
Superconducting Magnets for Nuclear Fusion

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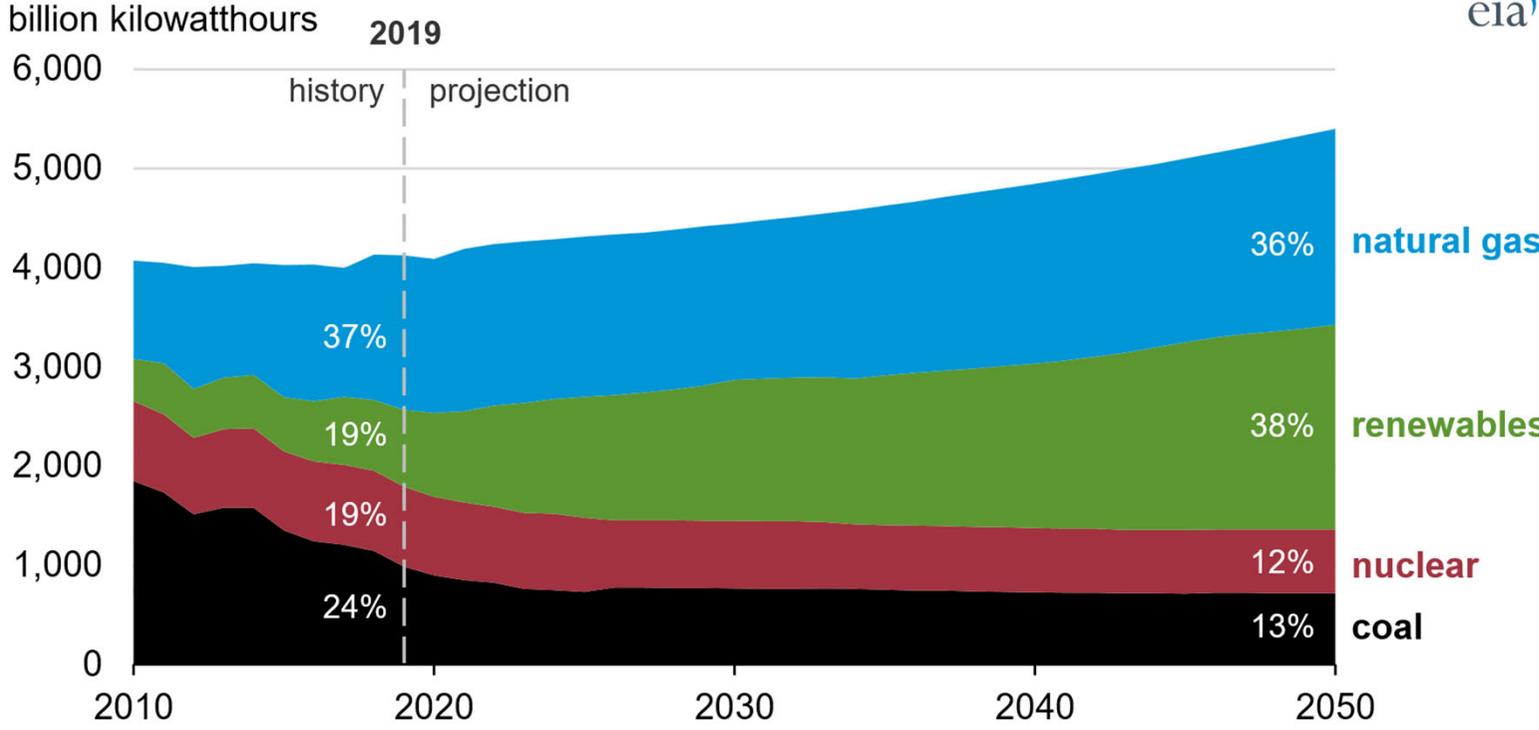
Climate Change and New Energy Source



The potential future effects of global climate change include more frequent **wildfires**, longer periods of **drought** in some regions, and an increase in the duration and intensity of **tropical storms**.
Credit: left - Mellimage/Shutterstock.com, center - Montree Hanlue/Shutterstock.com, right - NASA..

Climate Change and New Energy Source

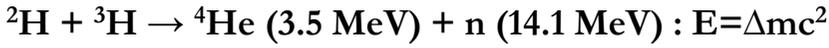
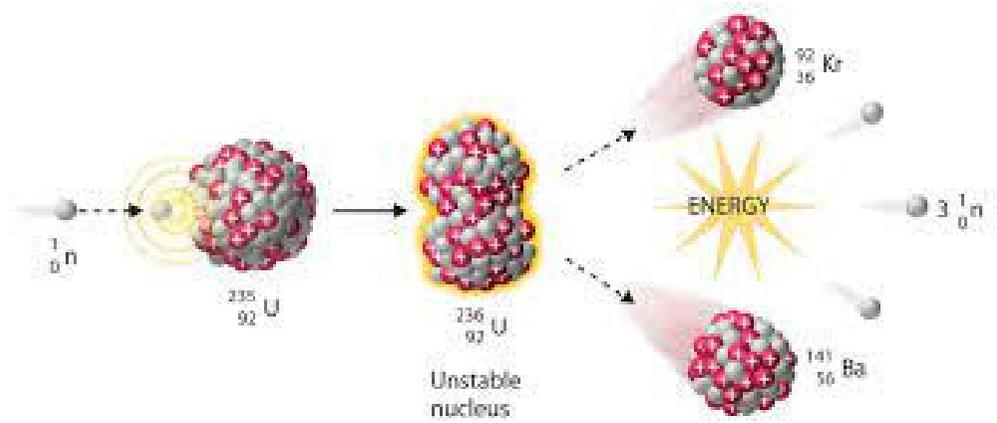
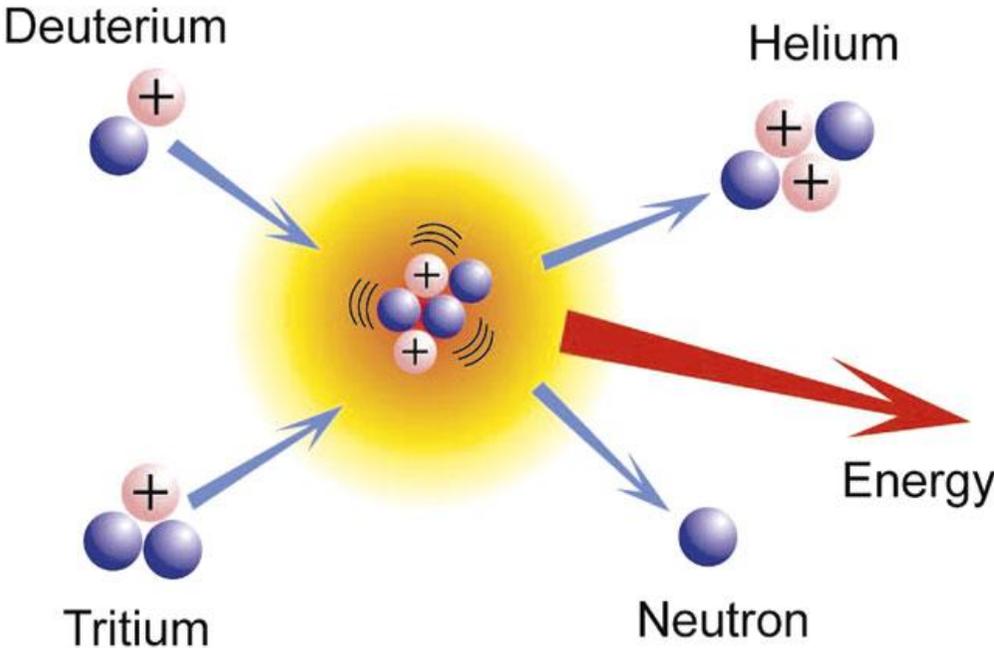
U.S. electricity generation from selected fuels (AEO2020 Reference case)



- We need energy sources such as
- No emission of greenhouse gases
 - Safe for environment and human
 - Abundant fuel supply
 - Capability for the base energy

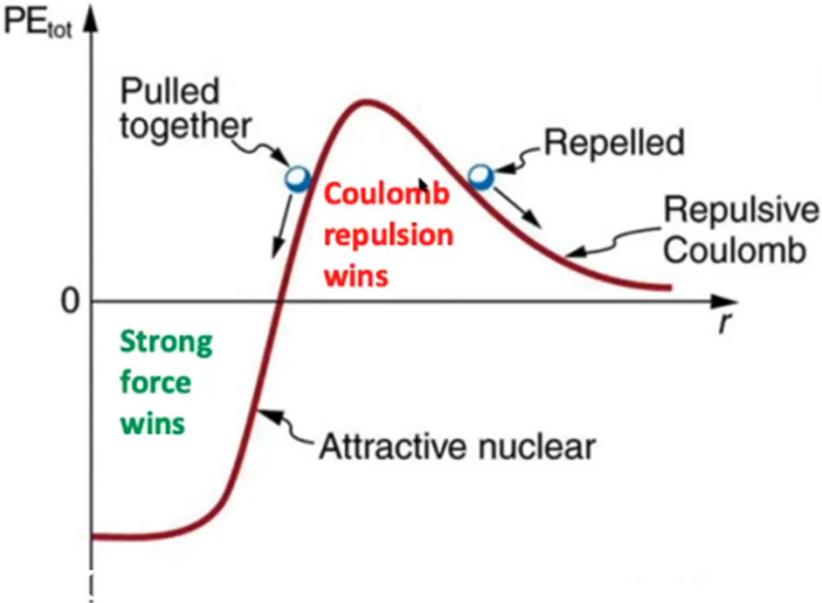
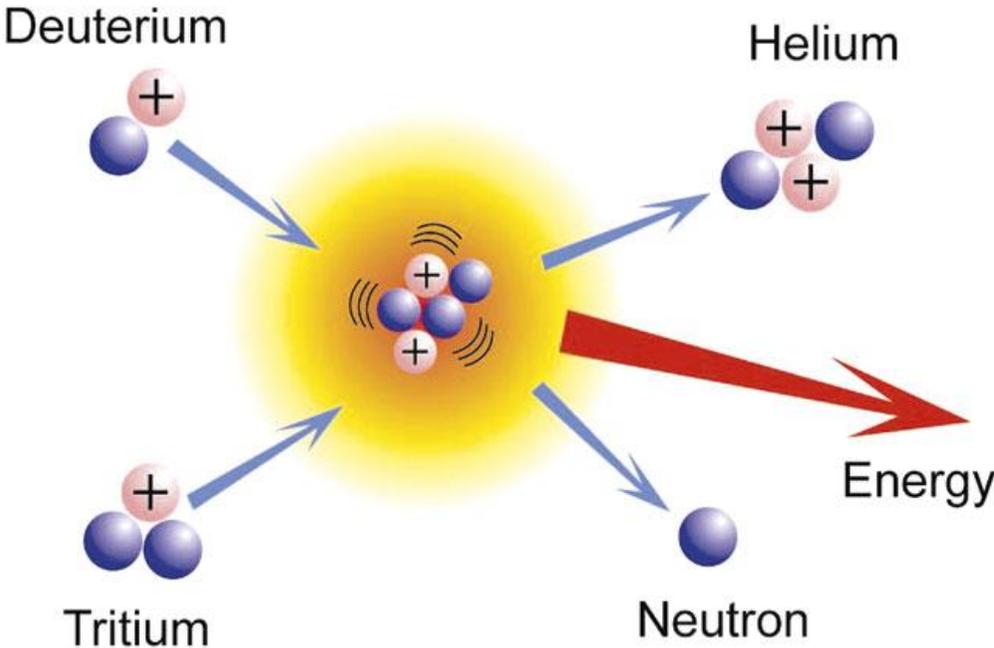
Fusion and Fission Energy

- Fusion is the energy source of the Sun
- Reaction which reconstructs of nuclei towards stability

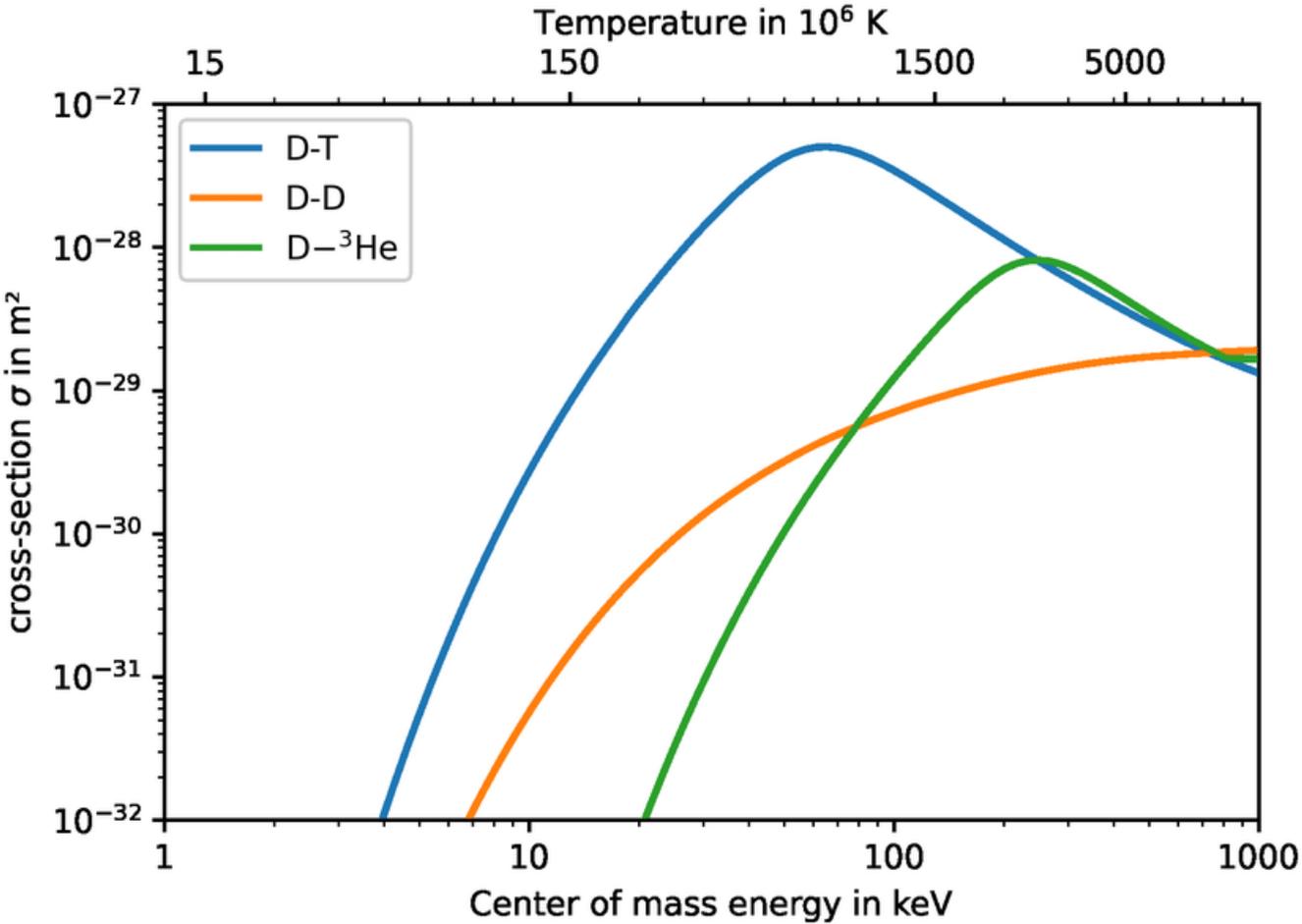


Fusion Energy

- Fusion can occur only at high temperature (~150 million C) due to the Coulomb barrier
- How can we contain the nuclei of that high temperature?

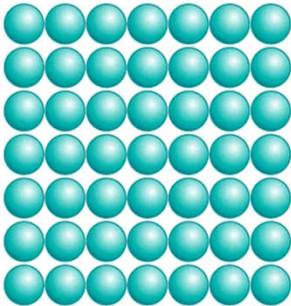


Cross Section of Nuclear Reaction as a function of energy (temperature)



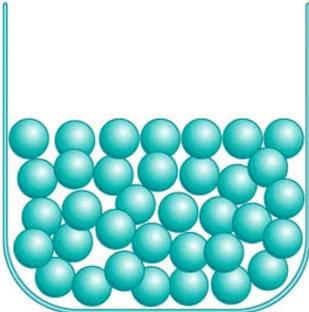
States of Matter

Physical states



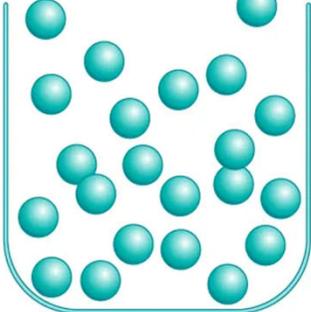
Solid

The molecules that make up a solid are arranged in regular, repeating patterns. They are held firmly in place but can vibrate within a limited area.



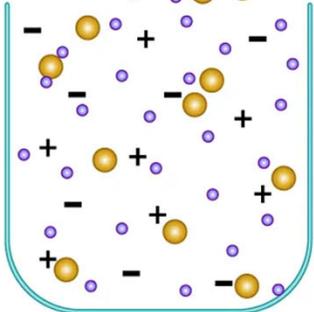
Liquid

The molecules that make up a liquid flow easily around one another. They are kept from flying apart by attractive forces between them. Liquids assume the shape of their containers.



Gas

The molecules that make up a gas fly in all directions at great speeds. They are so far apart that the attractive forces between them are insignificant.

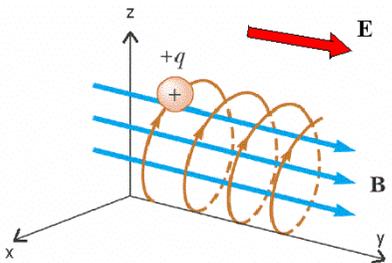


Plasma

At the very high temperatures of stars, atoms lose their electrons. The mixture of electrons and nuclei that results is the plasma state of matter.

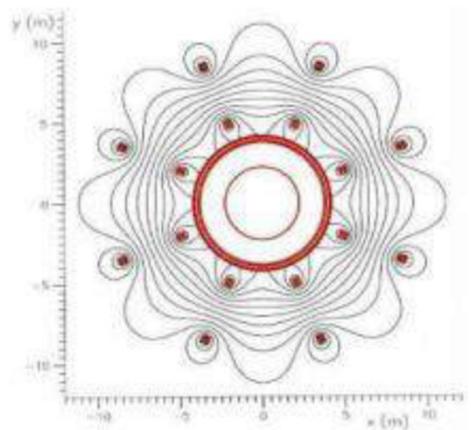
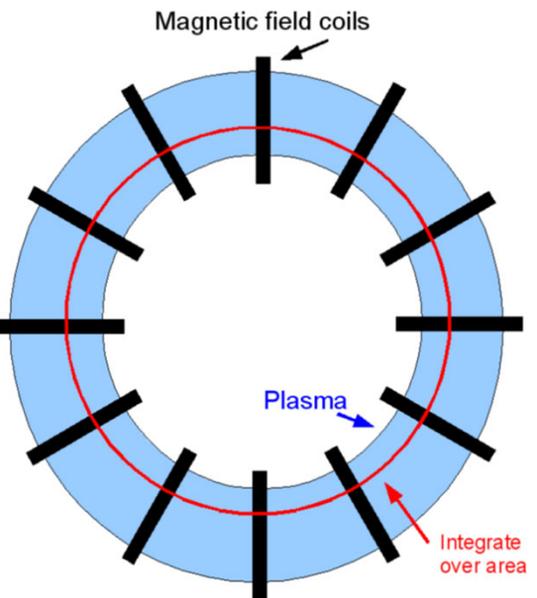
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Confinement of Plasma by Magnetic Fields



Motion of charged particle in magnetic field

- How can we contain the nuclei of that high temperature (~150 million C)?
- A key issue for nuclear fusion reactors is plasma confinement, which can be achieved by means of strong and properly shaped magnetic fields.



- The simplest configuration is to rely on a toroidal field.
- But practical field strength varies as a function of plasma radius

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

$$2\pi R B_\phi = \mu_0 I$$

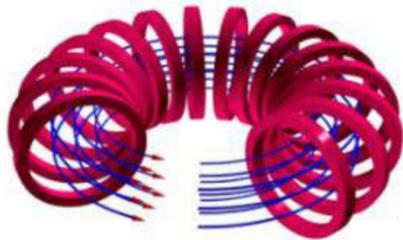
$$B_\phi = \frac{C}{R} \quad \nabla B = \nabla \left(\frac{C}{R} \right) = -\frac{C}{R^2} \mathbf{e}_R = -\frac{B}{R} \mathbf{e}_R$$

$$F = -\mu \nabla B$$

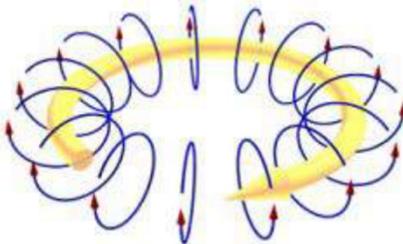
Which leads motion to the torus wall.

Tokamak (toroidal chamber with magnetic coils)

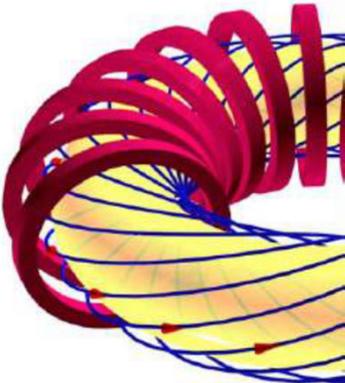
- A toroidal plasma current will generate a poloidal field, and the drift will be balanced by a return flow along the field.
- In a tokamak, the desired field lines are obtained by the combination of a toroidal magnet system and the circulation of a strong current in the plasma.
- The magnetic flux through the iron core is increase ($-\frac{\partial B}{\partial t} = \nabla \times E$) and it generates a toroidal current/poloidal field.
- The tokamak concept was developed by I. Tamm and A. Sakharov in the 1950's.



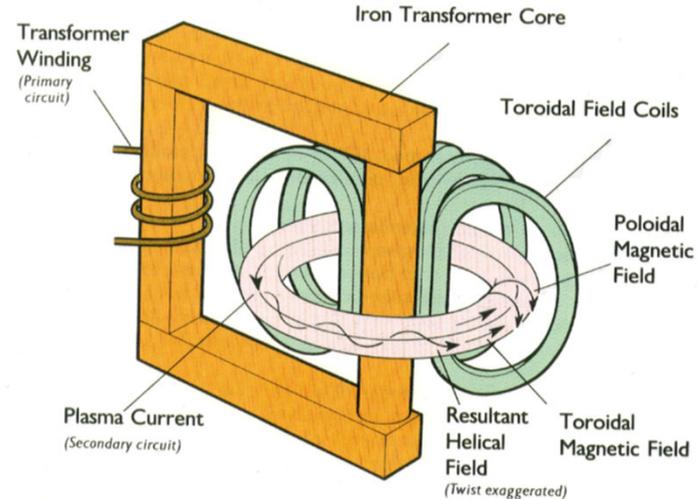
Toroidal Field



Poloidal Field Induced by Plasma Current

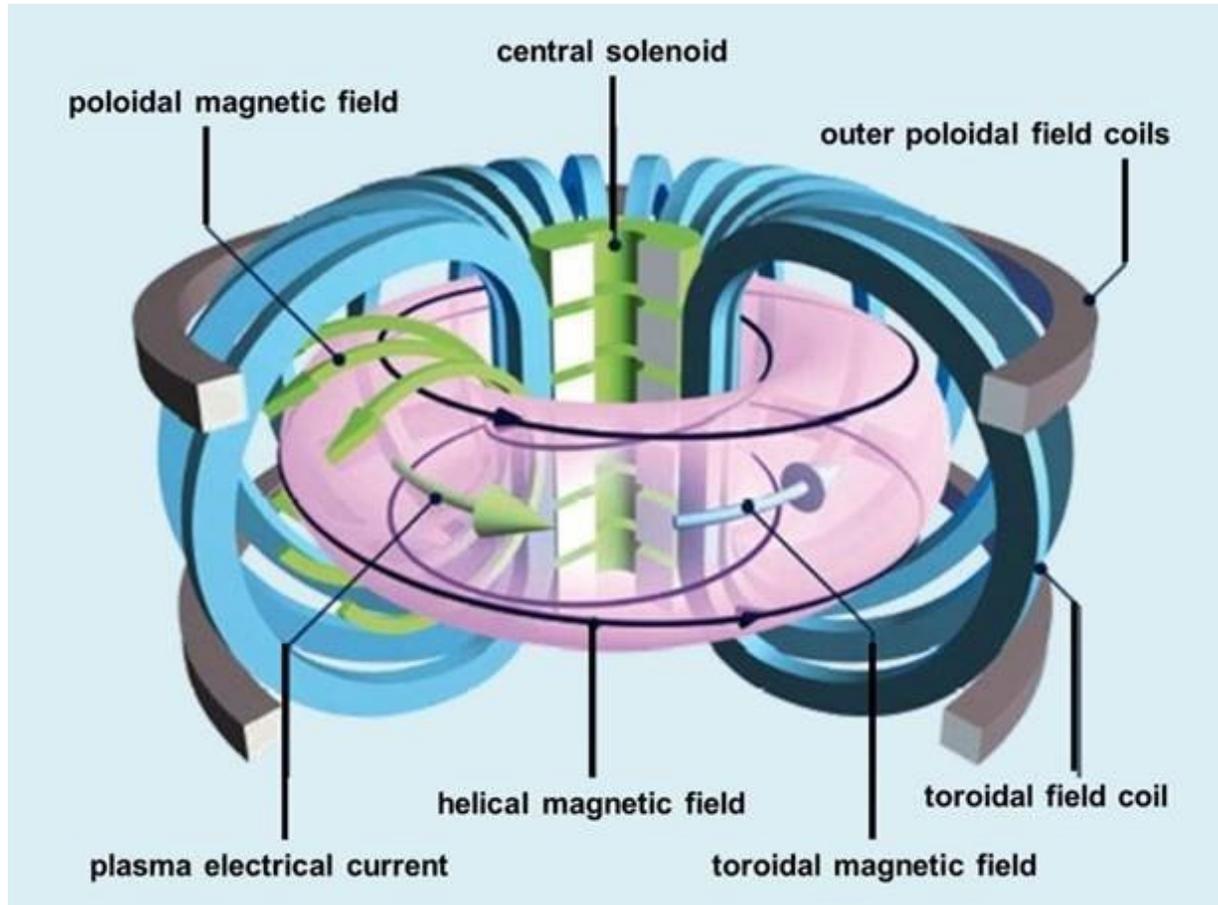


Toroidal & Poloidal Fields Combination



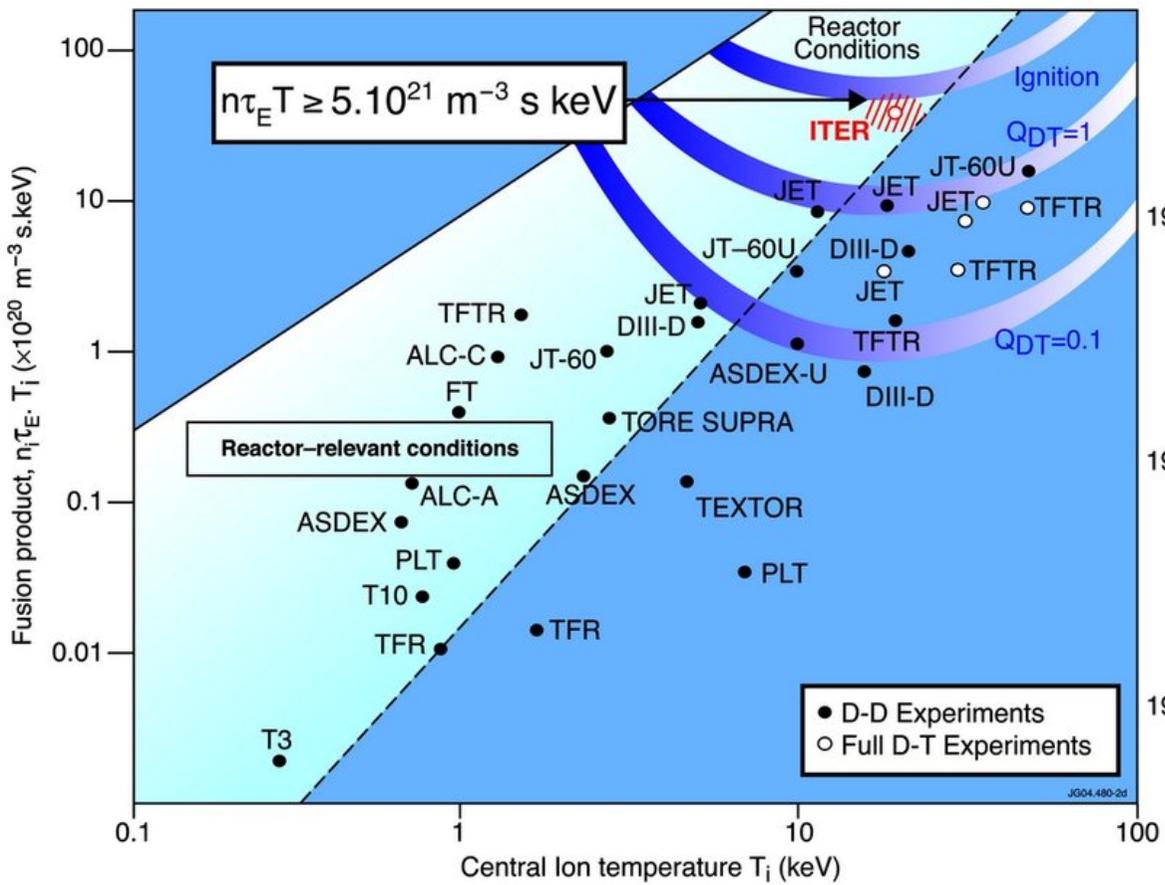
The plasma is the second winding of a transformer.

Magnets in a Tokamak



- **TF Coils** are used for charged particles' confinement in plasma.
- **CS coils** are used to produce inductive flux and to ramp up plasma current; they also play a role in plasma shaping and vertical stability.
- **PF coils** are used to control radial position of plasma, as well as for plasma shaping and vertical stability.

Can Tokamak be Energy Source?



- There are more than 100s of tokamaks in the world.
- Record of fusion was in JET in 1993.

$$Q_{DT} = \frac{P_{fus}}{P_{in}} < 0.6$$

- For fusion as an energy source

$$Q_{DT} \gg 1$$

- Results of Nuclear physics is

$$P_{fus}/V \propto \left(\frac{\beta_N}{q^*}\right)^2 \left(\epsilon \frac{1 + \kappa^2}{2}\right)^2 B_T^4$$

$$\frac{\beta_N}{q^*} : \text{safety factor,}$$

$$\epsilon \frac{1 + \kappa^2}{2} : \text{geometrical factor}$$

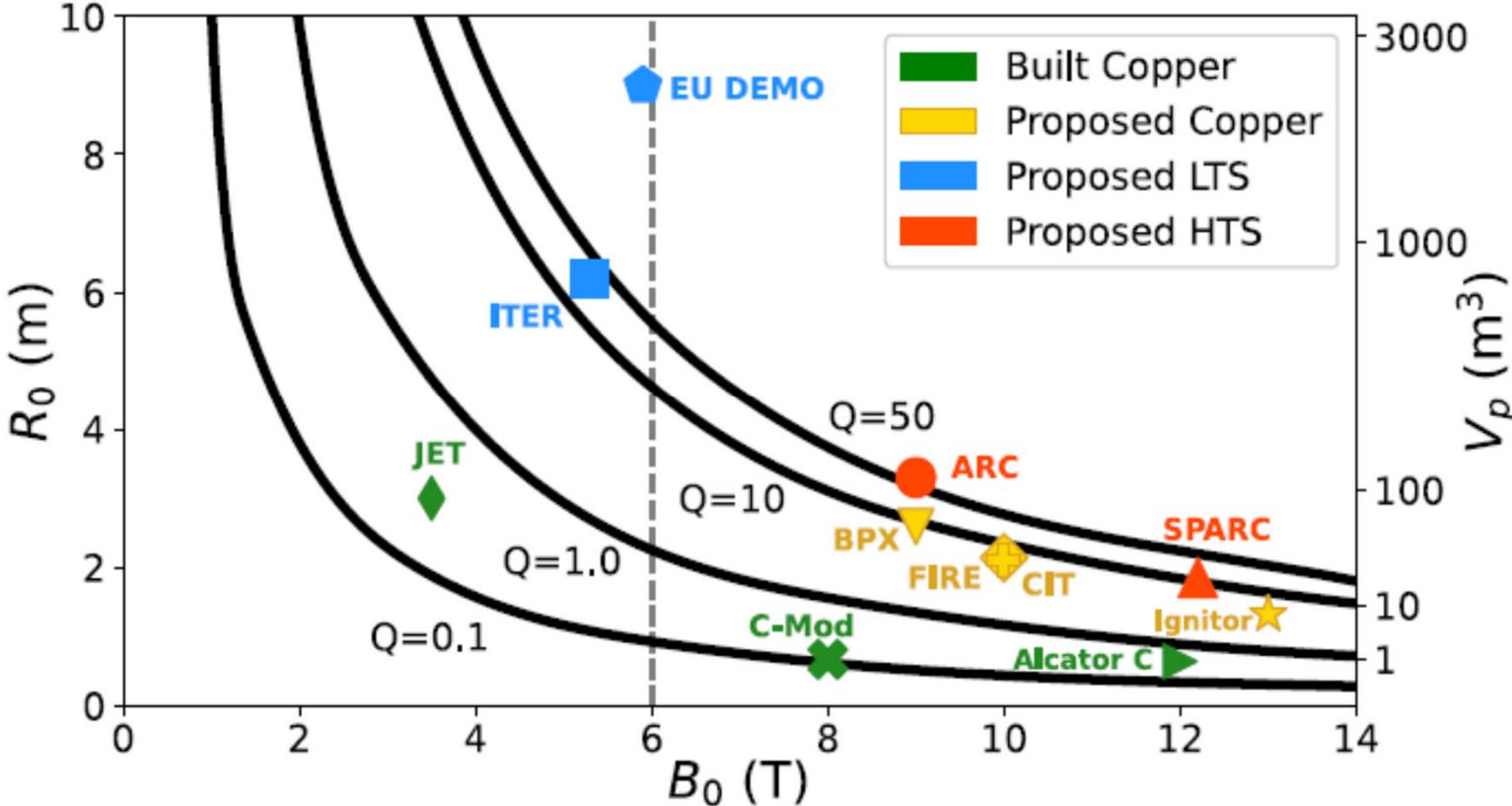
Do not vary significantly from tokamak to tokamak, so

$$\Rightarrow P_{fus} \propto R^3 B_T^4$$

Size of the Tokamak

Creely, A. J., Greenwald, M. J., Ballinger, S. B. et al. (42 more authors) (2020) Overview of the SPARC tokamak. Journal of Plasma Physics. 865860502

$$P_{fus} \propto R^3 B_T^4$$



Parameters of Tokamaks

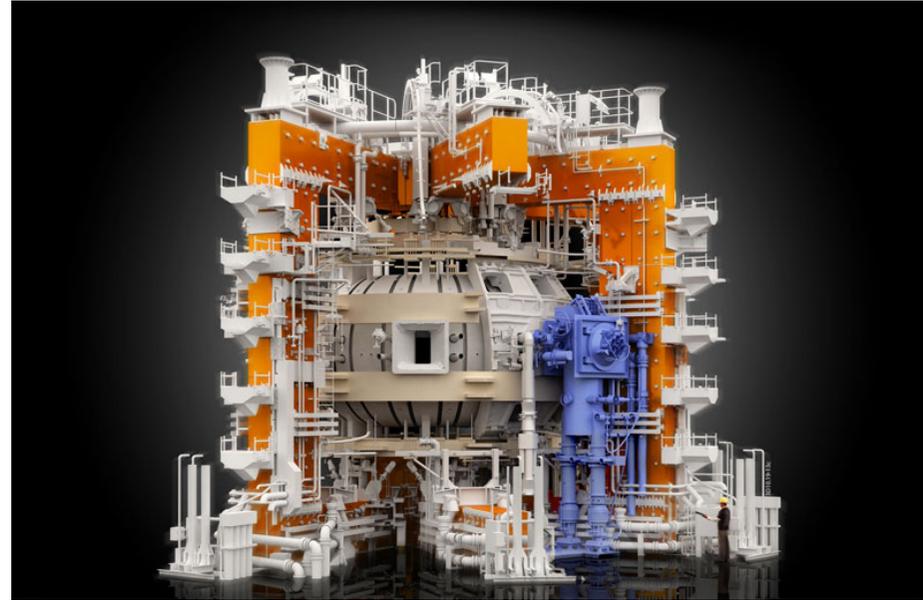
Parameter		SPARC (CFS)	C-Mod	AUG	DIIII-D	EAST	KSTAR	Ignitor	CIT	FIRE	BPX	ITER
R	m	1.85	0.67	1.65	1.66	1.70	1.80	1.32	2.10	2.14	2.59	6.2
a	m	0.57	0.21	0.50	0.67	0.40	0.50	0.47	0.65	0.60	0.80	2.0
B _T	T	12.2	8.0	3.9	2.2	3.5	3.5	13.0	10.0	10.0	9.0	5.3
I _p	MA	8.7	2.0	1.6	2.0	1.0	2.0	11.0	11.0	7.7	11.8	15.0
P _{aux,max}	MW	25	6	30	27	28	16	24	20	20	20	73
P _{flattop}	s	10	1	10	6	1000	300	4	5	20	10	400
P _{fus}	MW	140						96	800	150	100	500
Q		11						9	∞	10	5	10

Planned and/or under construction

Existing

Conventional vs. Superconducting

- At present, the largest fusion machine is the Joint European Torus (JET) Tokamak, located in Culham, UK
 - major plasma radius: ~ 3 m,
 - plasma volume: ~ 100 m³,
 - magnetic field: ~ 3.45 T.
- The JET Tokamak relies on conventional magnets and requires up to 500 MW of electrical power!
- Larger machines (in size and/or magnetic field) call for the use of superconducting magnets.



Views of JET Tokamak (2.96 m; 1983)

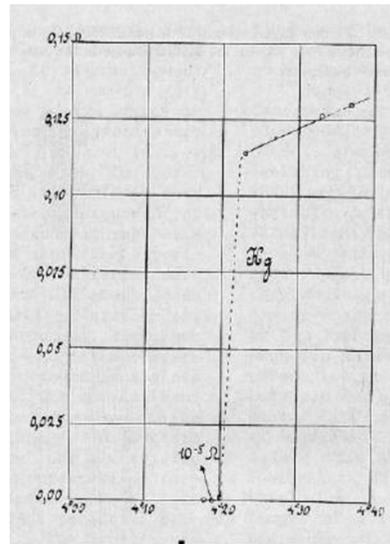


What is Superconductivity?

- Superconductivity is a unique property exhibited by some materials, whose resistivity drops to zero when cooled down below a threshold temperature called the critical temperature, T_C .
- As a result, materials in the superconducting state can transport current without power dissipation by the Joule effect.



H. Kammerling-Onnes
(1853–1926)



Discovery of Superconductivity On a Hg Sample (1911)

- Superconductivity was discovered in 1911 in a Laboratory of Leiden University, in the Netherlands, headed by Heike Kamerling-Onnes.

What is Superconductivity?

- Superconductivity is a rule rather than an exception.
- BCS (Bardeen, Cooper, Shrieffer) Theory gives T_c as follows

$$k_B T_c = 1.134 E_D e^{-1/N(0)V}$$

KNOWN SUPERCONDUCTIVE ELEMENTS

■ BLUE = AT AMBIENT PRESSURE
■ GREEN = ONLY UNDER HIGH PRESSURE

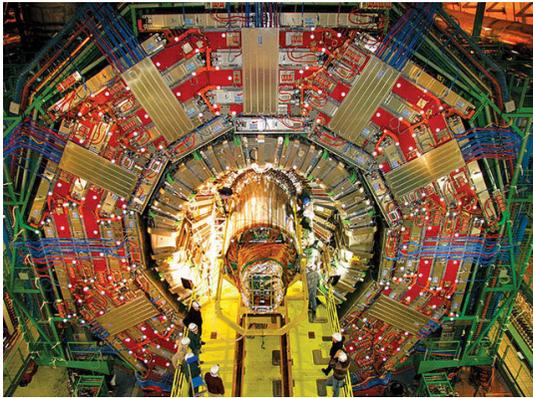
1	IA	1	H	IIA	4	2	0	2	He														
3		3	Li	4	Be	5	6	7	8	9	10	Ne											
11		11	Na	12	Mg	13	14	15	16	17	18	Ar											
19		19	K	20	Ca	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	Kr	
37		37	Rb	38	Sr	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	Xe	
55		55	Cs	56	Ba	57	*La	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	Rn
87		87	Fr	88	Ra	89	+Ac	104	105	106	107	108	109	110	111	112							

SUPERCONDUCTORS.ORG

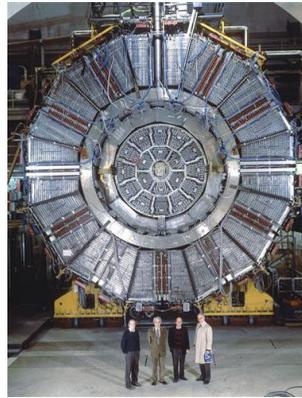
* Lanthanide Series	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
+ Actinide Series	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Pros of Superconductivity

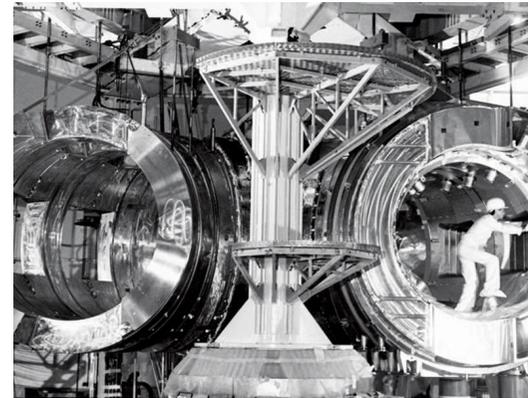
- Superconductivity offers at least two advantages
 - a significant reduction in electrical power consumption,
 - the possibility of relying on much higher overall current densities in the magnets coils (thereby resulting in more compact windings).
- This enables the design and manufacture of large and powerful magnet systems.



CMS @CERN



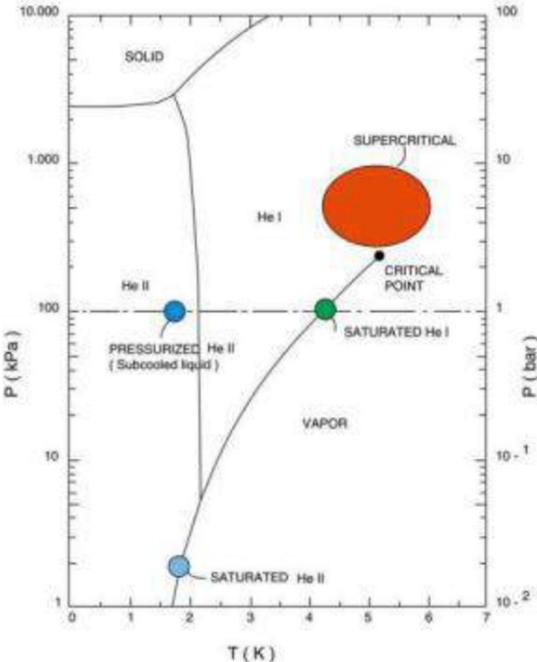
ALEPH Experiment
@CERN (1989)



Tore Supra @CEA (1988)

Cons of Superconductivity

- The main drawback of superconductivity is that the magnet coil must be cooled down and kept below T_C throughout operation.
- The T_C of practical superconductors (NbTi and Nb₃Sn) calls for the use of liquid helium (LHe) whose boiling temperature is 4.2 K (-269°C) at 1 atm.
- Production and handling of LHe requires dedicated infrastructures and the magnet must be mounted inside a cryostat.



He Phase Diagram



Cryo Plant of CERN

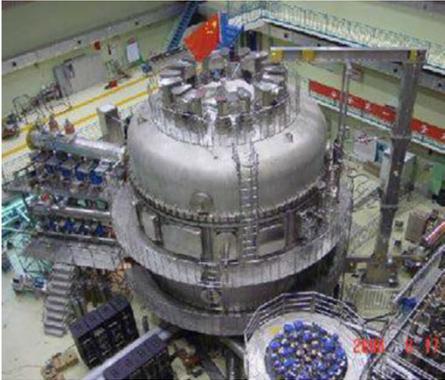


Cryo Test Facility (CEA/Saclay)

Superconducting Tokamak in the World



Tore Supra, CEA, France
(2.4 m; 1988)



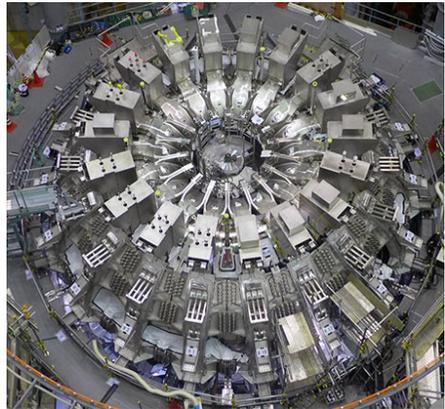
EAST, ASIPP, China
(1.8 m; 2006)



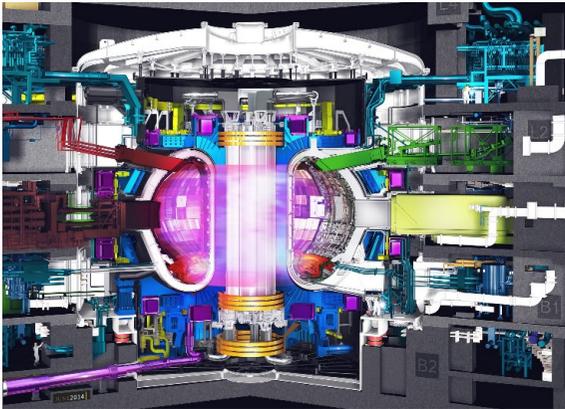
KSTAR, KFE, Korea
(1.8 m; 2008)



SST-1, IPR, India
(1.1 m; 2012)



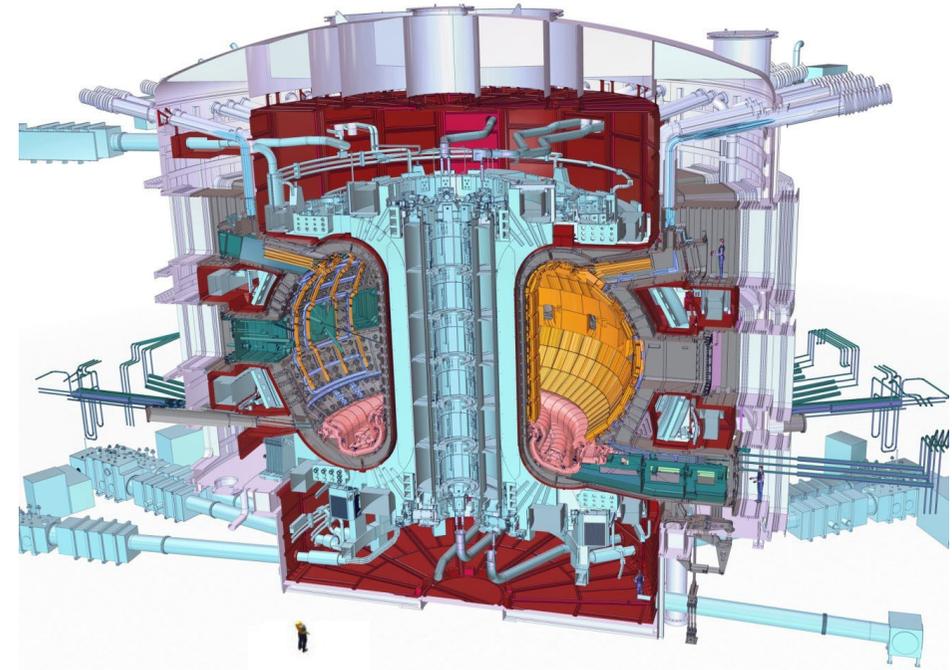
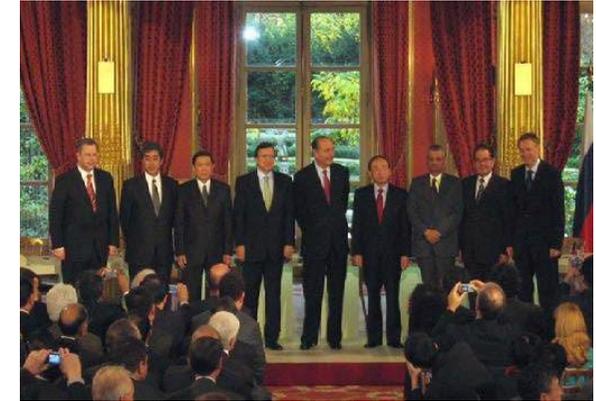
JT-60SA, QST, Japan
(3 m; 2023)



ITER, France
(6.2 m; 2033?)

ITER

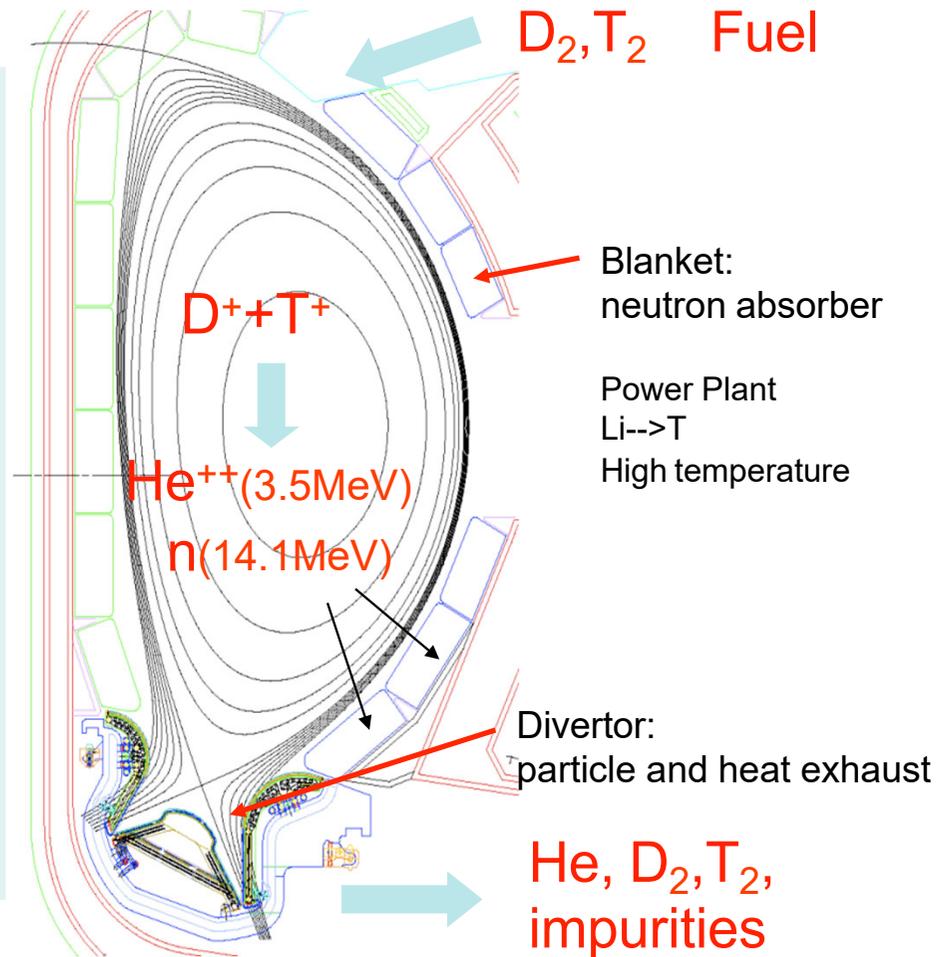
- **ITER** (“The way” in Latin) is an acronym of **I**nternational **T**hermonuclear **E**xperimental **R**eactor.
- The ITER project was born in 1985 at a superpower summit meeting in Geneva between R. Reagan and M. Gorbachev.
- 7 partners (China, EU, India, Japan, Korea, Russia and US) have been participating in ITER since 2006.
- ITER is designed to produce 500 MW of fusion power ($Q=10$) for extended periods of time (several 100s).



ITER

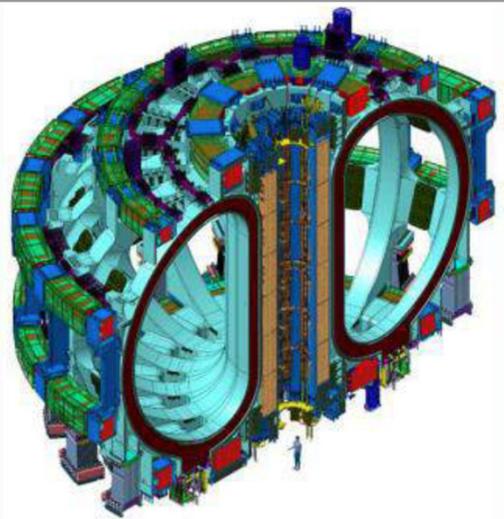
ITER Plasma:

R/a: V_0	6.2 m / 2 m
Volume:	830 m ³
Plasma Current:	15 MA
Toroidal field:	5.3 T
Density:	10 ²⁰ m ⁻³
Peak Temperature:	2 × 10 ⁸ K
Fusion Power:	500 MW
Plasma Burn	300 - 500 s
("Steady-state")	~3000 s)



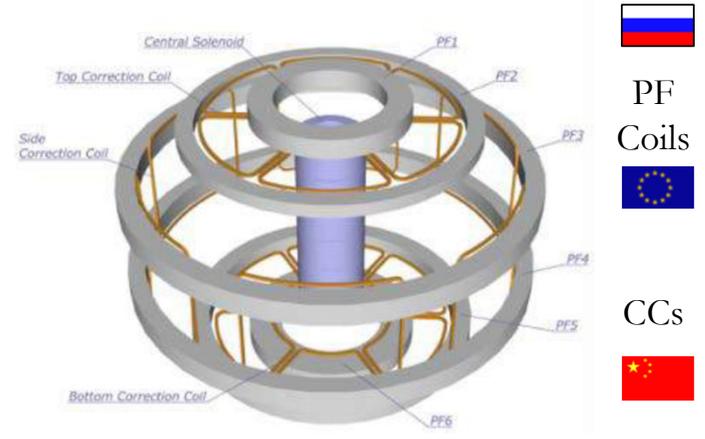
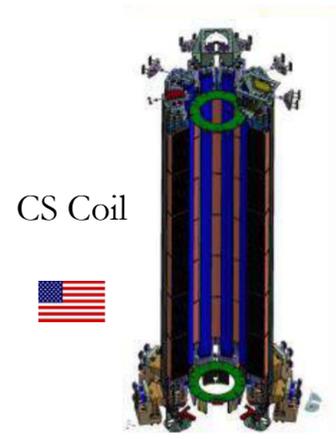
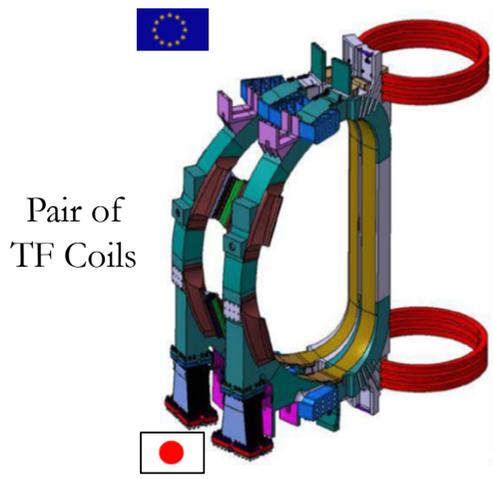
D.J. Campbell, Fusion Plasma Physics and ITER: An Introduction, CERN Academic Training Programme, 12-13 April 2011

ITER Magnet System



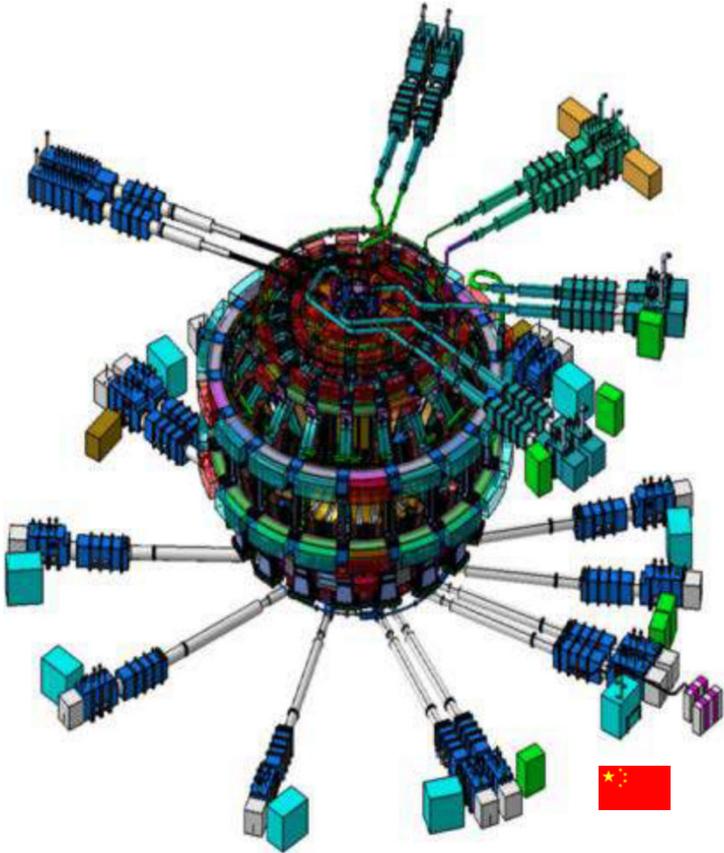
ITER Magnet System ~10,000 t

- The ITER magnet system is made up of
 - 18 Nb₃Sn Toroidal Field (TF) Coils,
 - a 6-module Nb₃Sn Central Solenoid (CS),
 - 6 NbTi Poloidal Field (PF) Coils,
 - 6 NbTi pairs of Correction Coils (CCs).



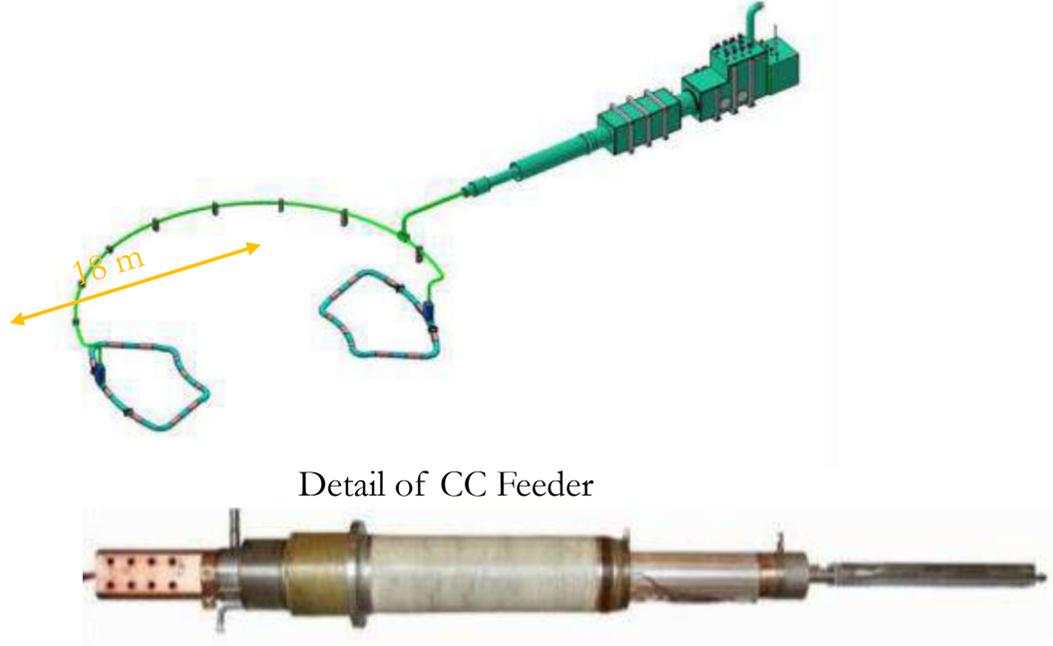
Feeders

- ITER magnets are supplied with current/cryogenic fluids by 31 Feeders.



ITER Feeder System

- The magnet Feeders include
 - NbTi CICC busbars (MB & CB),
 - Ag-Au(5.4%) BiSCCO 2223 HTS current leads.

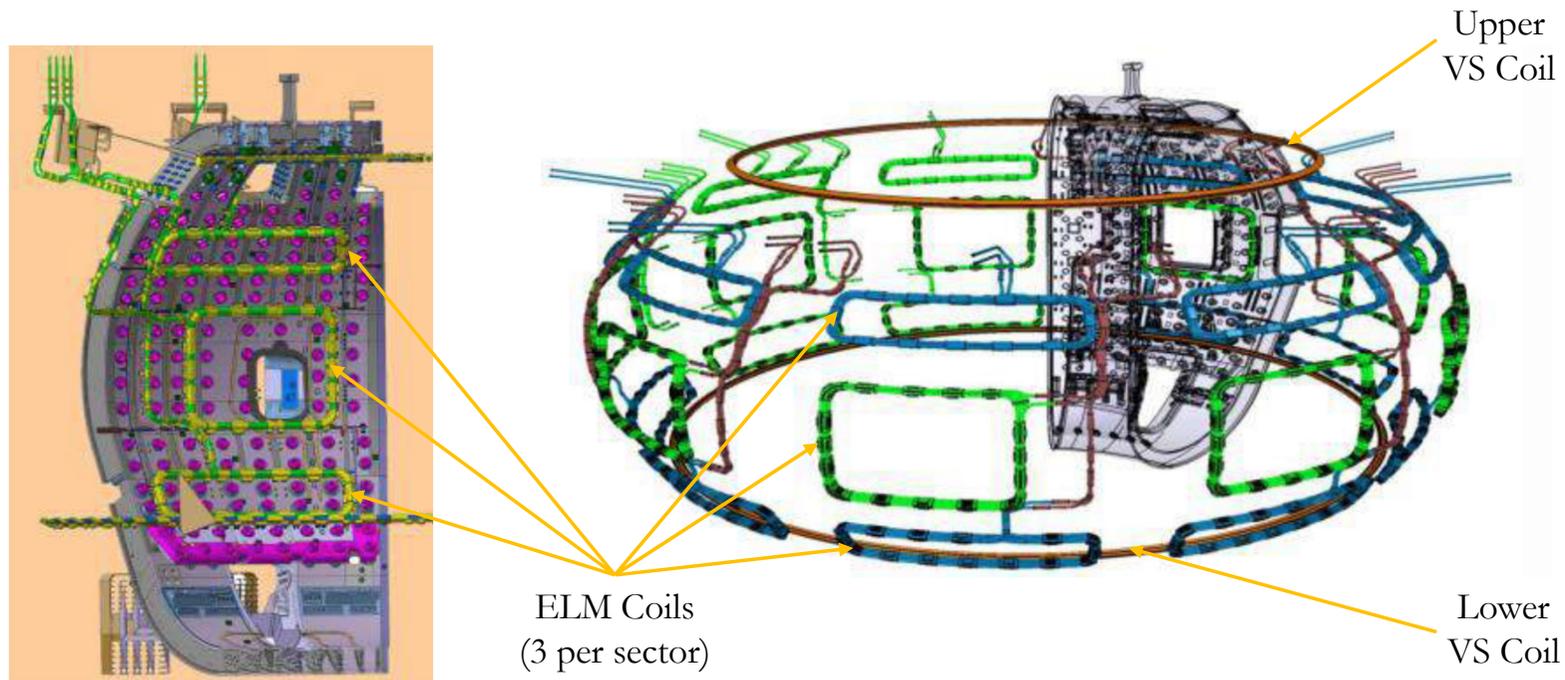


Detail of CC Feeder

68 kA Trial Lead Developed by ASIPP

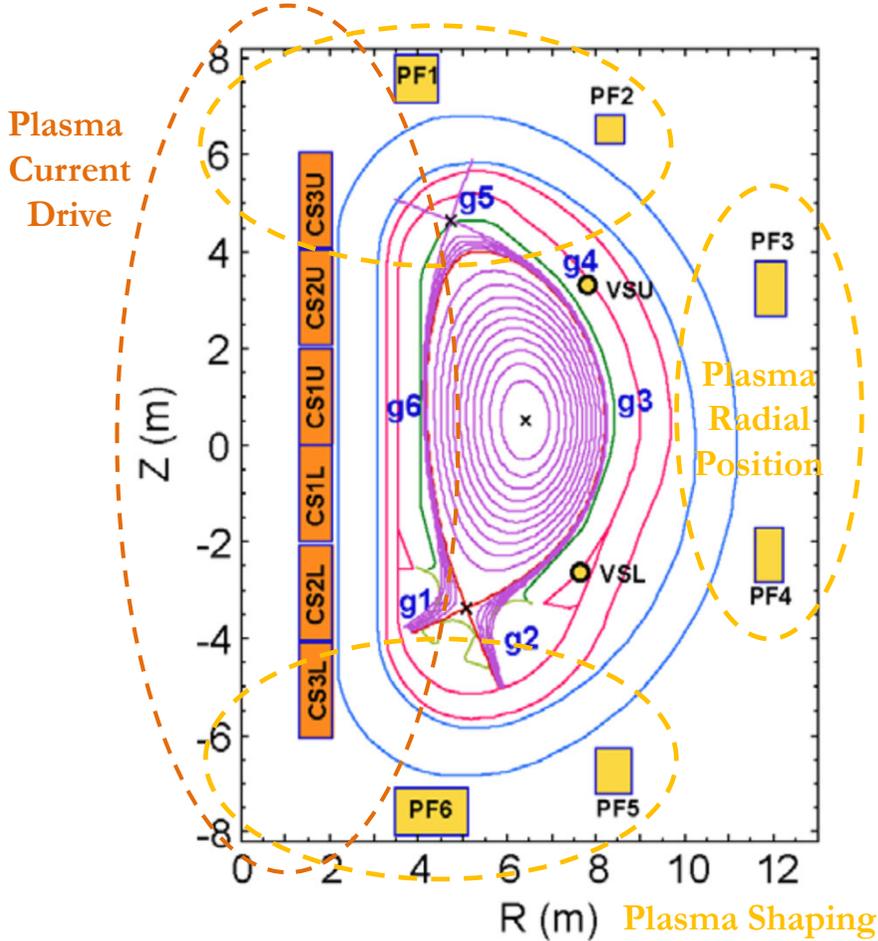
In-Vessel Coils

- In addition, the ITER tokamak is equipped with conventional, water-cooled, In-Vessel Coils, attached via rails to the outboard part of the inner wall of the vacuum vessel (underneath the blanket modules).



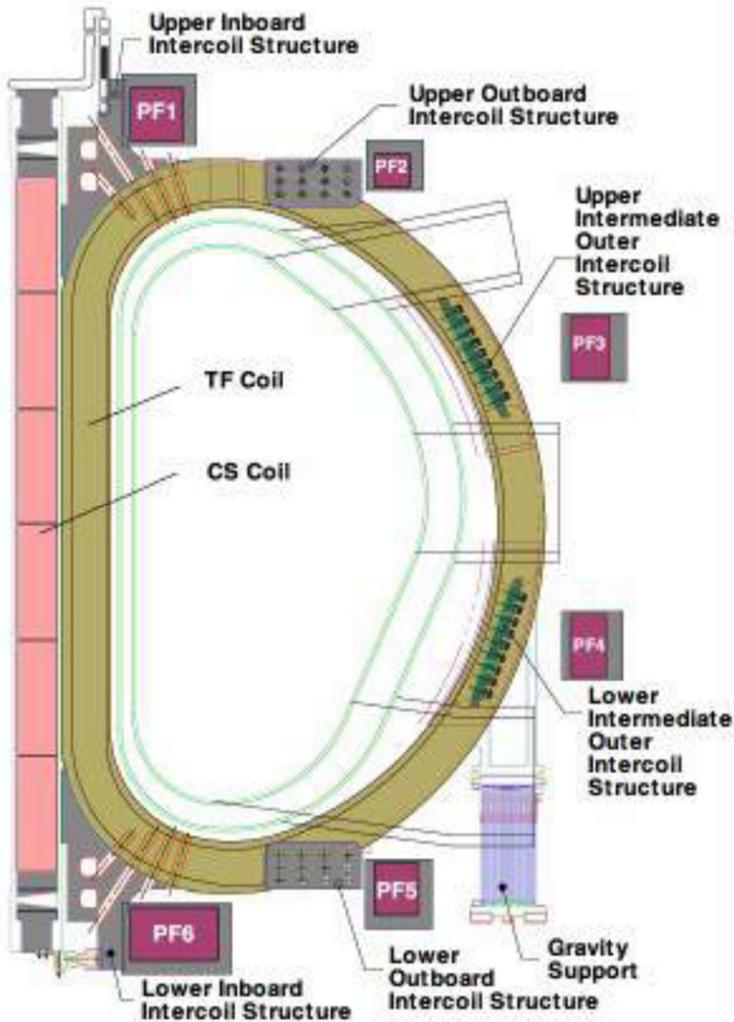
- The In-Vessel coils comprise: 3 x 9 picture-framed, ELM coils (aimed at suppressing Edge Localized Modes) and 2 ring, VS coils (aimed at better controlling Vertical Stability).

Roles of ITER Magnet Coils



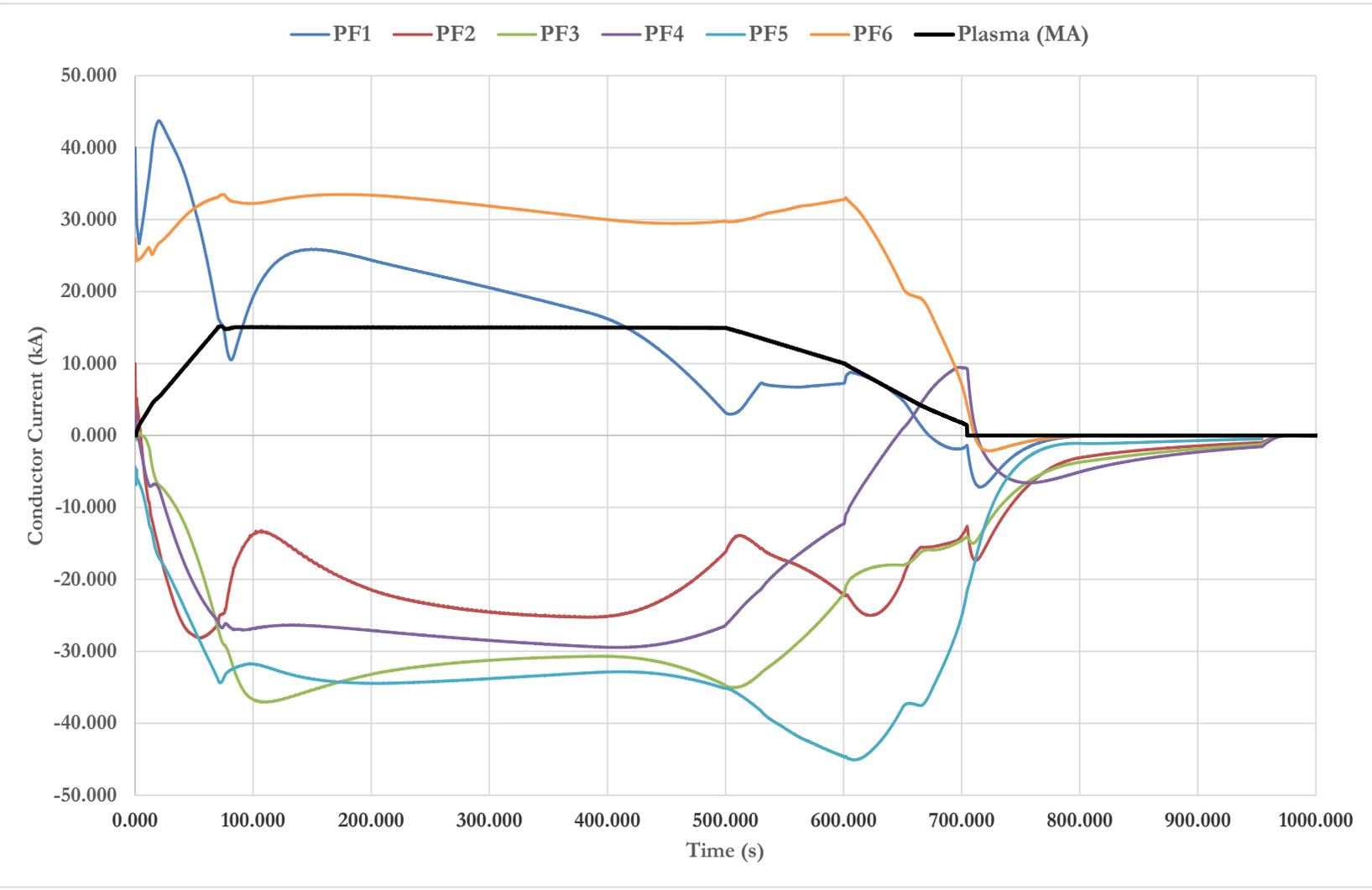
- **TF Coils** are used for charged particles' confinement in plasma.
- **CS coils** are used to produce inductive flux and to ramp up plasma current; they also play a role in plasma shaping and vertical stability.
- **PF coils** are used to control radial position of plasma, as well as for plasma shaping and vertical stability.
- **CCs** are used to correct field harmonics errors.

Parameters of ITER Magnets

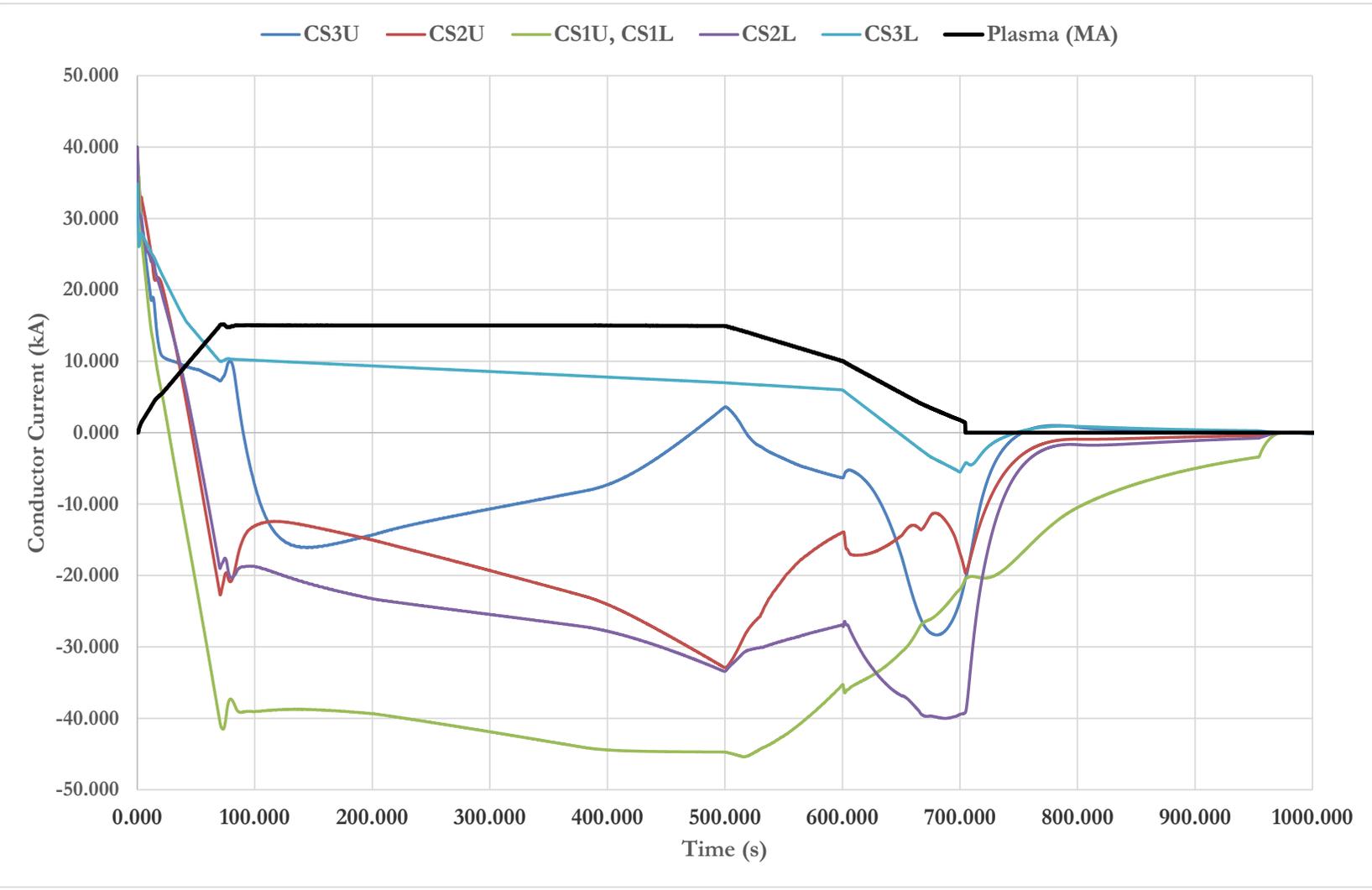


	TF	CS	PF
Number of Coils	18	1	6
Dimension	14x9 m	12x4 m	8 to 24 m
Conductor Type Quantity	Nb ₃ Sn CIC 88 km	Nb ₃ Sn CIC 42 km	NbTi CIC 65 km
Operating Current	68 kA	46 kA	52 kA
Operating Temperature	5 K	4.5 K	4.5 K
Peak Field	11.8 T	13.0 T	Up to 6.0 T
Stored Energy	41 GJ	6.4 GJ	4 GJ
Total Weight	6540 t	974 t	2163 t

PF Coil Reference Scenario (15 MA Plasma Current)



CS Coil Reference Scenario (15 MA Plasma Current)



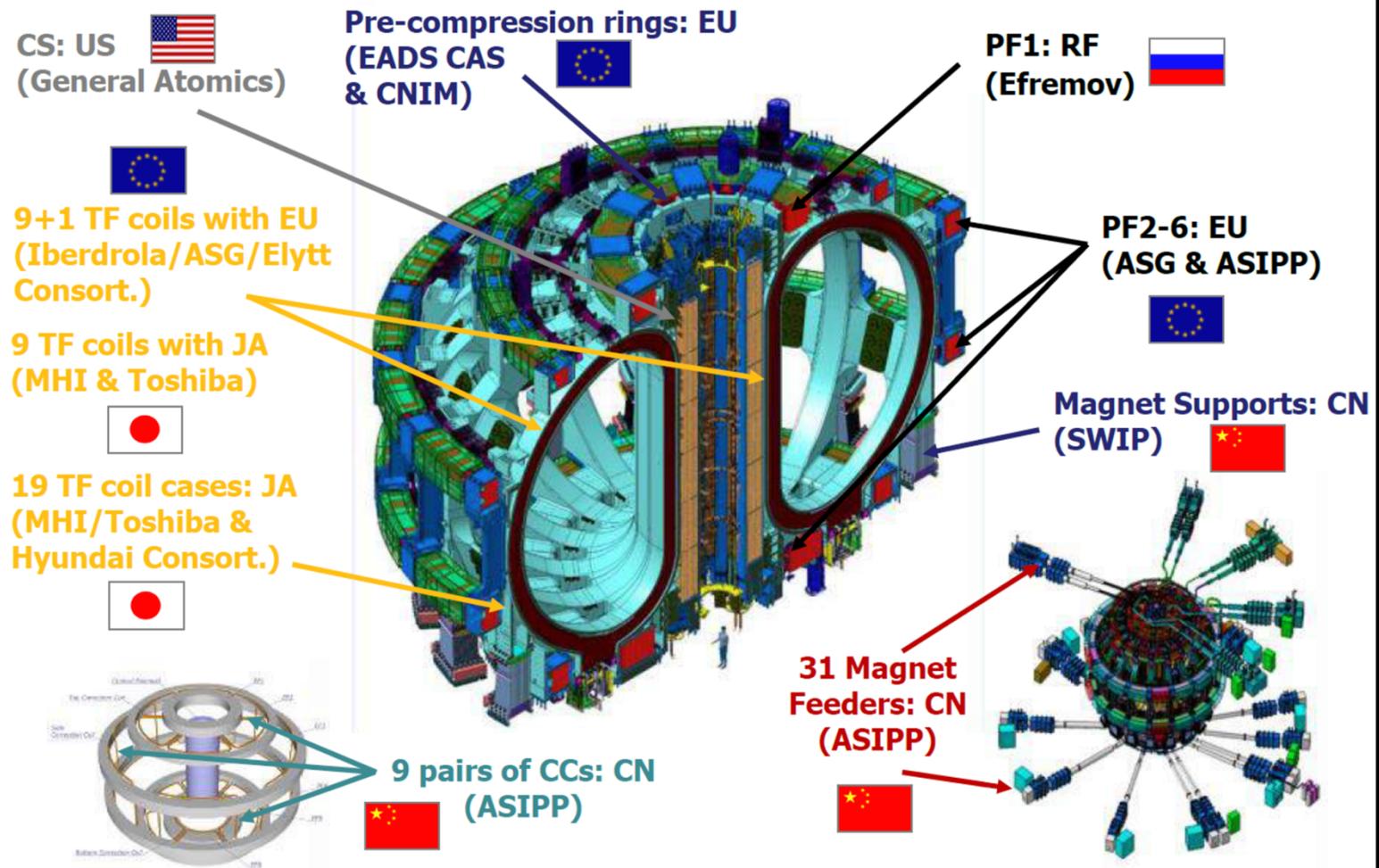
Operational Requirements of ITER Magnets

- The basic design requirements are **30,000 plasma pulses** of 15 MA current with a burn length of 400 s, and a total fusion power of 500 MW.
- The magnets will be designed for **100 cooldown and warm-up cycles, 1,000 TF charging cycles, 50 TF fast discharges and 10 quenches**. These operations are all big stress to TF Coils.
- A fast discharge of the TF system will require a fast discharge of all coils (TF, CS, PF and CC). Fast discharge of a CS or PF coil will require an associated fast discharge only of the CS and PF system. A quench of a CC will require a fast discharge only of the CC system.
- The magnets need not be ready for further operation (i.e. completely re-cooled) until 96 hrs after a fast discharge of the TF system. In the event of a fast discharge of only CS, PF or CC, the magnets will be re-cooled ready for further operation within 2 hrs.

Magnet Design Criteria

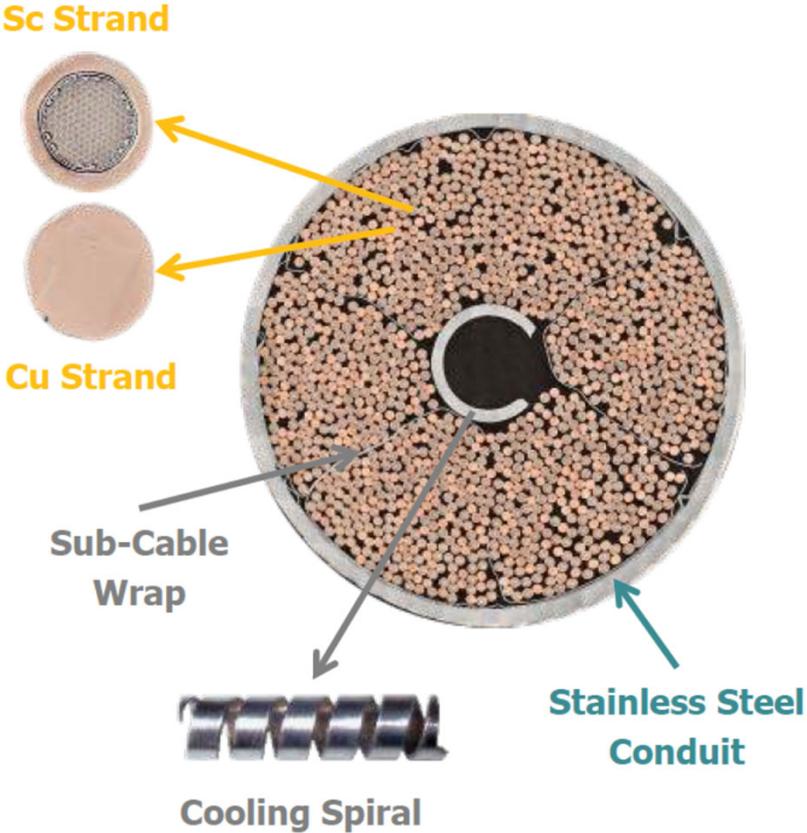
- The magnets operate 4K-77K, mostly 4K. Compared to high temperature, yield and ultimate strength are increased but fracture toughness similar. **Fracture is relatively much more important as a failure mode than plastic yielding.**
- **Extensive use of non-metallic materials** especially for bonding and compressive load transmission.
- The **loads** have strong **cyclic** components.
- **Pressure is not significant design factor.** Electromagnetic loads cause 3D stress systems, generally need FE analysis, different to pressure vessels.
- Combination of structural support functions in a High Voltage environment; **the structural limits could be defined by the electrical functionality.**
- **No previous experience with such a design**
- **Needs for specific set of design criteria**

ITER Magnet Supply: 10 PAs/5 DAs



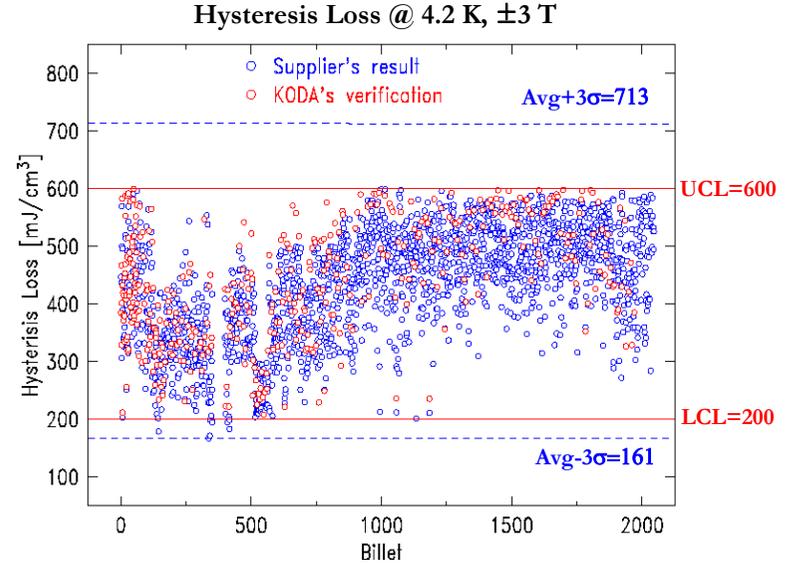
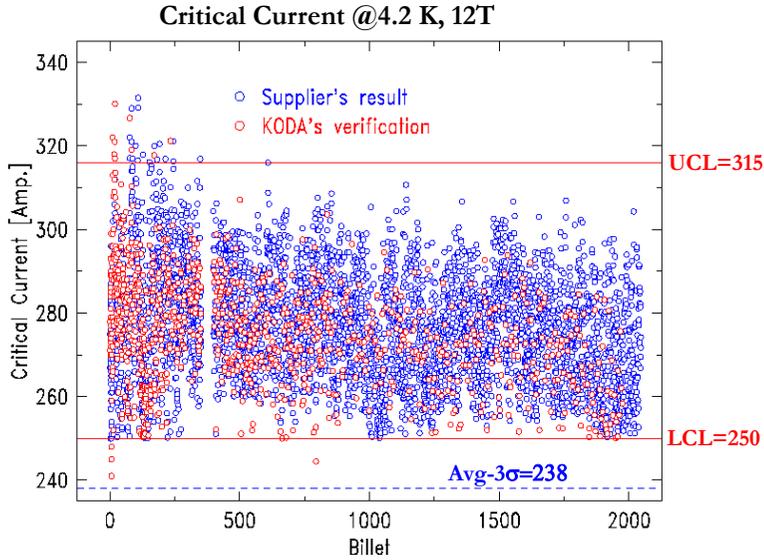
Cable-In-Conduit Conductors

- ITER magnets rely on Cable-In-Conduit Conductors (CICCs).
- Main features are
 - Nb₃Sn or NbTi superconducting (sc) strands mixed with Cu strands,
 - multi-stage, rope-type cable with stainless steel cable/subcable wraps and a central cooling spiral (save for CC/MB conductors),
 - circular, rectangular or circle-in-square, austenitic stainless steel conduit made up of butt-welded jacket sections.
- Cooling is provided by forced flow of supercritical helium.



Specifications and Characteristics of Nb₃Sn Strand (Korean Share)

- Nb₃Sn strand specifications are **functional** and call for
 - Diameter (un-reacted, Cr-plated) 0.820 ± 0.005 mm
 - Cu-to-Non-Cu volume ratio 1.00 ± 0.10
 - I_C at 4.22 K and 12 T (on ITER Barrel) > 250 A
 - Hysteresis loss per strand unit volume < 600 mJ/cm³
(± 3 T at 4.2 K cycle on a sample longer than 100 mm)
 - RRR (after Cr-plating & heat treatment) > 100
- Statistical Process Control is applied for monitoring the strand performance.



Cable (Korean Share)

- Cable specifications are **built-to-process** and call for
 - Cable pattern $((2sc+1Cu) \times 3 \times 5 \times 5 + core) \times 6$
 - Twist pitches 80/140/190/300/420 mm
- 29 Cables have been manufactured, and the final ATPP was cleared in May 2014.
- All the final stage cablings and destructive tests have been witnessed by KODA.

Planetary Cabling Machine



Compaction Rollers



Pulling Capstan



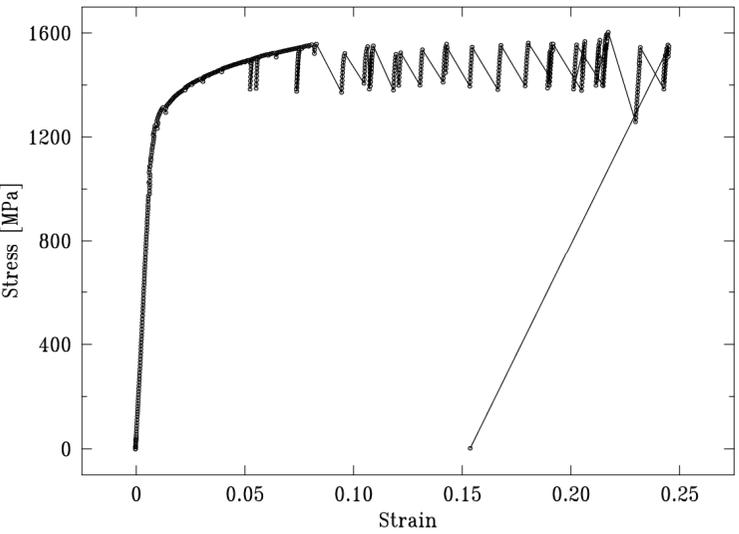
Take-up Spool



Jacket Sections (Korean Share)

- Seamless **Modified 316LN** Tubes have been produced from EAF/ESR melting.
- **Low Carbon/Cobalt** and **High Nitrogen** contents were strictly controlled during production.
- The requirement for the cryogenic tensile tests (**elongation > 20 %**) is tough to satisfy.
- POSCO Specialty Steel completed the production of ~20 km length Jacket Sections successfully and the final ATPPs were cleared in June, 2012.

Cryogenic Tensile Test
A30728-1



Hot Extrusion



Final Product



Highlights of Jacketing (Korean Share)

- Conductor specifications are **built-to-process** and call for
 - Seamless Jacket Sections, **butt-welded** together
 - Cable **pulled through** jacket assembly + **compaction**
 - Conductor outside/inside diameter **43.7/39.7 mm**
- 29 conductors were fabricated successfully and the final Hold Point was cleared in September, 2014.

Spoiled Conductor



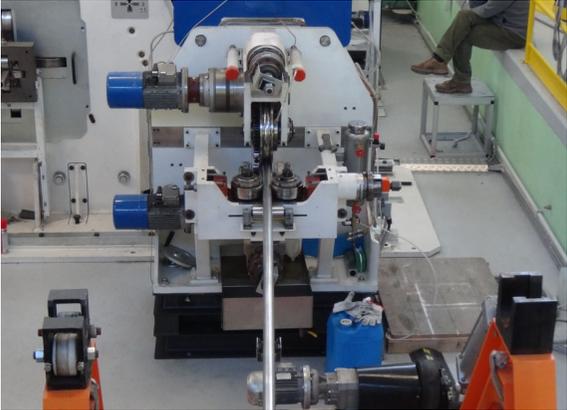
Cross Section



Orbital Butt Welding



Compaction

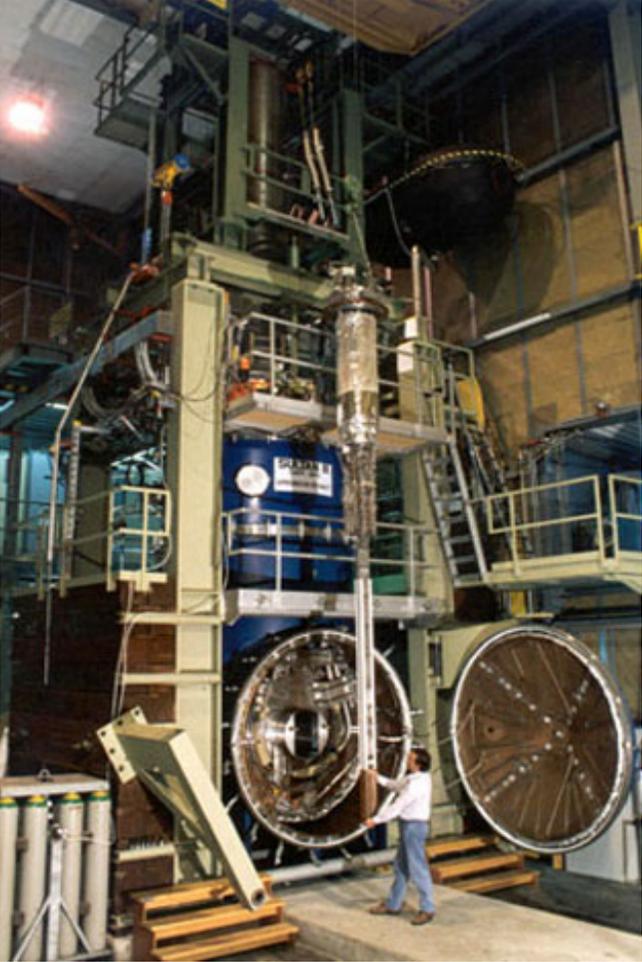


Spooling



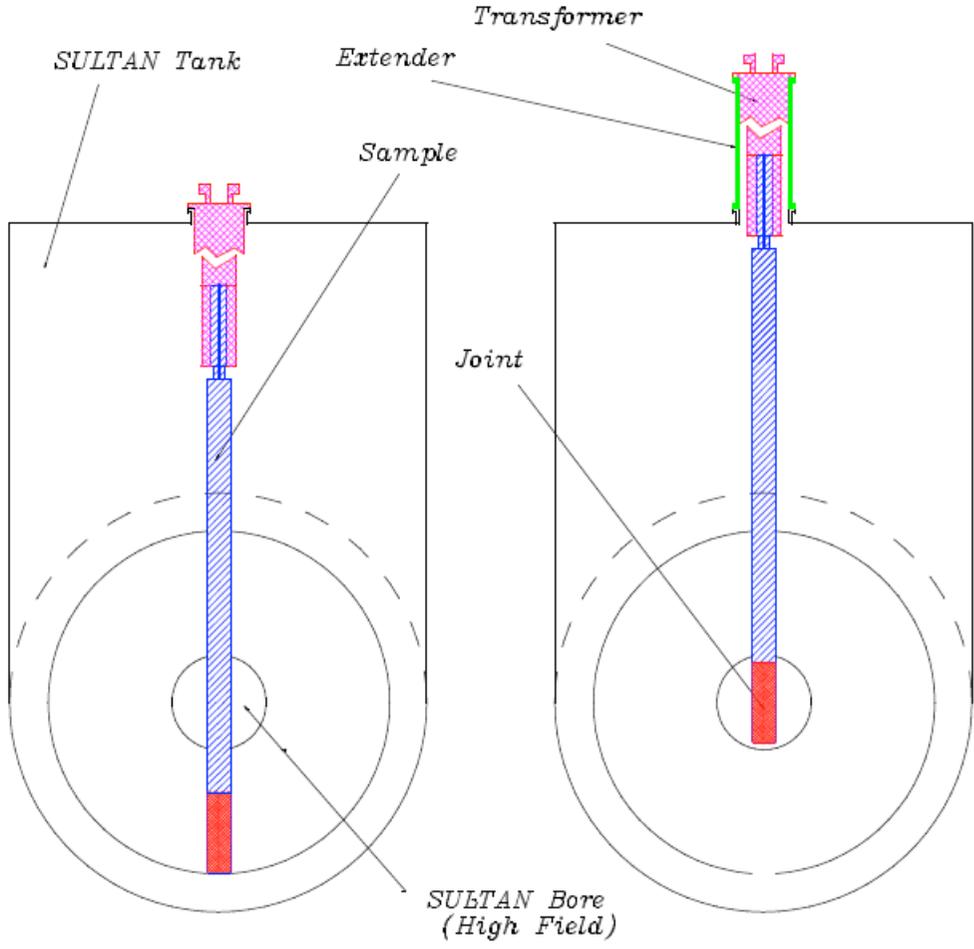
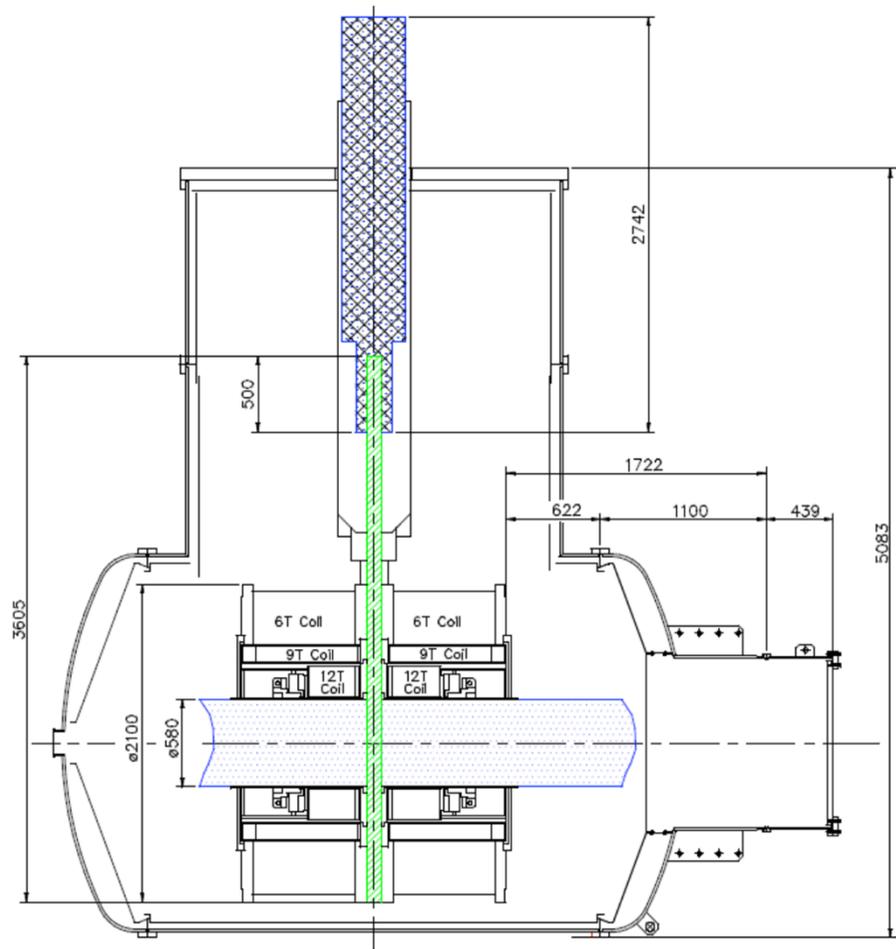
Qualification and Final Acceptance of the Conductor (SULTAN Test)

- SULTAN is the abbreviation of “SUpraLeiter Test Anlage”



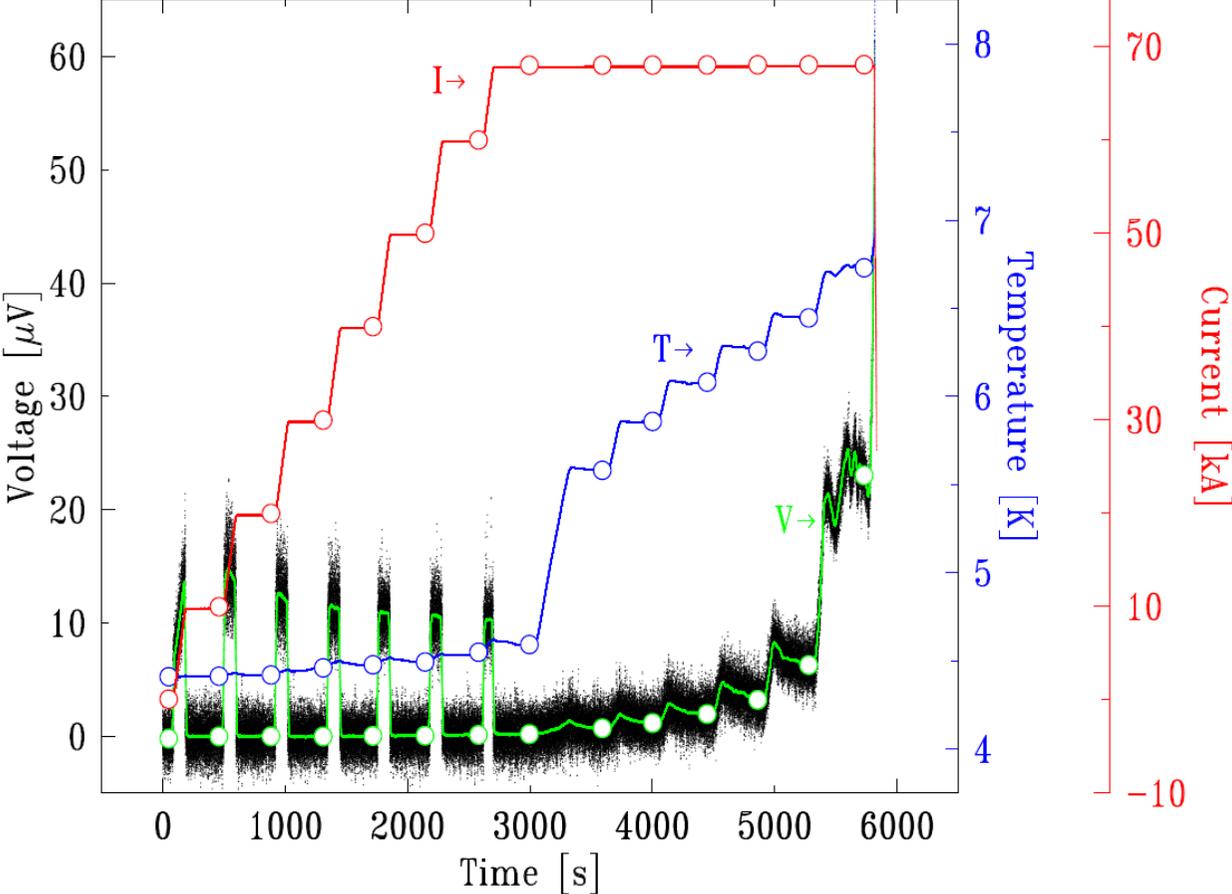
Background Magnet

- Magnetic field is generated by three concentric pairs of superconducting split coils



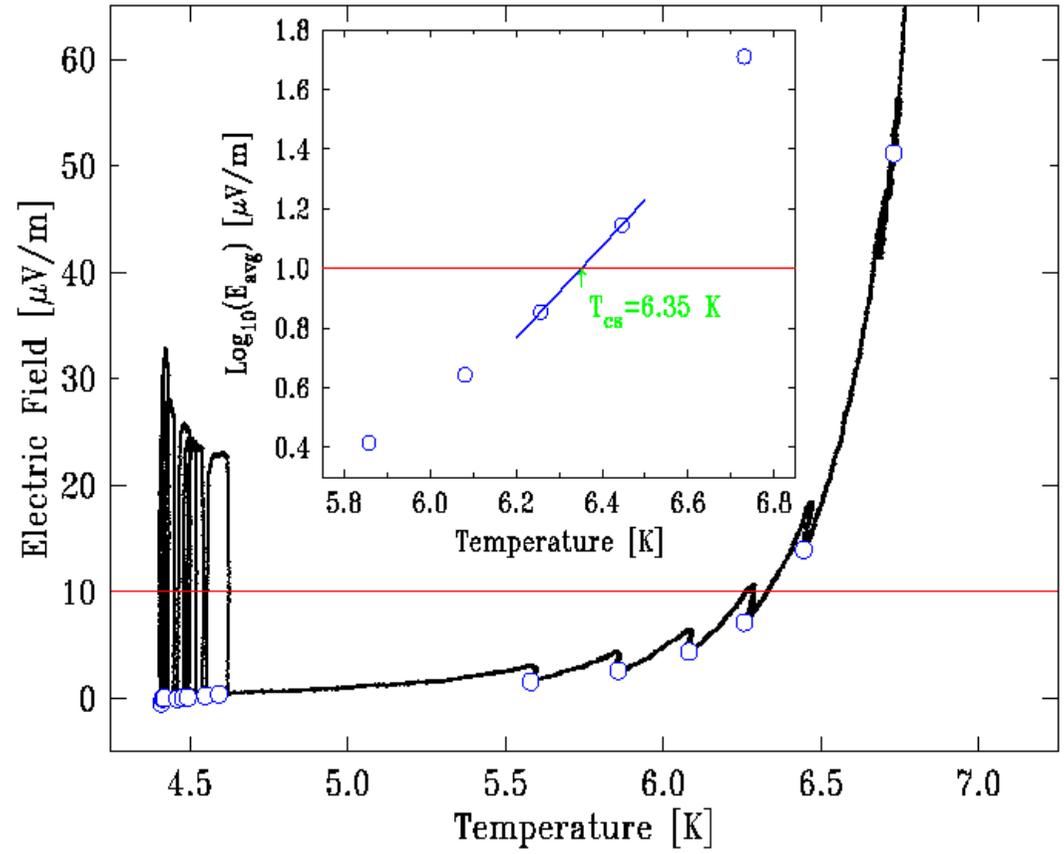
SULTAN Test (for ITER TF Conductor)

- Measurement of Current Sharing Temperature (T_{cs}) of short (~3.6 m), full sized conductor sample @68 kA, 10.78 T.
- Ramping up the current, step by step up to 68 kA, followed by ramping up the temperature, step by step till the conductor quenches (T_{cs} is defined as the temperature @ $E = 10 \mu\text{V/m}$).



T_{cs} Assessment

- Open circles are average point used for the calculation of T_{cs}. Black points are centered moving average of the electric field. Inset is the illustration of the T_{cs} assessment for Right Leg at N=1. Red lines are criteria for the critical electric field.

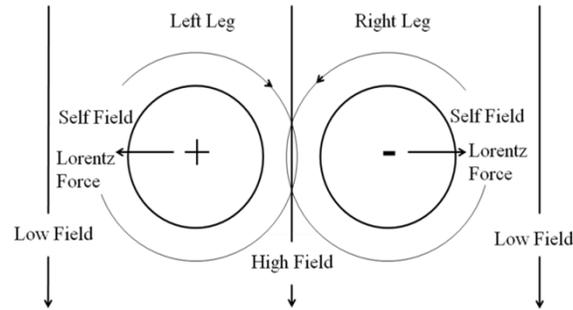


ϵ_{eff} and n value (TFKO8)

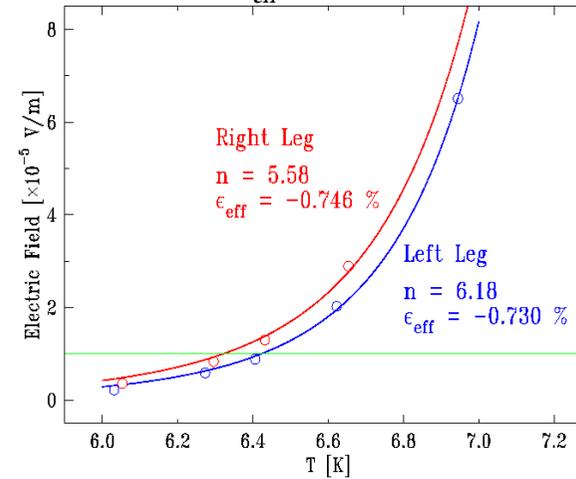


TFJA5

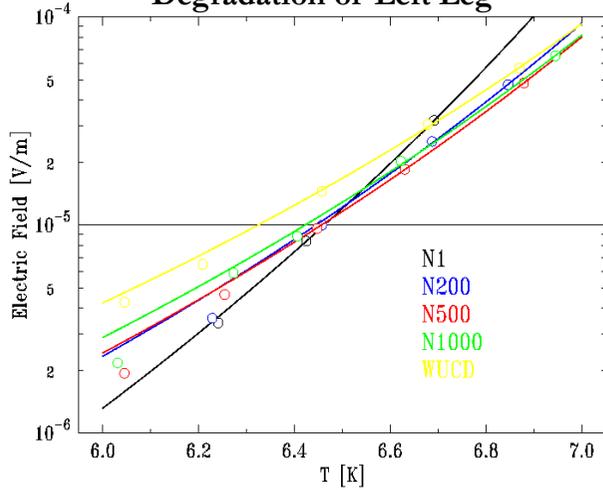
$$E(T) = \frac{E_0}{LA} \iint_{LA} \left[\frac{J_{op}}{J_C(B, T, \epsilon_{eff})} \right]^n dAdz$$



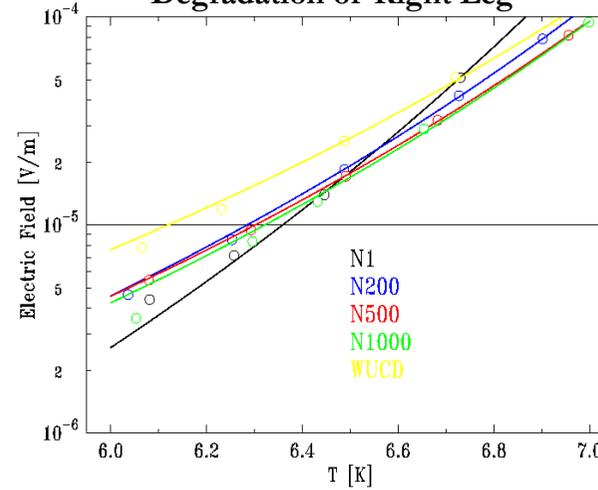
ϵ_{eff} and n at N=1000



Degradation of Left Leg



Degradation of Right Leg



$J_C(B, T, \varepsilon)$ for Nb_3Sn Strand

- See more details in IEEE Trans. Appl. Supercond., vol 19, no.3, pp. 1521-1524, Jun. 2009.

$$J_C = \frac{C}{B} s(\varepsilon) (1 - t^{1.52}) (1 - t^2) b^p (1 - b)^q \quad t = \frac{T}{T_{C0}^*(\varepsilon)} \quad b = \frac{B}{B_{C2}^*(T, \varepsilon)}$$

$$B_{C2}^*(T, \varepsilon) = B_{C20 \max}^* s(\varepsilon) (1 - t^{1.52})$$

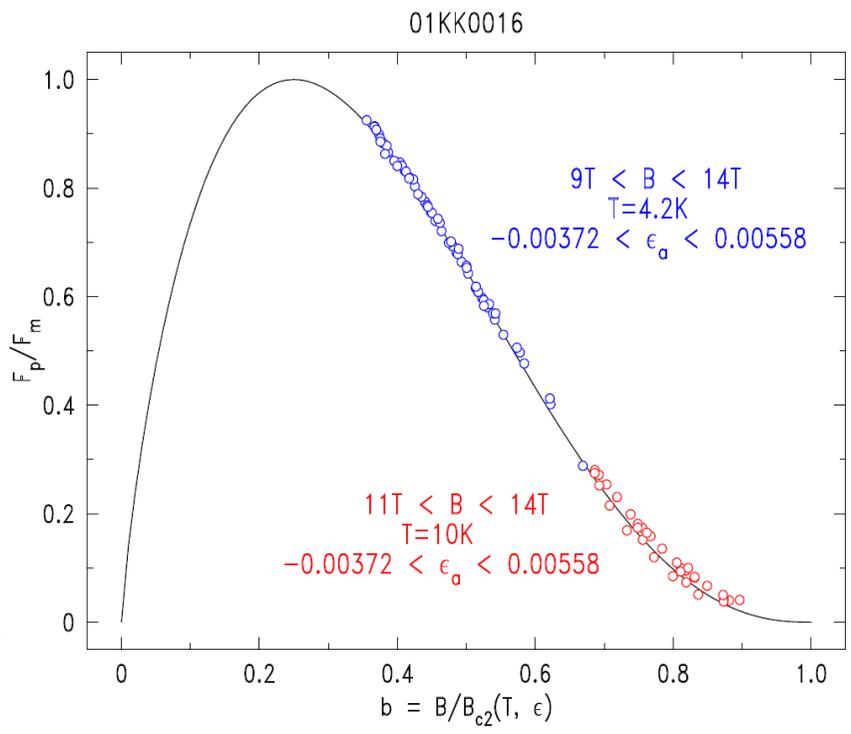
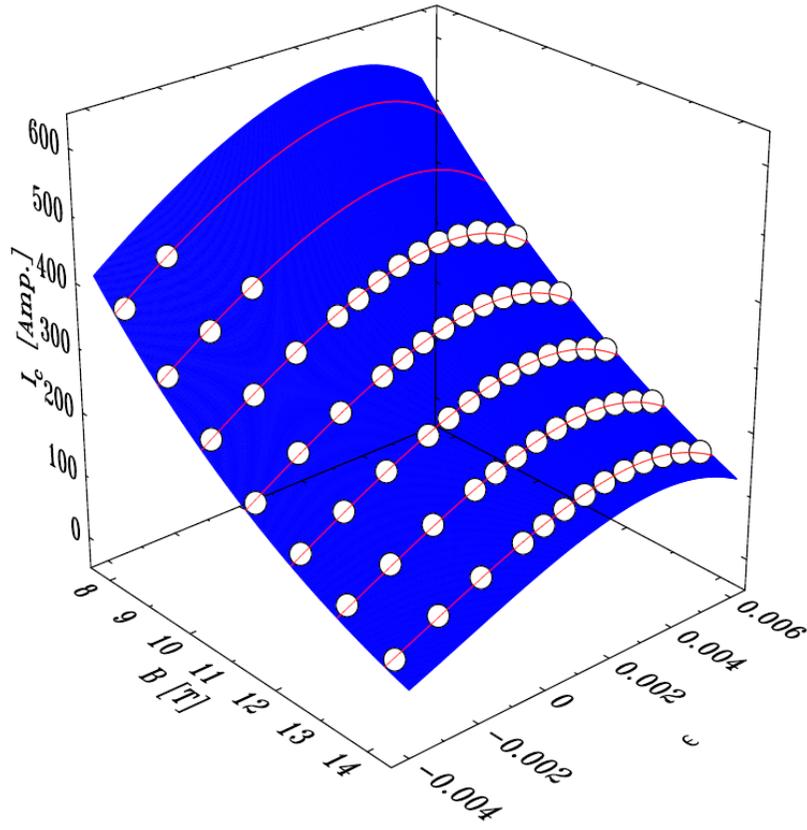
$$T_{C0}^*(B, \varepsilon) = T_{C0 \max}^* [s(\varepsilon)]^{\frac{1}{3}} \left(1 - \frac{B}{B_{C2}^*(0, \varepsilon)} \right)^{\frac{1}{1.52}}$$

$$s(\varepsilon) = 1 + \frac{C_{a1} \left(\sqrt{\varepsilon_{sh}^2 + \varepsilon_{0,a}^2} - \sqrt{(\varepsilon - \varepsilon_{sh})^2 + \varepsilon_{0,a}^2} \right) - C_{a2} \varepsilon}{1 - C_{a1} \varepsilon_{0,a}}$$

$$\varepsilon_{sh} = \frac{C_{a2} \varepsilon_{0,a}}{\sqrt{C_{a1}^2 - C_{a2}^2}}$$

$$F_P = J_C(B, T, \varepsilon) B$$

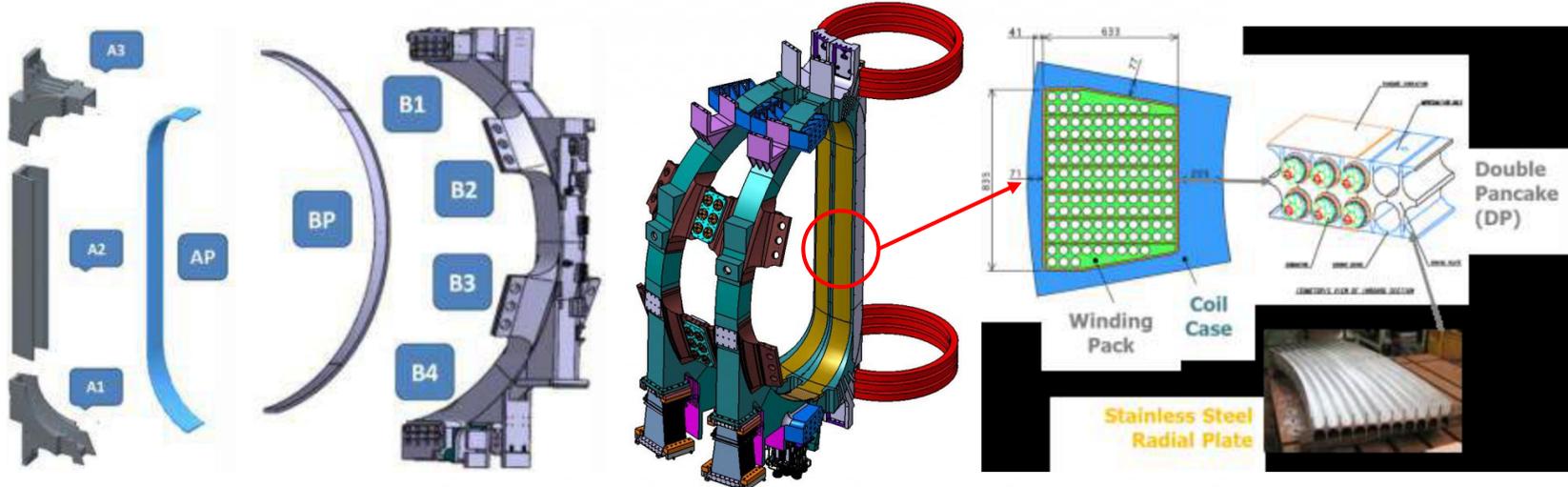
$J_c(B, T, \epsilon)$ for 01KK0016 (Representative of Korean Strand)



C	B_{c20m} (T)	T_{c0m} (K)	Ca_1	Ca_2	$\epsilon_{0,a}$ (%)	ϵ_m (%)	p	q
35986	31.58	15.95	70.28	32.91	0.44	0.34	0.83	2.49

ITER TF Coils

- The TF coil is made up of a winding pack (WP) inserted inside a thick coil case consisting of welded, stainless steel segments.



TF Coil Structure

Pair of TF Coils

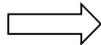
TF Coil Winding Pack

- Each winding pack (WP) comprises 7 double pancakes (DPs), made up of a radial plate with precisely machined grooves into which the CICC is transferred upon heat treatment completion.

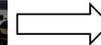
ITER TF DP Manufacture – 1



Conductor Spool



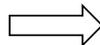
DP Winding



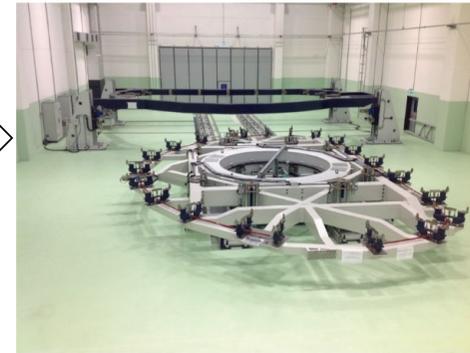
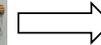
DP Heat Treatment



Radial Plate
Machining/Welding



Radial Plate Assembly



Transfer of DP into
Radial Plate

ITER TF DP Manufacture – 2



DP Turn Insulation
inside Radial Plate



Cover Plate
Welding



DP Ground Insulation



Impregnated DP



DP Loading into Vacuum
Impregnation Mold

ITER TF WP Manufacture



7 DP Stacking



WP Insulation



Terminal Preparation



Completed WP

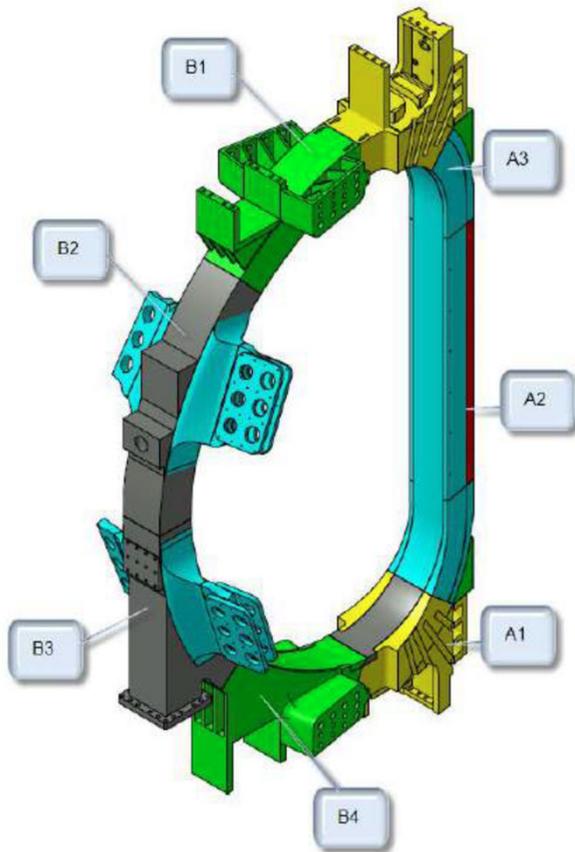


Vacuum Pressure Impregnation



TF Coil Structure – 1

TF Coil Structure
Breakdown

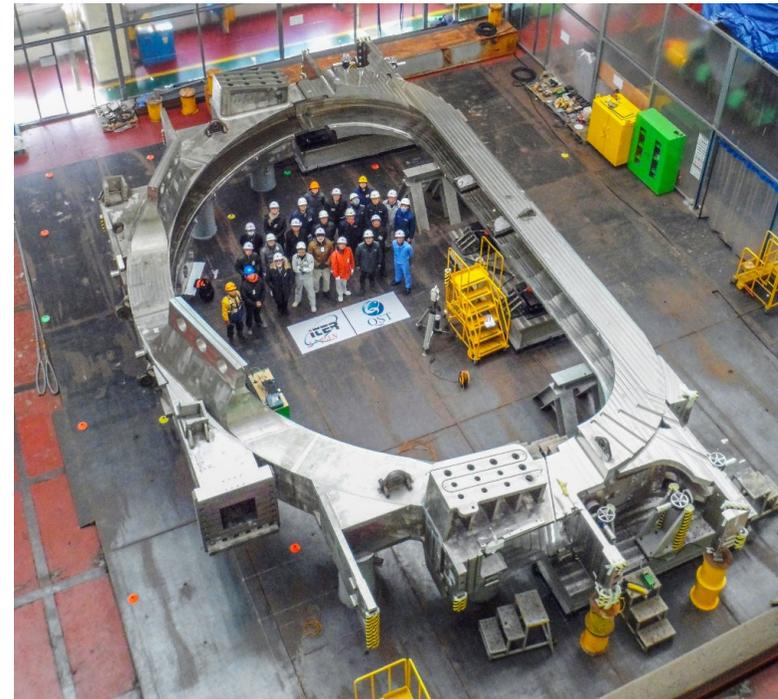


- TF structure calls for mass production of ~ 4500 tons of large, high-strength, 316LN steel components.
- Components are made of TIG welded assemblies of forged plates up to 200 mm and require tight deformation control to achieve final shape.
- Three suppliers have been selected: MHI and Toshiba (Japan) and HHI (Korea).
- Series production of AU, AP, BU and BP sub-assemblies are completed.

TF Coil Structure – 2



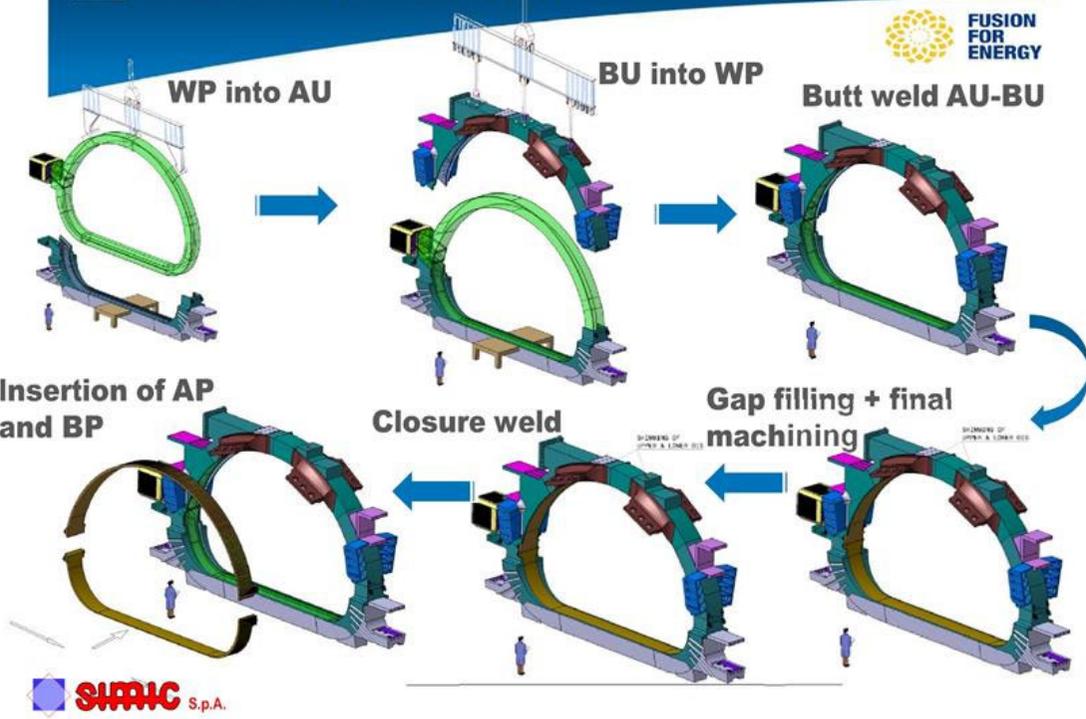
At Hyundai Heavy Industries in Ulsan, Korea, the outboard leg sub-assemblies were first fitted together to verify manufacturing precision



The two legs were successfully matched in fitting tests at Hyundai Heavy Industries in December

ITER TF Coil

TF Coil Insertion - Overview



Europe's first Toroidal Field coil has been inserted in its case

Manufacturing ITER PF Coil



Technicians preparing for Vacuum Pressure Impregnation on PF6, ASIPP, Hefei, China



Completion of Vacuum Pressure Impregnation on 8 DP for PF1, Efremove, Russia



7 DPs of PF5 are stacked in the stacking area

Manufacturing ITER CS Coil



Winding of CS Coil, GA, USA

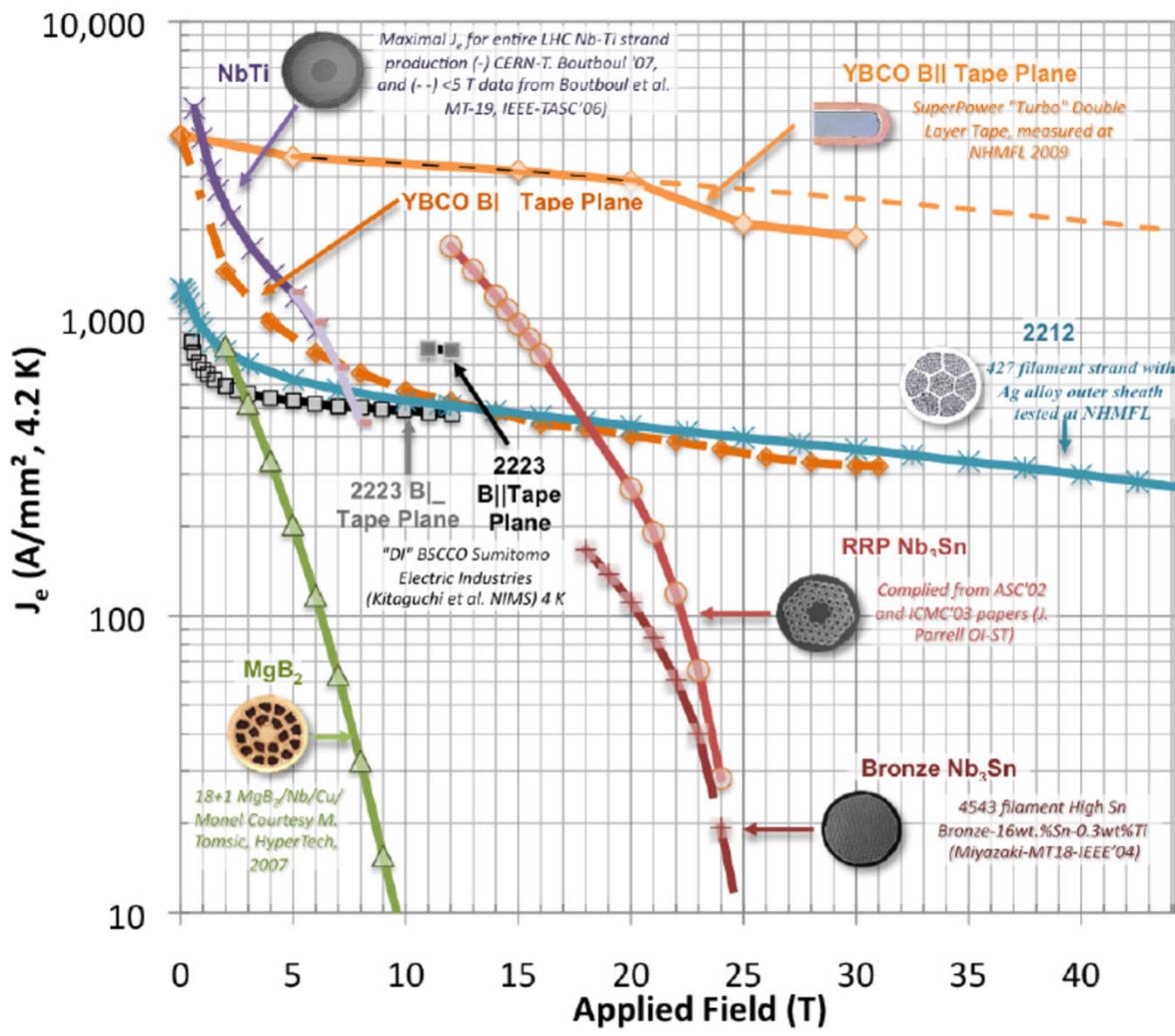


The module during completion of helium piping



Transfer of central solenoid module coil to the heat treatment furnace

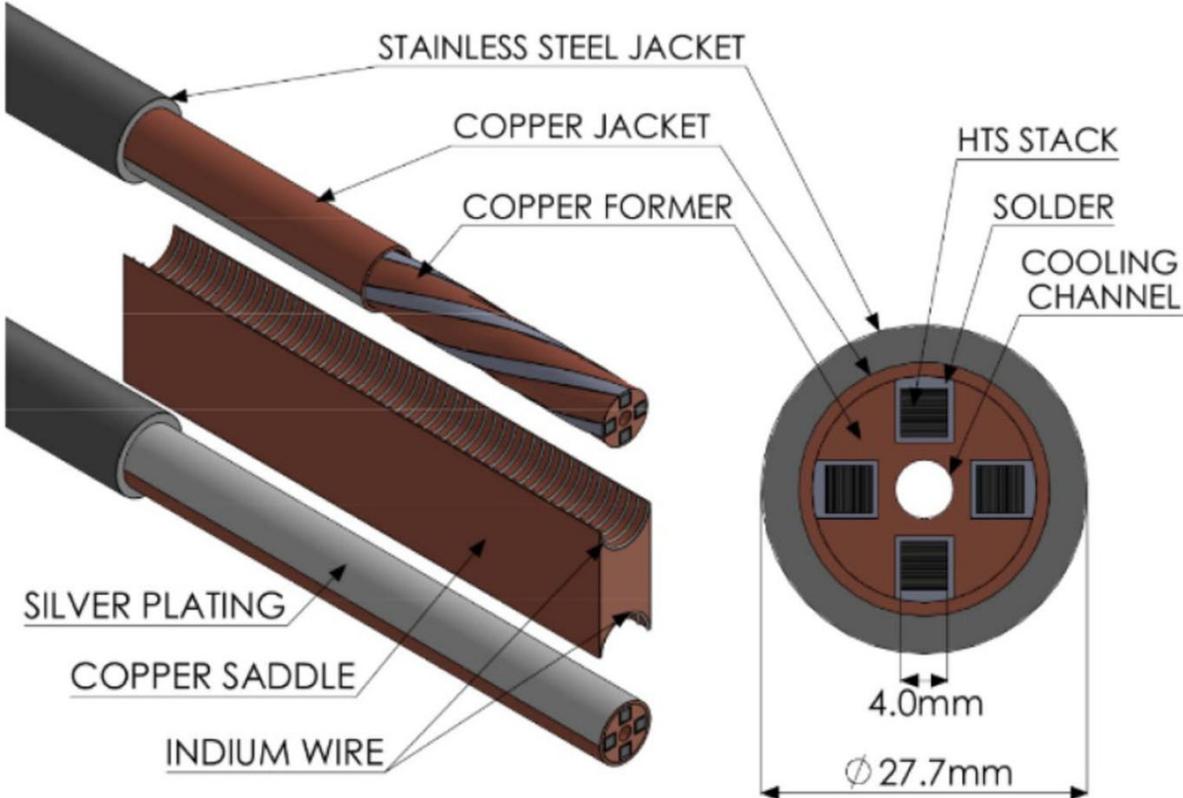
Digression: High Tc Superconductor



Superconducting Tokamaks

Parameter		SPARC	EAST	KSTAR
R	m	1.85	1.70	1.80
a	m	0.57	0.40	0.50
B _T	T	12.2	3.5	3.5
I _p	MA	8.7	1.0	2.0
P _{aux,max}	MW	25	28	16
P _{flattop}	s	10	1000	300
P _{fus}	MW	140		
Q		11		

Digression: High Tc Superconductor



VIPER cables for high-field superconducting fusion magnets.
(Right) HTS stacks are VPI soldered into channels in a twisted copper former containing a central cooling channel and surrounded by roll-formed copper and optional stainless-steel jacket.
(Left) A cut-away showing that joints are easily created by silver plating the cable ends and compressing them into a copper saddle.

Digression: High Tc Superconductor (SPARC)

