# Mitigation Concepts

C. Gohil, E. Marin, D. Schulte, M. Buzio

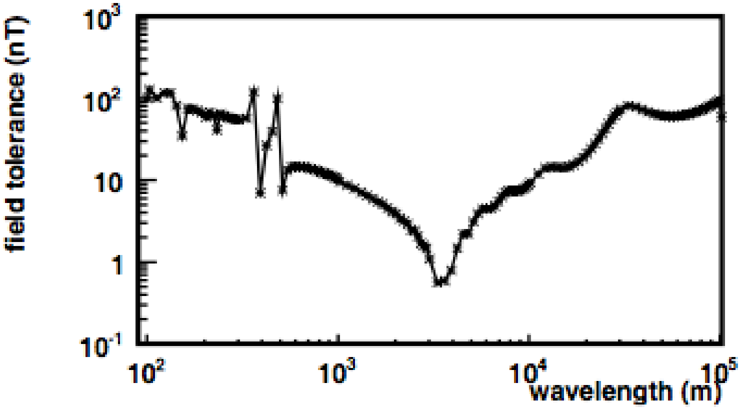
CERN

# Contents

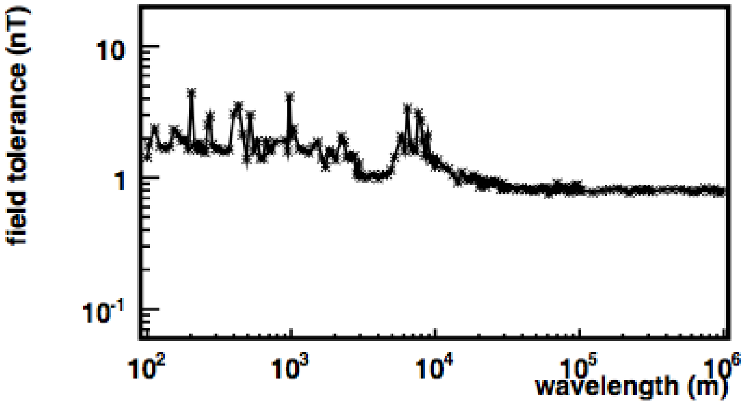
# Recap

# CLIC Simulations

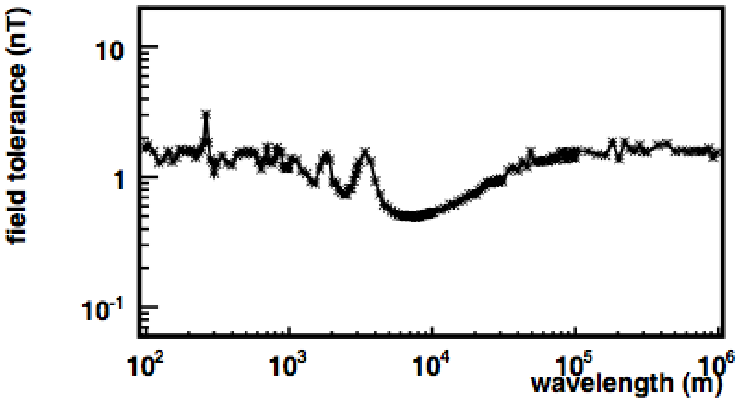
- Simulations show a stray field sensitivity down to the nT level.



RTML Transfer Line



BDS



Main Linac

Field tolerance for 0.4 nm emittance growth

Field tolerance for 2% luminosity loss

# Sources of Stray Fields

- Not all stray fields have equal importance.
- Frequencies less than 1 Hz will be reduced by the train-to-train feedback.
- Not sensitive to 50 Hz because $f_{rep} = 50$ Hz (removed by tuning).

| Type | Examples | Amplitude | Frequency |
|---|---|---|---|
| Natural | Geomagnetic storms | O(100 nT) | < 1 Hz |
| Environmental | Power lines | O(nT) | 50 Hz |
| Technical | RF systems, etc. | O($\mu$T) | > 1 Hz |

# Mitigation

# Active vs. Passive

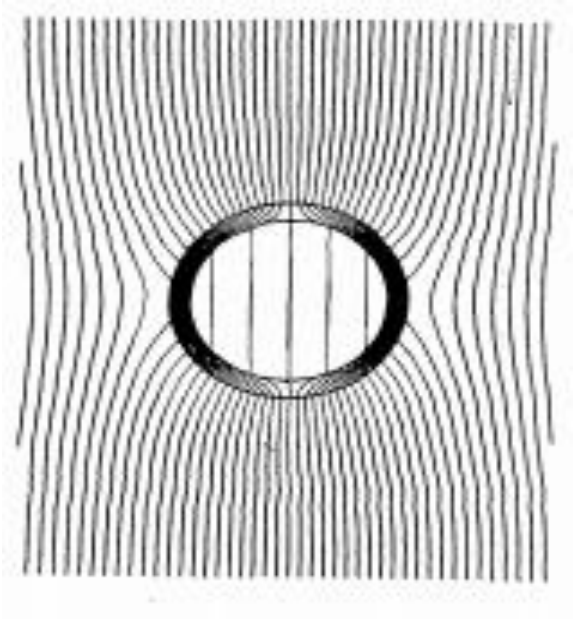
- Involves measuring a quantity in real-time.
- Using this measurement to influence the accelerator with an active device.
- Feedback and feedforward possible.

- Requires no measurement.
- A passive device just needs to be placed into the accelerator.
- Removes the need for a correction.

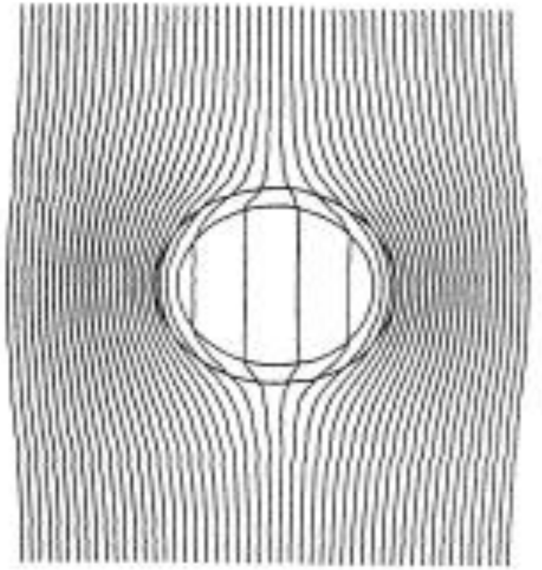
# Passive Mitigation

# Passive Shielding - Mechanisms

- There are two mechanisms of shielding magnetic fields:



Magnetostatic shielding



Eddy current shielding

# Passive Shielding - Considerations

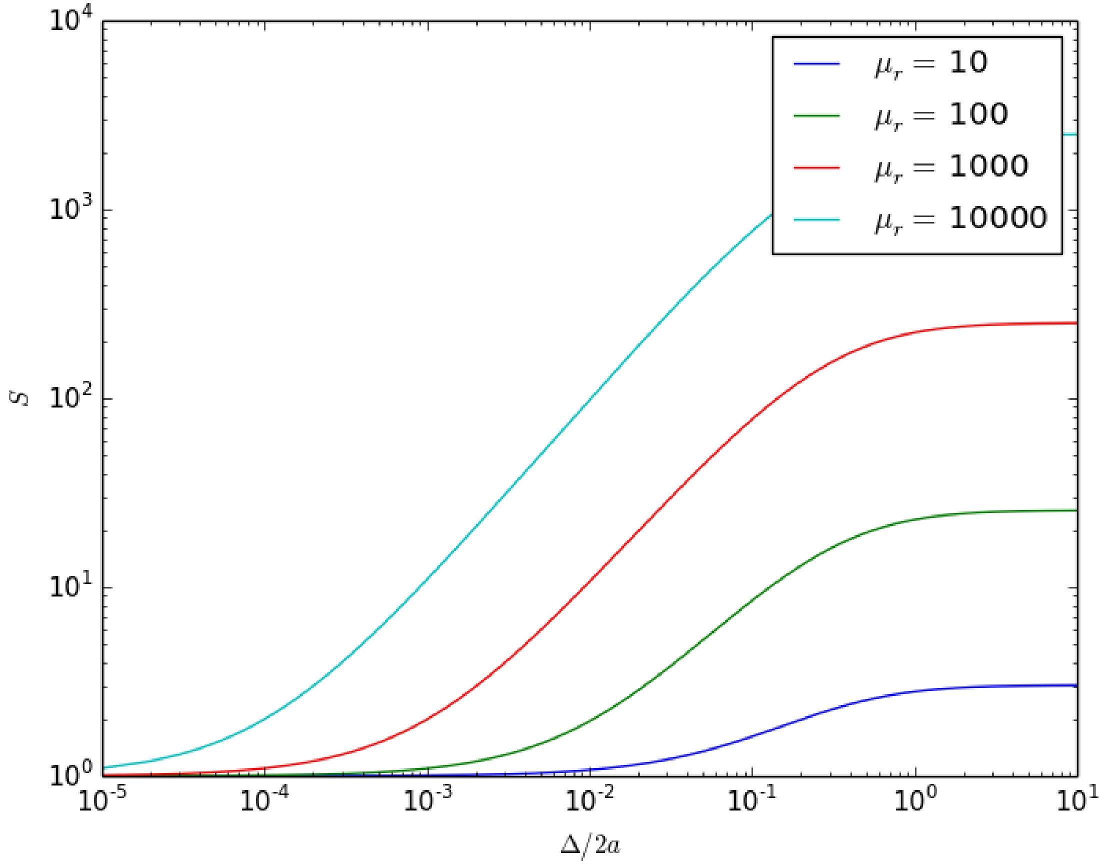
- The effectiveness of a magnetic shield depends on:
    - Shape geometry.
    - Material properties: $\mu, \sigma$.
    - Frequency of external magnetic field: affects material properties.
    - Strength of external magnetic field.
- These parameters also determine which mechanism is dominant.

# Passive Shielding – Magnetostatic Shielding

- The effectiveness of magnetostatic shielding of a cylindrical shell is given by

$$S = \frac{(\mu_r + 1)^2 - \dfrac{(\mu_r - 1)^2}{4(\frac{\Delta}{2a})^2 + 4\left(\frac{\Delta}{2a}\right) + 1}}{4\mu_r}$$

- This increases with permeability and ratio of thickness $\Delta$ to radius $a$.



# Passive Shielding – Eddy Current Shielding

- To be effective the thickness of the shield must be greater than the skin depth:

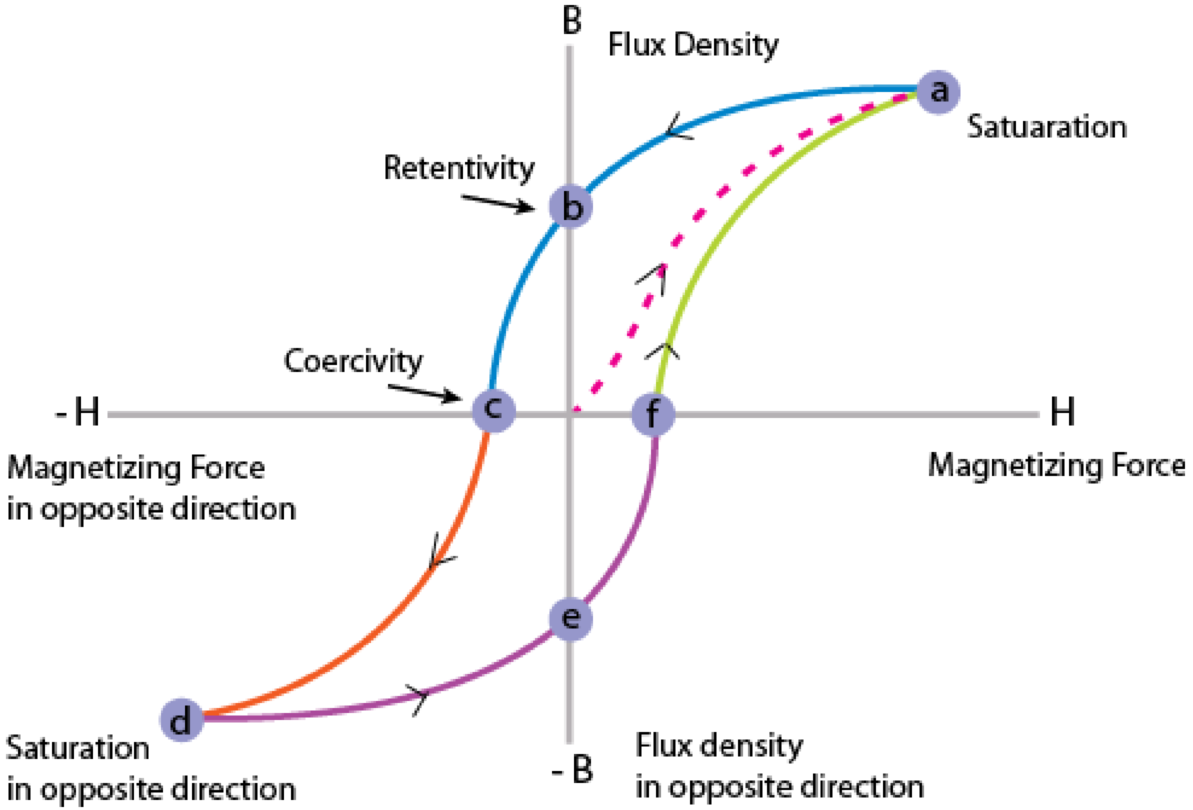
$$\delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \sigma}}$$

- $\sigma =$ conductivity
- $\mu = \mu_0 \mu_r =$ permeability
- $\omega =$ frequency

- Effectiveness increases with frequency, permeability and conductivity.

# Passive Shielding – Permeability

- Permeability of ferromagnetic materials varies greatly with magnetic field strength.
- Data of permeability for weak magnetic fields O($\mu$T, nT) not easily found.
- Is there a minimum external field required for shielding?



# Passive Shielding – Material Choice

- High permeability :
  - ferromagnetic materials, such as Ni-Fe alloys: mu-metals, permalloys.
- Highly conductive:
  - Silver, Copper, high temp. superconductor
  - would be effective for high frequency magnetic fields.
- Must be effective in mitigating weak magnetic fields.
  - Currently unclear.

# Passive Shielding - Copper

- Coating the beam pipe with 2 mm of copper:

$$\omega = \frac{2}{\mu\sigma\delta^2}$$

- $\sigma = 5.9 \times 10^7$ S/m
- $\mu = 1.26 \times 10^{-6}$ H/m

- Frequencies greater than $\omega = 6.6$ kHz will have field strength diminished by 1/e.
- To attenuate frequencies down to 1 Hz requires 16 cm of copper.

# Passive Shielding – Ferromagnetic Materials

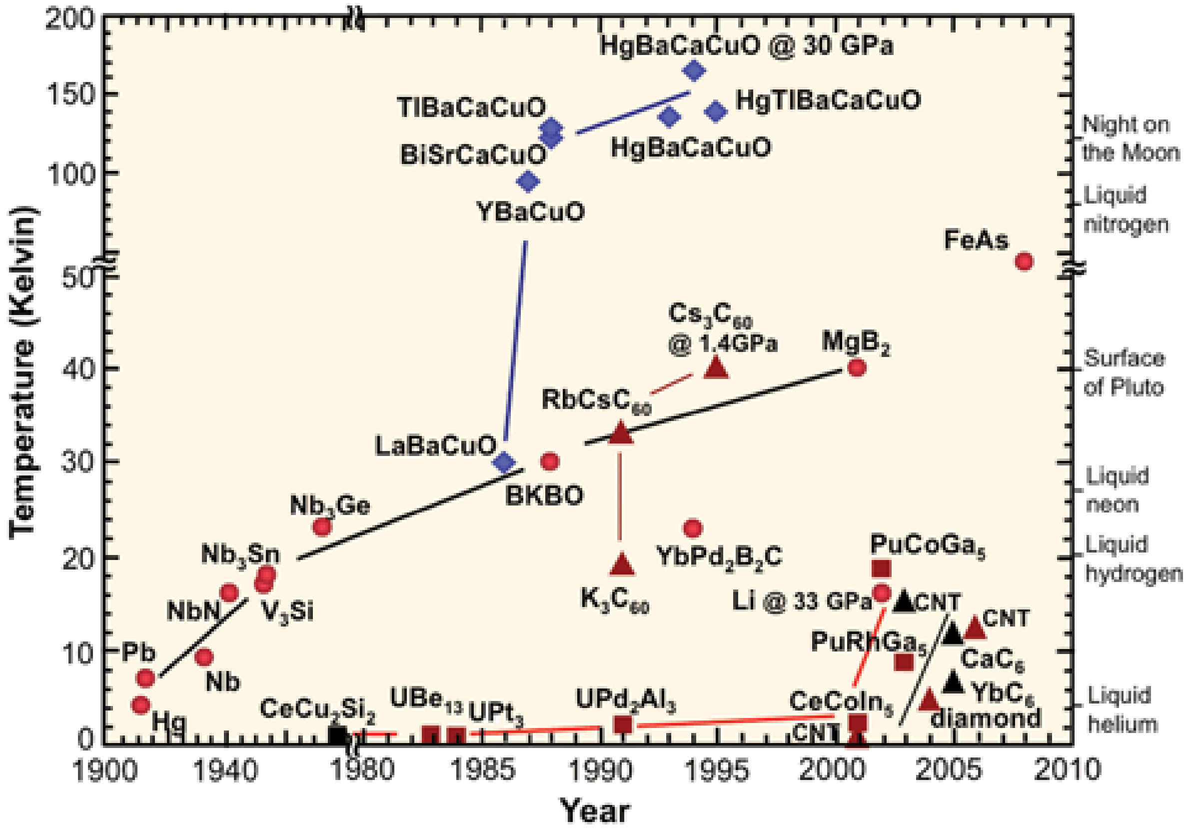
- For frequencies less than O(kHz) large amounts of Copper required.
- Better to use a high permeability material.
- Mu-metals have:
  - $\mu_r$~O(10 000).
  - $\sigma \sim 10^7$ S/m

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \sigma}}$$

- For $\omega = 1$ Hz, $\delta =$1.3 mm.

# Passive Shielding - Superconductors

- Have a $\sigma = \infty$, therefore could attenuate all frequencies.
- High temperature superconductors: $Bi_2Sr_2Ca_2Cu_3O_{10}$, $Tl_2Ba_2CaCu_2O_8$, $HgBa_2CaCu_2O_6$, etc. are superconducting above 100 K.
- Still far away from room temperature.



# Passive Shielding – Comparison of Materials

| **Material** | **Advantages** | **Disadvantages** |
|---|---|---|
| Conductive materials:<br>E.g. Copper/Silver | - Effective for high frequencies | - Expensive.<br>- Not effective for low frequencies |
| Ferromagnetic materials:<br>E.g. Mu-metals/Permalloys | - High permeability<br>- Good frequency range | - Not effective for weak fields?<br>- Availability |
| High temperature superconductors | - Would attenuate all frequencies | - Expensive<br>- Availability<br>- Temperature requirements |

- Comments:
  - There is always a residual field.
  - Mechanical imperfections can lead to inhomogeneous fields inside the shield.

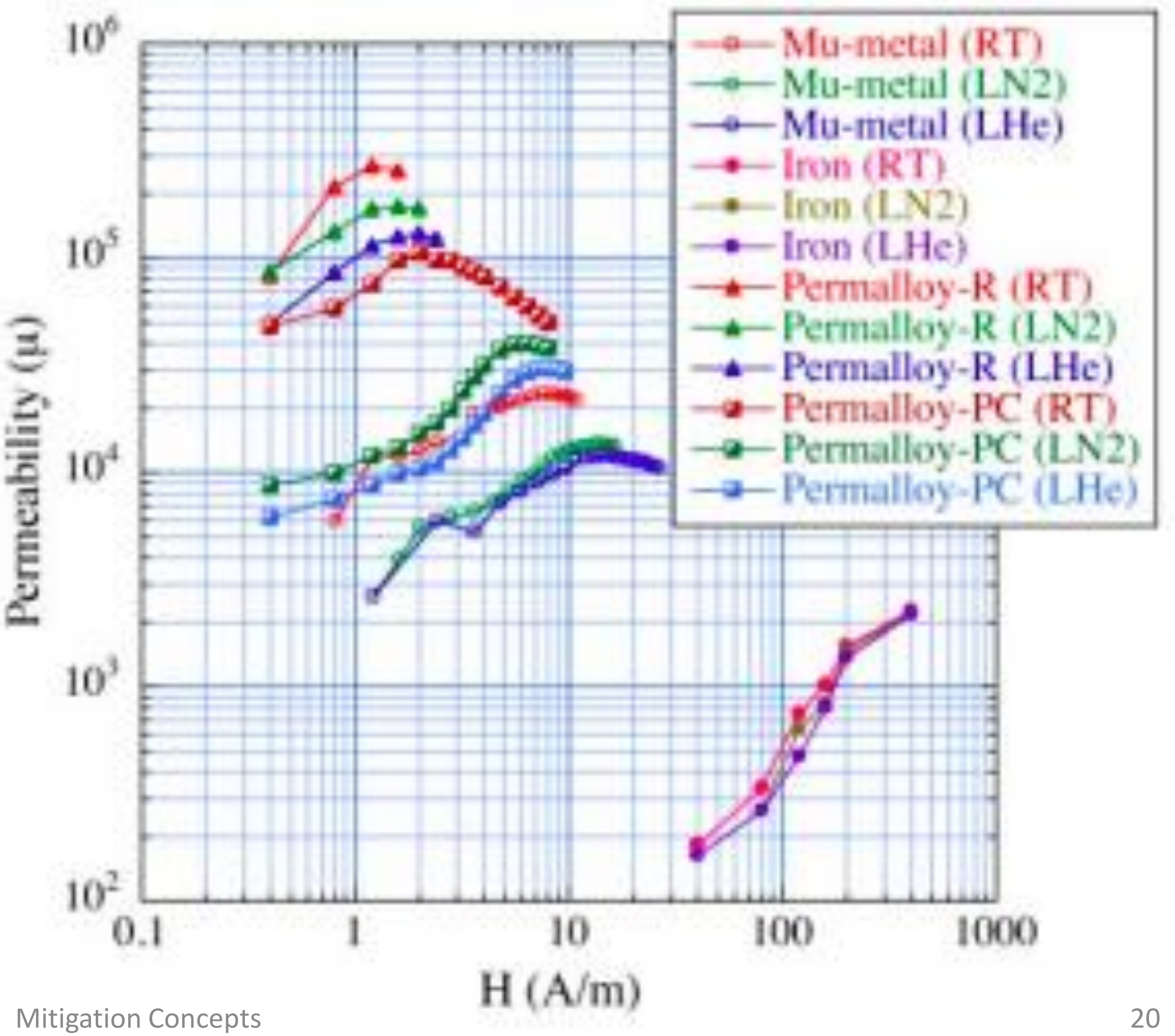
# Passive Shielding – Superconducting Cavities

- DC magnetic fields in the vicinity of superconducting cavities for the ILC lead to power losses – lowers Q.
- Magnetic shields to protect against the Earth's magnetic field are being investigated at KEK by:

Tsuchiya K., Higashi Y., Hisamatsu H., Masuzawa M., Matsumoto H., Mitsuda C., Noguchi S., Ohuchi N., Okamura T., Saito K., Terashima A., Toge N., Hayano H. Proc. EPAC' 2006 (Edinburgh, Scotland, 2006) pp 505–507.

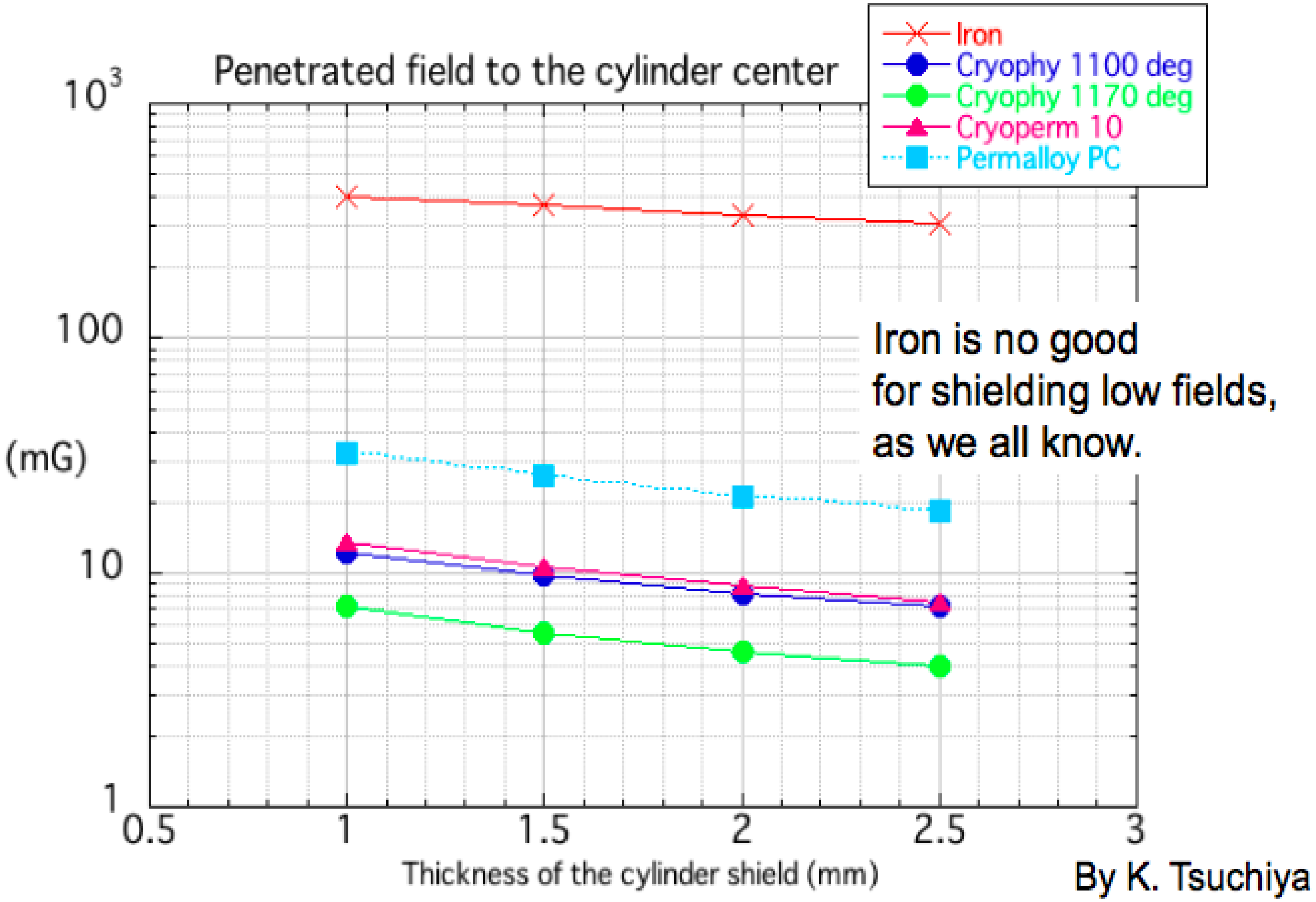
# Passive Shielding – Superconducting Cavities

- They have measured relative permeability at room temp. as well as at cryogenic temp.
- Iron: $\mu_r \sim 1000$
- Mu-metal: $\mu_r \sim 10\,000$
- Permalloy: $\mu_r \sim 100\,000$



# Passive Shielding – Superconducting Cavities

- They also measured the effectiveness of magnetic shields in DC fields.
- External magnetic field of 0.5 G = 50 $\mu$T (Earth).
- Cylinder of diameter 1.1 m and varying thickness.
- Iron: $B_{int}\sim 35\ \mu$T
- Permalloy-PC: $B_{int}\sim 12\ n$T



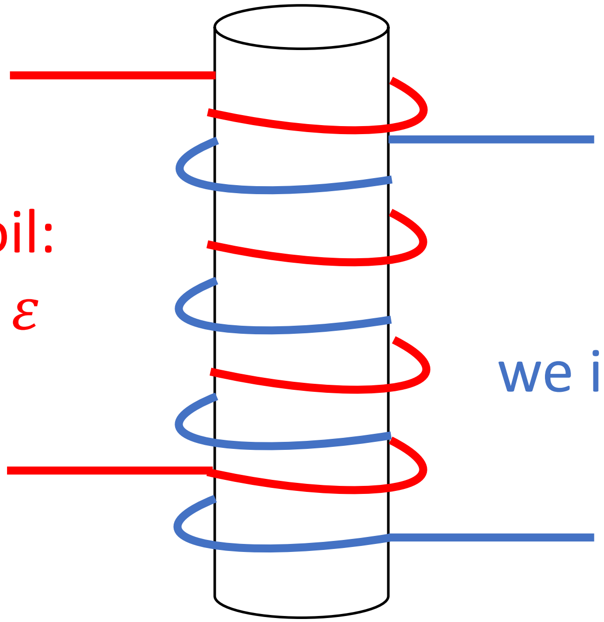
# Active Mitigation

# Active Compensation

- The train-to-train feedback system for CLIC is optimised for ground motion.
- Will remove the effects of stray fields of less than 1 Hz.
- An alternative to a beam-based feedback is to correct the stray field itself.

# Active Compensation – Two Coil Scheme

- Measure magnetic field variations with one coil – the measurement coil.
- Correct the magnetic field variations with another coil – the corrector coil.



Measurement coil:
records voltage $\varepsilon$

Corrector coil:
we induce voltage $\varepsilon_{corr}$

# Active Compensation – Two Coil Scheme

- If the measurement coil has a sampling frequency of $f = \frac{1}{\Delta t}$ then the voltage measured at time $t = i\Delta t$ is

$$\boxed{\varepsilon_i = -NA\mu_e f \Delta B_i}$$

- $N$= number of turns
- $A$= cross-sectional area
- $\mu_e$= effective permeability
- $\Delta B_i$= stray field

# Active Compensation – Two Coil Scheme

- The magnetic field generated by a solenoid is given by

$$B = \frac{\mu_e N I}{L}$$

- $N$= number of turns
- $\mu_e$= effective permeability
- $I$= current
- $L$= length

$$\boxed{\Delta B_{corr,i} = \frac{\mu_e N}{L} \Delta I_i}$$

# Active Compensation – Two Coil Scheme

- The measurement coil sees both the stray field and the corrector:

$$\varepsilon_i = -NA\mu_e f \Delta B_i \qquad \boxed{\Delta B_i = \Delta B_{stray,i} + \Delta B_{corr,i}}$$

Known from $\varepsilon_i$

Known because we calculated this

- If we impose $\Delta B_{corr,i+1} = -\Delta B_{stray,i}$ we find

$$\boxed{\Delta B_{corr,i+1} = \Delta B_{corr,i} - \Delta B_i}$$

# Active Compensation – Two Coil Scheme

- We can use $\Delta B_{corr,i+1} = \Delta B_{corr,i} - \Delta B_i$ to derive the change in current we should put on the corrector coil:

$$\frac{\mu_e N \Delta I_{i+1}}{L} = \frac{\mu_e N \Delta I_i}{L} + \frac{\varepsilon_i}{N A \mu_e f} \quad \Longrightarrow \quad \boxed{\Delta I_{i+1} = g\varepsilon_i + \Delta I_i}$$

where $g = \dfrac{L}{\mu_e^2 N^2 A f}$

# Active Compensation – Two Coil Scheme

- To work out voltage, model the corrector coil as a $\mathcal{LR}$-circuit:

$$V(t) = \mathcal{R}I(t) + \mathcal{L}\frac{dI(t)}{dt}$$

$$\Longrightarrow \quad \boxed{V_{corr,i+1} = \mathcal{R}I_{corr,i+1} + \mathcal{L}f\Delta I_{corr,i+1}}$$

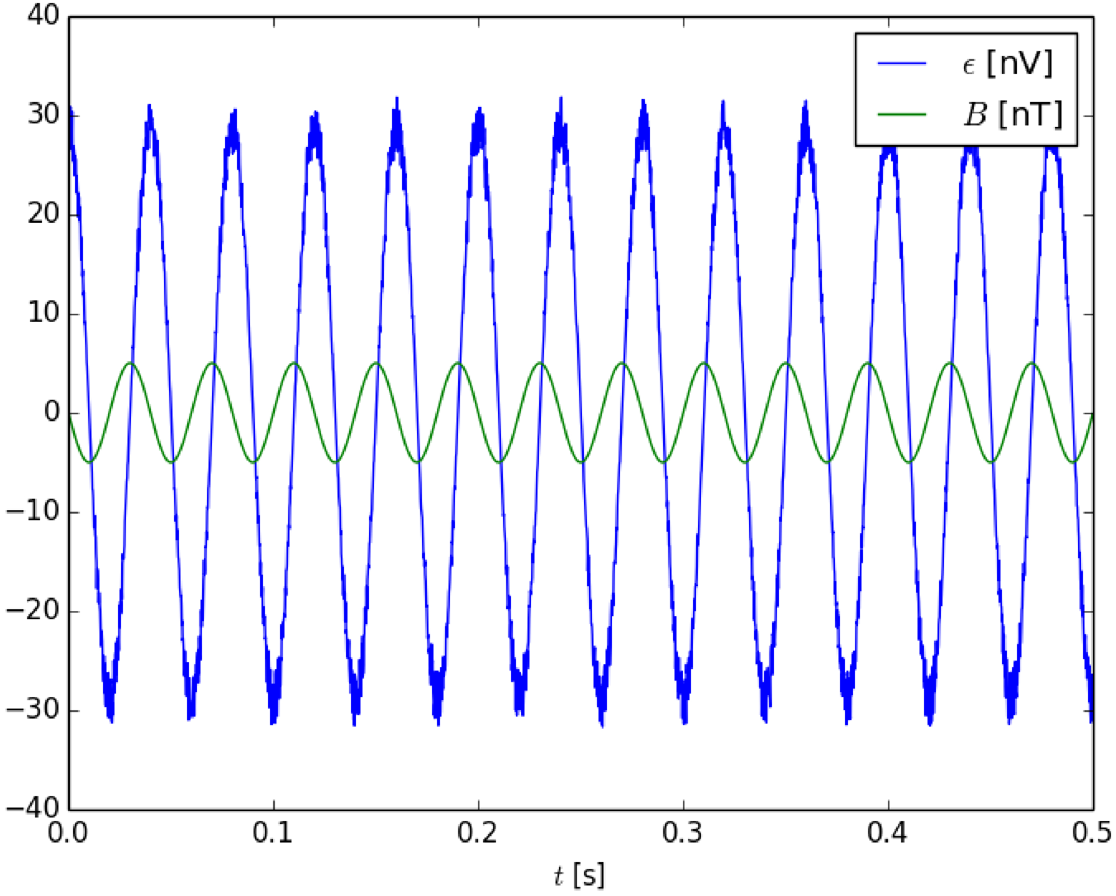
- This is solvable with initial condition $I_0 = 0$.

# Active Compensation – Two Coil Scheme

- A simulation of this model was written with parameters:

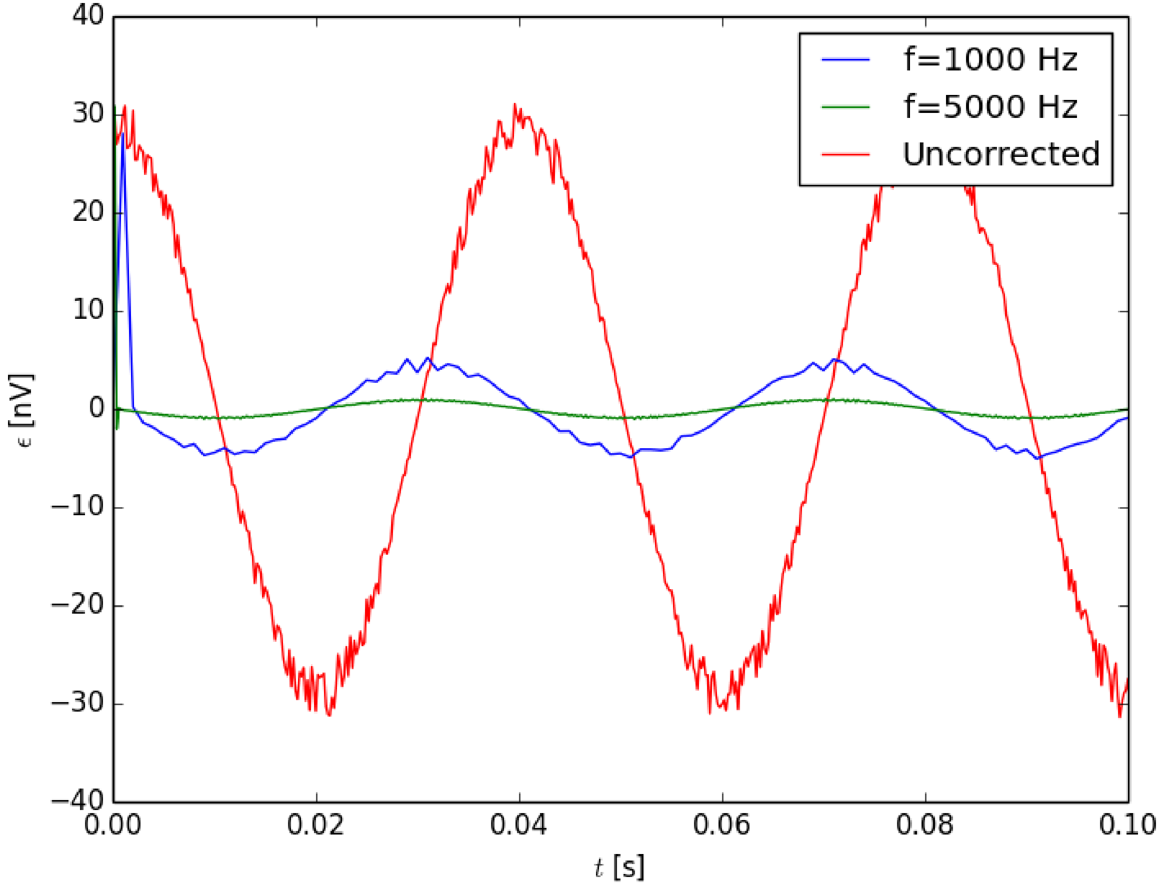
| **Parameter** | **Value** |
|---|---|
| Number of turns | 10 |
| Stray field amplitude | 5 nT |
| Stray field frequency | 25 Hz |
| Radius of coils | 10 cm |
| Length of coils | 30 cm |
| Permeability of coil core | 0.126 H/m |

# Active Compensation – Two Coil Scheme



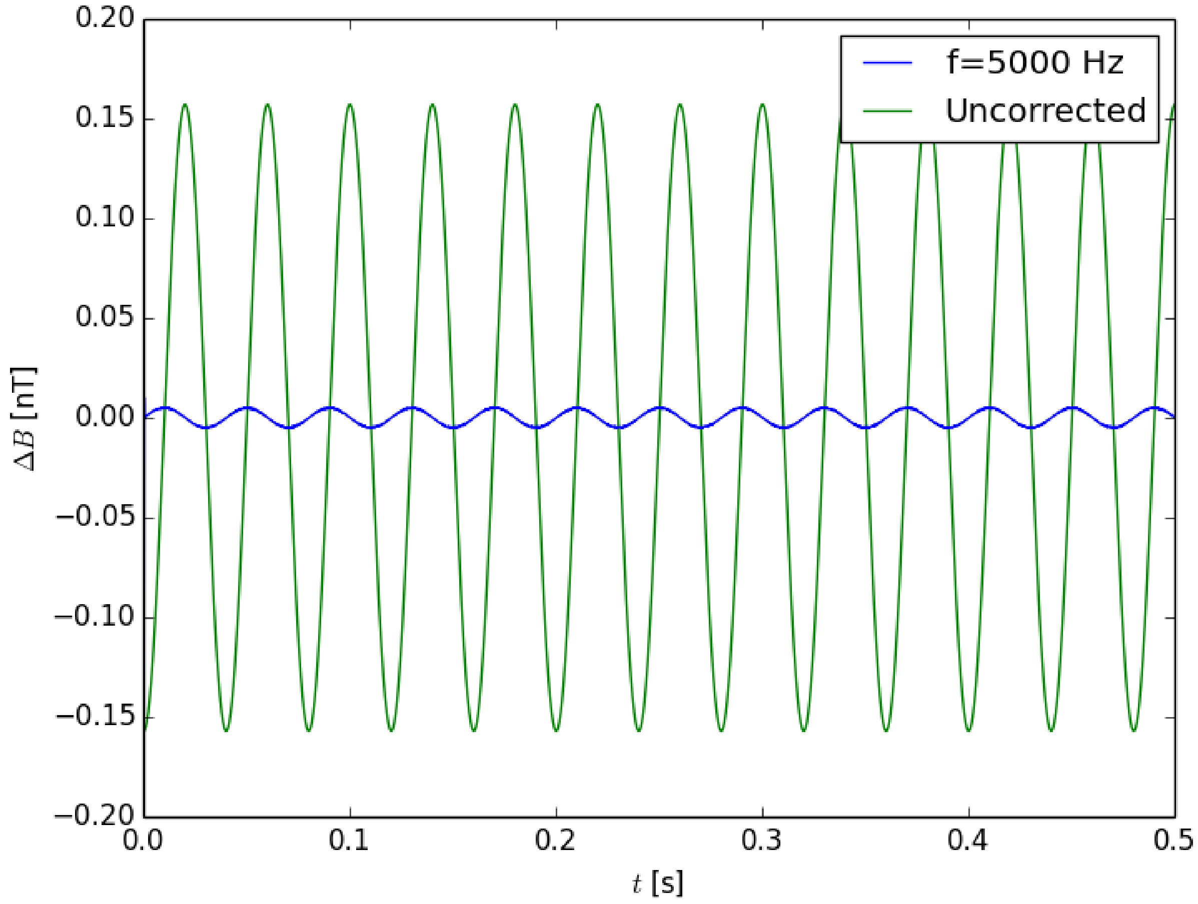
- Signal induced by a sinusoidal magnetic field with frequency 25 Hz.
- An error of $\pm 10\%$ was also added.

# Active Compensation – Two Coil Scheme



- The effect of varying the sampling frequency.
- This scheme is only effective with sampling frequencies much greater than in the stray field.

# Active Compensation – Two Coil Scheme



- Magnetic field variations with and without the correction running.
- A reduction of about 90% occurs with these parameters.

# Active Compensation – Two Coil Scheme

## Pros:

- Would reduce stray fields that are above 1 Hz, less than a few kHz.

## Cons:

- Doesn’t completely remove the stray field.
- Only works for stray fields of frequency much less than the sampling frequency.
- Possibility of introducing noise.

# Active Compensation – Sensor Requirements

- There are requirements on the sensors that can be used in such a corrector:
    - Ideally small enough to fit into an accelerator.
    - Radiation hard.
    - Give a real-time reading.
    - High sampling frequency and band.
    - Low noise.
    - (Cheap.)

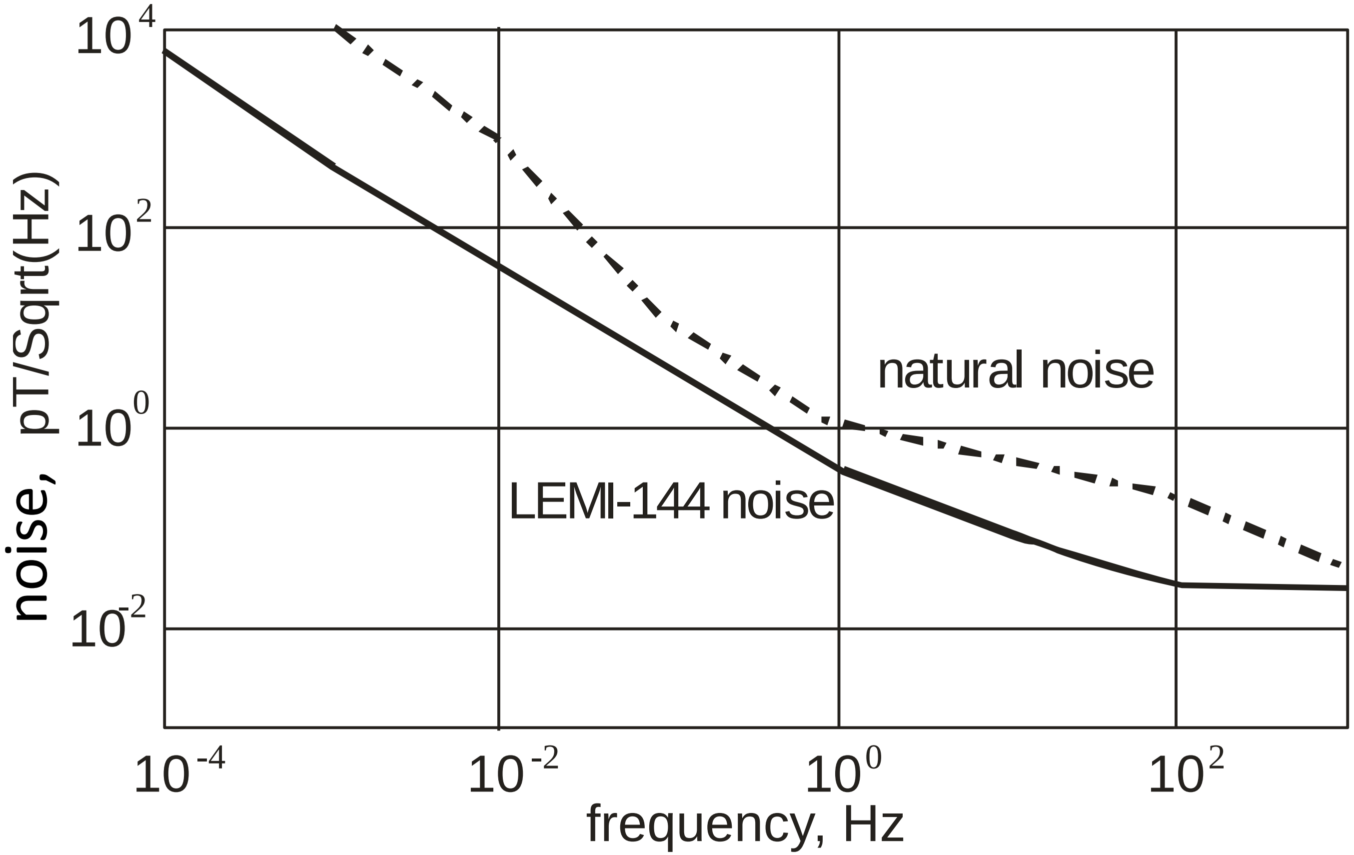
# Status of Instrument

# The Instrument – LEMI-144

- We have a sensor for surveying stray field sources.
- Induction coil magnetometer.
- Principle of operation:
    - Changing magnetic field in the coil induces a voltage.
- One long coil with core made of a number of $\mu$-metal tapes insulated from one another.
- Has frequency band 0.0001–300 Hz.

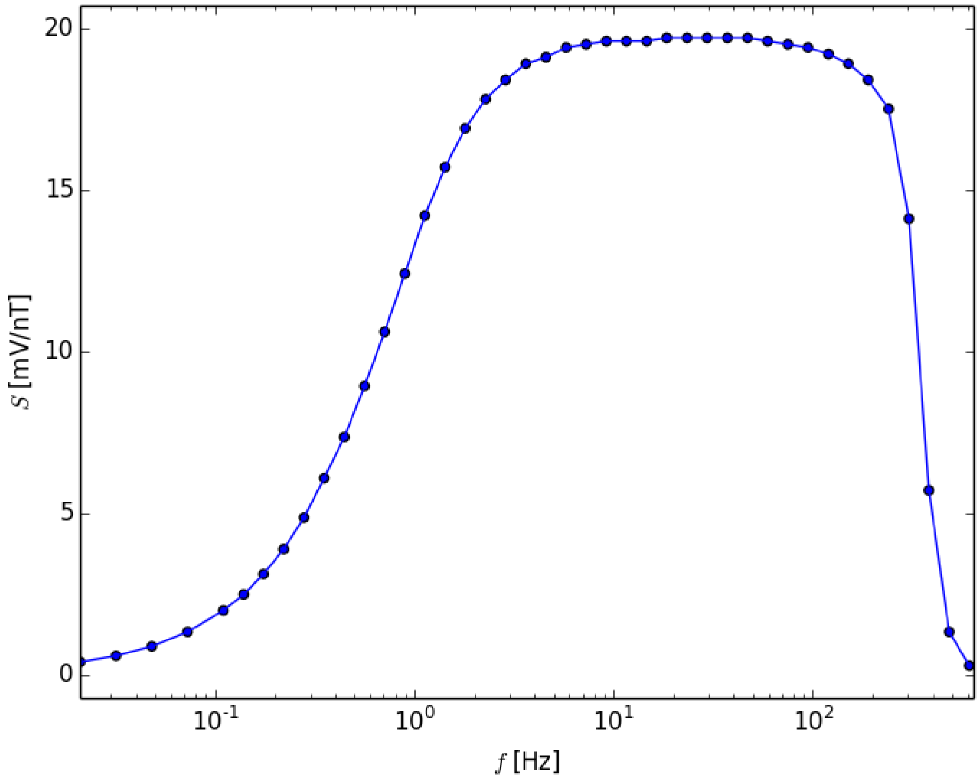
# The Instrument – LEMI-144

- Has an extremely high sensitivity and excellent signal-to-noise ratio.



# The Instrument – LEMI-144

- Bimodal transfer function.
- Upper part kept approx. flat with feedback loop.
- Worse linearity compared with a simple coil.



# The Instrument – LEMI-144

- Pros:
  - Low noise - sub nT precision.
  - Has a low power consumption: can be used for long periods.
- Cons:
  - Not radiation protected: cannot be used in the vicinity of a running accelerator.
  - Geometry not practical to place in an accelerator.
  - Only measures one component of the magnetic field variations.

| **Main Technical Parameters** | |
|---|---|
| Frequency band of received signals | 0.0001 – 300 Hz |
| Shape of transfer function | Linear - flat |
| Transfer function corner frequency | 1 Hz |
| Transformation factor at differential output<br>- At flat part<br>- At linear part | <br>20 mV/nT<br>20*f mV/nT |
| Magnetic noise level<br>- At 0.01 Hz<br>- At 1 Hz<br>- At 100 Hz | <br>$\leq 65\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$<br>$\leq 0.6\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$<br>$\leq 0.01\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$ |
| Length of connecting cables | ≤200 m |
| Power supply voltage | ±(9…12) V |
| Current consumption (nominal) | +14 mA<br>-10 mA |
| Temperature range of operation | -20…50°C |
| Outer dimensions | l=560 mm, d=60 mm |
| Design | Rugged and waterproof |
| Weight | 2.2 kg |

# DAQ – National Instruments USB-6366

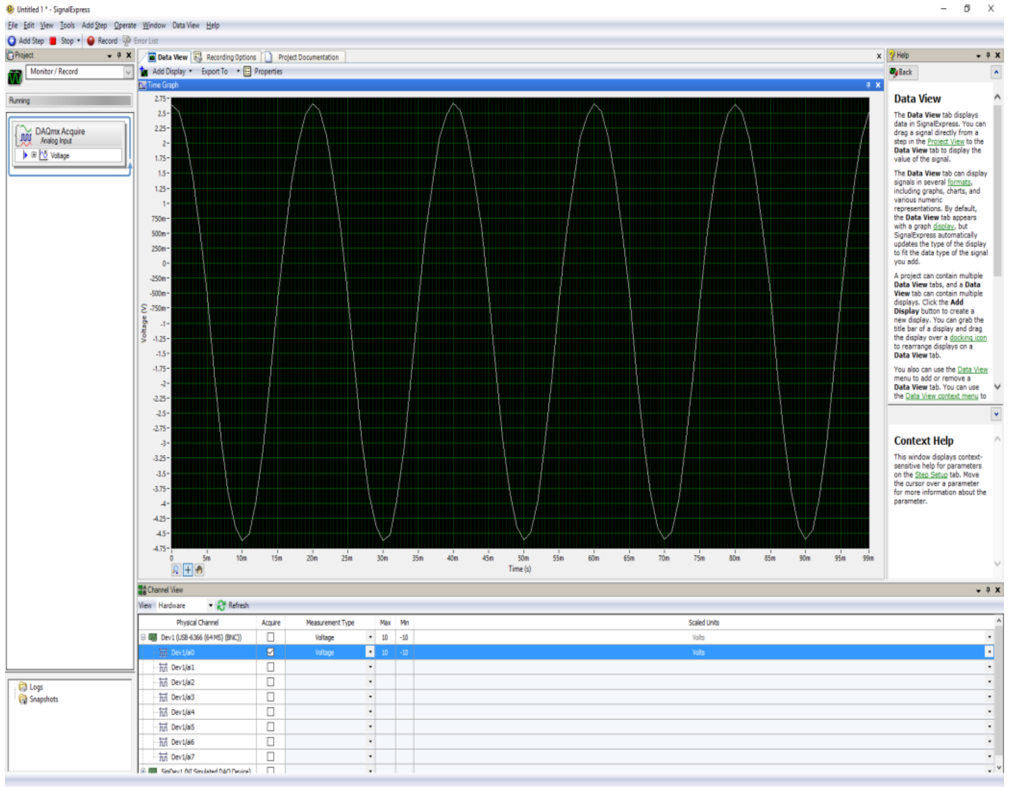
- Sampling rate up to 2 MHz.
- 8 independent differential channels.
- 16 bit ADC resolution.
- Best linearity of its class.

# Power Supply

- Would like a completely mobile device.
- Currently using a Yuasa Y7-12 battery (7 Ah) for LEMI-144.
- Using a windows laptop (DELL E7480) running LABVIEW to record voltage.
- Laptop battery life approx. 8 hours.

# Initial Tests And Calibration

- The sensor outputs a voltage.
- Calibration must be done to translate this into a magnetic field variation.
- Initial setup of the sensor shows a voltage reading of 50 Hz from the mains power supply.



| Physical Channel | Acquire | Measurement Type | Max | Min | Scaled Units |
|---|---|---|---|---|---|
| Dev1 (USB-6366 (64 MS) (BNC)) | ☐ | Voltage | 10 | -10 | Volts |
| Dev1/ai0 | ☑ | Voltage | 10 | -10 | Volts |
| Dev1/ai1 | ☐ | | | | |
| Dev1/ai2 | ☐ | | | | |
| Dev1/ai3 | ☐ | | | | |
| Dev1/ai4 | ☐ | | | | |
| Dev1/ai5 | ☐ | | | | |
| Dev1/ai6 | ☐ | | | | |
| Dev1/ai7 | ☐ | | | | |
| SimDev1 (NI Simulated DAQ Device) | ☐ | | | | |

**Data View**

The **Data View** tab displays data in SignalExpress. You can drag a signal directly from a step in the Project View to the **Data View** tab to display the value of the signal.

The **Data View** tab can display signals in several formats, including graphs, charts, and various numeric representations. By default, the **Data View** tab appears with a graph display, but SignalExpress automatically updates the type of the display to fit the data type of the signal you add.

A project can contain multiple **Data View** tabs, and a **Data View** tab can contain multiple displays. Click the **Add Display** button to create a new display. You can grab the title bar of a display and drag the display over a docking icon to rearrange displays on a **Data View** tab.

You also can use the Data View menu to add or remove a **Data View** tab. You can use the Data View context menu to

**Context Help**

This window displays context-sensitive help for parameters on the Step Setup tab. Move the cursor over a parameter for more information about the parameter.

# Feedback Performance

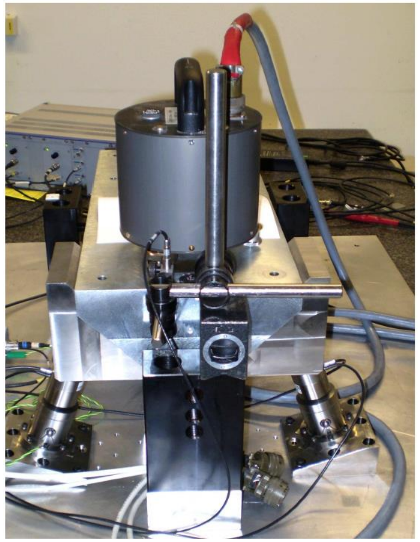
# Feedback Performance

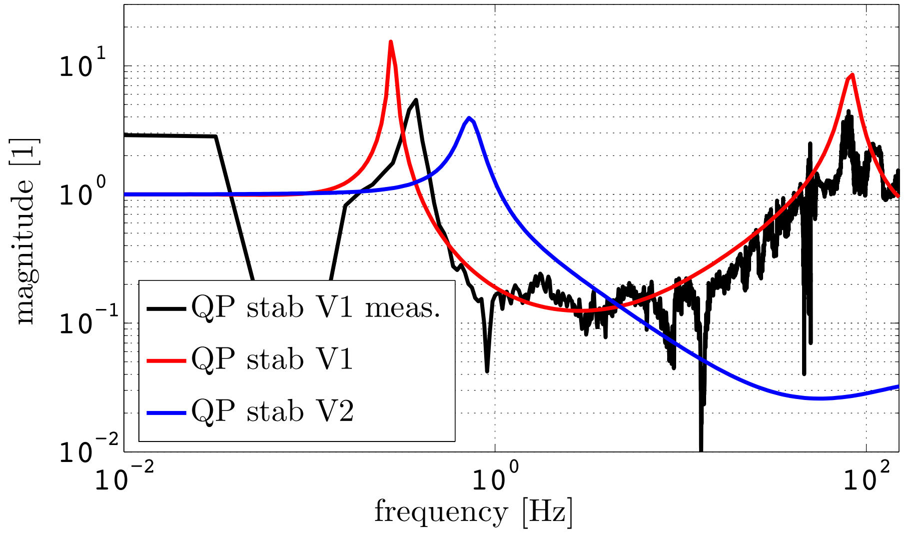
- Luminosity loss due to a dynamic imperfection is given by

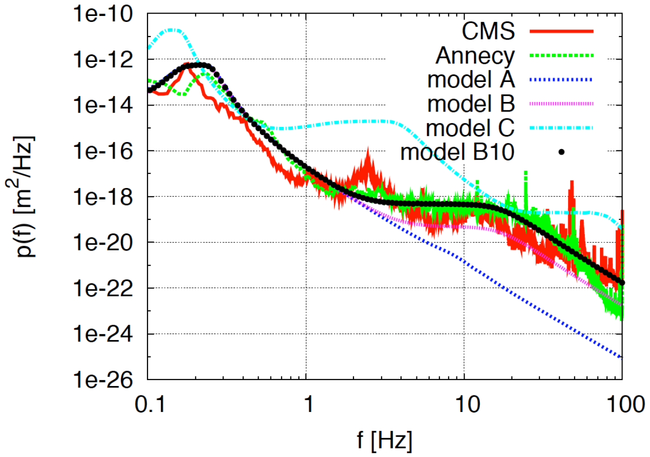
$$\Delta\mathcal{L} = \int |T(k,\omega)|^2 \, P(k,\omega) \, dk \, d\omega$$

- $P(k,\omega) =$ Power spectrum density
  - Characterises the stray fields.
  - Obtained from measurements.
- $T(k,\omega) =$ Transfer function
  - Characterises how a dynamic perturbation with $(k,\omega)$ affects luminosity.
  - Obtained from studying the response of the feedback system and its effect on the beam.

# Feedback Performance: Ground Motion







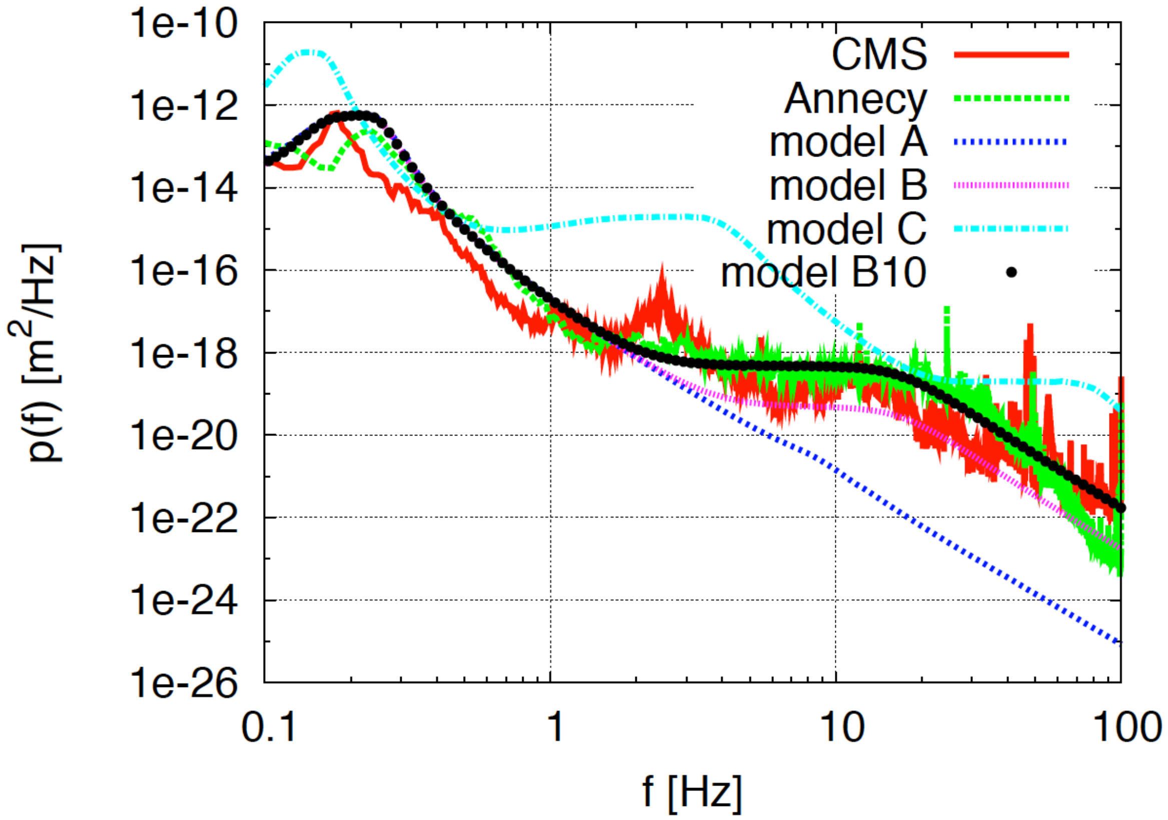
Code

Machine model
Beam-based feedback

Luminosity achieved/lost [%]

| | model B10 |
|---|---|
| No stab. | 53%/68% |
| Current stab. | 108%/13% |
| Future stab. | 118%/3% |

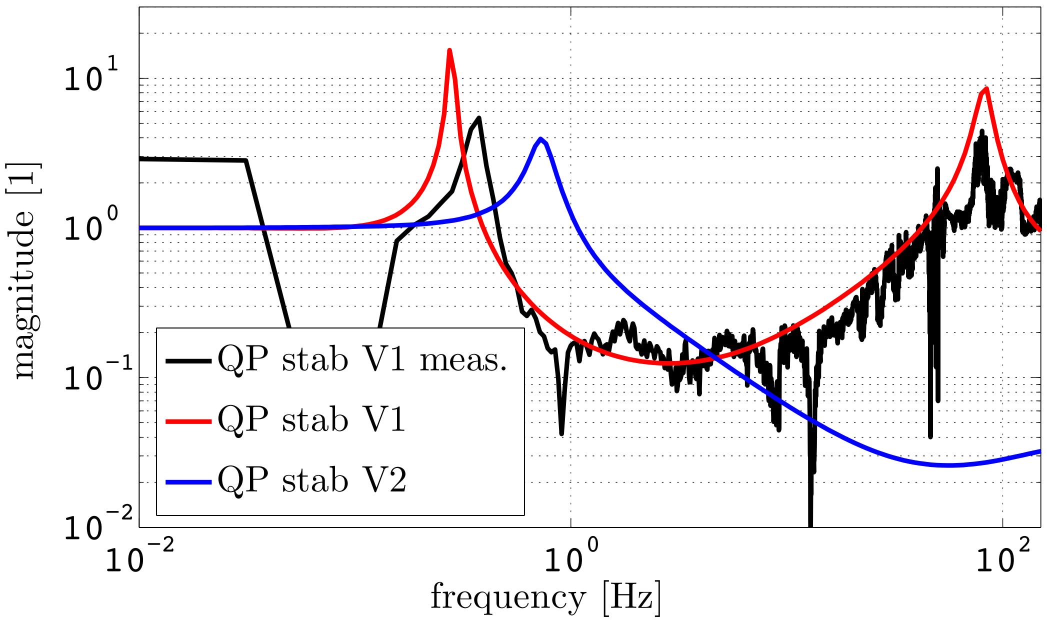
# Power Density Spectrum: Ground Motion



$$P(k,\omega) = \sum_{k,l}^{N_k,N_l} C_{kl}\left[\sin(\omega_k t)\sin(k_l s + \phi_{kl})\right.$$

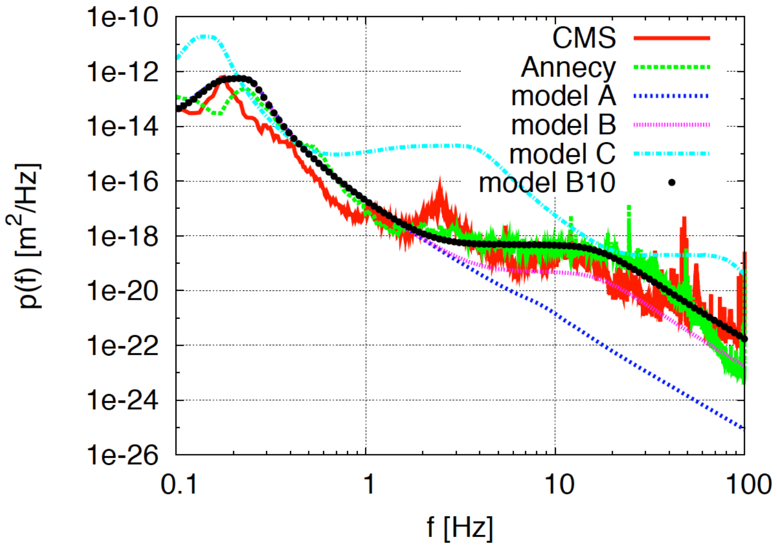
$$\left. + (\cos(\omega_k t) - 1)\sin(k_l s + \psi_{kl})\right]$$

# Transfer Function: Ground Motion



- Left shows the magnitude of quadrupole motion after active stabiliation.
- Also need the response of the beam to quadrupole motion.
- Gives $T(k, \omega)$.
- Effective for frequencies O(1 Hz).

# Feedback Performance: Ground Motion



Luminosity achieved/lost [%]

| | Model B10 |
|---|---|
| No stab. | 53%/68% |
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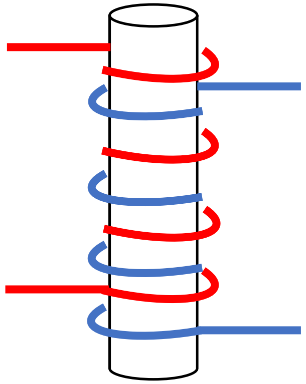
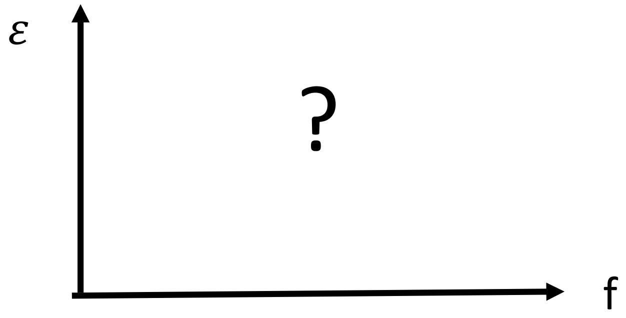
$$\Delta\mathcal{L} = \int |T(k,\omega)|^2 \, P(k,\omega) \, dk \, d\omega$$

- Using $T(k,\omega)$ and $P(k,\omega)$ we can examine the feedback performance.

# Feedback Performance: Stray Fields

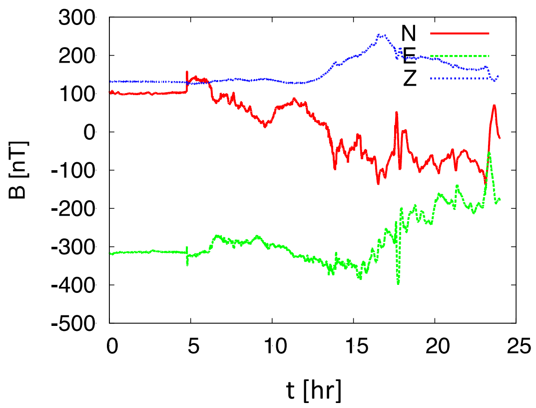
Correction device





Frequency response of
The correction device

Stray field, e.g.
natural source



Code

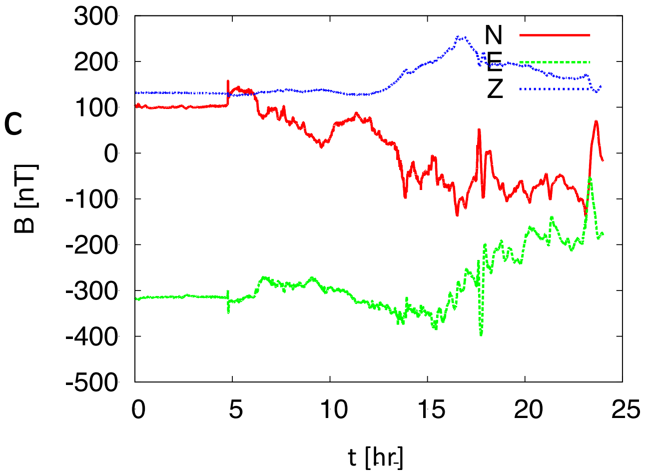
Luminosity achieved/lost [%]

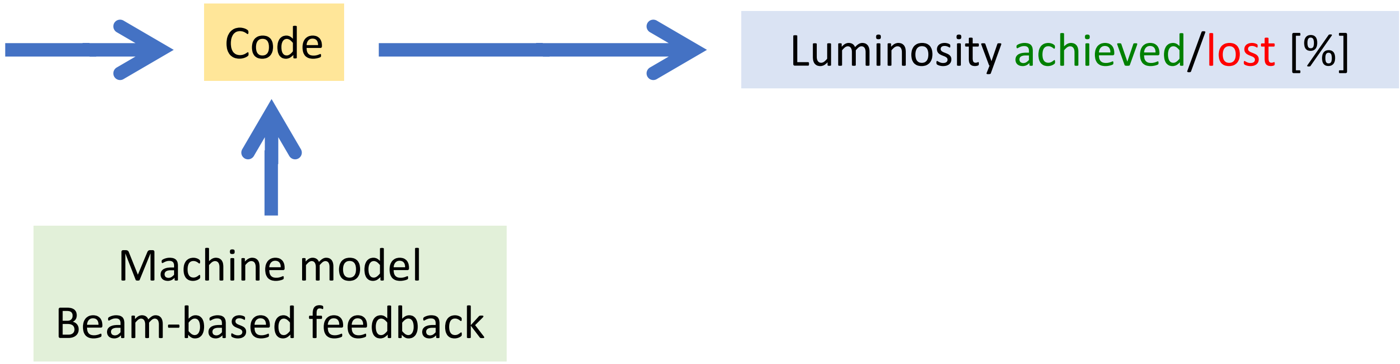
Machine model
Beam-based feedback

# Feedback Performance: Natural Source

Geomagnetic storm

(B. Heilig)





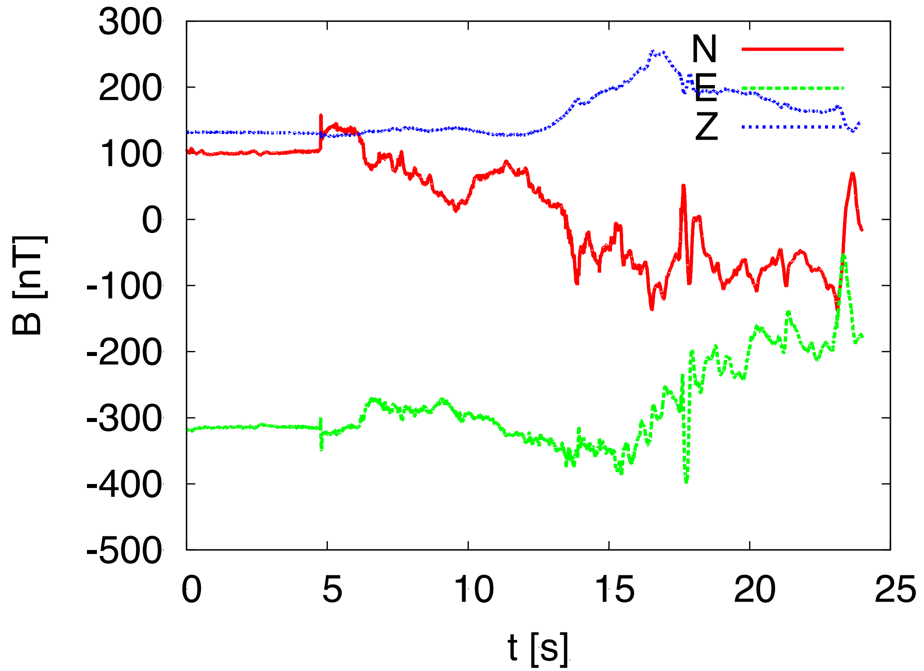
Code

Luminosity achieved/lost [%]

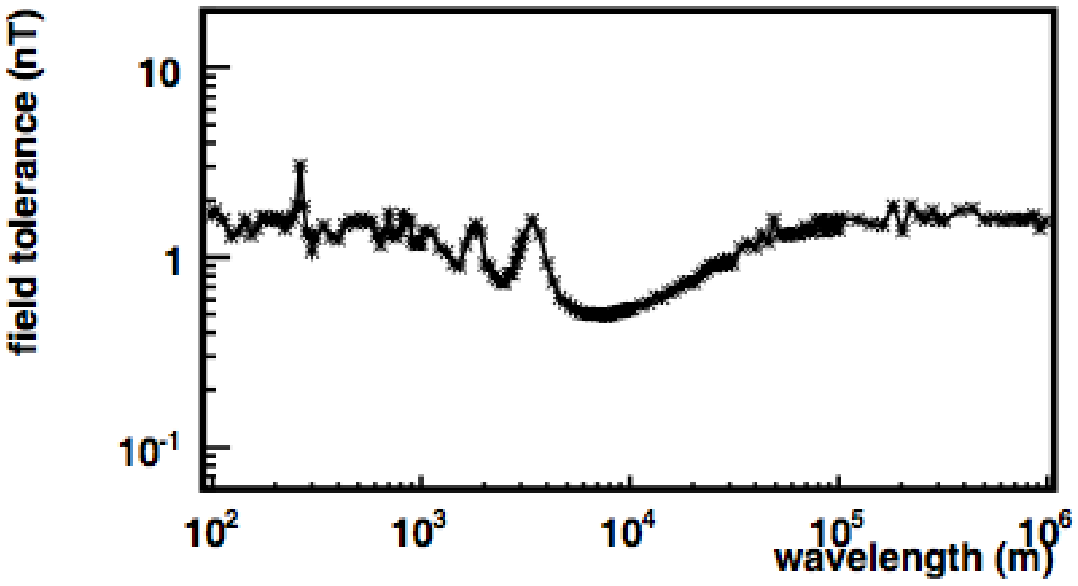
Machine model
Beam-based feedback

- Sampling rate of data is 1 Hz.
- Could evaluate the performance with a feedback system acting at 1 Hz.

# Feedback Performance: Natural Source



- Assuming a perfect beam-based orbit correction, each pulse sees a change in field of about 1 nT.



- No significant luminosity loss.

# Work Programme

# Stray Field Work Programme

- Understand (and model) sources
  - Natural
  - Environmental, e.g. trains, …
  - Technical, e.g. accelerator components
- Understand (and model) transfer to beam
  - Field at the beam is important
  - E.g. beam pipe can modify field
  - E.g. steel in walls of tunnel
  - …
- Understand (and model) impact on the beam
  - Here we have the tools
- Develop (and model) mitigation methods
- Make performance predictions
- Validate methods
- Choose most effective and cost effective method(s)

Here, we need to learn more

Based on models can predict collider performance

Experiments to develop and verify models including mitigation methods