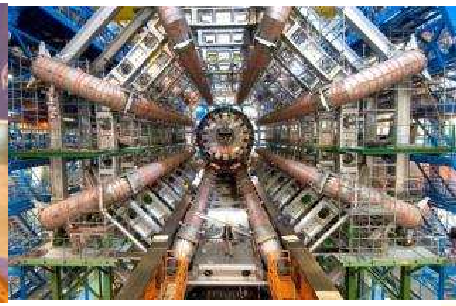
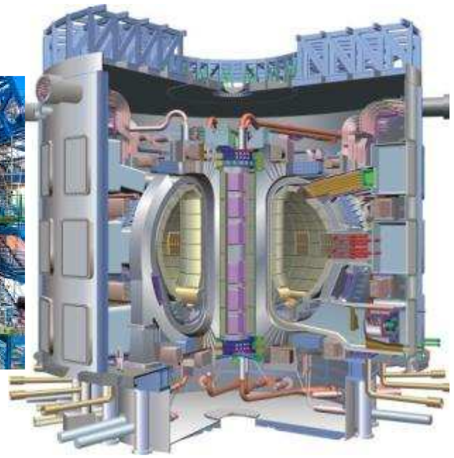
FROM RESEARCH TO INDUSTRY

LARGE SC MAGNET SYSTEMS

CERN ACCLERATOR SCHOOL | Pierre VEDRINE

4 MAY 2013

SUMMARY

Overview of large scale applications of superconductivity

Accelerator magnets: review of the four major projects (Tevatron, HERA, RHIC, LHC), magnet parameters, construction choices, operation experience and performance.

Detector magnets: from the first bubble chambers to CMS and ATLAS.

Fusion magnets: review of machines built (Mirror MTF, T-15, Tore Supra, K-STAR, SST, EAST) and in construction (W7-X, ITER, JT60-SA)

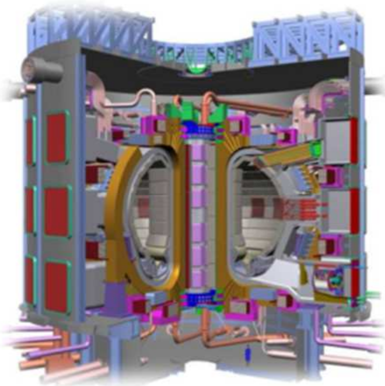
OVERVIEW OF LARGE SCALE APPLICATIONS OF SUPERCONDUCTIVITY

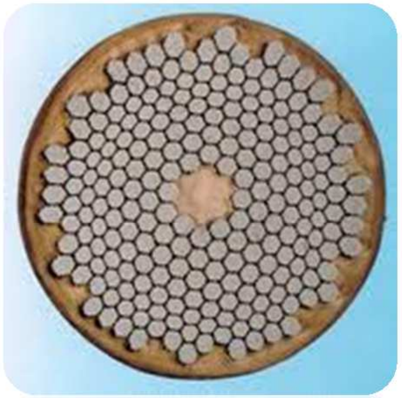
LARGE SCALE APPLICATIONS OF SUPERCONDUCTIVITY

Inductive Heating

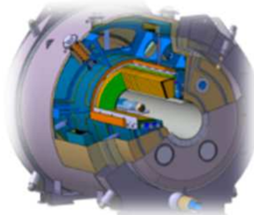
High Energy Physisc

Fusion





NMR MRI



Magnetic Separation

Power Applications

Transportation

MAIN ADVANTAGES OF SC

Large Scale Applications of Super-Conductivity	
Application	**Major Technical Features**
Power Cables	higher current densities, smaller conductor diameters, lower transmission losses, (side effect: oil-free)
Current Limiters	highly non-linear super-normal-conductor transition, self-controlled current limitation
Transformers	higher current densities, smaller size, lower weight, lower losses, (side effect: oil-free)
Motors / Generators	higher current densities, higher magnetic fields, smaller size, lower weight, lower losses
Magnets for RTD, Magnetic Energy Storage, Magnetic Separation, . NMR Spectroscopy, MRI, .. Magnetic Levitation Systems	higher current densities, higher & ultra-high magnetic fields, higher magnetic field gradients, smaller size, lower weight, lower losses persistent currents, ultra-high temporal field stabilities stronger levitation forces, larger air gaps
Cavities for Accelerators (based on LTS sheets or coatings)	lower surface resistances, higher quality factors, higher microwave-power handling capability
Magnetic Bearings (based on HTS bulk material)	higher current densities, lower losses, stronger levitation forces, self controlled autostable levitation

From Conectus

OPPORTUNITIES

Possibility to generate **very large volumes** of (high) **magnetic field** using superconductors.

$$E_{beam} \cong B_{dipole} \cdot R$$

Accelerator

$$\frac{S}{B} \propto B_0^{\frac{3}{2}}$$

NMR/MRI

$$\frac{\Delta p}{p} \propto \frac{p}{qBL^2}$$

Detector

Performance factor ~ $\mathbf{B}^3\ \mathbf{R}^2$

Fusion machine

RELEVANT PARAMETERS

- **Basic parameters for the specification**

  . *Field B, length L, radius R*

  . *Field shape and homogeneity, field stability, radiation thickness, interaction length, etc…*

- **Parameters relevant for the physics**

  . *B, BL (deflection), d^mB/d^mR (gradients), BL^2 (sagitta), BL^2 (momentum resolution), B^3R^2, etc…*

- **Parameters relevant for the magnet designer**

  . *B^2 R (mechanical forces)*

  . *B^2 R/ΔR (stresses , protection in case of quench, Δ R : coil thickness)*

- **Parameters relevant for the ressource manager**

  . *Cost :* $C = \alpha\,(RL)^{0.8} + \beta\,(B^2 R^2 L)^{0.7}$ *(from A. Hervé)*

  $C(M\$) = 0.5(E_s(MJ))^{0.662}$

  $C(M\$) = 0.4(B(T)V)^{0.635}$ *(from Green and Lorant)*

CHALLENGES

- **B** *: intrinsic value :* B_c *~ 10 T for NbTi*

  ~ 20 T for Nb_3Sn

-**Mechanical forces/stresses**

. Forces must be held by the conductor and/or the external support structure

(coil thickness $\propto RB^2/(E/M) \propto RB^2 \rho/\sigma_h$ *(*ρ *=density))*

. Electrical insulation must also withstand the stress (shear stress in particular)

- **Protection in case of quench**

. Importance of the value of the stored energy per unit of cold mass (E/M ratio) peak temperature at homogeneous energy dump ($E = 0.5\mu_0 \int B \cdot dV$ *;* $E/M = H = \int C_p dT$*)*

. Necessity of fast quench propagation (active/passive propagation techniques, high RRR in stabilizer, energy extraction by external dump)

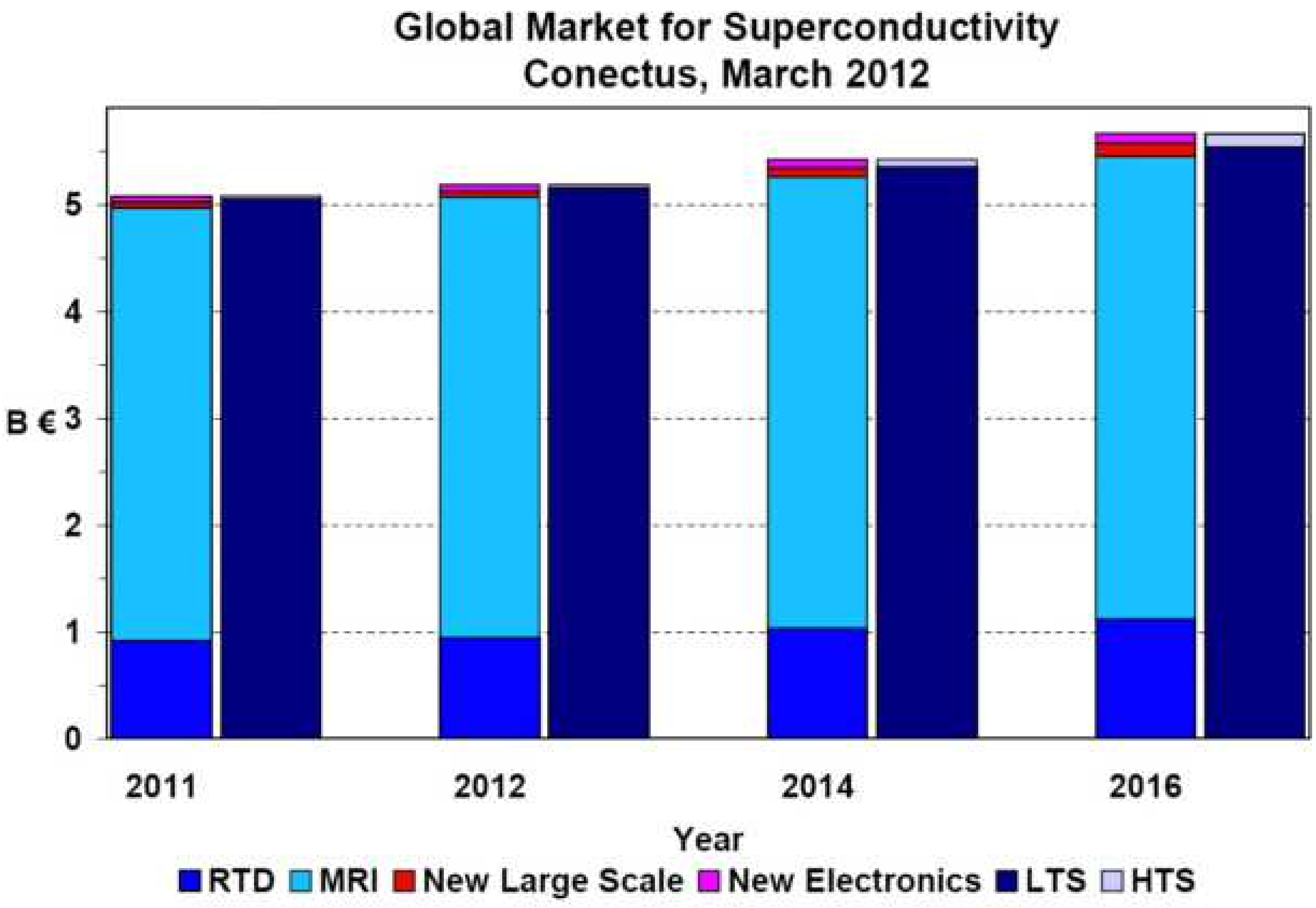
- **Dimensions:** . Manufacturing dimensions and tolerances, handling

  . Road transportation R_{max} ~ 3.5 m

- Enabling technologies : Conductor, insulation, cooling, manufacturing techniques

World SC Market

SC market repartition and evolution



From Conectus

SC NEW MARKETS

New Markets for Large Scale & Electronics Applications of Superconductivity
Conectus, March 2012

Application	2012		2013		2014		2015		2016	
Magnets for New Medical Applications	▣	▣	▣	▣	■	■	■	■	■	■
Fault Current Limiters	□	□	▣	▣	▣	▣	▣	▣	■	■
Power Cables	□	□	□	□	□	□	▣	▣	▣	▣
Rotating Electric Machines	□	□	□	□	□	□	□	□	▣	▣
Magnetic Bearings & Levitation	□	□	□	□	□	□	□	□	▣	▣
Magnetocardiography	□	□	□	□	▣	▣	▣	▣	▣	▣
Digital Circuits	□	□	□	□	▣	▣	▣	▣	▣	▣
Other Electronic Devices & Sensors	□	□	□	□	▣	▣	▣	▣	▣	▣

New Large Scale & New Electronics Applications:

- □ □ pre-commercial orders related to RTD activities, field tests and prototype operation
- ▣ ▣ emerging market
- ■ ■ established market

From Conectus

NMR/ MRI FOR THE FUTURE

Push the limits of NMR/ MRI systems

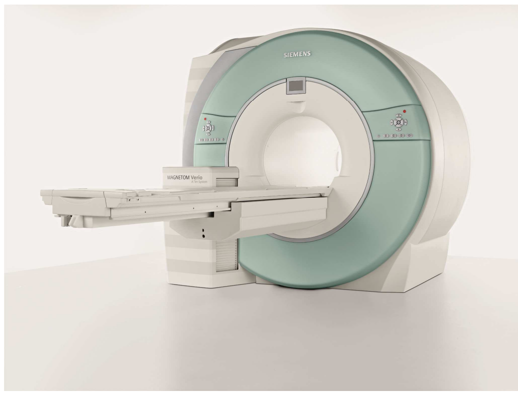
Varian 400 Mhz

Varian 900 Mhz

Bruker 950 Mhz

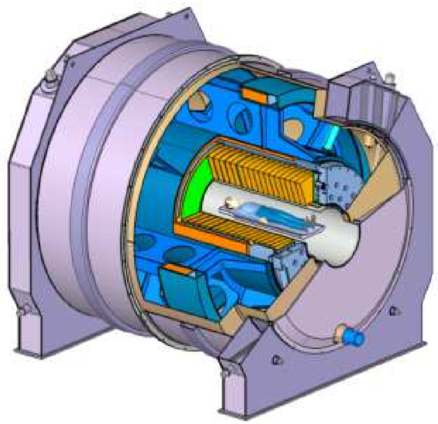
Bruker 1 Ghz

GE 1.5 T magnet
(SHFJ/CEA)



Siemens 3 T magnet

GE 9.4 T 600 mm



Iseult 11.7 T
(CEA)

1 mm
1s

Increase spatial and time resolution →

0.1 mm
0.1s

POWER CABLES

Cable System	AC		DC
	Conventional	HTS	HTS
Voltage (kVrms)	275	66	130
Current (kA/phase)	1	3.3	12
Loss (kW/km)	740	200	20

138 kV, 600 m, 2.5 kA, 574 MVA cable installed and operating since April 2008 in LIPA grid

American Superconductor

LIPA Long Island Power Authority

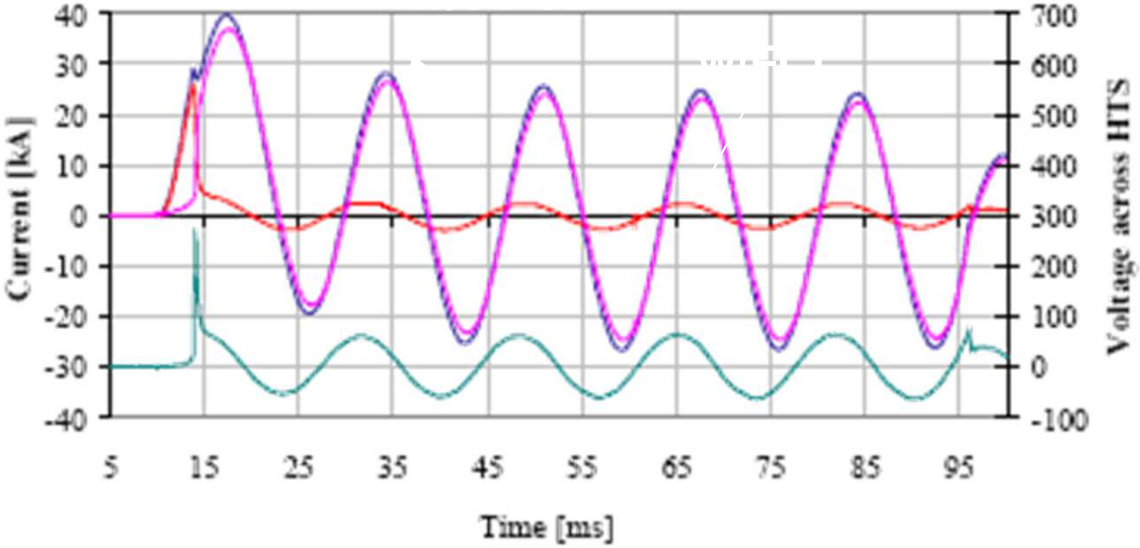
Nexans

AIR LIQUIDE

Superconductors switch to resistive state above critical current

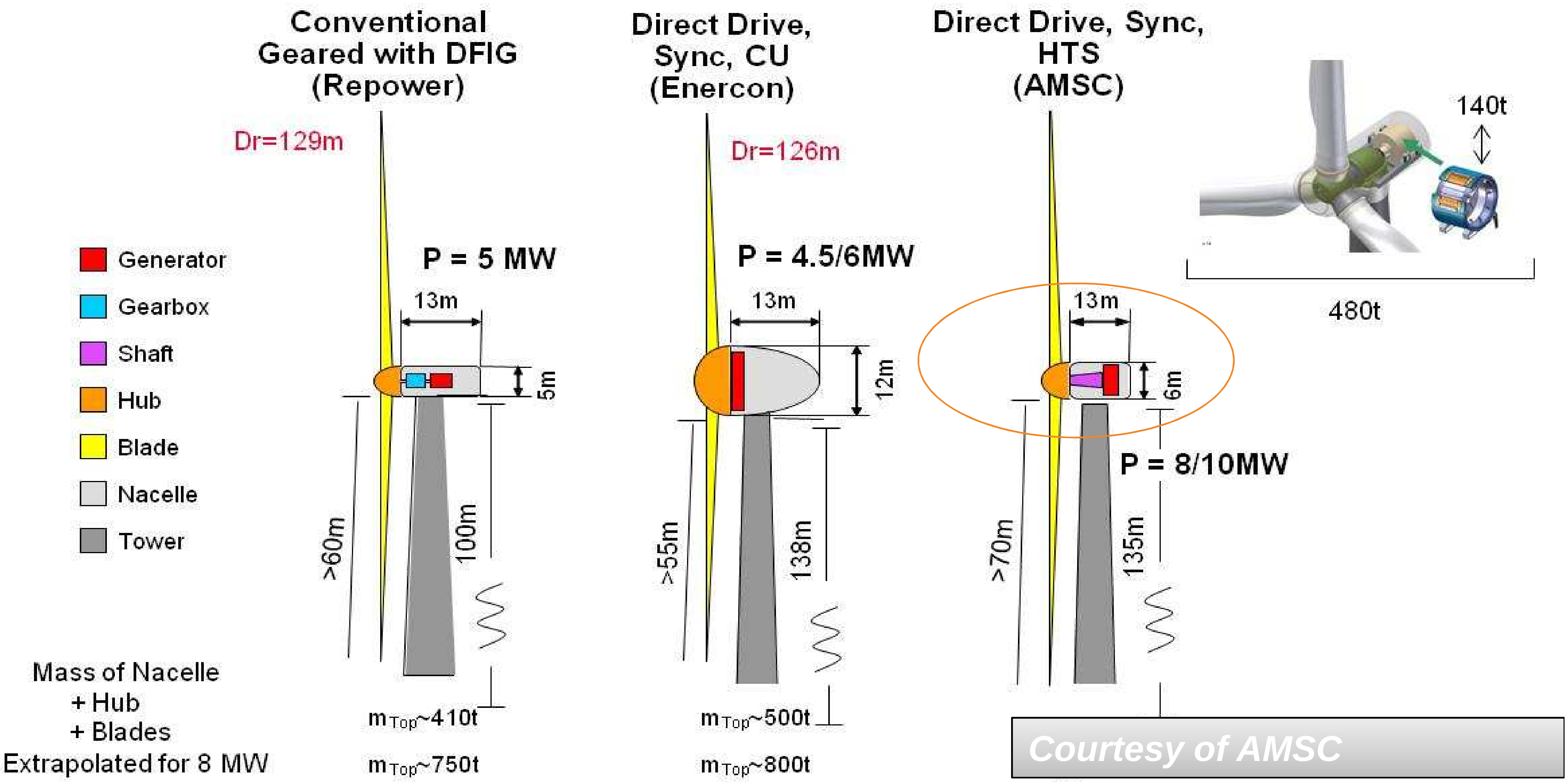
Increased resistance limits current flow

Many FCLs demonstrated; commercialization beginning



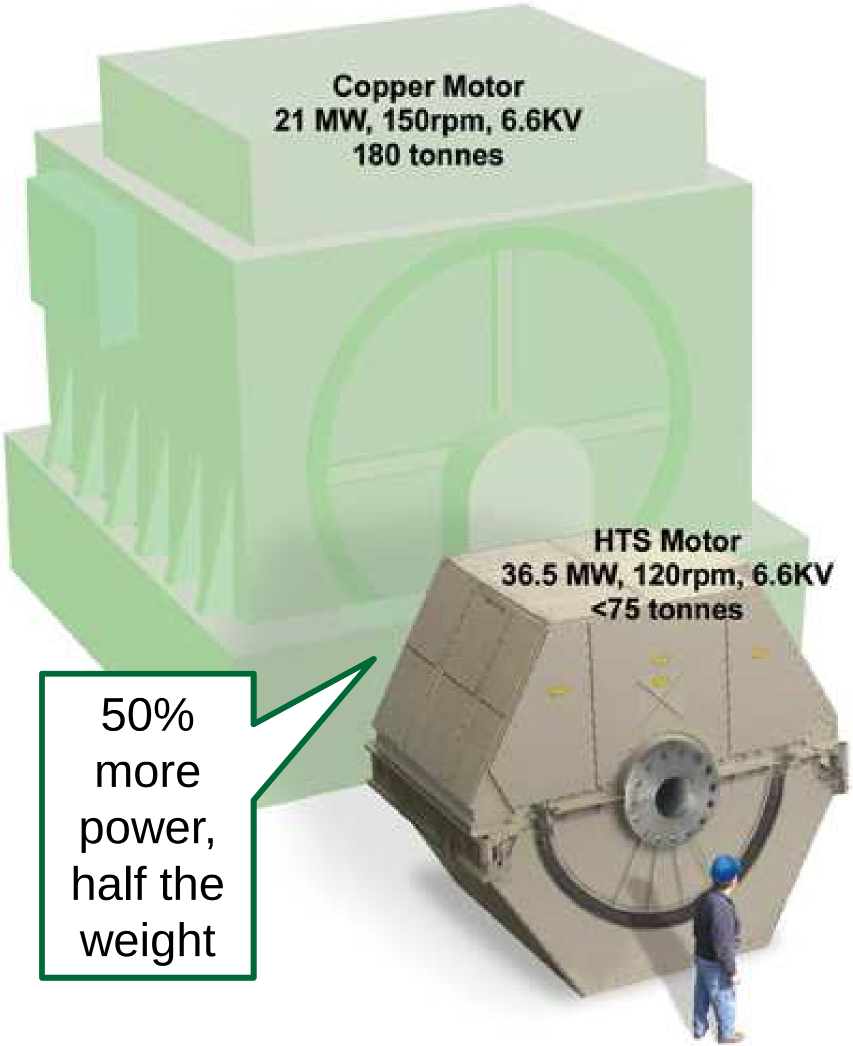
Bifilar coil switching module

WIND POWER GENERATORS

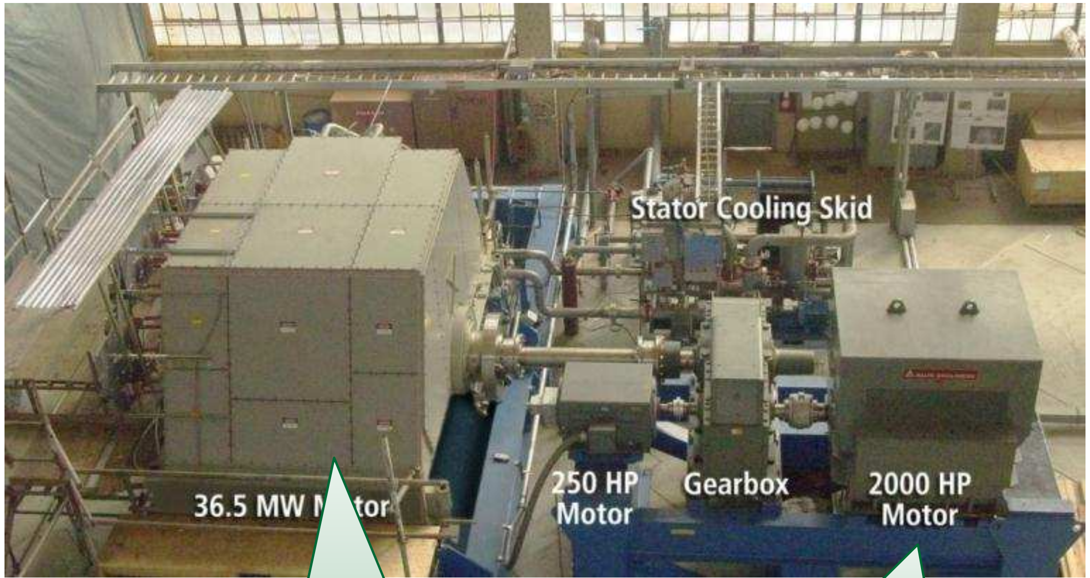


HTS generators reduce size and weight for 8-10 MW wind turbine
Lowest cost of energy: lowest installed cost per MW, highest efficiency, longest maintenance interval

ROTATING MACHINERY



50% more power, half the weight



AMSC's 36.5 MW HTS Motor

1.5MW Copper Motor

Key Advantages:

- Less than half the size and weight
- Higher efficiency
- Less noise

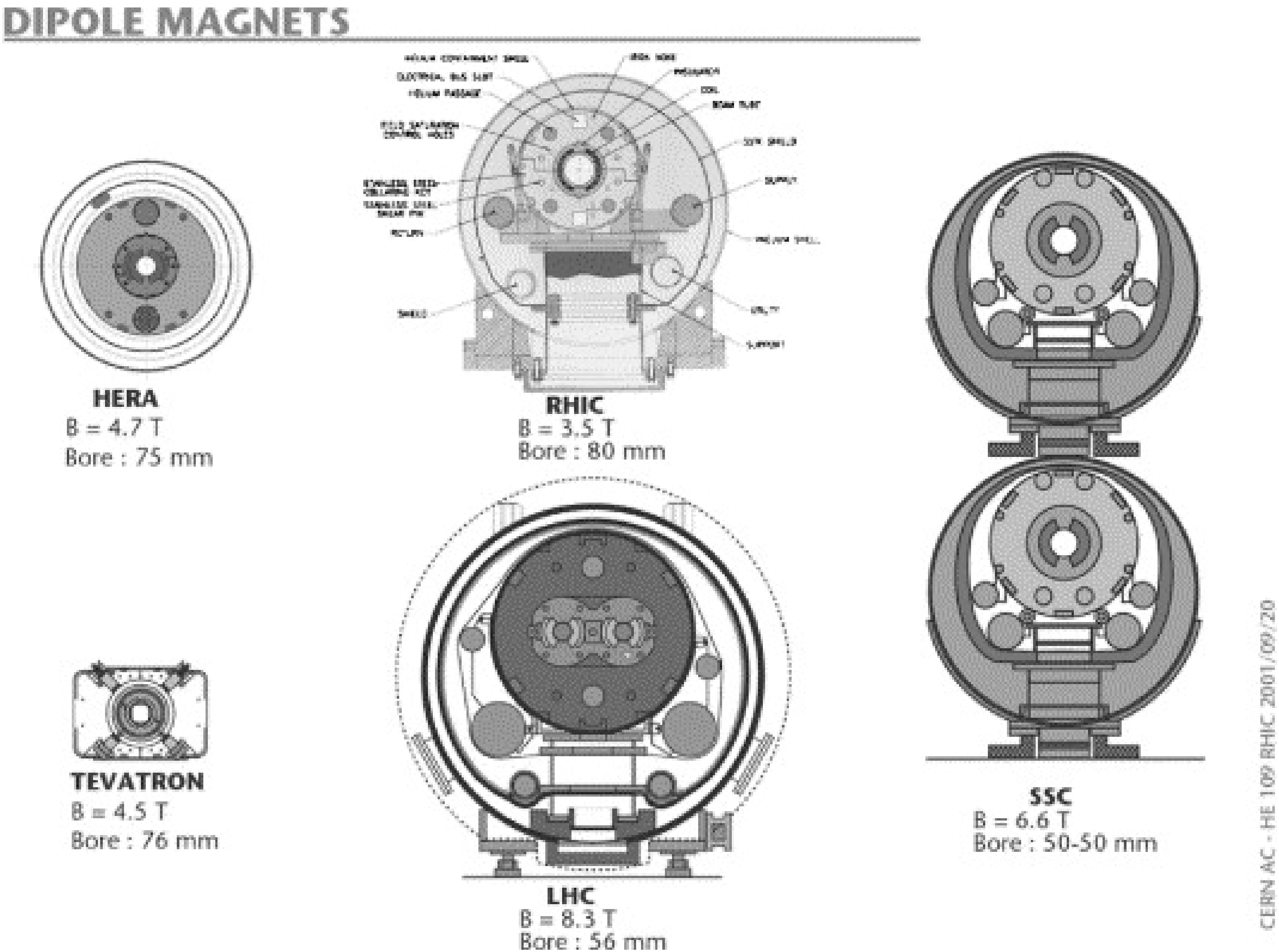
TRANSPORTATION APPLICATION : MAGLEV

Maglev uses magnetic forces to levitate

Strong magnetic field are produced by superconducting coils, as in MRIs.

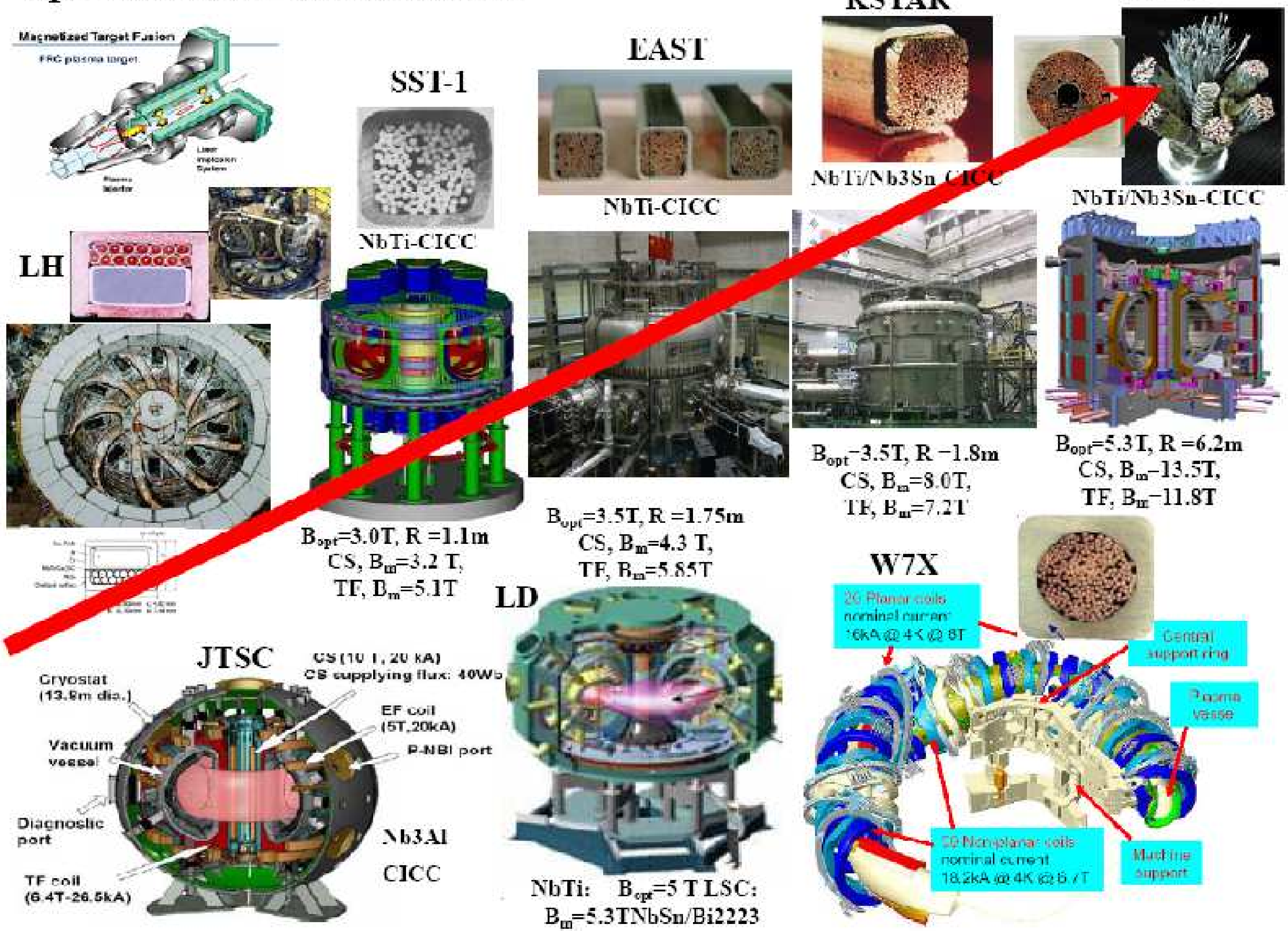
Japanese Railway Technical Research Institute (JR-RTRI) built a 40 km long track to test their Maglev in Yamanashi region, in Japan. It was on this track that the prototype MLX01 won the speed record for a train: 581 km/h

ACCELERATOR MAGNETS

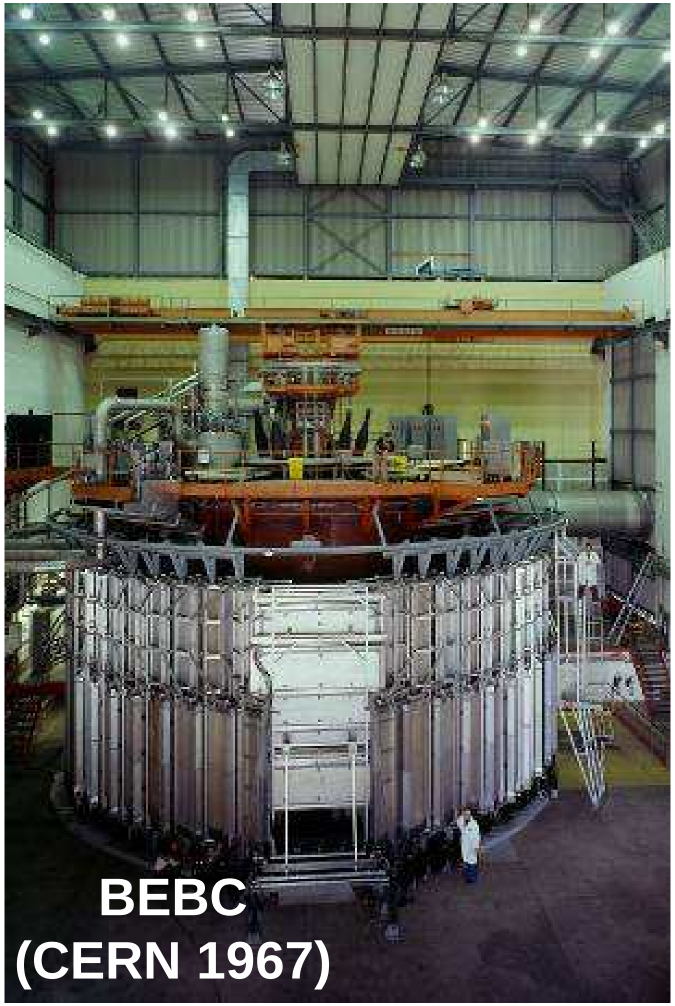


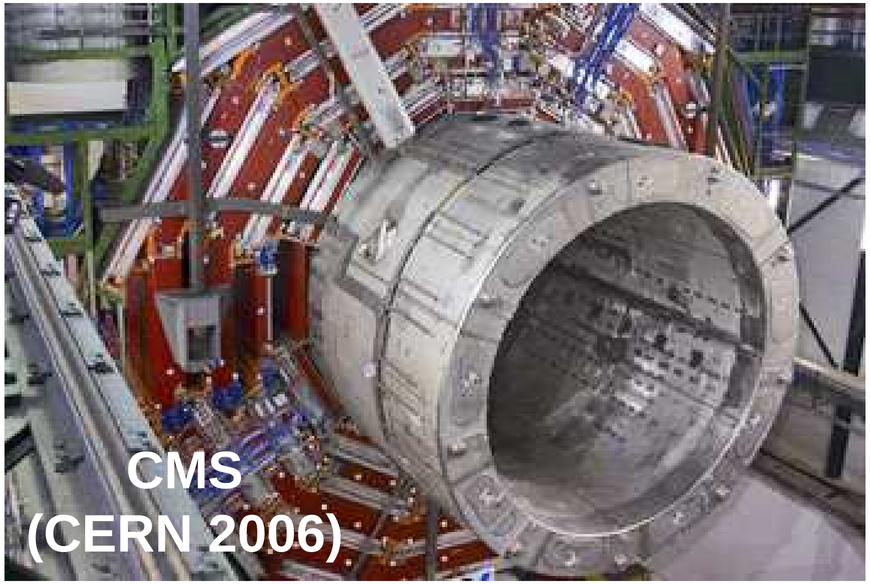
FUSION MAGNETS

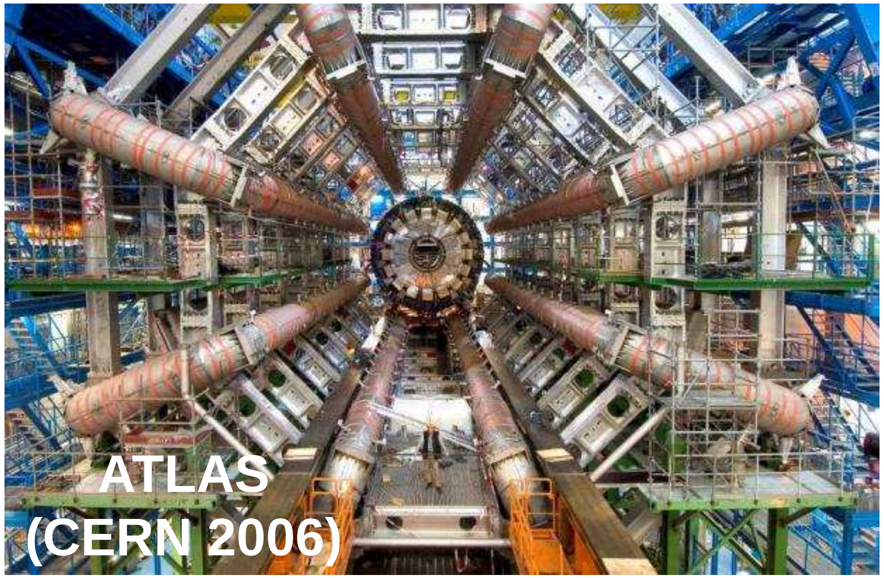
Specifications on Tokamaks



DETECTOR MAGNETS



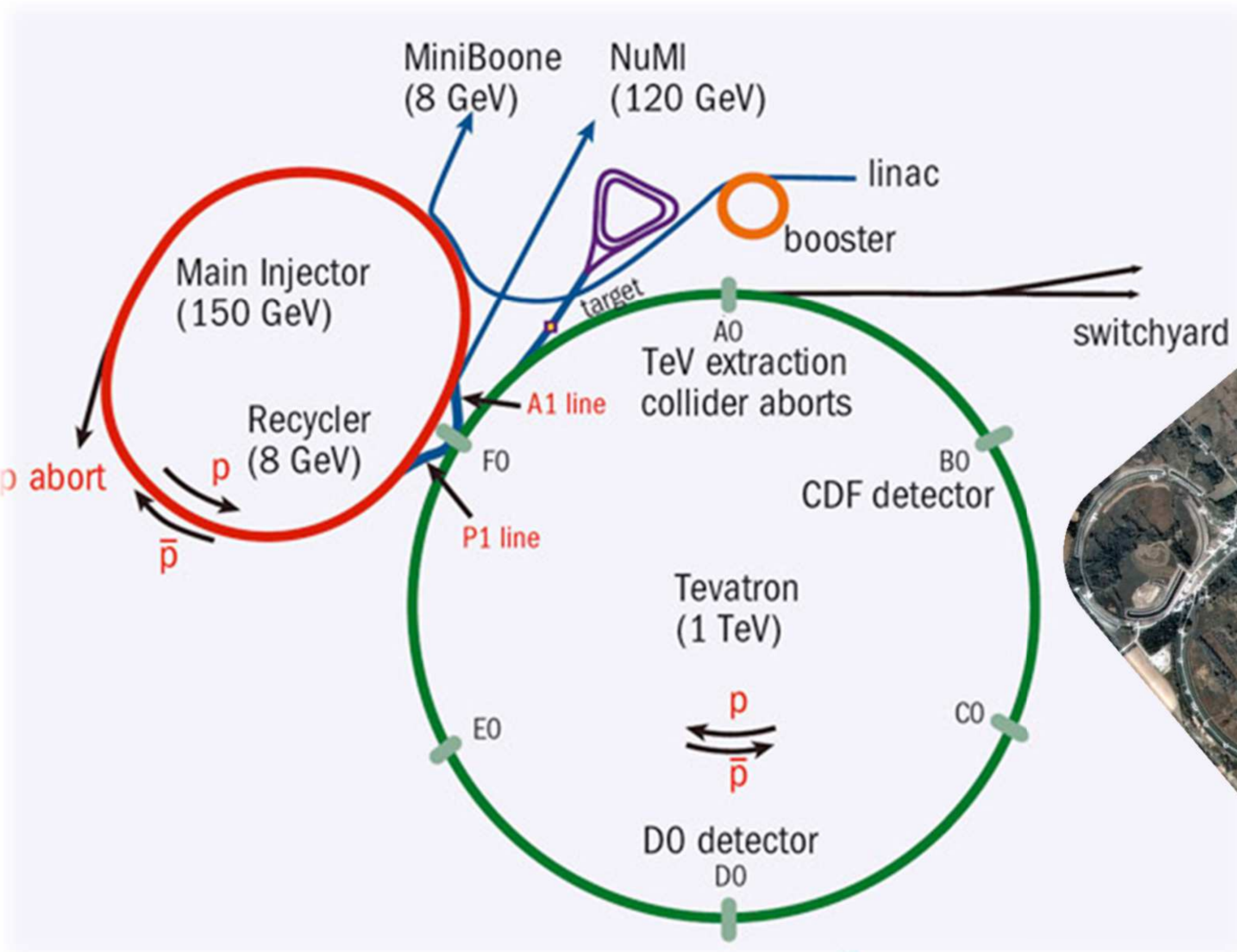




ACCELERATOR MAGNETS

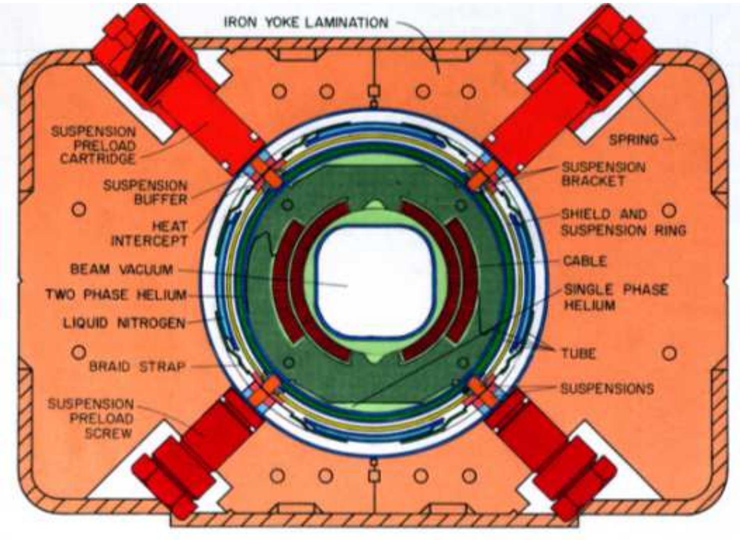
TEVATRON

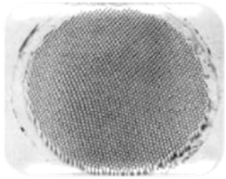
900 GeV proton/antiproton 6.3 km ring collider at Fermilab IL

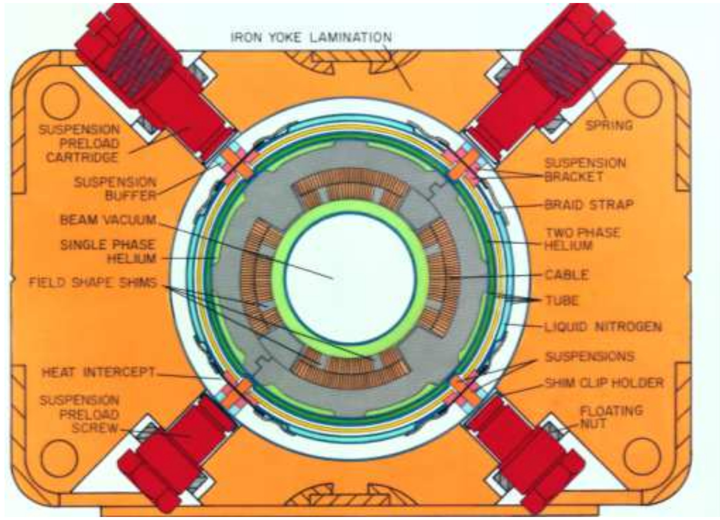


Commissioning 1983 Closed 2011

TEVATRON MAGNETS







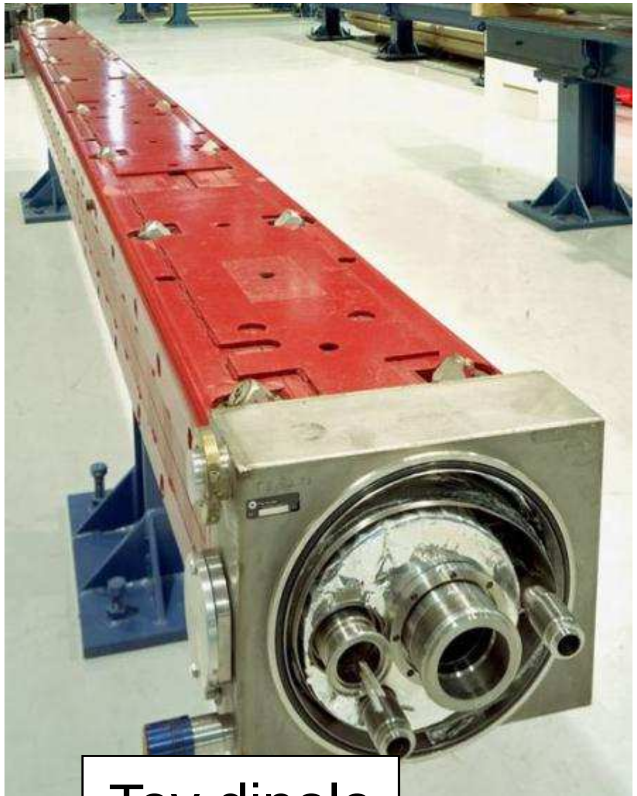
774 6.1-m-long dipole magnets

216 1.7-m-long quadrupole magnets

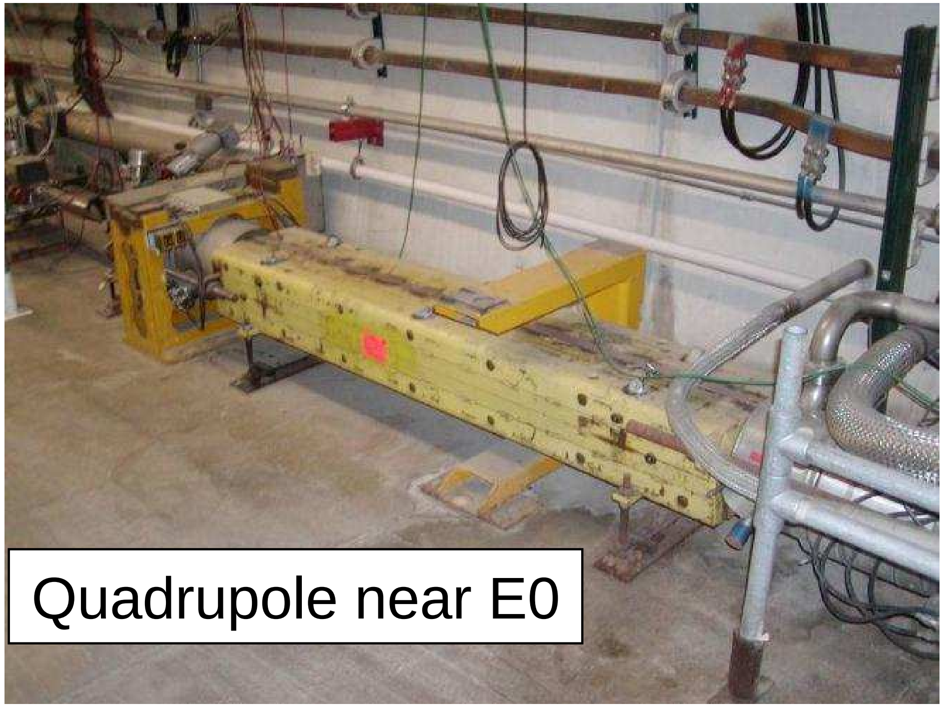
	DIPOLE	QUADRUPOLE
Operating temperature (K)	4.6	4.6
Central field (T)	4.4	
Gradient (T/m)		75.8
Field length (m)	6.11	1.679
Inner coil diameter (mm)	76.2	88.9
Number of coil layers	2	2
Superconducting material	NbTi	NbTi
Collar material	Stainless steel	Stainless steel
Yoke	warm	warm
Cryostat length (m)	6.4	2.31
Total number	774	216

Strand diameter	0,68 mm
Filament diameter	9 µm
Cu/Sc	1,8
Jc @ 5T, 4.2 K	1800 A/mm^2
Nb of strands	23
Cable dimensions	1.372/1.067 x 7.671 mm

PICTURES OF TEVATRON MAGNETS



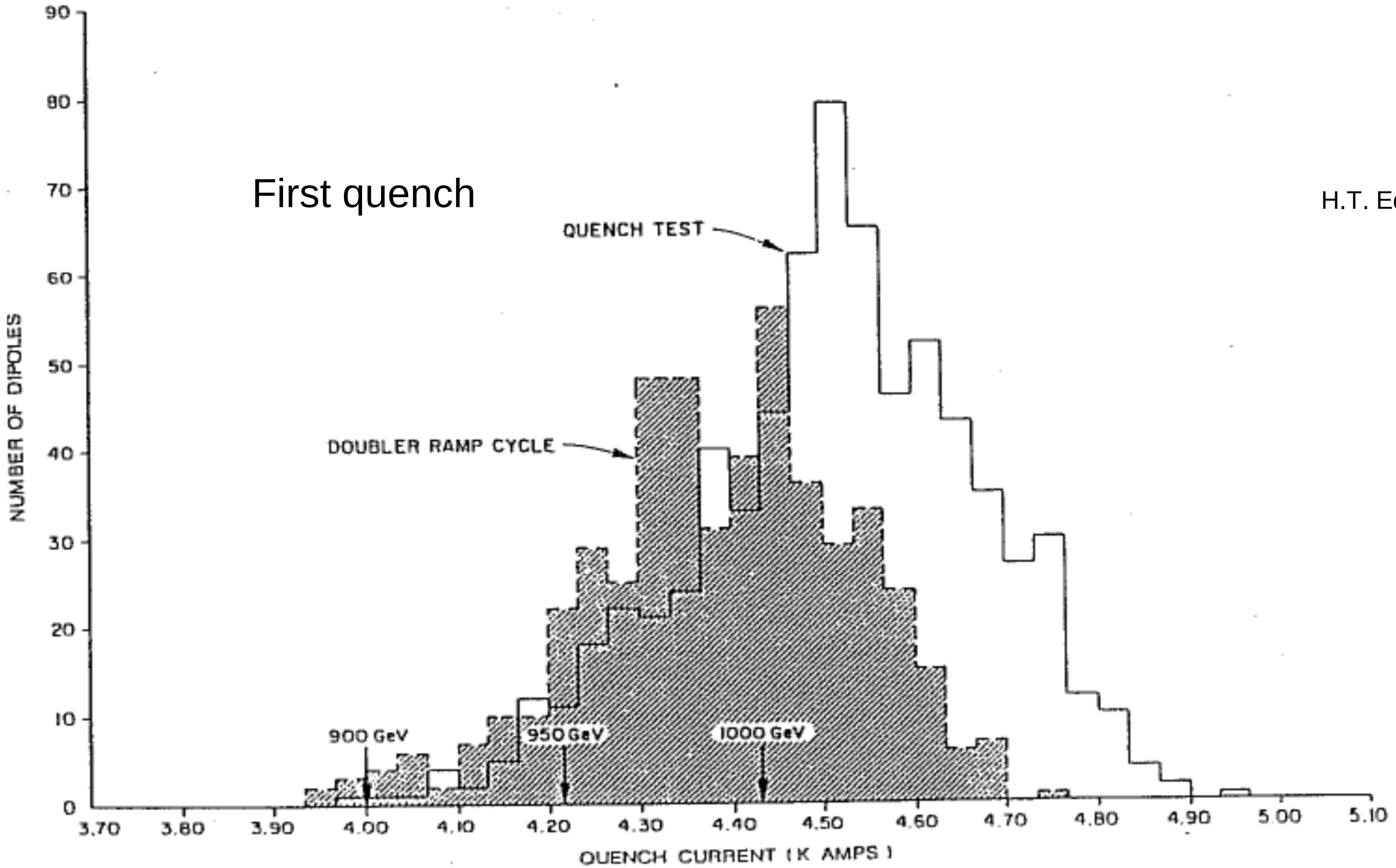
Tev dipole



Quadrupole near E0

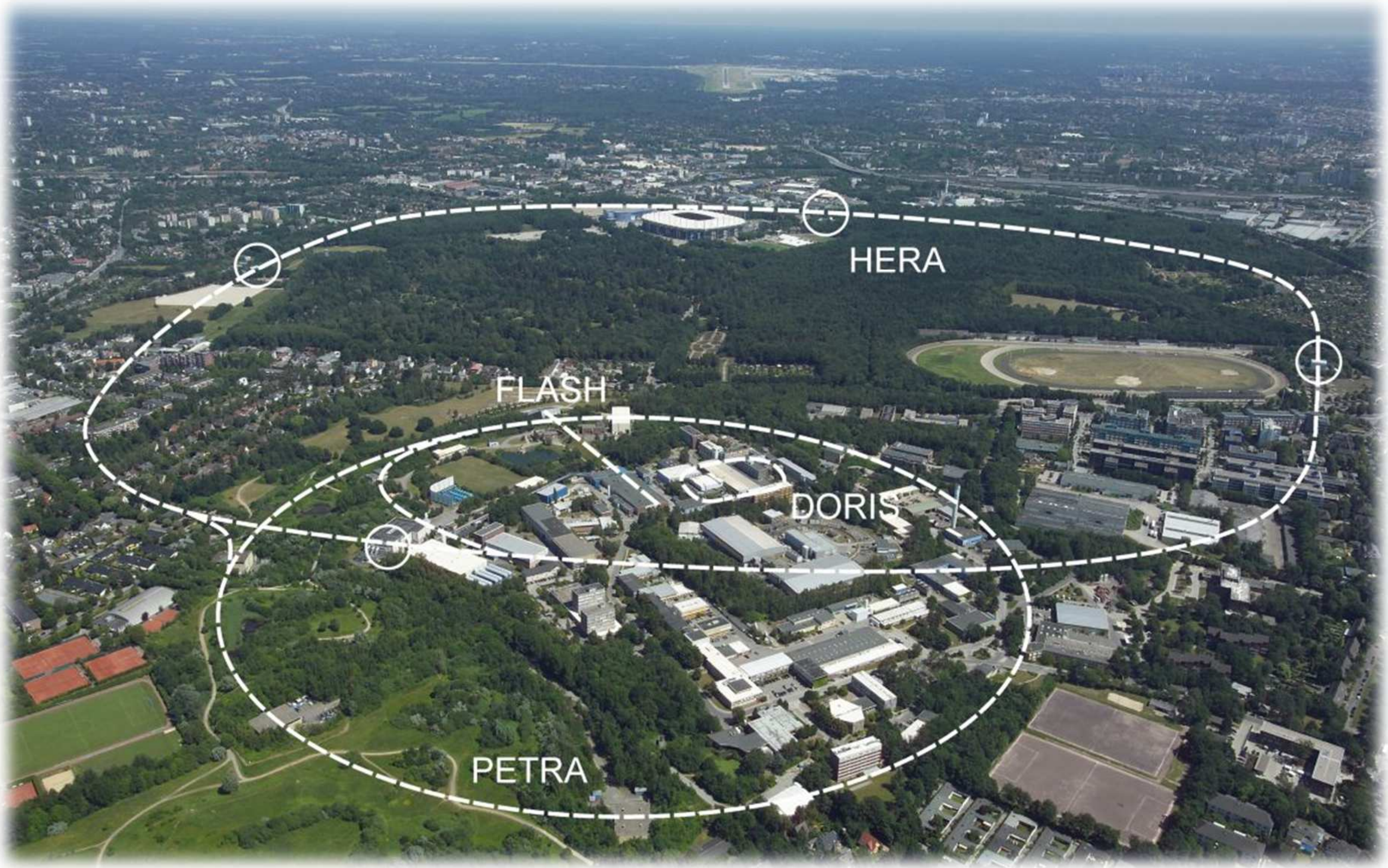
Image by courtesy of Fermi National Accelerator Laboratory

All magnet were measured under two different excitation cycles (different ramp rates).



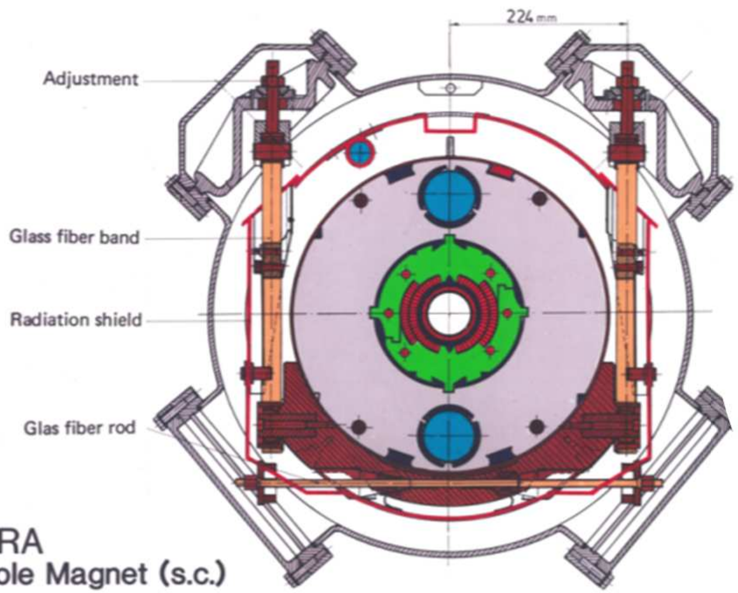
HADRON ELEKTRON RING ANLAGE (HERA)

30 GeV conventional electron ring and an intersecting 920 GeV proton ring built at DESY (Deutsches Elektronen-SYnchrotron near Hamburg

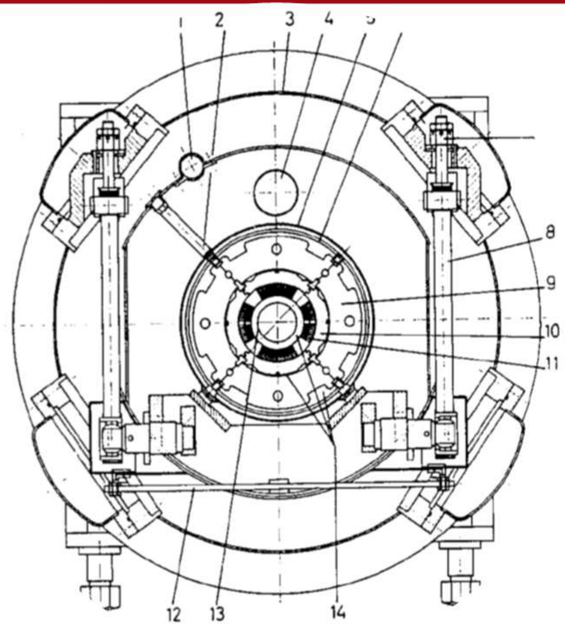


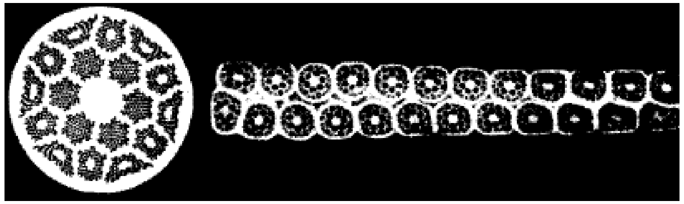
Commissioning 1990 closed 2007

HERA MAGNETS



HERA
Dipole Magnet (s.c.)

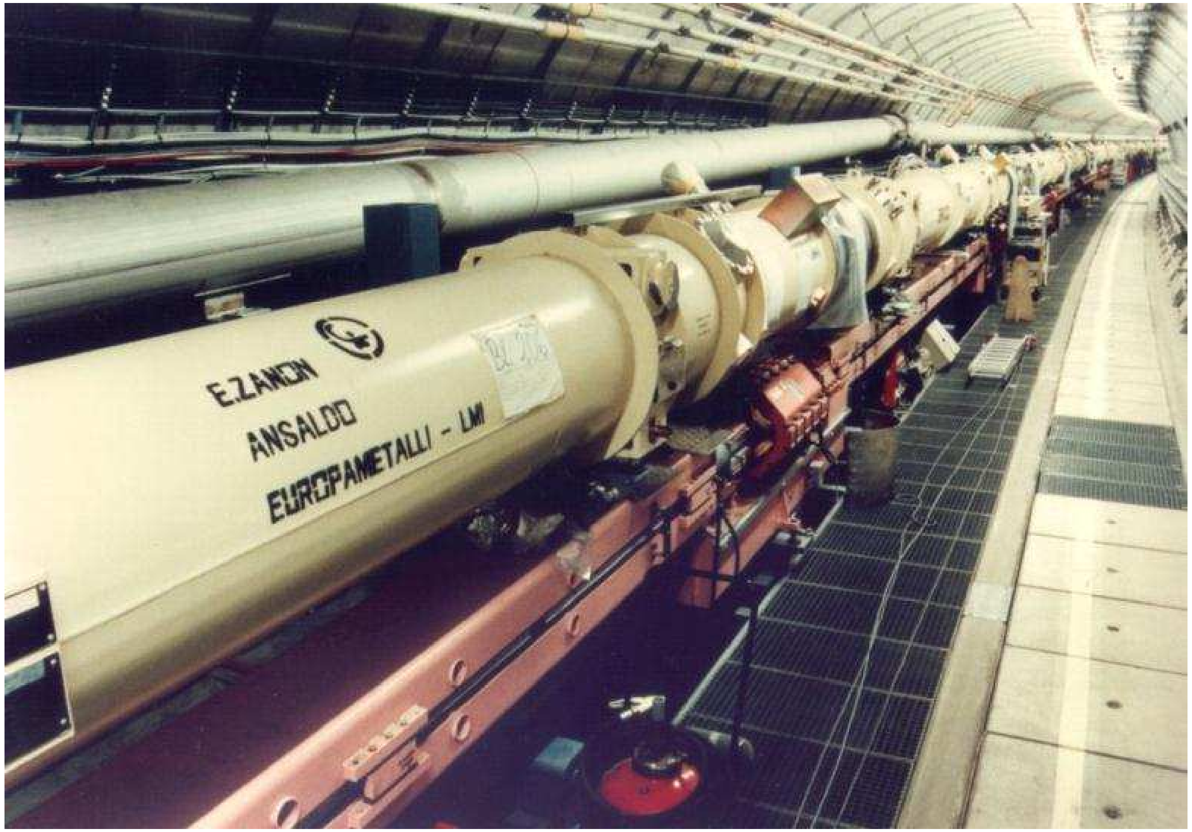


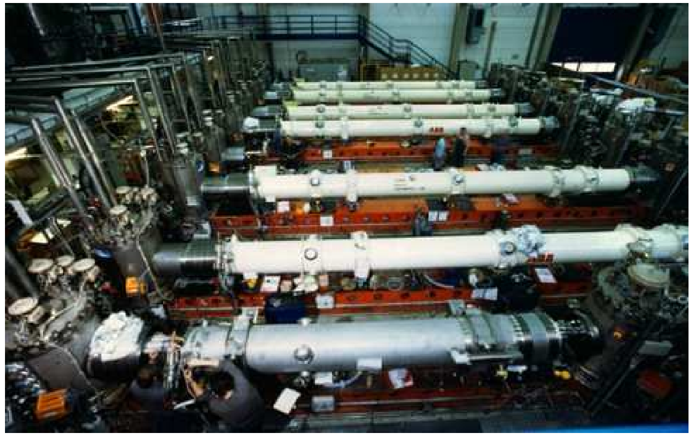


	DIPOLE	QUADRUPOLE
Operating temperature (K)	4.5	4.5
Central field (T)	4.68	
Gradient (T/m)		91.2
Field length (m)	8.82	1.861
Inner coil diameter (mm)	75	75
Nominal current (A)	5027	5027
Number of coil layers	2	2
Superconducting material	NbTi	NbTi
Filament diameter (mm)	14	19
Collar material	Al-alloy	Stainless steel
Yoke	cold	cold
Cryostat length (m)	9.77	3.98
Total number	422	224

Strand diameter	0,84 mm
Filament diameter	14 µm
Cu/Sc	1,8 mm
Jc @ 5.5 T, 4.2 K	> 2200 A/mm2
Nb of strands	24
Cable dimensions	1.67/1.28 x 10 mm

PICTURES OF HERA MAGNETS



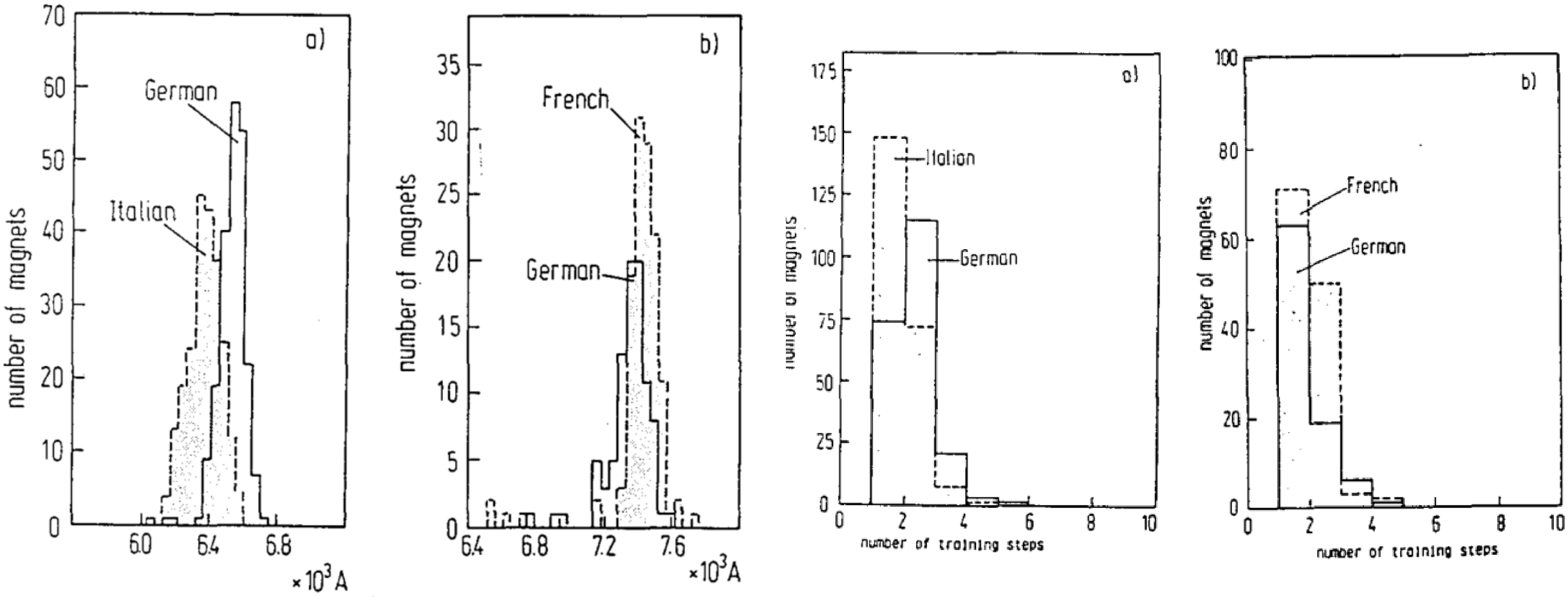


SC magnet testing

Reference magnets

HERA MAGNET QUENCH PERFORMANCES

Training is negligible: maximum quench current reached after few quenches.



Measurements of quench currents at 4.75 K, Mean (±σ):
Dipoles 6458 A (± 114 A); Quads: 7383 A (± 148 A)
Weakest: Dipole: 6154 A, Quad: 6518 A

SUPERCONDUCTING SUPER COLLIDER (SSC)

Main collider composed of two independent 87 km rings of 20 TeV for protons.

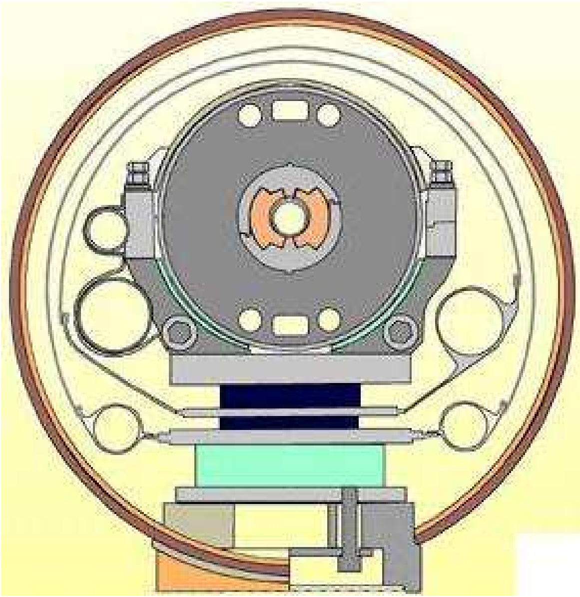
Injector complex includes a 600 MeV Linac, a 12 GeV rapid-cycling Low Energy Booster, a 200 GeV Medium Energy Booster, and a **2 TeV superconducting High Energy Booster (HEB) (10,8 km ring)**.

Construction site

SSC buildings

Cancelled Octobre 1993

SSC MAGNETS



	SSC Quadrupoles	
	Collider/LBL	HEB
Operating temperature (K)	4.35	4.35
Gradient (T/m)	204	186
Field length (m)	5.07	1.6
Inner coil diameter (mm)	40	50
Number of coil layers	2	2
Superconducting material	NbTi	NbTi
Filament diameter (mm)	6	6
Collar material	Stainless steel	Stainless steel
Yoke	cold	cold
Total number	1564	318

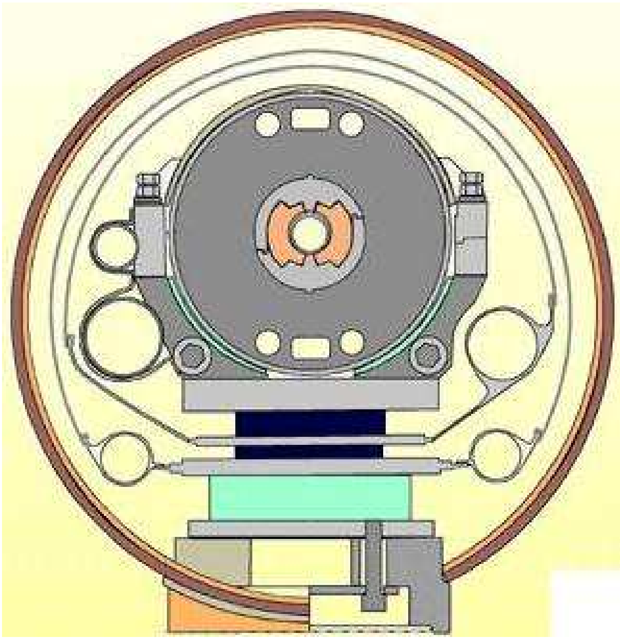
	SSC Dipoles	
	Collider	HEB
Operating temperature (K)	4.35	4.35
Central field (T)	6.7	6.7
Field length (m)	15.2	12.3
Inner coil diameter (mm)	50	50
Number of coil layers	2	2
Superconducting material	NbTi	NbTi
Collar material	Stainless steel	Stainless steel
Yoke	cold	cold
Total number	7634	512

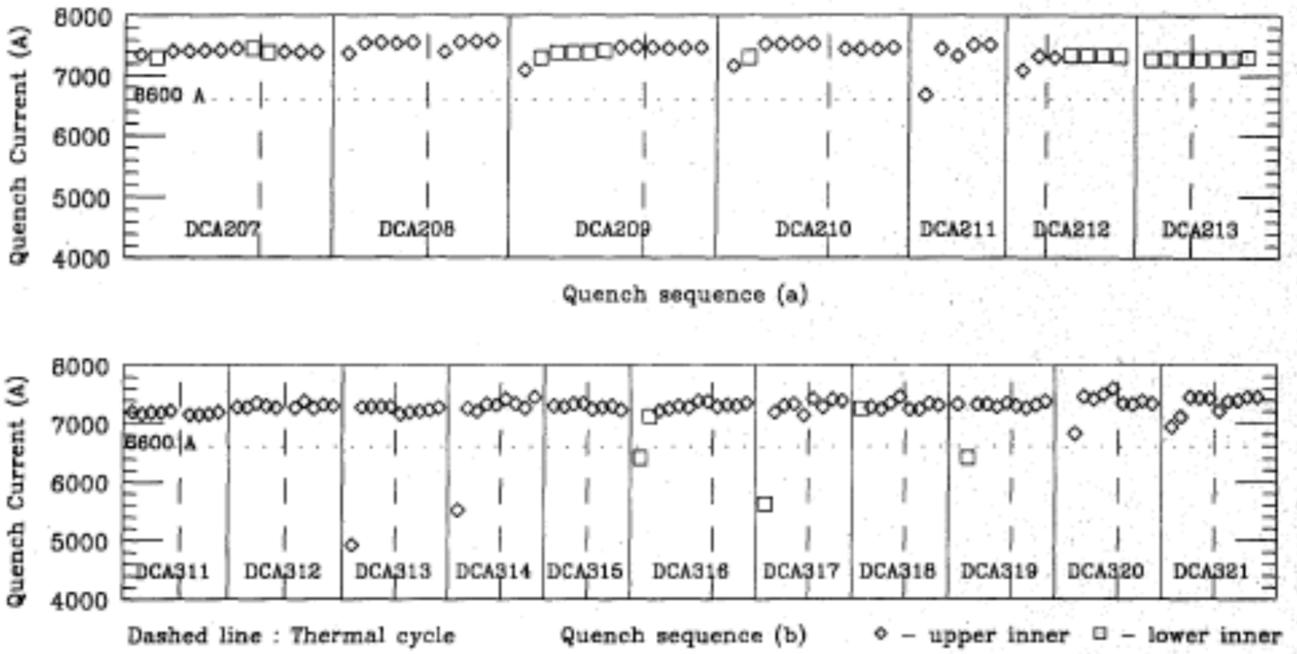
Strand diameter	0,648/0,808 mm
Filament diameter	8 µm
Cu/Sc	1,8 mm
Jc @ 5T, 4.2 K	> 2750 A/mm2
Nb of strands	30/30/36
Cables dimensions	1.33/1.15 x 12.3 mm 1.062/1.268 x 9.73 mm 1.05/1.26 x 11.7 mm

SSC DIPOLE MAGNET QUENCH PERFORMANCES

Test results from 18, 50 mm aperture, SSC dipole prototypes

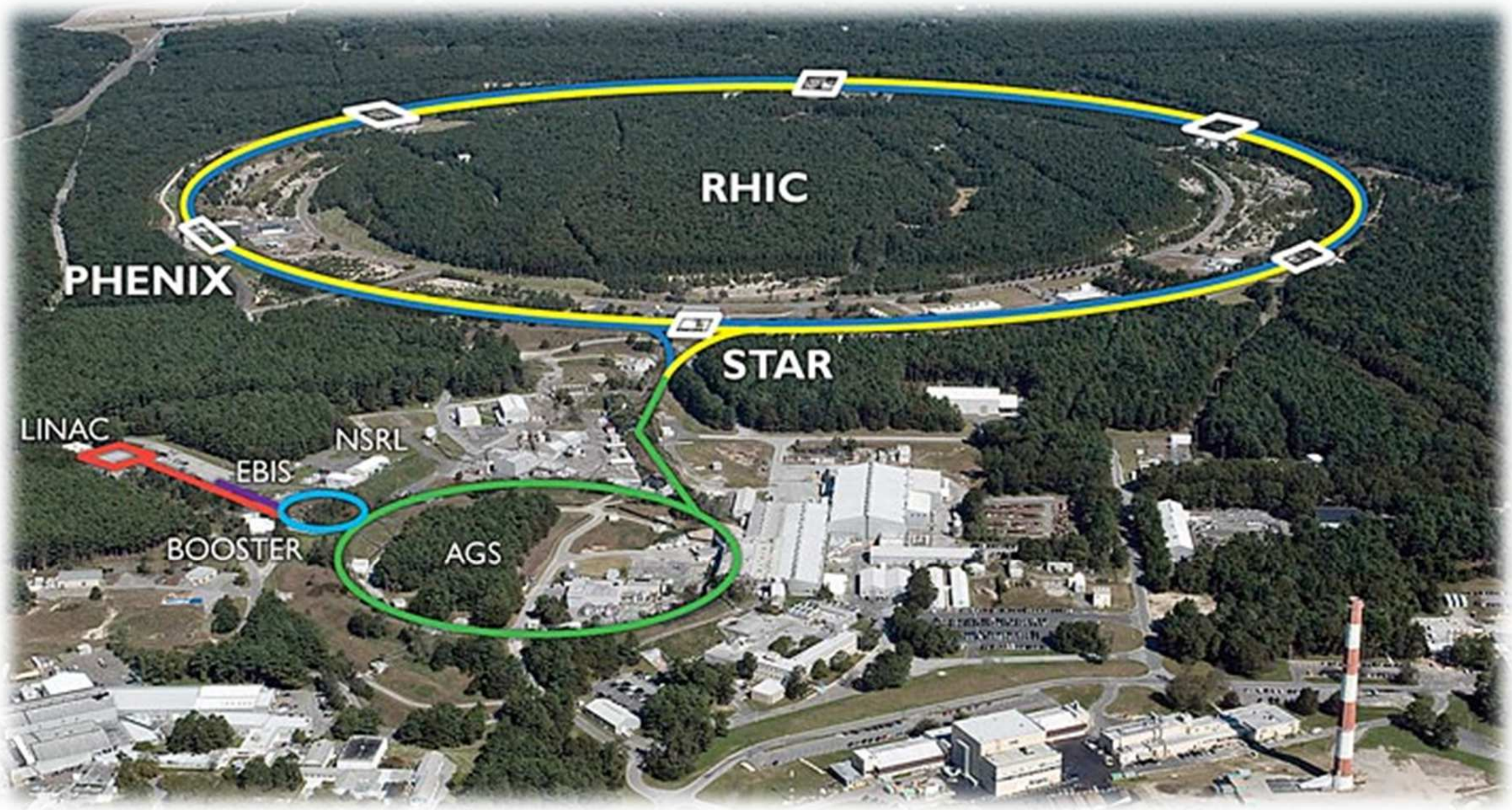
No or very little training to 6600 A (operating current).
All the magnets tested reached a plateau current very close to the short sample current.





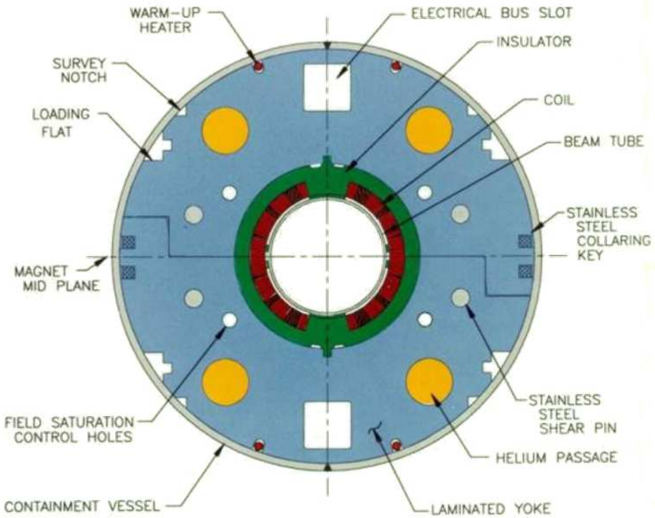
RELATIVISTIC HEAVY ION COLLIDER RHIC

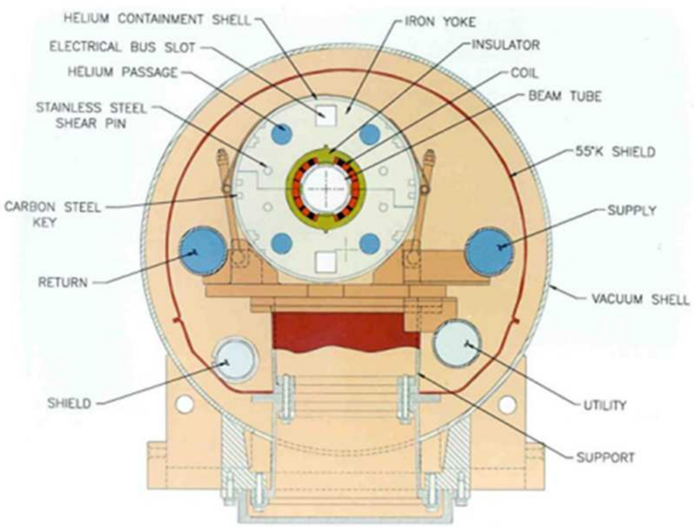
Relativistic Heavy Ion Collider at Brookhaven National Laboratory accelerates and collides an extremely wide range of particles, from protons up to gold ions in the energy range 30 to 100 GeV/u , with two separate rings of 3,8 km.

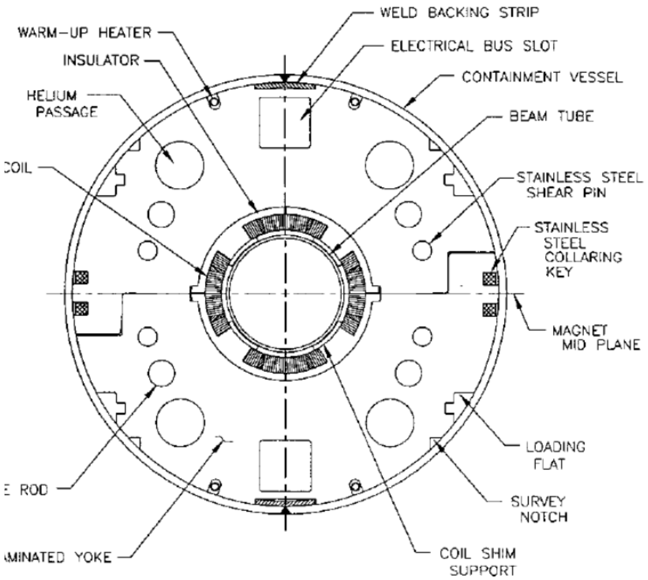


Commissioning 2000

RHIC ARC MAGNETS



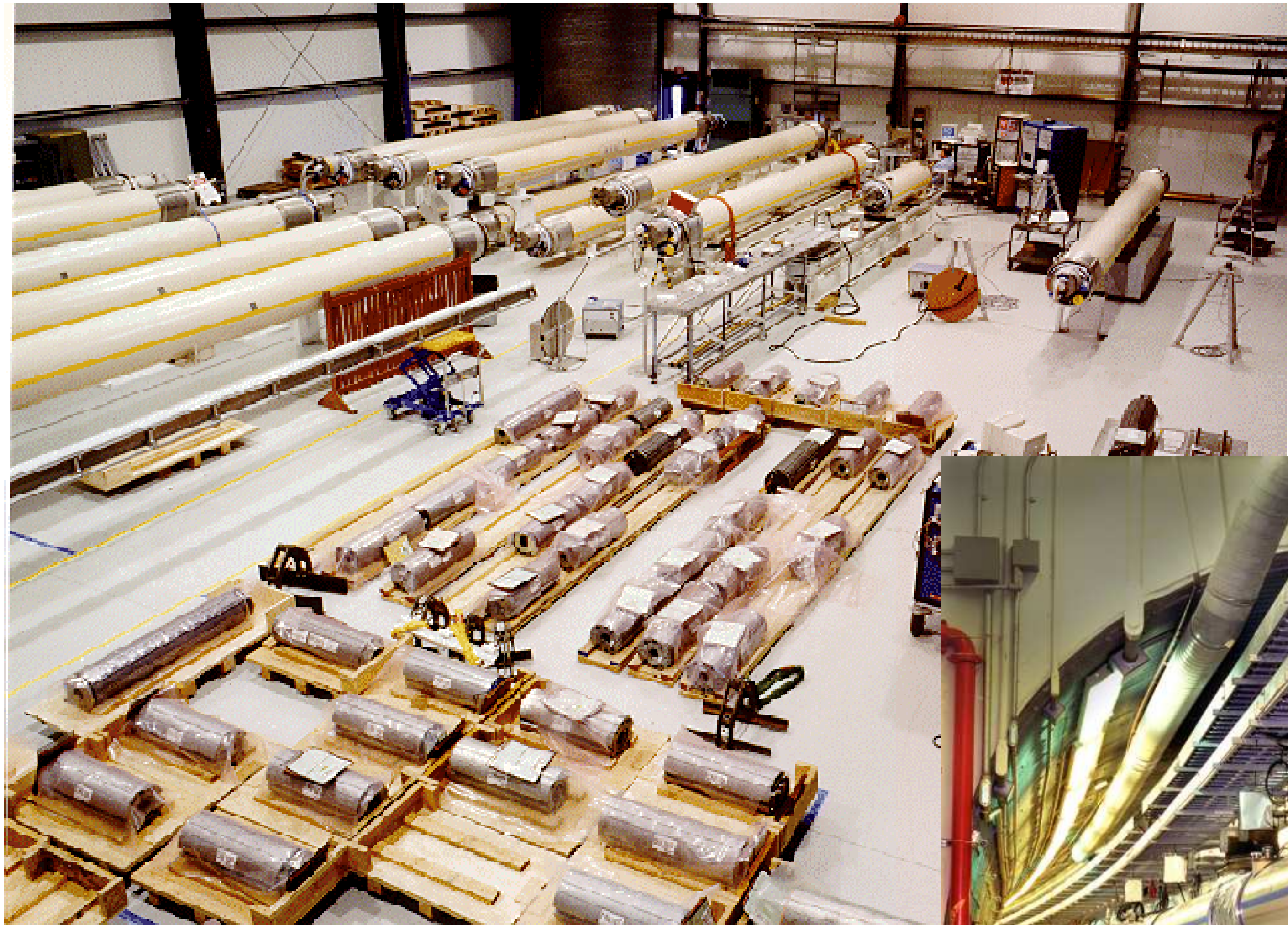




	RHIC	
	Dipole	Quadrupole
Operating temperature (K)	4.6	4.6
Central field (T) Gradient (T/m)	3.45	 71.8
Field length (m)	9.46	1.13
Inner coil diameter (mm)	80	80
Number of coil layers	1	1
Superconducting material	NbTi	NbTi
Collar material	none	none
Yoke	cold	cold
Cryostat length (m)	9.728	3.023
Total number	372	492

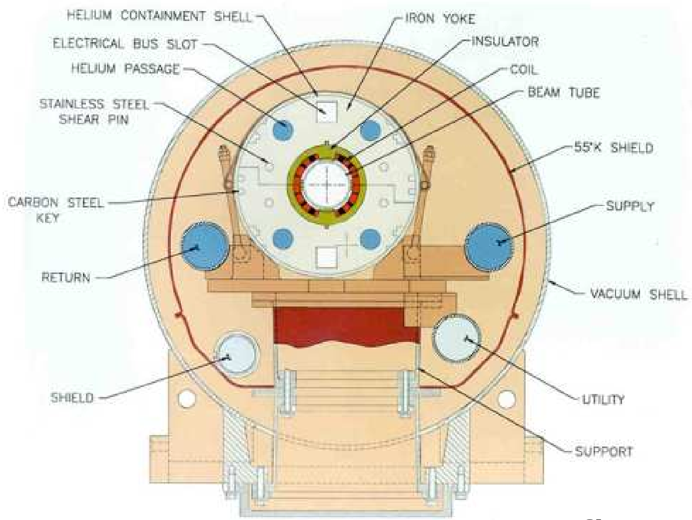
Strand diameter	0,648 mm
Filament diameter	6 µm
Cu/Sc	2;25
Jc @ 5T, 4.2 K	2750 A/mm2
Nb of strands	30
Cable dimensions	1.166 x 9.73 mm

PICTURES OF RHIC MAGNETS

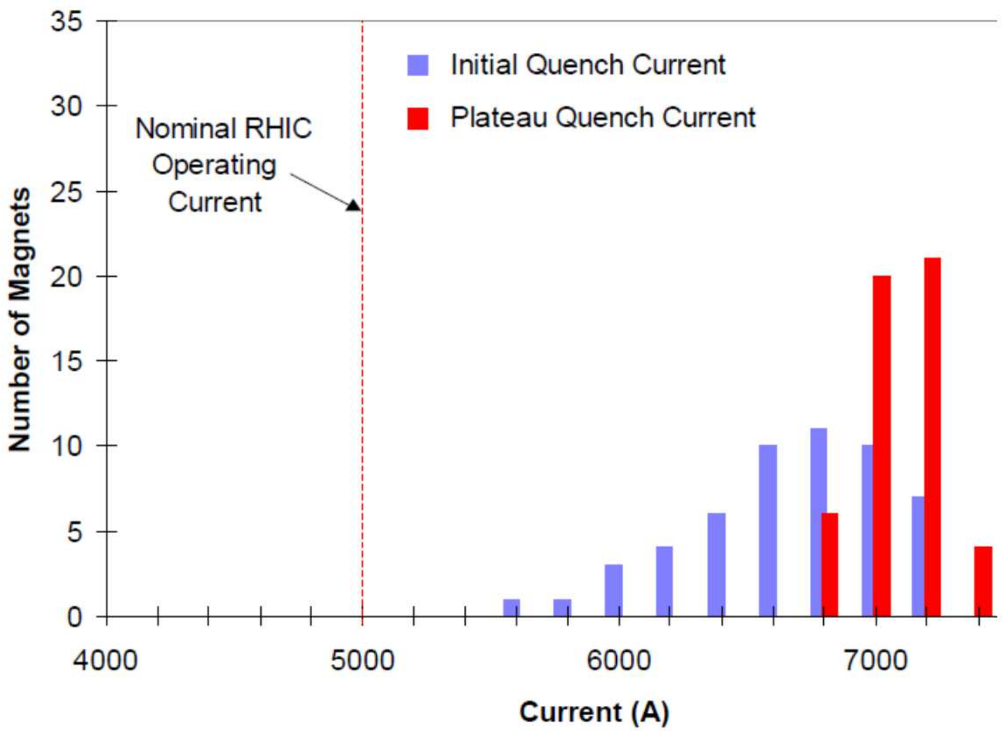


Images by courtesy of
Brookhaven Accelerator Laboratory

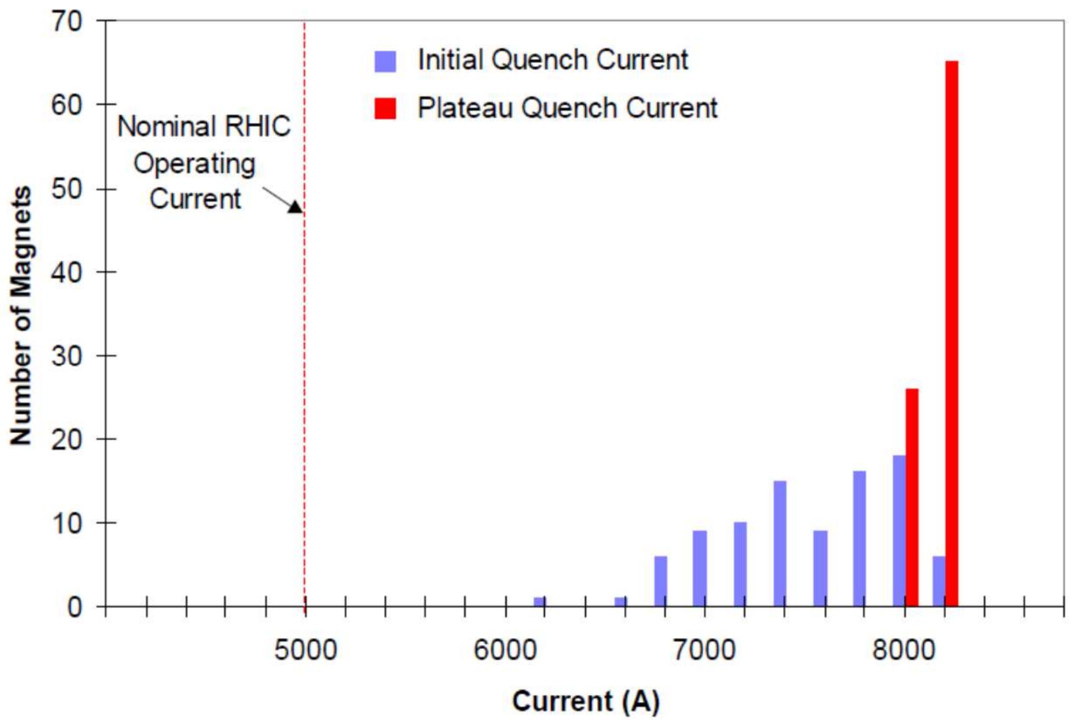
RHIC MAGNET QUENCH PERFORMANCES



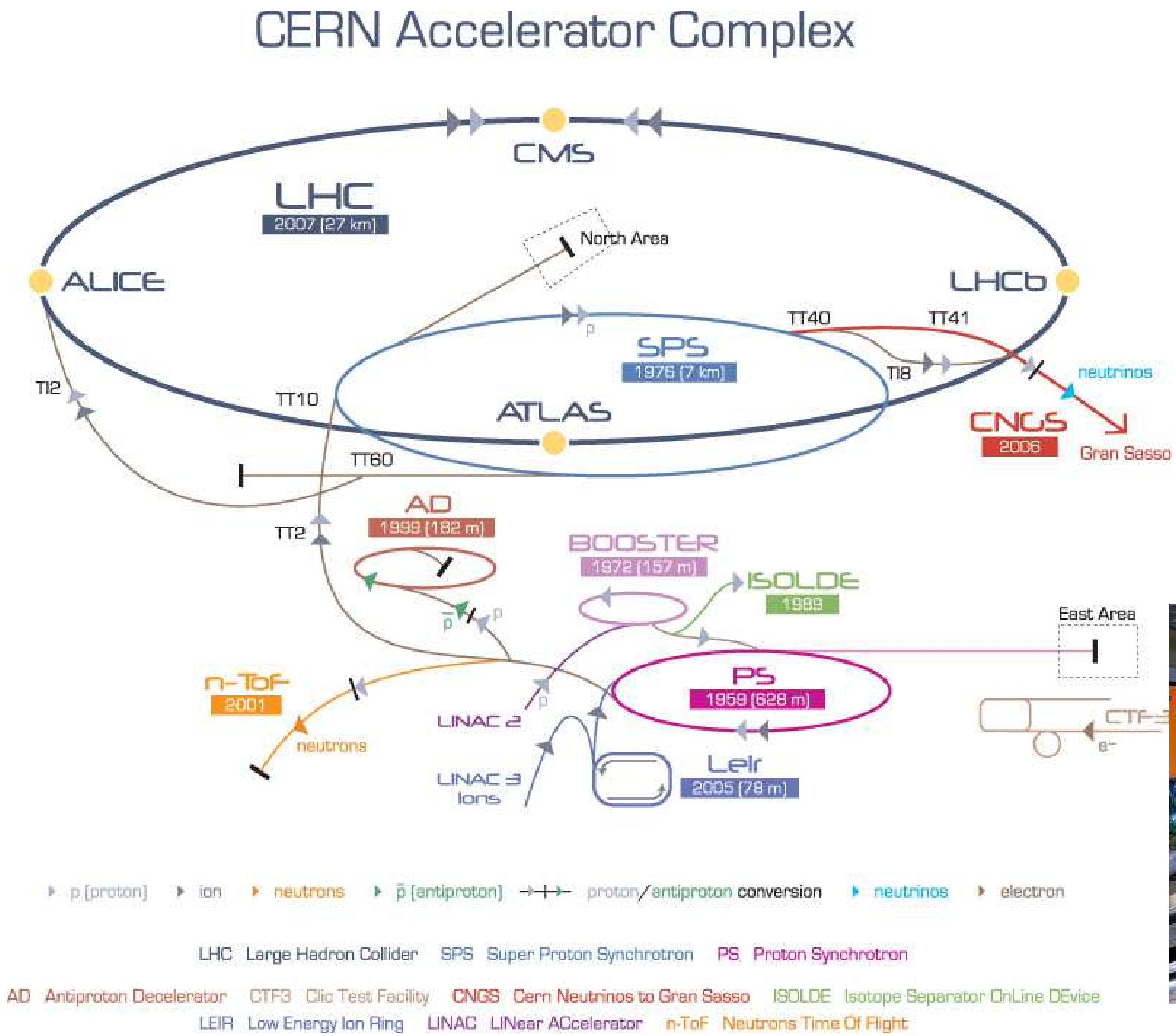
first 51 RHIC dipole magnets



first 91 RHIC quadrupole magnets

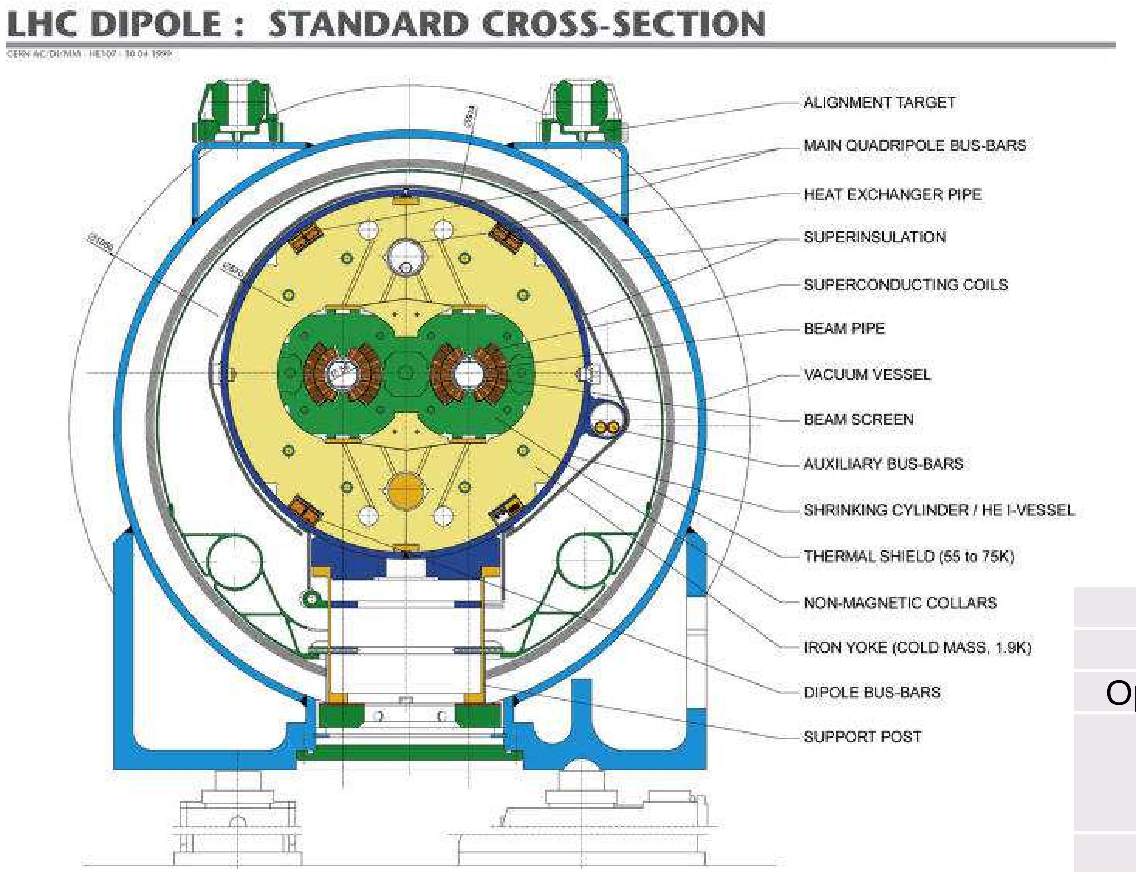


LARGE HADRON COLLIDER



Injection	(GeV)	450
Flat-top	(TeV)	7
Length	(km)	26.7
Dipole field	(T)	8.3
Aperture	(mm)	56
Temperature	(K)	1.9
Commisioned		2008

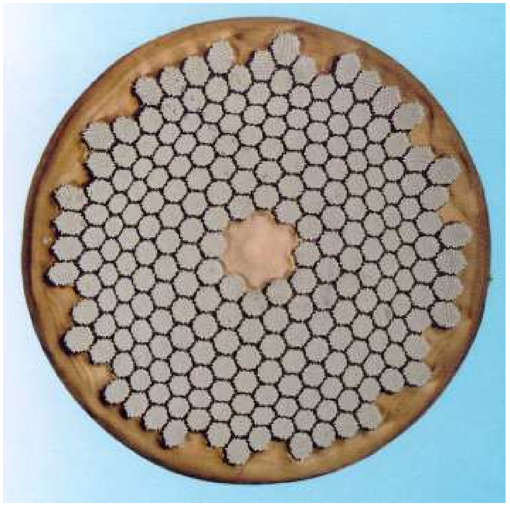
LHC ARC MAGNETS



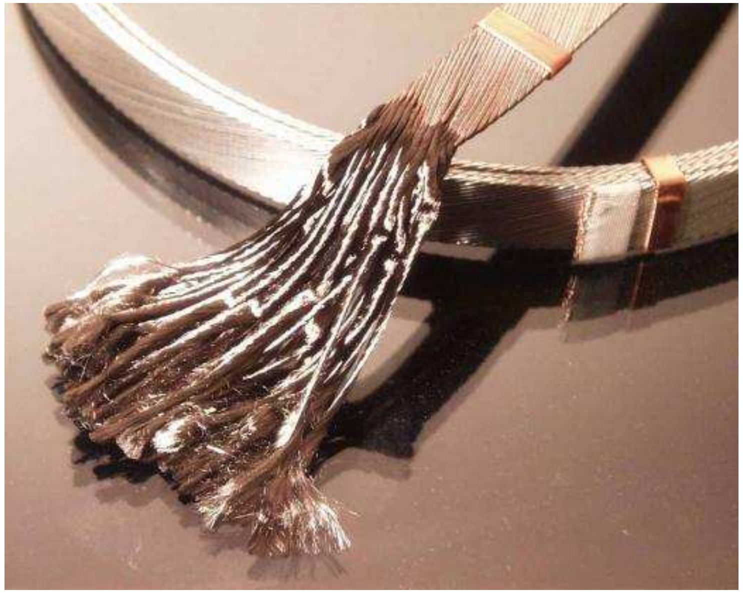
	LHC	
	Dipole	Quadrupole
Operating temperature (K)	1.9	1,9
Central field (T)	8,36	
Gradient (T/m)		223
Field length (m)	14,2	3,1
Inner coil diameter (mm)	56	56
Number of coil layers	2	2
Superconducting material	NbTi	NbTi
Collar material	none	None
Yoke	cold	Cold
Total number	1232	386

LHC CABLE PARAMETERS

	Dipole Inner layer	Dipole Outer Layer, Quadrupole
Diameter (mm)	1.065	0.825
Copper to Superconductor Ratio	1.6	1.9
Filament size (µm)	7	6
Number of filaments	8900	6500
RRR	>70	>70
Twist pitch (mm)	25	25
Critical current density (A/mm2)		
10 T, 1.9 K	>1530	
7 T, 1.9 K		>2100

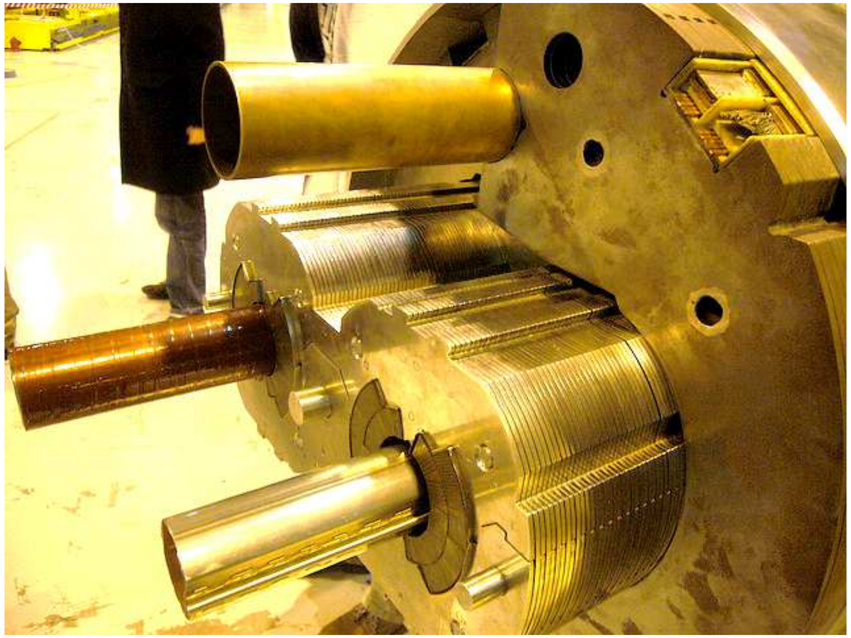


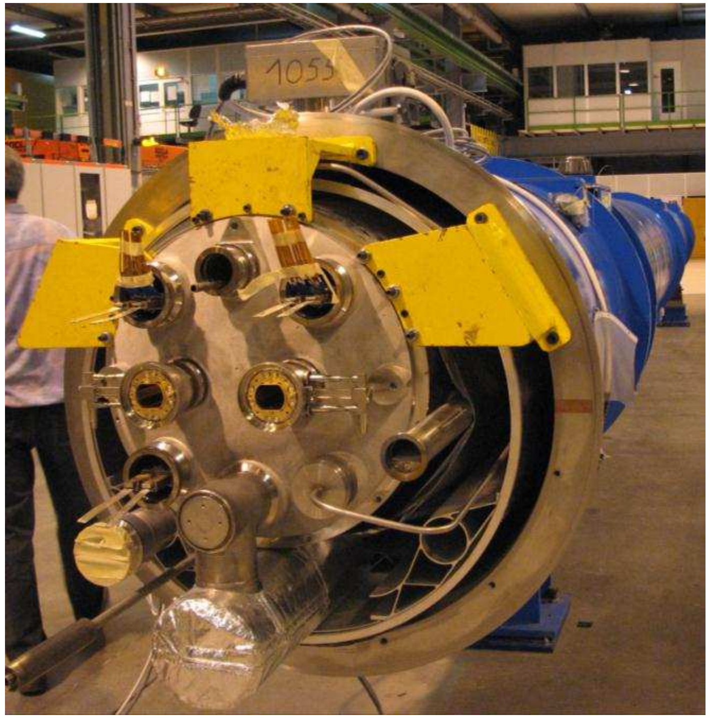
	Dipole Inner layer	Dipole Outer Layer	Quadrupole
Number of strands	28	36	28
Cable dimension			
Thin edge (mm)	1.736	1.362	1.362
Thick edge (mm)	2.064	1.598	1.598
Width (mm)	15.1	15.1	11.6
Transposition pitch (mm)	115	100	95
Keystone angle (°)	1.3	1	1.3
Critical current Ic(A)			
10T, 1.9 K	>13750		
9T, 1.9 K		>12950	>10060
dIc/dB (A T-1)	>4800	>3650	>3040



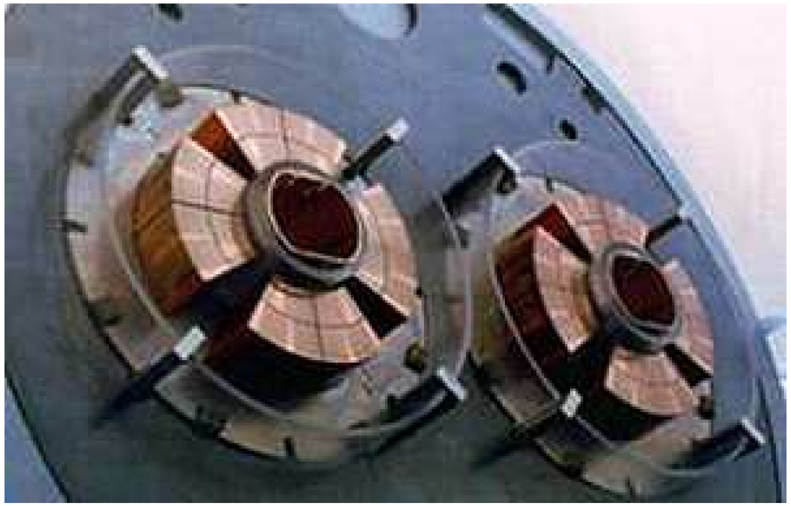
PICTURES OF LHC MAGNETS

Dipole

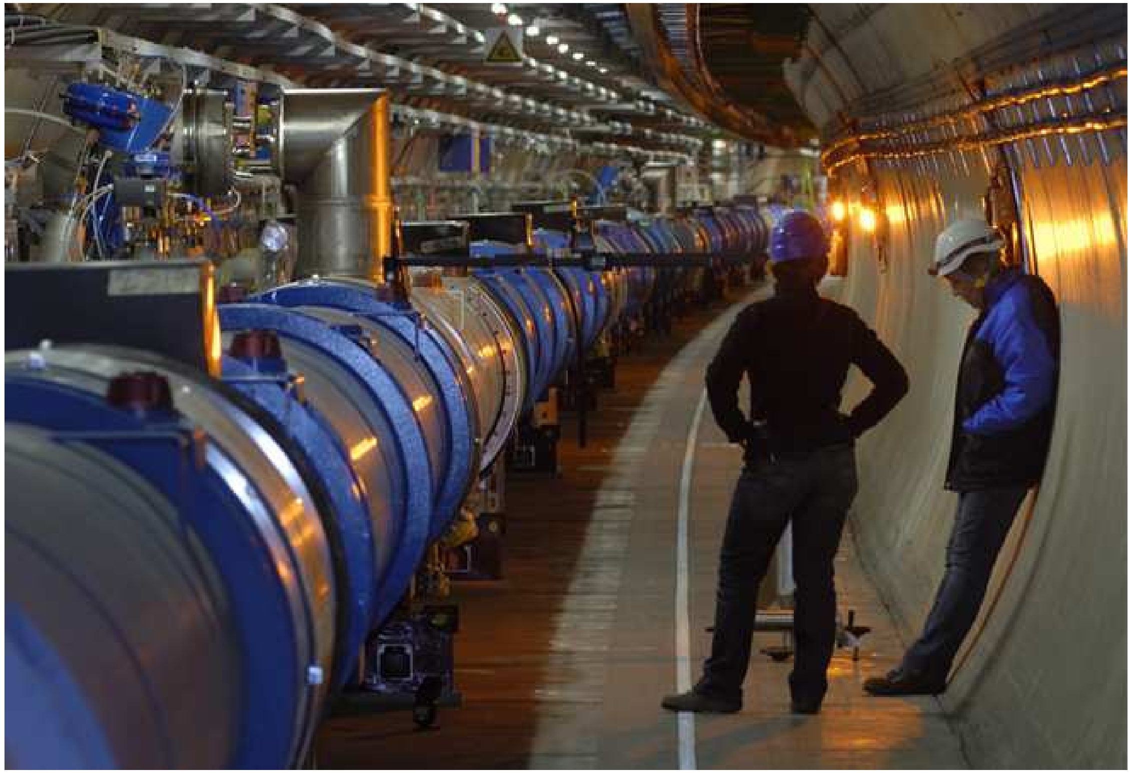


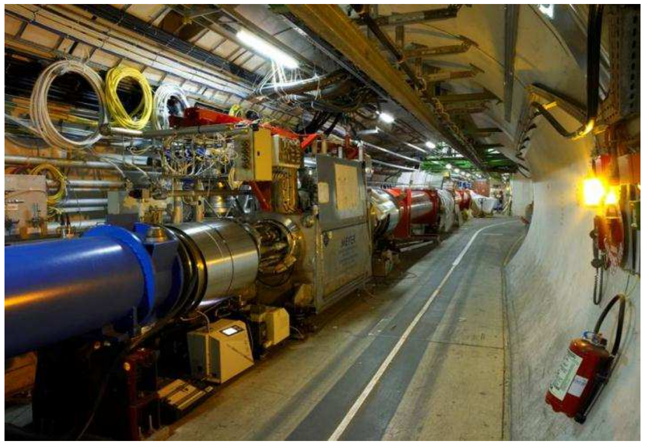


Quadrupole



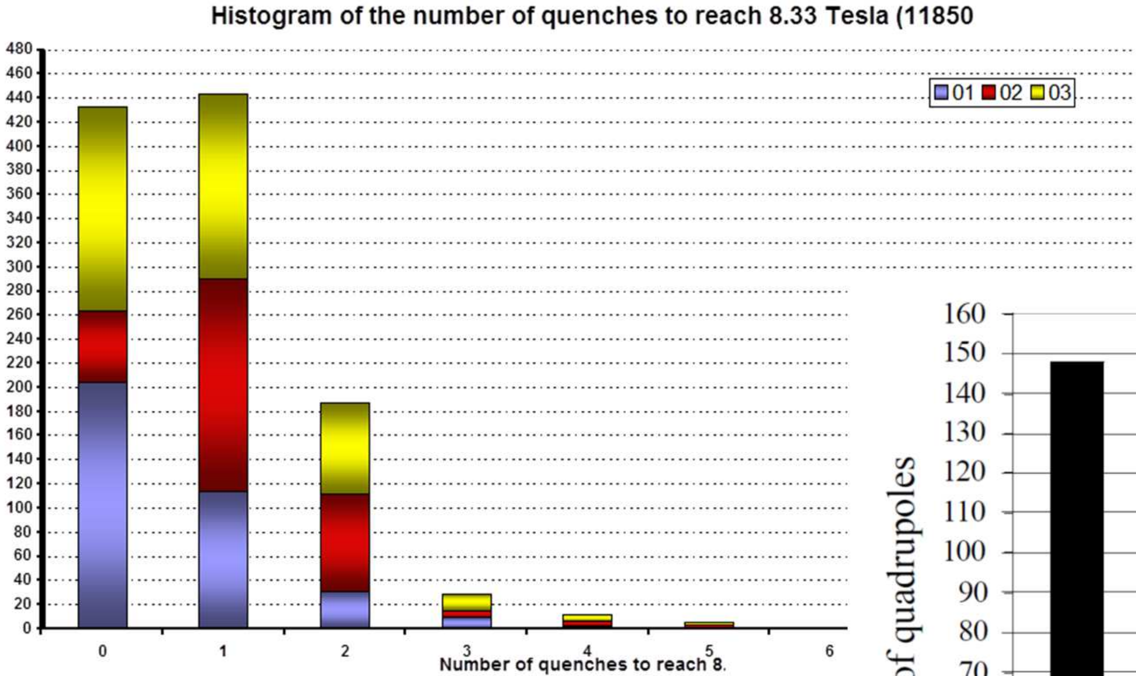
LHC MAGNET INSTALLATION

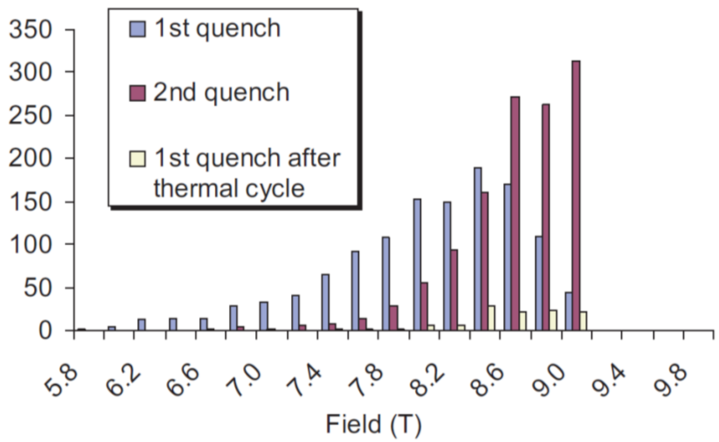




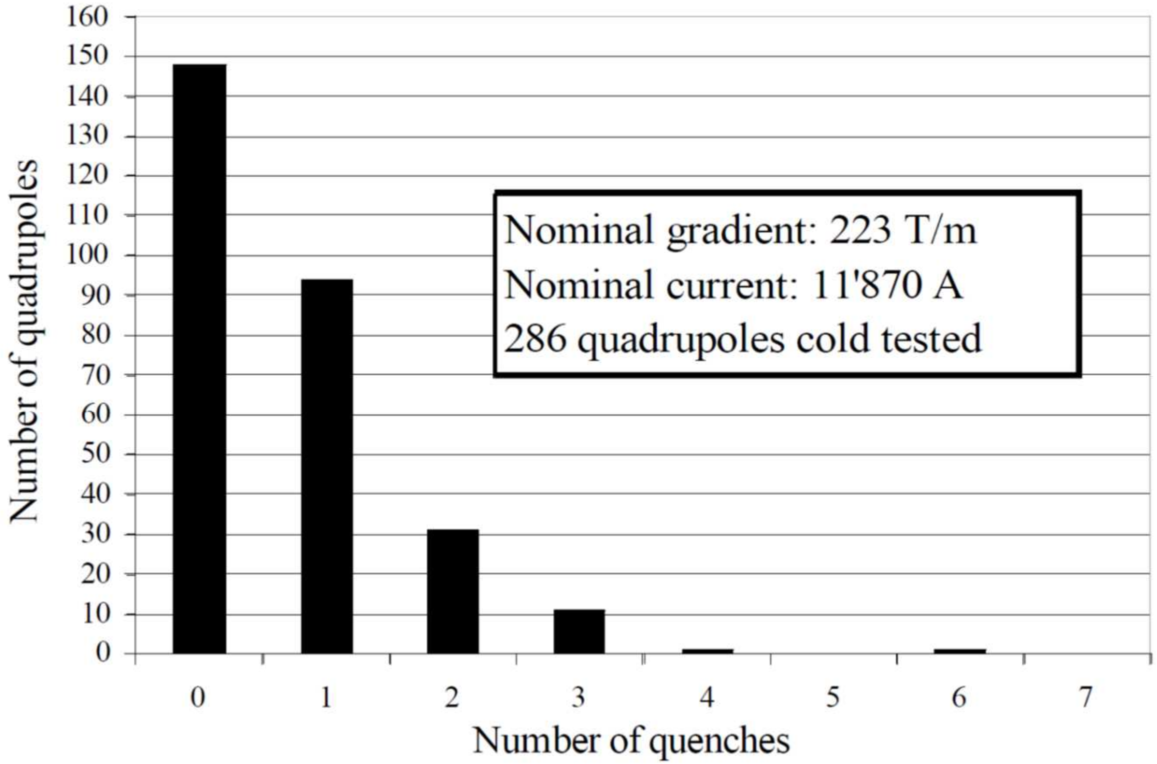
LHC MAGNET QUENCH PERFORMANCES

Most of the magnets reached the nominal current of 11850 A (about 86% of I_{ss}) with two quenches.





Quadrupole

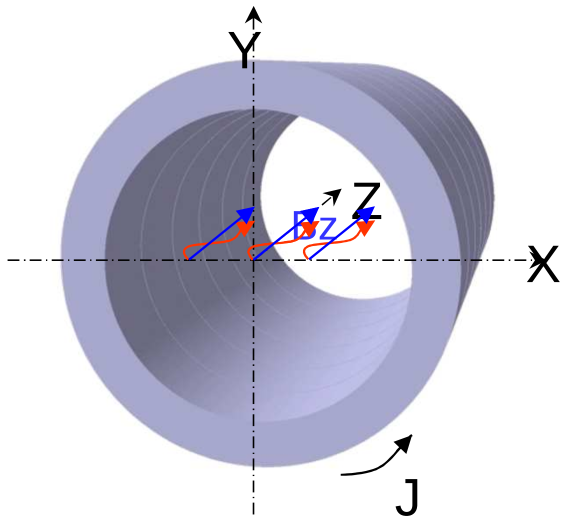


DETECTOR MAGNETS

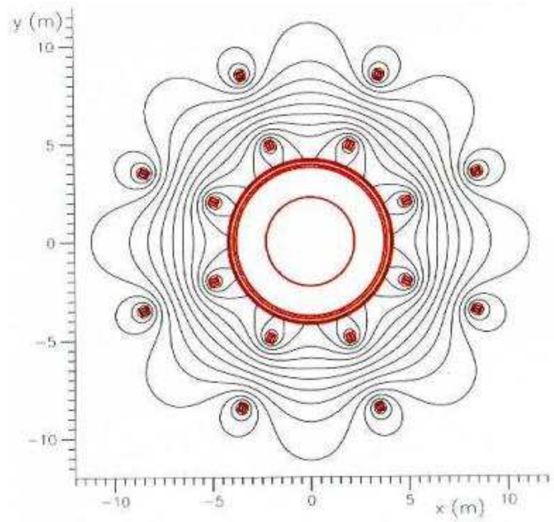
DETECTOR MAGNET DESIGN

Two main types of large, superconducting detector magnets:

solenoids (*e.g.*, ALEPH and CMS at CERN) and toroids (*e.g.*, ATLAS at CERN).



$Bx = 0$
$By = 0$
$Bz = B_0$



$B_r = 0$,
$B_\theta = B_0$
$B_z = 0$

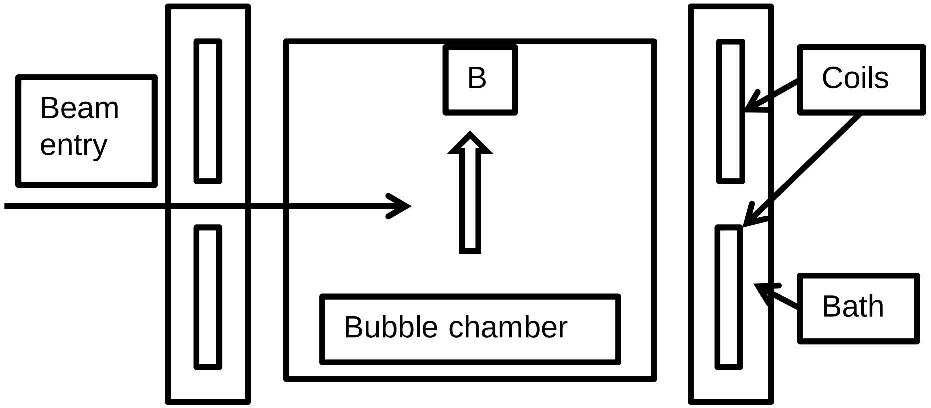
\+ Very good momentum resolution at large angle, compact and efficient structure.

\- requires an iron yoke, inefficient for small-angle particles.

\+ No field along the axis, magnetic field always transversal to the particle momentum, low fringe field, best momentum resolution at low angle.

\- Very inhomogeneous magnetic field, high peak field on the conductor, complicated magnet structure.

EARLY BUBBLE CHAMBER MAGNETS



First superconducting bubble chamber magnet constructed at Argonne National Laboratory by John Purcell 1968

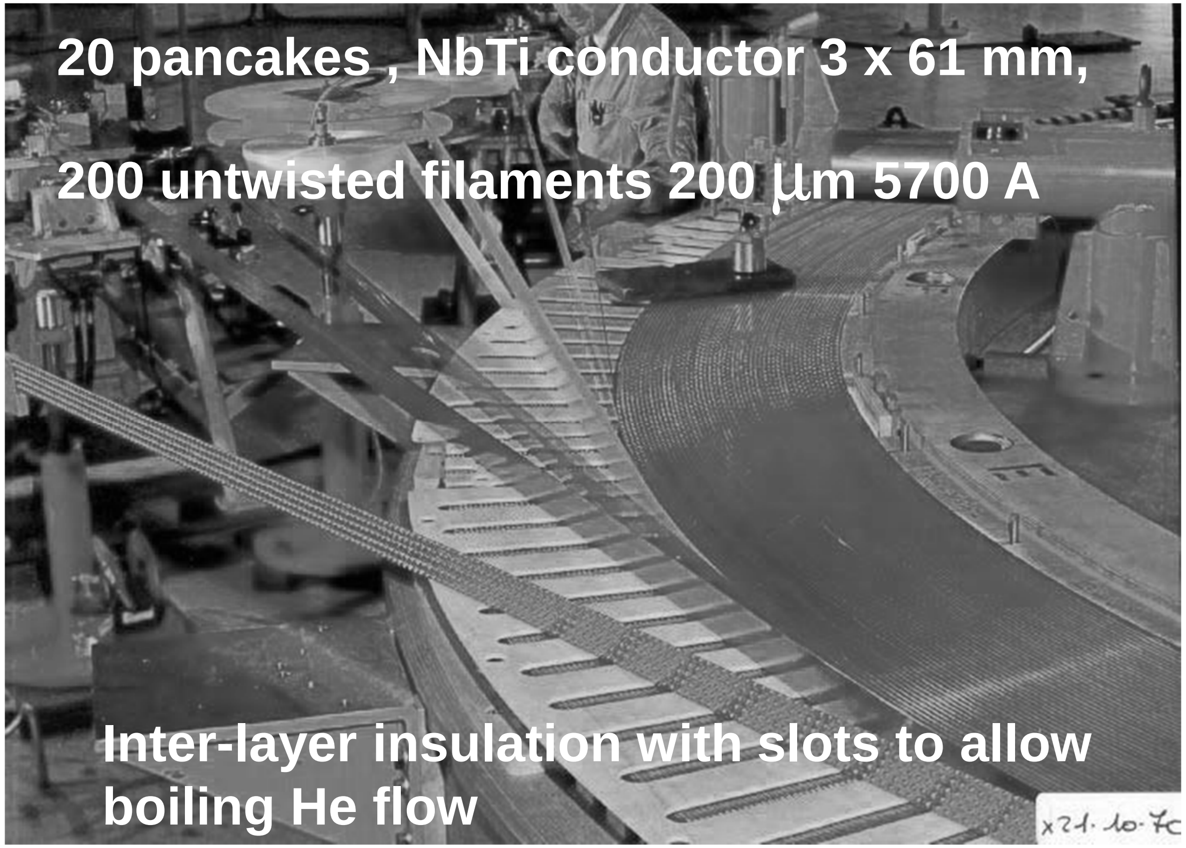
Split pair solenoid with vertical axis and gap to allow beam entry

Bath cooled coils – NbTi copper stabilised conductor operated in cryostable mode

Low current density ~ 8A/mm^2

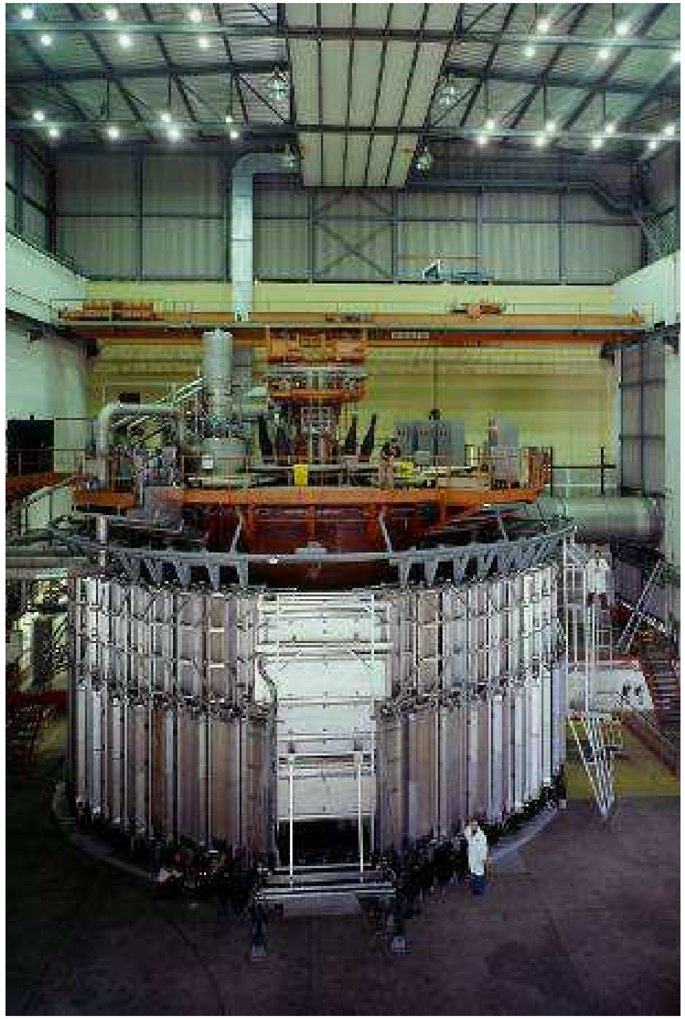
	Argonne 12 ft BC	Fermilab 15 ft BC	Cern BEBC
	1968	1972	1972
Field (T)	1.8	3	3.5
Winding ID (m)	4.8	4.3	4.7
Stored Energy MJ	80	400	800

BEBC - BIG EUROPEAN BUBBLE CHAMBER



BEBC cooling power at 4K ~ 900W equivalent to ~ 0.5MW at 300K

Corresponding power for a resistive version ~ 60MW

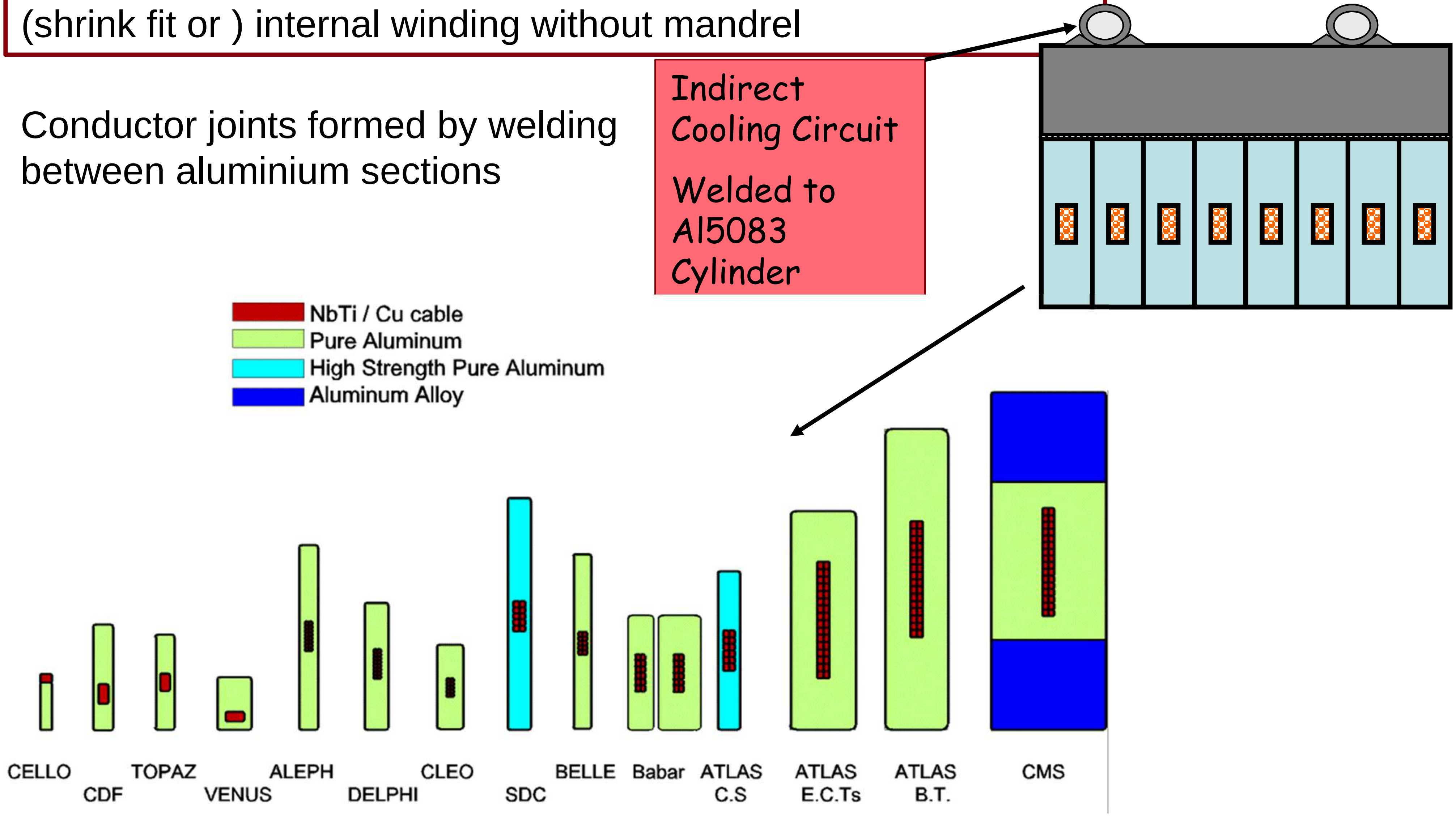


BEBC magnet 1967
750 MJ

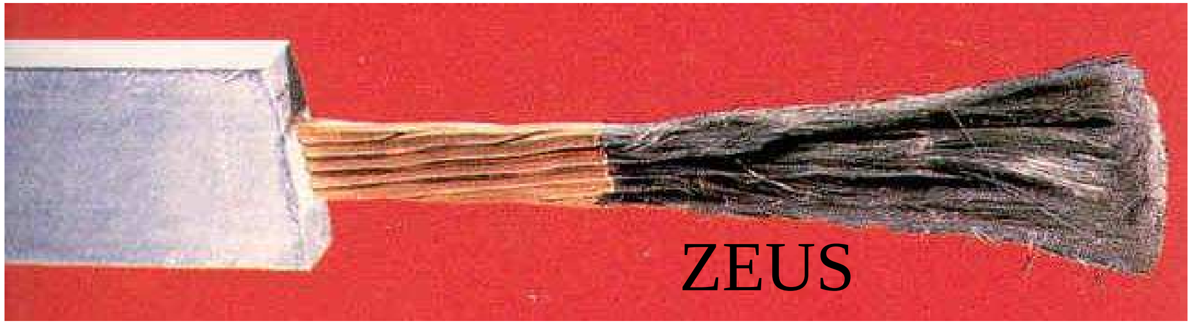
Co-extruded monolithic conductor – Al alloy support cylinder –

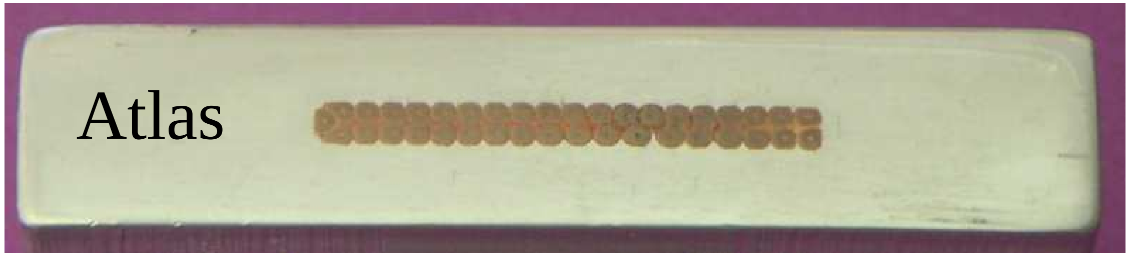
(shrink fit or) internal winding without mandrel

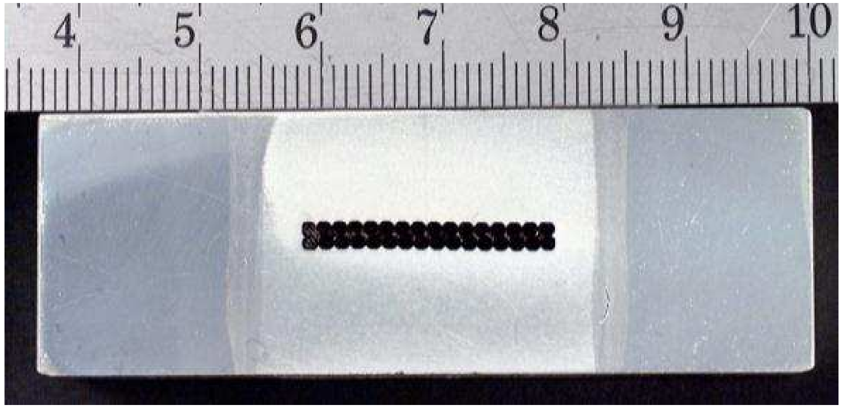
Conductor joints formed by welding between aluminium sections



ALUMINUM STABILIZED CONDUCTORS







CMS reinforced conductor

Example

ATLAS Conductor
65 kA at 5 T

1.25mm dia. NbTi/Cu strand,

2900A/mm^2 at 5T, 4.2 K

40 strands Rutherford cable,

Co-extrusion with high purity Al (RRR>1500)
(Al for low density and high RRR)

Inter-metallic bonding Cu-Al necessary

size 57 x 12 mm^2, 56 km

DETECTOR MAGNETS IN THE 1980S

Name	ALEPH	DELPHI	CLEO2	ZEUS	H1
Accelerator	LEP	LEP	CESR	HERA	HERA
Laboratory	CERN	CERN	Cornell	DESY	DESY
Designed by	Saclay	RAL	Cornell Oxf.	Milan Un.	RAL
Manufactured by	Saclay	RAL	Oxford Inst.	Ansaldo	RAL
Inner Bore (m)	4.96	5.2	2.88	1.72	5.2
Outer Bore (m)	5.98	6.2	3.48	2.22	6.08
Winding Length (m)	6.35	6.8	3.48	2.5	5.16
Overall length (m)	7	7.4	3.78	2.8	5.75
Conductor (mm2)	35 x 3.6	24 x 4.5	16 x 5	15 x 4.3	26 x 4.5
Stabiliser	Al	Al	Al	Al	Al
Cold Mass (t)	25	25	7	3.4	
Conductor mass (tons)	8	7		2.4	7
Current (A)	5000	5000	3300	5000	5500
Design field (T)	1.5	1.2	1.5	1.8	1.2
Stored energy (MJ)	137	108	25	16	120
Cooling method	Thermo siphon	Forced flow pumps	Thermo siphon	Forced flow pumps	Forced flow pumps
Radiation length (X0)	2	7.4		0.9	4
Year of completion	1987	1988	1988	1989	1989

ALEPH-DELPHI-H1 Solenoids RAL and Saclay 1988

LHC DETECTOR MAGNETS…THE GIANTS !

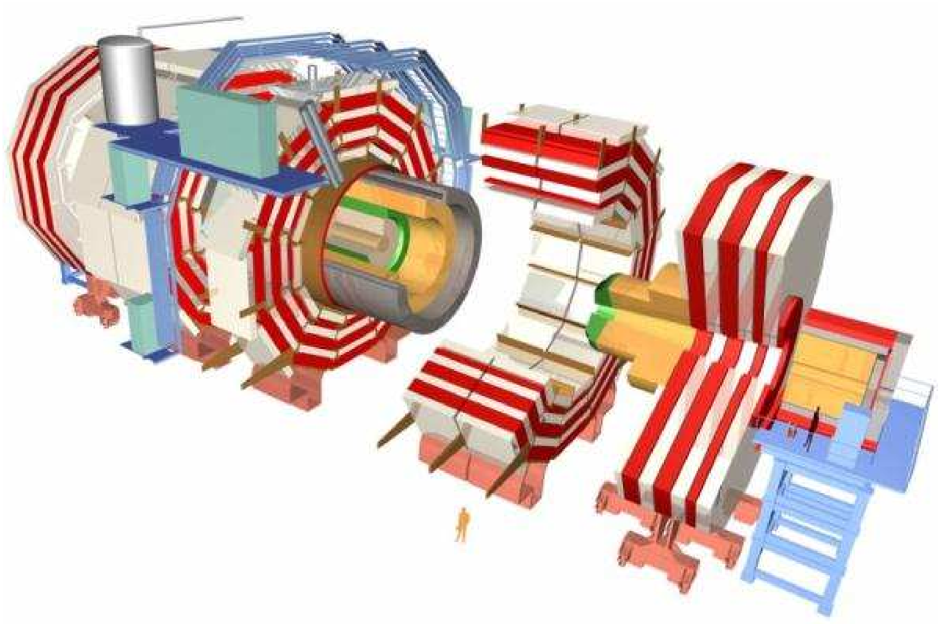
CMS

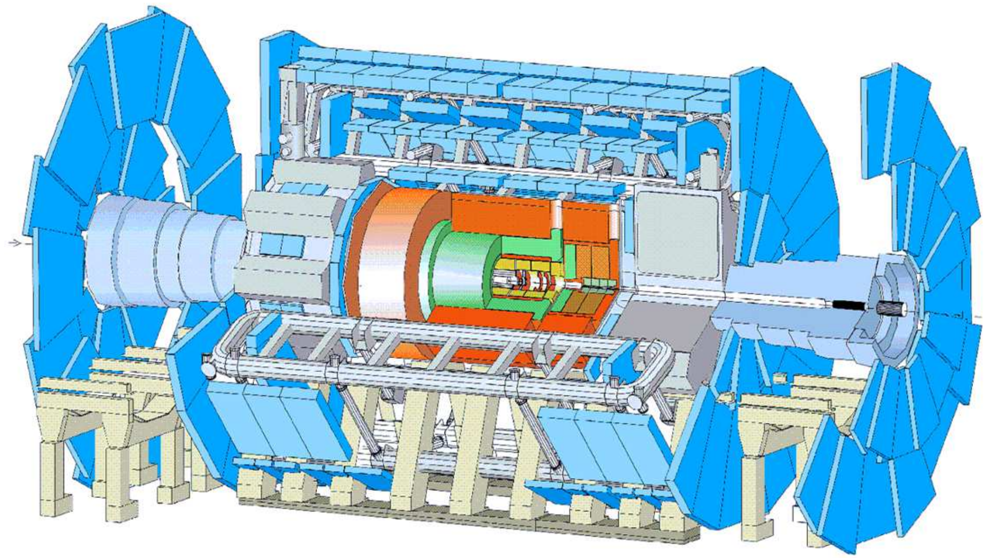
Largest Solenoid – 4T, 2.7 GJ, 7m dia, 12m long

ATLAS TOROIDS

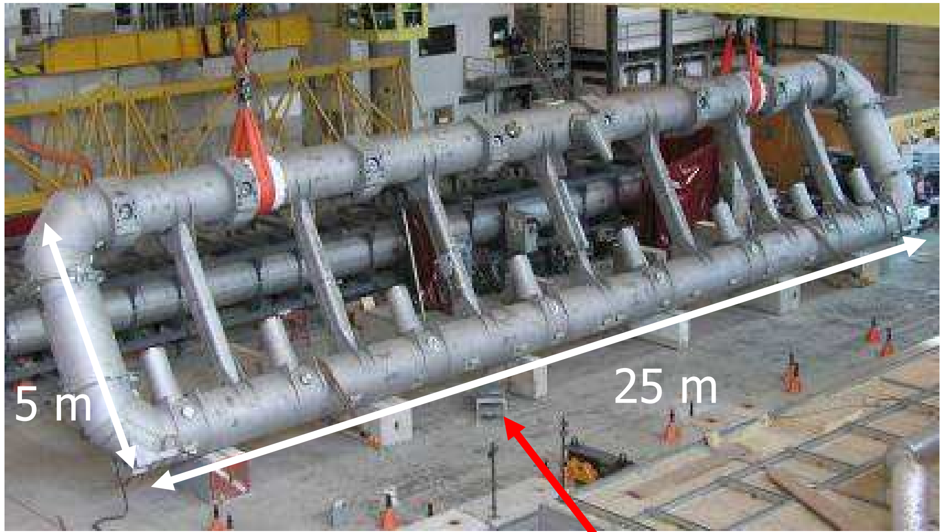
Largest field volume – 8200 m3 self contained field (no yoke) open structure

1.55 GJ, 20 m dia, 25 m long

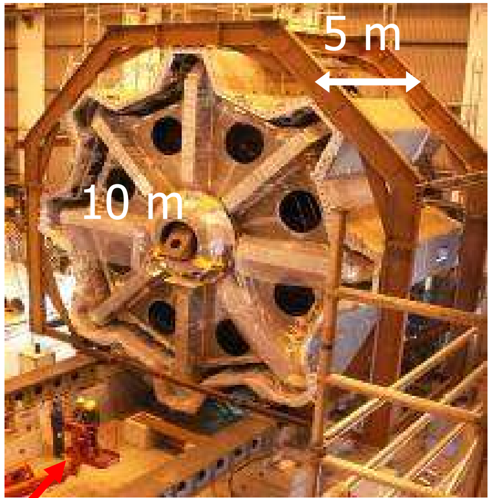




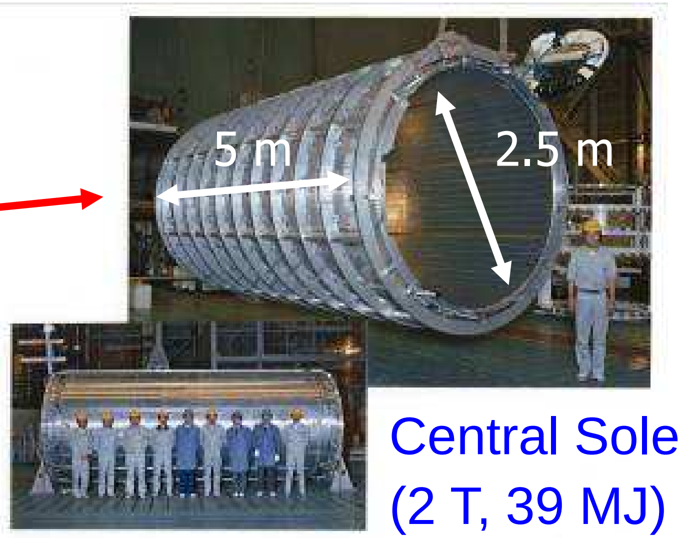
ATLAS COILS



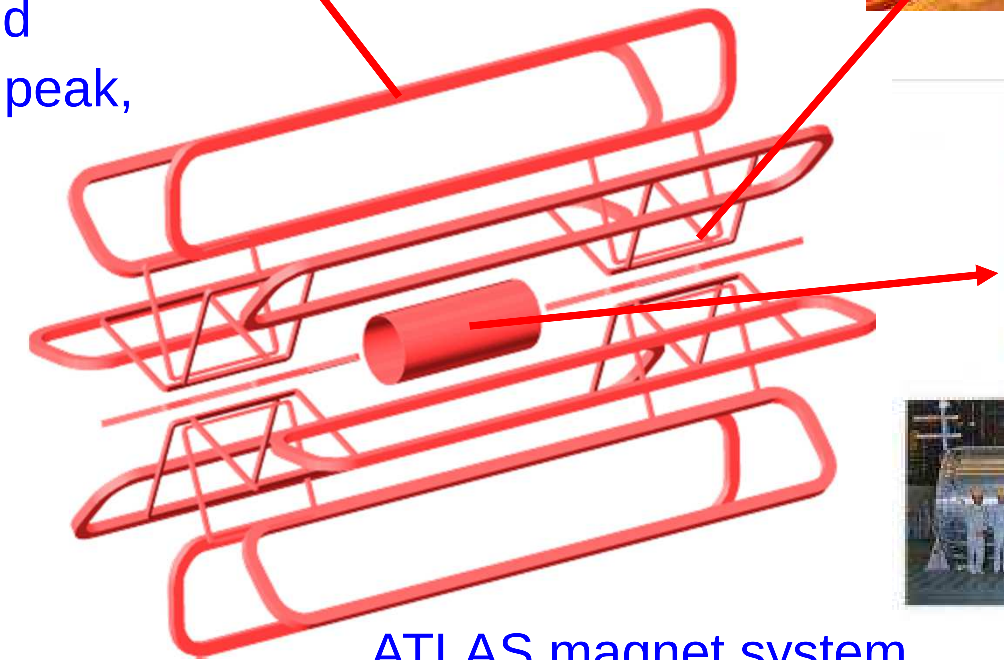
Barrel Toroid
(8 coils,4 T peak,
1080 MJ)



End Cap
Toroid
(8 coils,
4 T peak,
250 MJ,)



Central Solenoid
(2 T, 39 MJ)



ATLAS magnet system

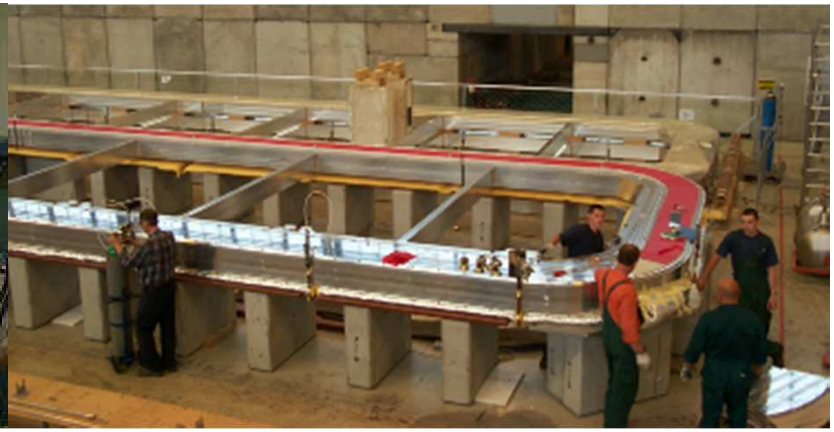
ATLAS TOROIDS

	Barrel	End Cap
Torus inner bore (m)	9.6	0.8
Outer diameter (m)	19.3	10.6
Overall length (m)	26	5.6
Number of coils	8	8
Total Amp x turns (MA)	24	22
Stored Energy (MJ)	1200	350
Operating current (kA)	20	20
Peak field (T)	3.8	4
Total Weight (t)	800	240
Conductor		
Overall size (mm2)	70 x 11	70 x 7
Type	Rutherford cable + pure Al coextruded	
Cooling	Indirect cooling with flow of pressurized supercritical helium 4.5 K	

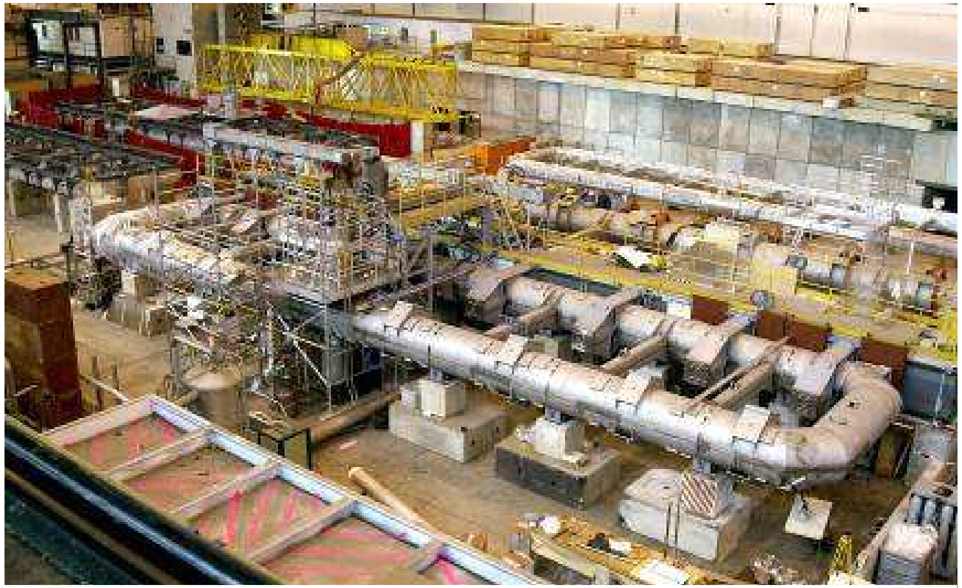
ATLAS BARREL TOROID MANUFACTURING

BT coil manufacture at Ansaldo

BT coil encasing at CERN

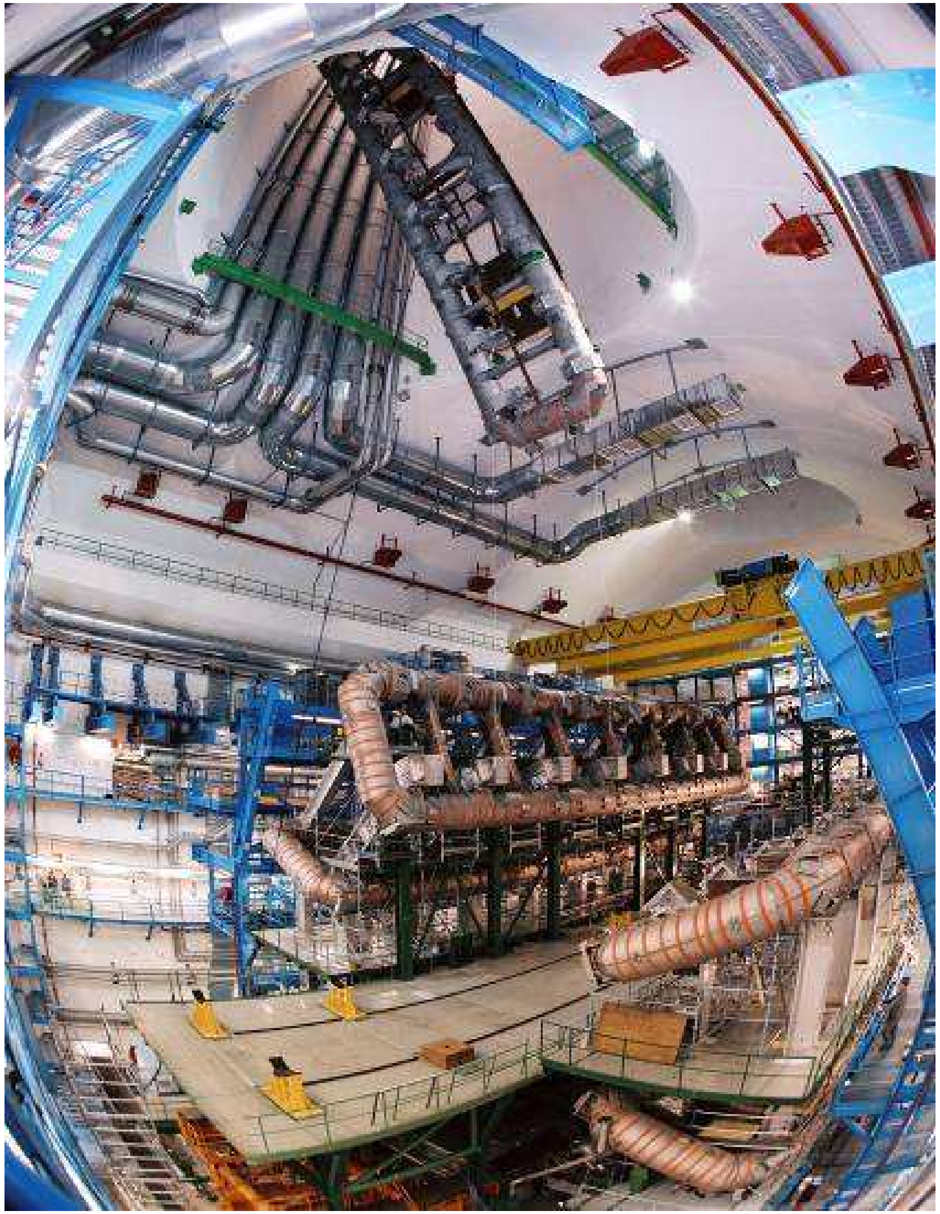


Cryostating at CERN



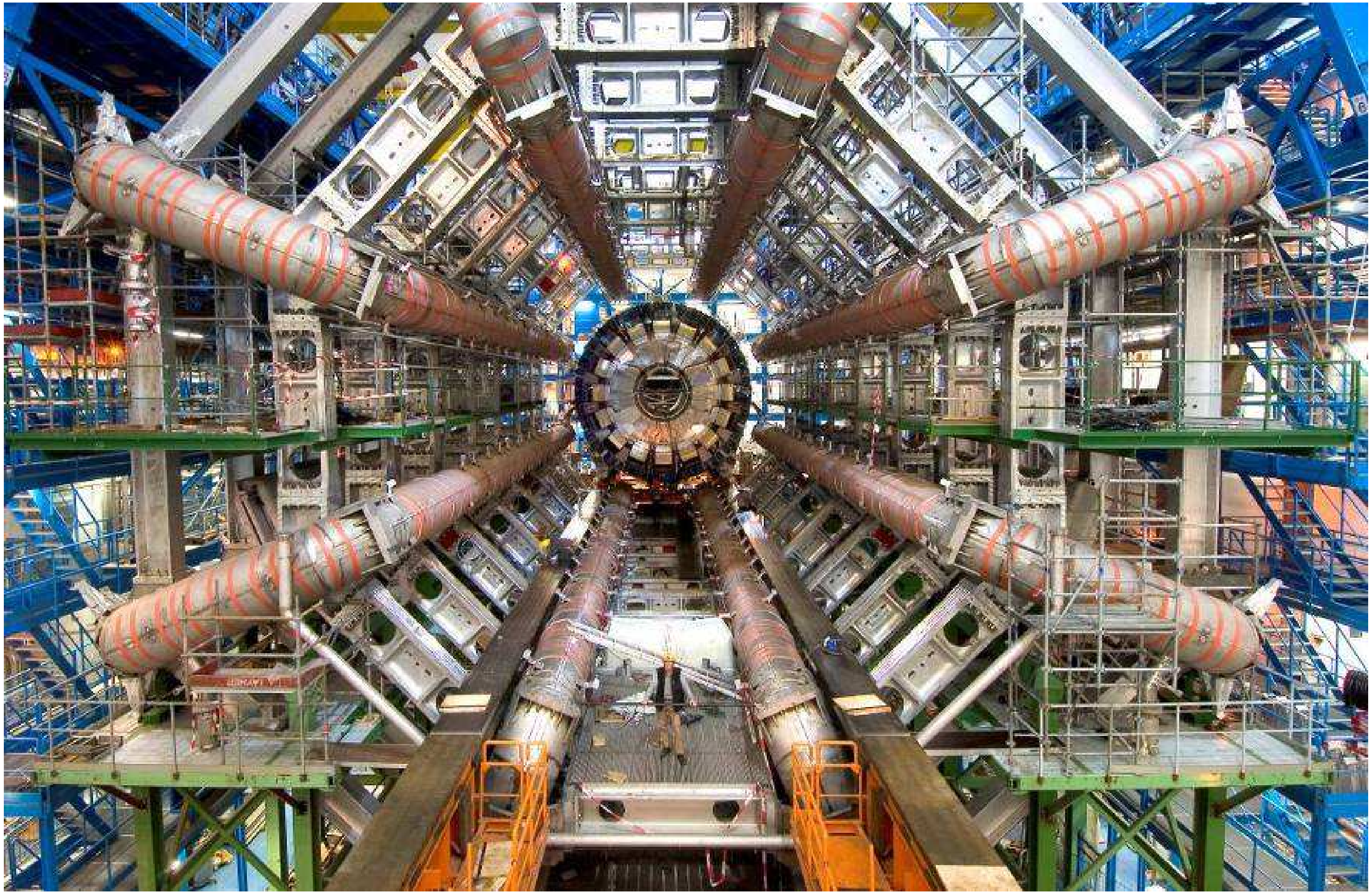
Cold test of individual BT coil at CERN

ATLAS BARREL TOROID ASSEMBLY



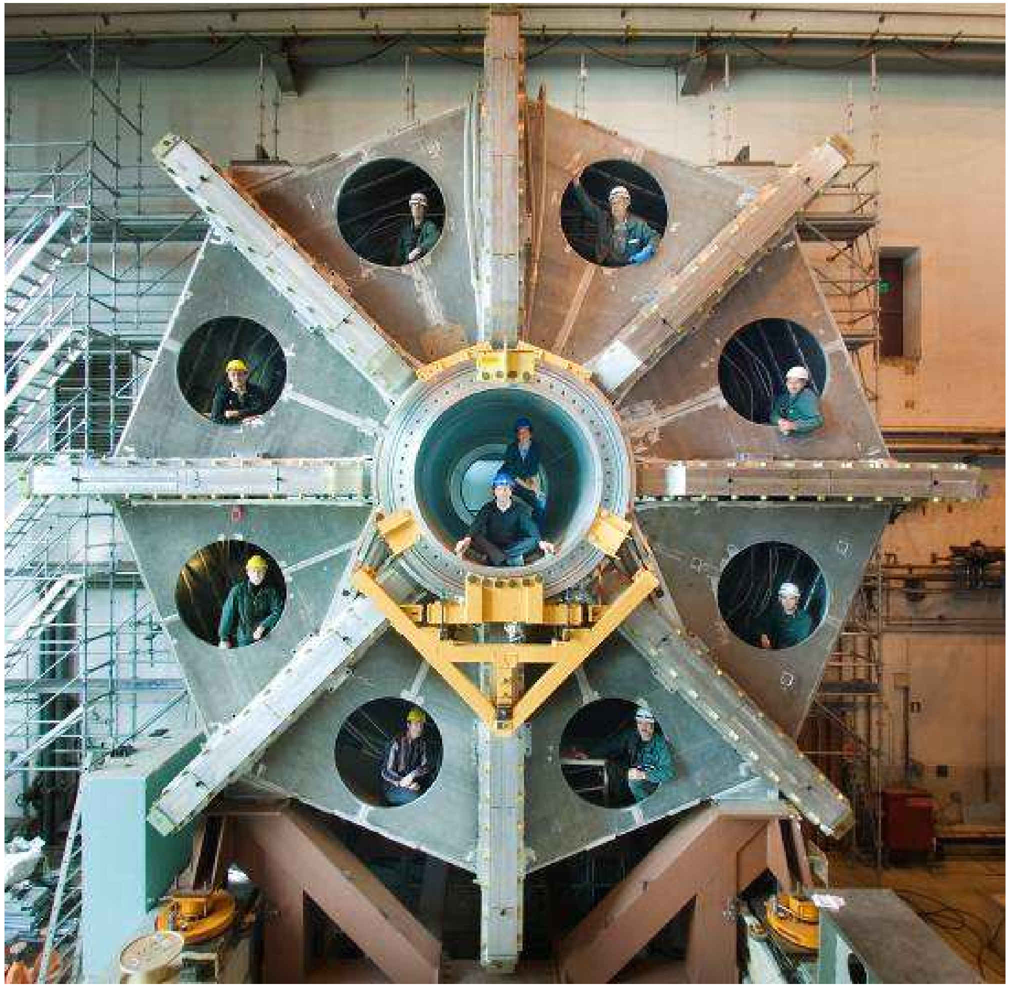
Descent of 8th Barrel Toroid coil
(4 August 2005)

ATLAS BARREL TOROID FINAL ASSEMBLY

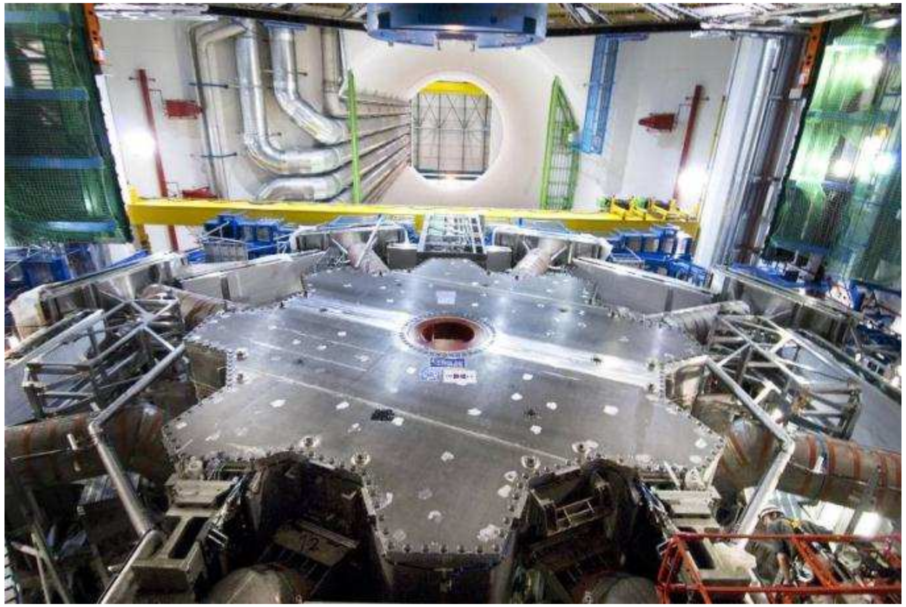


Installation of ATLAS magnet system (BT & CS) at the bottom of CERN pit (November 2005)

ATLAS END CAP TOROID

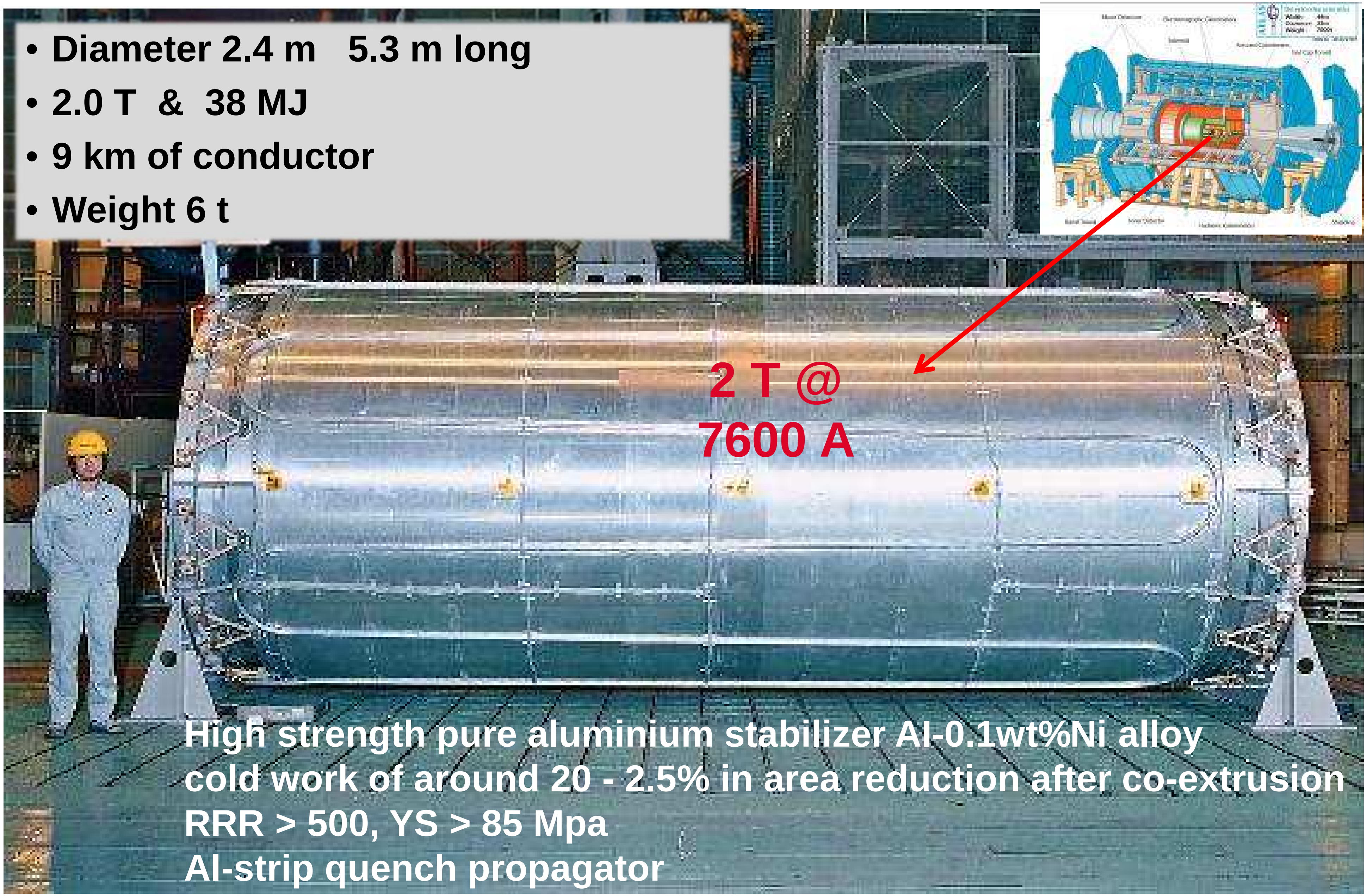


ATLAS END CAP TOROID INSTALLATION



ATLAS CENTRAL SOLENOID

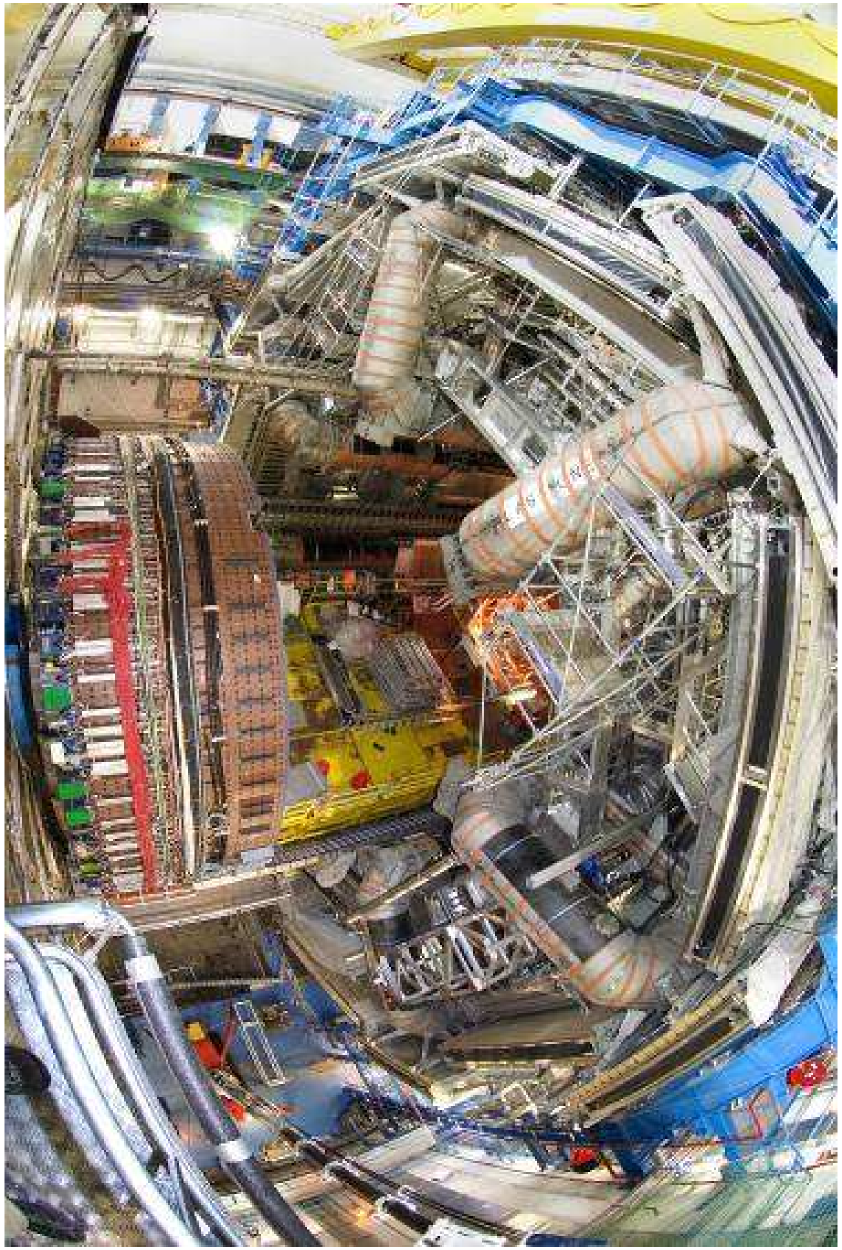
- Diameter 2.4 m   5.3 m long
- 2.0 T & 38 MJ
- 9 km of conductor
- Weight 6 t



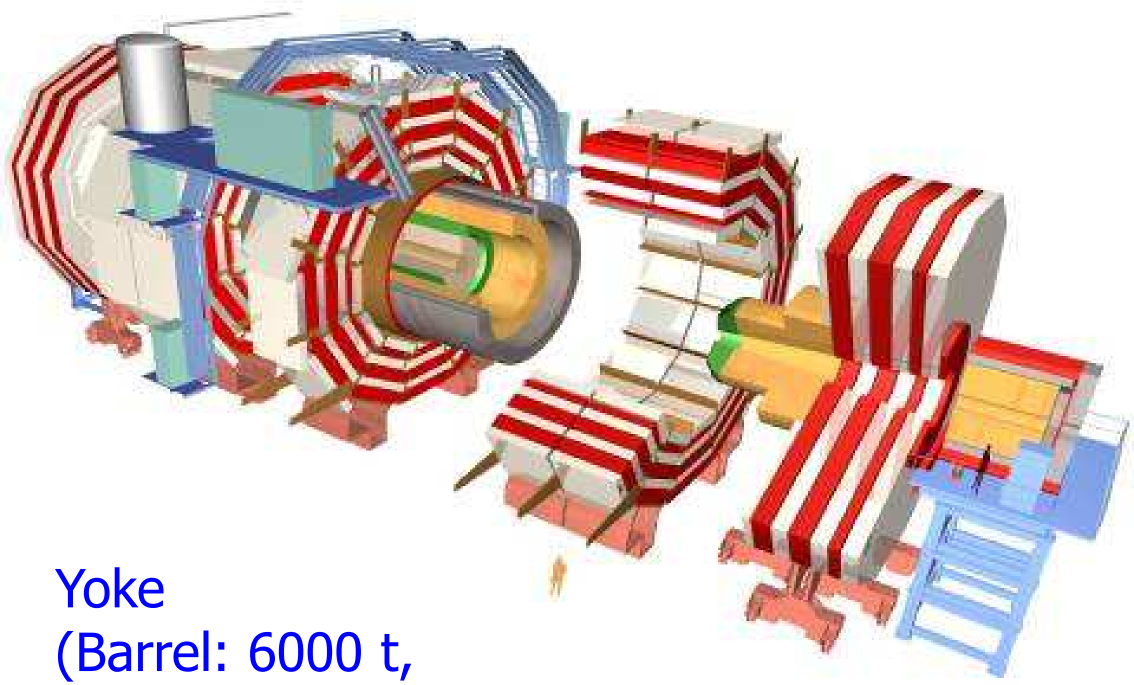
High strength pure aluminium stabilizer Al-0.1wt%Ni alloy
cold work of around 20 - 2.5% in area reduction after co-extrusion
RRR > 500, YS > 85 Mpa
Al-strip quench propagator

ATLAS CENTRAL SOLENOID IN THE PIT…

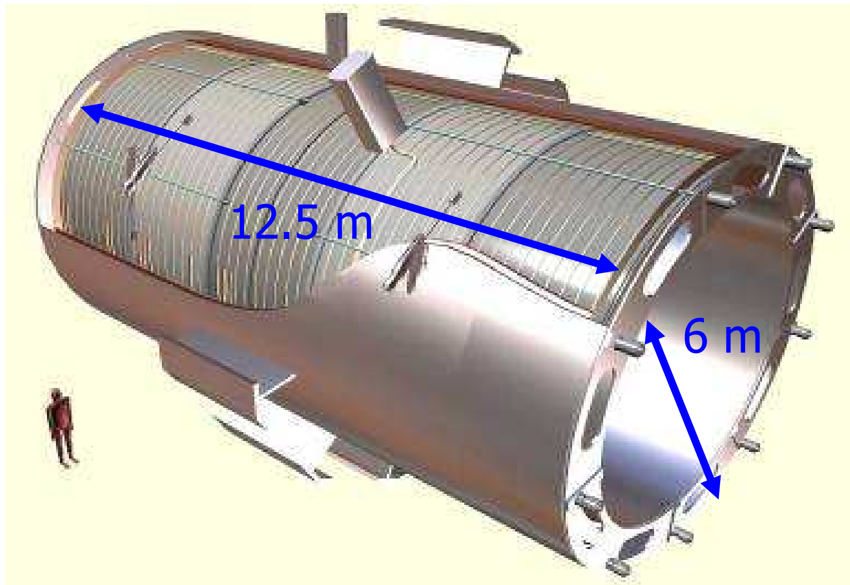
ATLAS MAGNET SYSTEM INSTALLED



CMS SOLENOID



Yoke
(Barrel: 6000 t,
End Cap Disks: 2x2000 t)



Solenoid
(4 T, 2.7 GJ, 220 t)

CMS Solenoidal Coil

Central field : 4 T

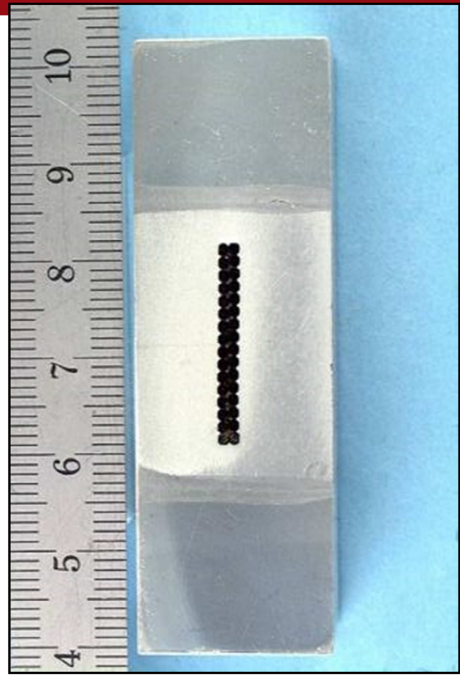
Nominal current : 20 kA

Stored energy : 2.7 GJ

Length : 12.5 m

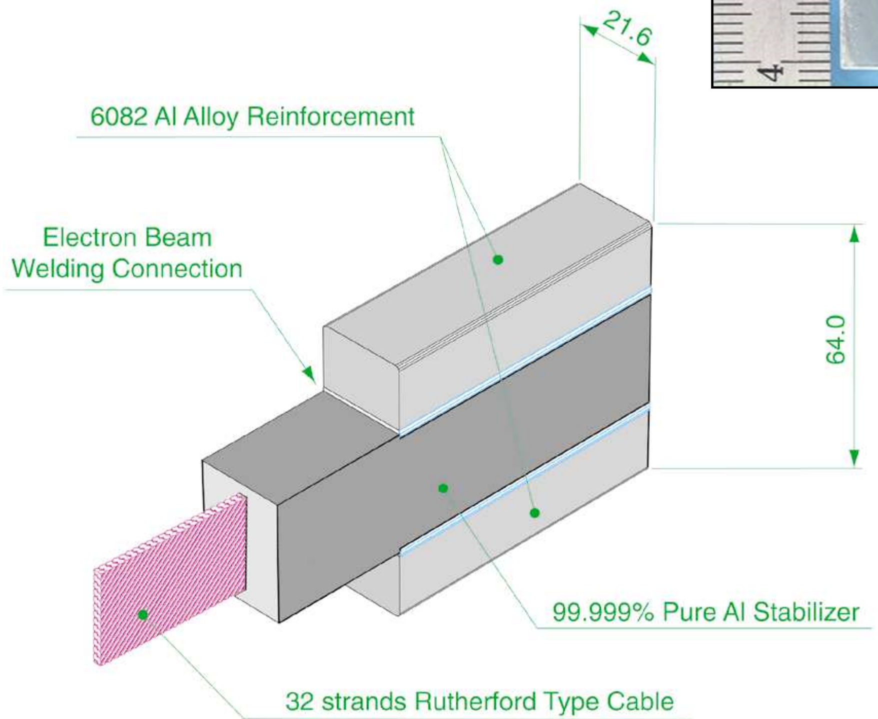
Internal diameter : 6 m

Weight : 220 t



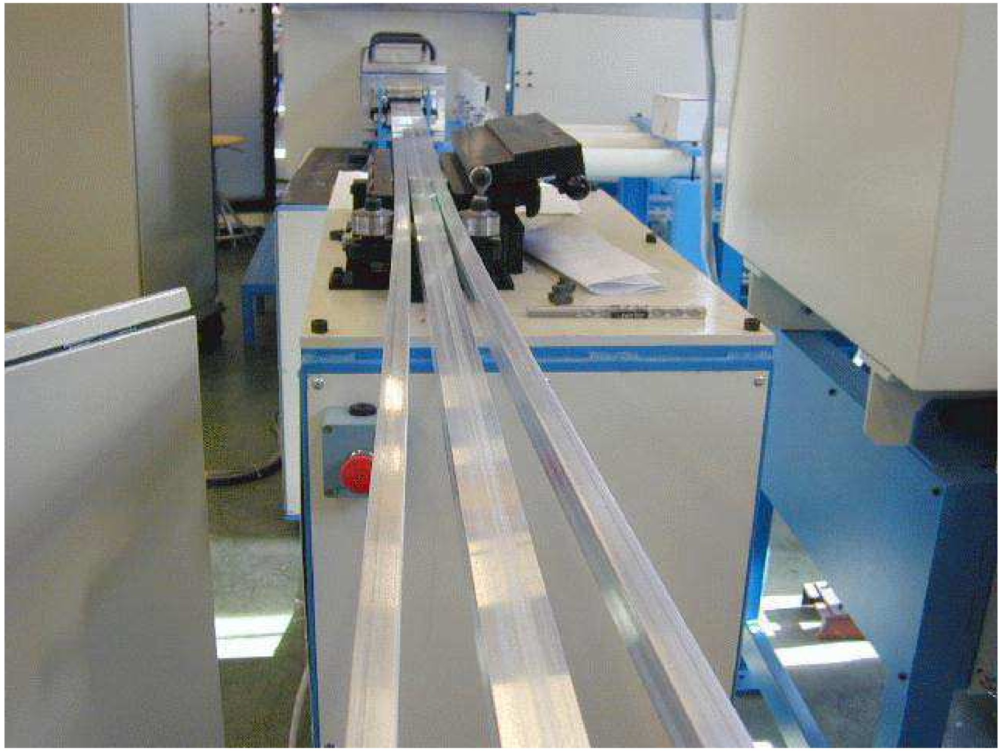
Conductor

- Pure Al + high strength alloy 6082
- YS > 250MPa @ 4K
- RRR 1400



4 layers reinforced conductor

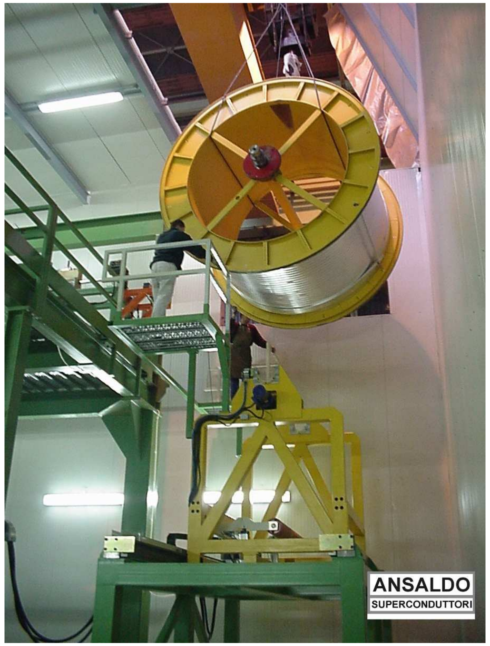
CMS COIL WINDING

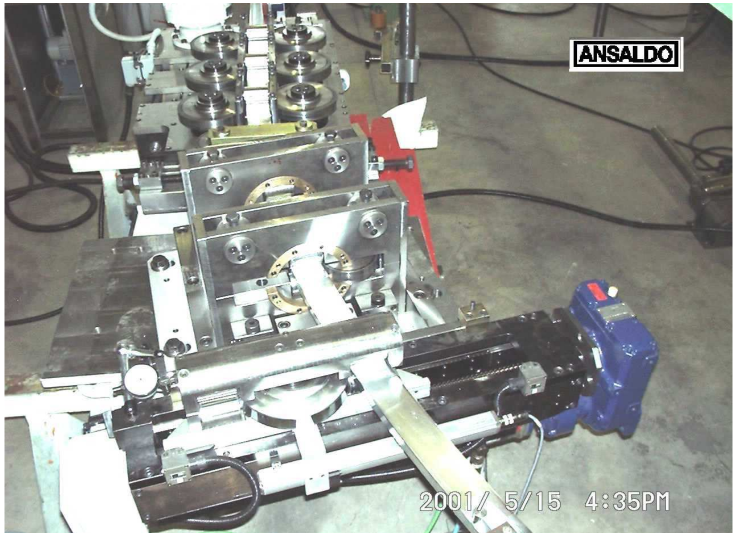


Conductor manufacturing

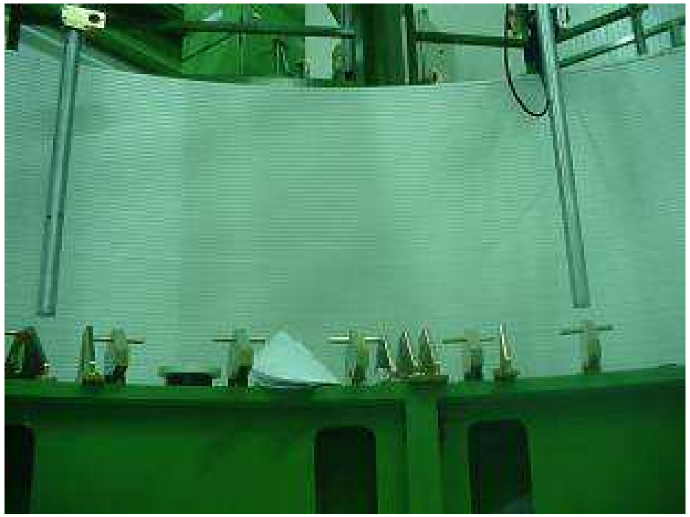
Winding mandrel

CMS COIL WINDING





wrapping

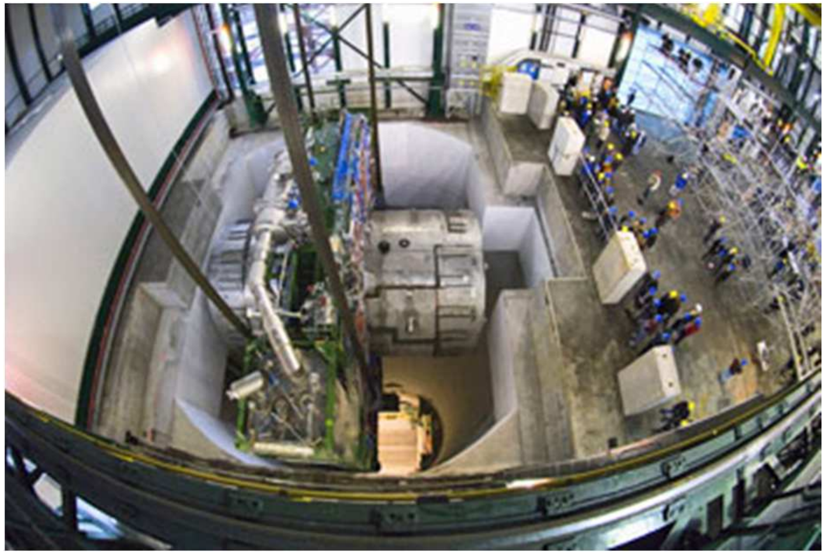


CMS SOLENOID ASSEMBLY at CERN

CMS SOLENOID ASSEMBLY IN THE DETECTOR

Yoke reception at CERN (June 2002)

Magnet insertion into barrel yoke (Fall 2005)

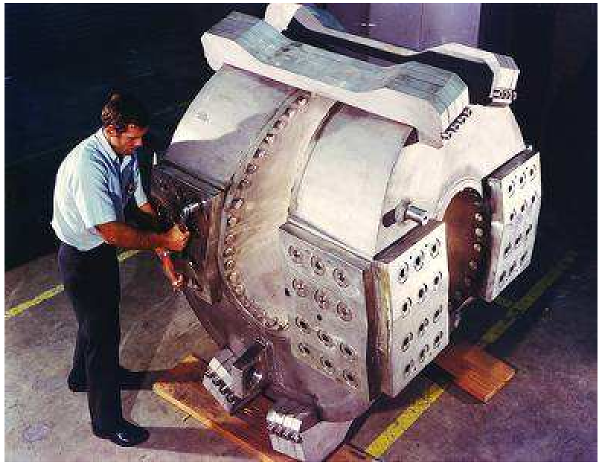


Lowering of the central part of the CMS detector to the bottom of its CERN pit (Feb. 2007)

FUSION MAGNETS

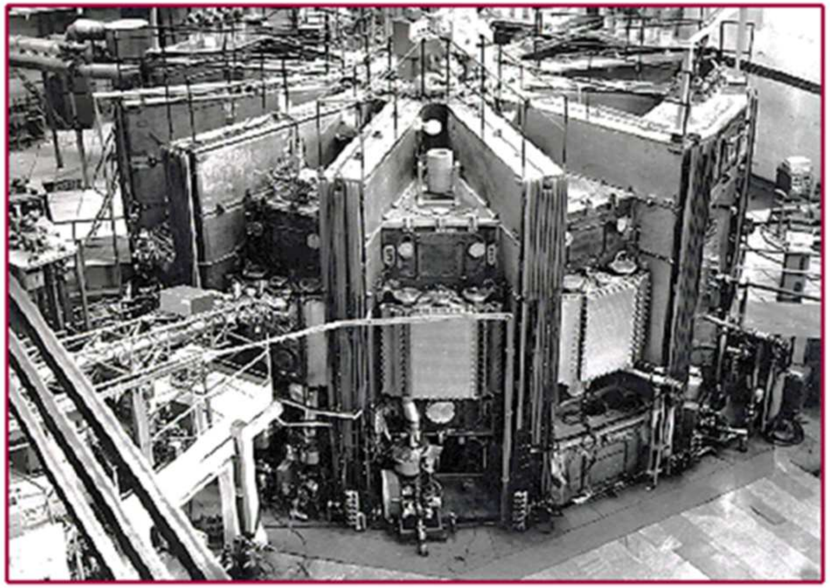
SUPERCONDUCTING TOKAMAK HISTORY

Magnetic Mirror SC coils in the early 70's and early 80s



Large tokamak SC experiment T-15, Tore Supra 1988

Baseball I and II, hot plasma confined by magnetic mirrors. 1965

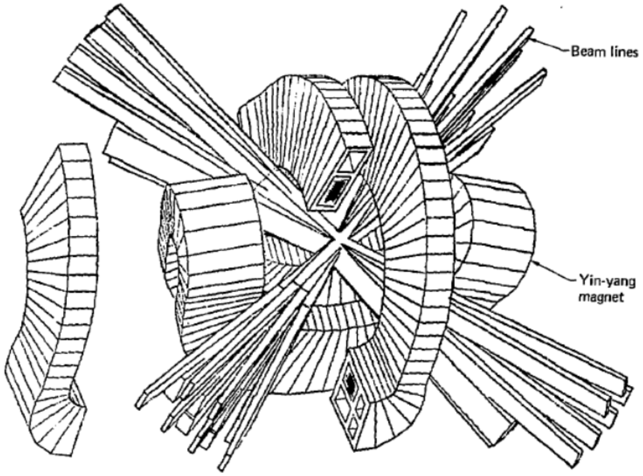


MIRROR FUSION TEST FACILITY

The Mirror Fusion Test Facility (MFTF) at Lawrence Livermore Laboratory (now Lawrence Livermore National Laboratory)

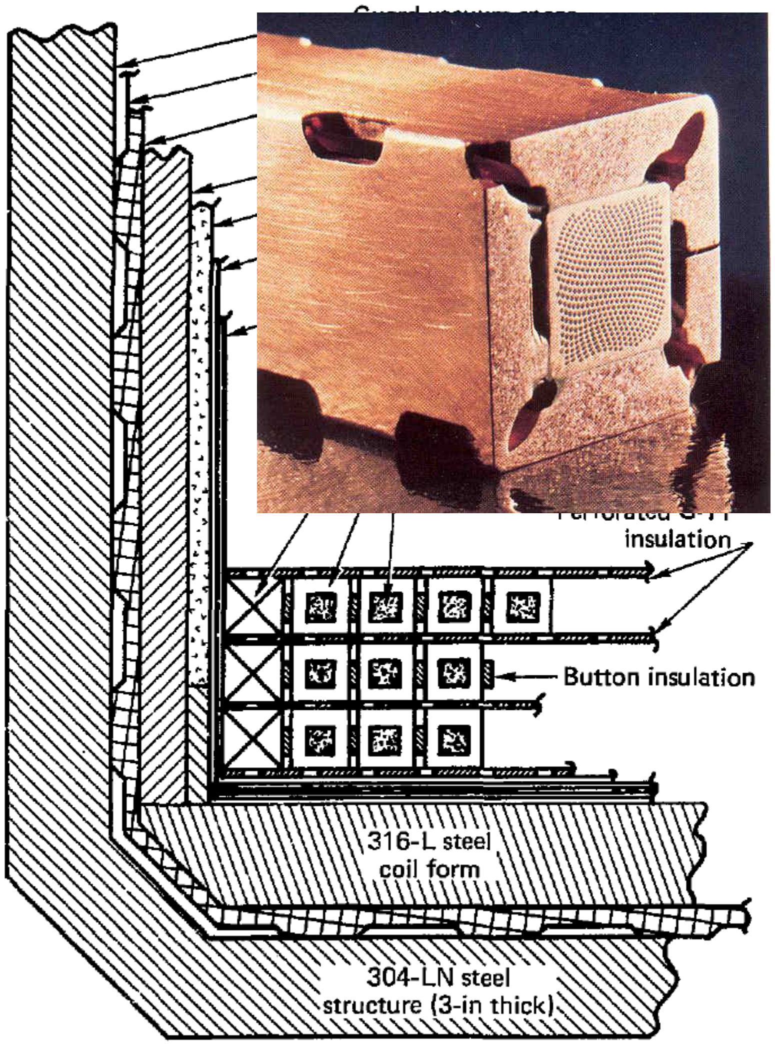
Two 400-ton yin-yang magnets.

Major plasma radius :	2.5 m
Minus plasma radius :	0.75 m
magnetic field at the plasma centre	2 T
Maximum magnetic field on the conductor	7.68 T
Operating current	5775 A
Number of coils:	2
Total lengtht of superconductor :	~ 50 km
Total weight of magnet:	~ 341 t
Total magnetic energy :	409 MJ



Completed and cancelled 1986

MFTF COIL



Superconductor	NbTi
Conductor type	monolithic + copper stabilized 12.4 mm x 12.4 mm
Filament diameter	200 µm
Number of filament	480
Copper ratio	6.7
Maximum field	7.68 T
Conductor current	5 775 A
Critical current	10 kA @ 7.5 T, 4.2 K
Discharge voltage	1 kV
Cooling system	4.3 K, 1.3 bars helium bath
Cryogenic power	1.1 MW

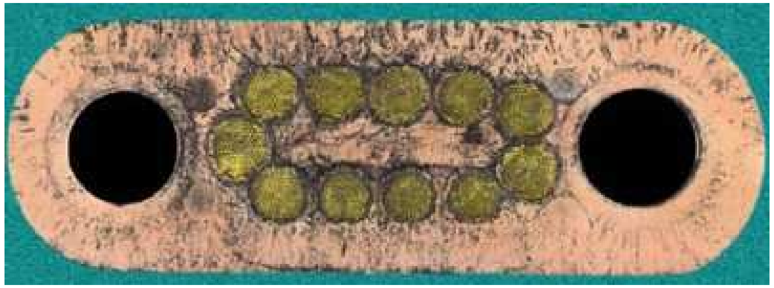
T-15 TOKAMAK - KURCHATOV INSTITUTE

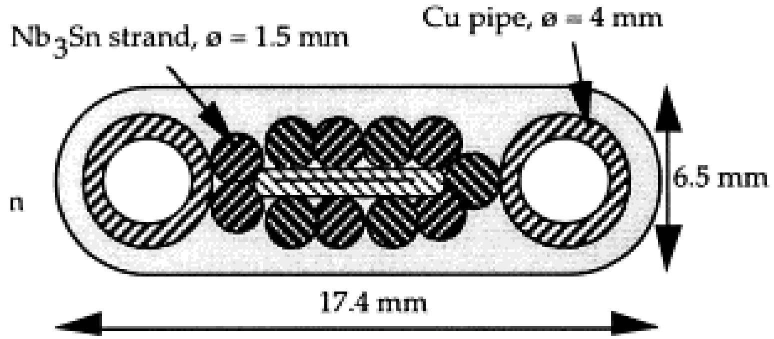
Largest Nb3n based device worldwide

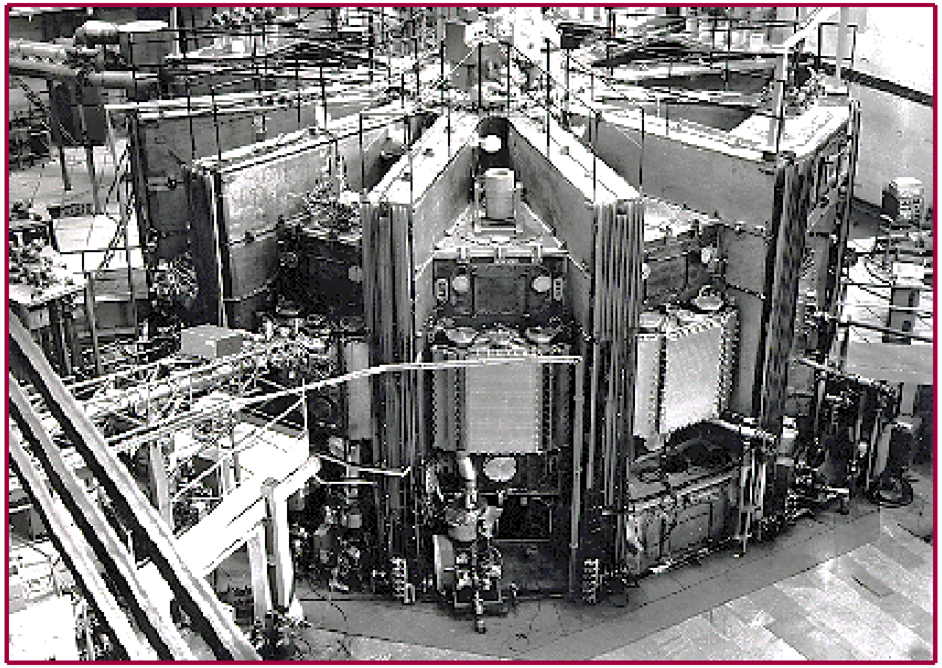
24 circular coils, average diameter 2.4 m, over 100 km conductor

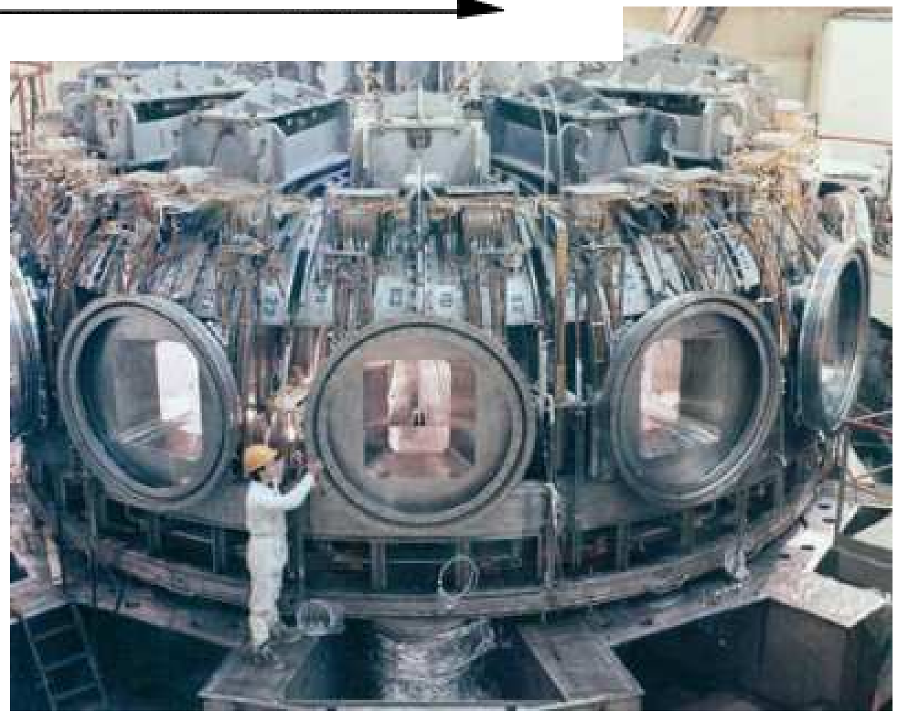
6.5 T, 3.9 kA, 384 MJ

T-15 produced First Plasma in 1988 and was shut down in 1995

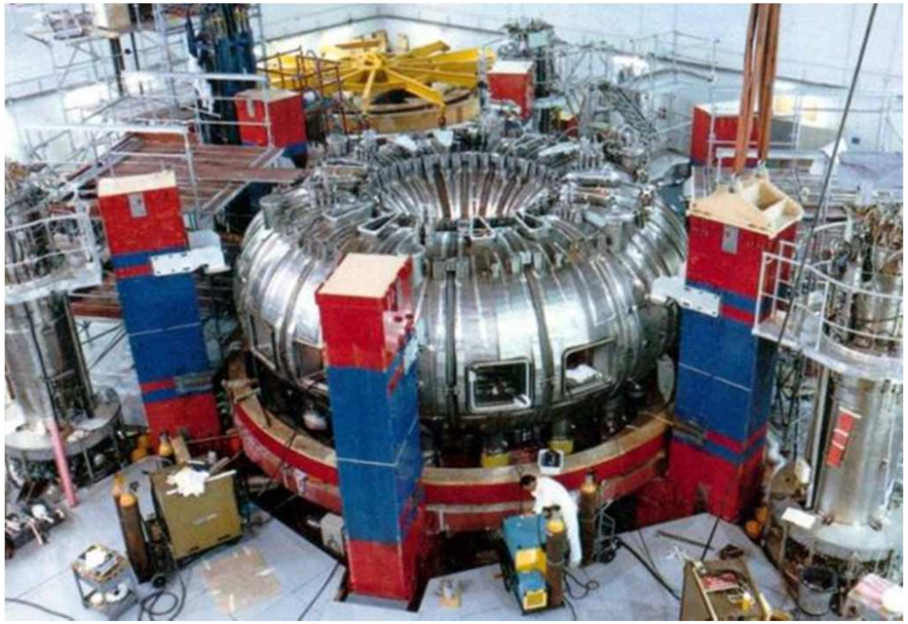


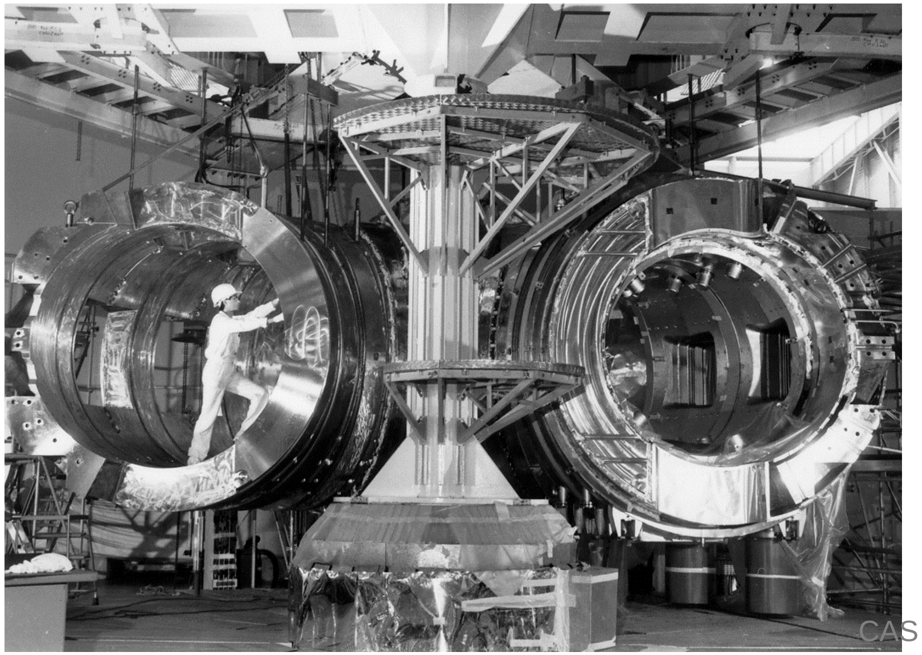






TORE SUPRA - CEA CADARACHE

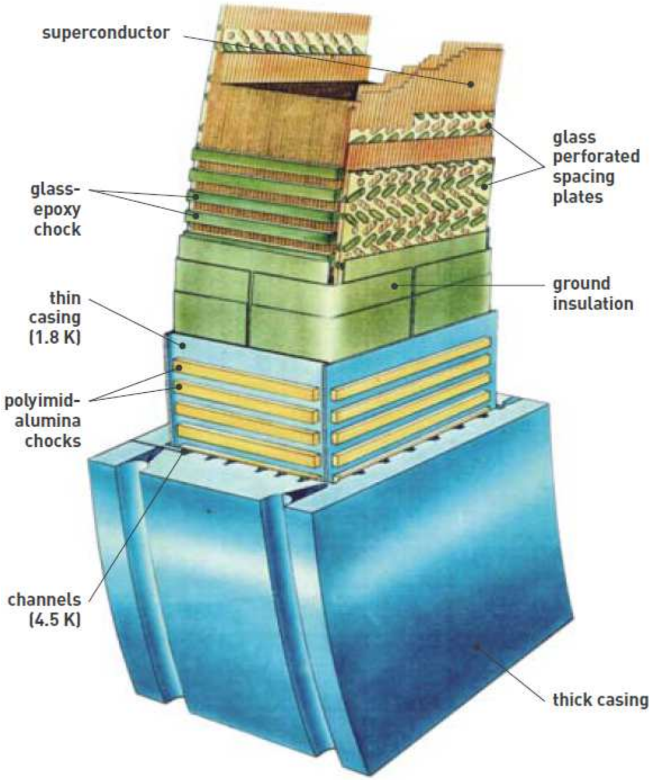




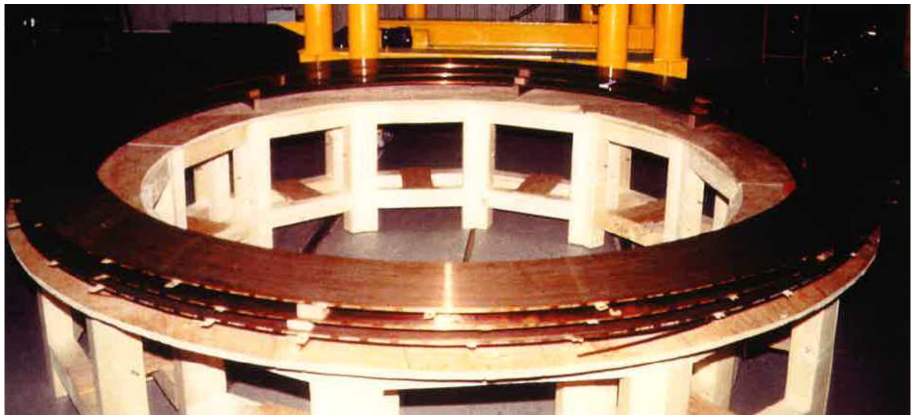
Major plasma radius :	2.25 m
Minus plasma radius :	0.70 m
Diameter :	11.5 m
Height :	7.2 m
Internal vacuum vessel diameter :	1.80 m
Toroidal magnetic field at the plasma centre	4.5 T
Maximum magnetic field on the conductor :	9.0 T
Operating current	1400 A
Average diameter of a magnet coil :	2.60 m
Number of TF coils:	18
Weight of superconductor :	~ 45 t
Total weight of magnet:	~ 160 t
Total magnetic energy :	600 MJ

In operation since 1988

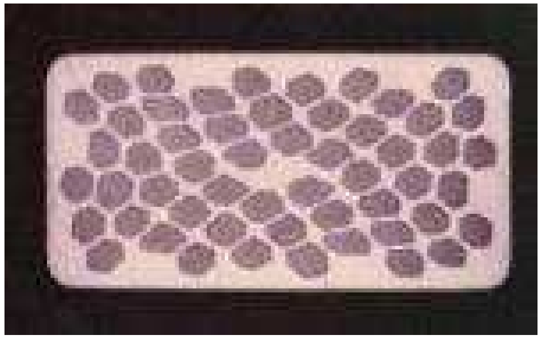
TORE SUPRA COIL



TF system	Tore Supra
Superconductor	NbTi
Conductor type	monolithic bare conductor 2.8 mm x 5.6 mm
Nbr of double pancakes	468
Conductor current	1.4 kA
Discharge voltage	0.5 kV
Cooling system	Superfluid helium bath
Cryogenic power	1.1 MW



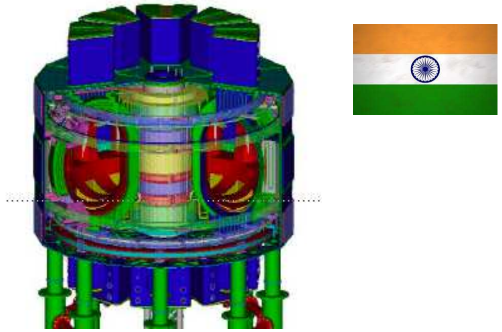
Double pancakes



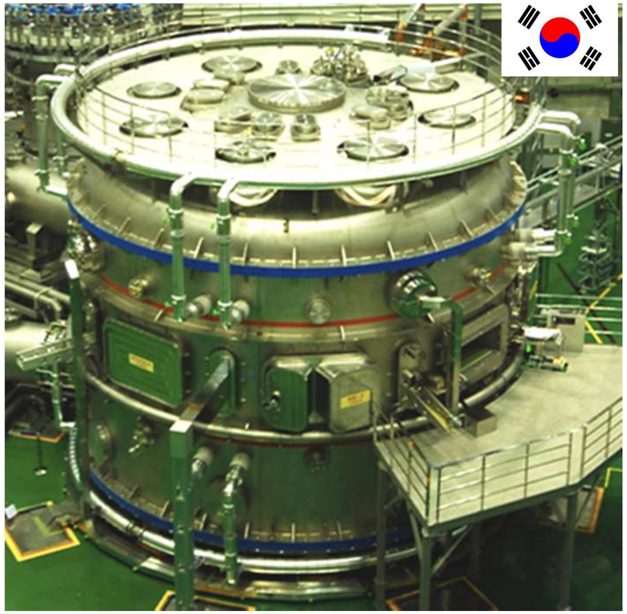
Conductor

NEW SUPERCONDUCTING TOKAMAKS

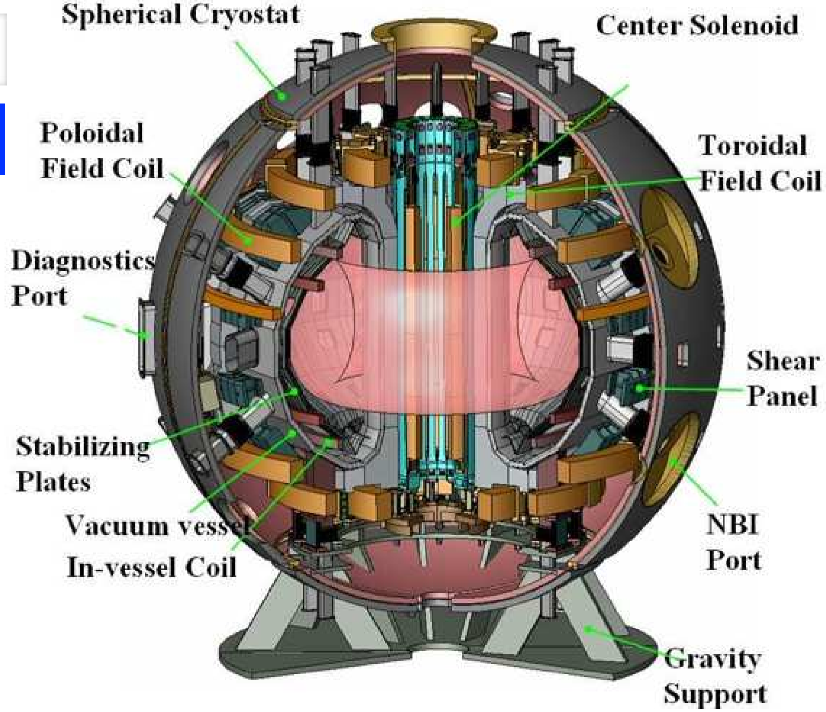
EAST: R = 1.7m, 2MA, 2006



SST-1: R =1.1m, 0.22MA, 2008

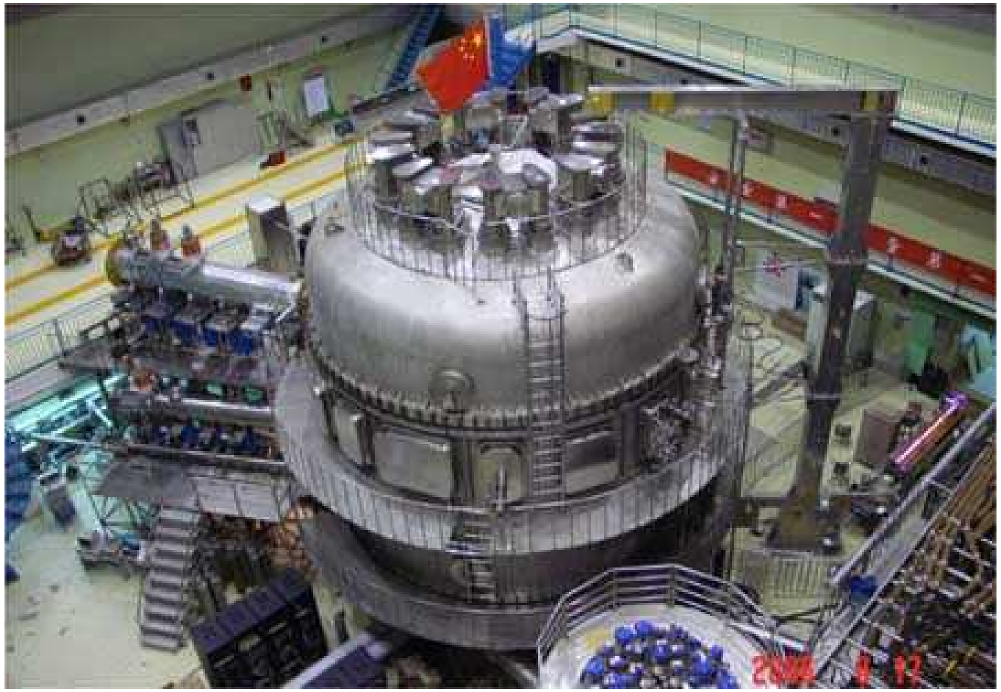


KSTAR: R = 1.8m, 2MA, 2008



JT-60SA: R = 3m, 5.5 MA, 2019

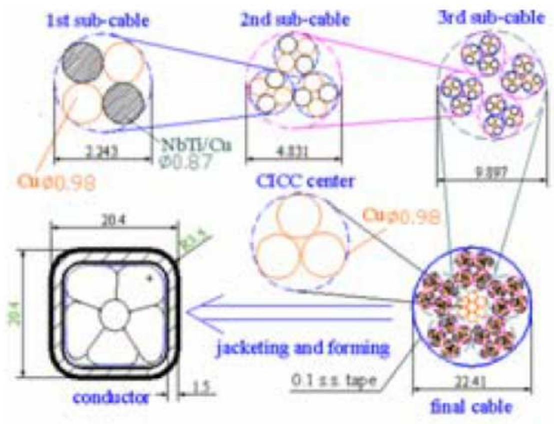
EXPERIMENTAL ADVANCED SUPERCONDUCTING TOKAMAK (EAST)



Chinese Academy of Sciences Institute of Plasma Physics - HEFEI

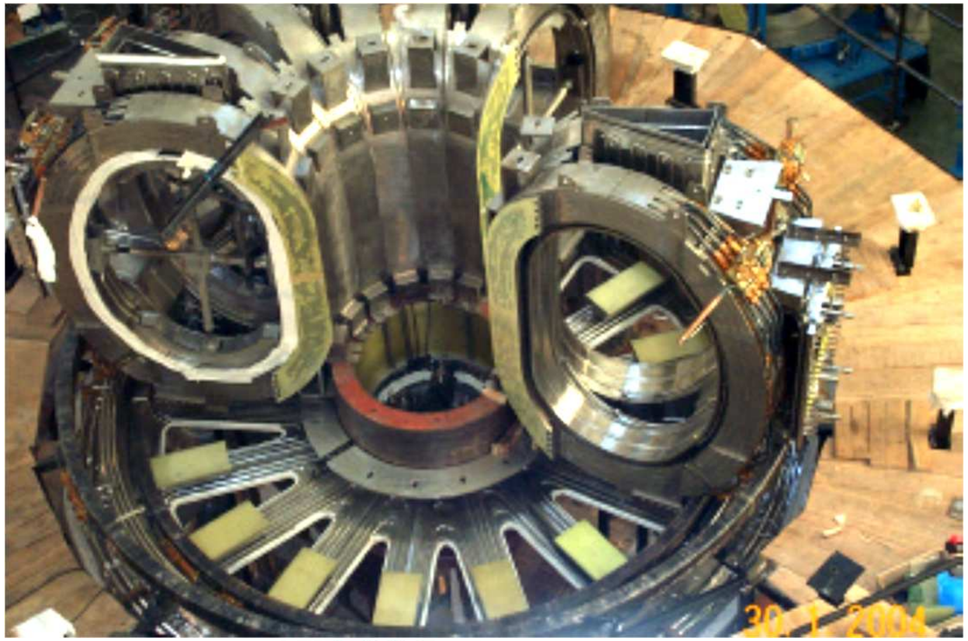
Major plasma radius :	1.7 m
Minus plasma radius :	0.4 m
Diameter :	7.6 m
Height :	10 m
Toroidal magnetic field at the plasma centre	3.5 (4) T
Maximum magnetic field on the conductor :	5.8 (6,5) T
Operating current	14.3 (16.4) kA
Operating temperature	4.2 K (3.8 K)
Number of TF coils	16
Total length of CICC of TF system:	~ 19 km
Total weight of magnet:	~ 160 t
Total magnetic energy :	300(390) MJ

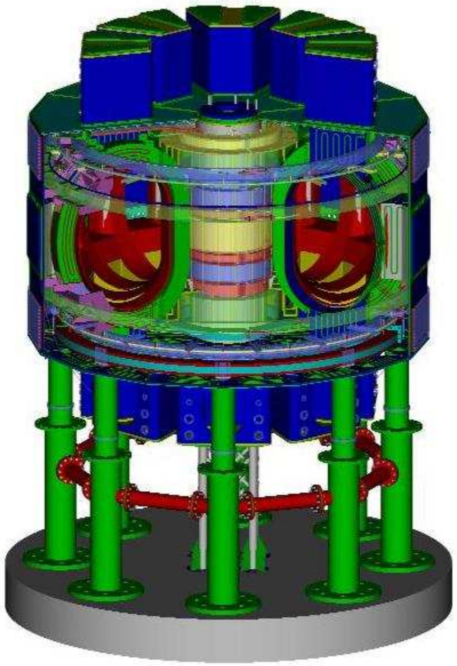
EAST TF COILS



Superconductor	NbTi
Configuration of CICC	(2SC + 2Cu) × 3 × 4 × 5 +1 copper cable core
Conductor dimension (mm × mm)	20.4 × 20.4
Number of superconducting strands	120
Number of copper strands	120 + 21
Diameter of superconducting strands (mm)	0.87
Diameter of copper strands (mm)	0.98
Jacket material	316 LN
Operating current, I_{op} (kA)	14.3
Ratio of I_{op}/I_c	0.28
Current sharing temperature, T_{cs} (K)	6.08
Temperature margin (K)	1.88
Upper limited current, I_{lim} (kA)	18.1

SST-1

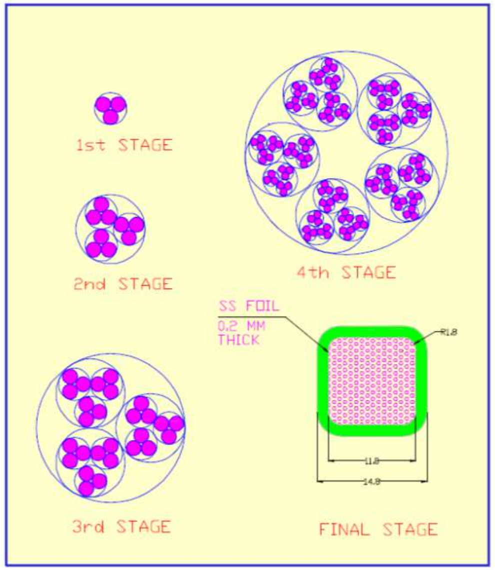


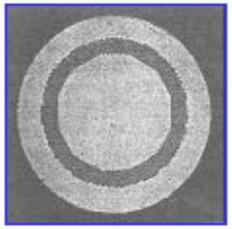


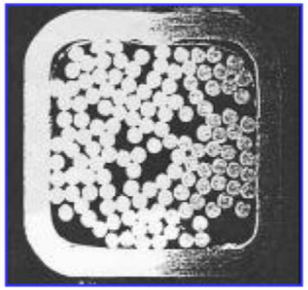
Institute for Plasma Research, Bhat, Gandhinagar

Major plasma radius :	1.1 m
Minus plasma radius :	0.2 m
Diameter :	4.4 m
Height :	2.6 m
Toroidal magnetic field at the plasma centre	3 T
Maximum magnetic field on the conductor :	5.1 T
Operating current	10 kA
Average diameter of a magnet coil	1.8 m
Number of TF coils	16
Number of PF coils	9
Total length of CICC of TF system:	~ 19 km
Total weight of magnet:	~ 160 t
Total magnetic energy :	56 MJ

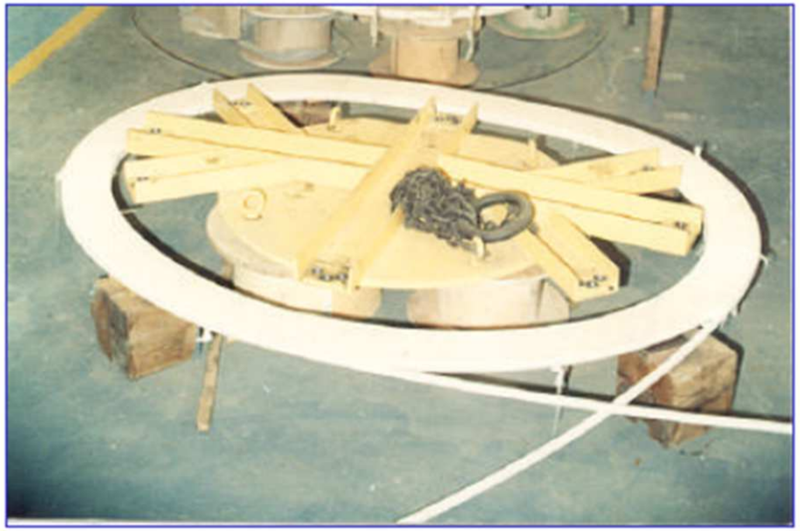
SST-1 TF COILS





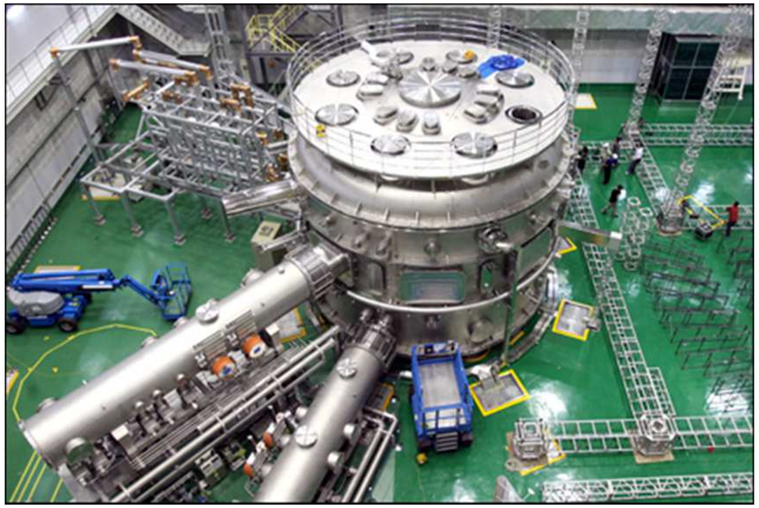


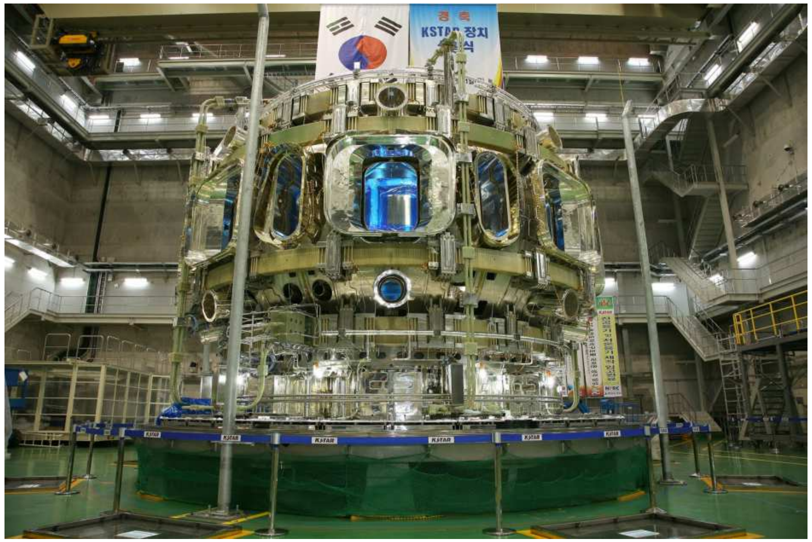
Superconductor	NbTi
Configuration of CICC	3× 3× 3 × 5
Conductor dimension (mm × mm)	14.8 × 14.8
Number of superconducting strands	135
Cu/NbTi	5
Diameter of superconducting strands (mm)	0.86
Jacket material	304 L
Operating current, I_{op} (kA)	10
Ratio of I_{op}/I_c	0.28



KSTAR

Korea Superconducting Tokamak Advanced Research at the National Fusion Research Institute in Daejon, South Korea.





Major plasma radius :	1.8 m
Minus plasma radius :	0.5 m
Diameter :	8.8 m
Height :	8.6 m
Toroidal magnetic field at the plasma centre	3.5 T
Maximum magnetic field on the conductor :	7.2 T
Operating current	35.2 kA
Average diameter of a magnet coil :	
Number of TF coils	16
Number of PF coils	6
Total length of CICC of TF system:	~ km
Total weight of magnet:	~ 270 t
Total magnetic energy :	470 MJ

Completed in 2007; first plasma in July 2008

KSTAR TF COIL

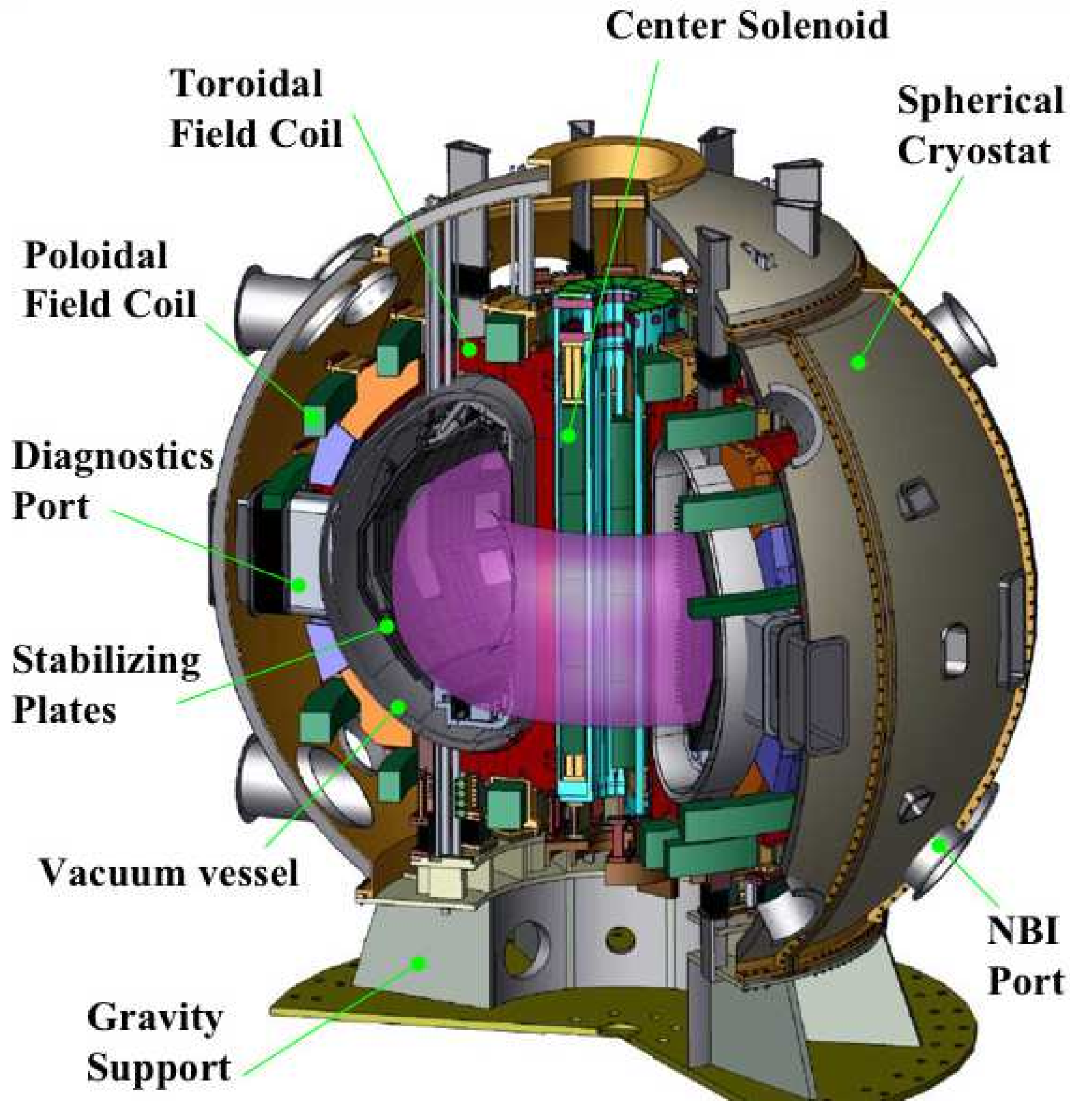
Superconductor	Nb_3Sn
Configuration of CICC	(2Sc+1Cu)×3×3×3×6
Conductor dimension (mm × mm)	25.65 × 25.65
Number of superconducting strands	324
Number of copper strands	162
Diameter of superconducting strands (mm)	0.81
Diameter of copper strands (mm)	0.81
Jacket material	Incoloy Alloy 908
Operating current, I_{op} (kA)	35.2 kA
Critical current density @12T, 4.2K	> 750 A/mm2
Operating margin	4.8 K
Helium fraction	0.34

Central Solenoid - Nb_3Sn CICC with Incoloy Alloy 908 Jacket 25 kA
Poloidal Field Coils - NbTi CICC with modified 316LN Jacket

JT 60-SA

Japan Atomic Energy Agency, Naka

Fusion for Energy, Europe

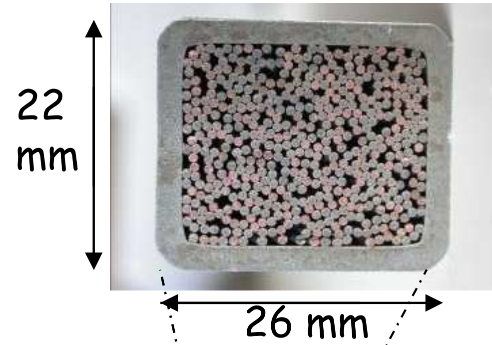


Major plasma radius :	3.1 m
Minus plasma radius :	1.15 m
Toroidal magnetic field at the plasma centre	2.68 T
Maximum magnetic field on the TF conductor :	6.5 T
Operating current	25.7 kA
Operating temperature	4.6 K
Number of TF coils	18
Total weight of magnet:	~ 1300 t
Total magnetic energy :	1060 MJ

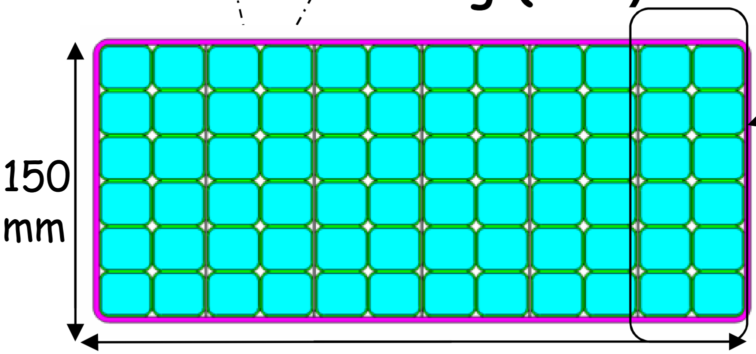
First plasma 2019

JT60-SA TF COIL

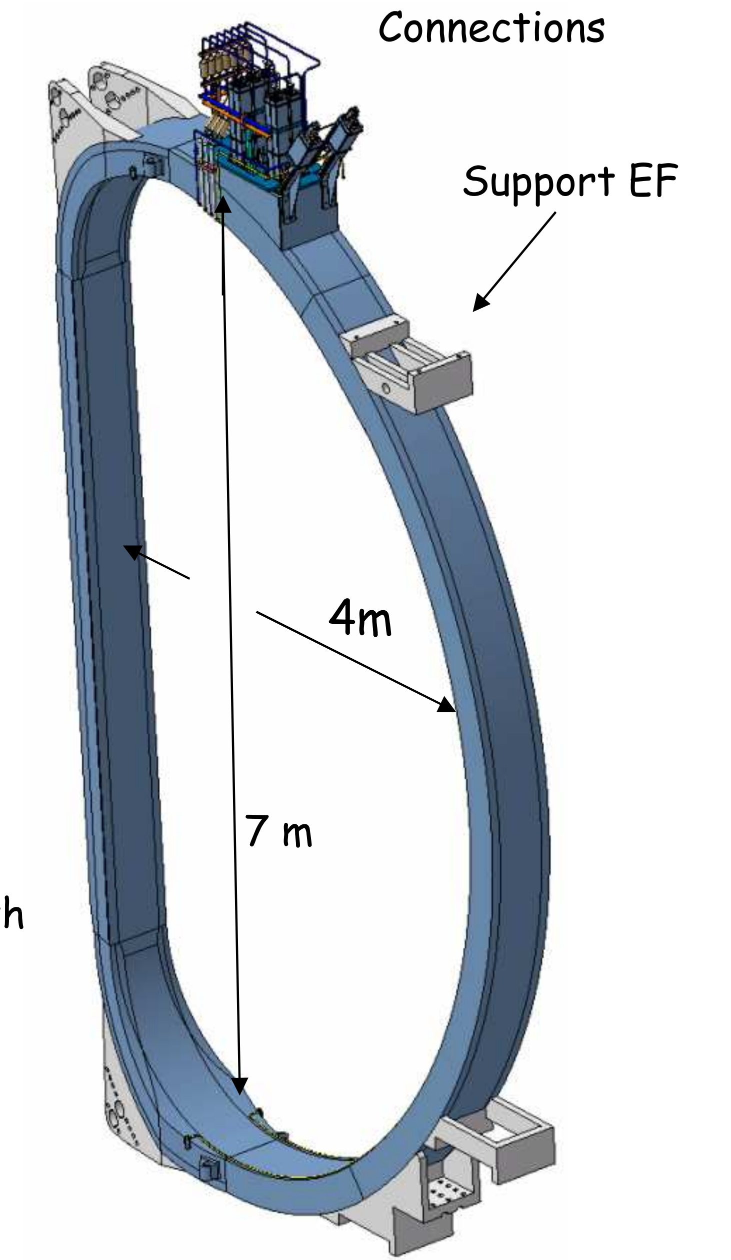
Conductor
NbTi CICC
Jacket 316 LN th 2 mm
Vf: 32%
324 NbTi strands+ 162 Cu strands



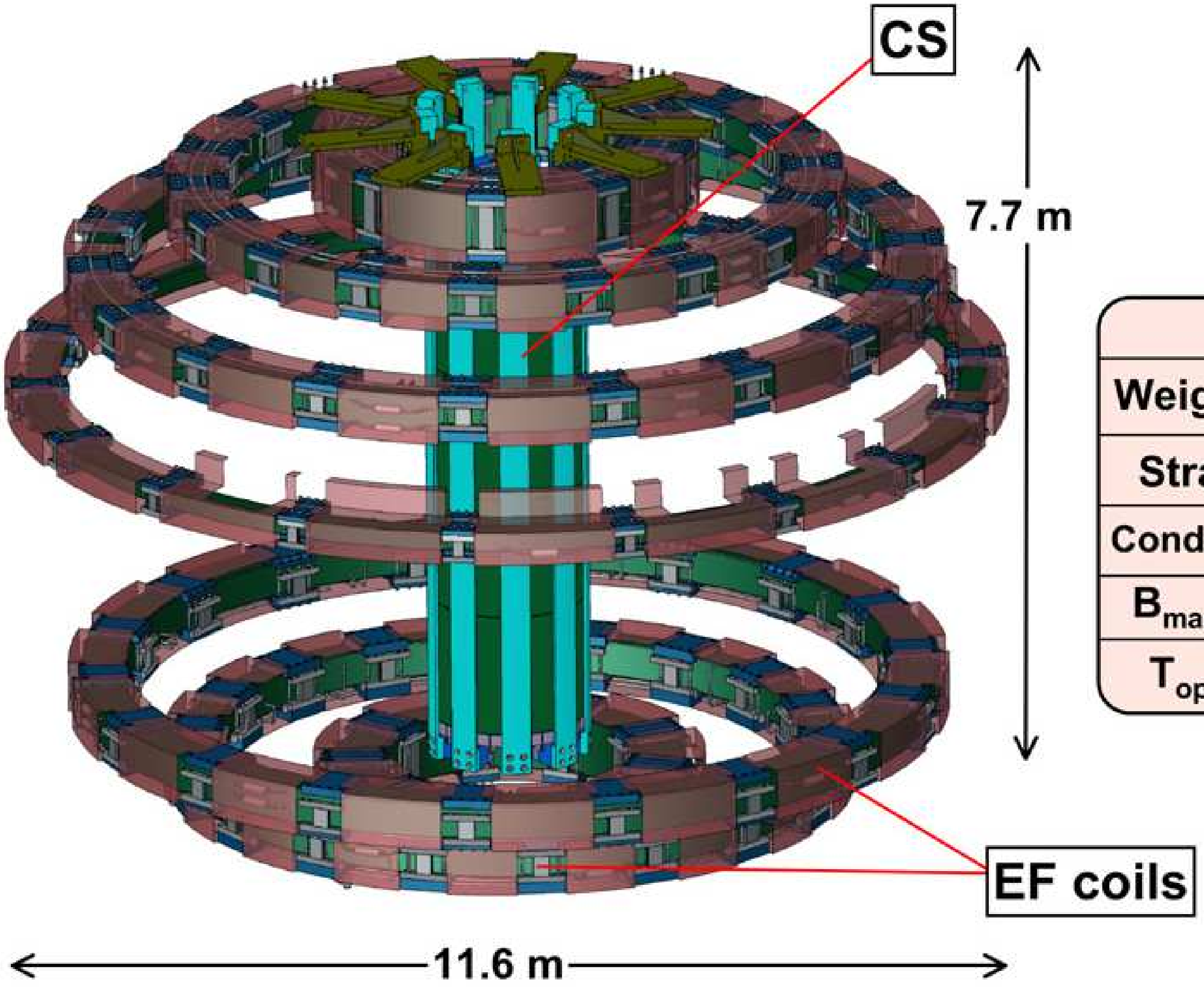
Winding (~ 5 t)



6 Double pancakes
Conductor unit length
230 m



JT60-SA CS+PF COILS



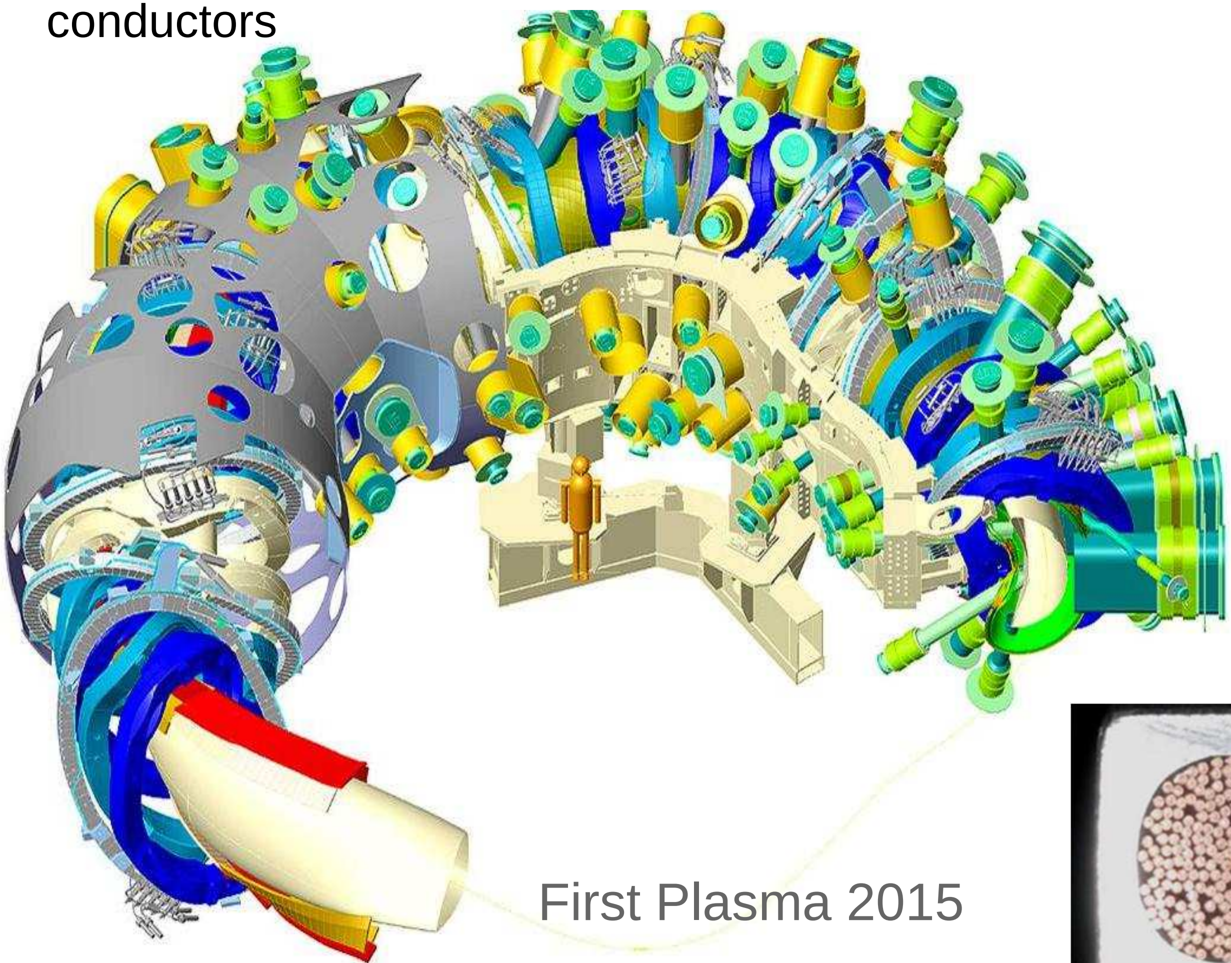
	CS	EF
Weight (t)	120	375
Strand	Nb_3Sn	NbTi
Conductor	cable-in-conduit	
B_{max} (T)	10	6.1
T_{op} (K)	4.6	5.0

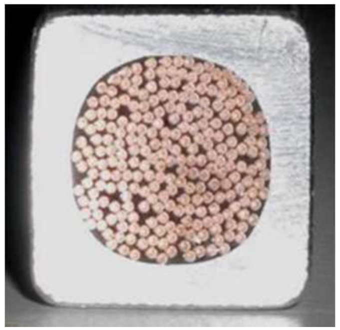
WENDELSTEIN 7-X

Stellarators use a single coil system with no longitudinal net-current in the plasma and hence without a transformer (continuous operation and inherent stability).

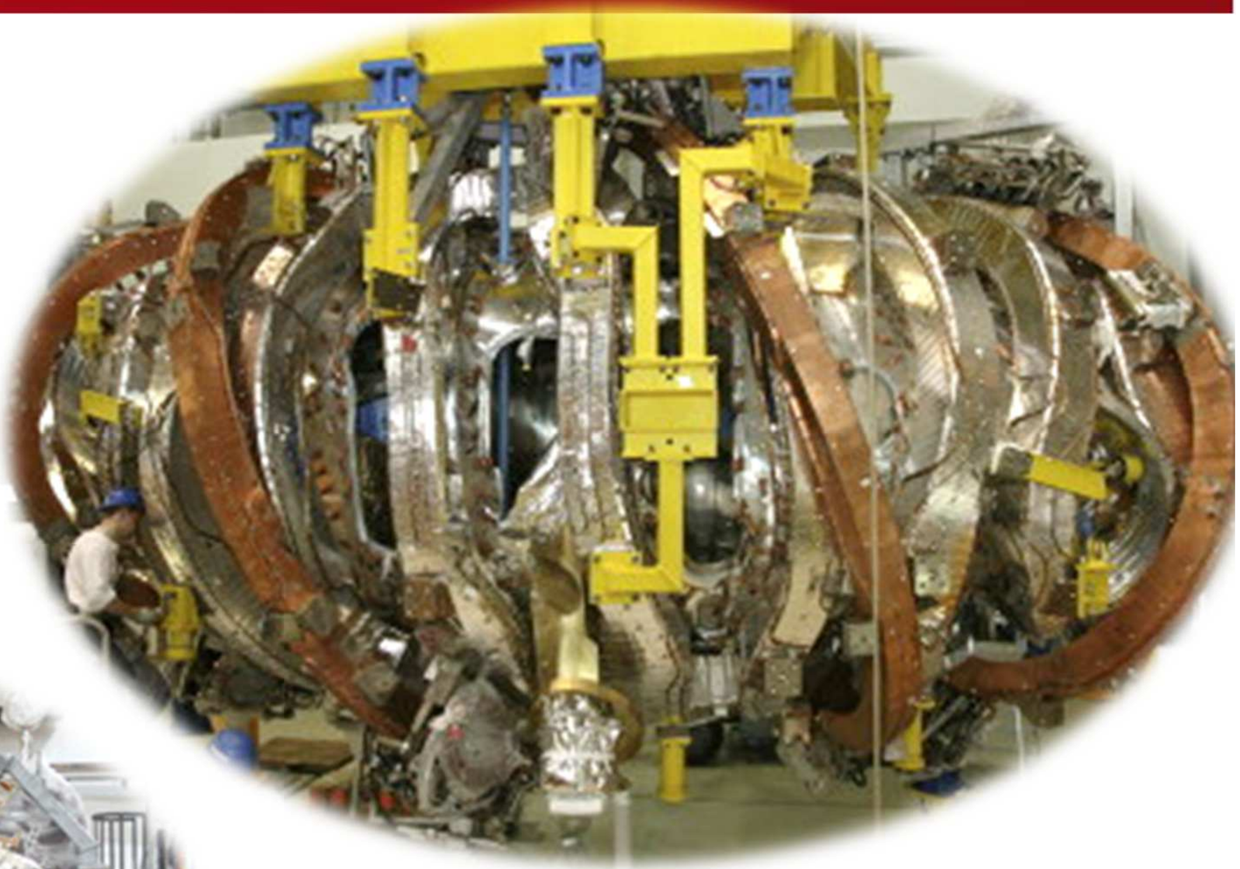
The W7-X magnet system includes 20 planar and 50 non-planar coils which rely on NbTi CIC conductors

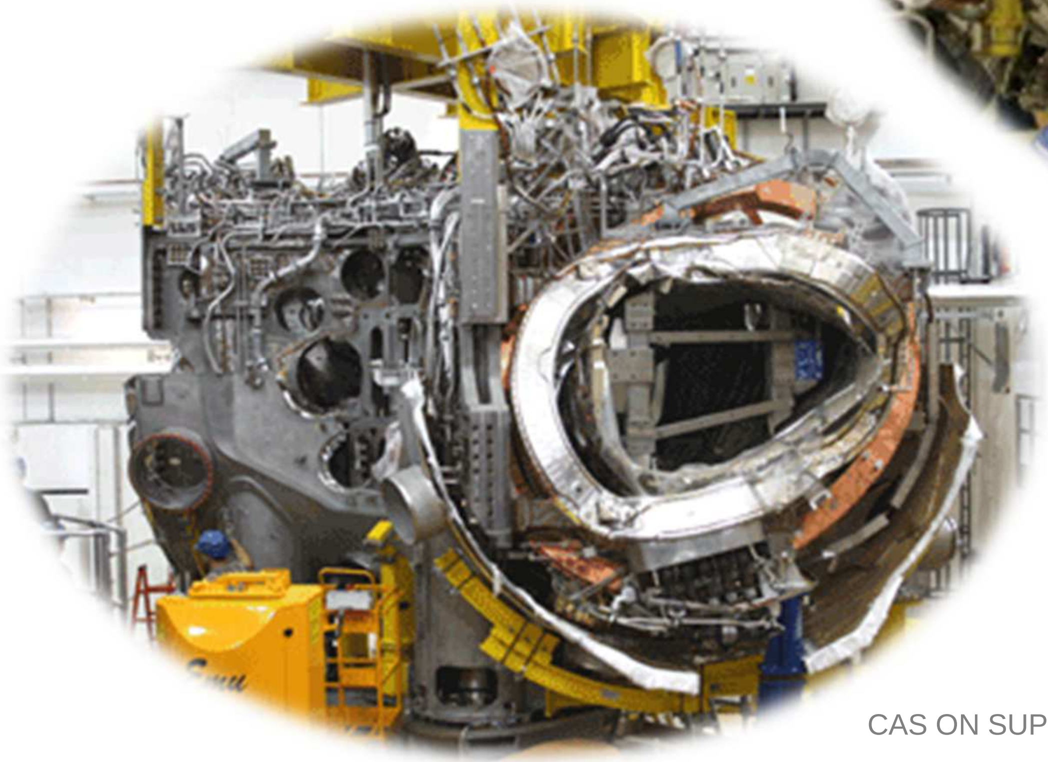
Major radius:	5.5 m
Minor radius:	0.53 m
Plasma volume	30 m^3
Induction on axis:	3T
Stored energy:	600 MJ
Machine mass:	725 t



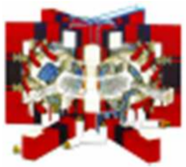


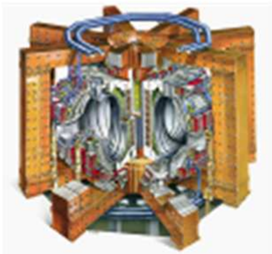
W7-X ASSEMBLY

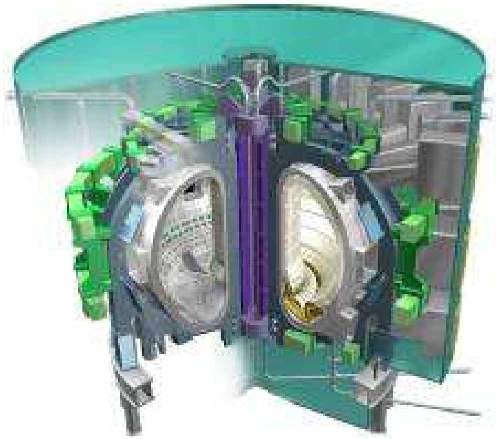


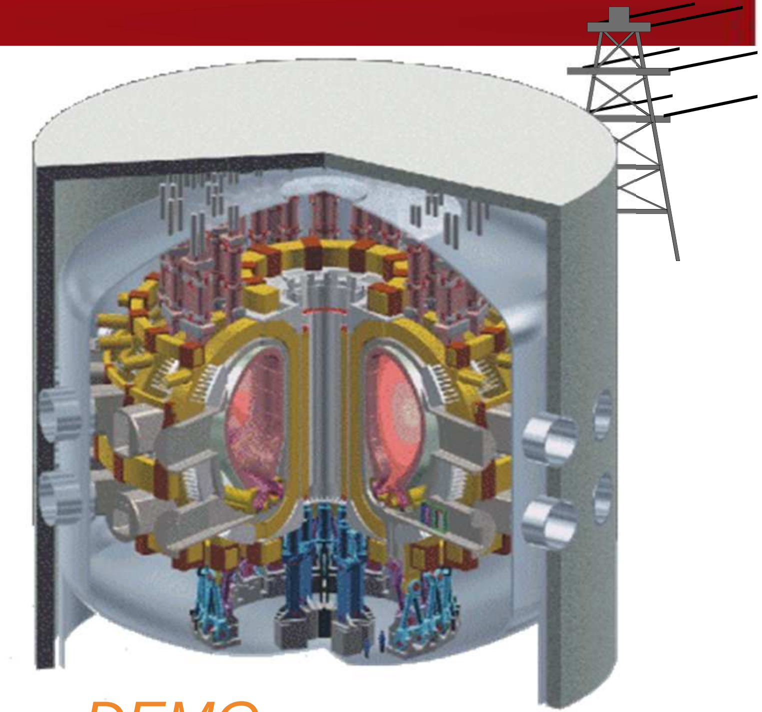


NEXT STEP TOWARDS FUSION ENERGY : ITER



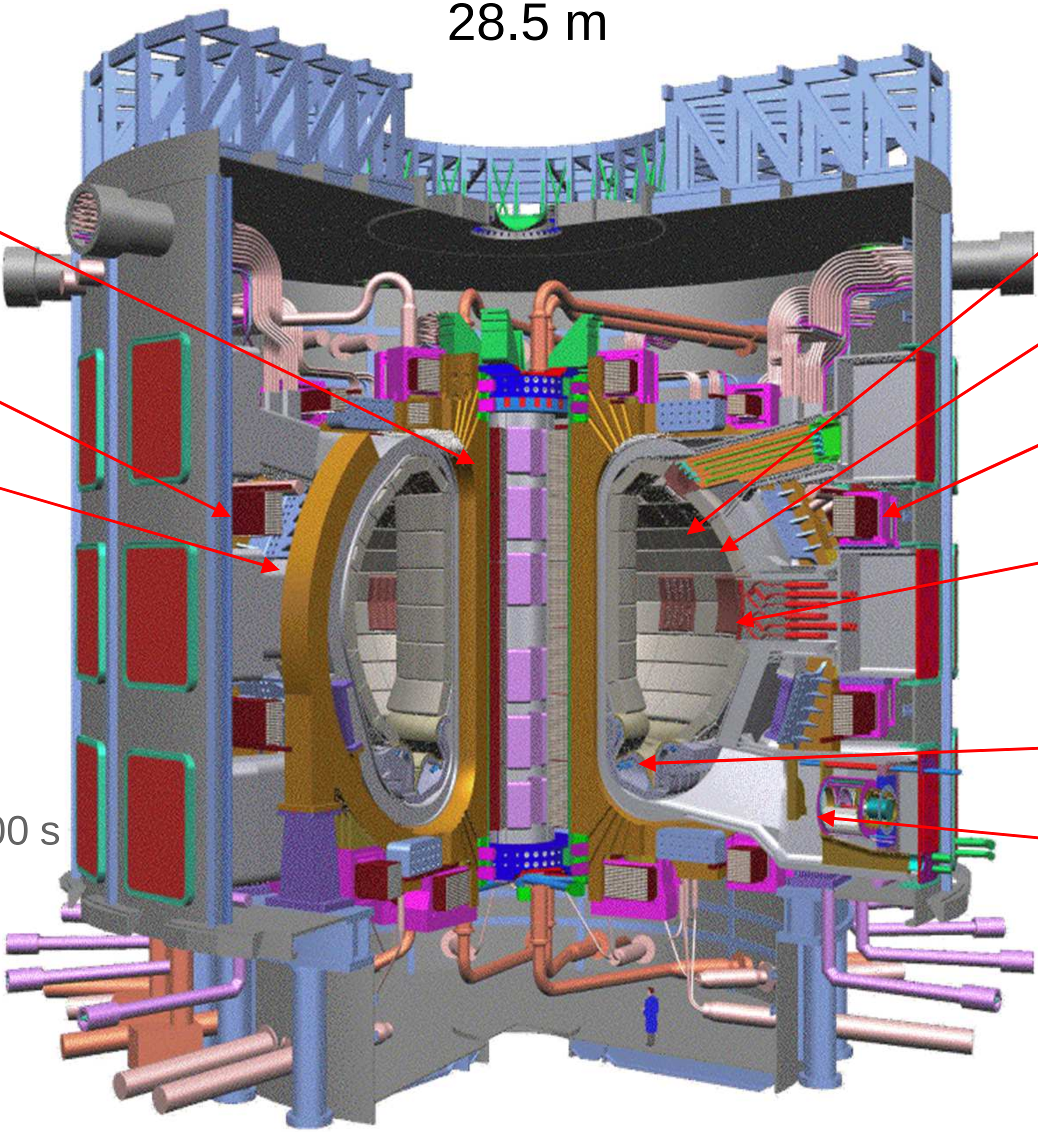






Tore Supra	*JET*	*ITER*	*DEMO*
25 m^3	*80 m^3*	*800 m^3*	*~ 1000 - 3500 m^3*
400 s	30 s	400 s-1000 s	
1,5 MA	5 MA	15 MA	
4.2 T	3.5 T	5.3 T	
~ 0	*~ 16 MW_{th}*	*~ 500 MW_{th}*	*~ 2000 - 4000 MW_{th}*
Q ~ 0	Q ~ 1	Q ~ 10	Q ~ 30
0%	10 %	70 %	80 to 90 %

First plasma in 2020, Operation in 2027



Fusion Power: 500 MW

Plasma Volume: 840 m^3

Q ≥ 10

Plasma Inductive Burn Time ≥ 400 s

Nominal Plasma Current: 15 MA

Toroidal field 5.3 T

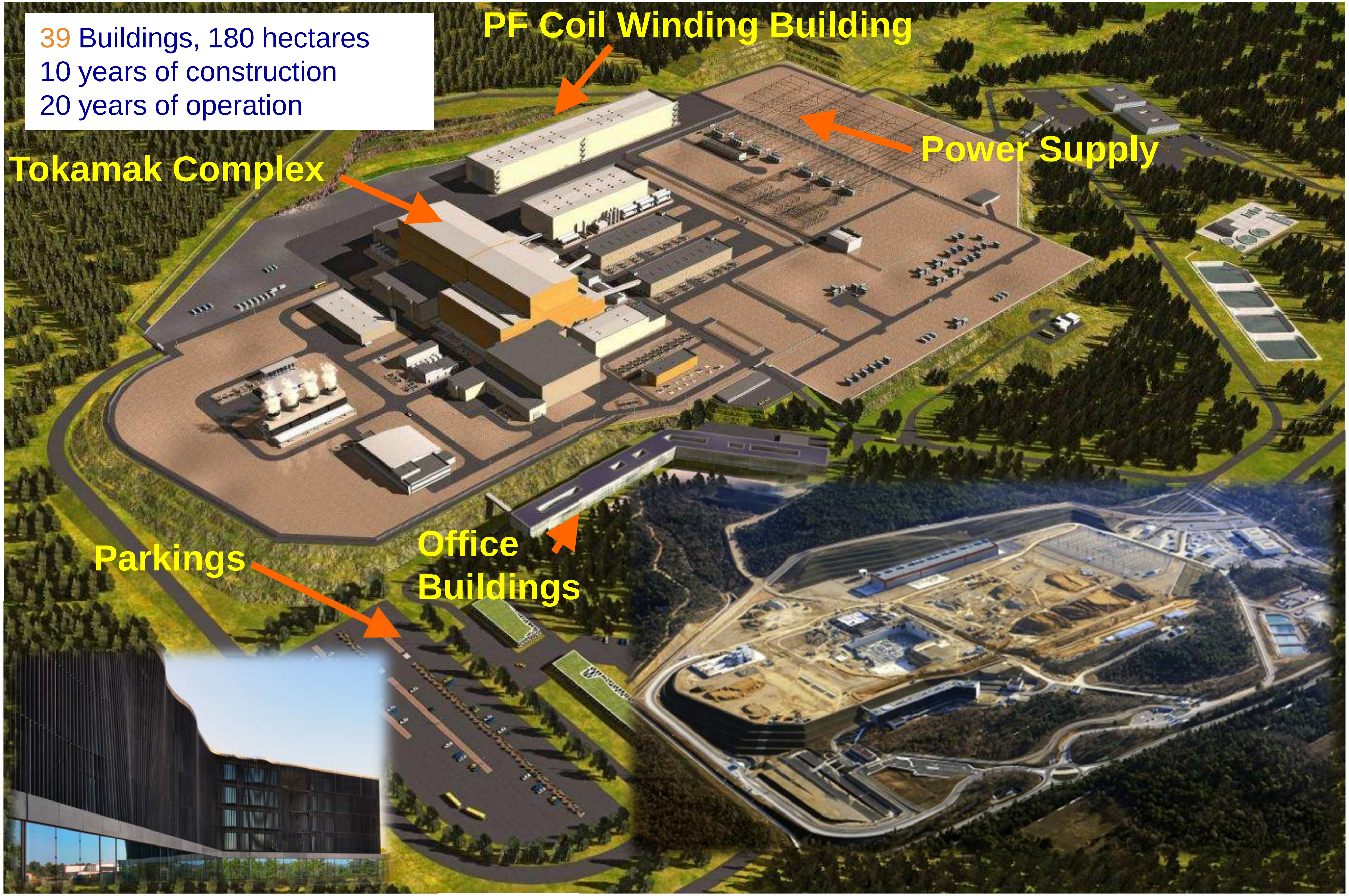
Major radius 6.21 m

Minor radius 2 m

Typical Temperature: 20 keV

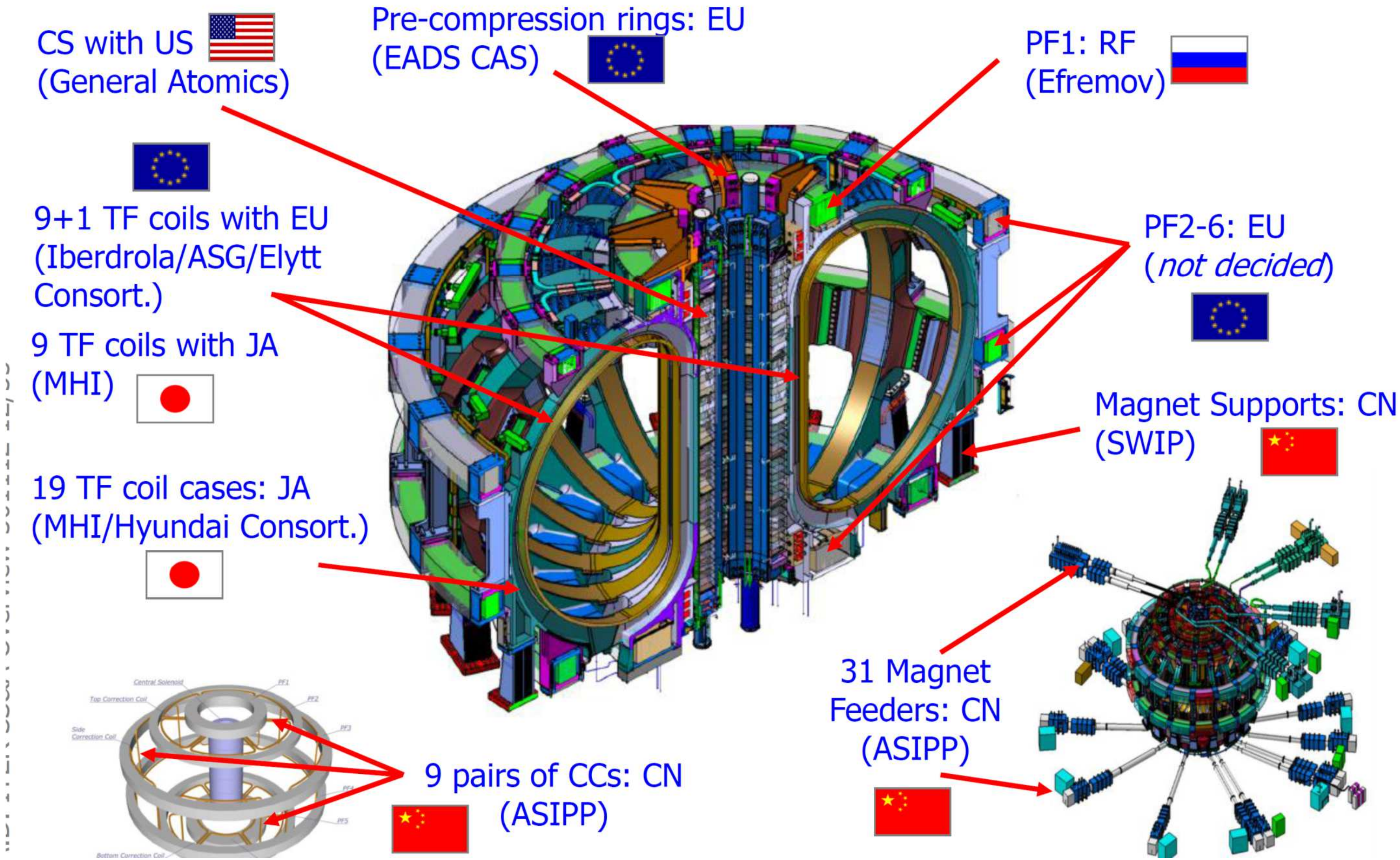
Typical Density: 10^{20} m^{-3}

ITER SITE



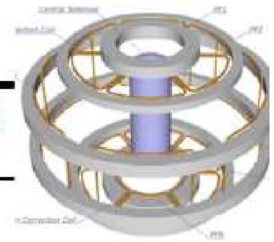
39 Buildings, 180 hectares
10 years of construction
20 years of operation
PF Coil Winding Building
Tokamak Complex
Power Supply
Office
Buildings
Parkings

ITER MAGNET SYSTEM SHARING



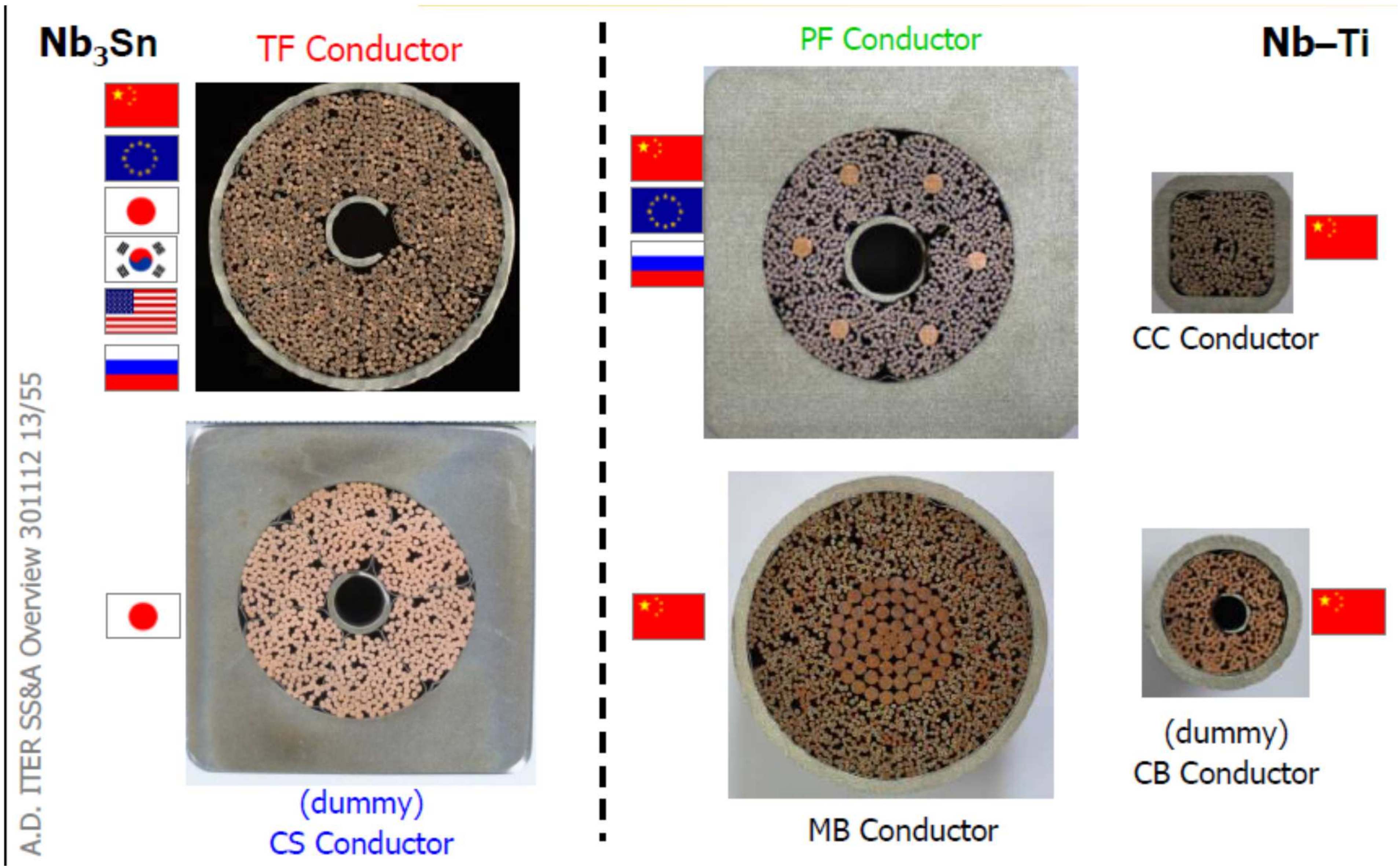
Courtesy of ITER

ITER COILS

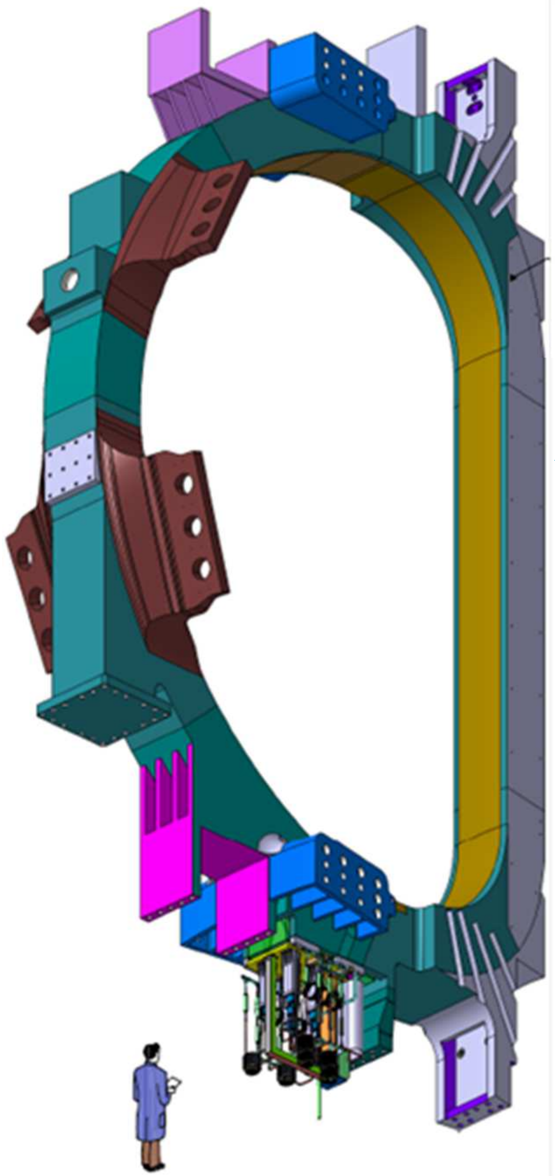


	TF	CS	PF
Number of Coils	18	1	6
Dimension	14x9 m	12x4 m	8 to 24 m
Conductor Type	Nb_3Sn CIC	Nb_3Sn CIC	NbTi CIC
Quantity Total Weight Sc Strand Weight	88 km 826 t 384 t	42 km 728 t 122 t	65 km 1224 t 224 t
Operating Current	68 kA	46 kA	52 kA
Operating Temperature	5 K	4.5 K	4.5 K
Peak Field	11.8 T	13.0 T	Up to 6.0 T (P6)
Stored Energy	41 GJ	6.4 GJ	4 GJ
Total Weight (Incl. Supports)	6540 t	974 t	2163 t

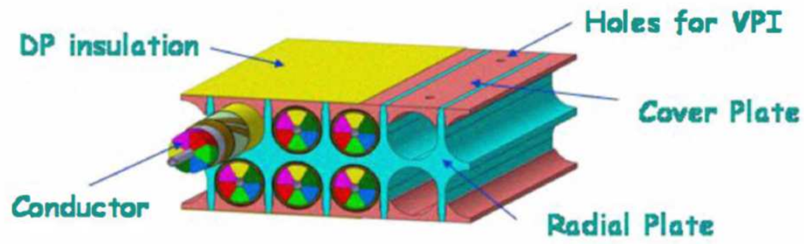
ITER CONDUCTORS



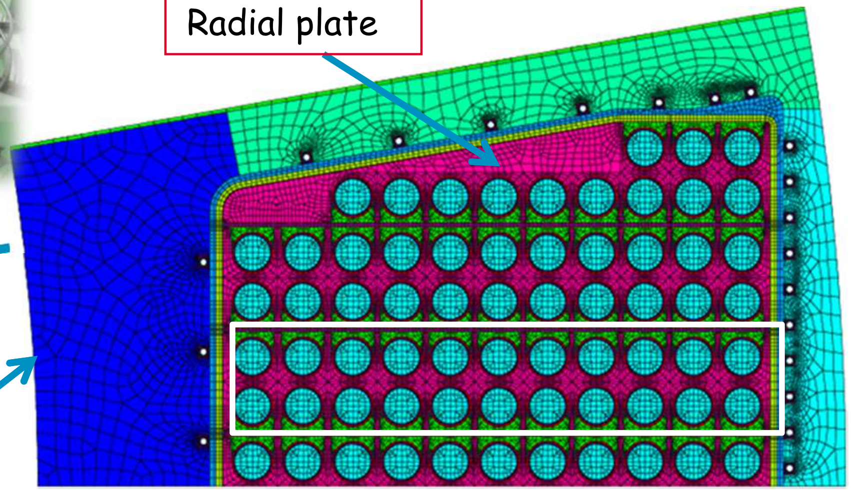
ITER TF COIL



Section of nose



Radial plate

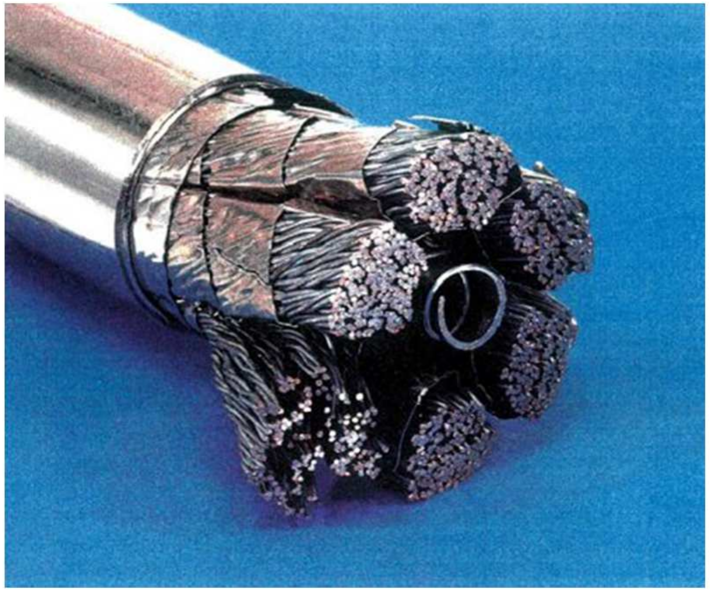


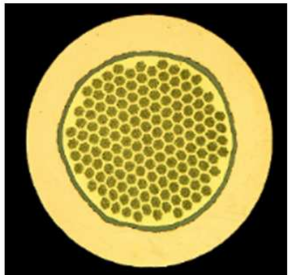
Coil Casing
High strength 316LN
0.2% YS > 1000MPa

Maximum magnetic field on the conductor :	11.8 T
Operating current	68 kA
Dimensions of a magnet coil :	16.5 m x 9 m
Number of TF coils	18
Operatin temperature:	~ 5 K
Max. operatin voltage	7 kV
Total magnetic energy :	41 GJ
Total weight	5362 t

Courtesy of ITER

ITER TF CONDUCTOR

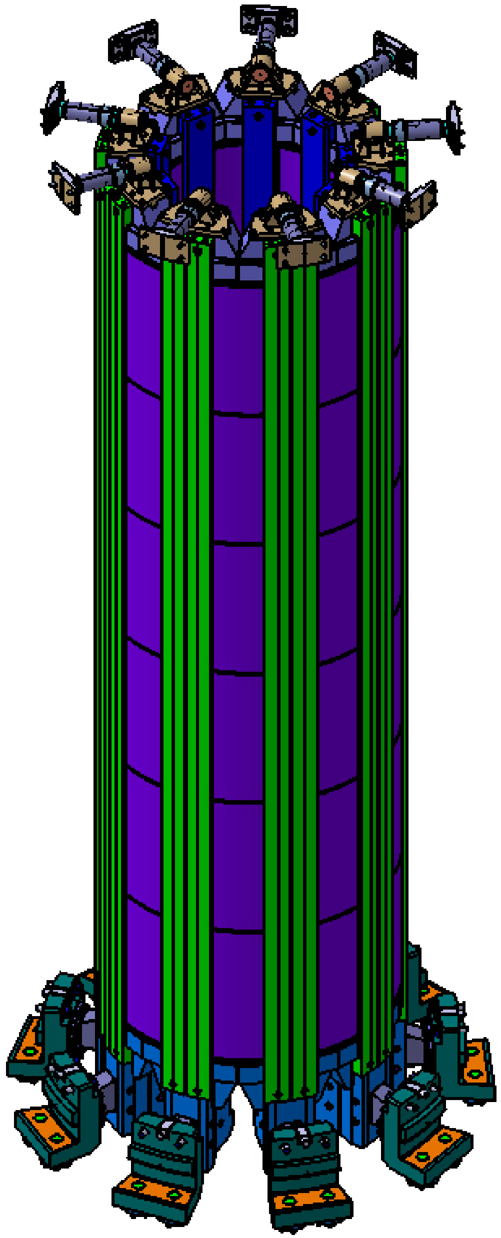




Nb$_3$Sn bronze route

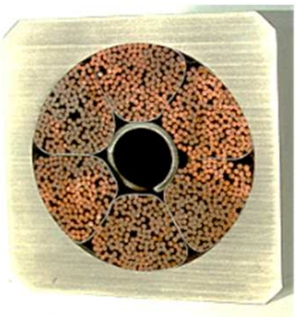
Superconductor	Nb$_3$Sn
Configuration of CICC	((2Sc+1Cu)×3×5×5 +core) ×6
Conductor dimension (mm)	43.7
Number of superconducting strands	900
Number of copper strands	522
Diameter of superconducting strands (mm)	0.82
Diameter of copper strands (mm)	0.81
Jacket material	316 LN
Operating current, I_{op} (kA)	68 kA
Critical current/strand@12T, 4.2K	> 190 A
Operating margin	0.8 K
Helium fraction	33 %

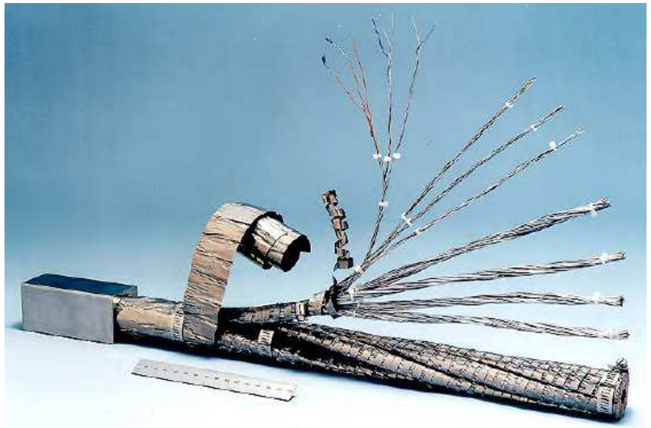
ITER CS COIL



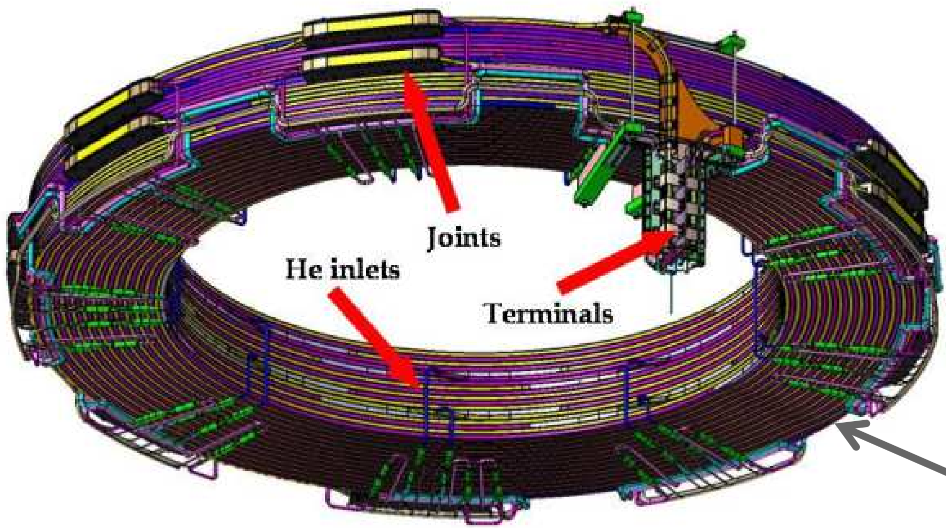
Number of CS modules **6**
Magnetic energy in CS coil (GJ) **21**
Operating current (kA) **41.8/46**
Maximum field (T) **13.5/12.8**
Weight (t) **1000**

Superconductor	Nb_3Sn
Configuration of CICC	(2Sc+1Cu)×3×4×4×6
Conductor dimension (mm)	49 x 49
Number of superconducting strands	576
Diameter of superconducting strands (mm)	0.83
Jacket material	316 LN
Operating current, I_{op} (kA)	46 kA
Helium fraction	33.5 %



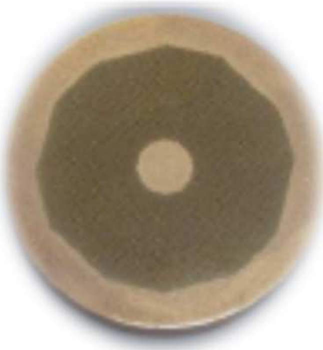


ITER PF Coils



Number of PF coils	6
Maximum diameter (m)	24
NbTi conductor	
Magnetic energy in PF coils (GJ)	4
Operating current (kA)	52
Maximum field (T)	6.5
Weight (t)	2163

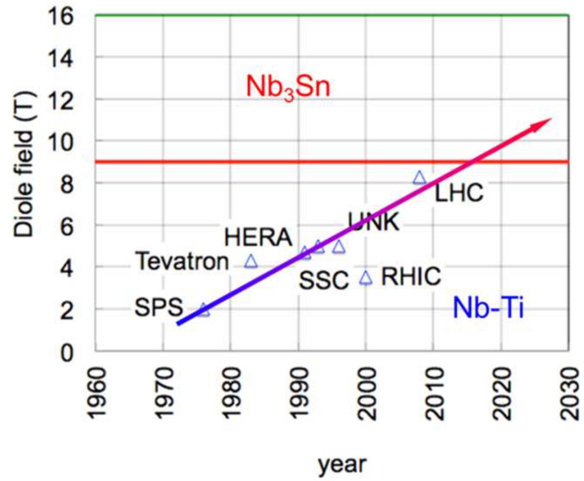
Cabling layout	3 sc x 4 x 4 x 5 x 6
Twist direction	Right hand
Cable twist pitches	45/85/145/250/450 mm
Sub-cable and cable wrap thickness	0.05 and 0.1 mm
Central spiral OD/ID	12/10 mm
Spiral and wraps material	304L or 316 L
Jacket material	316 L
Final conductor outer dimension	53.8 mm



CONCLUSION

Important developments in the technology over the last 40 years for the large scale applications of the superconductivity :

- Field strength - Scale - Field volume - Stored energy
- Conductors - advances in scale, strength, current
- Coil winding and assembly
  - technology - materials – impregnation - bonding
  - engineering – scale + accuracy



•Next step will be to use Nb_3Sn and HTS materials to increase the field level

•Need for a strong R&D to reinforce conductor mechanical strength and protect the coils against quenches.

ACKNOWLEDGEMENTS

Many thanks for contribution of material

Jean-Luc Duchateau (CEA)

Arnaud Devred (ITER)

François Kircher (CEA)

Elwyn Baynham (RAL)

Akira Yamamoto (KEK)

Lucio Rossi (CERN)

Luca Bottura (CERN)

Paolo Ferracin (CERN)

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Saclay | 91191 Gif-sur-Yvette Cedex
T. +33 (0)1 69 08 71 28 | F. +33 (0)1 69 08 69 29

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Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019