High-Luminosity CLIC Studies

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Baseline Parameters at 380 GeV

- The baseline design for CLIC at 380 GeV is described in detail in the Project Implementation Plan.

- The key beam parameters are:

Parameter	Symbol	Unit	Stage 1
Centre-of-mass energy	E_{CM}	GeV	380
Particles per bunch	N	10^9	5.2
Train repetition frequency	f_{rep}	Hz	50
Bunches per train	n_b		352
Bunch spacing	Δt_b	ns	0.5
Accelerating gradient	G	MV/m	72
Site length		km	11.4
Horizontal/vertical IP beam size	σ_x^*/σ_y^*	nm	150/3
Luminosity	$\mathcal{L}$	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.5

Beam Parameter Choices and Luminosity

- Luminosity of a linear e^+e^- collider: $\mathscr{L} = \frac{H_D}{4\pi}\frac{N}{\sigma_x}\frac{1}{\sqrt{\beta_y\epsilon_y}}Nn_bf_{\text{rep}}$.
- Most of these factors are fixed by various constraints:
  - $\frac{N}{\sigma_x}$ is proportional to the number of beamstrahlung photons.
  - N is limited by emittance growth due to short-range wakefields.
  - n_b is limited by long-range wakefields and RF pulse length.
  - f_{rep} is limited by power consumption.
  - β_y must be greater than the bunch length to avoid luminosity loss from the hourglass effect.
  - We make ϵ_y as small as possible.

Options for Increasing Luminosity

- In this talk we will look at two options for increasing the luminosity above the baseline:
  - Lowering the vertical emittance:
    - The baseline normalised vertical emittance at the interaction point is 30 nm. Can we do better?
  - Increasing the repetition frequency:
    - Can we double the luminosity by doubling the repetition frequency?
- These options are discussed in: [CLIC Note 1143](#).

Lower Vertical Emittance

- The beam is transported from the source to the interaction point through four systems:
    - The Damping Ring
    - The Ring to Main Linac (RTML)
    - Main Linac (ML)
    - Beam Delivery System (BDS)
- Emittance preservation is important in the RTML, ML and BDS.
    - Strict emittance growth budgets have been defined to ensure we reach the baseline luminosity:

Section	ϵ_x **[nm]**	$\Delta\epsilon_x$ **[nm]**			ϵ_y **[nm]**	$\Delta\epsilon_y$ **[nm]**		
		Design	**Static**	**Dynamic**		**Design**	**Static**	**Dynamic**
DR	700	-	-	-	5	-	-	-
RTML	850	100	20	30	10	1	2	2
ML	900	0	25	25	20	0	5	5
BDS	950	0	25	25	30	0	5	5

Integrated Simulations with Static and Dynamic Imperfections

- Comprehensive simulation studies were recently published:
    - Phys. Rev. Accl. Beams 23, 101001 (2020).
- The RTML, ML and BDS were combined into a single tracking simulation.
- Static and dynamics imperfections were simulated.
- The effectiveness of different tuning procedures was evaluated.

- Simulating a perfect collider (no imperfections) a luminosity of 4.3×10^{34} cm^{-2}s^{-1} would be achieved.

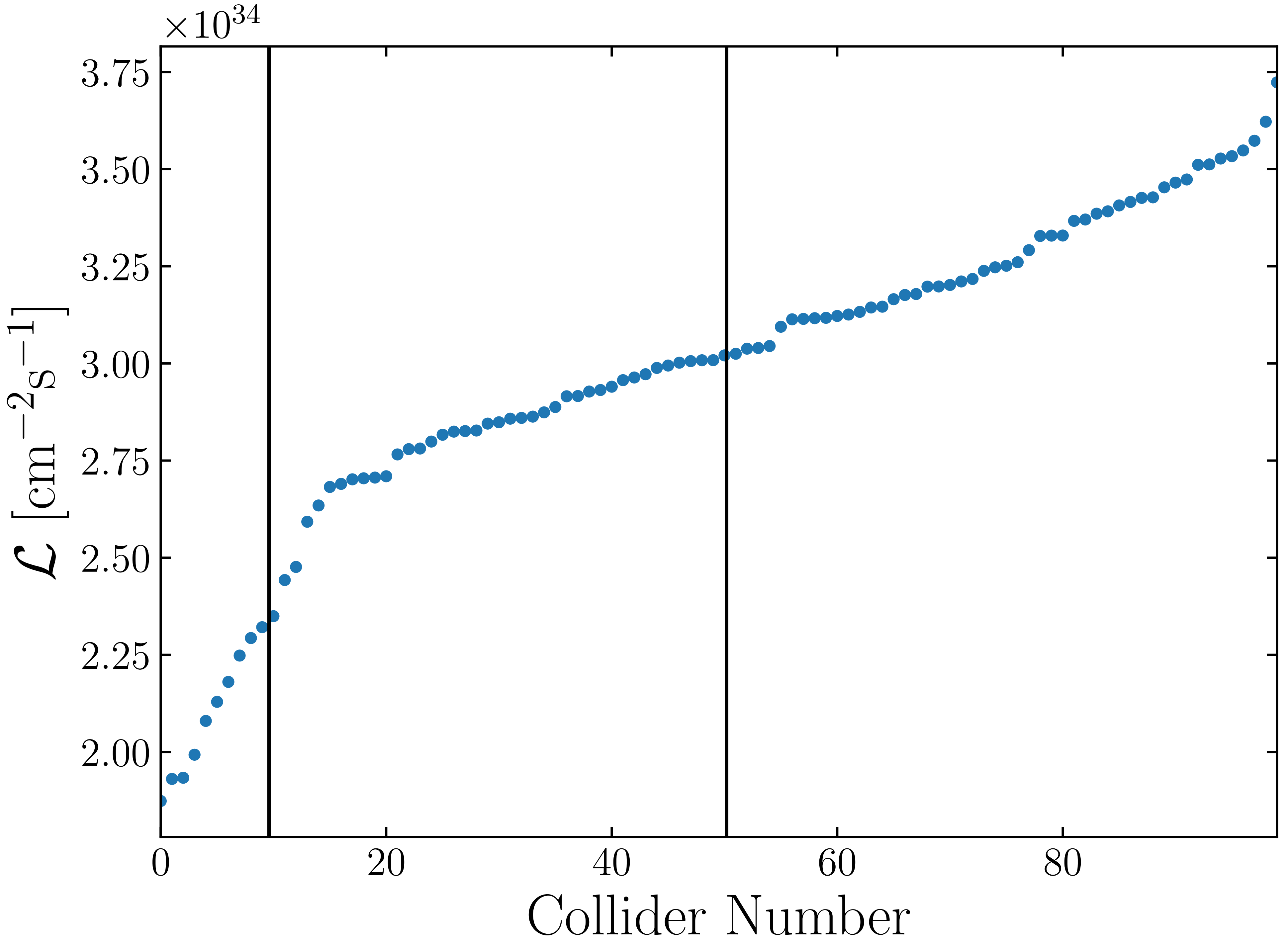
Integrated Simulations with Static Imperfections

Section	Imperfection	Value
RTML		
	Magnet and BPM offset	30 μm
	Magnet and BPM roll	100 μrad
	BPM resolution	1 μm
	CA and TA quadrupole strength errors	0.01%
	All other magnet strength errors	0.1%
ML		
	Magnet and BPM offset	14 μm
	Magnet and BPM roll	100 μrad
	BPM resolution	0.1 μm
	Magnet strength errors	0.01%
	Girder end point with respect to reference wire	12 μm
	Girder end point with respect to articulation point	5 μm
	Accelerating structure offset	14 μm
	Accelerating structure tilt	141 μrad
	Wakefield monitor offset	3.5 μm
BDS		
	Magnet and BPM offset	10 μm
	Magnet and BPM roll	100 μrad
	BPM resolution	20 nm
	Magnet strength errors	0.01%

- The following tuning procedures were also simulated:
  - 121 steering
  - DFS
  - RF realignment / Sextupole tuning

Integrated Simulations with Static Imperfections

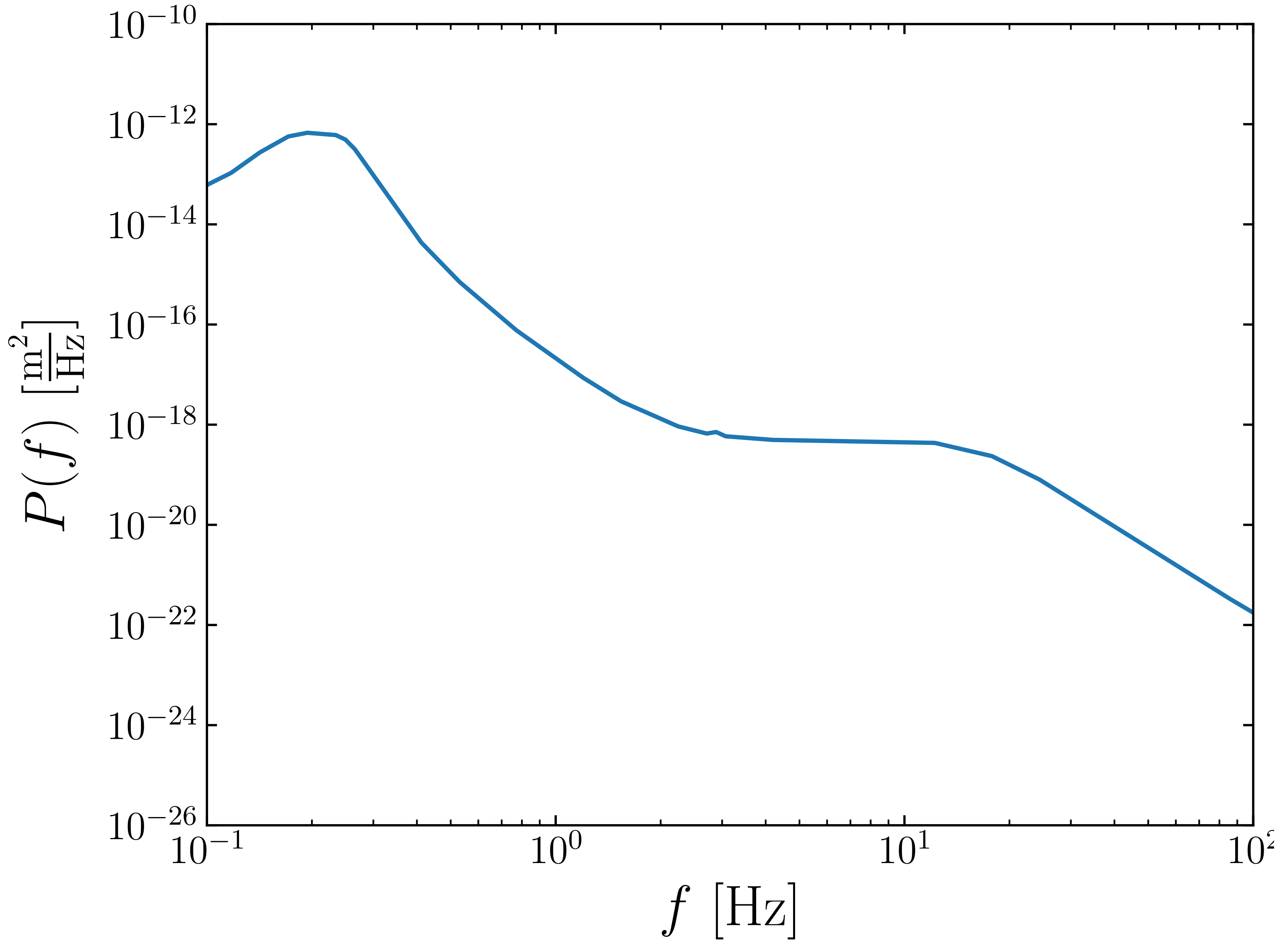
- Luminosity of 100 tuned colliders with static imperfections:
    - 90% of colliders have a luminosity above 2.35×10^{34} cm^{-2}s^{-1}.
    - The average collider achieves a luminosity of 3×10^{34} cm^{-2}s^{-1}.



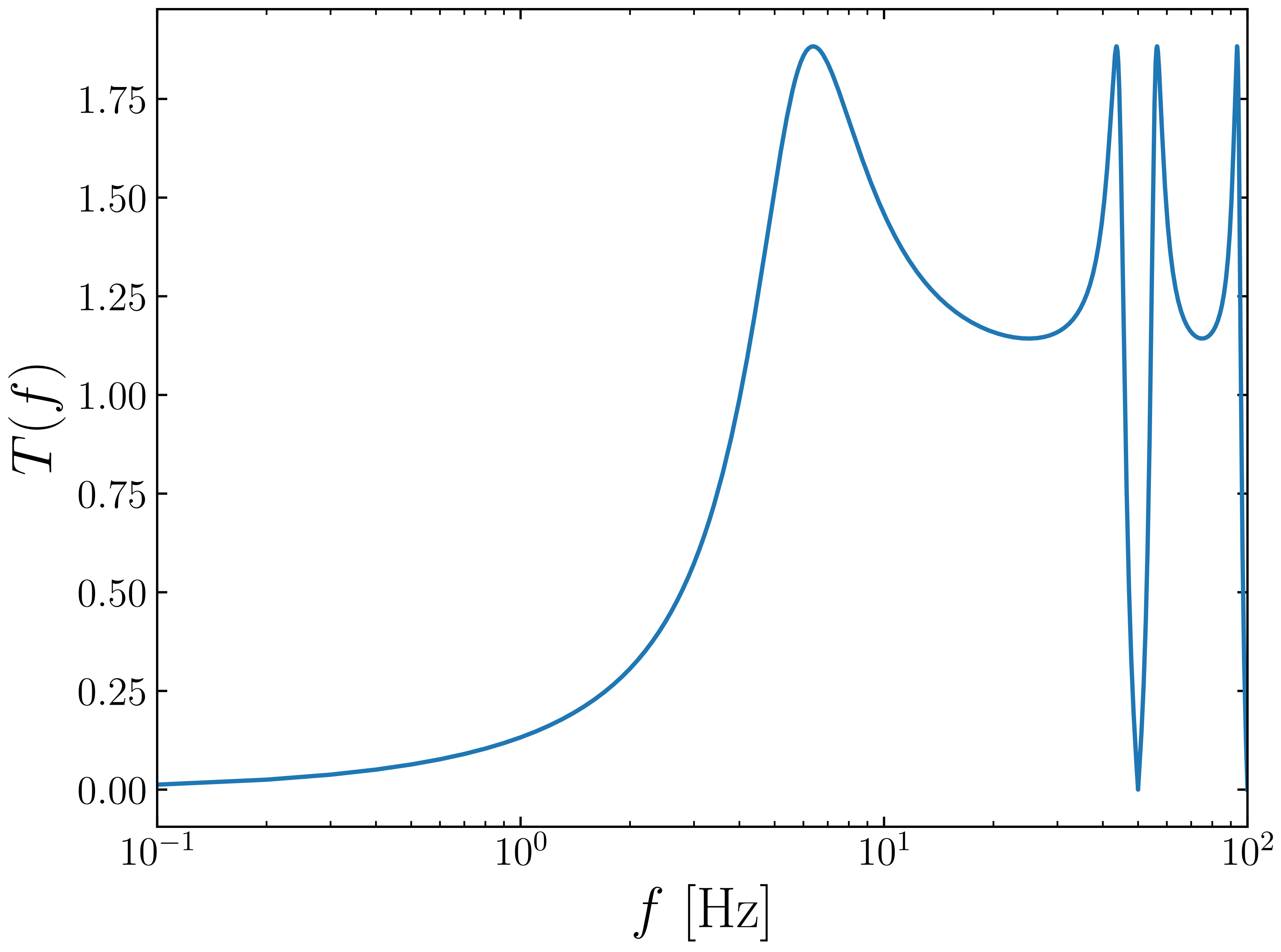
Integrated Simulations with Static Imperfections and Ground Motion

- Including ground motion:
  - Using model D.
    - This is a pessimistic assumption.
- Including mitigation systems:
  - A beam feedback system.
  - A quadrupole stabilisation system.

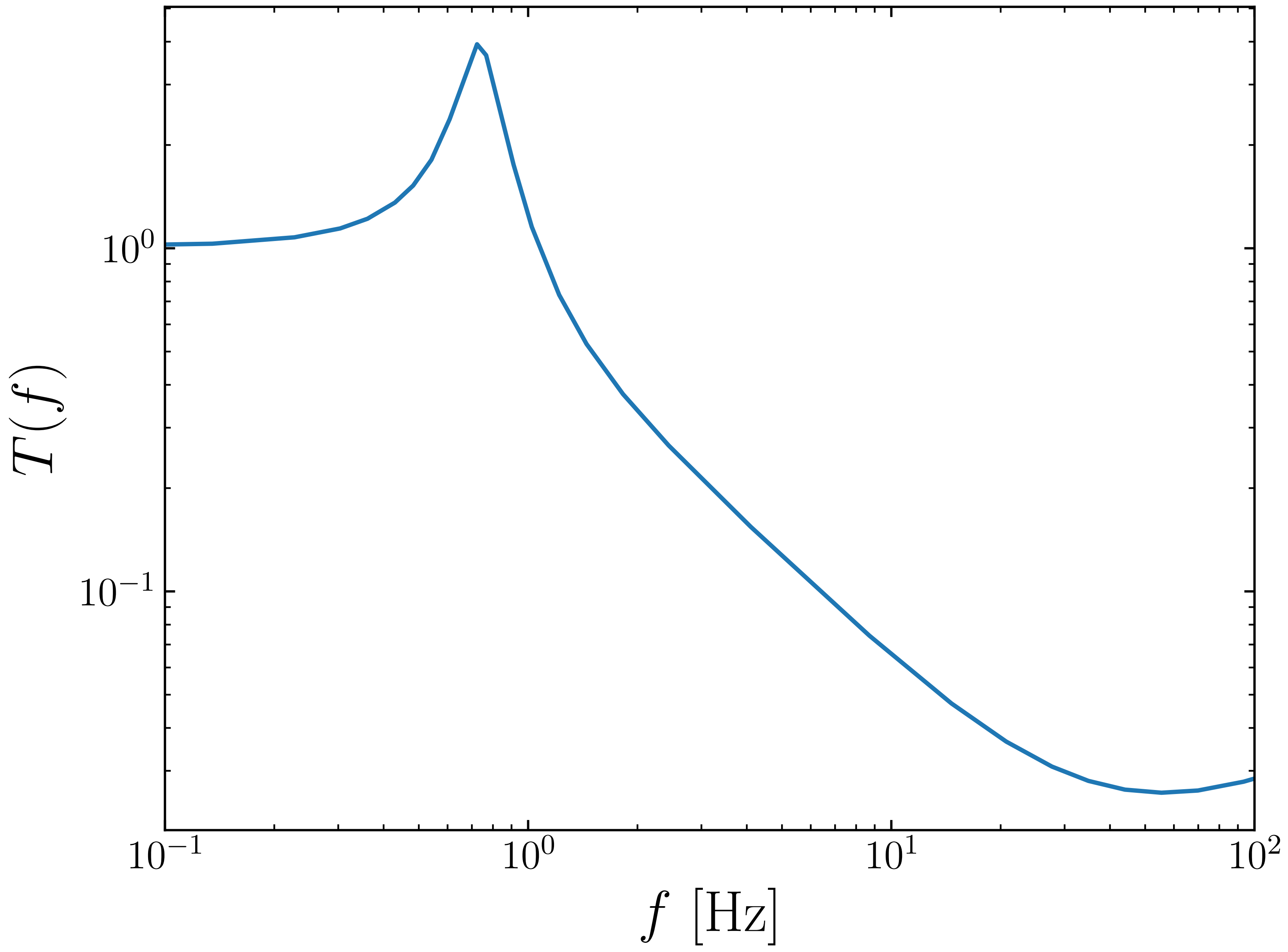
GM PSD



Beam Feedback Transfer Function

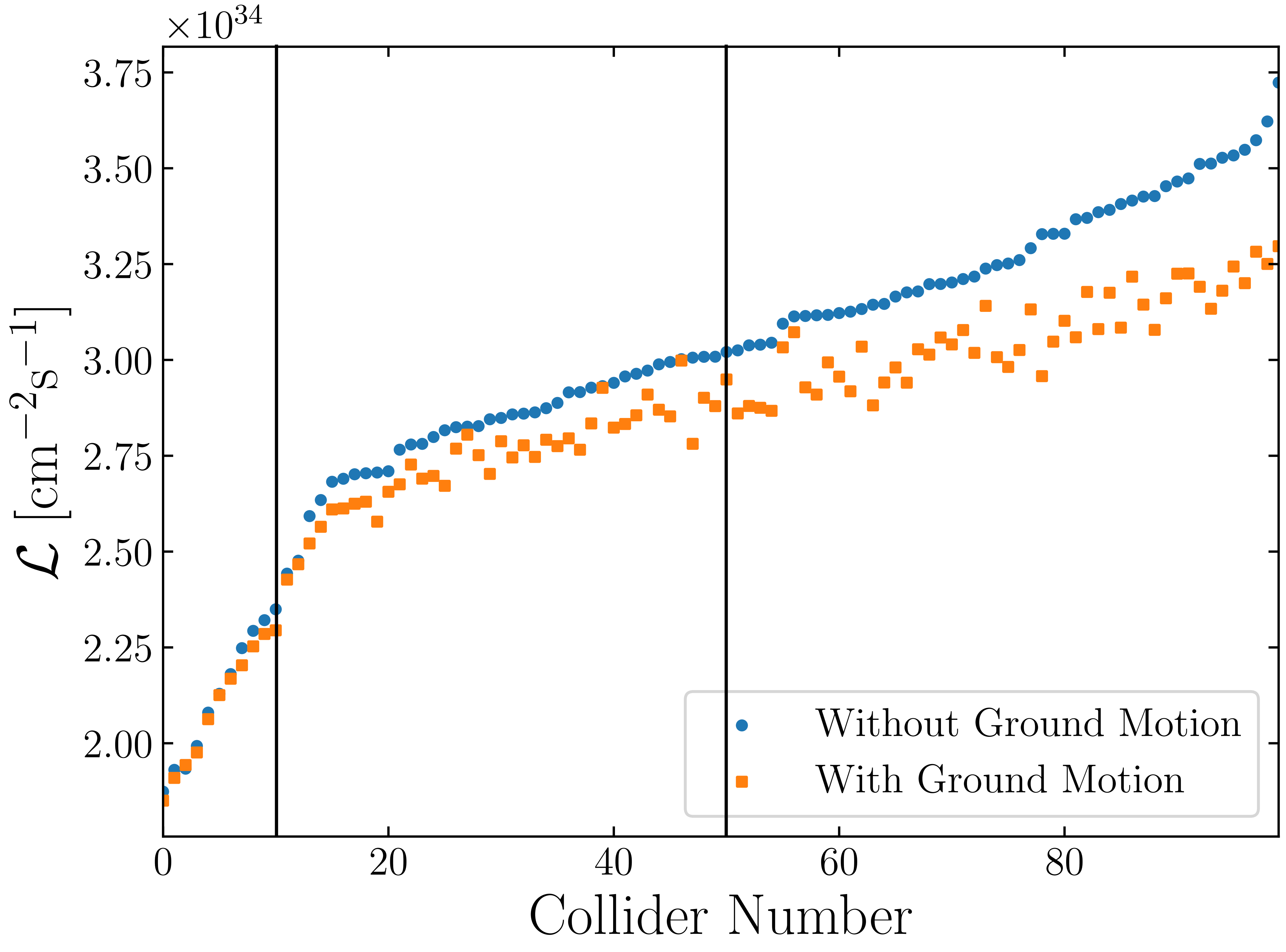


Quadrupole Stab. Transfer Function



Integrated Simulations with Static Imperfections and Ground Motion

- Luminosity 100 tuned colliders with ground motion model D:
  - 90% of colliders achieve a luminosity above 2.3×10^{34} cm^{-2}s^{-1}.
  - The average collider achieves a luminosity of 2.8×10^{34} cm^{-2}s^{-1}.
  - We have a large reserve for other dynamic imperfections and/or other unforeseen imperfections.



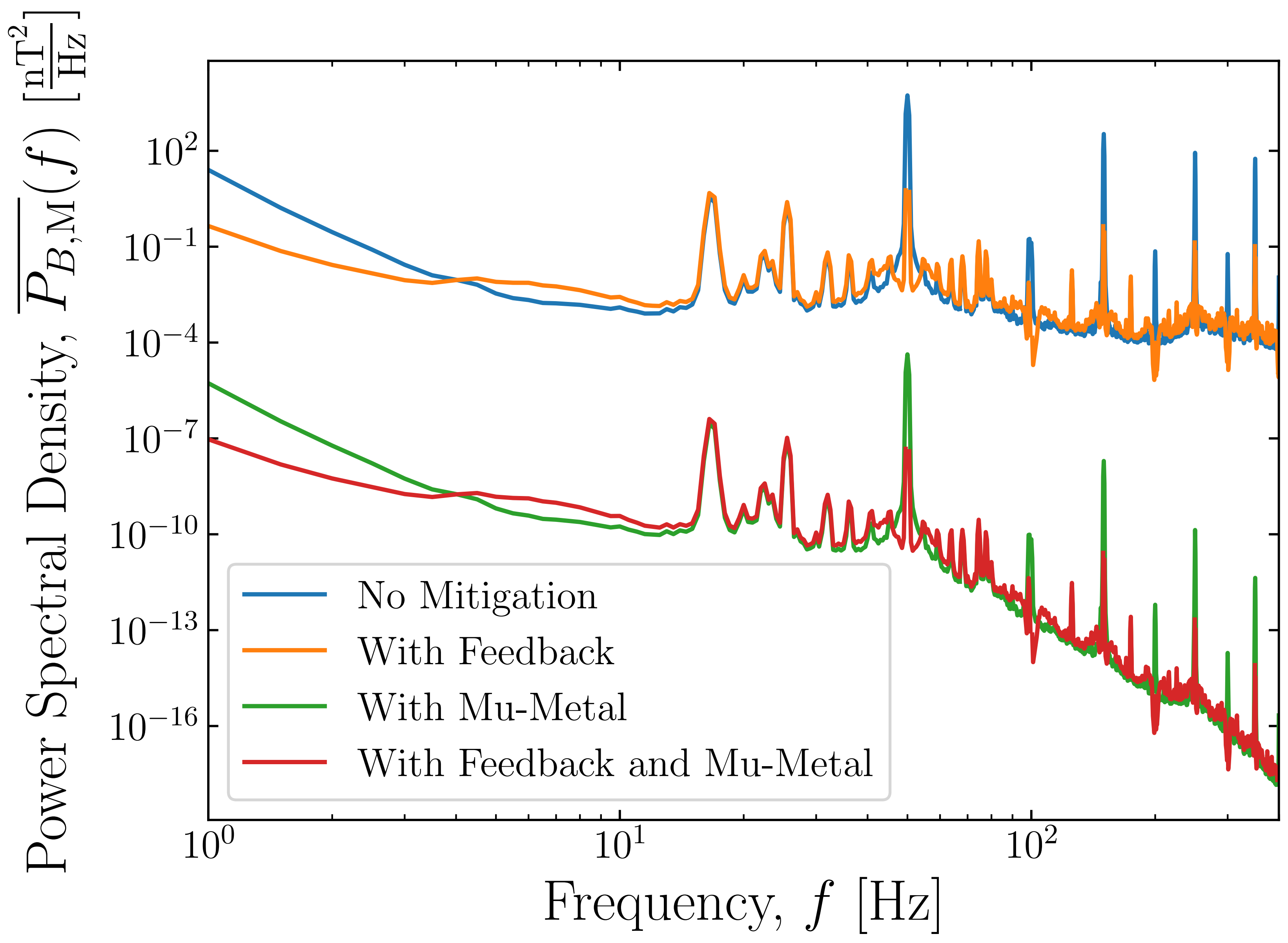
Higher Repetition Frequency

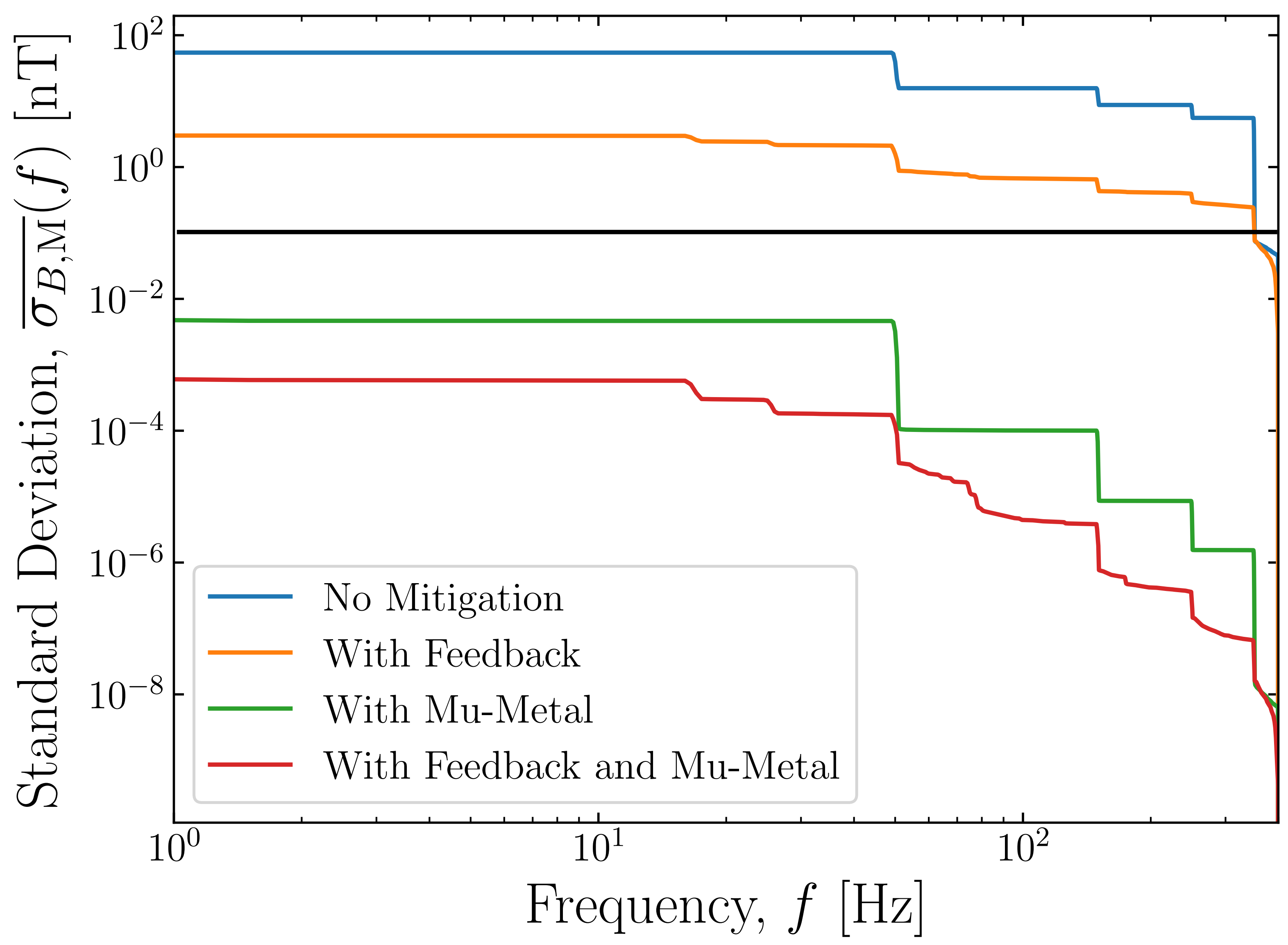
- Technologically, we can double the repetition frequency with are a relatively small increase in overall power consumption.
  - The cost increase is expected to be at the ~5% level.

- The choice of $f_{\mathrm{rep}} = 50$ Hz was driven by the presence of external dynamic magnetic fields, termed ‘stray fields’.
  - The electrical grid in Europe operates at 50 Hz.
  - There will be large amplitude stray fields at 50 Hz that will be seen by the beam.
  - Operating at $f_{\mathrm{rep}} = 50$ Hz reduces our sensitivity to these stray fields.
  - Operating at $f_{\mathrm{rep}} = 100$ Hz, the beam is able to resolve these stray fields.

Stray Magnetic Fields

- CLIC has a sensitivity to O(0.1) nT stray fields in a worst-case scenario.
- An extensive measurement campaign was undertaken at CERN to characterise stray magnetic fields.
  - c.f. DPhil Thesis, Dynamic Imperfections in the Compact Linear Collider.
- Stray fields were measured in the LHC tunnel:

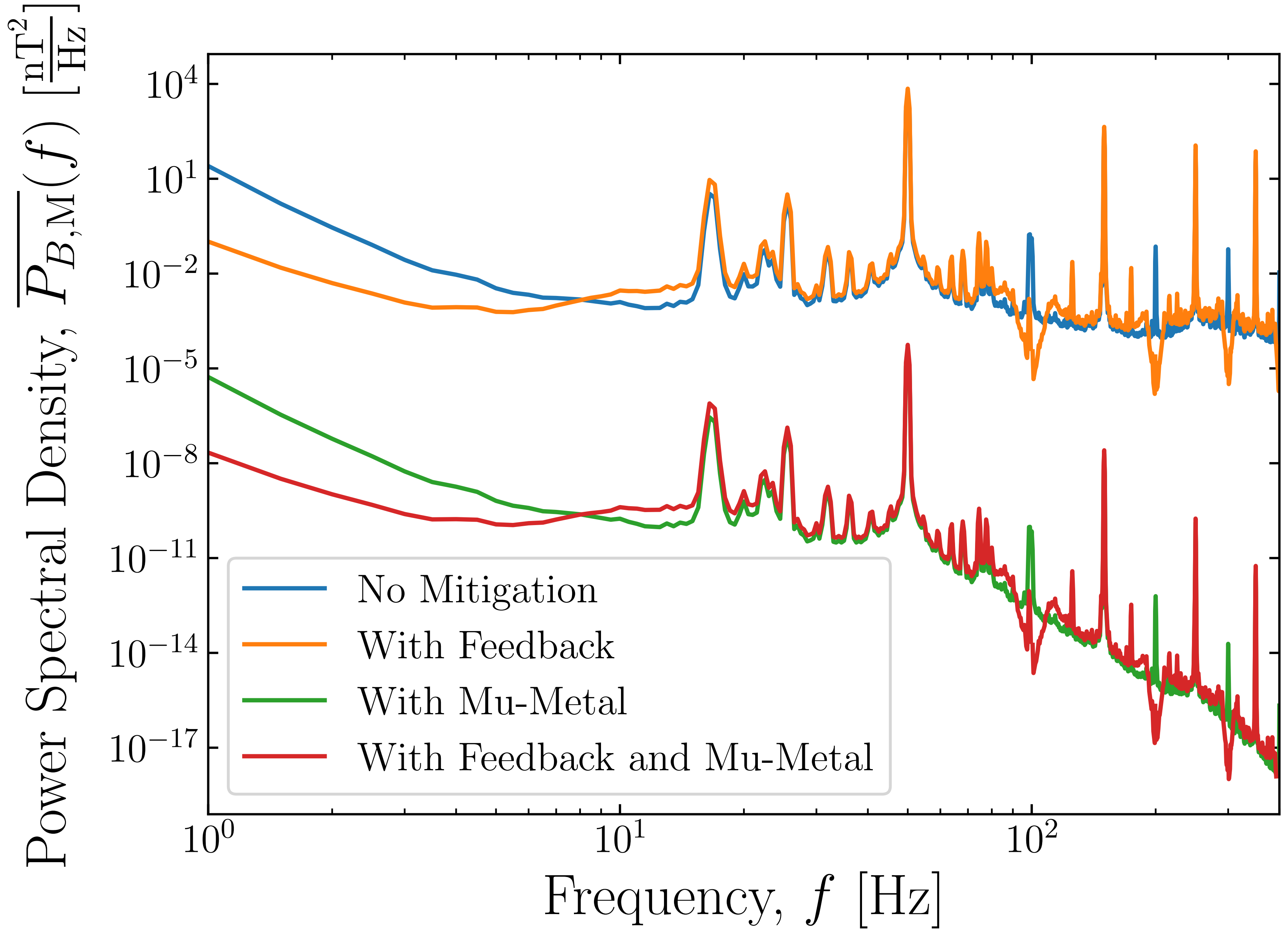


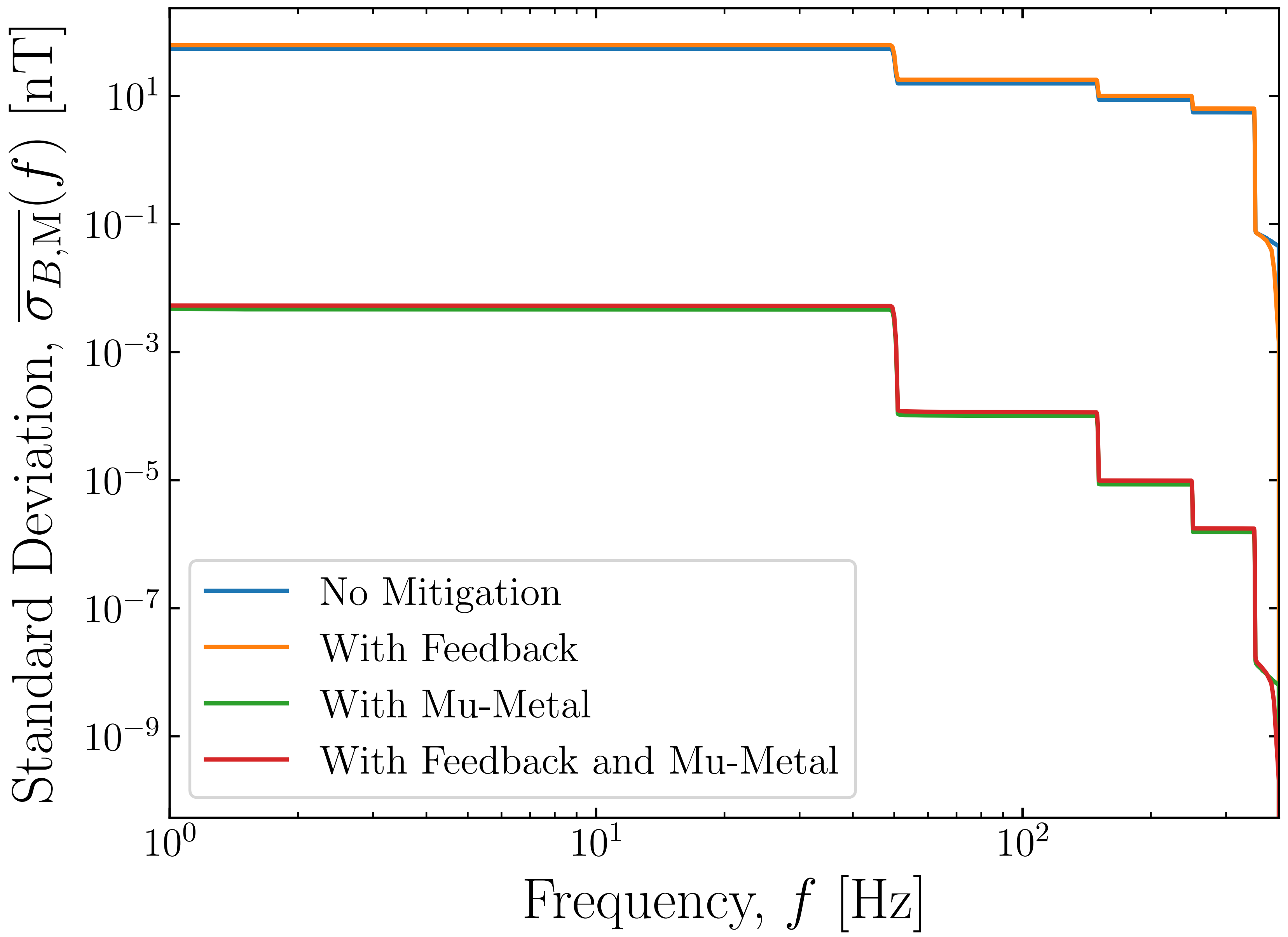


Without mitigation, we are an order of magnitude above the tolerance.

Mitigation of Stray Magnetic Fields with Mu-Metal

- Shielding the beam pipe with mu-metal is an effective strategy for mitigating stray magnetic fields.
- At $f_{\text{rep}} = 100$ Hz, the feedback system will amplify perturbations to the beam at 50 Hz.
- Effective stray field in the LHC tunnel with a feedback operating at 100 Hz:





Even with the amplification the mu-metal shield is effective at mitigating the stray fields.

Other Considerations

- Drive beam complex:
  - Modulators:
    - Charging supplies of the modulators would need to double in capacity.
    - Technologically straightforward - matter of cost.
  - Drive beam combination kickers:
    - Need to be redesigned, but this is expected to be straightforward.
  - Decelerator beam dumps:
    - Needs to be dimensioned for twice the power.
- Main beam complex:
  - Twice the heat will be deposited in the ML structures.
    - Cooling and ventilation systems must be improved.
- The detector must also be able to cope with the higher repetition frequency

Summary

- Integrated simulations with static imperfections and ground motion. show the average collider can achieve a luminosity of 2.8×10^{34} cm^{-2}s $- 1$.
  - Almost twice the baseline target.
- Integrated simulations of stray magnetic fields are discussed in: Phys. Rev. Accl. Beams 23, 011001 (2021).
  - Shows stray fields should not be a problem if a mu-metal shield is included in the design.
- A high-luminosity design is feasible provided stray magnetic fields are mitigated with a mu-metal shield.