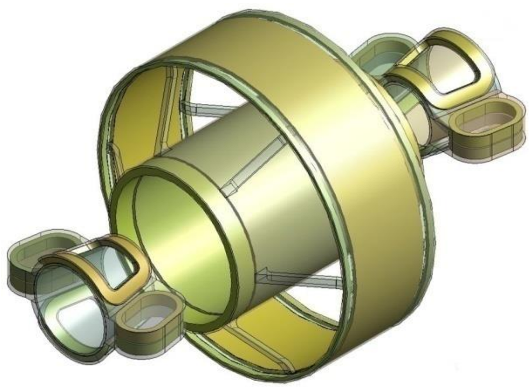
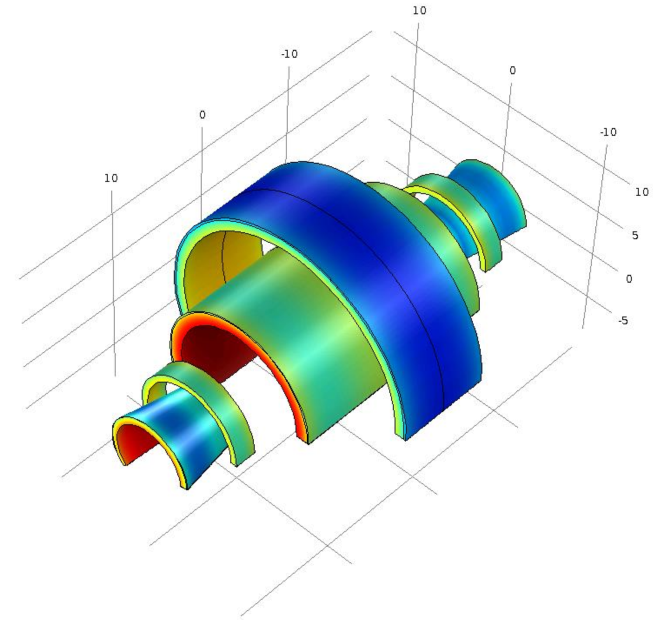
Magnet Options

Forward dipoles vs. forward solenoids





Matthias Mentink

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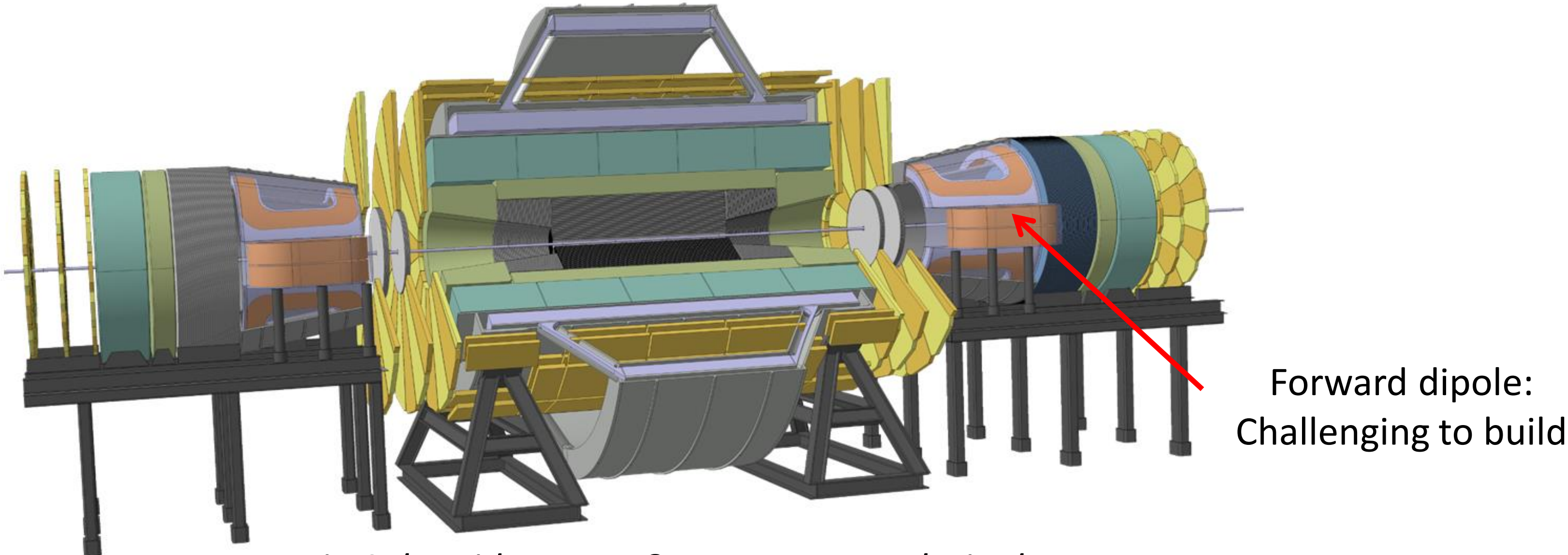
H. Gerwig, C. Berriaud , U. Wagner, and H. ten Kate

Motivation



Twin Solenoid + Force & Torque Neutral Dipoles

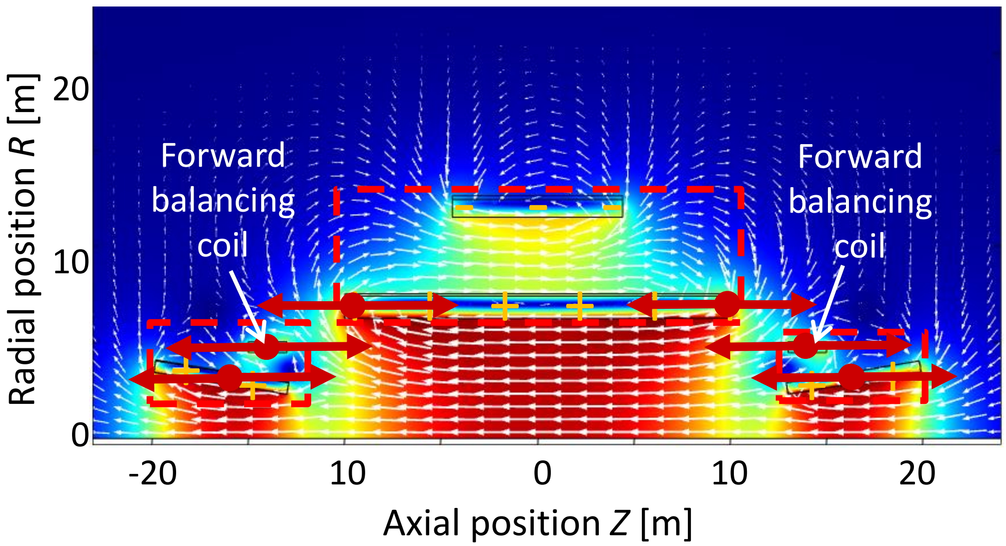
Today's default: Twin Solenoid + Force & Torque Neutral Dipoles

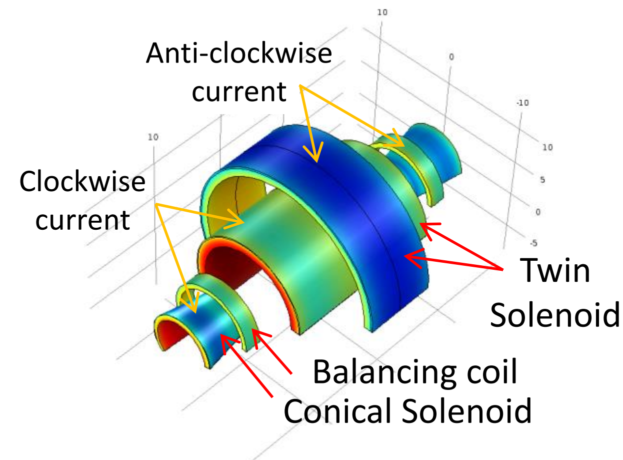
- Full coverage, i.e. good field integral for η = 0 to ∞
- Twin Solenoid: Inner coil provides 6 T over 12 m free bore, and outer coil reduces stray field.
- Force & Torque Neutral Dipole: Provides 10 Tm of bending power in forward direction. Combination of lateral and main coils makes cold mass force & 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’





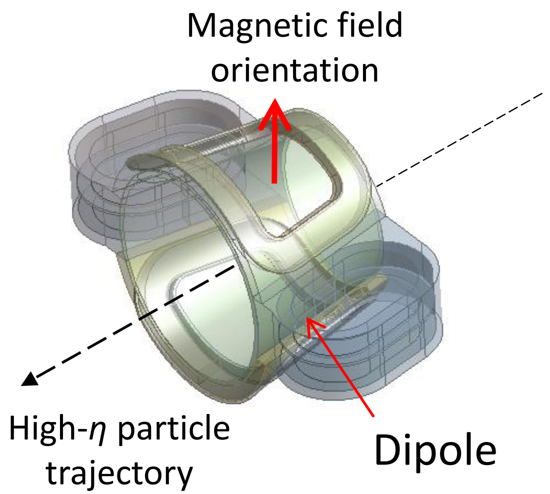
Forward solenoid needs to be force & torque neutral

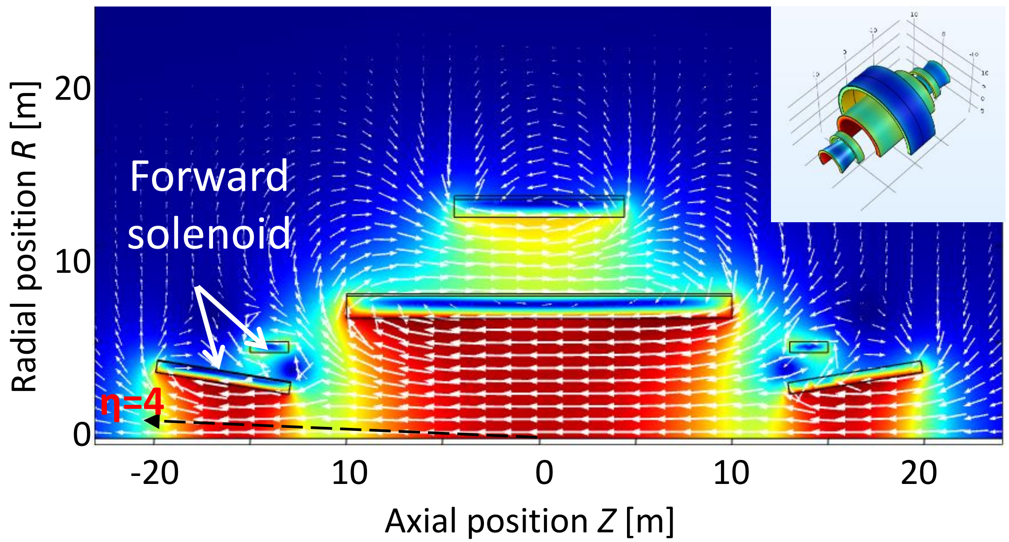
- Forward system needs to be movable, to access inner tracker and calorimeters → No direct mechanical connection to cold mass of Twin Solenoid
- Forces and torques that can be handled with cold-to-warm supports is limited.

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**

Forward dipole vs. forward solenoid





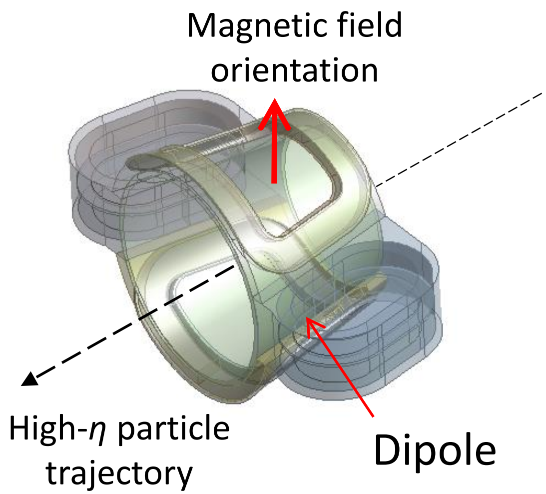
Advantages of forward dipole:

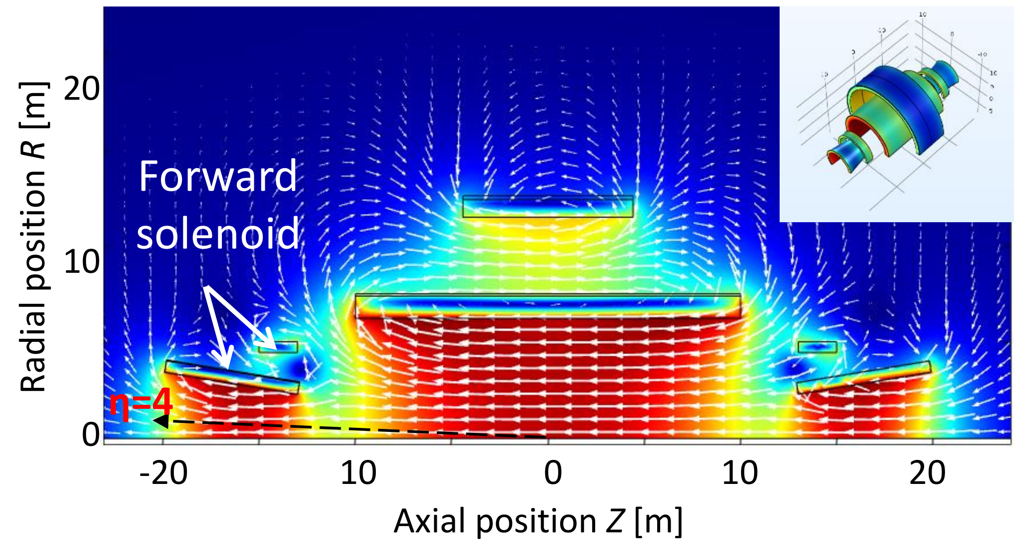
- Field is oriented nearly perpendicular to high-η particles → Efficient for providing bending power

Advantages of forward solenoid:

- Evenly distributed windings: Magnetic field magnitude in bore is over 90% of field on conductor (Dipole: field in bore is ~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





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 $\eta = 4$, $z_{max} = 22$ m: $I_{2,\mathrm{Dipole}}(\eta = 4) = 38\ \mathrm{Tm}^2$, $I_{2,\mathrm{TS+BCS}}(\eta = 4) = 43\ \mathrm{Tm}^2$
- Performance of forward solenoid improves with decreasing η

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

$$I_2 = \int_0^l \int_0^l B_T \, dl^2$$

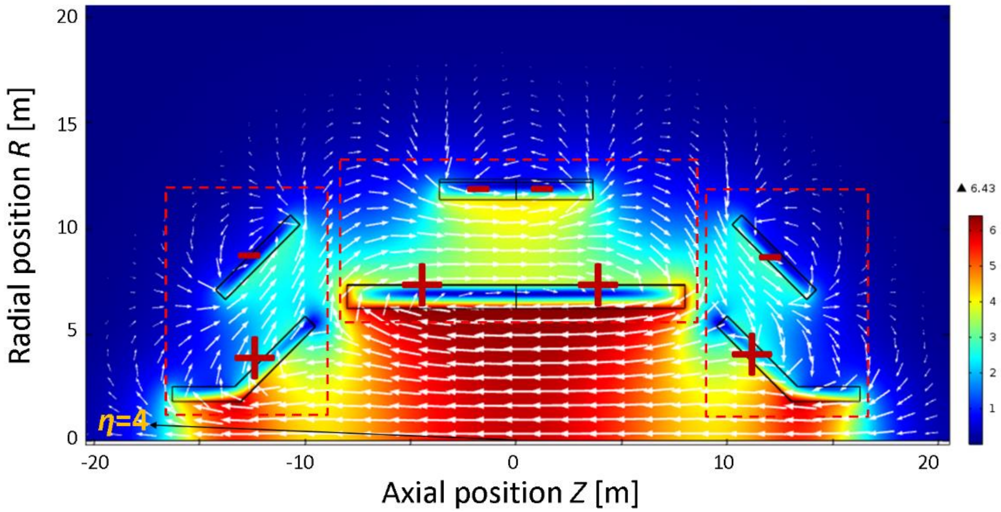
$$B_T = B_Z \sin(\alpha) - B_R \cos(\alpha)$$

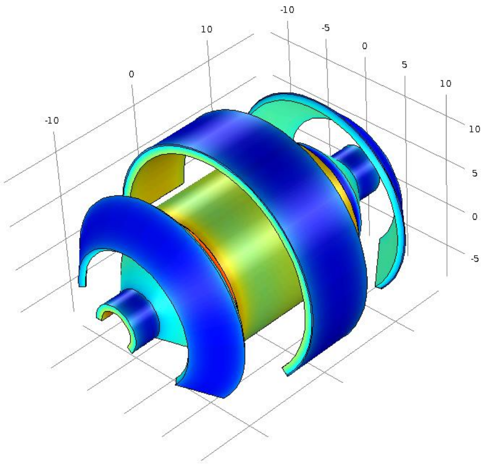
$$\alpha = 2 \times \mathrm{atan}(\exp(-\eta))$$

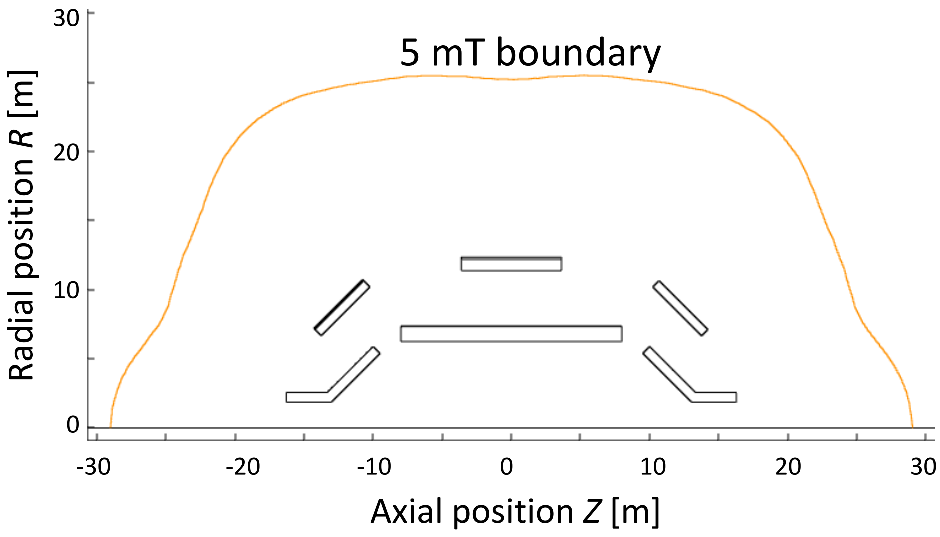
→ Preliminary conclusion: For high-momentum particles, forward solenoid gives better tracking resolution than dipole, provided precise alignment of inner and forward tracker can be achieved. This still needs to be studied from a pattern recognition perspective [2].

[1] Klyukhin – Field integrals for the ATLAS tracking volume (1993)
[2] Z. Drasal, FCC-hh detector meeting 6/4/16

Variant 1/3: Spherical Detector Assembly



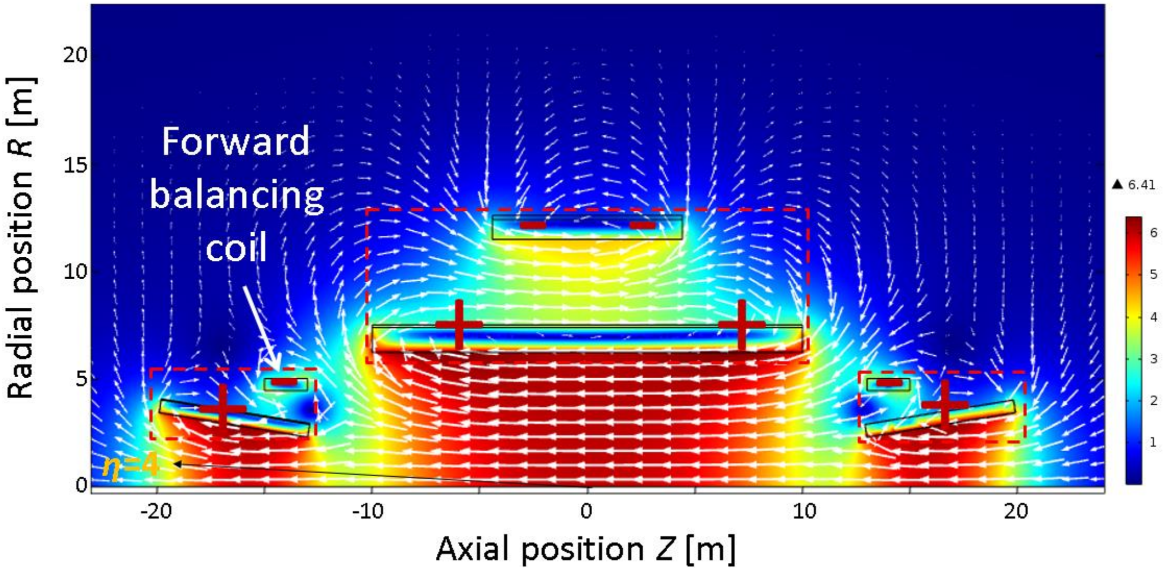


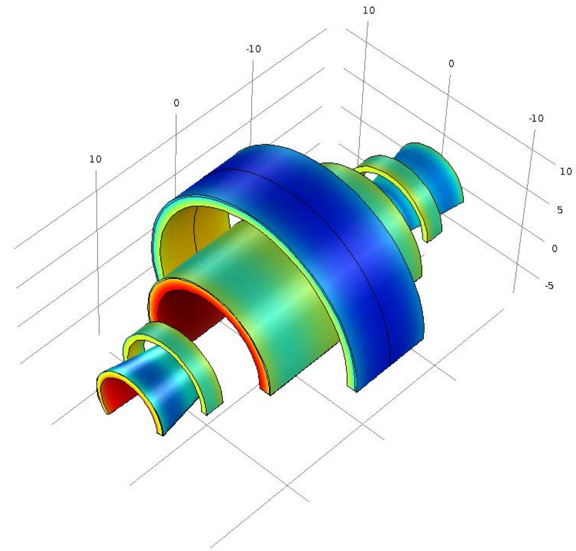


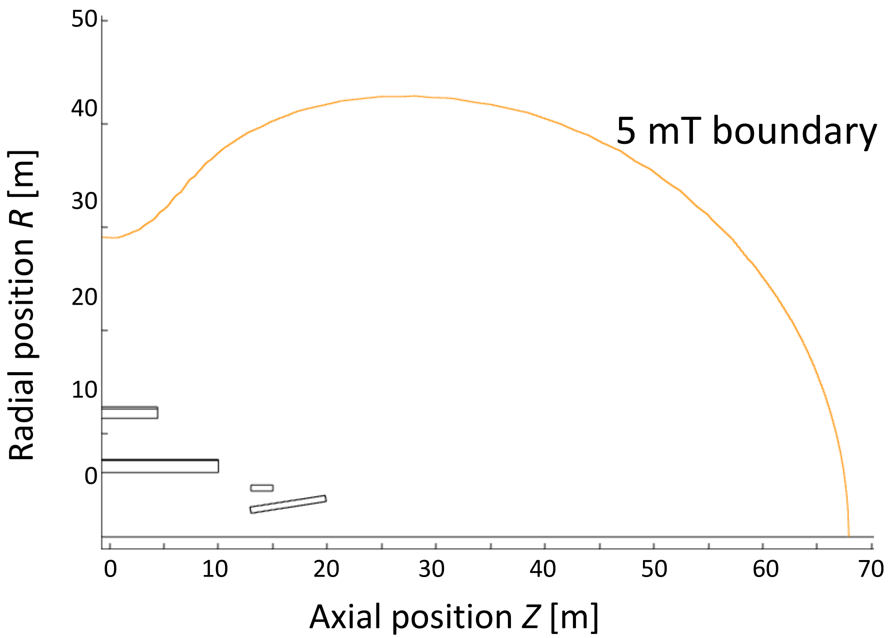
Spherical Detector Assembly:

- 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



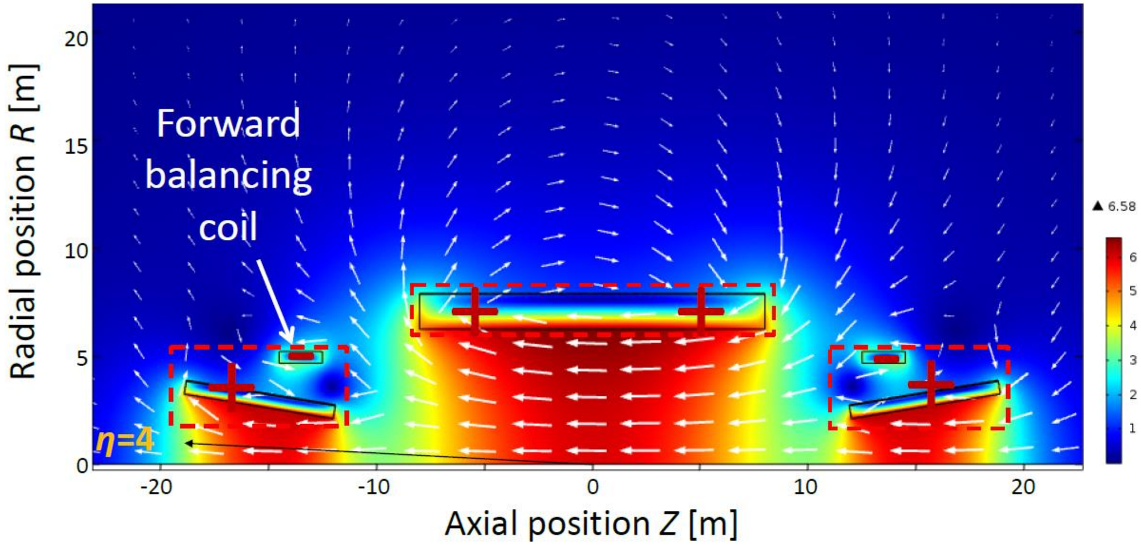


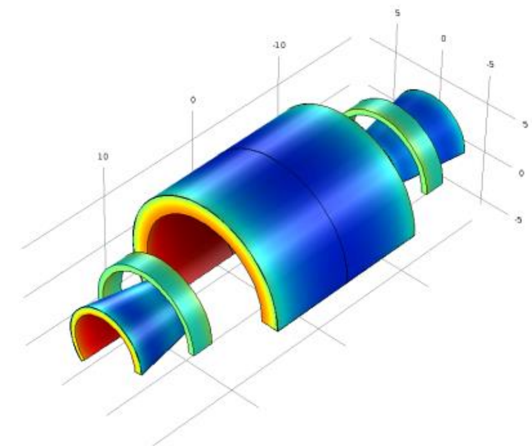


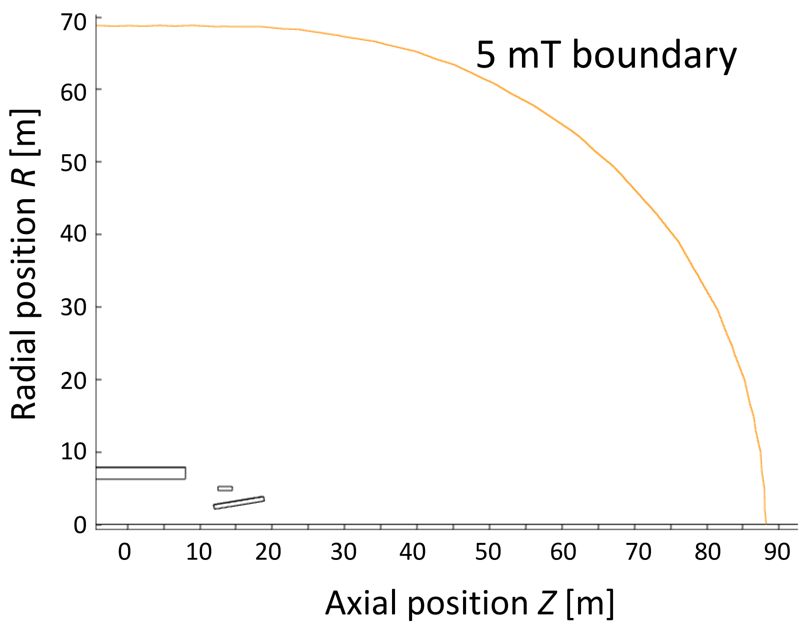
Twin Solenoid + Balanced Conical Solenoid

- 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)

Property	1. Twin Solenoid + dipole	2. Spherical Detector Assembly	3. Twin Solenoid + BCS	Solenoid + BCS
B_{center} [T]	6	6	6	6
Free bore	12	12	12	12
Cold mass middle [kT]	5.0	4.0	5.0	3.2
Vacuum vessel weight of main magnet [kt]	~2	~2	~2	~1
Cold mass of forward system [kT]	2 × 0.3	2 × 0.8	2 × 0.34	2 × 0.34
Stored energy [GJ]	65	57	68	47
Minimum Shaft Diameter [m]	27.5	26.5	27.5	16.3*
Peak tensile strain [%]	0.14	0.14	0.14	0.14
Peak stress in windings [MPa]	110	105	110	104
Bending power η = 4, between z = 0…22 [Tm^2]	38	35	43	40

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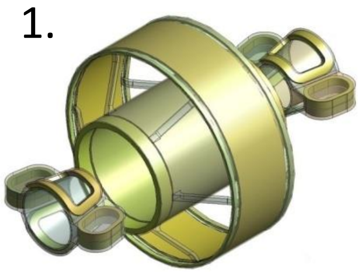

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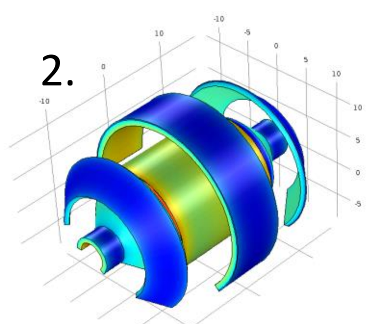

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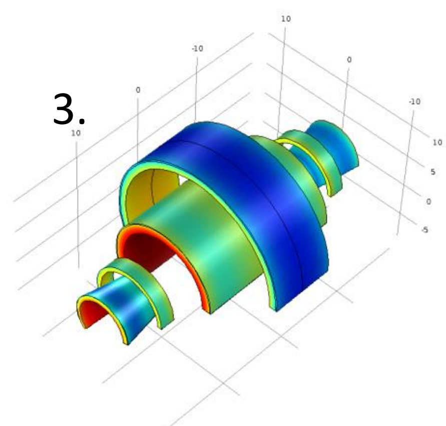

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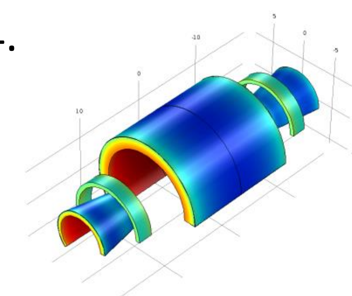
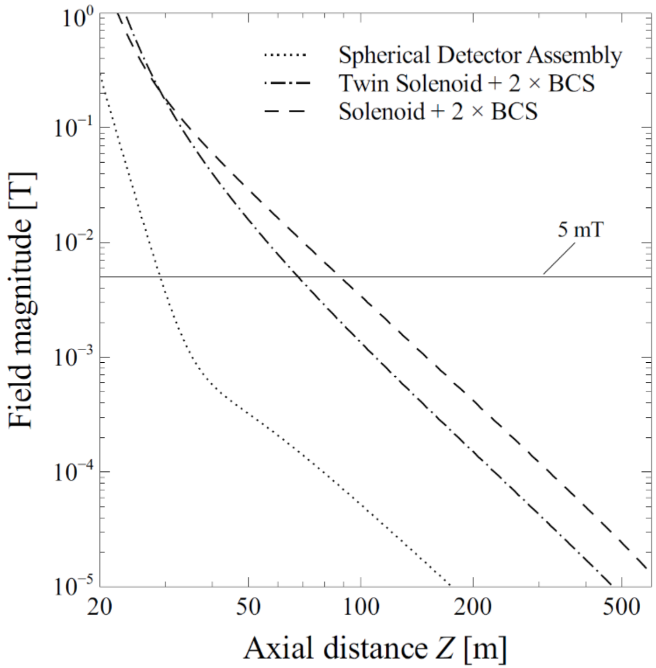
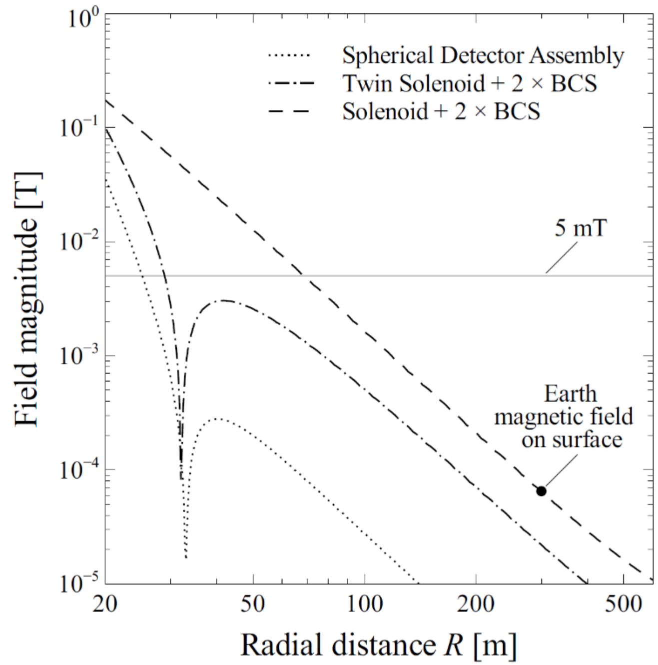
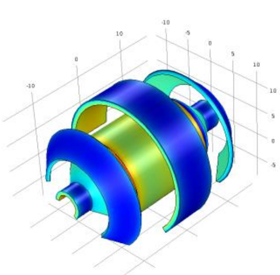


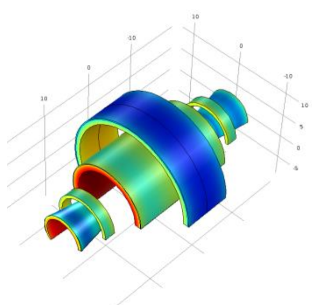
* = Assuming rotation after lowering to cavern



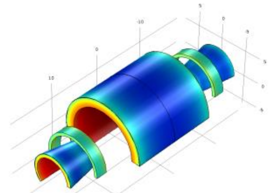




Spherical Detector Assembly



Twin Solenoid + 2x BCS



Solenoid + 2x BCS

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)