Tuneable permanent magnets: Power saving solutions for the next generation of high energy accelerators.

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Motivation - CLIC

- 326 klystrons
- 33 MW, 139 μs
- Drive beam accelerator 2.36 GeV, 1.0 GHz
- 1 km delay loop
- CR1
- CR2
- 42000 quadrupoles
- 288 dipoles
- Decelerator, 24 sectors of 876 m
- Booster linac, 9 GeV
- e⁻ injector, 2.4 GeV
- e⁺ DR 365 m
- PDR 365 m
- e⁻ DR 365 m
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- e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km
- TA radius = 120 m
- 42000 quadrupoles
- 288 dipoles
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Motivation - CLIC

The plan to use normal conducting systems on CLIC will result in high electrical power consumption and running costs.

- 289MW (RF)
- 21% (124MW) Magnets
- 5% (31MW) Exp+ Area
- 3% (17MW) BIC
- 5% (28MW) NWork
- 16% (93MW) CV

Whole CLIC project estimated to draw >580 MW, 124 MW projected for resistive electromagnets alone!
The Challenge

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>Number</th>
<th>Length</th>
<th>Strength</th>
<th>Range</th>
<th>0.1% good field</th>
<th>Power/total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive Beam Quads</td>
<td>41400</td>
<td>0.2 m</td>
<td>63 T/m</td>
<td>100-10%</td>
<td>26x26 mm</td>
<td>20 MW</td>
</tr>
<tr>
<td>Drive Beam Dipoles</td>
<td>576</td>
<td>1.5 m</td>
<td>1.6 T</td>
<td>100-50%</td>
<td>40x40 mm</td>
<td>12.4 MW</td>
</tr>
<tr>
<td>Linac Quads</td>
<td>1061</td>
<td>0.5 m</td>
<td>14 T/m</td>
<td>100-10%</td>
<td>80x80 mm</td>
<td>6.3 MW</td>
</tr>
<tr>
<td>Linac Quads</td>
<td>1638</td>
<td>0.25 m</td>
<td>17 T/m</td>
<td>100-10%</td>
<td>87x87 mm</td>
<td>10.3 MW</td>
</tr>
<tr>
<td>Main Beam Dipoles</td>
<td>666</td>
<td>1.5 m</td>
<td>0.5 T</td>
<td>100%</td>
<td>30x30 mm</td>
<td>2.5 MW</td>
</tr>
<tr>
<td>Damping Ring Quads</td>
<td>408</td>
<td>0.4 m</td>
<td>30 T/m</td>
<td>100-20%</td>
<td>80x80 mm</td>
<td>4.7 MW</td>
</tr>
<tr>
<td>Damping Ring Quads</td>
<td>408</td>
<td>0.2 m</td>
<td>30 T/m</td>
<td>100-20%</td>
<td>80x80 mm</td>
<td>3.3 MW</td>
</tr>
<tr>
<td>Chicane Dipole</td>
<td>184</td>
<td>1.5 m</td>
<td>1.6 T</td>
<td>100-10%</td>
<td>80x80 mm</td>
<td>7.7 MW</td>
</tr>
<tr>
<td>Chicane Dipole</td>
<td>236</td>
<td>1 m</td>
<td>0.26 T</td>
<td>100-10%</td>
<td>80x80 mm</td>
<td>1.1 MW</td>
</tr>
</tbody>
</table>
High Energy Quadrupole

- Max gradient = 60.4 T/m
- Min gradient = 15.0 T/m
- Pole gap = 27.2 mm
- Field quality = ± 0.1% over 23 mm
- NdFeB magnets with $B_r = 1.37$ T (VACODYM 764 TP)
- 4 permanent magnet blocks each 18 x 100 x 230 mm

Patent WO 2012046036 A1

Low Energy Quadrupole

- Max gradient = 43.4 T/m
- Min gradient = 3.5 T/m
- Pole gap = 27.6 mm
- Field quality = ± 0.1% over 23 mm
- NdFeB magnets with $B_r = 1.37$ T (VACODYM 764 TP)
- 2 PM blocks are 37.2 x 70 x 190 mm

doi: 10.1109/TASC.2012.2191632
Dipoles-International interest

Interest in storage rings – PM dipoles very useful where only small field strength adjustments are required.

Spring-8 dipoles
Large tuning range designs, high field H-dipole and low field C-dipole
doi:10.1103/PhysRevAccelBeams.20.072401

Sirius storage ring
Small tuning range but 0.5T and 2T variants
doi: 10.1109/TASC.2012.2185771

Permanent magnet
Outer plate

TUPRO092 Proceedings of IPAC’14, Dresden, Germany

WEPD003 Proceedings of IPAC’10, Kyoto, Japan
Dipole Prototype

• Original plan was to build a 0.5m version of full size DB TAL magnet
  – Not possible within available budget £100,000 (~110,000 EUR)
• So, instead we are building a scaled version
  – Cost dominated by one off PM block costs (>50%)
  – Will still demonstrate the tuneable PM dipole principle as well as achieving the same field quality and the same relative tuning range.

<table>
<thead>
<tr>
<th>Type</th>
<th>Length (m)</th>
<th>Max Field Strength (T)</th>
<th>Pole Gap (mm)</th>
<th>0.1% good field (integrated)(mm)</th>
<th>Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB TAL</td>
<td>1.5</td>
<td>1.6</td>
<td>53</td>
<td>40 x 40</td>
<td>50–100</td>
</tr>
<tr>
<td>Original Prototype</td>
<td>0.5</td>
<td>1.6</td>
<td>53</td>
<td>40 x 40</td>
<td>50–100</td>
</tr>
<tr>
<td>Scaled Prototype</td>
<td>0.4</td>
<td>1.1</td>
<td>40</td>
<td>30 x 30</td>
<td>50–100</td>
</tr>
</tbody>
</table>
Dipole Prototype

- Settled on C-design that uses a single sliding PM block to adjust field

- Advantages:
  - Tunes without changing gap!
  - PM moves perpendicular to largest forces
  - Curved poles possible
Magnet Block

- Magnet block dimensions are **500x400x200 mm**, with 4 holes on 400mm axis for mounting rods.
  - Constructed from 80 individual blocks (each 100x50x100mm) in resin
- Manufactured, measured & delivered by Vacuumschmelze
- Magnet material **NdFeB, Vacodym 745TP**
- Br 1.38T min, 1.41T typical
Modelling

Magnet simulations performed in OPERA 3D

Mesh deals with small gaps and non-magnetic fasteners

Not component deflection

MODEL DATA
Position 150.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
4202266 elements
2036289 nodes
Nodally interpolated fields
Activated in global coordinates
Reflection in XY plane (Z field=0)
Reflection in ZX plane (Z+X fields=0)
Predicted Flux Density

Predicted magnetic flux density at the geometric center of the magnet as a function of block displacement.

OPERA’s 2 calculation methods agree to within the width of the fitting line.

50 % tuning mark reached at 355 mm displacement.
Block affects longitudinal field profile differently at different positions in beam pipe.

Big effect just outside magnet

Field clamping plates may solve
Shim Structure

Need to counter effect of block on Homogeneity!

Use asymmetric shim – roll-off on side of magnet to weaken field, shim on far side to strengthen.

Effect on higher harmonics? Likely adds quadrupole effect – rotating coil measurements interesting!
The optimised pole design meets the target to 20mm each side of the beam axis.

Balancing pole shape with saturation makes homogeneity relatively independent of PM block position.
Magnetic Forces

![Graph showing magnetic forces vs block displacement]

- $F_{yg}$
- $F_{ym}$
- $F_X$

Block Displacement / mm

Magnetic Force / N
Engineering

- Sliding assembly using rails, stepper motor and gearbox.

3 support rods hold jaws of magnet fixed
Can be independently adjusted

Poles held 2 mm from surface of block
Assembly
Conclusions

• Tuneable permanent magnets are becoming a reality, merging the versatility of electromagnets with savings in operating costs (both financial and environmental) and infrastructure.

• A pure PM dipole with large tuning range is under construction. This follows successful developments in PM quadrupoles and is in parallel with other tuneable dipole developments around the world.

• There are additional challenges over conventional electromagnets – moving ferromagnetic components results in shift of magnetic axis or changing homogeneity. Magnetic forces hinder movement and require careful mechanical design.
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