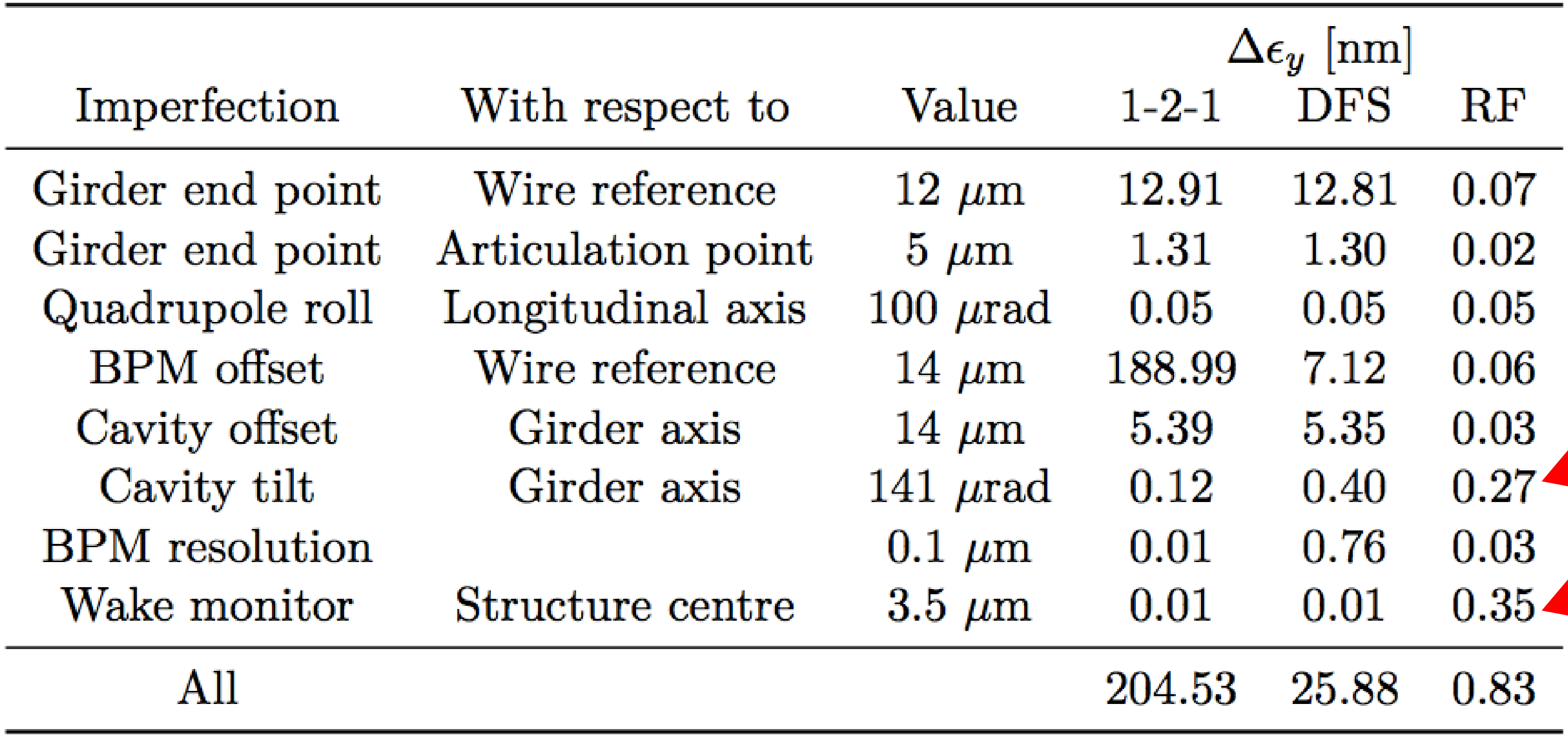
Static Imperfections: Main Linac



			$\Delta\epsilon_y$ [nm]		
Imperfection	With respect to	Value	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:
- Bookshelfing
- 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 = sqrt(30/18) x L_0 = 1.94 x 10^{34} $cm^{-2}s^{-1}$

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

Simulation average L = 3.0 x 10^{34} $cm^{-2}s^{-1}$

Simulation 90% L = 2.35 x 10^{34} $cm^{-2}s^{-1}$

	$\Delta\epsilon_x$ [nm]	$\Delta\epsilon_y$ [nm]		
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Damping ring exit	700	5	0	0
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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

Potential Further Improvements

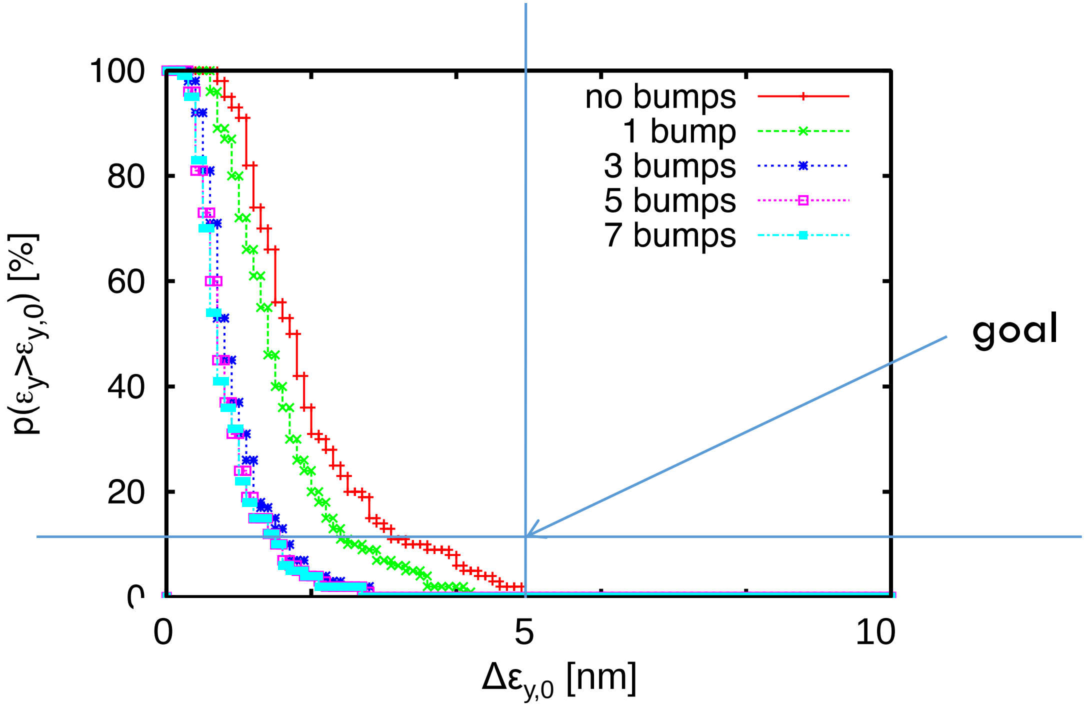
Can consider a number of improvements were in part kept as reserve for more margin

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



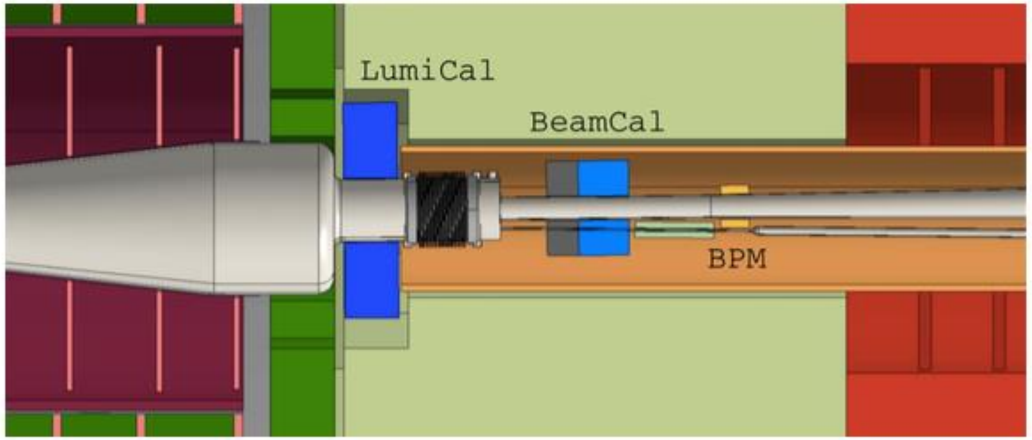
For highest luminosity pushing damping ring and RTML is important

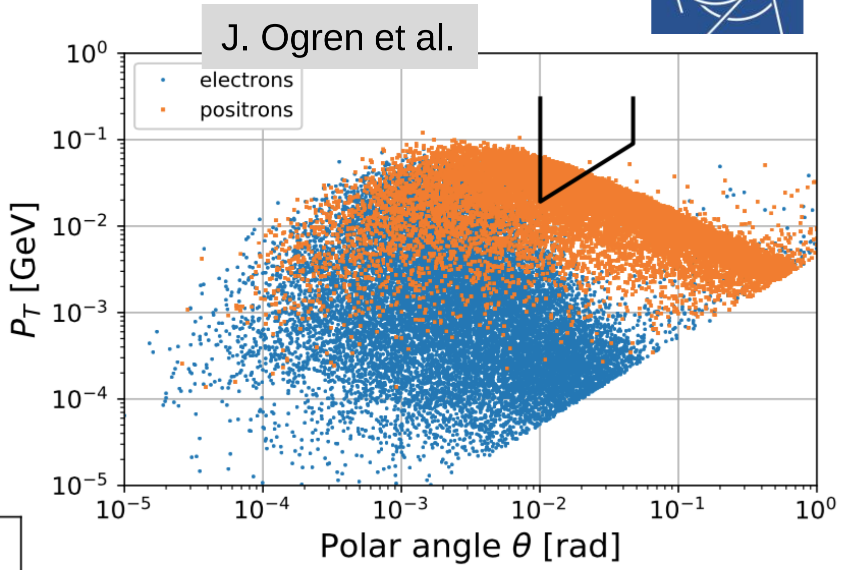
And continued BDS effort

Realistic Luminosity Signals

An essential worry:
Luminosity measurement is slow:

- bremstrahlung is not visible in background

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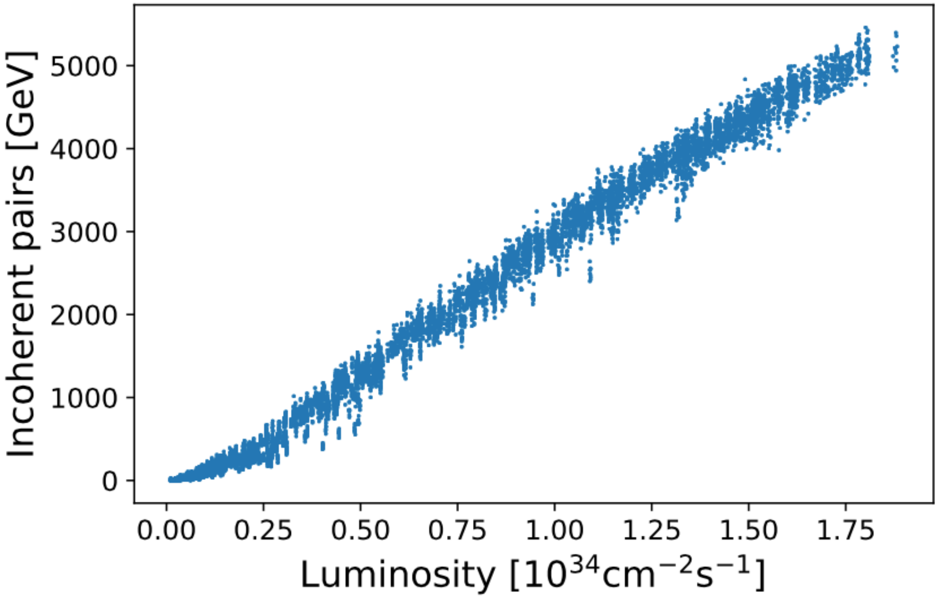
Other signals are not strictly proportional to luminosity

- 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

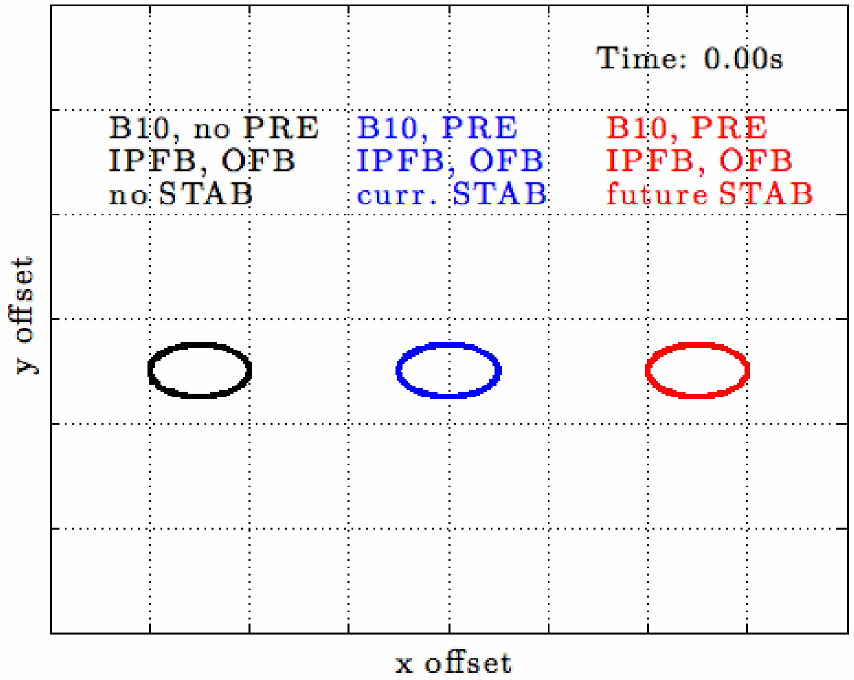
- beamstrahlung for first phase
- switch to pairs as luminosity increases

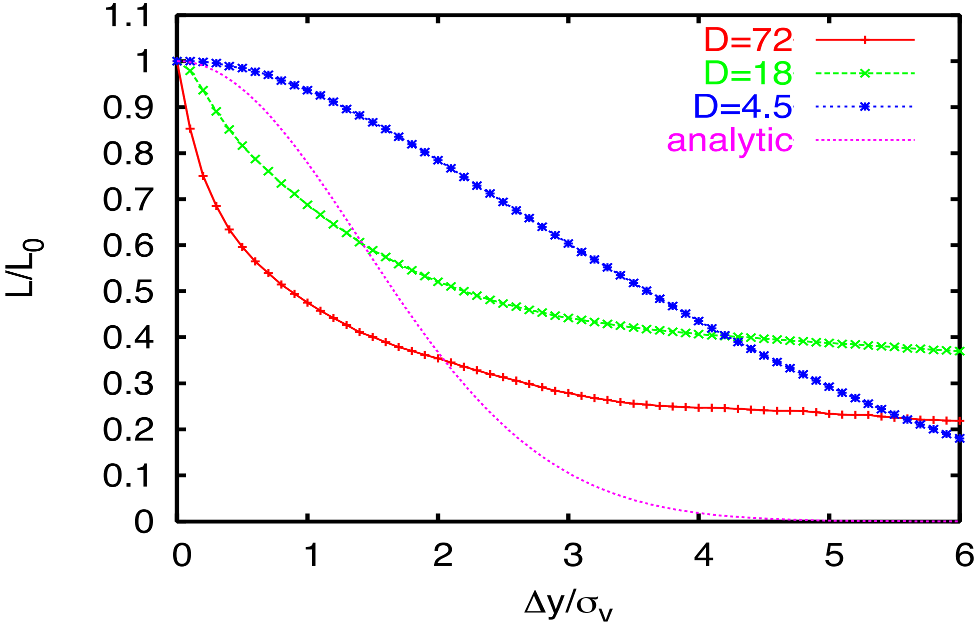
Luminosity and Jitter Tolerance

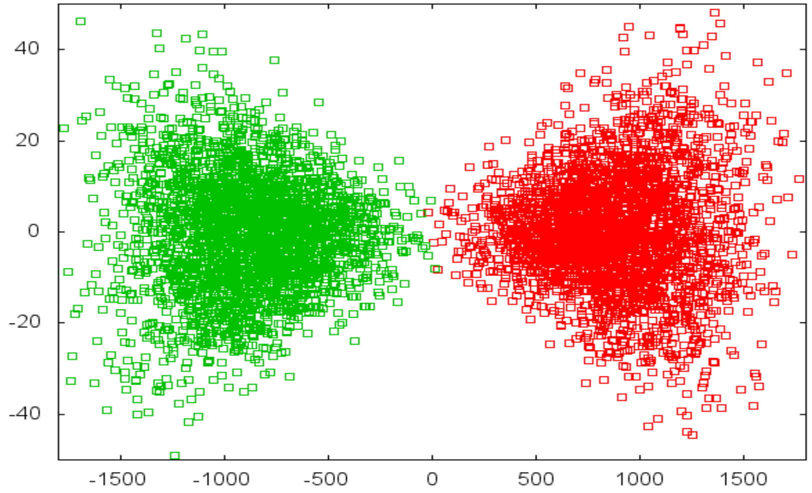
Luminosity loss for rigid bunches with offset

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

Actual loss depends strongly on disruption

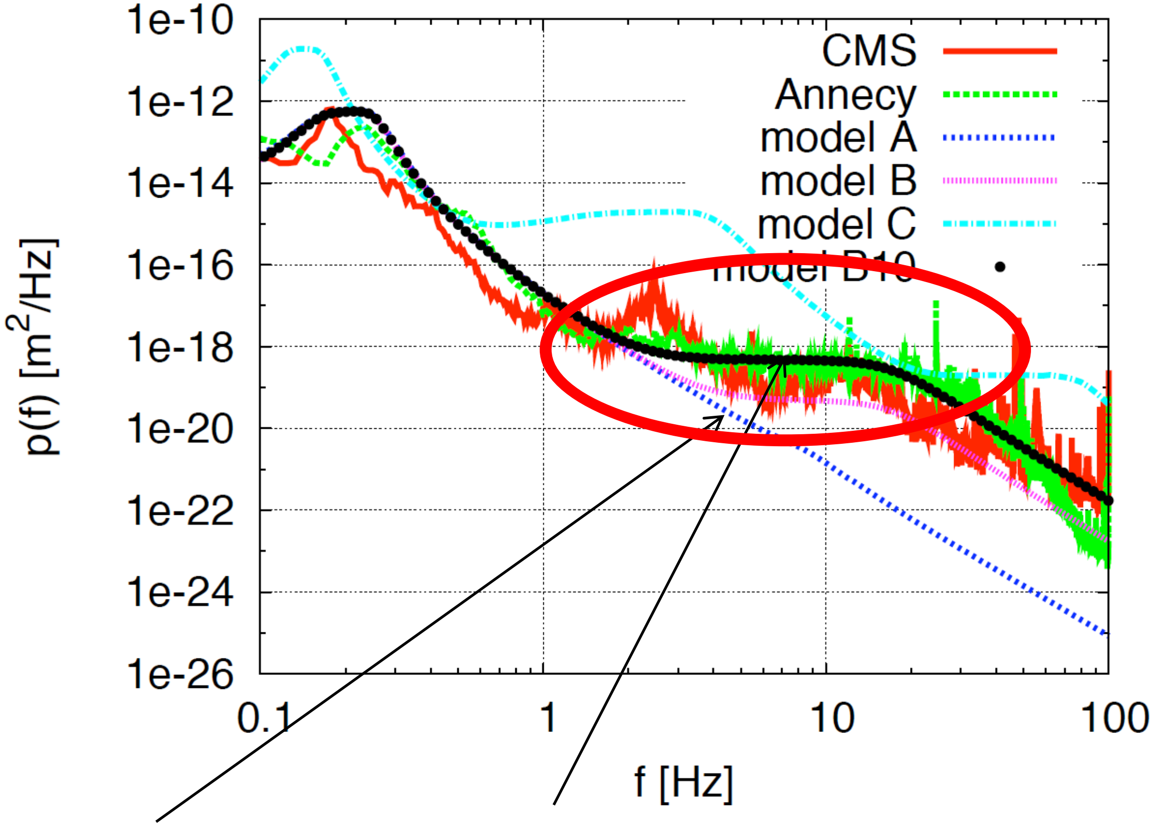






Dynamic Imperfection: Ground Motion

Ground motion can impact beam trajectory



LEP tunnel

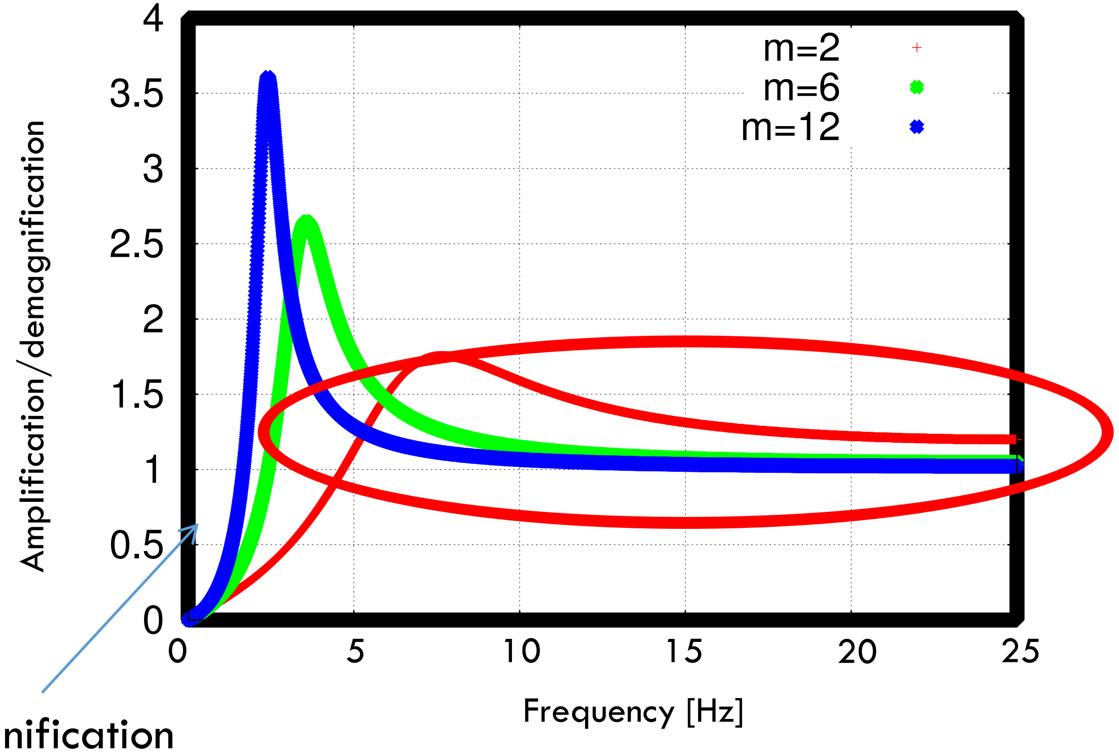
Want to be able to cope with this
(Model B10 similar to CMS hall)

Beam-trajectory feedback corrects pulse-to-pulse (20 ms)

⇒ Cures low frequency ground motion

⇒ But not higher frequencies

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

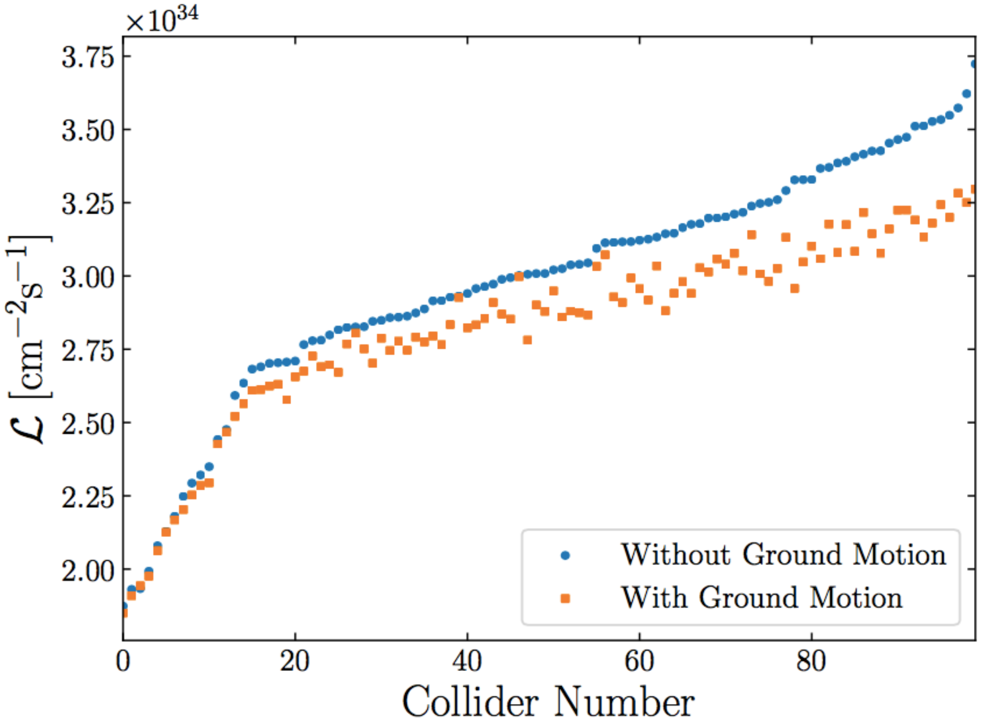


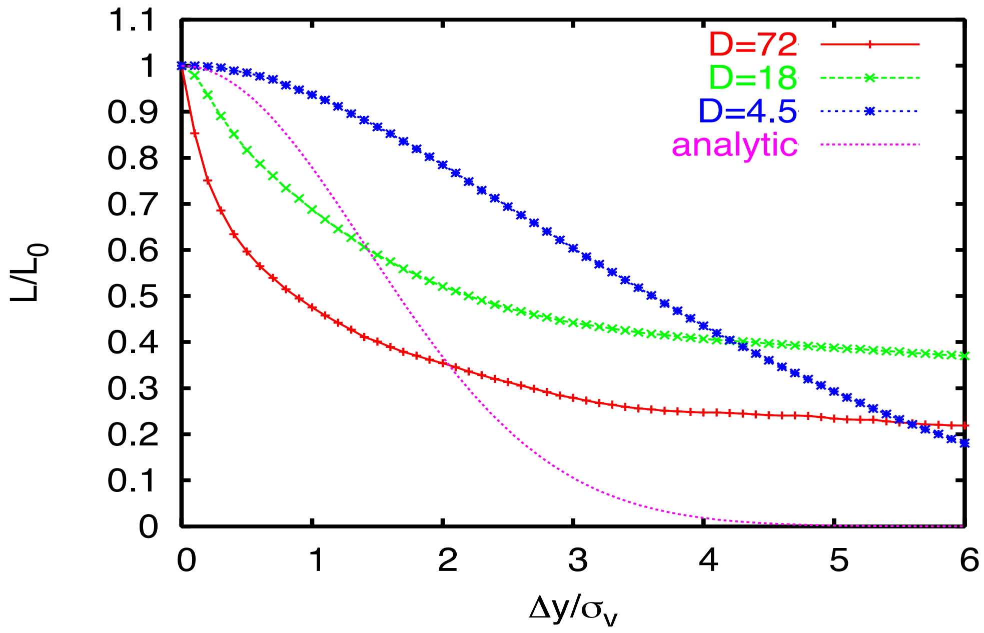
demagnification

Luminosity and Jitter Tolerance

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

Including static imperfections and ground motion representing a conservative estimate:
Simulation average L = 2.8 x 10^{34} $cm^{-2}s^{-1}$
Simulation 90% L = 2.3 x 10^{34} $cm^{-2}s^{-1}$





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 Stray Fields

C. Gohil et al.

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

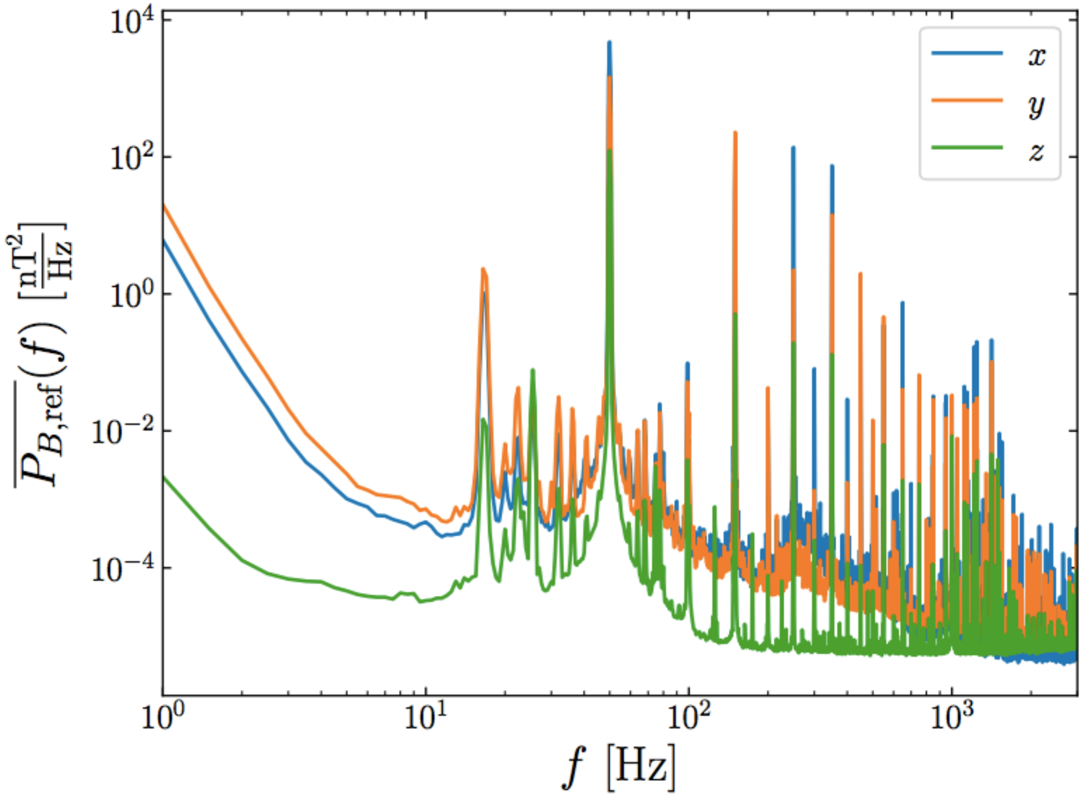
$\Rightarrow$ this is the reason to run at 50 Hz

$\Rightarrow$ 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



Dynamic Magnetic Stray Fields

Calculate integrated effective field
- corresponds to the field that has the same impact on luminosity

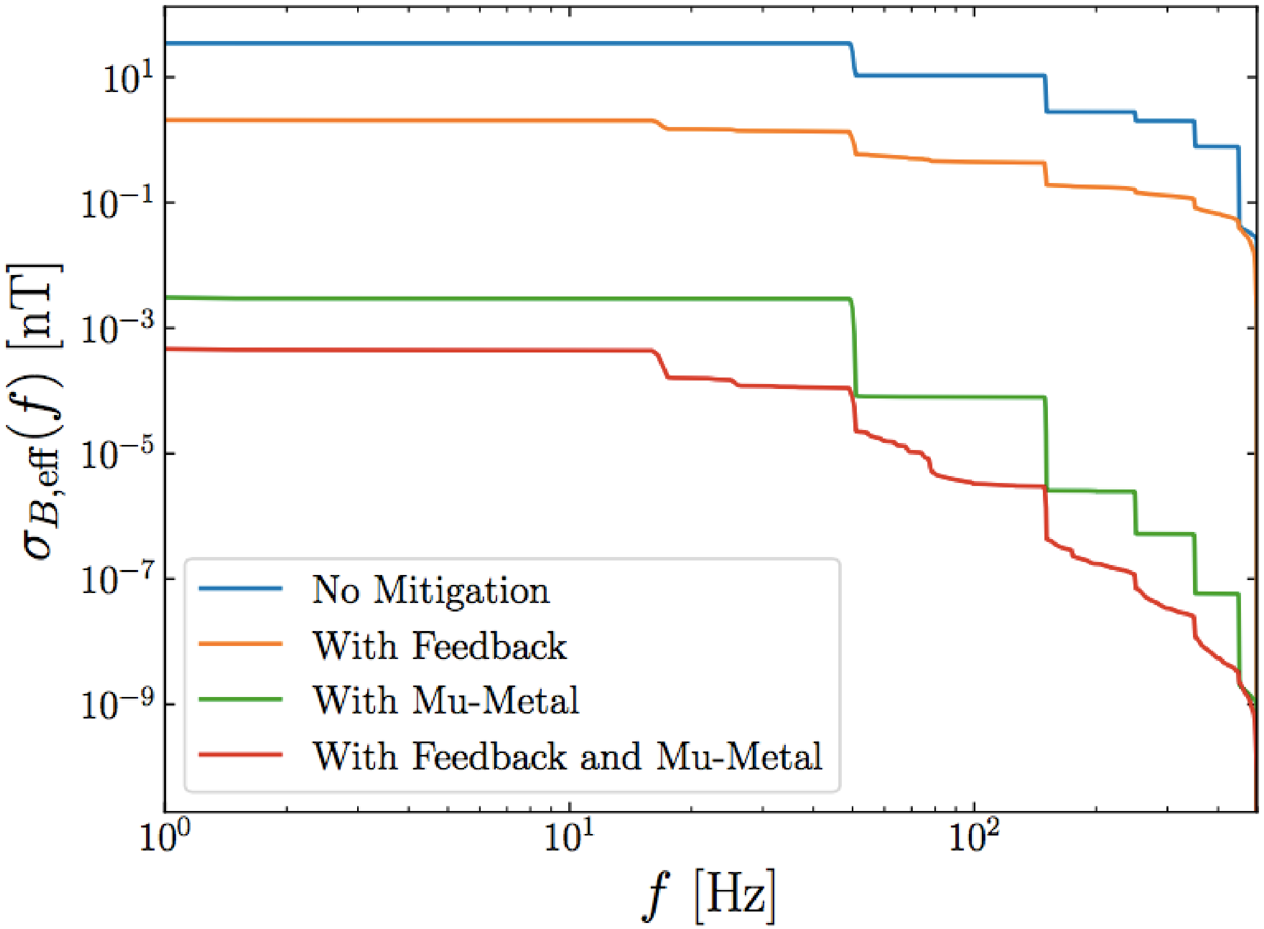
Conclusion
- feedback (and 50 Hz sampling) alone is a bit marginal
- mu-metal is sufficient
- the combination is best

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

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

	$\Delta\varepsilon_x$ [nm]	$\Delta\varepsilon_y$ [nm]		
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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

Recovery from Failure

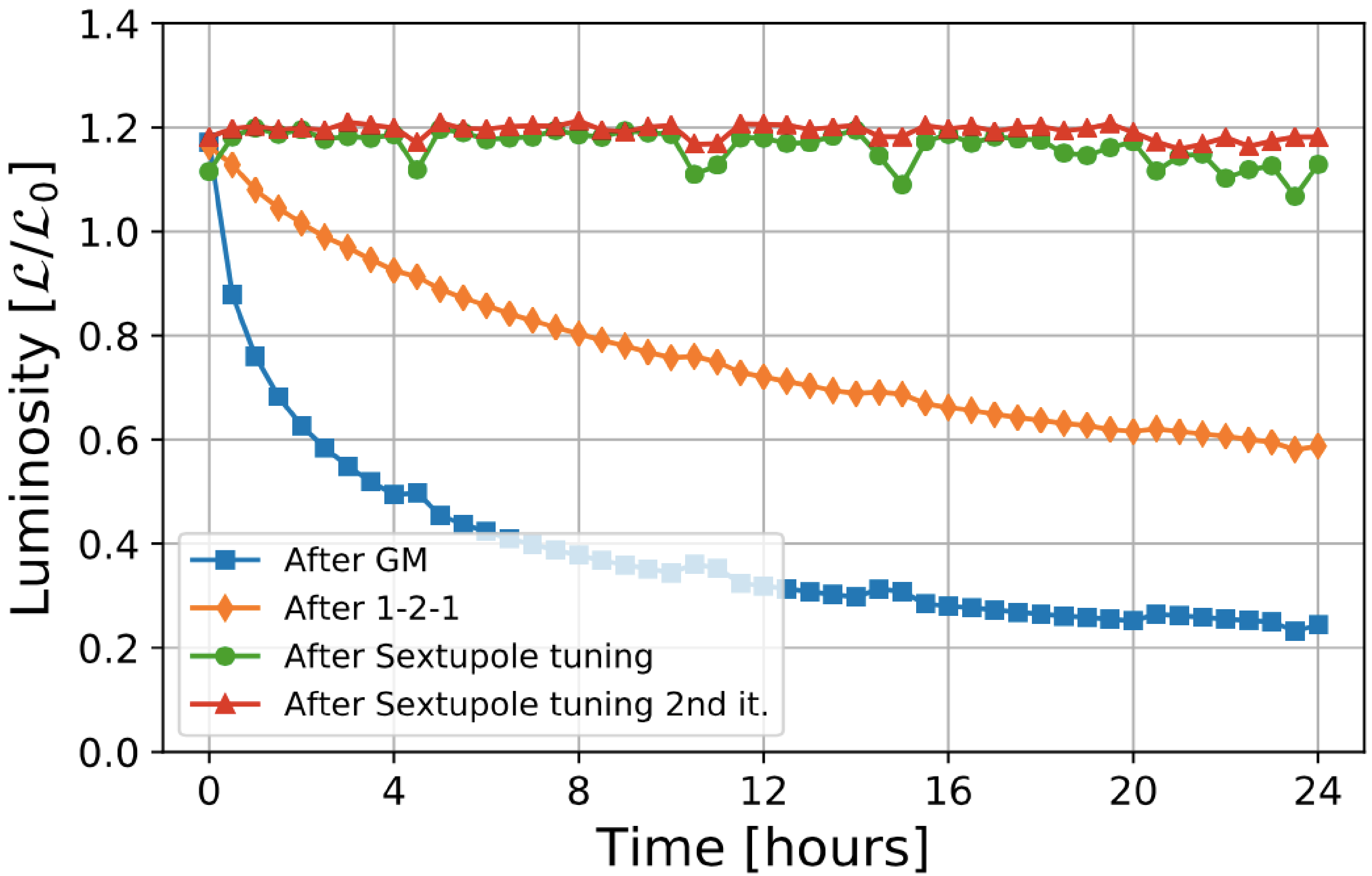
J. Ogren et al.

How bad is an interruption of the operation?

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

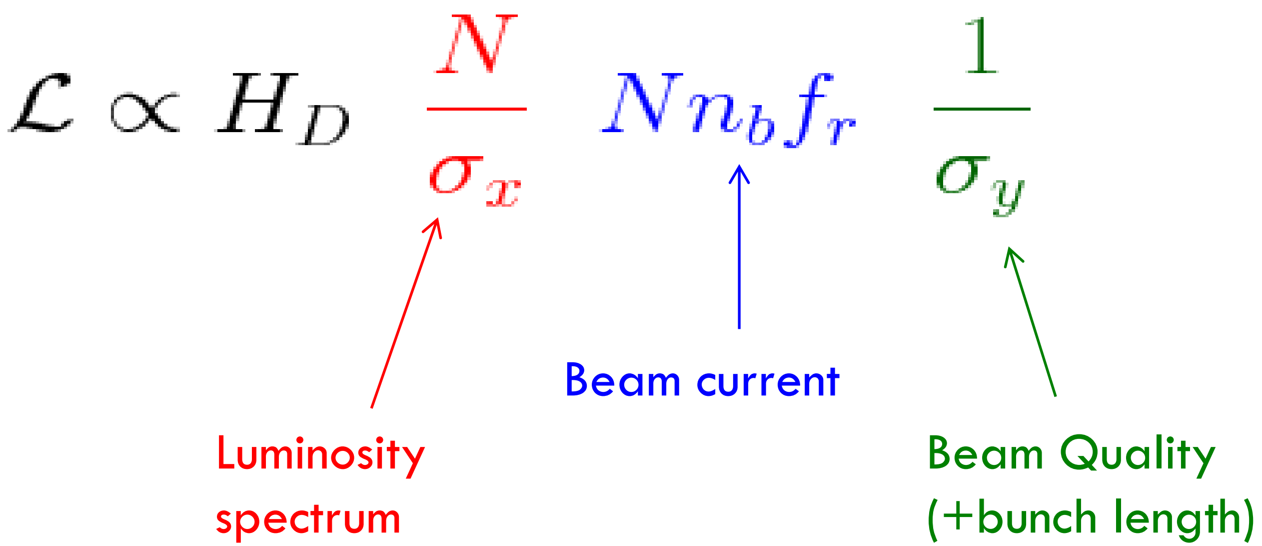
Can recovers relatively quickly
- flat steering
- sextupole know scans

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



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

Beam current

Luminosity spectrum

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

Dynamic Magnetic Stray Fields

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

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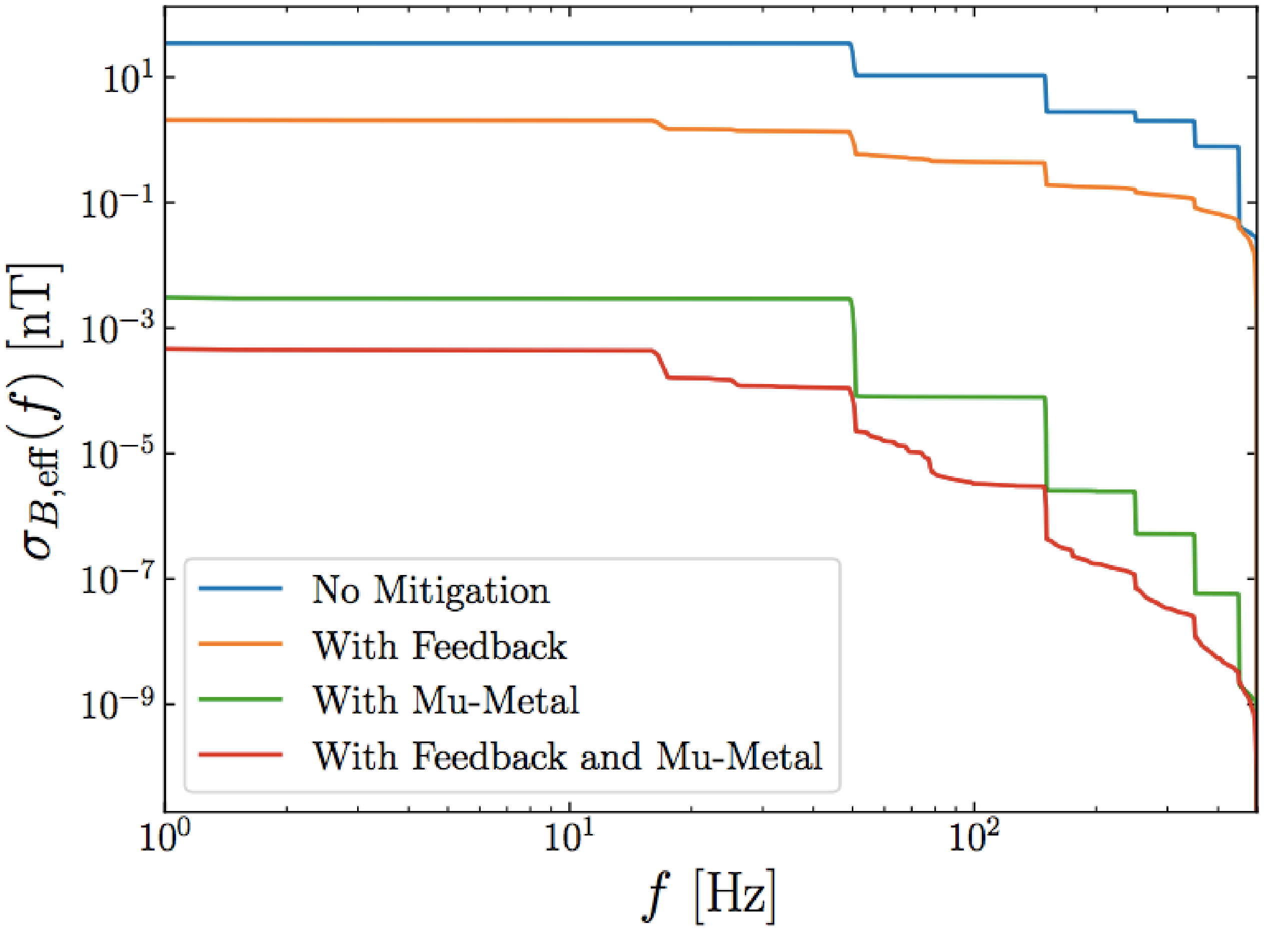


Conclusion

- PIP performance predictions contain some margin
- But there are still some areas where robustness can be added
    - Accelerating structure wake monitors and bookshelfing
    - 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 bookshelfing
        - 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

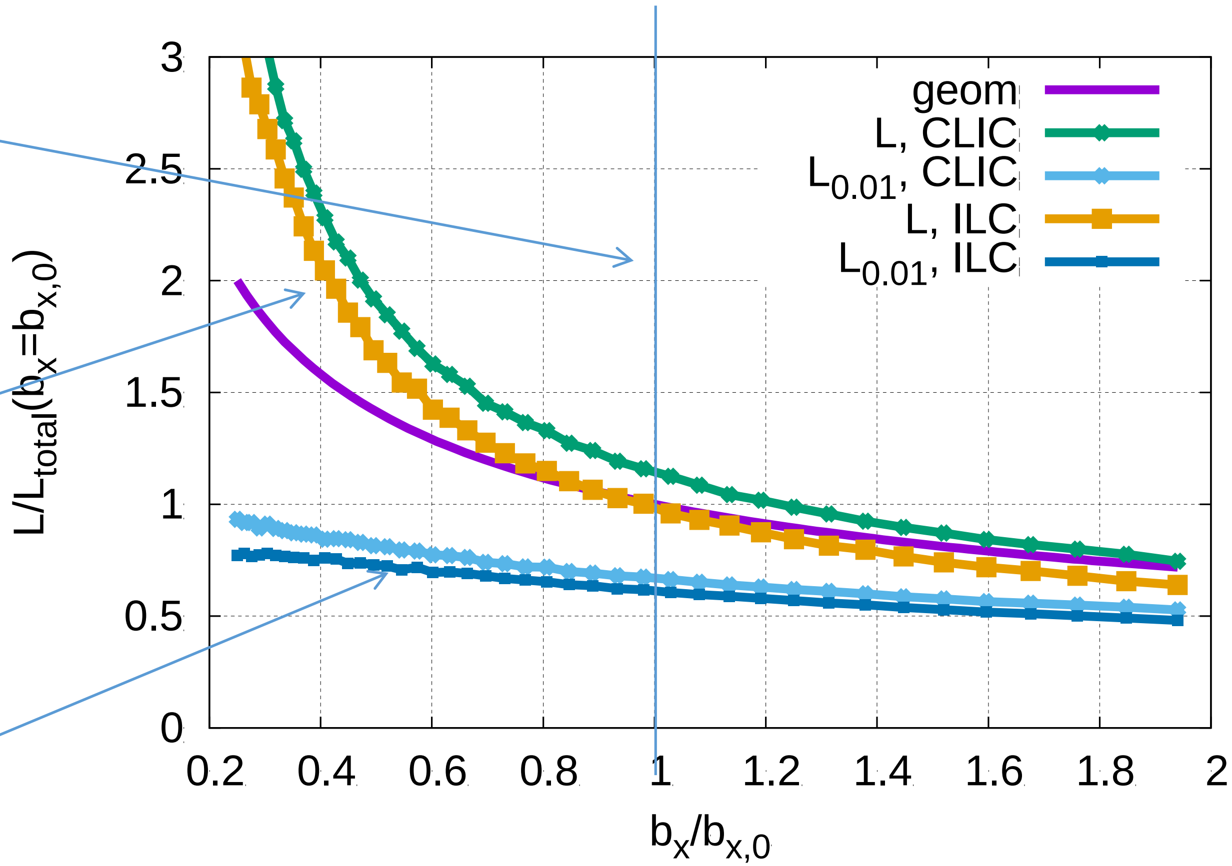
Design value β_x= 8 mm

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



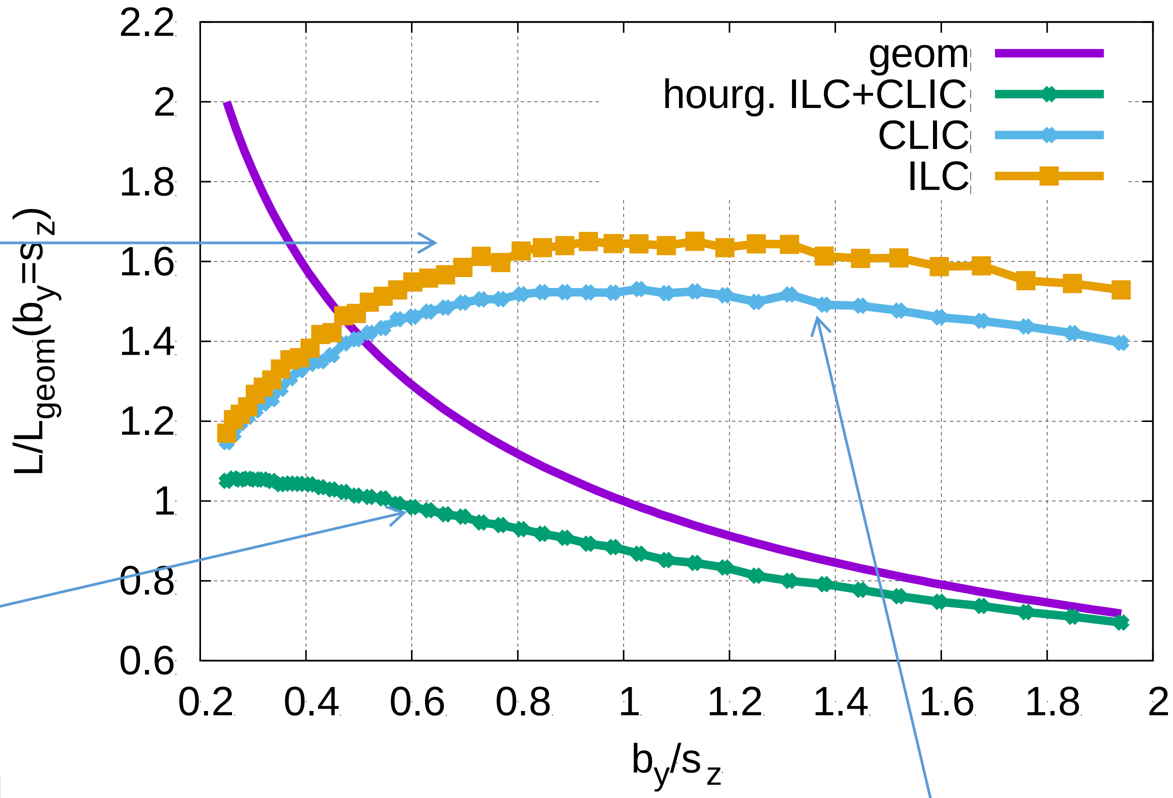
Use $L_{0.01}$/L=60% as criterion
Reasonable compromise for most physics studies

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

Vertical Optimum

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