ITER conductor design and (we hope) nuclear heating

china eu india japan korea russia usa

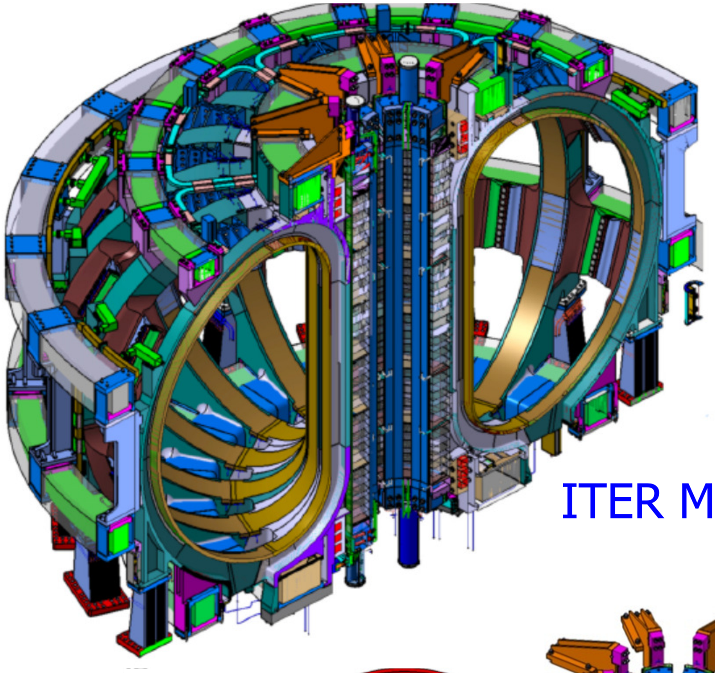
Matt Jewell
ITER Organization

Background slides courtesy A. Devred

15 April 2011
MAP meeting

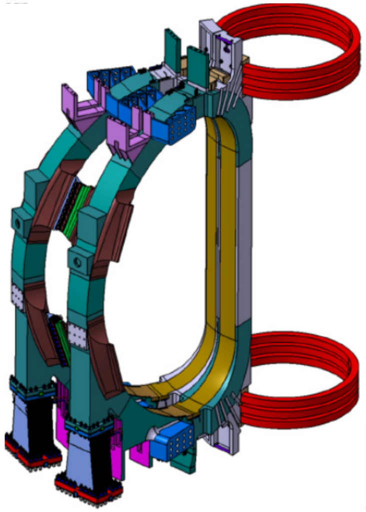
ITER Magnet System (1/2)

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

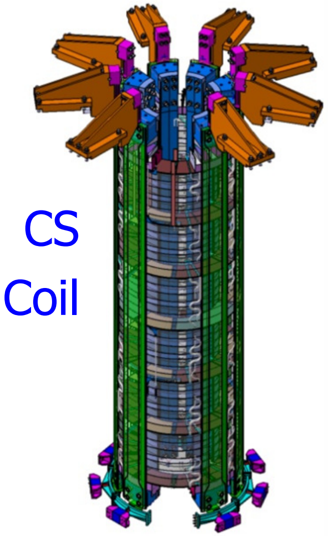


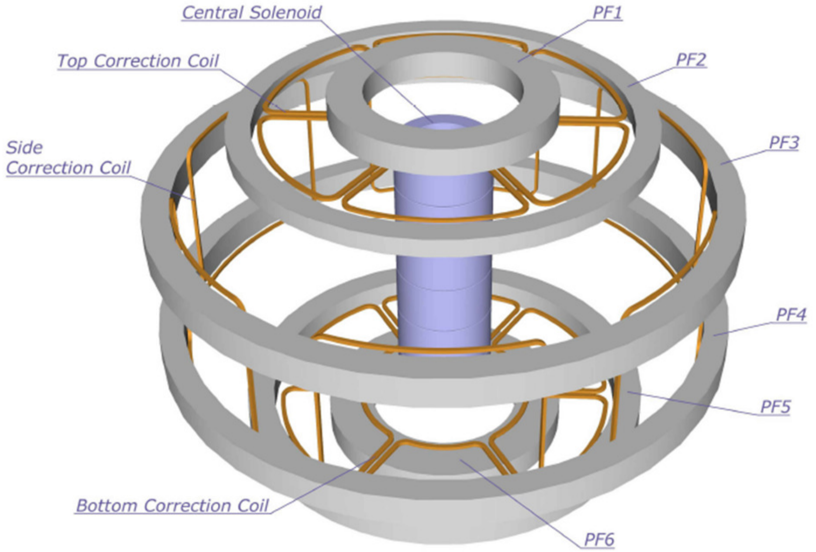
ITER Magnet System

Pair of TF Coils



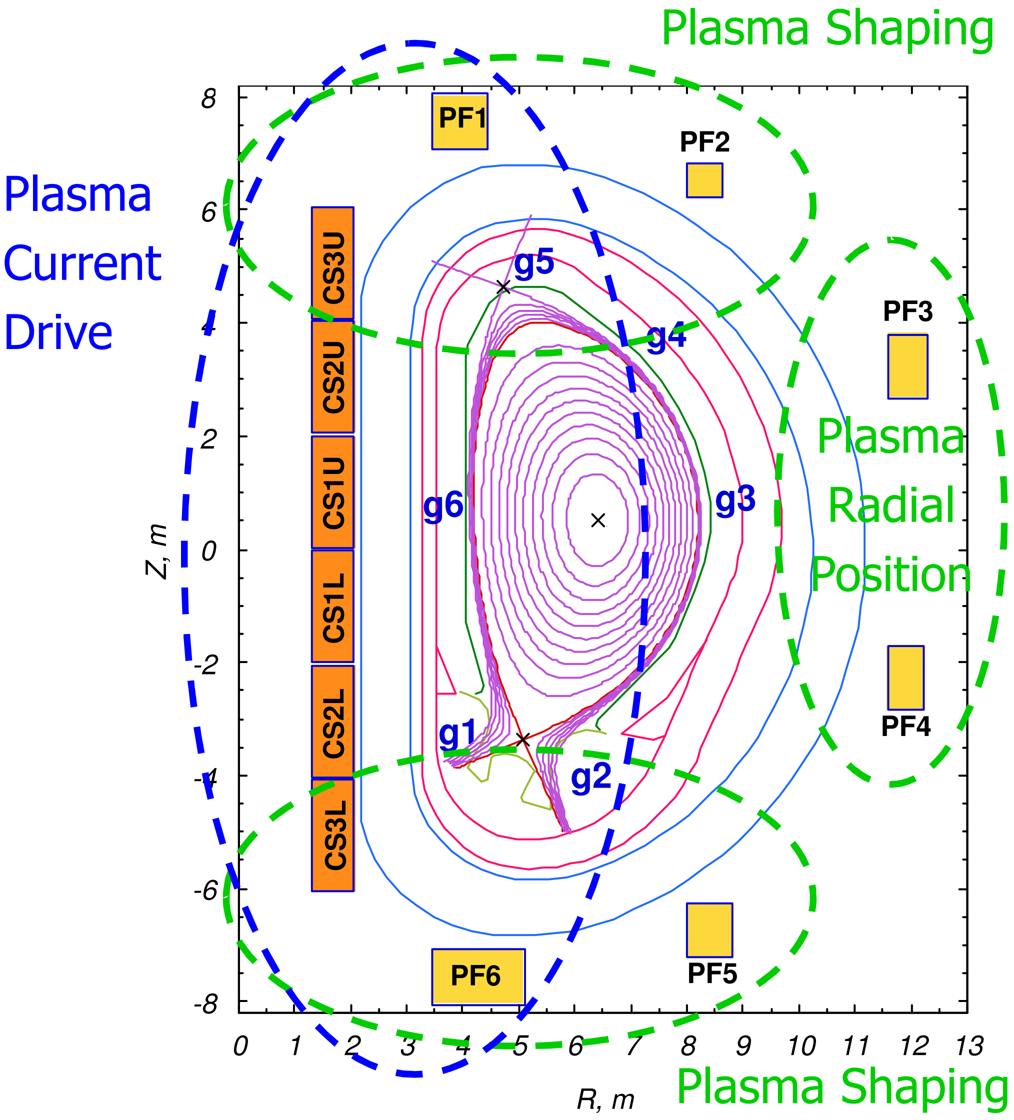
CS Coil





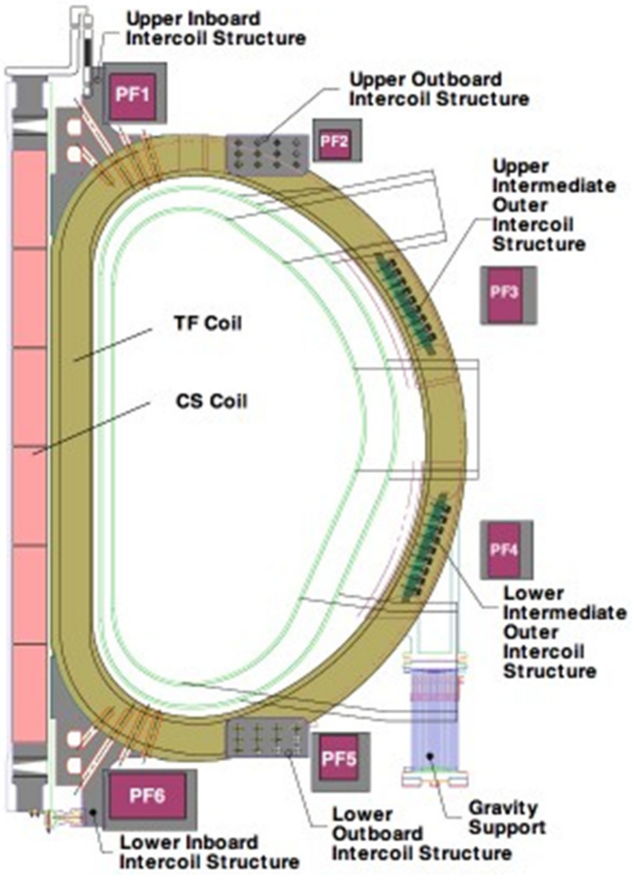
PF Coils & CC’s

ITER Magnet System (2/2)

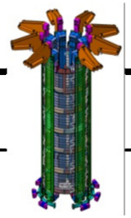
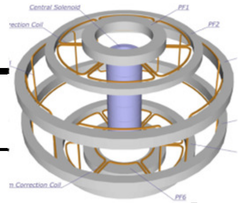


- TF Coils are used for charged particles' confinement in plasma.
- CS coils are used to produce inductive flux and to ramp up plasma current; they also play a role in plasma shaping and vertical stability.
- PF coils are used to control radial position equilibrium of plasma, as well as for plasma shaping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

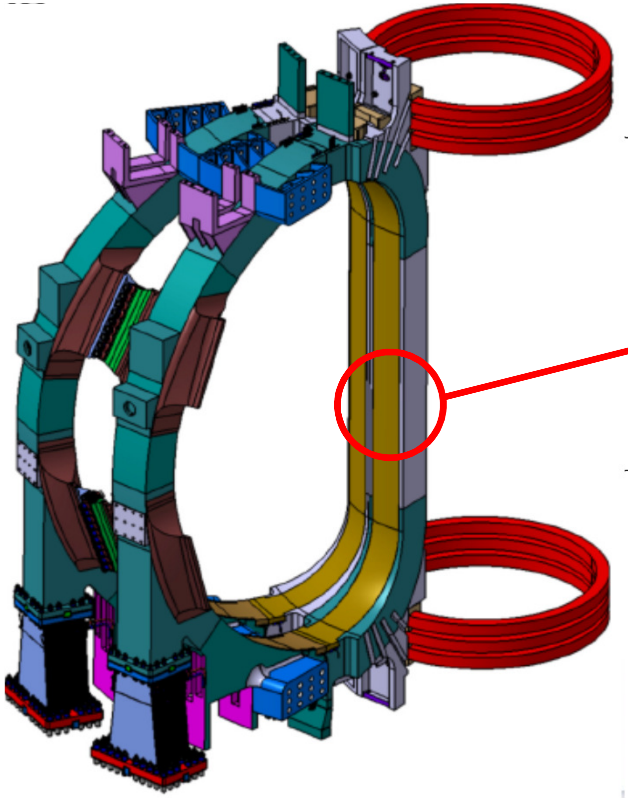
Salient Paremeters of ITER Magnets



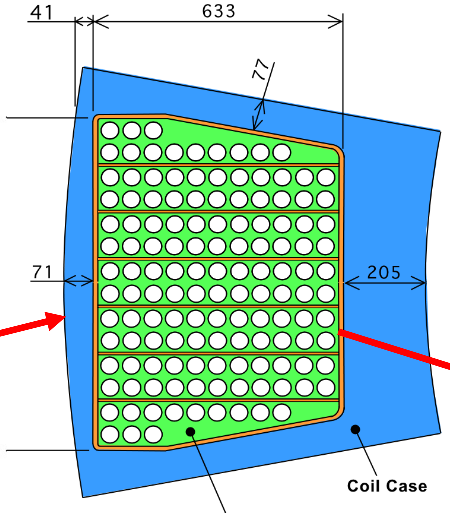
ITER Magnet System Parameters

	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	88 km	42 km	65 km
Total Weight	826 t	728 t	1224 t
Sc Strand Weight	384 t	122 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

Detailed Features of ITER TF Coils

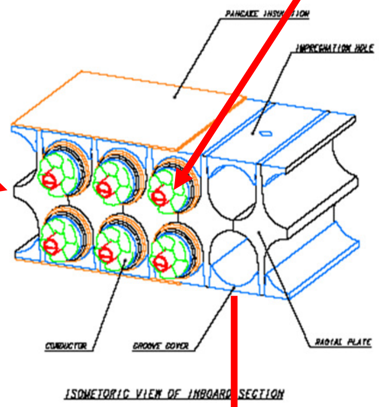


Pair of TF Coils



Winding Pack

CIC Conductor



Double Pancake

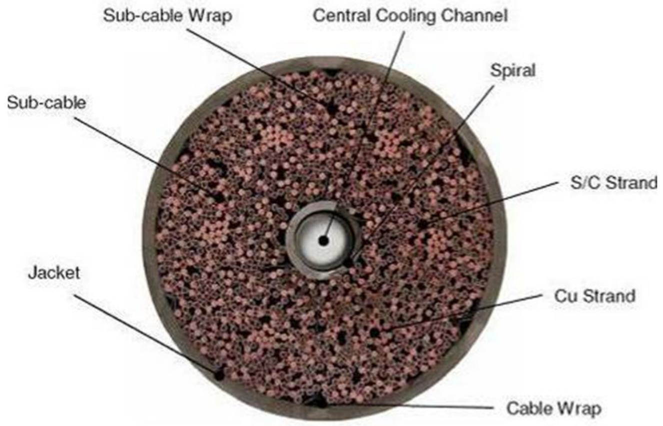
Stainless Steel Radial Plate

Scope of ITER Conductor Supply

Coil	Total Length (km) [Weight (t)]	SC Strand Type	SC Strand Weight (t)	Jacket Type	Jacket Material	Jacket Weight (t)	ITER Credit [kIUA (M€)]	ITER Credit Sharing (%)					
								CN	EU	JA	KO	RF	US
TF	88 (826)	Nb_3Sn	384	round-in-round	Mod. 316LN	185	215 (323)	7.5	20	25	20	20	7.5
CS	42 (728)	Nb_3Sn	122	round-in-square	JK2LB or mod. 316LN	530	90 (135)	–	–	100	–	–	–
PF	65 (1224)	NbTi	224	round-in-square	316L	900	81 (122)	67	13	–	–	20	–

- A typical TF Conductor Unit Length is 760 m and requires a minimum of 3.3 t of Nb_3Sn strands and of 1.6 t of stainless steel tubes.
- A typical CS Conductor Unit Length is 905 m and requires a minimum of 2.6 t of Nb_3Sn strands and 11.3 t of stainless steel tubes.

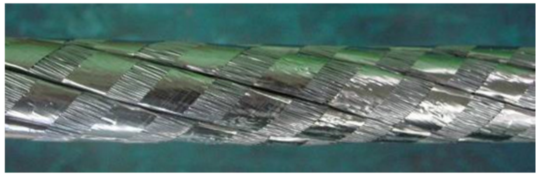
ITER Cable-In-Conduit Conductors



ITER TF CICC

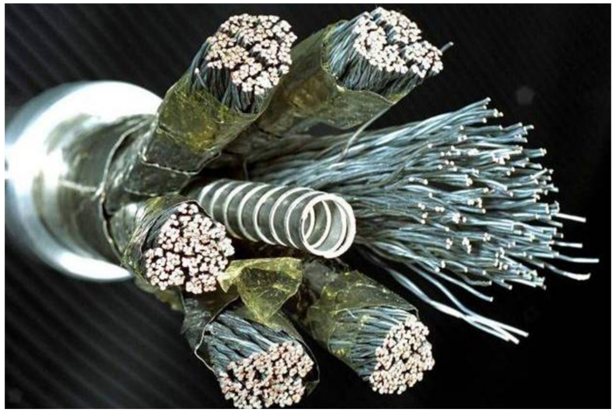
- ITER coils are wound from Cable-In-Conduit Conductors (CICC's), relying on superconducting multifilament composite strands mixed with pure copper strands/cores.
- The strands are assembled in a multistage, rope-type cable around a central cooling spiral.
- The cable is inserted in a stainless steel conduit where supercritical helium is forced to flow.

Cooling Spiral (Courtesy of VNIIKP, KO)



Rope-Type Cable (Courtesy of NFRI, KO)

Stainless Steel Conduit (Courtesy of ASIPP, CN)

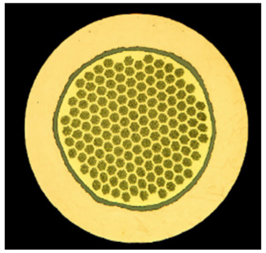


(Courtesy of ENEA/Frascati, EU)

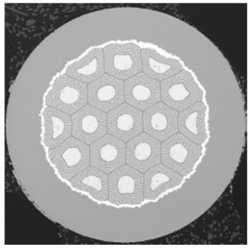
ITER Conductor Types

TF Conductor

- TF coils rely on Nb_3Sn strands and a modified 316LN, round-in-round jacket,
- CS coil modules rely on Nb_3Sn strands and an austenitic steel, round-in-square jacket.



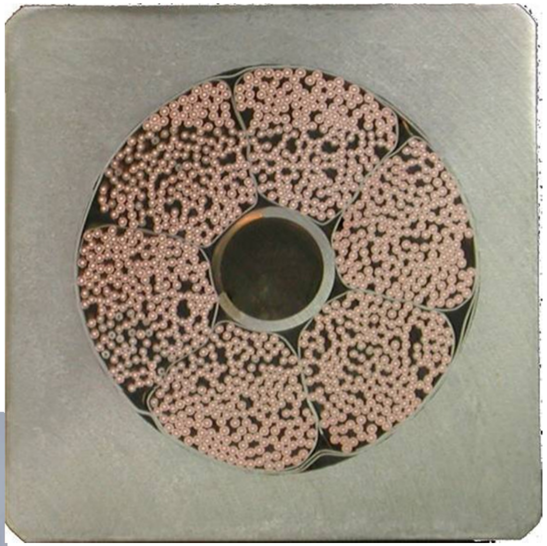
Bronze Nb_3Sn strand developed by BAS, EU

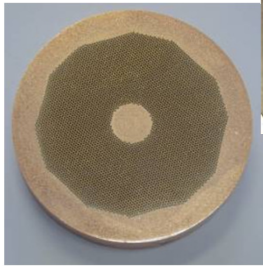


Internal-tin Nb_3Sn strand developed by OST, US

- PF coils rely on NbTi strands and a 316L, round-in-square, jacket.

PF Conductor





NbTi strand developed by VNIINM, RF

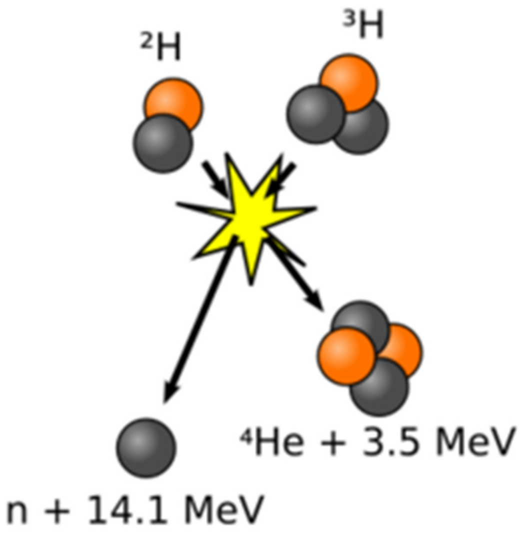
TF and CS conductor design

	TF	CS
Sc strand type	Nb_3Sn	Nb_3Sn
Cable pattern	((2sc + 1cu) x 3 x 5 x 5 + Core) x 6	(2sc + 1) x 3 x 4 x 4 x 6
Cable twist pitches (mm)	80/140/190/300/420	45/85/145/250/450
Core pattern	3 Cu x 4	n/a
Central spiral	8 x 10 mm	7 x 9 mm
Petal wrap	0.10 mm thick, 50% cover	0.05mm thick, 70% cover
Cable wrap	0.10 mm thick, 40% overlap	0.08 mm thick, 40% overlap
Cr coated strand diameter (mm)	0.82	0.83
Nb_3Sn strand Cu-to-non-Cu ratio	1.0	1.0
Number of sc strands	900	576
Non copper (mm^2), untwisted [twisted]	235.3 [242.6]	154.3 [160.8]
Total copper (mm^2), untwisted [twisted]	508.3 [524.0]	308.6 [321.5]
Void fraction (annulus)	29.7 %	33.5 %
Cable diameter (mm)	39.7	32.6
Jacket (mm)	Circular 316LN ∅ 43.7	Circle in square 316LN 49 x 49

- CICC design allows for flexibility in managing heat via management of AC losses (twist pitches) and cooling pattern (void fraction, channel)

Nuclear heating

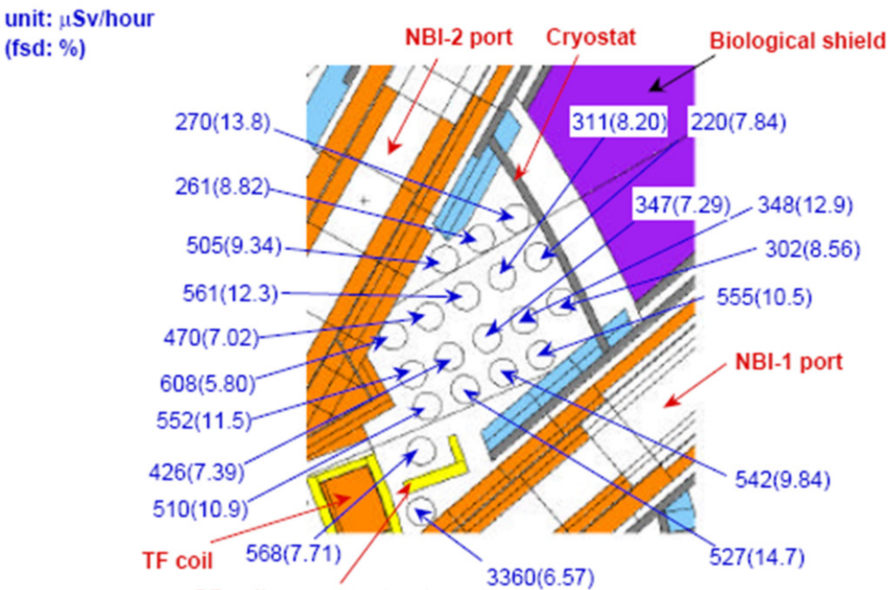
- "If ITER has a nuclear heating problem, then ITER was a fantastic success"
- Neutrons are a concern for at least the following reasons:
    - Direct human health hazard
    - Indirect health hazard (maintenance on activated components)
    - Reduction of component performance (insulation and superconductor; almost always limited by the insulation)
    - Direct nuclear heating of cryogenic magnet conductor



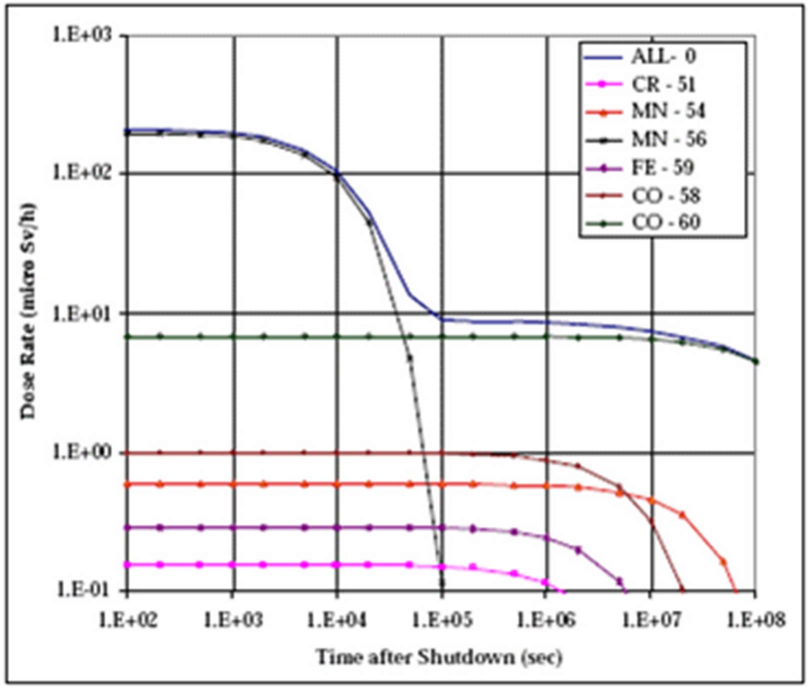
D-T fusion reaction

Dose rates during maintenance

- Only gamma-rays from activation
- We have the restriction:
  - In areas of hands-on maintenance the dose rate <100 µSv/hour 10^6s (~12 days) after shutdown.

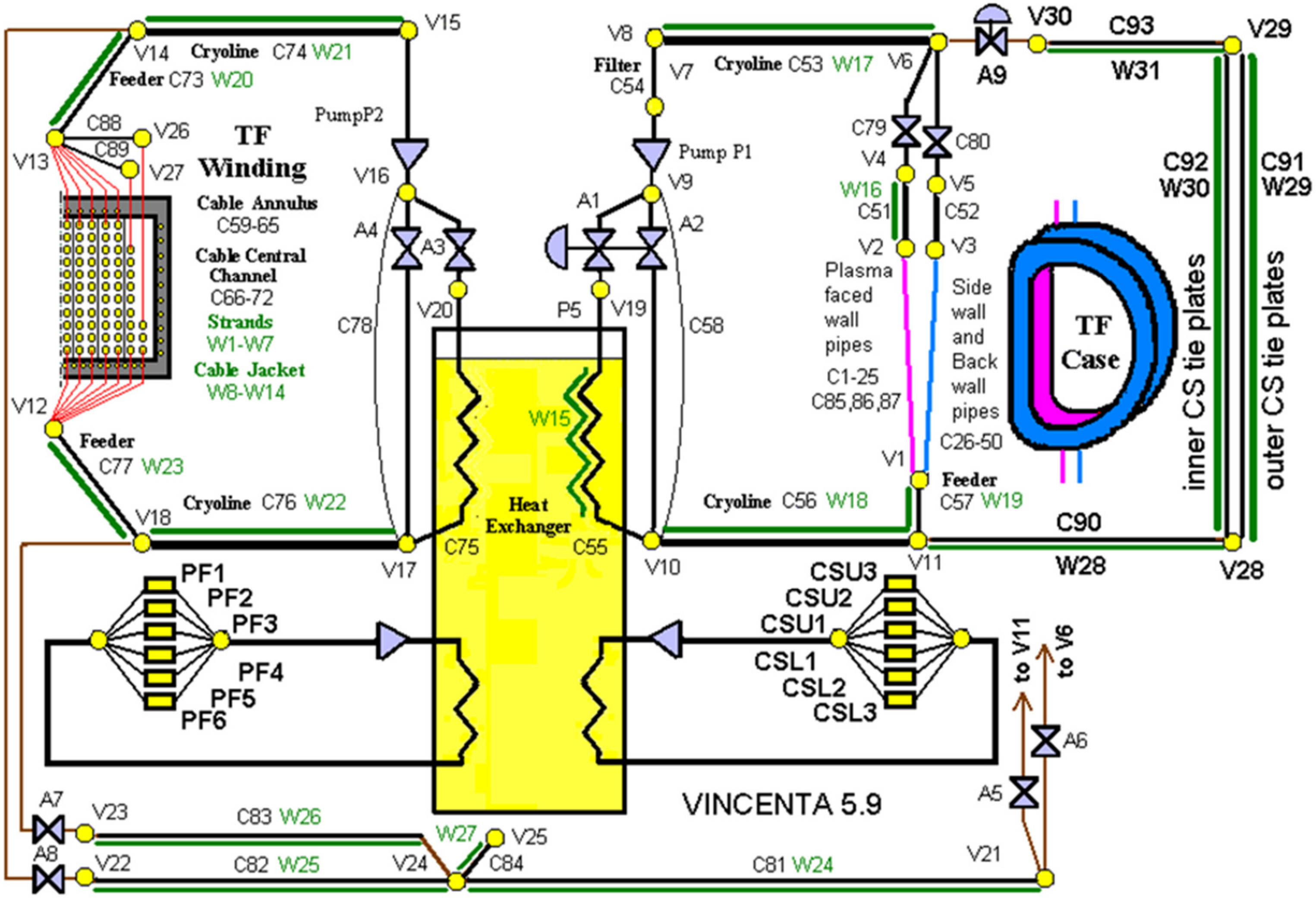


Shutdown dose rate distribution (10^6sec) on the equatorial plane between the two NBI ports



Analysis courtesy
M. Loughlin

Magnet cooling scheme



Design criteria and cooling parameters

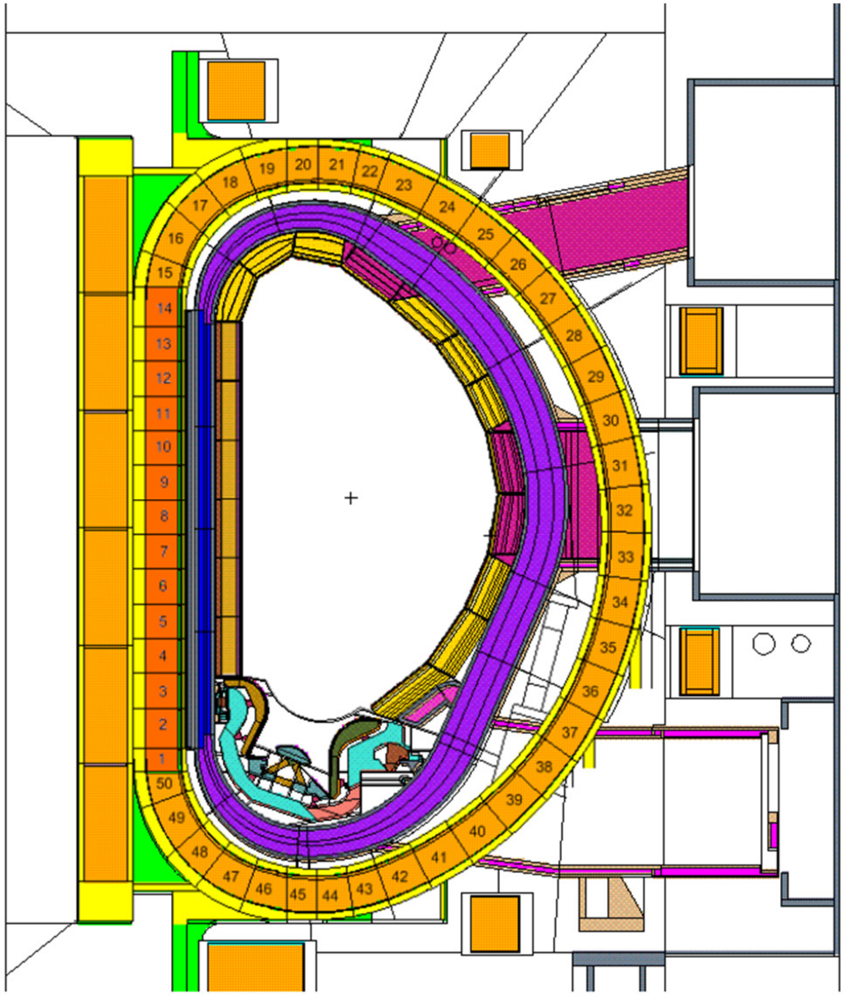
From the ITER System Requirements Documents:

- The total TF coil heating should not exceed 14kW during a 500MW fusion power pulse
- Limit of fast neutron fluence in Winding Pack (WP) magnet superconductor is 1×10^{19} n/cm^2
- Limit of fast neutron fluence in WP's insulator is 5×10^{17} n/cm^2
- Limit of peak local nuclear heating in magnet steel case is 2×10^{-3} W/cm^3
- Limit of peak local nuclear heating in magnet conductor is 1×10^{-3} W/cm^3

	Mass flow rate (kg/s)	**Helium Volume (m^3)**	**Pump Pressure Drop (bar)**
TF winding loop	2.0	42.2	1.0
TF case loop	2.5	13.3	1.0
CS loop	2.0	15.7	1.0
PF & CC loop	1.8	27.9	0.8

Geometrical considerations

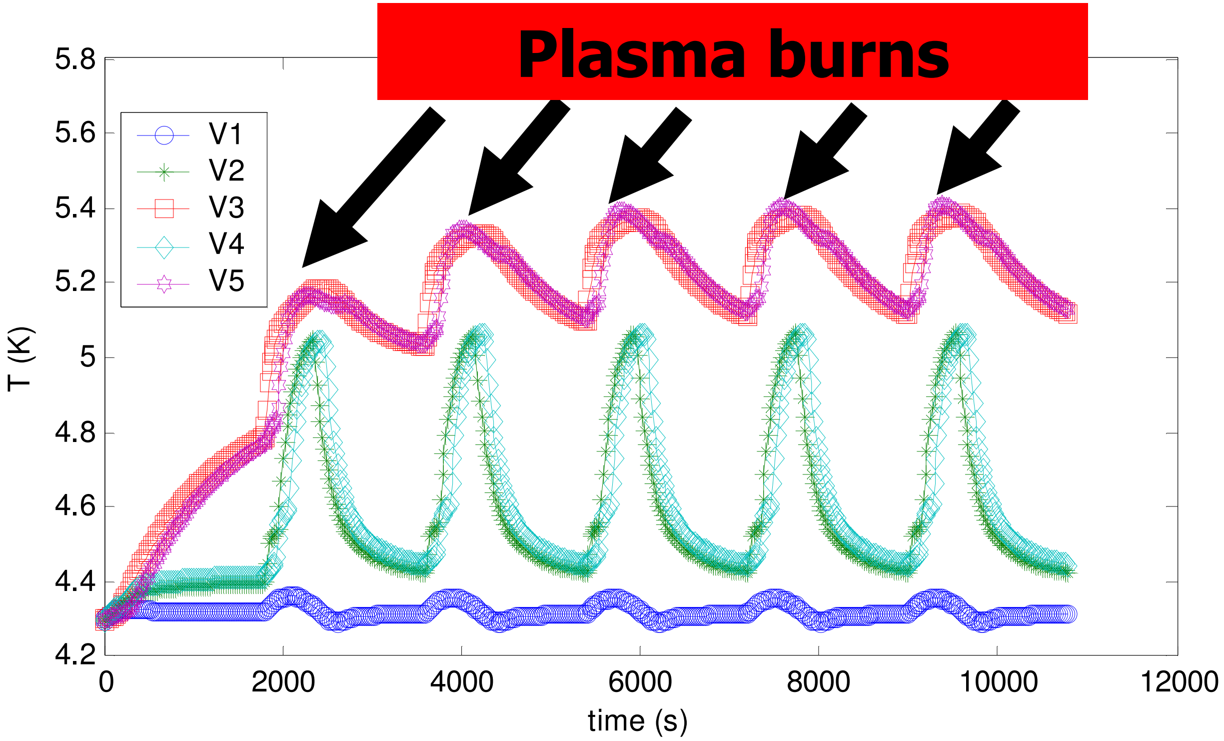
- Area of highest concern for nuclear heating is the inboard leg of the TF coil. This is a combination of:
    - Highest field (lowest operating margin on the superconducting strands)
    - High neutron flux (CS, PF shielded by TF)
    - Tightest geometrical restrictions for shielding
- Other areas of "local" concern also exist, e.g. in the vicinity of the NBI ports



TF coil heat load inventory

Type of Heat Load	CASE	Winding Pack
Steady state		
Conductor joints		1.00 kW
Thermal radiation to case and structure	1.33 kW	
Thermal conduction from the vacuum vessel and thermal shield supports	0.05 kW	
Thermal conduction from the coil gravity supports	2.30 kW	
Feeders, sc bus bar and cold terminal box	0.20 kW	0.55 kW
Cryolines	0.01 kW	0.40 kW
Transient		
Nuclear heating (during 400s burn)	7.6 kW	6.2 kW
AC losses in conductors, eddy current losses in the radial plate		1.73 MJ
Eddy current losses in the 4 case walls	2.6 MJ	
Eddy current losses in other structures	2.9 MJ	

Conductor temperature evolution



Analysis courtesy
D. Bessette

ITER magnet system does NOT operate in steady-state mode!

- TF conductor heating limits plasma duration (400-500 s)
- TF coils exhibit overall slow transient behavior, limiting number of consecutive pulses

How ITER designs for nuclear heating

Conductor design:

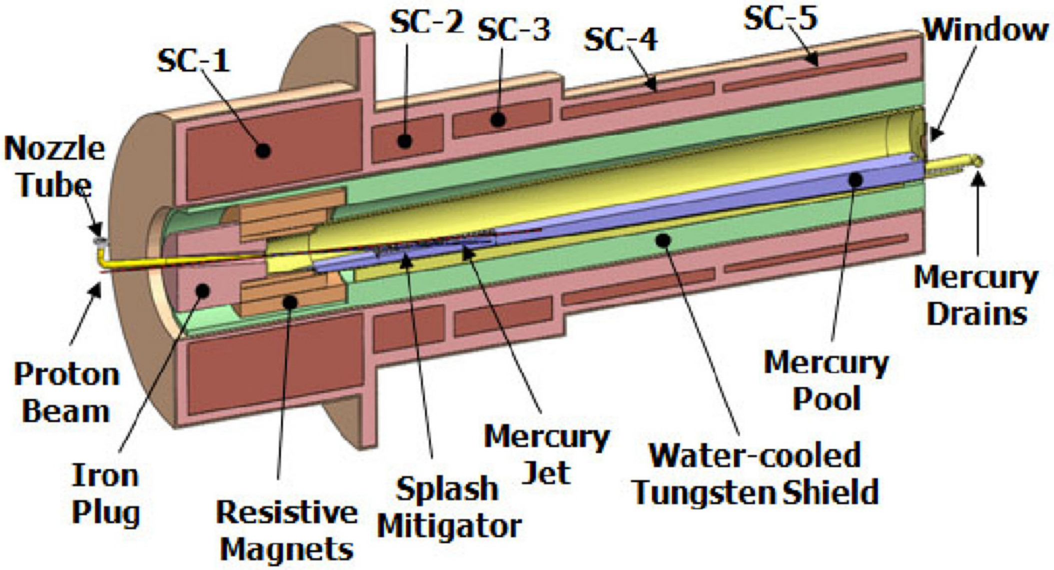
- Void fraction
- Temperature margin (i.e. performance and number of superconducting strands)
- Annular cable (central channel)
- Management of other heat sources (e.g. AC losses – cable twist pitches)
    - Many of the basic design choices in ITER relate to heat and energy management during a plasma disruption

System design:

- Helium flow path
- Operating scenario optimization
- Geometric optimization (e.g. placement of ports)
- ……

Considerations for MAP

Some thoughts based on my (limited) understanding of the project:

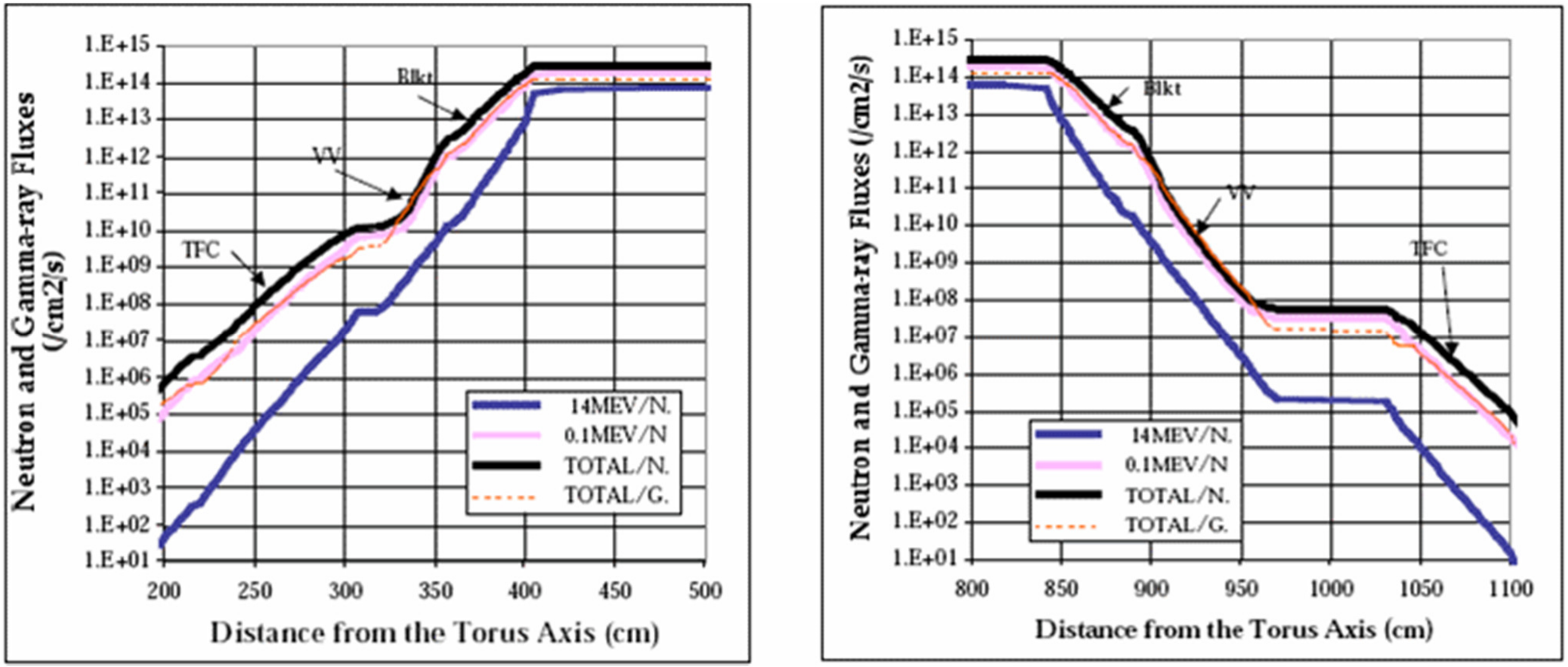


- Presence of the Cu magnet may drive some design considerations, e.g. losses
    - Series or parallel?
- Smaller stored energy gives greater design flexibility
    - Consider higher aspect ratio conductors
    - Look to other existing hybrid magnet projects using CICC
- What is the energy deposition map? CICC design can offer increased flexibility if (for example) highest neutron flux is occurring in area of lower IxB

THE END

Neutron and Gamma Fluxes

Fluxes through blanket, VV and shield



Inboard

Outboard