Optimization of ILD Yoke B-Field Calculations

MDI Workshop, Tsukuba

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Europe -Japan Accelerator Development Exchange Programme

HELMHOLTZ ASSOCIATION

DESY

Outline

- Requirements
- Present design and challenges
- Review of B-field calculations
- Alternative designs
- Conclusions

Work in progress. Should start discussion

Part time involvement:

- K.Büsser, M.Lemke, A.Petrov, K.Sinram, R.Stromhagen, U.S.

Yoke Functions and Challenges

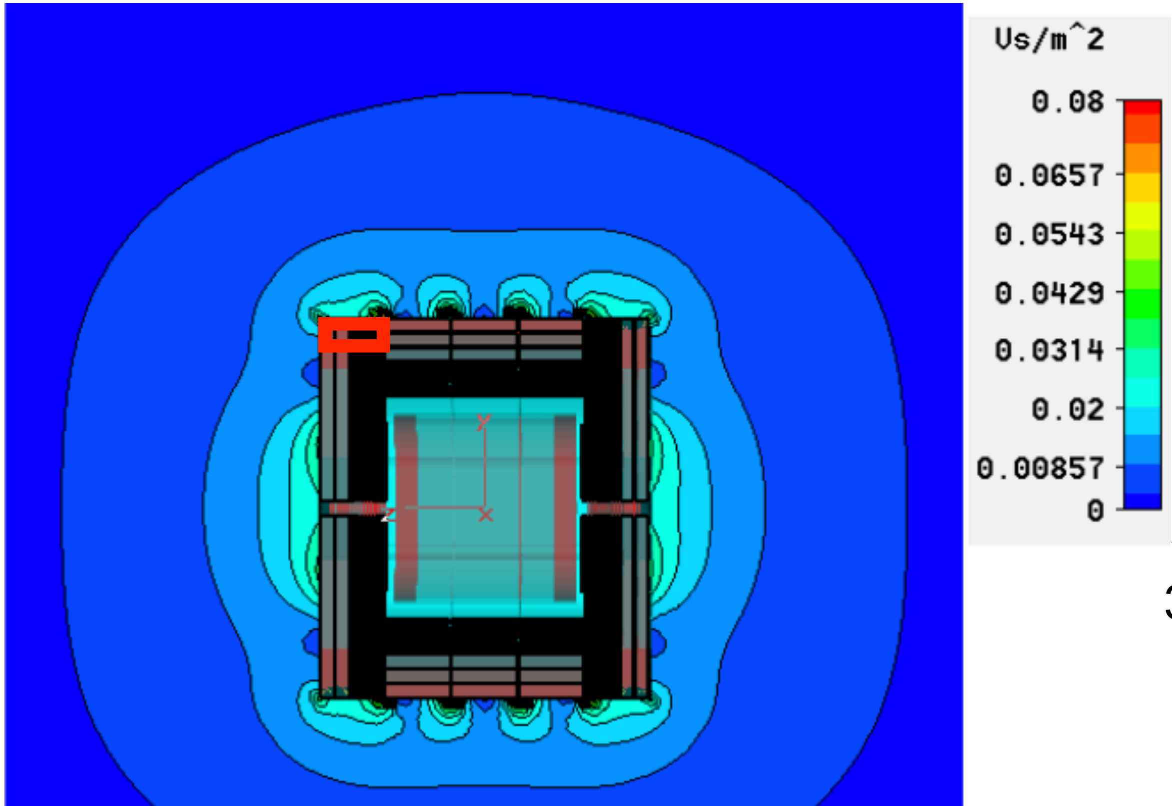
- Muon identification and hadron rejection
- Tail-catcher/backing calorimeter
- Flux return
  - Stray field (determines thickness and cost of yoke)
  - Large magnetic forces
  - Field homogeneity in TPC
- Main mechanical structure of detector
- Radiation shielding (should be self-shielding)

- Transportation issues in Japan
- Alternative design of yoke modules
- ILD cost/performance optimization in progress
  - Size might be reduced

Stray Field Calculations

4 T

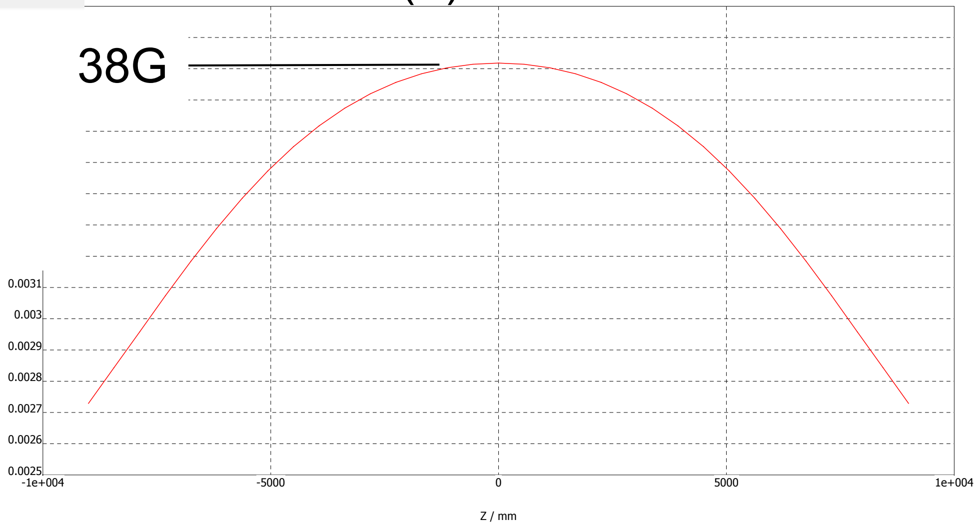
CST Studio 3D, A. Petrov, 2008



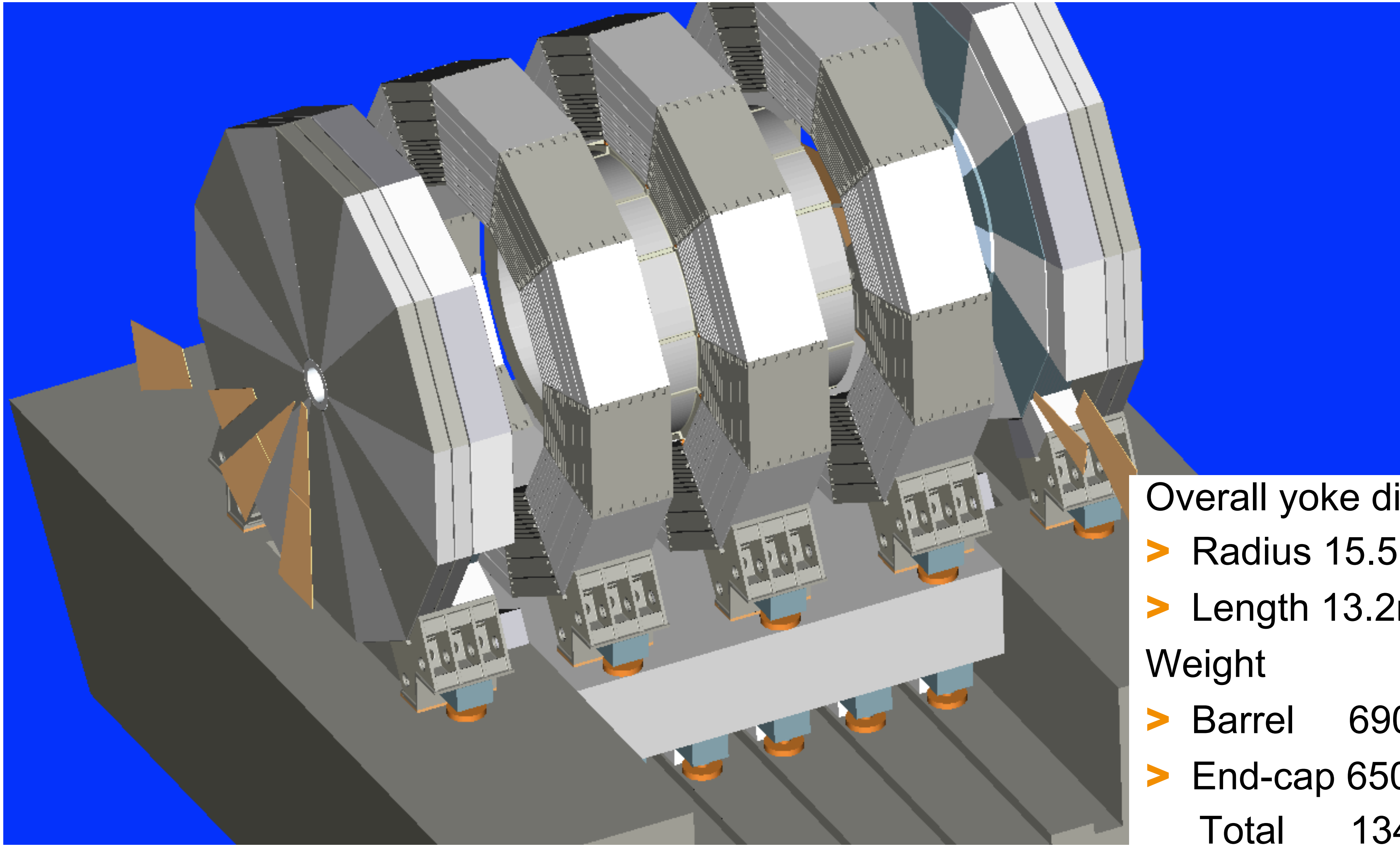
iron thickness 2.68/2.12m
total thickness 3.16/2.56m

r_{out} = 7.655m, z = 6.605m

B (T) vs. z at r = 15m



Present Design



Overall yoke dimensions

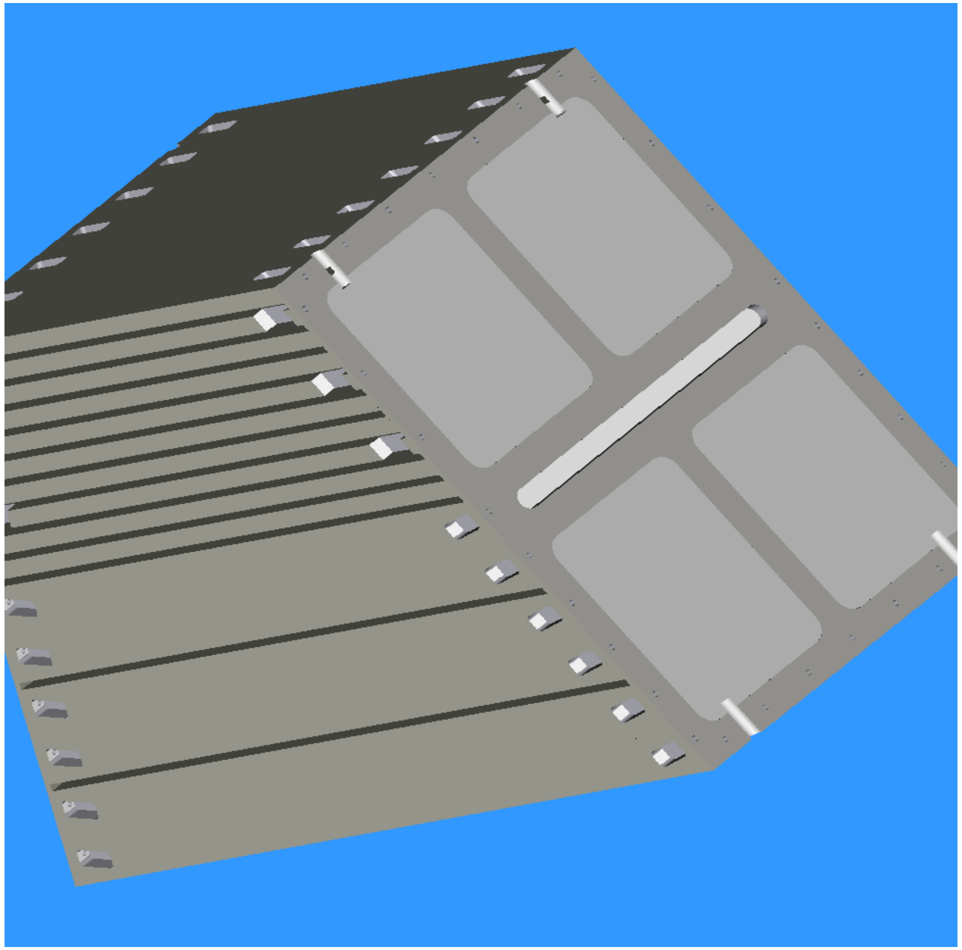
- Radius 15.5m
- Length 13.2m

Weight

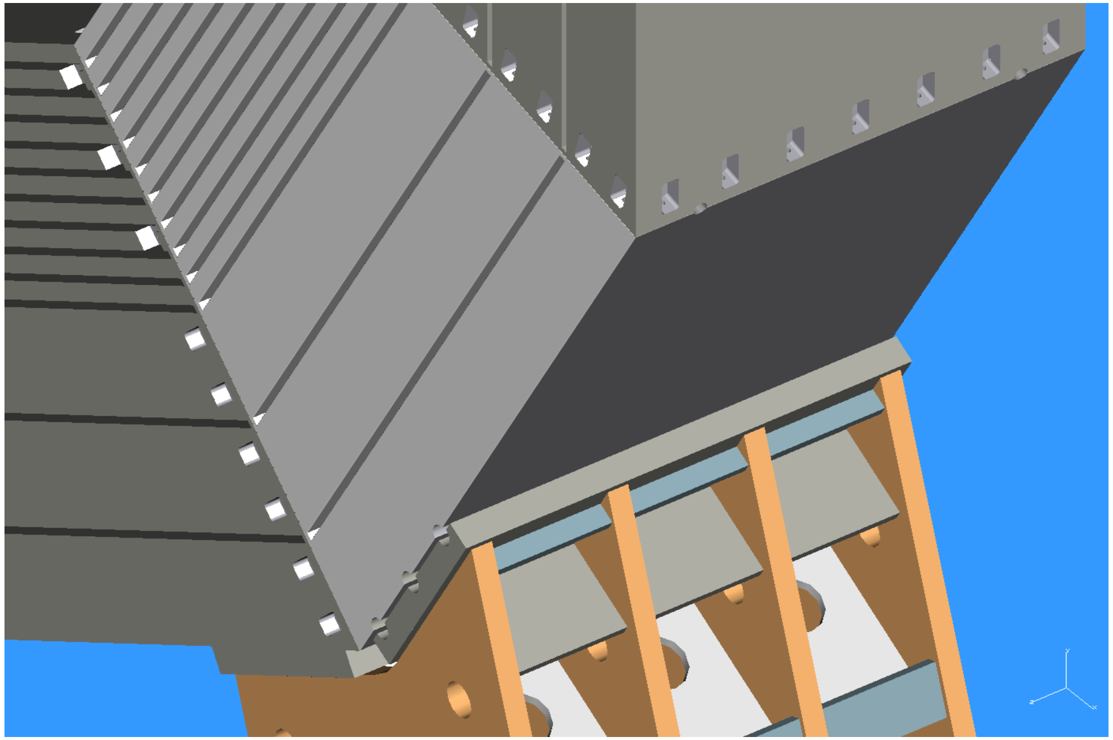
- Barrel 6900t
- End-cap 6500t

Total 13400t

Barrel Design



Module weight ~210 t



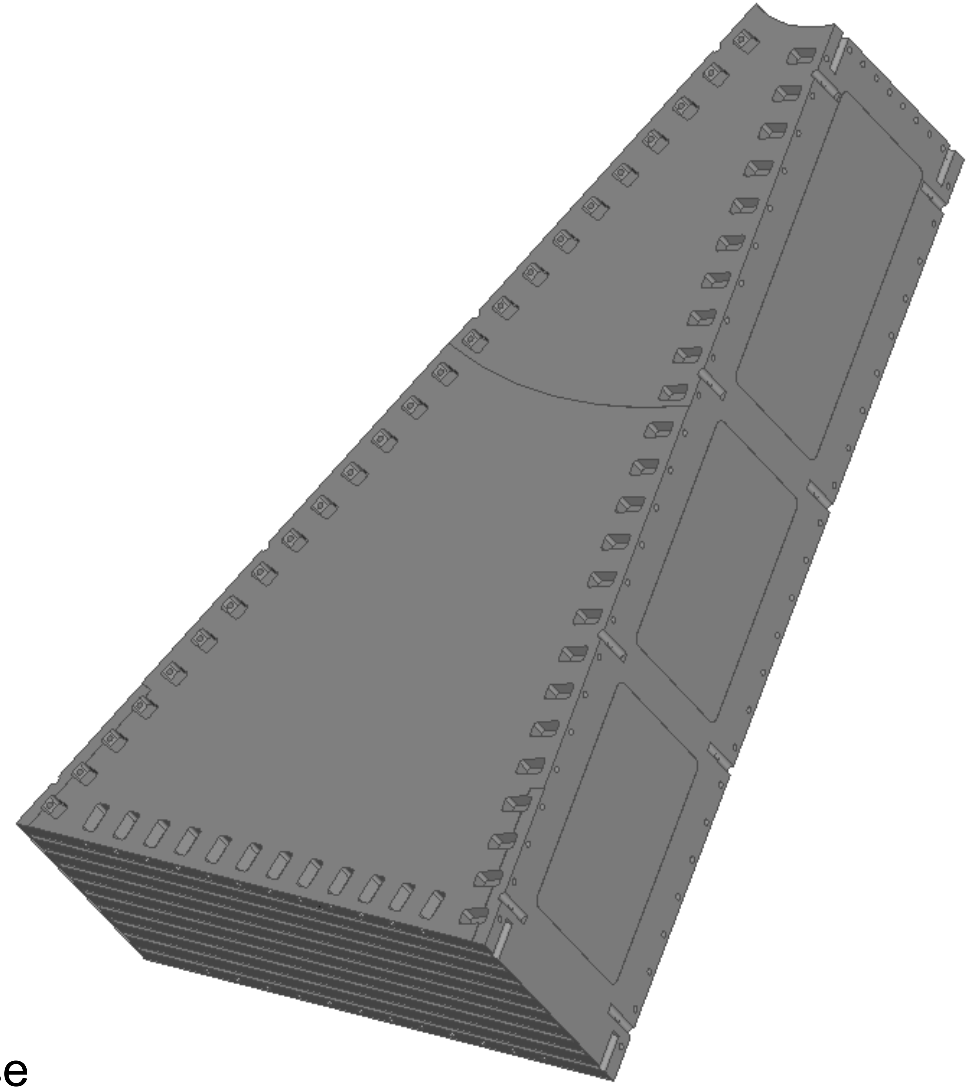
End-cap Design

Inner end-cap

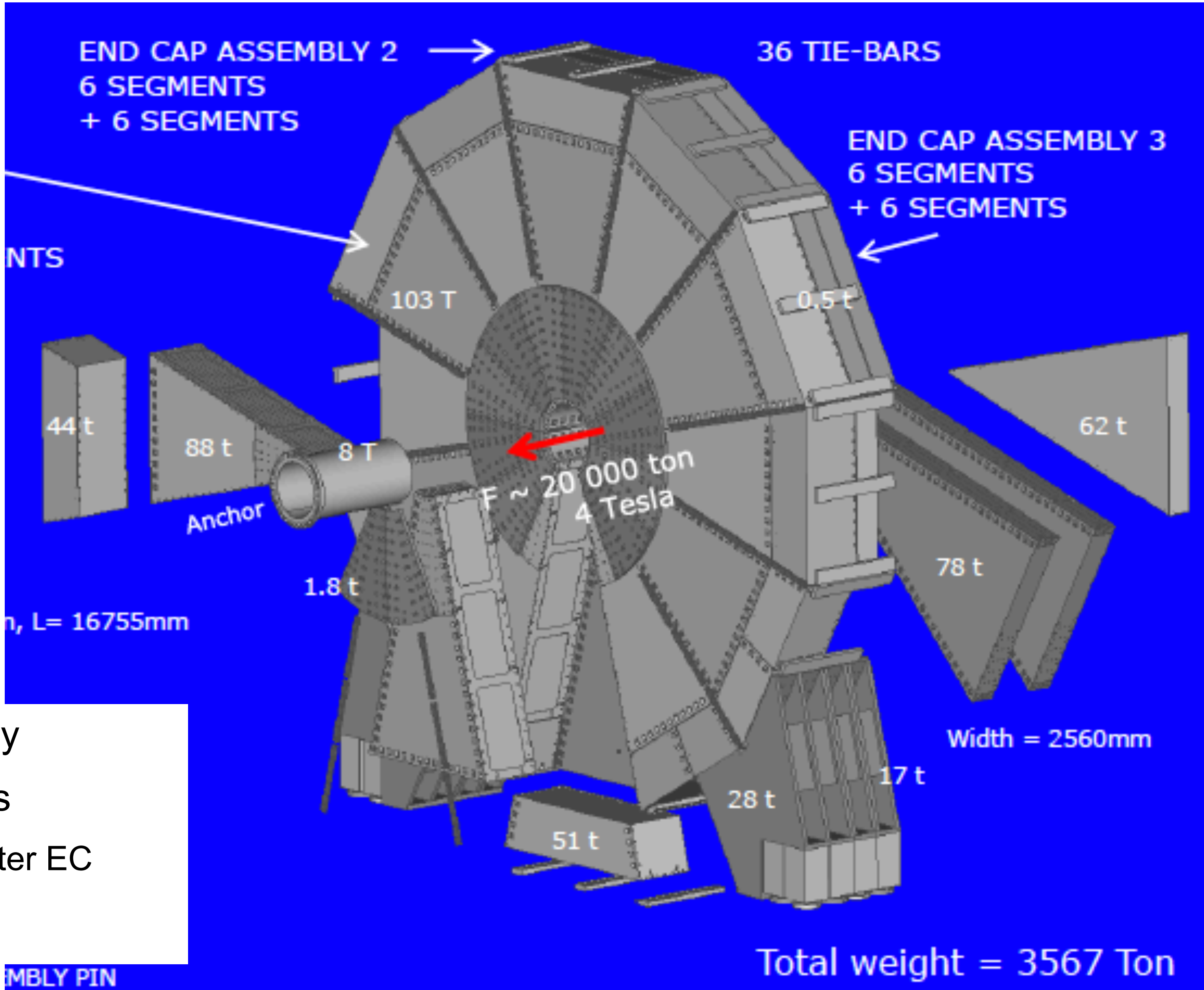
- Consisting of 12 wedge-shaped modules
- 10 100mm thick plates welded together
  - 25mm x 40mm spacers
- Modules bolted together using M36 screws
- Field shaping plate 100mm thick part of (or attached to) first plate
  - Welded, 200mm total thickness or
  - bolted to 1st plate (module overlap)

Outer end-caps

- Two disks, 560mm thick plates
- Wedge-shaped modules bolted together
- In addition, iron pieces at outer radius to close gaps of inner end-cap plates (muon chambers)



End-cap Design



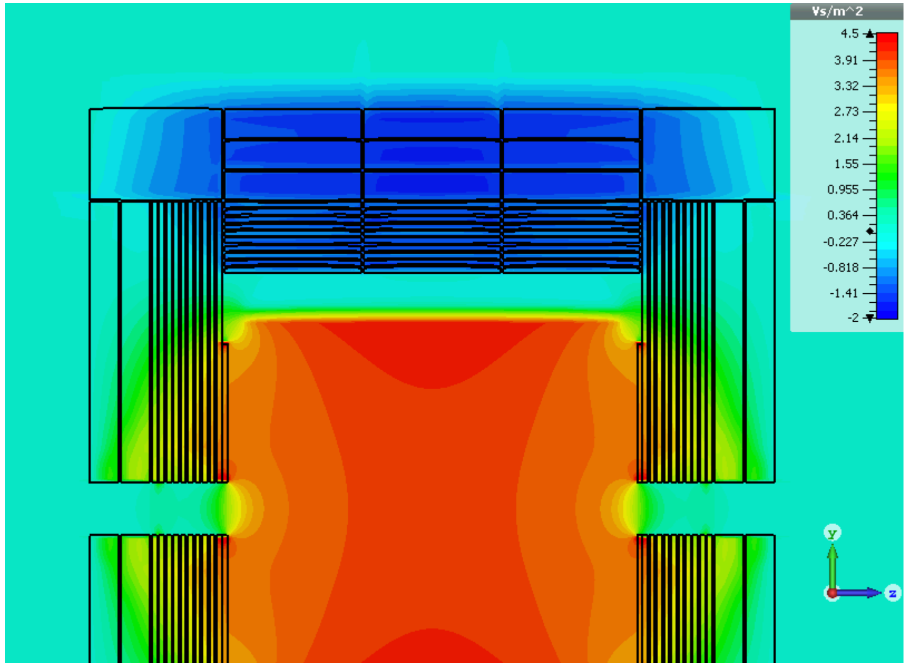
Quite detailed study

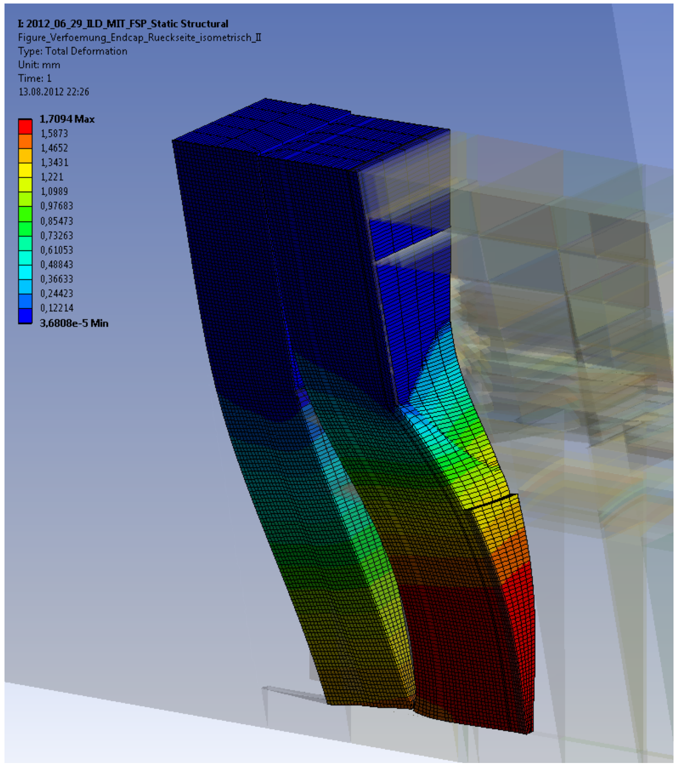
Still two EC options

- Split inner and outer EC
- One EC

End-cap Design – Magnetic Forces

- EC Design with radial supports chosen due to large magnetic forces
  - Optimize deformation, stress and transfer of forces
- In total $F_z \cong 2$ MN (20000 tons) acting on each EC
  - CST Studio and ANSYS FEM calculations in agreement





very small deformation 2mm

Yoke Transportation

Present design

> Barrel: 36 modules ~200t each (without heavy load truck)

> End-caps:

  - Inner EC: 24 segments ~90t each
  - Outer EC 48 segments ~60t each plus outer radius pieces

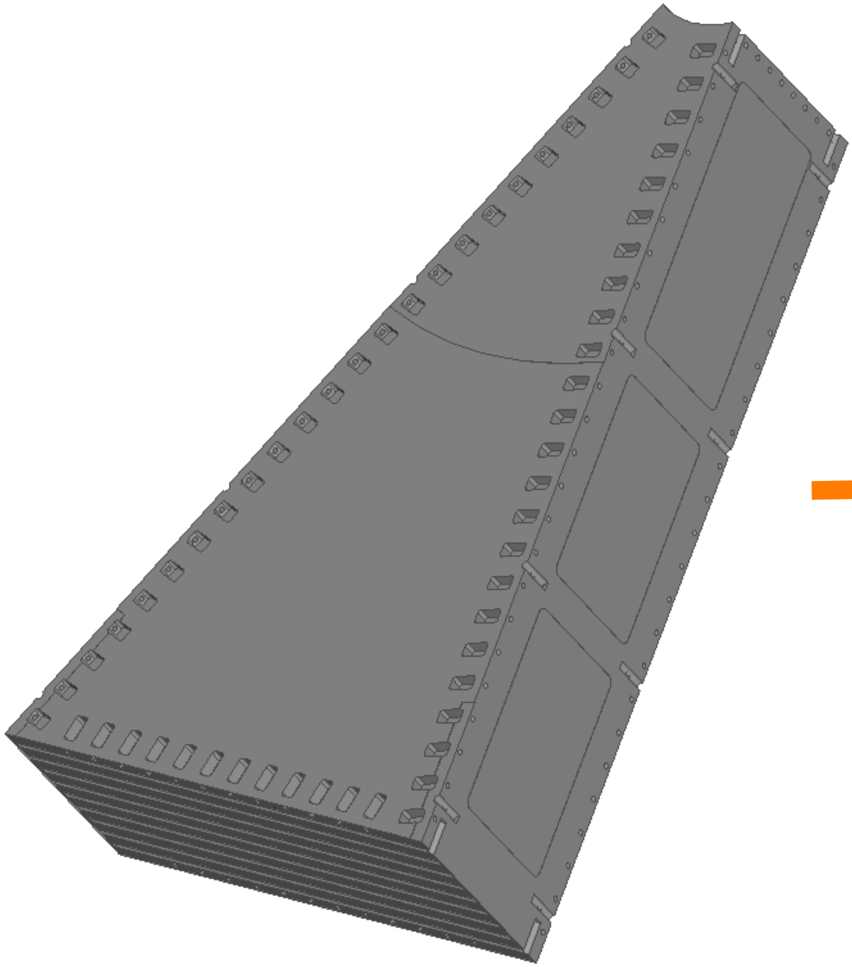
Severe road transportation limits in Japan, although only ~25km distance from harbor

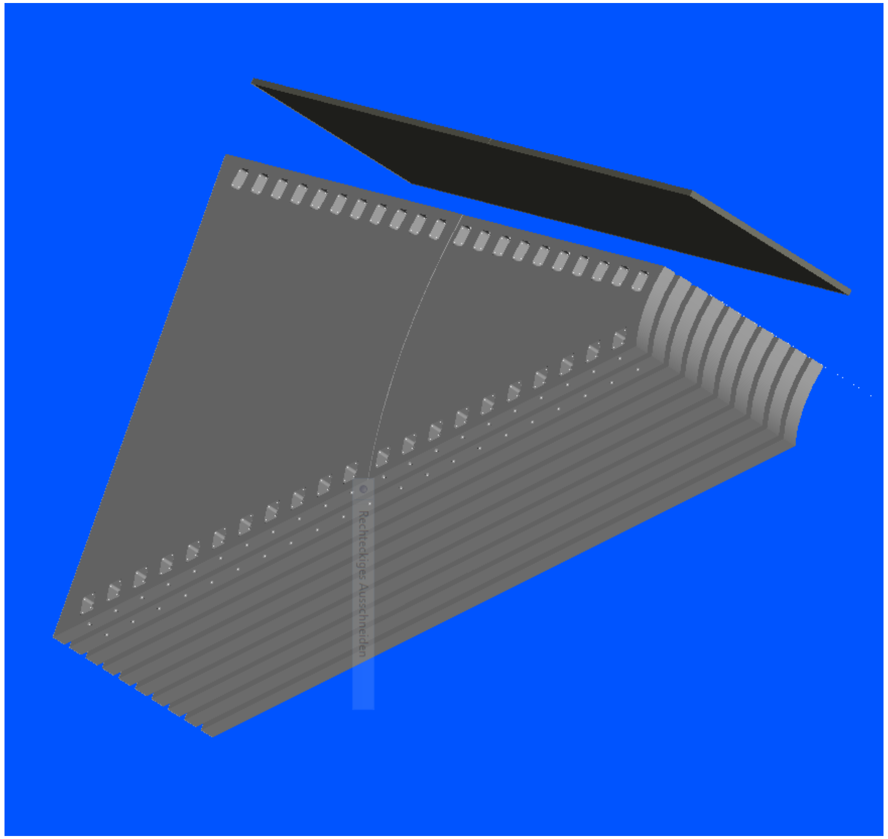
> Maximum load 44t including truck (24t net weight)

Alternative design with bolted plates

Alternative Module Design

Going from welded structure to plates bolted to side plates

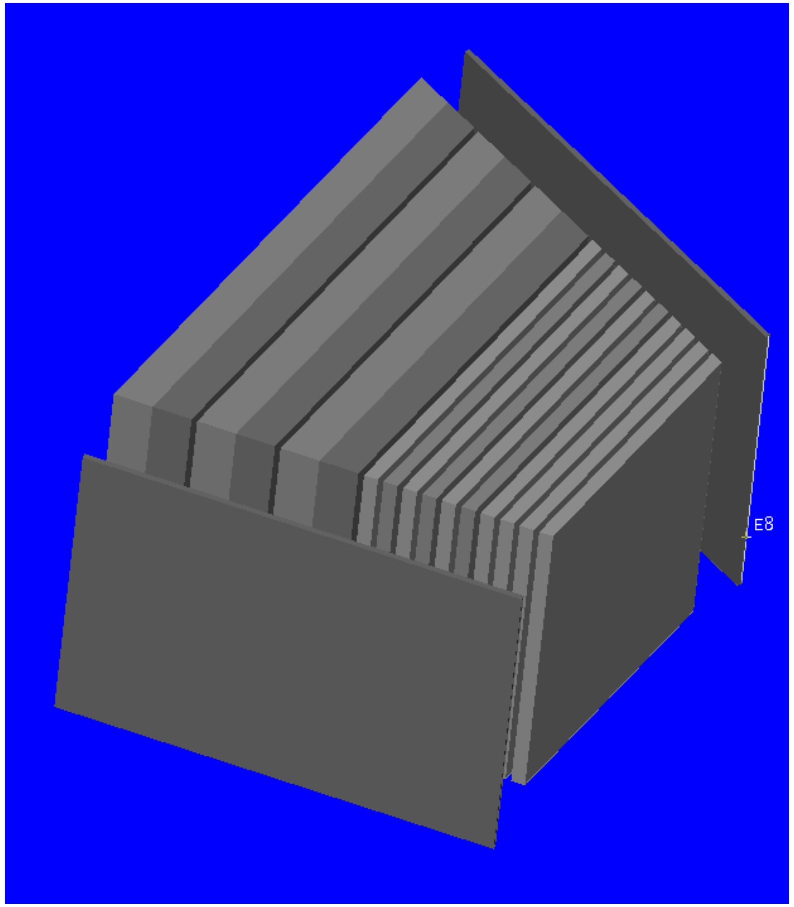


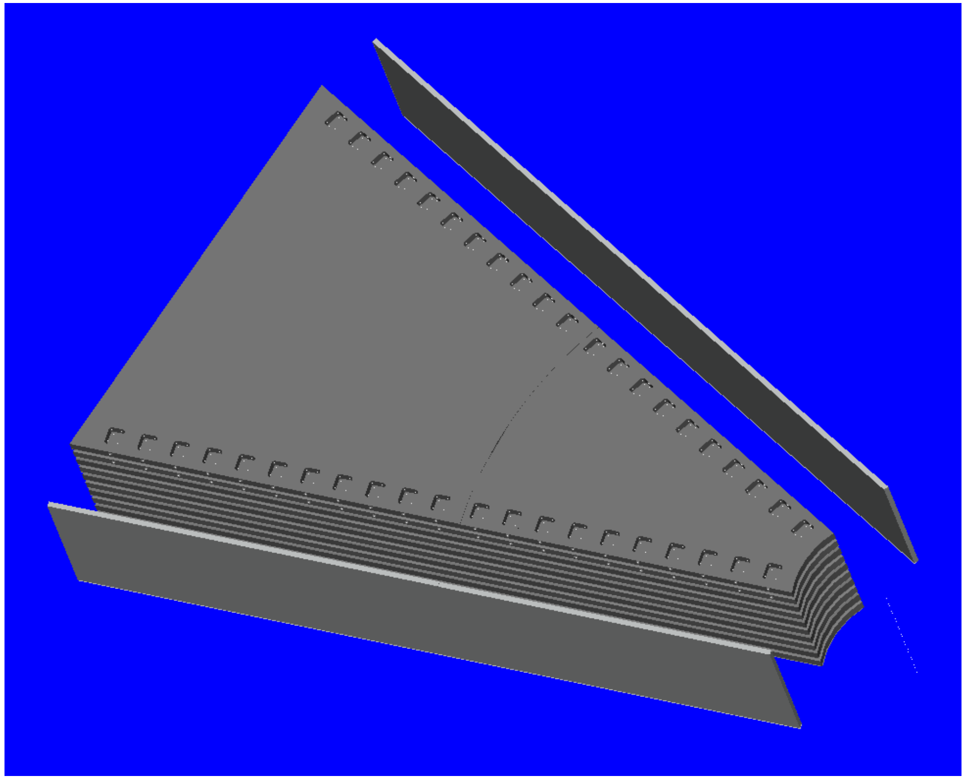


About 60 M30 screws each plate, each side

plus sheer bolts

Alternative Module Design



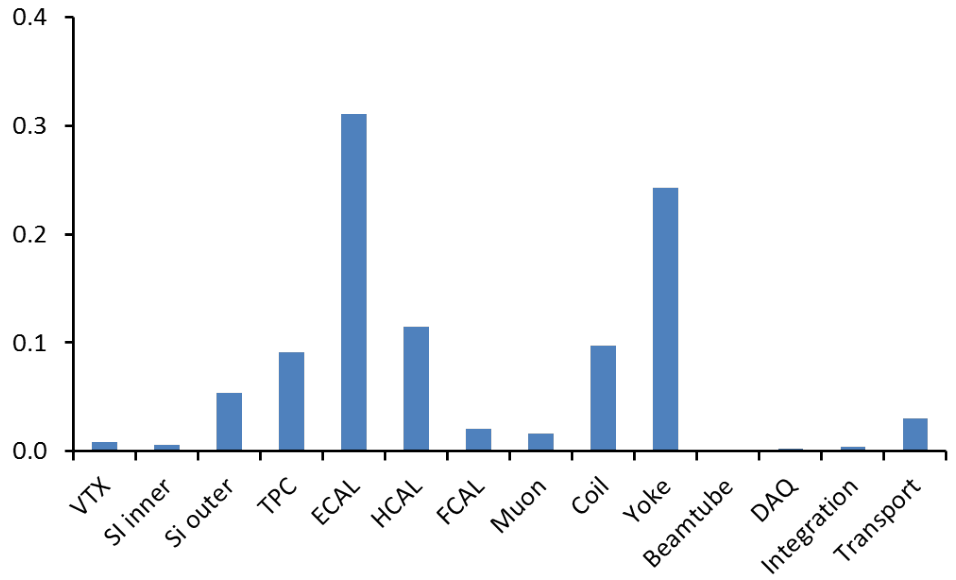


Module assembly more time consuming and probable more expensive

Yoke Issues and Cost

- Road transport limits in Japan require redesign of modules/assembly
  - Conceptual redesign ready
  - Module production will take longer, higher cost likely
- Thickness and cost of yoke is determined by stray field requirements
- Look at cost vs. size and field
- Review stray field limits and field calculations
  - Need good understanding of FEM calculations
- Alternatives
  - Modified segmentation/geometry?
  - Double solenoid???
  - Inner yoke with compensation coil ??

Relative cost of ILD components



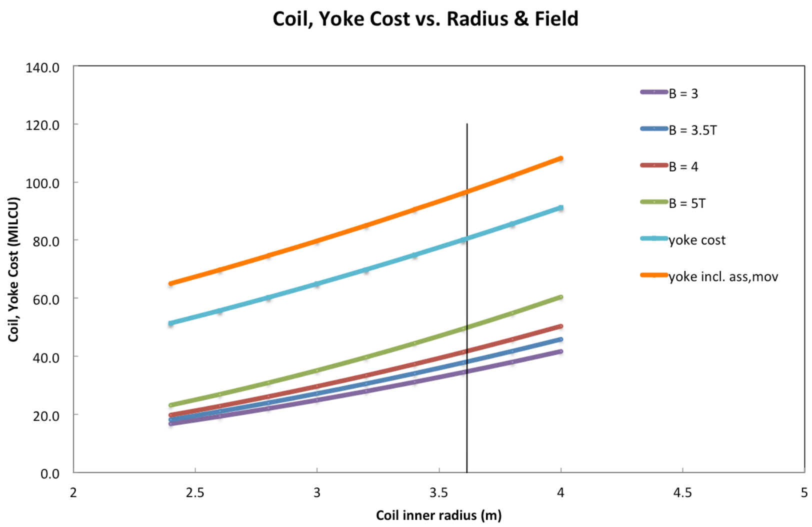
Magnet most expensive part of ILD

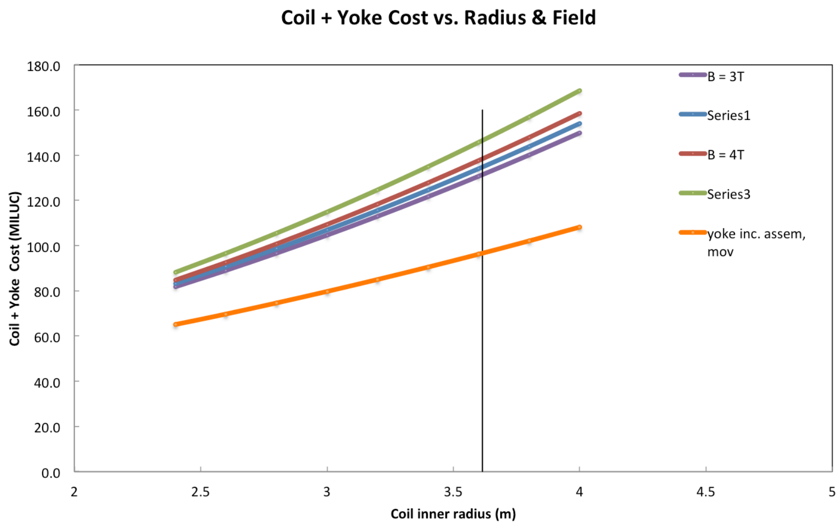
Yoke Cost vs. Size and Field

- Rough cost estimate similar to DBD (1 ILCU = 1$ = 0.97€ , 1 € = 1.5 CHF)
- Coil cost using parametrization of A.Herve

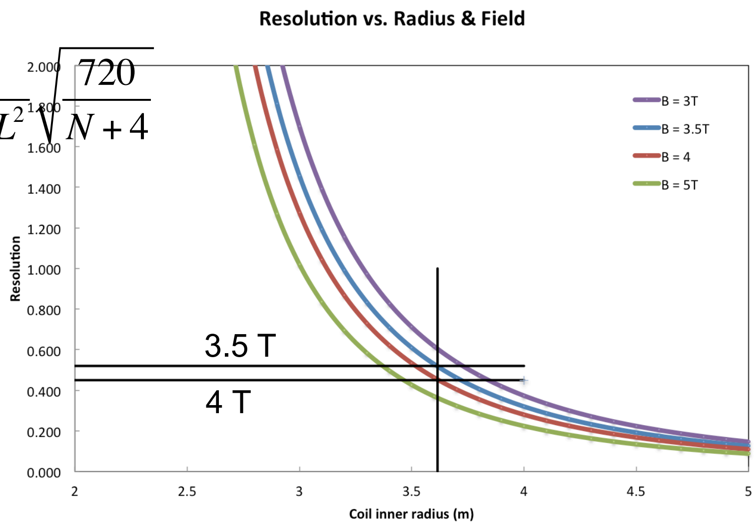
Cost of yoke for fixed iron thickness

Thickness increases with B field and radius





$$\frac{\sigma(p_T)}{p_T^2 \sigma_x} = \frac{1}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$



thick plates	Cost of steel (MILCU) ri 3.615	ri 3.165	Steel and Coil (MILCU) ri 3.615	ri 3.165
B3	81	68	123	104
B2	66	55	108	91

ILD Field Calculations since 2008

B (mT)
z=y=0, x = 15m

- O. Delferriere (CEA), OPERA 3D/TOSCA old model: coil design, stray field — 5.5
- A. Petrov (DESY), 2008-11, CST Studio 3D, simple model and CAD model: stray field and forces — 3 - 4
- B. Krause (DESY), 2008, OPERA 2D, simple model: stray field
- Y. Sugimoto, Y. Yamaoka (KEK), 2008: mainly GLD
- M. Lemke (DESY), 2012 ANSYS, CAD model: forces, stress and deformation — 15
- B. Curé (CERN), 2012 ANSYS, simple model — 5
- Efremov group, 2014, several codes, reduced yoke (600mm less in radius): stray field, hoping to reduce size of yoke — (10)
- K. Büsser (DESY), 2015 CST Studio 3D, CAD model: stray field — < 3
- Recently U.S., CST Studio, simple model: systematic studies, stray field, forces, alternatives — initially 3 – 4, finally 6 – 7

So far have assumed stray field of ≤4 mT at 15m from beamline

No systematic review so far

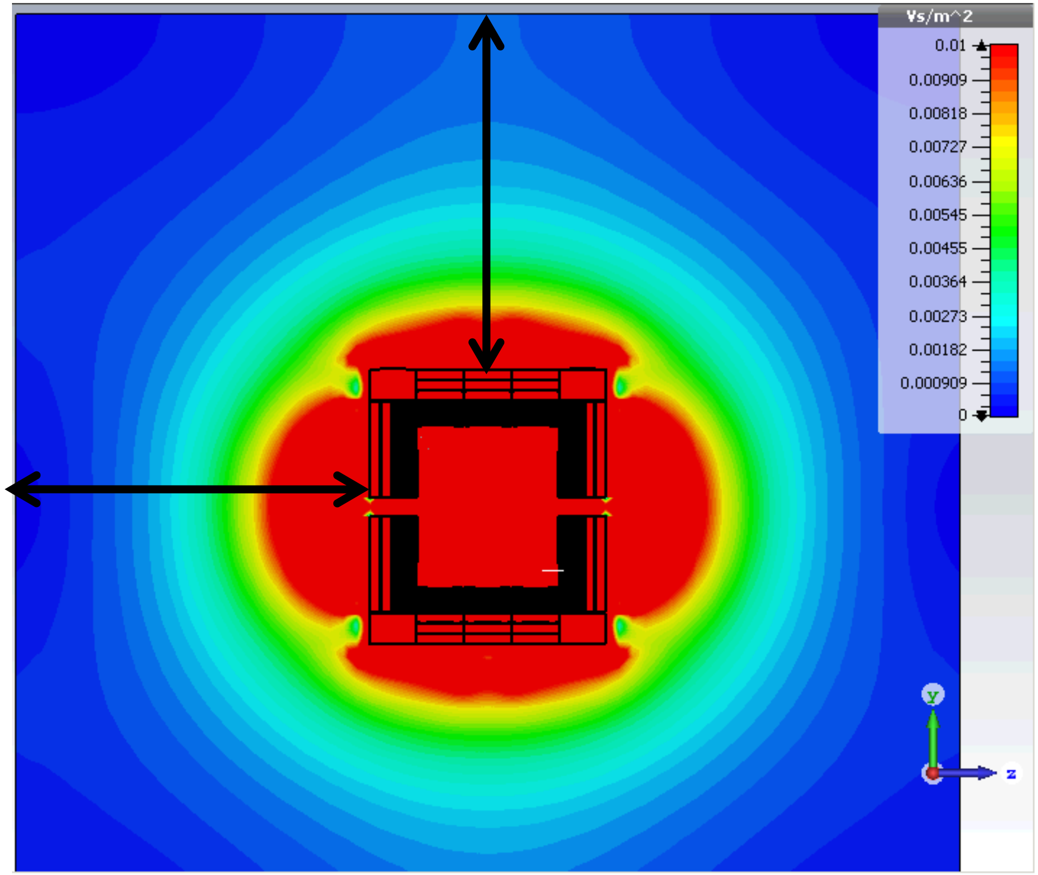
Remarks on FEM Calculations

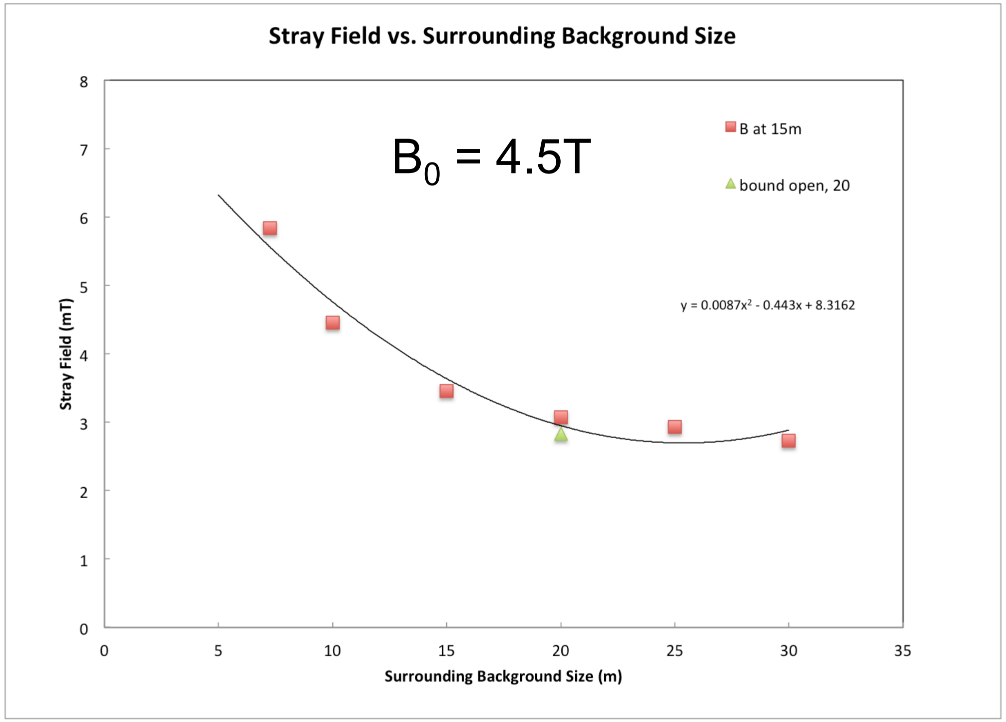
- Required precision 5mT at 15m, ≈ 0.1% of full field is at limit of FEM calculations
  - Mesh type, size, volume, optimization, boundary conditions, other parameters
- Large model ~15m radius, with small gaps (40mm)
  - Surrounding background in FEM calculation ~20m in each dimension
- “Can fake any number”, CMS expert
- In principle, need full modeling of material near detector (platforms, stairs, racks, supports, pipes, concrete reinforcement, …) and other detector
- Systematic studies:
  - Compare different FEM codes, mesh types, vary parameters in FEM calculation
  - Include items in hall
- Should use similar parameters for comparison of different options/alternatives

Field Calculations

- CST EM Studio 3D
- Initially, used hexahedral mesh with default optimization

Size surrounding of background



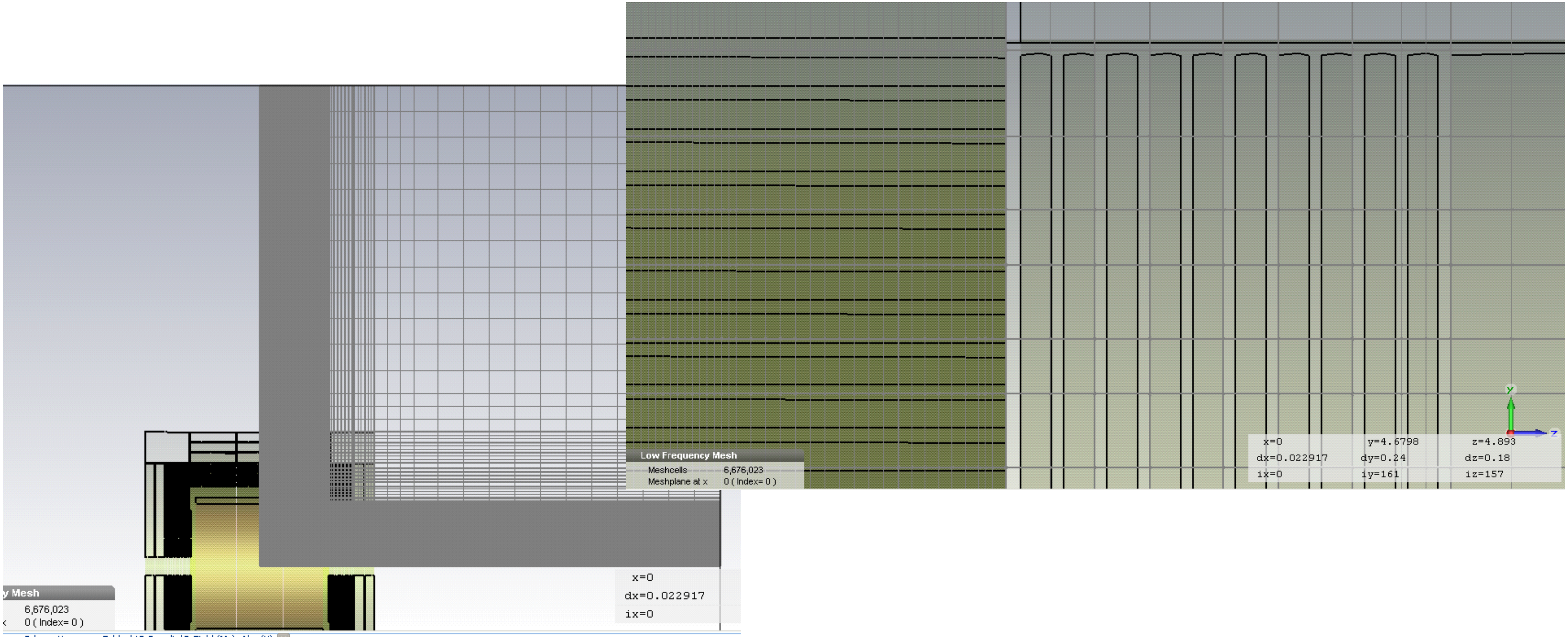


Should use ≥ 20m
Detector not in free space
In principle, have to model hall as well

Recent Field Calculations

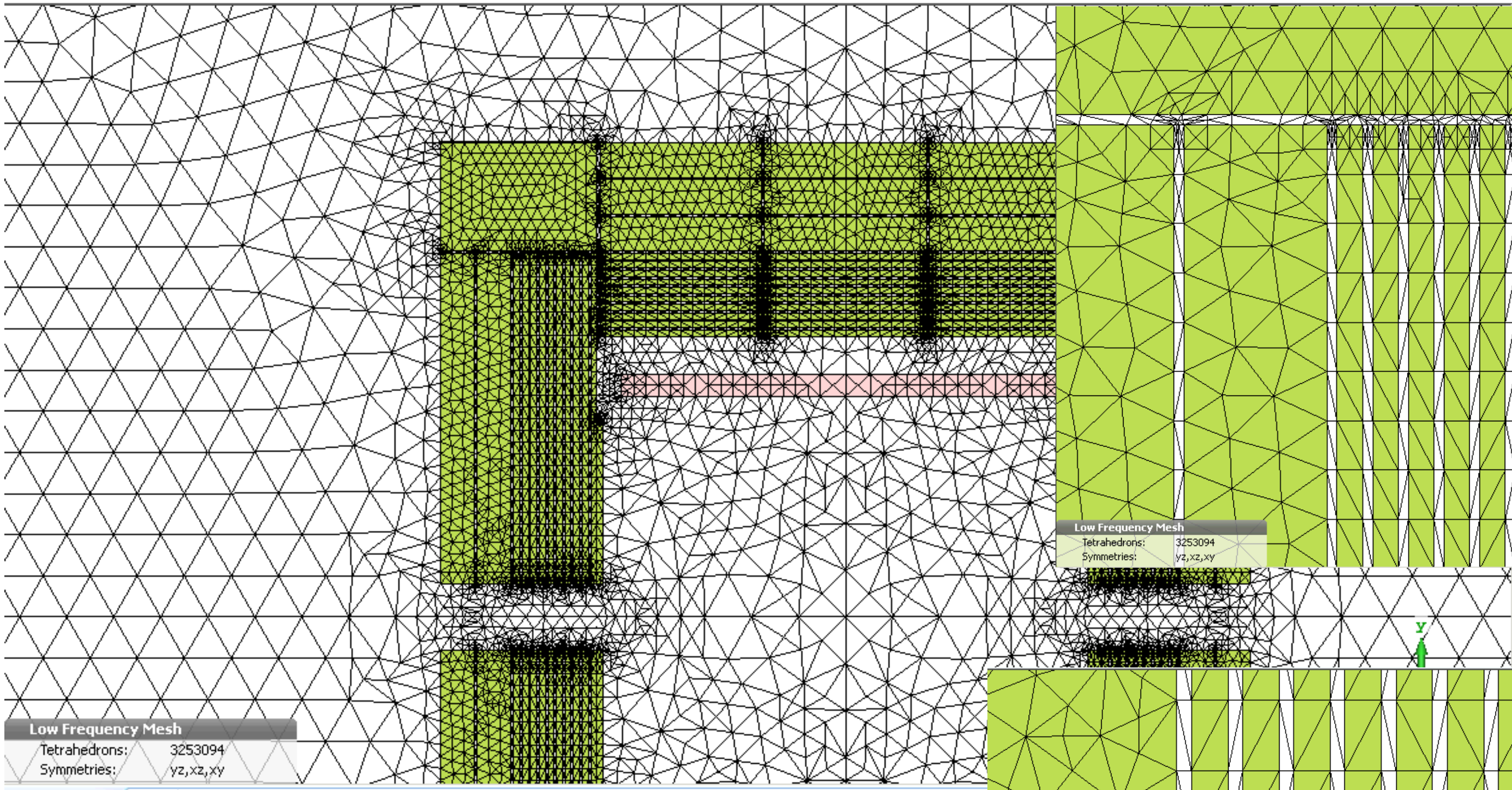
- CST EM Studio 3D
- Initially, used hexahedral mesh with default optimization
- Observations
  - B_{15m} ≅ 3mT,
  - B field shows some jumps during iterations (with increasing number of mesh cells in EC)
  - Stray field depends on number of mesh cell
  - End-cap forces no smooth distribution
  - Not able to reproduce SiD improvement due to new design
  - B_{15m} ≅ 6.5mT with tetrahedral mesh
- Reason
  - Gaps in end-caps not properly meshed (hex mesh with default optimization)

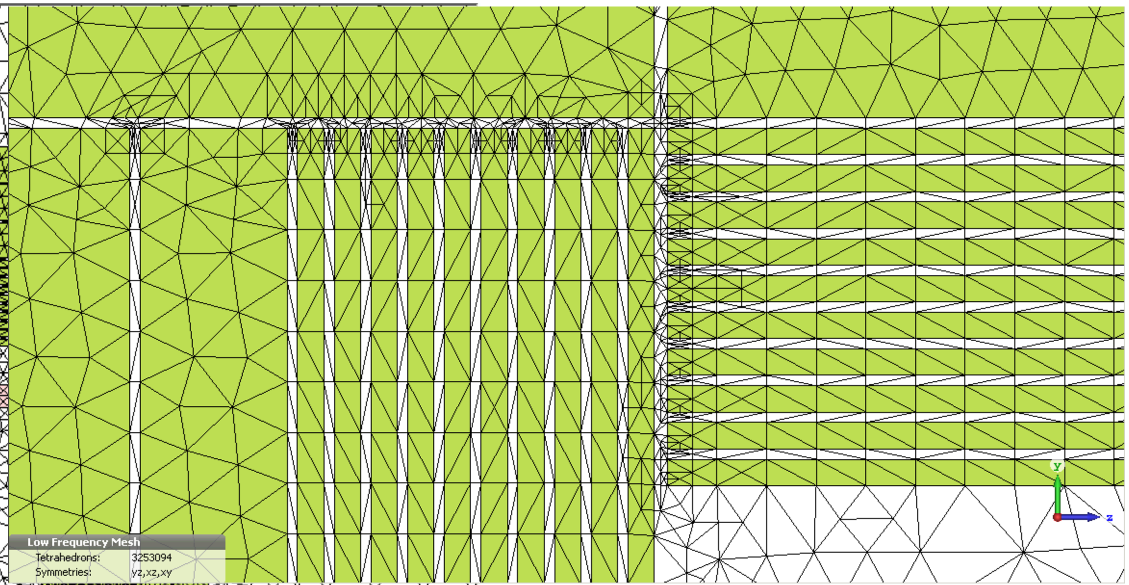
Field Calculations: Hexahedral Mesh

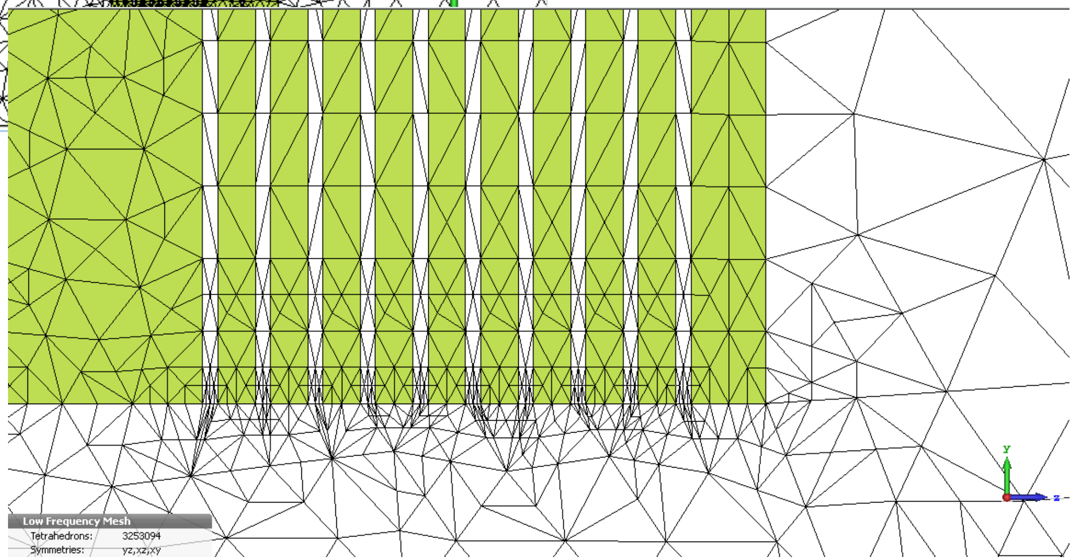


- 40mm gaps not sufficiently meshed, in particular in end-caps
- Field distribution in end-cap region not correct, including outside of iron
- Not able to improve EC mesh locally, too many cells

Field Calculations: Tetrahedral mesh

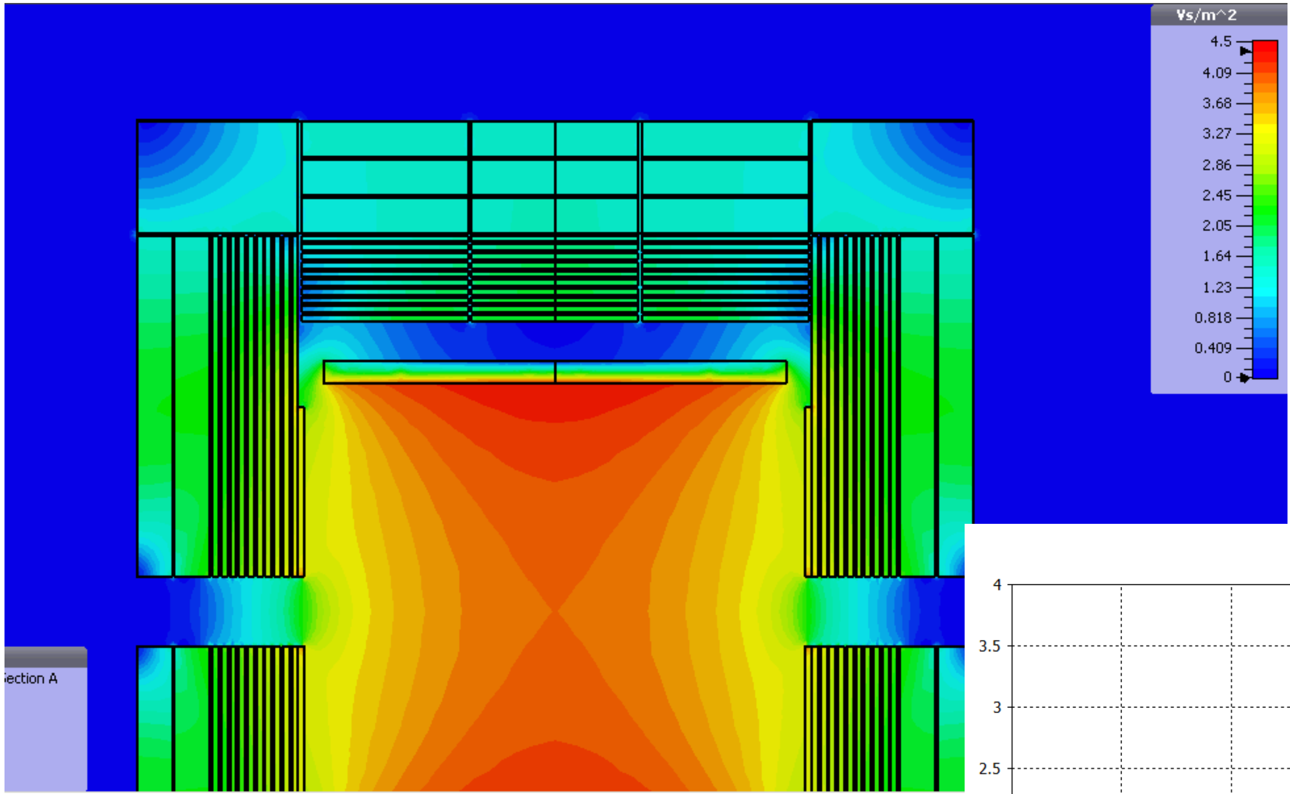






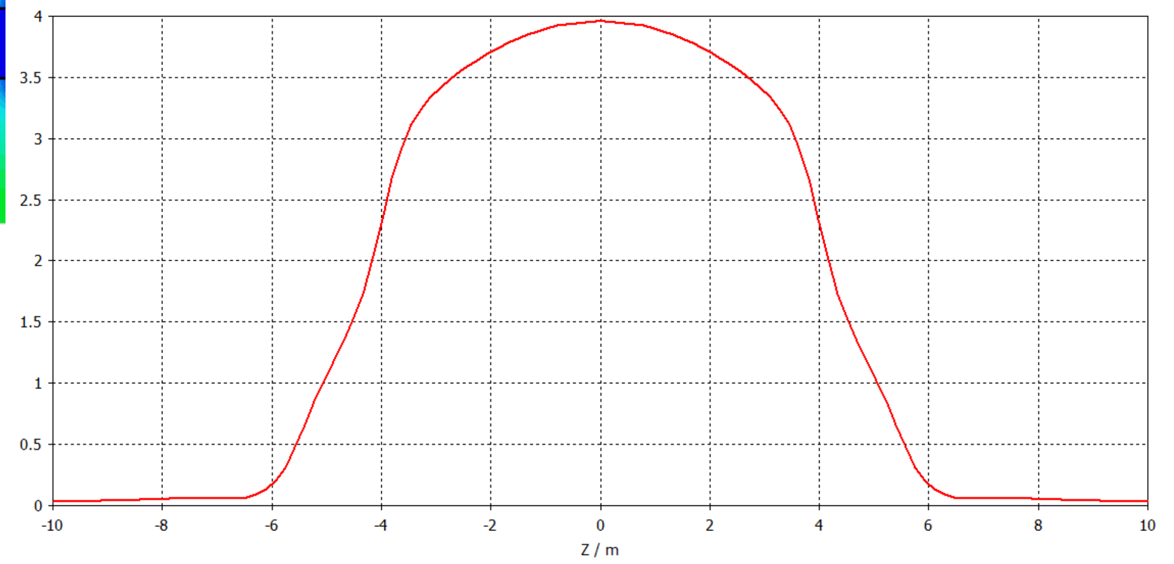
Much better mesh, in particular in gaps and end-cap region

Field Calculations: Tetrahedral mesh

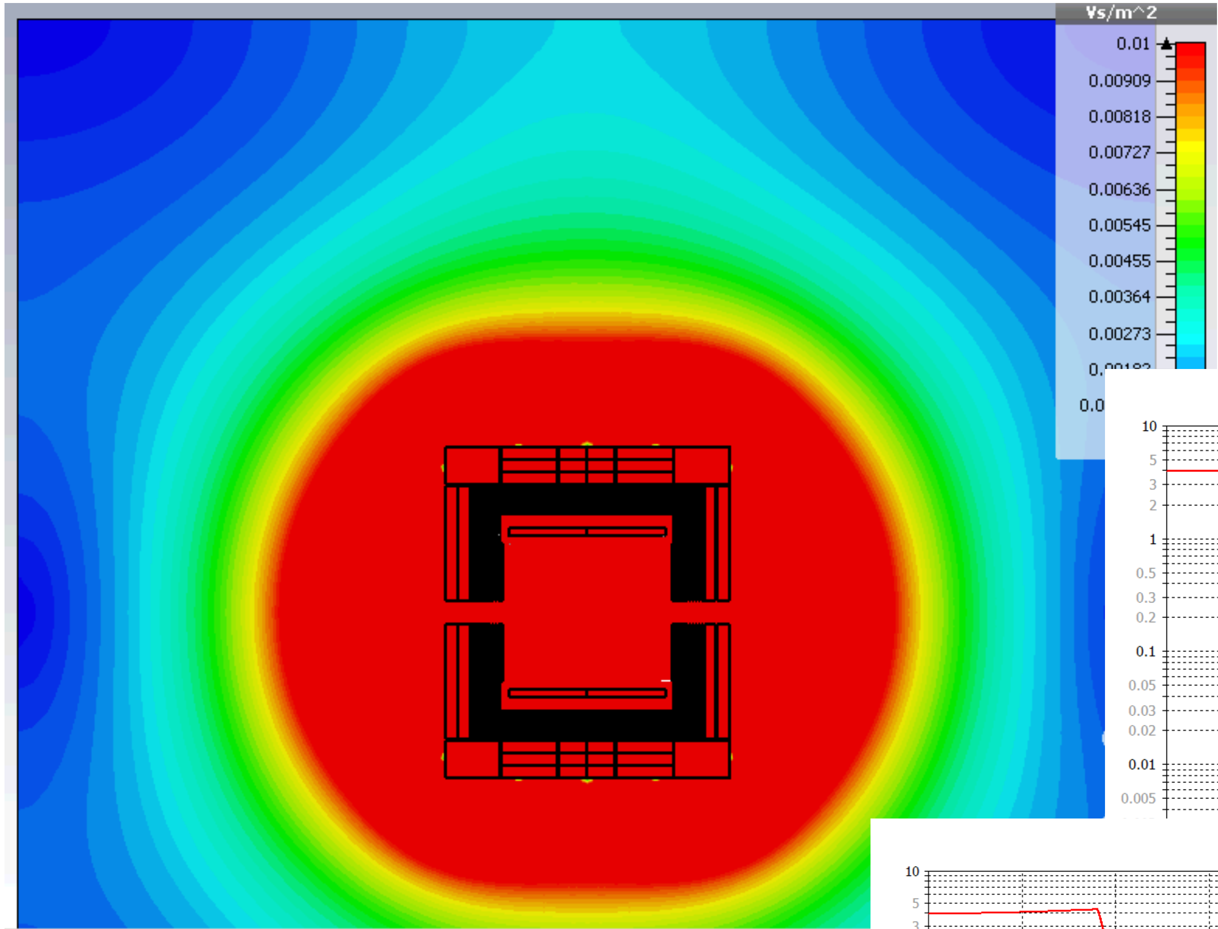


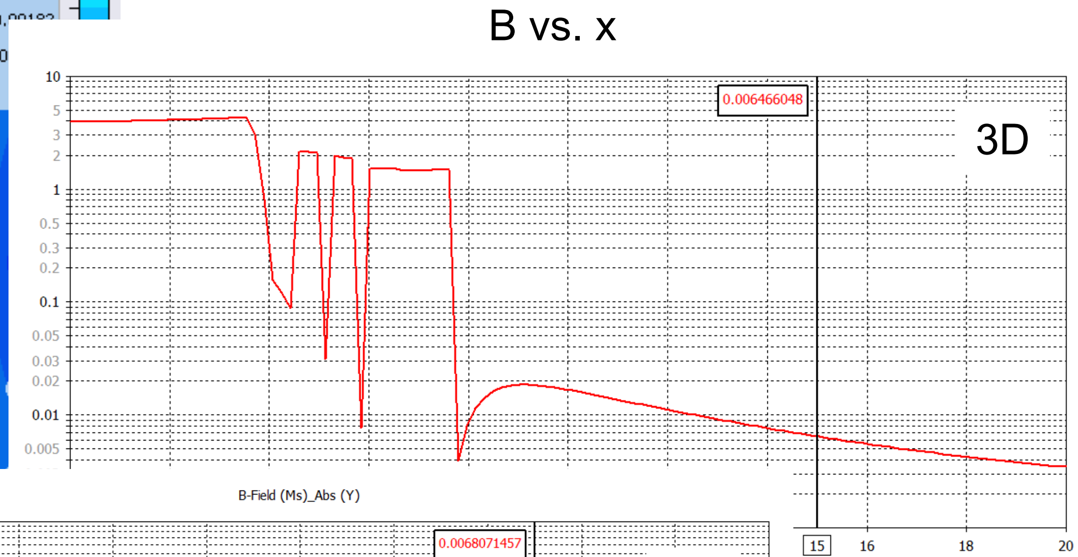
Uniform current distribution

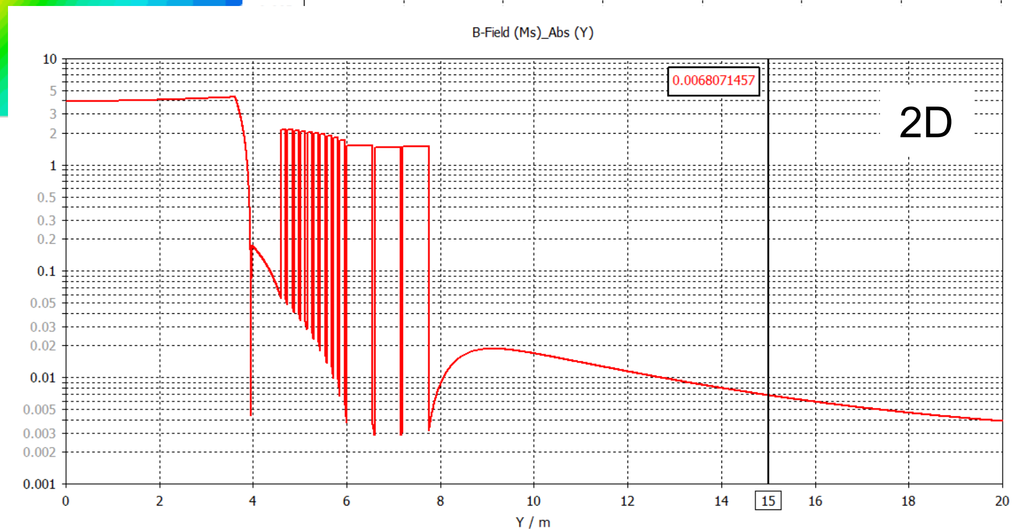
B along beam line



Field Calculations: Tetrahedral mesh







Stray field now 6.5 (6.8)mT

Was 3-4mT with hexa mesh

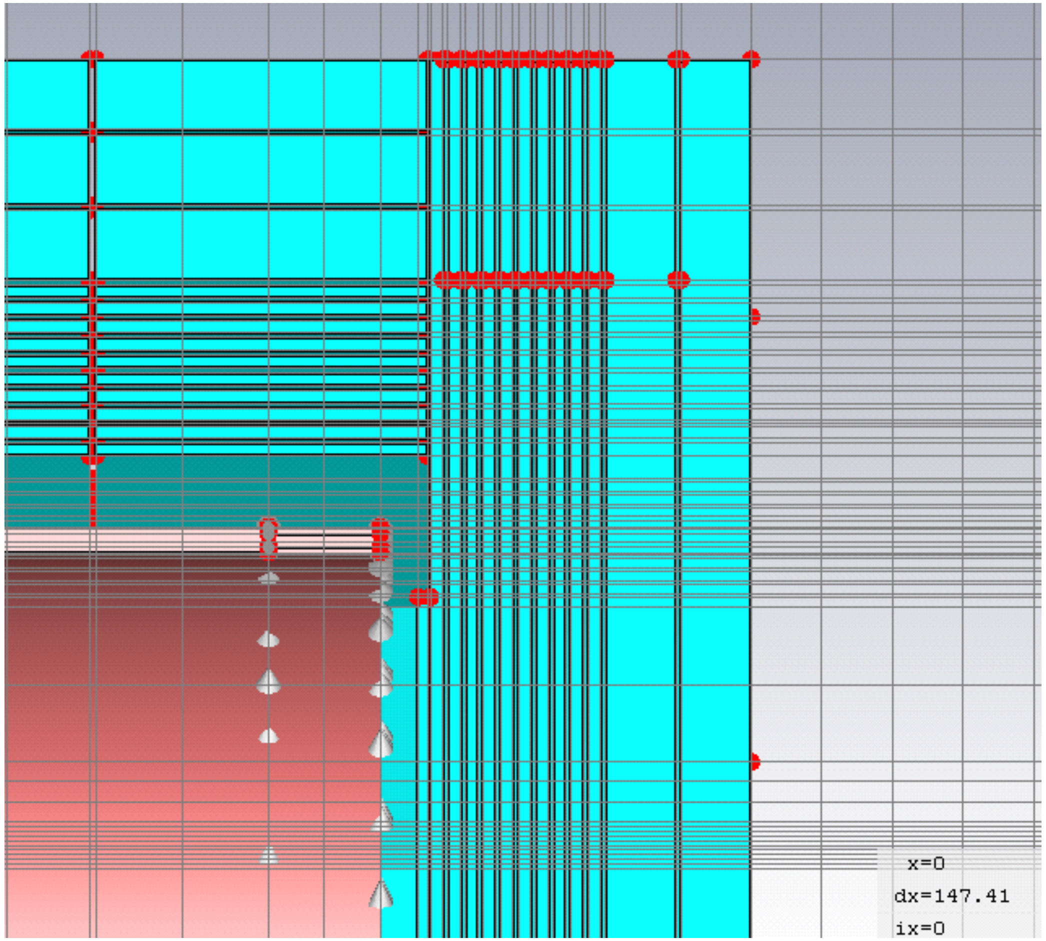
Comparison with previous Calculations

A. Petrov (2008) CST Studio 3D B_{15m} 3.8mT

- Hexahedral mesh
- Optimized locally in EC region
- Still not sufficiently well meshed

K. Büsser (2015) CST Studio 3D, $B_{15m} < 3$mT

- Hexahedral mesh
  - Not able to get sufficiently fine mesh in EC
- Tetrahedral mesh did not work, model too large



Remarks

- Until few years ago CST recommended hexahedral mesh for magnetostatic solver
- Now strongly recommending tetrahedral mesh

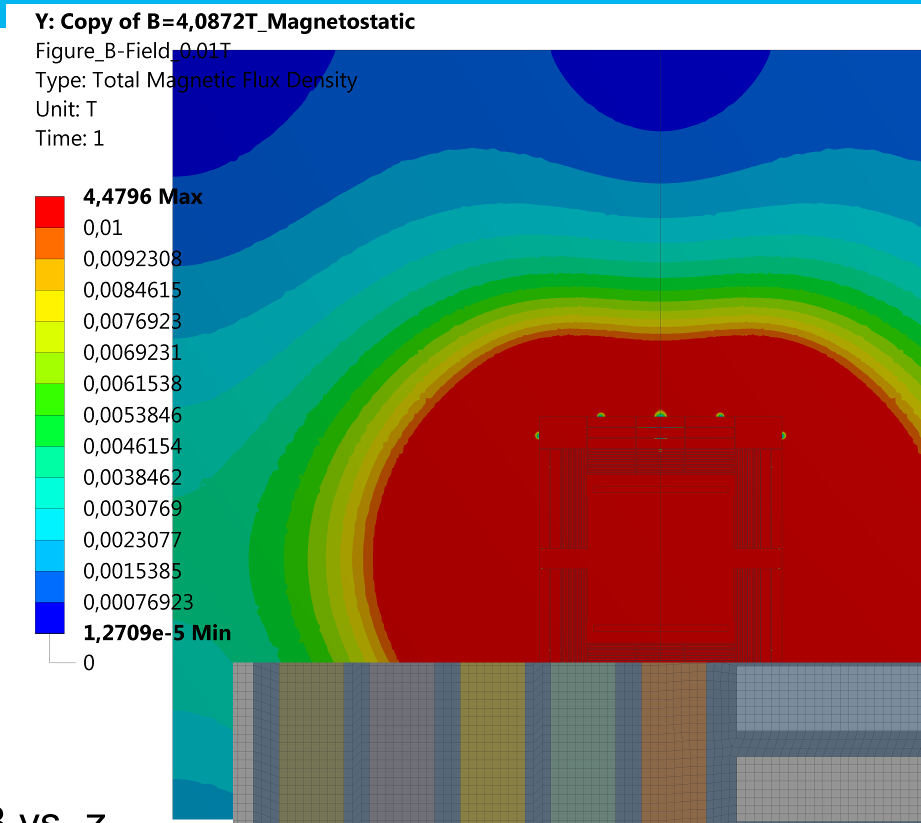
Comparison with previous Calculations

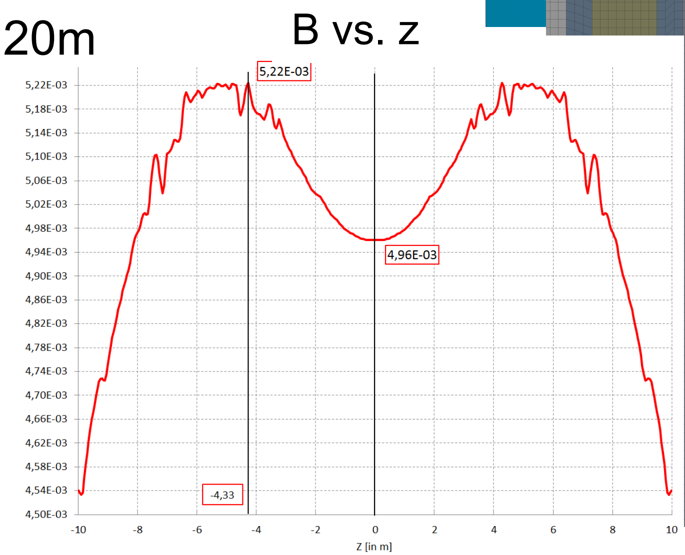
M. Lemke (2012) ANSYS B_{15m} 15mT

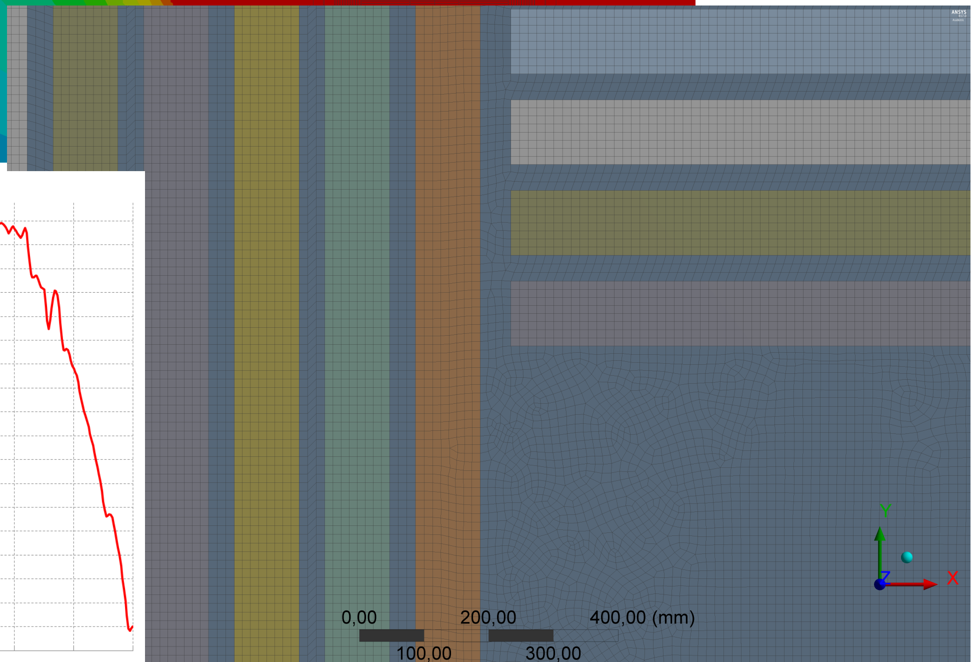
- Purpose: stress and deformation due to magnetic forces, not stray field
- Full CAD model
- Gaps well meshed
- Surrounding background only 7.5m

Recently, repeated calculations

- Cylindrical model 5° section
- Surrounding background 20m
- Very detailed mesh
- B_{15m} 5.0mT z=0,
  5.2mT in EC region



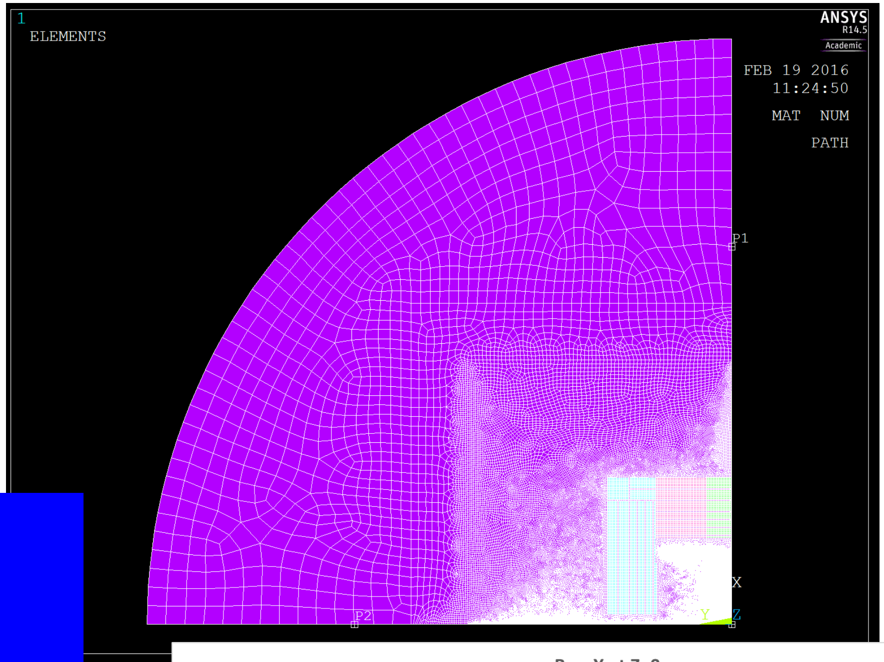


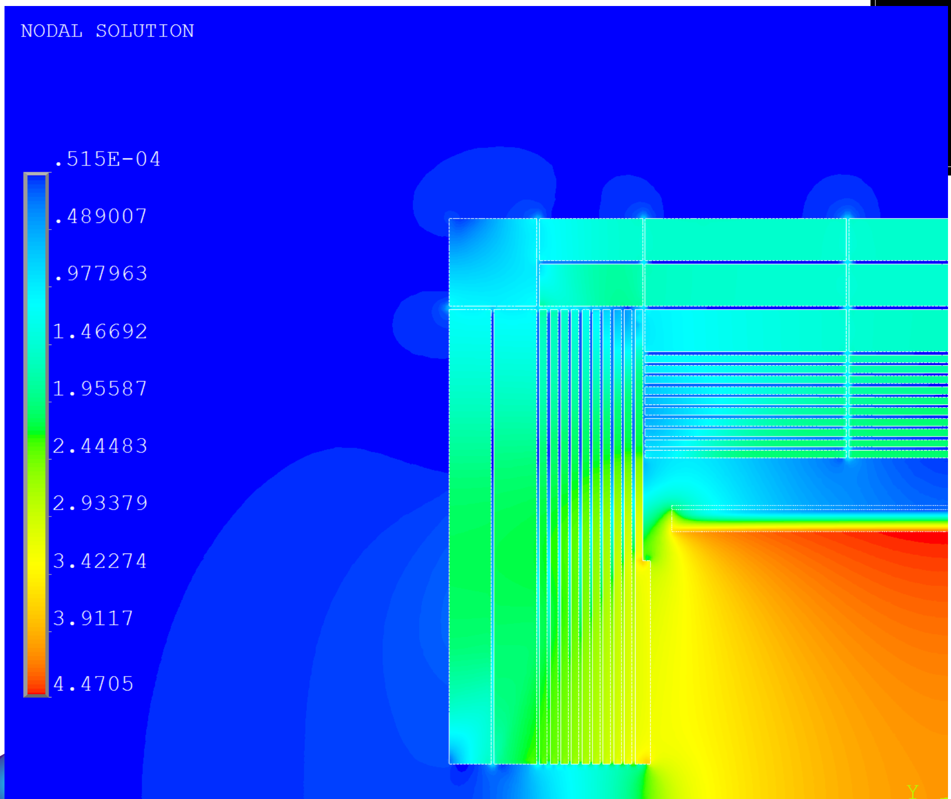


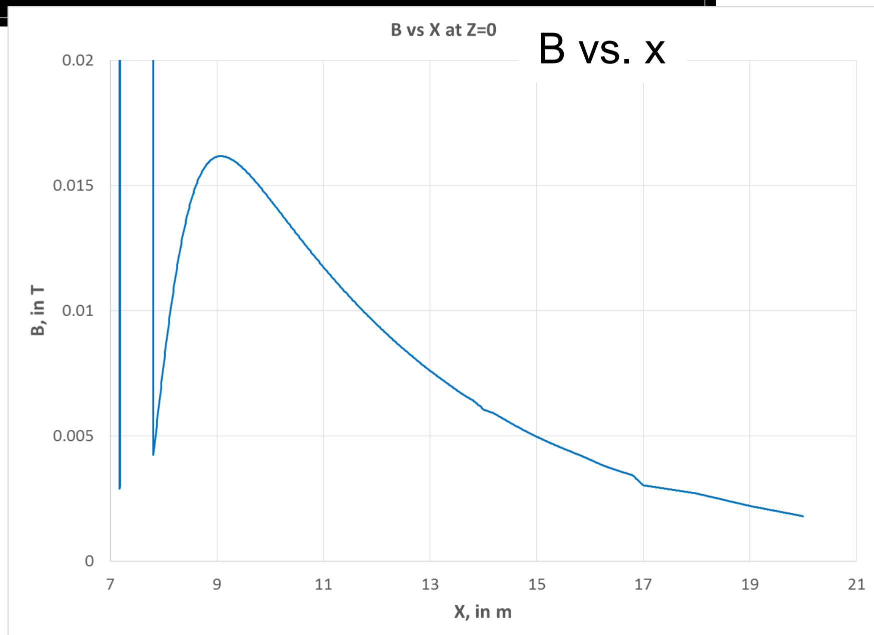
Comparison with previous Calculations

B. Curé (2012) ANSYS, B_{15m} 5mT

- Simple model
- Gaps well meshed
- Volume radius 31m
- Boundary represents an exterior sub-domain of semi-infinite extent



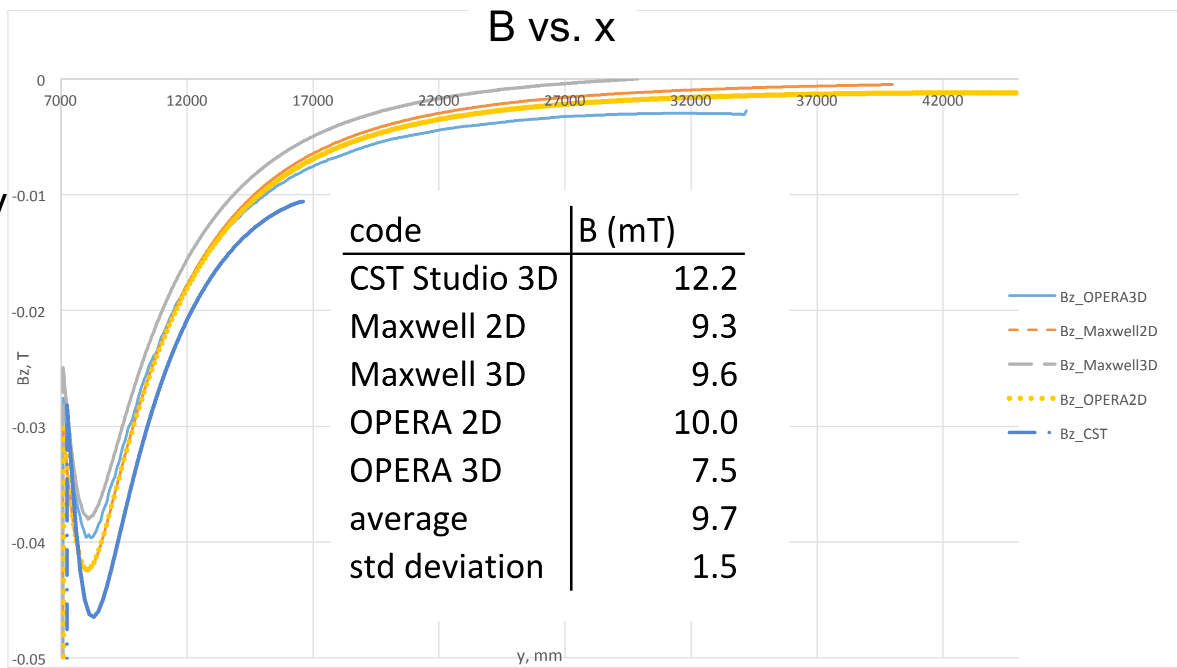




Comparison with previous Calculations

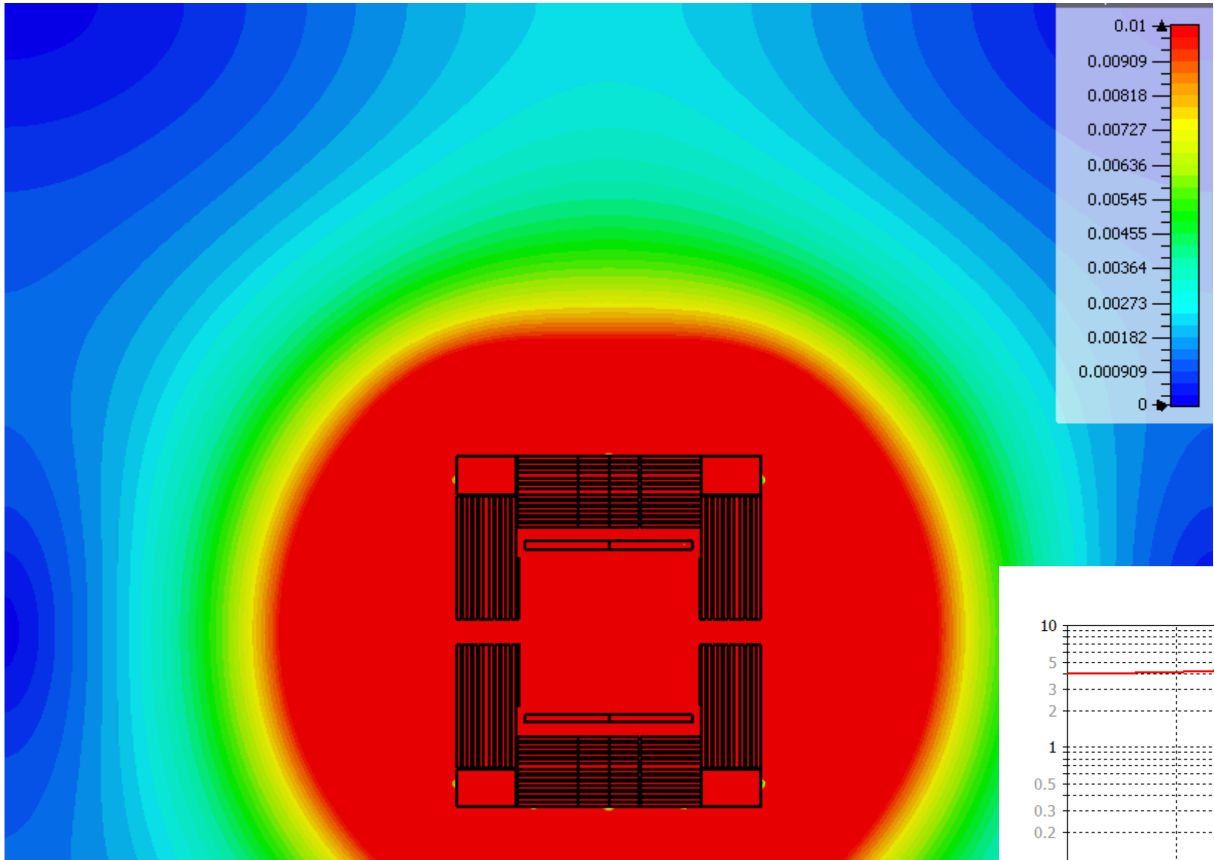
Efremov Institute, St.Petersburg 2014

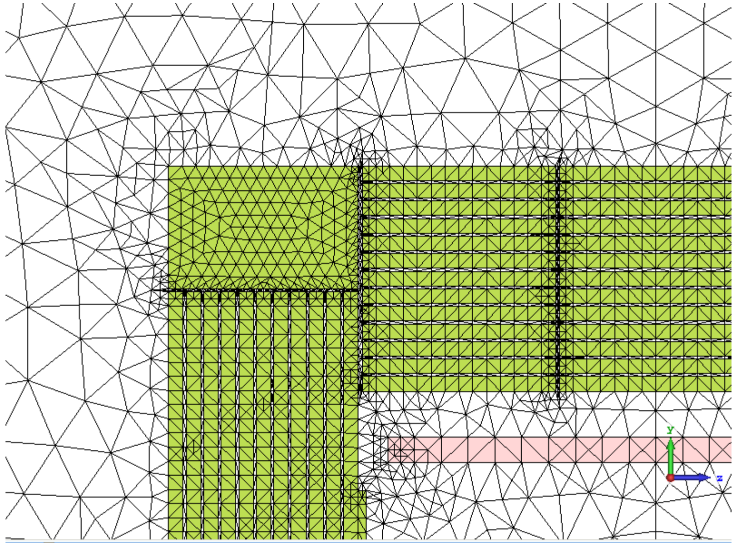
- Motivation: hoping to reduce size of yoke (600mm less in radius), stray field, compare FEM codes
- Detailed meshing of gaps
  - CST Studio calc. volume limited by memory
- Average B_{15m} 9.7 ± 1.5mT
- Recent calculations (U.S.):
  B_{15m} 9.5mT (tetra mesh),
  8.0mT (poor hexa mesh)



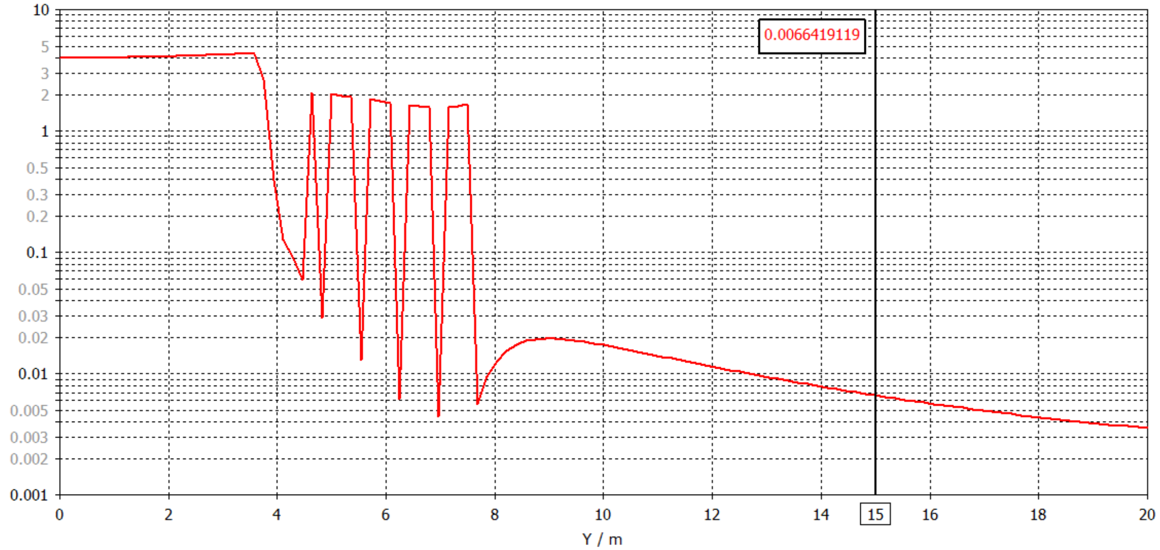
code	B (mT)
CST Studio 3D	12.2
Maxwell 2D	9.3
Maxwell 3D	9.6
OPERA 2D	10.0
OPERA 3D	7.5
average	9.7
std deviation	1.5

Alternative Geometries: 200mm Plates





B vs. x



Stray field 6.6mT

Same as present design (6.5mT)

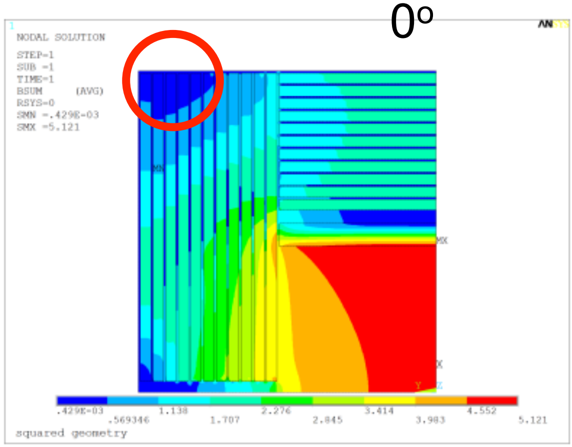
Manufacturing would be easier

Recent Re-Design of SiD

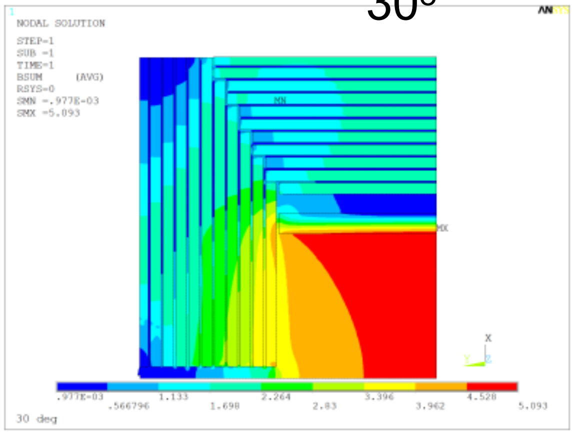
Barrel-end-cap partition/transition

11 plates 200mm thick, 2.2m steel in total

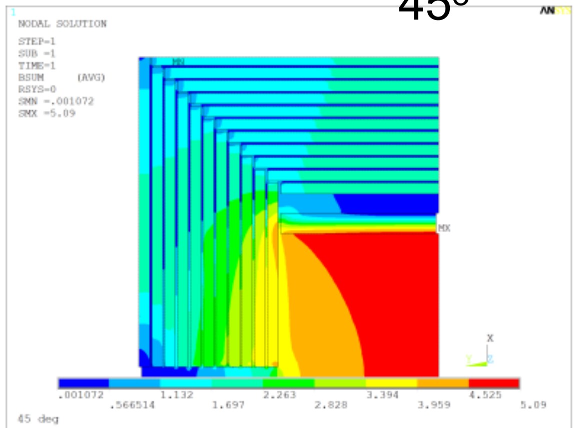
0^o



30^o



45^o



	0^o	30^o	45^o
SiD calc. B_{15m}	6.3	4.0	1.4mT
U.S.	6.1		1.7mT

New SiD design 30^o instead of 0^o partition/transition

Advantage

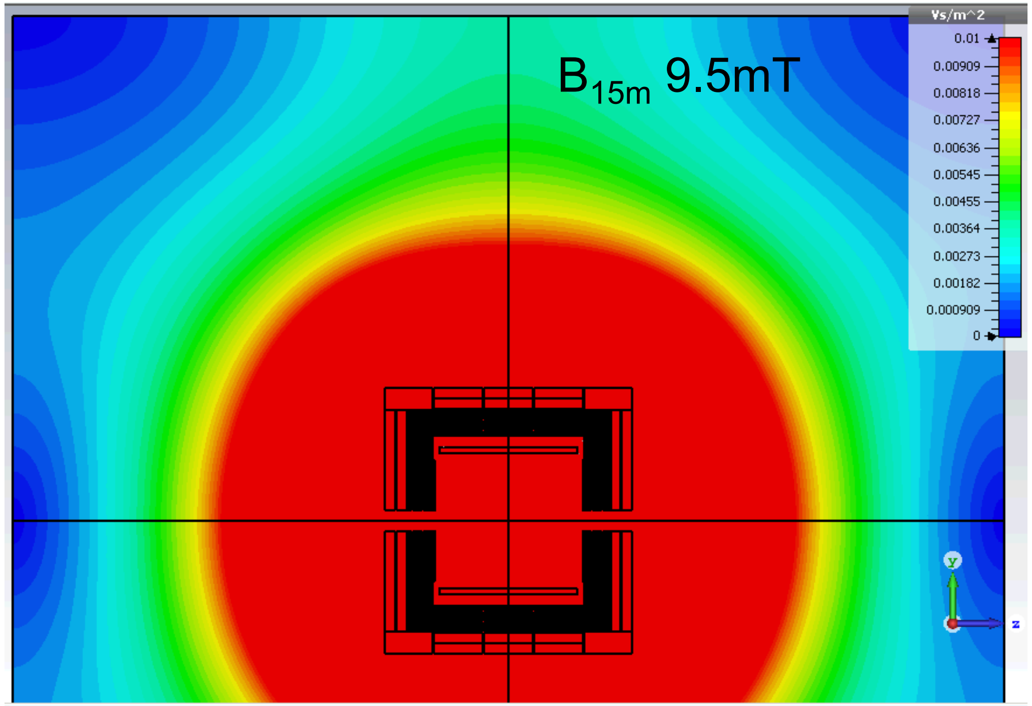
- Significant reduction of stray field

Disadvantage

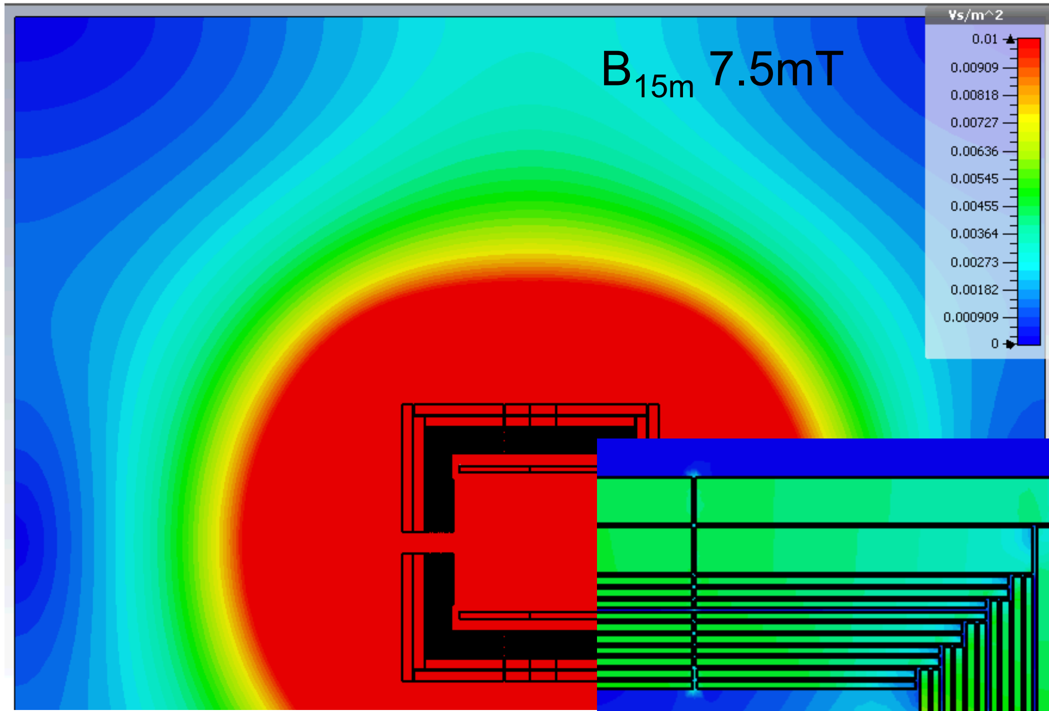
- Design, fabrication and assembly more complicate (more expensive)
- Complicated transfer of forces between end-caps and barrel
- Reduced access

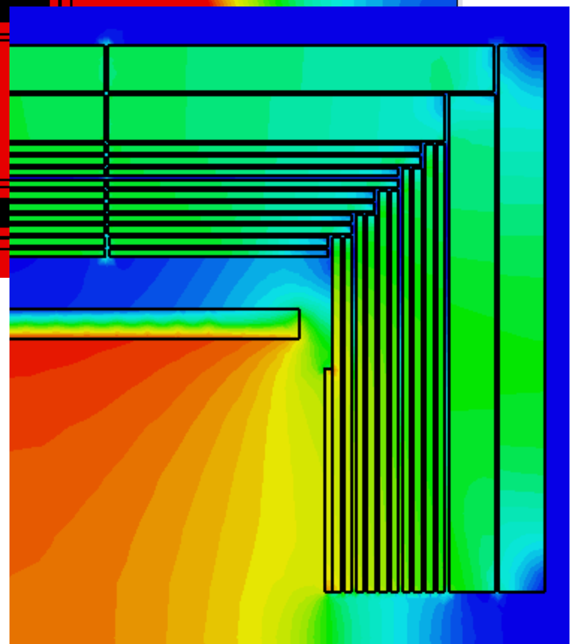
Alternative Geometries: 45° Transition

ILD Barrel 2 thick plates (in total 2.12m)



Barrel 2 thick plates 45°



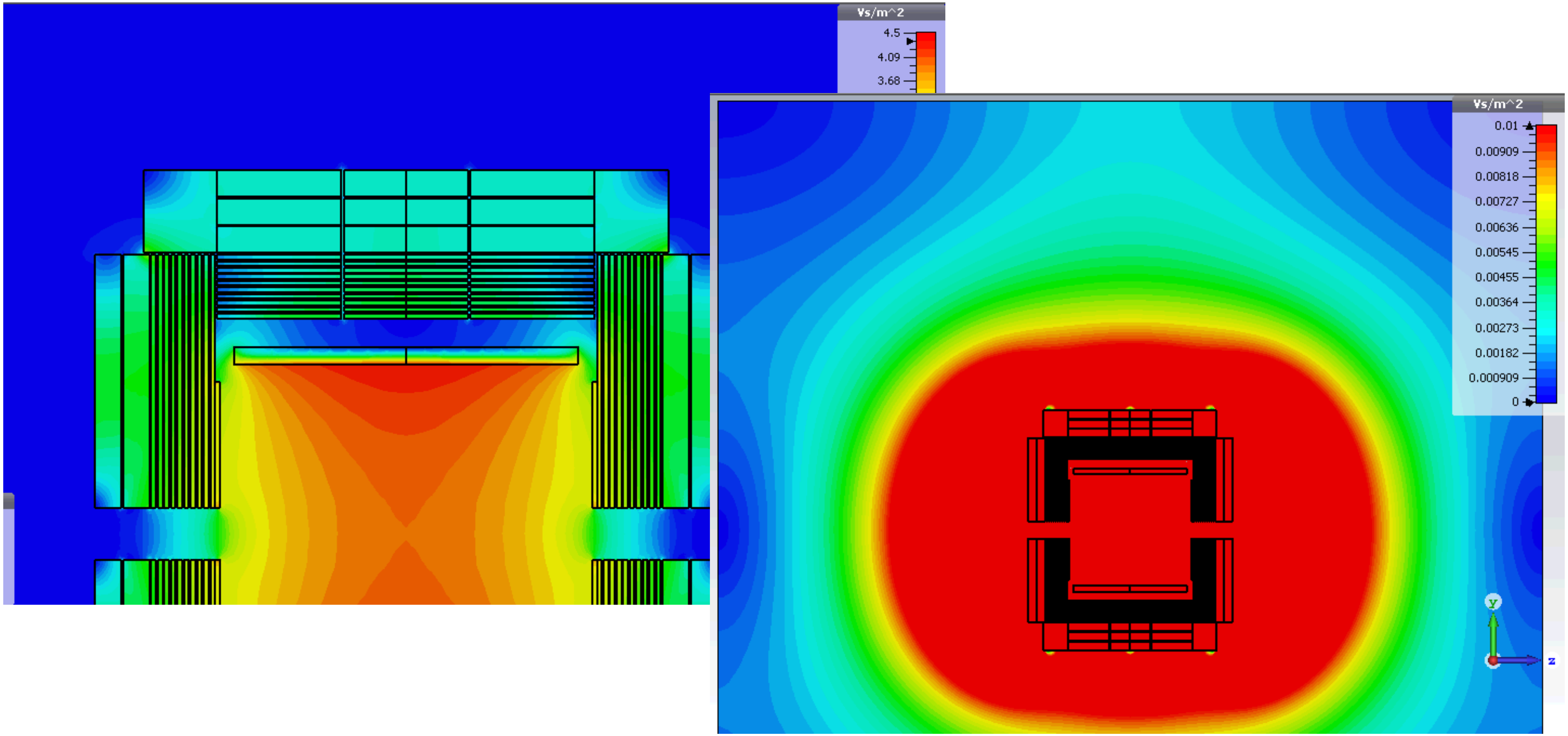


Stray field reduction not as much due to outer end-cap pieces

Disadvantage

- Design, fabrication and assembly more complicate and expensive
- Complicated transfer of forces between end-caps and barrel
- Reduced access, problem with pillar support of GO

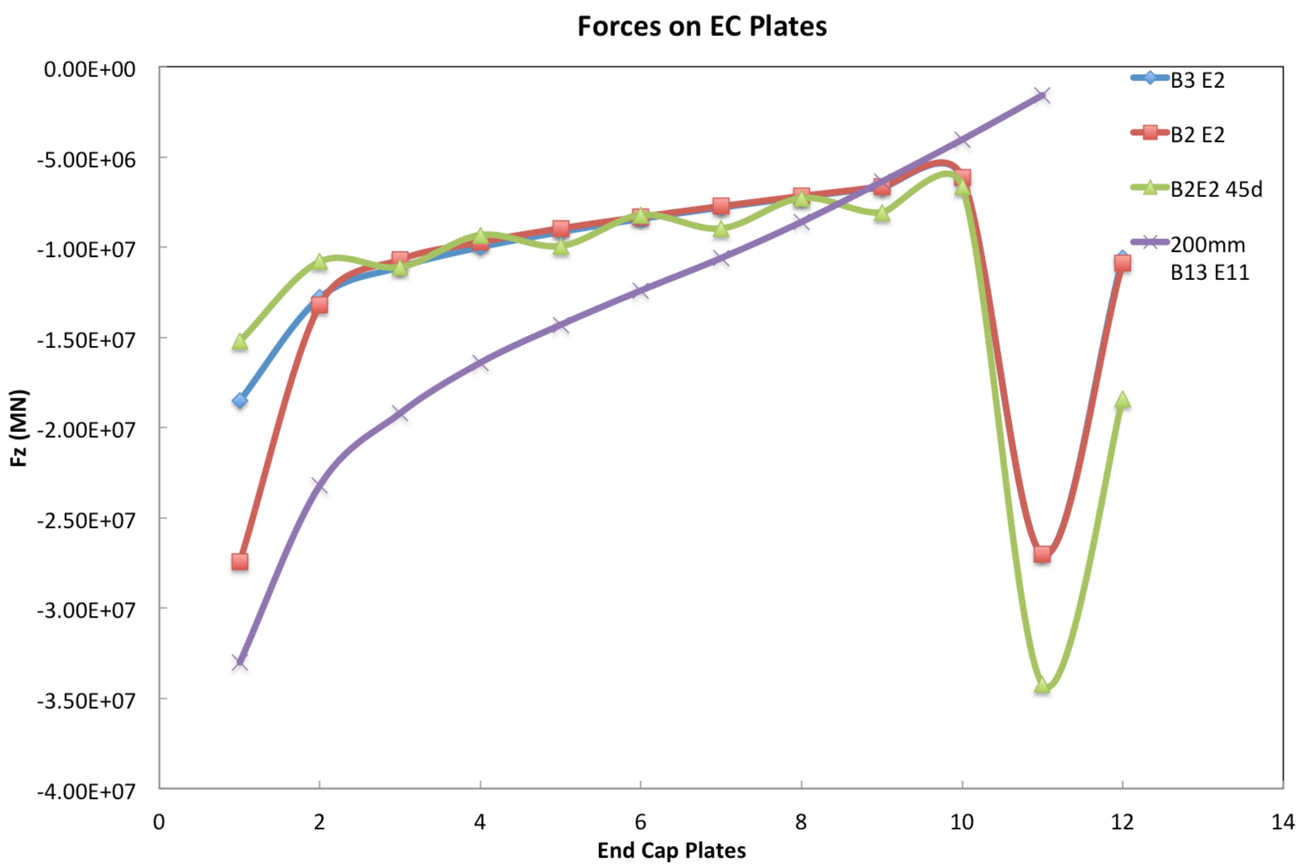
Outer Shieding Modified



Outer EC shielding attached to barrel, no gap

B_{15m} 6.0mT instead of 6.5mT

Alternative Geometries: End-cap Forces



- Force distribution on plates depends on geometry
- Total force similar 15000tons w/o, 19000tons with outer pieces

Magnetic Field in Central Region

- All recent calculations ($\geq$ 2012) done with uniform current distribution in coil
  - No correction coils
  - Usually no anti-DID
- Central field depends on yoke
  - In particular on end-caps, correct meshing of gaps
  - Make sure correct simulation is used for generating field map
- How important is field uniformity in TPC volume?
- Accidentally, reduced coil length from 7.35 to 6.135m: (initial mesh)
  - Field along z less uniform: 3.5T at TPC end-plate, instead of 3.8T
  - Field integral should not be affected $\int_{l_{drift}} \frac{B_r}{B_z} dz$
  - End-cap forces reduced from 19 to 10ktons
  - Cost of coil reduced by 5MILCU

ILD Field Calculations: Summary

		B (mT) z=y=0, x = 15m
O. Delferriere, OPERA 3D/TOSCA old model: detailed mesh		(5.5)
A. Petrov, 2008-11, CST Studio 3D:	mesh not sufficient	(3 – 4)
M. Lemke (DESY), 2012 ANSYS:	limited surrounding background	(15)
repeated with sufficient background		5
K. Büsser, 2015 CST Studio 3D:	mesh not sufficient	(< 3)
B. Curé (CERN), 2012 ANSYS, simple model		5
Recently U.S., CST Studio 3D	mesh not sufficient	(3 – 4)
	detailed mesh	6 - 7
Smaller yoke (600mm less in radius):		
Efremov group, 2014, several code	detailed mesh	9.7
Recently U.S., CST Studio 3D	mesh not sufficient	(8.0)
	detailed mesh	9.5

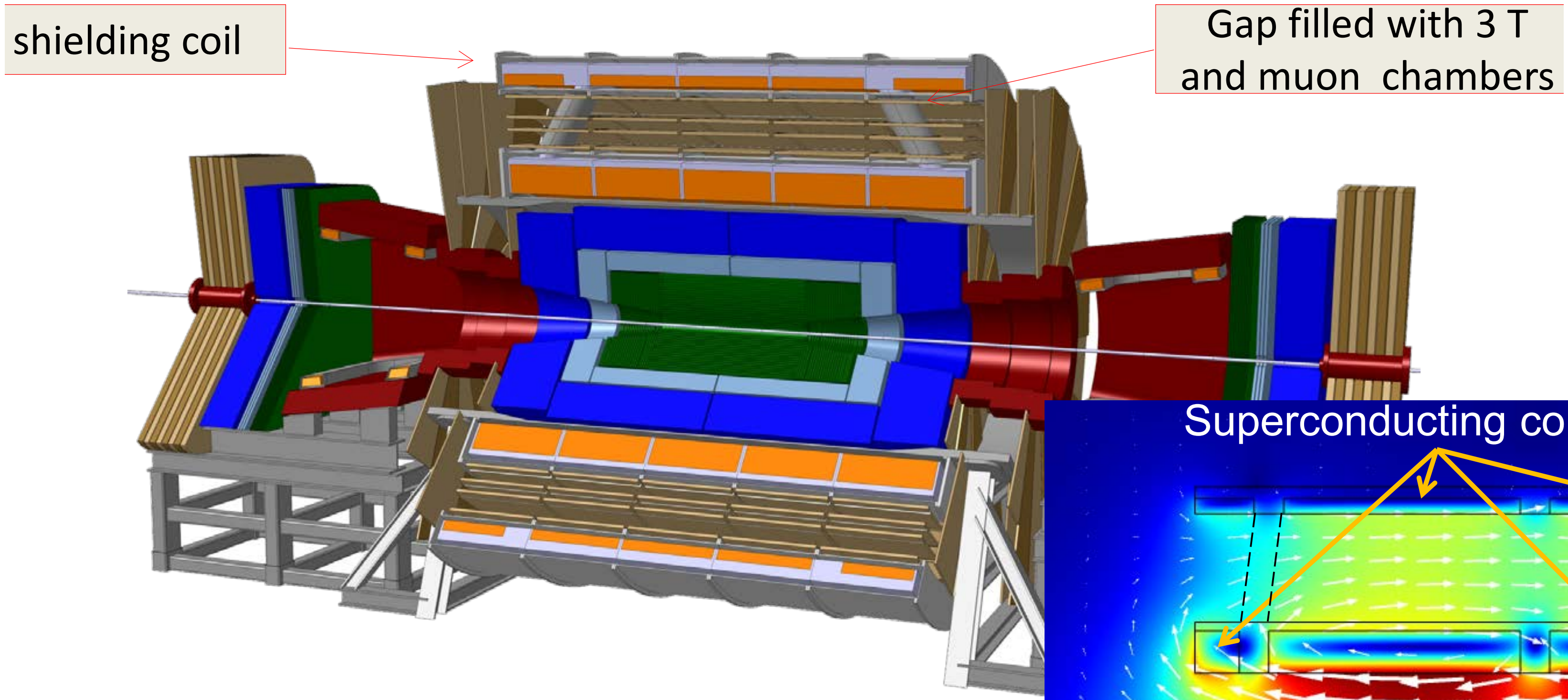
Calculations now very consistent

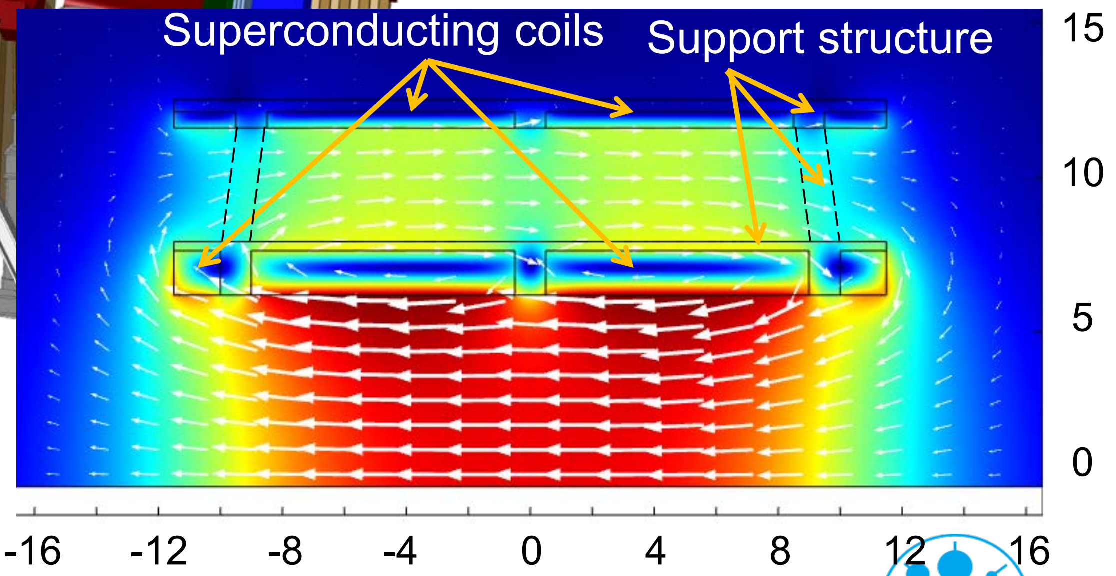
- Stray field now 5 - 6mT, instead of 3 - 4mT
- Some fine tuning still possible

Double Solenoid Without Yoke

Flux return by outer solenoid: much lighter, muon tracking space, possibly cheaper

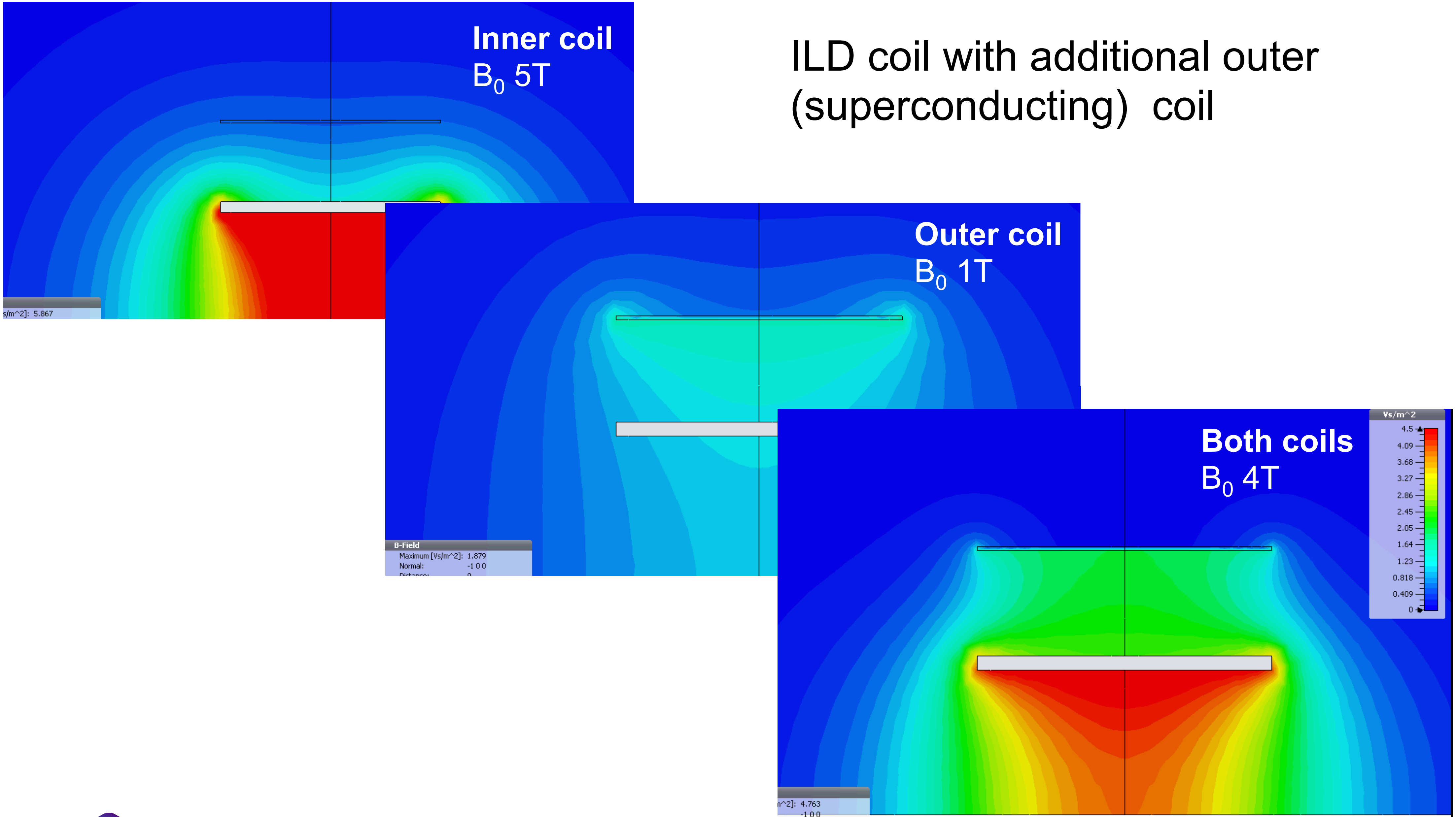
- 4th Concept
- Recently being studied by FCC Detector Working Group, H. ten Kate et al.





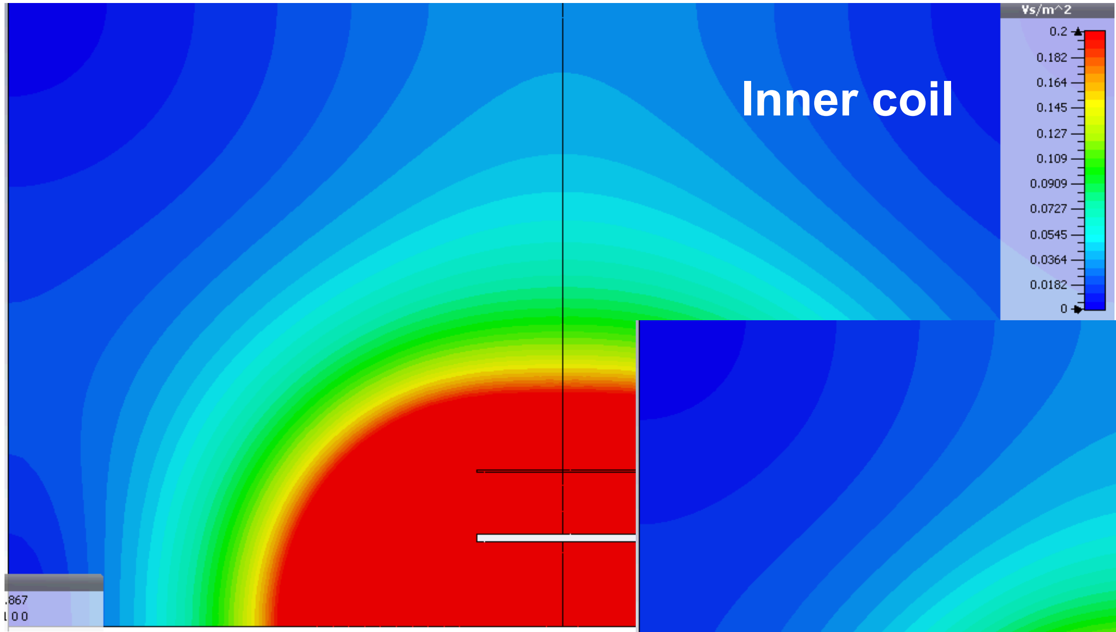
Several options being studied
Not cheap

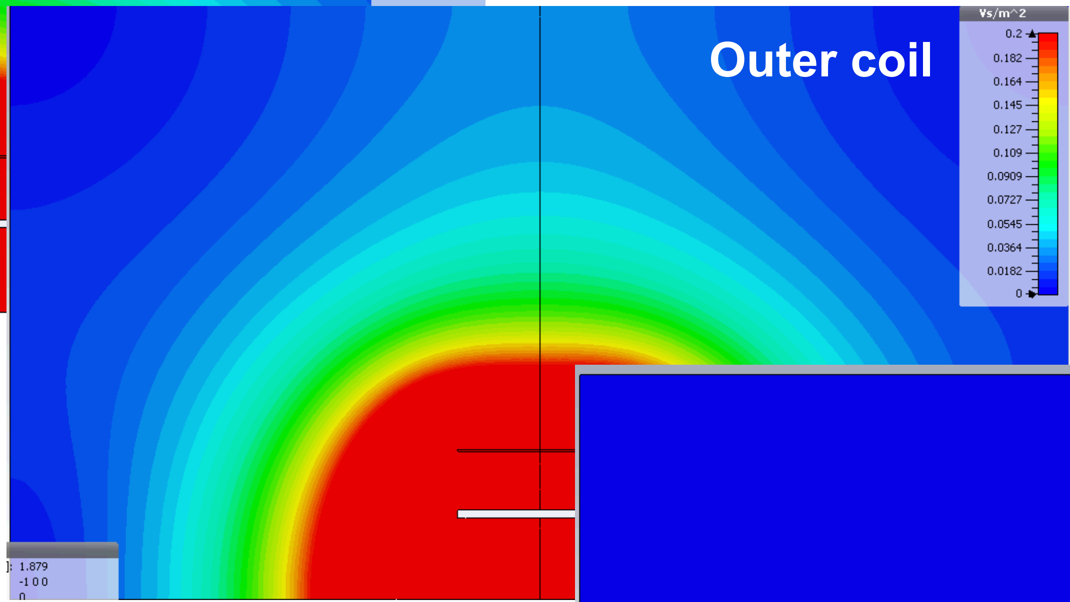
Double Solenoid Without Yoke

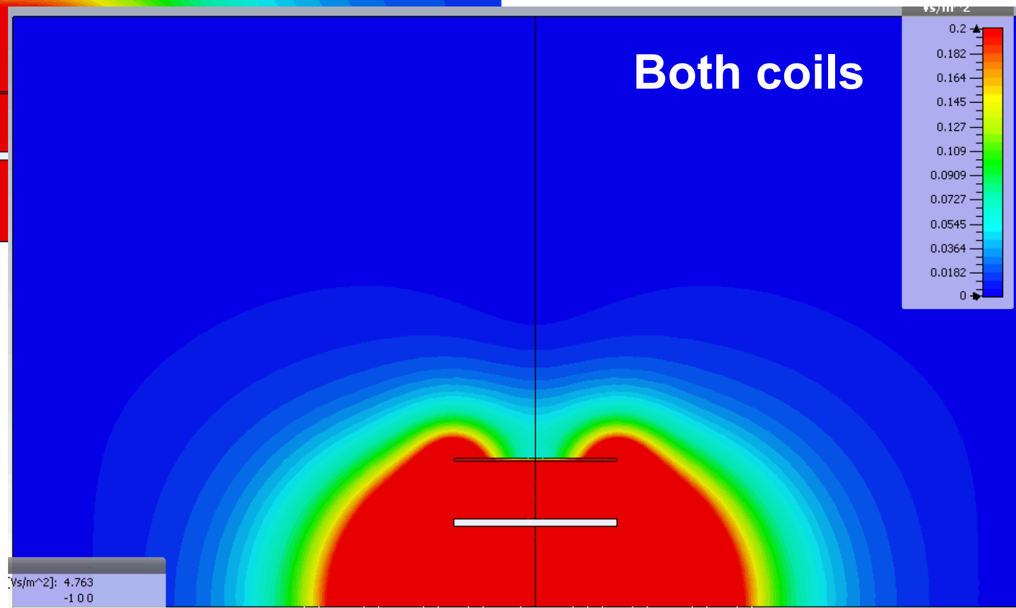


ILD coil with additional outer (superconducting) coil

Double Solenoid Without Yoke



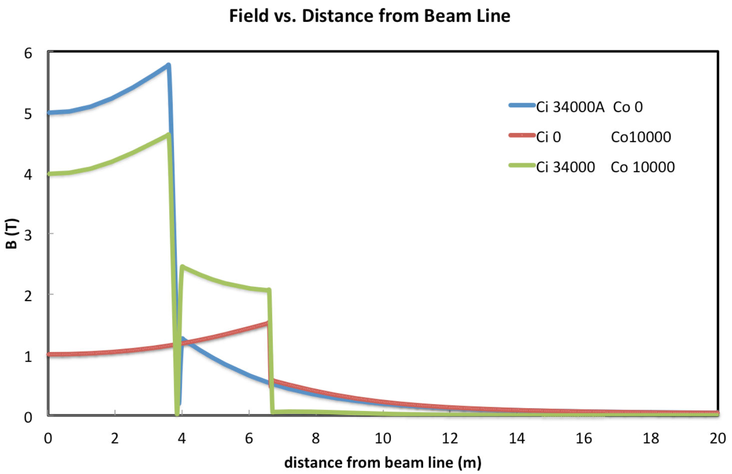


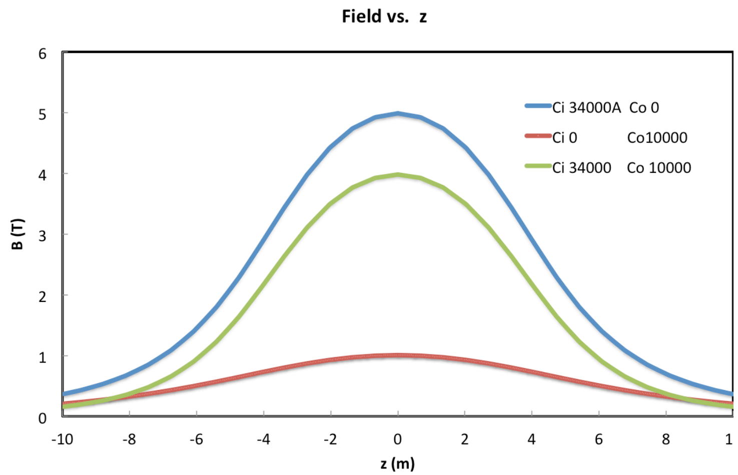


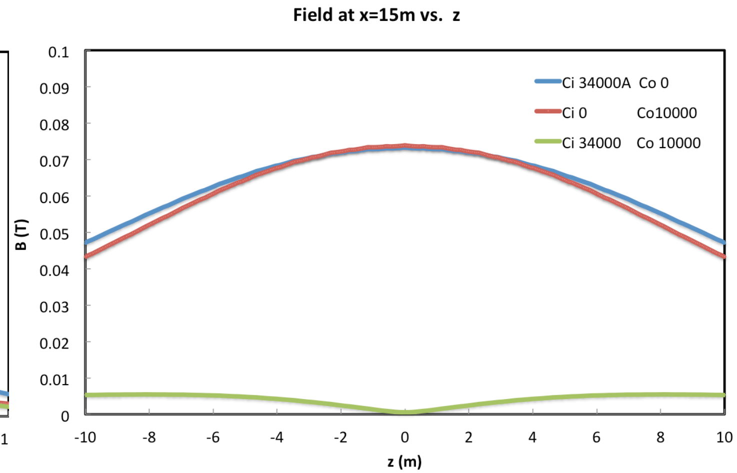
ILD coil with additional outer (superconducting) coil

- Stray field reduced by compensating coil
- Could be tuned, less dependent on field calculations

Double Solenoid Without Yoke







field less homogeneous

Rough cost estimate (MILCU)

	Present design	Double solenoid
Inner coil	43	56
Outer coil	-	47
Yoke	81	-
Support	12	12
Sum	136	115*

*) in addition

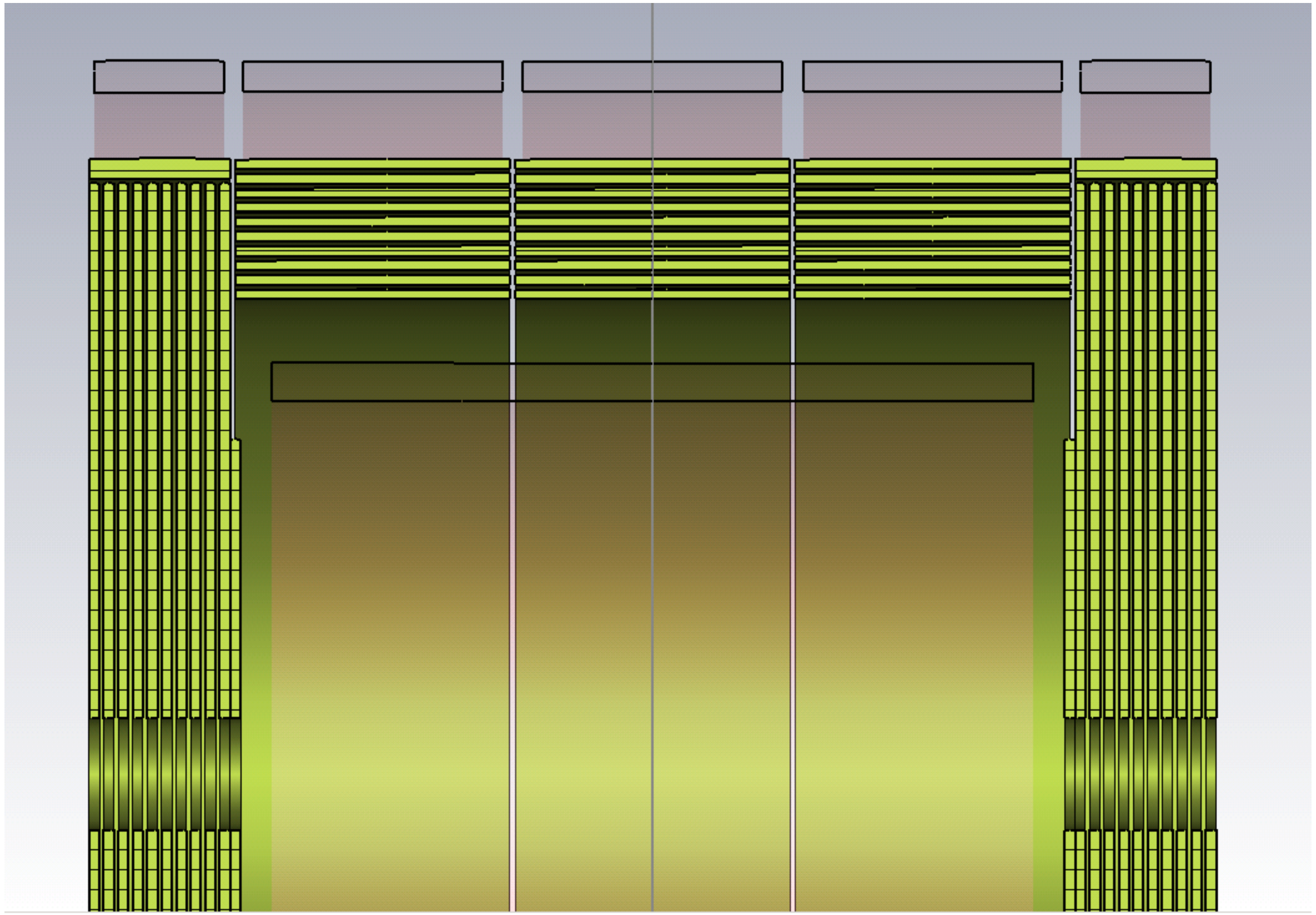
- Radiation shielding (concrete)
- Power supply for outer coil
- Infrastructure and larger cryo plant

Similar cost

Inner Yoke with Compensating Coil

Stray field reduced by compensating coils

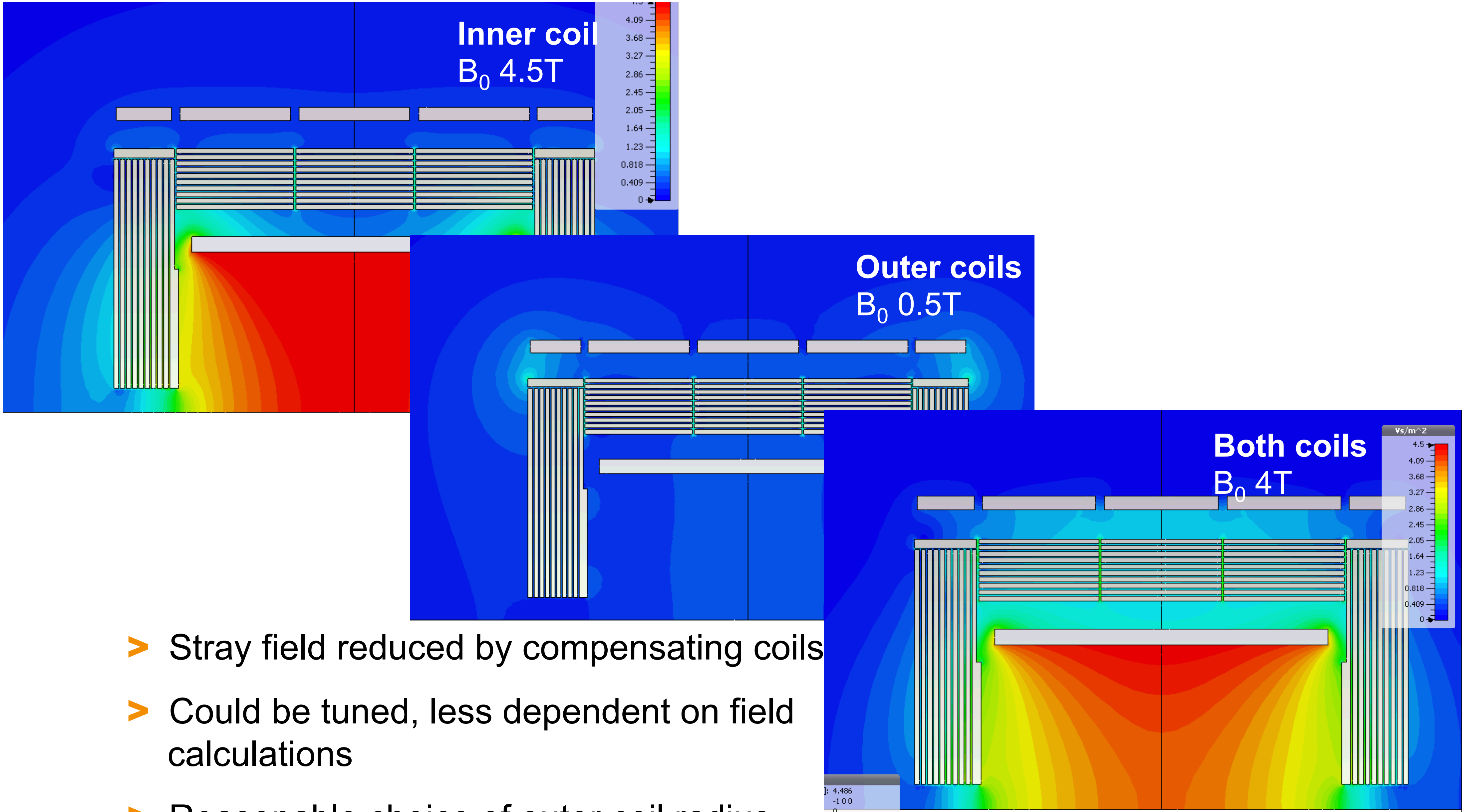
Radius not optimized



Yoke

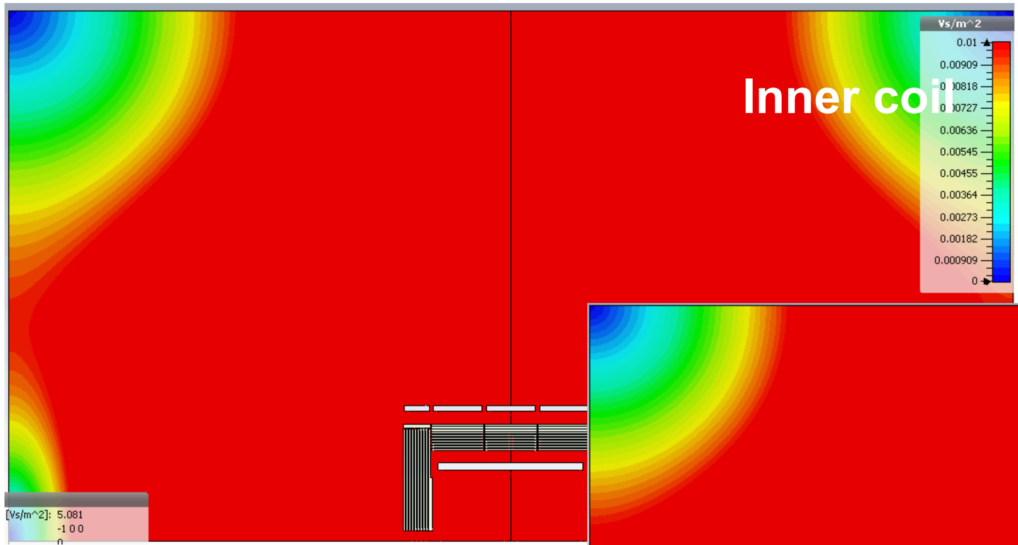
- weight 4000 instead of 13400t
- cost 24 instead of 81MILCU

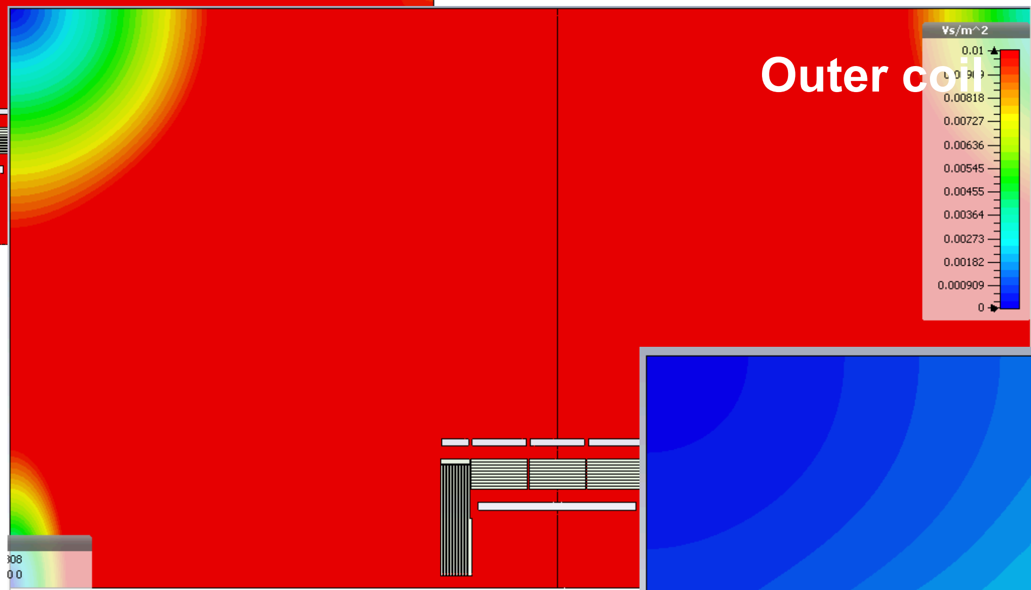
Inner Yoke with Compensating Coil

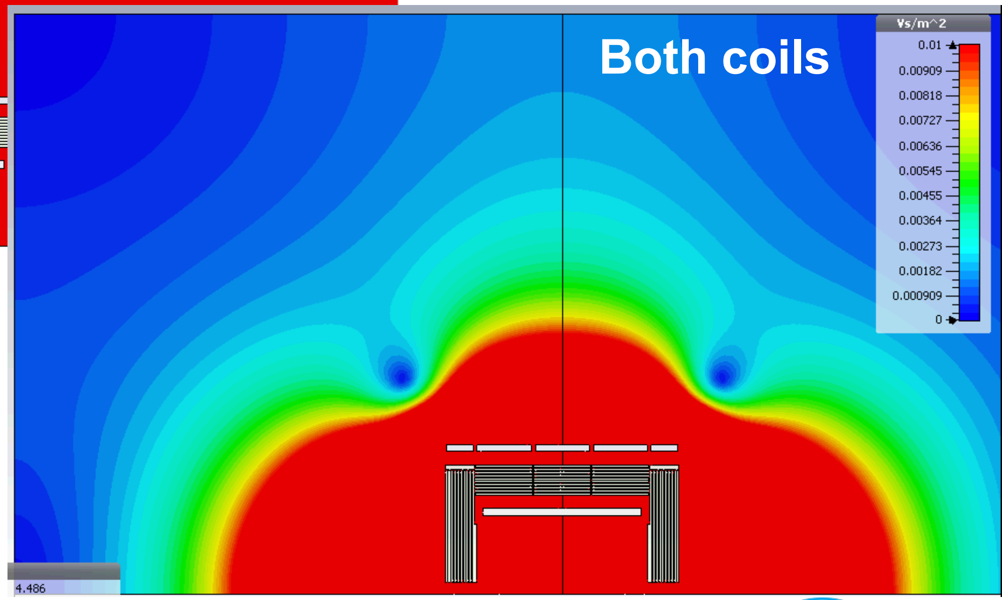


- Stray field reduced by compensating coils
- Could be tuned, less dependent on field calculations
- Reasonable choice of outer coil radius, not optimized

Inner Yoke with Compensating Coil







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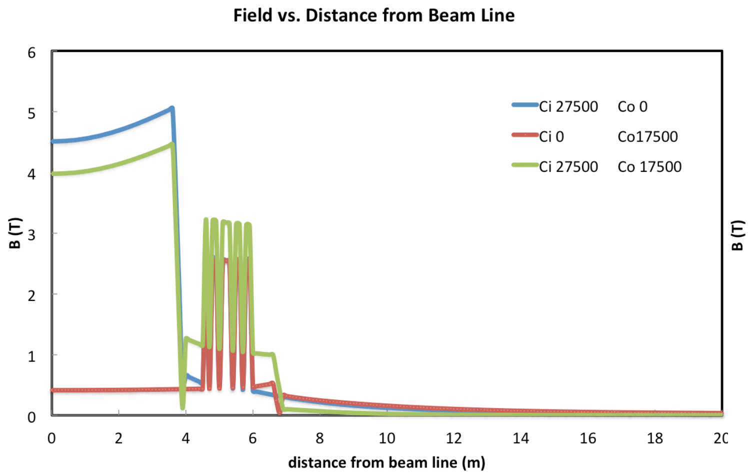
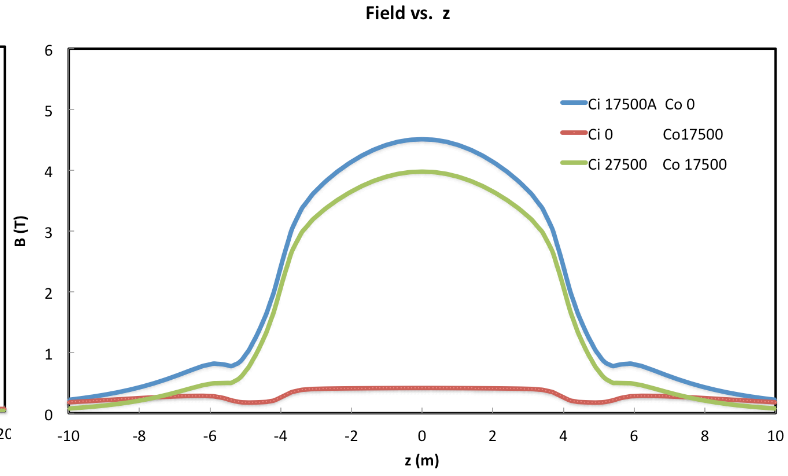
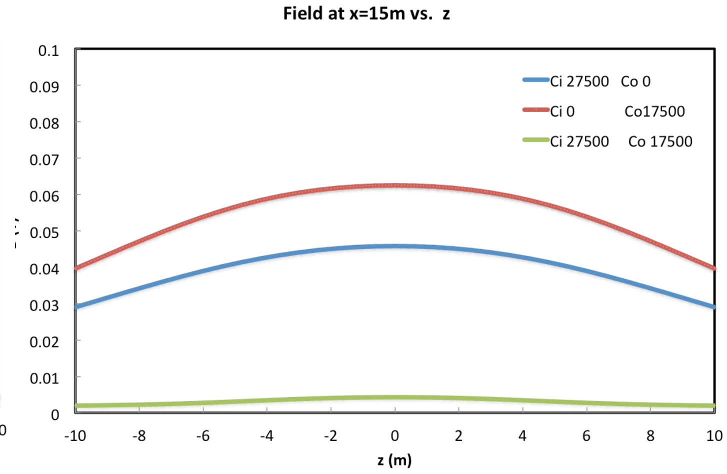
Inner Yoke with Compensating Coil







Rough cost estimate (MILCU)

	Present design	Inner yoke compensating coil	
		SC coil	NC coil (Cu)
Inner coil	43	46	46
Outer coils	-	51	18 (34) 17(8.7)MW, 9(4.5)MILCU/y
Yoke	81	24	24
Support	12	12	12
Sum	136	133	100 (116) power bill 90(45)MILCU 10y

In addition

- Some radiation shielding (concrete)
- Infrastructure, larger cooling or cryo plant

Electricity cost assuming:
ILC 80%, push pull 50%, 15ct/kWh

Conclusions

- Field calculations now quite consistent
- Stray field increase due to more realistic FEM mesh
- No significant improvement with alternative geometries
- Stray field 5 – 6 mT at 15m from beamline
- Some optimization still possible
  - Could reduce size of gaps on side facing other detector,…
- Field compensation by outer solenoid
  - Double solenoid w/o yoke no option
  - Inner yoke with compensation ???
- B field in tracking region
  - Make sure to use proper field calculations
  - Forces could be reduced by shorter coil
- Should include hall items in field calculations (platform,…)