Concepts for Detector Magnets for a 100 TeV proton-proton collider

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following discussions with D. Fournier, F. Gianotti, A. Henriques, L. Pontecorvo

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Content

1. Requirements, design drivers

Bending power: higher collision energy 14>100TeV, same tracking resolution

BL^2 has to be increased by factor 7!

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

---> higher field, in single solenoid, up to 6.0 T

---> higher field, longer track in inner solenoid around ID, 3.5T/3m or 2T/4m, and a toroid of 1.8T useful field and increase of tracking length.

Low angle coverage in forward direction, solenoid useless, toroid difficult since all current has to pass the inner bore

---> add a dipole for on-beam bending, some 10Tm!

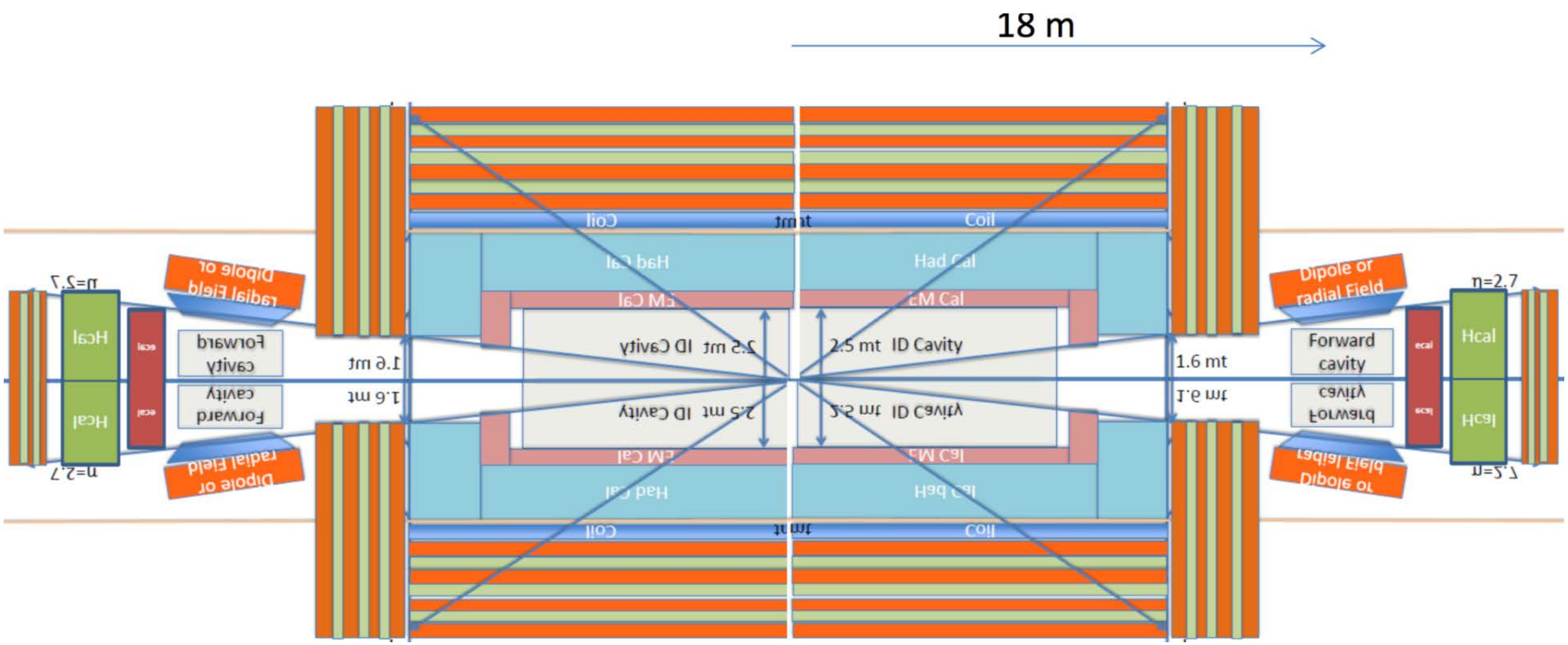
HCAL depth from 10 λ to 12λ (iron) radial thickness some 3.0 m!

---> bore of big solenoid or inner radius toroid increases to 6m and length increases accordingly.

ECAL to cover low angles, move unit out, from 5 to 15 m, system gets longer.

Thus: higher field, larger bore and longer system. 3 options analyzed.

Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



Solenoid: 5-6 m diameter, 5-6 T, 23 m long

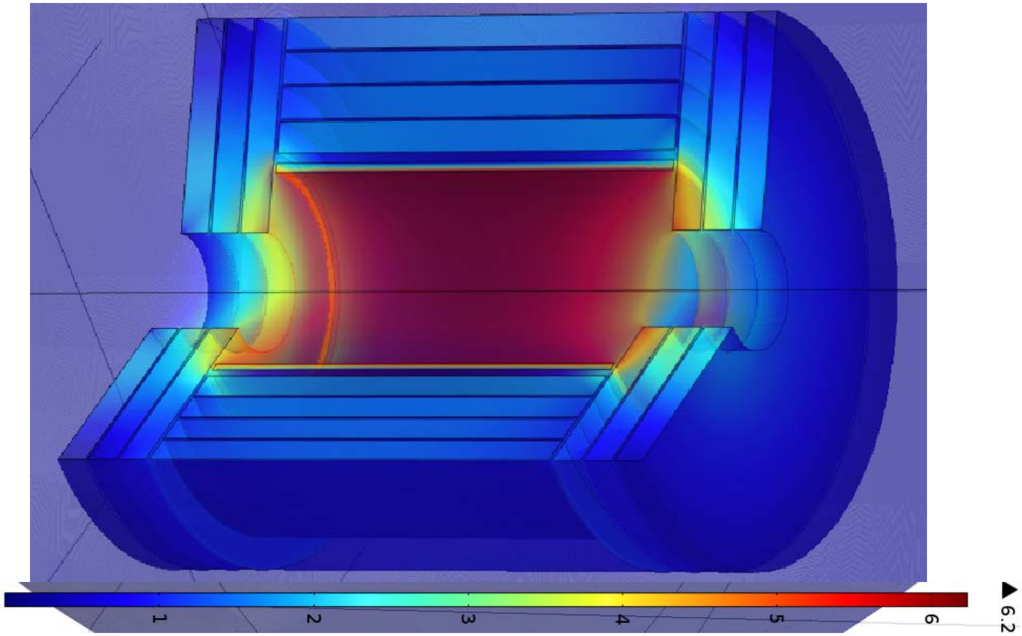
+ massive Iron yoke for flux return (shielding) and muon tagging.

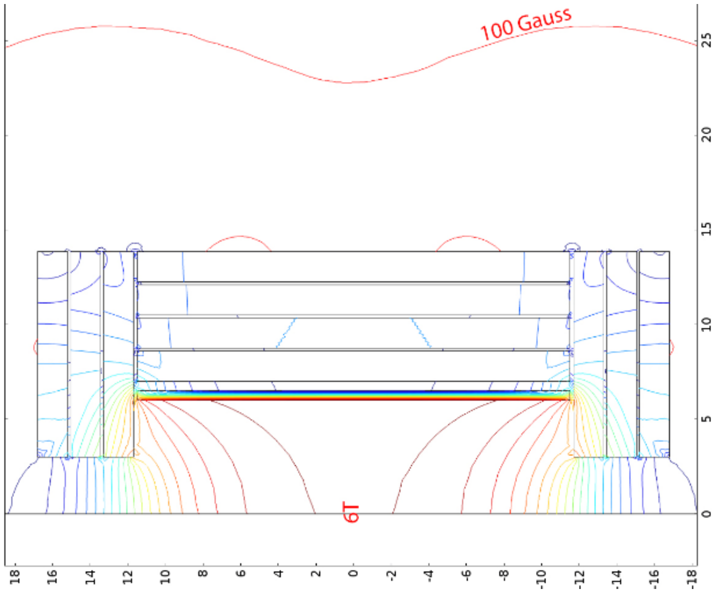
Dipoles: 10 Tm with return yoke placed at 18 m.

Practically no coupling between dipoles and solenoid.

They can be designed independently at first.

Option 1: Solenoid-Yoke + Dipoles

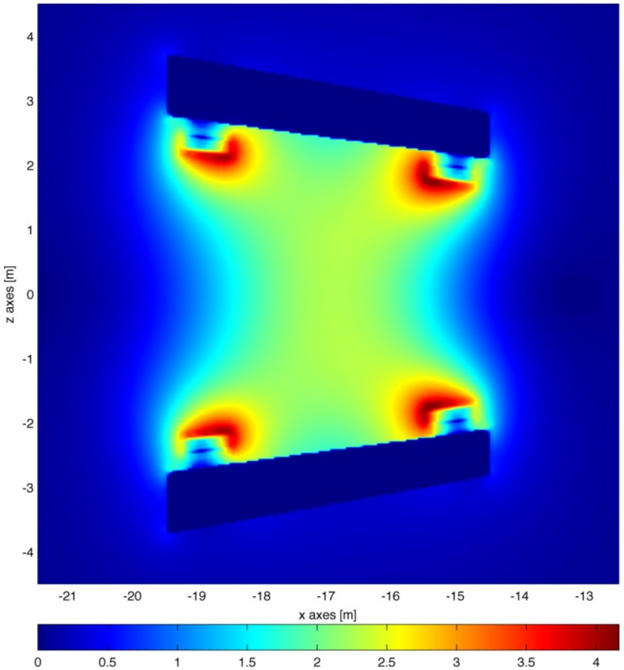


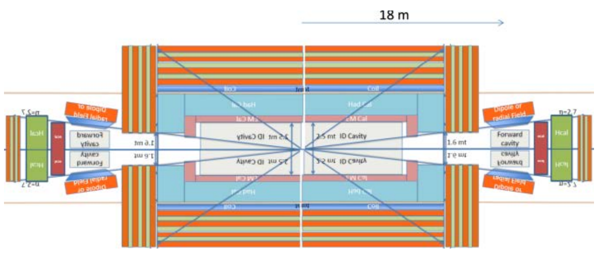


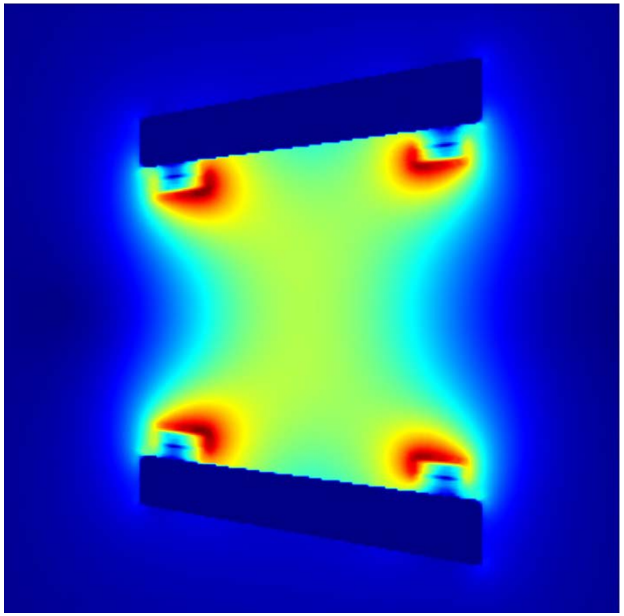
6 T in a 12 m bore, 23 m long, 28 m outer diameter.

- Stored energy 54 GJ, 6.3 T peak field.
- Yoke: 6.3 m thick iron needed to have 10 mT line at 22 m , 15 m^3,
  mass ≈120,000 ton (>200 M€ raw material).
- Note this huge mass! Realize consequences for cavern floor, installation, opening -closing system ---> bulky, not an elegant design.

Option 1: Solenoid-Yoke + Dipoles

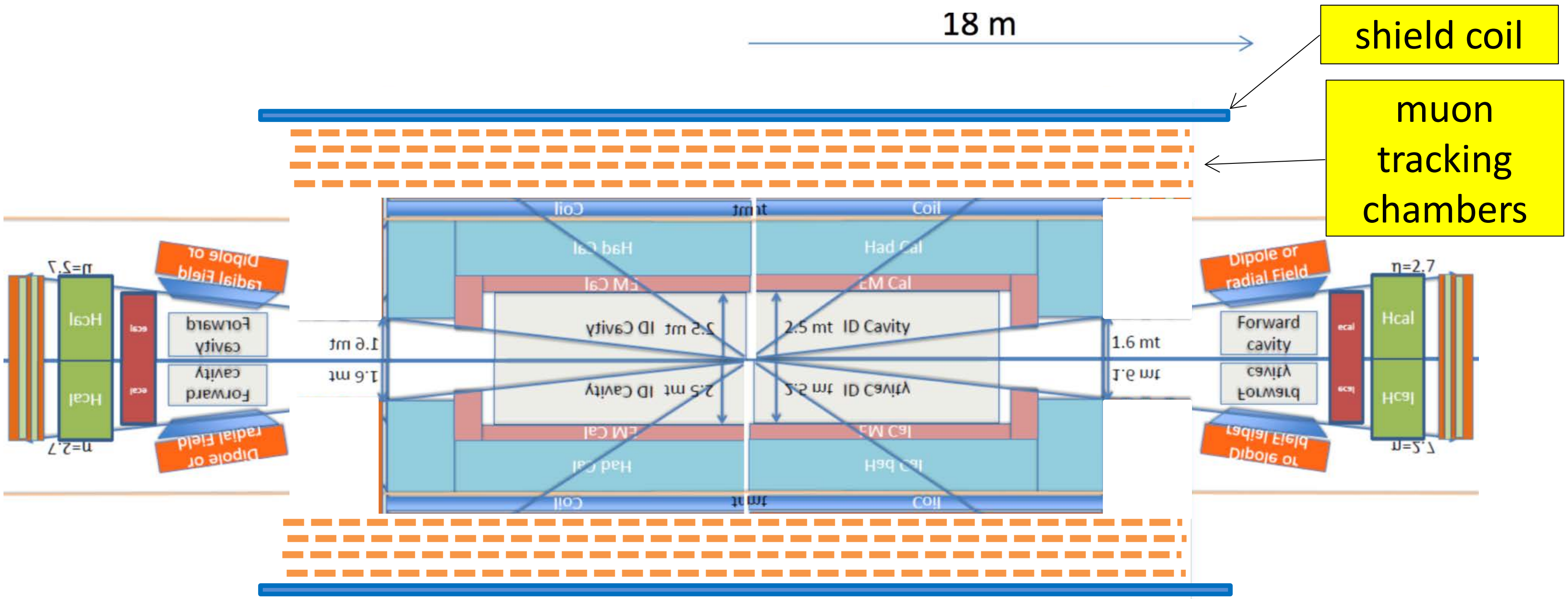






- 2 dipoles generating 10Tm in forward directions.
- Inclined racetrack coils in upper and bottom deck, square section.
- 2.2 T in the bore, 5.6 T in the windings (to be minimized further).
- 0.2 GJ per coil.
- Iron yoke to guide the field and shield the coils.

Option 2: Twin Solenoid + Dipoles

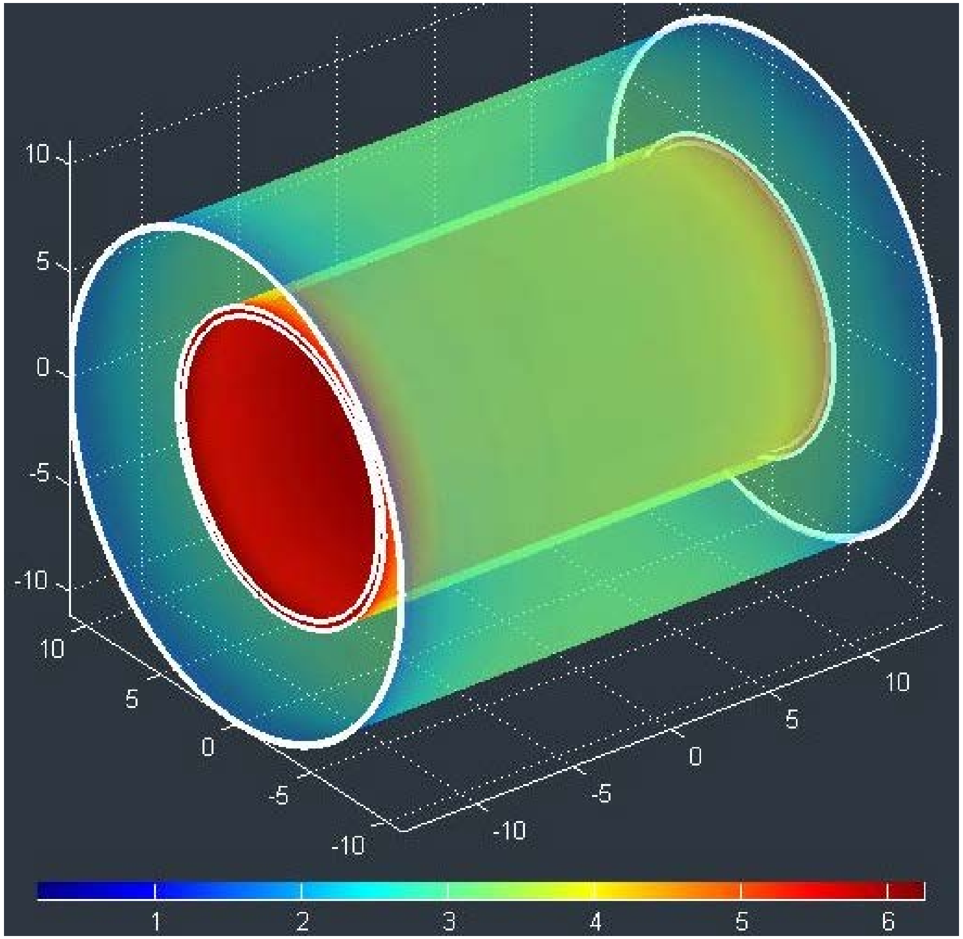


Twin Solenoid: the original 6 T, 12 m x 23 m solenoid + now with a shielding coil {concept proposed for the 4th detector @ILC, also an option for the LHeC in the case of large solenoid; and this technique is in all modern MRI magnets!}.

Gain?

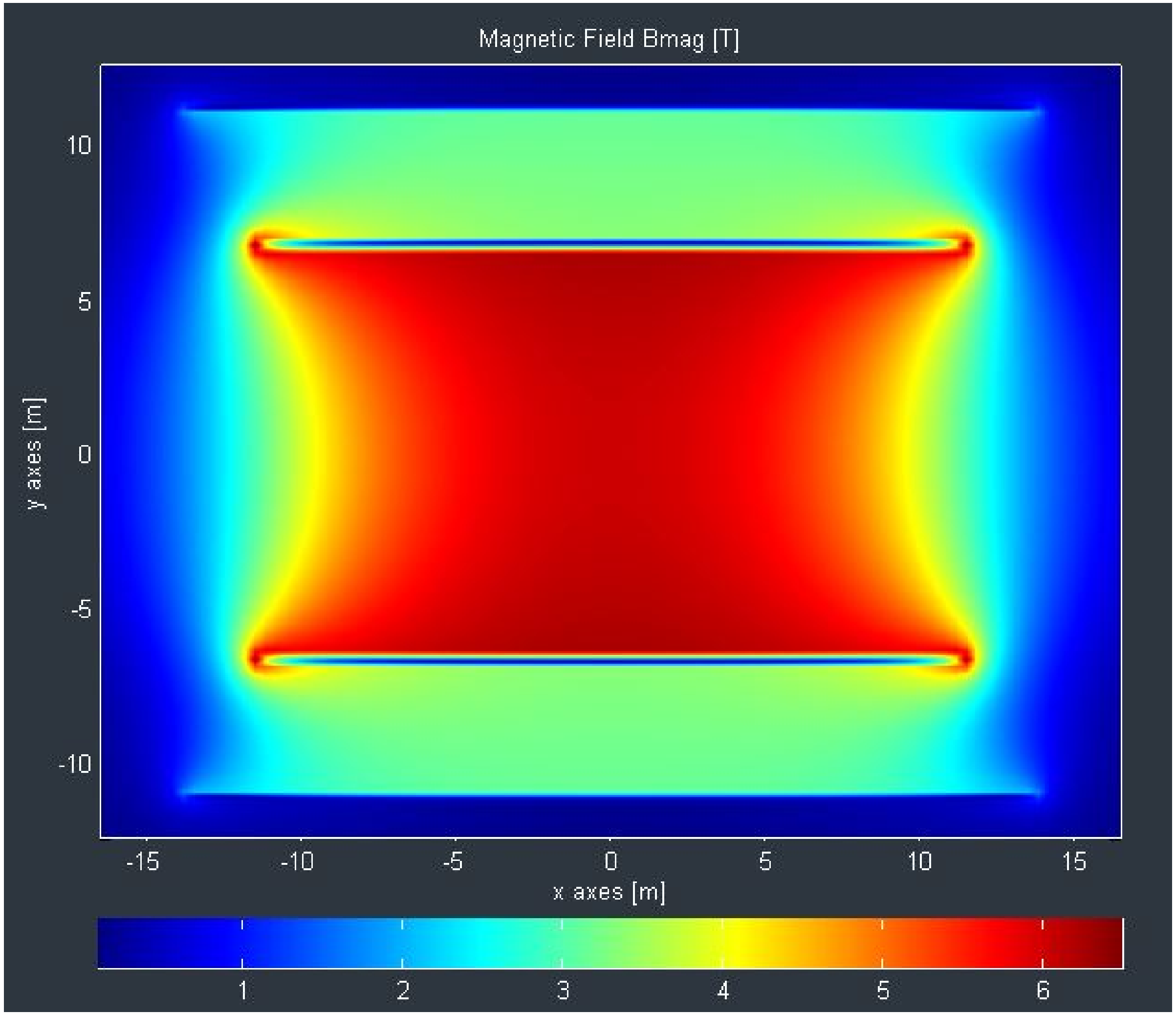
+ **Muon tracking space:** nice new space with 3 T for muon tracking in 4 layers.
+ **Very light:** 2 coils + structures, ≈ 5 kt, only ≈4% of the option with iron yoke!
+ **Smaller:** outer diameter is less than with iron .

Option 2: Twin Solenoid + Dipoles



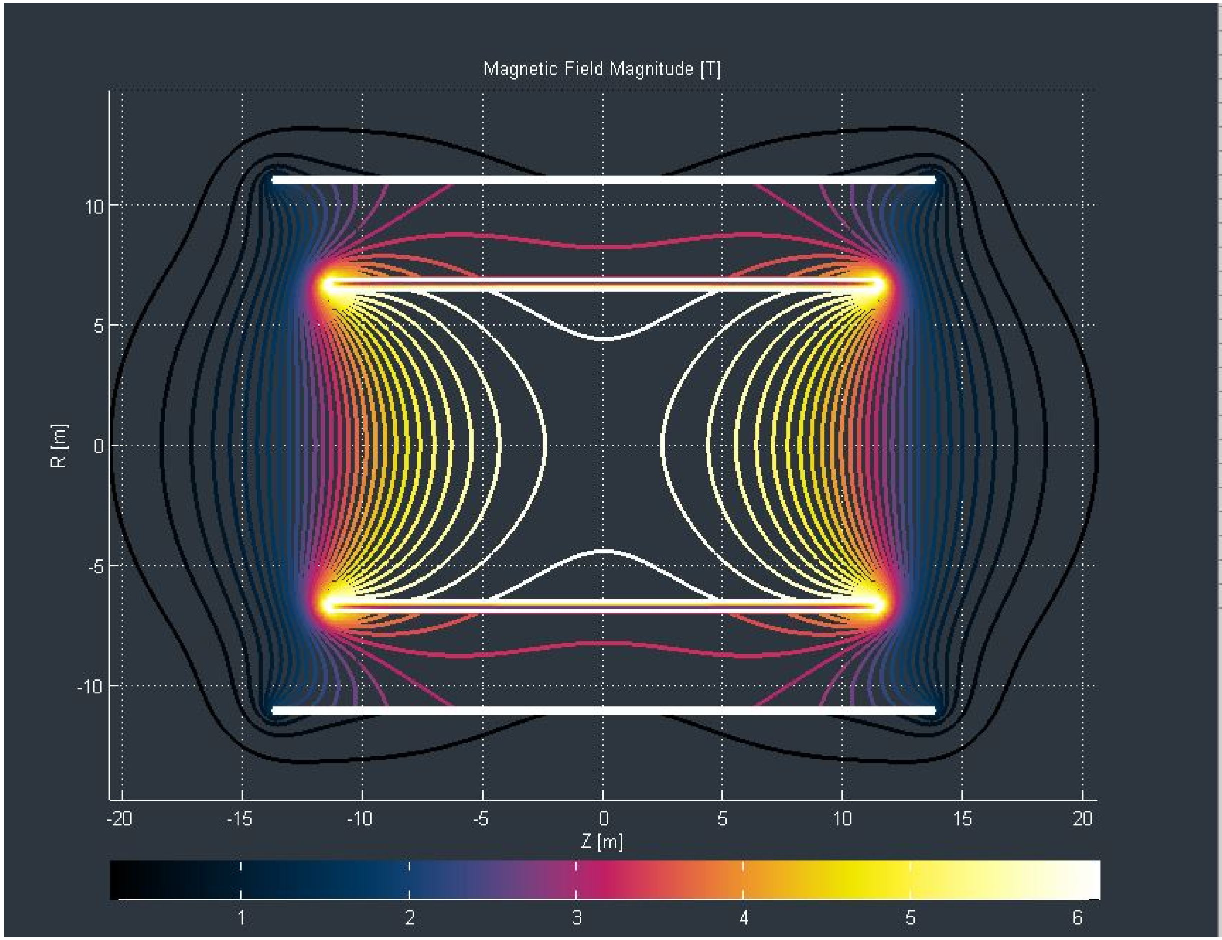
- Main solenoid: 6 T in 12 m bore, 12 m long, 6.3 T peak field, 20 A/mm^2
- Shielding solenoid: 3 T in 3.5 m gap, 22 m bore, 28 m long, 20 A/mm^2
- Stored energy 65 GJ.

Option 2: Twin Solenoid + Dipoles



Mass: ≈2 kt inner coil, ≈1.8 kt outer coil, in total with supports 4-5 kt.

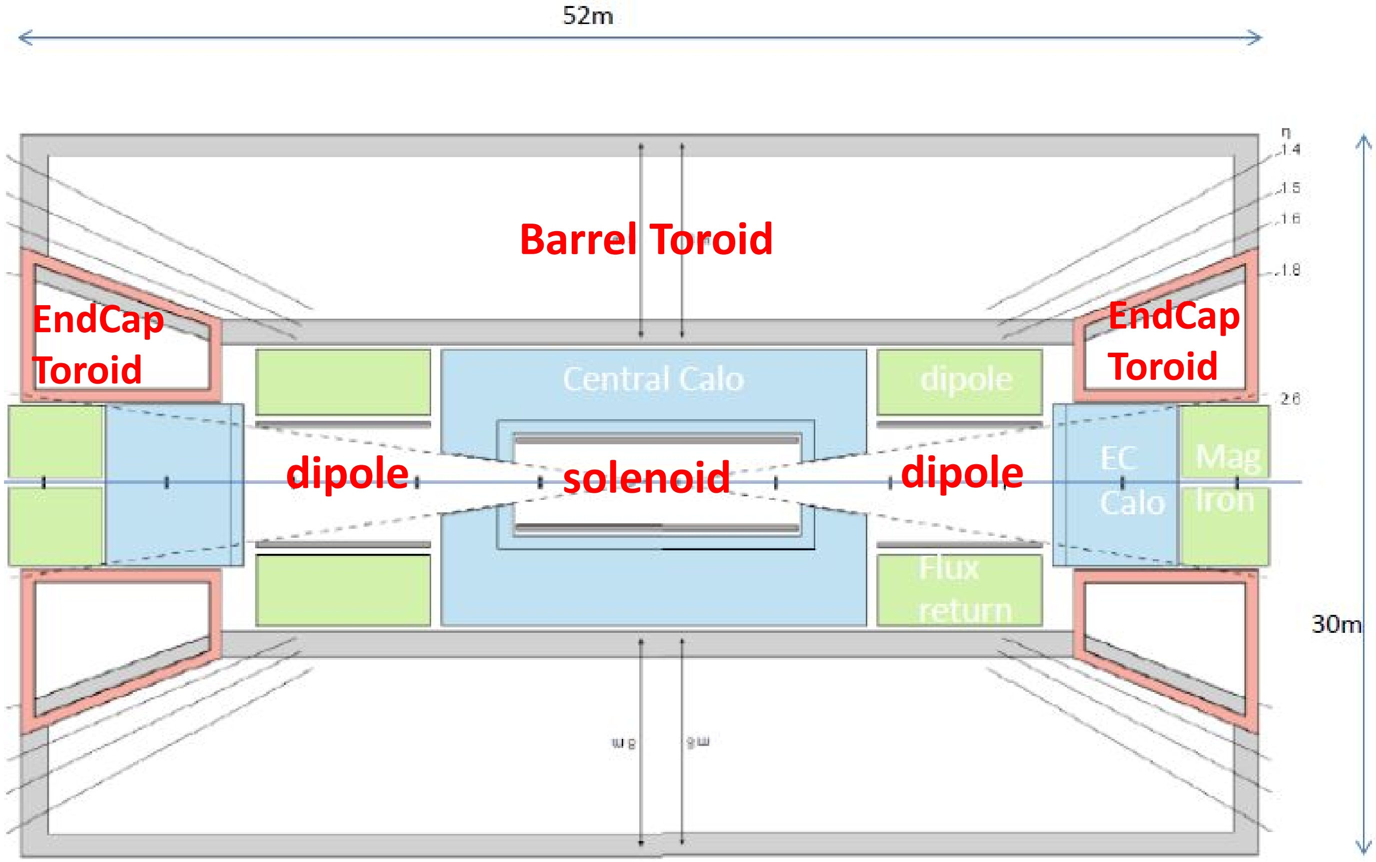
Option 2: Twin Solenoid + Dipoles



1	Peak Field [T]:	
2	Main	6.5253
3	Shield	3.1309
4		
5	kA-turns:	
6	Main	1.7561e+05
7	Shield	-6.4449e+04
8	total	1.1116e+05
9		
10	kA-meters:	
11	Main	7.3927e+06
12	Shield	4.4792e+06
13	total	1.1872e+07
14		
15	Inductance Matrix:	
16	Main X Main	5.9647e-06
17	Main X Shield	-4.6859e-06
18	Shield X Main	-4.6859e-06
19	Shield X Shield	1.2797e-05
20	total	9.3899e-06
21		
22	Stored Energy [J]:	6.5514e+10
23		
24	0.5 mT line [m]:	47.8456
25	5.0 mT line [m]:	34.7594

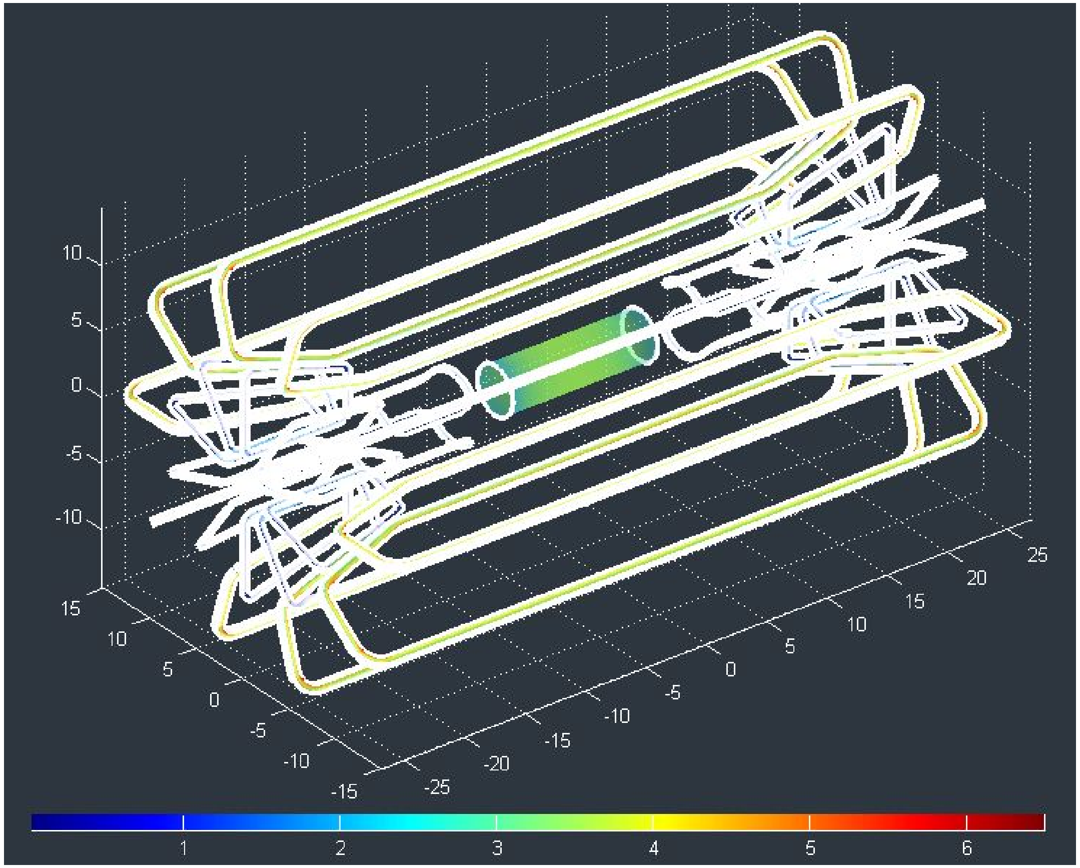
- Nice gap for muon tracking: 3.5m gap with 3 T (local ≈10 Tm or ≈35 Tm^2).
- Shielding: 5 mT line at 34 m from center.
- Field in gap can be tweaked by splitting or adding coils, many options.

Option 3: Toroids + Solenoid + Dipoles (ATLAS +)



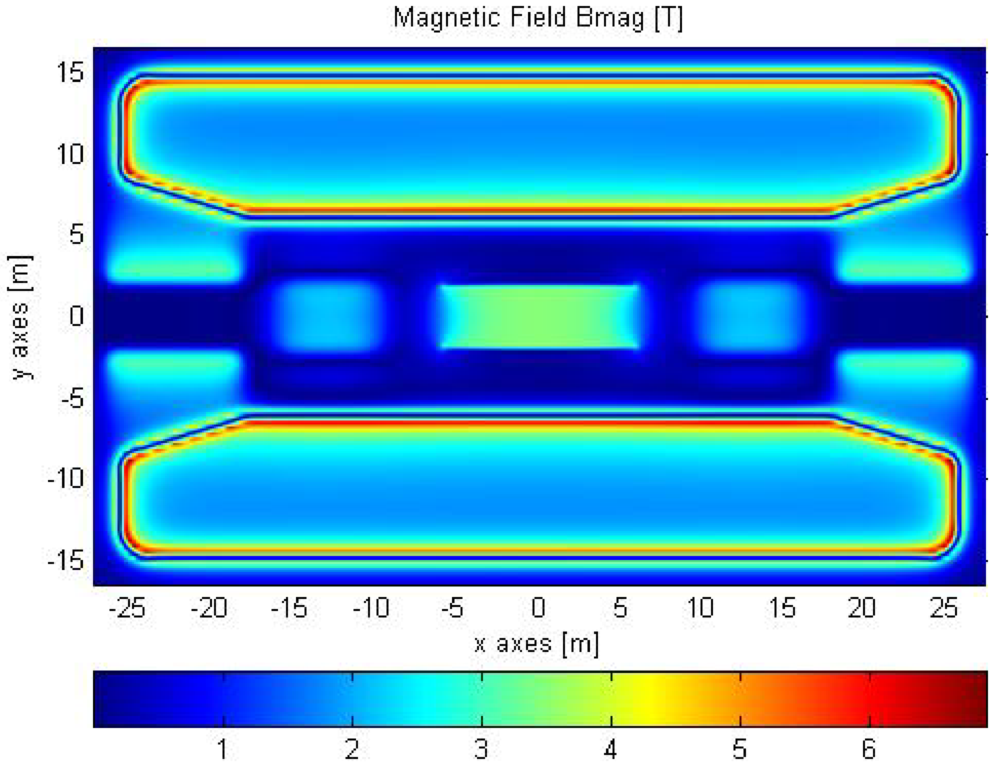
- Air core Barrel Toroid with 7 x muon bending power BL^2.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m^3).

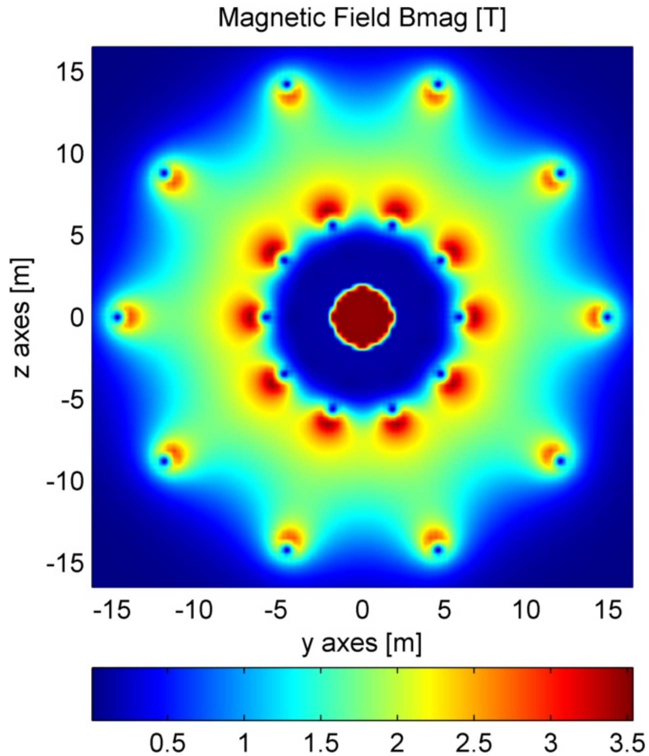
Option 3: Toroids + Solenoid + Dipoles



- 10 coils in Barrel Toroid + 2 x 10 coils in End Cap Toroids.
- Peak field on the conductor in ≈6.5 T for 16 Tm and ≈8 T for 20 Tm, to be minimized by locally reshaping the coil and/or dilute current density.
- Can still be done with NbTi technology (for cost reasons).

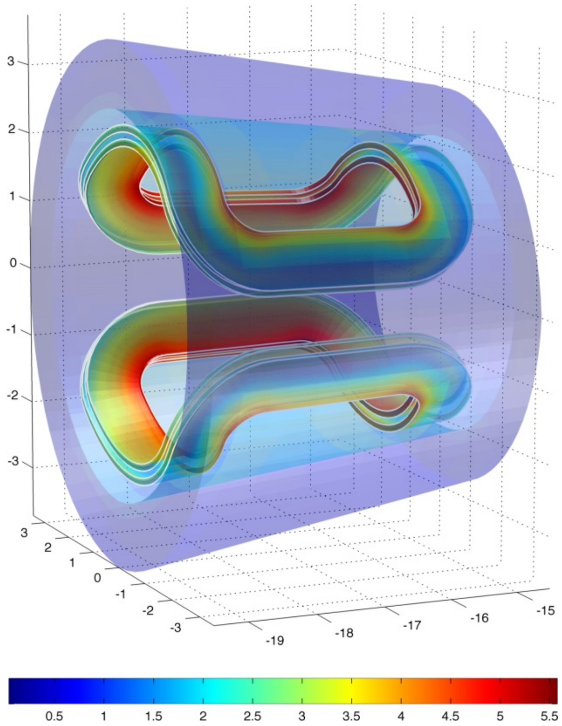
Option 3: Toroids + Solenoid + Dipoles

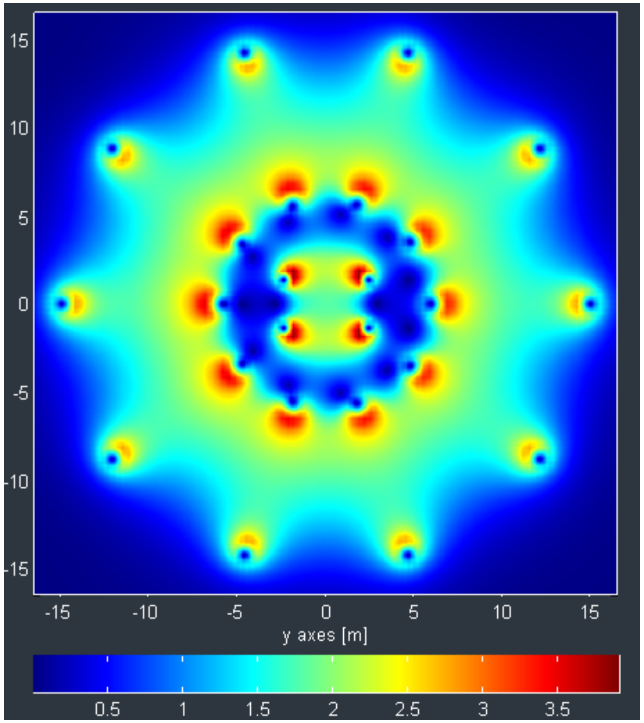




- 3.5 T in Solenoid, 2 T - 10 Tm in dipoles and ≈1.7 T in toroid.
- 55 GJ stored energy (for 16Tm; 130 Tm^2)!
- Stored energy sharing S(0.6)+2D(0.9)+ECT(2x2.1)+BT(47.5) = 55 GJ.

Option 3: Toroid + Solenoid + Dipoles





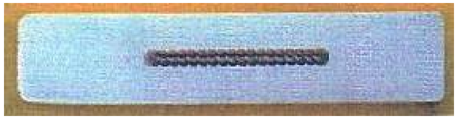
- 2 T, 10 Tm cylindrical dipole with iron yoke allowing a cylindrical calorimeter.
- Inclined set of saddle coils.
- Peak field 5.5 T.

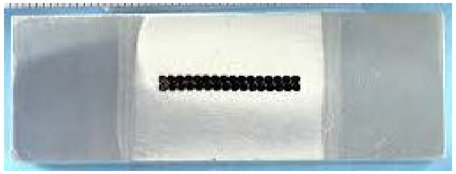
Superconductors - change of technology

- The peak magnetic fields of 7-8 T leads to high winding stress and a low temperature margin,

  just in reach of NbTi provided correctly cooled.

- Classical Ni doped Al-stabilized NbTi Rutherford cable may be used for the "small" 3.5 T / 4 m bore solenoid requiring transparency.



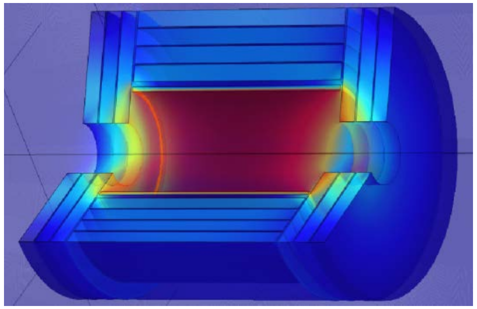


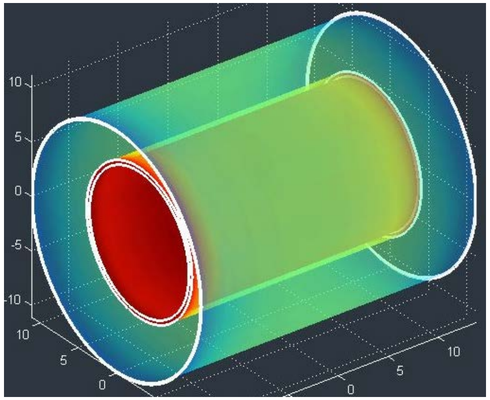
- All other coils require higher-strength materials and direct cooling of the superconductor, asking for use of cable-in-conduit type of conductor.

Sizes - Stored Energy and Protection

Sizes: 12m bore, 30m diameter, 30-50m length…….

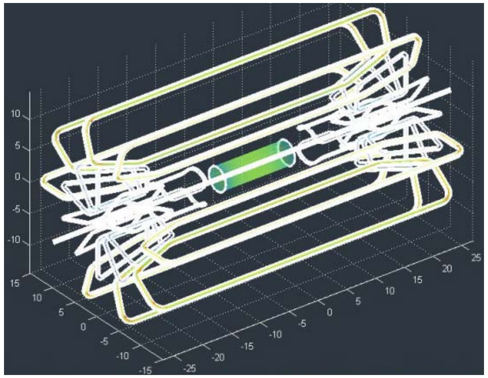
- It looks gigantic but similar sized magnets are being made these days (ITER PF coils, 26m).
- Production is required on site, in smaller modules, but very well possible.





Stored Energy: 50 - 100 GJ……

- Looks scaring but it isn't.
- In practice always solvable!
- A clever combination of energy extraction and dumping in cold mass, controlled by a redundant, fail-safe quench protection system.



I don't see a principle technical problem that would stop us from constructing such systems………

Conclusion

Three options for detector magnets probing 100 TeV p-p collisions

- Option 1: Single 6 T Solenoid Design + 2 Dipoles + **120 kt yoke.**
- Option 2: Twin Solenoid design, 6T solenoid + 3T shielding coil,
  good for muon tracking +2 external 2T dipoles;
  65 GJ, mass 4-5 kt.
- Option 3: 3.5T solenoid + Toroids + 2 internal 2T dipoles,
  54 GJ, mass 4-5 kt.

Option 1 looks like a no-go design.

Options 2 and 3 will be further analyzed in more details to discuss and specify advantages of both designs for physics performance as well as feasibility of construction and margins for operation.