Superconducting Coils for Fusion Devices: R&D needs

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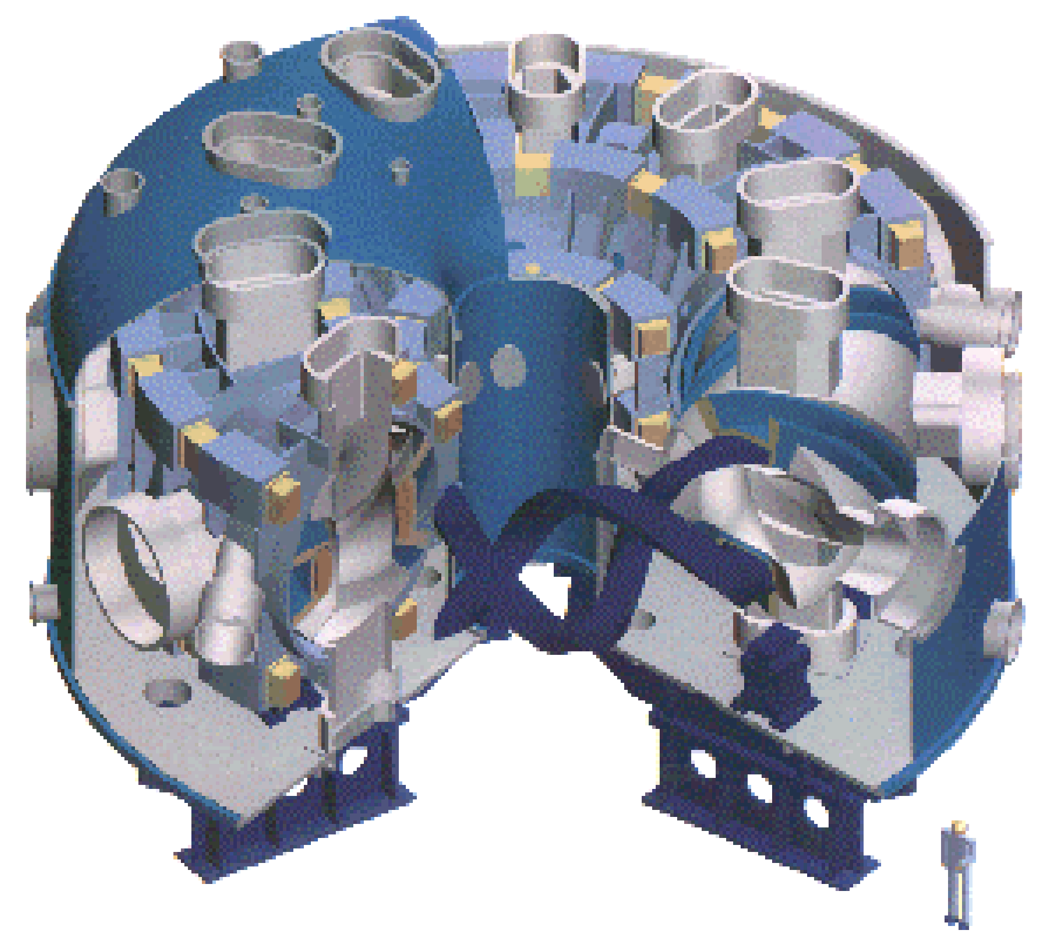
Outline

- Fusion Devices Status
- Critical issues
- R&D strategy

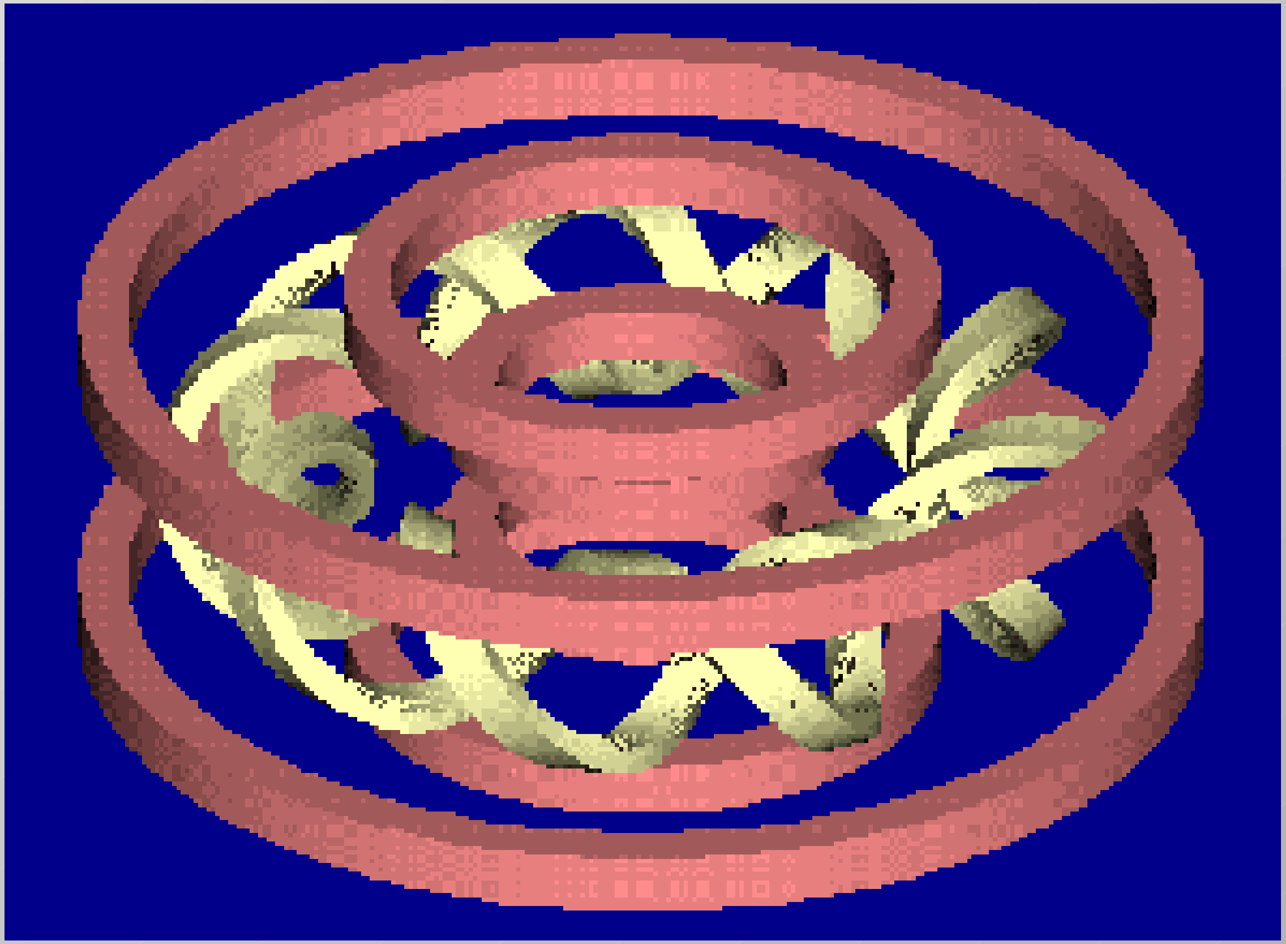
Fusion Devices Status

- **LHD:**	**operation**
- **W7-X:**	**construction**
- **Kstar:**	**construction**
- **ITER:**	**feasibility demonstration (CSMC, TFMC, Inserts)**

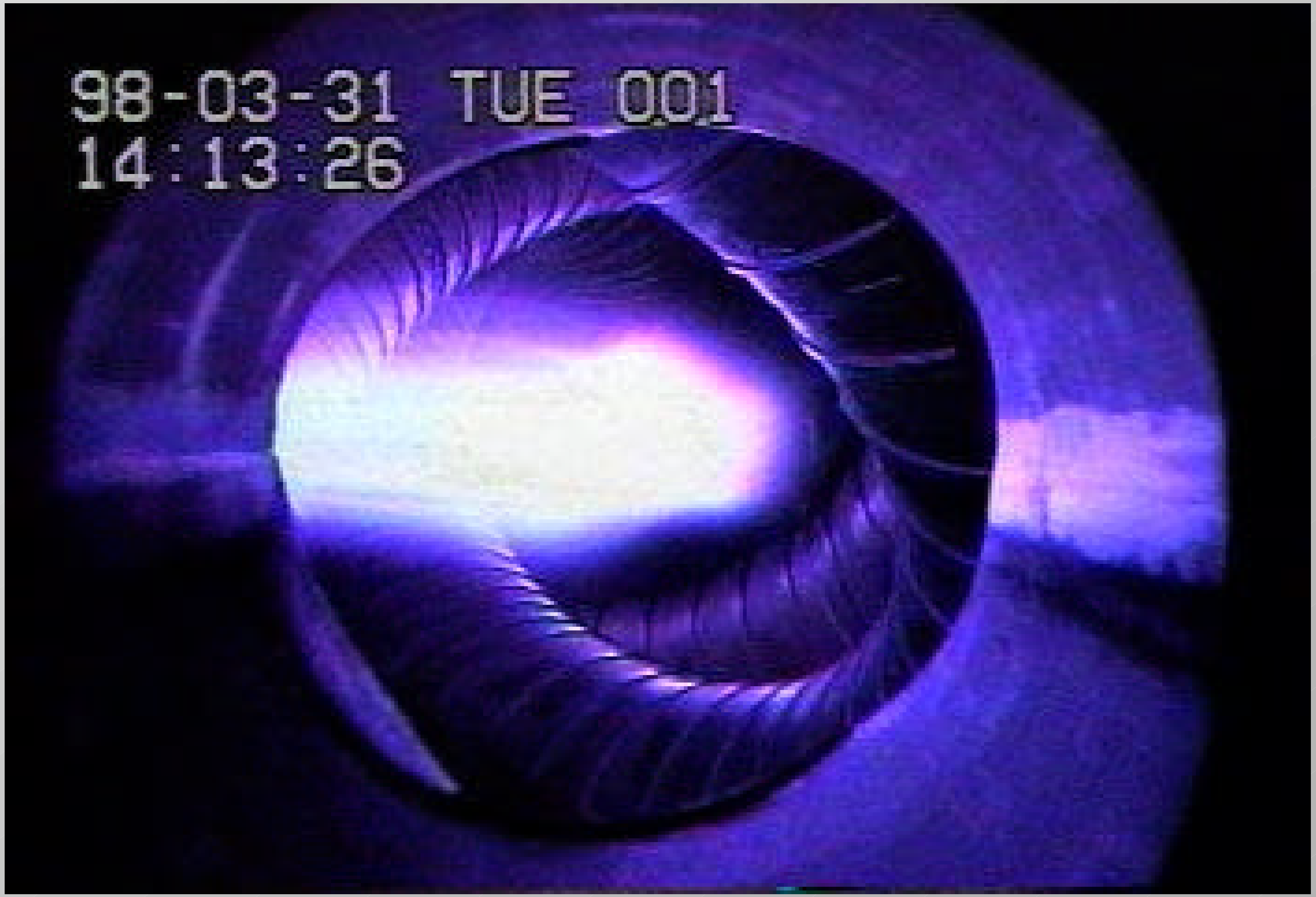
LHD Device



LHD Coils



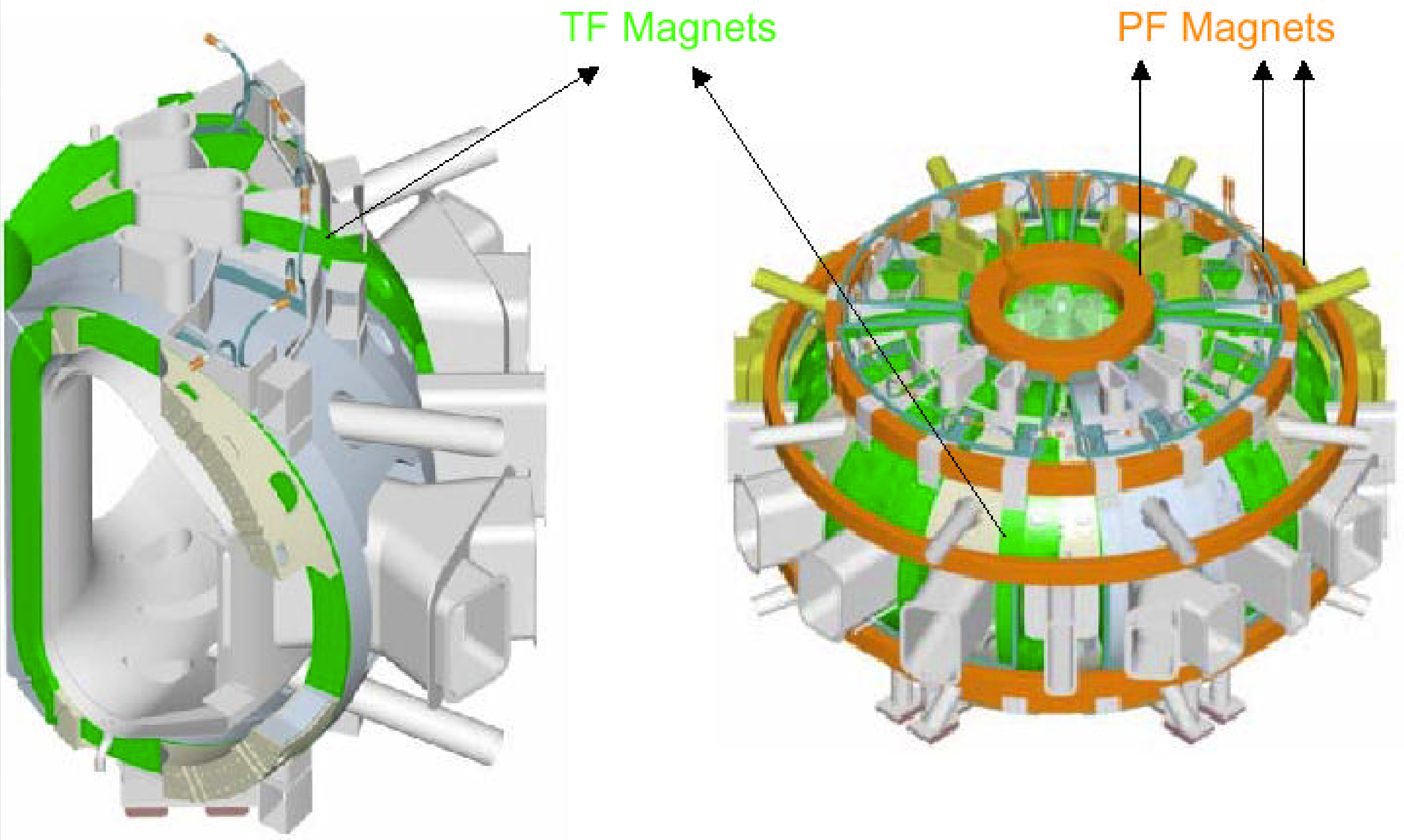
LHD Fist Plasma



LHD Coils Parameters

	V coil	IS coil	OV coil
Diameter(inside)	3.2m	5.4m	10.4m
Diameter(outside)	4.2m	6.2m	11.6m
Weight	16ton	25ton	45ton
B max	6.5T	5.4T	5.0T
Current	20.8 kA	21.6kA	31.3kA
Turn number	240	208	144

KSTAR Superconducting Magnet System

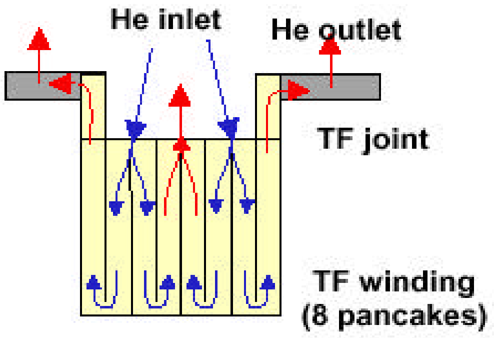


Features of TF Coils

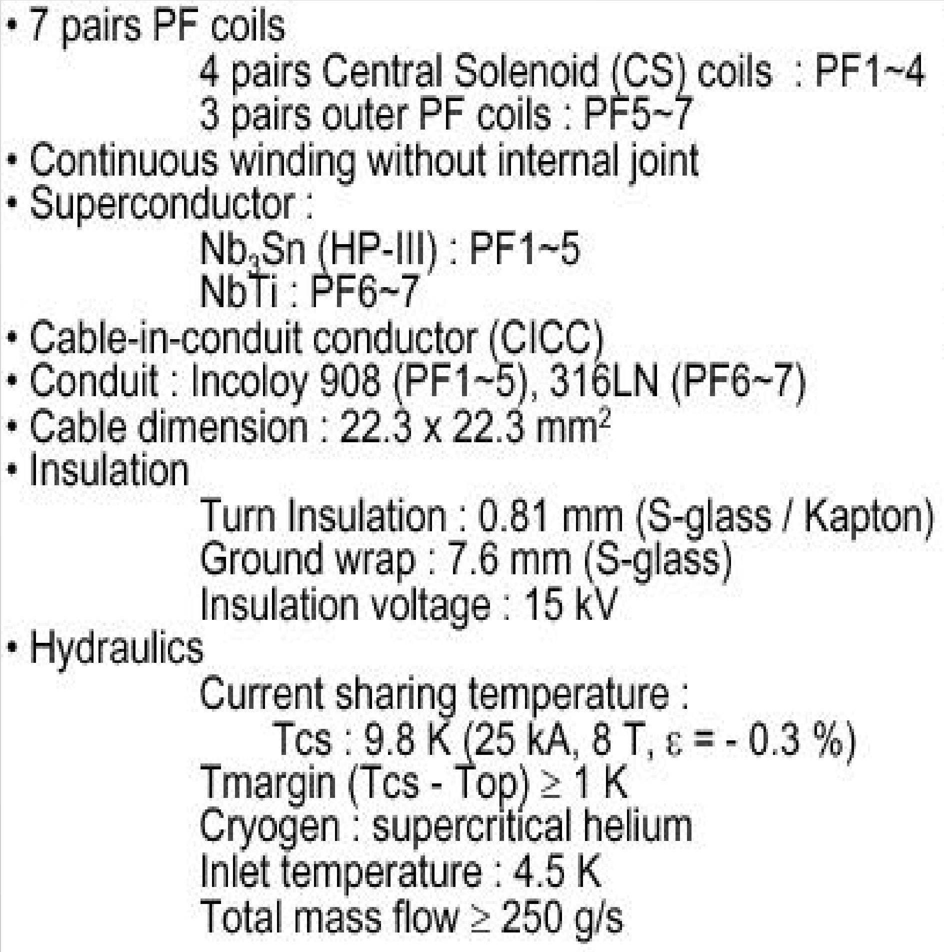
- 16 TF coils
- Continuous winding without internal joint
- B_T = 3.5 T, $B_{max,\ conductor}$ = 7.2 T
- Coil current : 35.2 kA
- Superconductor : Nb_3Sn (HP-III)
- Cable-in-conduit conductor (CICC)
- Conduit : Incoloy 908
- Cable dimension : 25.65 x 25.65 mm^2
- Insulation
  Turn Insulation : 0.81 mm (S-glass / Kapton)
  Ground wrap : 5.6 mm (S-glass)
  Insulation voltage : 15 kV
- Hydraulics
  Current sharing temperature :
  Tcs : 10.2 K (35.2 kA, 7.2 T, ε = - 0.3 %)
  Tmargin (Tcs - Top) $\geq$ 1 K
  Cryogen : supercritical helium
  No. cooling channel per coil : 4
  Inlet temperature : 4.5 K
  Total mass flow $\geq$ 300 g/s

➢ TF Magnet System Major Parameters

Parameter	Units	Value
Number of coils		16
Major Radius, R_0	(m)	1.8
B-field @ R_0, B_t	(T)	3.5
B_{max}, calculated	(T)	7.2
Total TF current, I	(MA-t)	31.5
I_{cond}	(kA)	35.2
N_{layers}		7
$N_{pancakes}$		8
$n_{turns,\ coil}$		56
$V_{dump,system}$	(kV)	6
Stored Energy, Em	(MJ)	500
Height (ground wrap, 293 K)	(m)	4.06
Width (ground wrap, 293 K)	(m)	2.91

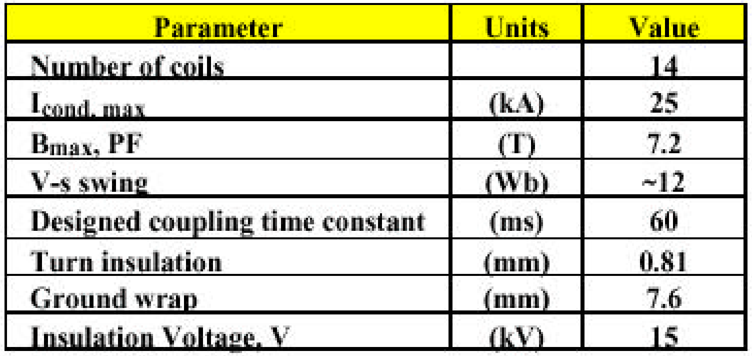


Features of PF Coils

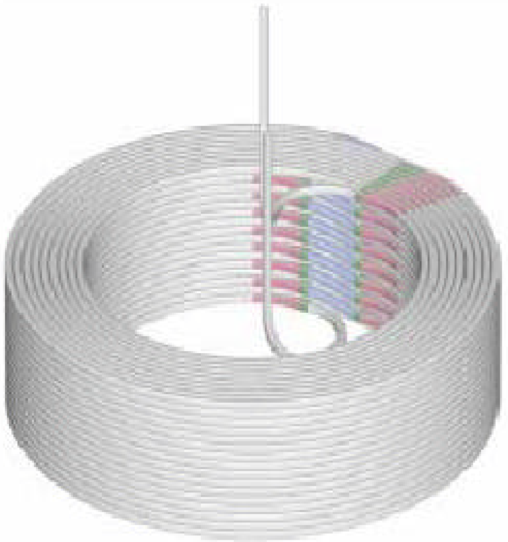


- 7 pairs PF coils
  - 4 pairs Central Solenoid (CS) coils : PF1~4
  - 3 pairs outer PF coils : PF5~7
- Continuous winding without internal joint
- Superconductor :
  - Nb_3Sn (HP-III) : PF1~5
  - NbTi : PF6~7
- Cable-in-conduit conductor (CICC)
- Conduit : Incoloy 908 (PF1~5), 316LN (PF6~7)
- Cable dimension : 22.3 x 22.3 mm^2
- Insulation
  - Turn Insulation : 0.81 mm (S-glass / Kapton)
  - Ground wrap : 7.6 mm (S-glass)
  - Insulation voltage : 15 kV
- Hydraulics
  - Current sharing temperature :
    - Tcs : 9.8 K (25 kA, 8 T, ε = - 0.3 %)
  - Tmargin (Tcs - Top) ≥ 1 K
  - Cryogen : supercritical helium
  - Inlet temperature : 4.5 K
  - Total mass flow ≥ 250 g/s

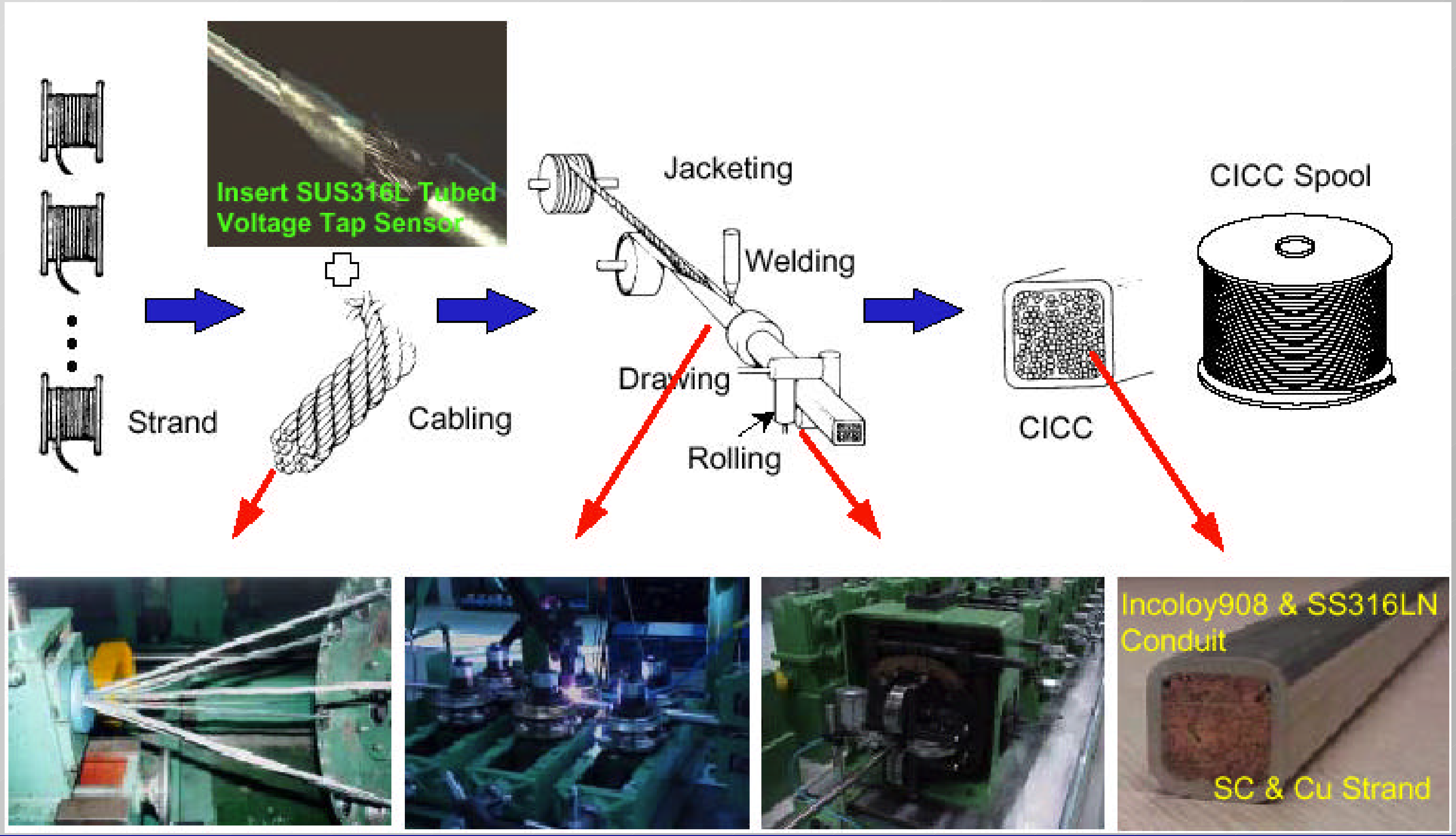
➢ PF Magnet System Major Parameters

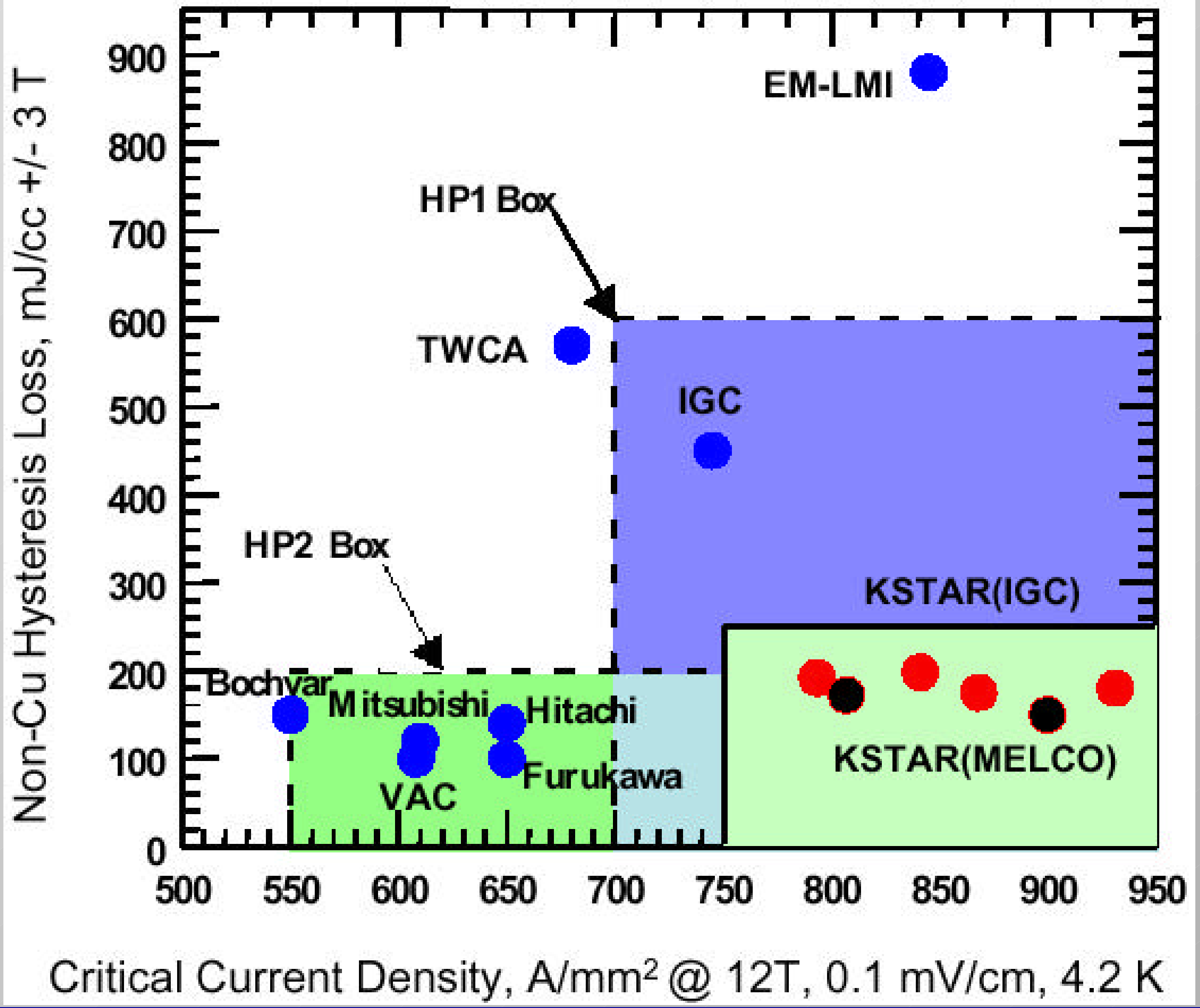


Parameter	Units	Value
Number of coils		14
$I_{cond,\,max}$	(kA)	25
$B_{max,\,PF}$	(T)	7.2
V-s swing	(Wb)	~12
Designed coupling time constant	(ms)	60
Turn insulation	(mm)	0.81
Ground wrap	(mm)	7.6
Insulation Voltage, V	(kV)	15



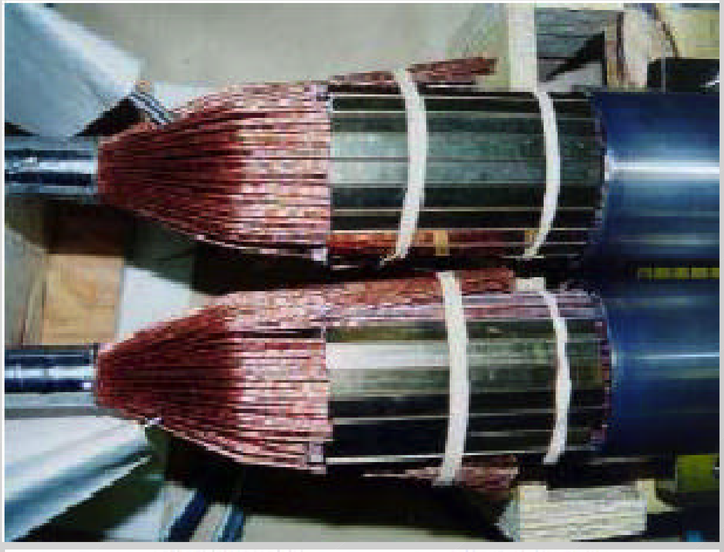
CICC (Cable-In-Conduit Conductor) Fabrication

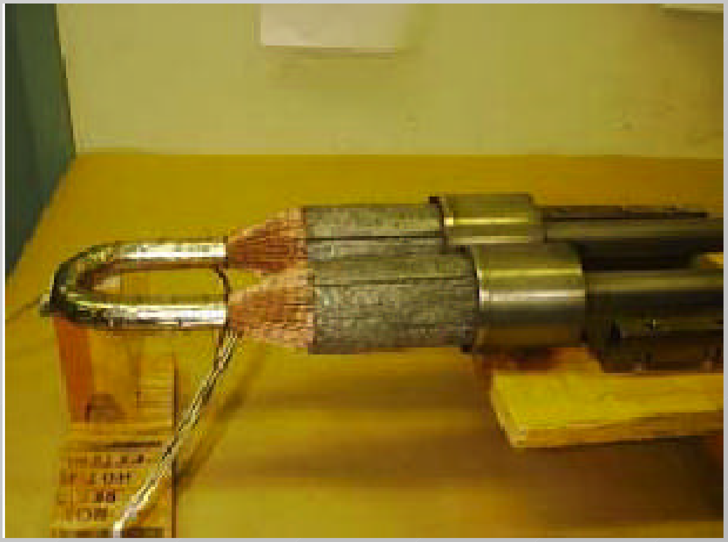


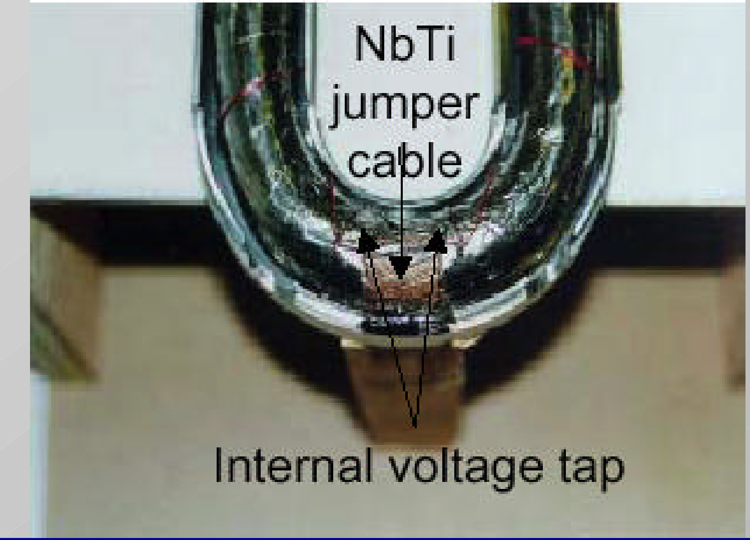

Non-Cu Hysteresis Loss, mJ/cc +/- 3 T
0
100
200
300
400
500
600
700
800
900
500
550
600
650
700
750
800
850
900
950
Critical Current Density, A/mm² @ 12T, 0.1 mV/cm, 4.2 K
EM-LMI
HP1 Box
TWCA
IGC
HP2 Box
KSTAR(IGC)
Bochvar
Mitsubishi
Hitachi
VAC
Furukawa
KSTAR(MELCO)

CICC for TF00 Coil

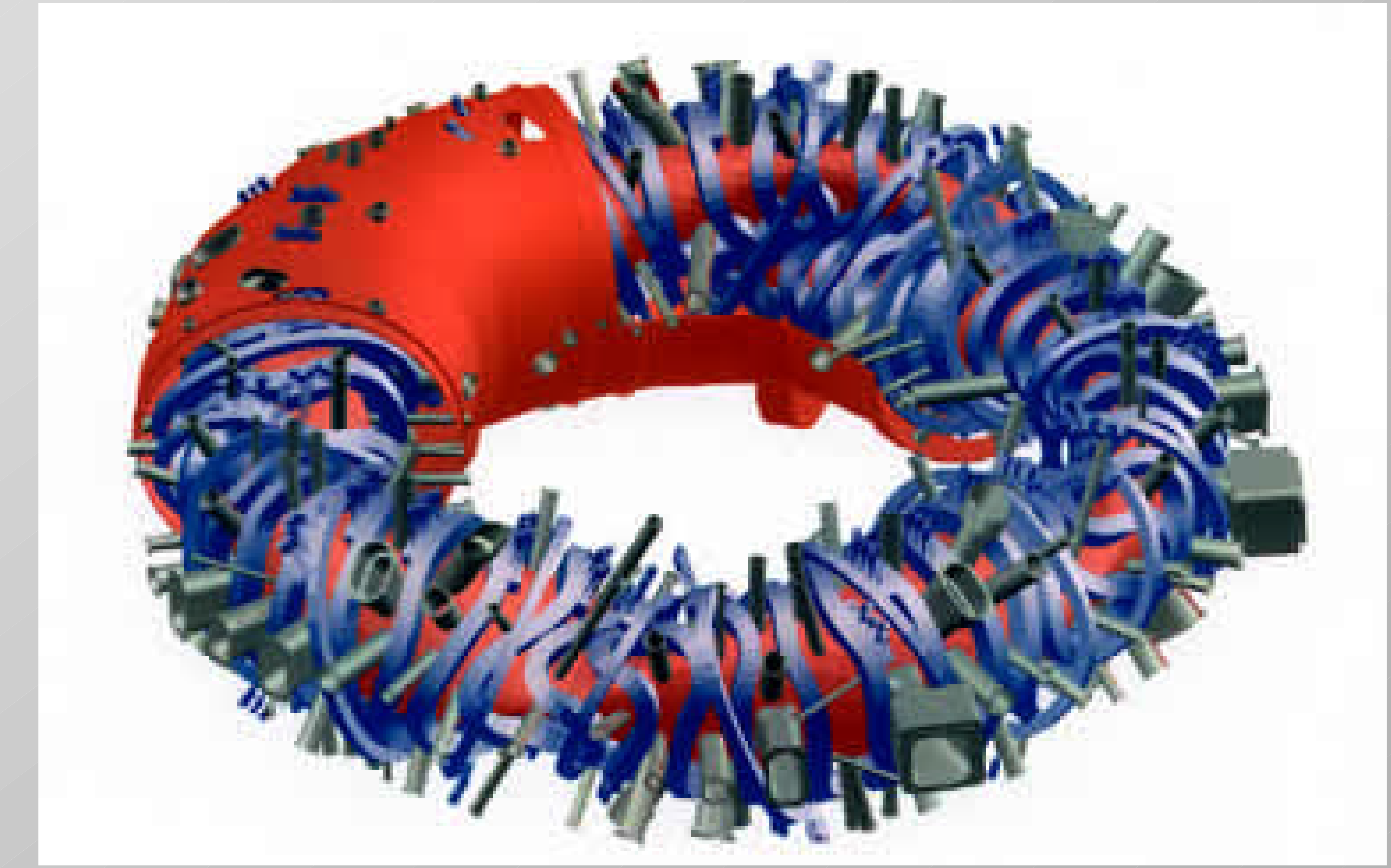
Strand-to-strand CICC Joint Fabrication (III)

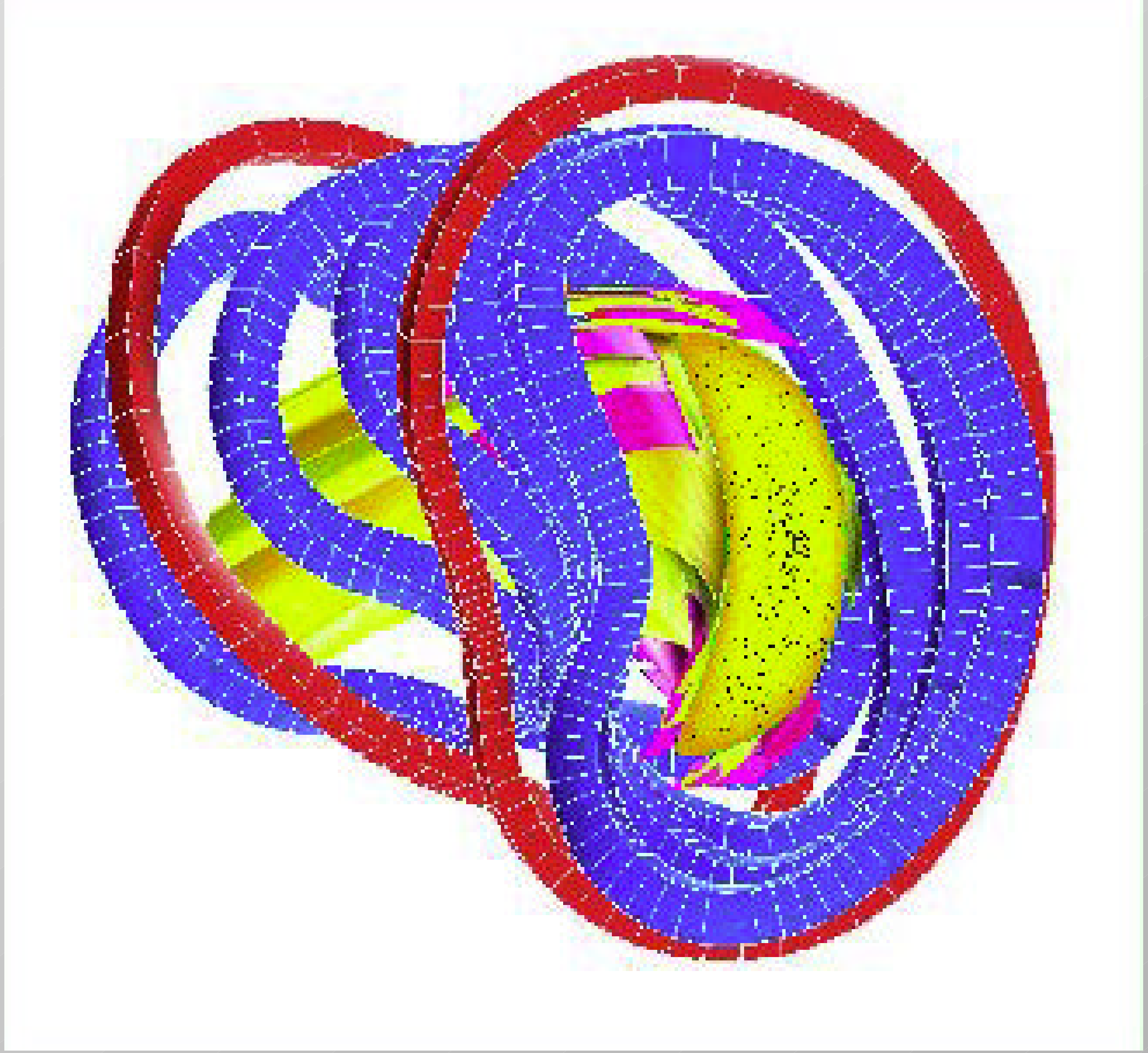




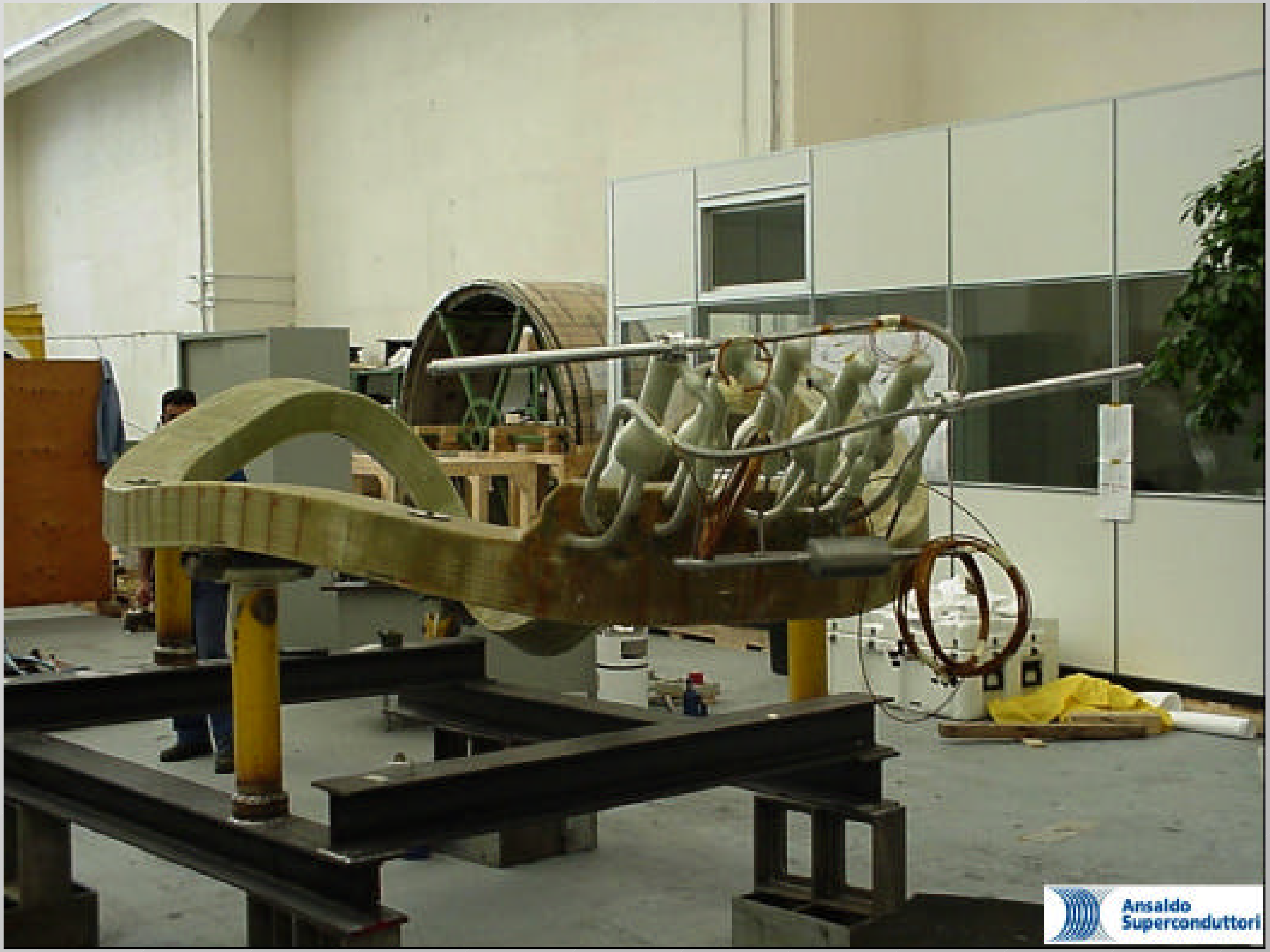


Wendelstein 7X: Coils and Cryostat

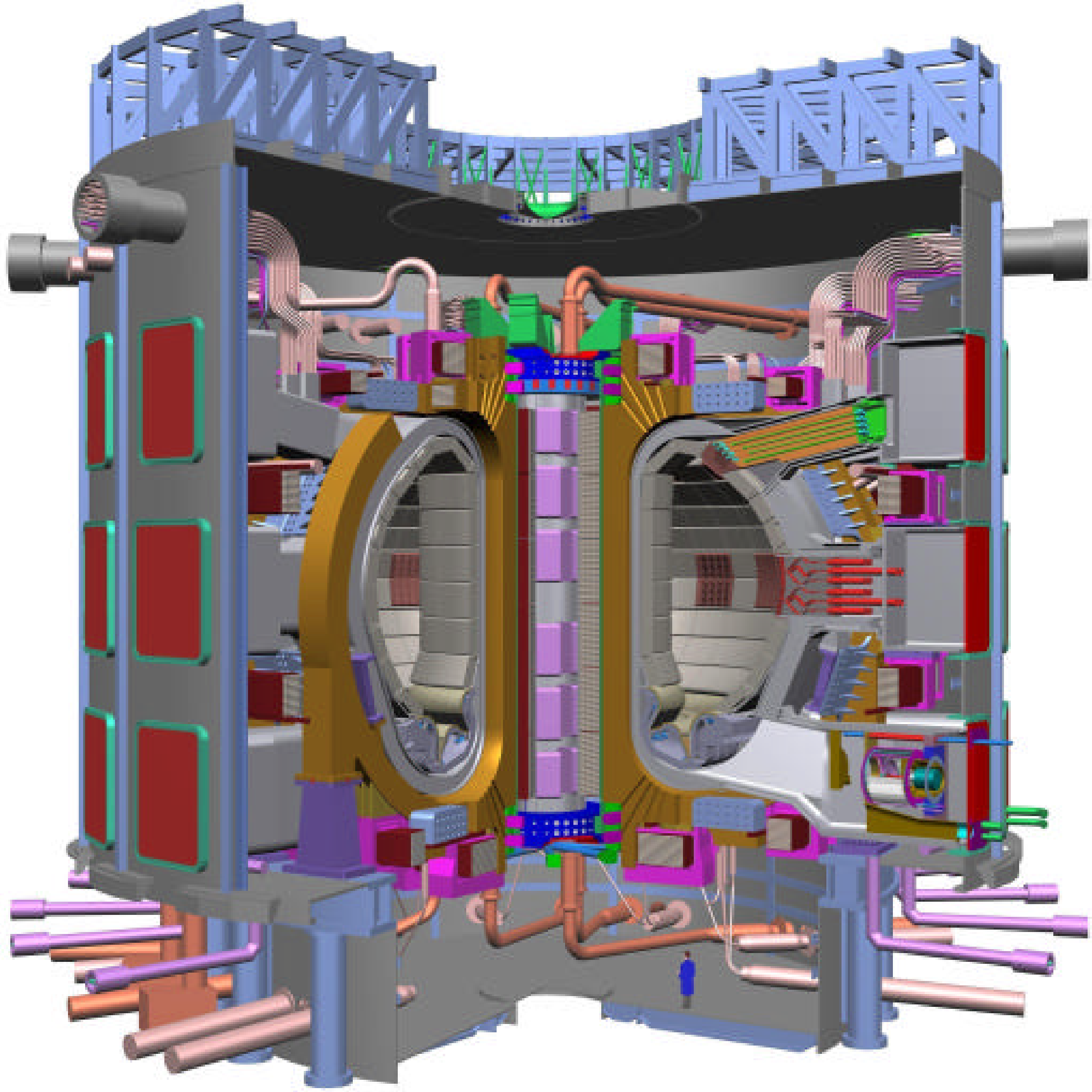




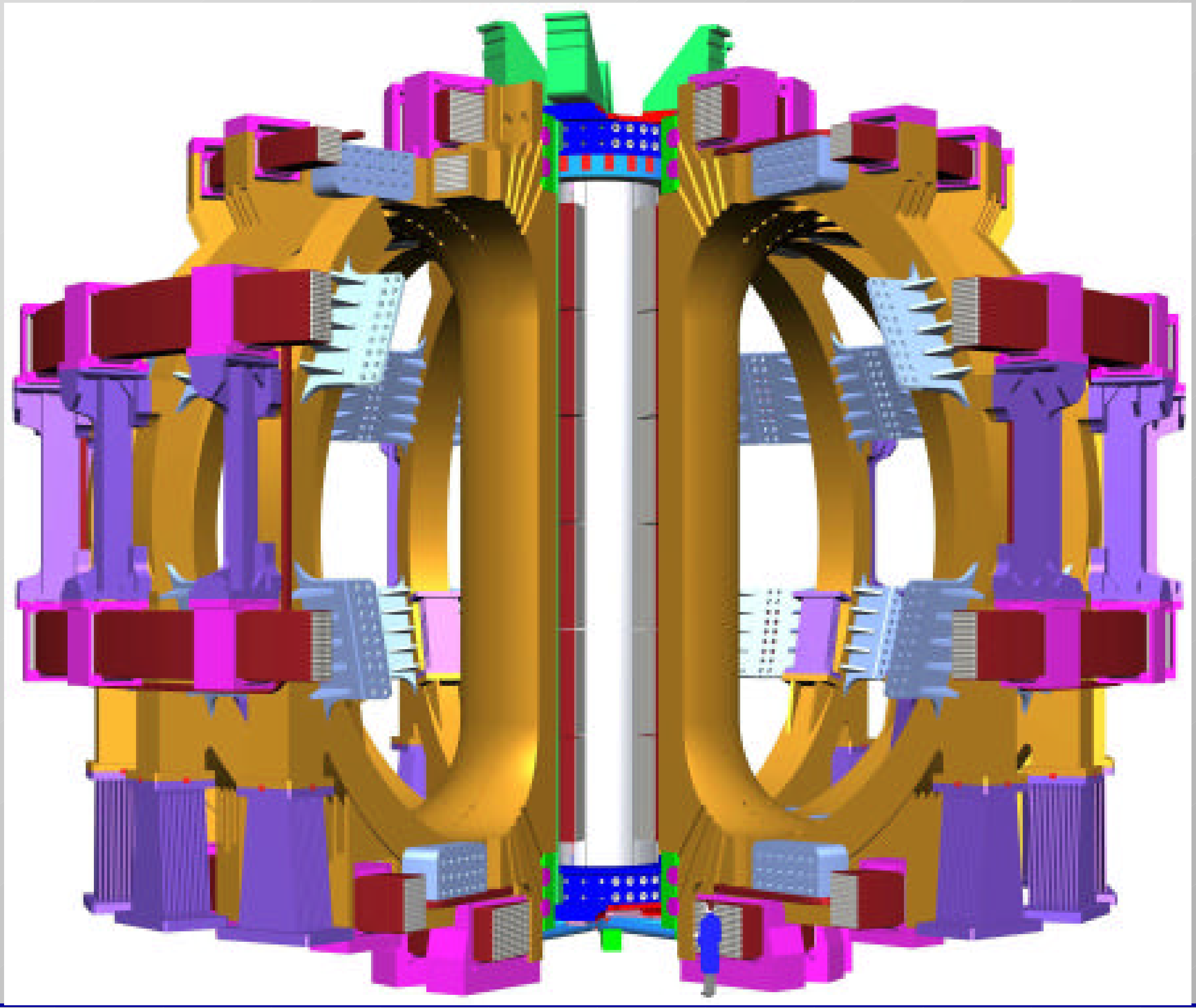
W7X Coil



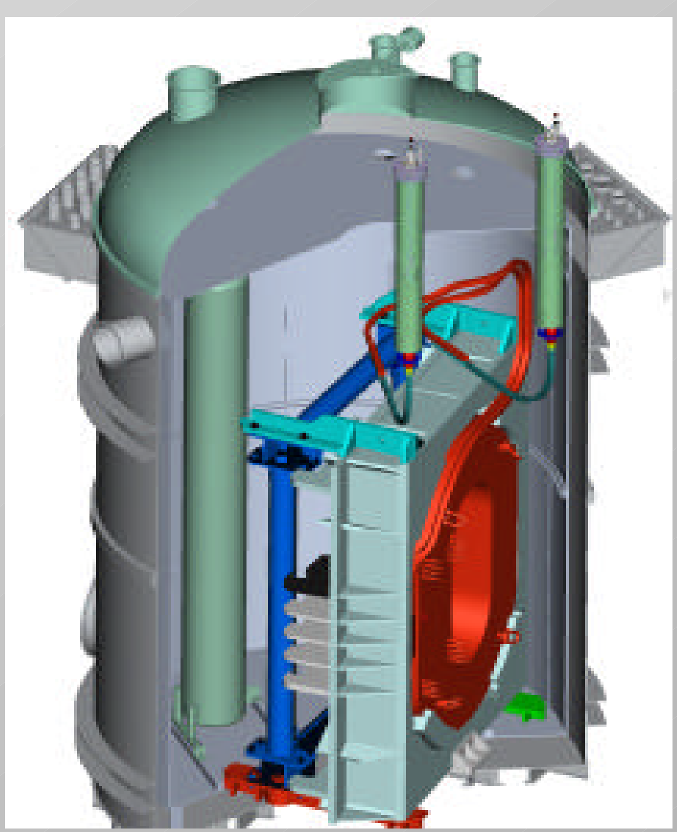
ITER-FEAT Device



ITER Magnets System



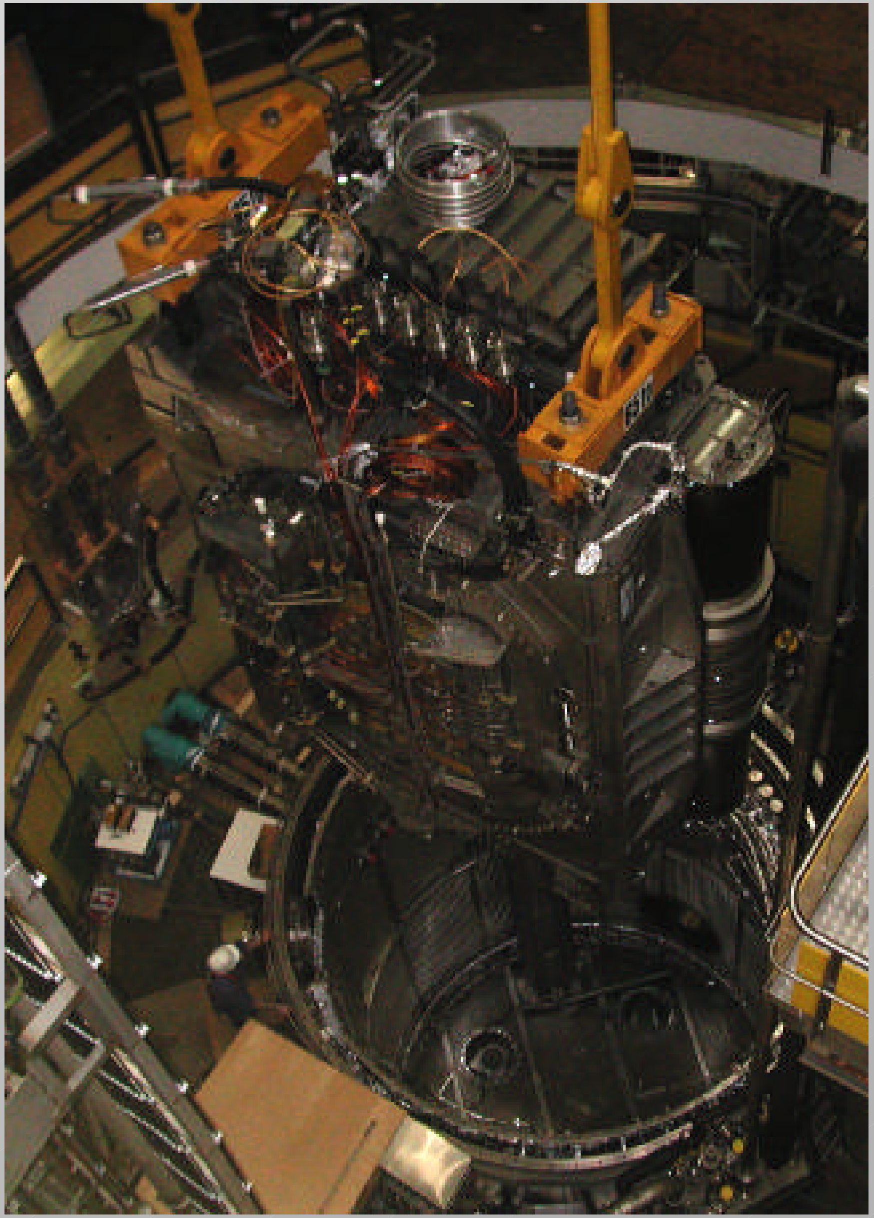
TFMC and Auxiliary Structure in TOSKA vessel

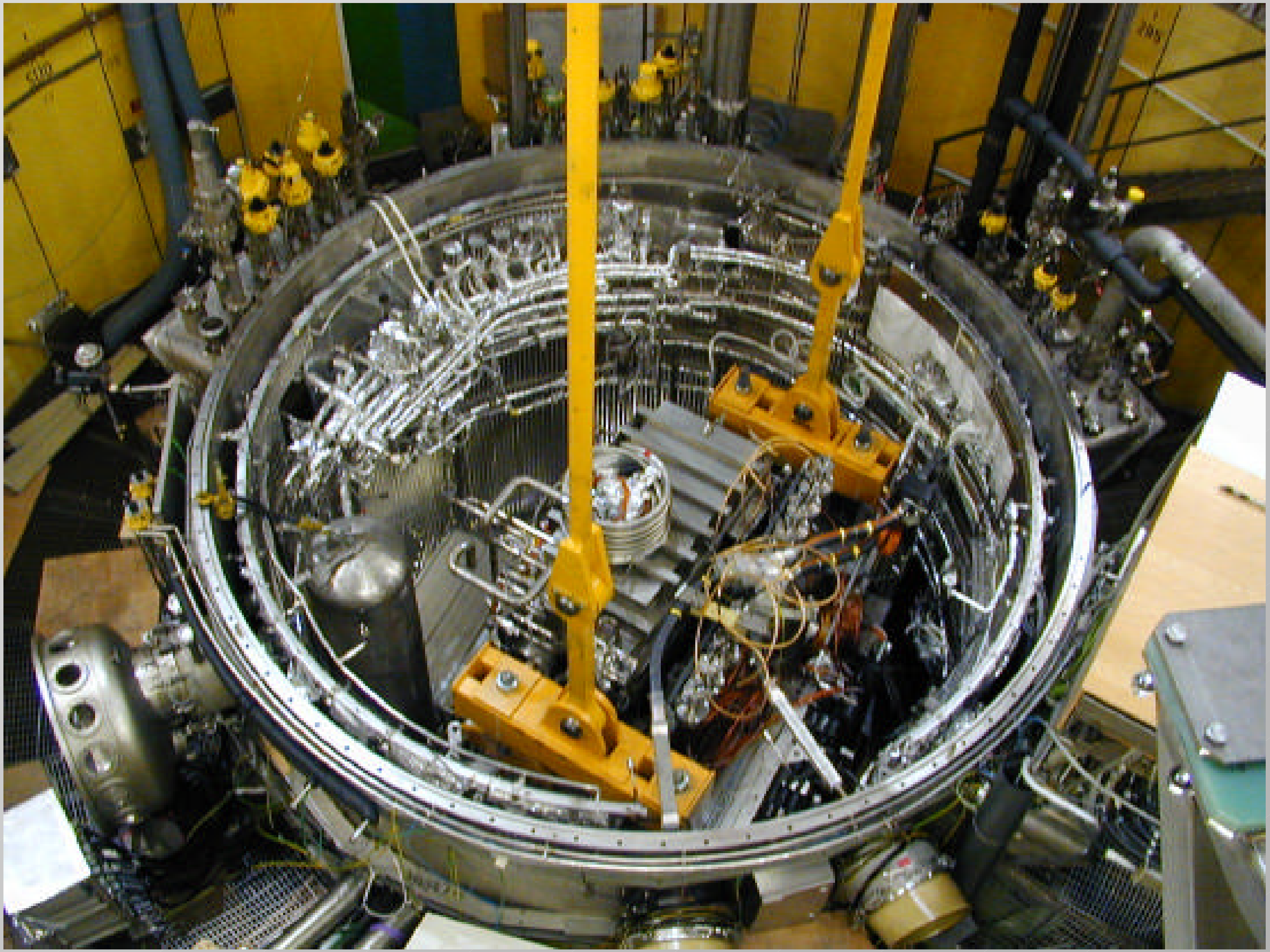


LCT+TFMC

Installation of the ITER TF model coil into the TOSKA Vacuum Vessel

4 April 2002





Conductors of the two ITER model coils

left: CSMC conductor, right: exploded view of the TFMC conductor

Company	Europa Metalli (EM)
Process	Internal tin
Wire diameter	0.81 mm
Cr plating	2 m
Cu/non-Cu	1.5
Twist pitch	10 mm
Ternary	NbTa 7.5 w/o
Number of filaments	5400
Filament diameter	3.5 µm

TFMC strand specifications

Cable pattern	3x3x5x4x6
Corresponding twist pitches	25mm/62mm/109 mm/168 mm/425 mm
number of superconducting strands	720
number of copper strands	360
local void fraction in the annulus	36 %
central hole inner diameter	10 mm
Cable space diameter	37.5 mm
Jacket thickness	1.6 mm

TFMC Cable specification

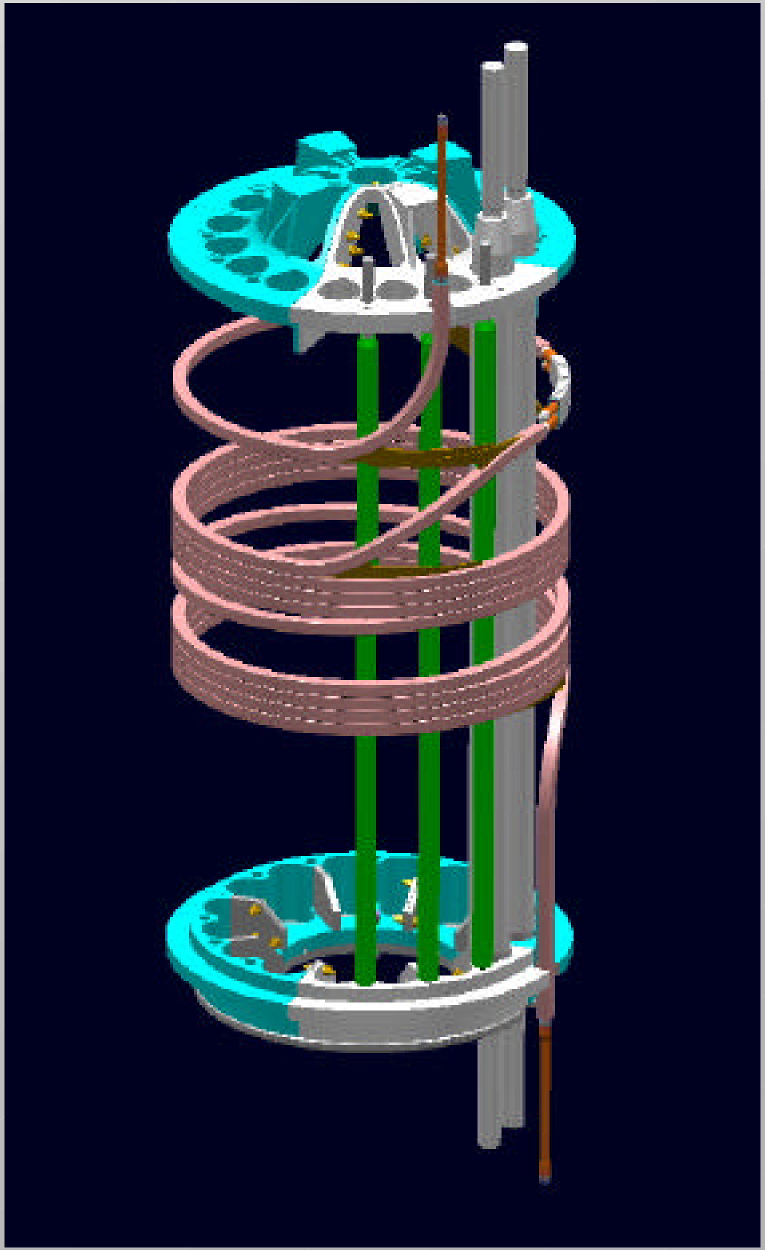
Central Solenoid Model Coil Fabricated Modules

CS Insert Coil

Inner Module

Outer Module

PF Conductor Insert Winding



Critical Issues

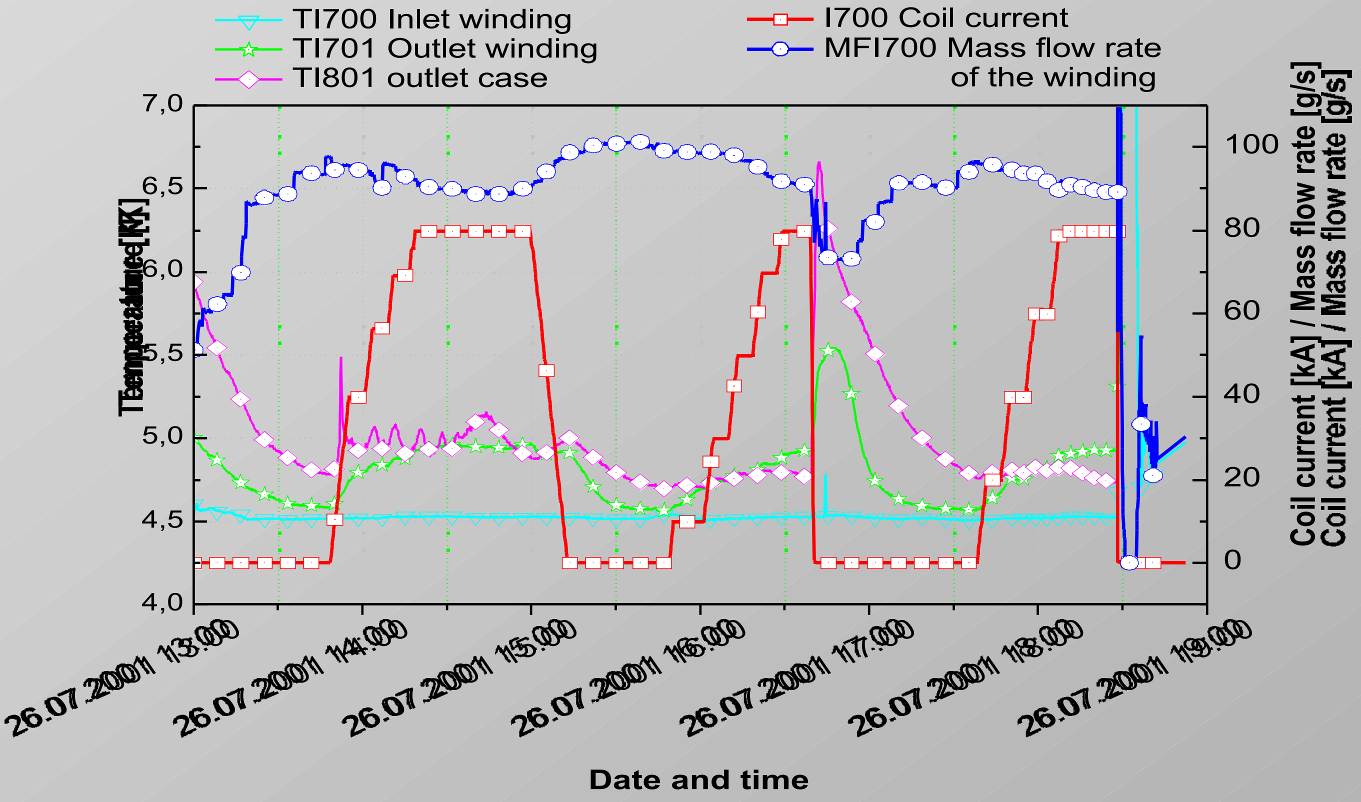
- Tcs, Ic, n, Ploss (strand and cable)
- Cable strain and current distribution
- Stability
- Quench propagation
- AC losses
- Joints
- Conductor cross section lay-out
- Nb_3Sn versus NbTi

Tcs, Ic, n, Ploss

- Tcs and Ic in ITER model coils are close to extrapolated value from strands, except for CS insert

- within (10≤E[µV/m]≥100) n and Ploss evolve with strain and transversal resistance, which are cycle and load dependent.
- With E≤10µV/m n is affected also by the cable current distribution

The ITER TF Model Coil reached 80 kA on 26 July 2001

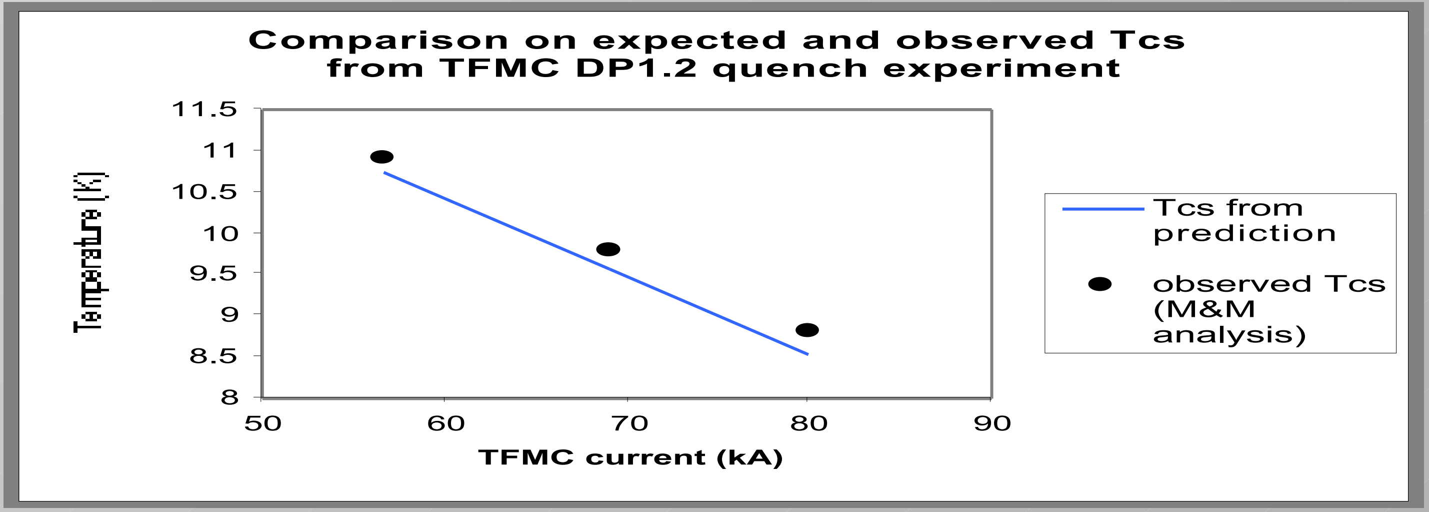


Three types of test: 1) Ramp down with 100 A/s; 2) Inverter mode discharge (-30 V); 3) Safety discharge (~600V)

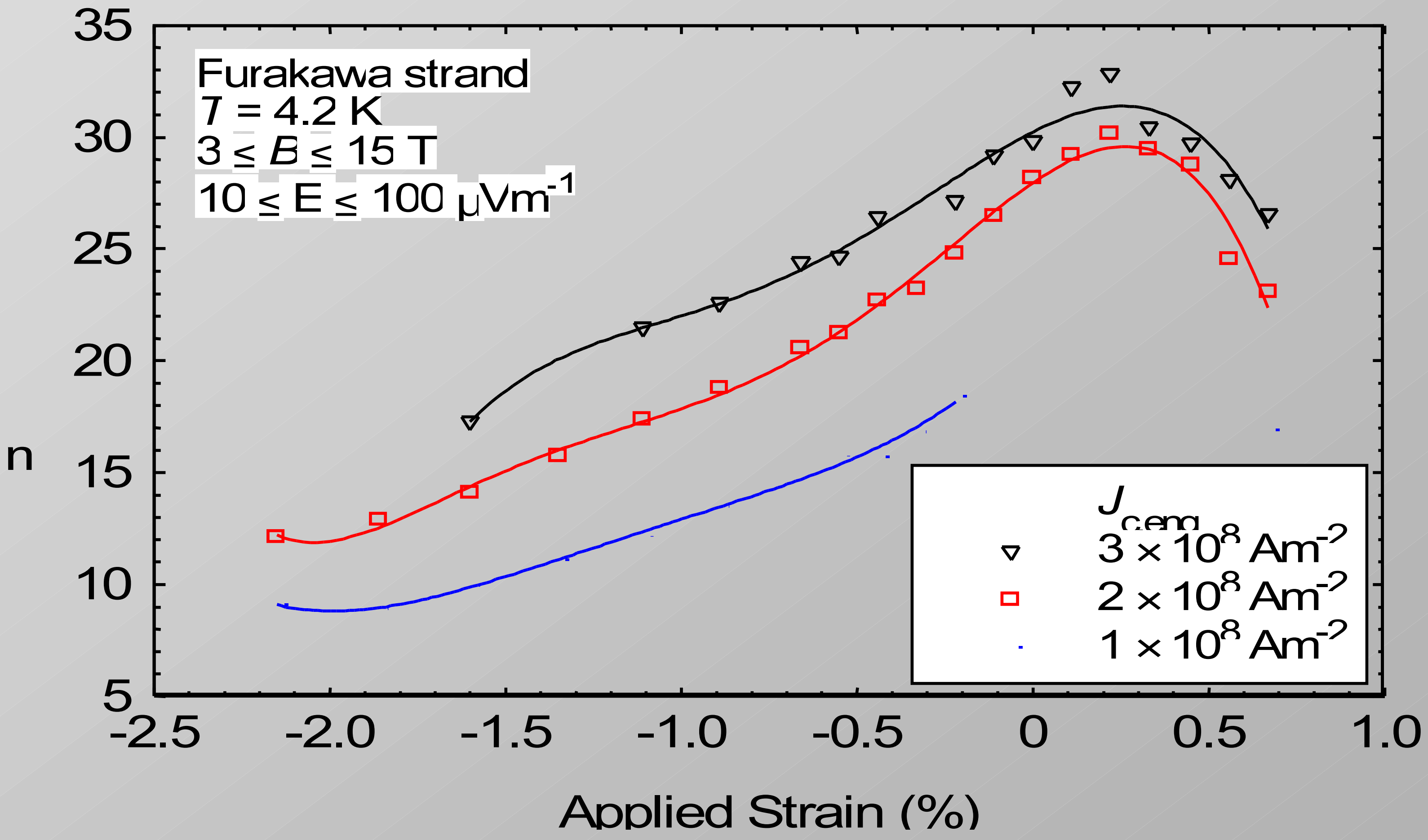
The maximum error bar on observed Tcs (taken from M&M analysis) can be evaluated to 0.4 K from the TFMC-FSJS tests at Sultan.

Even with this very pessimistic assumption the predicted Tcs is coherent with the observed Tcs.

The expected Tcs presented in the graph takes into account the TFMC magnetic load and ε has been modified according to the load at each given current.



N versus strain at given Jc

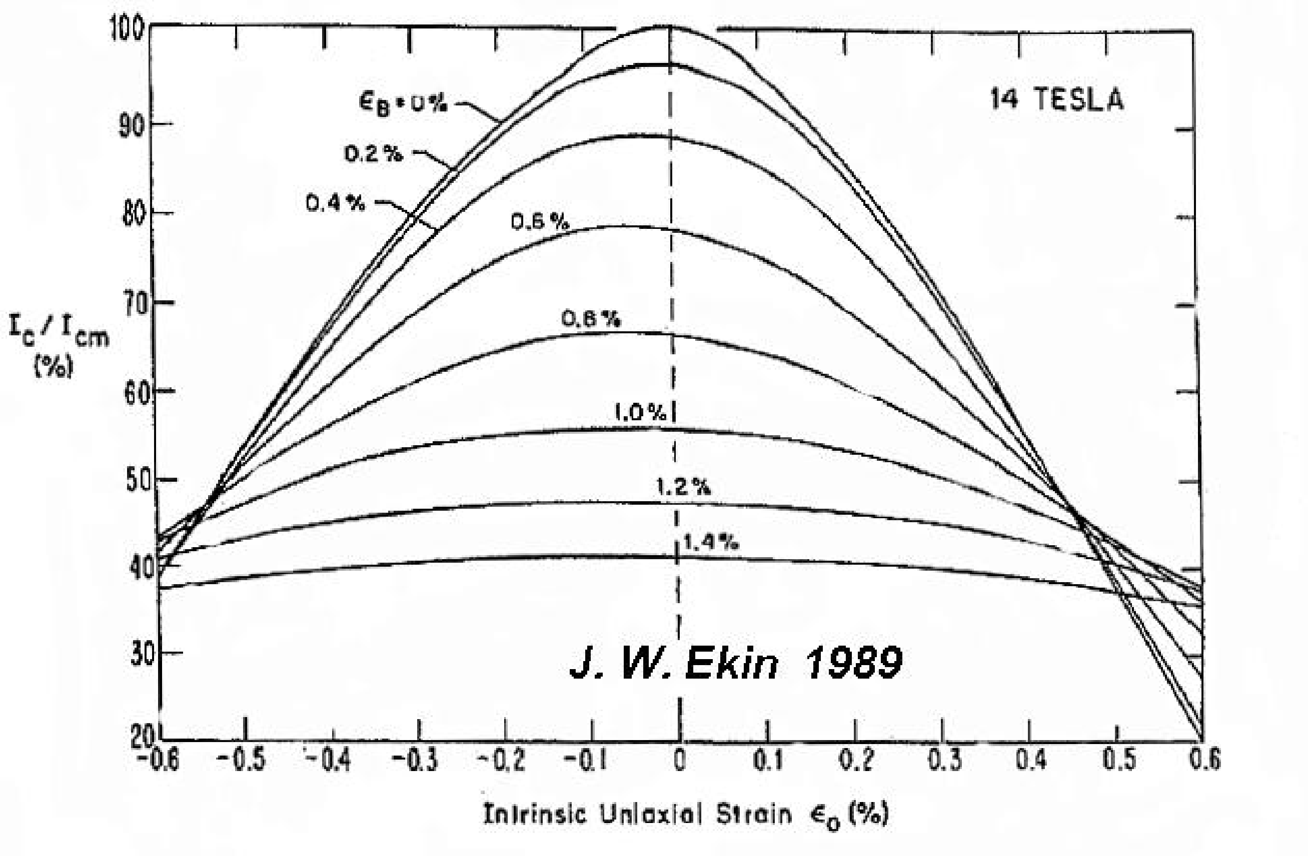


Cable Strain and Current Distribution Issues

- Strand strain is affected by loading history

- Cable current distribution is a non-linear function of strain, temperature, magnetic field along the cable strands and transversal resistance at joints and cable length.

Bending Strain Impact on Ic



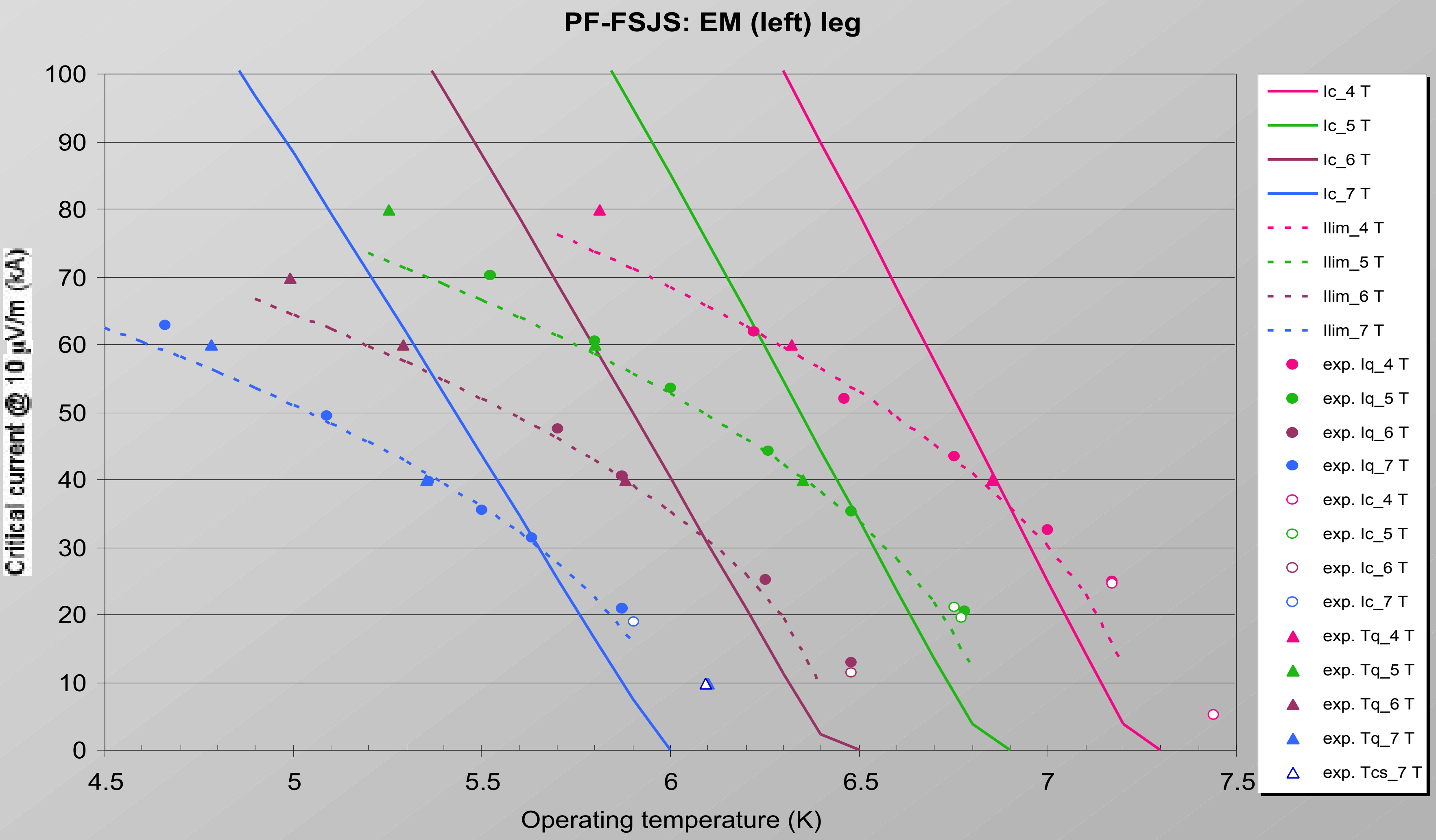
Uniaxial-strain characteristics for multifilamentary Nb_3Sn at 14 Tesla for a range of bending strains ε_B.

Stability

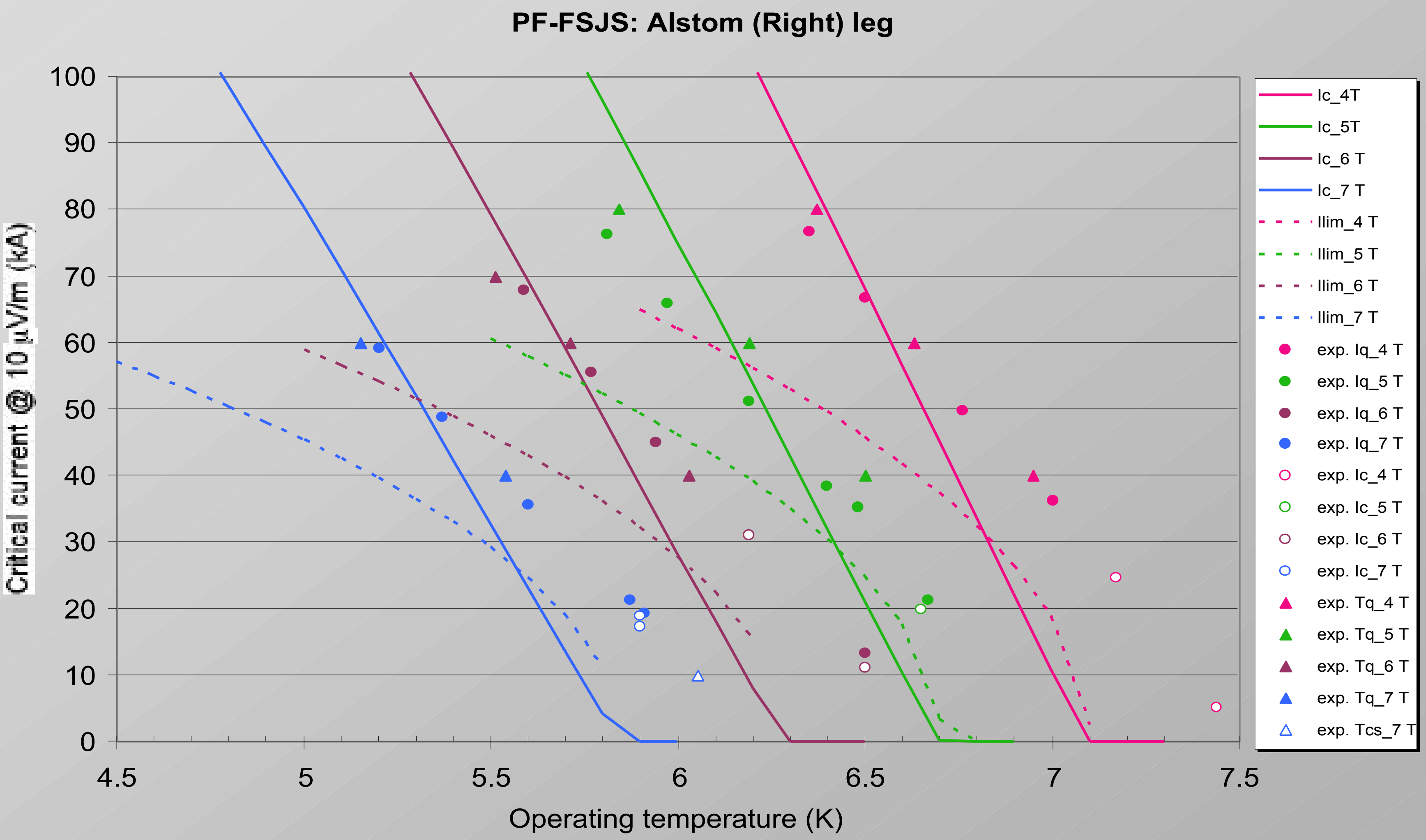
- All Nb_3Sn model coils attain Tcs and Ic smoothly without training

- Two NbTi Sultan full size samples show sharp transition close to Ic and One of them at operating current limit before Ic.

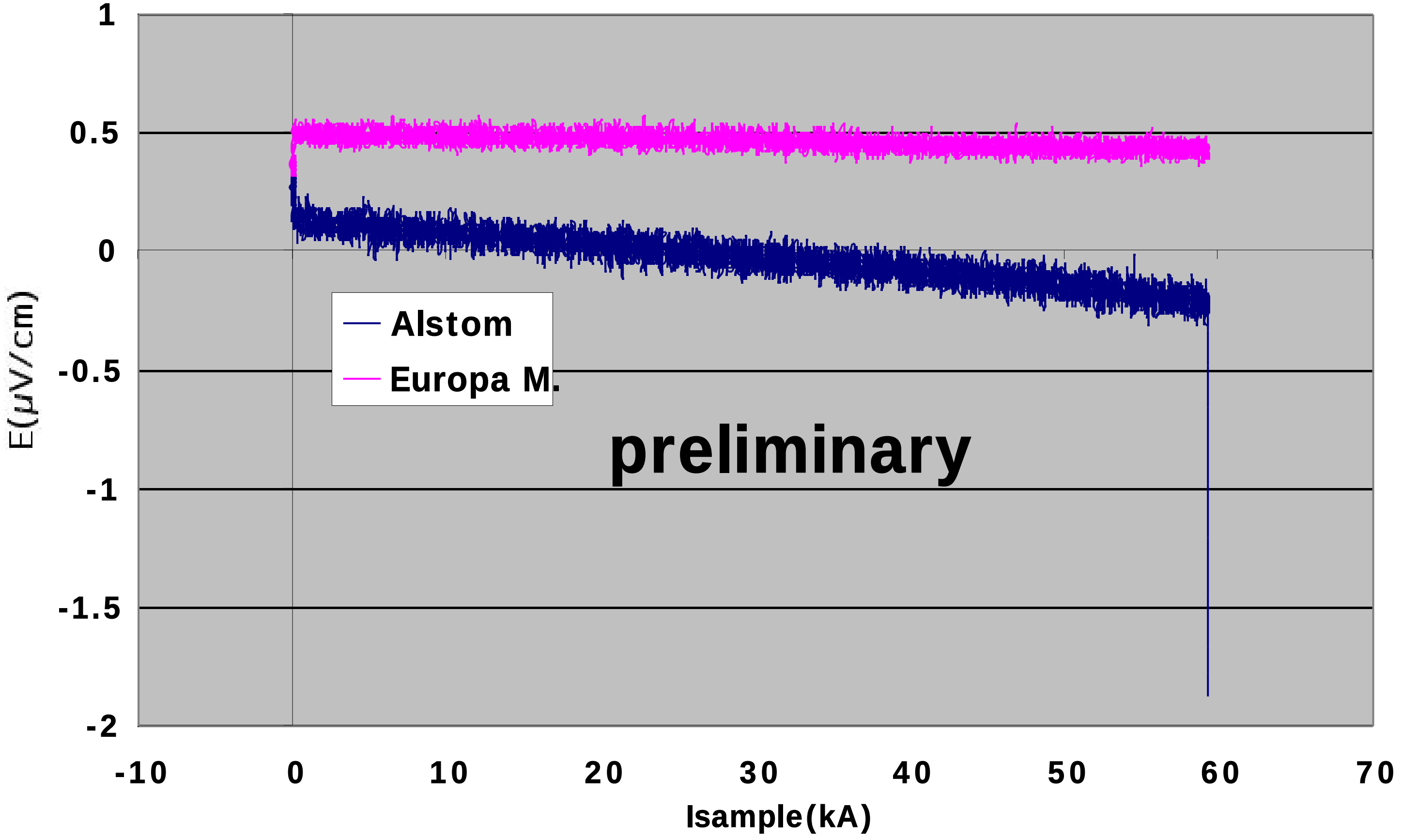
PF Conductor-Sultan Test

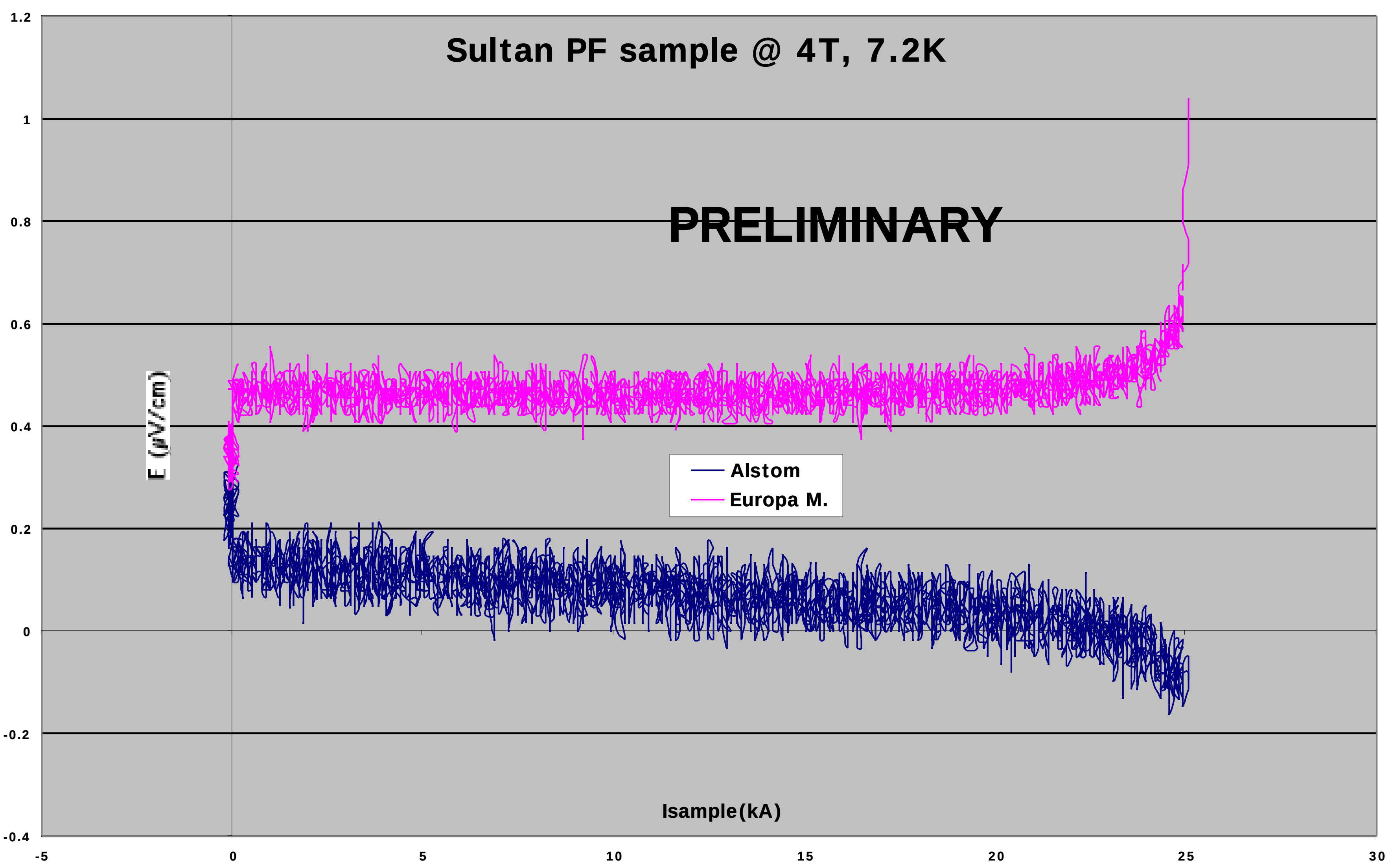


PF Conductor-Sultan Test



Sultan PF sample @7T,5.2K (Alstom),4.6K (Europa M.)




Sultan PF sample @ 4T, 7.2K
PRELIMINARY
E (µV/cm)
Isample(kA)
Alstom
Europa M.
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-5
0
5
10
15
20
25
30

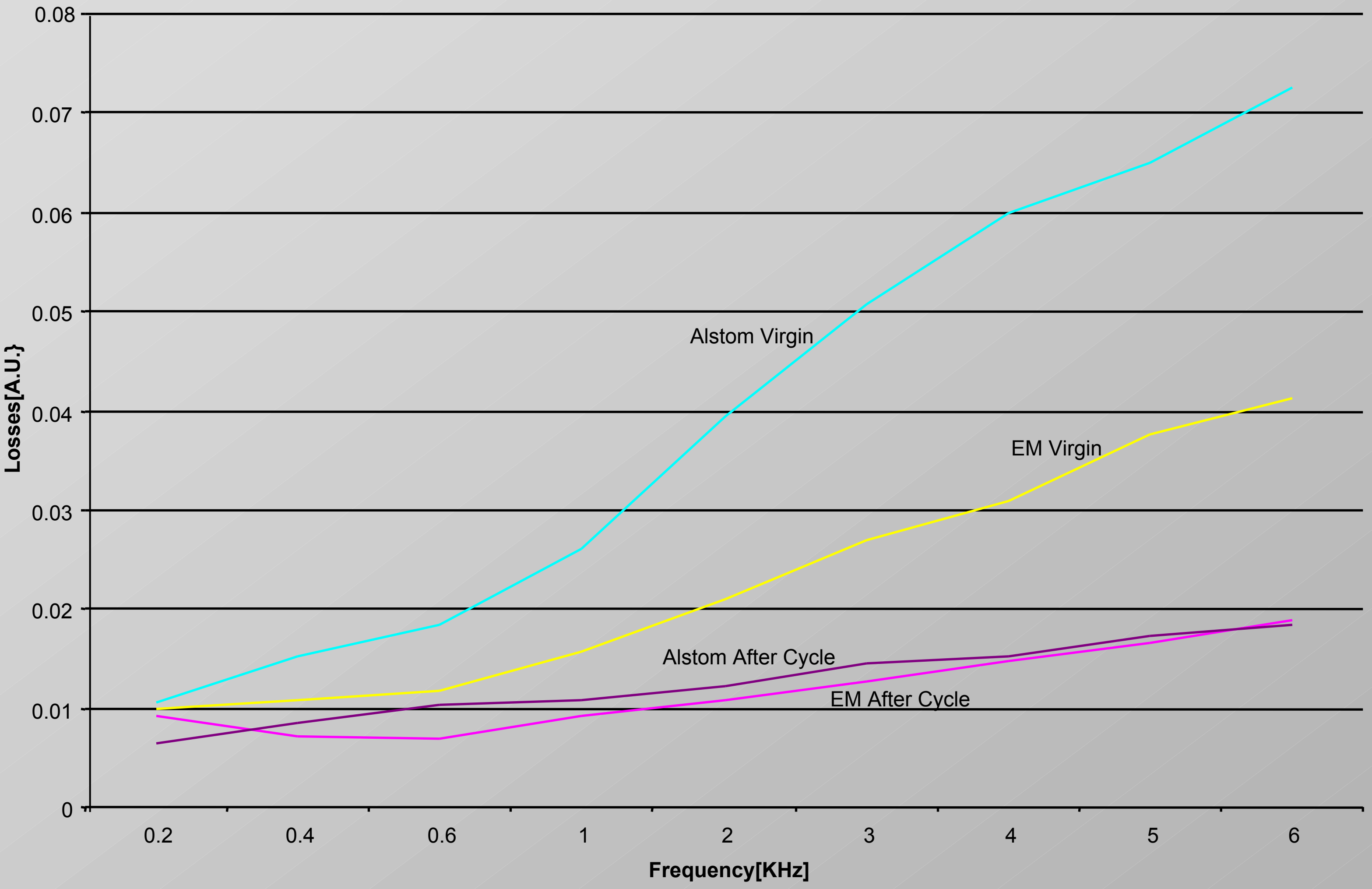
TFMC electromagnetic

- The M&M code is adequate to determine Tcs
- Heating strategy for TFMC adequate to explore conductor’s properties
- Conductor’s Tcs found in agreement with data from strand values(within error bar)
- Tcs does <u>not</u> change with quenches in TFMC contrary to CS insert

AC losses

- Coupling losses decrease within tens of cycles by a factor≈3
- Can the last but one stage wrapping and central cooling channel be removed?
- What's the minimum acceptable void fraction?

Mag.Losses PFFS sample



Pressure Drop and Friction Factor

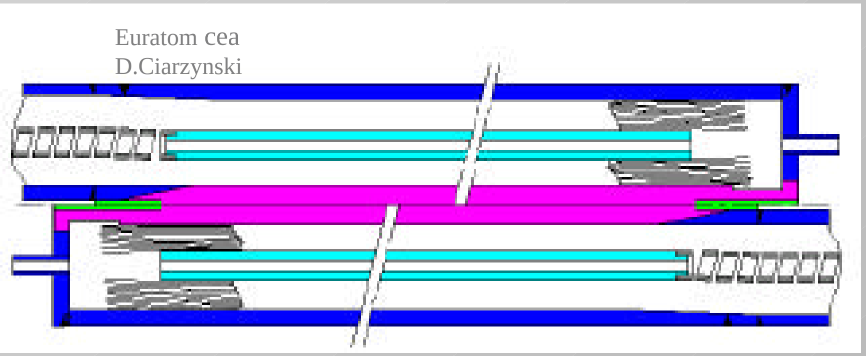
- In the TFMC,contrary to CSMC and inserts, no difference in pressure drop with current
- Reasonable agreement between test results and analysis
- Large spread of measured values

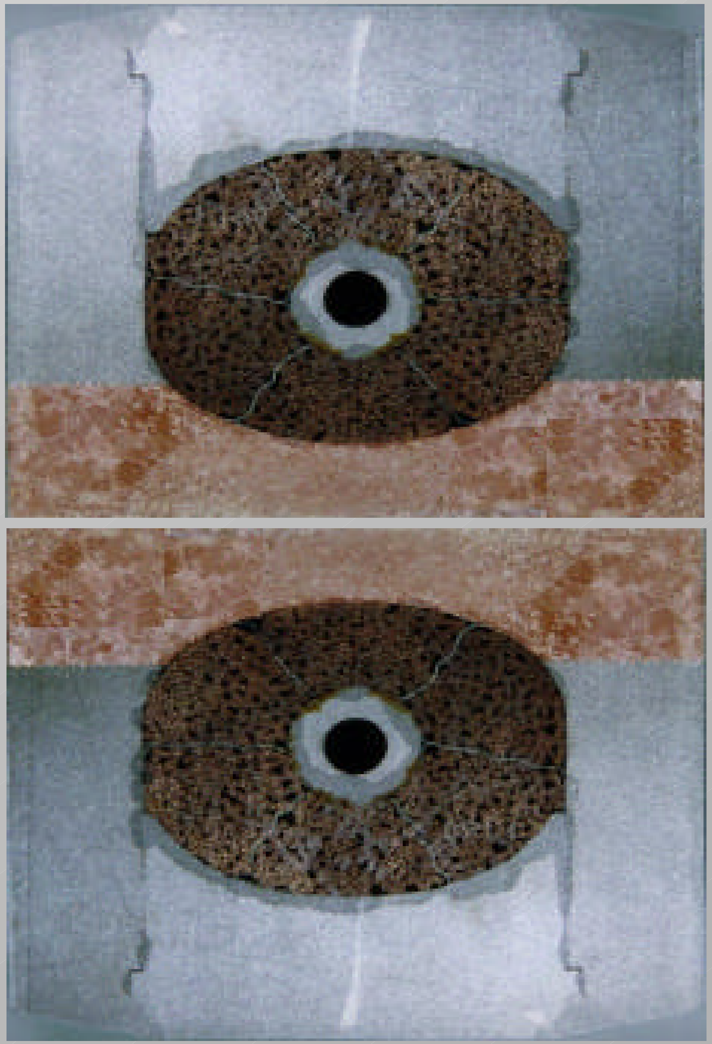
Quench

- In the TFMC,contrary to CSMC and inserts, Quenches do not affect Tcs
- Hot spot temperature is predictable
- Maximum pressure correlated to quench energy
- Voltage, temperature distribution, mass flow rate, pressure time dependence and quench propagation velocity not predictable: modeling to be improved.

TFMC – Joints Technical realisation of the joints

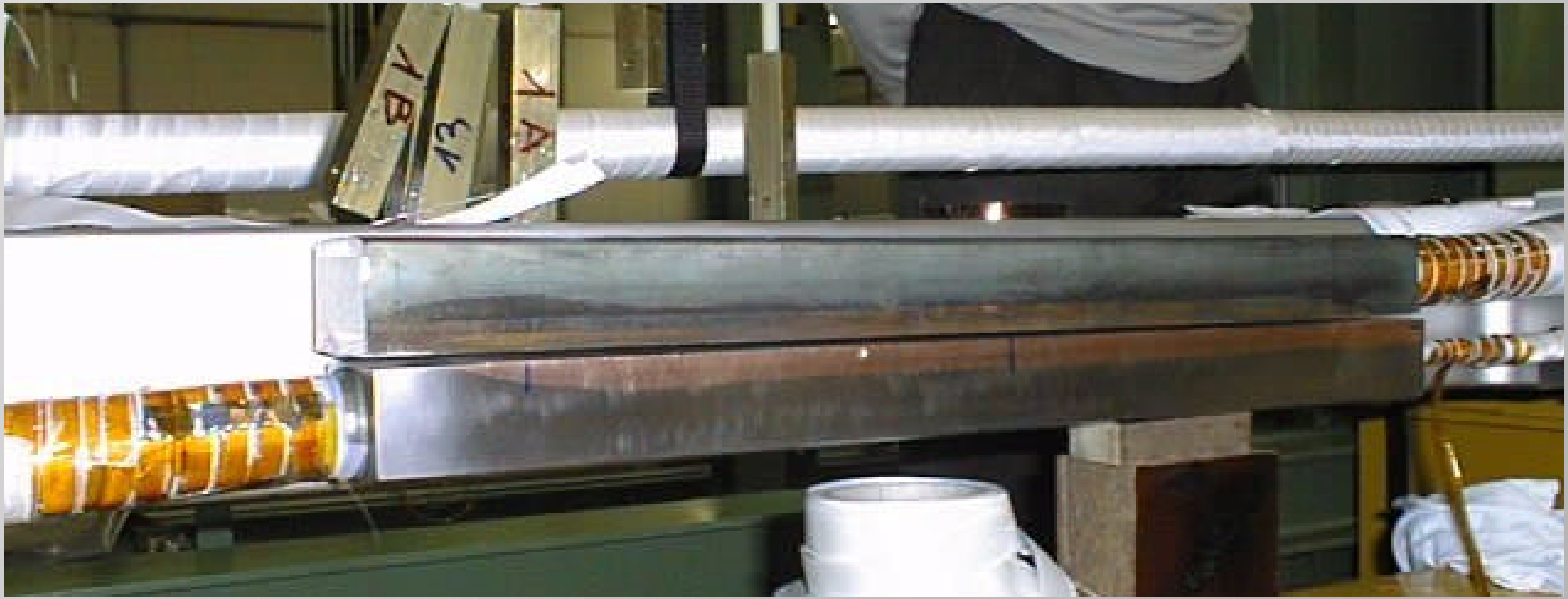
Cables are compacted in twin-material boxes of stainless steel and copper. The boxes are then soldered


Euratom cea
D.Ciarzynski



TFMC - Joints

Technical realisation of the joints



Shaking hand joint: inner joint of double pancake 1

TFMC – Joints Types of joints

	-TFMC -inner joints	-TFMC -outer joints	-TFMC to busbar joints	-Busbar 1/2 -joints	-Busbar to CL -joints
-Strand	-Nb3Sn internal tin 36 islands in Cu	-Nb3Sn internal tin 36 islands inCu	-Nb3Sn internal tin 36 islands in Cu	-NbTi with int... CuNi barrier	-NbTi with int... CuNi barrier
-Strand surface	-Cr-coating removed	-Cr-coating removed	-Cr-coating removed	-Contact points -Ag - coated	-Contact points -Ag - coated
-Cu sole surface	-Oxide layer removed	-Oxide layer removed	-Oxide layer removed	-Indium coated	-Indium coated
-Sole – strand contact	-Cu – Cu 650°C “sintering”	-Cu – Cu 650°C “sintering”	-Cu – Cu 650°C “sintering”	-Imprints into Indium layer	-Imprints into Indium layer
-Cu interface	-Ag - coated	-Ag - coated	-Ag - coated	-Ag - coated	-Gold coated
-Interface shim	-None	-Cu - pins	-Cu – plate -Ag – coated	-None	-None
-Interface contact	-Soldered (PbSn)	-E – beam welded	-Soldered (PbSn)	-Indium wires squeezed	-Indium foil pressed
-Cu interface	-Ag - coated	-Ag - coated	-Ag - coated	-Gold coated	-Gold coated
-Sole – strand contact	-Cu – Cu 650°C “sintering”	-Cu – Cu 650°C “sintering”	-Contacts points In-soldered	-Imprints into Indium layer	-Sc-rods soldered to Cu
-Cu sole surface	-Oxide layer removed	-Oxide layer removed	-Indium coated	-Indium coated	
-Strand surface	-Cr-coating removed	-Cr-coating removed	-Contact points -Ag - coated	-Contact points -Ag - coated	-Brazed on -Cu -rods
-Strand	-Nb3Sn internal tin 36 islands in Cu	-Nb3Sn internal tin 36 islands in Cu	-NbTi with intern CuNi barrier	-NbTi with internal CuNi barrier	-Nb3Sn bronze

Joints

- All TFMC Joints showed lower resistance than expected
- The TFMC joints curried current up to 80 KA
- All CSMC Joints performed satisfactorily
- An optimization of the joints is possible

HTSC Materials versus LTS

♦ Much higher superconducting transition temperatures up to 135 K

♦ Very high upper critical fields of the order of 100 T

♦ Excellent critical current densities even at intermediate (≈ 20 K) temperatures and high magnetic fields (≈ 20 T)

HTSC Compounds: Bi-2212

- $Bi_2Sr_2CaCu_2O_{8-X}$: superconducting transition temperature 87 K
- Various fabrication processes: powder-in-tube (wires & tapes)
  dip-coating (tapes)
  melt cast processed (tubes)
- Available in long lengths (100 m) and high transport currents (10 kA)

- High operating temperatures: $J_c \approx 300$ kA/cm^2 (4.2 K, self field)
  (Rutherford cable) $J_c \approx 100$ kA/cm^2 (30 K, self field)
  (LFZ fibers) $J_c \approx 5$ kA/cm^2 (77 K, self field)
- Weak J_c field dependence at 4.2 K: 200 kA/cm^2 at 10 T
  50 kA/cm^2 at 26 T
- Mechanical properties: max. bending strain 6 %
  (Rutherford cable) tolerable tensile strength 180 MPa (at RT)

HTSC Compounds: Bi-2223

- $Bi_2Sr_2Ca_2Cu_3O_{10-X}$: superconducting transition temperature 110 K
- Well optimised powder-in-tube fabrication processes of wires & tapes
- Tapes available in km lengths
- Long length engineering critical current densities of the order of 15 kA/cm² at 77 K and self field

- Operating temperature 20 - 77 K: $J_c \approx 250$ kA/cm² (20 K, self field)
  $J_c \approx 130$ kA/cm² (50 K, self field)
  $J_c \approx 50$ kA/cm² (77 K, self field)
- Inferior J_c field dependence: $\mu_0 H_{irr} \approx 0.7$ T (77 K)
  J_c (2 T) decreases by a factor of 2.5 at 20 K
- Mechanical properties: max. bending strain 0.3 %
  tolerable tensile strength 50 - 200 MPa (at 77 K)

HTSC compounds: Y-123 coated conductor

- $YBa_2Cu_3O_{7-X}$: superconducting transition temperature 92 K
- Slow and complicated fabrication processes of biaxially textured films
- Coated conductors on metallic substrates available in 10 m lengths
- Maximum $I_c \approx 750$ A at 77 K and self field
- Large non-superconducting/superconducting ratio ≈ 10 - 50

- Excellent irreversible properties at 77 K: $J_c \approx 2.5$ MA/cm^2 (self field)
  $\mu_0 H_{irr} \approx 7$ T
- Low operating temperatures: $J_c > 10$ MA/cm^2 (self field)
- Mechanical properties: max. bending strain 0.5 %
  tolerable tensile strength 100 - 200 MPa (at 77 K)

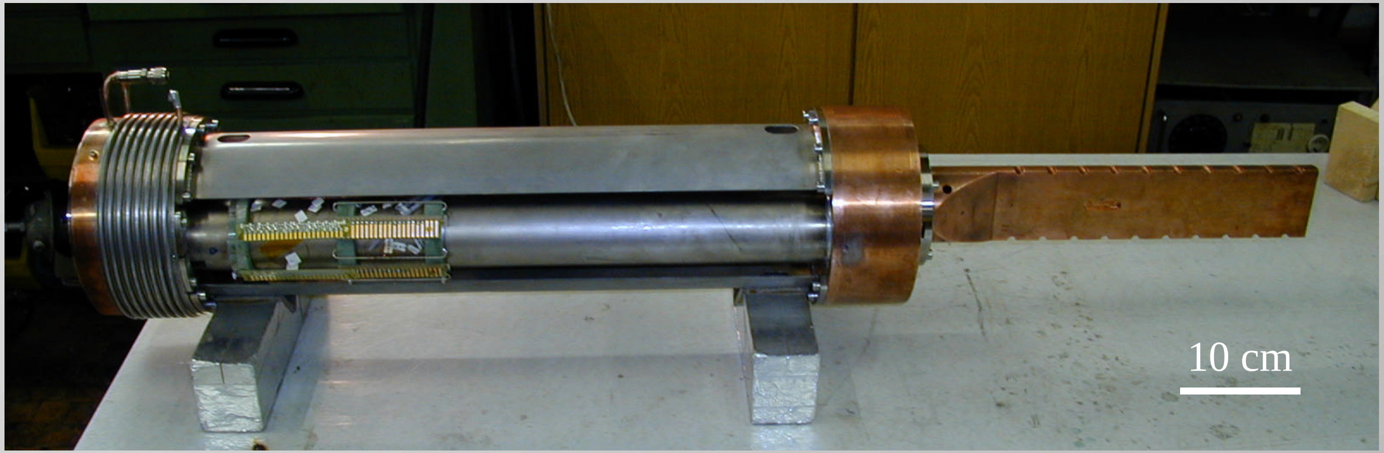
Possible of HTS Applications in Magnet System

- Central solenoid (CS) coils: very high fields and currents
- Toroidal field (TF) coils: high fields and very high currents
- Poloidal field (PF) coils: intermediate fields and currents
- CS, TF and PF coil Busbars: low fields, high currents
- Current leads: low fields, low current densities

Status of HTS Large-Scale Applications

- Detroit Edison Cable: 100 MW power (24 kV), 120 m long, Bi-2223 at 77 K tested, installation should be completed in 2002
- Currents leads for LHC magnet powering system at CERN: T = 20 - 50 K 13 kA and 6 kA prototypes of Bi-2212, Bi-2223 and Y-123 compounds successfully tested, series production started 2002 installation of 64 (13 kA) and 310 (6 kA) current leads until 2005
- HTSC filters in base stations (cellular phones): Y-123 in operation, approx. 1000 conventional filter units are replaced in the USA
- 70 kA current lead for TFMC: Bi-2223 at 20 -50 K Technical specification and design completed, first tests in 2003

20 kA HTS Current Lead



♦ Ag/Au sheated Bi-2223 wires, 20 kA steady state (40 kA short time)

♦ T_{warm} (warm end of HTS) ≈ 70 K

τ Heat load at 20 kA (4.5 K): 3.6 W

♦ Current imbalance ratio: 1.44 (due to different resistances of contacts between modules and copper block: 17.2 nΩ vs. 2.4 nΩ)

♦ Contact resistances: 5.9 nΩ (cold region), 3 nΩ (HTS module), 6.6 nΩ (clamp)

R&D Strategy

- Separate the effects to be tested
- Develop interpretation codes
- Develop advanced diagnostic
- Assess the use of HT superconducting materials

Conductor Cross Section Issues

- Optimum conductor aspect ratio
- Last but one-stage wrapping
- Central cooling channel
- Cooling circuit connection to conductor (CS, PF)