Ground motion feed-forward control for the future linear colliders

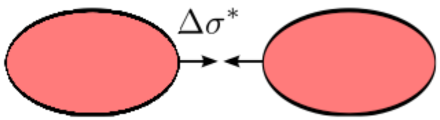
J. Pfingstner, K. Artoos, C. Charrondiere,
St. Janssens, M. Patecki*, Y. Renier,
D. Schulte, R. Tomas (*CERN*),
A. Jeremie (*LAPP-IN2P3-CNRS*),
K. Kubo, S. Kuroda, T. Naito, T. Okugi,
T. Tauchi, N. Terunuma (*KEK*)
**Also at Warsaw University of Technology, Faculty of Physics*

Outline

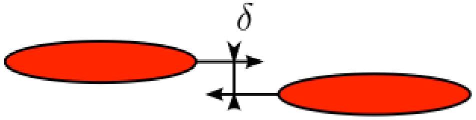
- Motivation
- Concept of GM feed-forward system
- Simulation studies for the ATF2 GM experiment
- Experimental setup in ATF2
- Ground motion measurements in ATF2
- Correlation results
- Orbit jitter reduction
- Conclusions

Motivation

- The future particle colliders are going to be more and more sensitive to ground motion (GM) effects.
- GM causes the accelerator magnets misalignments which can result in:
    - the beam size growth:



    - the beam-beam offset at the IP:

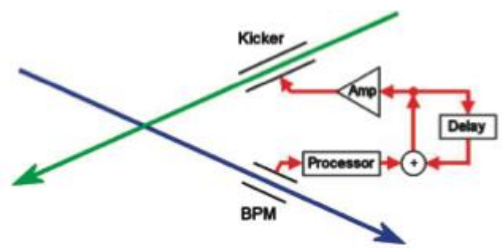


Motivation (II)

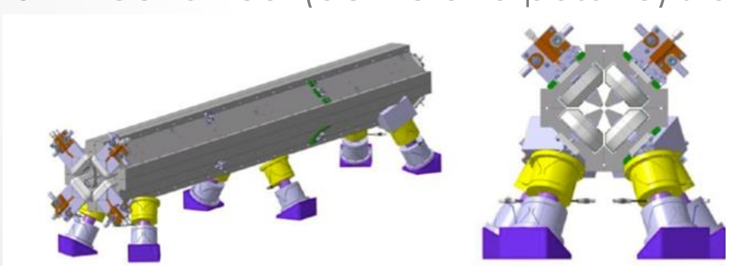
- The GM effects can be suppressed by the orbit feedback systems, which are efficient for low frequencies (factor $f_R/20$ by the rule of thumb).
- For ILC f_R= 5 Hz
- For CLIC f_R= 50 Hz
- For ATF2 f_R= 3.12 Hz
- **The orbit feedbacks are not sufficient to suppress all relevant ground motion effects.**

Motivation (III)

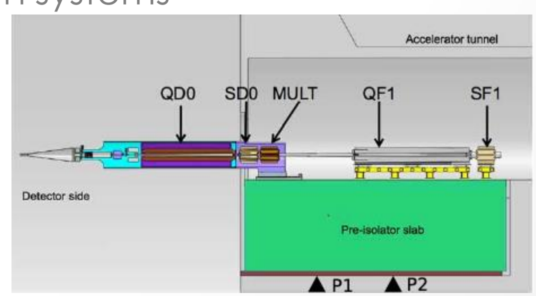
- For the frequencies (higher than about $f_R/20$) not corrected by the orbit feedback system, there are other correction methods:
  - Intra-train feedback systems - J. Resta-Lopez, P. Burrows, and G. Christian, Journalof Instrumentation 5, 09007 (2010).



    - More efficient for ILC than CLIC (short bunch spacing (0.5 ns))
    - May cause the luminosity loss
  - Mechanical (active and passive) stabilization systems



K. Artoos et al.



A. Gaddi et al.

Motivation (IV)

- For the frequencies (higher than about $f_R/20$) not corrected by the orbit feedback system, there are other correction methods:

Feed-forward system based on Ground Motion

- Cheaper than mechanical systems,
- Easy to integrate into accelerator modules,
- Possibility to apply corrections that are distributed over many correctors (global scheme),
- High demands on the speed of the system,
- High demands on the system model accuracy.

GM feed-forward system

- The vibrations are measured by the sensors in order to determine in real-time the quadrupoles position change $\boldsymbol{x}(t)$.
- The beam orbit change $\boldsymbol{b}(t)$ is predicted with the use of orbit response matrix $\boldsymbol{R}_q$

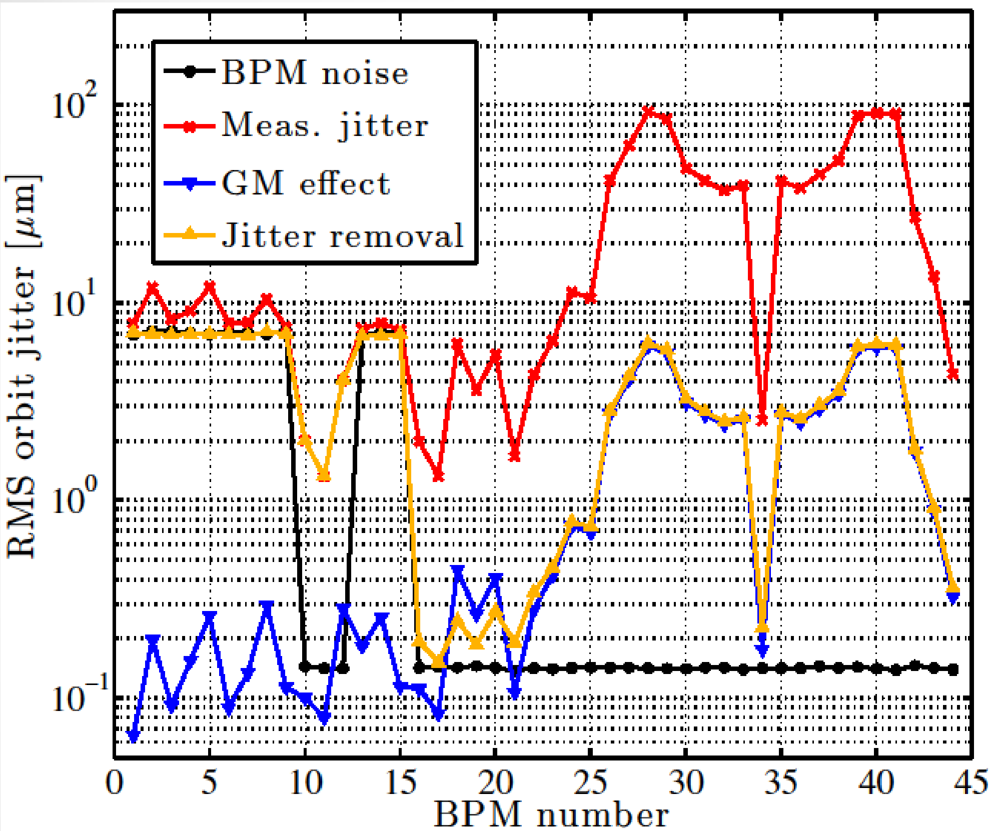
$$\boldsymbol{b}(t) = \boldsymbol{R}_q \boldsymbol{x}(t).$$

- The actuations $\mathbf{c}(t)$ of corrector magnets that compensate $\boldsymbol{b}(t)$.

Simulation studies for the ATF2 GM experiment

- The simulations were conducted in order to evaluate the expectable performance of the feed-forward mitigation method.
- PLACET and ATF2 Flight Simulator were used showing good agreement.
- GM generator integrated into PLACET.
- Two setups with 14 and 30 sensors located in the optimized positions.
- Quadrupole magnets field errors of 0.01%,
- BPM scaling errors of 1%,
- Stripline BPMs resolution set to 5μm, and cavity BPMs to 0.1 μm
- Initial orbit jitter with an amplitude of 10% (horizontal) and 25% (vertical),
- Sextupole magnets turned off.

Simulated orbit jitter



- Low resolution of BPMs at the beginning of the beam line,
- GM effect very small comparing to the full orbit jitter,
- Incoming orbit jitter removed by the de-correlation technique:

Incoming orbit jitter can be measured by high-resolution BPMs (10,11,12) and then removed from the downstream BPMs:

$$\Delta B_i^{(r)} = \Delta B_i - K_{up}\Delta B_i$$

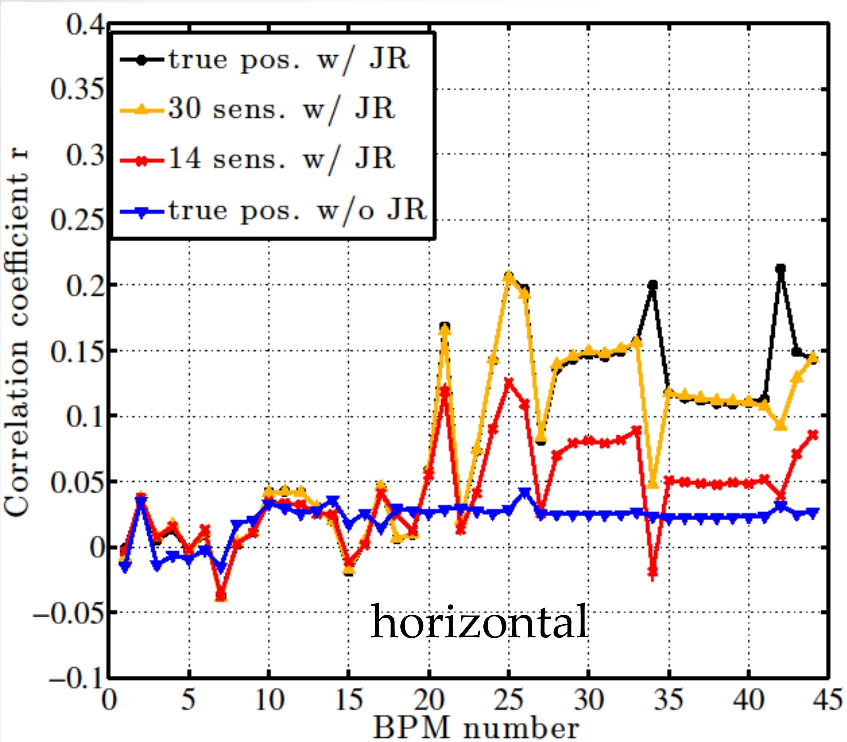
$$K_{up} = \Delta B_{up}\Delta B_{up}^{\dagger}$$

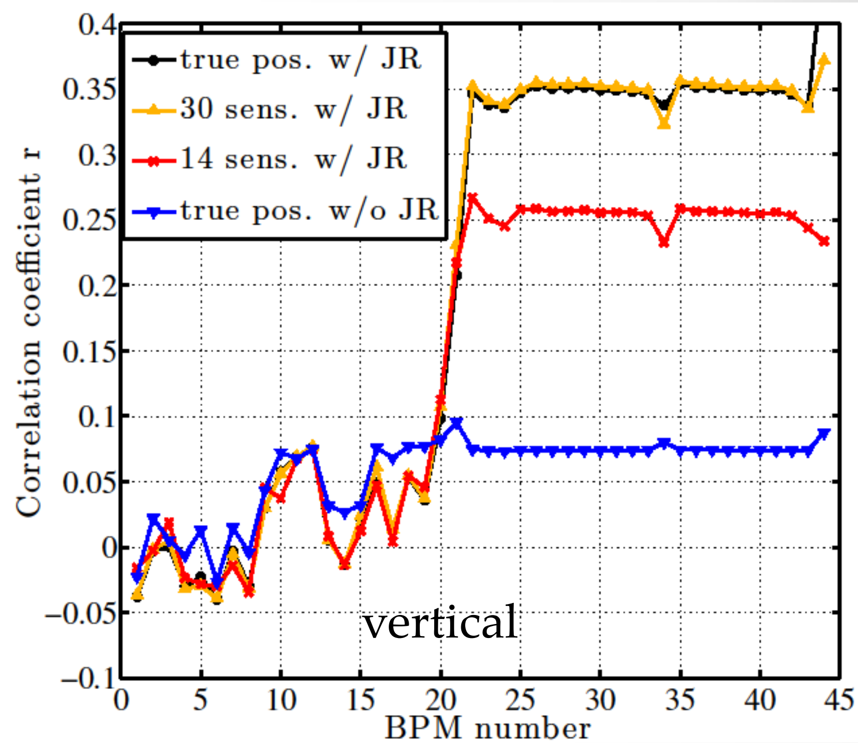
$$\Delta B_{up} = [B_{10}, B_{11}, B_{12}]$$

$\Delta B_i^{(r)}$ are the decorrelated data with the incoming jitter removed, and † stands for the pseudo-inverse of a matrix.

- **The ground orbit effect can be measured after the jitter removal.**

Correlation coefficient

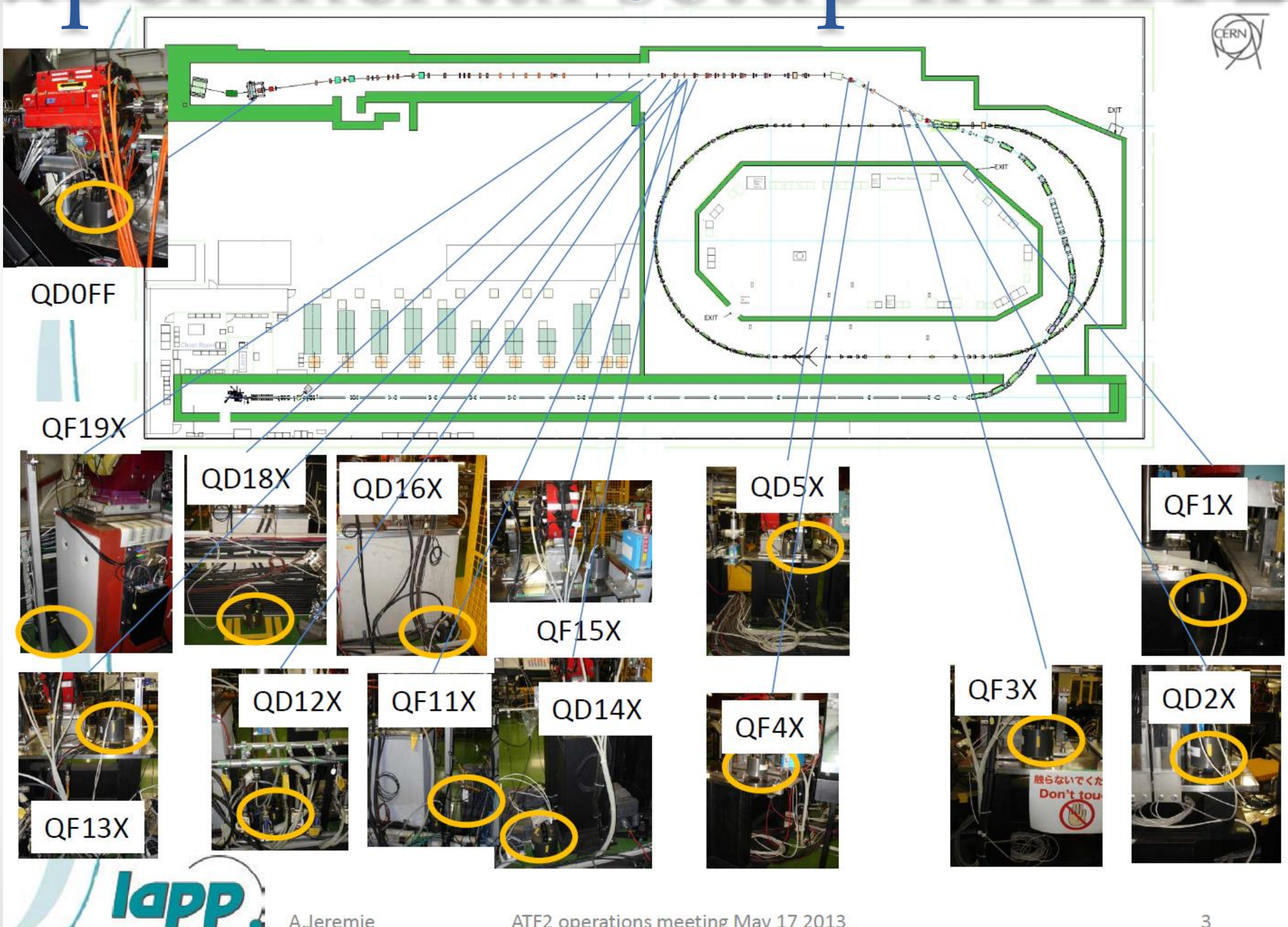




- $\Delta b_k = b_k - b_{k-1}$ - BPM data (high pass filtering)
- $\Delta \widehat{x_k}$ - estimated position changes of quadrupoles
- $\Delta \widehat{b_k} = R_q \Delta \widehat{x_k}$ - predicted beam orbit at BPM locations

- $r_i = \frac{cov(\Delta B_i, \Delta \widehat{B_i})}{\sigma(\Delta B_i)\sigma(\Delta \widehat{B_i})}$ - **correlation coefficient**
- $\Delta B, \Delta \hat{B}$ - matrices for measured and predicted beam orbit for all BPMs and time steps
- $\sigma(b_i)$ – standard deviation of any vector b_i
- $cov(b_i, b_j) = \frac{1}{1-N} \sum_{k=1}^{N} (b_i(k) - \overline{b_i})\,(b_j(k) - \overline{b_j}))$

Experimental setup in ATF2

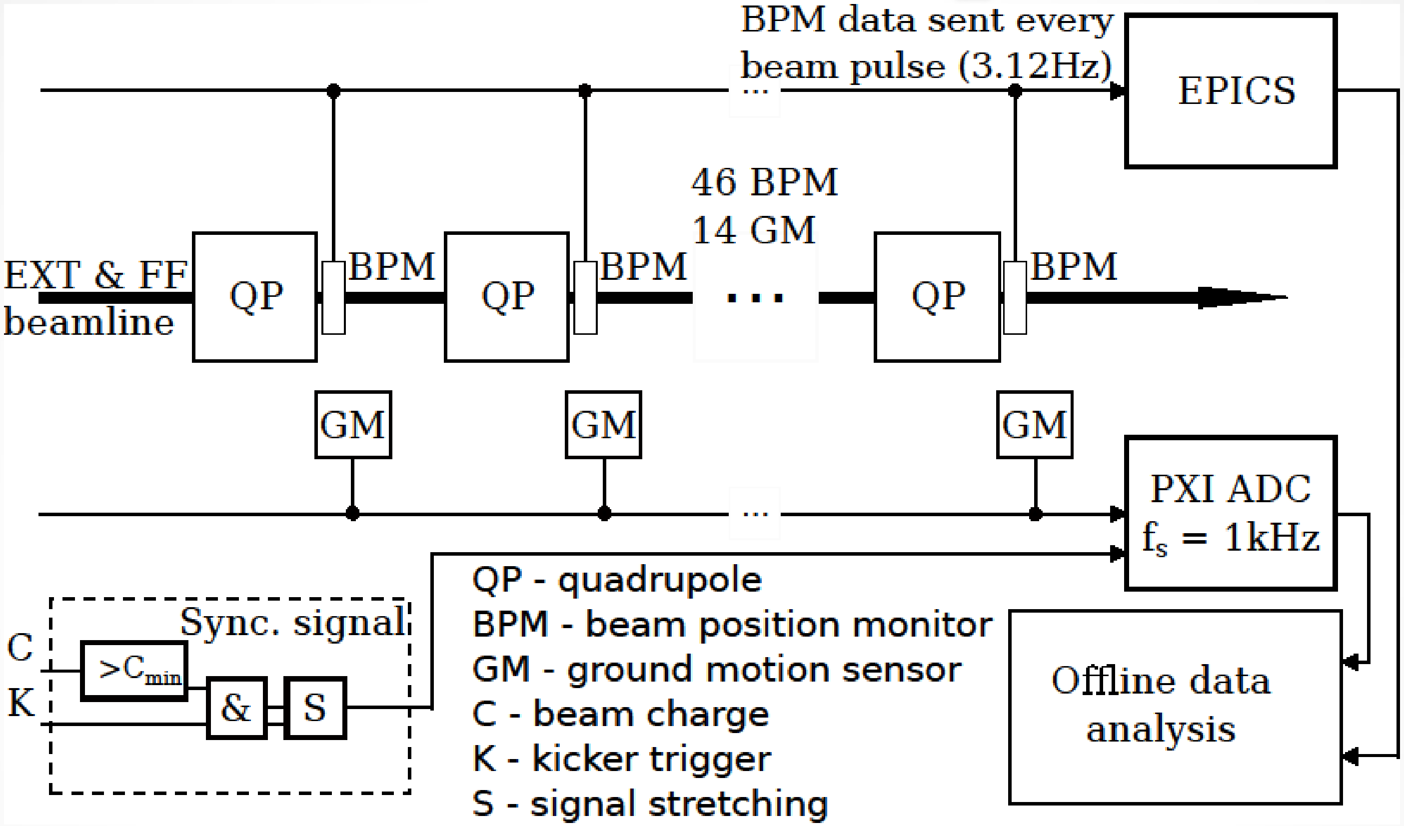


GM sensors

Velocity output bandwidth	*1 s – 100 Hz (Model CMG-6T-1),* *10 s – 100 Hz (Standard) or* *30 s – 100 Hz*
Velocity output sensitivity	*2 × 1200 V/m/s, (Standard)* *2 × 2000 V/m/s or* *2 × 1000 V/m/s*
Peak output	*±10 V (20 V peak-to-peak)*
ptional high gain sensitivity	*2 × 10000 V/m/s (adjustable)*
Lowest spurious resonance	*450 Hz*
Linearity	*> 90 dB*
Cross-axis rejection	*> 65 dB*
Electronics noise level	*–172 dB (rel. 1m2s-4Hz-1)*
Operating temperature	*–40 to +75 °C*
Temperature sensitivity	*< 0.6 V per 10 °C*
Mass recentring range	*±3 ° from horizontal*
Materials	*Hard anodised aluminium case* *Gold plated contacts* *O-ring seals throughout*
Case diameter	*154 mm*
Case height (with handle)	*207 mm*
Weight	*2.49 kg*
Power supply	*10 – 36 V DC*
Optional low power sensor	*5 V DC supply (output ±4.5 V)*
Current at 12 V DC	*38 mA*

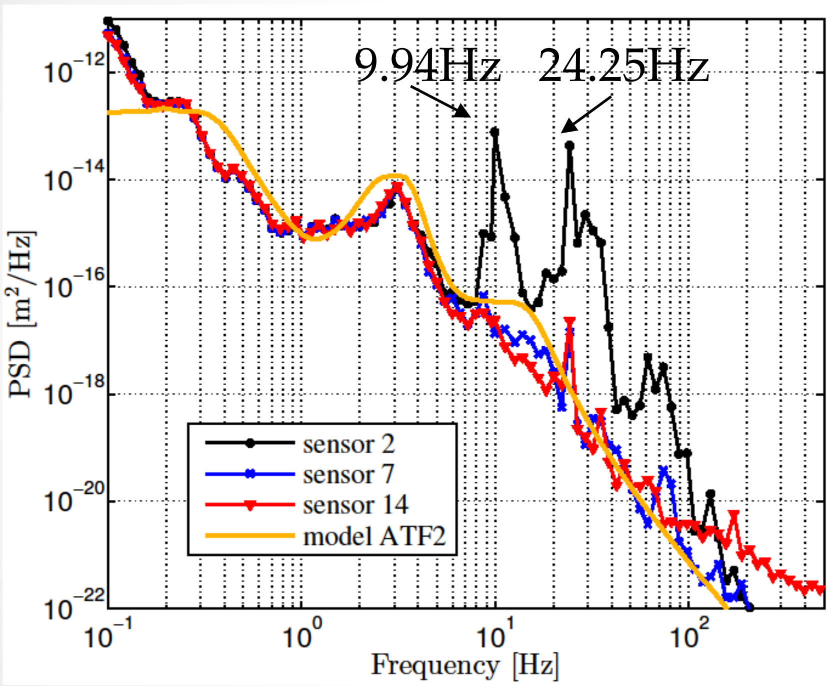
CMG-6T

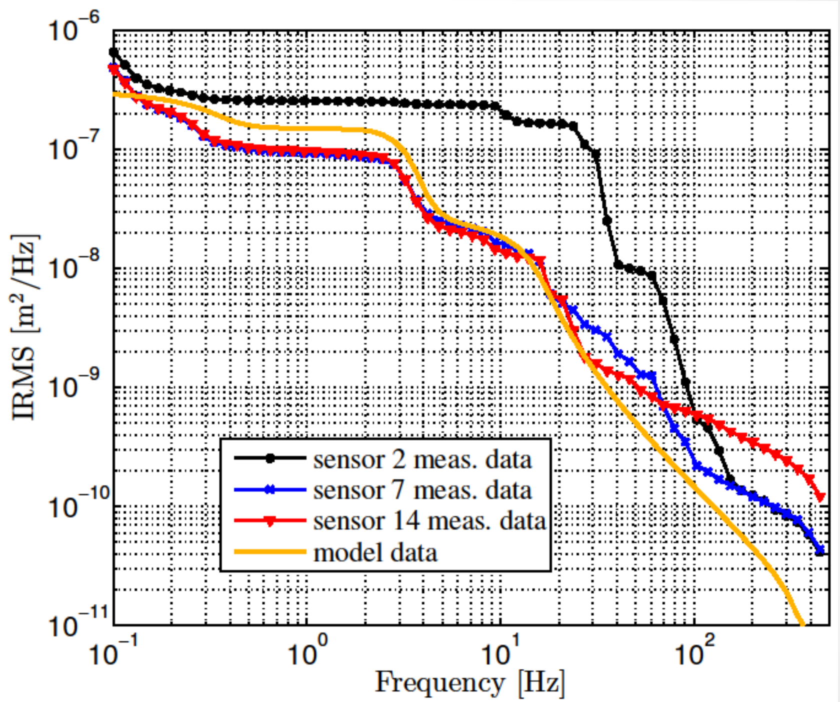
Experimental setup in ATF2



- 46 BPMs for the beam orbit measurements. Data sent to EPICS every beam arrival (3.12 Hz),
- 14 GM sensors connected to NI PXI 8109 RT via low noise cables and digitized by a card NI 6289 with sampling frequency of 1024 Hz,
- Synchronization signal recorded by PXI enabling to select the GM data corresponding to BPM data.

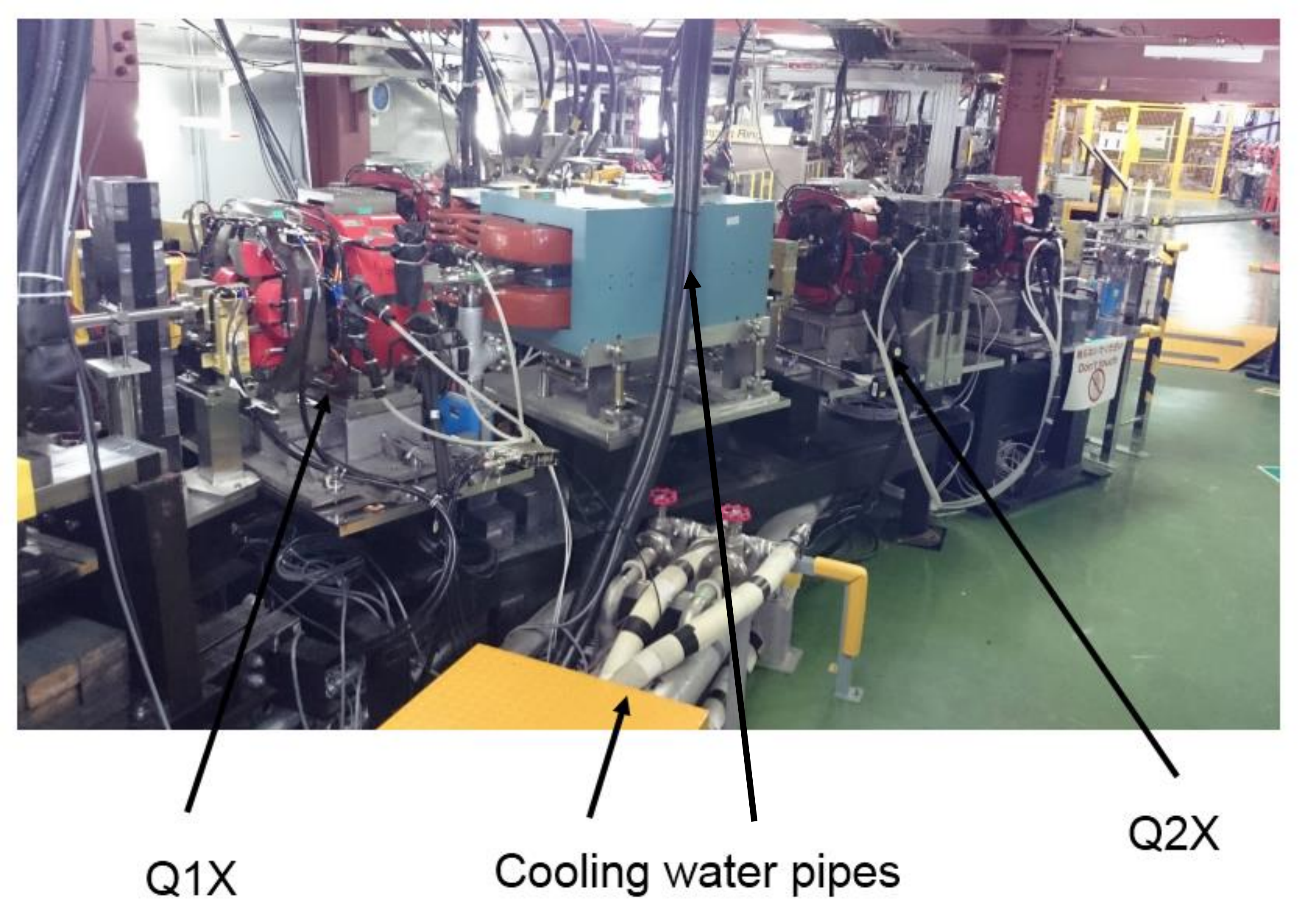
Ground motion measurements



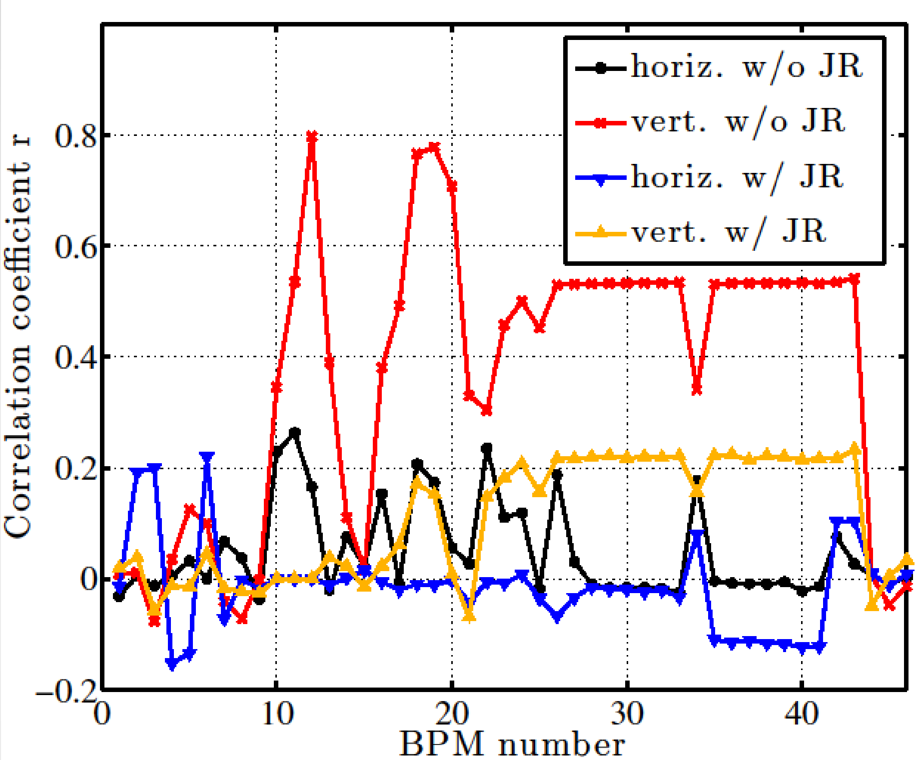


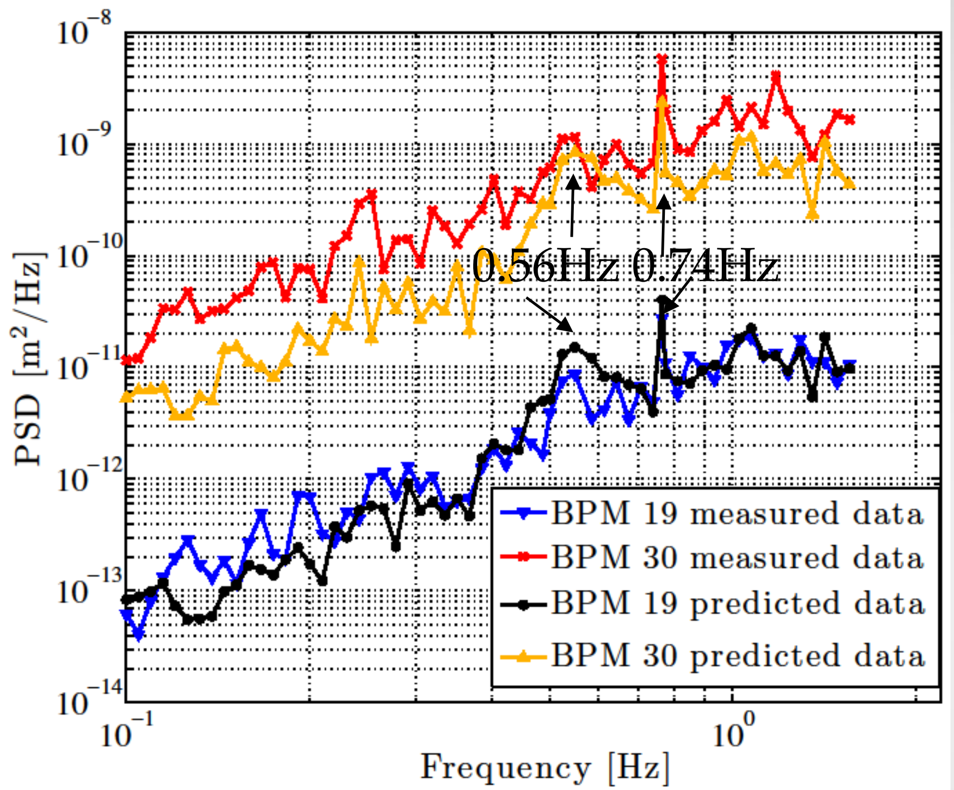
High, unexpected vibration around sensor 2

Sensor 2 region



Correlation coefficient

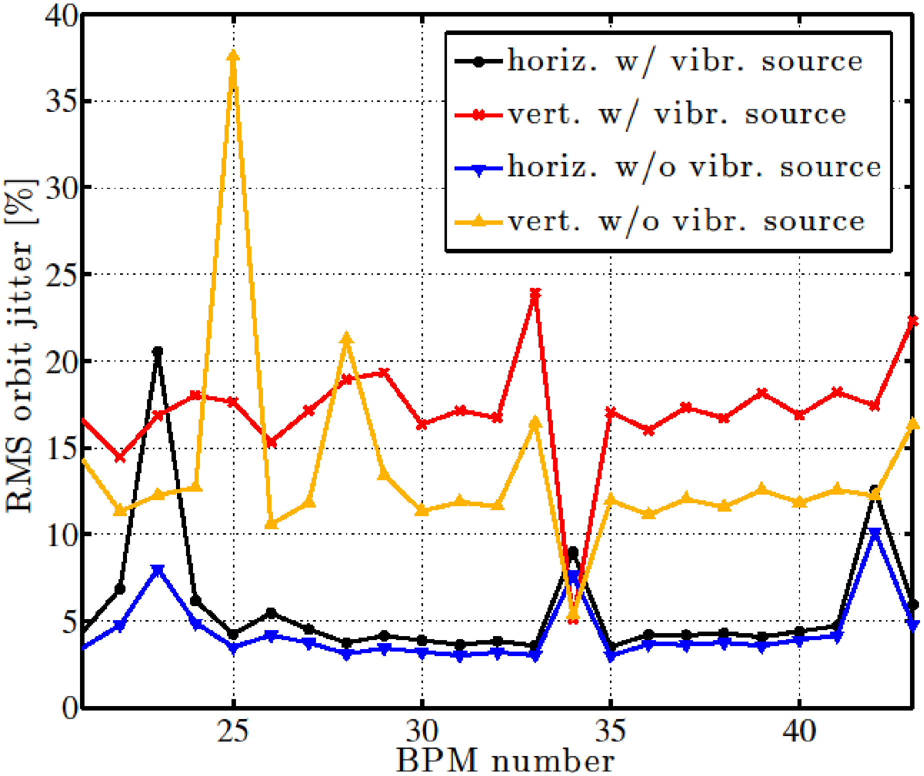


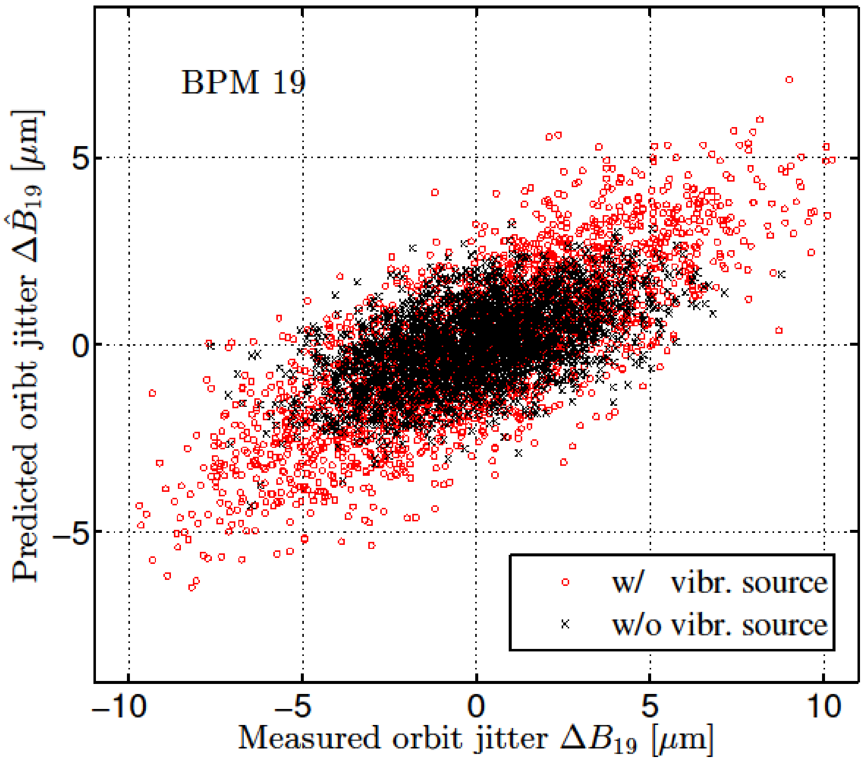


- Very high correlation between actual and predicted beam orbit.
- Still some correlation after applying jitter reduction (JR).
- **GM sensors can be used for the orbit distortions predictions.**

- Correlation also visible in frequency space of BPM data.
- Two peaks at 0.56Hz and 0.74Hz correspond to peaks in PSD of GM sensor 2 (9.94Hz and 24.25Hz).

Orbit jitter removal





- After removing the vibration source around sensor 2, the jitter level was decreased by a factor of 1.4 in amplitude which corresponds to halving the orbit jitter power.

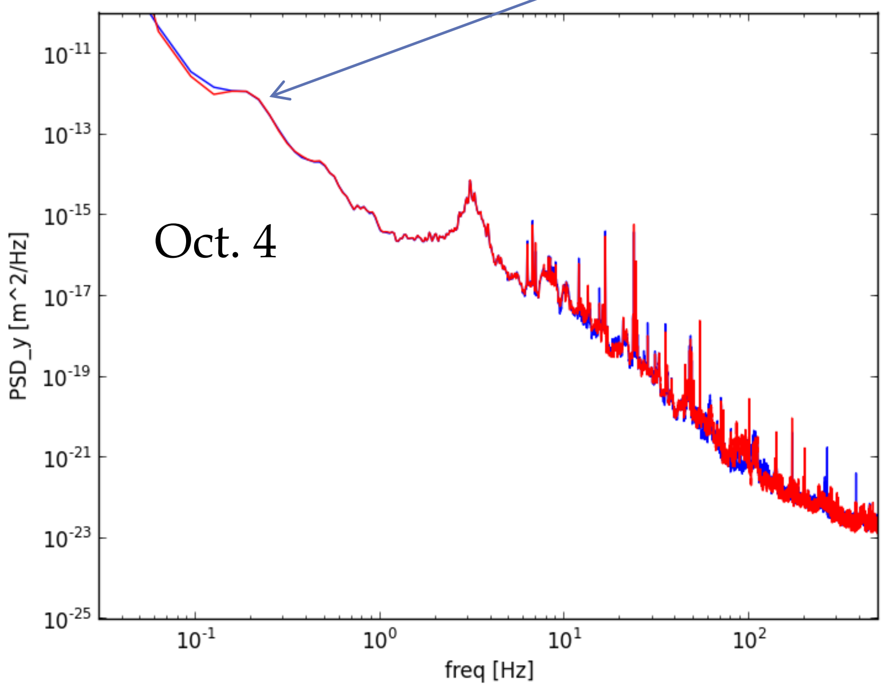
- The correlation between measured and predicted orbit jitter for BPM 19. The correlation visibly decreased after removing the vibration source. Mind the scaling factor probably coming from imperfect response matrix R_q used for predicting the beam orbit aberrations.

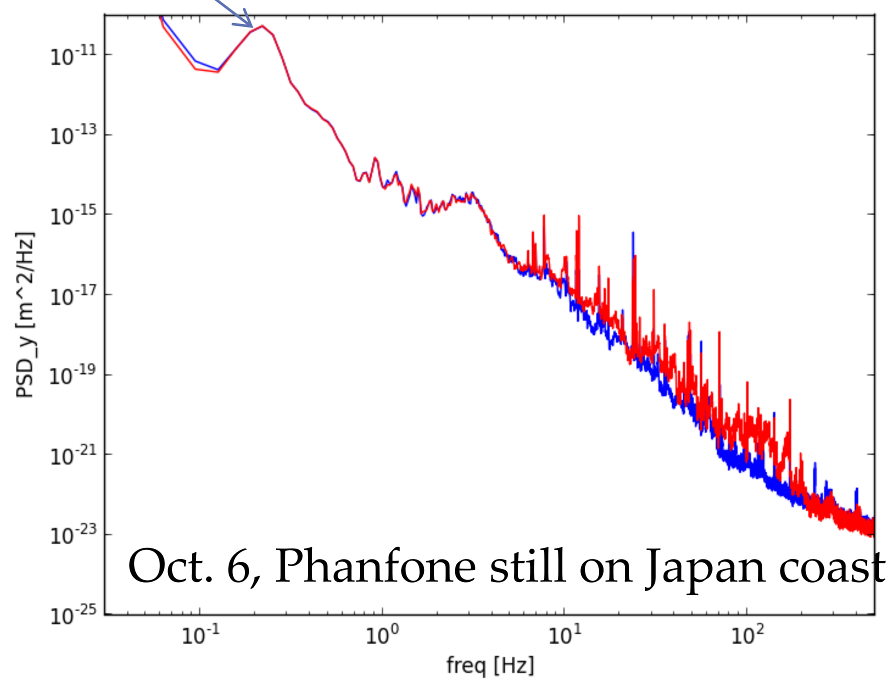
Summary

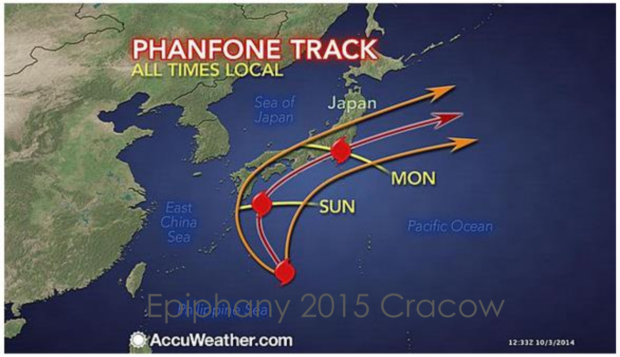
- Novel mitigation method based on GM-feed-forward system is studied in order to counteract the ground motion impact on the beam.
- It was experimentally proved that the GM sensors can be used for beam orbit distortions predictions.
- One vibration source in the ATF2 beam line was found and eliminated which shows the potential of the system to discover the installation issues and model mismatches.
- The real-time GM-feed-forward system needs the fast electronics in order to collect the GM data, calculate the correction and apply it to actuators.

Thank you!

Effect of waves called “7second hum”







PSD in vertical direction => Blue curve : near QF1FF, Red curve: near other magnet upstream

Not the same measurement, so the PSDs are different.