DEVELOPMENT OF ADVANCED MECHANICAL SYSTEMS FOR STABILIZATION AND NANO-POSITIONING OF CLIC MAIN BEAM QUADRUPOLES

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Outline

- Introduction & Requirements
- Active Support for Main Beam Quadrupoles
- Analytical & Finite Element models
- Experimental set-ups & sensors
- Future developments
- Conclusions
Luminosity, beam size and alignment

\[ L = \frac{A}{\sigma_x \sigma_y} \]

\(~40\ \text{nm}\)

\(\sim1\ \text{nm}\)

Acoustic noise, ventilation, cooling system...

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Alignment requirements

Mechanical prealignment $\pm 0.1$ mm

Active prealignment of external references of the accelerating structures and quadrupoles within a few microns

Sliding window: zero of component shall be included in a cylinder with radius:
17 $\mu$m for MB Quad over 200 m
10 $\mu$m BDS over 500 m

H. Mainaud Durand, “Validation of the CLIC alignment strategy on short range”, IWAA 2012

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Stability requirements

Stability (magnetic axis):

<table>
<thead>
<tr>
<th></th>
<th>Vertical</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 nm at 1 Hz</td>
<td>5 nm at 1 Hz</td>
<td></td>
</tr>
</tbody>
</table>

\[ \sigma_x(f) = \sqrt{\int_{f}^{\infty} \Phi_x(\nu) d\nu} \]

Integrated r.m.s. displacement

**ground vibration**

Earth motion
- Coherent

Cultural noise
- Human activity
- Incoherent
- Highly variable

Micro seismic peak
- Reduced by Beam based feedback

Depth tunnel

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Other requirements

Stiffness-Robustness

Applied forces (water cooling, vacuum, power leads, cabling, interconnects, ventilation, acoustic pressure)

- Compatibility alignment
- Transportability/Installation

Available space
Integration in two beam module
620 mm beam height

Accelerator environment
- High radiation
- Stray magnetic field
Soft or rigid support?

- Artoos K. et al., “Status of a Study Stabilisation and Fine Positioning of CLIC Quadrupoles to the Nanometre Level”, IPAC11
- Janssens S. et al., “System Control for the CLIC Main Beam Quadrupole Stabilization and Nano-positioning”, IPAC11

Soft system is not robust against external forces  ➔  Active stabilization
Nano-positioning

Modify position quadrupole in between pulses (~ 5 ms)
Range ± 5 μm, increments 10 to 50 nm, precision ± 1 nm

- In addition/ alternative dipole correctors
- Use to increase time to next realignment with cams
stabilisation support section made of

Inclined stiff piezo actuator pairs with flexural hinges (vertical + lateral motion)

(each magnet will have 2 or 3 sections depending on its length)
X-y guiding mechanism

- Blocks longitudinal movements
- Increases lateral stiffness by factor 200, no modes < 100 Hz
- Introduces a stiff support for nano-metrology
- Transportability

Flexural pins

- Capacitive gauge
- Optical encoder
- 52 kg mass
Analytical model (1)

Coordinate systems

Coordinate transformation

\[ q_1 = \sin \beta x + \cos \beta y + (d_v \sin \beta - d_h \cos \beta) \theta \]
\[ q_2 = -\sin \beta x + \cos \beta y + (-d_v \sin \beta + d_h \cos \beta) \theta \]
\[ \alpha_1 = -\frac{\cos \beta}{r} x + \frac{\sin \beta}{r} y + \left( -d_v \frac{\cos \beta}{r} - \frac{d_h \sin \beta}{r} \right) \theta \]
\[ \alpha_2 = -\frac{\cos \beta}{r} x - \frac{\sin \beta}{r} y + \left( -d_v \frac{\cos \beta}{r} - \frac{d_h \sin \beta}{r} \right) \theta \]
Analytical model (2)

**Constraints**

\[(R + q_1) \cos(\beta - \alpha_1) + L_m \sin(\theta) + (R + q_2) \cos(\beta + \alpha_2) = 0\]

\[(R + q_1) \sin(\beta - \alpha_1) + L_m \cos(\theta) + (R + q_2) \sin(\beta + \alpha_2) - L_b = 0\]

**Principle of virtual work**

\[F_x dx = M_{o1} \, d\alpha_1 + M_{o2} \, d\alpha_2 + M_A \, (d\beta - d\alpha_1) + M_B \, (d\beta + d\alpha_2)\]

\[F_y dy = (M_{o1} + M_{o2} + M_A + M_B) \, d\alpha_1 + F_1 \, dq_1 + F_2 \, dq_2\]

**Lagrangian method for Modal Analysis**

\[\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{s}} \right) - \frac{\partial L}{\partial s} = 0\]

with

\[L = T - V\]

and

\[T = \frac{1}{2} M \ddot{x}^2 + \frac{1}{2} M \ddot{y}^2 + \frac{1}{2} I \ddot{\theta}^2\]

\[V = \frac{1}{2} k_a(q_1^2 + q_2^2) + \frac{1}{2} k_e [\alpha_1^2 + \alpha_2^2 + (\alpha_1 - \theta)^2 + (\alpha_2 - \theta)^2]\]

\[M \ddot{s} + Ks = 0\]

\[s(t) = s_0 e^{-i\omega t}\]

\[-\omega^2 M + K = 0\]

\[\omega^2\] are the eigenvalues of matrix \(M^{-1}K\)

\[f = \frac{\omega}{2\pi}\]
Finite Element models

ANSYS Classic
- Rigid links
- Concentrated mass
- Rotational joints
- Beam elements

ANSYS Workbench

DISPLACEMENT
STEP=1
SUB =2
FREQ=91.1157
DMX = .384E-07

AUG 18 2011
15:11:15

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### Analytical & FE results

<table>
<thead>
<tr>
<th></th>
<th>Hz $k_h$</th>
<th>$Vt k_v$</th>
<th>4-bar mode</th>
<th>θ mode</th>
<th>Vertical mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[N/μm]</td>
<td>[N/μm]</td>
<td>f [Hz]</td>
<td>shape</td>
<td>f [Hz]</td>
</tr>
<tr>
<td><strong>Without xy guide</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analytical</td>
<td>0.21</td>
<td>203</td>
<td>9.2</td>
<td></td>
<td>255</td>
</tr>
<tr>
<td>Ansys classic</td>
<td>0.21</td>
<td>204</td>
<td>9.2</td>
<td></td>
<td>255</td>
</tr>
<tr>
<td>Ansys WB</td>
<td>0.21</td>
<td>203</td>
<td>8.3</td>
<td></td>
<td>245</td>
</tr>
<tr>
<td><strong>With xy guide</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analytical</td>
<td>35</td>
<td>229</td>
<td>153</td>
<td></td>
<td>310</td>
</tr>
<tr>
<td>Ansys classic</td>
<td>44</td>
<td>225</td>
<td>125</td>
<td></td>
<td>275</td>
</tr>
<tr>
<td>Ansys WB</td>
<td>38</td>
<td>220</td>
<td>145</td>
<td></td>
<td>303</td>
</tr>
</tbody>
</table>

**Type 1 MBQ with xy guide**

- $k_h = 69$ [N/μm]
- $k_v = 227$ [N/μm]
- 119 [Hz]
- 303 [Hz]
- 319 [Hz]

**Longitudinal stiffness**

- **Without xy guide**
  - 0.03 N/μm
  - 278 N/μm
- **With xy guide**
  - (pins totally fixed on 1 end)
  - 3.4 Hz
  - 280 Hz

**Longitudinal mode**

- **Without xy guide**
  - (pins fixed to steel plates)
  - 65 Hz
Simulated Kinematics (1)

- 3 DOF system
- Only 2 DOFs are controlled

\[ q_1 = \sin \beta \ x + \cos \beta \ y + (D_v \ \sin \beta - D_h \ \cos \beta) \theta \]
\[ q_2 = -\sin \beta \ x + \cos \beta \ y + (-D_v \ \sin \beta + D_h \ \cos \beta) \theta \]

2 controlled DOFs

\[ \alpha_1 = -\frac{\cos \beta}{R} \ x + \frac{\sin \beta}{R} \ y + \left( -D_v \ \frac{\cos \beta}{R} - \frac{d_h \sin \beta}{R} \right) \theta \]
\[ \alpha_2 = -\frac{\cos \beta}{R} \ x - \frac{\sin \beta}{R} \ y + \left( -D_v \ \frac{\cos \beta}{R} - \frac{d_h \sin \beta}{R} \right) \theta \]

2 equations necessary to fully describe the kinematics

The system is not fully determined without taking into account the reaction forces

Constraints
\[ C_v = (R + q_1) \ \cos (\beta - \alpha_1) + L_m \ \sin(\theta) + (R + q_2) \ \cos (\beta + \alpha_2) \]
\[ C_h = (R + q_1) \ \sin (\beta - \alpha_1) + L_m \ \cos(\theta) + (R + q_2) \ \sin (\beta + \alpha_2) - L_b \]

Potential Energy
\[ V = \frac{1}{2} k_a (q_1^2 + q_2^2) + \frac{1}{2} k_e [\alpha_1^2 + \alpha_2^2 + (\alpha_1 - \theta)^2 + (\alpha_2 - \theta)^2] \]

NMinimize\{V, C_v == 0, C_h == 0, dq_1 == 1, dq_2 == -1\}

(find a minimum of potential energy respecting the constraint equations and fixing the input values of the actuator displacements)
### Simulated Kinematics (2)

<table>
<thead>
<tr>
<th></th>
<th>Hz movement</th>
<th>Vt movement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x/q$</td>
<td>$y/q$</td>
</tr>
<tr>
<td><strong>8 PINS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analytical model</td>
<td>1.3</td>
<td>1.06</td>
</tr>
<tr>
<td>FE model</td>
<td>1.24</td>
<td>1.03</td>
</tr>
<tr>
<td>$\theta / x$ [$\mu$rad/$\mu$m]</td>
<td>5.15</td>
<td>0</td>
</tr>
<tr>
<td>$\theta / y$ [$\mu$rad/$\mu$m]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>NO PINS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analytical model</td>
<td>1.4</td>
<td>1.06</td>
</tr>
<tr>
<td>FE model</td>
<td>1.15</td>
<td>1.06</td>
</tr>
<tr>
<td>$\theta / x$ [$\mu$rad/$\mu$m]</td>
<td>4.64</td>
<td>0</td>
</tr>
<tr>
<td>$\theta / y$ [$\mu$rad/$\mu$m]</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Pins do not change the “shape” of the movement
- Less than 1% of coupling between horizontal and vertical
- $\approx 5$ $\mu$rad/$\mu$m of roll per unit lateral displacement
- Translation/actuator elongation ratio is $\approx 1:1$ (Vt) and $\approx 1.4:1$ (Hz)
## 3D simulated Kinematics

<table>
<thead>
<tr>
<th></th>
<th>PITCH</th>
<th>YAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 MBQ</td>
<td><img src="image" alt="T1 PITCH" /></td>
<td><img src="image" alt="T1 YAW" /></td>
</tr>
<tr>
<td>T4 MBQ</td>
<td><img src="image" alt="T4 PITCH" /></td>
<td><img src="image" alt="T4 YAW" /></td>
</tr>
</tbody>
</table>

- No loss of translation range for T4
- About 25% of loss of vertical translation range for T1 pitch
- About 80% of loss of lateral translation range for T1 yaw

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X-y prototype and sensors

Capacitive sensor

Actuators equipped with strain gauges

Optical ruler

3 beam interferometer

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X-y positioning: lateral and vertical 6 nm steps
X-y Positioning

Parasitic roll

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## Comparison sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Resolution</th>
<th>Main +</th>
<th>Main -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator sensor</td>
<td>0.15 nm</td>
<td>No separate assembly</td>
<td>Resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No direct measurement of magnet movement</td>
</tr>
<tr>
<td>Capacitive gauge</td>
<td>0.10 nm</td>
<td>Gauge radiation hard</td>
<td>Mounting tolerances</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gain change w. α</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Orthogonal coupling</td>
</tr>
<tr>
<td>Interferometer</td>
<td>10 pm</td>
<td>Accuracy at freq.&gt; 10 Hz</td>
<td>Cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mounting tolerance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sensitive to air flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Orthogonal coupling</td>
</tr>
<tr>
<td>Optical ruler</td>
<td>0.5*-1 nm</td>
<td>Cost</td>
<td>Rad hardness sensor head not known</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1% orthogonal coupling</td>
<td>Limited velocity displacements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mounting tolerance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small temperature drift</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possible absolute sensor</td>
<td></td>
</tr>
<tr>
<td>Seismometer (after integration)</td>
<td>&lt; pm at higher frequencies</td>
<td>For cross calibration</td>
<td></td>
</tr>
</tbody>
</table>
Noise level in frequency domain (PSD)

Cross check between different instrumentation + resolution measurements

14 nm sine wave

14 pm sine wave

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Stabilization on Type 1 MBQ

- Water cooling 4 l/min
- With magnetic field on
- With hybrid circuit

![Image of experimental setup]

<table>
<thead>
<tr>
<th>Figure</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.m.s @ 1Hz magnet</td>
<td>0.5 nm</td>
</tr>
<tr>
<td>R.m.s @ 1Hz ground</td>
<td>6.3 nm</td>
</tr>
<tr>
<td>R.m.s. attenuation ratio</td>
<td>~13</td>
</tr>
<tr>
<td>R.m.s @ 1Hz objective</td>
<td>1.5 nm</td>
</tr>
</tbody>
</table>

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Future developments

Monolithic approach of the design:
• To simplify the assembly + increase precision
• Reduce assembly stresses on actuator + magnet
• Improve sensor installation: inertial ref. mass and displacement gauges
• Optimise vertical, lateral and longitudinal stiffness
• Decrease parasitic motion if needed
• Mechanical locking for transport
• Improve interface with alignment

Work in progress: T1 test module

K. Artoos

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An actuator support for the stabilization and nano-positioning of CLIC MBQ is under development

The mechanics has been studied in detail using Analytical and FE models

A prototype has been built and measurements using 4 different types of sensors have been realized

Experimental results show that the support and some of the sensors can reach sub-nanometre resolution
Publications

The end

Thank You for your attention!

(Questions?)
Spare slides
Comparison

Very Soft (1 Hz)  Soft (20 Hz)  Stiff (200 Hz)

- Pneumatic actuator
- Hydraulic actuator

- Electromagnetic in parallel with a spring
- Piezo actuator in series with soft element (rubber)

- Piezoelectric actuator in series with stiff element (flexible joint)

\[ k \approx 0.01 \text{ N/\mu m} \quad k \approx 1 \text{ N/\mu m} \quad \text{Piezo } k \approx 100-500 \text{ N/\mu m} \]

+ Broadband isolation
- Stiffness too low
- Noisy

+ Passive isolation at high freq.
+ Stable
- Low dynamic stiffness
- Low compatibility with alignment and AE

+ Extremely robust to forces
+ Fully compatible with AE
+ Comply with requirements
- Noise transmission
- Strong coupling (stability)
Active Isolation Strategies

Feedback control principle

\[ F(t) = k_d x + k_v \dot{x} + k_a \ddot{x} \]

\[ \frac{X(s)}{W(s)} = \frac{cs+k}{(m+k_a)s^2+(c+k_v)s+(k+k_d)} \]

Comparison

RMS integrated @ 1 Hz

- Quadrupole
- Ground

- DESY, 1996
- SLAC, 2001
- CERN, 2004
- LAPP, 2007
- CERN, 2009
- CERN, 2011

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X-y guide in the analytical model

For each pin:

\[ F_{ri} = k_p * d_{si} \]

\[ d_{si} = \sqrt{(x-\theta*y_{pi})^2 + (y+\theta*x_{pi})^2} \]

Potential Energy

\[ V = \frac{1}{2} k_a (q_1^2 + q_2^2) + \frac{1}{2} k_e [\alpha_1^2 + \alpha_2^2 (\alpha_1 - \theta)^2 + (\alpha_2 - \theta)^2 + k_p [(x - \theta * y_{p1})^2 + (y + \theta * x_{p1})^2 + (x - \theta * y_{p2})^2 + (y + \theta * x_{p2})^2 + (x - \theta * y_{p3})^2 + (y + \theta * x_{p3})^2 + (x - \theta * y_{p4})^2 + (y + \theta * x_{p4})^2]] \]

Flexural stiffness

\[ k_p = 3.2 \text{ N/\mu m} \]

Axial stiffness

\[ k_a = 69 \text{ N/\mu m} \]