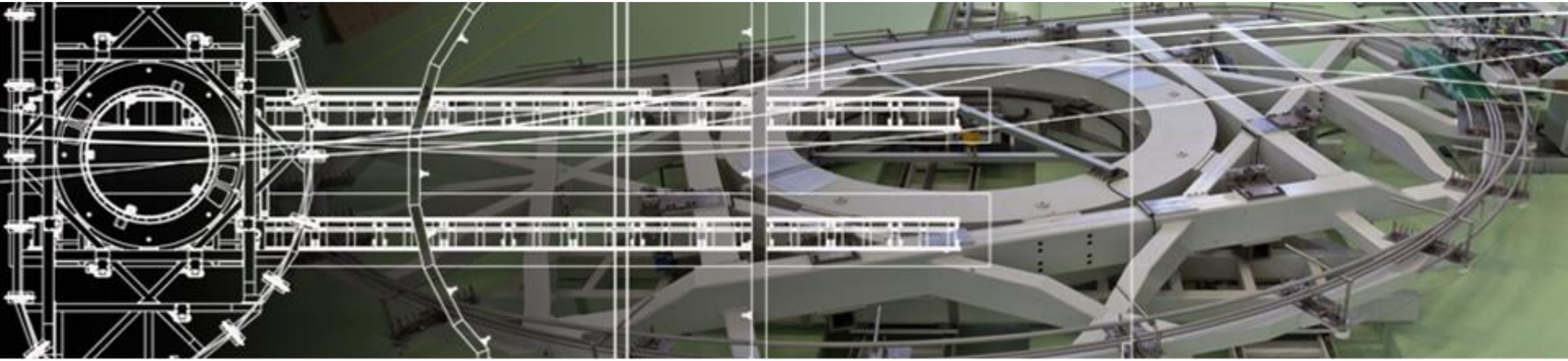


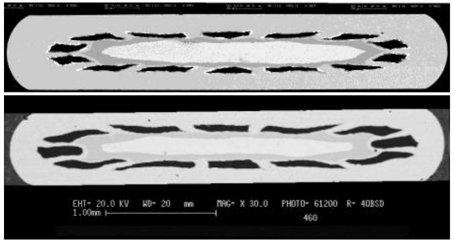
MAGNET CONSTRUCTION AND PROBLEMS IN SUPERCONDUCTING MAGNETS
at EASYTRAIN SCHOOL
Genoa, October 5, 2020

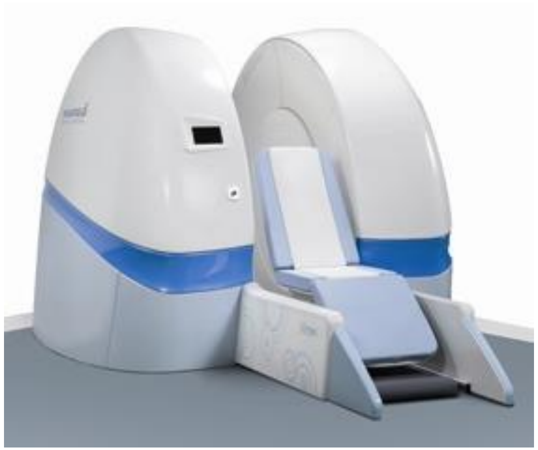
N. Valle

www.asgsuperconductors.com

ASG Superconductors -> One Company -> Three Business Units

- Magnets & systems Unit
- Columbus MgB2 Unit
- Paramed MRI Unit





Magnets & Systems Unit (MBU) Magnets: Superconducting / Resistive Magnet

Research, nuclear fusion, particle physics, industrial applications for energy and mri systems: thanks to experience accumulated through participation in the main superconductivity technology research projects ASG's skills go from design to production till the complete test.

The ASG Superconductors magnets & systems unit has acquired industry-leading know-how in the design, development, production, installation and testing of superconductive and resistive magnets, cryogenic systems, resonance cavities, superconducting solenoids and coils, magnets for cyclotrons.

Magnets for different purposes as:

- **MAGNETS FOR FUSION**
- **MAGNETS FOR HIGH ENERGY PHYSICS**
- **MAGNETS FOR MEDICAL APPLICATIONS**
- **SYSTEMS FOR ENERGY**

Superconducting cables used:

- *NbTi*
- Nb_3Sn
- MgB_2

WORKING FOR THE ENERGY OF THE FUTURE

The production of clean energy through fusion, which reconciles the energy needs of the modern world with safeguarding the environment, is a challenge that researchers and industries have been striving to meet. The quality of ASG's nuclear fusion offering is the result of unequalled technical and productive expertise: our magnets have been used in all the main fusion experiments undertaken so far in Europe during the last 60 years.
ASG nowadays plays a leading role - as a supplier of magnets - in ITER (Europe) and JT-60SA (Japan), the two principal research projects which aim to study the feasibility of producing clean energy by replicating the process that takes place in the sun and stars. For nuclear fusion ASG develops and produces:

- Superconducting and resistive toroidal coils
- Superconducting and resistive poloidal coils
- Coils for divertors
- Central Solenoid and resistive solenoid coils
- Stellarator coils
- Gyrotron system coils.

ASG also undertakes prototyping and research activities aimed at evaluating the feasibility and/or characterization of materials and production processes.

WORKING FOR THE ENERGY OF THE FUTURE

Main Fusion Projects

- ITER Model Coil for Net TEAM (D) – (1996-2000)
- W7X – Stellarator for IPP (D) – (1998-2006)
- JT60 for ENEA (I) (2011-2019)
- ITER Toroidal Coils for F4E (EU) – (2010-2020)
- ITER Poloidal Coil for F4E (EU) – (2013-in progress)

MAGNETS FOR HIGH ENERGY PHYSICS

ASG is currently the largest European producer of magnets for particle accelerators and for applications in high-energy physics. From solenoids, dipoles and cyclotrons to the CMS and ATLAS detectors at Geneva's CERN as well as magnetic systems for the Katrin project: ASG is involved in all the main international projects.
Our magnets are testimony to the company's ability to meet precisely the needs of the research world. They have contributed to reaching important scientific goals, like - for example - the discovery of the Higgs Boson in 2012.
Thanks also to its continuous dialog with the main institutes and research centers worldwide - including ENEA, INFN, CNR, KIT, IPP, ITER and Fusion4Energy - ASG is able to offer support in designing magnets starting from the requested field specifications or in the optimization and industrialization of existing designs. ASG can develop:

- dipolar cosθ magnets
- dipolar “steering” magnets, both superconducting and copper
- superconducting and copper multipolar magnets for focusing particle beams
- detector magnets
- particle beams with characteristics specific to the experiment being considered.

ASG also carry out installation, on-site commissioning of built magnets and systems and provides personnel training, offering its clients a complete service which ranges all the way from defining the specifications of the magnet to its operation and maintenance.

MAGNETS FOR HIGH ENERGY PHYSICS

Linear accelerators

- HERA Dipoles for Desy (D)
- LHC Dipoles for CERN (CH)
- SYS 300 for CERN (CH)
- D2–Model for INFN-CERN
- D2–Prototype for INFN-CERN
- Falcon–D for INFN-CERN
- GSI–Multipolar magnets for FAIR's project GSI (D)

MAGNETS FOR HIGH ENERGY PHYSICS

Main «Thin» solenoids / Detectors

ZEUS for Desy (D) [1987-1990]
BABAR for SLAC (USA)
FINUDA for INFN (I)
CMS for CERN (CH) (1999-2003)
MPD for JINR (USSR) (2016-2020)

MAGNETS FOR MEDICAL APPLICATIONS

Superconducting technologies and magnets are increasingly finding application in medical diagnostics and therapies. Capitalizing on skills and experiences derived from research and industrial collaborations, ASG is constantly improving its competences and is able to design and build the following types of magnets for medical diagnostics:

- Magnets for “whole body” MRI or dedicated systems
- Closed bore and open sky magnets
- “Zero-boil-off” or “cryogen-free” magnets
- Magnets based on LTS and HTS technology
- Actively and/or passively shielded magnets.

Furthermore, also for medical diagnostics, ASG designs and builds the following "whole body" superconducting magnet systems:

- Cryogen free - gantry mounted magnets able to rotate around an isocenter in order to deliver IMPT/IMRT.

In the medical therapy sector ASG designs and builds superconducting or resistive magnets for hadron therapy accelerators:

- High-medium-low energy beamline magnets for synchrotrons
- Superconducting, cryogen-free or helium cooled magnets, using either LTS or HTS technology for cyclotrons and synchro-cyclotrons
- Gantry mounted bending magnets for the delivery of particle beams.

We design and build magnets for MRI applications able to provide magnetic field intensities ranging from fractions of 1T up to Ultra High Field (UHF).

MAGNETS FOR MEDICAL APPLICATIONS

MRO 0,5T

In the framework of R&D activities aimed at demonstrating the feasibility of a “cryogenfree” magnet using a MgB2 conductor, produced by Columbus Superconductors, ASG has designed, manufactured and tested a 0.5 T cryogen free MRI scanner in open configuration (MROpen). For this project windings using magnesium diboride conductors (MgB2), operating at 20 K have been developed.

S2C2 SYNCHROCYCLOTRON FOR IBA

ASG has been involved for some years now in the design and construction of superconducting coils used in superconducting proton synchrocyclotrons for IBA. The coils used in this type of application are made up of cryogen-free niobium titanium windings. Particle therapy is used to treat many types of cancer, particularly in situations where normal treatments and radiotherapy are too risky for patients, including tumours of the central nervous system, eye, spine, prostate, liver, breasts and in childhood.

Ultra High Field MRI MAGNETS

Since its introduction in the 1980 magnetic resonance imaging has imposed itself as one of the main diagnostic techniques, as it is witnessed by the ever-growing number of installations of MRI machines per year since then. Low sensitivity of MRI imaging has always been a limitation to the number body regions that could be analysed by this technique, thus the necessity of developing technologies that could enhance the signal to noise ratio (SNR) of the MRI images. Ultra-high field MRI, i.e. the magnetic resonance imaging using magnetic fields of intensity equal to or higher than 7T is currently becoming the main method of obtaining high SNR images. ASG is designing and manufacturing magnet systems for UHF MRI in close collaboration with some of the most illustrious luminary sites for MRI related scientific research around the globe.

SYSTEMS FOR ENERGY

Efficiency and power quality will play a key role in the energy scenario in the near future and industry and utilities are increasingly interested in innovations that make use of superconducting technologies. Capitalizing on our knowledge we can design and realize magnets and systems for energy storage, transport and grid stabilization.

ASG magnets & systems unit is able to design and produce cryogen-free or liquid helium-cooled magnetic systems for Fault Current Limiters (FCL and SFCL) for the protection and stabilization of electrical grids. Our systems can use both superconducting (LTC, MgB_2, BSSCO) and standard technologies, depending on the specific needs of the grid or client.

We can also design coils and magnetic systems for Superconducting Magnetic Energy Storage (SMES) used to stabilize load fluctuations in electricity grids or to guarantee power quality in specific grid situations or in industrial applications.

Organization of the activities

Almost all the products realized by ASG have been realized under the Specifications of the Customer.
Only the medical system has been realized with an internal design, internal conductor and subsequent industrialization of the product.

The Specifications of the Customers can be of different types:

- **Ready to built (very rare)**
- **To industrialize a Customer project/design (more common)**
- **To make an internal project and carry out the construction respecting the Customer overall requirements (mostly)**

Organization of the activities – Organization of the factory

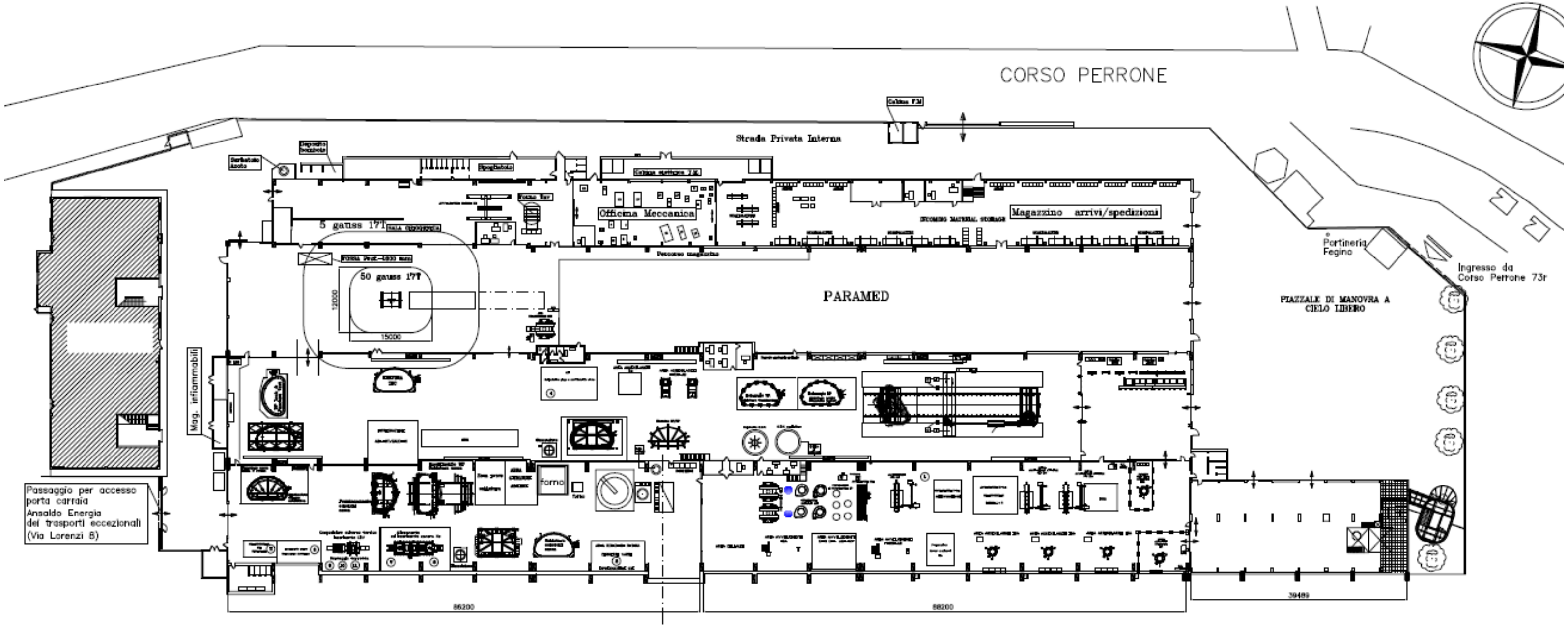
- For Prototypes realization it is necessary to (re)-organize the factory layout according to the prescription of the Customer temporary (one-two years).

- For Series Production it is necessary to organize the factory according to the prescription of the Customer for a medium-long period (two-ten years).

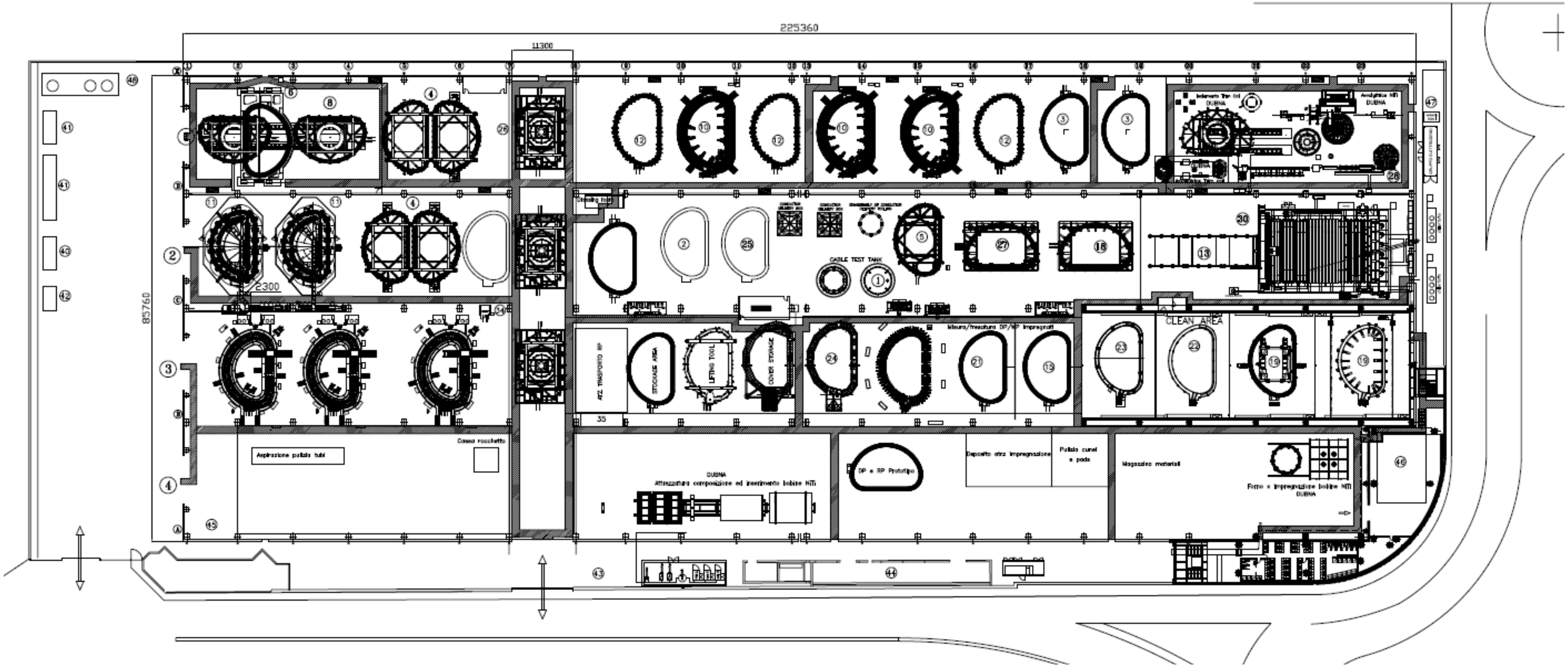
- Realize the tooling design with our subsupplier(s) as winding lines, insulation devices, welding devices, VPI Plants.

- The factory services like gas supply (Nitrogen, Argon, He), water, cryoplant(s), LN2 and LHe dewars, electric power, cranes shall be sligthly modified according to the principle that is necessary to reduce the movement of the details to be built.

The factories of the Magnet Business Unit – GENOA - Corso Perrone, 73r — 12.000 m^2



The factories of the Magnet Business Unit – LA SPEZIA, Via Melara, 40 - -> 24.000 m^2



Why realize superconducting magnets ?

The construction of very large and powerful magnets is possible in practice only using the superconductivity.

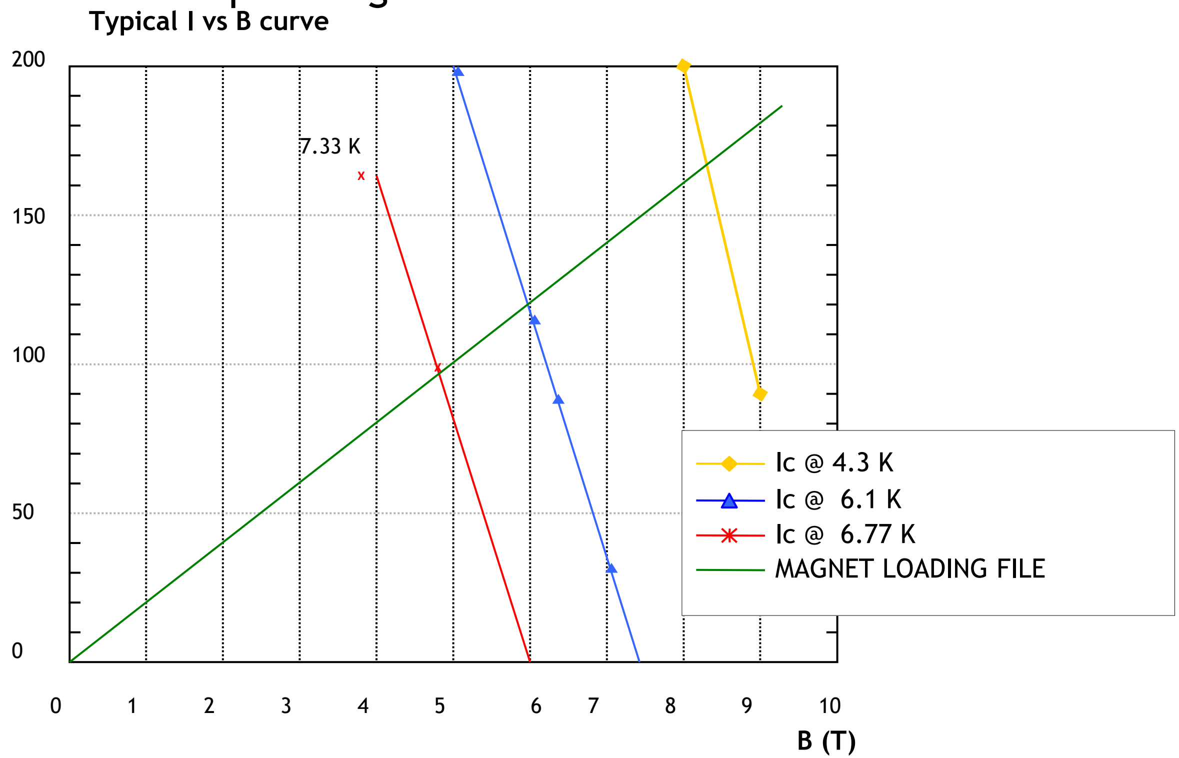
The conventional magnets are made normally with copper/aluminium cable cooled by water ($J_{overall}$ ~ 5 A/mm^2)

The superconductive magnet can be made using different techniques [$J_{overall}$ ~ 500 A/mm^2 function of (T, B, I)]

$J_{overall}$ 100 times higher !!

Example of resistive dipole built by Ansaldo in the '90.

RISK LEVEL - Distance from the operating current to the Ic



The "safety" margin to be used in magnet design is NOT regulated by law or by a Rule/Norm (as for the pressure vessel, for structures and so on).

METHOD TO DETERMINE THE RIGHT MARGIN IN THE DESIGN

Experimental.

By calculation.

By previous experiences with similar magnets.

MARGIN EVALUATED BY EXPERIMENTAL METHOD

It can be used only if the number of magnet to be built is big enough = SERIES PRODUCTION.

Many equal prototypes have to be built and tested.

A Gaussian distribution of the reached quench values is determined:

the larger possible value for the nominal current is fixed to minimize the rejected pieces.

This choice is mainly used for MRI, bending and focalizing magnets for accelerators

MARGIN EVALUATED BY CALCULATION

STABILITY vs. **DISTURBANCE**

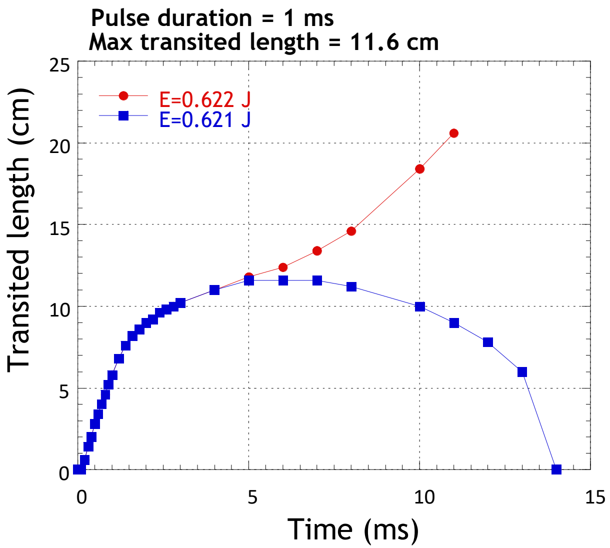
Stability is related to design.
It is possible to increase it by a proper choice of conductor, cooling mode, etc.

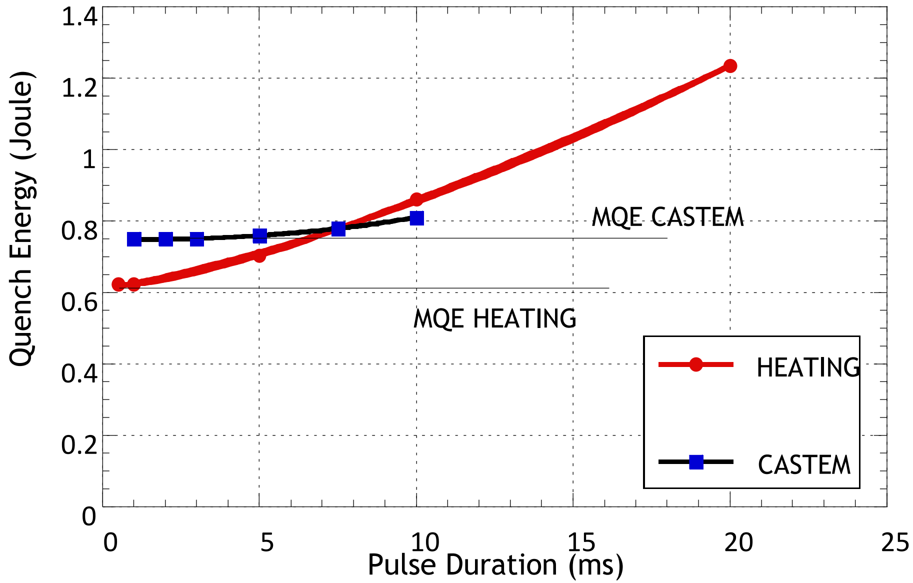
Disturbance is related to design but also to the fabrication techniques and good construction

Disturbances are very difficult to be evaluated by calculation.

TRANSIENT ANALYSIS - LOCALIZED DISTURBANCES (Example for CMS solenoid)

Study of Minimum Propagating Zone and Minimum Quench Energy, performed at CEA (using CASTEM Code) and at INFN (using HEATING Code), for disturbances inside the conductor found MQE=[0.6-0.8 J] and MPZ= 10-15 cm





MQE for different location of disturbance

Disturbance inside conductor	0.6-0.8 J
Crack in the resin at the interface insulation/conductor	3.5 J
Inter-layer resin crack	8.3 J

Evaluation of DISTURBANCES - Examples for CMS Compact Muon Solenoid

Strand movement: In a Rutherford cable inside pure aluminum, we can observe the existence of voids. Under the action of the axial force, half of the Rutherford may move against the other half. The energy dissipation for unit length is 0.56 J/m (0.08 J on MPZ)

Complete cracks (event very pessimistic) in the fiber-glass epoxy insulation:

E~ 2000 J/m^3 corresponding to 17 J/m (25 J on MPZ).

MARGIN EVALUATED BY PREVIOUS EXPERIENCES

For medium size vacuum impregnated magnets **bath cooled**, a temperature margin of 1K is considered good enough…. But it is not a law, just only an assumption !

For **indirect cooled** thin solenoids a nominal current of 50% of the critical one is quite normal.

For large magnets we can expect disturbance of 100 mJ/cm^3.

FOR LARGE MAGNETS IT IS NOT POSSIBLE TO USE THE EXPERIMENTAL METHOD

It is not possible to build several prototypes.

The feasibility has to be decided by the design and by the test of the fabrication techniques on **scaled samples -> R&D activity is so mandatory on samples !!!**

RESULT: *conservative choices*

DIFFERENT COOLING METHODS

- **Bath cooled cryogenically stabilized magnets.**
- **Indirect cooled**
- **Internally cooled (Cable in conduit named CICC).**

FABBRICATION TECHNOLOGIES TO DECREASE THE MECHANICAL MOVEMENTS AND RESIN CRACKS

Reinforce directly the conductors by adding structural material as:

- *Coestrusion,*
- *Welding stiffening bars*
- *Cabled around bar/pipes*

Use an external structure to withstand the Lorentz force as:

- *External cylinders,*
- *bolted structures*
- *tie-rods*
- *Collars*

Shrink fitting technique by heating the external structure or cooling the magnet

Very conservative:
BATH COOLED CRYOGENICALLY STABILIZED MAGNETS

BARE CABLE IN HELIUM BATH

Built in the ’70 with overall current density of 10-20 A/mm^2 (BNL Coil , BEBC)

In the ’80 reach $J_{overall}$ = 40-50 A/mm^2 (Tore Supra, CDIF MHD, GD LCT)

In the end of ’80 and ’90 long dipoles for accelerators are an evolution of these coils $J_{overall}$ = = 350 A/mm^2 (Hera Dipoles)

S/C Magnet assembly main phases:

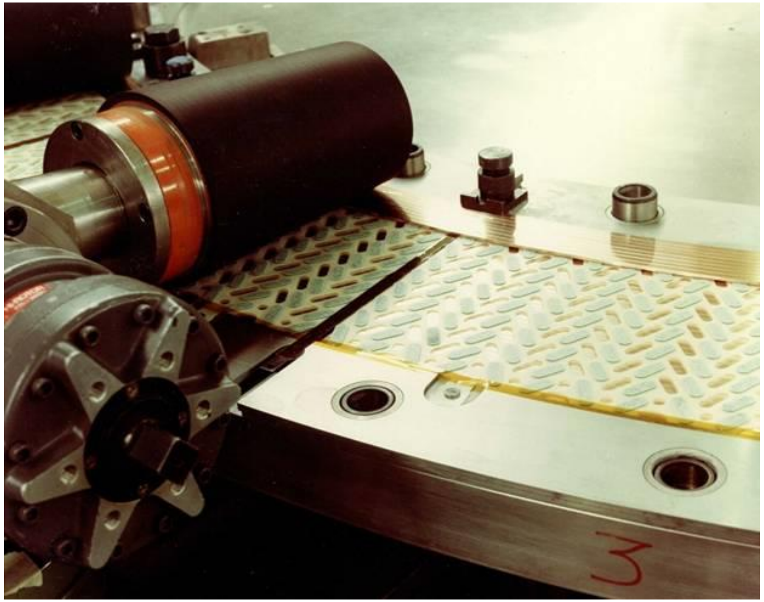
- Winding with turn insulation application
- Reaction heat treatment (for Nb_3Sn conductors)
- Ground insulation application
- VPI process
- Resin excess removal
- Assembly into the structure (shrink fitting, tie-rods assembly)
- Instrumentation Assembly
- Insertion into the cryostat (if forecast)
- Connection to current leads/instrumentation
- Test at Room Temperature (geometrical, electrical, leak)

Test at 4K

- Cooldown at 4K (cooling speed ~ 1 K/h) -> this parameter is influenced by the mass and by the max allowed gradient within the magnet (order 10K)
- Energization at partial/full current
- Testing @4K (Turn insulation, ground insulation, tan δ, Impulse test, armonics, etc.)
- Field mapping
- Warming-up to RT

TORE SUPRA (Tokamak 1986)

B_{nom} = 9T
Circular double pancake 2.3-2.8 m of diameter
I_{nom} = 1400 A



COOLING

Bare conductor superfluid He bath cooled

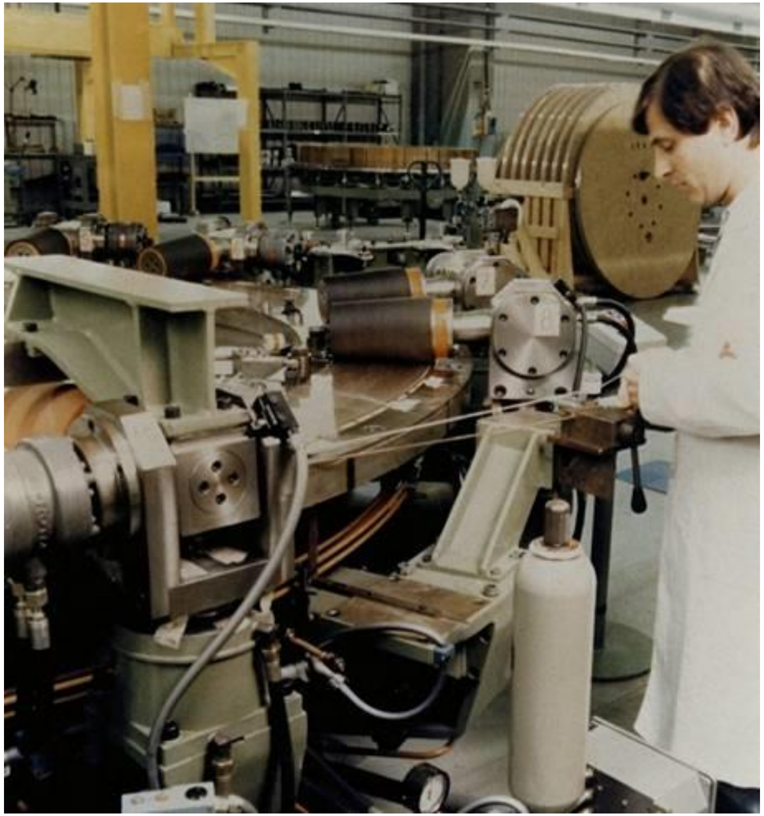
Prepreg tape and pellets

FORCE CONTAINMENT

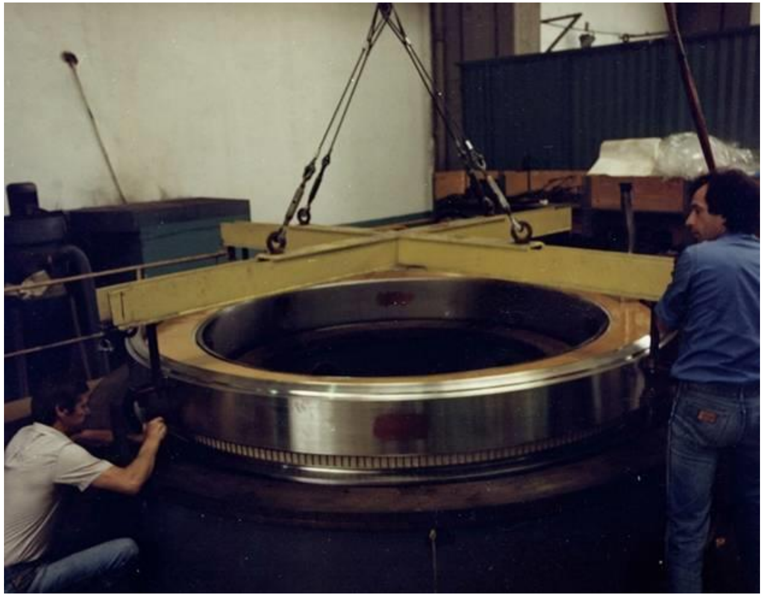
Internal and External ring (shrink fitted)

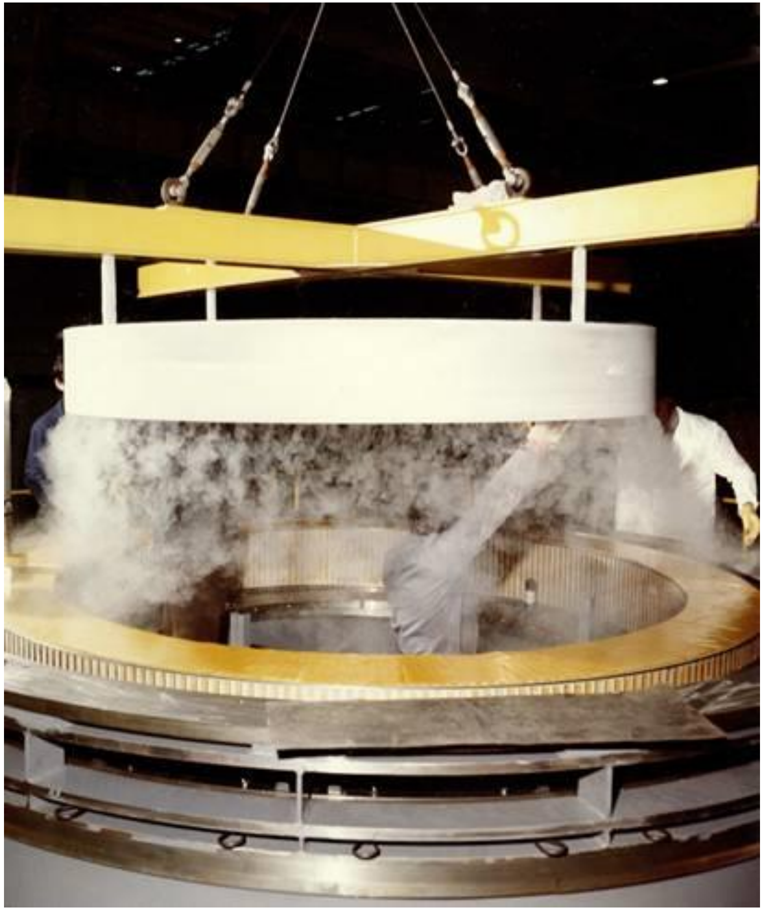
Lateral flanges welded under axial pressure

TORE SUPRA (Tokamak 1986)



TORE SUPRA (Tokamak 1986)





TORE SUPRA (Tokamak 1986)

BENDING DIPOLES, QUADRUPOLES ecc. (Tevatron, HERA, LHC etc.)

COOLING

He-bath cooled (SUPERCRITICAL/SUPERFLUID)

Adesive Kapton or Prepreg tape with voids

FORCE CONTAINMENT

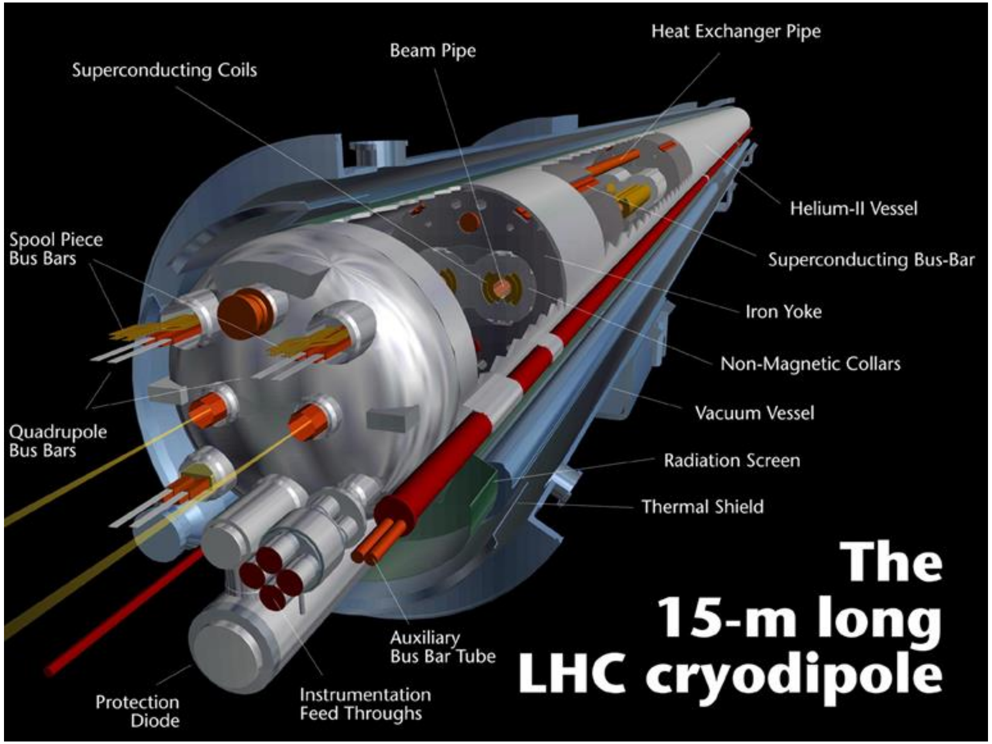
Prestressed by Collars and/or welding and/or shrink fitting

LHC - Dipoles Cold masses [1998-2007]

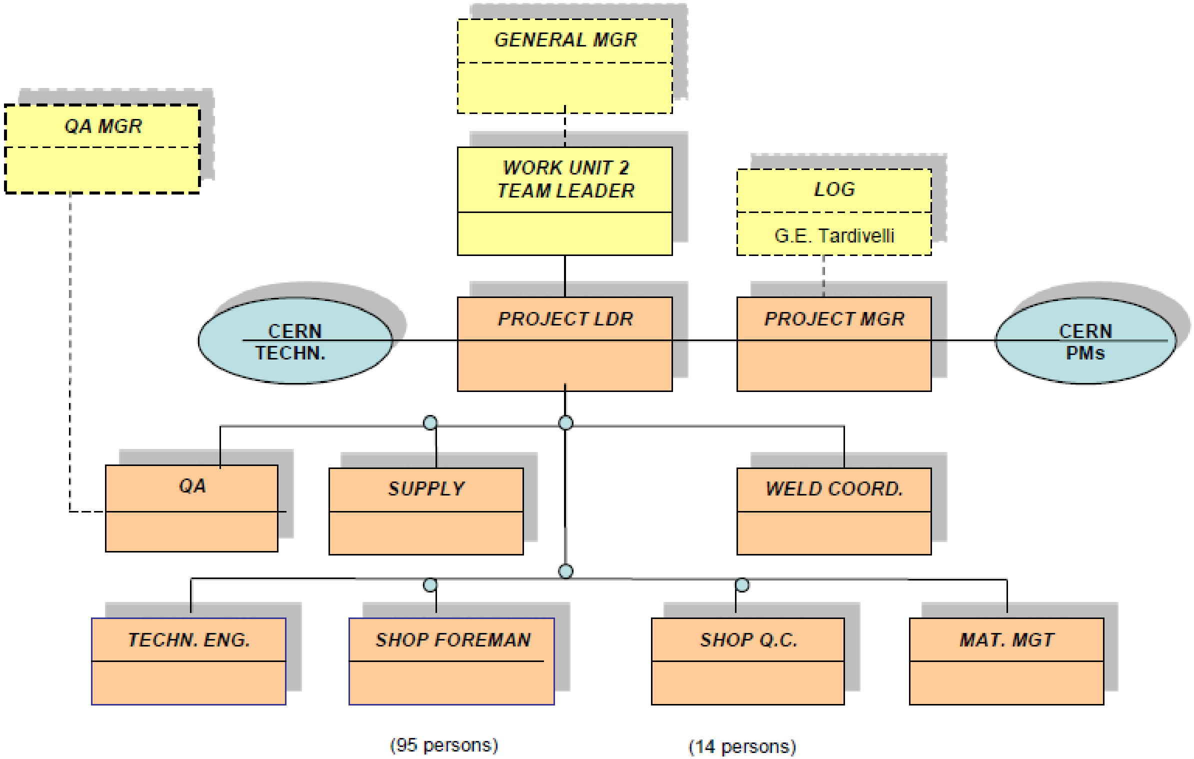
- N° 416 + 30 Spare Dipoles
- Production rate: 4 magnets/week
- Beginning: Jan 2001
- End: Sept 2006

TOTAL: 446 Dipoles of 15 m length each.
Each dipole contains 8 coils -> about 3600 coils 15 meters long

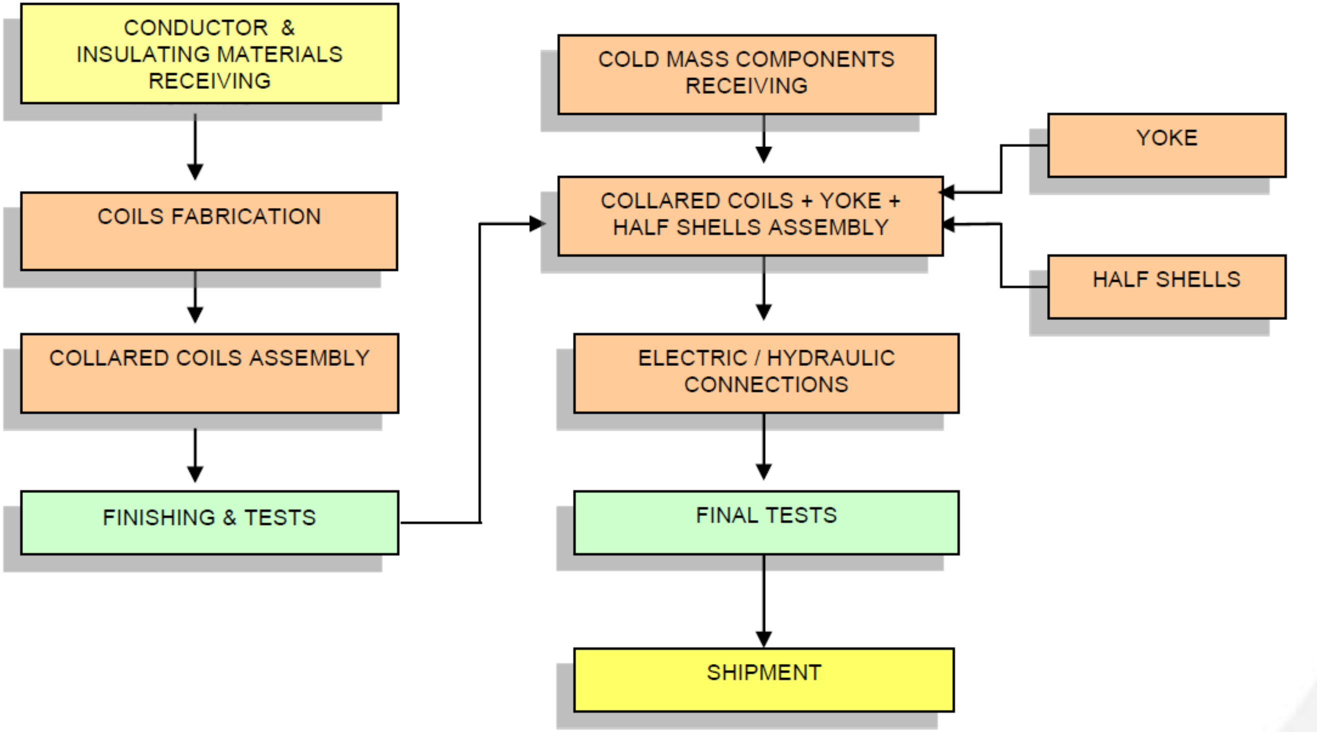
For this huge series production it has been necessary to organize the workshop and the foremen accordingly



LHC - Dipoles [1998-2007] - Organization Board



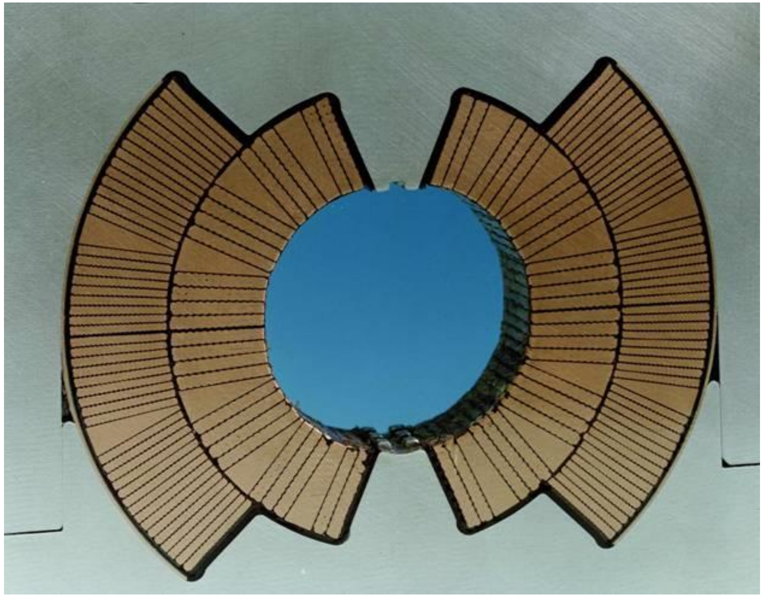
LHC - Dipoles [1998-2007] - Quality System Documents



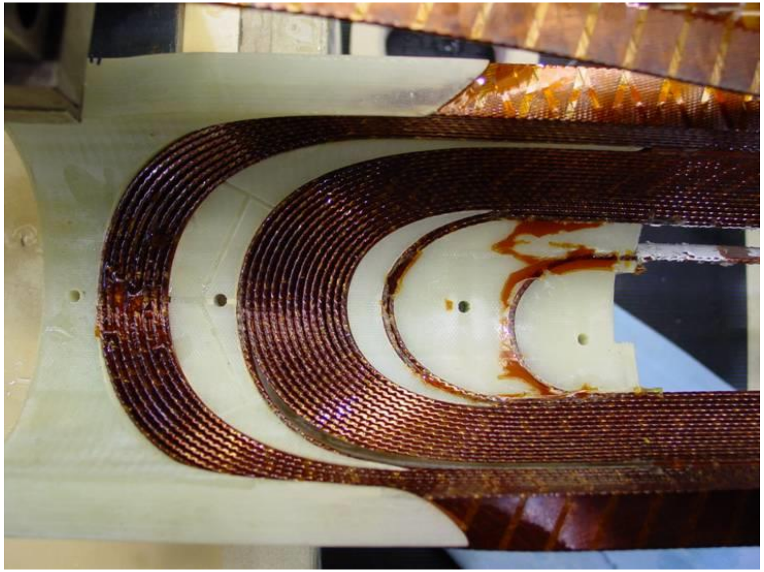
LHC - Dipoles [1998-2007] - Manufacturing Process Flow Charts

	Documents	*Issued by*
1	**Quality Assurance Plan**	**QA**
2	**Inspection & Test Plan** *(according to CERN doc. nr. xx)*	**QA**
3	**Manufacturing Procedures**	**ENG**
4	**Test Procedures**	**QA**
5	**Test Records**	**QC**
6	**Manufacturing & Test Plan**	**QA**
7	**Welding Book**	**ENG**
8	**Nonconformity Reports**	**QA**

LHC - Dipoles [1998-2007]



Cross section of one aperture

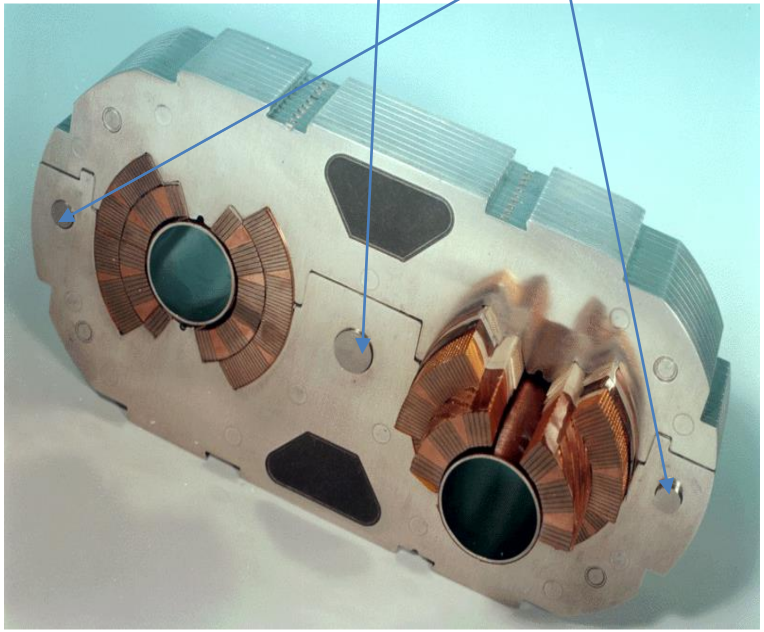


Detail of the LOC side end

LHC - Dipoles [1998-2007]

Rods Ø 22mmm Ø 14mm

Collaring press



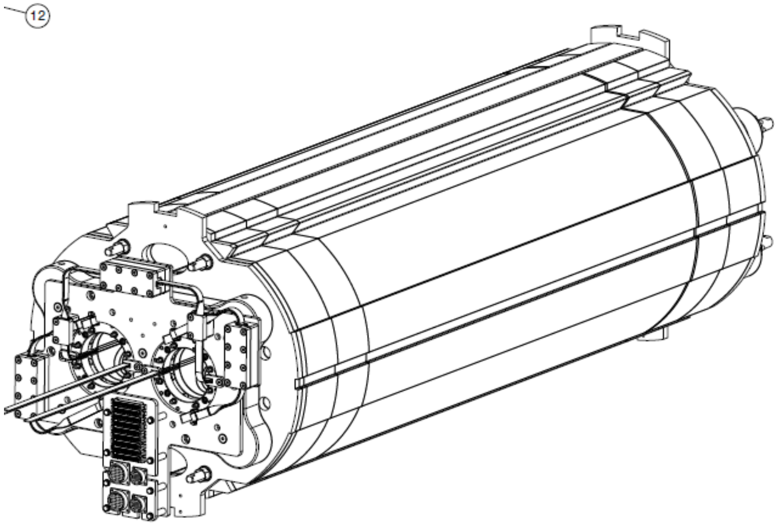
Maximum collaring force: 2 400 tons/meter (36 000 tons for 15 meters overall length)

LHC - Dipoles [1998-2007]

Collaring completed

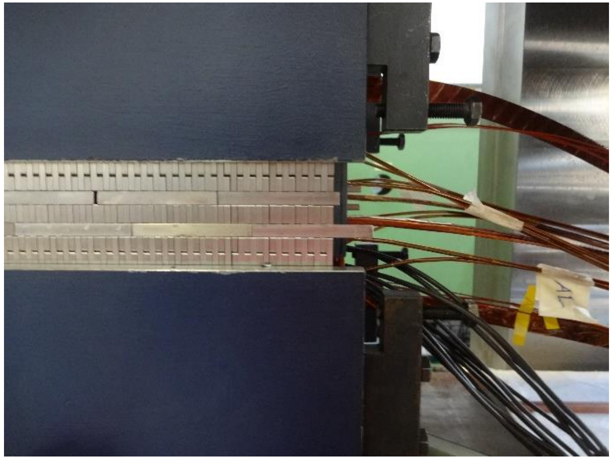
Welding of the outer structure around the iron yoke

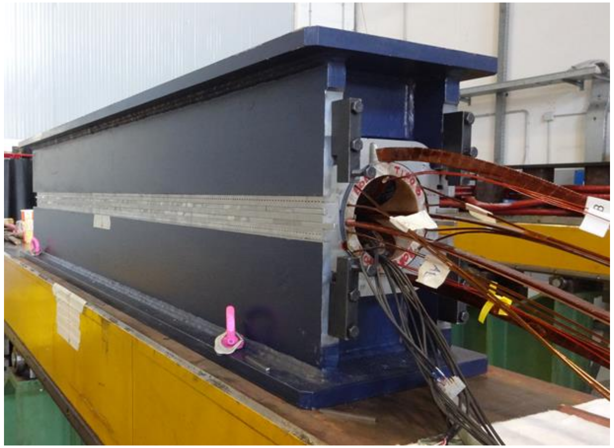
D2 - Model - INFN (2017-2020)



D2 - Model - INFN (2017-2020)

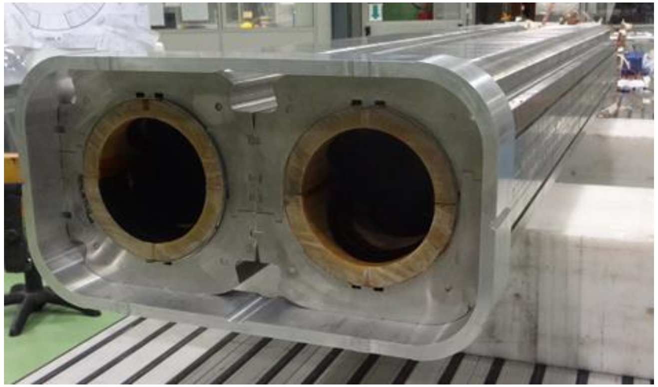
- Collaring operation

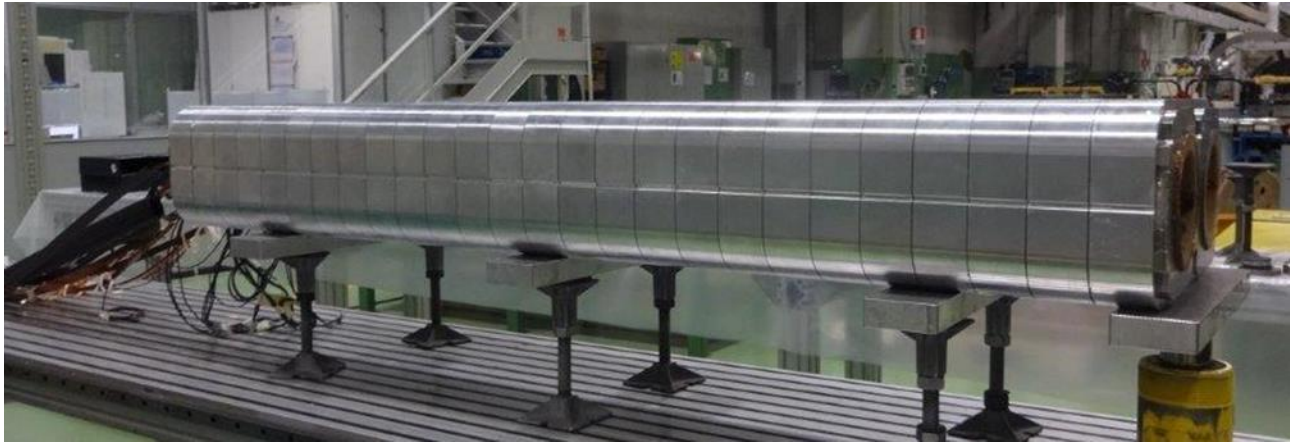




D2 - Model - INFN (2017-2020)

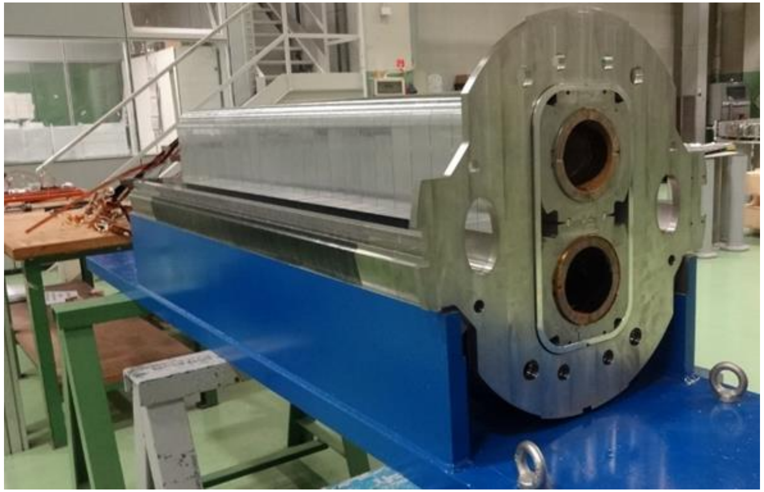
Aluminum sleeves introduction

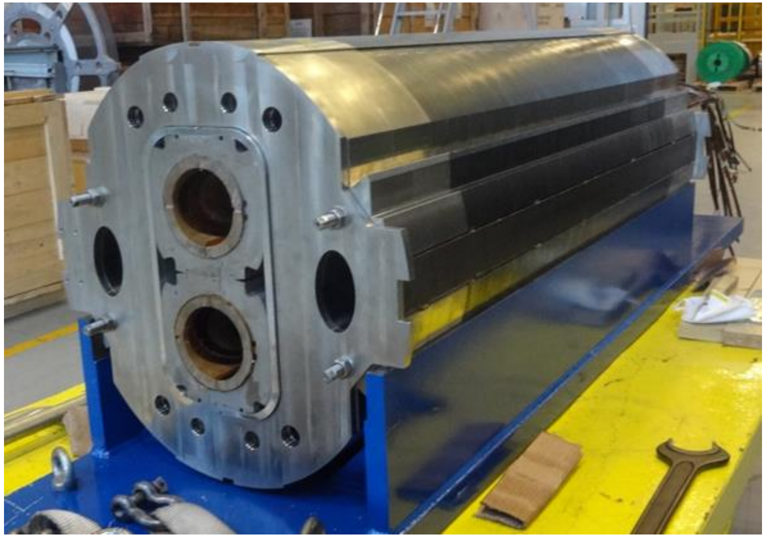




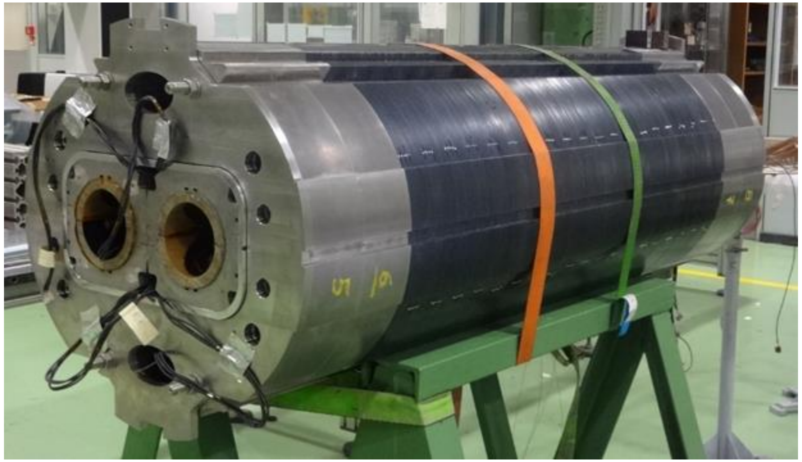
D2 - Model - INFN (2017-2020)

Integration inside the iron yoke



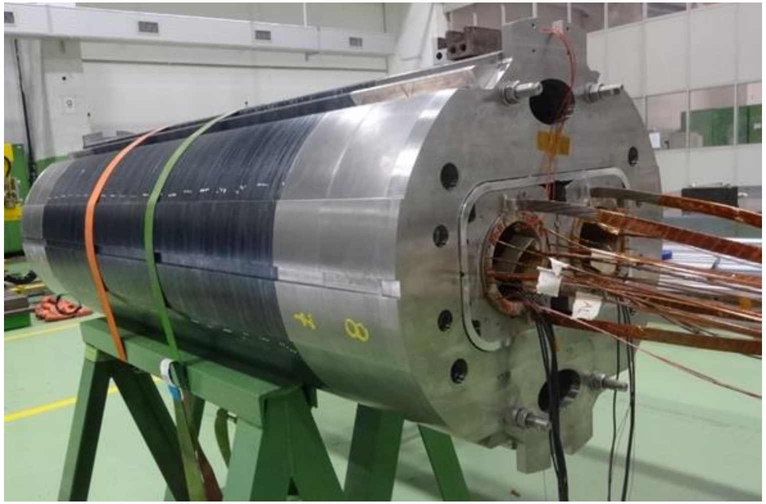


D2 - Model - INFN (2017-2020)

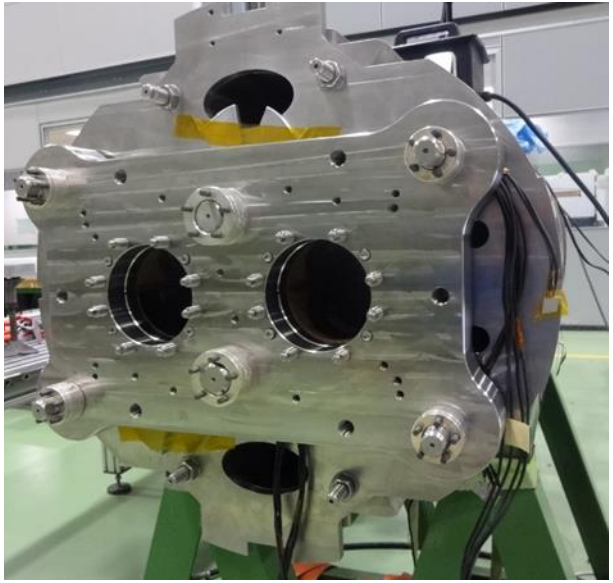


View from LOC Side

View from LC Side

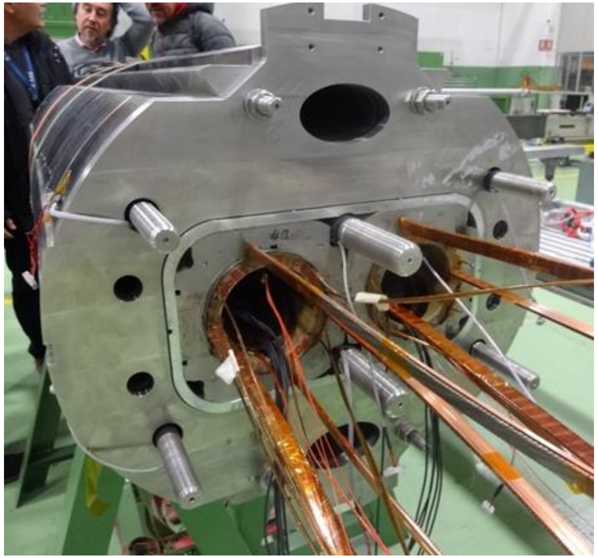


D2 - Model - INFN (2017-2020)



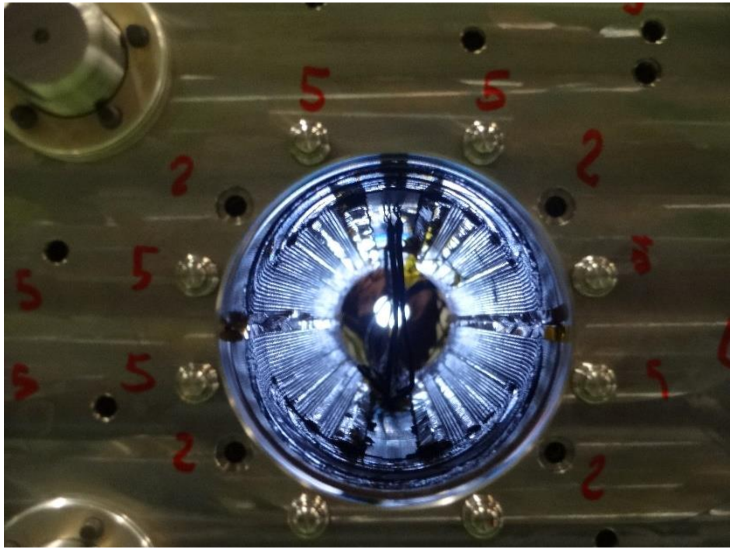
View from LOC Side

View from LC Side



D2 - Model - INFN (2017-2020)

Transport to CERN



D2 - Prototype - INFN(2019-in progress)

The Large Hadron Collider (LHC) is the most recent and powerful accelerator constructed on the CERN site. The LHC machine accelerates and collides proton beams but also heavier ions up to lead. It is installed in a 27 km circumference tunnel, about 100m underground.

The LHC design is based on superconductive twin-aperture magnets which operate in a superfluid helium bath at 1.9K (-271°C).

The High Luminosity LHC (HL-LHC) is a project aiming to upgrade the LHC collider after 2026 in order to maintain scientific progress and exploit its full capacity.

By increasing its peak luminosity by a factor five over nominal value, it will be able to reach a higher level of integrated luminosity, nearly ten times the initial LHC design target. To this aim, HL-LHC is exploring new beam configurations and new advanced technologies in the domain of superconductivity, cryogenics, radiation hard materials, electronics and remote handling.

The HiLumi LHC study concerns new high and medium field superconducting magnets, superconducting radio frequency crab cavities, new collimation concepts and powerful superconducting links.

The project also requires a new technical structure with a cavern and a 300m long tunnel along the insertion region of IP1 (ATLAS) and IP5 (CMS).

In the frame of the first Contract, ASG realized the D2 Model during the 2019 that now is under testing at 1,9K at CERN Lab.

After that, ASG was awarded the Contract for the realization of the D2 Prototype too.

At present (September 2020) N.2 coils (Practice Coil and the first for the dummy aperture) have been realized.

The activity is preparatory for the realization of N.6 series cold masses of which ASG was awarded too.

D2 - Prototype - INFN(2019-in progress)

The Superconducting Magnet

In HL-LHC an important role is played by the dipoles recombining and separating the particle of the two proton beams around the interaction regions. This section is composed of two dipoles D and D2, which bend the particles of the two beams in opposite directions. In particular D2 is a twin aperture magnet (105mm each one) with a separation between apertures at 1,9K of 188mm, generating in both apertures an integrated magnetic dipolar field of 35 Tm with the same polarity.

The cross-section of the dipole is shown here below, which contains all the components cooled by superfluid helium. The magnet consists of a so-called *active part,* made of two coils with 105 mm diameter aperture in a mechanical structure (made of collars plus an Aluminium sleeve) and a magnetic structure (made of magnetic steel).

The dipole cold mass has a quasi-elliptic shape with an overall length of 8155mm (ancillaries included), a maximum diameter of 624m (at room temperature) and a mass of about 14 tons.

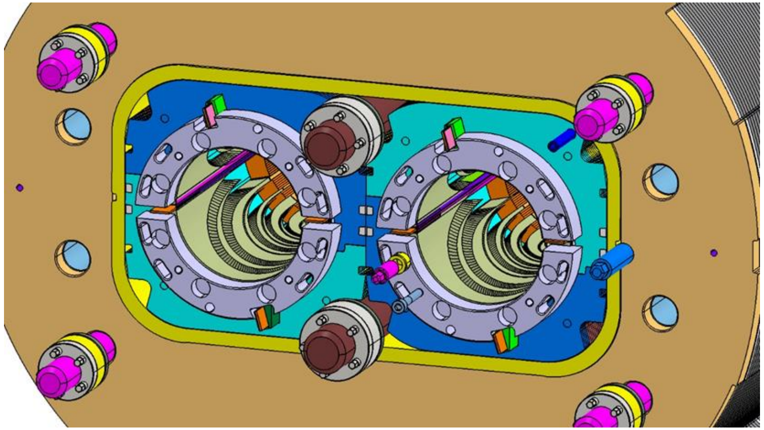
D2 - Prototype - INFN(2019-in progress)

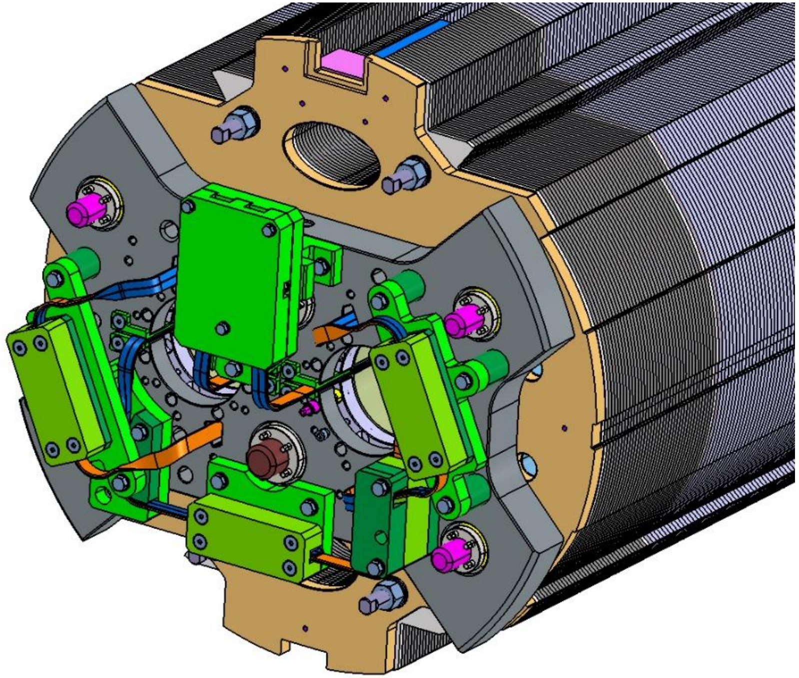
The Superconducting Magnet

Main parameters	Unit	Value
Aperture diameter	mm	105
Number of apertures per magnet	N	2
Distance between the two apertures (cold/warm)	mm	188,0/188,7
Cold mass outer diameter (min/max of iron yoke)	mm	550/614
Magnetic length	mm	7778
Bore Field	T	4,5
Peak Field	T	5,2
Operating Current	kA	12,340
Operating Temperature	K	1,9
Overall current density	A/mm^2	478
Stored Energy	MJ	220
Superconductor	-	NbTi Rutherford
Strand diameter	mm	0,825
Number of strand per cable	N	36
Coil Turns	N	31
Coil Length	mm	8010
Cold-mass weight	Tons	14

D2 - Prototype - INFN(2019-in progress)

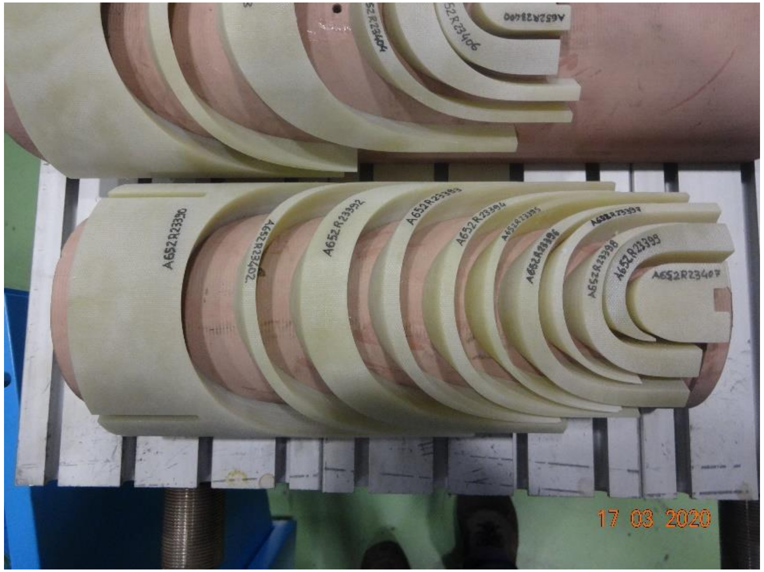
The Superconducting Magnet

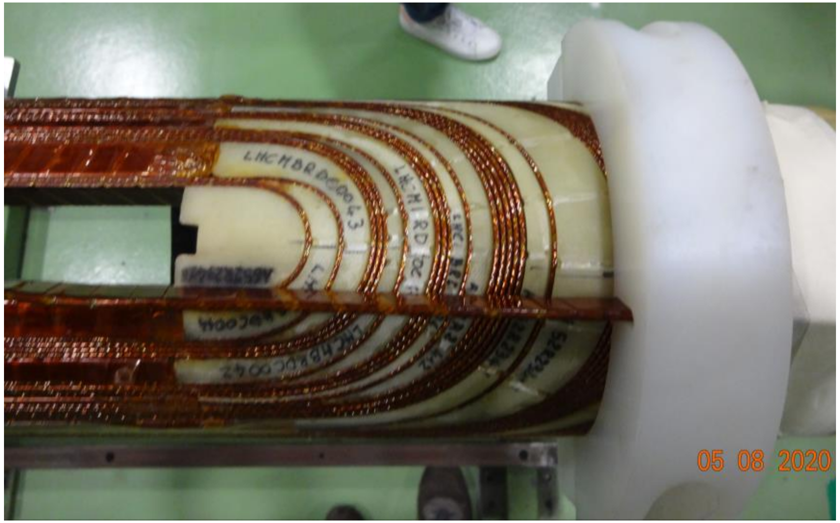




D2 - Prototype - INFN(2019-in progress)

G10 - Head fillers





IMPREGNATED BATH COOLED MAGNETS

Poor cryogenic stabilization but good mechanical performance.

Possible training due to resin crack.

Initially they were used only for static magnets with low stored energy, today also more large systems were made using this technique.

Collaring completed

Welding of the outer structure around the iron yoke

AGOR CYCLOTRON (1991)

B_{nom} 4.7 T
2+2 solenoids 2.1-2.6 m of diameter
900+1800 A on NbTi conductor

COOLING

Impregnated coils , He bath cooled

Glass tape+vacuum impregnation

FORCE CONTAINMENT

Radial prestress by shirk fitted rings

Axial pressure by springs + welding under pressure

AGOR CYCLOTRON (1991)

INDIRECT COOLED -> INTRINSICALLY STABLE

The thin solenoid and now the “cryogenic free” magnets are cooled only by thermal conduction from an outer cooling circuit not in direct contact with the coils

In the ’70: Levitron 1970 and muon channel 1974

In the ’80: CDF, VENUS, ALEPH, DELPHI, ZEUS(*), H1

In the ’90: D0, Babar(*),Finuda(*), BELL, CLOE

Around ‘2000: Atlas(*), CMS(*)

In 2020: FermiLab Transport Solenoids (*), MPD (*)

(*) realized by ASG

INDIRECT COOLED -> INTRINSICALLY STABLE

ZEUS (Desy 1989) 1.8 T
Solenoid diameter = 1.85 m x l=2.5 m Inom = 4987 A on Aluminium coextruded NbTi Rutherford

COOLING

Indirect cooled by bi-phase Helium

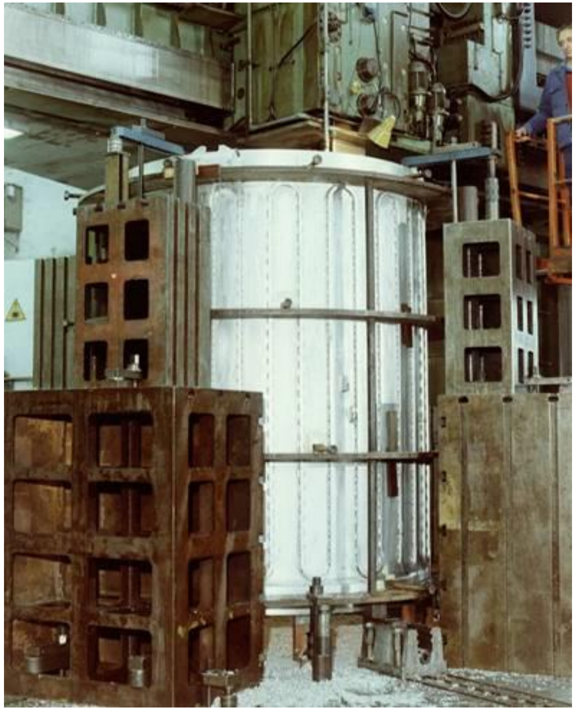
E-Glass taping + Vacuum impregnation

MECHANICAL STRUCTURE

Lorentz Forces supported by an external Aluminium 5083 cylinder

Winding on mandrel and the Coil shrink fitted inside the external cylinder

ZEUS (Desy 1989) 1.8 T



Outer cylinder during turning operation

Coil integration -> After the shrink fitting

ZEUS (Desy 1989) B_{nom} 1.8 T

The coil and its outer cylinder before the shrink fitting operation

Completed !

BABAR (SLAC-USA - 1996)

1.5 T Solenoid diameter = 1.85 m x l=2.5 m; Inom 4987 A on Aluminium coextruded NbTi Rutherford

COOLING

Indirect cooled by bi-phase Helium

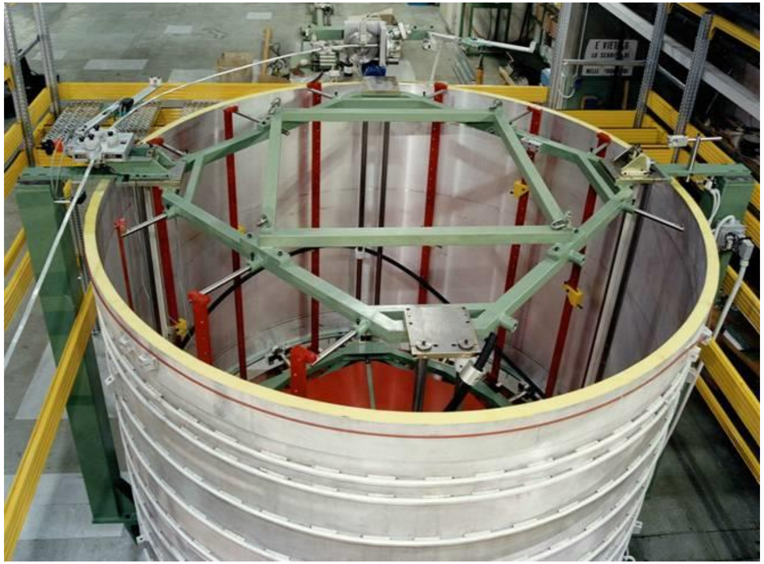
E - Glass taping + Vacuum impregnation

FORCE CONTAINMENT

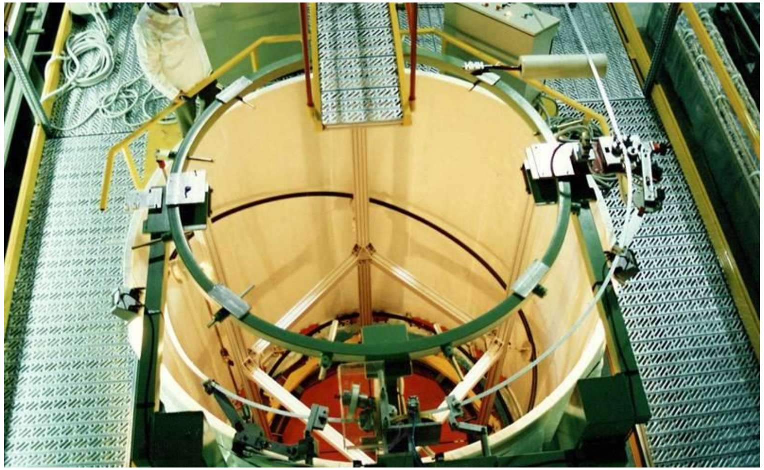
Forces supported by external Aluminium 5083 cylinder

INNER winding and Impregnation under axial prestress

BABAR (SLAC - 1996) - The winding activity at ASG premises

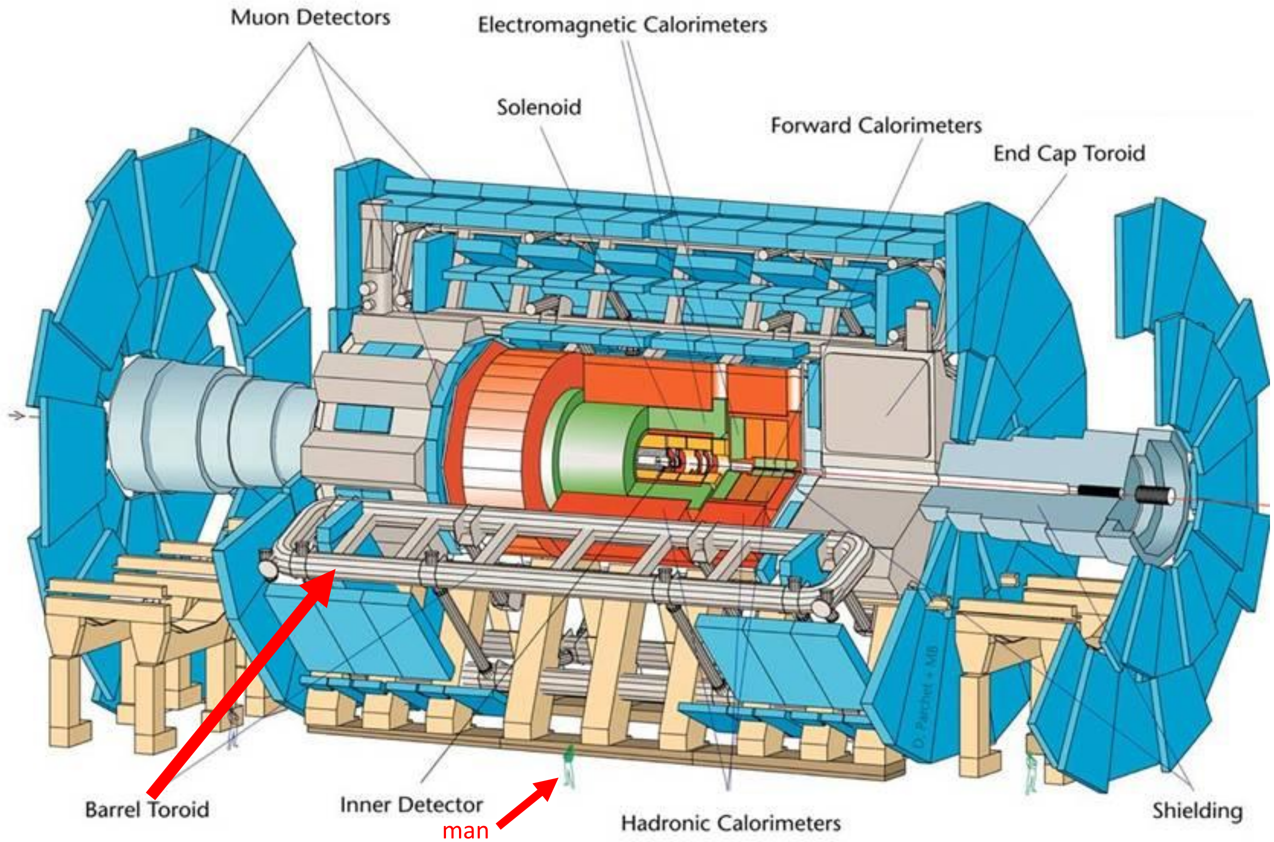


BABAR (SLAC - 1996)



BABAR (SLAC - 1996) - loaded into a Galaxy of USAF at Genoa Airport

ATLAS-CERN 2003



ATLAS-CERN 2003

B_{nom} =2 T
I_{nom} 20.5 KA in an Aluminium coextruded NbTi Rutherford

N. 1 B0 racetrack 8 x 5 m
N. 16 BT racetracks 25 x 5 m

COOLING

Double pancake indirect cooled by Helium

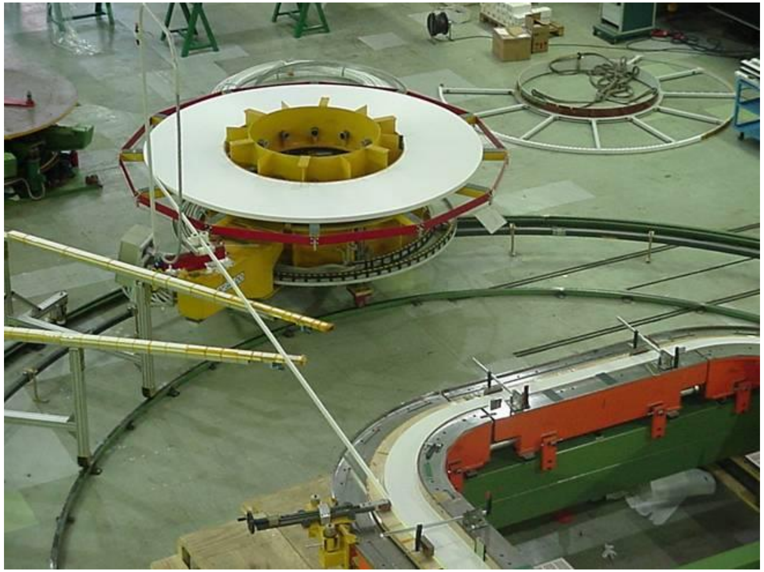
E-Glass taping + Vacuum impregnation under pressure

FORCE CONTAINMENT

Forces supported by an external Aluminium 5083 case

The windings are prestressed by epoxy pressurized bladders and tie-rods

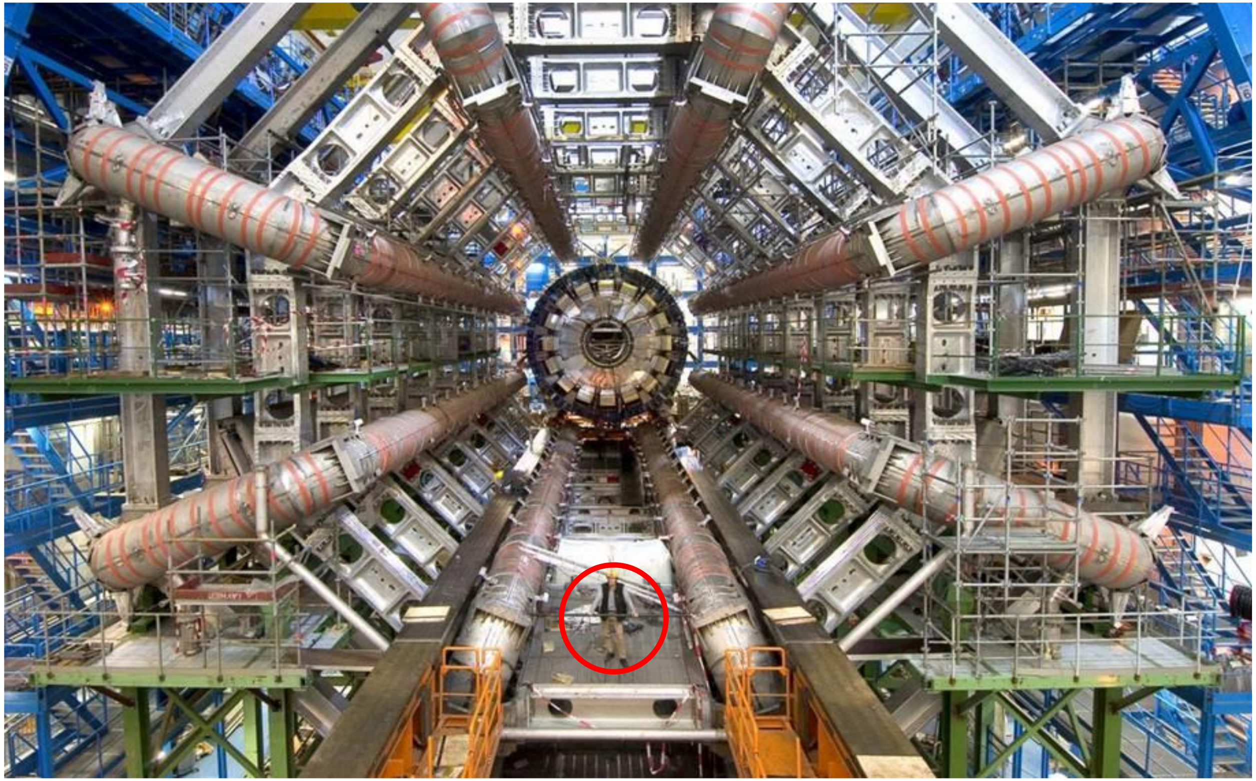
ATLAS-CERN 2003 - Winding at ASG premises



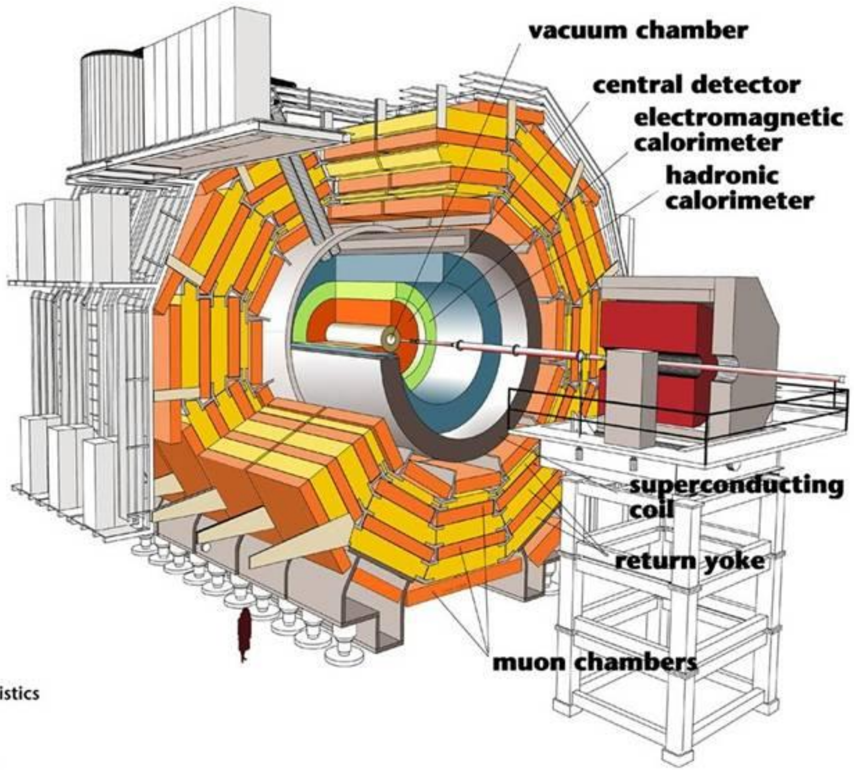
ATLAS-CERN 2003

ATLAS-CERN 2003
Transported to CERN by truck

ATLAS-CERN 2003 - In the pit at CERN



CMS - INFN/CERN 2004



Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

CMS - INFN/CERN 2004

B_{nom} 4T

Solenoid in 5 modules Outer diameter = 7 m Cold mass overall length L = 5 x 2.5 =12.5 m

4 layers coil of cable made of pure aluminium coextruded + NbTi Rutherford + structural aluminium alloy

COOLING

Indirect cooled by bi-phase Helium

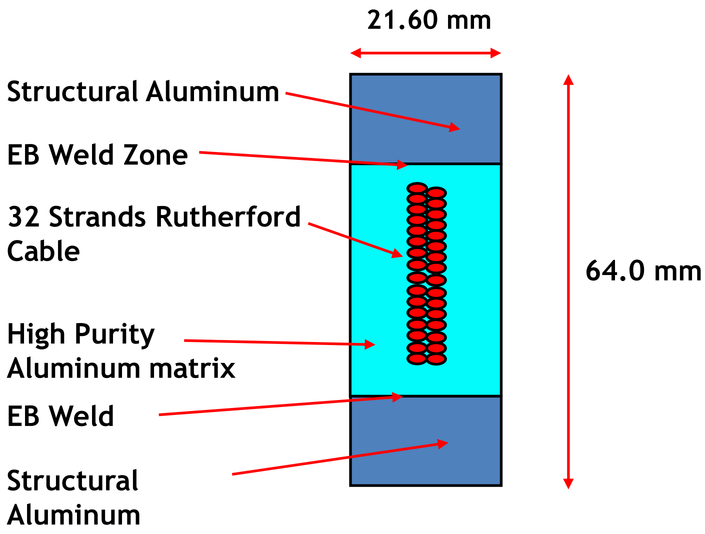
E-Glass taping + Vacuum impregnation

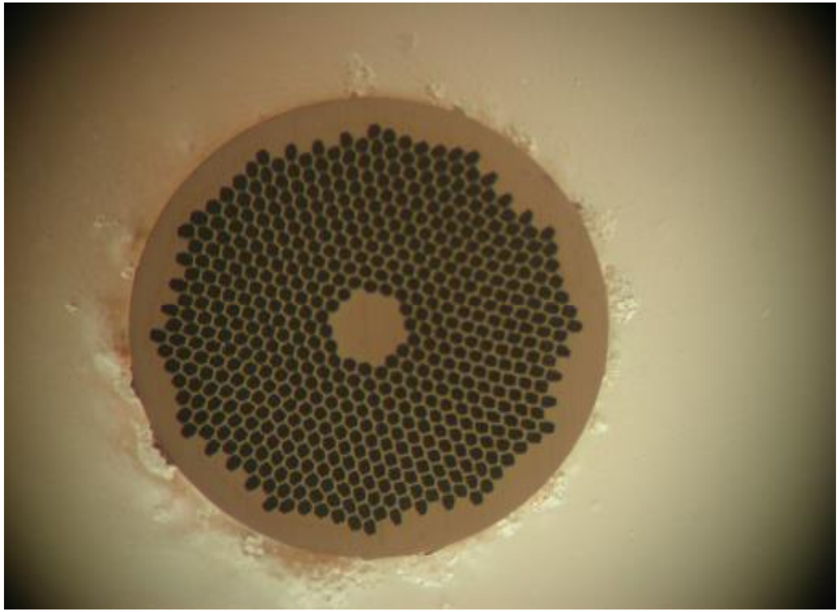
FORCE CONTAINMENT

INNER Winding with tangential force + axial compression during impregnation

Forces supported by the cable itself + external Aluminium 5083 H321 cylinder

CMS - INFN/CERN 2004 - The Conductor





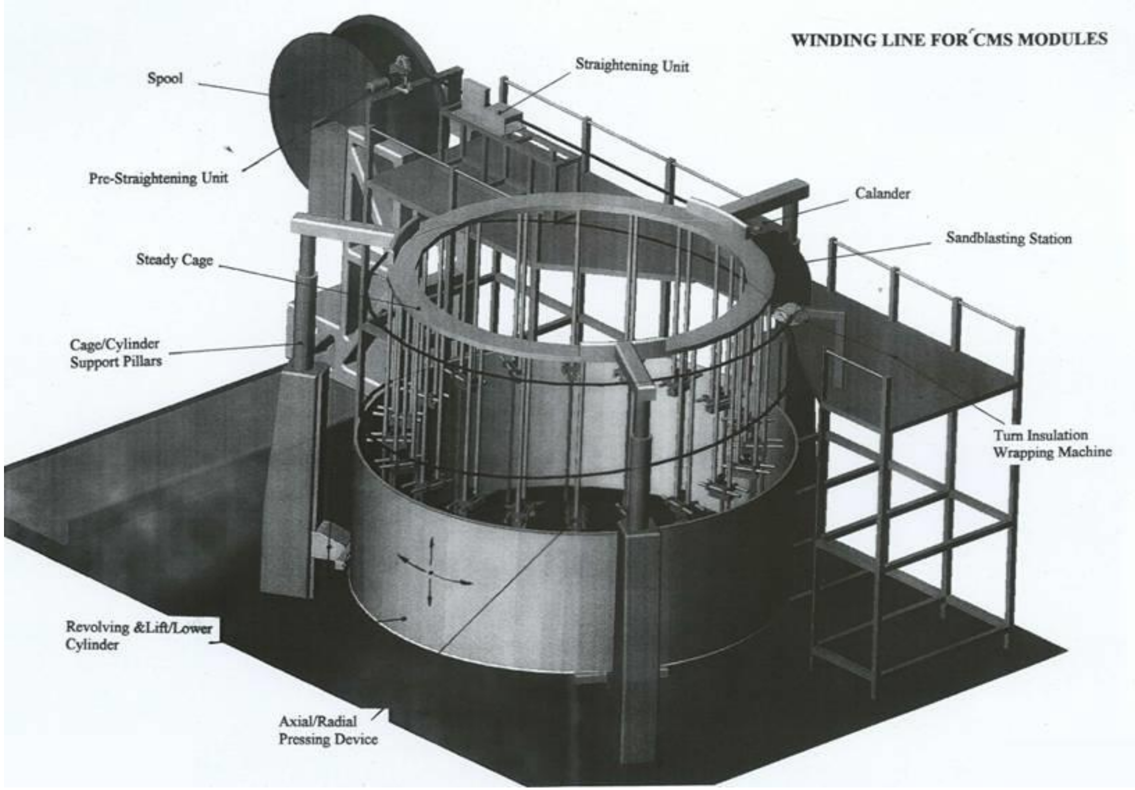
Conductor Ic = 55.6 kA @ 4.2K, 5T

1.28 mm Dia Strand, Cu:SC Ratio = 1:1

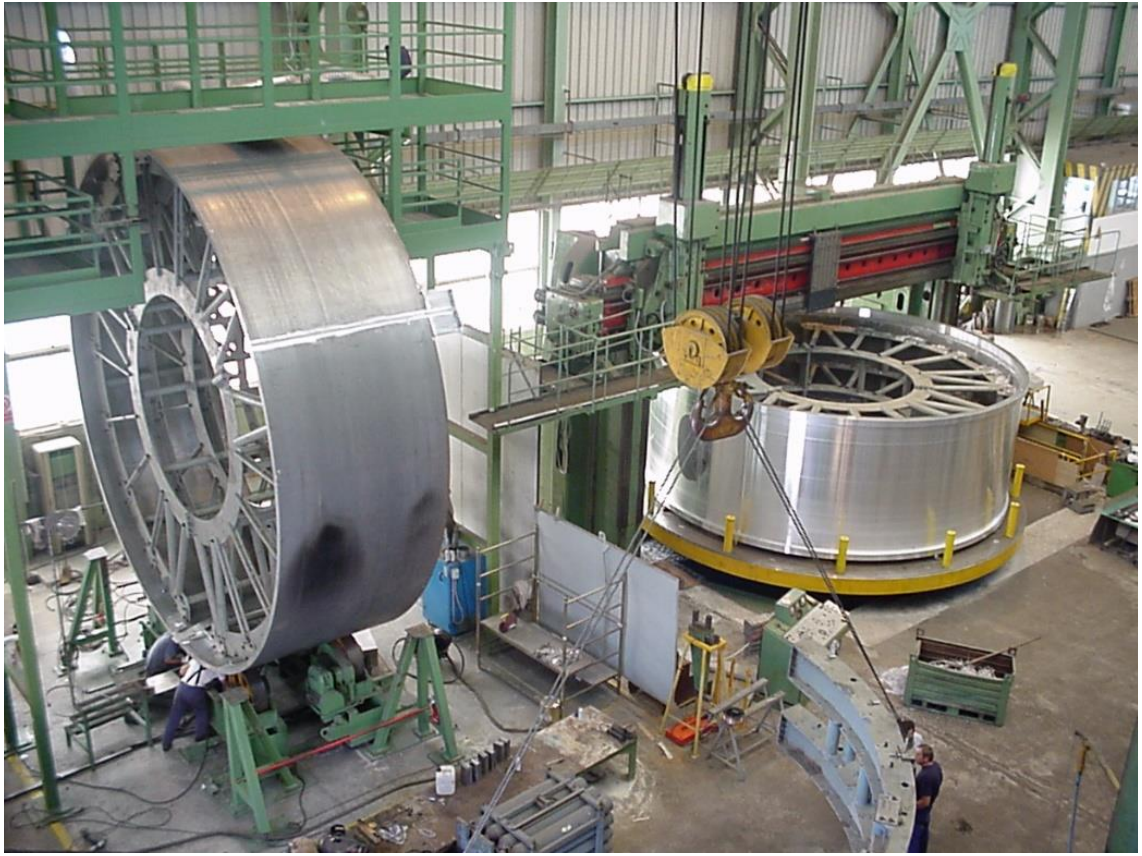
CMS - INFN/CERN 2004 Impregnation Test (throughout R&D activity)

CMS - INFN/CERN 2004 - Model Coil (Traditional winding System)

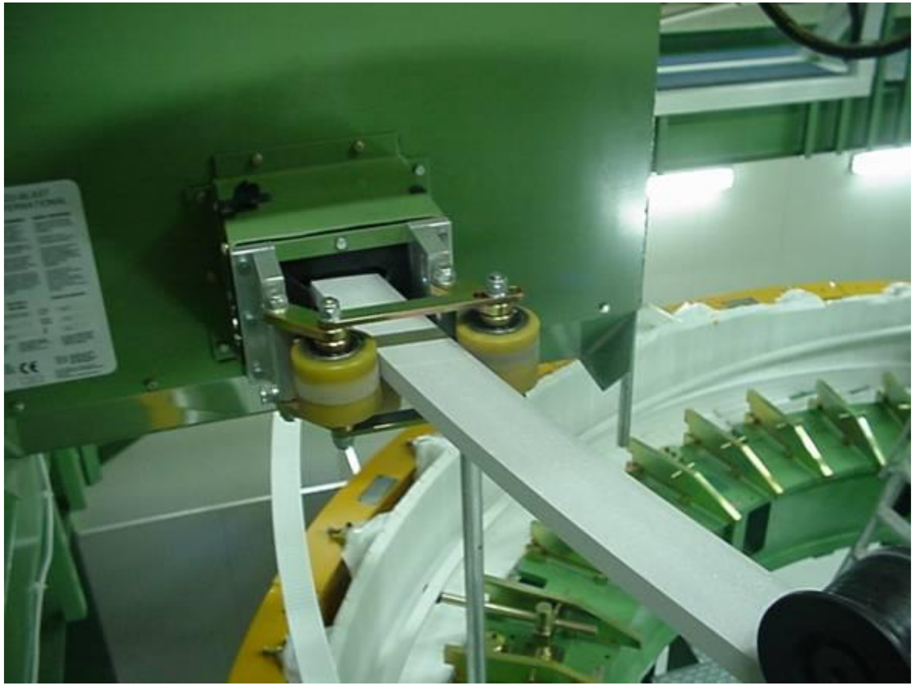
CMS - INFN/CERN 2004 - New winding line -> Inner winding technique



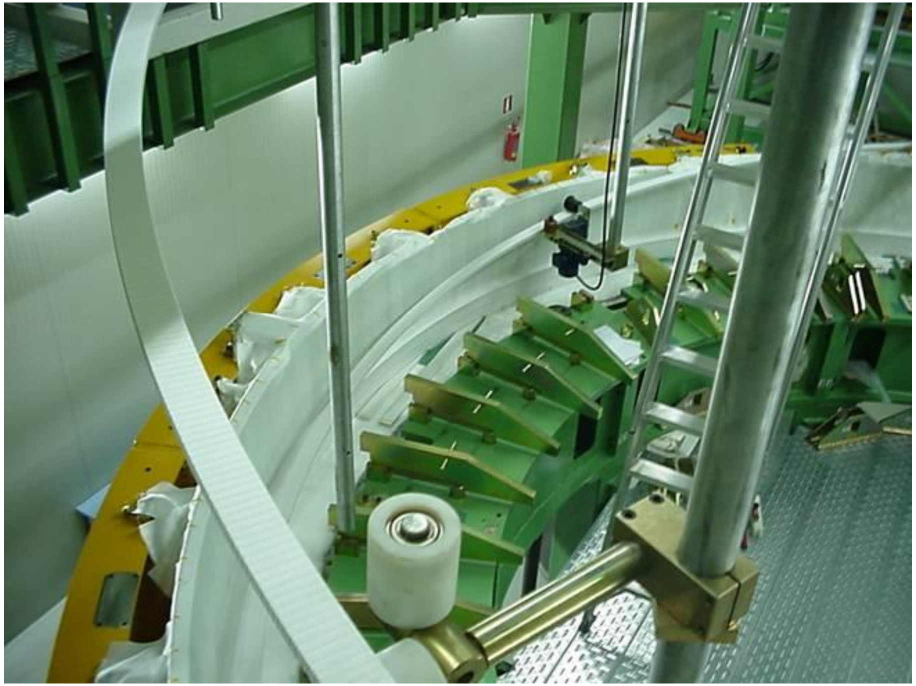
CMS - INFN/CERN 2004 - Outer Aluminium structures under fabrication at ASG premises



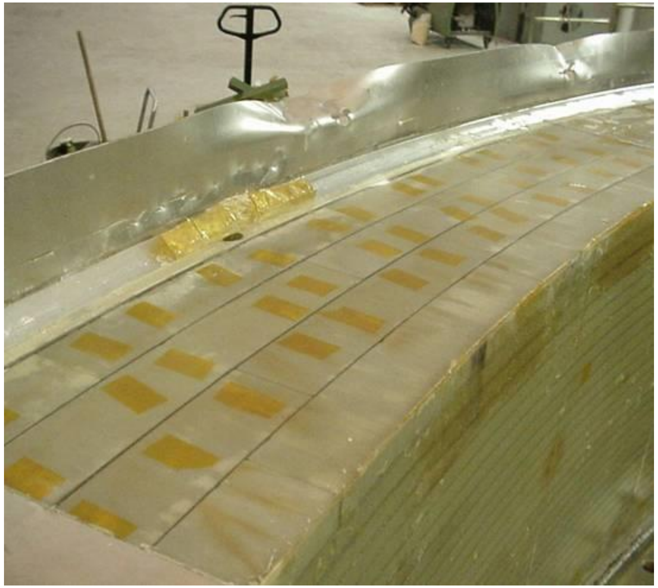
CMS - INFN/CERN 2004 - Sandlasting and turn insulation wrapping



CMS - INFN/CERN 2004 - Winding and ground insulation glass cloths positioning



CMS - INFN/CERN 2004 - Winding completion and resin excess removal



CMS - INFN/CERN 2004 - at CERN during the final assembly phase

INTERNALLY COOLED CABLE MAGNETS

Combine Cryogenic stabilization with resin impregnation

Good insulation

Hollow Conductor
(s.c. strand not directly cooled)
(BBC LCT, CERN DIPOLE, SULTAN 6T)

Cable in conduit (CICC)
(S/C Strands wet by helium, stability margin raise up to 300 mJ/cm^3 for NiTi to 2000 mJ/cm^3 for Nb_3Sn) (ITER_TFMC, ITER-TFC, JT-60, W7-X)

INTERNALLY COOLED CABLE MAGNETS

DIPOLE (CERN 1978)

B_{nom} 2 T

2 Saddle shape L= 2.5 m , Bore diameter = 1.6 m

I_{nom} 5500A on NbTi copper strand tin brazed over a copper pipe

WINDING

Direct cooled by forced flow of He

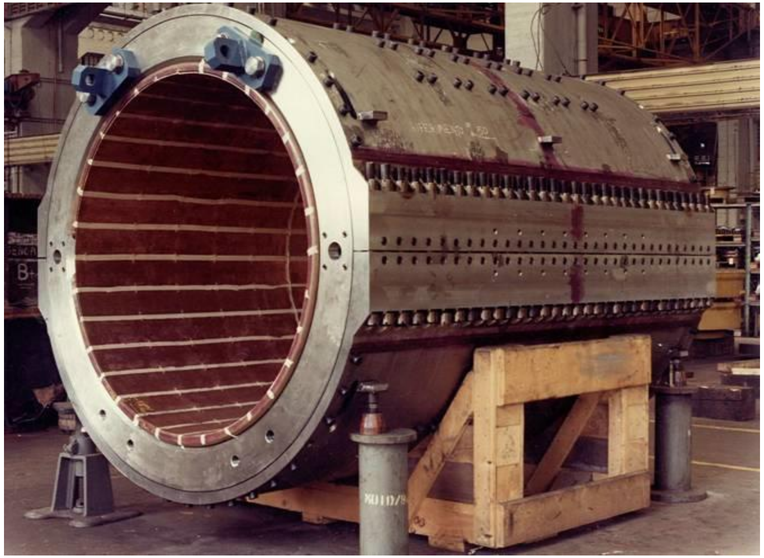
Glass taping + Vacuum impregnation

FORCE CONTAINMENT

Bolted Stainless Steel structure

INTERNALLY COOLED CABLE MAGNETS

DIPOLE (CERN 1978)



MHD for CNR-I (1997)

5T x 2 m active length
2 Saddle shaped coils (10 ton each)
0.7 x 0.5 m warm bore
Square cable in conduit (CICC) with copper+ NbTi strand + stainless steel jacket

WINDING

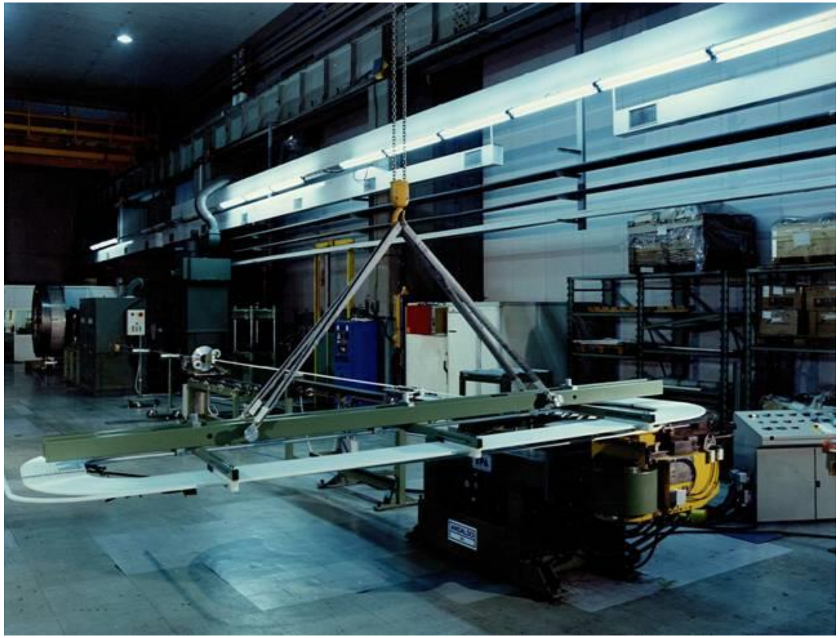
Stress free planar winding of racetrack double pancakes bent afterward

Glass taping + Vacuum impregnation

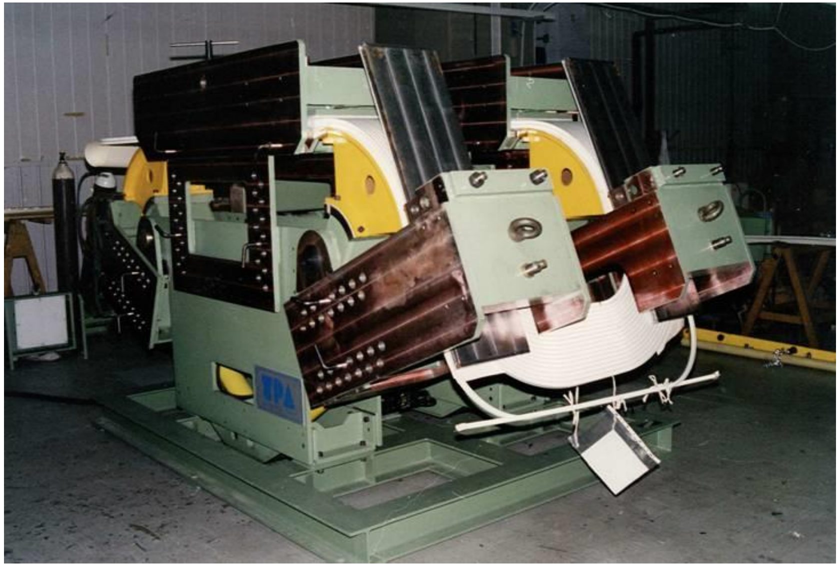
FORCE CONTAINEMENT

Coil assembled a stainless steel mechanical structure.
Prestress by longitudinal tie-rods.

MHD for CNR (1997)



Single racetrack pancake winding



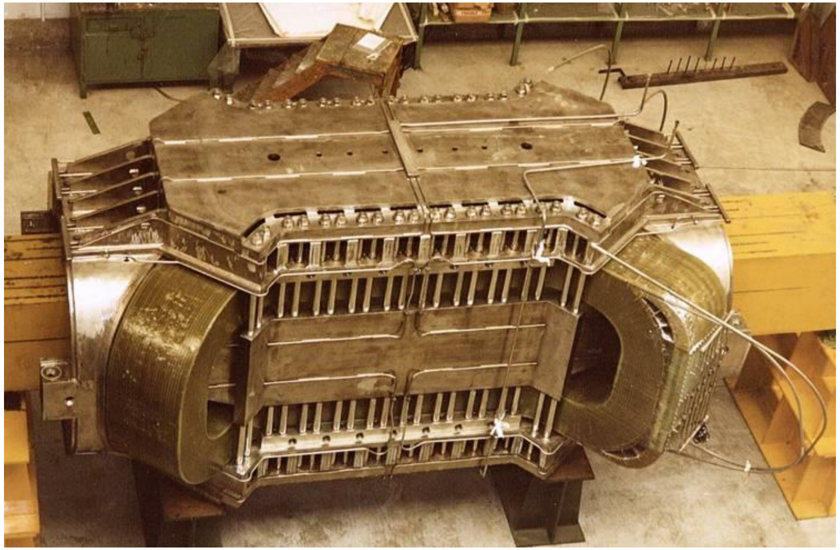
Pancake Bending

MHD for CNR (1997)

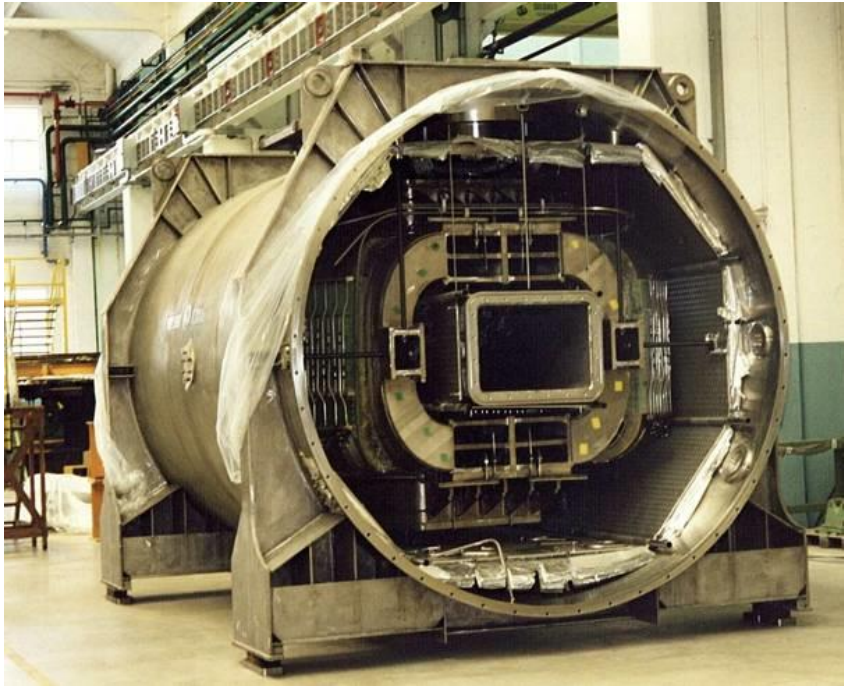
Pancakes stacking

Coils impregnated and completed

MHD for CNR (1997)



Coil assembly into the structure



Cold mass inside its cryostat

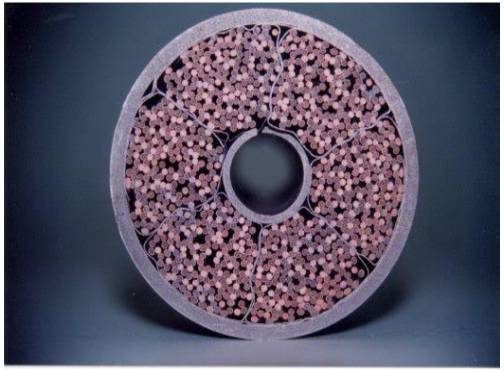
ITER Toroidal Field Model Coils TFMC(2000)

B_{nom} 6.5 T

5 racetrack double pancakes: 3.8m x 2.7m x 0.8m

- Coil weight: 32.000 kg
- Operating temp.: 3.5 K
- Operating current: 70kA reached 80kA

Nb3Sn strand inside a 316LN stainless steel pipe 2 mm thick



WINDING

Stress free winding in a mould + curing + insulation and transfer in a steel radial plate

Glass Kapton taping + Vacuum impregnation

FORCE CONTAINMENT

By radial plates + external box

Prestress by embedding with sand in the box

ITER Toroidal Field Model Coils TFMC(2000)

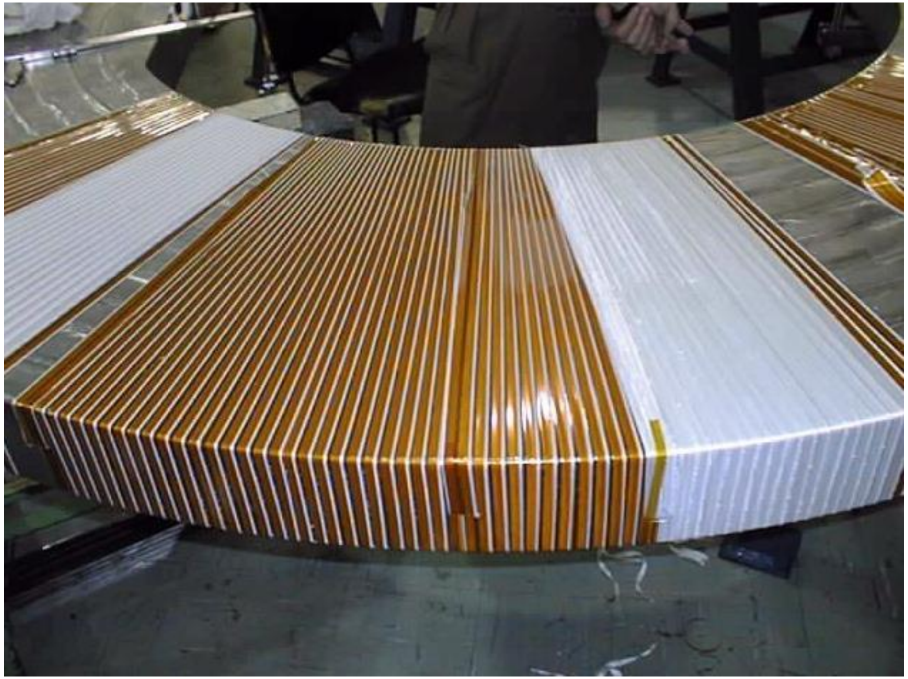
DP ready for Heat Treatment – superconducting samples of ENEA and FZK in front of top pancake.

ITER Toroidal Field Model Coils TFMC(2000)

Hand wrapped turn insulation

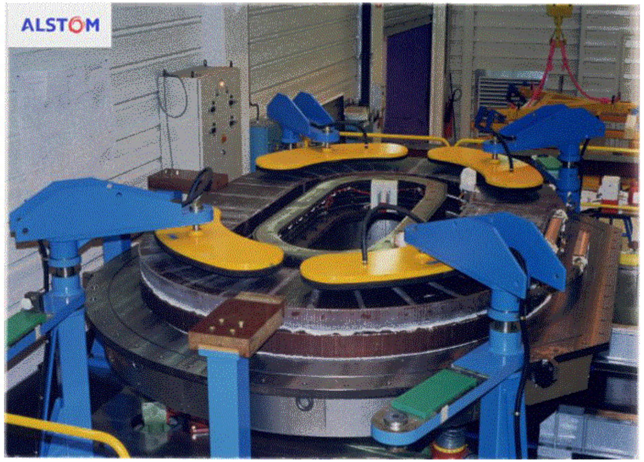
ITER Toroidal Field Model Coils TFMC(2000)

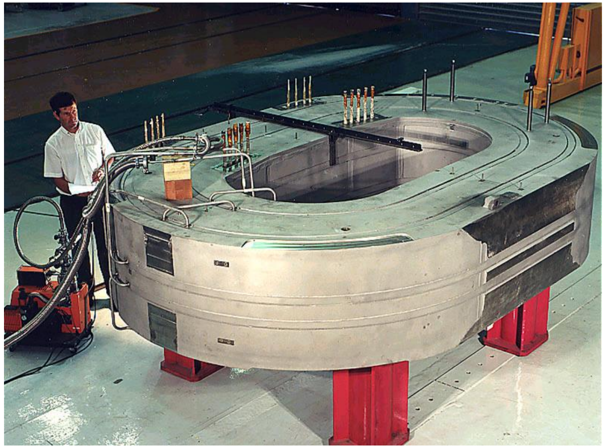
Ground insulation hand wrapping onto the single Double Pancake.



ITER Toroidal Field Model Coils TFMC(2000)

Model Coil Completed (together with Babcock + Alstom)





W7X (IPP 1998-2006)

B_{nom} 5T N. 50 non planar coils of 5 different shapes + 20 planar coils.

I_{nom} 17.6 kA in a NbTi Strands coextruded in an Al alloy pipe (CICC)

WINDING

Double pancake manual winding on a 3D form

Glass taping + Vacuum impregnation

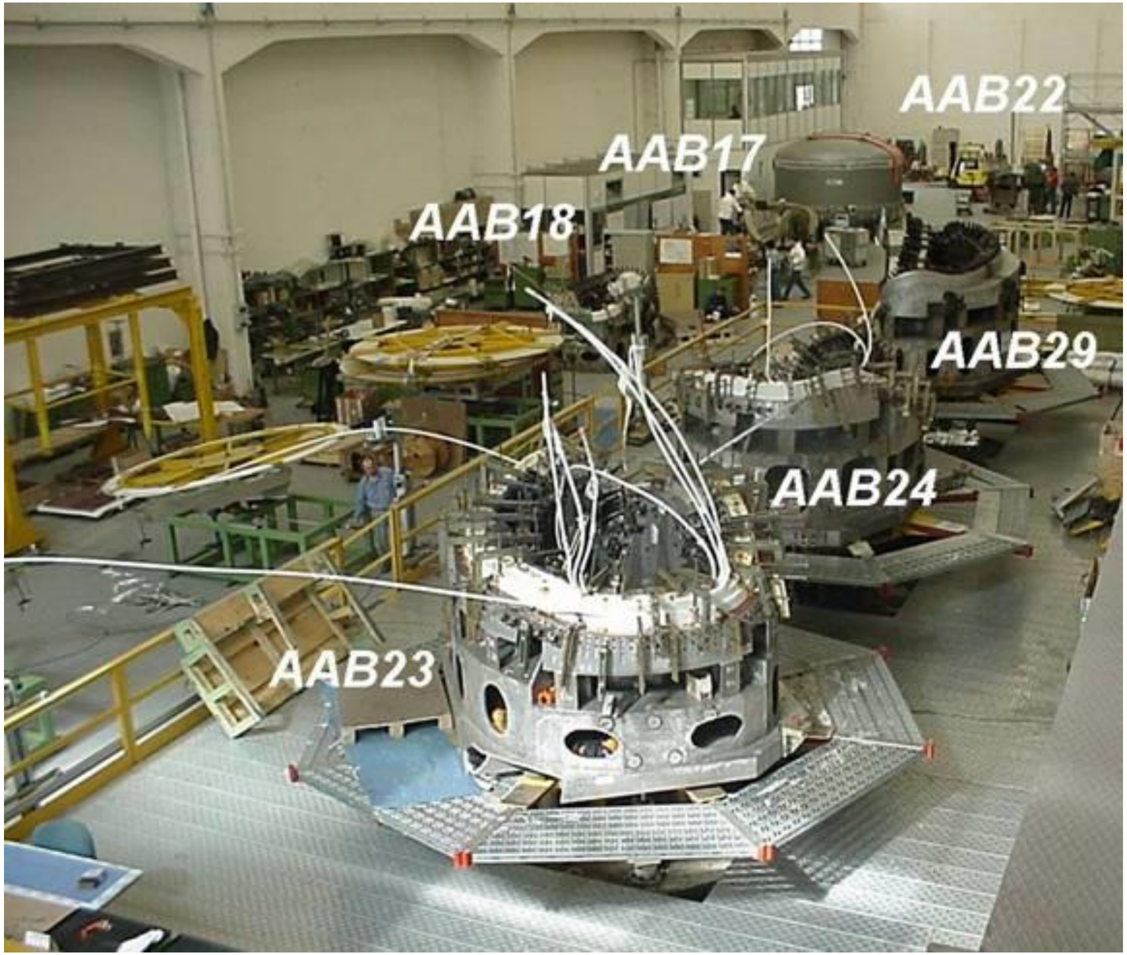
FORCE CONTAINMENT

Force supported by the cable itself and by external stainless steel case

Prestress by different thermal contraction during embedding

W7X (IPP 2004)

At ASG premises during fabrication

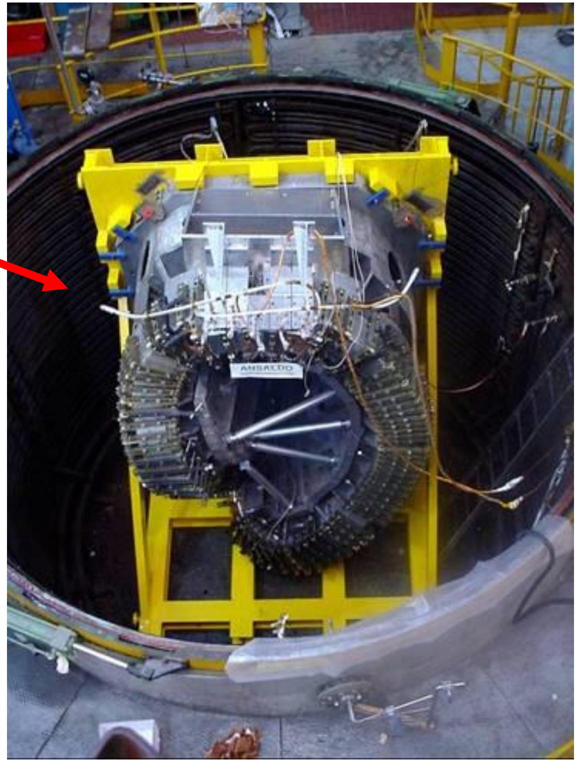


W7X (IPP 2004)
At ASG premises during fabrication

W7X (IPP 2004)

At ASG premises during fabrication.
In the autoclave for the artificial ageing of the jacket and for the subsequent impregnation process.

At Babcock premises during the insertion inside the stainless steel case.



W7X (IPP 2004)

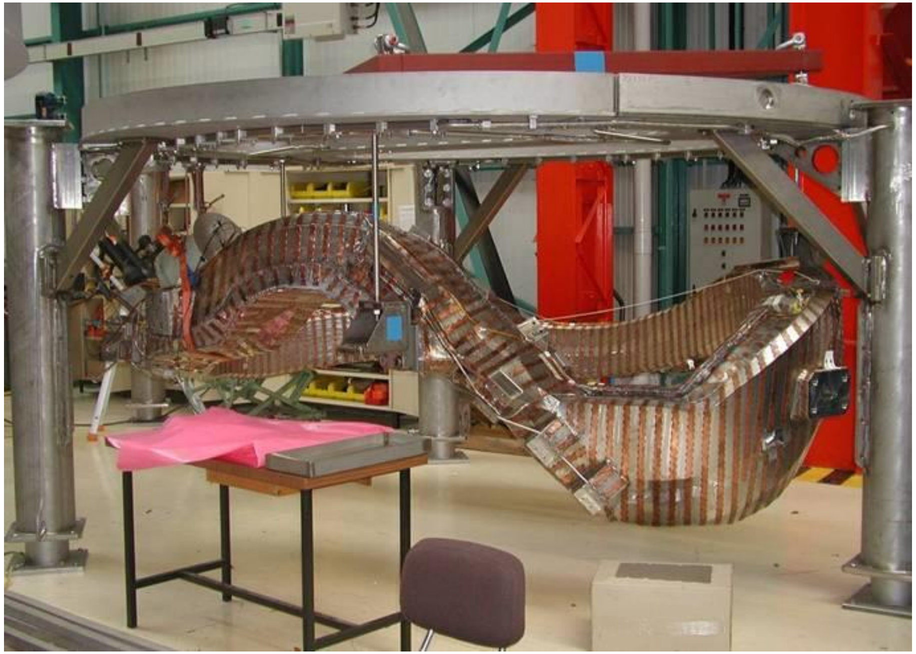
At Babcock premises during the application of the hydraulic circuit.

Double cooling system:

a) Inside the CIC Conductor
b) Indirect by cooling the case

W7X (IPP 2004)

First magnet under test at CEA Saclay France
reached nominal current 17.6kA



FERMILab Tsu & TSd (2016-2020)

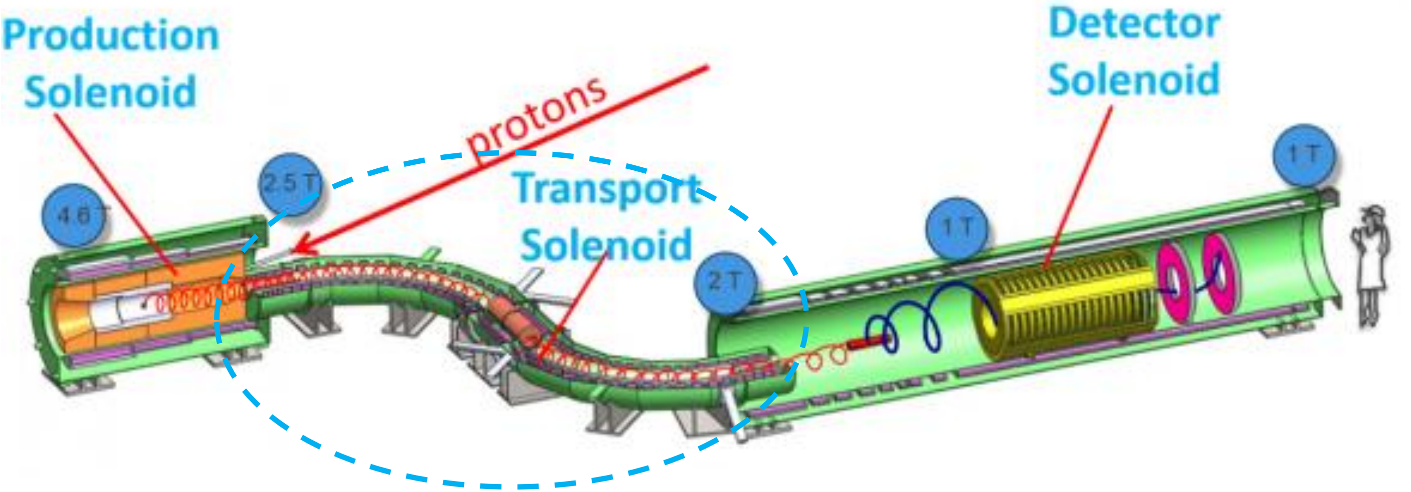
Scope of the Supply:
52 Coils inserted inside
27 Modules that compose a total of 14 Units

Units during assembly @ FLAB

The Transport Solenoid Magnet System is divided into two sections:

TSu:
- 25 Coils
- 13 Modules
- 7 Units

TSd:
- 27 Coils
- 14 Modules
- 7 Units



FERMILab Tsu & TSd (2016-2020)

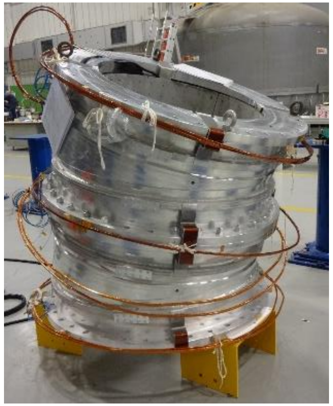
Main Fabrication steps

- Coils realizing (winding, VPI, resin excess removal)
- Coil turning (prescription to leave at least 4 mm of ground insulation)
- Housing pre machining
- Hydraulic circuit welding
- Housing final machining (coil slots that have an interference of 0,5 mm on the diameter
- Coils shring fitting heating the Al- structure at 110°C
- Module fininshing
- Modules coupling for forming the Unit
- Unit instrumentation assy (Voltage taps and temperature sensors)
- Coil Leads insulation
- Hydraulic circuit leak test
- Final Electrical Tests

FERMILab Tsu & TSd (2016-2020)

The Units completed at ASG premises

Unit-1



Unit-2

Unit-3

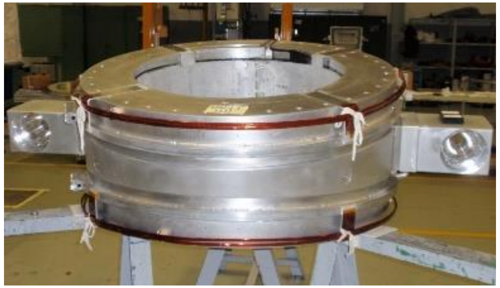
Unit-4

Unit-5

FERMILab Tsu & TSd (2016-2020)

The Units completed at ASG premises

Unit-6



Unit-8

Unit-7

Unit-9

FERMILab Tsu & TSd (2016-2020)

The Units completed at ASG premises

Unit-10

Unit-11

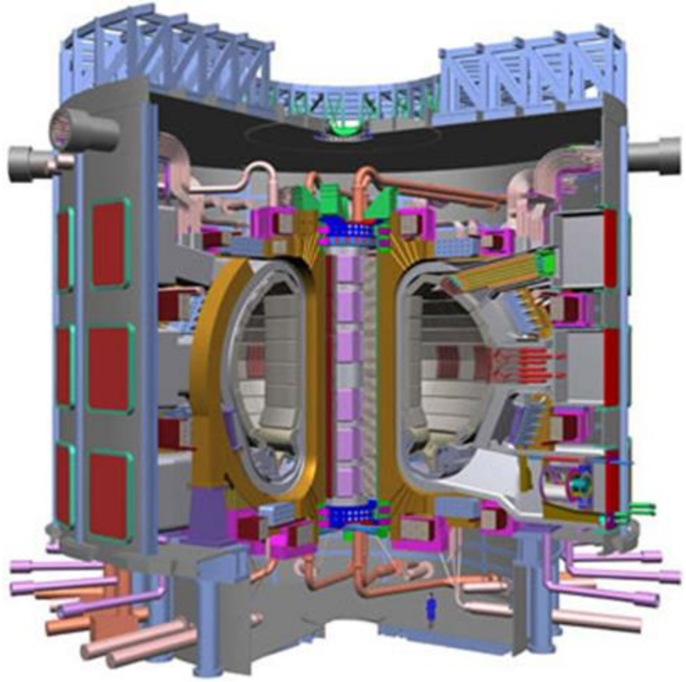
Unit-12

Unit-13

Unit-14

ITER-PROJET - PFC & TFC Magnets [2010 - in progress]

The ITER project is aimed at the construction of a nuclear fusion test-plant, a Tokamak, dedicated to the investigation of scientific principles and the technologies that will allow to exploit nuclear fusion as the world's primary source of energy. This device will allow to perform the controlled thermonuclear fusion in an industrial sized plant. ITER is based on the concept of magnetic confinement, in which the plasma is contained in a doughnut-shaped vacuum vessel. The fusion process involves two hydrogen isotopes, deuterium and tritium, heated to temperatures in excess of 150 million °C, forming a hot plasma. Strong magnetic fields are used to keep the plasma away from the walls; these are produced by superconducting coils surrounding the vessel, and by an electrical current driven through the plasma. The heat produced, through proper heat exchangers (steam generators), will allow the production of electric power by a standard turbo-alternator group.
ASG is manufacturing 10 of the 19 TF Coils and 4 of the 6 PF Coils.



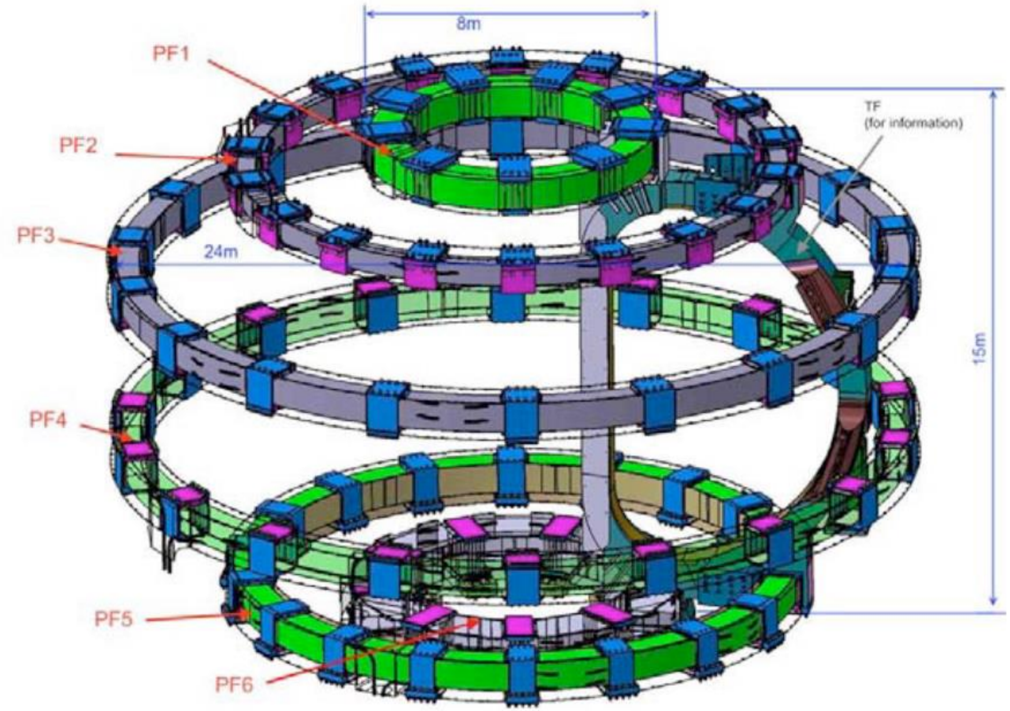
ITER-PROJET - PFC Magnets [2013 - in progress]

ASG Superconductors scope of supply:

- Manufacturing Plan
- Layout and workflow definition
- Manufacturing and Process Procedures
- Coils Manufacturing and Testing
- Project Management of the whole project

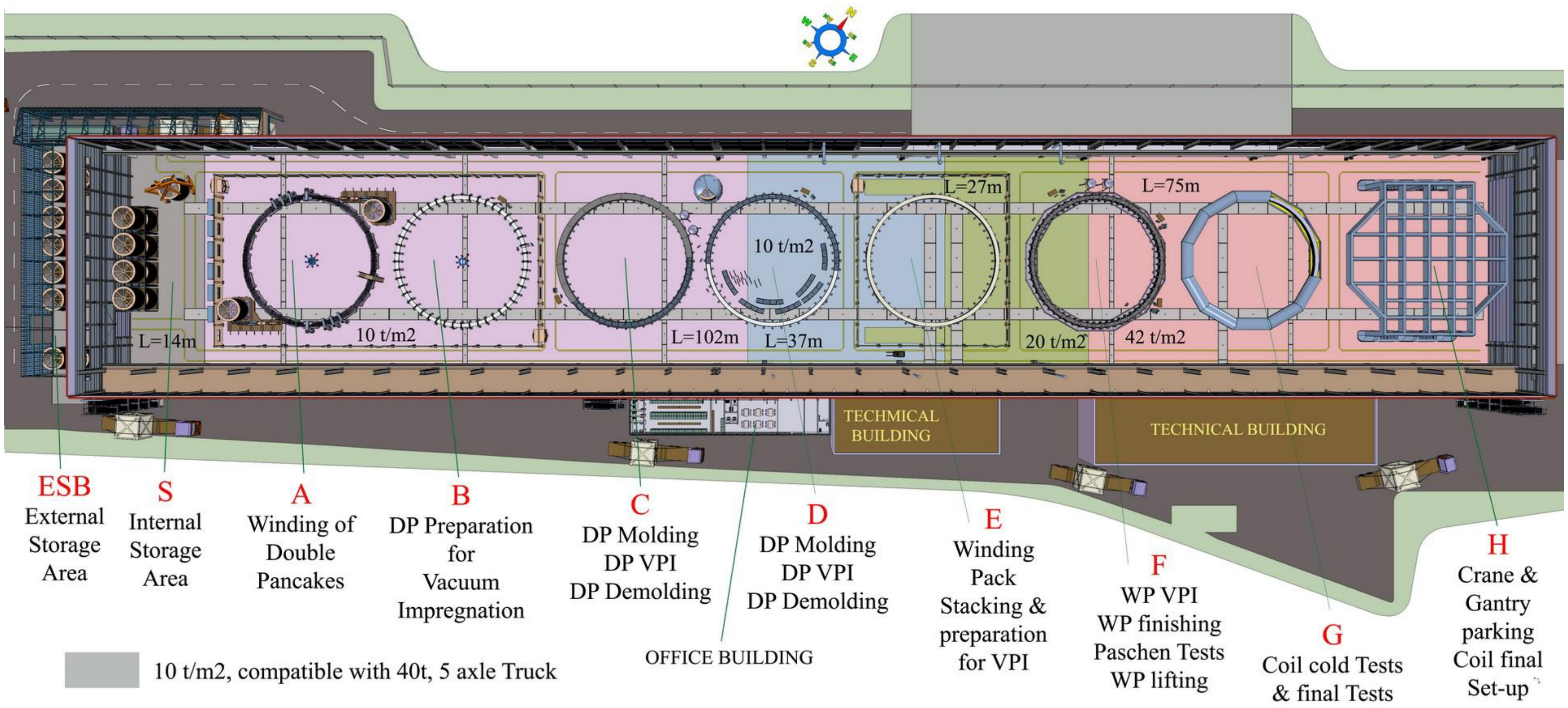
The PF magnet system is composed of six circular coils, consisting of superconducting winding packs (WP) made up from a stack of Double Pancakes (DP).

ITER-PROJET - PFC Magnets [2013 - in progress]

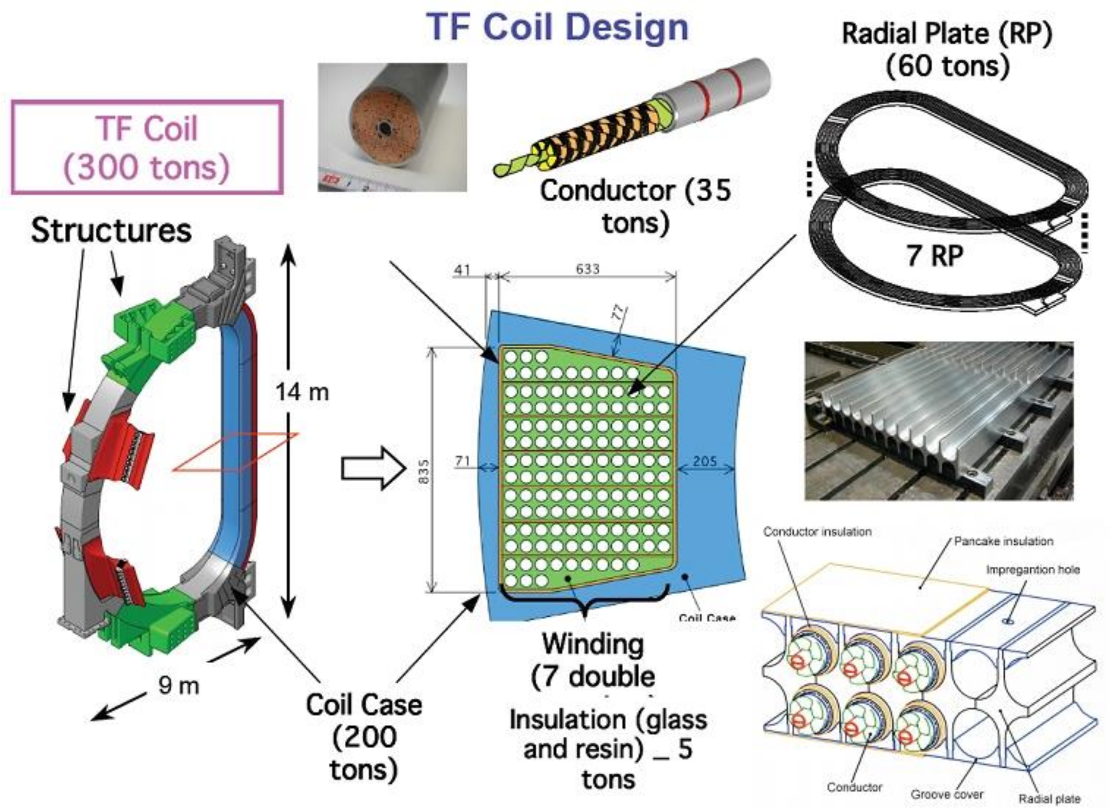


Schematics of the PF Coils Configuration

ITER-PROJET - PFC Magnets [2013 - in progress] - Layout at Cadarache (F)

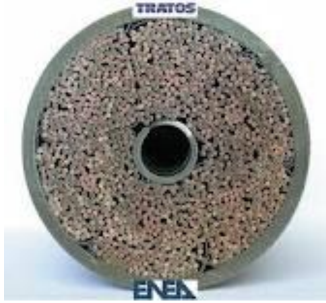


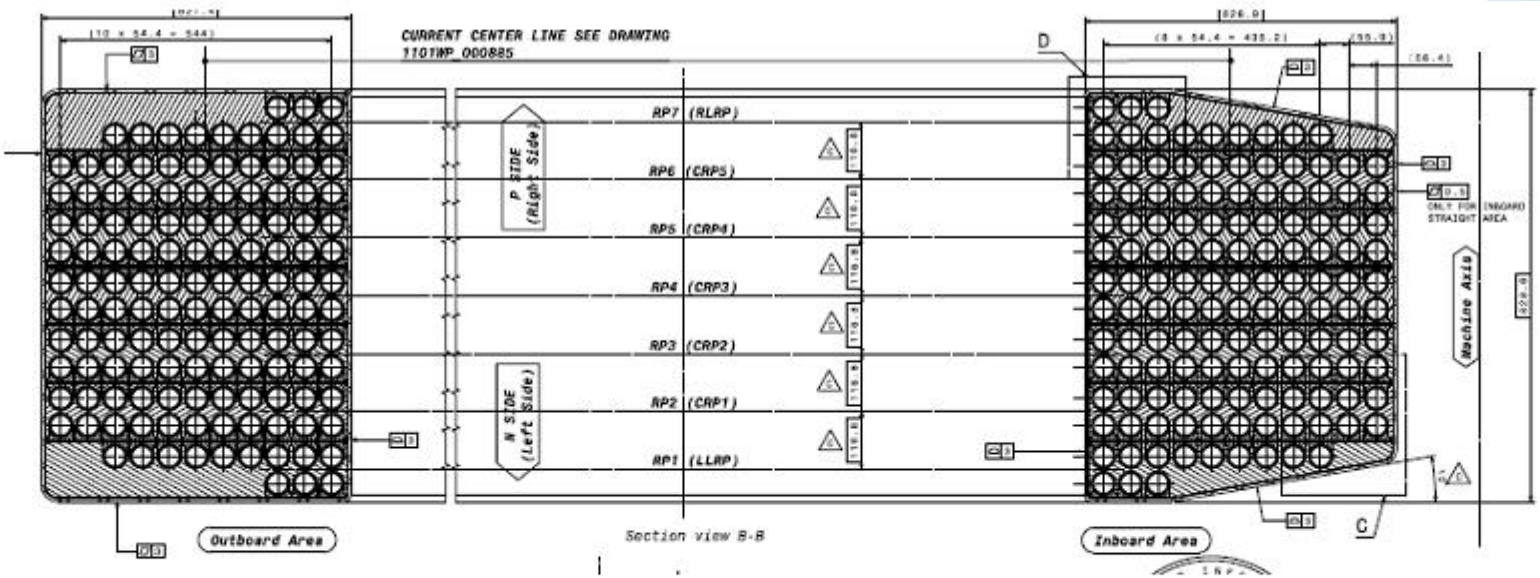
ITER-TFC - [2010-2020] - The Overall Design



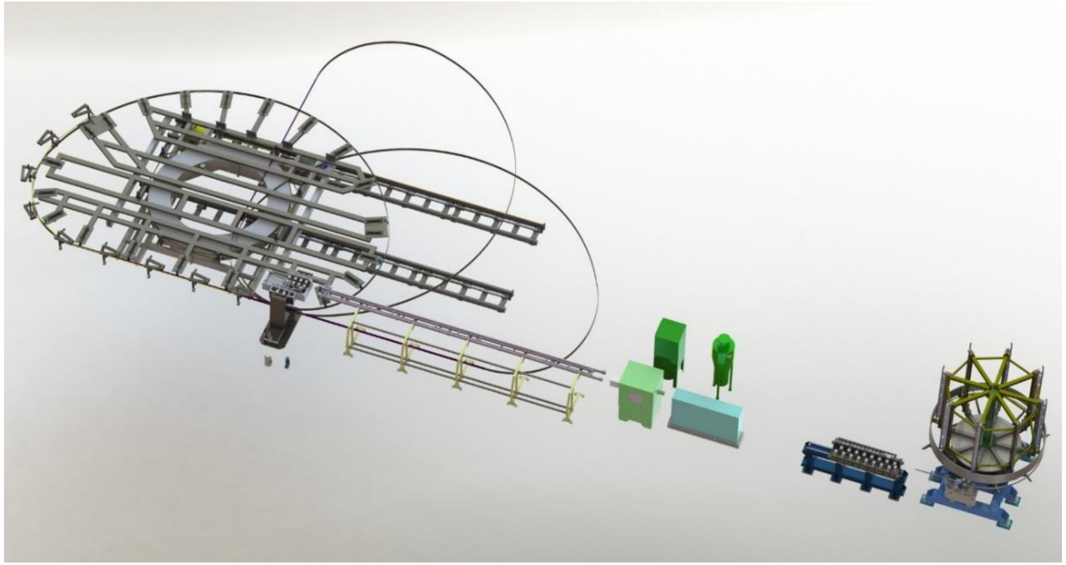
ITER-TFC - [2010-2020] The Winding Pack

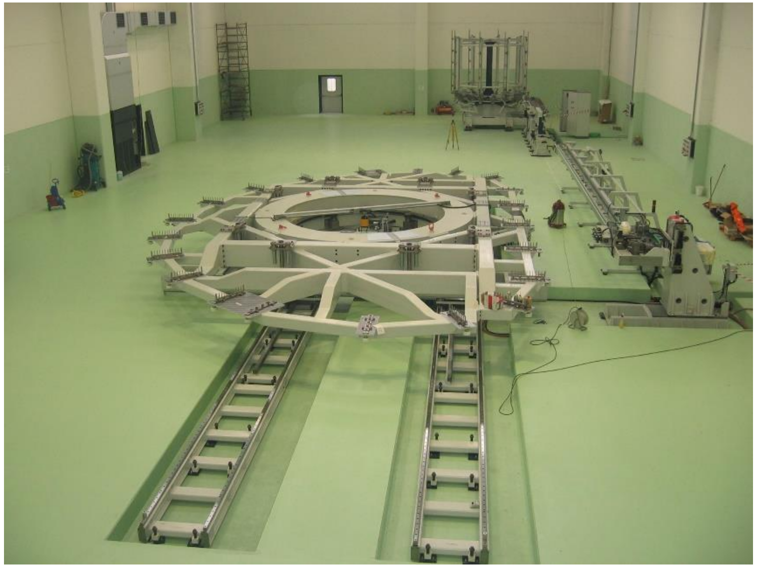
Conductor diameter: 43,7 mm
I_{nom}: 70 kA
Jacket: 316LN



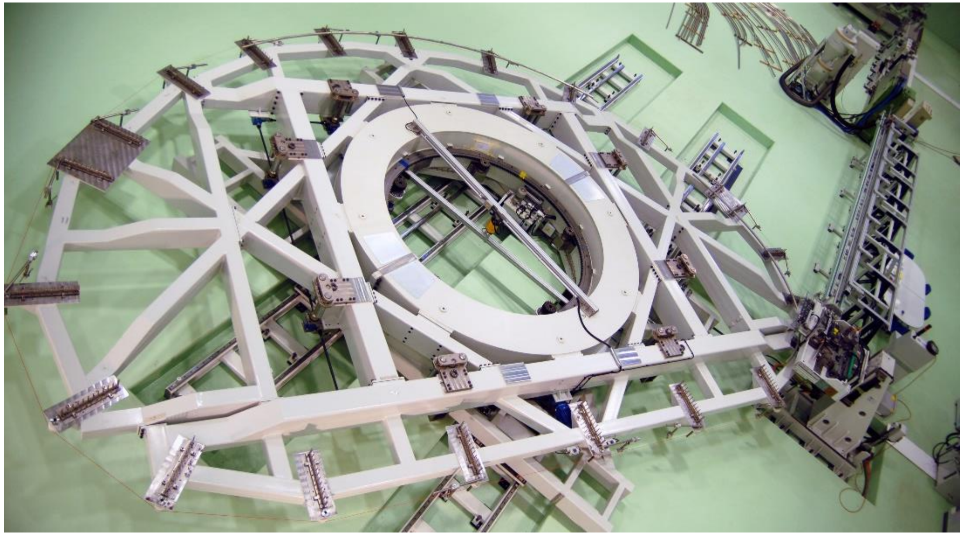


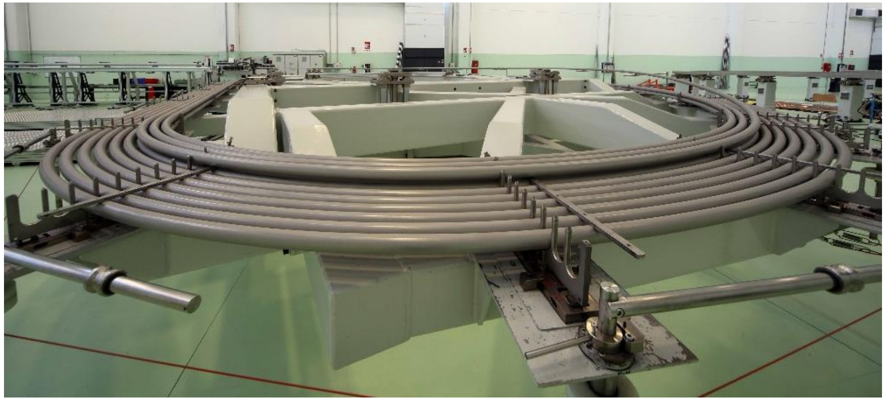
ITER-TFC - [2010-2020]
Winding Line Conceptual Design and plant erection





ITER-TFC - [2010-2020] Winding line details





ITER-TFC - [2010-2020] Oven for the Heat Treatment of the Nb3Sn Conductors.

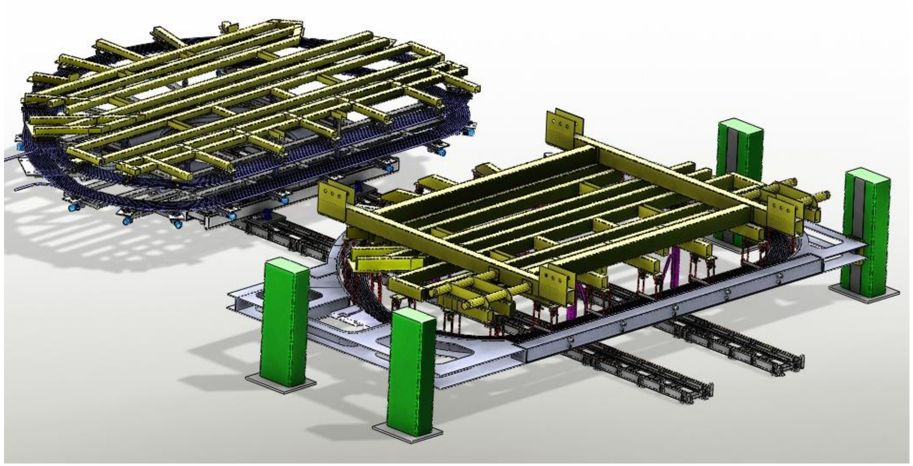
Chamber dimension: 16 x 10 x 2 m

Each heat treatment lasts 28 days.

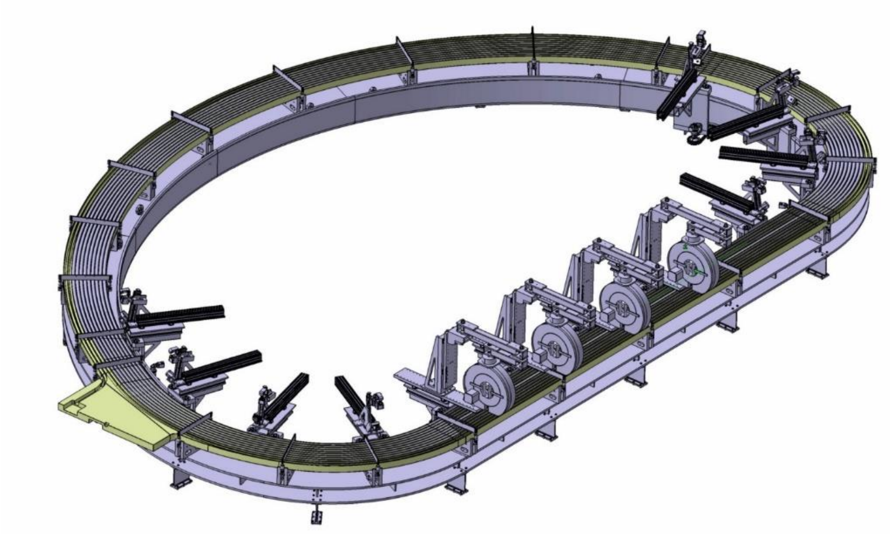
ASG carried out N. 30 Heat treatments in three years

It has been treated N. 71 Double pancakes plus (realized with six different types of conductors - both internal tin diffusion than bronze route technologies) spare turns in order to determine the residual elongation. This parameter was fundamental for realizing the subsequent windings shorter accordingly in order to fit inside the radial plates.

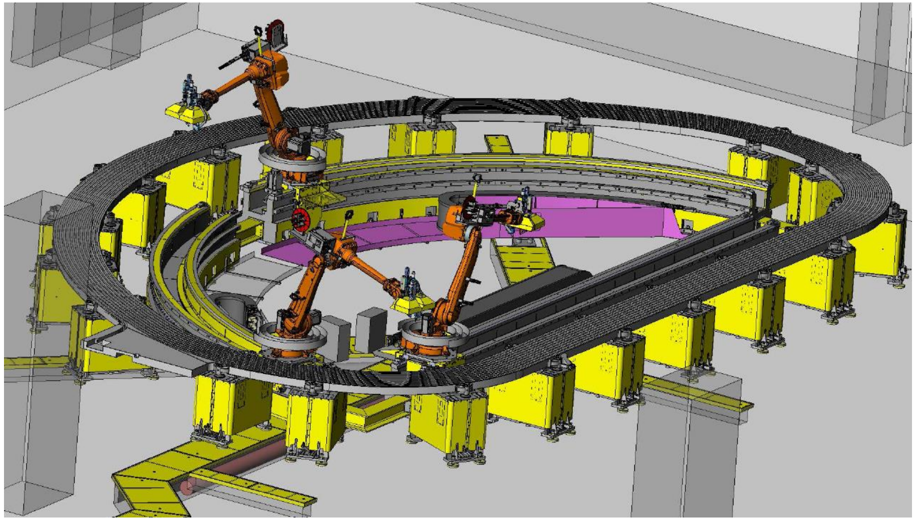
ITER-TFC - [2010-2020] Radial Plate Transfering Insertion Unit - Conceptual design and plant erection



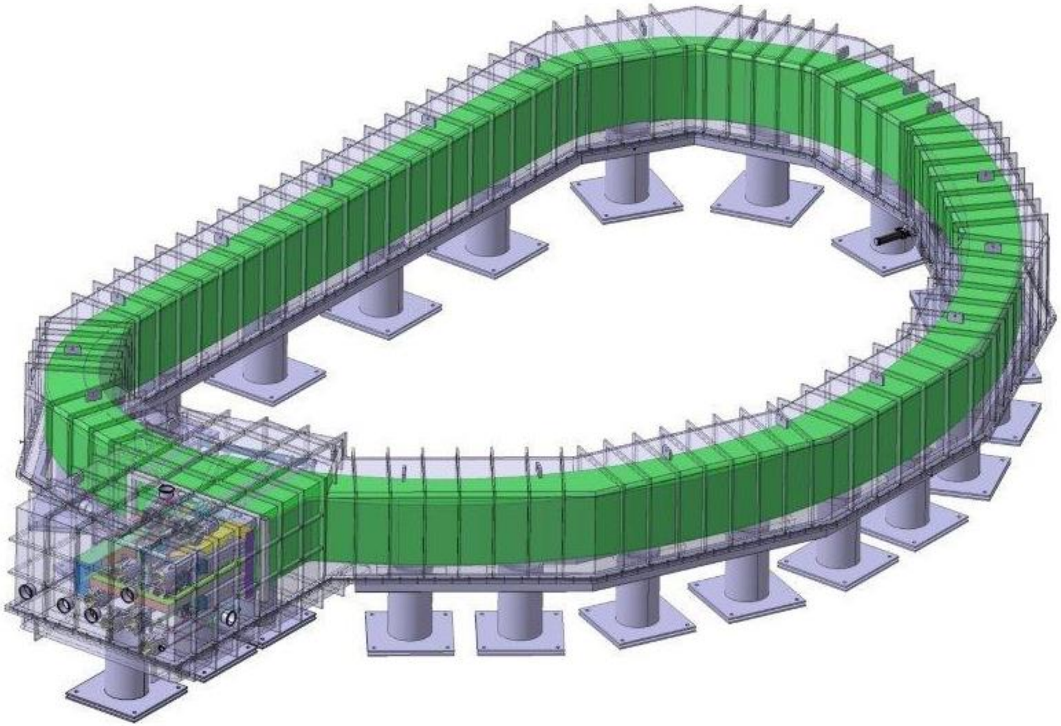
ITER-TFC - [2010-2020] Turn Insulation device



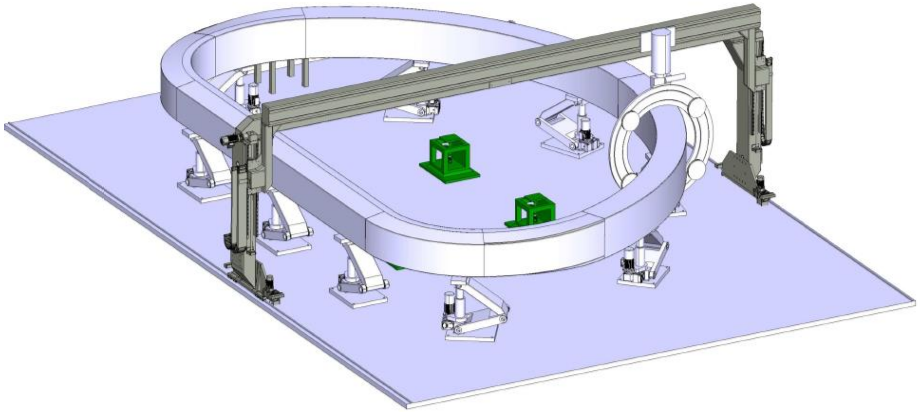
ITER-TFC - [2010-2020] Cover laser welding plant



ITER-TFC - [2010-2020] WP leak and electrical test vacuum chamber

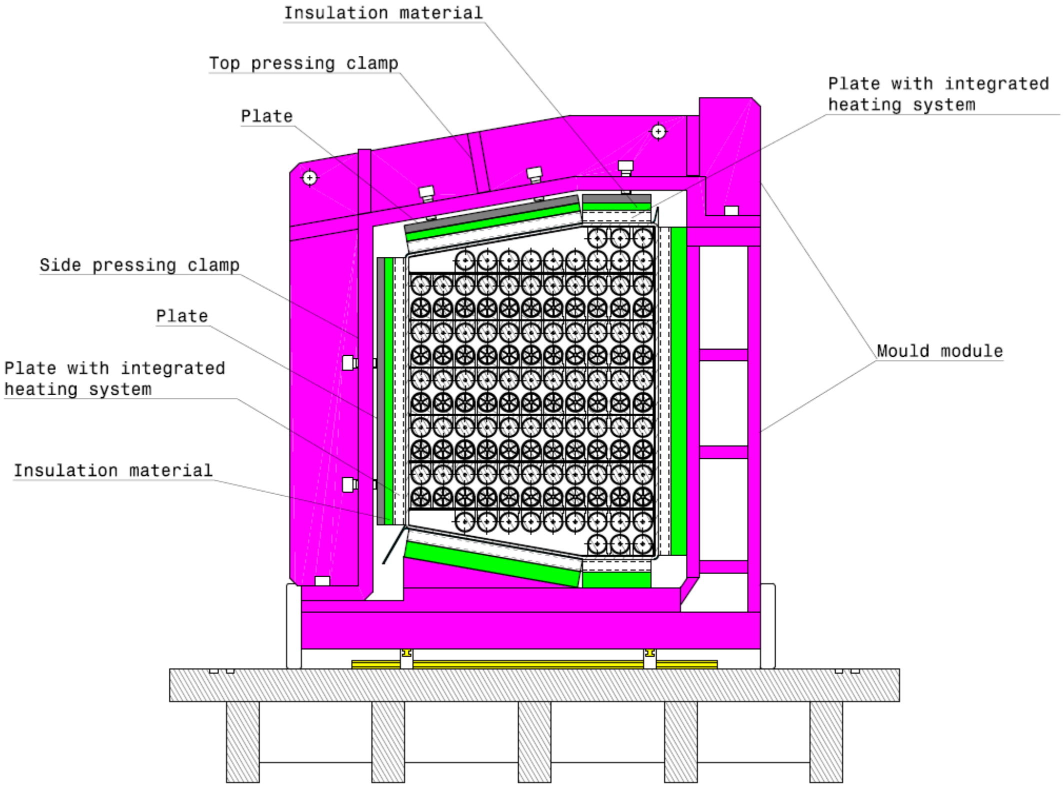


ITER – TFC WP ground insulation wrapping plant



ITER-TFC - [2010-2020]

WP VPI plant – Detail of the cross section of the WP

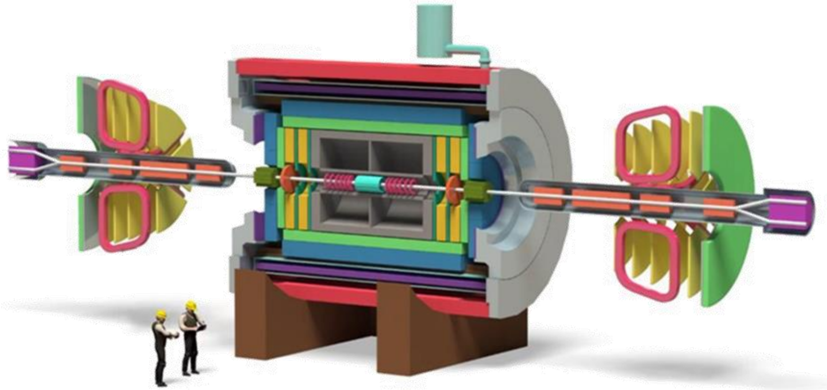


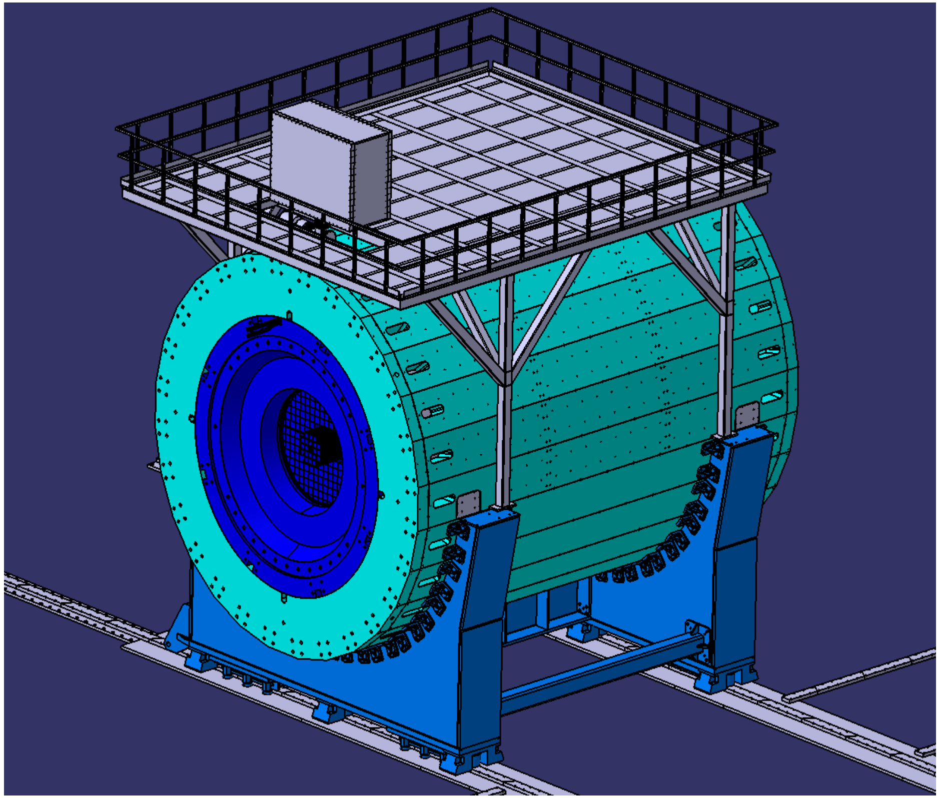
ITER-TFC - [2010-2020] The WP prior to be subjected to the VPI process

ITER-TFC - [2010-2020] the WP completed

ITER-TFC - [2010-2020]- The delivery

MPD – JINR [2016-2020] – The concept





MPD - JINR [2016-2020] - The main parameters

The main components of the MPD are the superconducting NbTi coil, two Trim Coils at both the ends (copper coils) and an iron yoke for the flux return.

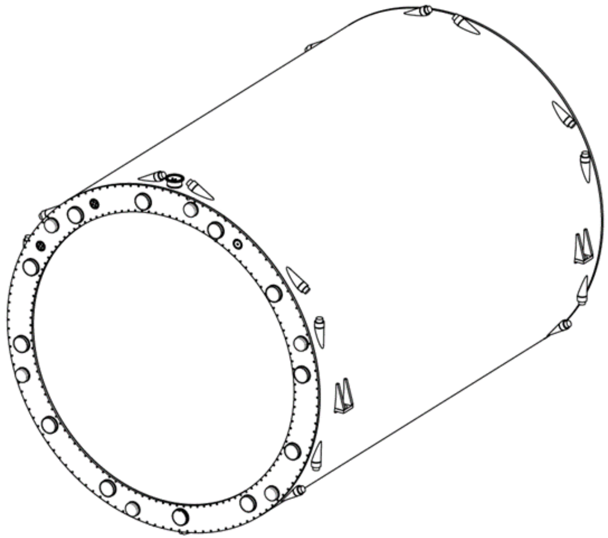
The cable (custom designed on purpose) is manufactured by coextrusion of stabilizing high-purity aluminum and superconducting NbTi strand.

The coil has an indirect cooling system that consists in a hydraulic LHe circuit welded directly on the coil.

The magnet provides a highly homogeneous magnetic field of 0.5 Tesla in a cylindrical volume (4.6 m diameter, 3.400 m length). Two resistive TRIM coils are installed at the ends of the solenoid to correct and trim the field.

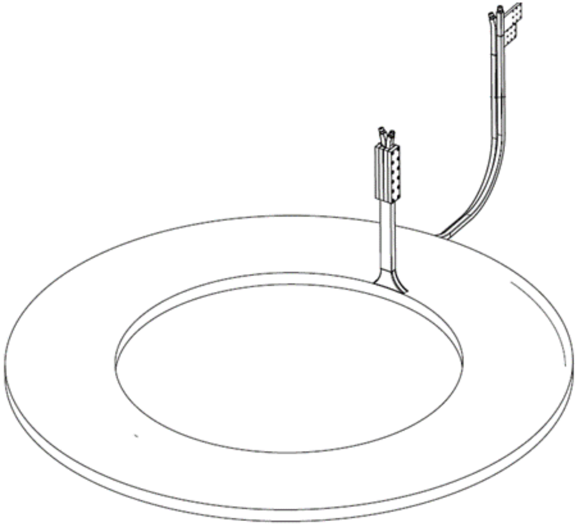
MPD – JINR [2016-2020] – The main parameters

SC Coil Ø:	5.2 m
SC Coil lenght:	7.6 m
SC Coil weight:	15 Tons
SC Coil + Criostat weight:	75 Tons
Cryostat diameter:	5.8 m
Cryostat lenght:	8.1 m
TRIM coil diameter:	3.2 m
TRIM coil height:	80 mm
Yoke + Coils weight:	835 Tons



MPD – JINR [2016-2020] – Trim Coils

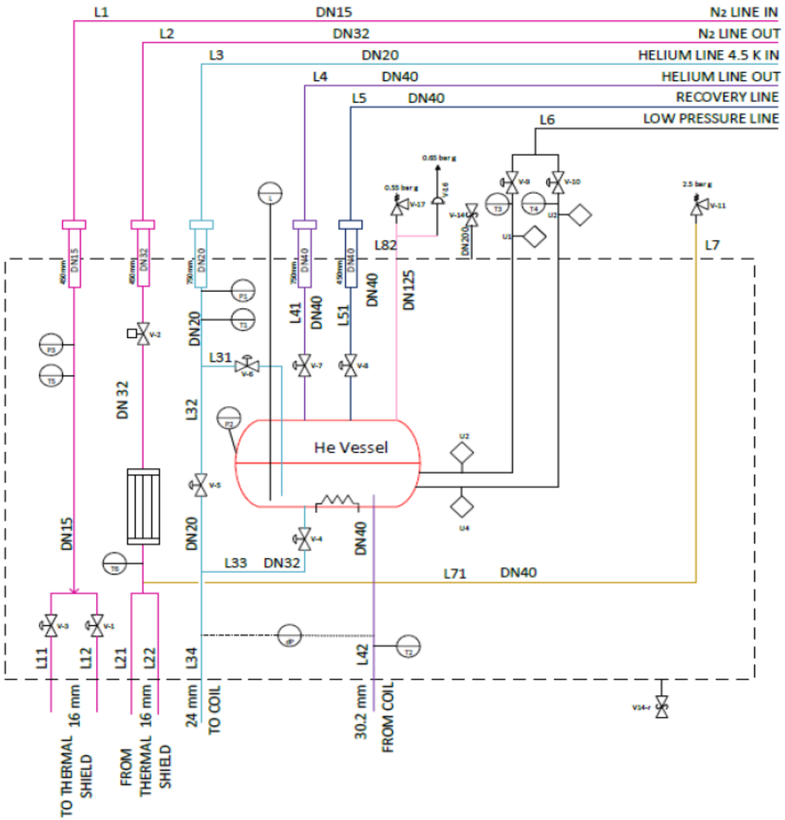
- External diameter: 3189 mm
- Internal diameter: 1952 mm
- Thickness: 76 mm
- Exit max height: 1245 mm



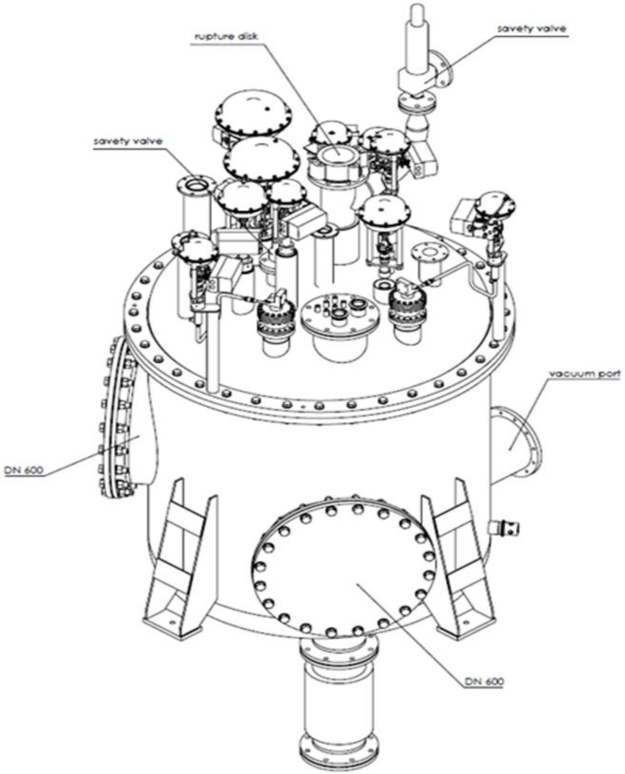
MPD – JINR [2016-2020] – Control Dewar

The Control Dewar is a vacuum vessel that hosts all the current leads needed to energize the magnet and the cryogenic lines, valves and vessels needed for the cooling of the magnet itself.

The pipes and superconductive cables coming from the magnet through the chimney goes to the Control Dewar.

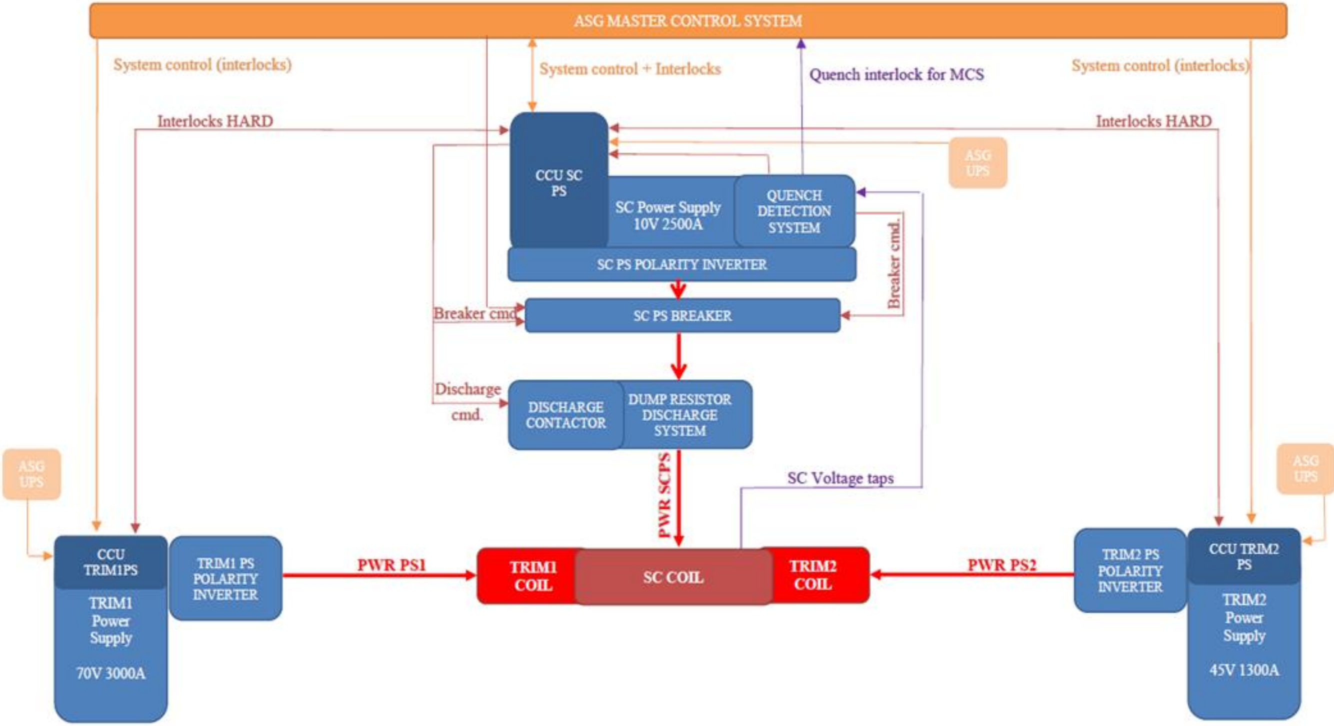


MPD – JINR [2016-2020] – Control Dewar

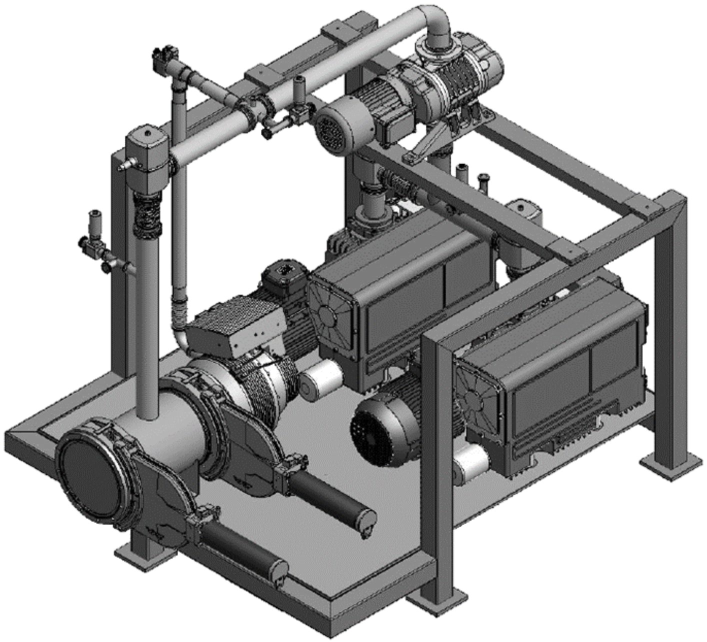


MPD – JINR [2016-2020] – Power Supply

The vacuum system is a pumping line with valves, two rotative pumps (for redundancy), a roots pump and a turbo pump in series, directly connected to the vacuum port of the Control Dewar. The system is used to evacuate the cryostat in order to allow the cool down of the magnet.



MPD – JINR [2016-2020] – Vacuum System



VACUUM SYSTEM

The vacuum system is a pumping line with valves, two rotative pumps (for redundancy), a roots pump and a turbo pump in series, directly connected to the vacuum port of the Control Dewar. The system is used to evacuate the cryostat in order to allow the cool down of the magnet.

MPD – JINR [2016-2020] – The cold mass assembly (three modules bolted together)

MPD – JINR [2016-2020] – The cold mass assembly – Intertion into the vacuum chamber

MPD – JINR [2016-2020] – The transport (at La Spezia harbour on Sept. 2020)

The conclusions are:

- The shape and the purpose of magnets are covering a very wide range of applications.
- We need different techniques/solutions for the different projects.
- There is not an unique BEST technique in general for fabrication but the one that allow us to reach the objectives taking into account the costs, the efforts and…..the Customer satisfaction.