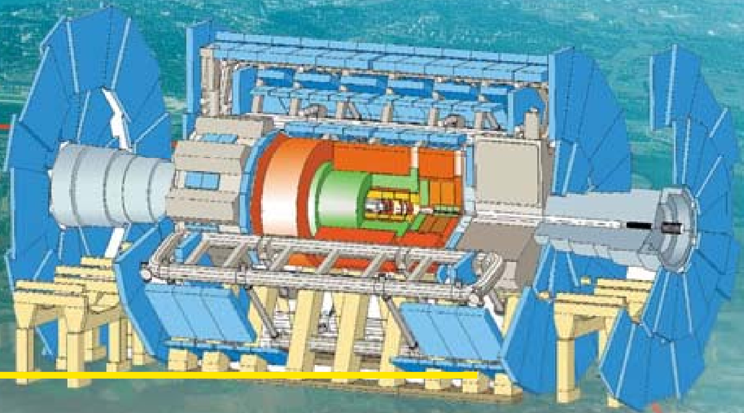
ATLAS
The World's Largest Magnet System



Roger Ruber

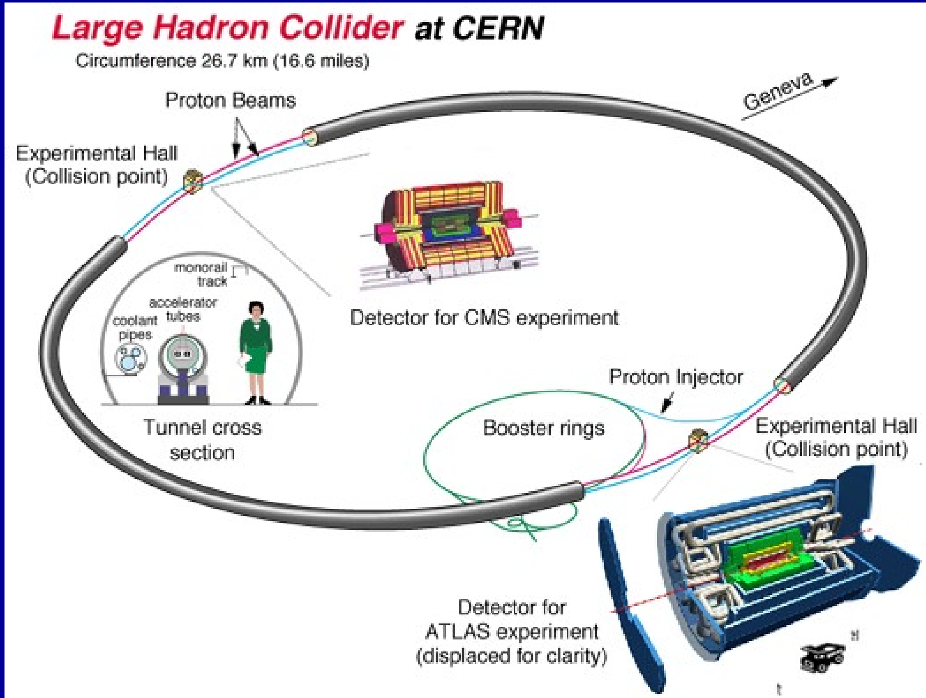
Contents:

- ATLAS & LHC
- Magnet System
- Cryogenics & Vacuum
- Current & Controls
- Conclusions

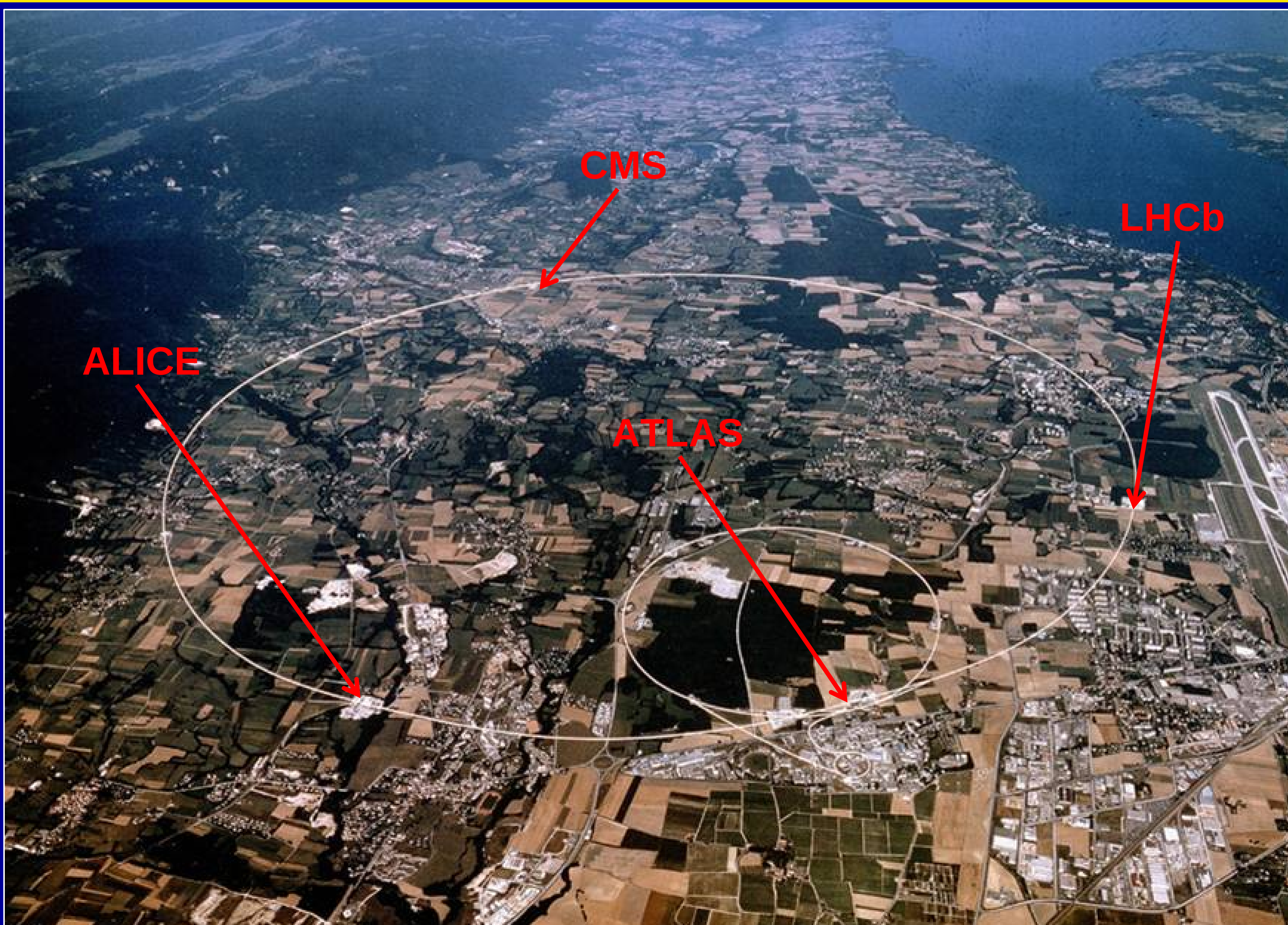
presented at Uppsala University, 8th December 2006

LHC: The Large Hadron Collider

- Circular accelerator and collider in the 27 km LEP tunnel
  - 10x higher energy
  - 100x higher luminosity then previous proton-proton colliders
- General purpose machine to study the universe
  - Unexplored aspects of the Standard Model
    - search for mass-generating mechanism: **Higgs boson**
    - search for origin of matter/antimatter asymmetry: **CP-violation**
  - Supersymmetry: a new frame-work for matter & interactions
    - many new particles within the mass scale of LHC



LHC Experimental Areas

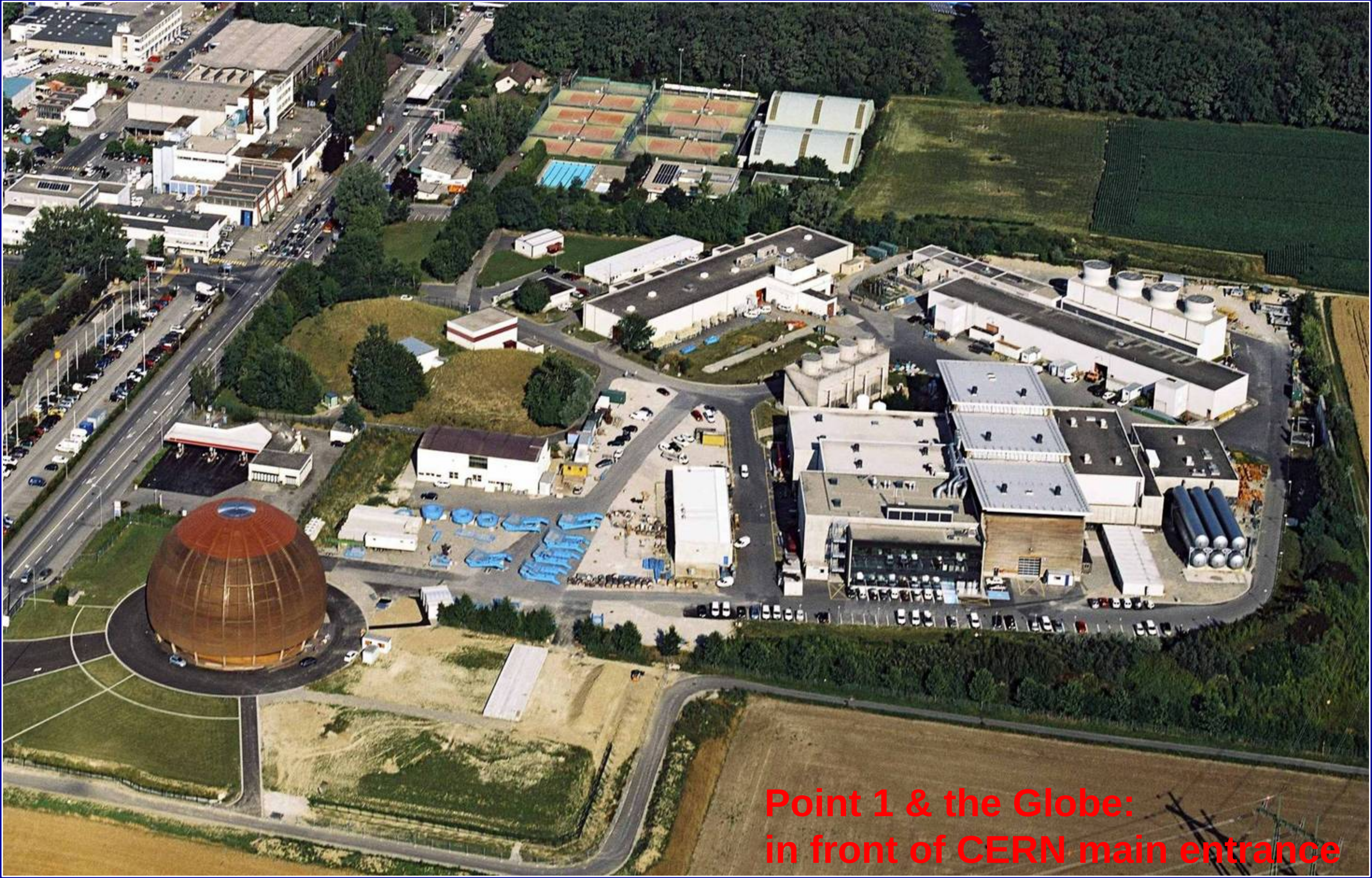


LHC Underground Installation

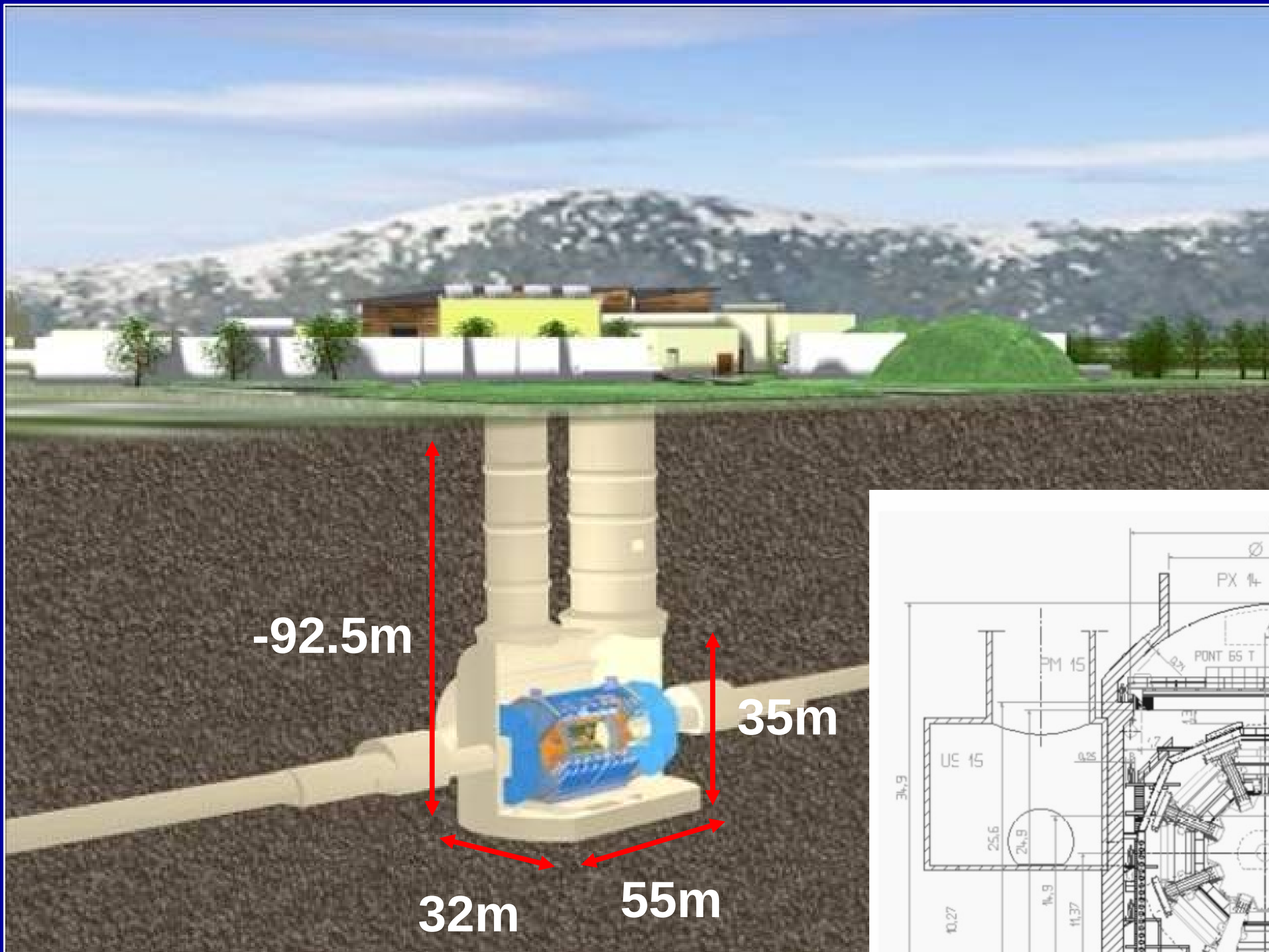
- **9135 magnets:**
  - **1232 main dipole (twins)**
  - **392 lattice quadrupole (twins)**
- **1000 main dipoles installed**
- **1 sector fully completed (interconnections)**

LHC Current Distribution Box

ATLAS Surface Buildings

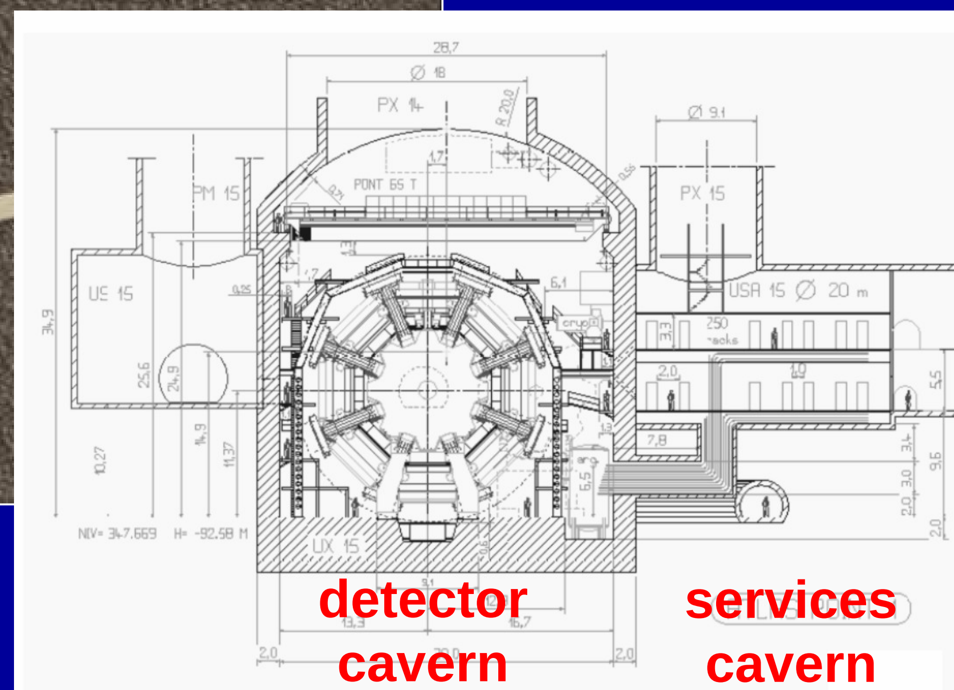


ATLAS Underground Installation



2 caverns

2 main shafts give access to 50,000m^3 cavern for detector



Cavern Preparation

Jan. 2003

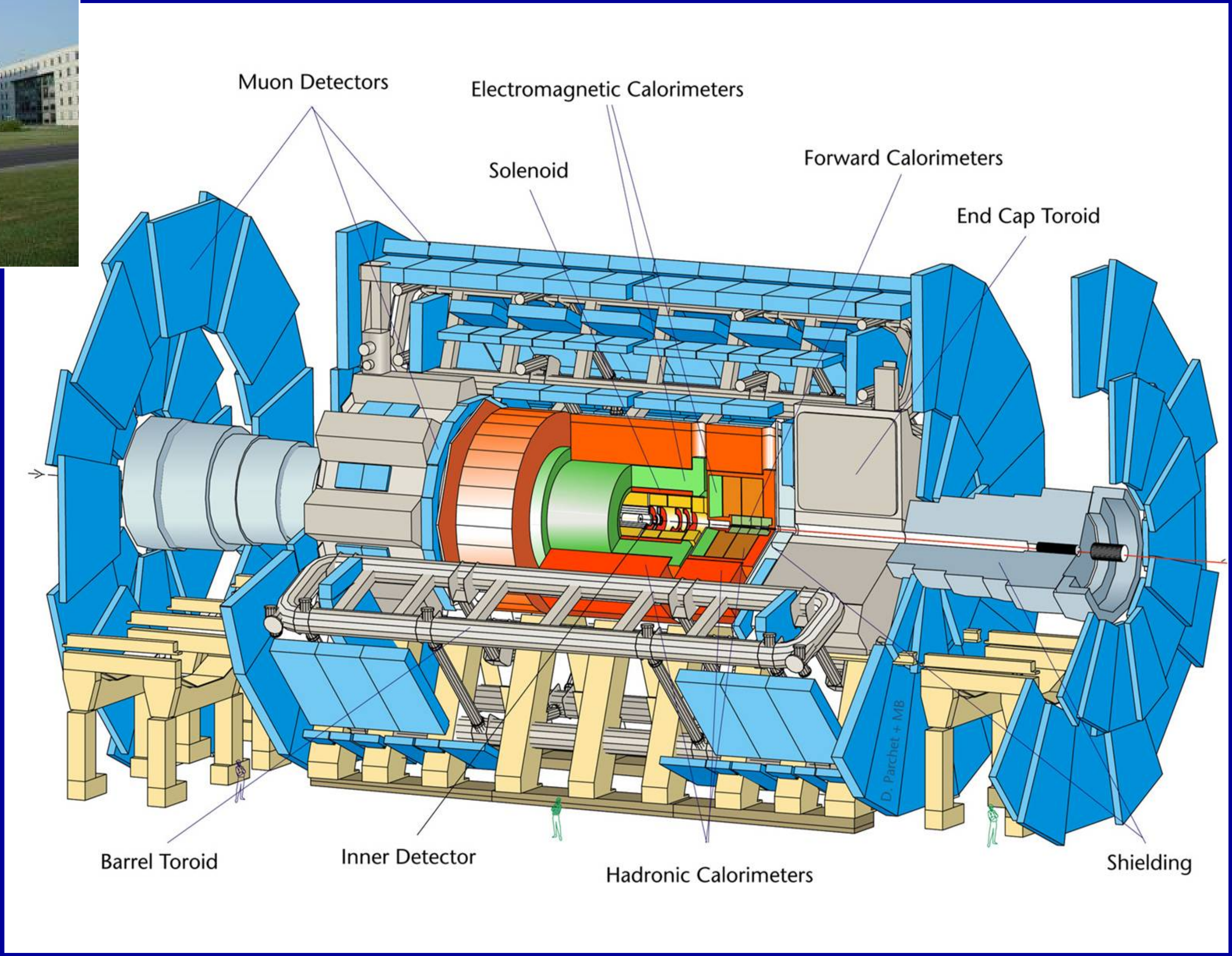
June 2003

March 2004
Ready for detector installation

The ATLAS Detector

25 m diameter
46 m length
7000 tons

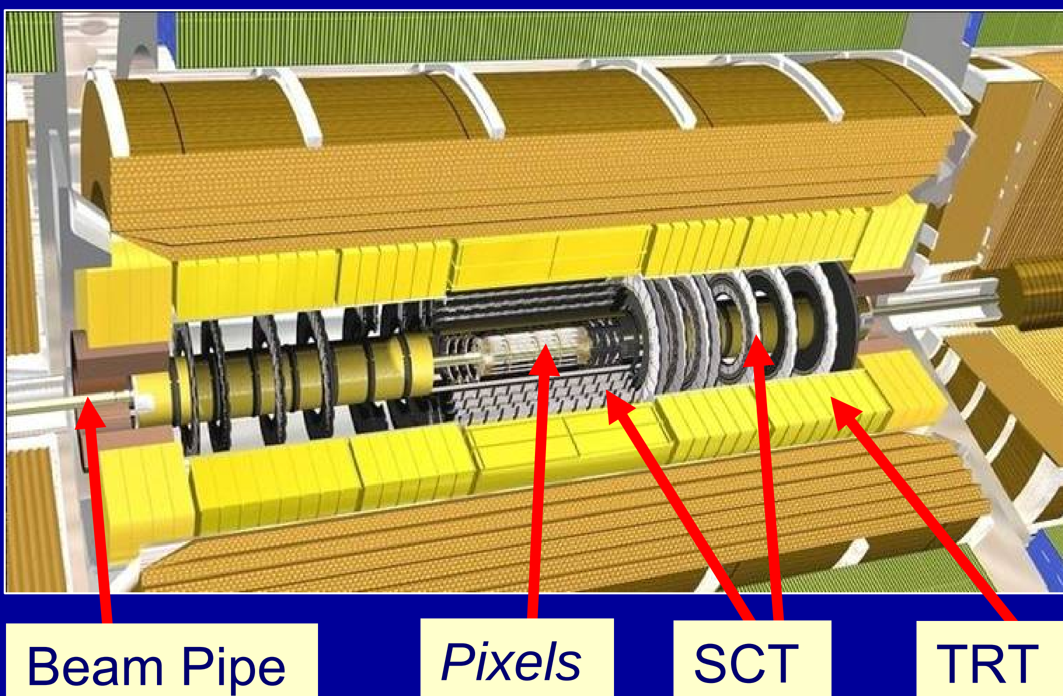
Toroids:
26 m length
1320 tons



The Inner Tracking Detectors

~6m long, 1.1 m radius

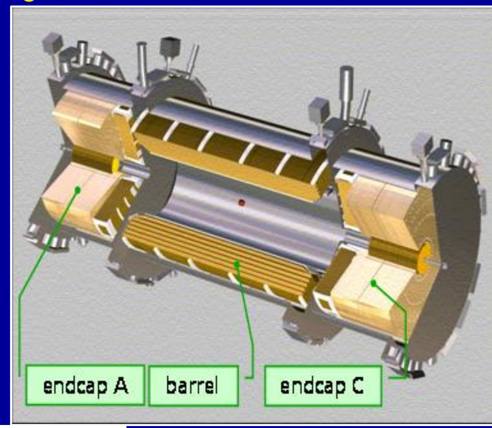
- Pixels
- Silicon Strip Tracker (SCT)
- Transition Radiation Tracker (TRT)

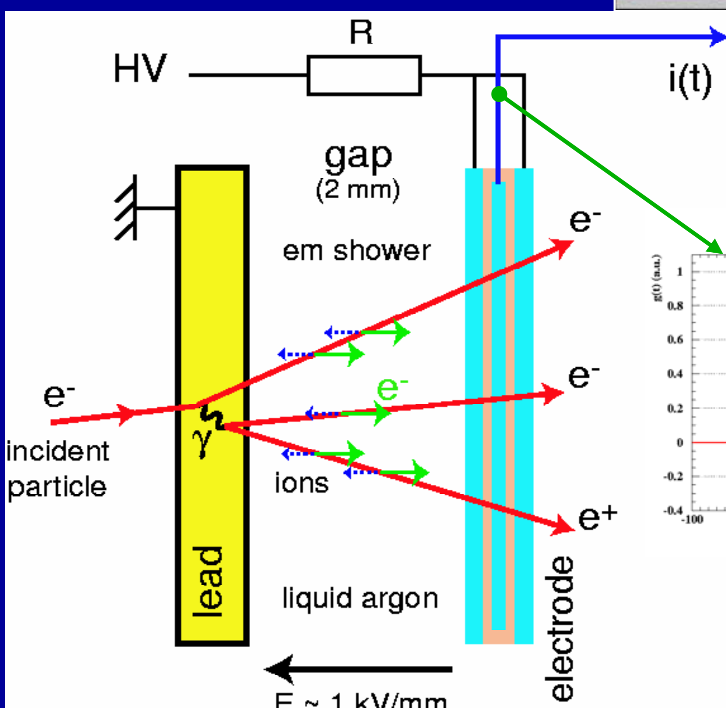


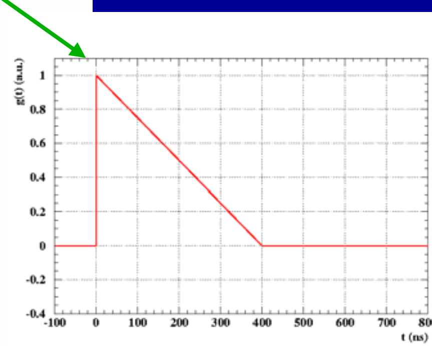
The Liquid Argon Accordion Calorimeter

E-M calorimeter (>22X_0)

- LAr as active material
  inherently linear
- hermetic coverage
  (no cracks)
- longitudinal segmentation
- high granularity
  (Cu etching)
- inherently radiation hard
- fast readout possible





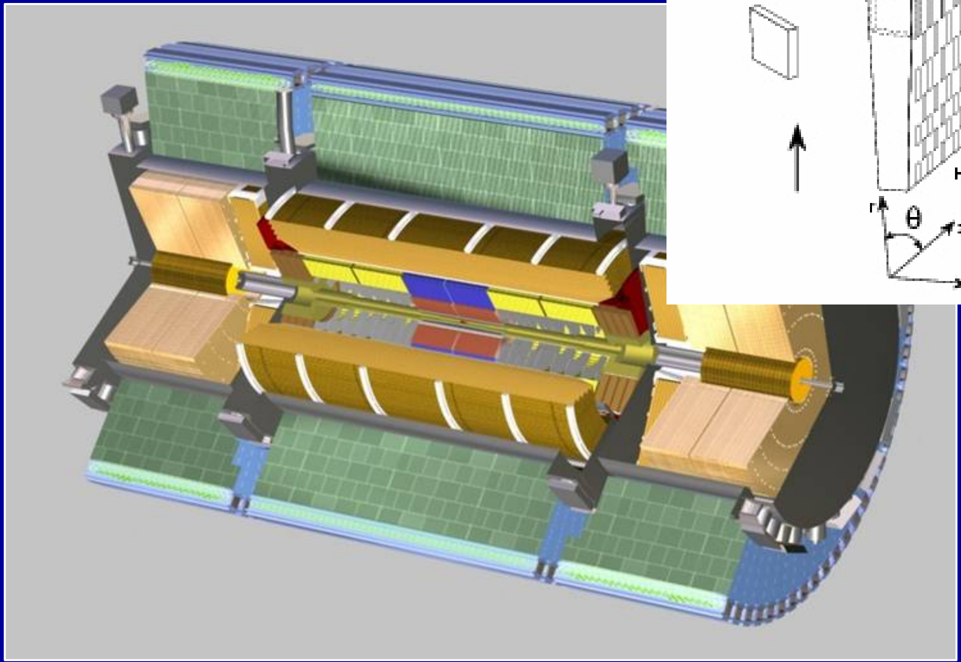


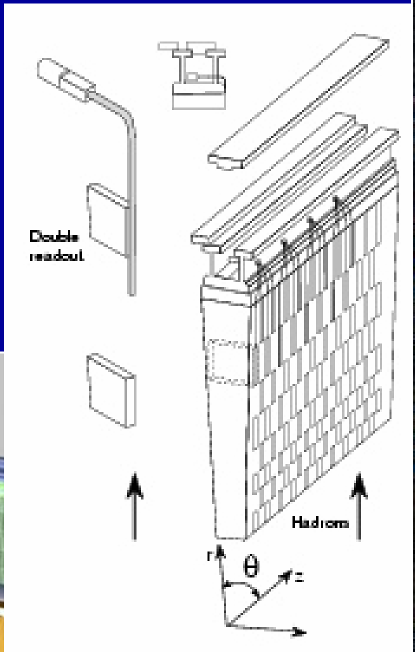
t_{drift} =450 ns

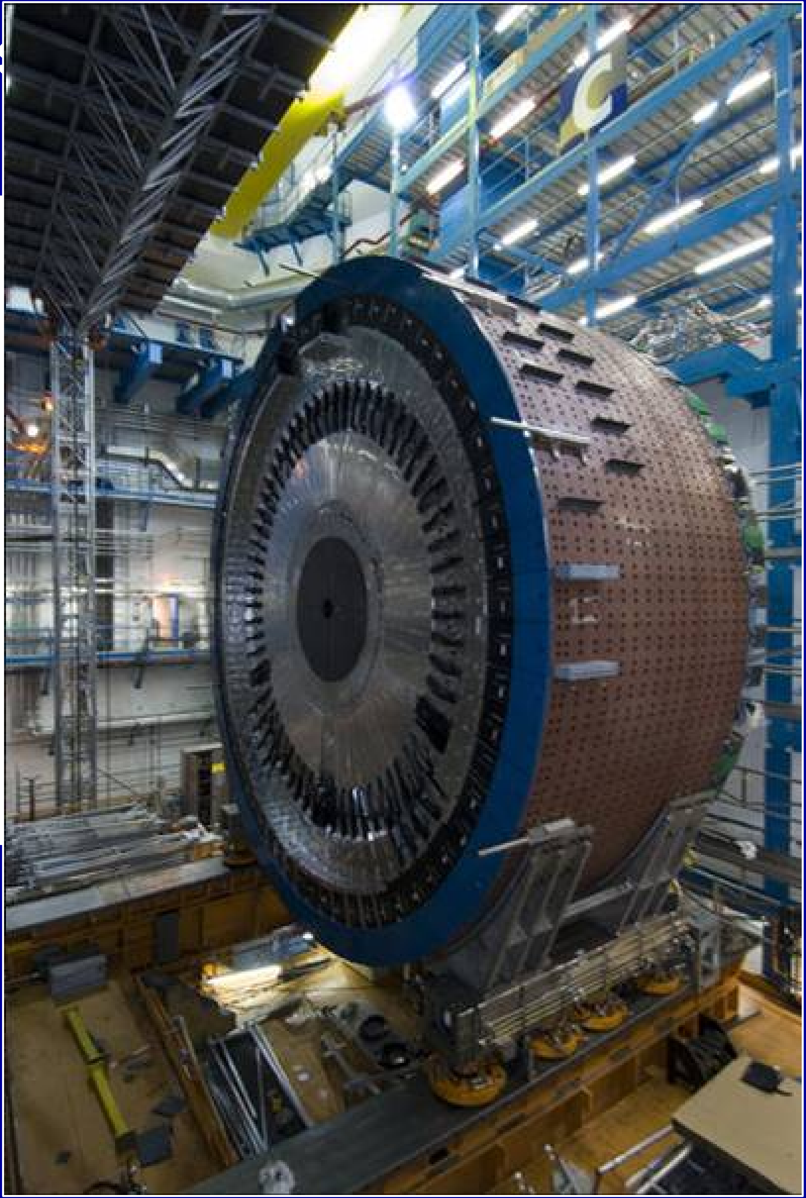
The Hadronic Tile Calorimeter

steel absorbers & plastic scintillators

- tiles perpendicular to beam
- staggered in depth
- 7.2λ thick
- 10k channels







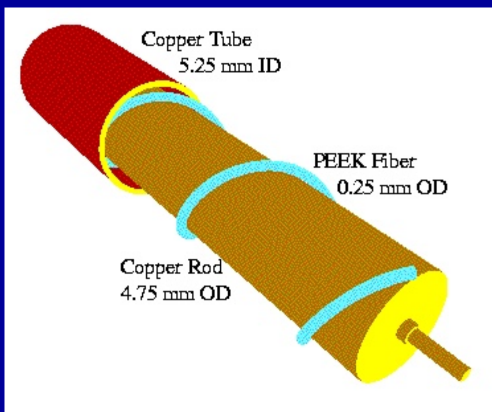
The Forward Hadronic Calorimeters

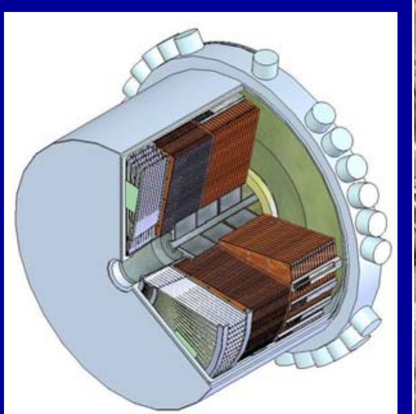
Forward Calorimeter (FCAL)

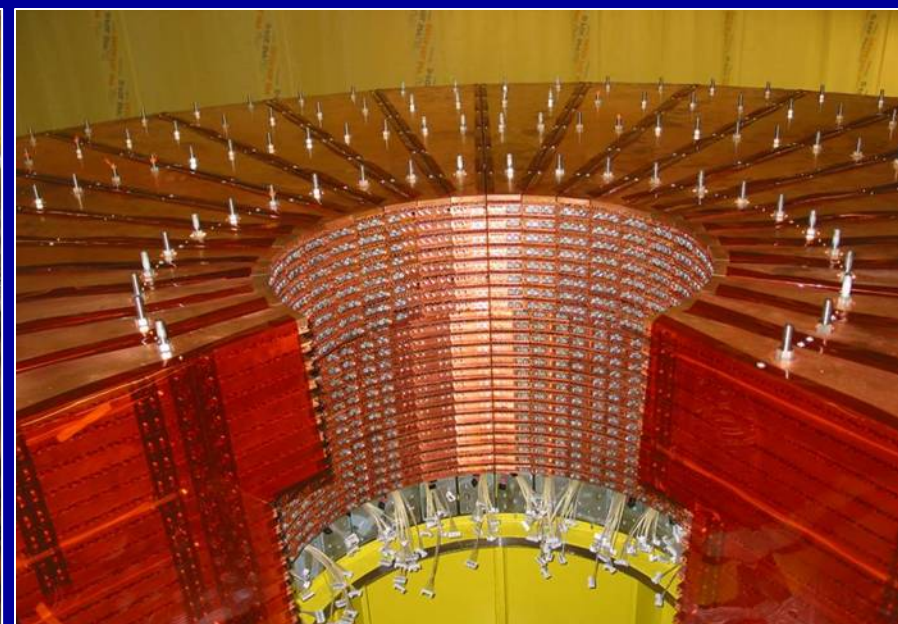
- 1^{st} wheel: Cu matrix (2.6λ, $28X_0$)
- 2^{nd},3^{rd} wheel: W matrix (2x3.6λ)

Hadronic End-Cap Calorimeter (HEC)

- share cryostat w/ 1 wheel LAr EMcal
- 2 wheels (10 λ):
  - Cu absorber (25/50mm)
  - 4x LAr filled 1.85mm gap



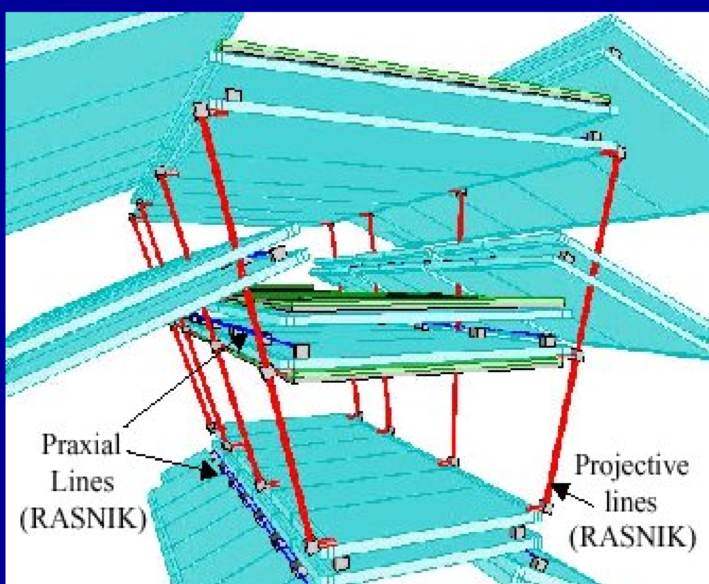




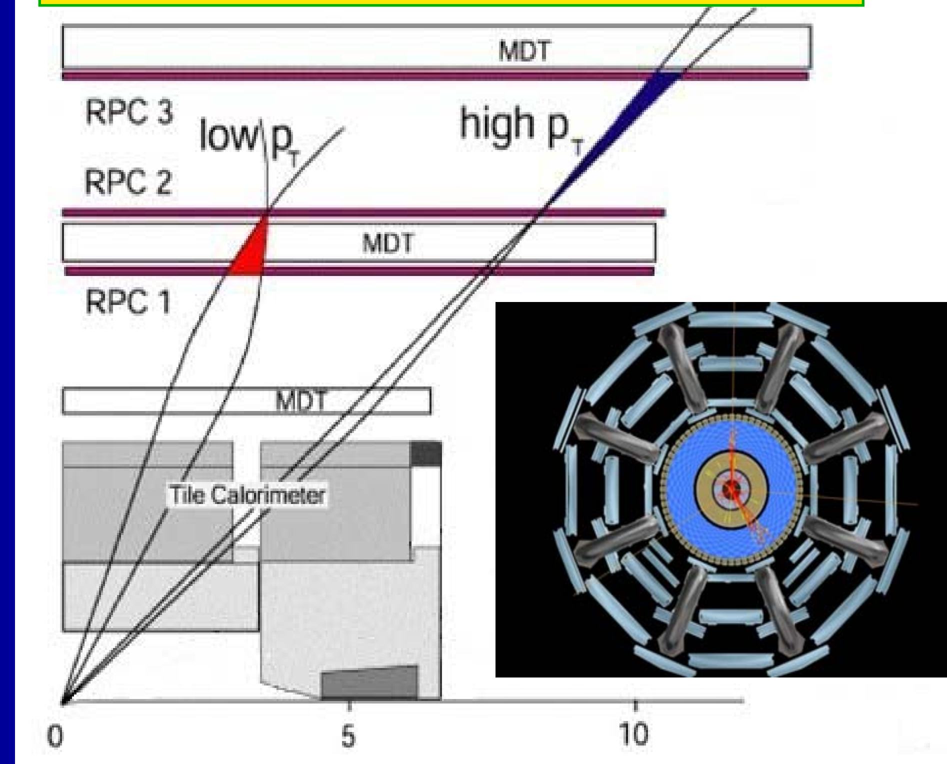
The Muon Spectrometer

Track & trigger μ trajectory

- 6 points
- precision 50μ (each point)
- maximum 4 T toroidal field
- background of γ & n
- **follow-up position** of every measuring element with a 30μ precision



Trigger chambers (RPC) rate capability required ~ 1 kHz/cm^2



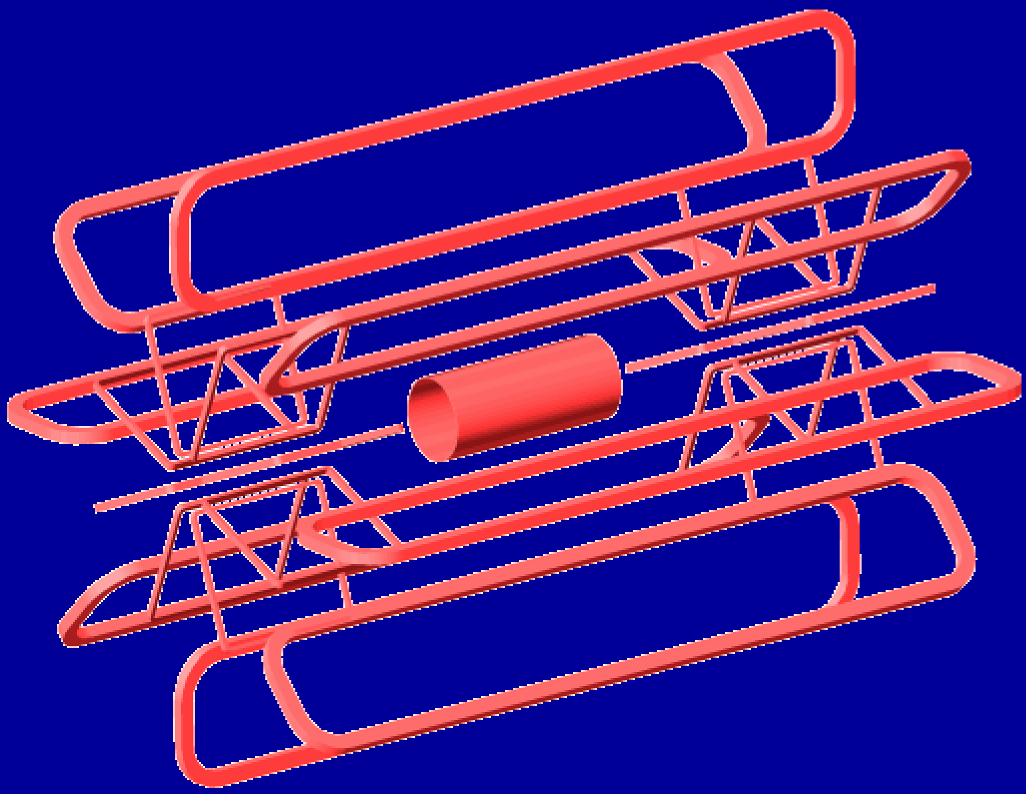
2 technologies:

- ***MDT*** *- Monitored Drift Tubes*
- ***RPC*** *- Resistive Plate Chambers (trigger)*

The Superconducting Magnets

Barrel Toroid + 2 End-Cap Toroids + Central Solenoid

- 4 magnets provide magnetic field for the inner detector (solenoid) and muon detectors (toroids)
- 20 m diameter x 25 m long
- 8200 m^3 volume
- 170 t superconductor
- 700 t cold mass
- 1320 t total weight
- 90 km conductor
- 20.5 kA at 4.1 T
- 1.55 GJ stored energy
- conduction cooled at 4.8 K
- 9 years construction 98-07



The largest superconducting magnet in the world !

Why Superconducting Magnets?

Technology Drivers

- momentum resolution
  - depends on sagitta term

$$s \approx \frac{qBL^2}{8p}$$

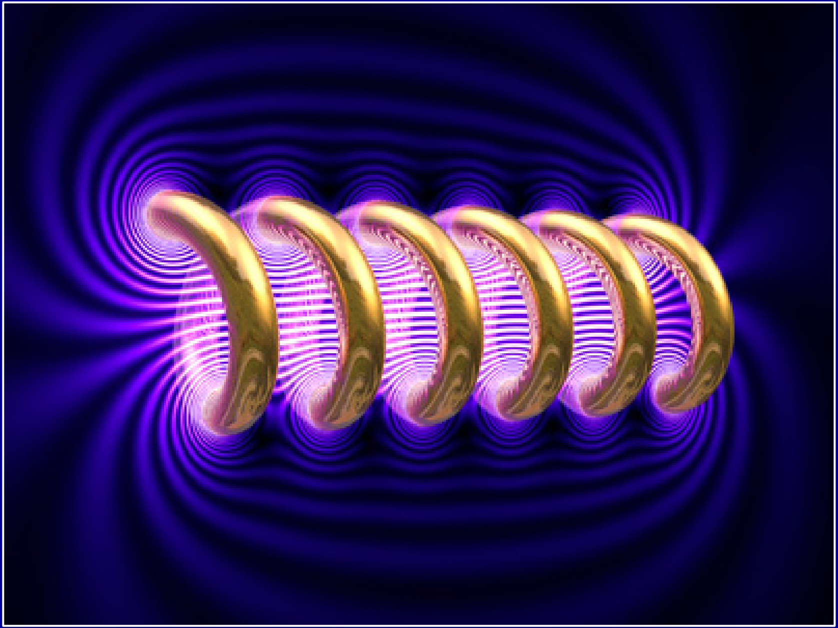
- transparency
  - reduction of material
  - choose low X_0 materials
- detector configuration
  - determines magnet configuration
- cost
  - construction
  - operation

Solutions

- high field
- large volume
- superconducting
- aluminium alloys
- dipole spectrometer
- solenoid or toroid (forward/backward symmetry)
- conductor, cryostat, iron yoke
- water or cryo cooling

Solenoid Magnet

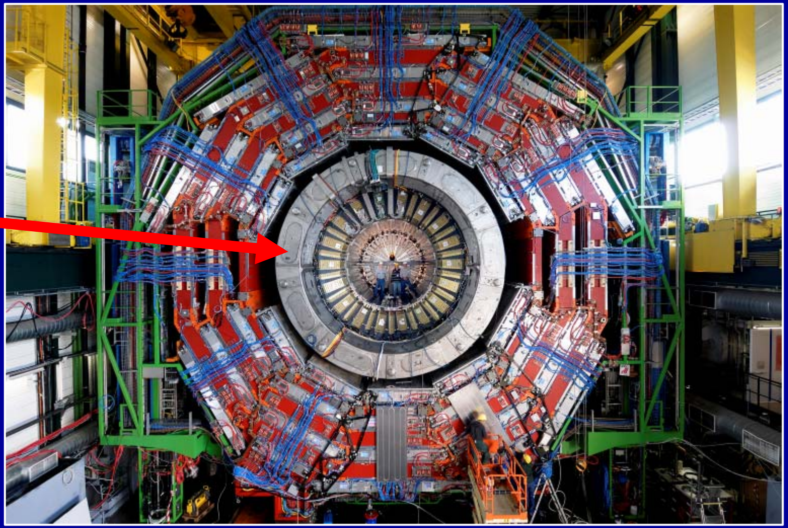
- **Resolution**
  - inside solenoid: $dp/p \sim \{B \cdot R^2_{solenoid}\}^{-1}$
  - outside solenoid: $dp/p \sim \{B \cdot R_{solenoid}\}^{-1}$

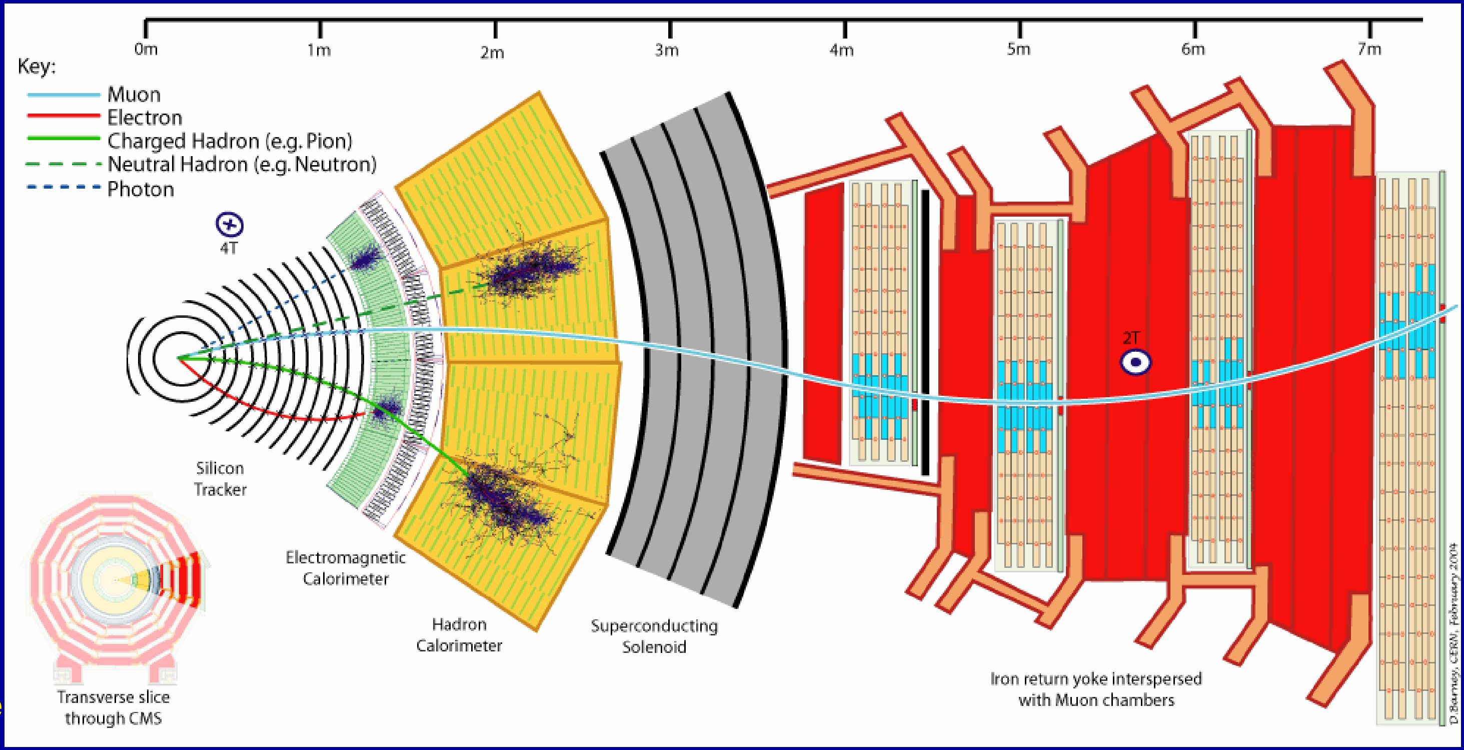


- **Field & Symmetry**
  - axial and uniform
  - but field lines *parallel* to particle path at small angles
- **Installation**
  - self supporting structure
  - iron yoke required to contain stray field (improves bending power at small angles)

CMS: Compact Muon Solenoid

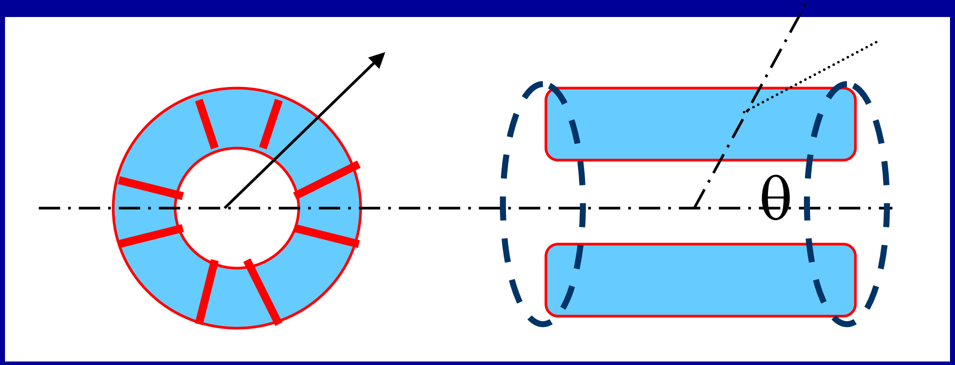
- 16 m diameter x 21 m long
- 12,500 tonnes total weight
- 6 m diameter x 12 m long solenoid
- 4 T at 19.5 kA
- 2.7 GJ stored energy
- 220 t cold mass, 4 layers, 5 segments





Toroid Magnet

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



CLAS/CEBAF 1995

- **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**
  - support required to keep self balance

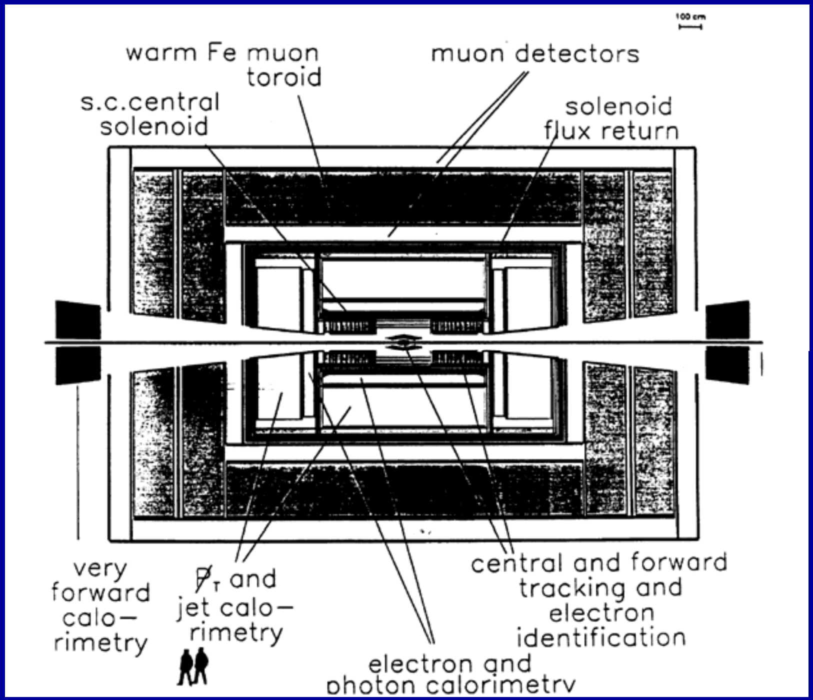
EAGLE

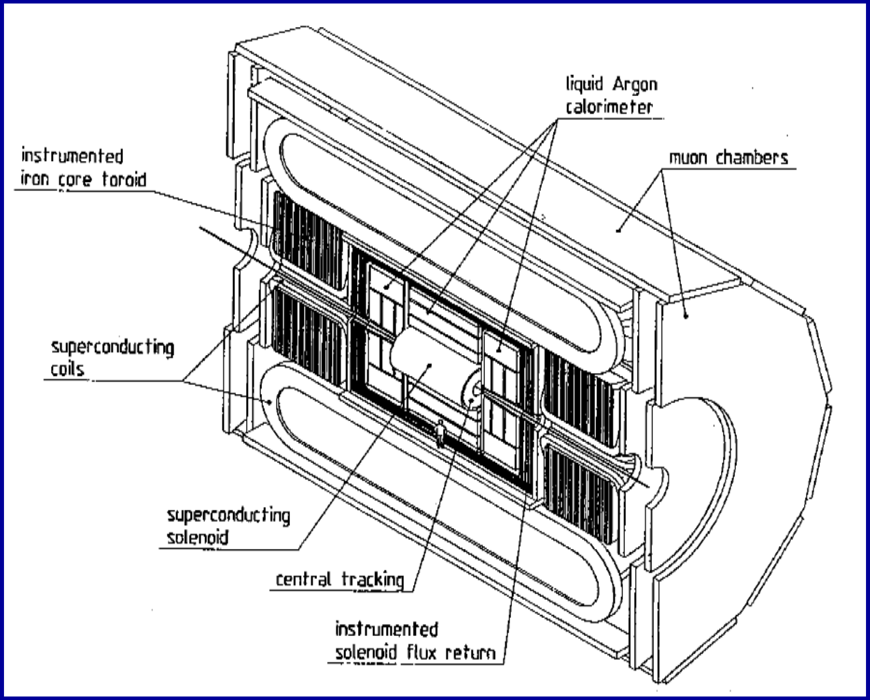
- 2 – 4 m thick warm iron toroid
- total weight 26,400 tonnes!
- SC central solenoid (r=1.2m)
- combined cryostat with liquid argon calorimeter

ASCOT

- 12 coil SC air core toroid with muon spectrometer
- 2x twin iron core end cap toroid
- separate cryostat solenoid/LAr

(ATL-TECH-92-003/4)



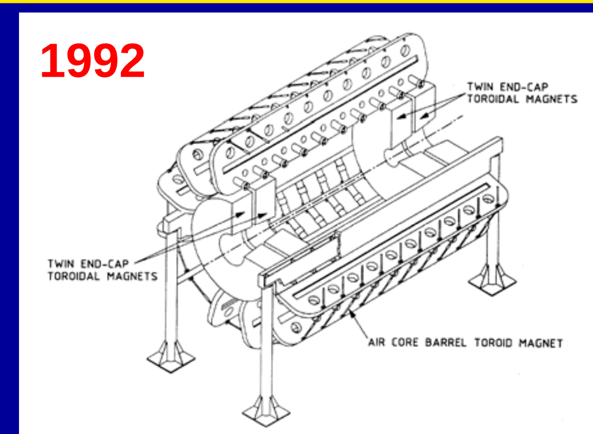


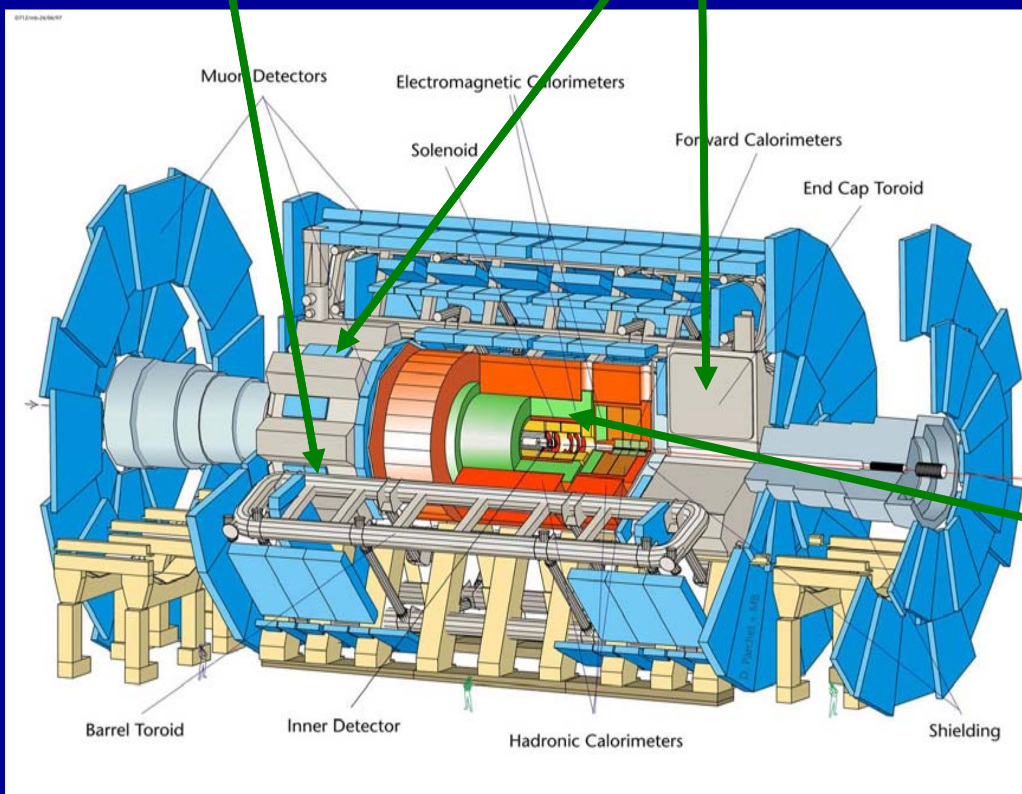
(ATL-TECH-93-008)

1996: ATLAS

Barrel Toroid
8 coils
4T on conductor

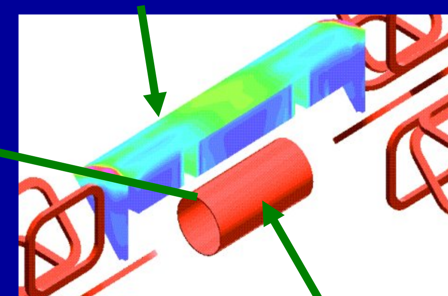
2 End-Cap Toroids,
8 coils each
4T on conductor





want the magnetic field
→ light, low density materials,
for enhanced transparency

hadron calorimeter
as return yoke



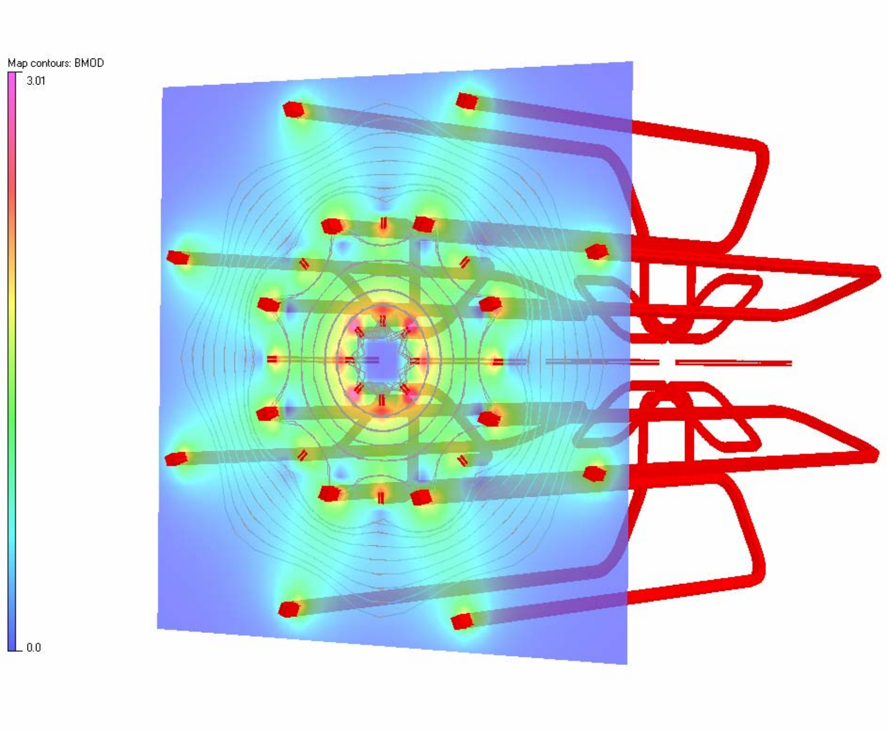
Central Solenoid
2 T in centre

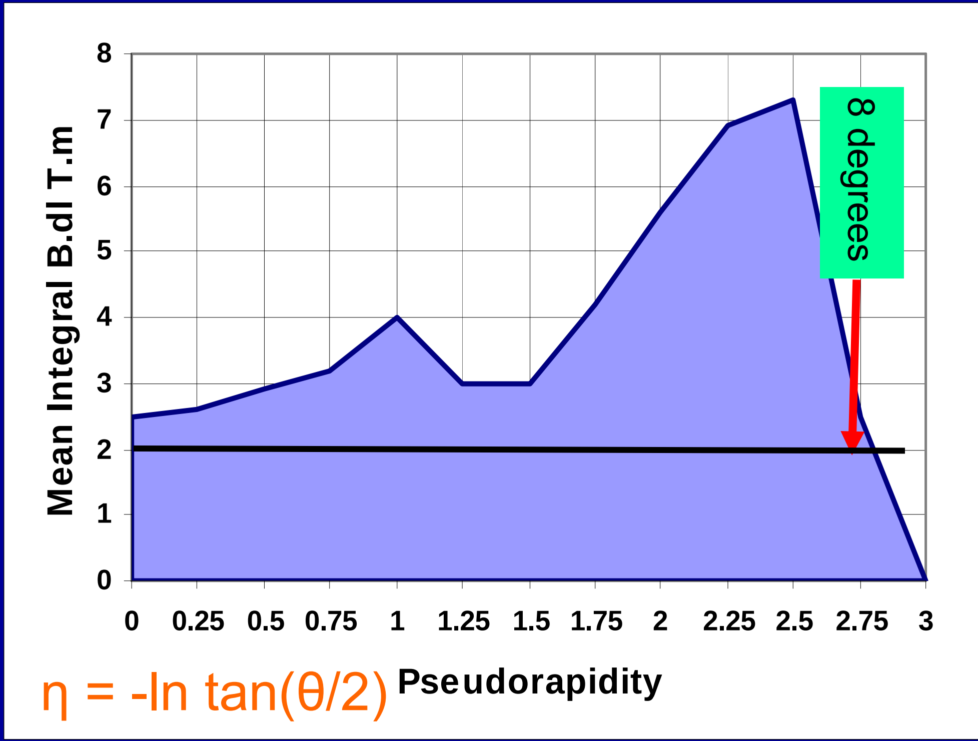
ATLAS Toroid Magnet

optimization of field uniformity & access vs. cost: 6 / **8** / 10 / 12 coils

- same ampere-turns
- less cryostats
- high peak to operating field ratio

- large field volume: ~7000m^3
- open structure for detector: cryostat occupies ~2% of total volume
- good resolution at small forward angles

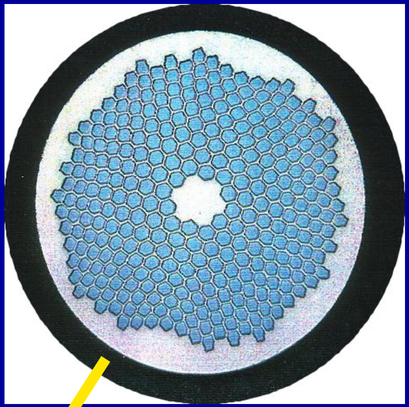


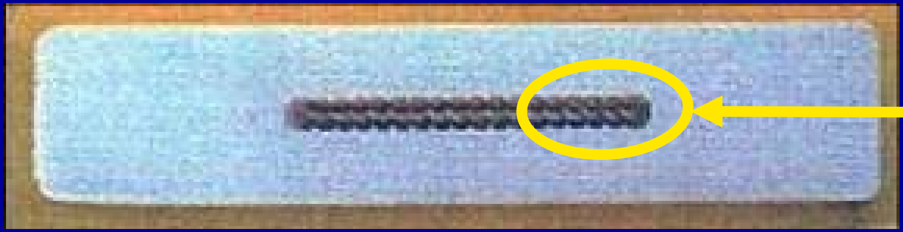


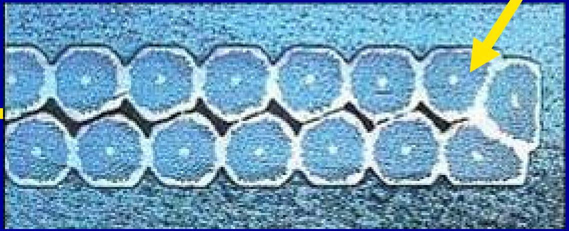
ATLAS Superconductors

90 km aluminium stabilized superconductor in 3 versions

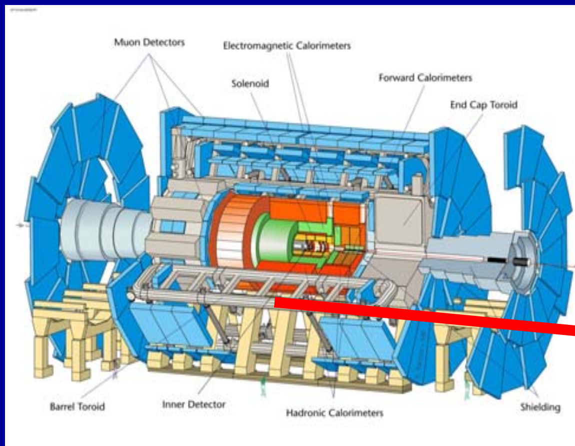
- Toroids (BT/ECT): 65 kA at 5 T
  - 40 x 1.25 mm NbTi/Cu strand, 2900 A/mm2 at 5 T (~1700 A/strand)
  - co-extrusion with high purity aluminium: high RRR > 1500
  - intermetalic Cu-Al bonding for current and heat transfer
  - size: BT = 57 x 12 mm^2, 56 km
    ECT = 46 x 12 mm^2, 25 km
- Solenoid (CS): 20 kA at 5 T
  - 12 x 1.22 mm NbTi/Cu strand, 2750 A/mm2 at 5 T
  - co-extrusion with Ni-doped aluminium
    RRR ~ 500; improved yield strength
  - size: 40 x 4.2 mm^2, 9 km

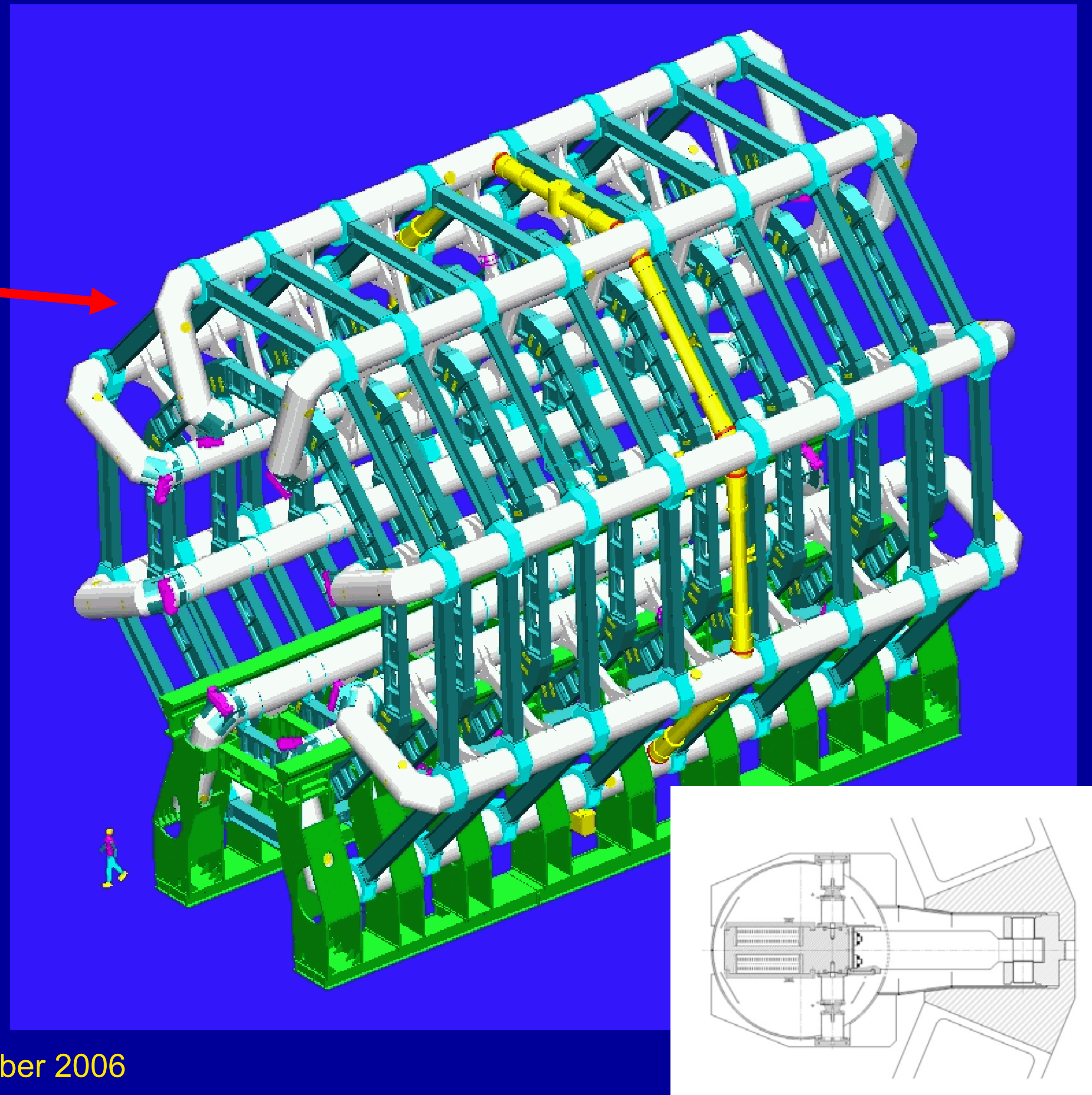






The Barrel Toroid





- 8 coils, 25 x 5 m^2
- 20 kA, 4 T peak field
- 16 support rings
- mounted on 18 feet & 6 bedplates
- services via top feed box and cryo-ring
- 2 rails for calorimeter

Barrel Toroid Cold Mass Integration

Scale

8 coils in separate cryostats – open structure

Force transfer ~ 1100t/coil

Cold mass ~ 450t

Barrel Toroid Cryostat Integration

Challenge

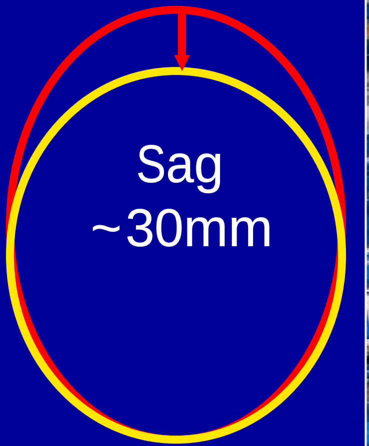
Scale of components and integration accuracy

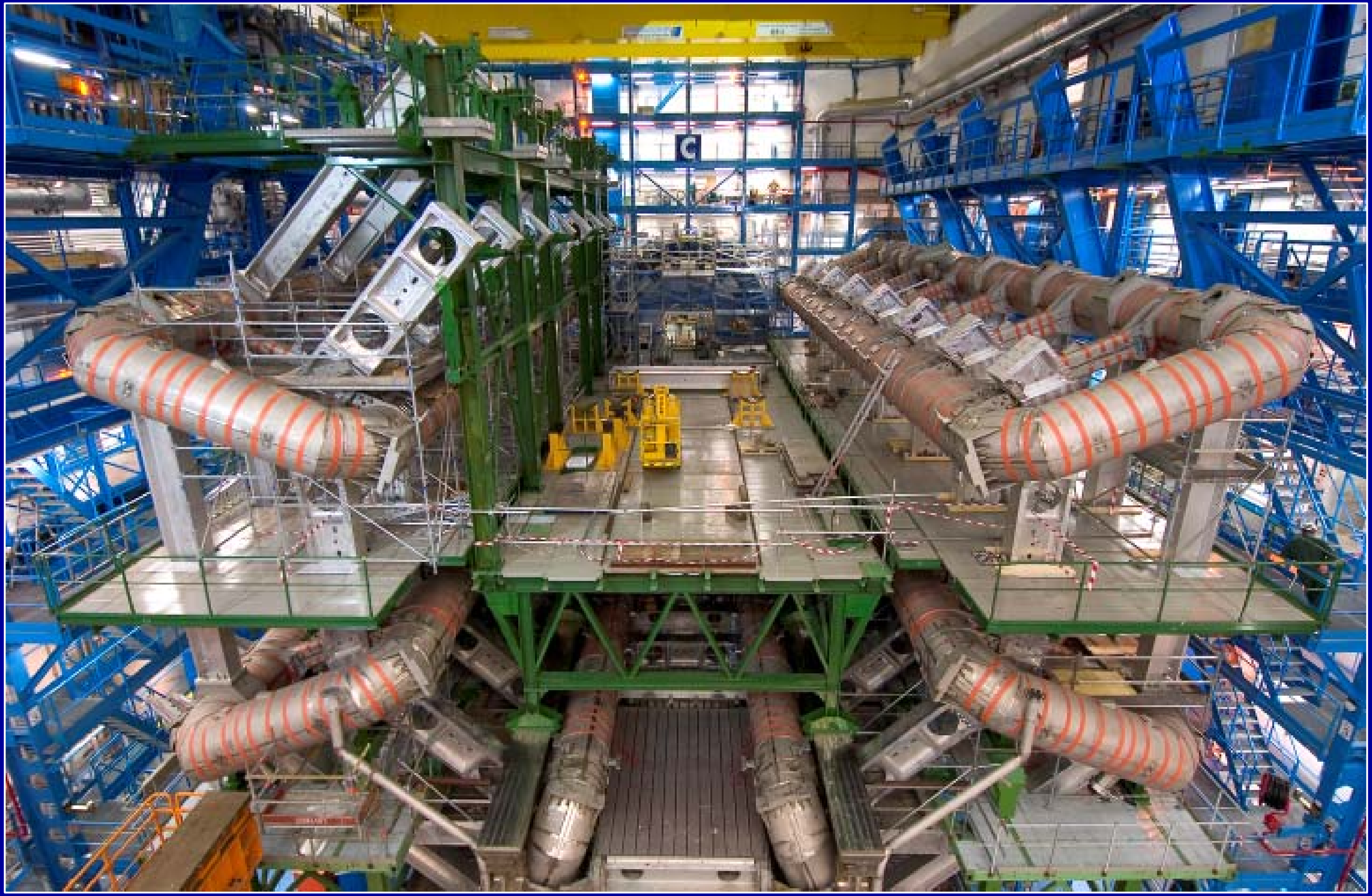
Tolerances << 1 mm in 26m

< 40 parts per milllion

Barrel Toroid Coil Installation

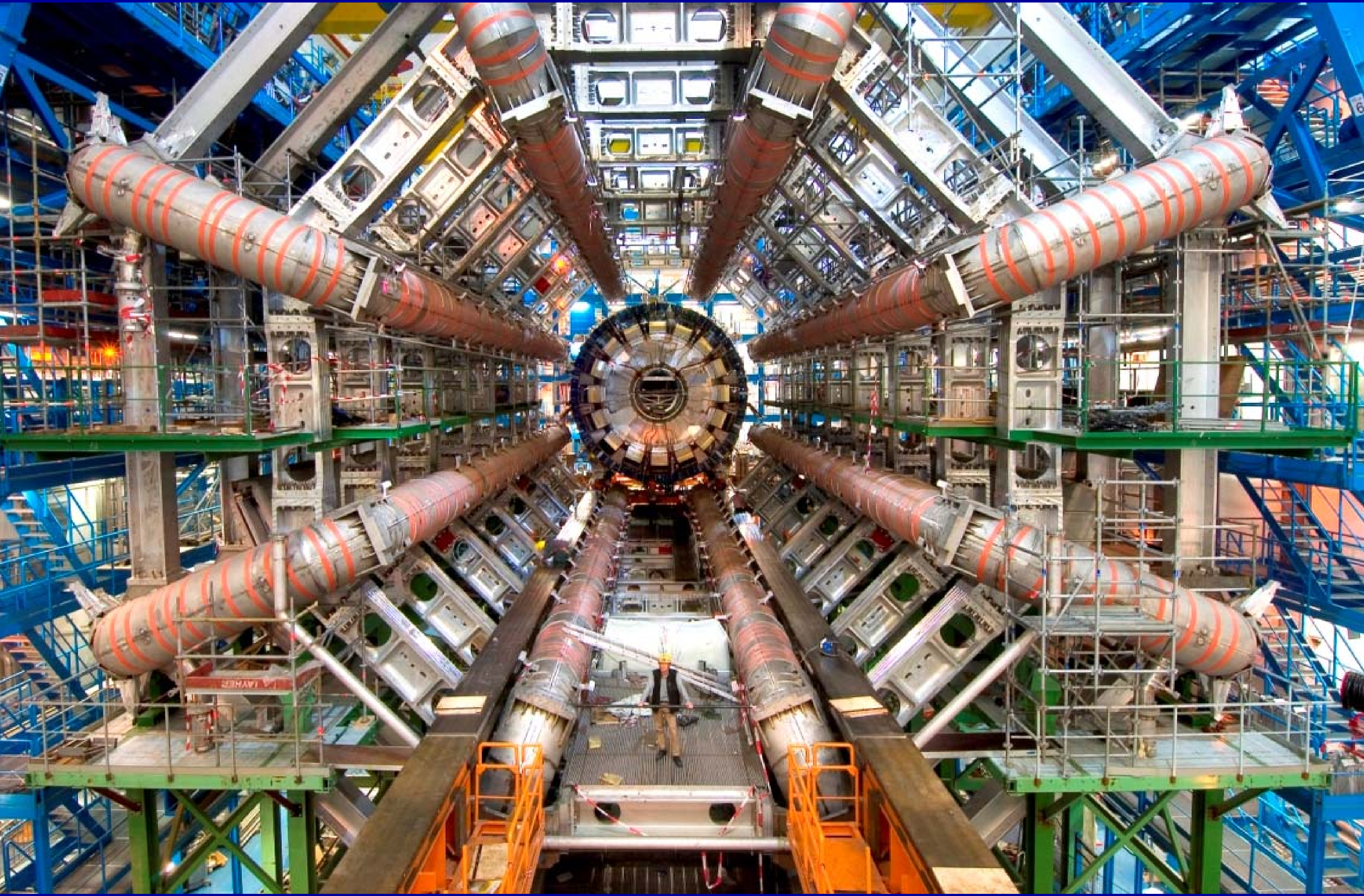
Barrel Toroid Assembly





- release BT: 830 tonnes → sag 18 mm
- 350 tonnes muon chambers → sag 27 mm

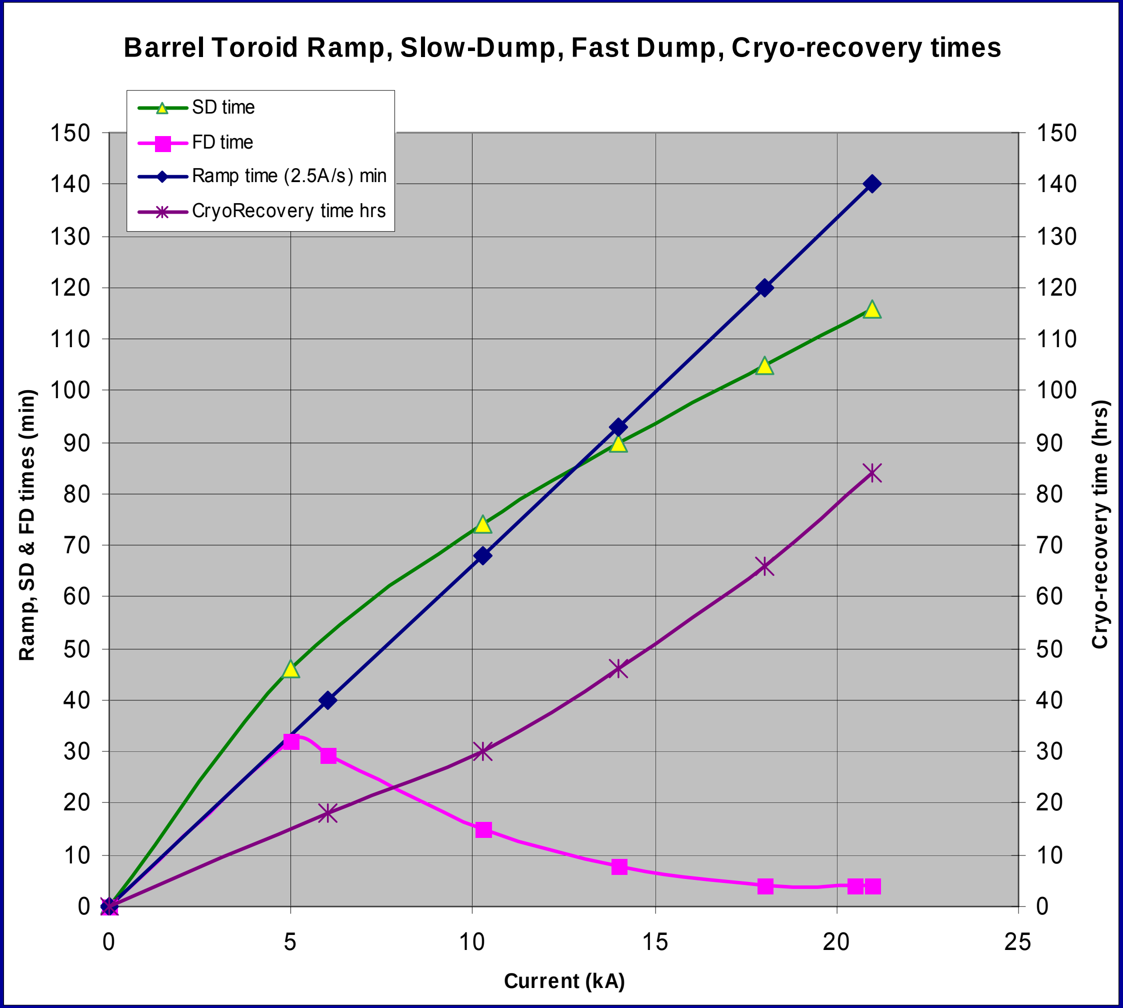
Barrel Toroid Completed

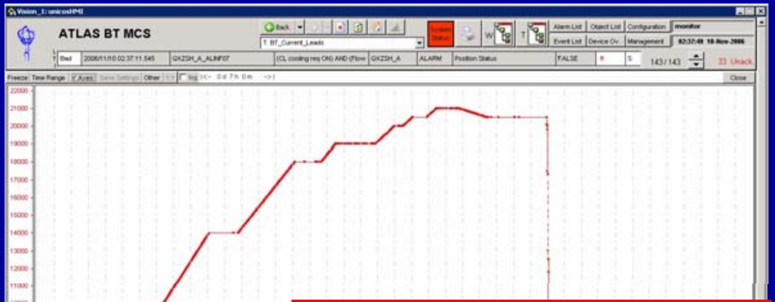


Commissioning up to Full Current (21 kA)

Cool down 6 weeks (Jul-Aug)

Powering step-by-step to 21 kA (9 Nov'06)





At each step: slow dump, fast dump & re-cool down

Full Current 21 kA

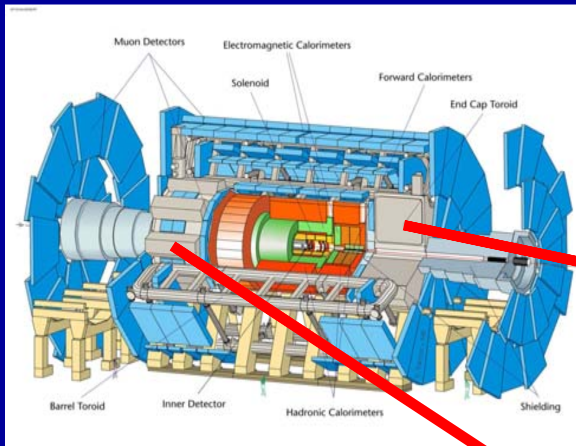
Ramp-up / down = 2 h + 2 h

E = 1.1 GJ

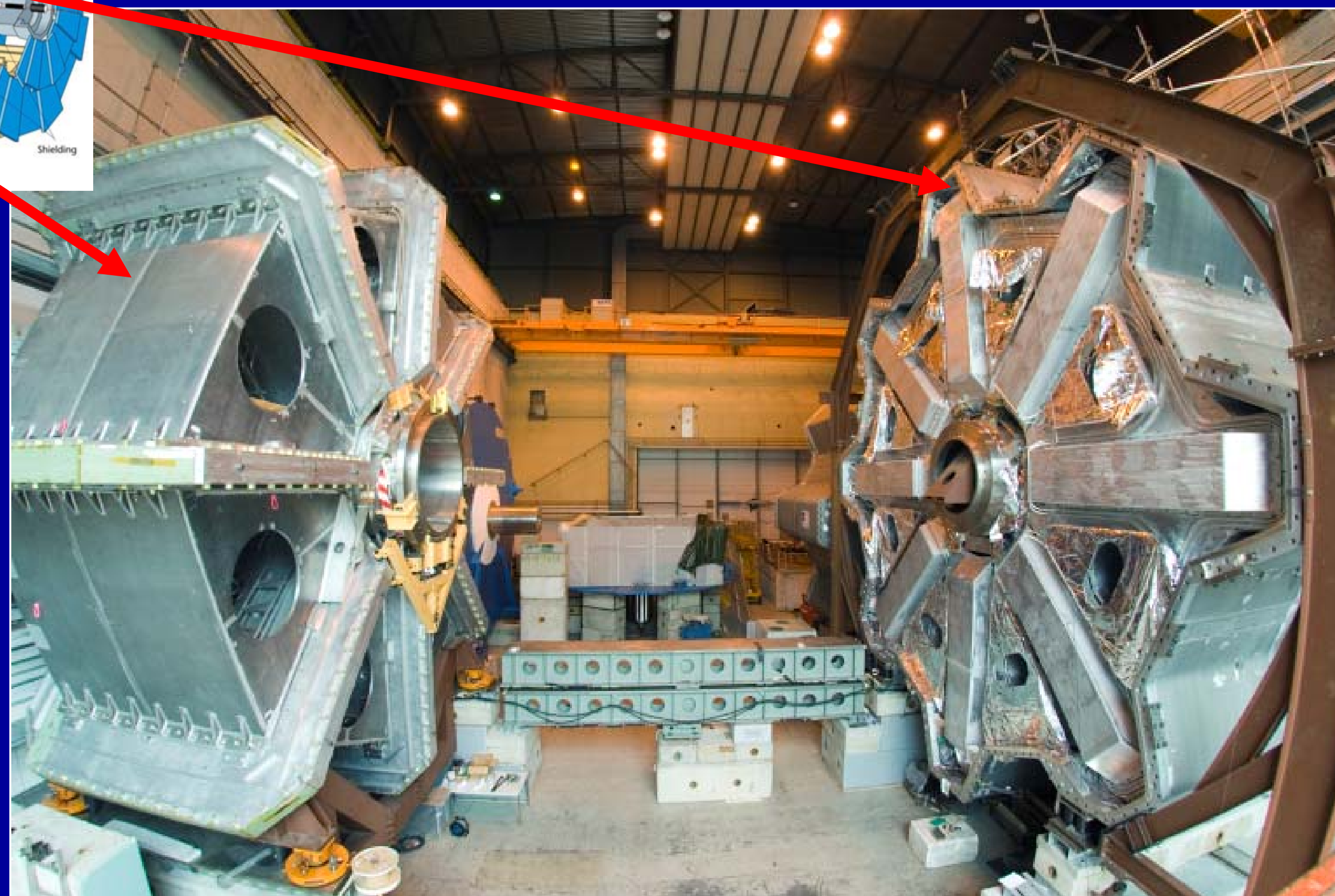
Fast dump T_{max} = 55 K

Cryo-recovery = 84 h

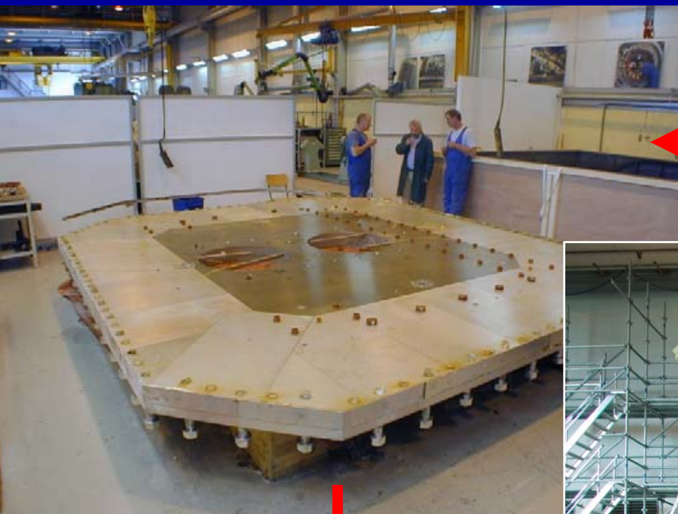
The End-Cap Toroids



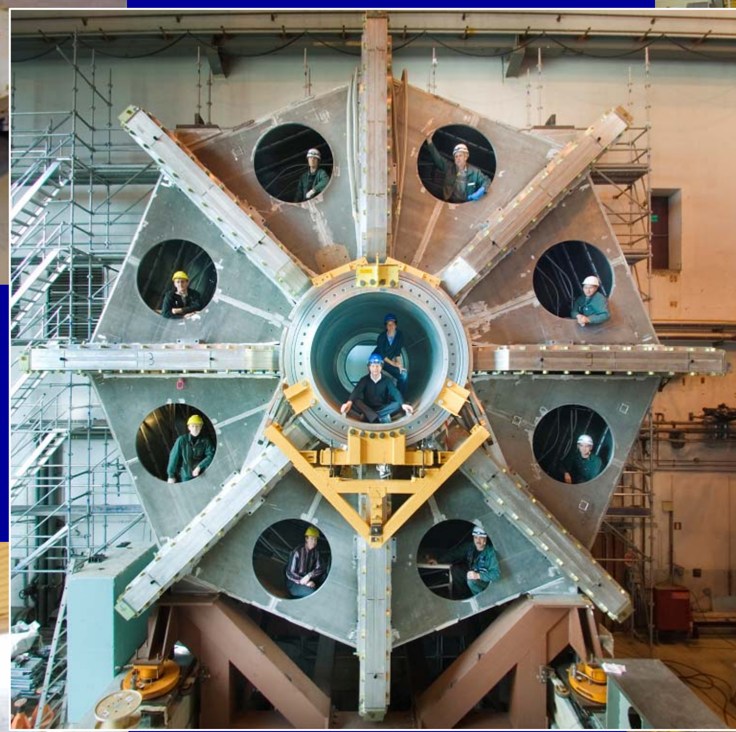
- 2 x 8 coils, 4 x 4.5 m^2
- 20 kA, 4 T peak
- torus assembly
- 8 keystone boxes
- hanging on bore tube



End-Cap Toroid Cold Mass Assembly

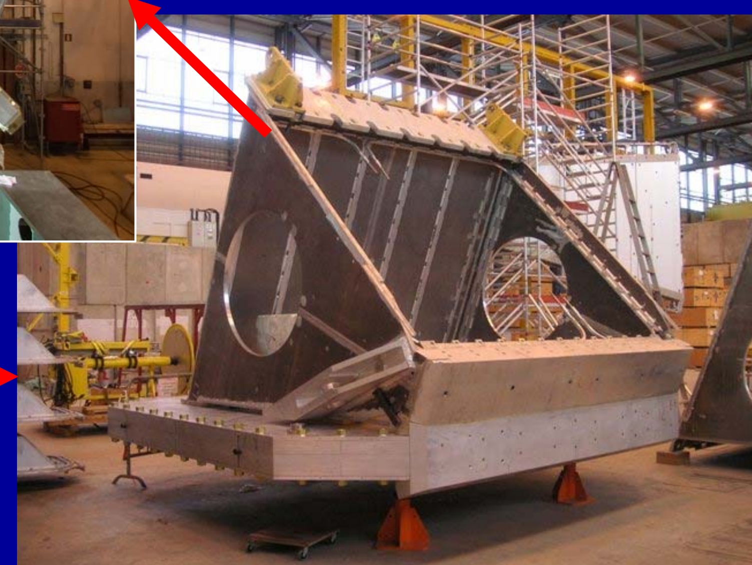


coil winding

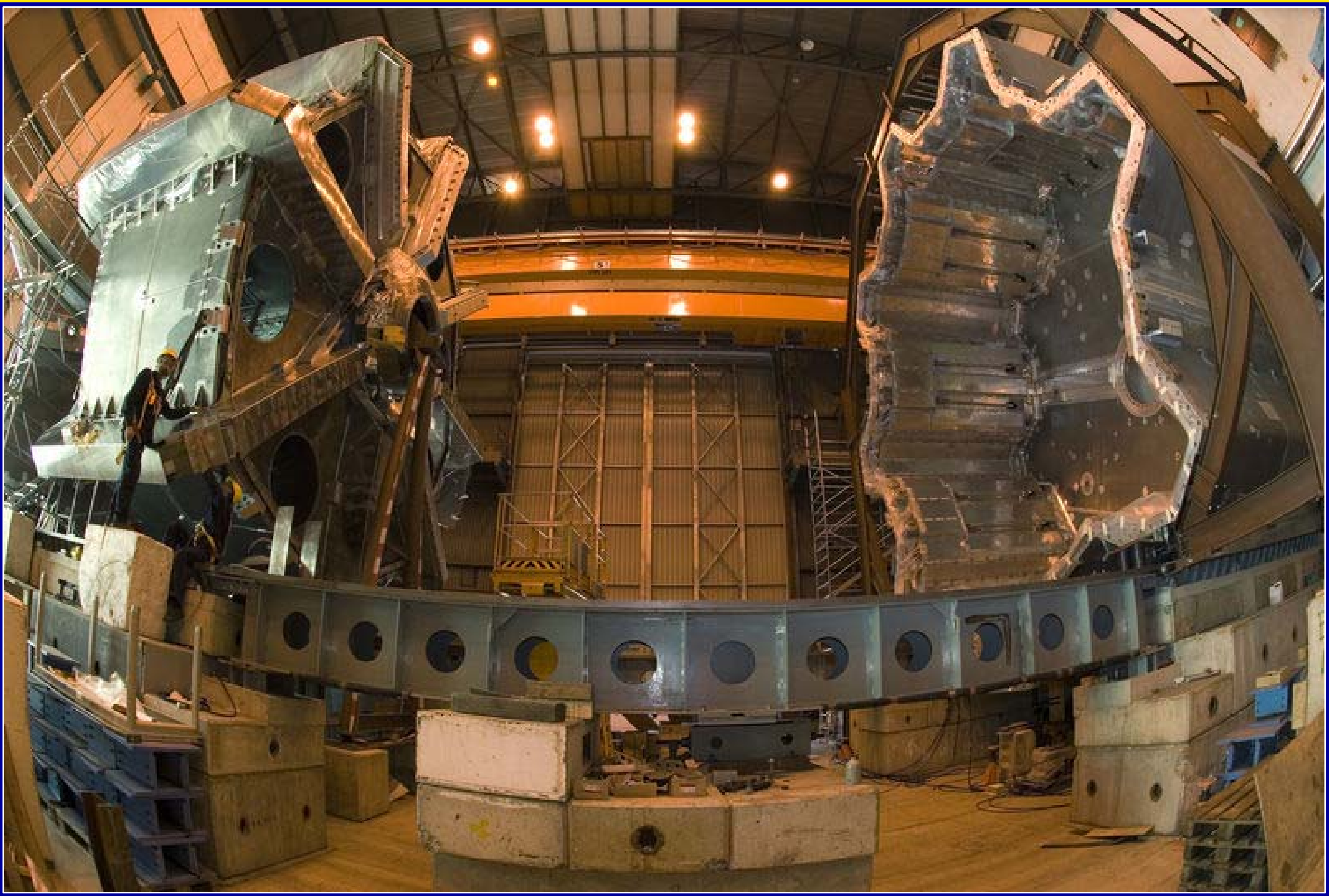


2x

+ KSB

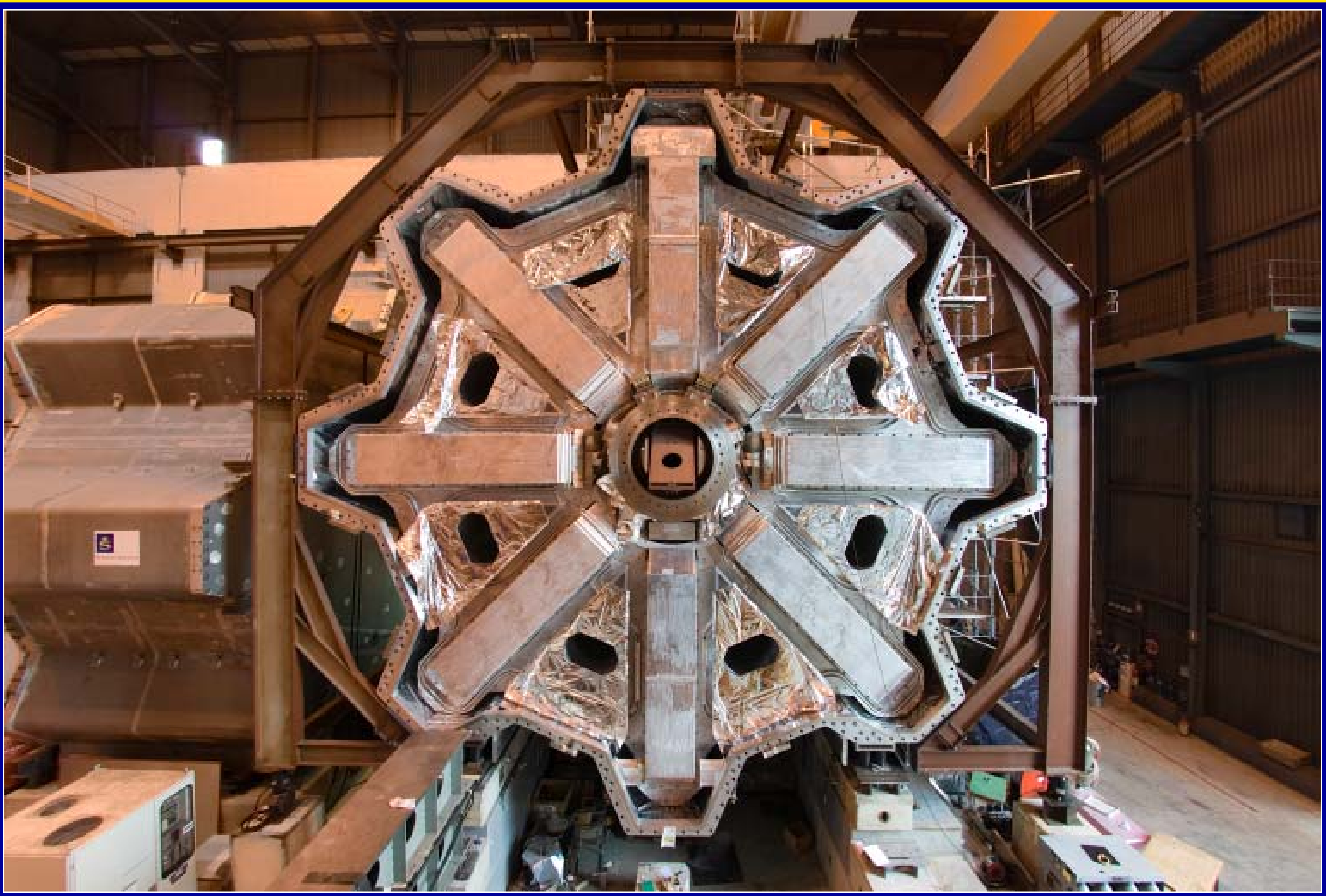


End-Cap Toroid Cryostating

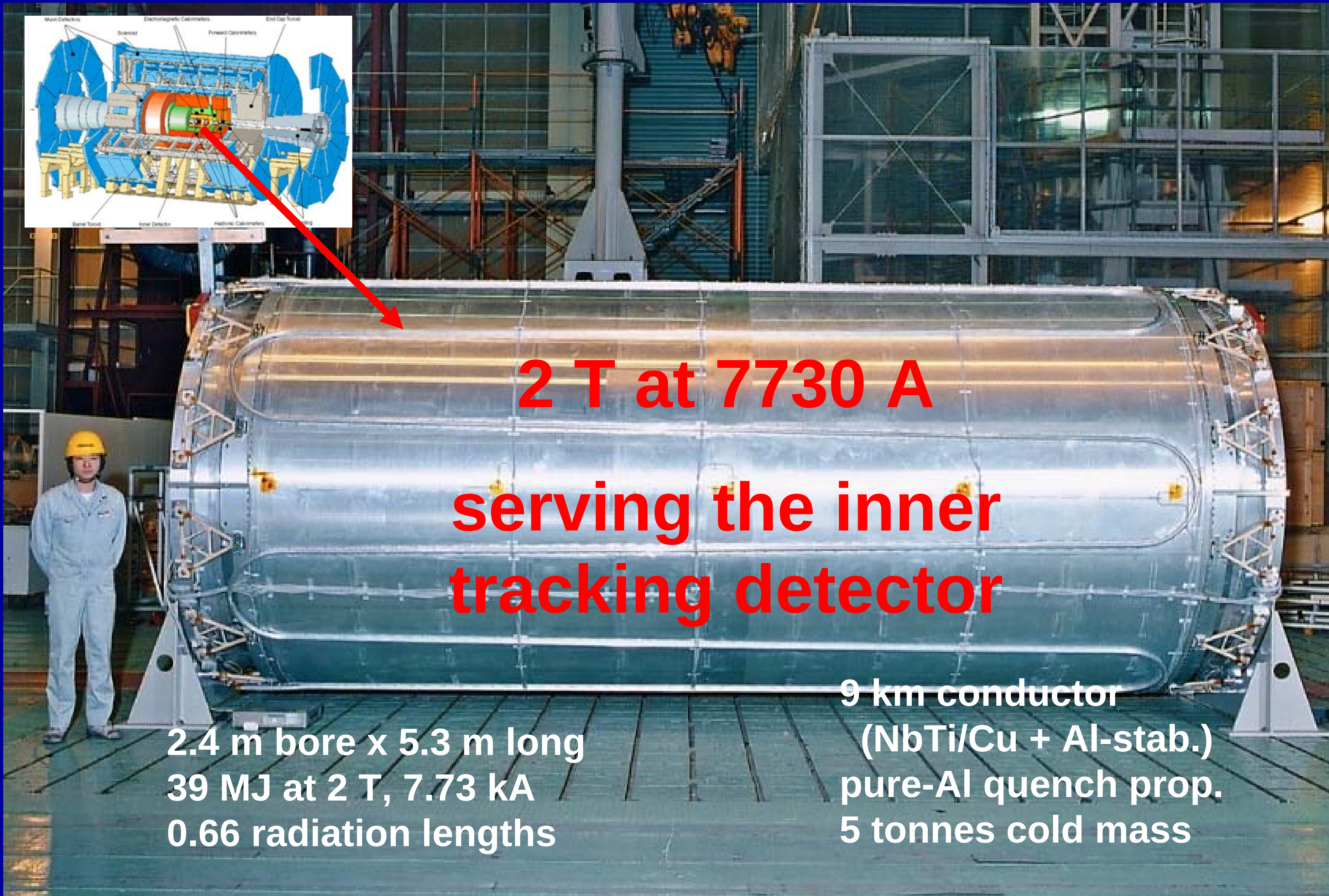


End-Cap Toroid Vacuum Vessel

End-Cap Toroid Ready for Closure



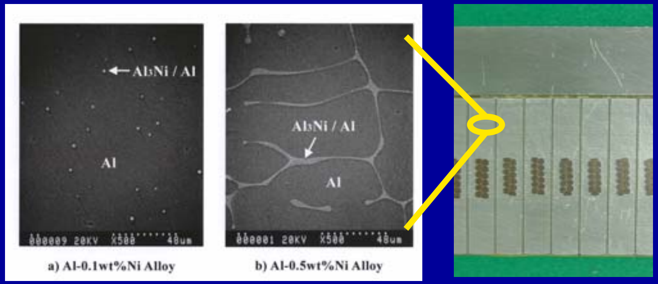
The Central Solenoid



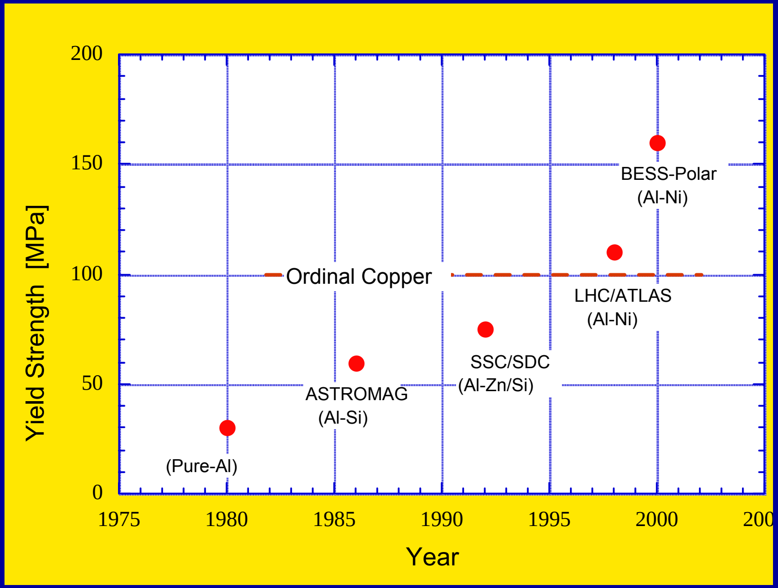
How to meet the Requirements?

To provide high field with minimizing wall material

- Develop high strength superconductor Ni-doped Aluminium-stabilizer:
  - mechanical reinforcement with keeping quench stability



- Integrate CS in common cryostat with LAr calorimeter
- pure Al-strip quench propagator



- Sophisticated current & cryogenics feeding
  - 3D chimney design
  - Full integration at CERN

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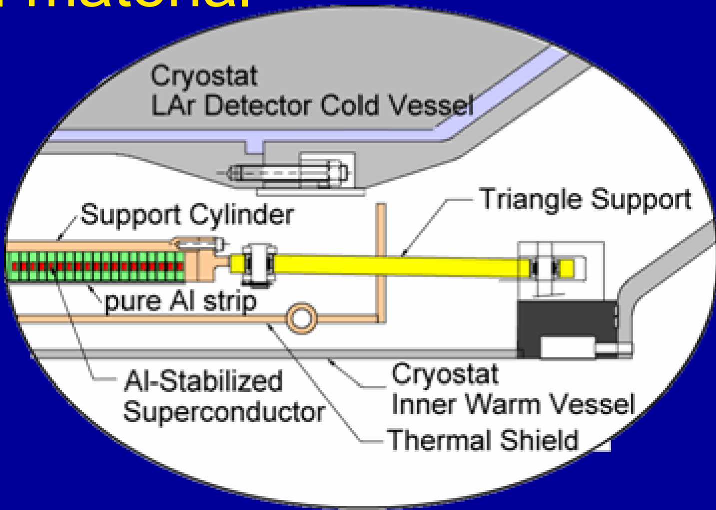

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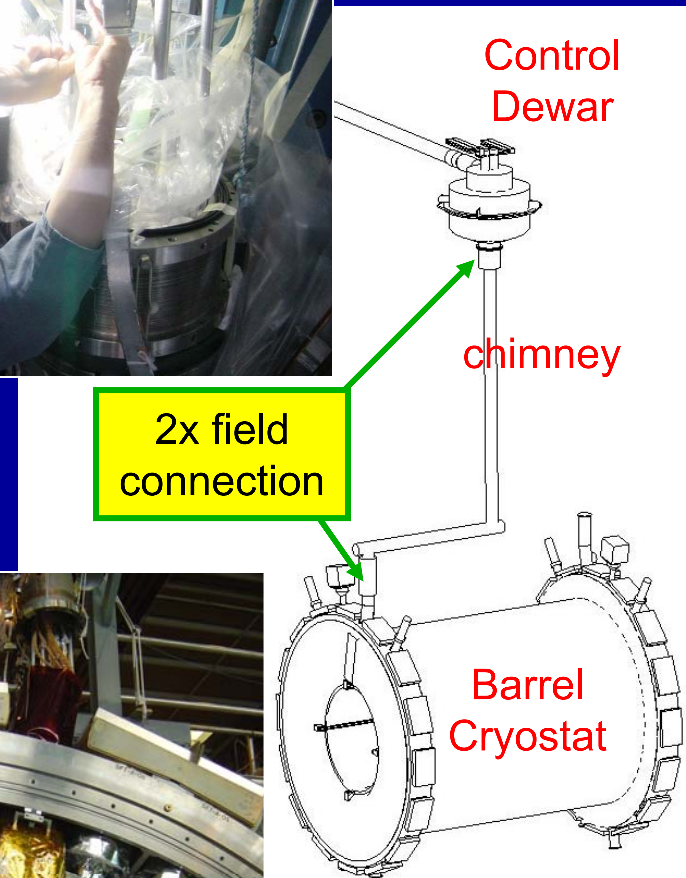
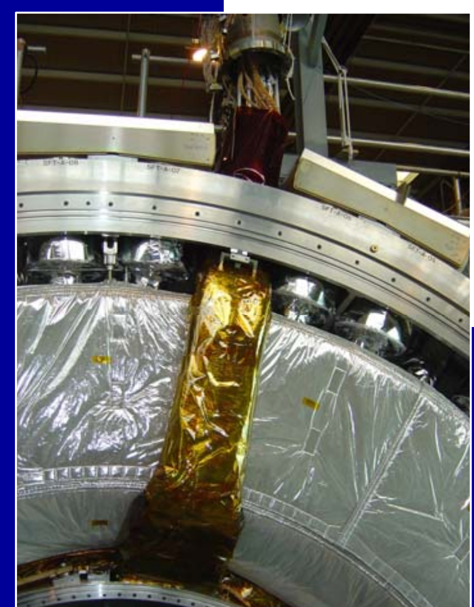
  - mechanical reinforcement with kee
    quench stability



- Integrate CS in common cryostat with LAr calorimeter
- pure Al-strip quench propagator

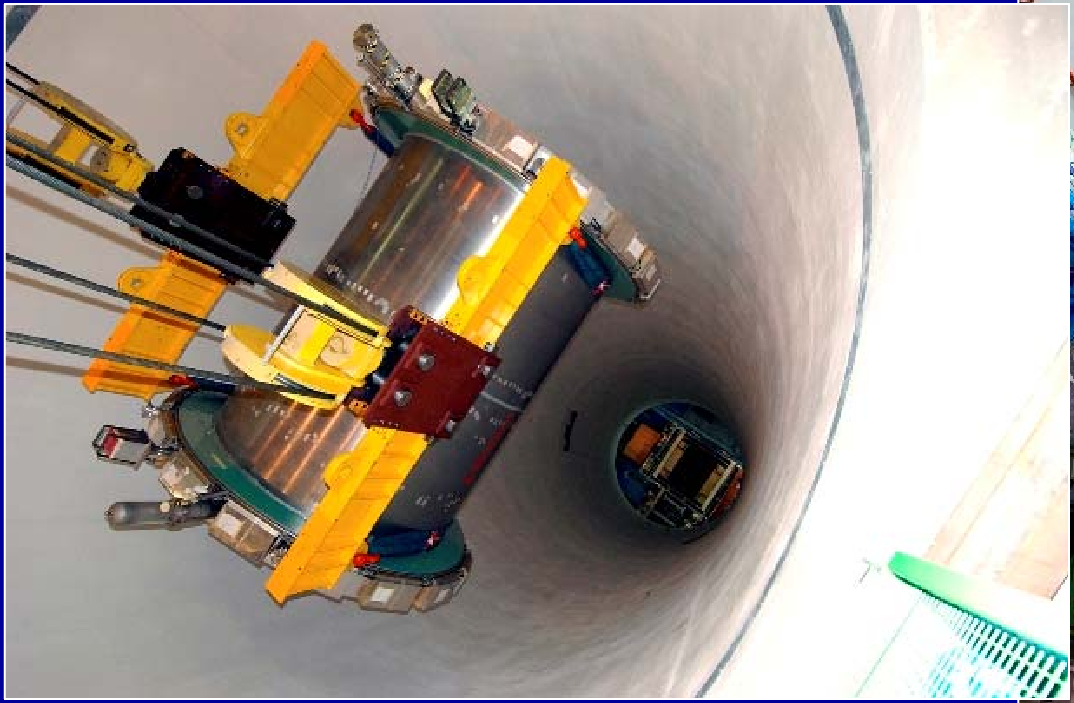
- Sophisticated current & cryogenics feeding
  - 3D chimney design
  - Full integration at CERN



Central Solenoid Installation

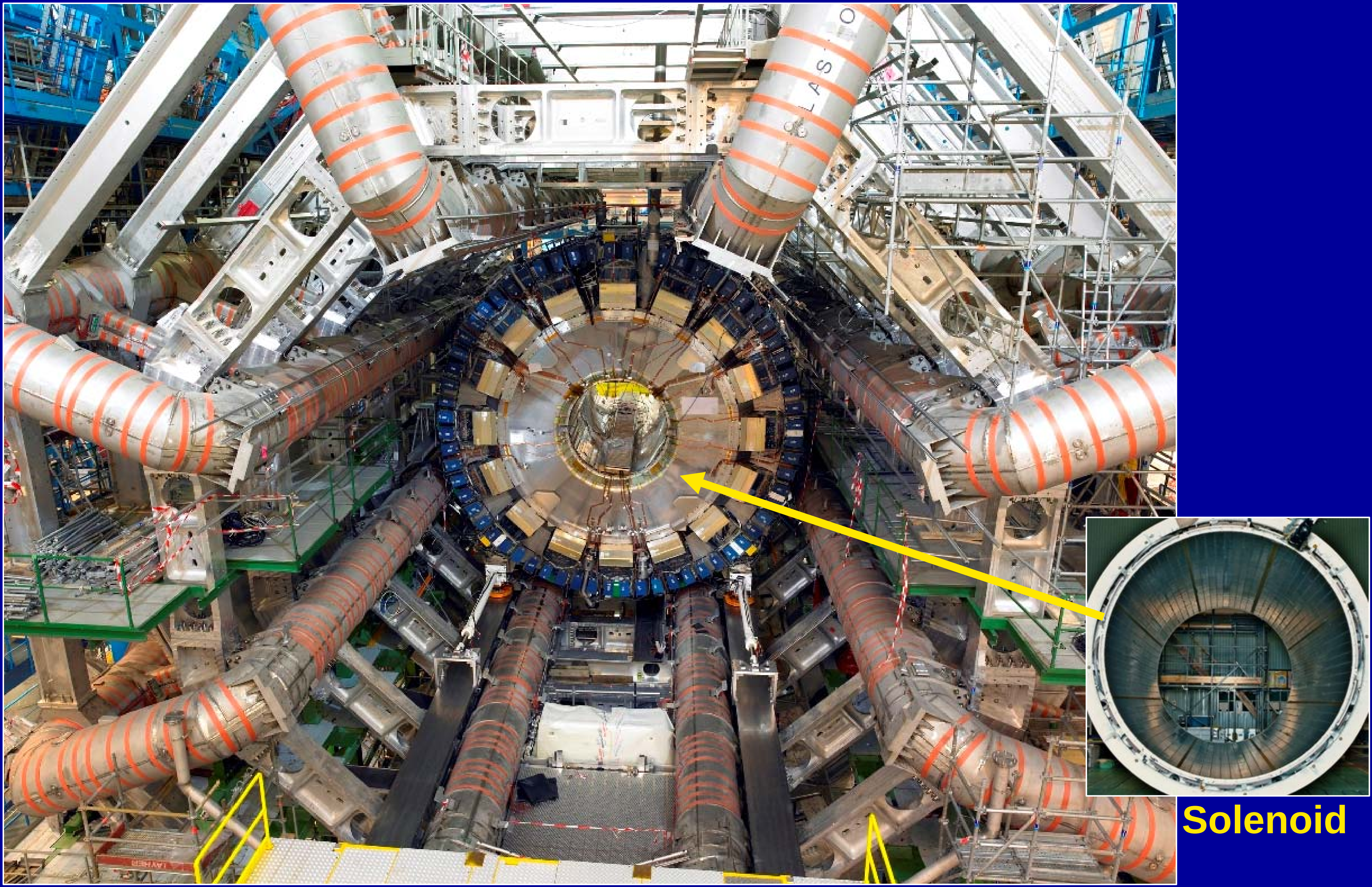
October 2004:

going down 100 m …



in the shaft

4 November 2005: in position

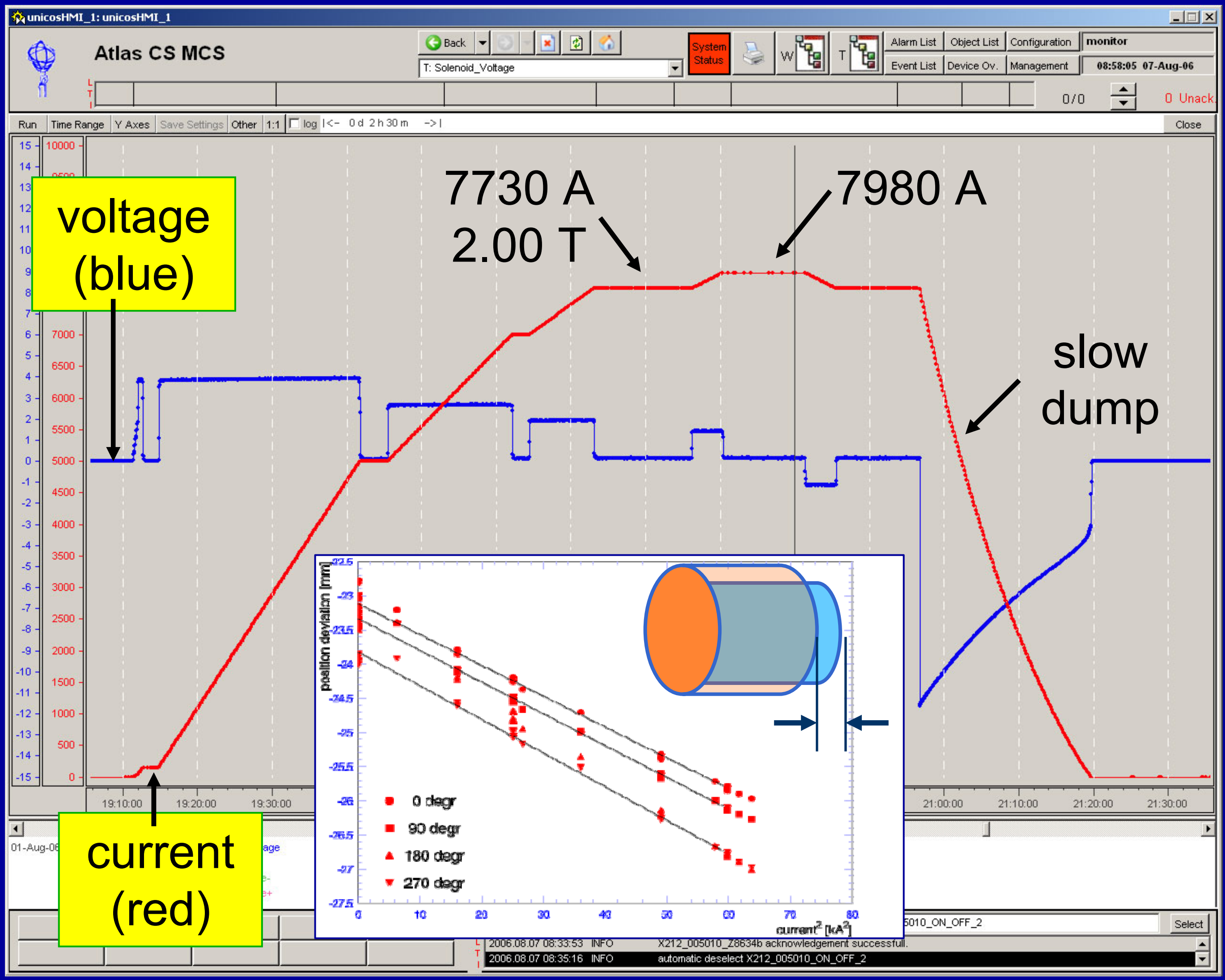


Solenoid

Excitation to full field: 8 kA (1 August)

after closing
TileCal End-Caps

- Ramp in steps:
  7730 A = 2 T
- repositioning accuracy ±0.1 mm
- final position 0.0 ± 1.4 mm (relative IP)

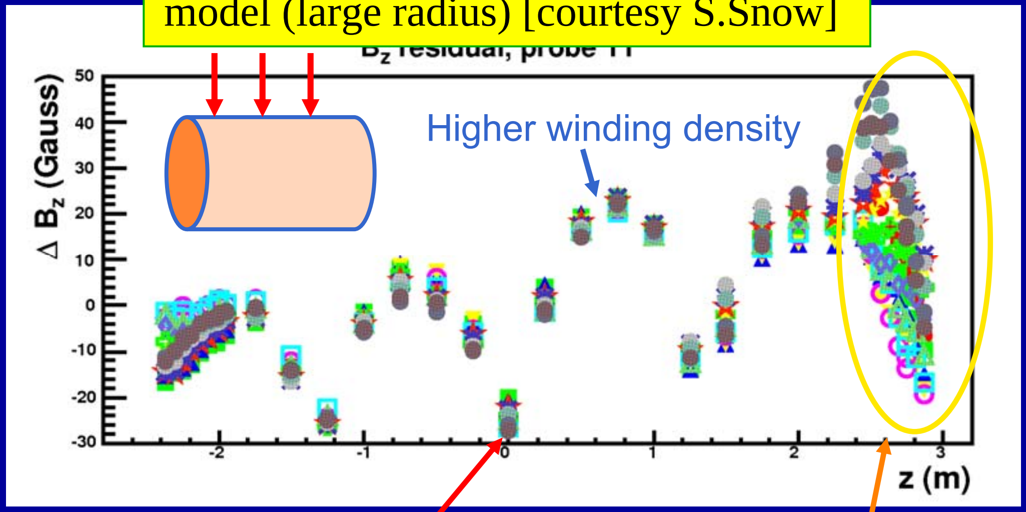


Coil length shrinkage, linear to I^2

The Magnetic Field

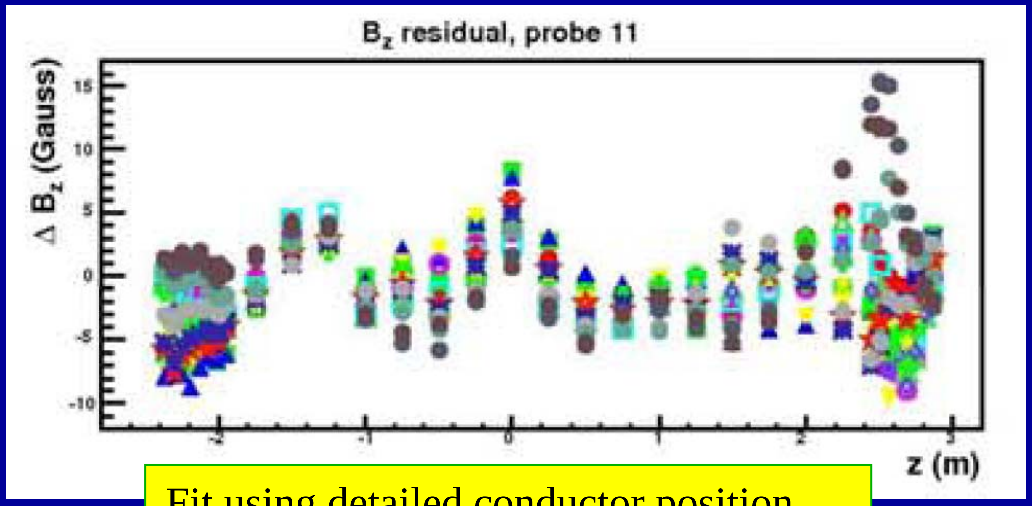
- Excitation reproducibility
  - field: < 0.1x10^{-4} T
  - current: < 5 ppm
- No hysteresis effect iron
  - iron contribution ~3.5 %
- Accurate measurements:
  - possible to identify details in winding structure
- After first corrections:
  - +7x10^{-4} ~ -13x10^{-4} T
- Improvements (8 Nov.'06)
  - ±4x10^{-4} T (RMS)

Fit using simple helical conductor model (large radius) [courtesy S.Snow]



Conductor joint = missing 1 turn

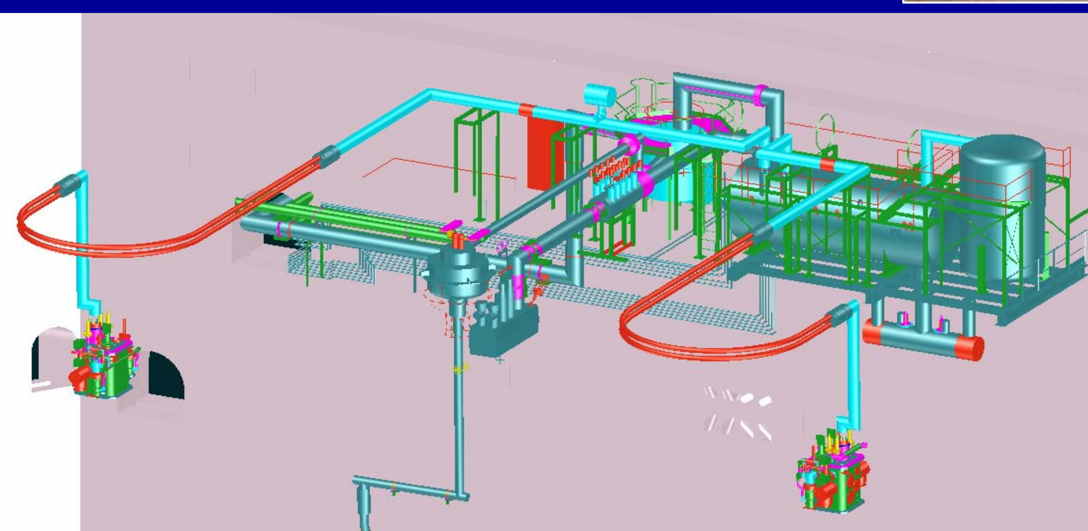
to be studied



Fit using detailed conductor position [courtesy S.Snow]

Helium Cryogenics

- shield refrigerator:
  20 kW at 40~80K
- helium liquefier:
  6 kW at 4.5 K
- toroid helium circulation pump
  1.2 kg/s at 0.4 b
- local valve boxes to regulate
  helium flow in each magnet



In case of power failure:

- thermo-syphon solenoid
- PCS for toroid pumps

Experience of a General Power Cut

Cryogenics Operation, 29 July 2006 (Central Solenoid)

05:50 UTC: (6:50 Geneva)

CERN wide power cut

- Auto-switch to thermo-syphon mode,
- Cooling kept for ~ 2 hours, (Sufficiently long for safe slow discharge)

07:40: LHe empty

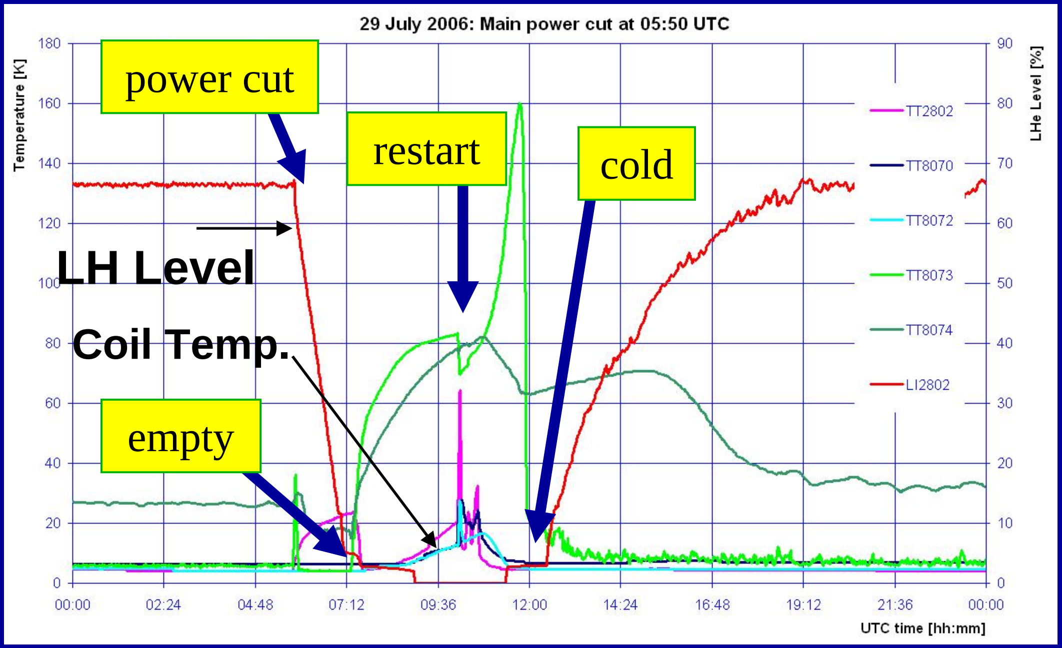
- Coil start to warm up

10:00: restart refrigerator

11:30: coil re-cooled down

19:00: LHe level recovered

~ 13 hours

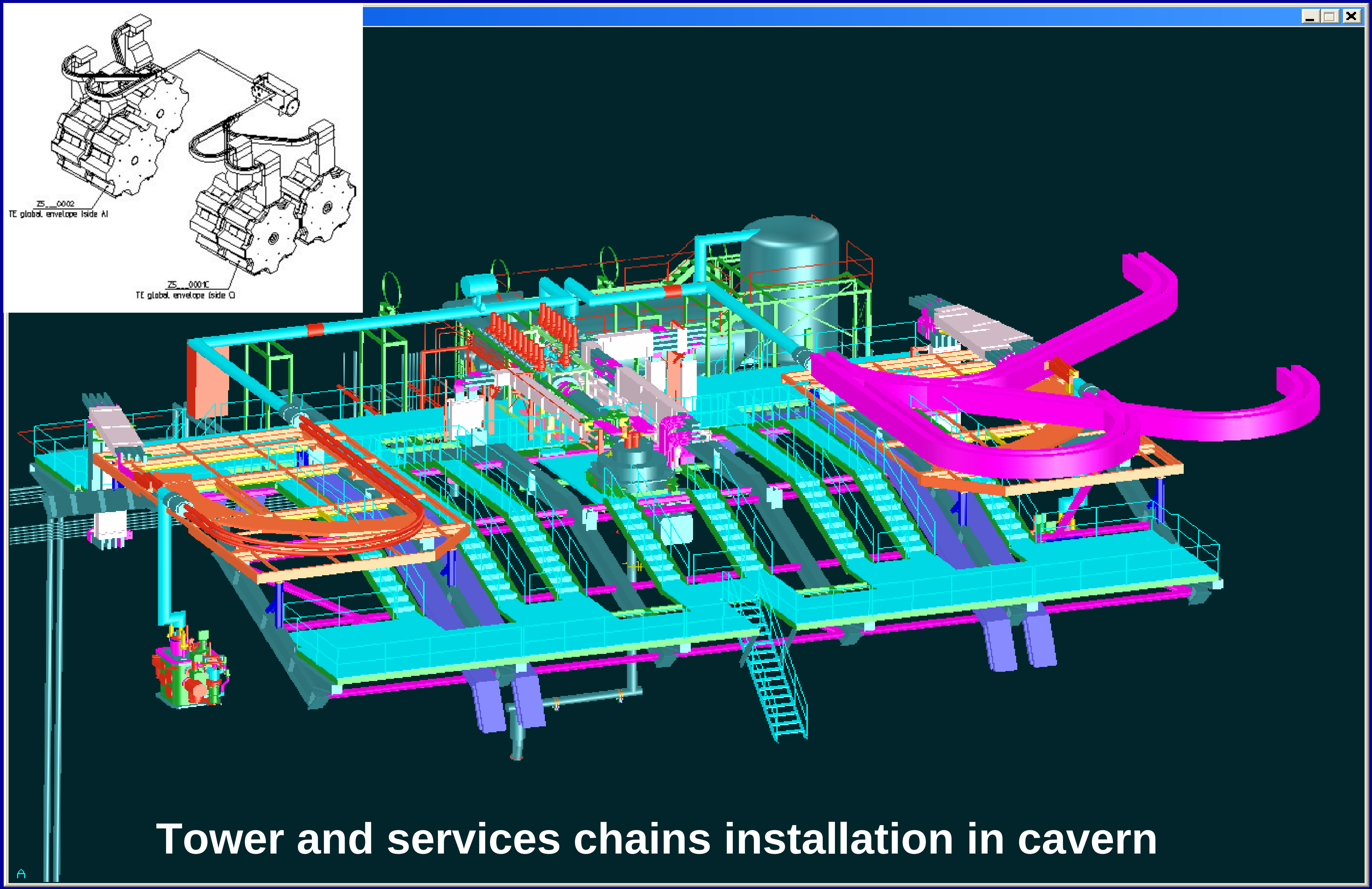


Current & Control

- 24 kA/24 V (T) + 8 kA/8V (S) power converters
- current run down unit solenoid / toroids
- 150 m Al. bus-bars

- magnet safety system quench detection and protection
- magnet control system

Connections ECT Services



Summary

CS & BT commissioned
- Operation without problems
- Field reproducible in 10^{-5}
- Safe operation confirmed

CS & BT completed
- Functioned as a front runner
  - First to deal with various challenges in construction and operation,
  - The first superconducting magnet operated in LHC underground areas!

ECT on fast track to completion

Many thanks to

all collaborators in ATLAS, CERN, KEK, CEA, RAL, cooperation of BNL, and a lot of companies, small and big.