Sub-nm Beam Motion Analysis
Using a Standard BPM with high resolution Electronics

CERN:
Marek Gasior: BBQ electronics
(Andrea Boccardi: VME electronics)
Juergen Pfingstner: Beam measurements
Magnus Sylte: Vibration measurements
Hermann Schmickler: not much useful

CESR-TA
Mark Palmer, Mike Billing, operations crew

PSI-SLS
Michael Boege, Micha Dehler
Outline

- Motivation
- Experimental Set-up; BBQ electronics
- First results at CESR-TA and PSI-SLS
  - amplitude calibration
  - residual beam motion
  - noise of detection system
- Conclusions and Perspective
CLIC stabilization requirements

- Mechanical stabilization requirements:
  Quadrupole magnetic axis vibration tolerances:

<table>
<thead>
<tr>
<th></th>
<th>Final Focus quadrupoles</th>
<th>Main beam quadrupoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>0.1 nm &gt; 4 Hz</td>
<td>1 nm &gt; 1 Hz</td>
</tr>
<tr>
<td>Horizontal</td>
<td>5 nm &gt; 4 Hz</td>
<td>5 nm &gt; 1 Hz</td>
</tr>
</tbody>
</table>

- Main beam quadrupoles to be mechanically stabilized:
  - A total of about 4000 main beam quadrupoles
  - 4 types: Type 1 (~ 100 kg), 2, 3 and 4 (~400 kg)
  - Magnetic length from 350 mm to 1850 mm

Taken from C.Hauviller et al.
How to quantify the performance?

Compute the integrated r.m.s. displacement at n Hertz from the measured PSD (Power Spectral Density)

\[ \sigma_x(1) = \sqrt{\int_{1}^{\infty} \Phi_x(f)df} \]

Taken from C.Hauviller et al.
Present design approach
(CLIC stabilization WG, C.Hauviller et al.)

- Mechanical active stabilization in a feedback loop using electromechanical sensors and (piezo) actuators
- Optimized mechanical design for
  - girders, magnets and electromechanical alignment system
  - best choice for number and position of actuators and sensors
  - low Q mechanical resonances in order to avoid vibration amplification
  - mechanical resonances at the highest possible frequencies
- Minimization of environmental noise through isolation from vacuum chamber vibration, coolant flows, cable vibration and microphonic coupling
- Experimental verification of the result of stabilization:
  - construction of real hardware based on a quadrupole prototype, an active stabilization system

Present work program: A type 4 quad ready for lab tests mid 2010.
Main Beam Quad Mock-up

- **Functionalities**
  - Demonstrate stabilization in operation:
    - Magnet powered, Cooling operating
  - Configurations
    - 1- Stand-alone
    - 2- Integrated in Module
    - 3- Interconnected
  - Accelerator environment

- **Parts / Measuring devices**
  - Floor (damping material)
  - Support
  - Pre-alignment
  - Stabilization
  - Magnet
  - Vacuum chamber and BPM
  - Independent measurement

Slide taken from C.Hauviller, ACE 2009
Main beam quadrupole

- Under final design.
- Plain material
- Assembly methods to be tested (accuracy of some microns!)
The demonstration of the stabilization of the magnet (Magnetic field?) is based on “zero” signals of electromechanical sensors on the outer shell of the magnet.

The physical size of the sensors do not allow to mount them close to the pole tips or inside the magnet.

Pole tip vibrations, coil vibrations might exist without the outer monitors measuring them.

The limited number of monitors might not catch all vibrations.

Question:

can another physical process be used to verify the stability of the magnetic field axis?

→ try a high energetic low emittance particle beam
Validation of Quad stabilization principle (1/2)
Validation of Quad stabilization principle (2/2)

- Insert a CLIC quadrupole (fully integrated into a CLIC module with a mechanical simulation of the environmental noise) into an electron synchrotron.

- In frequency bands in which the intrinsic motion of the particle beam is smaller than 1nm, observe the effect of quad stabilization on/off.

- In frequency bands, where the particle beam moves more than 1nm, the beam validation is limited to exciting mechanical vibrations of the quad at larger amplitudes and measuring the gain of the feedback. The performance of the feedback system at lower amplitudes would in this case to be estimated from the signal to noise ratio of the actuators and sensors.

→ Objective of the test experiments
- What is the residual eigen-motion of the electron?
- What are the limits in noise performance of the BPM electronics?
experimental set-up

- Excitation of beam with a vertical orbit corrector dipole, direct connection to dipole coil.
- Observation of beam oscillations on vertical pickups with modified BBQ electronics, heavy down-sampling in special acquisition cards, up to 17 minutes measurement time.
- Calibration of the system using a 300 um peak-peak oscillation measured in parallel with BBQ system and local orbit system.
- Measurement shifts at CESR-TA and PSI-SLS.
Diode detectors on PU-Q8W
Getting BPM resolutions below the nm

- Aperture of BPM approx. 50 mm or more
- Wide band electronics thermal noise limit: $10^{-5}$ of aperture
- Narrow band front-end gains factor 10…100
- State of the art commercial BPM system reach figures of 5nm/sqrt(Hz), i.e. with 1000 s measurement time 150 pm rms noise.
- Our approach:
  BBQ electronics: “Zoom in” getting high sensitivity for beam oscillations, but loosing absolute information of DC = closed orbit information.
Direct Diode Detection (3D) – the principle

- Peak detection of position pick-up electrode signals ("collecting just the cream")
- \( f_r \) content converted to the DC and removed by series capacitors
- Beam modulation moved to a low frequency range (as after the diodes modulation is on much longer pulses)
- A GHz range before the diodes, after the diodes processing in the kHz range
- Works with any position pick-up
- Large sensitivity
- Impossible to saturate (large \( f_r \) suppression already at the detectors + large dynamic range)
- Low frequency operation after the diodes
  - High resolution ADCs available
  - Signal conditioning / processing is easy (powerful components for low frequencies)
For CESRTA the system bandwidth is 10 Hz – 5 kHz
Amplitude calibration

- The BBQ electronics is linear over many decades and frequency independent within the bandwidth given by the electronic filters.
- Disconnect orbit steerer from control system and get two wires for own excitation...
- … inject AC modulation (0.5 A rms at CESR-TA) at various frequencies and measure resulting orbit oscillation with BPM system.
Amplitude Calibration

Measured in parallel with turn by turn orbit system:
measured amplitude: 300 um pp ~ 100 um rms
One tone amplitude [nm rms]

CesrTA

- average of 176 8K FFTs
- average of 22 64K FFTs

reference tones: 20, 40, 80, 160, 320, 640 Hz

both spectra from the same samples

spectrum #2 (red) shifted by 2 Hz (upper freq. axis)

5 GeV electrons, 1 bunch, 2.75 mA
SLS

- Orbit FB off, no excitation
- Orbit FB on, excitation on @ 80 Hz
- No beam signal

Spectrum #2 (red) shifted by 2 Hz (upper freq. axis)

Loudspeaker on @ 111 Hz
Average of 32 8K FFTs (all spectra)
One tone amplitude [nm]

average of 32 8K FFTs (both spectra)

3-100 Hz amplitude integrals:
CesrTA: 800 nm
SLS: 80 nm

CesrTA, excitation comp. removed
SLS, orbit FB off, no excitation
Noise evaluation

Beam excitation at 640Hz

<table>
<thead>
<tr>
<th>FFTs averaged</th>
<th>sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.07 pm</td>
</tr>
<tr>
<td>22</td>
<td>3.67 pm</td>
</tr>
</tbody>
</table>

Ratio: $4.92 \leftrightarrow \sqrt{22} = 4.69$

18 pm in 47 s measurement time = 0.12 nm/sqrt(Hz)

Compare to Libera Brillance with 0.25 um @ 2KHz = 5nm/sqrt(Hz)
Vibration Sensors on BPM

Accelerometer 1

Accelerometer 2

08/07/2009
Accelerometer 1

Average FFT

08/07/2009

Mechanical Measurement Lab
Magnus Sylte

EDMS 1004462
Comparison BPM vibration and beam spectrum

Average FFT BPM

Average FFT Accelerometer 1
Side product:
modified BBQ electronic with higher bandwidth:
perfect tune-monitor with 60 db signal/noise ratio
Conclusions and Perspectives (1/2)

- An electron beam (tens of um beam size) can be used to sense disturbances (vibrations) down to the sub-nm level
  - using an optimized BBQ electronics
  - using about $10^9$ samples in 17 minutes measurement time

- The noise figure of the BBQ electronics with beam was found to be $0.12$ nm/$\text{Sqrt (Hz)}$
  - the electronics alone much smaller
Conclusions and Perspectives (2/2)

- CESR-TA with 800 nm integrated (3 – 100 Hz) residual eigen-motion of the beam is “out” for future CLIC experiments.

- Even SLS with 80 nm and possible improvements: = better orbit corrections, 50 Hz filtering, even longer integration seems a factor 10 away as possible experimental field for CLIC.

- We might try in the future very small machines (like Maxlab4)…

- The method can be applied easily to any machine for diagnostics of vibration sources