Critical Issues and New Opportunities for Fusion Magnet Materials

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Overview of Requirements

- Magnet systems for present SC fusion devices are expensive
  - ~1/3 of core machine cost
  - Requires reduced cost
  - Compactness
- High reliability and maintainability is essential
- Ease of manufacture and mass production
- Fusion device designers should have wide range of
  - plasma field (magnitude and distribution)
  - Magnet system operating temperature (and thus operating costs)

Superconducting Magnets Present and Future

- Superconducting Magnet Technology is available now for up to ITER scale
  - ITER is built with 1990's technology

- Devices beyond ITER will require significant improvements to make fusion economical
  - These improvements can be demonstrated on any next thrust experiment

Future Magnet Requirements

- Very high performance
- Acceptable first cost
- Low operating and maintenance costs
- High reliability and easy maintainability

State-of-the-Art

Material	T_c [K]	$\mu_o H_{c2}$ [tesla]
Nb(metal)	9.1	0.2
Nb-Ti (alloy) ★	9.8	10.5 (4.2K)
NbN (metalloid)	16.8	15.3 (4.2K)
MgB_2	39	>15
Nb_3Sn (compound) ★	18.2	24.5 (4.2K)
Nb_3Al	18.7	31.0 (4.2K)
Nb_3Ge	23.2	35.0 (4.2K)
YBaCuO (oxide)	93	150
BiSrCaCuO	110	108
HgBaCaCuO	133	“high”

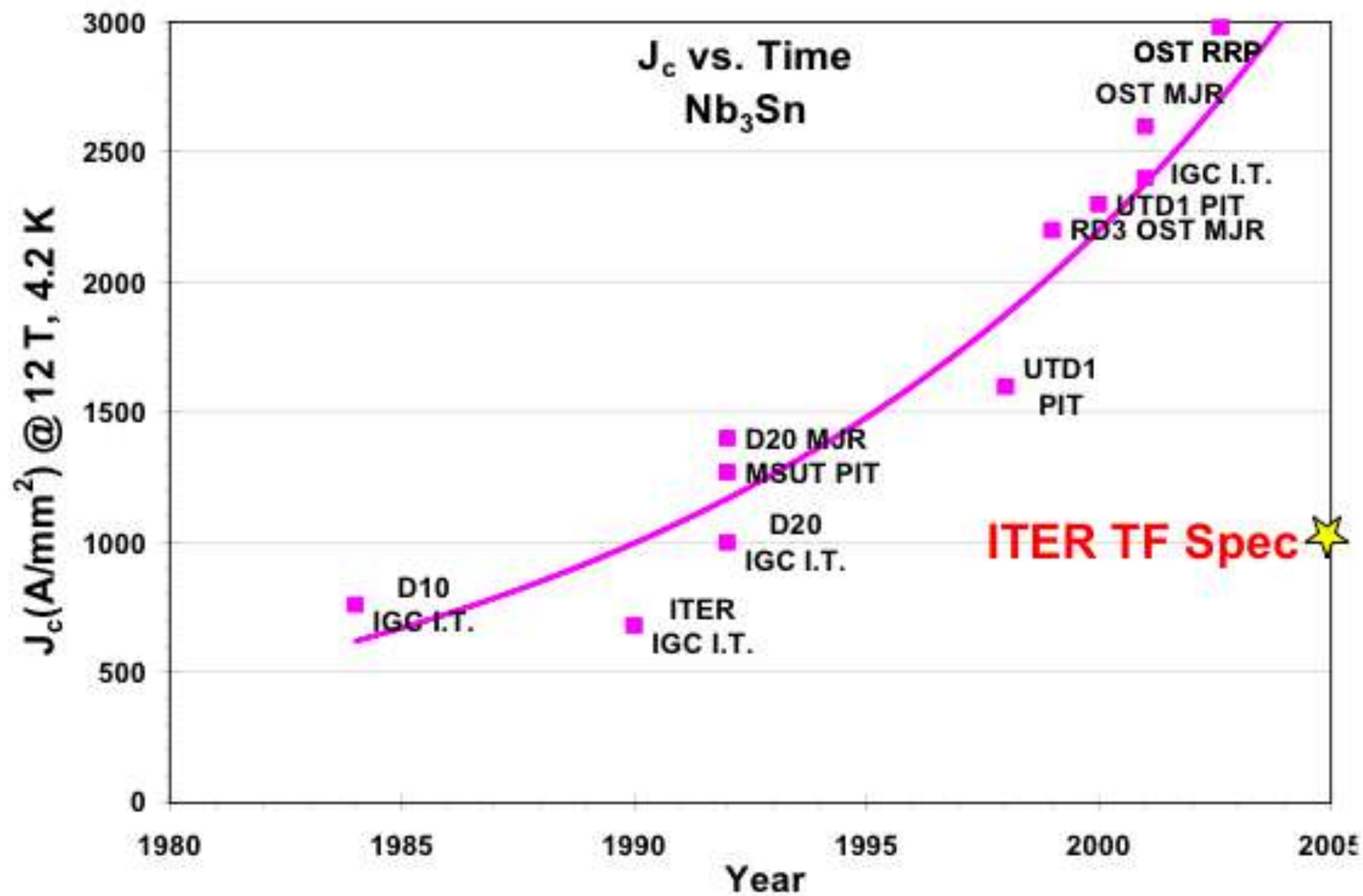
State-of-the-Art

- All existing SC fusion machines use Low Temperature Superconductors
  - NbTi
    - Ductile alloy easy to work with
    - Lowest cost practical superconducting material
    - Commodity item used in MRI magnets (several thousand magnets per year)
    - Relatively low critical temperature T_c and critical magnetic field B_{c2} (9.8 K and 10.5 T @ 4.2 K)
    - LIN-B (1976, Baseball),T-7 (1978,TF), MFTF-B (1985, All Coils), Tore-Supra (1987,TF), LHD (1998, Helical, PF), EAST (TF, PF, CS), KSTAR (PF only), Wendelstein 7-X (Stellarator, Planar, PF), ITER (PF only)
      - *DPC-U test coils (1989), Polo (1993), ITER PF Insert (2003) test coils*

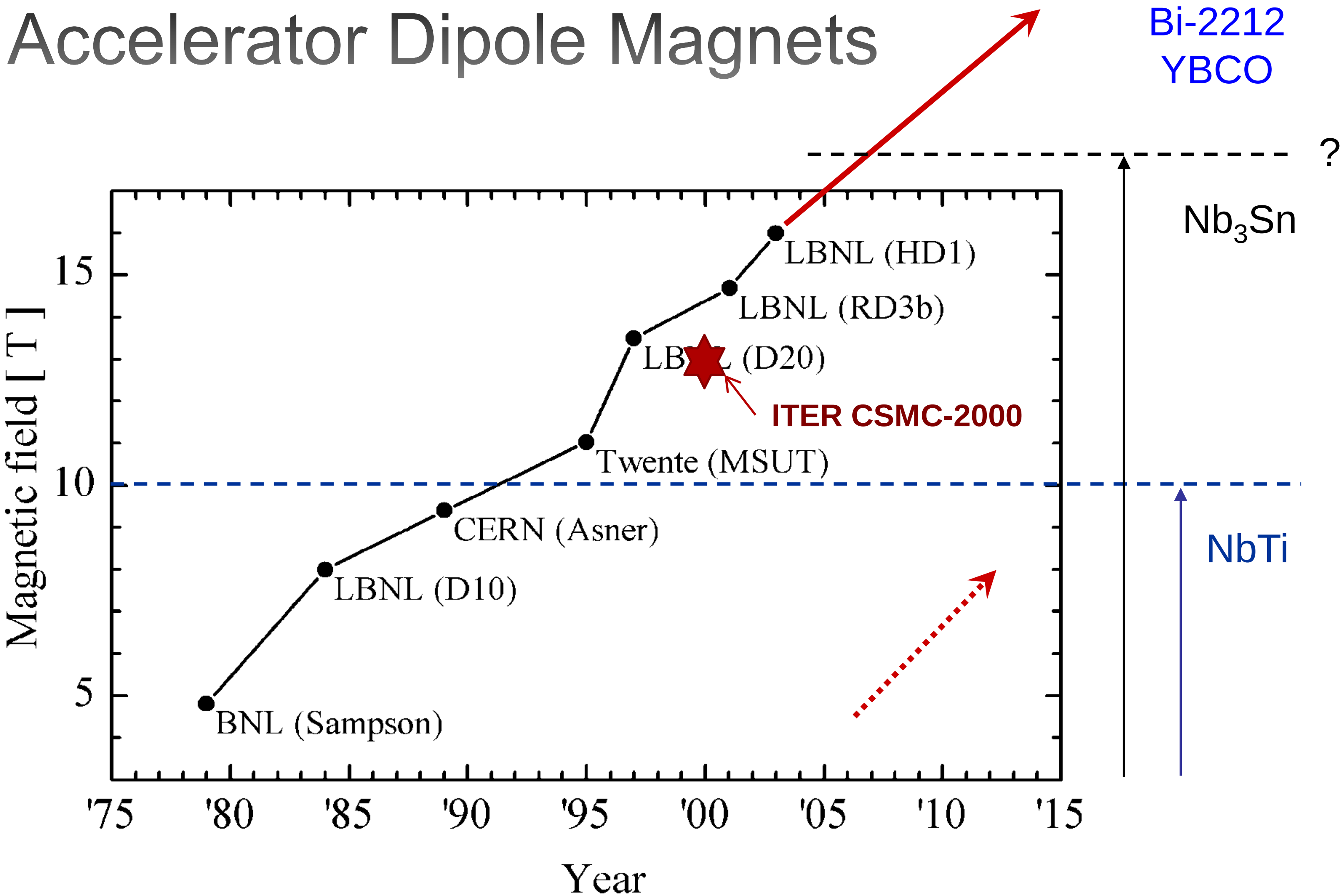
State-of-the-Art

- All existing SC fusion machines use Low Temperature Superconductors
  - Nb_3Sn
    - Brittle compound difficult to work with and must be formed by heat treatment after magnet fabrication.
    - Higher cost than NbTi (x 4-5)
    - Small worldwide production relative to NbTi (NMR, Lab research magnets)
    - Relatively high critical temperature T_c and critical magnetic field B_{c2} (18.2 K and 24.5 T @ 4.2 K)
    - TRIAM (1986, TF),T-15 (1989, TF), KSTAR (TF and CS), ITER (TF, CS)
      - *Plus DPC-EX and US-DPC (1990), ITER CSMC and TFMC (2000)*
    - React-and-Wind versus Wind-and-React
  - Note: LDX uses NbTi charging coil, Nb_3Sn floating coil, and HTS-$BSCCO_{2223}$ levitation coil

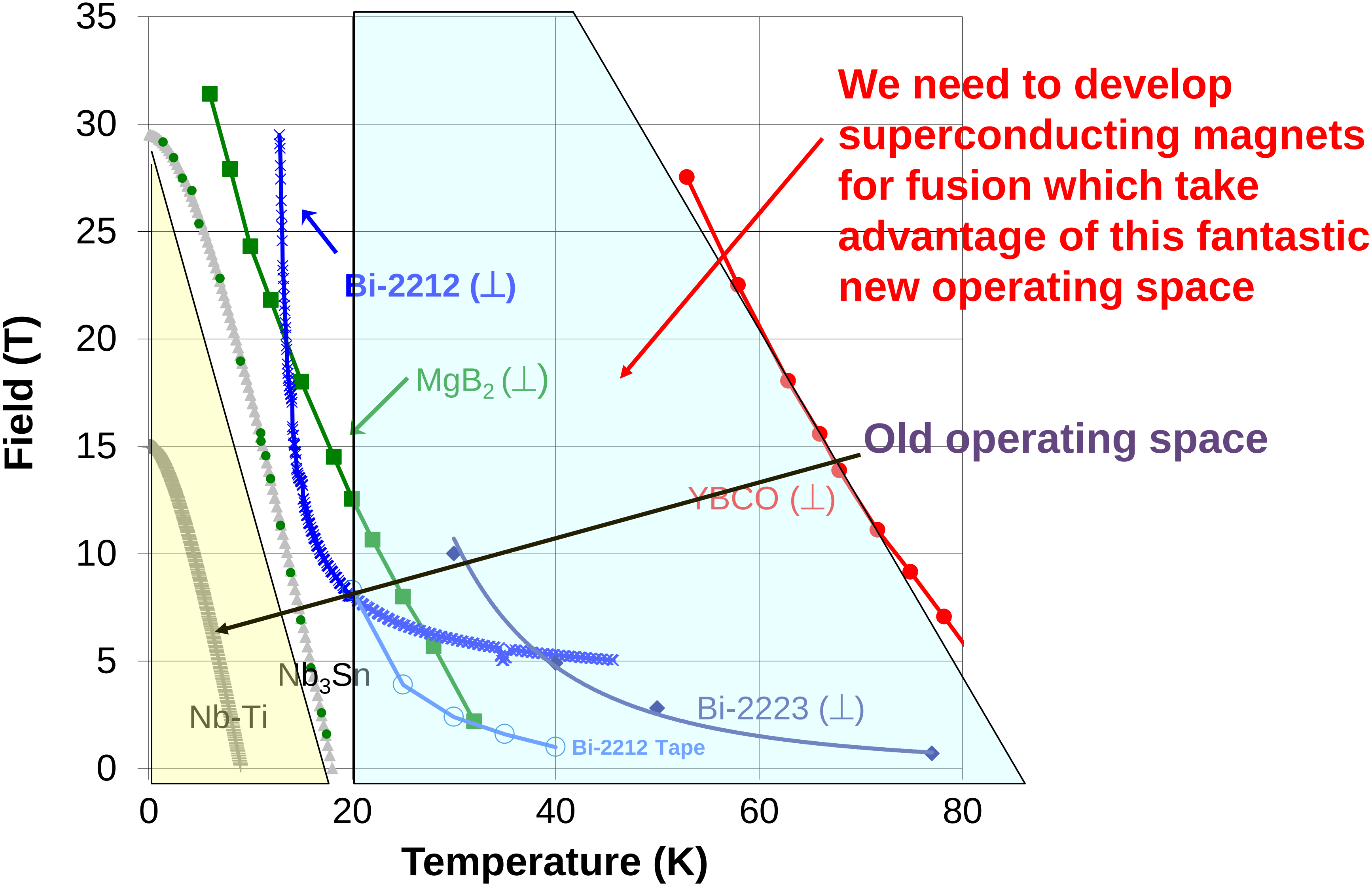
Nb_3Sn Conductor Development (HEP Program)



Maximum Field in Accelerator Dipole Magnets



HTS make much higher magnetic fields accessible . . .



Benefits for Magnetic Fusion Energy and Other Scientific Applications

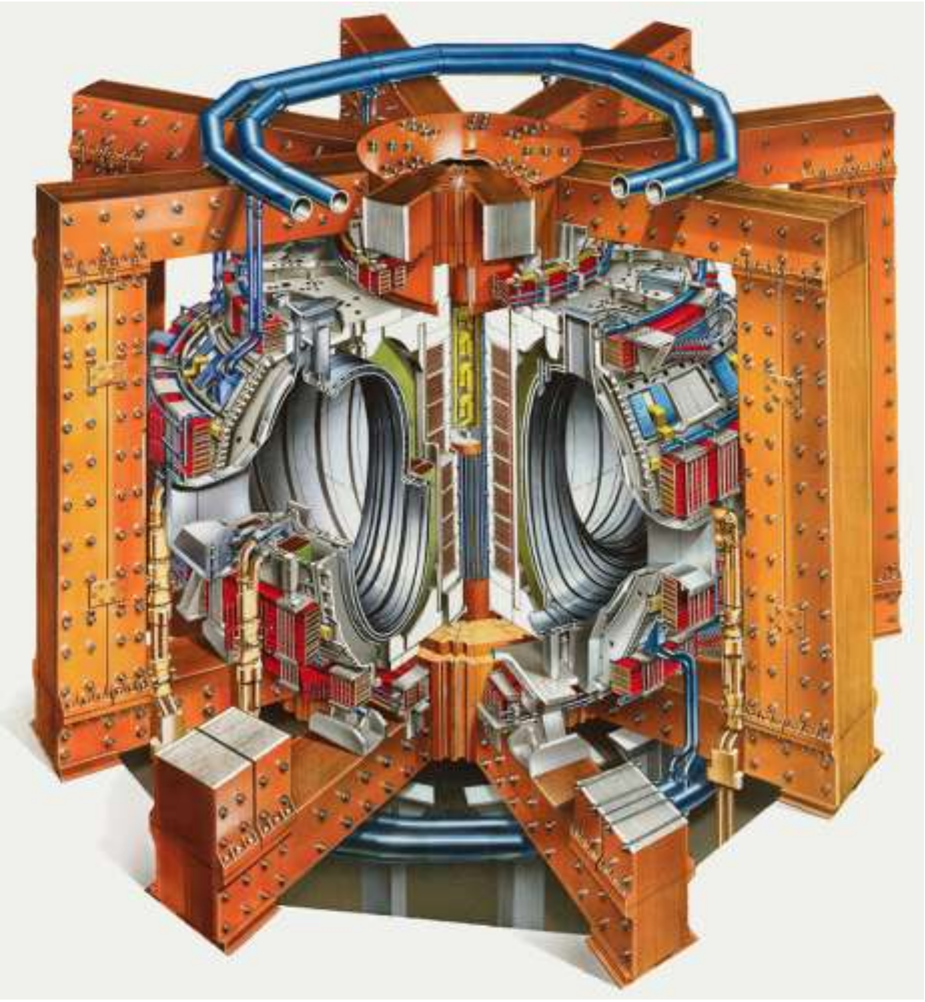
- HTS is potentially a *'game changer'* for fusion devices in several respects:
  - *high performance*
  - *high reliability, availability and maintainability*
  - *acceptable cost*
- Flexible experimental scale devices
- Steady-State tokamaks,
- Stellarators, and other 3-D magnetic configurations
- Synergism with other DOE and scientific programs:
  - High Energy Physics
  - Superconductivity for Electric Systems
  - High field NMR
  - Medical (MRI, Proton Radiotherapy)

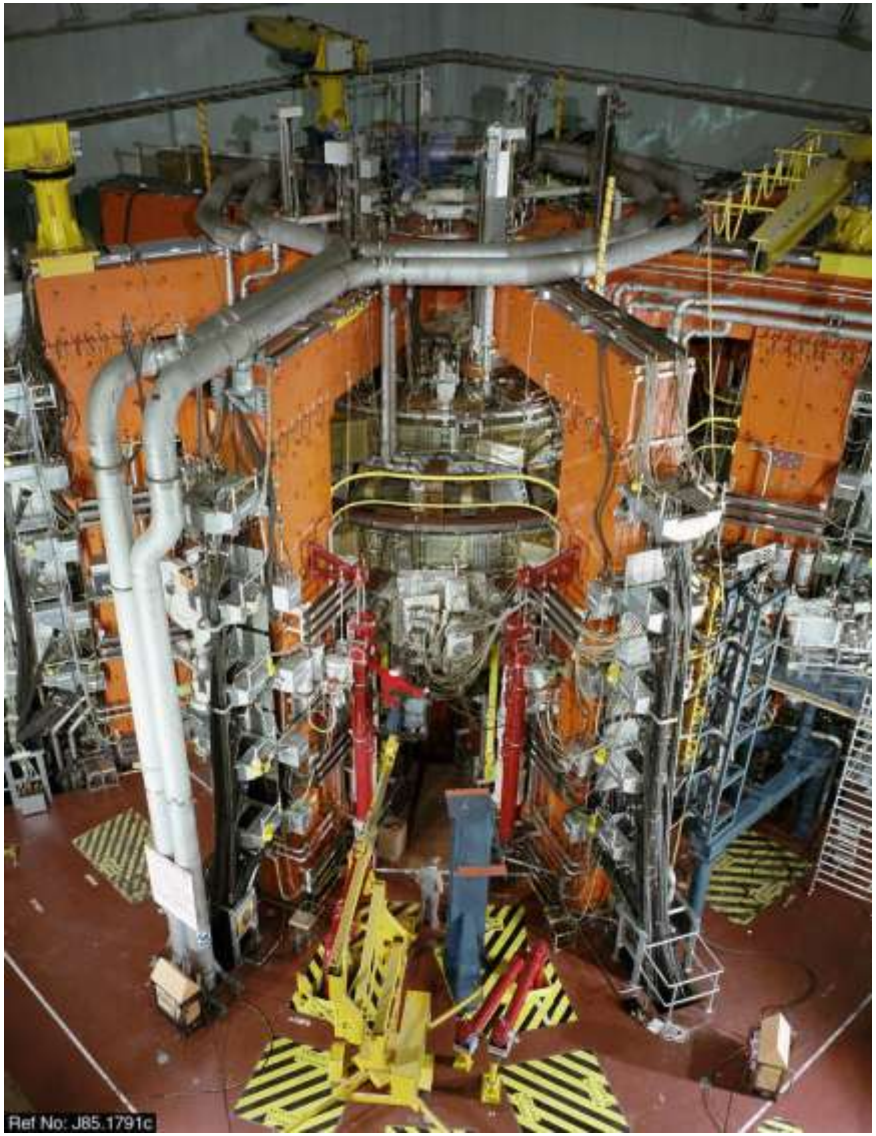
Key Issues for Future Development

- Magnet components
- Radiation effects
- Advanced conductors

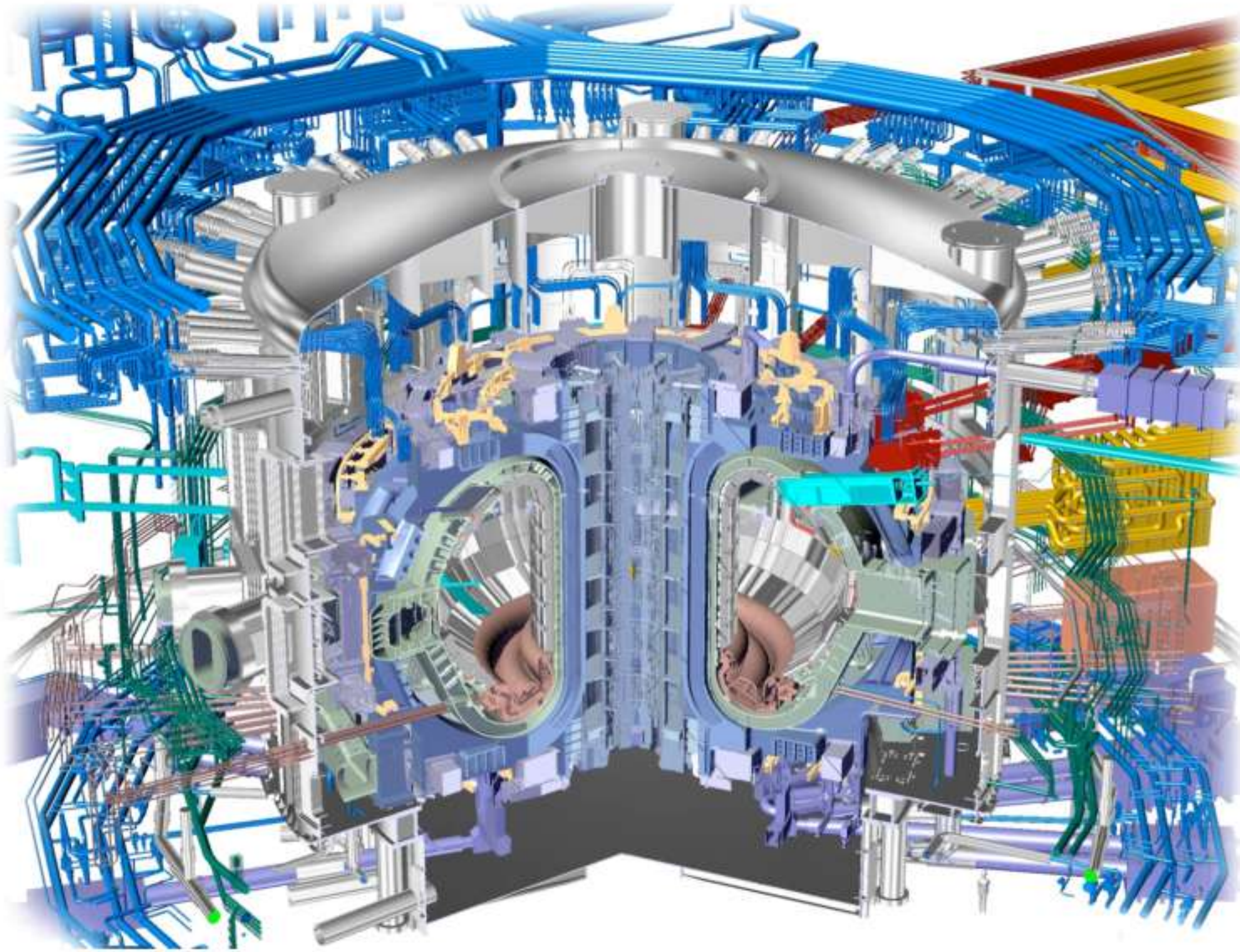
Joint European Torus (JET) Culham, England

- Water-cooled copper tokamak
- World's largest fusion device

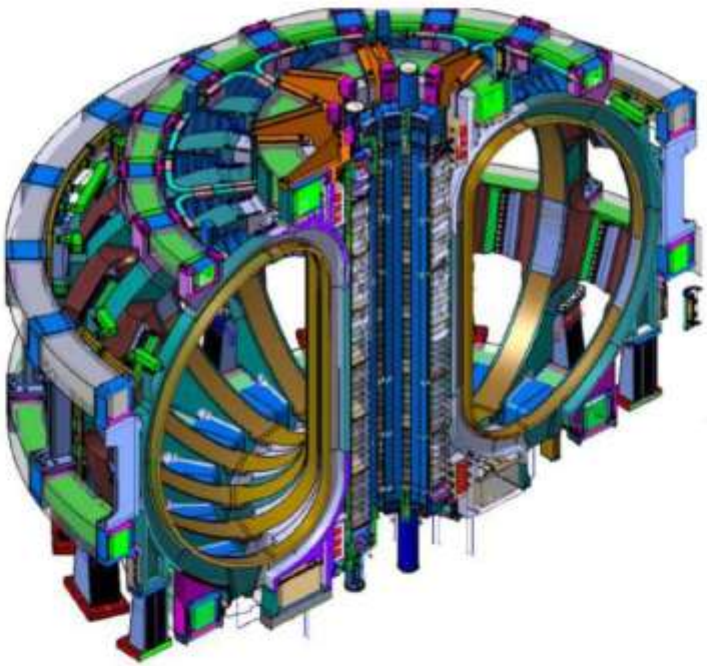




ITER Tokamak



ITER Magnet System Energy

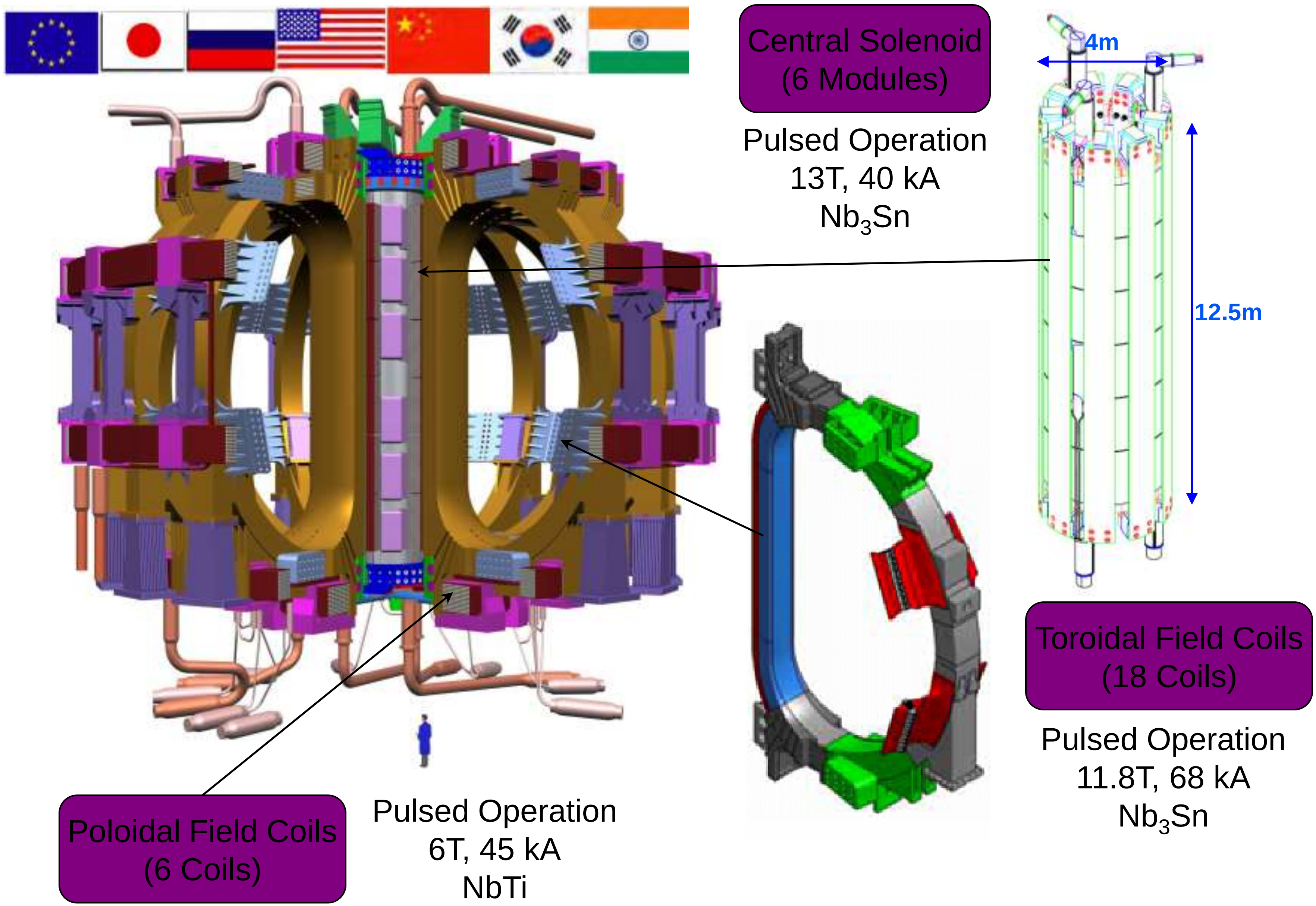


ITER Superconducting
Magnet System Energy
~51 GJ

Charles de Gaulle Airplane Carrier Energy
~38000 t at ~180 km/hr

(Courtesy of G. Johnson, ITER IO)

ITER Magnet System

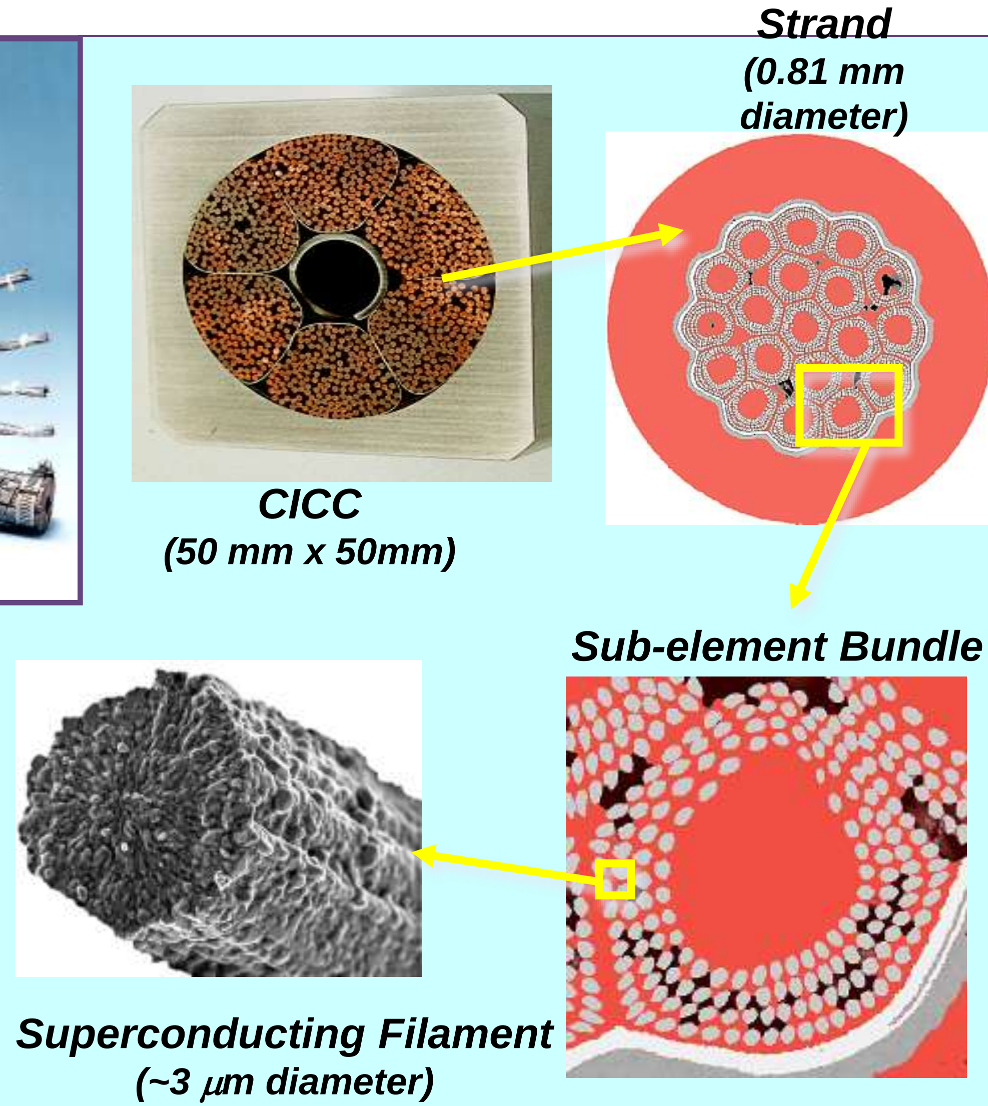


ITER CSMC Superconductor

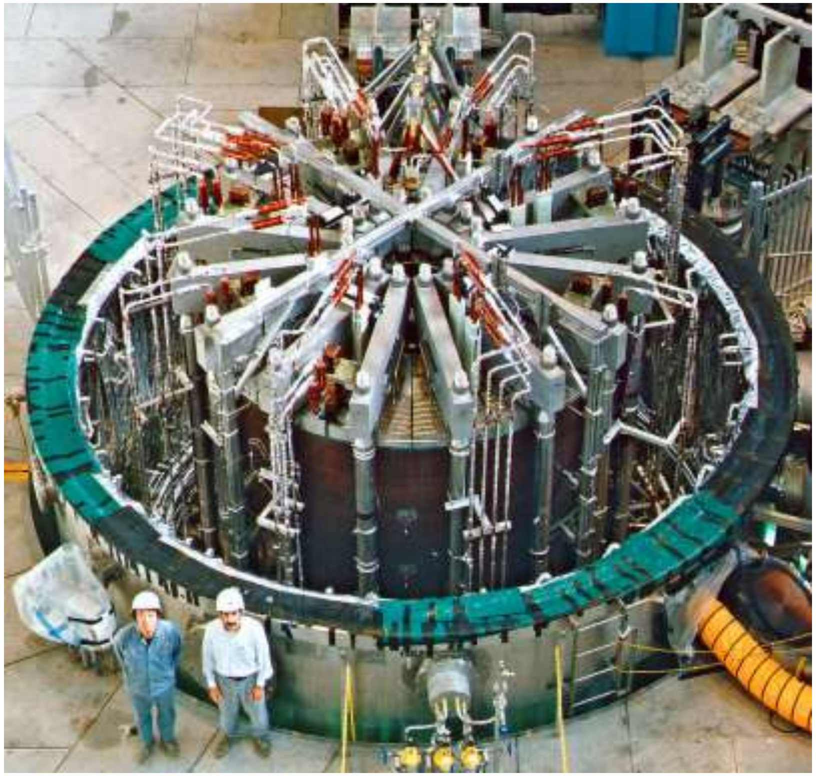
Incoloy Alloy 908 Conduit
(structural materials)

Supercritical helium flows in interstices
and central channel
(heat transfer, thermodynamics, fluid dynamics)

>1000 superconducting wires
(superconducting materials, electromagnetics)



Overview of Model Coil Test Facility at JAERI, Naka, Japan



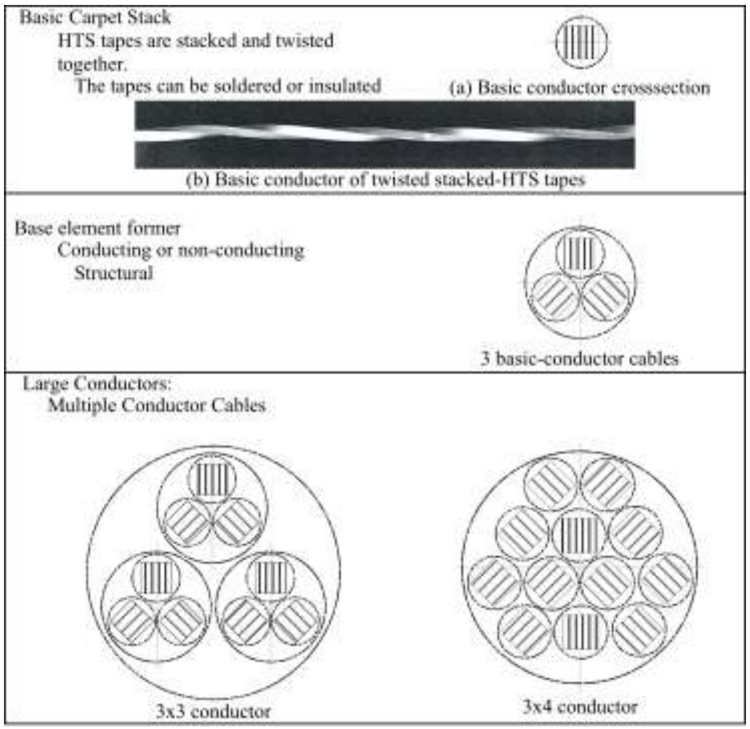
Coils assembled in the Vacuum Vessel

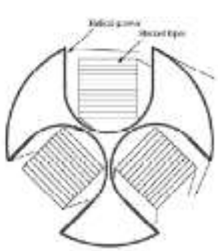
- Magnet stores 640 MJ at 13 Tesla peak field
- Fast Discharge in ~6 seconds

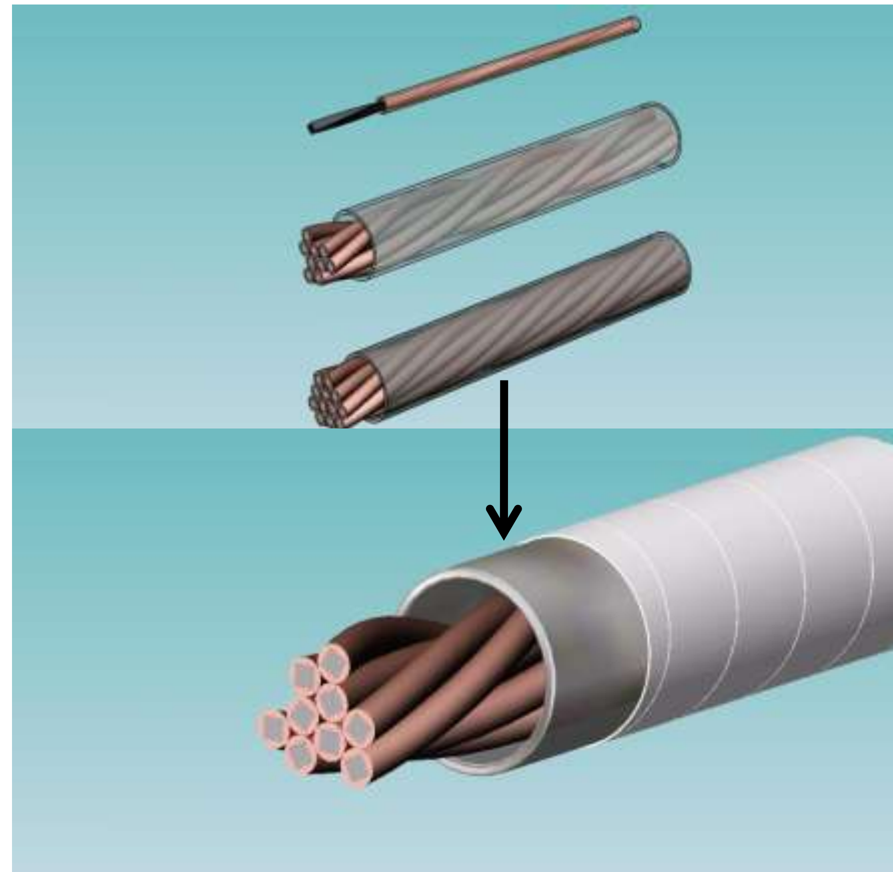
Fusion Conductors

- Require very high current at high magnetic fields
  - 50 kA – 100 kA at 12 T – 20 T
- High strength
- High magnetic fields improve plasma performance
- For HTS to be useful must be able to cable many conductors together
  - Tapes
  - Wires

Twisted Stacked Conductor Concept - With YBCO HTS Flat Tapes

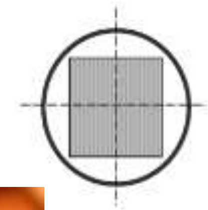


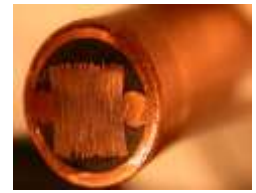




Cable Development Work

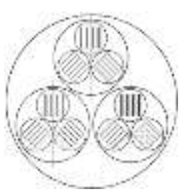
1. Basic elemental conductor development
   - Basic cables made of 1 mm – 5 mm width YBCO tapes
   - Multi-cable conductor

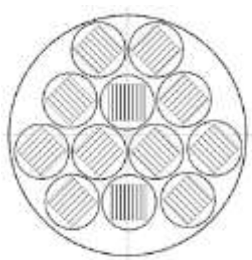




2. CICC development

3. Termination development for Multiple-cable conductor





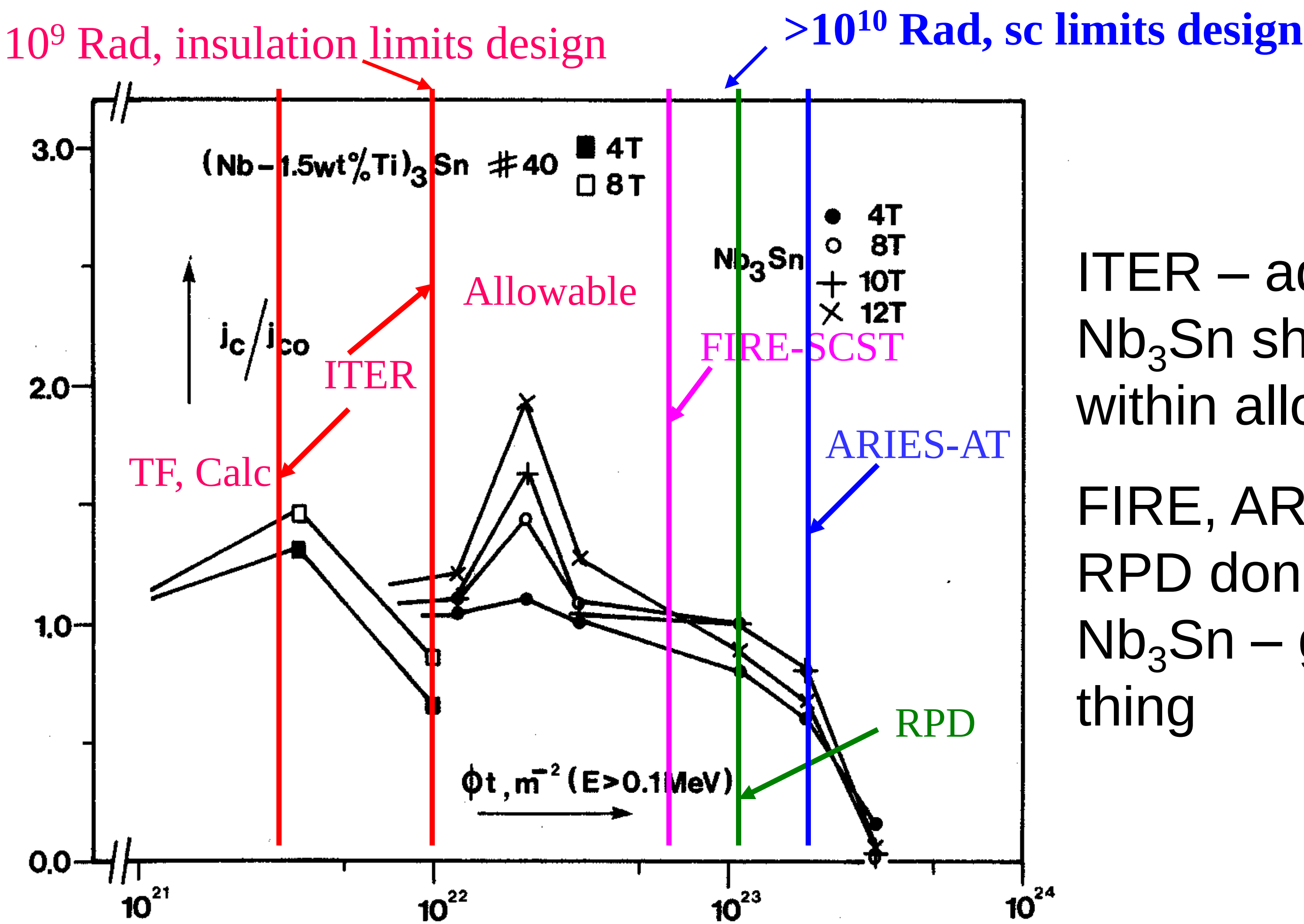
Radiation Effects on Conductors

- Superconductor Material
- Copper Stabilizer Material
- Insulation Materials

Superconductor Materials – LTS Nb_3Sn

- Significant (and later on drastic) effects on T_c
  - caused by disorder
- Significant enhancements of J_c (followed by a precipitous drop)
  - increase caused by an increase of H_{c2} - mean-free-path-effect
  - drop caused by the T_c degradation
- Results typical for materials with a high degree of order

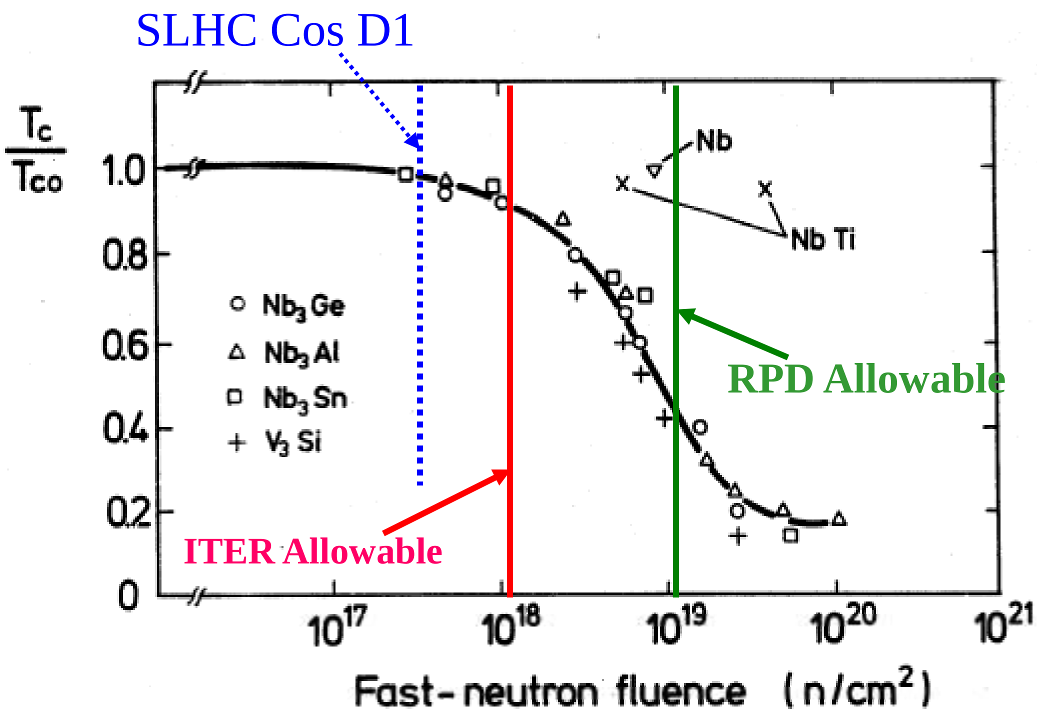
Reactor Fluence Levels vs. Nb_3Sn J_c/J_{co}

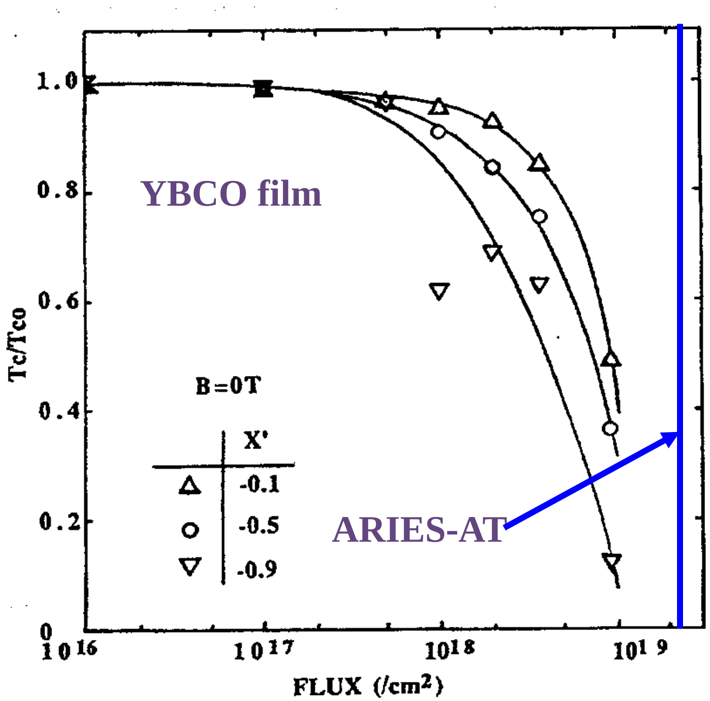


ITER – advanced Nb_3Sn should be within allowable

FIRE, ARIES-AT, RPD don't use Nb_3Sn – good thing

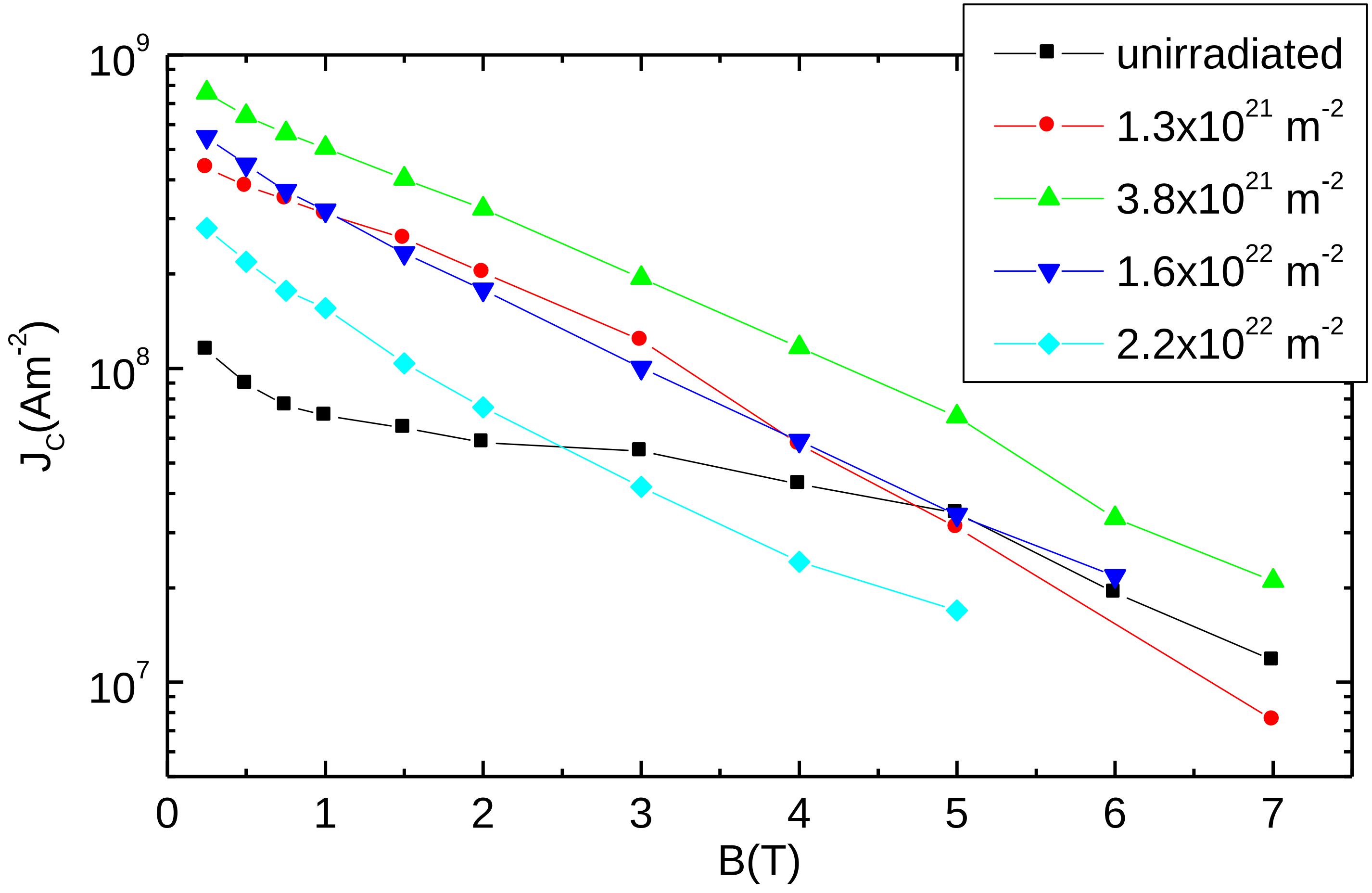
Neutron Degradation of T_c, A15's and YBCO





- All A15's have same T_c/T_{co} degradation vs. fluence
  - 1-2 orders of magnitude more sensitive than NbTi
- YBCO films have faster T_c/T_{co} degradation than A15's

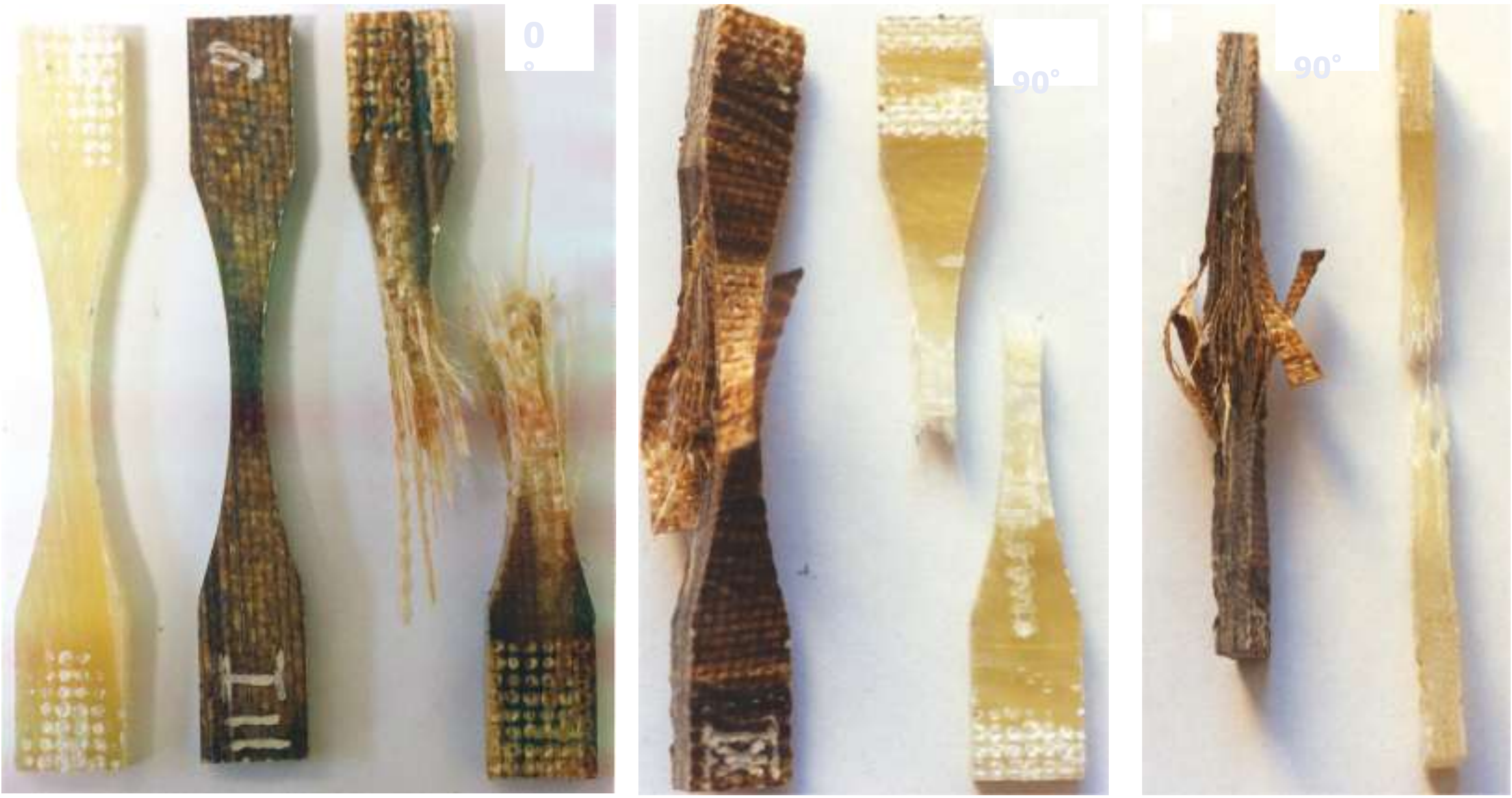
Critical currents in YBCO bulk superconductors at 77 K



Insulation Materials

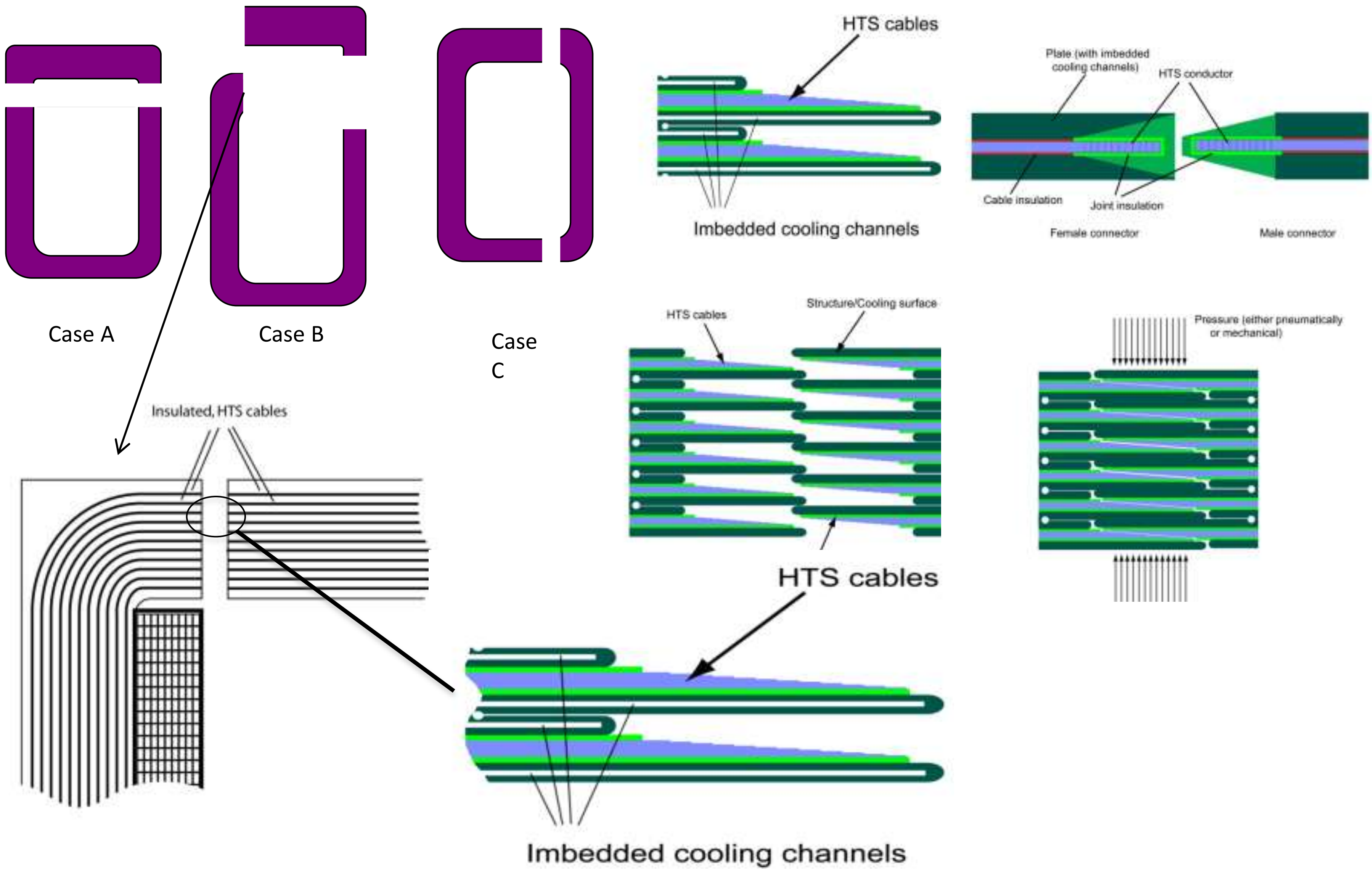
- Presently employed glass-fiber reinforced epoxies degrade at the ITER fluence level
- Novel cyanate esters may not withstand the DEMO fluence level
- New research efforts needed

Tensile Tests of Unirradiated and Irradiated ALSTOM ITER Samples

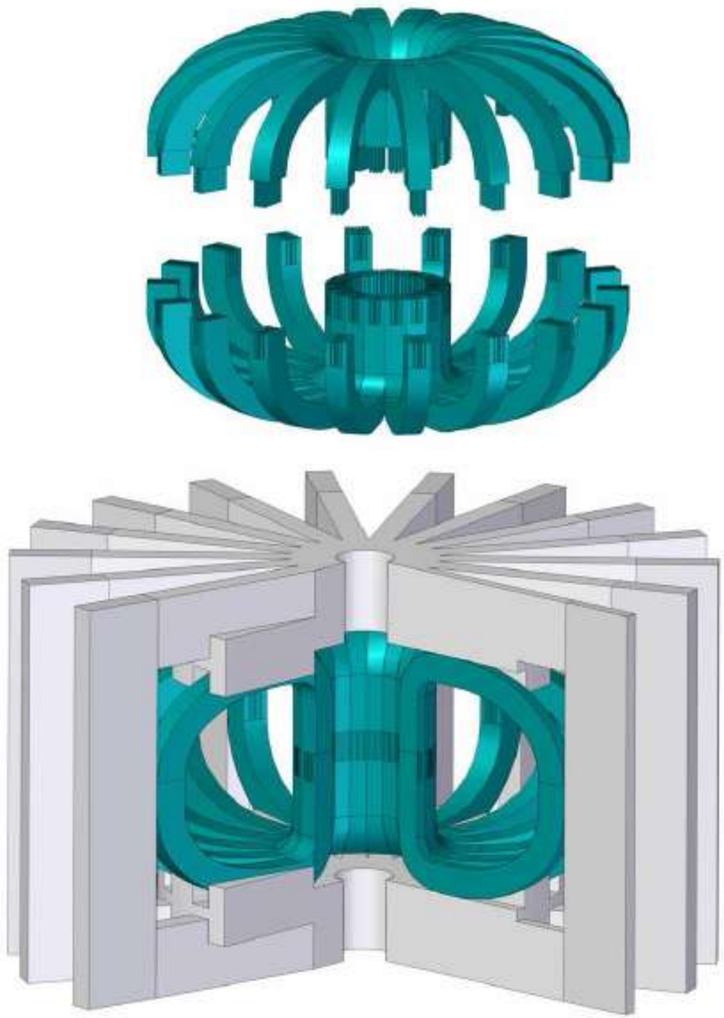


Fracture at 77 K before and after irradiation
to fast neutron fluence of $1x\ 10^{22}\ m^{-2}$ (E>0.1 MeV)

HTS Conductors Could Make Demountable Joints Possible



Demountable magnets could vastly improve maintenance and availability



Summary

- Demo and commercial fusion reactors will not be built with 1990‘s ITER technology
  - *We can‘t afford to wait 20-30 years and then try to catch up*
- Advanced superconducting technology is critical to development of a reliable and economical fusion reactor
  - *Need intensive HTS high current, high field conductor development*
- Significant further R&D of radiation tolerant insulation systems must be pursued
- Can radiation resistance of superconductors be improved?
- New facilities are required including ability to irradiate at cryogenic temperatures
  - *Ideally perform mechanical tests at low temperature*