Magnet Options
Forward dipoles vs. forward solenoids

Matthias Mentink
A. Dudarev, H. Silva, G. Rolando, B. Cure, A. Gaddi, V. Klyukhin,
H. Gerwig, C. Berriaud, U. Wagner, and H. ten Kate
Today’s default: Twin Solenoid + Force & Torque Neutral Dipoles

- Full coverage, i.e. good field integral for $\eta = 0$ to $\infty$
- Twin Solenoid: Inner coil provides 6 T over 12 m free bore, and outer coil reduces stray field.
- Force & Torque Neutral Dipole: Provides 10 Tm of bending power in forward direction. Combination of lateral and main coils makes cold mass force & torque neutral.

But: Large dipoles (1.5 GJ stored energy) in magnetic stray field of Twin Solenoid (>1 T)

- Very heavy magnet, large internal forces, and torques inside the cold mass → Challenging to build
- Can we find an alternative?
Forward solenoid: ‘Balanced Conical Solenoid’

Forward solenoid needs to be force & torque neutral

- Forward system needs to be movable, to access inner tracker and calorimeters → No direct mechanical connection to cold mass of Twin Solenoid
- Forces and torques that can be handled with cold-to-warm supports is limited.

How to design a force and torque neutral forward solenoid?

- Solenoids, in axial alignment, current flow in same direction → Large axial force (here: 280 MN)
- Balancing coils with current flow in opposite direction → Repulsive force on both Twin Solenoid and conical solenoid.
  - Interaction between balancing coil and Twin Solenoid → Repulsive force
  - Interaction between balancing coil and conical solenoid → Also repulsive force, but in opposite direction
  - Result: Net axial force (and torque) on each individual coil is zero
**Advantages of forward dipole:**
- Field is oriented nearly perpendicular to high-$\eta$ particles $\rightarrow$ Efficient for providing bending power

**Advantages of forward solenoid:**
- Evenly distributed windings: Magnetic field magnitude in bore is over 90% of field on conductor (Dipole: field in bore is $\sim$30% of field on conductor)
- Solenoidal field of forward solenoid is complementary to that of Twin Solenoid (behaves like very long solenoid)
- Relatively small coil needed for force balancing, i.e. relatively efficient in terms of space and stored energy
- Homogeneous distribution of forces, reduced need for support structure
- No compensation dipoles needed
Performance comparison between dipole and forward solenoid

- For high-momentum particles, transverse deflection \( x \) of particle is proportional to second field integral \( I_2 \), which in turn is related to the perpendicular field and the trajectory length [1].

- Requirement: Decent particle tracking at \( 0 \leq \eta \leq 4 \)

- At \( \eta = 4 \), \( z_{\text{max}} = 22 \) m: \( I_{2,\text{Dipole}}(\eta = 4) = 38 \text{ Tm}^2 \), \( I_{2,\text{TS+BCS}}(\eta = 4) = 43 \text{ Tm}^2 \)

- Performance of forward solenoid improves with decreasing \( \eta \)

\[ x(l) = \frac{0.3}{p_T} I_2 \]

\[ I_2 = \int_0^l \int_0^l B_T \, dl^2 \]

\[ B_T = B_z \sin(\alpha) - B_R \cos(\alpha) \]

\[ \alpha = 2 \times \tan(\exp(-\eta)) \]

Preliminary conclusion: For high-momentum particles, forward solenoid gives better tracking resolution than dipole, provided precise alignment of inner and forward tracker can be achieved. This still needs to be studied from a pattern recognition perspective [2].

**Variant 1/3: Spherical Detector Assembly**

Spherical Detector Assembly:
- Large outer conical solenoid for returning flux (similar to Twin Solenoid)
- Gives more control over field configuration:
  - Most optimal stray field reduction of variants presented here
  - Returned flux between coils highly suitable for independent muon tracking system, if needed
- But complex and mechanically challenging:
  - Rather large outer conical coils
  - 650 MN of tensile force between inner and outer conical coils
Variant 2/3: Twin Solenoid + Balanced Conical Solenoid

- Detector geometry currently optimized with emphasis on obtaining close vicinity 5 mT boundary in the radial direction
- Forward balancing coil makes all coils net force and torque neutral during regular operation
- Sufficient field integral for muon angle determination
Variant 3/3: Solenoid + Balanced Conical Solenoid

- **Solenoid + Balanced Conical Solenoid**
  - Same as Twin Solenoid + BCS, but without outer solenoid, and thus unshielded
  - Advantages:
    - Less complexity
    - Less cold mass + vacuum vessel mass (-40%)
    - Less outer surface area → Less cooling required
    - Much more compact (Minimum shaft diameter: 16.3 m* instead of 27.5 m)
  - Disadvantage: No active magnetic shielding, so localized shielding required for electronics
  - Sufficient field integral for muon angle determination

* = Assuming rotation after lowering to cavern
### Magnet property comparison (Also see FCC week Wednesday poster session)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{center}}$ [T]</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Free bore</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Cold mass middle [kT]</td>
<td>5.0</td>
<td>4.0</td>
<td>5.0</td>
<td>3.2</td>
</tr>
<tr>
<td>Vacuum vessel weight of main magnet [kt]</td>
<td>~2</td>
<td>~2</td>
<td>~2</td>
<td>~1</td>
</tr>
<tr>
<td>Cold mass of forward system [kT]</td>
<td>$2 \times 0.3$</td>
<td>$2 \times 0.8$</td>
<td>$2 \times 0.34$</td>
<td>$2 \times 0.34$</td>
</tr>
<tr>
<td>Stored energy [GJ]</td>
<td>65</td>
<td>57</td>
<td>68</td>
<td>47</td>
</tr>
<tr>
<td>Minimum Shaft Diameter [m]</td>
<td>27.5</td>
<td>26.5</td>
<td>27.5</td>
<td>16.3*</td>
</tr>
<tr>
<td>Peak tensile strain [%]</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Peak stress in windings [MPa]</td>
<td>110</td>
<td>105</td>
<td>110</td>
<td>104</td>
</tr>
<tr>
<td>Bending power $\eta = 4$, between $z = 0...22$ [Tm$^2$]</td>
<td>38</td>
<td>35</td>
<td>43</td>
<td>40</td>
</tr>
</tbody>
</table>

* = Assuming rotation after lowering to cavern
**Shielding comparison**

- Best shielding with the Spherical Detector Assembly, but relatively complex design
- Stray field of ‘Twin Solenoid + 2x dipole’ (not shown here) is about same as ‘Twin Solenoid + 2x BCS’
- Highest stray field with the Solenoid, but lowest mass, lowest complexity, most compact
- Field magnitude of all options drops to below 0.5 gauss at ~320 m away from experiment in radial direction, even in worst case scenario (6 T, 12 m free bore, unshielded)
**Summary**

**Force & torque free forward solenoid using balancing coils**
- Less complexity compared to dipole, i.e. easier to design and construct
- Preliminary conclusion: Better tracking resolution in the forward solenoid in the relevant pseudo-rapidity regime ($0 \leq \eta \leq 4$) for high-momentum particles. This still needs to be studied from a pattern recognition perspective.
  (Drasal, oral 323, FCC week, Wednesday 13/4/16, 11:30)

**Detector magnet variations with forward solenoid**
- A clear trade-off exists between complexity, mass, minimum shaft diameter on one side and active shielding efficiency on other side.
- Best stray field reduction: Spherical Detector Assembly
- Least complexity and cold mass, but without active shielding: Solenoid + Balanced Conical Solenoids
- Detector Magnet variants are discussed in detail in poster 149 (FCC Week, Wednesday 13/4/16, 17:30)