Workshop on Materials for Collimators and Beam Absorbers
September 3rd-5th, 2007
CERN, Geneva, Switzerland

Accelerometer and microphone measurements of the LHC collimator during impacts of proton beams

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Acknowledgments: ***O. Aberle, C. Bracco, A. Masi, T. Weiler***
Brüel&Kjær (C. Gozel), SPS-OP team, LHC-BLM team, A. Bertarelli, E. Chiaveri, A. Dallocchio, I. Efthymiopoulos, M. Eller, A. Fabich, M. Lazzaroni, J. Lendaro, J. Lettry, F. Loprete, R. Losito, M. Magistris, C. Mitifiot, R. Perret, H. Ritcher, P. Sievers, V. Vlachoudis, R. Wilfinger.

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LHC Collimation Project
CERN

Motivation

How can we detect beam impacts on the LHC collimators?

Other machines: damaged collimators mostly found “accidentally”

Robustness tests in 2004 and 2006 to validate the LHC collimator design provide an opportunity to tests beam impact detection systems!

Tests done with nominal LHC injection batches ($3.3 \times {}^{13}$ p at 450 GeV): already quite dangerous!

How can we localize beam impacts?

- *Beam orbit during failure?*
- *Beam loss monitors?*
- *Temperature sensors?*
- *Visual inspections?*
- *Residual activation?*
- *Laser vibrometer?*
- *...?*

- *Beam instrumentation can saturate!*
- *Losses are not local!*
- *Maximum energy deposition peak downstream of collimator that is hit!*
- *Cross-talk between opposing beams*
- *Windows in tank cause problem!*
- *Cameras would not survive*
- *Dose to personnel!*

LHC betatron cleaning (IR7): 19 moveable collimators per beam within the straight section of ~ 400m; will become ~30 for Phase II

*We investigated the possible usage of **accelerometers** and **microphones** as a way to monitor remotely the collimator in case of major failure scenarios.*

Can we detect beam impacts and locate the element that is hit?
Can we find a solution for the LHC?

Outline of my talk

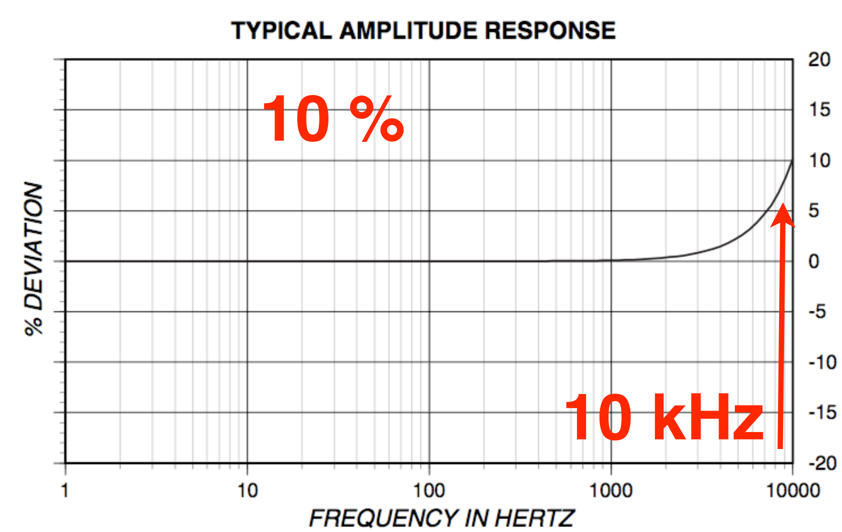
- **Sensors for vibration measurements**
  - Accelerometers and microphone
  - Laboratory tests, sensor calibrations
- **Beam experiment setup**
  - Tunnel layout
  - Sensor mounting
  - Beam conditions
- **Measurement results**
  - Analysis of measured signals
  - Collimator vibration spectra
  - Sound levels
- **Conclusion**

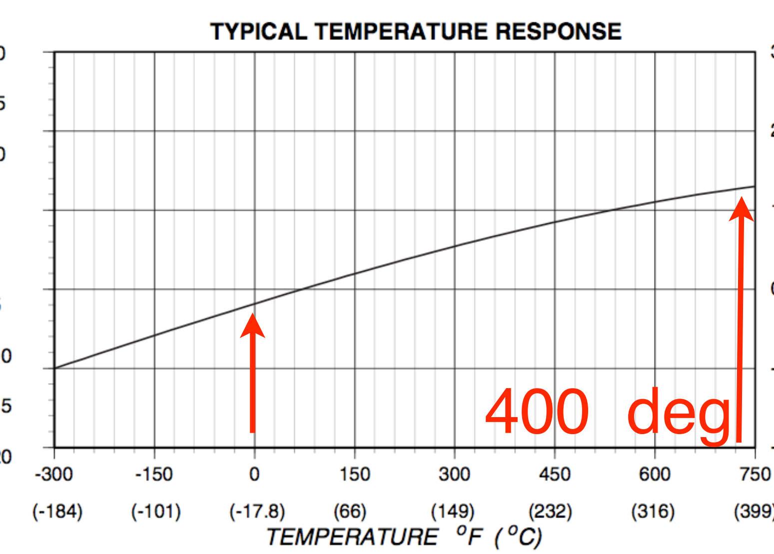
Accelerometers for vibration measurements

Manufacturer: Brüel & Kjær

Sensor type	N.	Sensitivity	Freq. range
B&K 2273AM1	1	1.1 pC/ms^{-2}	1Hz-6kHz
B&K 2273A	2	0.38 pC/ms^{-2}	1Hz-10kHz
AP40	2	2.1 pC/ms^{-2}	0.5Hz-10kHz
AP37	2	1 pC/ms^{-2}	0.5 Hz-20kHz
Mic. B&K4189	1	41.6 mV/Pa	6.3 Hz-20kHz

Conditioner amplifier NEXUS by B&K.



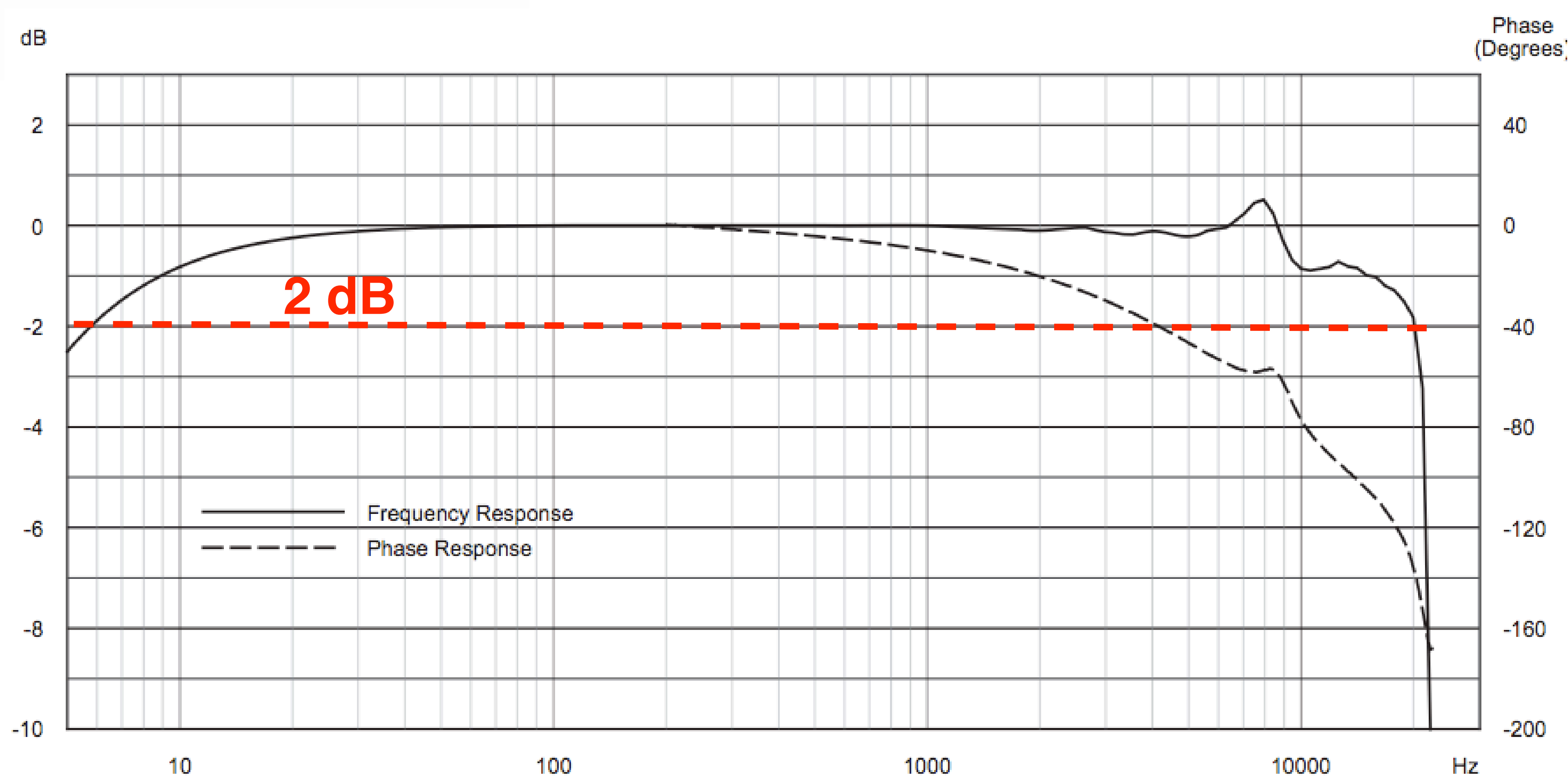


Good for radiation and high temperature environments!

Other, cost-effective solutions investigated for the LHC implementation (fixed gain acquisition system).

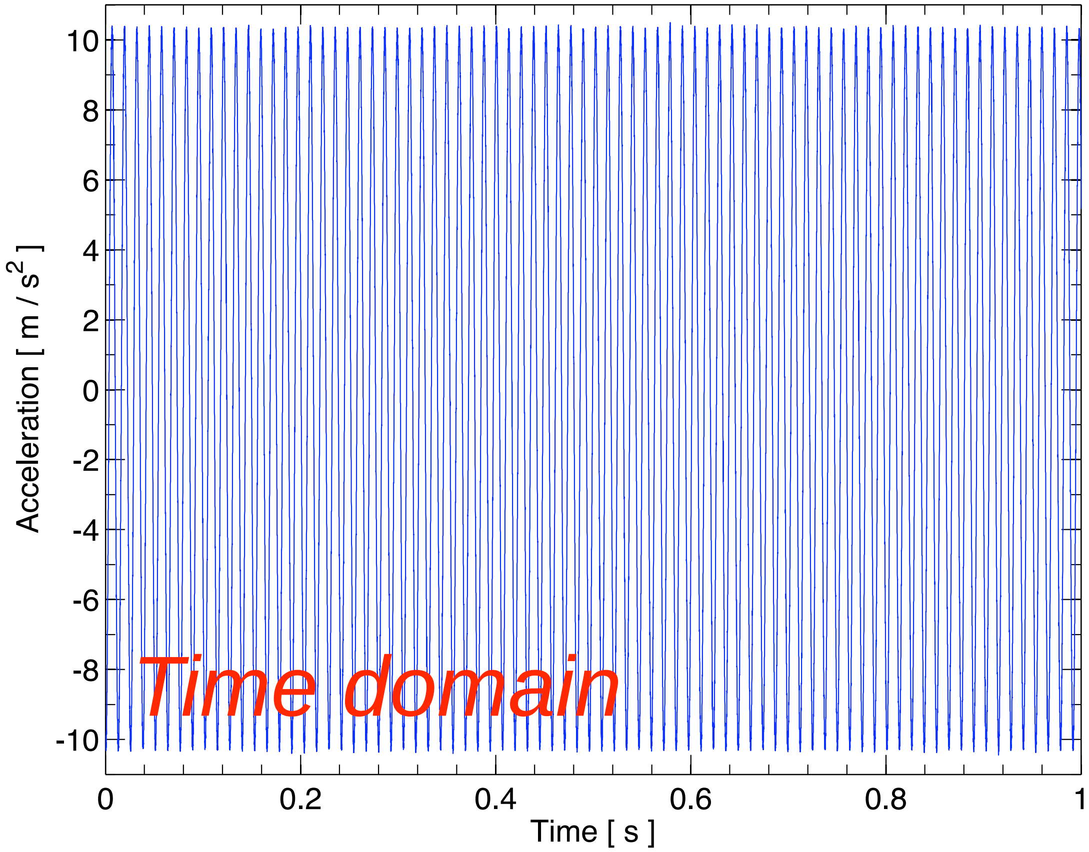
Microphone

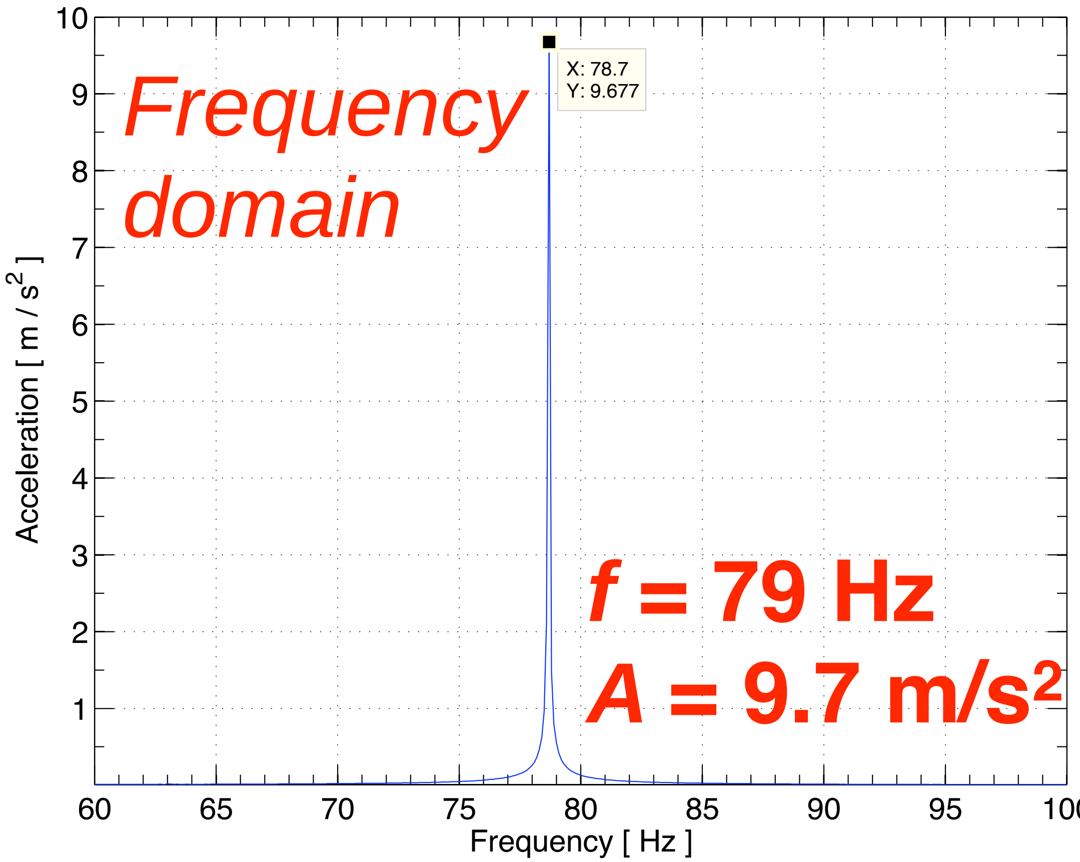
- Low-noise, free field microphone
- High-sensitivity
- Titanium case
- Build-in electronics for signal amplification
- Made by Brüel&Kjær
- Synchronized acquisitions with accelerometers



Details of full acquisition system in Diploma thesis of G. Spiezia (University of Napoli, 2005).
See also S. Redaelli et al., proceedings of PAC05 (2005).

Accelerometer calibration (1)



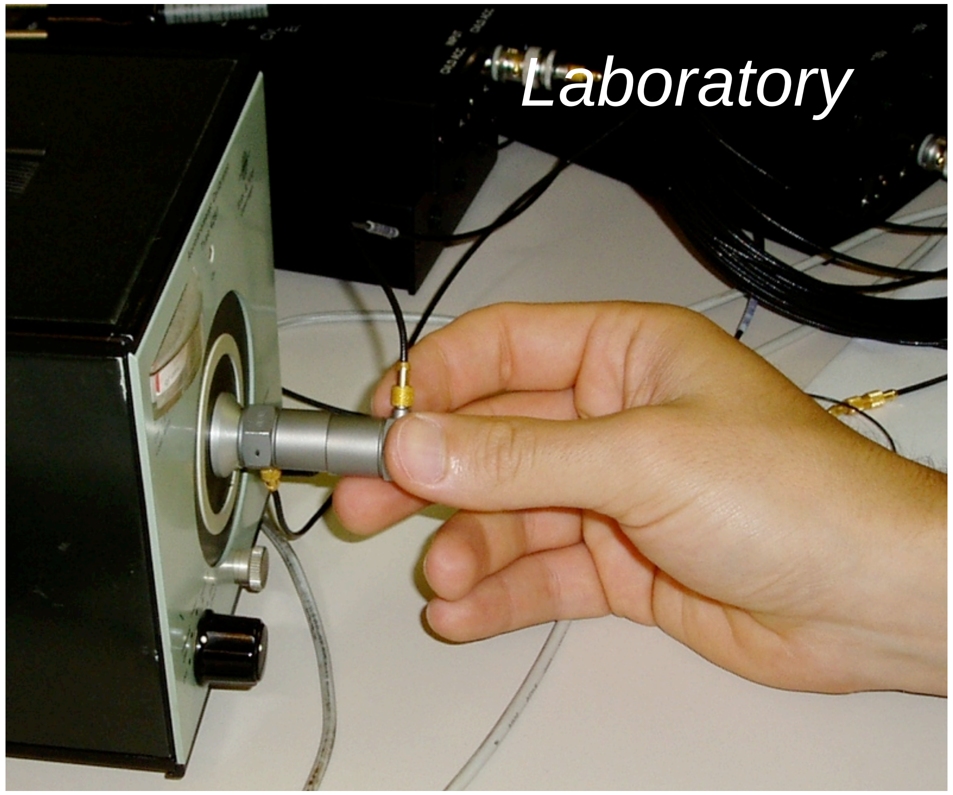


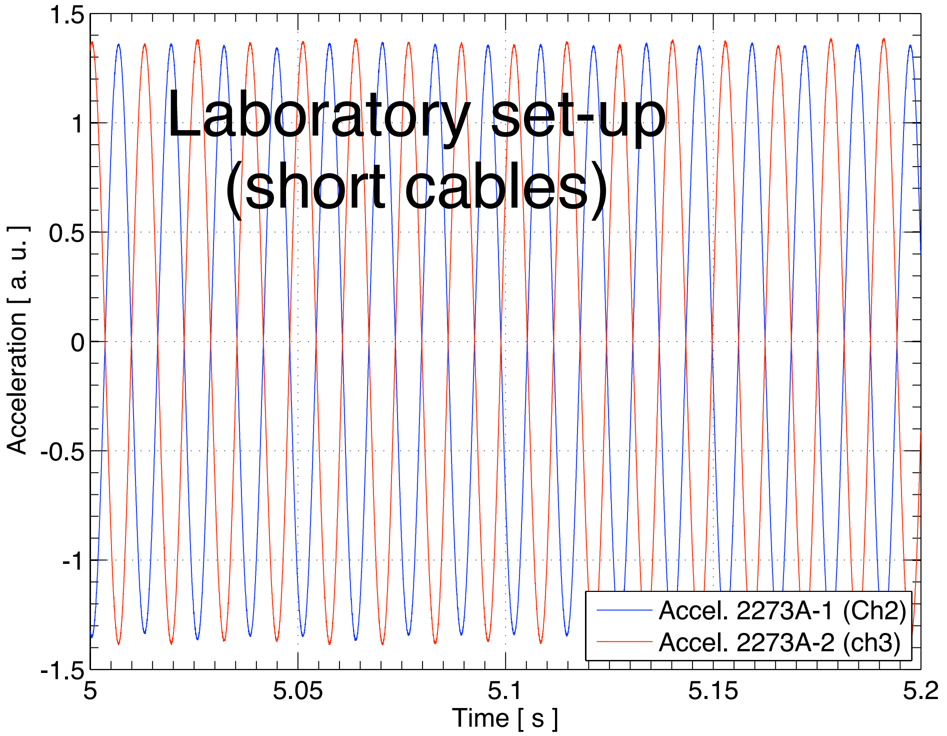
Calibration of the accelerometers was verified in the lab by means of a **calibrated vibrating surface**: Controlled acceleration of **1 g at 79.5 Hz**.

Calibration error ≈ 1 % !

Accelerometer calibration (2)

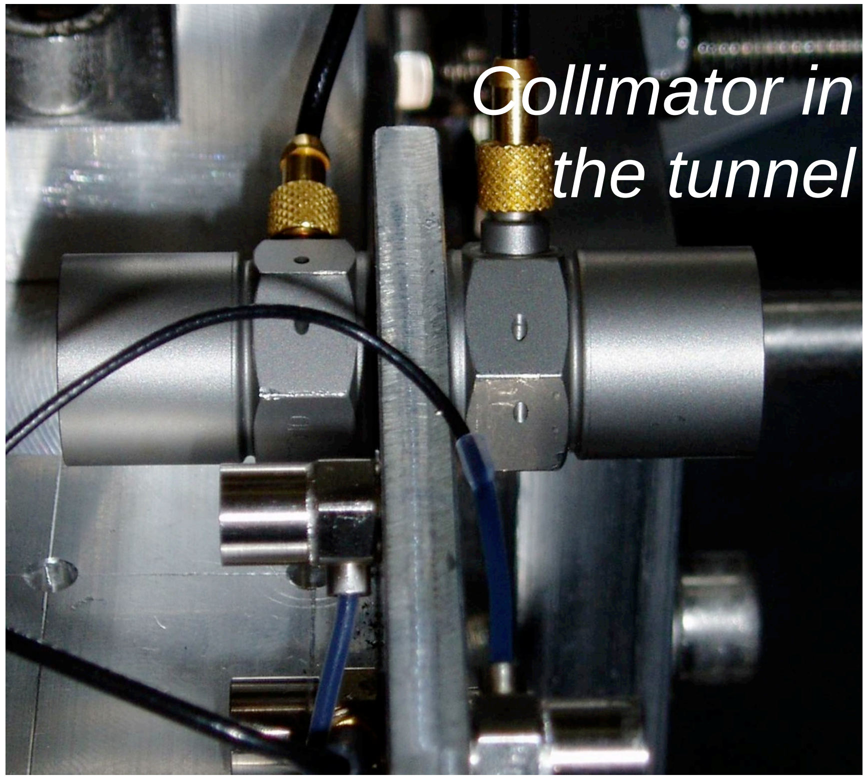
Simultaneous acquisition of identical sensors mounted such as to measure opposite directions

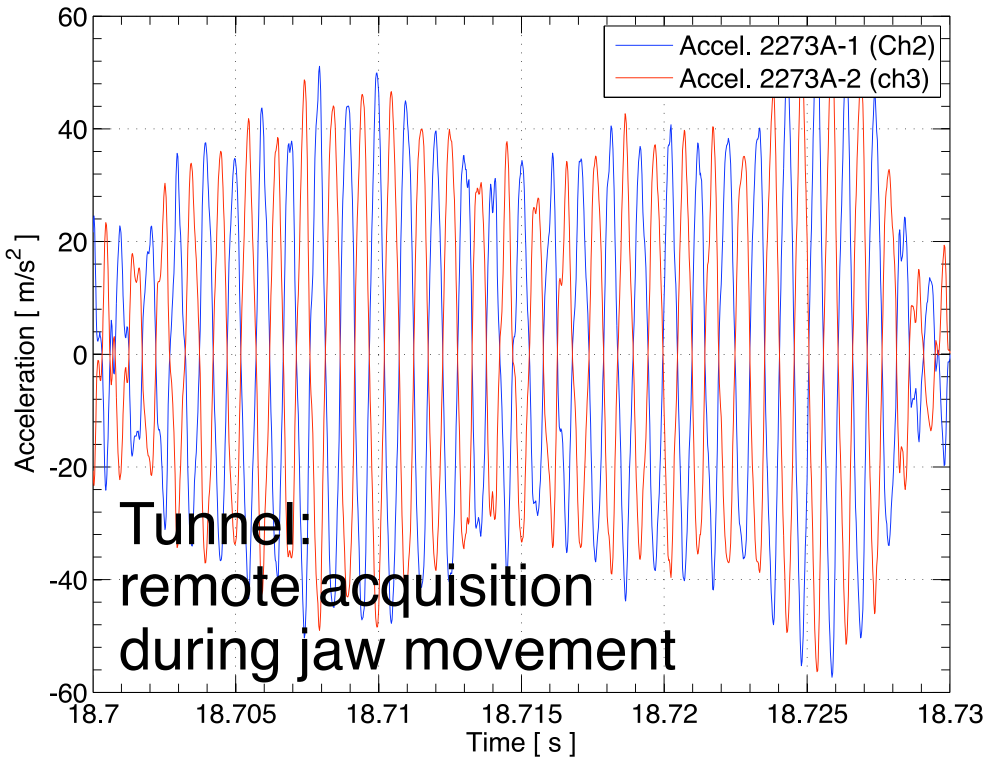




Verify amplitude and phase of two signals: for real vibrations, the two must sensors satisfy:

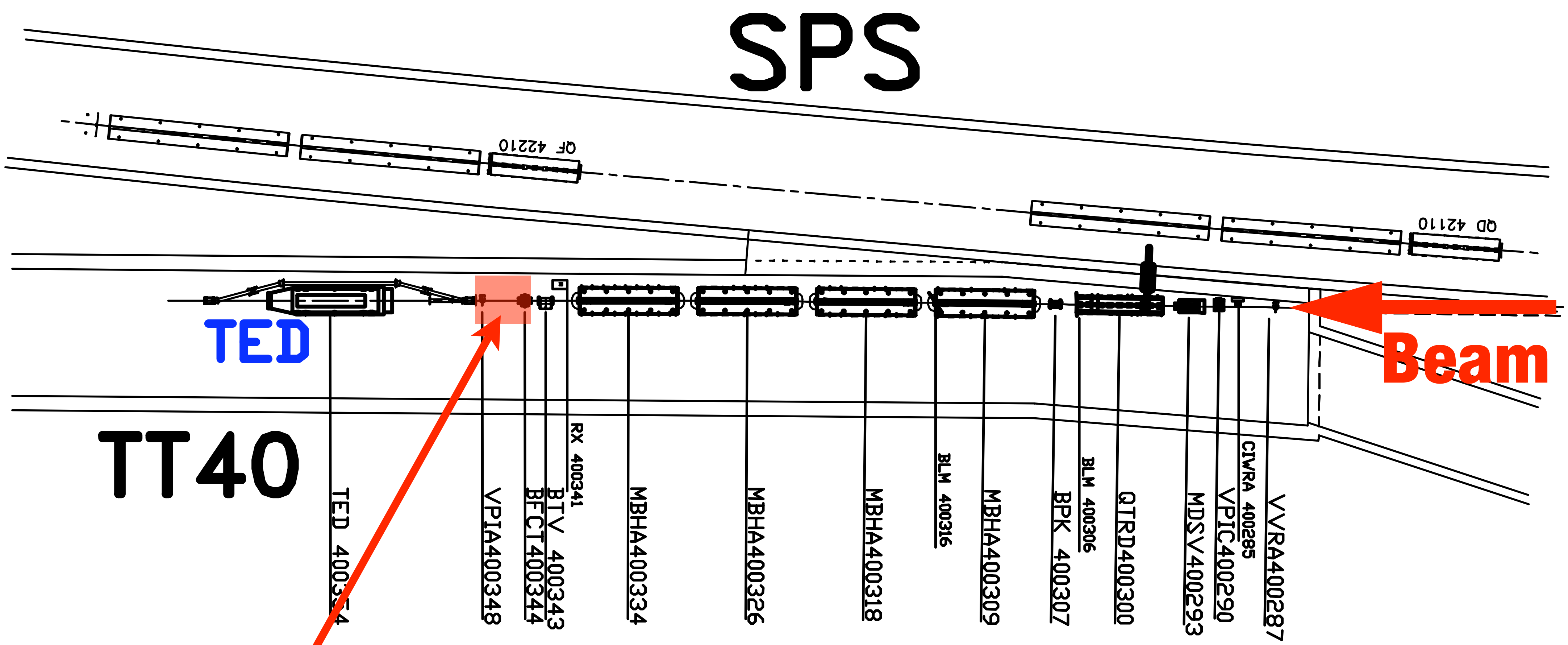
$A_1(t) = - A_2(t)$

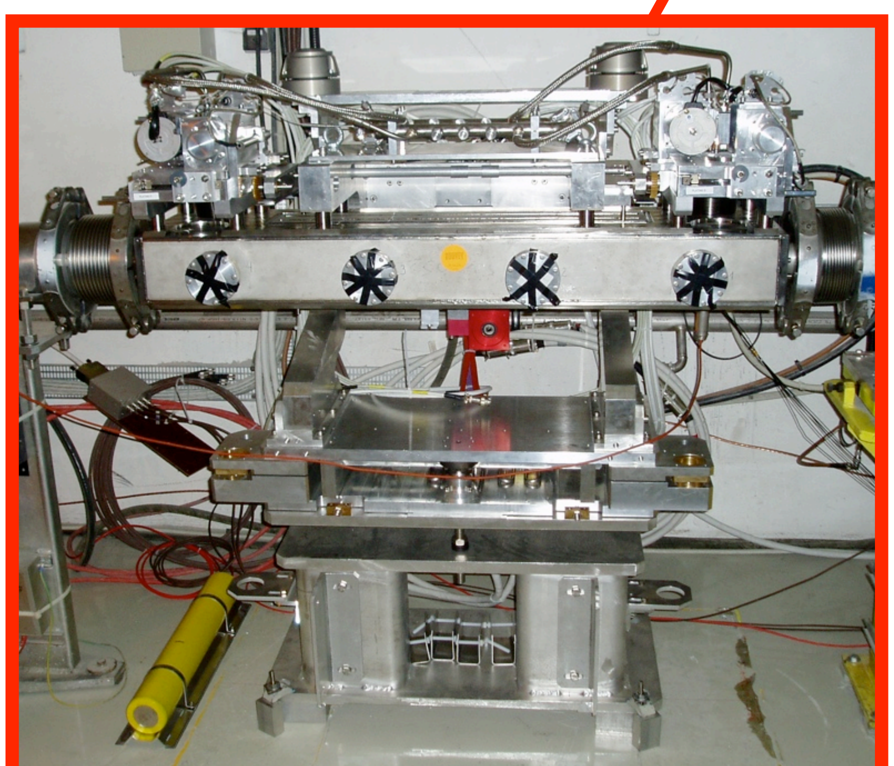




Confirmed with the final installation layout in the tunnel (beam test acquisition chain, long cables).

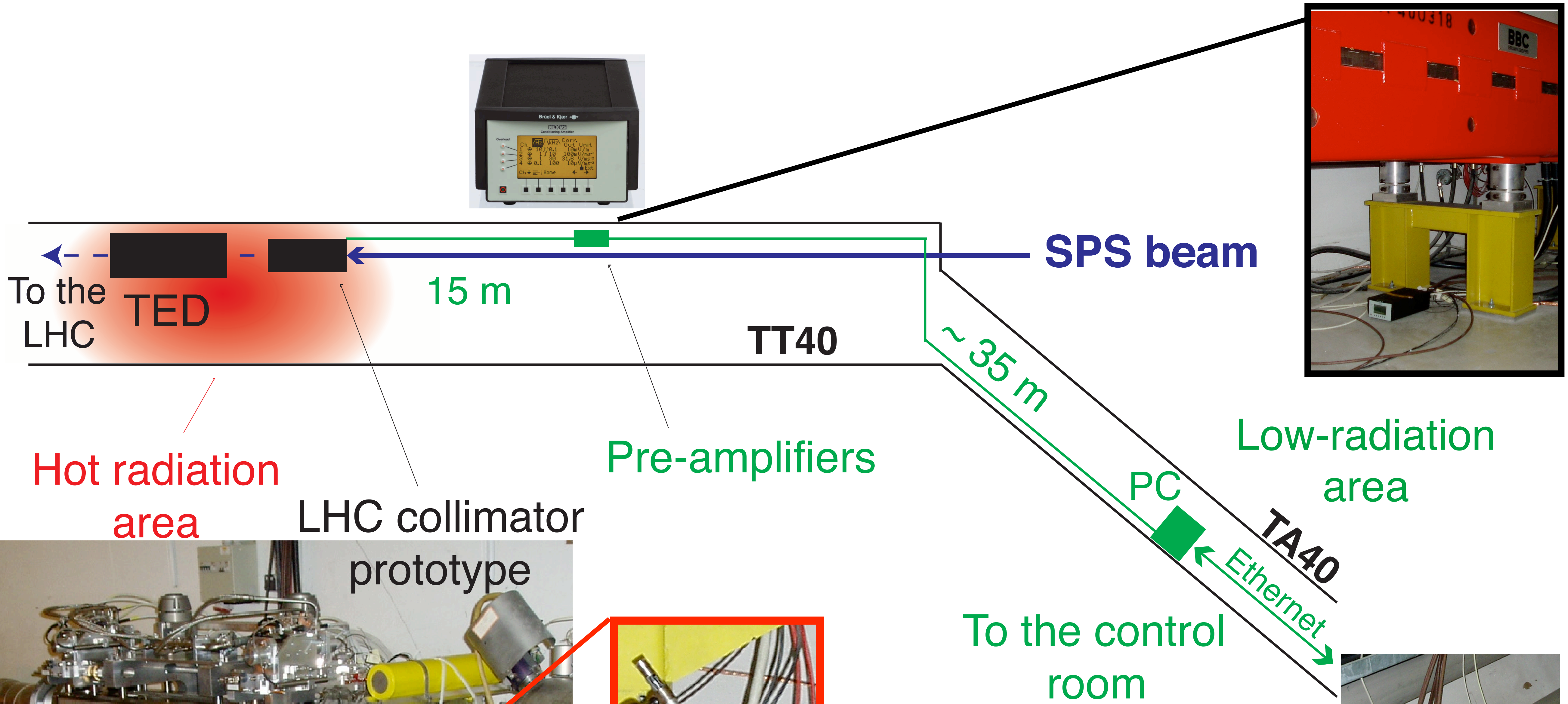
Beam experiment layout (1)

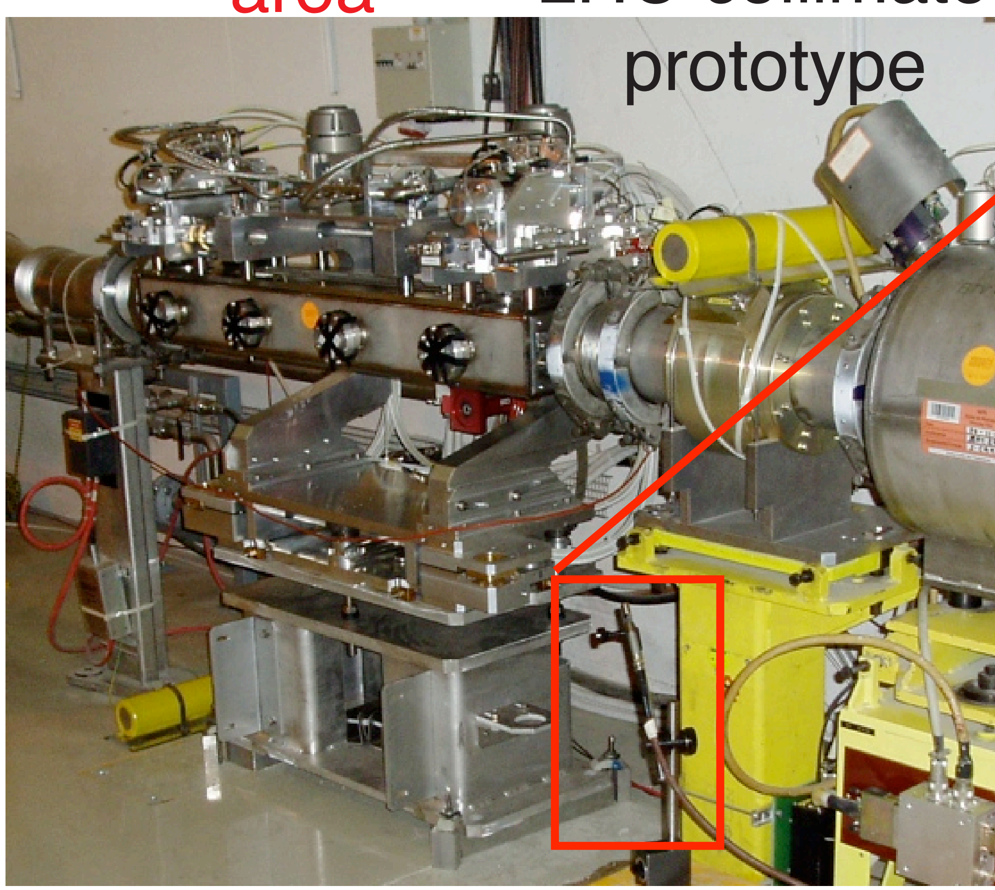


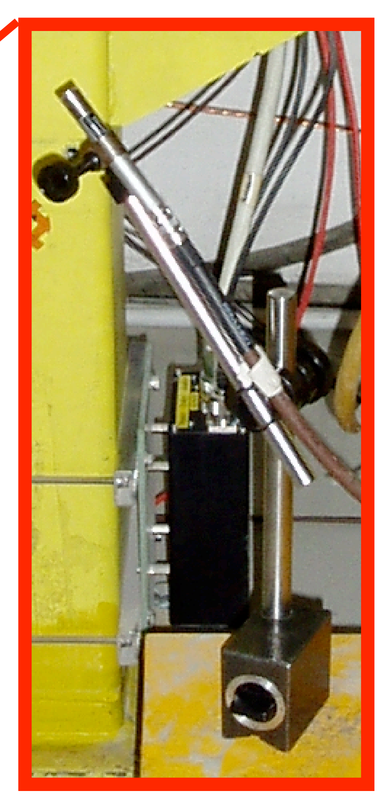


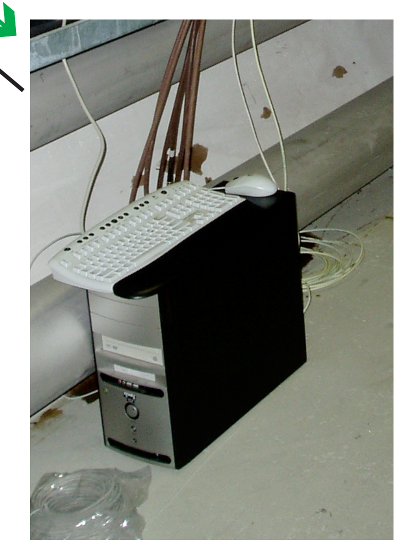
- Collimator installed in **TT40**: first part of transfer line from the SPS to the LHC (Beam2)
- Beam dump (TED) ~ 5 m downstream
- Beam types: pilots to nominal LHC injection batches at 450 GeV (few 10^9 p to 3.3 x 10^{13} p)
- Two experiments:
  - 2004 ➞ full LHC collimator prototype (2 jaws)
  - 2006 ➞ Special prototype with 1 jaw

Beam experiment layout (2)



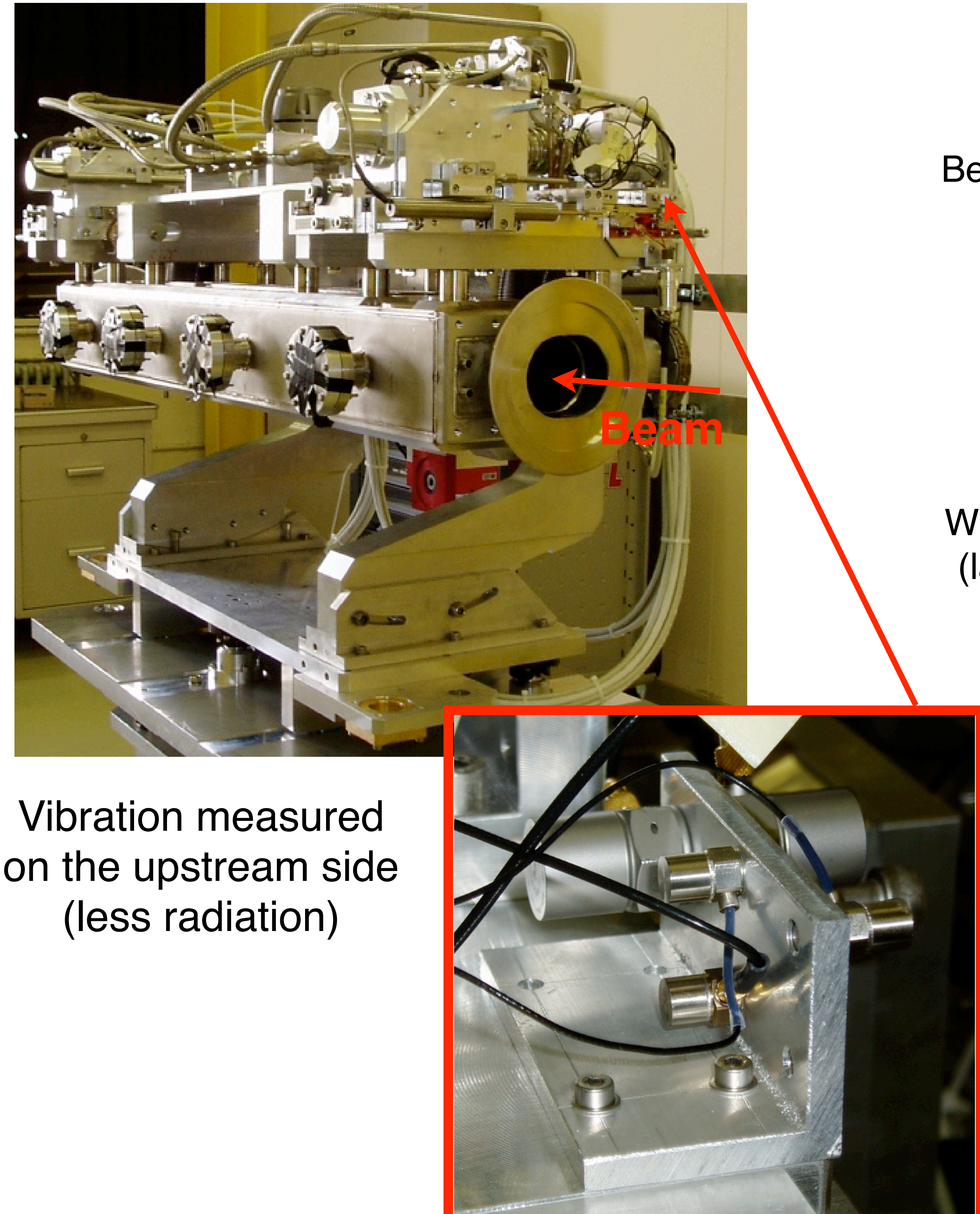




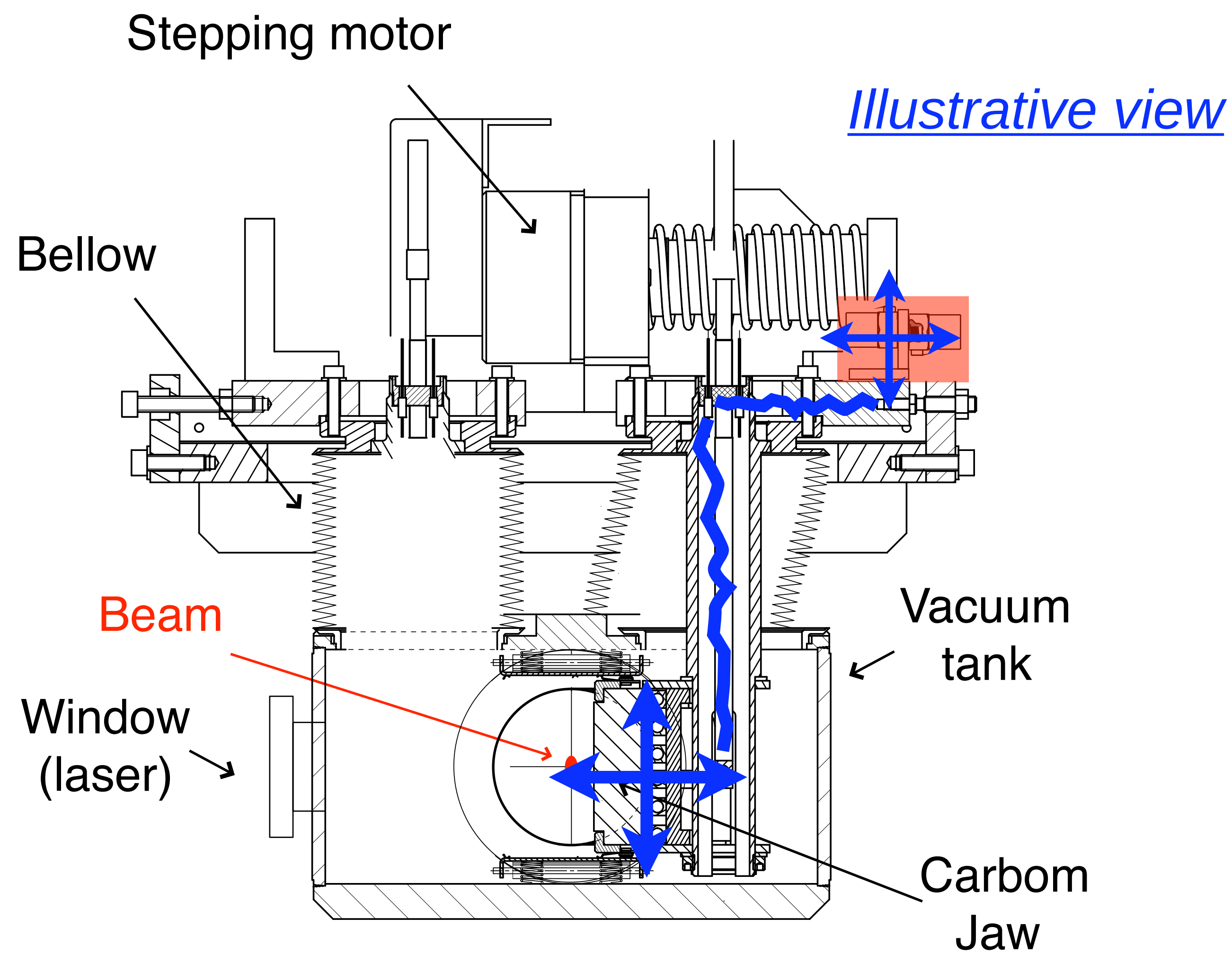


Full remote access from control room: ADC cards, acquisition triggers, amplifier settings, reset (internet switch)

Mounting of the accelerometers



Vibration measured on the upstream side (less radiation)



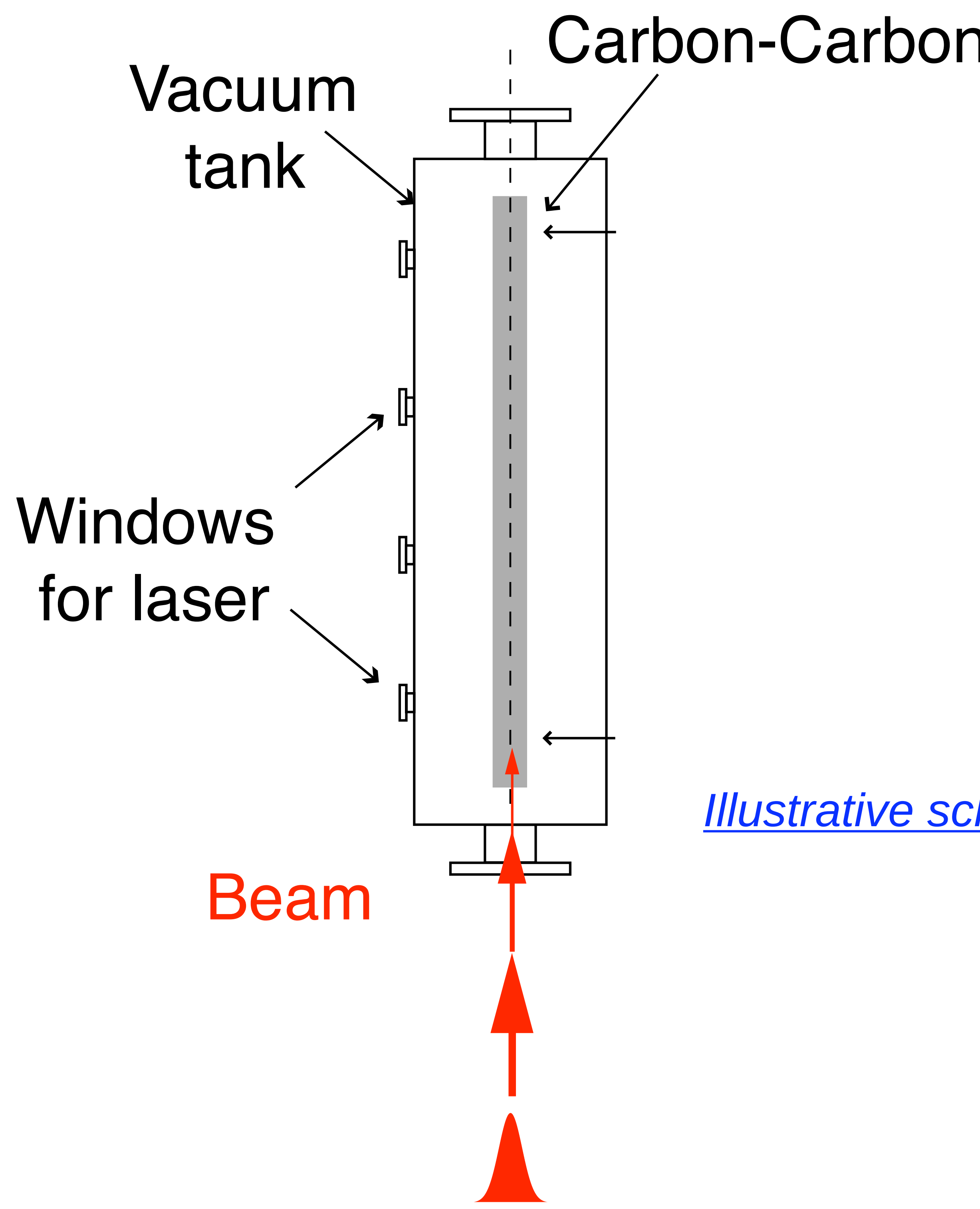
- Direct mechanical contact with the jaw
- Closest place outside the vacuum
- Two identical accelerometers measure opposite directions at the same location
- **BUT** we cannot measure directly jaw vibrations: the transmission is not known.
- *Can easily be implemented in the LHC!*

Beam conditions

E_b = 450 GeV
I_b^{max} = 3.5 x 10^{13} p
N_b = (1...6) x 42 bunches
Bunch spacing = 25 ns
$\varepsilon_x \approx \varepsilon_y \approx$ 3 μm
σ_x x $\sigma_y \approx$ 1.0 mm^2

1. Increasing intensity at constant impact parameter
2. Varying impact parameter at maximum intensity
3. Several low-intensity shots: statistics for laser measurements

Parameter scans of basic beam properties!



Illustrative scheme

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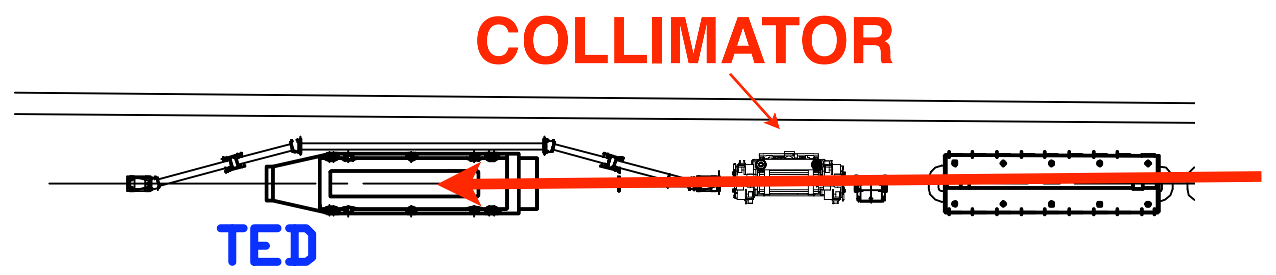
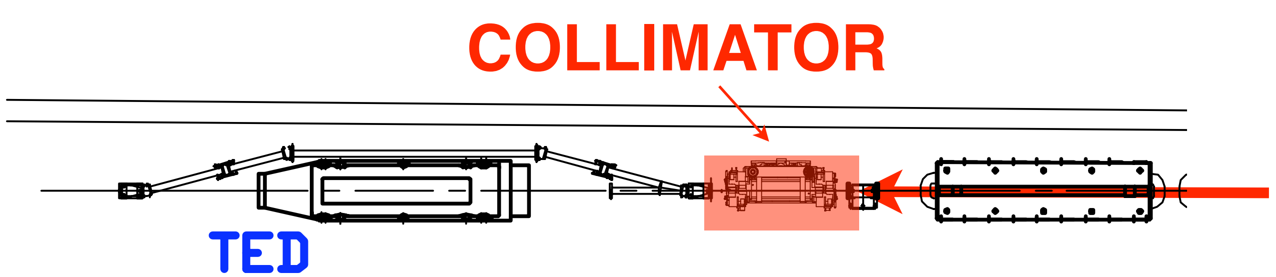
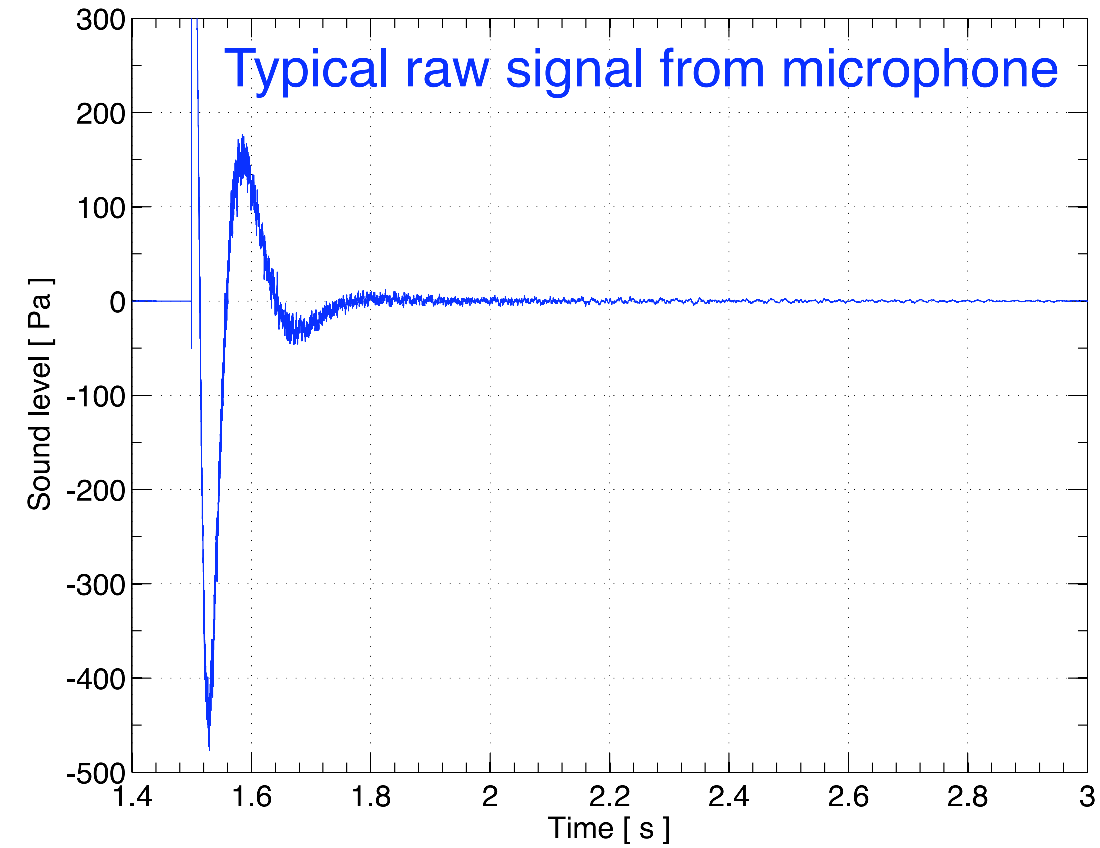
  - **Sound levels**
- **Conclusion**

Microphone measurements

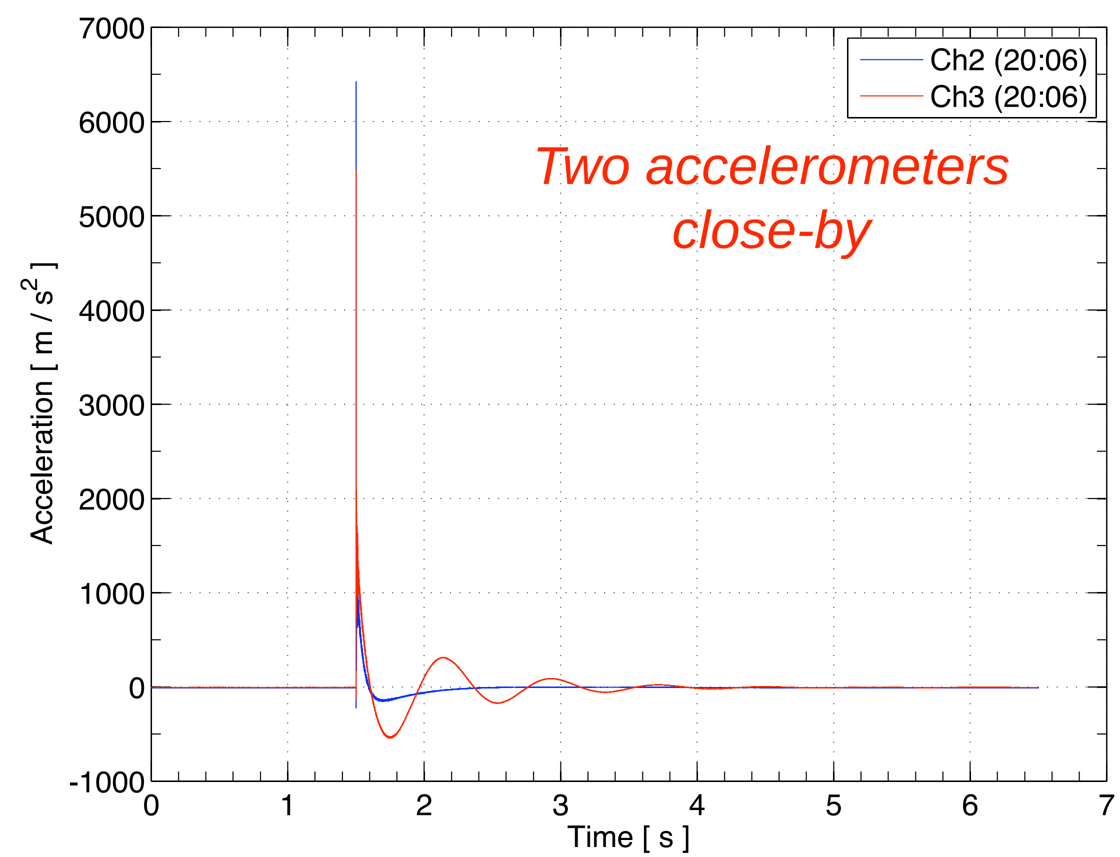






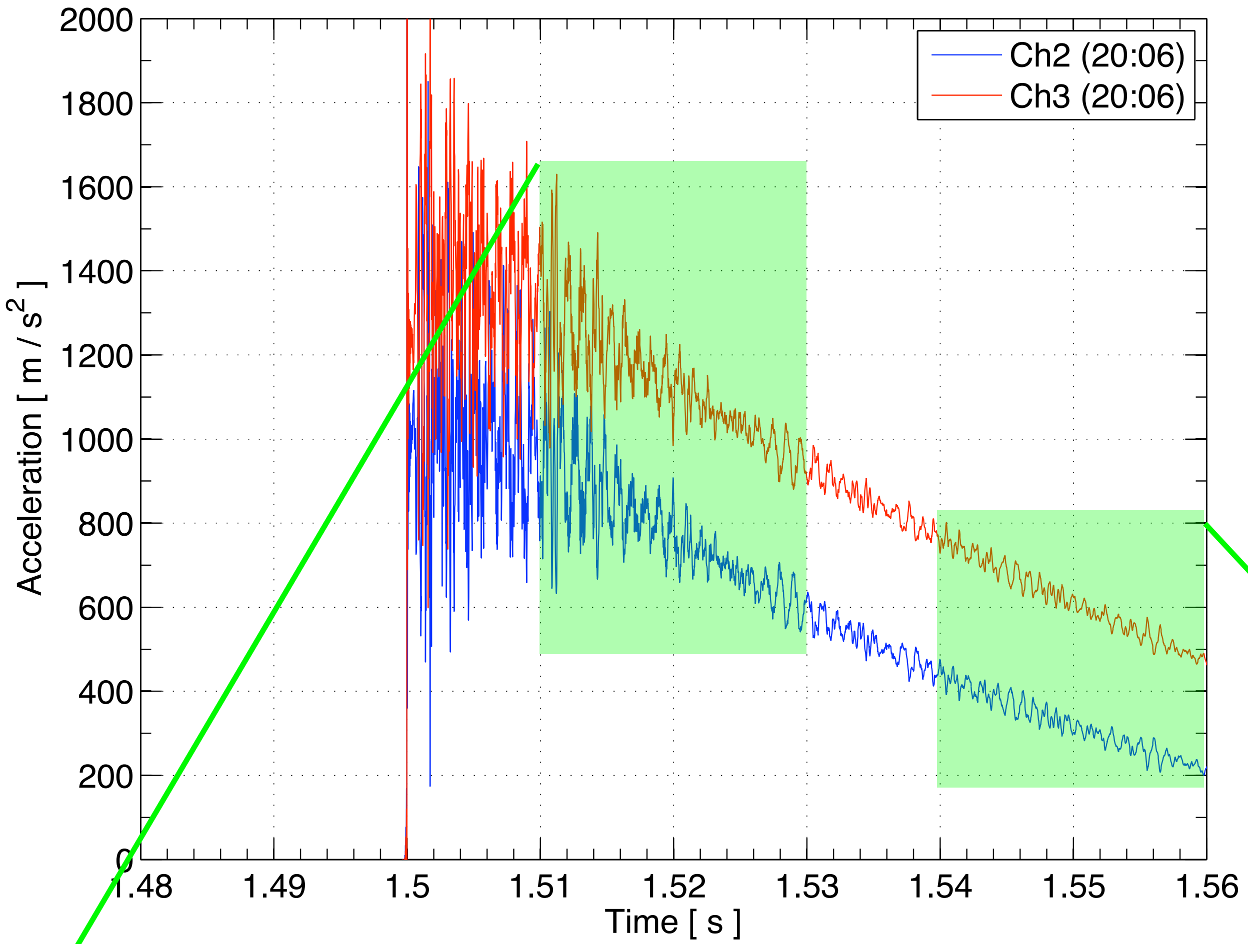
Impact detection is evident! Localization from microphone meas. is possible but not as evident...

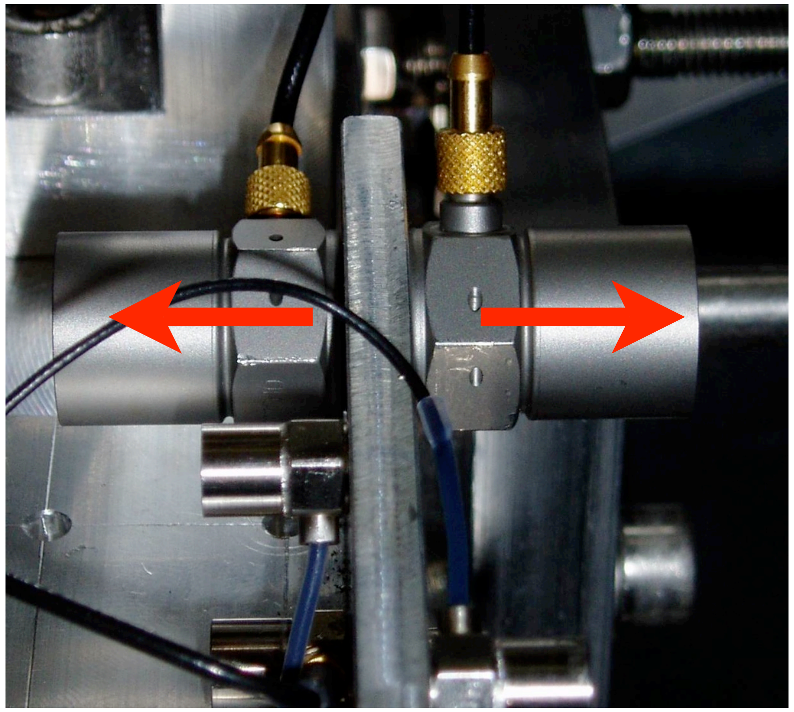
<u>Measured signals</u>:
Delta spike at beam passage + slow “ringing”.
Baseline shift, different for two sensors.
Radiation on electronics? E.M. effects?

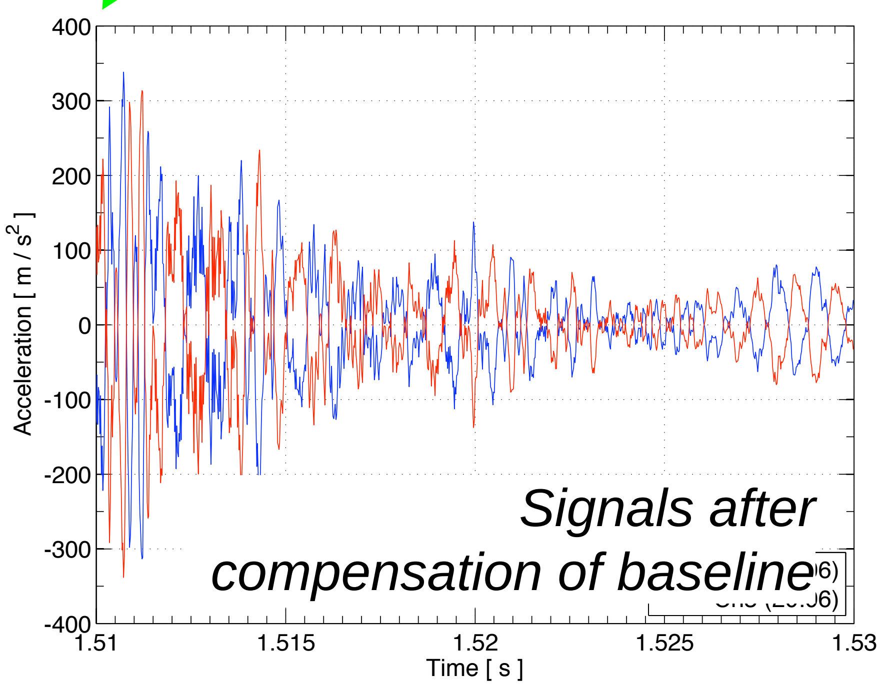


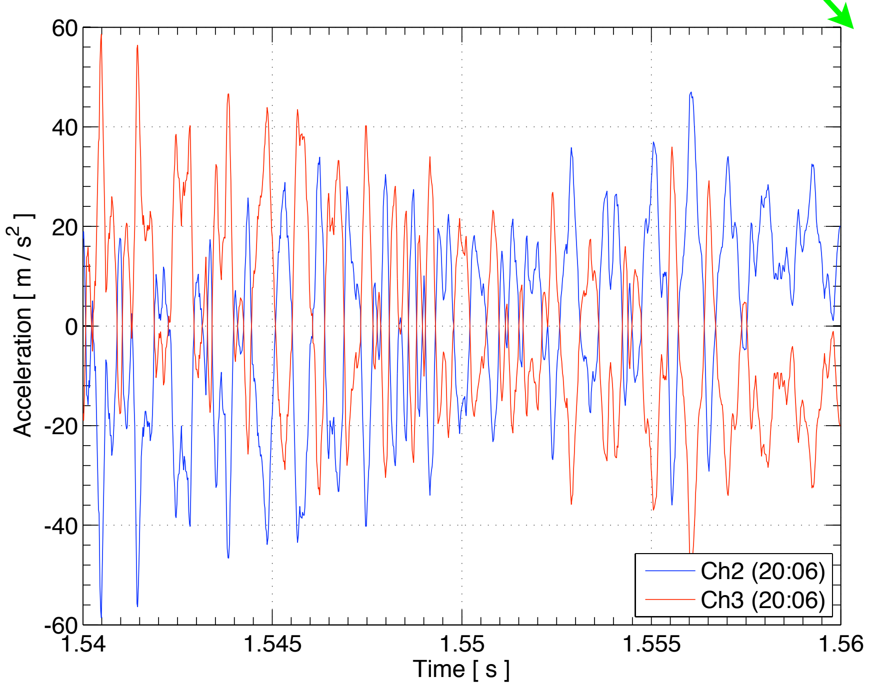
How can we extract and analyze the physical content of these signals?

Cancellation of low-frequency modulation









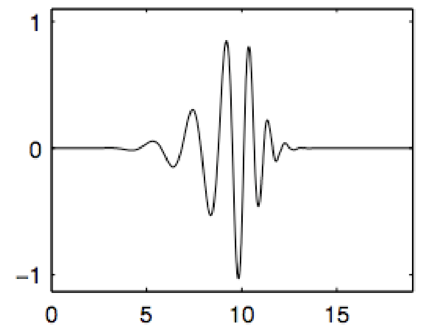
Calibration: for real vibrations opposite signals are expected.

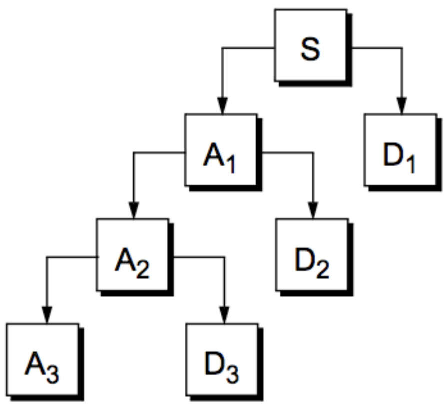
Expected behaviour found in the oscillations around the baseline (noise would be different!): we see real vibrations!

How can we compensate for the low-frequency modulation?

Signal correction with wavelets

Mother wavelet: Daubecheies





$$S = A_1 + D_1$$

$$= A_2 + D_2 + D_1$$

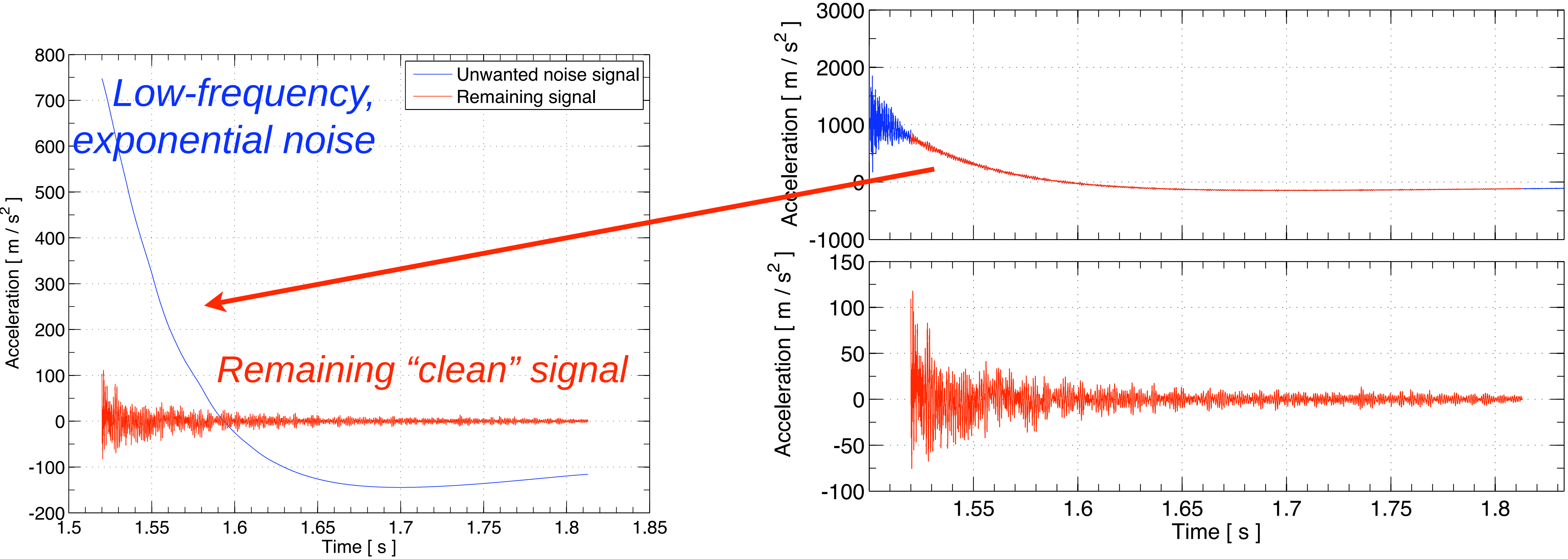
$$= A_3 + D_3 + D_2 + D_1$$

Wavelet decomposition can be efficiently used to subtract the “slow” baseline modulation (oscillation + exponential decay)

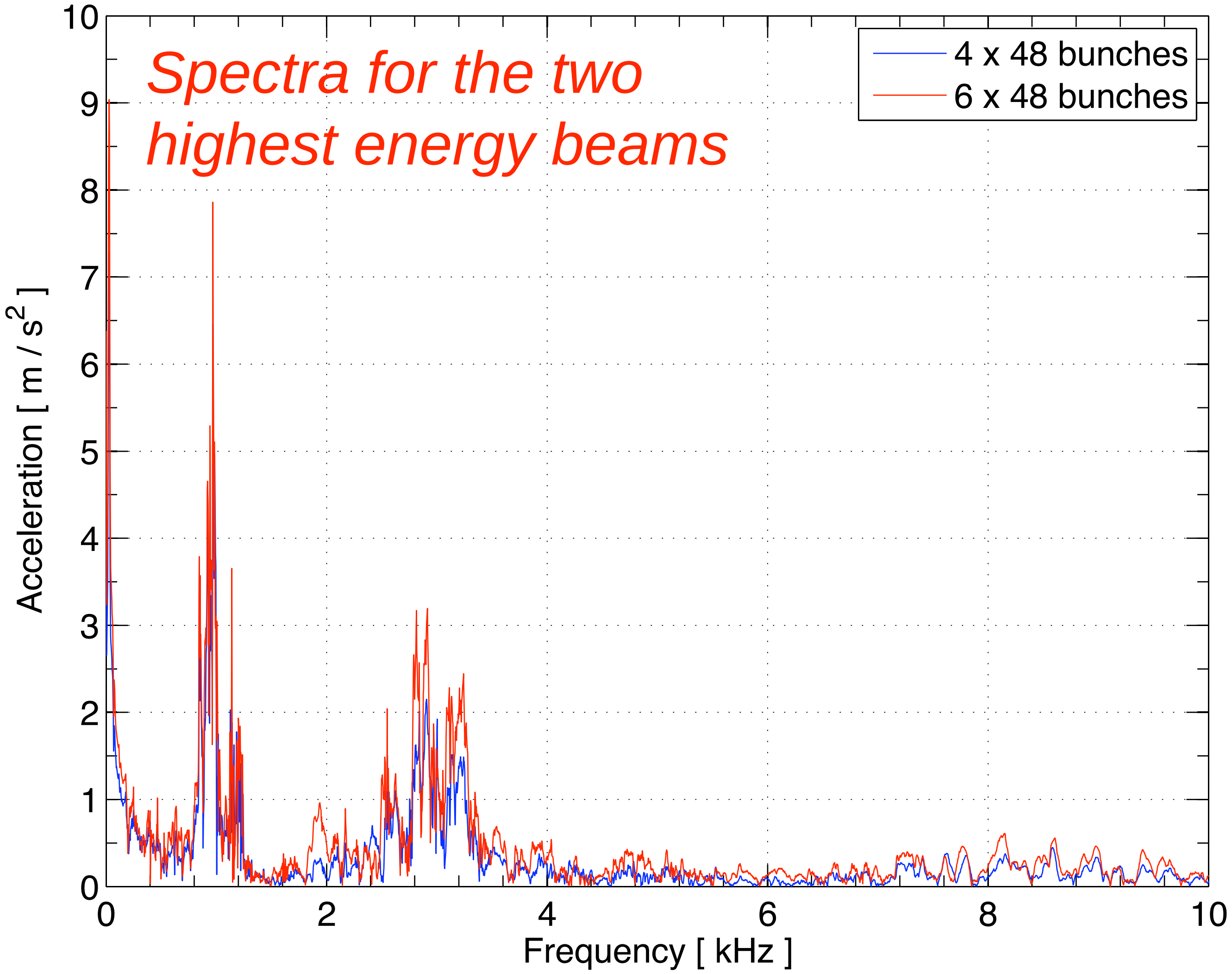
Remaining amplitudes are fully consistent with what is expected from sensor difference!

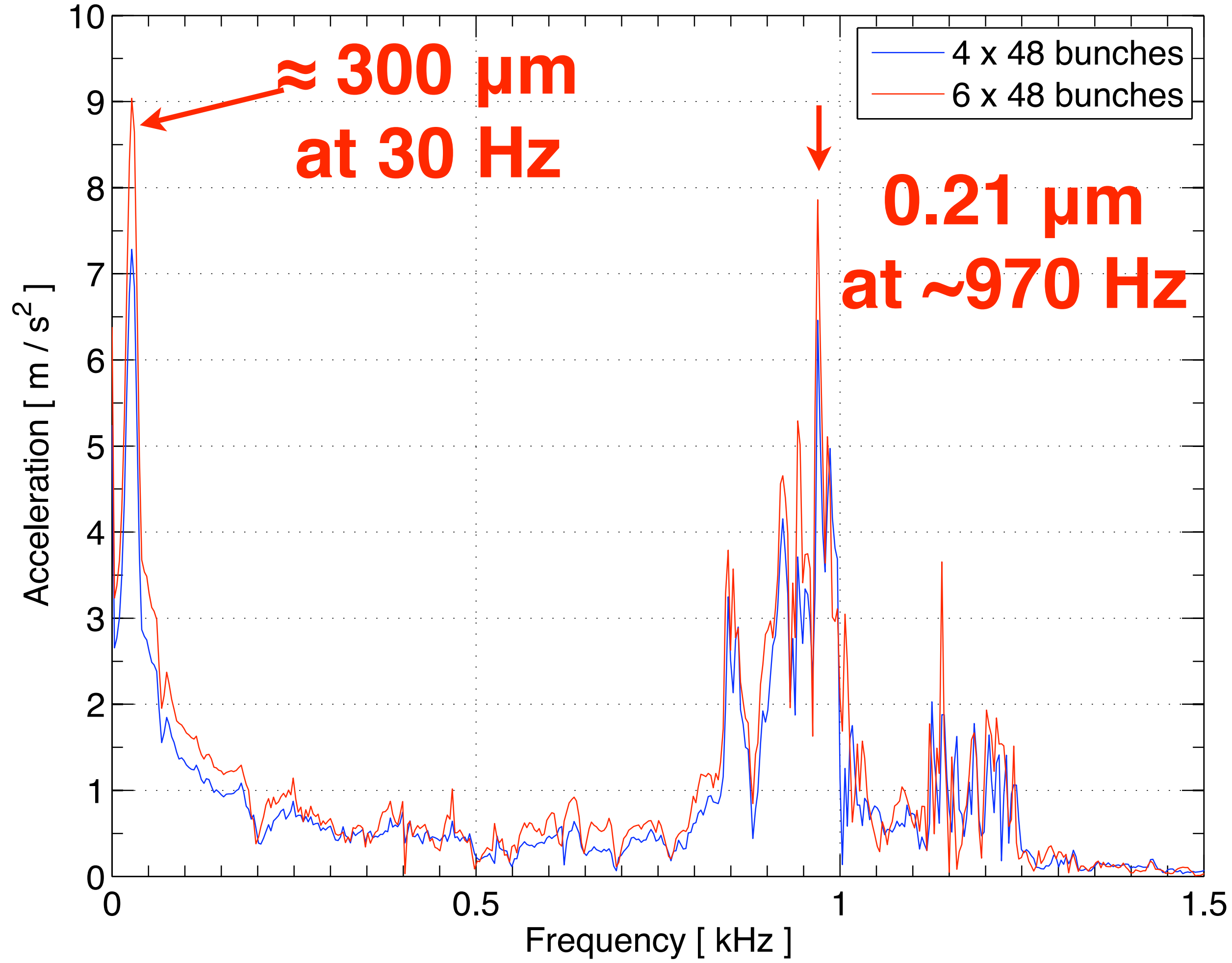
Wavelet analysis cuts amplitudes **below 20 Hz**

(no big concern for these measurements)



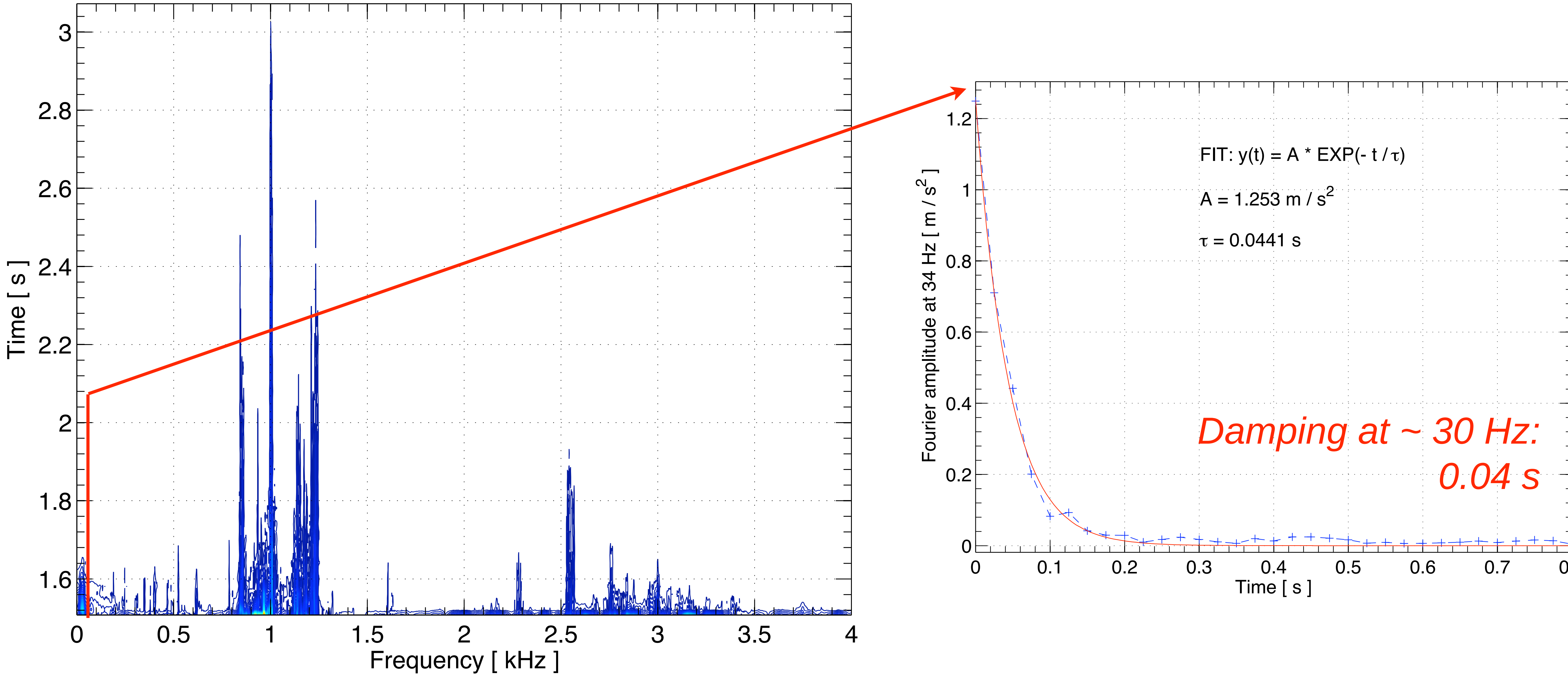
Spectrum of collimator vibrations





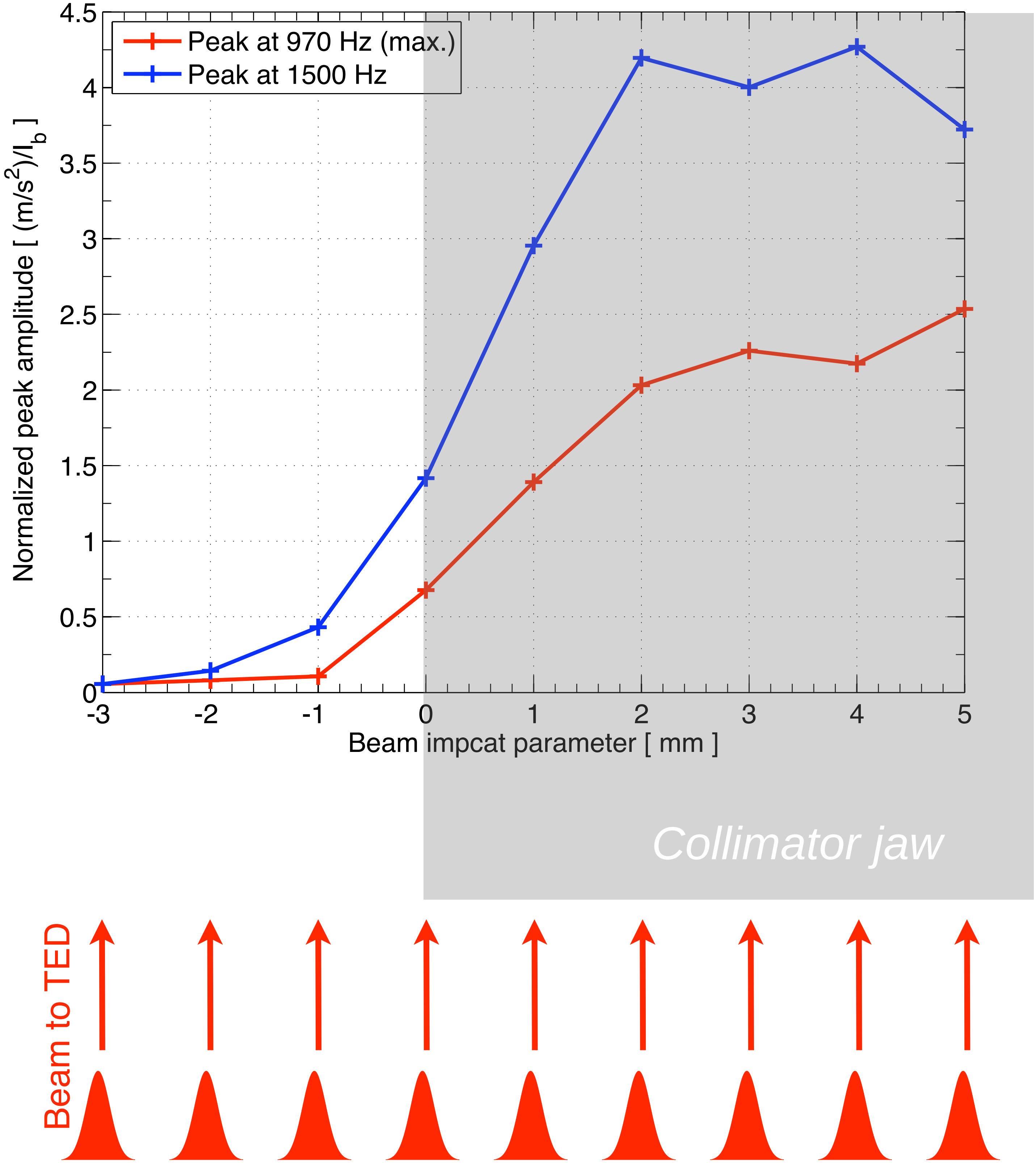
- Fourier spectrum calculated over Δt=300 ms after the impact
- Difficult to extract *initial amplitude* at beam impact: loose data due to electronics glitches
  - ➞ Can only start the analysis ~ 100 ms after beam passage
- Attempt to calculate the vibration amplitudes from double integral in frequency-domain
- Estimates are “optimistic”! Real vibrations are larger. Jaw might move even more!

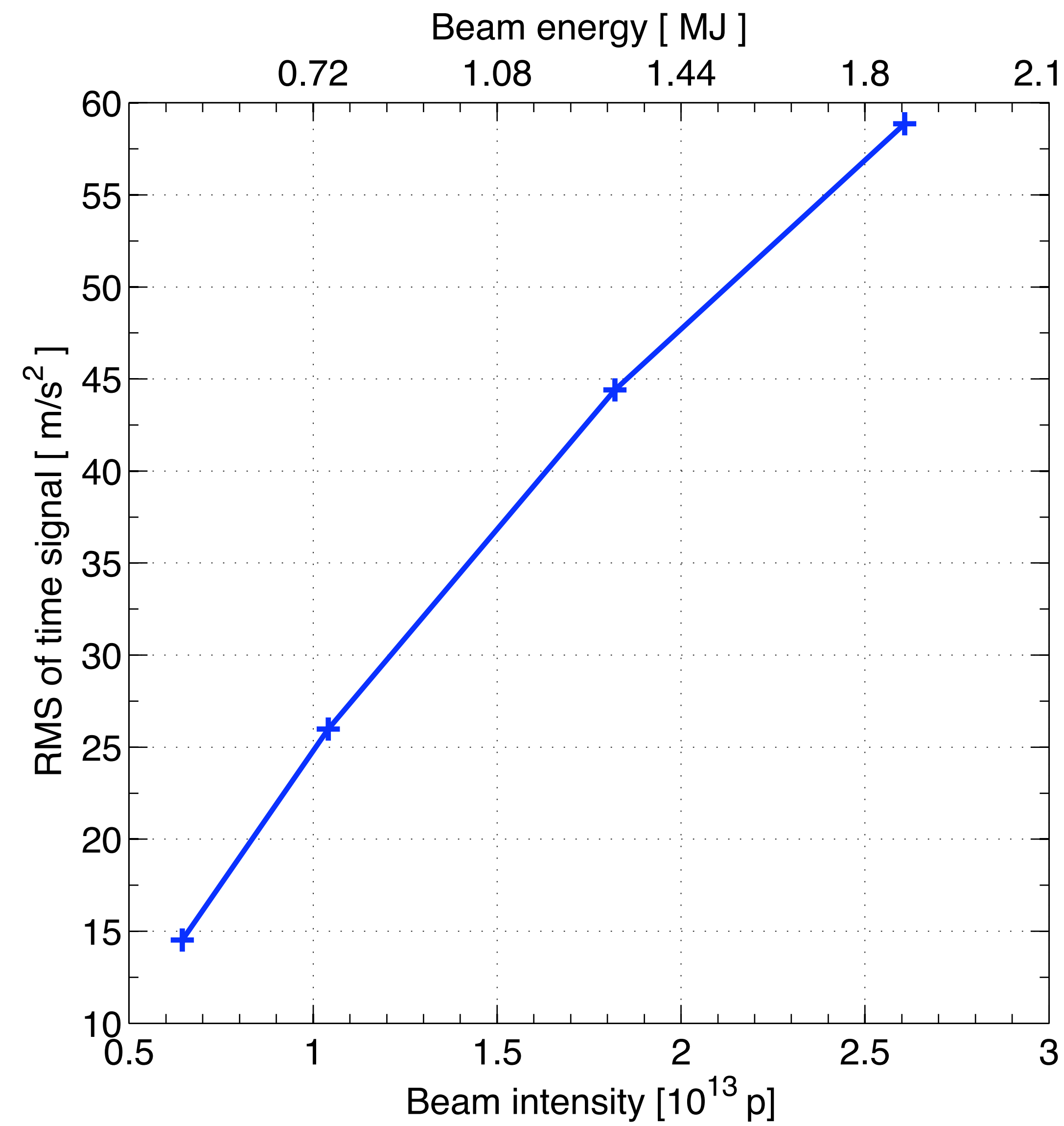
Time variation of vibration spectrum



- Sliding FFT used to calculate the spectrum versus time (Δt=300 ms)
- “Reach” frequency content of collimator vibrations! Different decay times
- Not only see jaw vibrations but also resonances of the full structure *(confirmed in laboratory)*
- Can estimate the damping of various radiation peaks...
- More inputs from simulations are needed: Which are the more interesting frequencies? *(see talk by A. Dallocchio)*

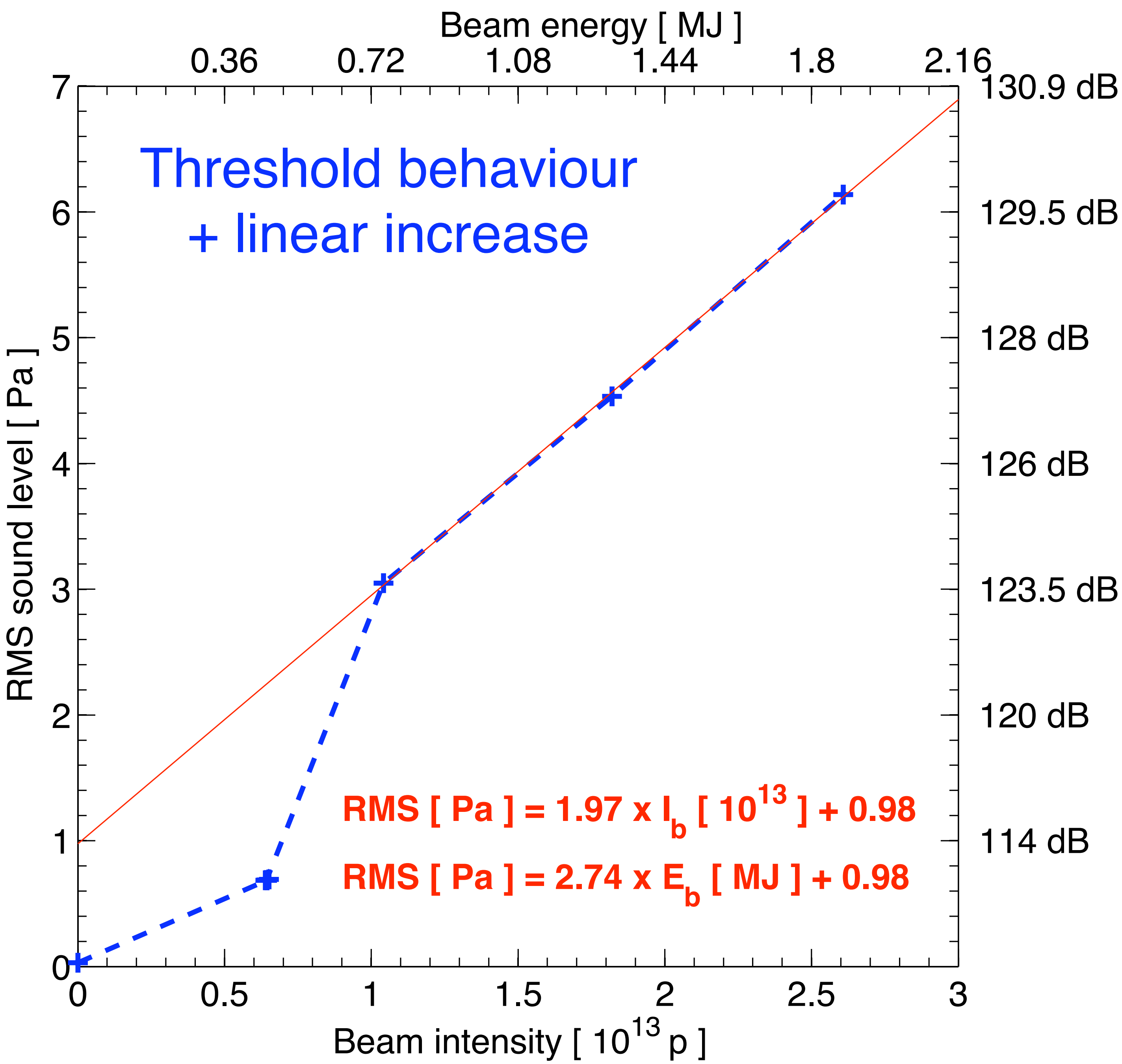
Scaling with beam parameters





Expected scaling against basic beam parameters (beam energy and intensity, impact parameter) is qualitatively confirmed!

Estimate of collimator sound levels



Approximate estimate:
energy scaling used to extrapolate sound of full LHC beam:

2.74x362+.98 = 993 Pa
= **154 dB**!!

140 dB ≈ threshold of pain

(Estimate relies on calibration from the manufacture only: no cross-calibrated independently)

Can we hear the "bang" from the LHC beam dump on surface?

Can we build a collimator Beam Impact Detector (BID)?

Yes!! All we need is:

(1) A few microphones in the tunnel, close to collimators: impact detection, signal trigger

(2) A pair of accelerometers per collimator, mounted in opposite direction, upstream side (less radiation)

(3) Circular acquisition buffer for accelerometers, *post-mortem* acquisition triggered by microphone

(4) Extract vibrations by compensating the “baseline”

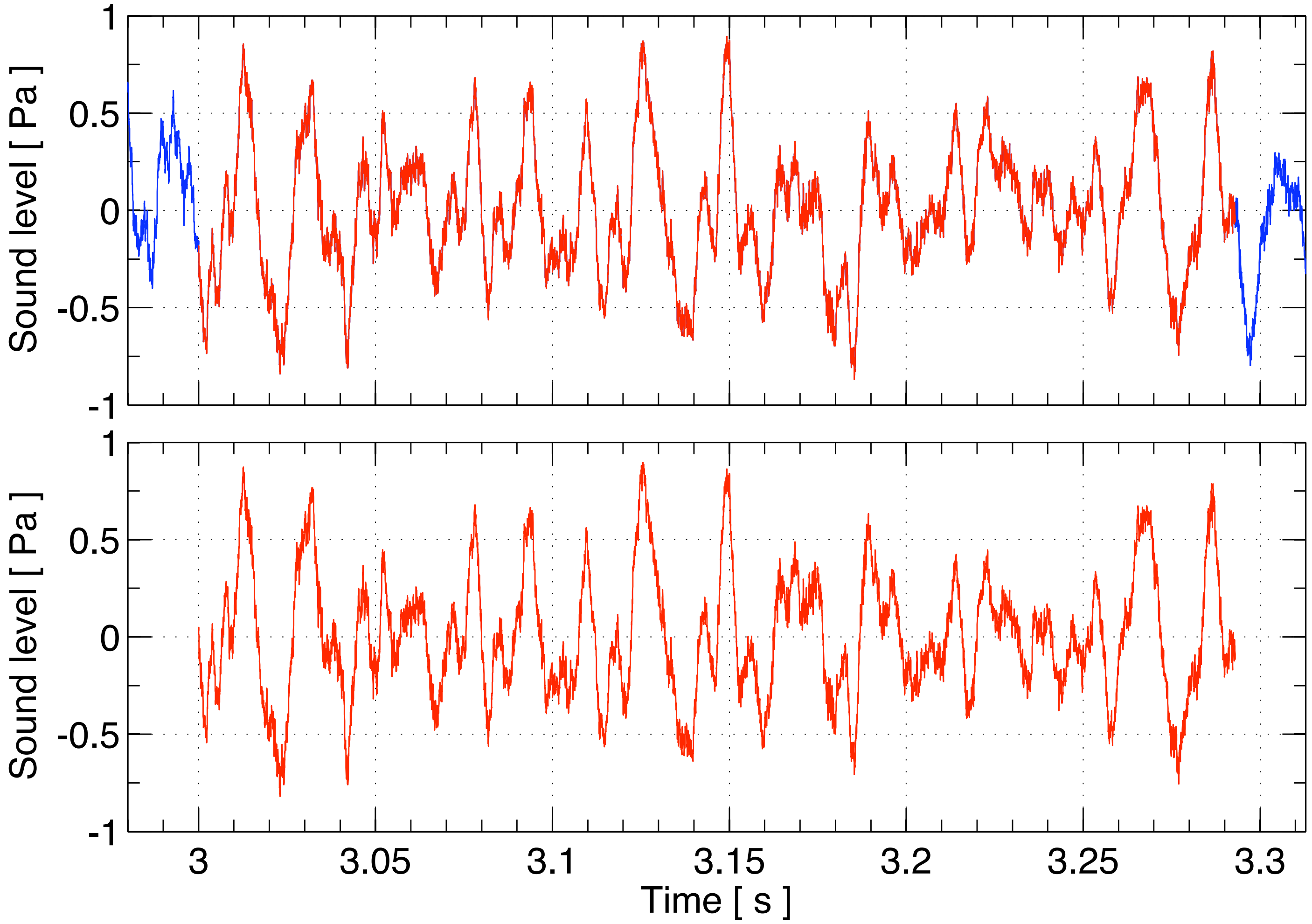
(5) Which collimator has the larger vibrations?

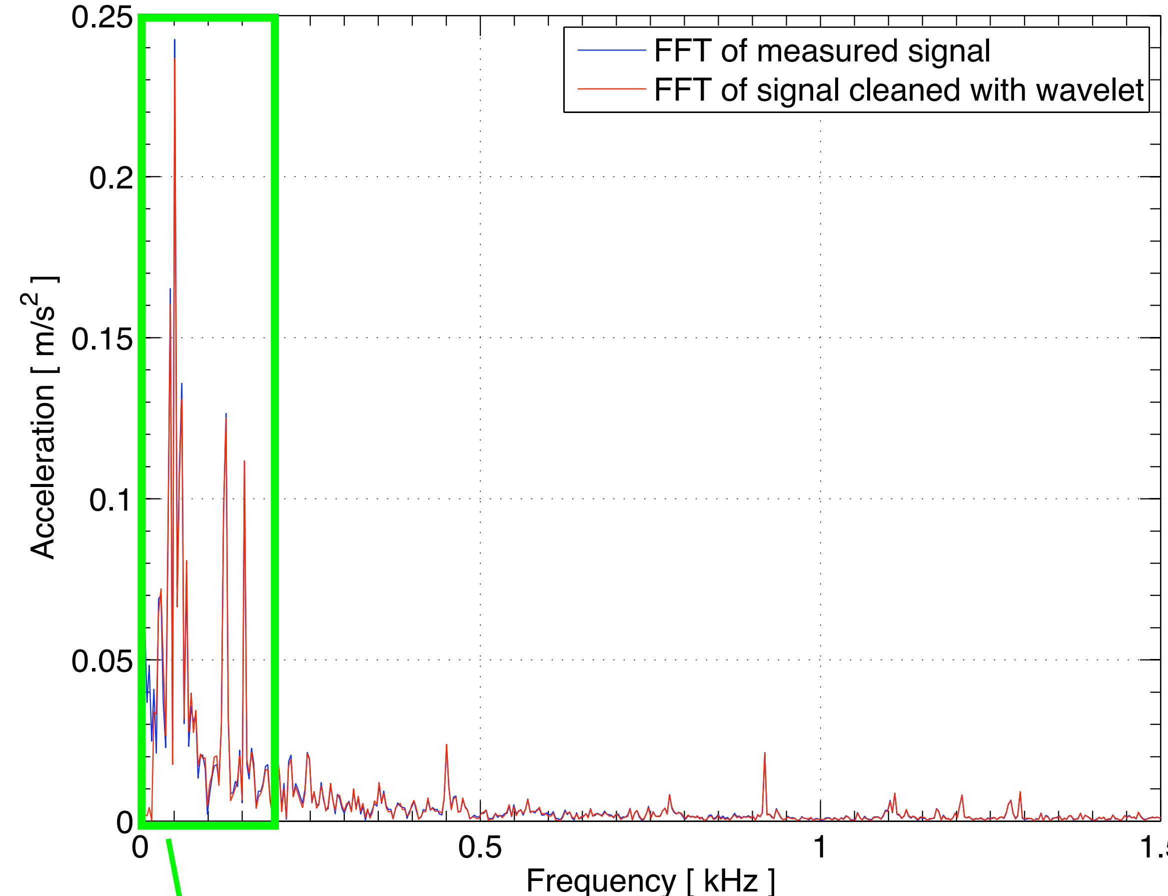
Conclusions

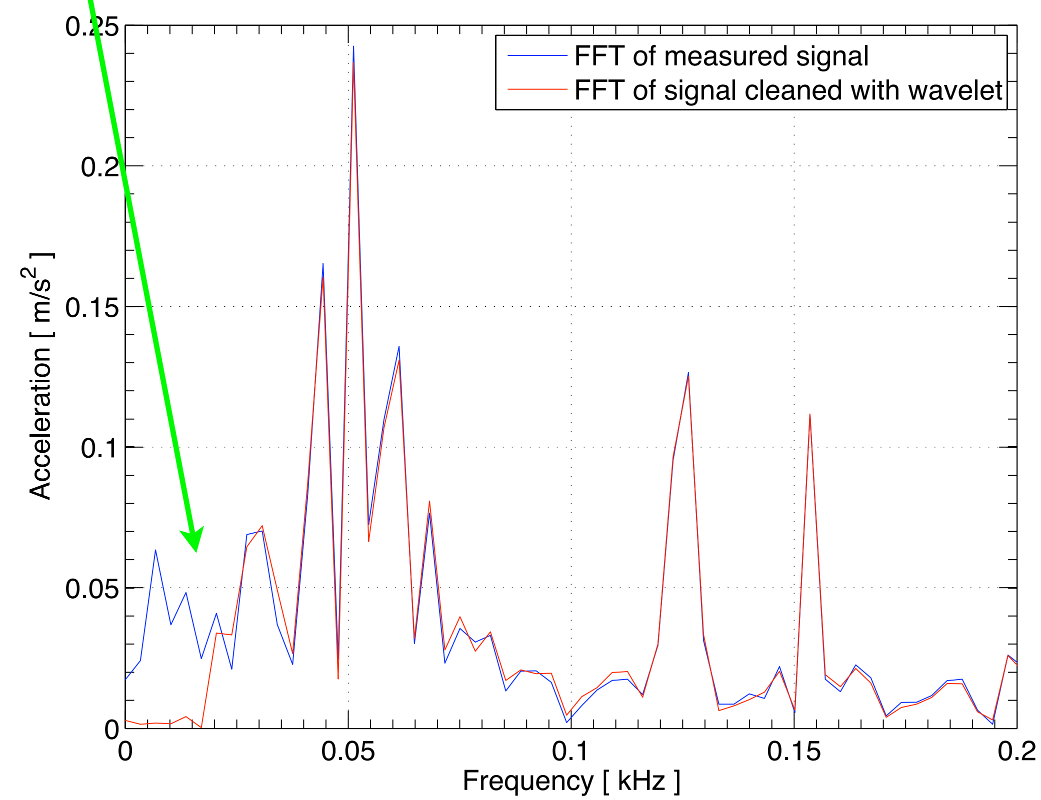
- We achieved our primary goal to demonstrate the localization of high energy beam impacts on the LHC collimators.
  - *- Detection with microphone*
  - *- Localization with accelerometers*
- Cost-effective and reliable solutions can in principle be found for direct localization of beam impacts
- We can achieve a local measurement of hit, and hence possibly damaged, collimators. Important for LHC multi-collimator system!
- Quantitative estimates are challenging due to the high radiation and high e.m. noise environment. We based our analysis on
  - (1) comparison of opposite accelerometers
  - (2) wavelet subtraction of low-frequency, exponential offsets
- We provided sound estimates. Dependence on beam parameters behaves as expected. More comparison with models are on-going.

Reserve slides

Example: wavelet correction does not change the relevant physical content



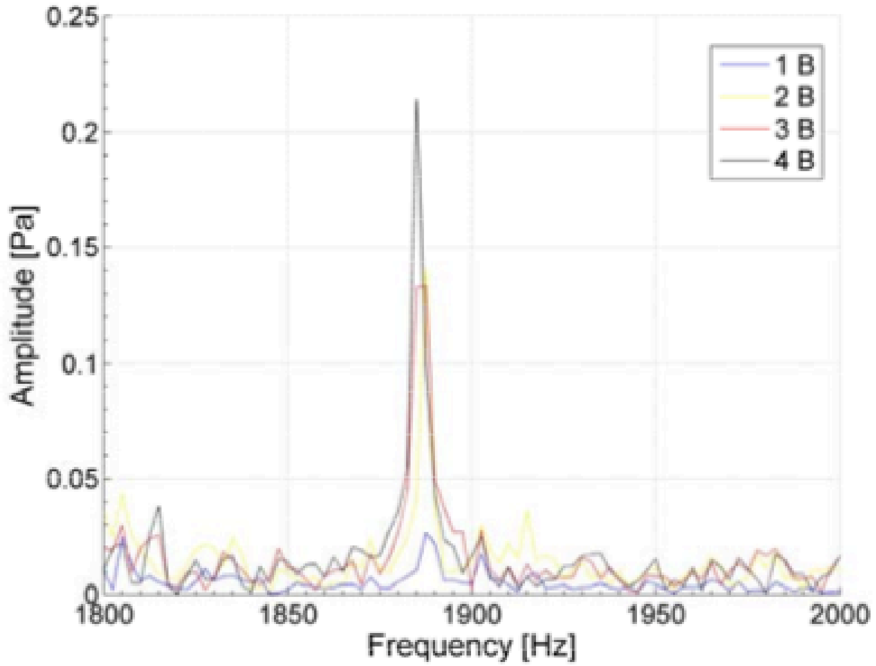


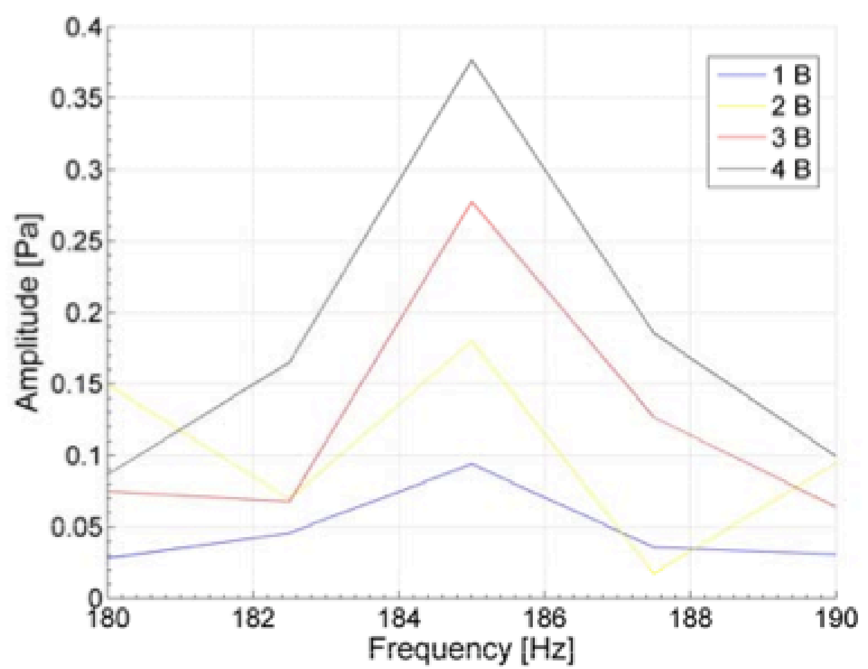


- Proposed wavelet analysis applied to a “clean” signal, not affected by low-frequency modulation
- FFT analysis compared for two signals before and after noise removal
- Very good agreement: wavelet analysis cut amplitudes **below 20 Hz**

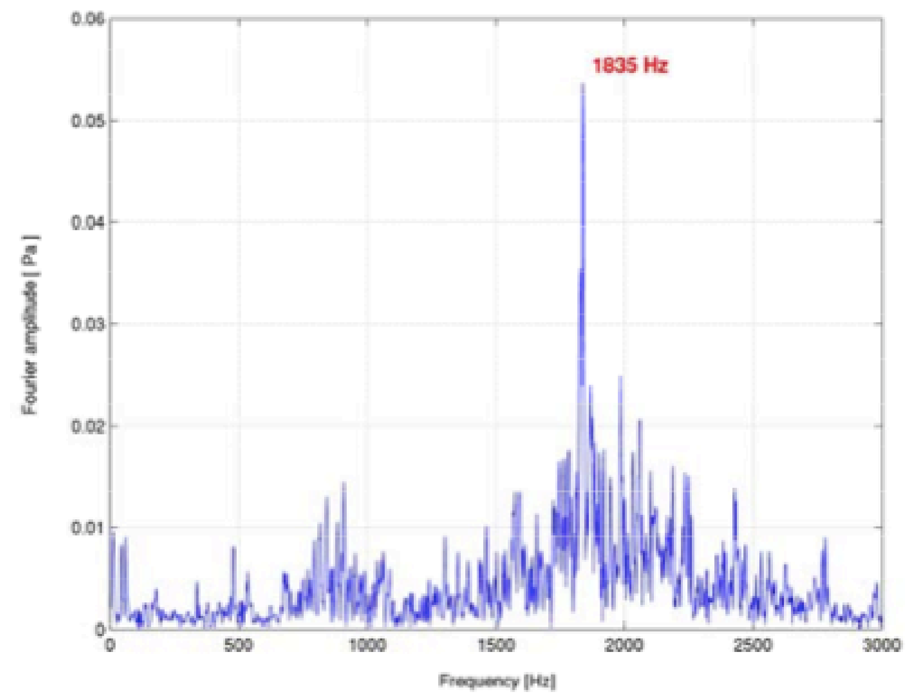
2004 test: collimator resonances

TT40 TEST





LAB TEST: Vacuum Tank



LAB TEST: Bellow