Status of FCC-ee Booster and Collider Magnet Developments

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Many thanks to all the members of the FCC collaboration.
Outline

Collider magnets
- Inter-beam distance
- Aperture reduction
- Specifications
- Twin aperture dipole
- Twin aperture quadrupole
- Single aperture sextupole

Booster magnets
- Specifications
- Dipole
- Quadrupole

Next steps for magnet development

Conclusions
Collider magnets
Inter-beam distance

Mechanical design studies in Arc Half-cell Mock-up WG identified need for *larger space* for **SR absorbers**:

- water cooling piping and fittings of SR absorber
- electrical insulation distance to busbar

→ **Inter-beam distance increased to 350 mm**

Conflict:
SR absorber - busbar

Courtesy: C. Tetrault

Dipole cross-section with SMA flanges

SR absorber integration in dipole

SR absorber
Aperture reduction

- **CDR baseline** for beam aperture (vacuum chamber inner radius) was $R = 35\,\text{mm}$
- **2023**: exploration of new baseline with $R = 30\,\text{mm}$ to reduce power consumption (mostly in SSS magnets) and saturation in sextupole
- **Clearances kept identical as CDR** to determine magnet bore apertures

→ Designs with $R = 35\,\text{mm}$ vs. $R = 30\,\text{mm}$ compared in next slides

<table>
<thead>
<tr>
<th></th>
<th>CDR baseline</th>
<th>Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dipole</td>
<td>Quad.</td>
</tr>
<tr>
<td>Vacuum chamber inner radius</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Vacuum chamber wall thickness</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Clearance for tolerances and alignment (radial)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Clearance for vacuum bake-out jackets (radial)</td>
<td>4 4 4 0</td>
<td></td>
</tr>
<tr>
<td>Magnet bore radius</td>
<td>42 42 38</td>
<td></td>
</tr>
</tbody>
</table>

Aperture dimensions in [mm] for arc collider magnets
Magnet specifications – latest update

- Includes **aperture reduction in SSS magnets**
- **Aperture in dipoles** depends on impedance studies (tapering of chambers upstream/downstream SSS)
- **Aperture in sextupole** assumes **no bake-out system** (as in CDR baseline)
- Field quality specifications from latest beam dynamic studies

<table>
<thead>
<tr>
<th>Mag. Length</th>
<th>Bore aperture (reduced)</th>
<th>Pole tip field</th>
<th>Number of units</th>
<th>Total mag. length</th>
<th>Ring filling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole (S)</td>
<td>19.30</td>
<td>42 / 37 ?</td>
<td>0.061</td>
<td>1128</td>
<td>21.77</td>
</tr>
<tr>
<td>Dipole (M)</td>
<td>20.95</td>
<td></td>
<td>0.061</td>
<td>284</td>
<td>5.95</td>
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<tr>
<td>Dipole (L)</td>
<td>22.65</td>
<td></td>
<td>0.061</td>
<td>1428</td>
<td>32.35</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>2840</td>
<td>60.08</td>
<td>65.9</td>
<td></td>
</tr>
<tr>
<td>Quadrupole</td>
<td>2.9</td>
<td>37</td>
<td>0.438</td>
<td>2836</td>
<td>8.22</td>
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<tr>
<td>Sextupole</td>
<td>1.5</td>
<td>33</td>
<td>0.442</td>
<td>4672</td>
<td>7.01</td>
</tr>
</tbody>
</table>

Arc magnet specifications from optics – May 2023 (K. Oide)

Magnet field quality specifications from optics – March 2023 (R. Tomas)
Collider dipole
Dipole design

Yoke
- Assembled from solid iron machined plates and beam
- Pole shape optimized with flat surfaces only to minimize machining operations for large scale production
- Slots for fiducialisation included

Busbars
- Main busbars in extruded copper (freedom for shape), water-cooled (requirement from cooling and ventilation)
- Choice of copper vs. aluminium to be finalized during cost optimization exercise (capital cost vs. operational cost, including water cooling distribution system)
- Insulation with inorganic coating to be explored (SR)

Trim coils
- Air cooled enameled conductors
Magnetic design - Case 1: peak current, trim coils off (182.5 GeV)

- ±1 unit range extends beyond $R_{ref}$, margin for manufacturing tolerances
- $b_2$ decreased to 0.5 unit (w.r.t. 3 units in CDR design)
Magnetic design - Case 2: peak current, trim coils on (182.5 GeV)

- Trim coils activated to tune $B_{\text{peak}}$ by $+3.5\%$ in one aperture and $-3.5\%$ in the other.
- Marginal effect from trims on field quality.

Computed field harmonics

Field homogeneity in aperture (top) and along X axis (bottom)
Magnetic design - Case 3: 1/4 current, trim coils off (45.6 GeV)

- Slight increase of $b_2$ at lower field
- Can be compensated with arc quadrupoles
- Will be further evaluated with prototype magnet
Dipole summary

Magnetic design

- The magnet geometry has been optimized to further limit $b_2$ to <1.5 units and other harmonics <0.5 units

Main parameters

- The magnet dimensions stay compact despite slightly larger inter-beam distance
- The **current density has increased** w.r.t. CDR due to conflict with SR absorber, so the new design has higher dissipated power at equivalent technology (Al busbars)
- **Copper busbars** allow ~35% of power consumption reduction (to be optimized with total costs)
- The aperture reduction would reduce the power consumption by ~10%

### Main magnet parameter comparison (**computed at $B_{t_bar}$**)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CDR</th>
<th>2023, ap. 84 mm</th>
<th>2023, ap. 74 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of units</td>
<td>3000</td>
<td>2840</td>
<td>2840</td>
</tr>
<tr>
<td>Total magnetic length</td>
<td>65 km</td>
<td>60.1 km</td>
<td>60.1 km</td>
</tr>
<tr>
<td>Central field, 45.6 GeV −182.5 GeV</td>
<td>mT</td>
<td>14.1 − 56.6</td>
<td>15.3 − 61.3</td>
</tr>
<tr>
<td>Inter-beam distance</td>
<td>mm</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Bore aperture</td>
<td>mm</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>m</td>
<td>10.6 − 15.2</td>
<td>19.30 − 22.65</td>
</tr>
<tr>
<td>Magnet overall transverse dimensions</td>
<td>mm</td>
<td>500 × 136</td>
<td>520 × 134</td>
</tr>
<tr>
<td>Iron mass per unit length</td>
<td>kg/m</td>
<td>219</td>
<td>243</td>
</tr>
<tr>
<td>Busbar mass per unit length</td>
<td>kg/m</td>
<td>15.3</td>
<td>75</td>
</tr>
<tr>
<td>Magnet unit mass (10.6 m average length)</td>
<td>kg</td>
<td>2678</td>
<td>3552</td>
</tr>
<tr>
<td>Total magnet mass, 69.1 km</td>
<td>tons</td>
<td>15529</td>
<td>19098</td>
</tr>
<tr>
<td>Maximum operating current ($I_{t_bar}$)</td>
<td>A</td>
<td>1900</td>
<td>4116</td>
</tr>
<tr>
<td>Maximum current density ($I_{t_bar}$)</td>
<td>A/mm²</td>
<td>0.79</td>
<td>0.16</td>
</tr>
<tr>
<td>Resistance per unit length</td>
<td>μΩ/m</td>
<td>2.22</td>
<td>8.22</td>
</tr>
<tr>
<td>Maximum voltage to ground per 1/2 octant (balanced at mid-point)</td>
<td>V</td>
<td>88</td>
<td>6.6</td>
</tr>
<tr>
<td>Maximum dissipated power per unit length ($I_{t_bar}$)</td>
<td>W/m</td>
<td>164</td>
<td>139</td>
</tr>
<tr>
<td>Total dissipated power, 60.1 km ($I_{t_bar}$, busbars interconn. not incl.)</td>
<td>kW</td>
<td>10.7</td>
<td>8.4</td>
</tr>
<tr>
<td>Total dissipated power, 83.0 km ($I_{t_bar}$, busbars interconn. incl.)</td>
<td>kW</td>
<td>11.3</td>
<td>11.6</td>
</tr>
</tbody>
</table>

**Computed field harmonics**

![BB cross-section](image_url)
Collider quadrupole
Collider quad: from FCC-week ’22

- Recall the twin aperture design with two racetrack coils from the CDR.
- By FCC-week ’22, an alternate design to the CDR was introduced.
- Magnetic gap between the apertures and chamfers on outer sides.
- Magnetic axis shift remained an issue, **up to ~0.2 mm shift**, when trim coils were activated.

- Recall the trim coils set-up:
  - Two trim coils on each aperture, mounted on the back-legs.
  - Trim coils for each aperture powered individually; needed for individual aperture trimming.
Cross-section optimization

Parameters of the cross-section design were varied to try and minimize the highest b1 case, and thus reduce magnetic axis shift:

- Main coil position
- Back-leg thicknesses
- Pole profile; chamfers and inserts / notches.

Three powering cases assumed for the optimization:

Case 1: Quarter current on main coils, trim coils off.
Case 2: Full current on main coils, trim coils off.
Case 3: Full current on main coils, max trim coils current

→ $B_{max} + B_{trim}$ on one aperture, $B_{max} - B_{trim}$ on the other.
Version 1: split design, with 350 mm inter-beam distance

• Adaptation of the split design, apertures were separated by 50 mm and chamfers were modified.
• Only marginal improvements compared to the corresponding design with 300 mm inter-beam distance.

• Magnetic axis shift remained an issue, up to ~0.2 mm shift, when trim coils were activated.
Version 2: alternate design, minimizing difference in b1

- Optimized to minimize the highest b1 + the difference in b1 over the three cases.
- Main coils distance increased, with inserts towards middle to steer flux.

- b1 in cases 1 and 3 are evened out.
- Magnetic axis shift roughly halved, \(~0.11 \text{ mm shift}\), but still remains high.
- b3 increases in all cases.
- Inserts complicate the geometry slightly.
Version 3: new design with trim coils on poles

- Trim coils moved to the poles, one trim coil per pole; four per aperture.
- Magnetic gap was closed to simplify construction.
- Back-legs not optimized yet; kept thick to avoid saturation.

- \( b_1 \) significantly reduced; trim coils help to force the path of the flux through the poles.
- Magnetic axis shift \(~0.01\) mm.
Comparison of all three design versions

- Solution with trim coils on poles looks best:
  - All harmonics and magnetic axis shift greatly reduced.
  - Trim coils on the poles gives better control compared to previous solution with trim coils on back-legs.
  - Depending on power-supply set-up, trim coils could potentially be used for correction.

<table>
<thead>
<tr>
<th>Design</th>
<th>Worst case mag. axis shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Version 1</td>
<td>± 0.2 mm</td>
</tr>
<tr>
<td>Version 2</td>
<td>± 0.11 mm</td>
</tr>
<tr>
<td>Version 3</td>
<td>± 0.01 mm</td>
</tr>
</tbody>
</table>

\[ b_1 \text{ [Units, } Bn/B2*1e4]\]

- `b_1` for all powering cases, for each design

\[ b_3 \text{ [Units, } Bn/B2*1e4]\]

- `b_3` for all powering cases, for each design
Reduction of aperture radius

- Reduction of beam aperture radius from 35 mm to 30 mm was investigated.
- 5 mm reduction of magnet aperture radius was assumed: 42 mm → 37 mm.
- Downsized version already looks feasible in terms of field quality; iron geometry could still be optimized further (thinner back-legs, reducing gaps around the main coils, etc.).
- Allows for significant reduction in power consumption and materials (see table).

<table>
<thead>
<tr>
<th>% change after downsizing</th>
<th>Ampere-turns</th>
<th>Dissipated power</th>
<th>Copper mass</th>
<th>Iron mass (preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-23 %</td>
<td>-25 %</td>
<td>-24 %</td>
<td>-27%</td>
</tr>
</tbody>
</table>

Power and materials savings after downsizing
Collider sextupole
Sextupole in CDR (2019)

- 300 mm inter-beam distance, compatible with **individual magnets** for each beam
- “Busy” cross section, **current** and **flux densities** at upper values, **dissipated power**
- Small space for Integration of **trim circuits** (H/V orbit correctors, skew quadrupoles) to be performed

✓ 1.5% Saturation

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### Table: Sextupole Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sextupole Strength</td>
<td>T/m²</td>
<td>807</td>
</tr>
<tr>
<td>Total current</td>
<td>At</td>
<td>6300</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>Conductor dimensions</td>
<td>mm²</td>
<td>8×8</td>
</tr>
<tr>
<td>Cooling diameter</td>
<td>mm</td>
<td>3</td>
</tr>
<tr>
<td>Current density</td>
<td>A/mm²</td>
<td>7.87</td>
</tr>
<tr>
<td>Voltage drop per magnet</td>
<td>V</td>
<td>34.5</td>
</tr>
<tr>
<td>Resistance per magnet</td>
<td>mΩ</td>
<td>77</td>
</tr>
<tr>
<td>Power per magnet</td>
<td>kW</td>
<td>15.5</td>
</tr>
<tr>
<td>Number of water circuits</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>Water temperature rise</td>
<td>ºC</td>
<td>10.5</td>
</tr>
<tr>
<td>Cooling water speed</td>
<td>m/s</td>
<td>2.77</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>bar</td>
<td>6</td>
</tr>
<tr>
<td>Reynolds No.</td>
<td>-</td>
<td>4150</td>
</tr>
</tbody>
</table>

S₀ max = 807 T/m², Bpole tip 0.59 T
### Fcc-ee Sextupole Specifications Updates

<table>
<thead>
<tr>
<th>Main Parameter</th>
<th>Unit</th>
<th>CDR (2019)</th>
<th>New</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sextupole strength (B’’)</td>
<td>T/m2</td>
<td>807</td>
<td>876.6</td>
<td>Including tapering (3%) &amp; tuning (5%) margins</td>
</tr>
<tr>
<td>Bore aperture radius (CDR)</td>
<td>mm</td>
<td>38</td>
<td>38/33</td>
<td>Considering 2 mm thickness of the vacuum chamber and 1 mm clearance.</td>
</tr>
<tr>
<td>Reference radius for good field region (GFR)</td>
<td>mm</td>
<td>±10</td>
<td>±10</td>
<td></td>
</tr>
<tr>
<td>Field quality in GFR</td>
<td></td>
<td>1.0E-04</td>
<td>≈1</td>
<td></td>
</tr>
<tr>
<td>Magnetic length</td>
<td>mm</td>
<td>1400</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Drift space between two consecutive sextupole</td>
<td>mm</td>
<td>100</td>
<td>150</td>
<td>Considering in 3D designing</td>
</tr>
<tr>
<td>Magnetic lengths in inter-beam distance</td>
<td>mm</td>
<td>145</td>
<td>170</td>
<td>Considering that beam inter distance of 350 mm.</td>
</tr>
<tr>
<td>Horizontal orbit correction integrated field strength</td>
<td>Tm</td>
<td>-</td>
<td>0.02</td>
<td>B=0.013 T</td>
</tr>
<tr>
<td>Vertical orbit correction integrated field strength</td>
<td>Tm</td>
<td>-</td>
<td>0.02</td>
<td>B=0.013 T</td>
</tr>
<tr>
<td>Skew quadrupole correction integrated gradient</td>
<td>T</td>
<td>-</td>
<td>0.6</td>
<td>G=0.4 T/m</td>
</tr>
</tbody>
</table>

Info K.Oide and R. Tomas: 19th April 2023

- It gets worse in the updates in point of magnet design with (R=38)
  - S=880 T/m2
  - L=1.5 m

- Inter-beam distance D=350 mm! The created space could be utilized for more iron or more coil turns!
Sextupole (D=350 mm)-I

- More coil windings
  - Pole width is saved as before
  - N=32 turn
  - Auxiliary solid coils = 32+16 turns (too high current density)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sextupole Strength</td>
<td>T/m²</td>
<td>880</td>
</tr>
<tr>
<td>Total current</td>
<td>A</td>
<td>7500</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>-</td>
<td>32</td>
</tr>
<tr>
<td>Conductor dimensions</td>
<td>mm²</td>
<td>6.5×6.5</td>
</tr>
<tr>
<td>Cooling diameter</td>
<td>mm</td>
<td>3.5</td>
</tr>
<tr>
<td>Current density</td>
<td>A/mm²</td>
<td>7.24</td>
</tr>
<tr>
<td>Voltage drop per magnet</td>
<td>V</td>
<td>77</td>
</tr>
<tr>
<td>Resistance per magnet</td>
<td>mΩ</td>
<td>326</td>
</tr>
<tr>
<td>Power per magnet</td>
<td>kW</td>
<td>18.1</td>
</tr>
<tr>
<td>Number of water circuits</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>Water temperature rise</td>
<td>°C</td>
<td>13.5</td>
</tr>
<tr>
<td>Cooling water speed</td>
<td>m/s</td>
<td>1.85</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>bar</td>
<td>6</td>
</tr>
<tr>
<td>Reynolds No.</td>
<td>-</td>
<td>3250</td>
</tr>
</tbody>
</table>

- The saturation is increased to 9%.
- The power is more than 18 kW.
- Problems in cooling (18 cooling circuits, not fully in turbulent regime)
- Small space for Corrector coils
Sextupole (D=350 mm)-II

➢ Wider Pole width

☐ Reserving space for Iron
☐ N=22 turn
☐ Auxiliary coils = 32+16 turns (too high current density)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sextupole Strength</td>
<td>T/m²</td>
<td>880</td>
</tr>
<tr>
<td>Total current</td>
<td>A</td>
<td>6920</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Conductor dimensions</td>
<td>mm²</td>
<td>6.5×6.5</td>
</tr>
<tr>
<td>Cooling diameter</td>
<td>mm</td>
<td>3.5</td>
</tr>
<tr>
<td>Current density</td>
<td>A/mm²</td>
<td>9.6</td>
</tr>
<tr>
<td>Voltage drop per magnet</td>
<td>V</td>
<td>70</td>
</tr>
<tr>
<td>Resistance per magnet</td>
<td>mΩ</td>
<td>223</td>
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<tr>
<td>Power per magnet</td>
<td>kW</td>
<td>22.1</td>
</tr>
<tr>
<td>Number of water circuits</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>Water temperature rise</td>
<td>°C</td>
<td>13.2</td>
</tr>
<tr>
<td>Cooling water speed</td>
<td>m/s</td>
<td>2.3</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>bar</td>
<td>6</td>
</tr>
<tr>
<td>Reynolds No.</td>
<td></td>
<td>4030</td>
</tr>
</tbody>
</table>

➢ The current density is increased to 9.6 A/mm².
➢ The saturation is about 1.5% but the power is increased to 22 kW.
   ○ Problems in cooling (18 cooling circuits)
➢ Small space for Axillary coils.

➢ It seems that this created space (D=350 mm) could not compensate effects of increasing the field strength and magnetic length in the specifications update.
Sextupole (R=33 mm)

Field quality better than 5.0E-05

\[ \Delta S/S \]
Sextupole (R=33 mm)

Electrical and Cooling Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sextupole strength</td>
<td>T/m²</td>
<td>880</td>
</tr>
<tr>
<td>Current</td>
<td>A</td>
<td>4250</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>-</td>
<td>24</td>
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<tr>
<td>Operation current</td>
<td>A</td>
<td>177</td>
</tr>
<tr>
<td>Operation current</td>
<td>A</td>
<td>177</td>
</tr>
<tr>
<td>Operation current</td>
<td>A</td>
<td>177</td>
</tr>
<tr>
<td>Operation current</td>
<td>A</td>
<td>177</td>
</tr>
<tr>
<td>Conductor dimensions</td>
<td>mm²</td>
<td>6.5×6.5</td>
</tr>
<tr>
<td>Coolin diameter</td>
<td>mm</td>
<td>3.5</td>
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<td>Current density</td>
<td>A/mm²</td>
<td>5.4</td>
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<td>Voltage drop per magnet</td>
<td>V</td>
<td>43.2</td>
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<tr>
<td>Voltage drop per magnet</td>
<td>V</td>
<td>43.2</td>
</tr>
<tr>
<td>Voltage drop per magnet</td>
<td>V</td>
<td>43.2</td>
</tr>
<tr>
<td>Resistance per magnet</td>
<td>mΩ</td>
<td>243</td>
</tr>
<tr>
<td>Power per magnet</td>
<td>kW</td>
<td>7.7</td>
</tr>
<tr>
<td>Number of water circuits</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>Water temperature rise</td>
<td>°C</td>
<td>4.8</td>
</tr>
<tr>
<td>Cooling water speed</td>
<td>m/s</td>
<td>2.2</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>bar</td>
<td>6</td>
</tr>
<tr>
<td>Reynolds no.</td>
<td>-</td>
<td>3850</td>
</tr>
</tbody>
</table>

- The power is decreased to 7.2 kW.
- 1/3 of R=38 (880 T/m²), ½ of CDR (807 T/m²)
- The saturation is less than % 1.
Correctors

Green Coils: Main Sextupole
Orange Coils: Vertical Corrector
Brown Coils: Horizontal Corrector
Yellow Coils: Skew Quadrupole

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Strength (Tm) (T)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.6</td>
</tr>
<tr>
<td>Magnetic field (mT)/(T/m)</td>
<td>13</td>
<td>13</td>
<td>0.4</td>
</tr>
<tr>
<td>Effective length (mm)</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Ampere-Turns per pole (A.t)</td>
<td>400/200</td>
<td>345</td>
<td>378</td>
</tr>
<tr>
<td>Number of turns</td>
<td>48-24</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>Conductor size (mm²)</td>
<td>3.75 × 1.6</td>
<td>3.75 × 1.6</td>
<td>3.75 × 1.6</td>
</tr>
<tr>
<td>Current (A)</td>
<td>8.3</td>
<td>7.2</td>
<td>15.8</td>
</tr>
<tr>
<td>Current Density (A/mm²)</td>
<td>1.4</td>
<td>1.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Resistance per magnet (Ω)</td>
<td>1.7/0.8</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Total Voltage (V)</td>
<td>14/7</td>
<td>12.1</td>
<td>20</td>
</tr>
<tr>
<td>Total Power (W)</td>
<td>118/59</td>
<td>87</td>
<td>315</td>
</tr>
</tbody>
</table>
Sextupole Conclusion

➢ The sextupole with the updated parameters (R=38 mm, D=350 mm) was investigated:
  • The power is too high (20 kW).
  • There is little space for auxiliary coils.
  • The created space of inter beam distance (D=350 mm) could not compensate the effects of increasing the field strength and the magnetic length.

➢ Reducing the aperture radius to 33 mm was simulated.
  • The field quality, higher order multiples, electrical and cooling parameters were investigated and presented.
  • The required power (7.2 kW) is decreased significantly that is not comparable with the power in R=38 mm case (1/3) and the value in CDR(1/2).

➢ The horizontal and vertical correctors and skew quadruples are simulated and electrical parameters were investigated.
  • The field quality of sextupole plus correctors should be investigated and approved by beam dynamics.
Booster magnets
# Summary of requirements

<table>
<thead>
<tr>
<th></th>
<th>Minimum Field</th>
<th>Maximum field</th>
<th>Magnetic length</th>
<th>Good field radius</th>
<th>Field homogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>7.1 mT</td>
<td>65 mT</td>
<td>11.1 m</td>
<td>17 mm</td>
<td>10 units</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>1.7 Tm⁻¹</td>
<td>22.5 Tm⁻¹</td>
<td>1.5 m</td>
<td>10 mm</td>
<td>2 units</td>
</tr>
<tr>
<td>Sextupole</td>
<td>148.6 Tm⁻²</td>
<td>1574.5 Tm⁻²</td>
<td>0.5 m</td>
<td>17 mm</td>
<td></td>
</tr>
</tbody>
</table>
 Booster dipole candidate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of units</td>
<td></td>
<td>2944 x 2</td>
</tr>
<tr>
<td>Central field, 20 GeV–182.5 GeV</td>
<td>mT</td>
<td>7.1 - 65.0</td>
</tr>
<tr>
<td>Aperture (horizontal x vertical)</td>
<td>mm</td>
<td>123 x 55</td>
</tr>
<tr>
<td>Good field region (GFR) radius</td>
<td>mm</td>
<td>17</td>
</tr>
<tr>
<td>Field quality in GFR</td>
<td></td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>m</td>
<td>11.1</td>
</tr>
<tr>
<td>Magnet overall transverse dimensions</td>
<td>mm</td>
<td>228 x 100</td>
</tr>
<tr>
<td>Iron mass per unit length</td>
<td>kg/m</td>
<td>55.5</td>
</tr>
<tr>
<td>Aluminium mass per unit length</td>
<td>kg/m</td>
<td>7.68</td>
</tr>
<tr>
<td>Magnet unit mass (11.1 m length)</td>
<td>kg</td>
<td>701</td>
</tr>
<tr>
<td>Total magnet mass, 65.4 km</td>
<td>tons</td>
<td>~ 4500</td>
</tr>
<tr>
<td>Maximum operating ampere-turns (tt_bar extraction)</td>
<td>A</td>
<td>2844</td>
</tr>
<tr>
<td>Maximum RMS current density (tt_bar)</td>
<td>A/mm²</td>
<td>0.92</td>
</tr>
<tr>
<td>Peak current (coil 4 turns)</td>
<td>A</td>
<td>711</td>
</tr>
<tr>
<td>Resistance per unit length (coil 4 turns)</td>
<td>μΩ/m</td>
<td>596</td>
</tr>
<tr>
<td>Inductance per unit length (coil 4 turns)</td>
<td>μH/m</td>
<td>55</td>
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<tr>
<td>Peak voltage per 1/2 octant (coil 4 turns)</td>
<td>kV</td>
<td>1810</td>
</tr>
<tr>
<td>Maximum RMS power per unit length (tt_bar)</td>
<td>W/m</td>
<td>64</td>
</tr>
<tr>
<td>Maximum total peak power, 65.4 km (tt_bar; cabling not incl.)</td>
<td>MW</td>
<td>20</td>
</tr>
<tr>
<td>Maximum total RMS power, 65.4 km (tt_bar; cabling not incl.)</td>
<td>MW</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Booster quadrupole candidate

- Current density in copper: $5.1 \text{ A}_{\text{RMS}} \text{ mm}^{-2} @ \text{tt2}$
  
<table>
<thead>
<tr>
<th>Power Loss [MW]</th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>\text{tt1}</th>
<th>\text{tt2}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9</td>
<td>1.5</td>
<td>5.0</td>
<td>18.9</td>
<td>20.8</td>
</tr>
</tbody>
</table>

- $B_{\text{peak}} < 1.6 \text{ T} @ \text{tt2}$, $\eta > 98\%$
- Active mass: 750 kg (2210 tons total)
- Assumes 1.5 mm for vacuum tube and 5 mm bake-out jacket
- 6 turns per coil, [1.8 kA; 1.8 kV] per 92 magnet circuit
- ΔP cooling water 5.4 bar, ΔT < 22 K
- 70 mm coil overhang vs. 165 mm quad. to sext. distance
- **Matches key requirements, to be optimised...**
Next steps for magnet development
Prospects for magnets development

• Electromagnetic design
  o Global cost optimization (capital and operational for magnet and cooling infrastructure) to find optimal working point (J in coils, ΔT, electrical parameters for converter efficiency)
  o Cross-section of collider quadrupole to minimize gaps in cross-section, optimize $B_{mod}$ in iron
  o Alternative design of collider sextupoles with coils out of mid-plane (SR damage to evaluate)
  o Optimisation of booster dipole for remnant effects ($Hc$)

• Mechanical design
  o Manufacturing processes for large series (automatized machining, assembly, measurements)
  o Design of inter-connections to quantify exact drift space needed (dipoles with $B$-covered interconnects)

• R&D, prototyping, and arc half-cell mock-up
  o Model magnets for performance validation as well as integration checks
  o Inorganic coatings for insulation (dipole busbars, sextupole coils)
Conclusions
Conclusions

The latest specifications – inter-beam distance, magnetic parameters, trim coils in collider sextupoles, etc. - have been reflected in the magnet design updates.

The aperture coupling in the collider quadrupole has been significantly mitigated.

The collider magnet designs evaluated with reduced aperture, can bring significant savings in materials, as well as power consumption (~10% for dipoles, ~25% for quadrupoles, ~50% for sextupoles), and is necessary for sextupole design with correction windings.

A preliminary cross-section of the booster quadrupole is proposed, which matches the optics requirements.

The next steps of the magnet development work will address the lifetime cost optimization, performance in the low fields, and large series manufacturing aspects through the production, test and measurement of model/prototype magnets.
Thank you for your attention!

Questions?
SPARE SLIDES
Dipole 1-m long models

- 2 versions, S235 vs. ARMCO yoke
- Systematic b2 not included in field homogeneity budget (agreed with optics)

<table>
<thead>
<tr>
<th>NI [A]</th>
<th>ARMCO AP1</th>
<th>ARMCO AP2</th>
<th>S355 AP1</th>
<th>S355 AP2</th>
<th>FEM AP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>52.1</td>
<td>-53.4</td>
<td>60.5</td>
<td>-62.0</td>
<td>-22.2</td>
</tr>
<tr>
<td>1000</td>
<td>34.4</td>
<td>-35.3</td>
<td>47.3</td>
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<td>22.1</td>
<td>-30.3</td>
<td>28.3</td>
<td>-22.2</td>
</tr>
</tbody>
</table>

Prototype 1m-long, 2017

Quadrupole component

Transfer function
Quadrupole magnetic axis shift

Magnetic measurements performed on 1-m prototype [3]

- ~0.4 mm shift for each aperture between low and high fields
- Mismatch MM vs. FEM (3D) at low fields not completely explained
  ➔ To be further investigated

| I [A] | $x_{02}$ [mm] | $|b_3| [10^{-5} @ 10$ mm] |
|-------|---------------|-----------------------------|
|       | AP1 | AP2 | FEM | AP1 | AP2 | FEM |
| 25    | 0.75 | -0.75 | 0.17 | 13.1 | -14.4 | -57.9 |
| 50    | 0.22 | -0.23 | 0.17 | 34.7 | -35.4 | -57.9 |
| 100   | -0.07 | 0.07 | 0.17 | 46.6 | -46.6 | -58.0 |
| 150   | -0.17 | 0.16 | 0.17 | 50.9 | -50.9 | -58.2 |
| 200   | -0.22 | 0.22 | 0.18 | 53.5 | -53.6 | -59.0 |
| 250   | -0.29 | 0.27 | 0.22 | 57.8 | -57.2 | -62.5 |
| 300   | -0.33 | 0.32 | 0.18 | 53.1 | -53.3 | -59.0 |
| 150   | -0.18 | 0.17 | 0.17 | 51.0 | -50.6 | -58.2 |
| 100   | -0.10 | 0.09 | 0.17 | 46.9 | -46.9 | -58.0 |
| 50    | 0.15 | -0.16 | 0.17 | 35.7 | -35.2 | -57.9 |
| 25    | 0.59 | -0.59 | 0.17 | 15.9 | -14.9 | -57.9 |

The simulation results are for AP2, as 1/4 of the magnet is modeled; furthermore, no hysteretic behavior is considered in the BH curve.

Measured magnetic axis shift and $|b_3|$

Magnetic axis shift
Correctors

**Vertical Corrector**

**Horizontal Corrector**

**Skew Quadrupole Corrector**

**Horizontal Dipole**

$B_x = 0.013$ T

**Vertical Dipole**

$B_y = 0.013$ T

**G**

$G = 0.4$ T/m