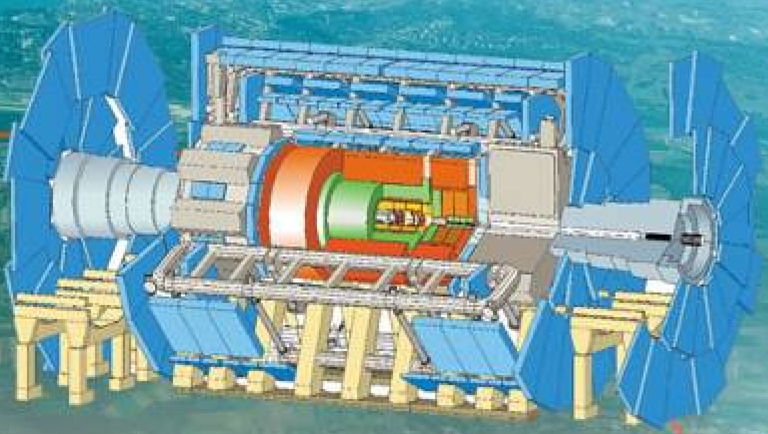
Design and realization of the ATLAS Magnets S
- options for LHeC -

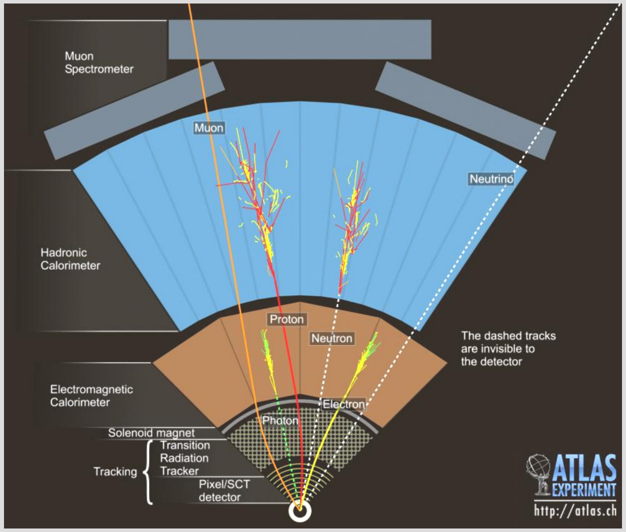
Herman ten Kate

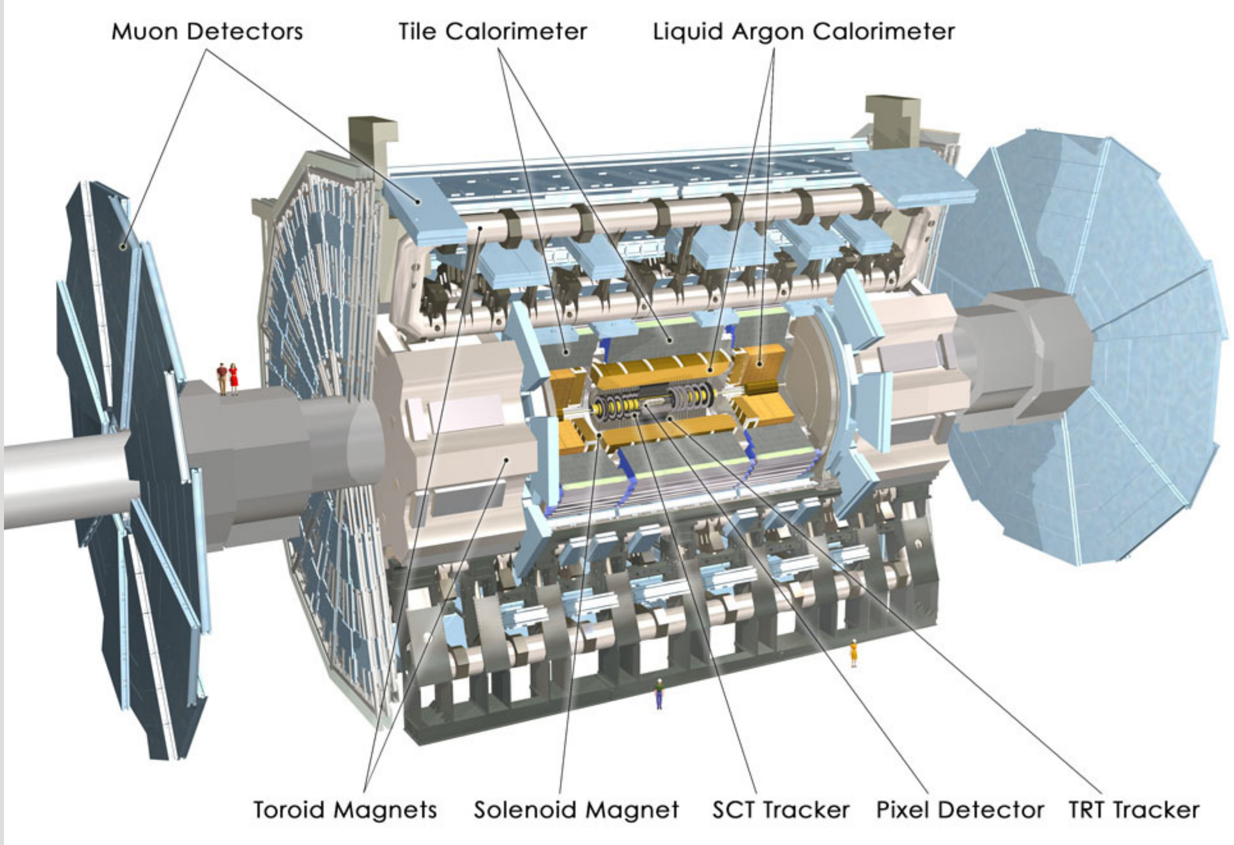


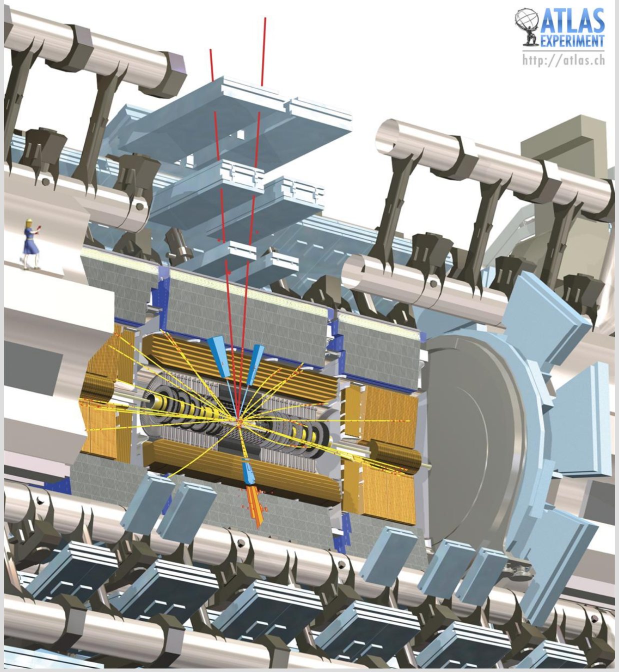
Content: ATLAS and the LHC
- Inner trackers Solenoid
- Muon system Toroids
- Planning & Cost
- LHeC magnet issues

LHeC workshop Divonne 2 Sep 08

ATLAS particles detection





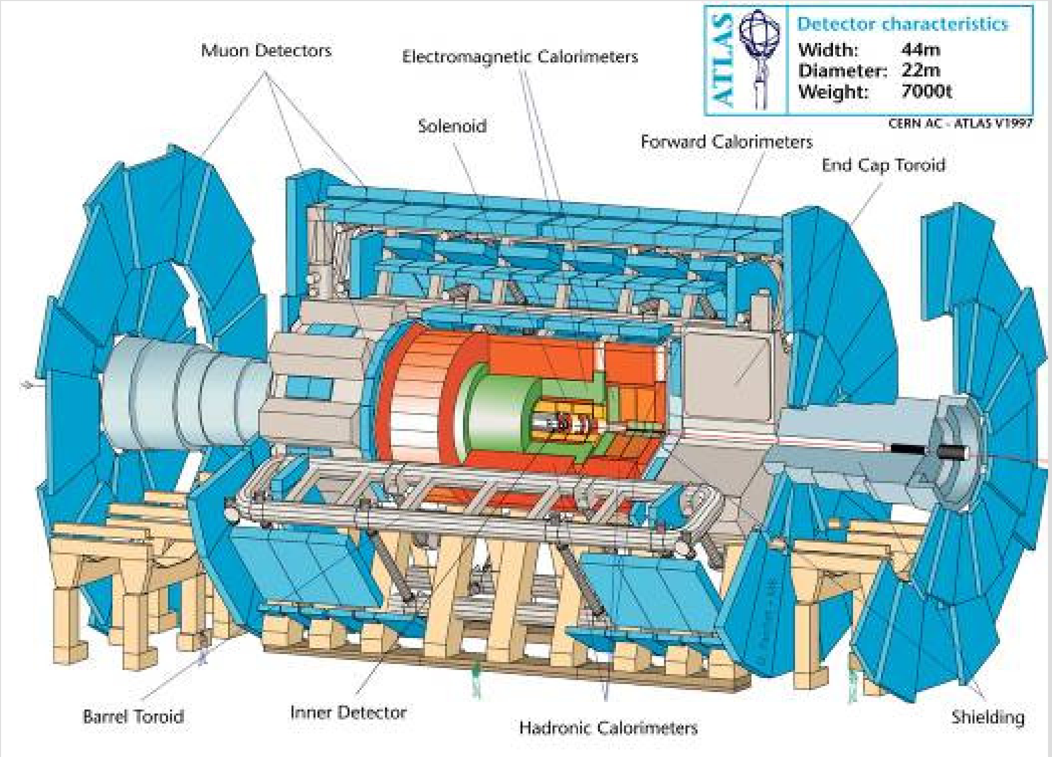


Charge identification and momentum measurement require curved trajectories of collision products, thus magnetic field

Solenoid for Inner trackers, Toroids for outer muon tracing (example Higgs event)

ATLAS superconducting magnets

- 1 Barrel Toroid, 2 End Cap Toroids and 1 Central Solenoid
- 4 magnets provide 2 T magnetic field for the inner detector (solenoid) and ~1 T for the muon detectors in blue (toroids)
- 20 m diameter x 25 m long
- 10000 m^3 volume with field
- 170 t superconductor
- 700 t cold mass
- 1320 t magnets
- 7000 t detector
- 90 km superconductor
- 20.5 kA at 4.1 T
- 1.6 GJ stored energy
- 4.7 K conduction cooled
- 9 yrs of construction 98-07



- **So far the largest trio of toroids ever built**

Why superconducting magnets?

Technology drivers

momentum resolution

- depends on sagitta term

$$s \approx {qBL^2}/{8\,p}$$

transparency

- reduction of material
- choose low X_0 materials

detector configuration

- determines magnet configuration

cost

- construction
- operation, MW installed

Solutions

- ✓ high field
- ✓ large volume

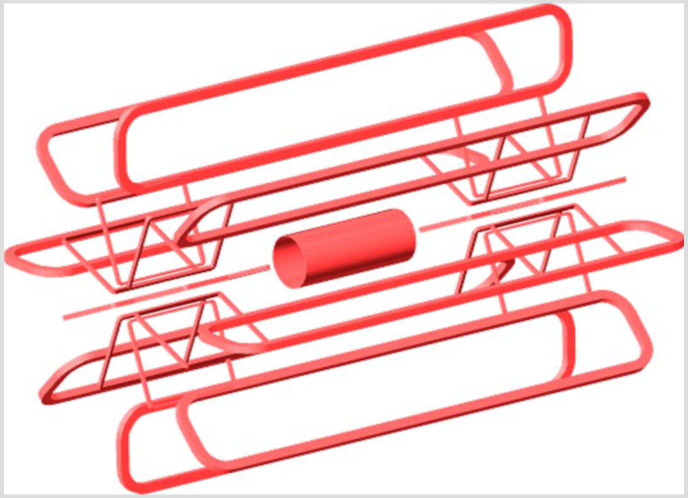
- ✓ superconducting
- ✓ aluminum alloys
- ✓ dipole spectrometer
- ✓ solenoid or toroid
- ✓ forward/backward symmetry

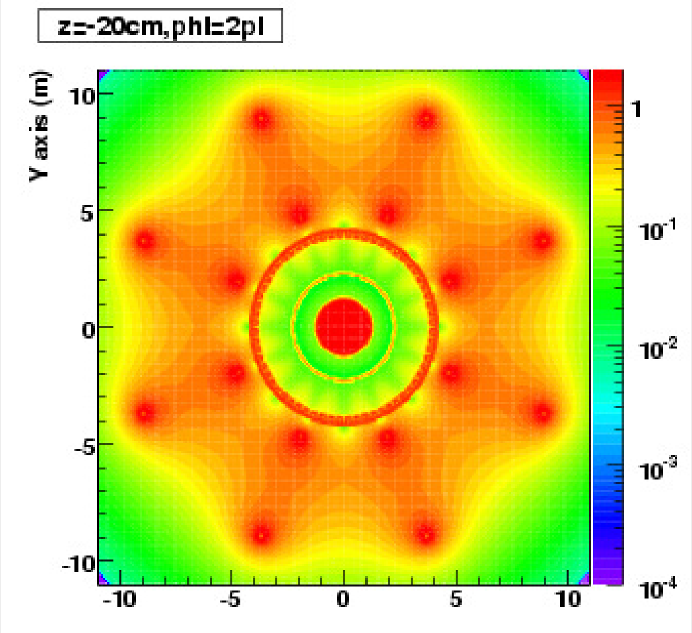
- ✓ conductor, cryostat, iron yoke
- ✓ water or helium cooling

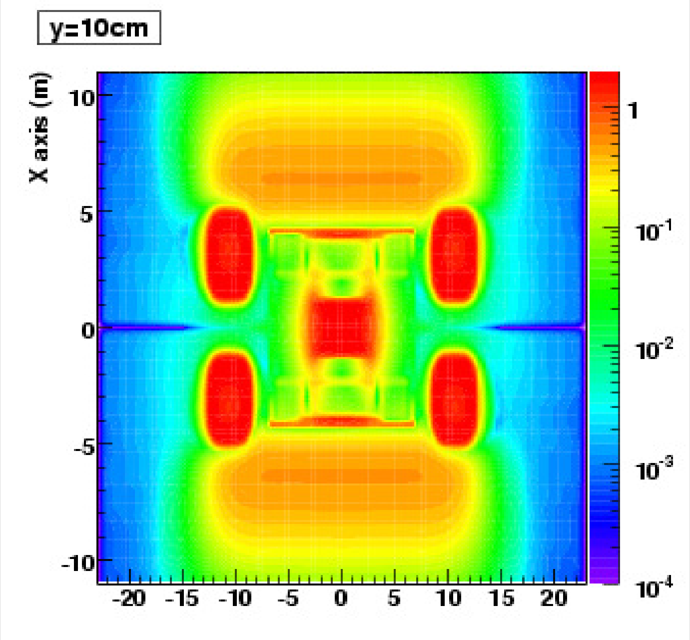
Magnetic field configuration

- 2 T in solenoid closed via return yoke
  2.6 T peak in windings
- ~0.8 T average in Barrel Toroid torus
- 3.9 T peak in windings
- ~1.3T average in End Cap Toroid
- 4.1 T peak in windings

✓ Magnetically uncoupled

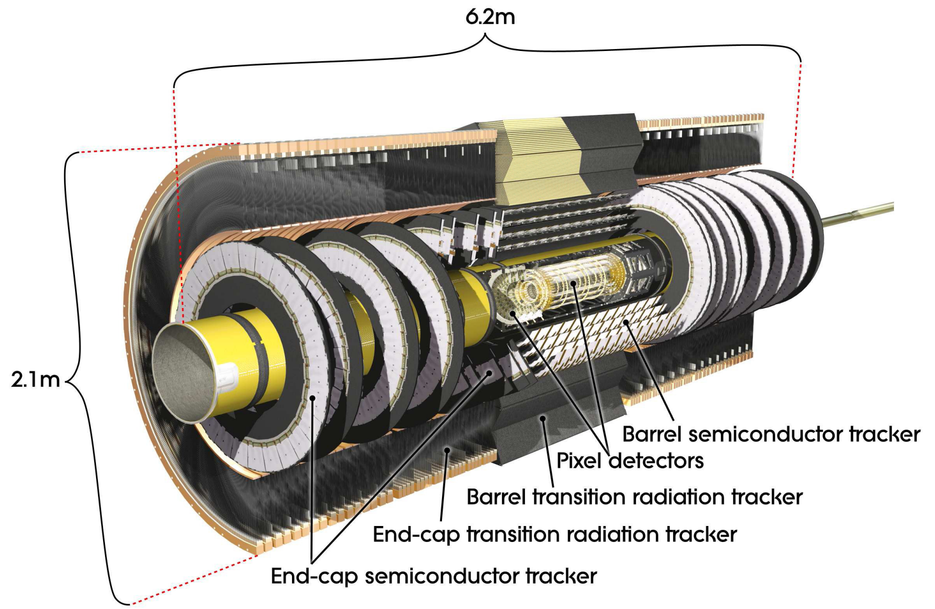


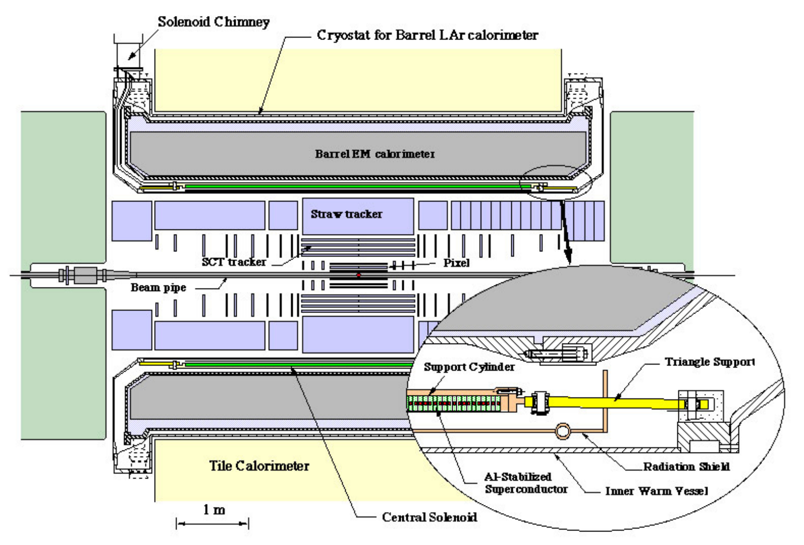


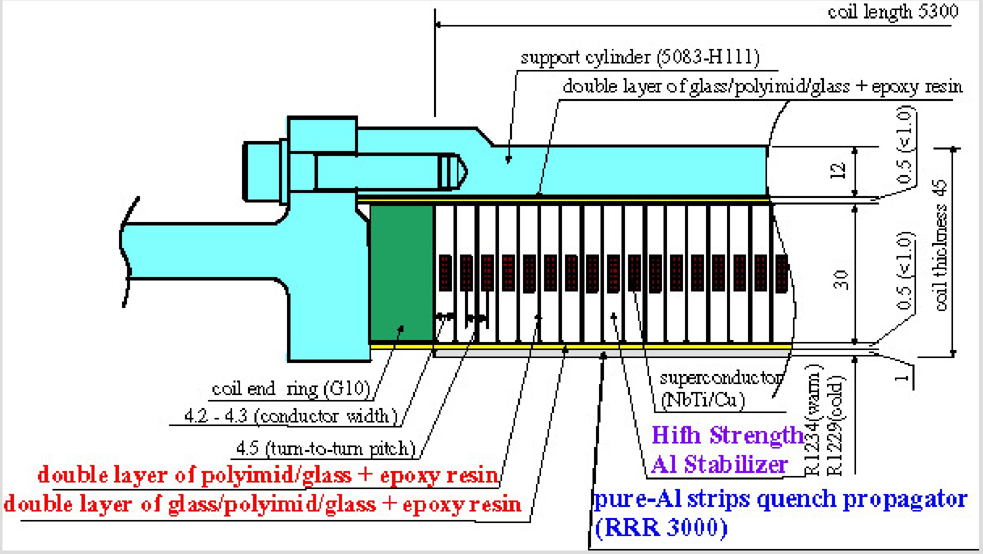


ATLAS Inner Detector Solenoid

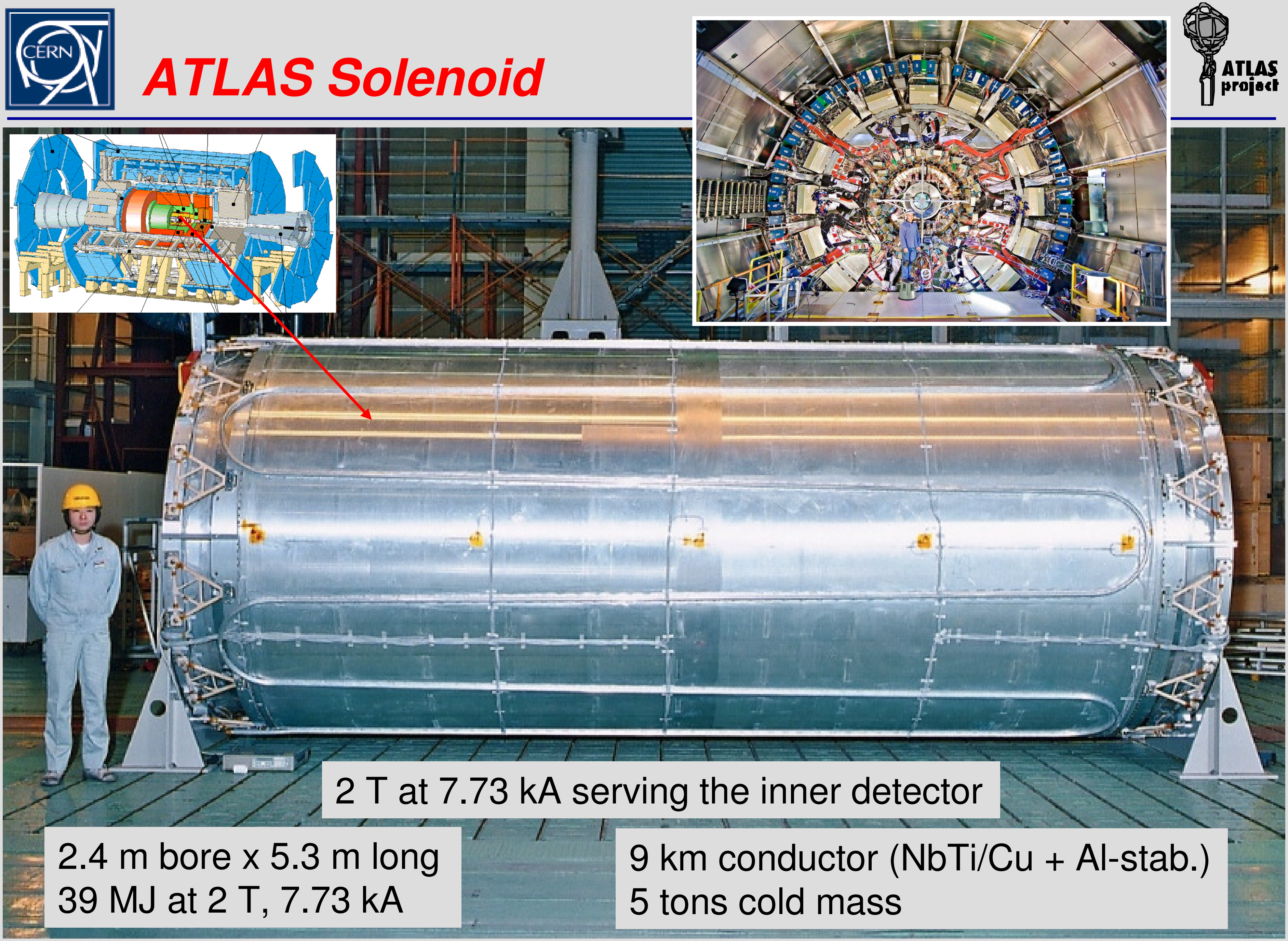
- Maximum transparency for reaching calorimeters
- Do thin and light!
- ✓ High-strength 30mm Al plated NbTi conductor in side 12mm thin Al5082 support cylinder
- ✓ Common cryostat with LiAr calorimeter







ATLAS Solenoid



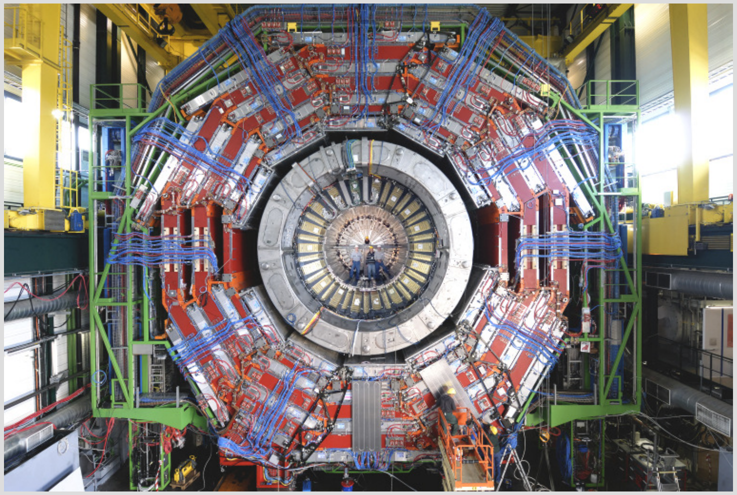
2 T at 7.73 kA serving the inner detector

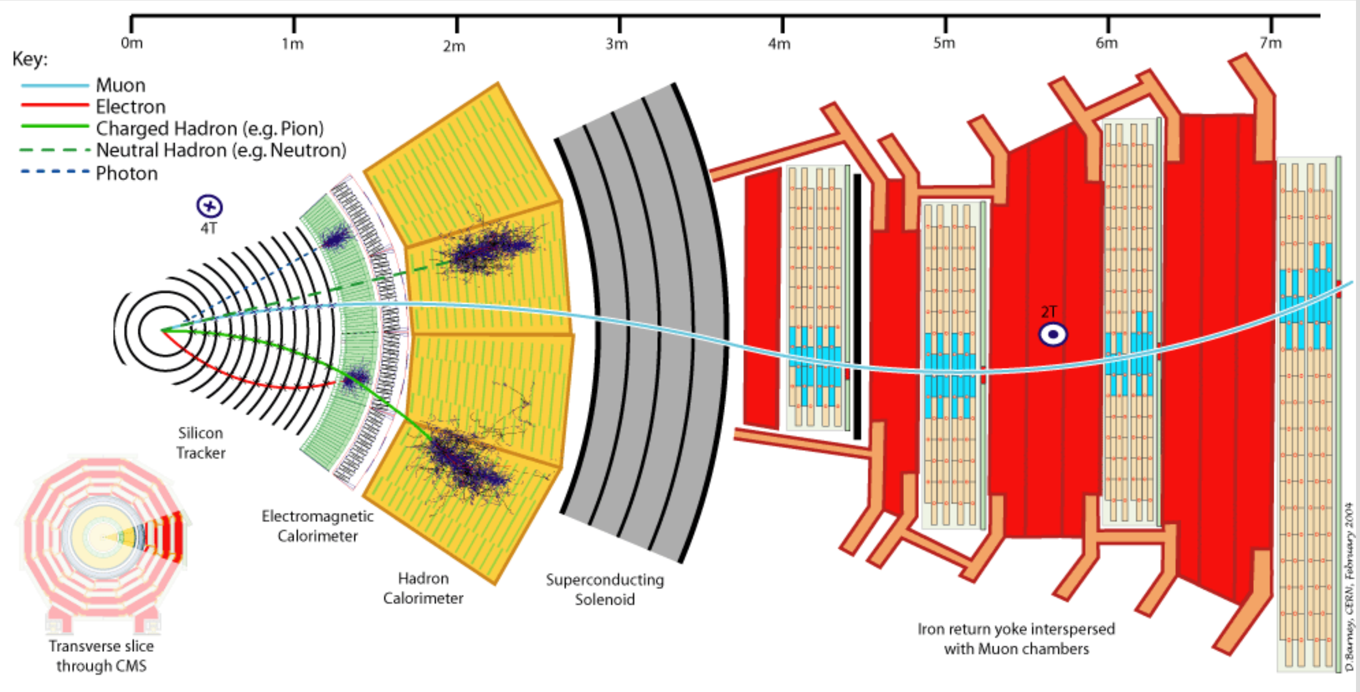
2.4 m bore x 5.3 m long
39 MJ at 2 T, 7.73 kA

9 km conductor (NbTi/Cu + Al-stab.)
5 tons cold mass

CMS Compact Muon Solenoid

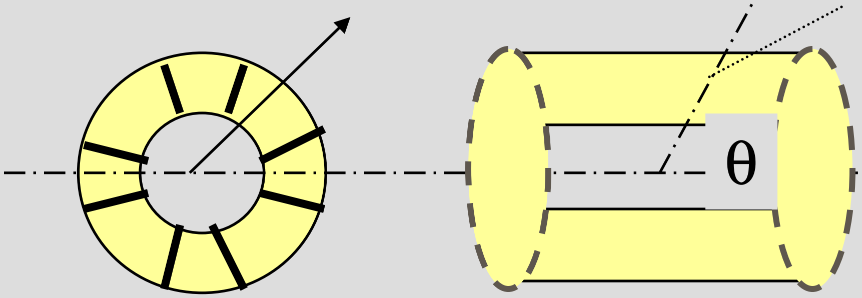
- 16 m diameter x 21 m long
- 12500 tons total weight
- 6 m diameter x 12 m long
- 4 T at 19.5 kA
- 2.7 GJ stored energy
- 220 t cold mass, 4 layers, 5 segments

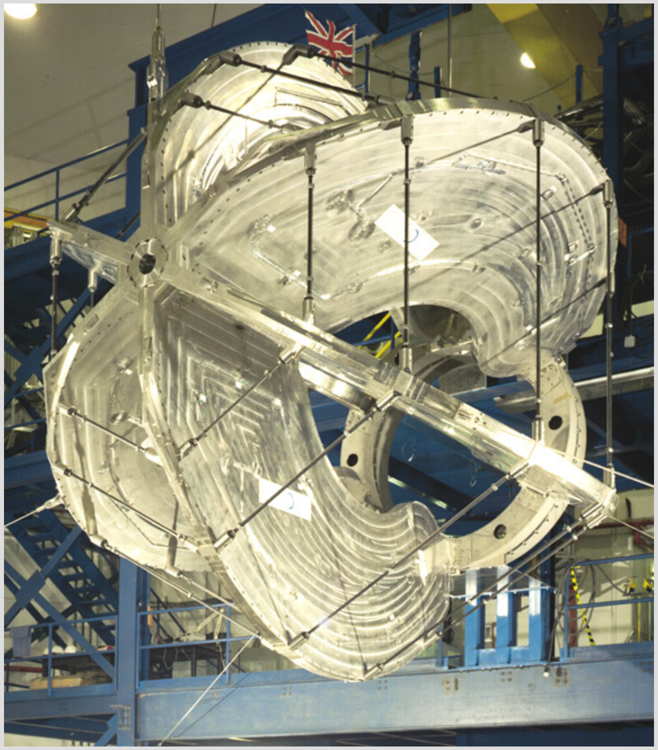




Toroïdal magnets

- Resolution
  - inside toroid: $dp/p \sim \sin\theta \{B_\varphi \cdot R_{in} \cdot \ln(R_{in}/R_{out})\}^{-1}$



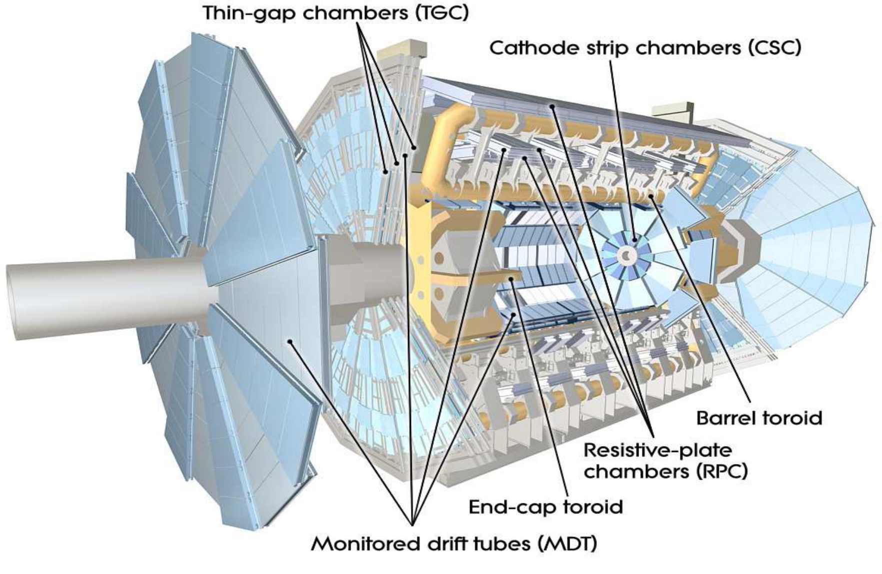


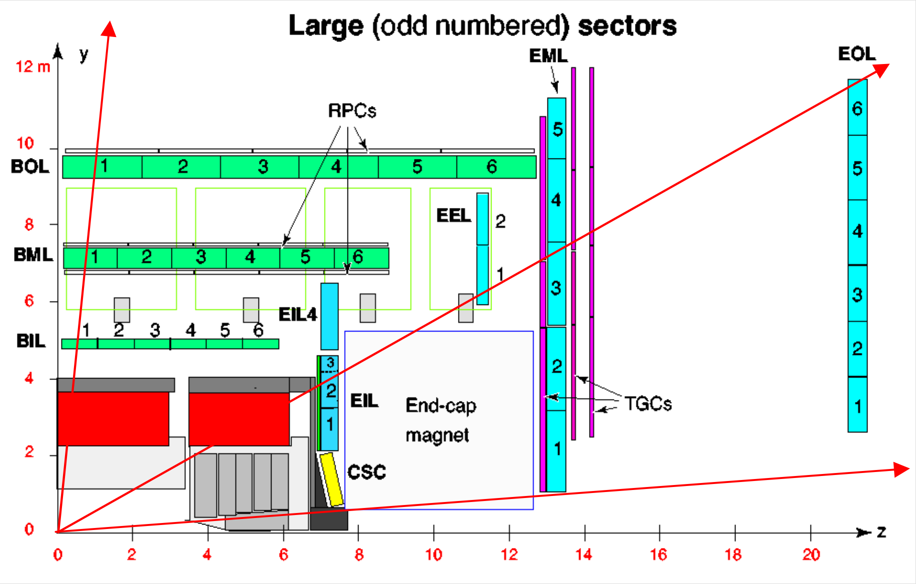
CLAS/CEBAF 1995

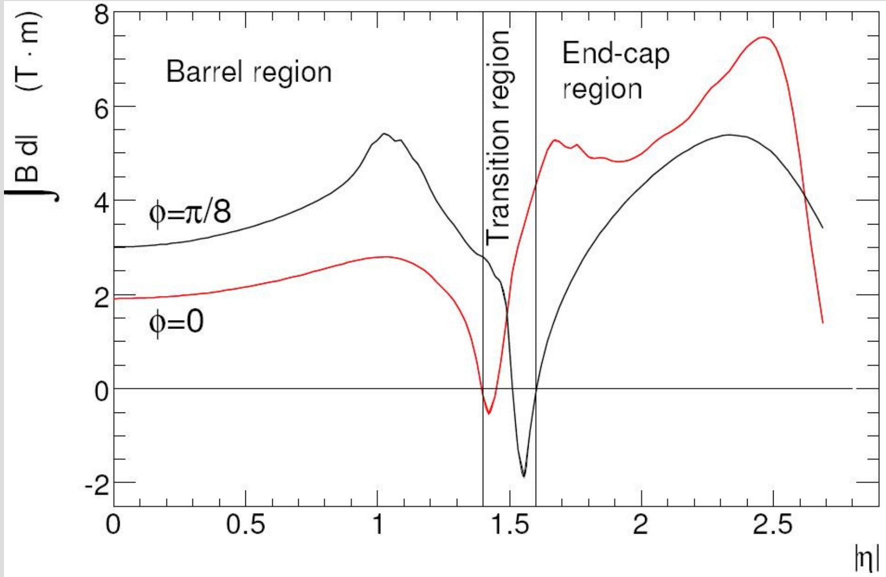
- Magnetic field & symmetry
  - tangential field ($\propto 1/r$)
  - field lines perpendicular to particle path
  - closed field, centred on and circulating around beam, no influence on beam
  - no stray field, no iron yoke required
- Installation
  - Supports between coils required to keep integrity

ATLAS Muon system

- Designed for maximum bending power in large volume
- In radial direction (barrel) and forward direction (end caps)
- High field integral in particular in forward direction, better than solenoid







ATLAS Toroid Magnet

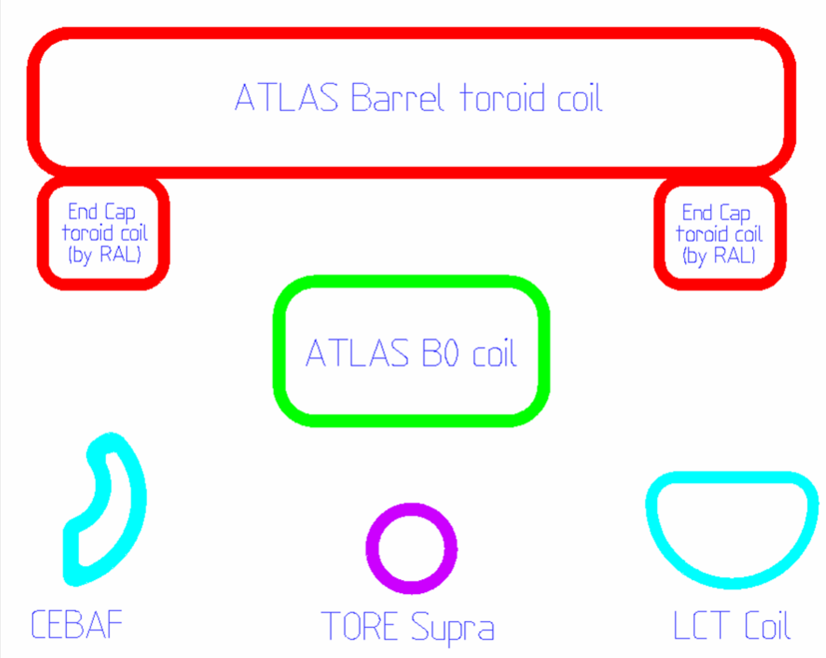
Record size!

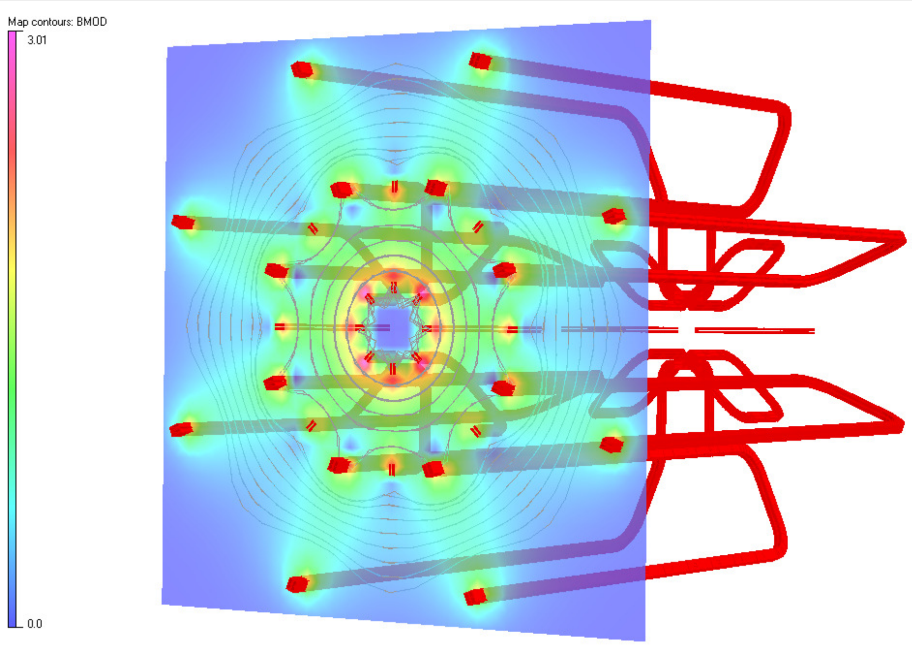
- Scaling up risk reduced with extra-step model coil

Optimization of field uniformity and access versus cost: 6-**8**-10-12 coils

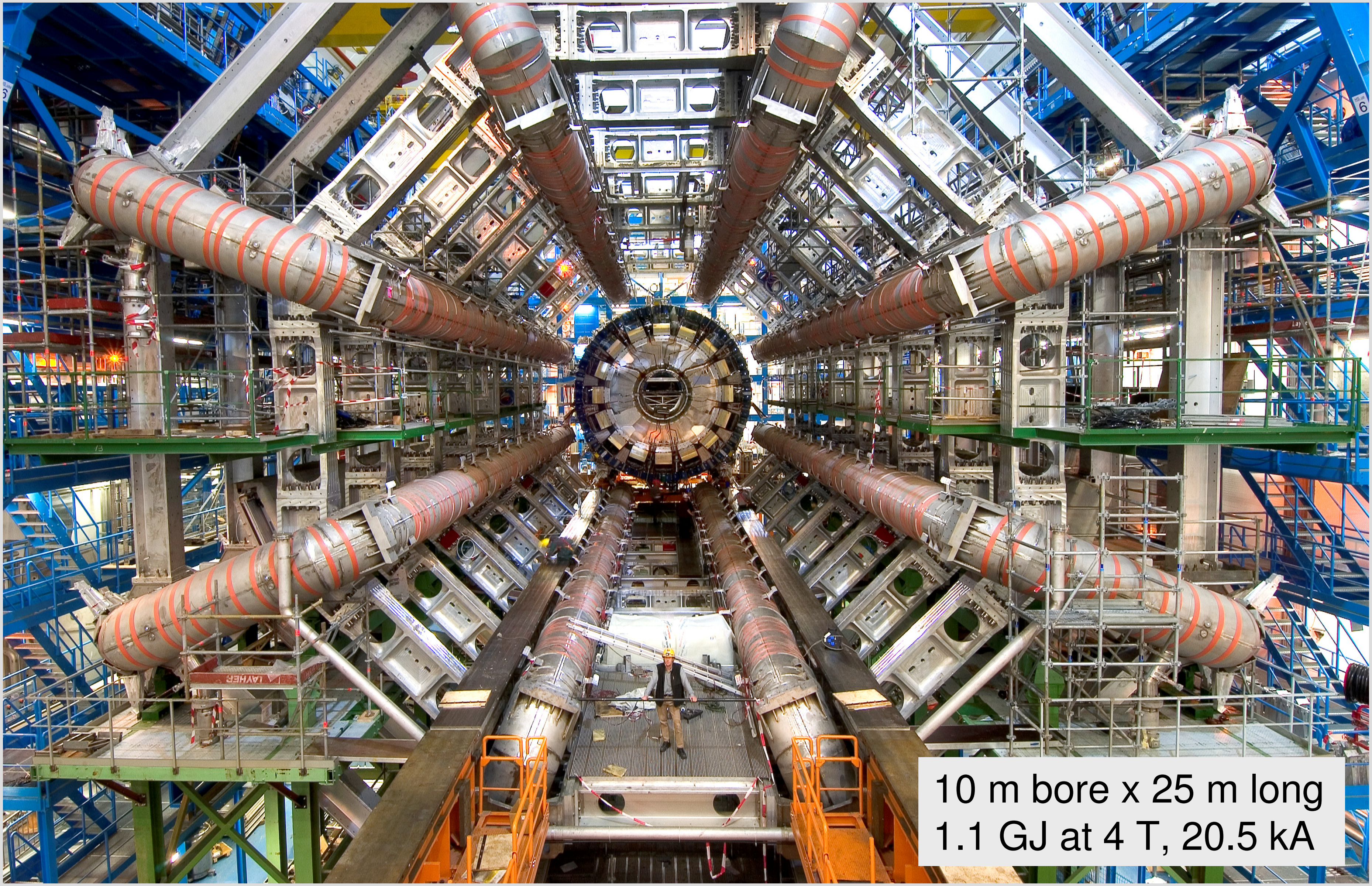
- same ampere-turns
- less cryostats

- high peak to operating field ratio
- large field volume: ~10000 m^3
- open structure for detector, cryostat occupies ~2% of total volume
- good resolution at small forward angles >8^{o}





Bare Barrel Toroid in cavern (Nov 05)



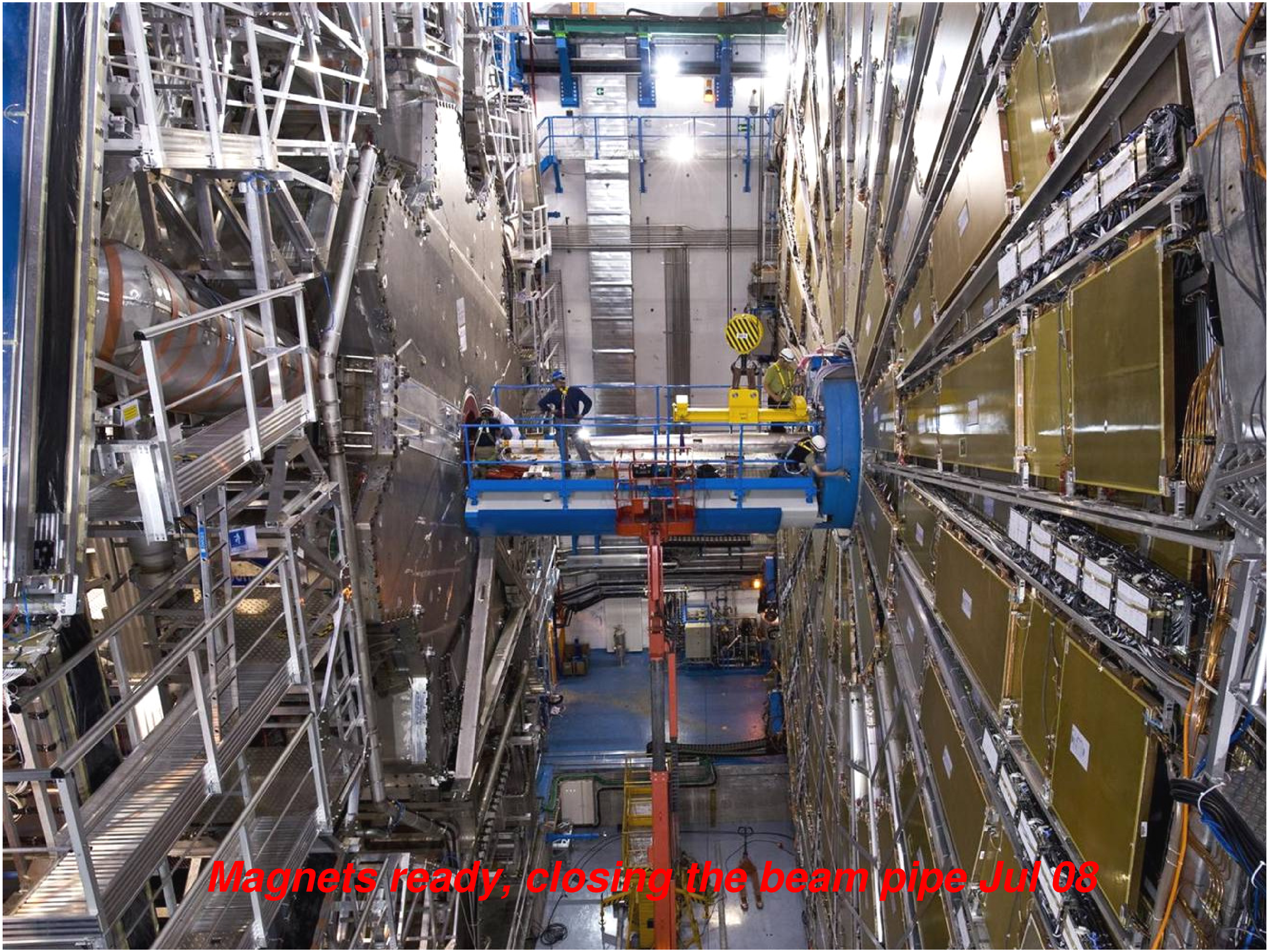
10 m bore x 25 m long
1.1 GJ at 4 T, 20.5 kA

End-Cap Toroids for forward direction

2 x 8 coils 4 x 4.5 m^2

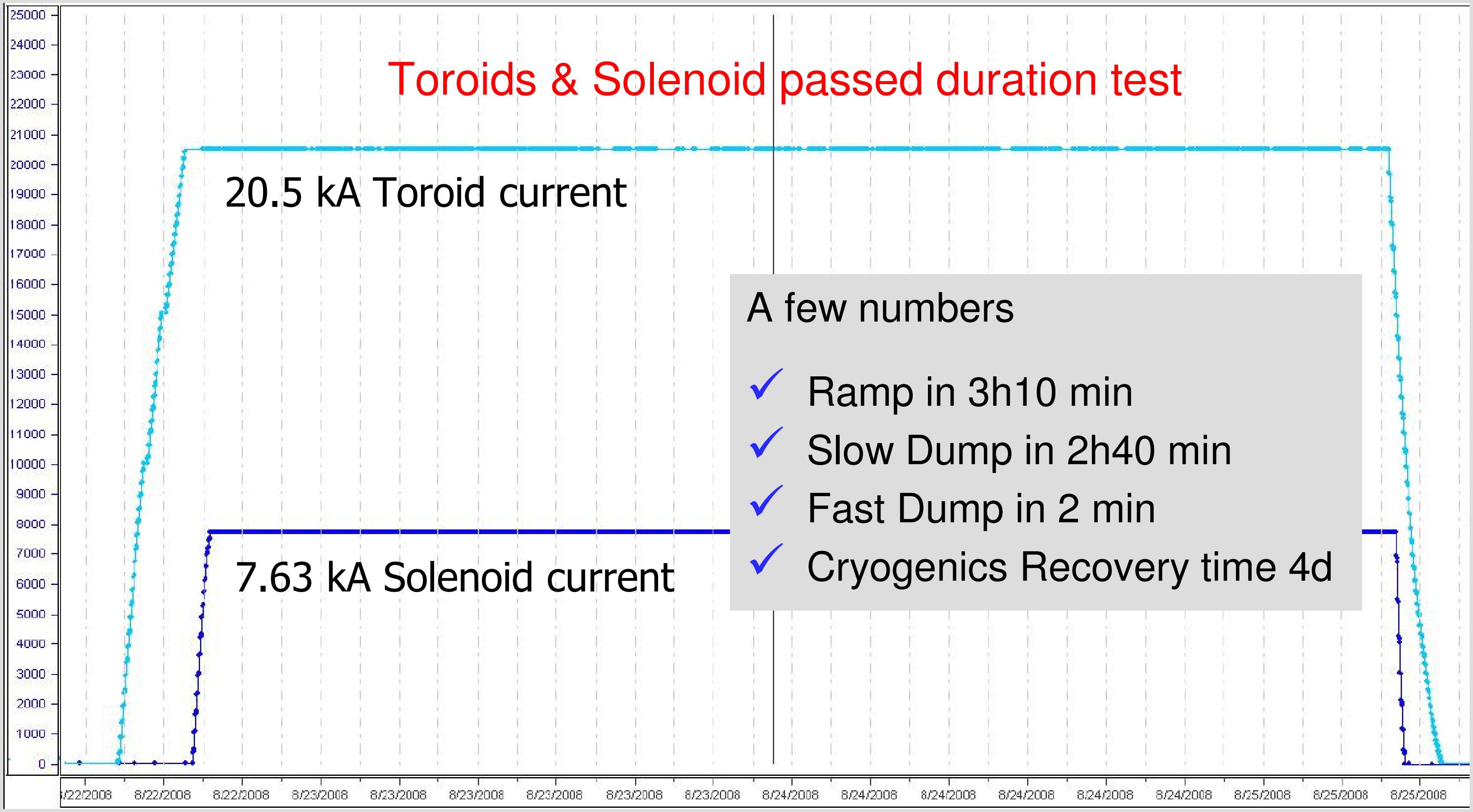
20 kA, 4.1 T, 250 MJ

140 t cold mass



Magnets ready, closing the beam pipe Jul 08

And.......it works !



Toroids & Solenoid passed duration test

20.5 kA Toroid current

7.63 kA Solenoid current

A few numbers

- ✓ Ramp in 3h10 min
- ✓ Slow Dump in 2h40 min
- ✓ Fast Dump in 2 min
- ✓ Cryogenics Recovery time 4d

- ramp to full field on 22 Aug, slow dump on 25 Aug 08
- 3 days duration test completed
- ✓ system works fine and is now ready for continuous operation

Time span

Concepts, seeking consensus	1990-1993
Pre-design	1993-1994
Engineering design LHCC approval	Sept 1997
First contract with for superconductor	Dec 1997
Industrial components production	1998-2005
Integration at CERN	2002-2006
Integration and installation	2005-2007
Installation completion	Dec 2007
Test and commissioning	2006-2008
Stable operation	Aug 2008

- And another 10-15 yrs M&O depending on physics results……..

Cost

	Total in MCHF
Barrel Toroid	80
End Cap Toroids	37
Central Solenoid	11
Vacuum, Cryogenics, Current & Controls	$\underline{31}_{+}$
Recognized total cost by ATLAS	159 MCHF
Initial budget, no reserve, no inflation correction	137
✓ Extra cost across 10 yrs of construction, only:	22 (16%)
✓ ~ 65% was financed and produced as in-kind contributions, worked fine!	
Free contributions, hidden and cheap manpower, and cost savings through simplifications:	~ 40
True cost of original design (already anticipated in 1996!):	~ 200 MCHF

✓ Financially the project was concluded in a satisfactory way

LHeC ep detectors THERA-like design ?

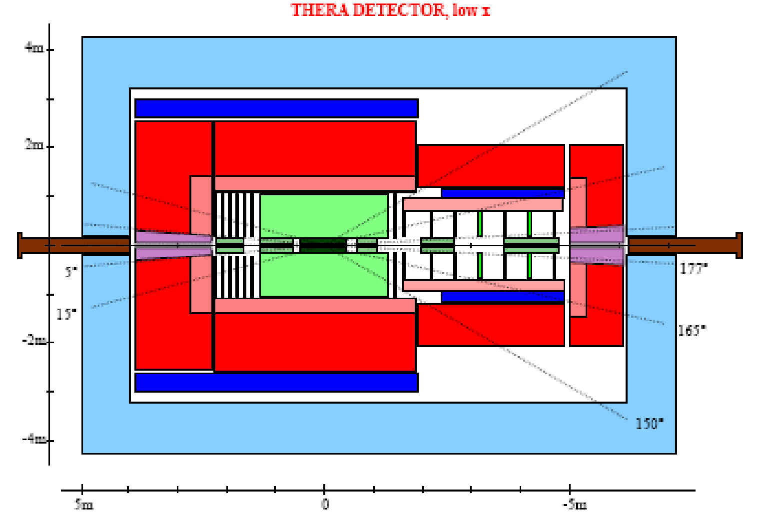
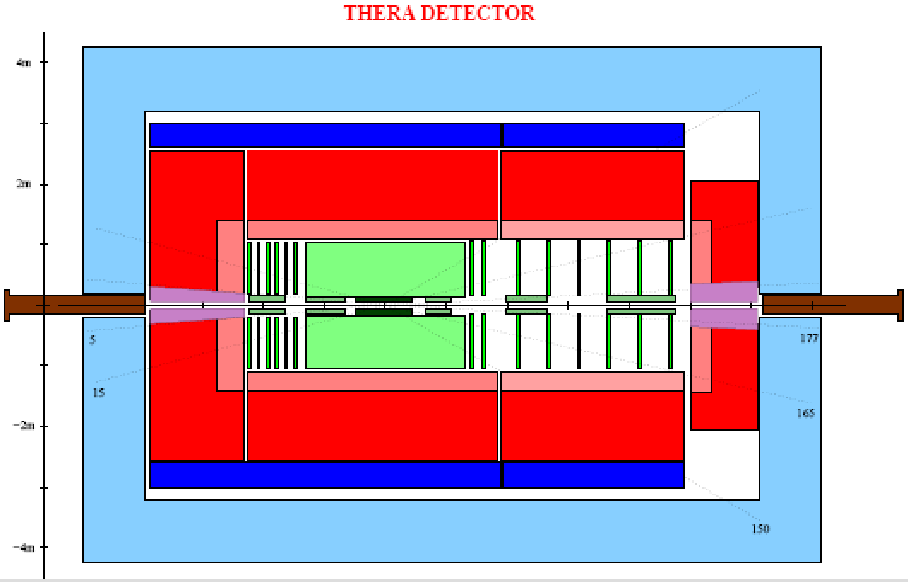
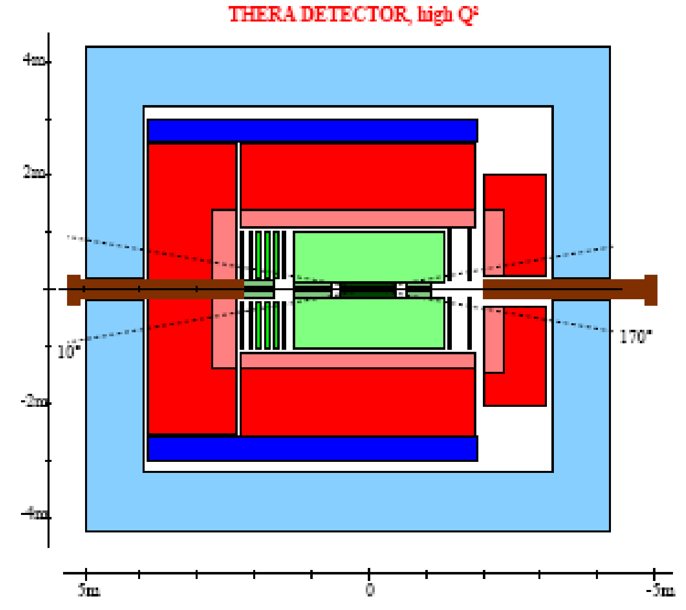


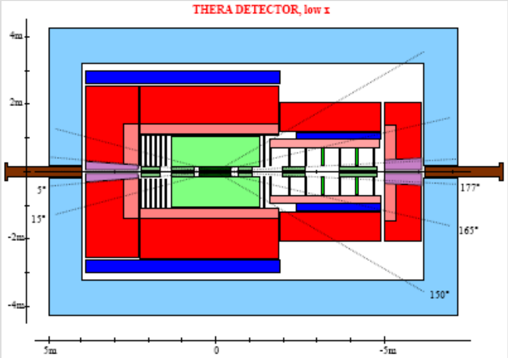
Figure 2.3.4: *Basic design of the THERA detector in the low-x configuration. The electrons enter from left, the protons from right. Around the beam-pipe, modules of 6-inch silicon strip detectors are positioned (dark-green). Tracking is complemented by planar and circular track chambers (light-green). Electromagnetic (pink) and hadronic (red) calorimetry ensures hermetic, accurate reconstruction of the final-state energy depositions. A homogenous, solenoidal field over 9 m length is provided by the large-diameter H1 coil and the smaller ZEUS coil (blue). The return yoke iron structure (light-blue) is instrumented for shower tail catching and muon detection. The focusing magnets (brown) are placed near the plug calorimeters (magenta).*





- Left side, low-x: low luminosity, detector close on IP
- Right side, high Q^2 option: high luminosity, quads inside detector magnet

LHeC detector magnets issues



Cost driver 1: magnetic field 2-3-4 T,

- inner radius and length, stored energy

Symmetry: 1 solenoid or 2 solenoids,

- same bore or different,
- check cost efficiency of 1 large, light solenoid (1 technology, 1 procurement and no funny forces)
- time in use, simultaneously or sequentially, adaption options

Asymmetric system:

- forces between solenoids and iron require robust in-vessel axial tie rod system and vessel-to-vessel axial force transfer supports (will work provided properly designed)
- Combinations and coupling with other magnets
- integrated dipoles and quadrupoles

Many questions to be answered to reduce options and before next steps can be done……

Conclusion

- ✓ ATLAS magnets designed, engineered, constructed, integrated and tested in a period of 15 years
- ✓ All magnets-on duration test in August 08 successful. It works!
- ✓ Thus very light large solenoids and

  huge 4 T and GJ class of superconducting toroids, conduction cooled at 4.6 K are feasible!
- ✓ Next is the start of normal detector operation with p-p collisions expected very soon……………….
- ✓ Magnets for a possible LHeC detector may be based on THERA layouts, but …..consider more options to balance physics requirements with construction, operation challenges and cost
- ✓ For a next step a list of basic requirements defining magnetic field, dimensions and symmetries should be developed