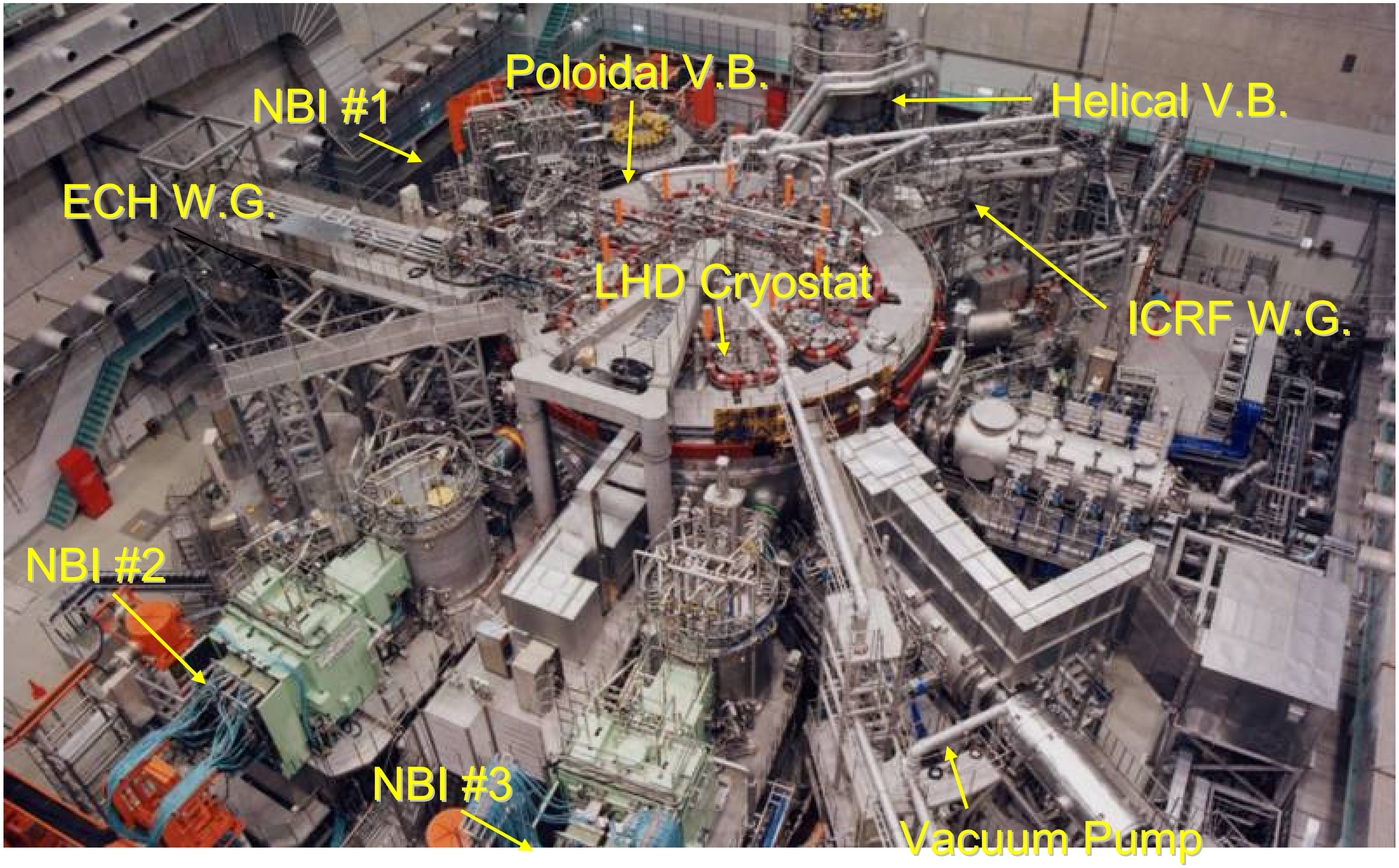
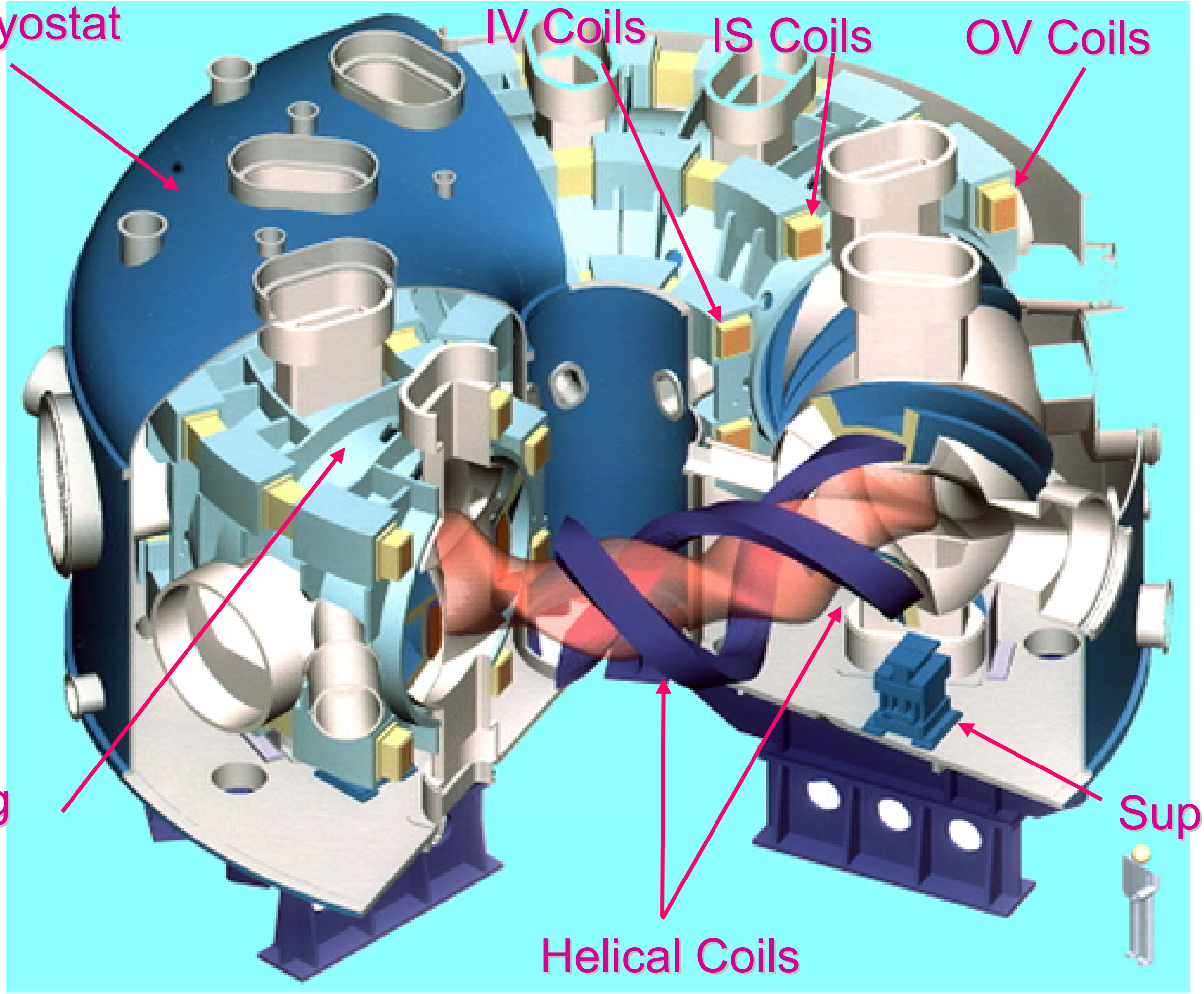
Overview of LHD



Inside of LHD Cryostat



Poloidal Coils

LHD Cryostat

IV Coils

IS Coils

OV Coils

Outer dia.
13 m

Height.
8 m

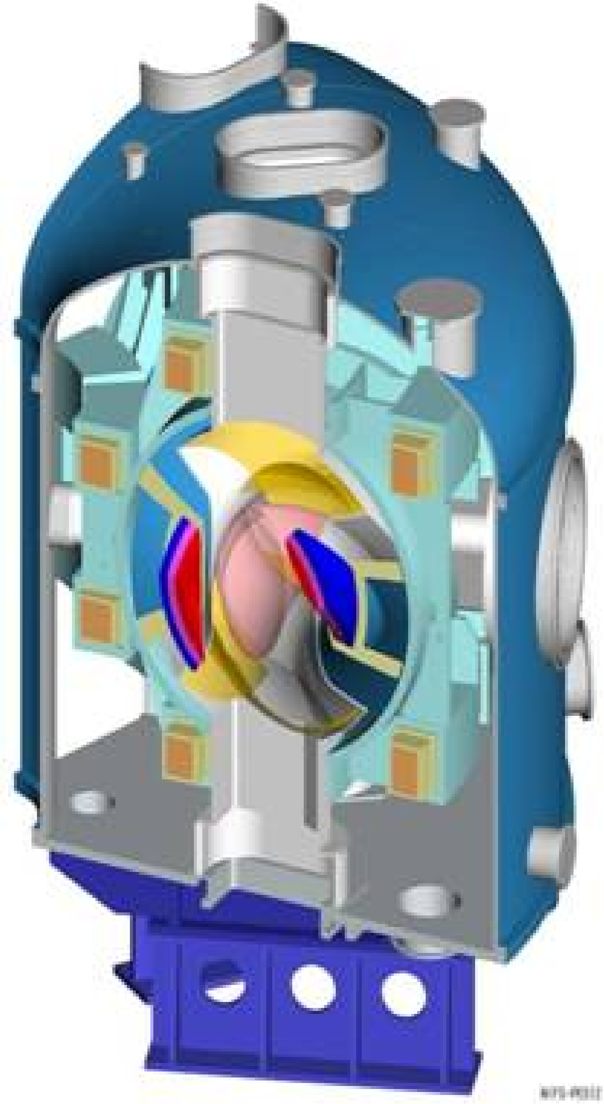
Cold mass
820 t

Total weight
1500 t

Supporting
Structure

Supporting Posts

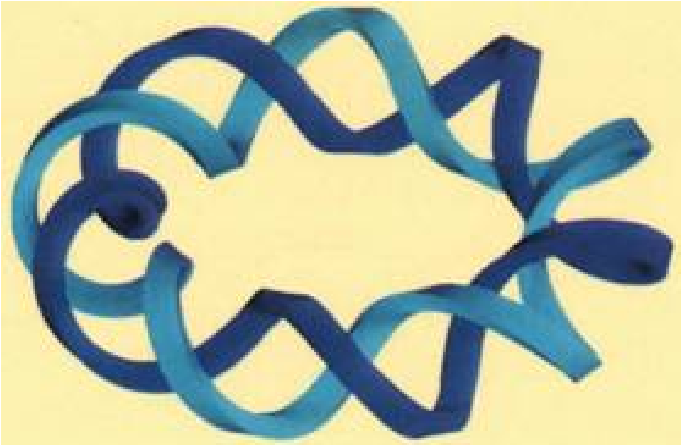
Helical Coils



Major Specifications of LHD

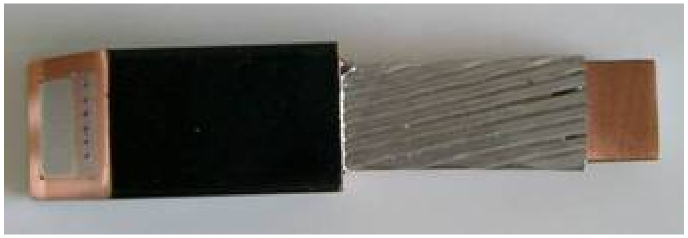
Plasma major radius	**3.9 m**
Av. plasma minor radius	**0.5 – 0.65 m**
Plasma volume	**20 – 30 m^3**
Toroidal magnetic field	**3 (4) T**
Field period	**10**
Coil stored energy	**0.9 (1.6) GJ**

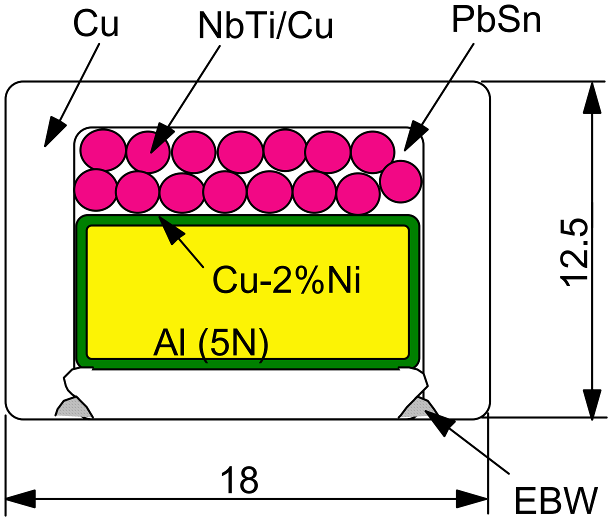
Specifications of Helical Coils



Major radius	**3.9 m**
Minor radius	**0.975 m**
Poloidal pole number	**2**
Toroidal pitch number	**10**
Electromotive force	**5.85 (7.8) MA**
Nominal current	**13.0 (17.3) kA**
Coil current density	**40 (53) A/mm^2**
Central toroidal field	**3.0 (4.0) T**
Maximum field in coil	**6.6 (9.2) T**
Magnetic stored energy	**0.92 (1.64) GJ**
Coil weight	**75.24 t /coil**
Cooling method	**Pool boiling of LHe (P. Superfluid He)**

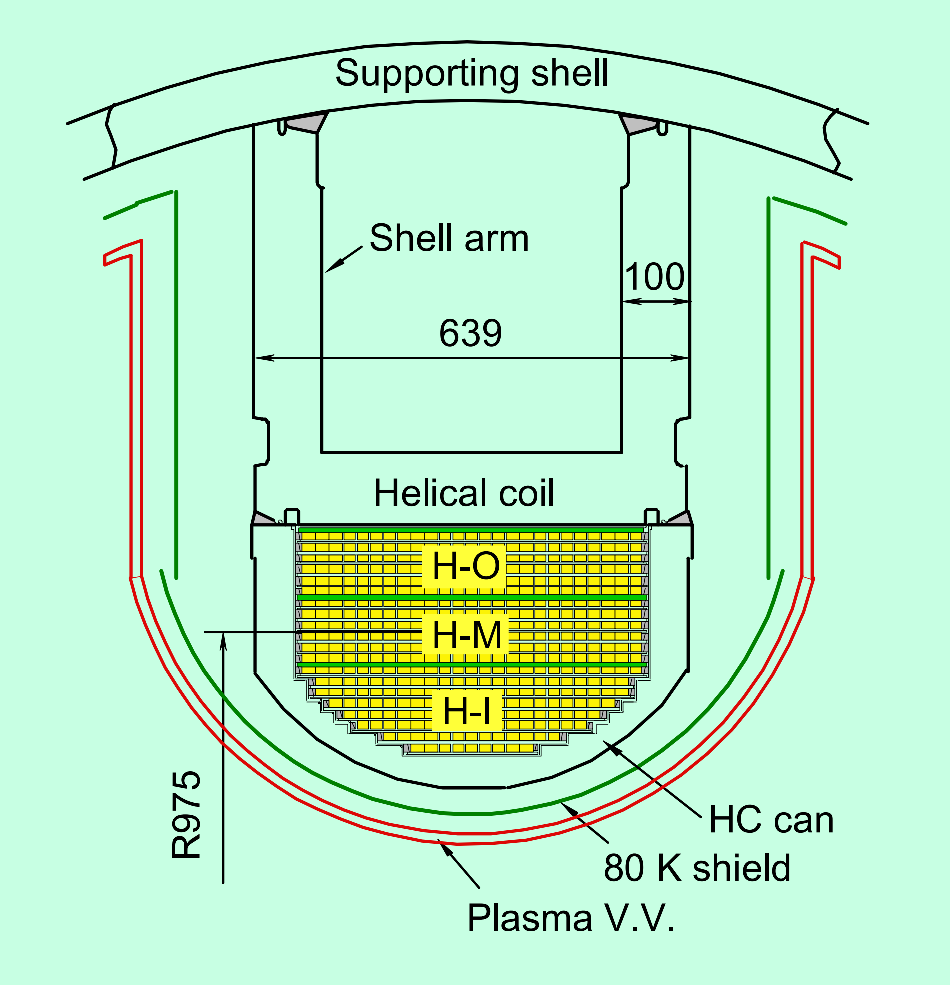
Specifications of HC Conductor

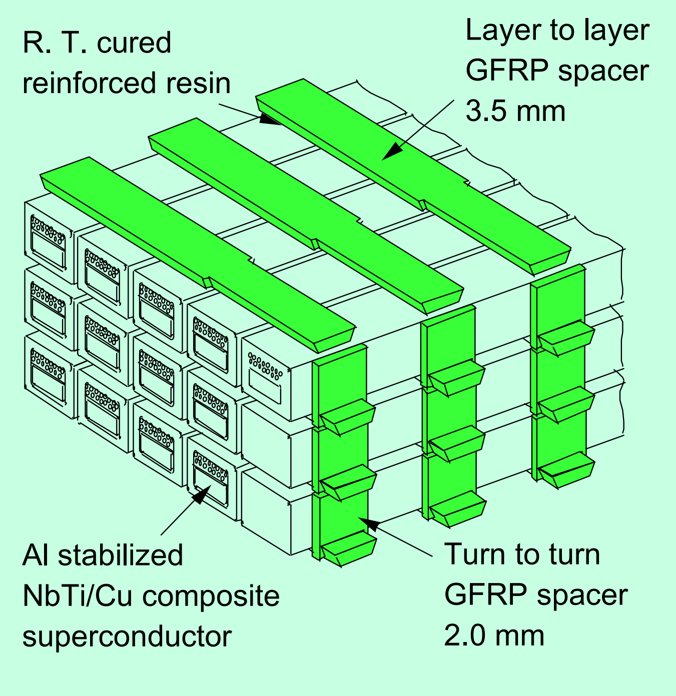




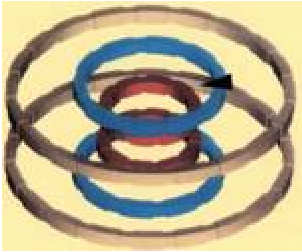
Conductor type	**Al stabilized Nb-Ti/Cu composite**
Conductor size	**12.5 mm x 18.0 mm**
Nominal current	**13.0 (17.3) kA**
Superconductor	**Nb-Ti/Cu compacted strand cable**
Critical current	**21 kA (@ 7 T, 4.4 K)**
Nb-Ti J_c	**1360 A/mm^2**
Stabilizer	**Pure aluminum (5N)**
Clad material of Al	**Cu-2%Ni**
Mechanical reinforcement	**Half-hard copper**
Assembling method	**E. B. welding**
Surface treatment	**Oxidized copper**
Cooling method	**Pool boiling**

Windings of Helical Coils





# coil blocks	**3**
# layers	**20** **(H-I:8, H-M,-O:6)**
# total turns	**450 (150 x 3)**
Stress	**< 100 MPa**
Recovery current	**> 13 kA**



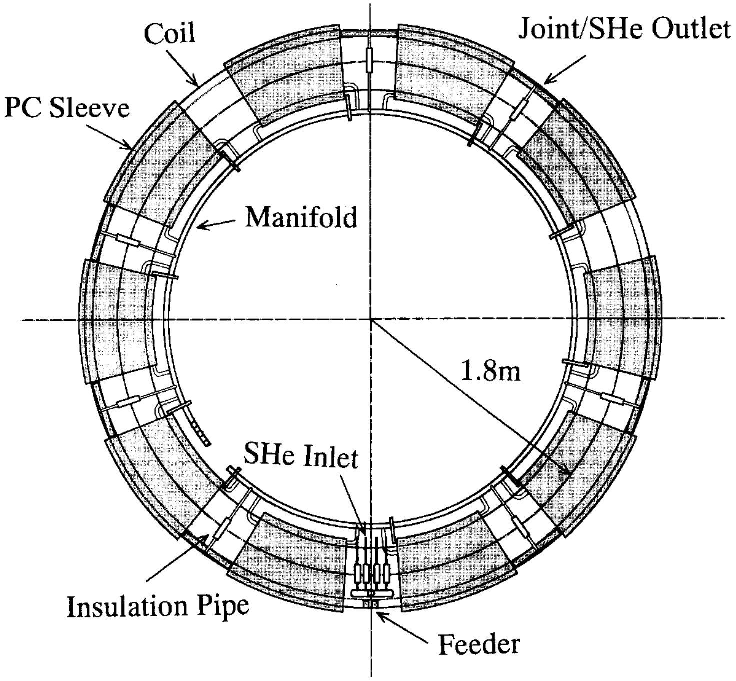
Specifications of Poloidal Coils

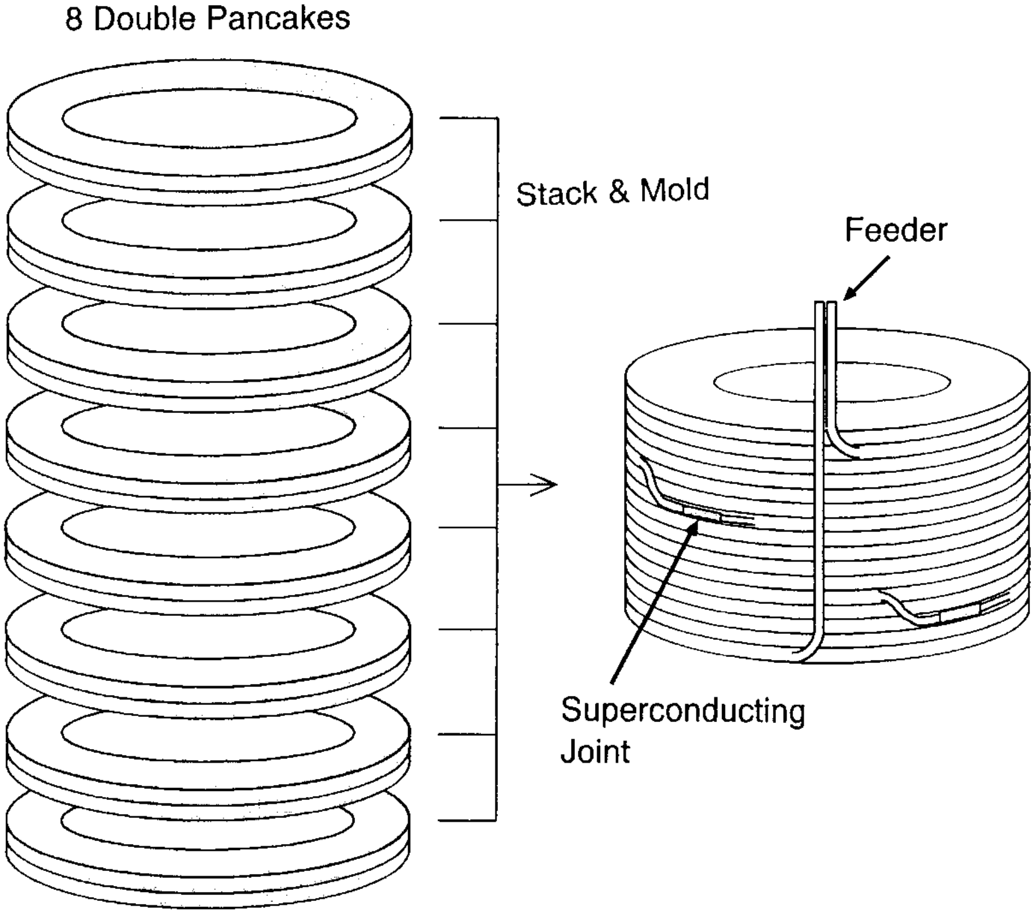
Coil	IV	IS	OV
Cooling method	Forced flow of SHe		
Center diameter (m)	3.6	5.64	11.1
Height (m)	0.47	0.47	0.54
Total weight (t)	16	25	45
Magnetomotive force (MA)	5.0	4.5	4.5
Stored energy of a single coil (MJ)	68	104	251
Flow path length (m)	170	230	314
Inlet pressure (MPa)	1.0 (U. PC) / 0.8 (L. PC)		
Inlet temperature (K)	4.5		
Flow rate per path (g/s)	3.3	2.8	3.6
Pressure drop (MPa)	0.1	0.1	0.1

Winding Machine for Poloidal Coils

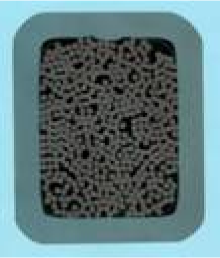
Coil	IV	IS	OV
Number of pancakes	16	16	16
Number of turns /layer	15	13	9
Total turns	240	208	144
Conductor length (km)	2.7	3.7	5.0

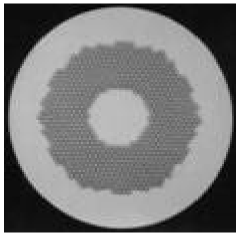
Winding Structure of Poloidal Coils

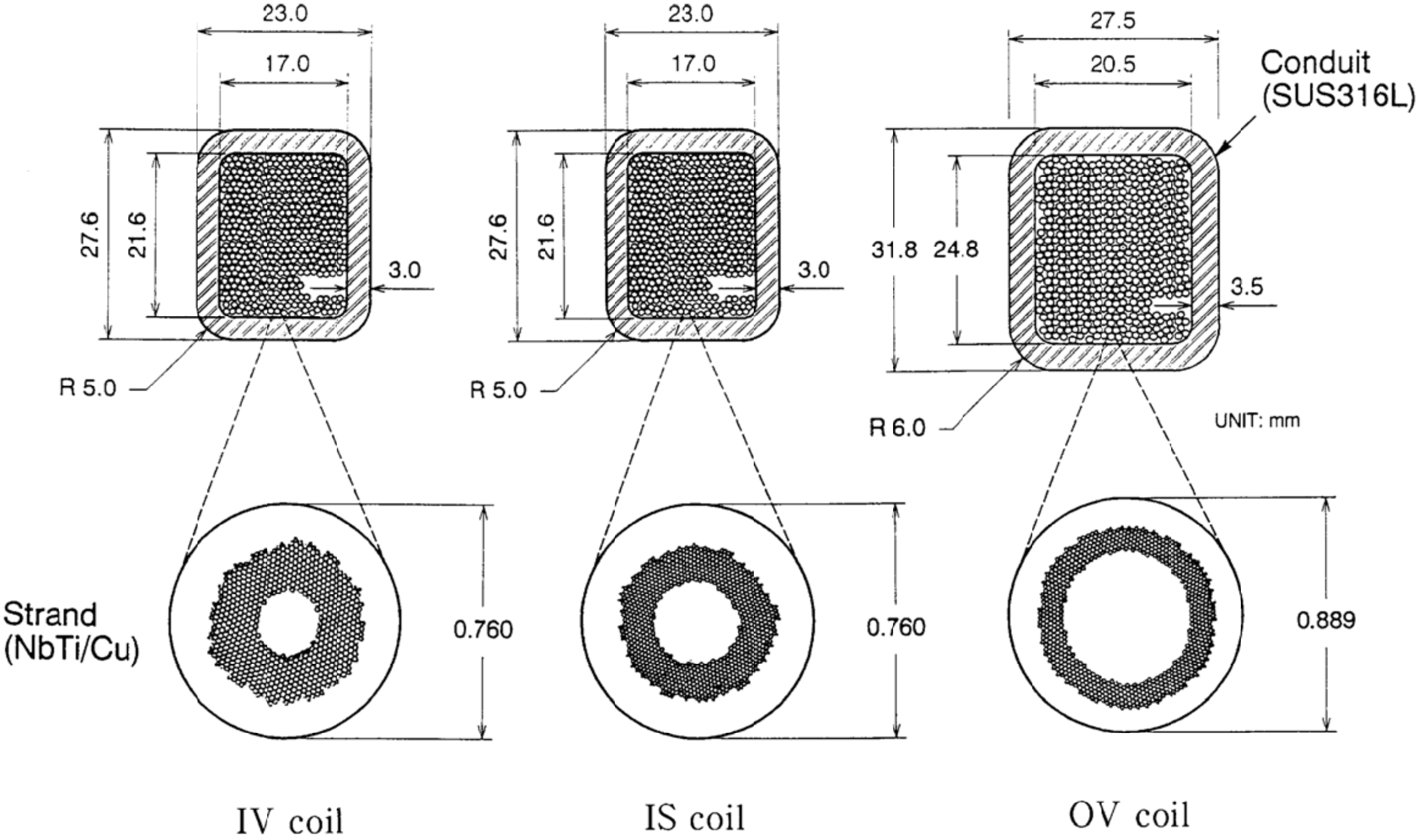




Cross-Section of PC Conductors







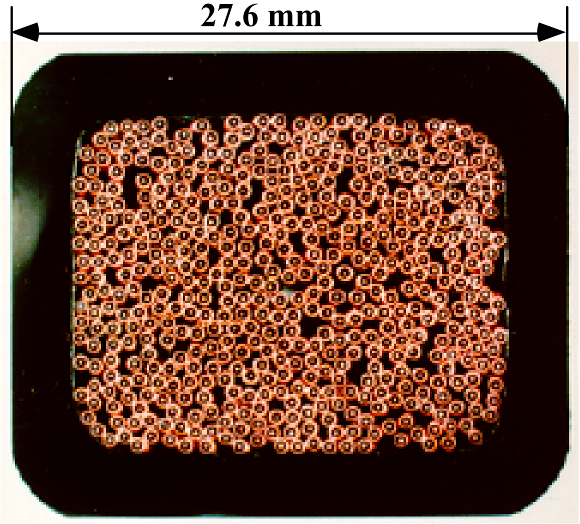
Specifications of PC Conductors (1)

Conductor	IV	IS	OV
Type	Cable in conduit conductor (CICC)		
Superconductor	NbTi/Cu		
Operating current (kA)	20.8	21.6	31.3
Critical current (kA)	62.4	64.8	93.9
Maximum field (T)	6.5	5.4	5.0
Conduit material	Stainless steel 316L		
Conduit size (mm)	23.0 x 27.6	23.0 x 27.6	27.5 x 31.8
Conduit thickness (mm)	3.0	3.0	3.5
Void fraction (%)	38		
Number of strands	3x3x3x3x6=486		

Specifications of PC Conductors (2)

Conductor	IV	IS	OV
Strand diameter (mm)	0.76	0.76	0.89
Cu/SC ratio of strand	2.7	3.4	4.2
Filament diameter (mm)	15	12	14
Filament twist pitch (mm)	10	8	10
Cabling pitch (mm)			
1st stage	60	60	70
2nd stage	100	100	120
3rd stage	150	150	170
4th stage	220	220	250
5th stage	400	400	400

LHD PF Coil



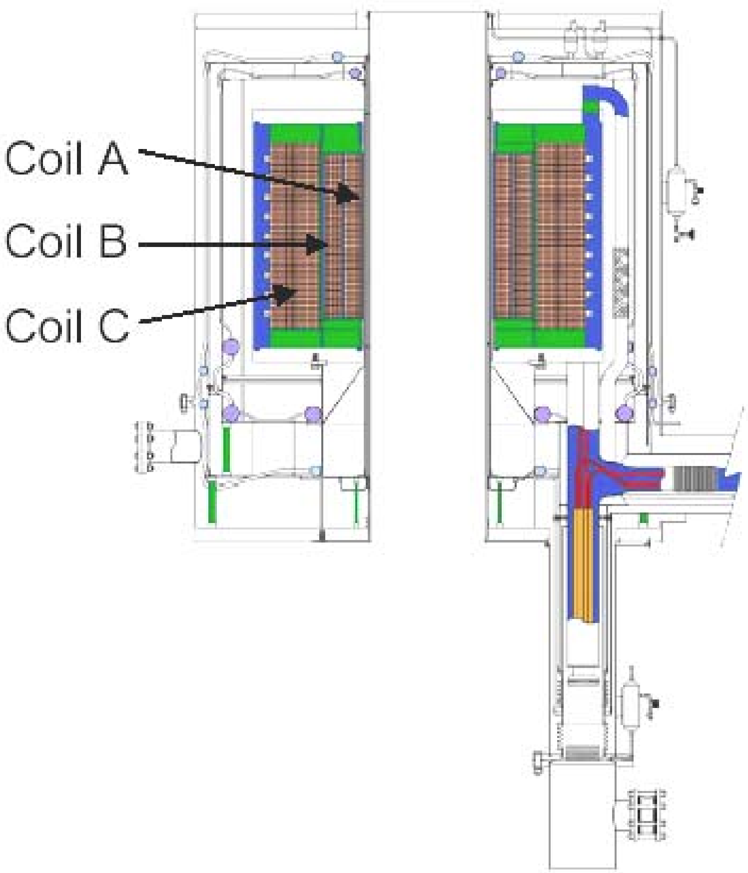
Cryostable

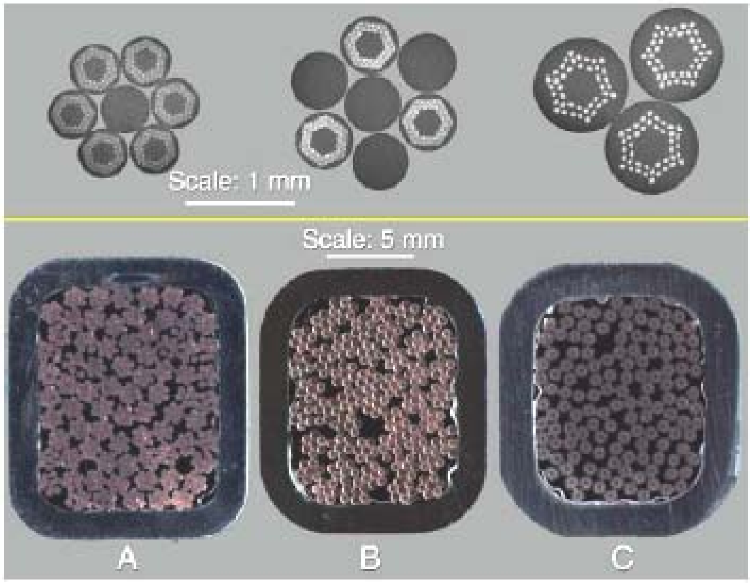
2. CICC: NHMFL 45-T Hybrid Magnet

45-T Hybrid Magnet Specifications

Maximum on-axis field	45 T
On-axis field contribution by resistive magnet	31 T
On-axis field contribution by SCM	14 T
Maximum field on axis Š SCM only	15.4 T
Maximum stored energy	115 MJ
Clear bore Š combined System	32 mm
Clear bore Š SCM only	616 mm
Field center to cryostat top	1.2 m
Cryostat height	2.8 m
Cryostat outer diameter	2.5 m
Resistive magnet housing height	3.6 m
Resistive magnet and housing mass	8 t
Total cold mass (SCM; magnet vessel; leads)	14 t
Total magnet mass (resistive and super conducting)	36 t
Minimum charging time to full field	1 hour
Typical cooldown time	7 days

Superconducting Magnet—Coils A, B, C





Courtesy of John R. Miller (NHMFL)

Parameters of Coils A, B, and C

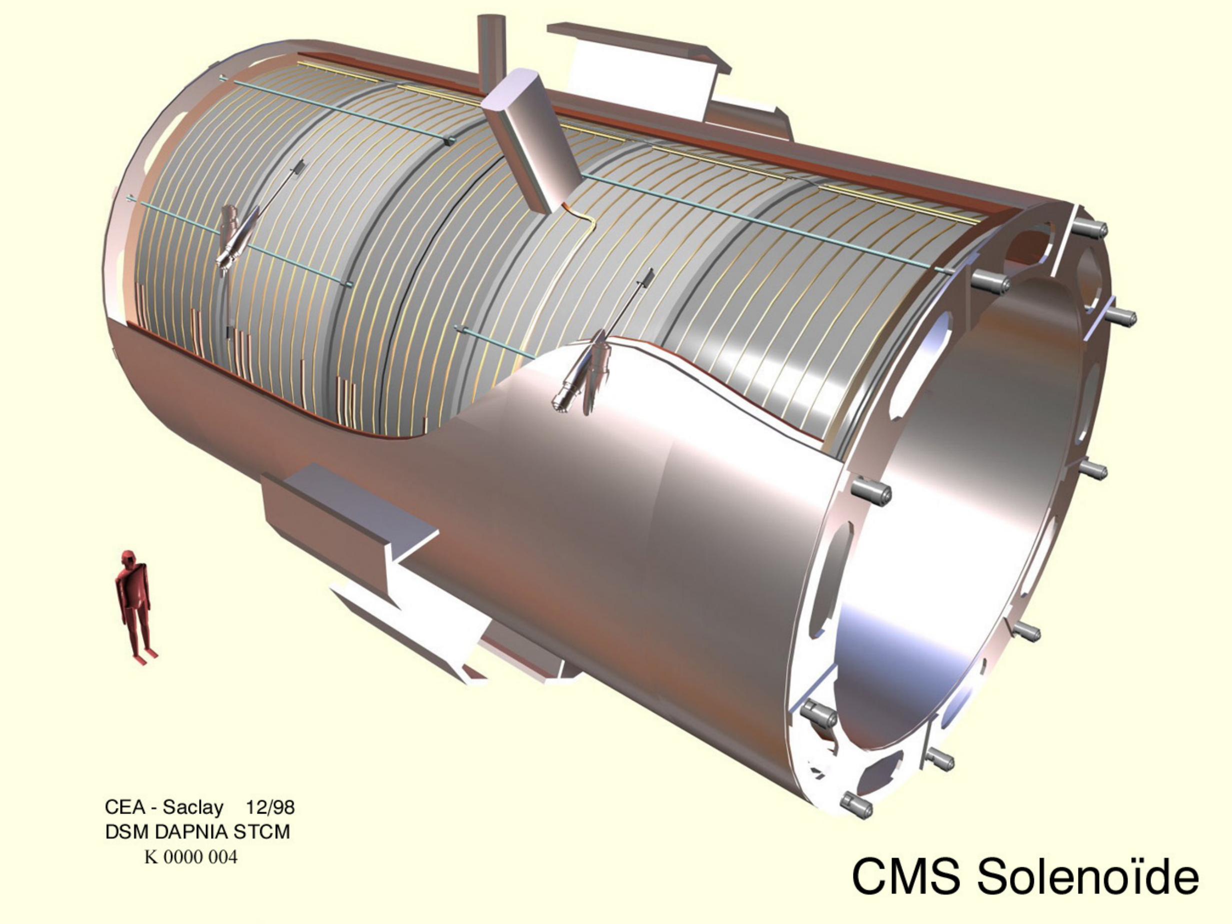
Configuration	3 series-connected subcoils		
Operating current (kA)	10 [a] (11) [b]		
Coil characteristics	Coil A	Coil B	Coil C
Type of windings	layer	layer	pancake
Conductor type	Nb_3Sn CICC	Nb_3Sn CICC	NbTi CICC
Number of turns	306 (6 layers x 51/layer)	378 (7 layers x 54/layer)	1015 (29 pancakes ×35/pancake)
Conductor length (m)	768	1195	4534
Winding i. d. (mm)	710	908	1150
Winding o. d. (mm)	888	1115	1680
Winding height (mm)	869	868	992
$J_{windingpack}$ (A/mm^2)	39.6 [a] (43.6) [b]	44.3 [a] (48.7) [b]	38.6 [a] (42.4) [b]
Field contribution (T) (individual coils)	3.26 [a] (3.59) [b]	3.58 [a] (3.94) [b]	7.38 [a] (8.12) [b]
Field contribution (T)	14.22 [a] (15.64) [b]		
Inductance (H)	1.96		
Stored energy (MJ)	97.9 [a] (118.4) [b]		

[a] Normal operation of outsert combined with insert

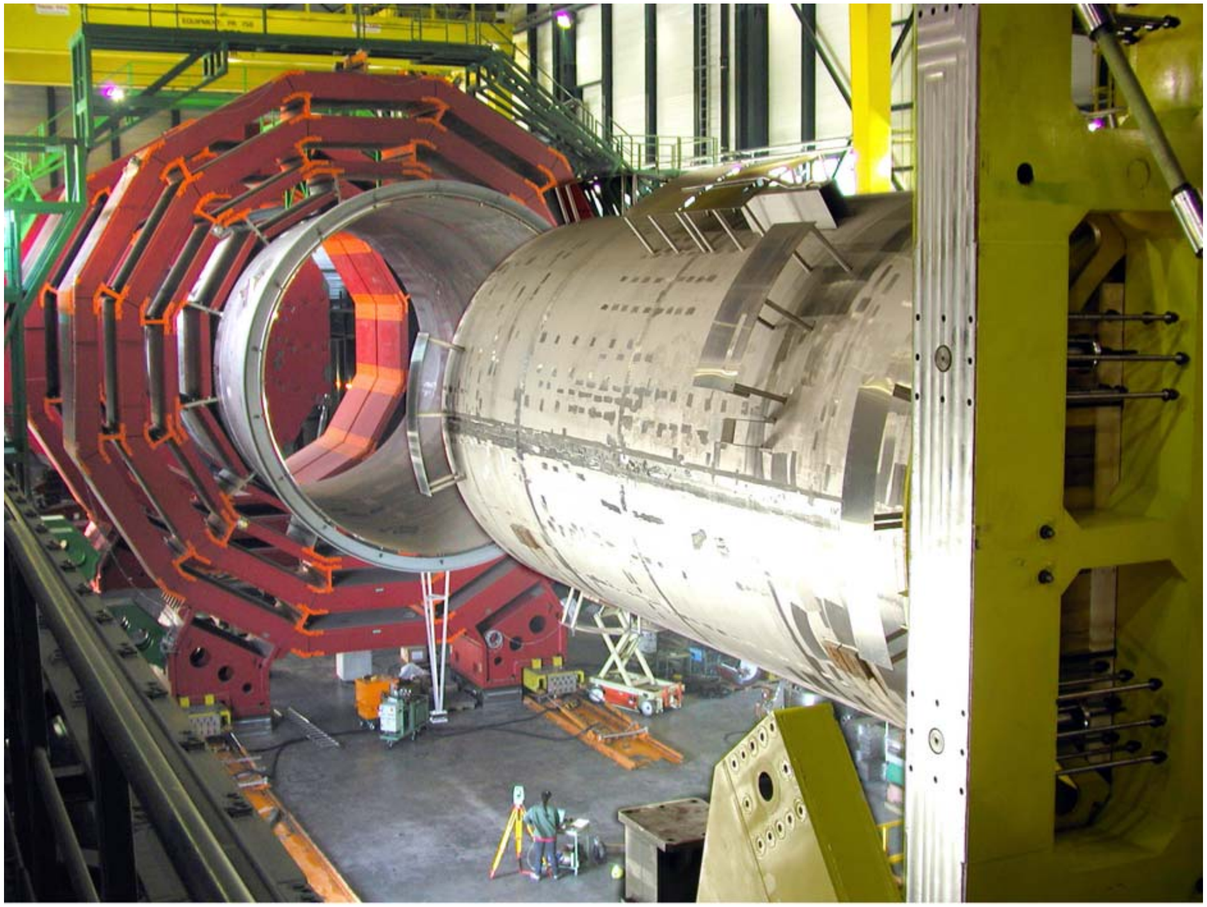
[b] Upset following an insert trip or operation of outsert alone

Cryostable

3. Reinforced Composite & Forced-Flow Cryogen: LHC CMS Magnet*

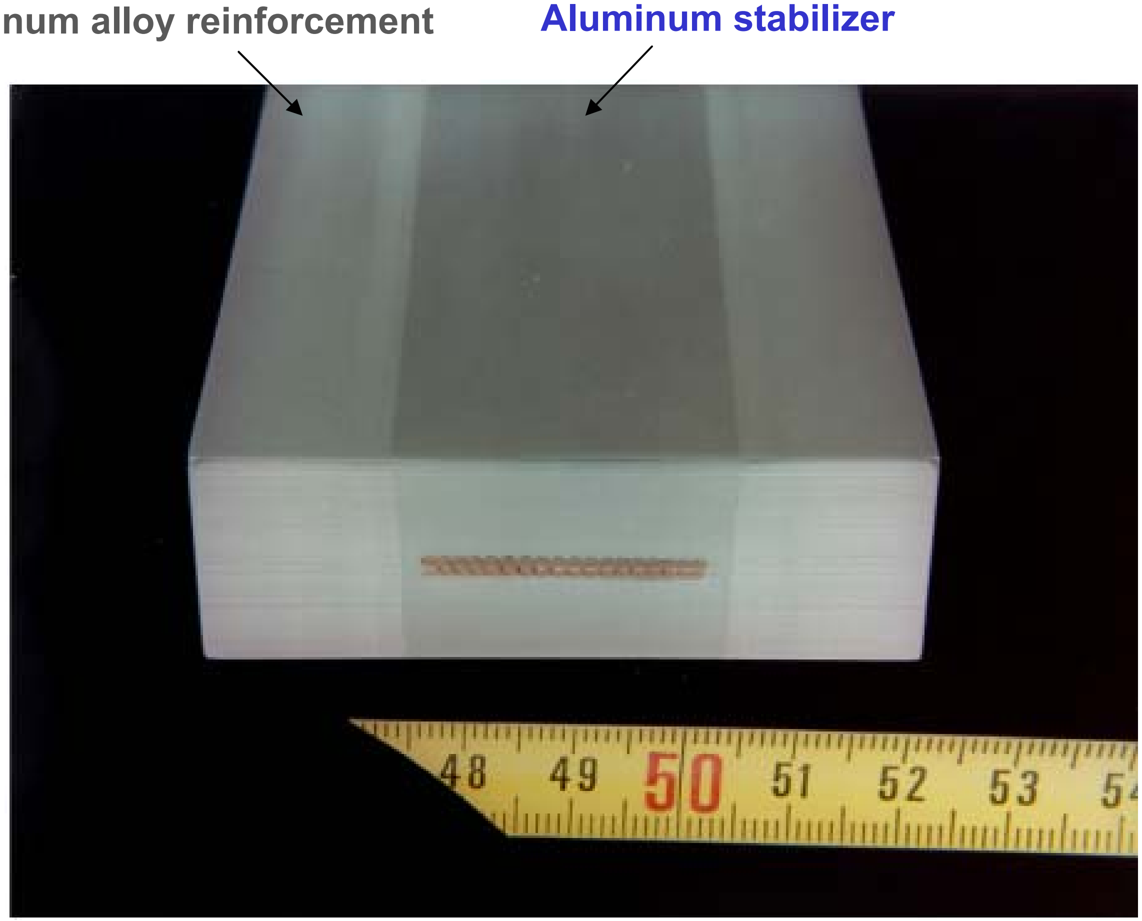


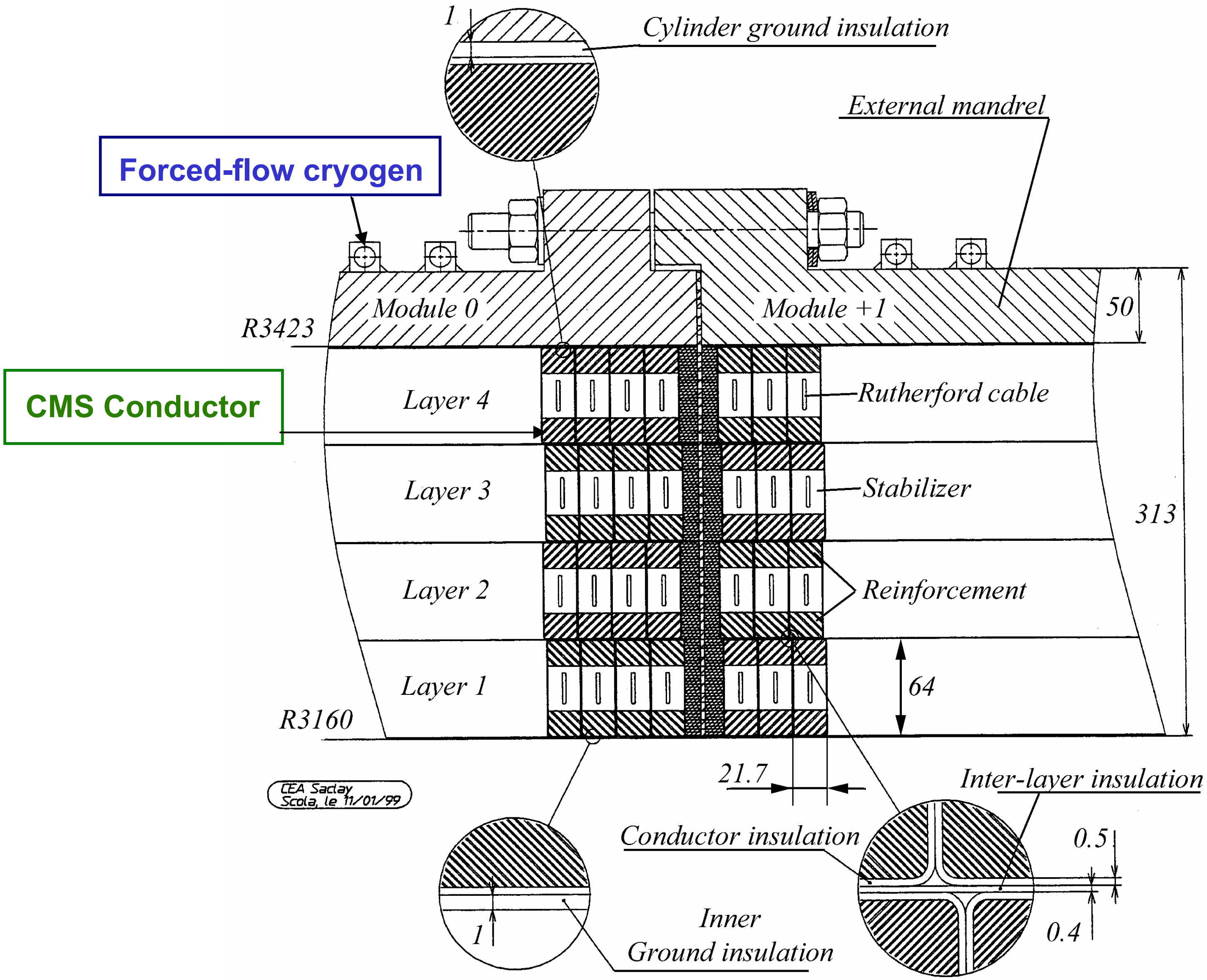
Courtesy of Fra



CMS Solenoid Insertion Tests 13 06 02 K 9000 001

CMS Conductor





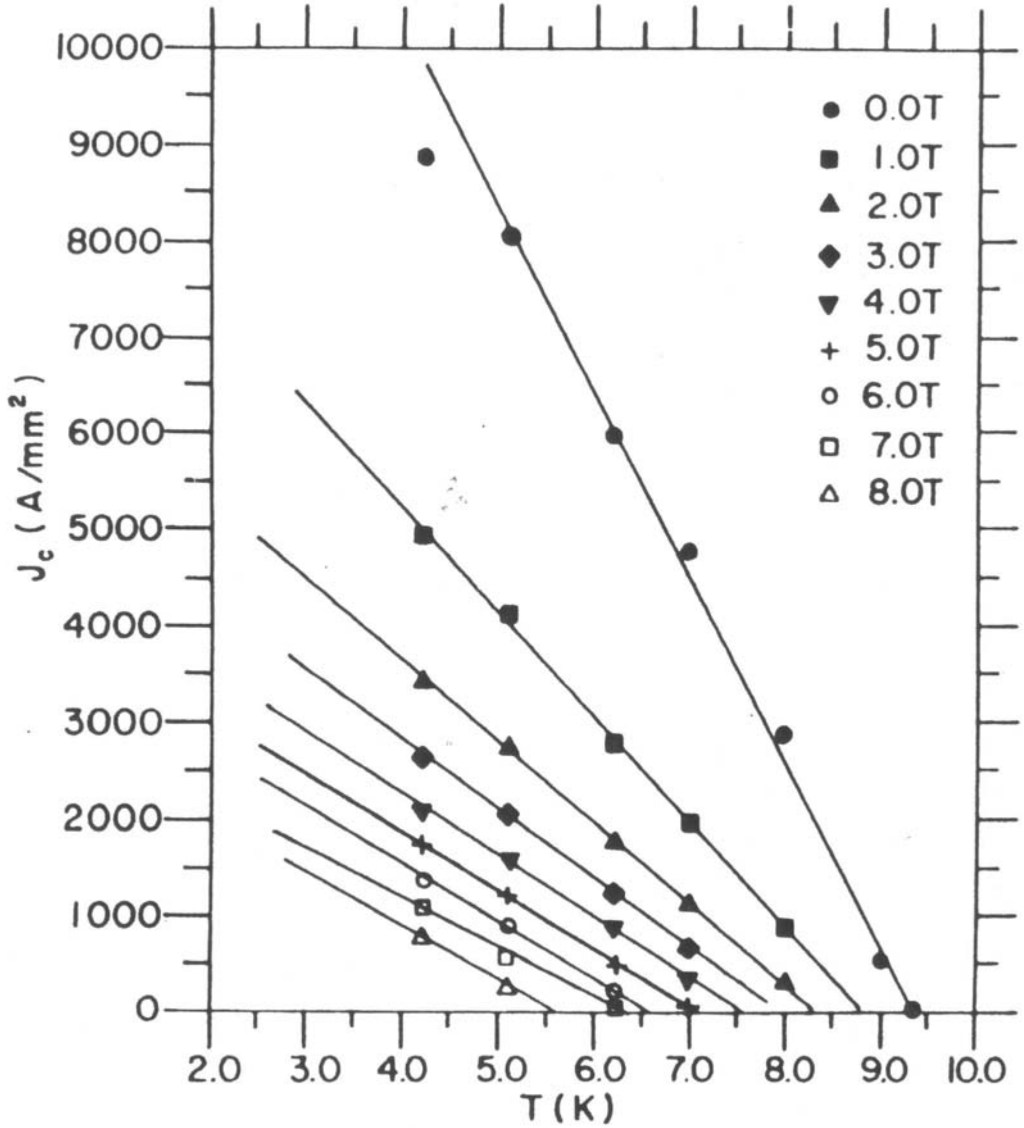
Forced-flow cryogen

CMS Conductor

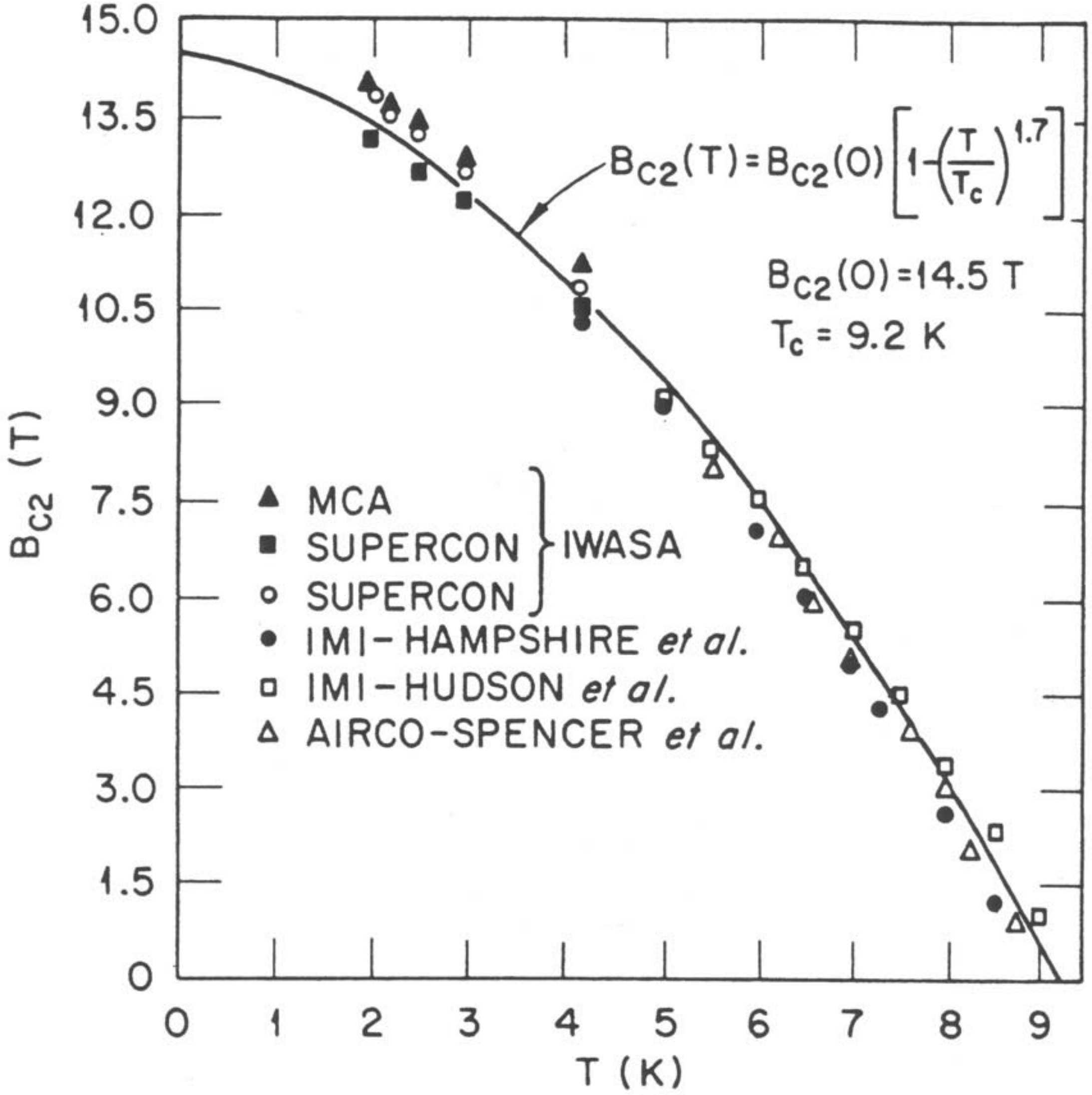
Selected Critical Parameters Data and Scaling Laws

- **Nb-Ti**
- **Nb_3Sn**

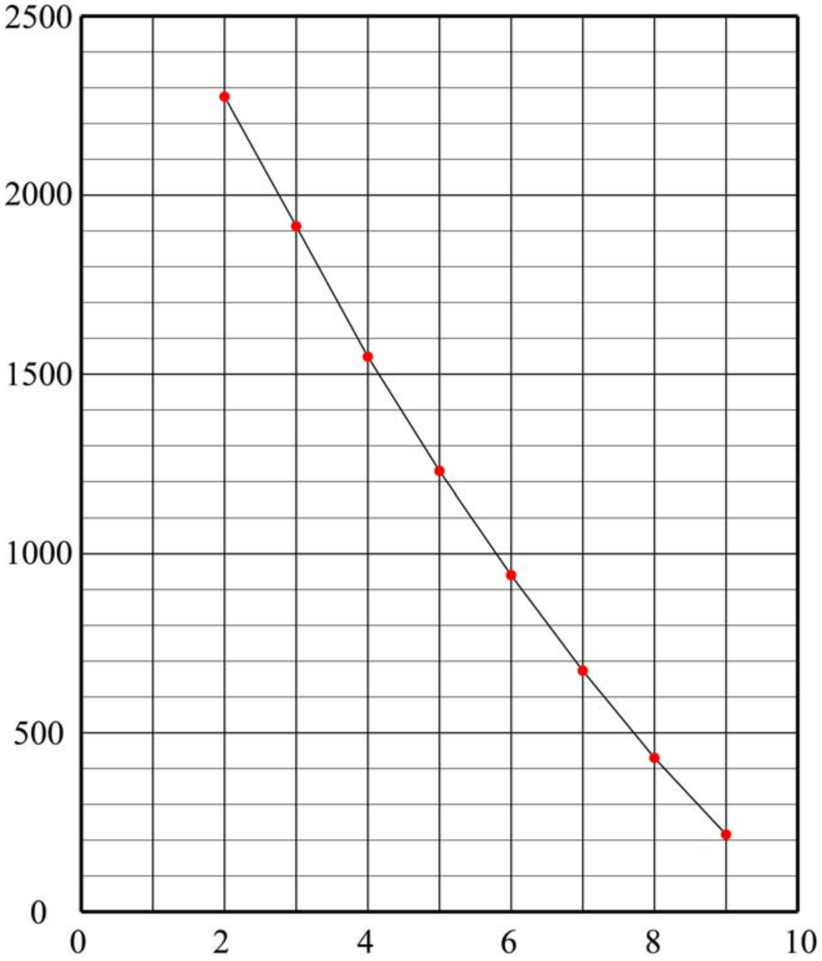
Nb-Ti: J_c vs T Plots at Different B

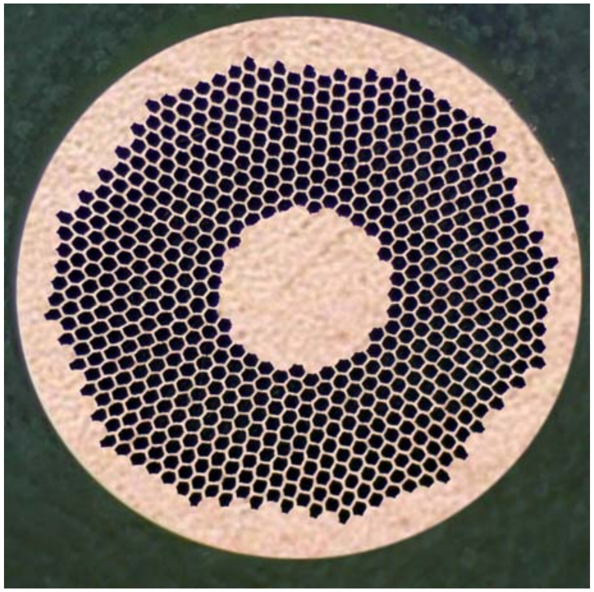


Nb-Ti: B_{c2} vs. T Plots



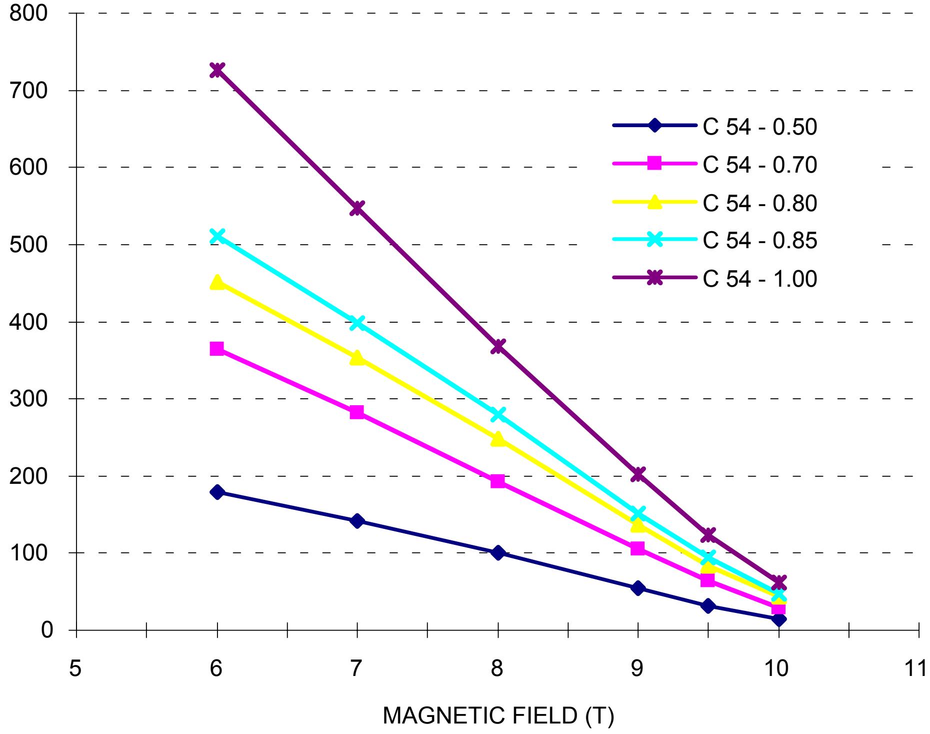
*MF Nb-Ti/Cu Composite**

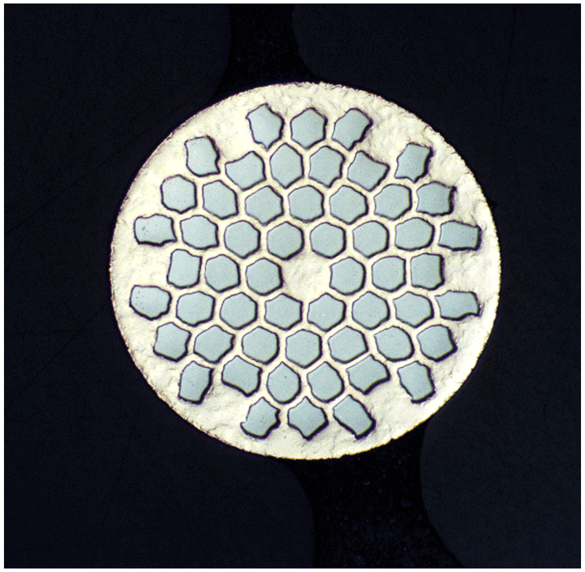




Diameter: 1.03 mm
 # Filaments: 642
Filament dia.: 30 μm
Cu/Nb-Ti: 1.1
Nb barrier: 0.5- μm thick around each filament

Courtesy of David Frost (SUPERCON, Shrewsbury)

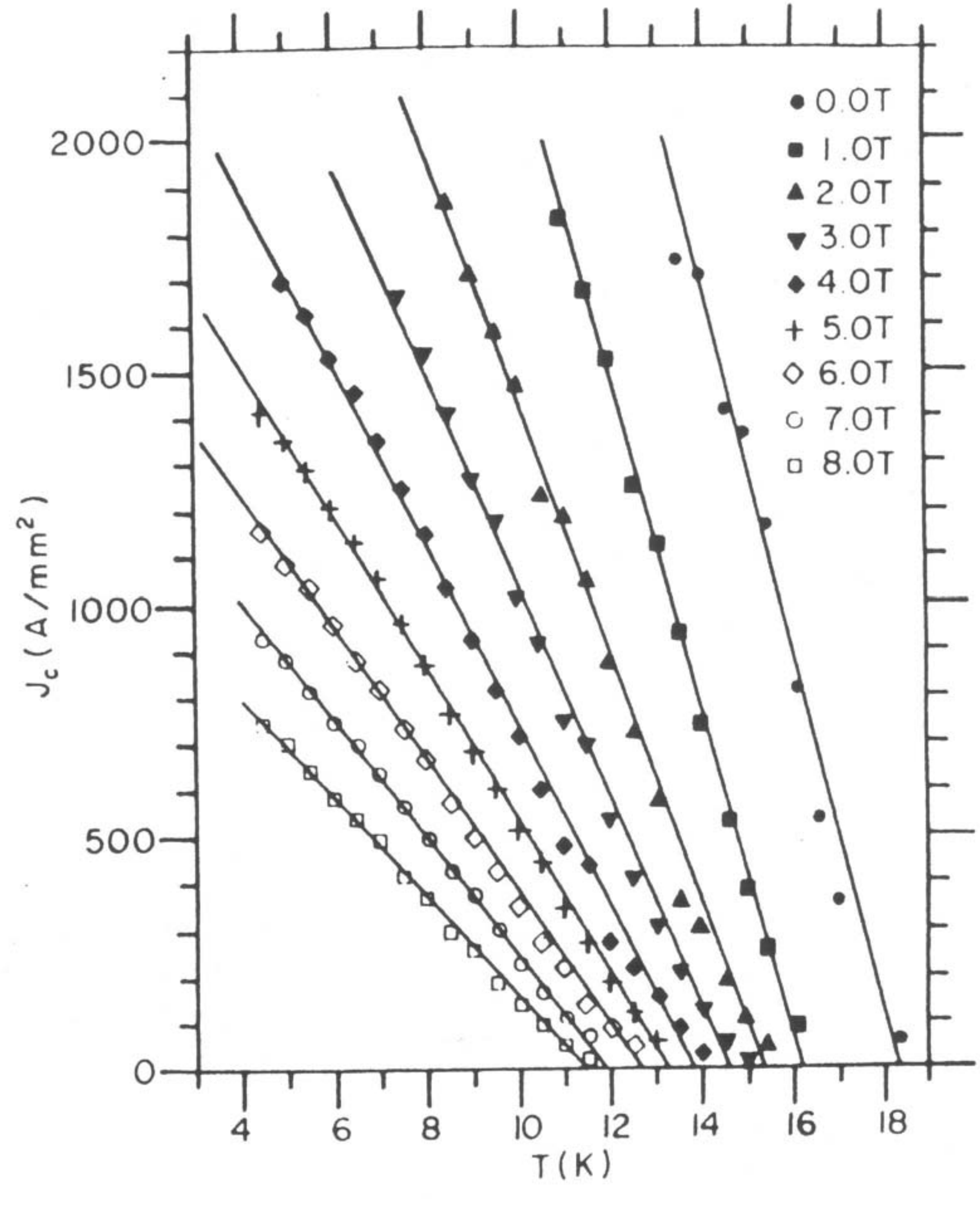




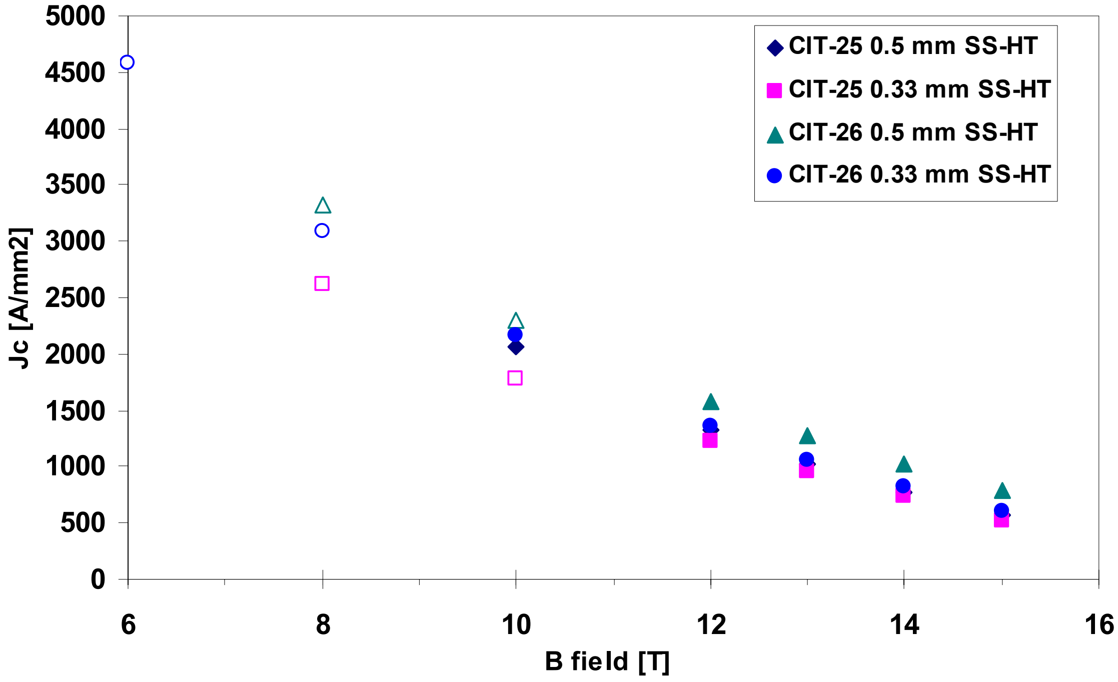
Diameters: 0.50/0.70/0.80/
0.85/1.00 mm
Filament dias.: 45/63/72
76/90 μm
Cu/Nb-Ti: 1.35

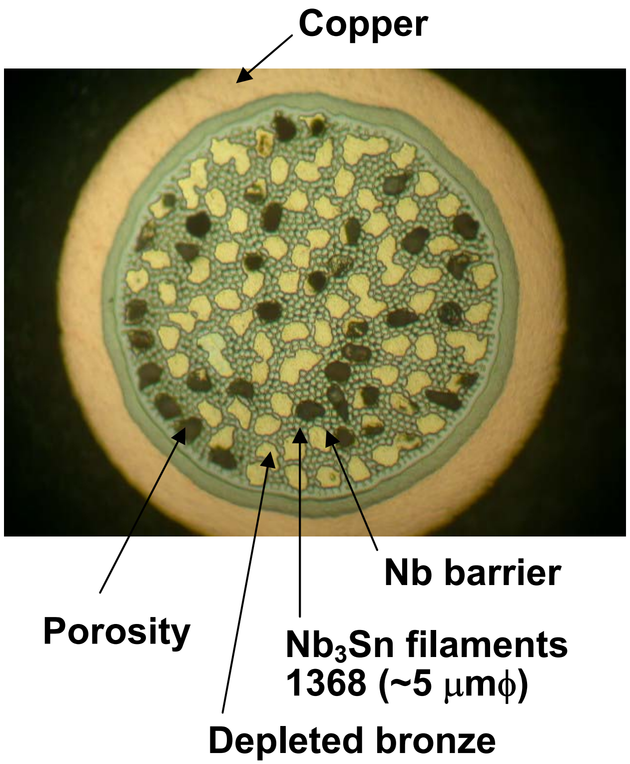
Courtesy of Claude Kohler (ALSTOM, Belfort)

Nb_3Sn: J_c vs T Plots at Different B



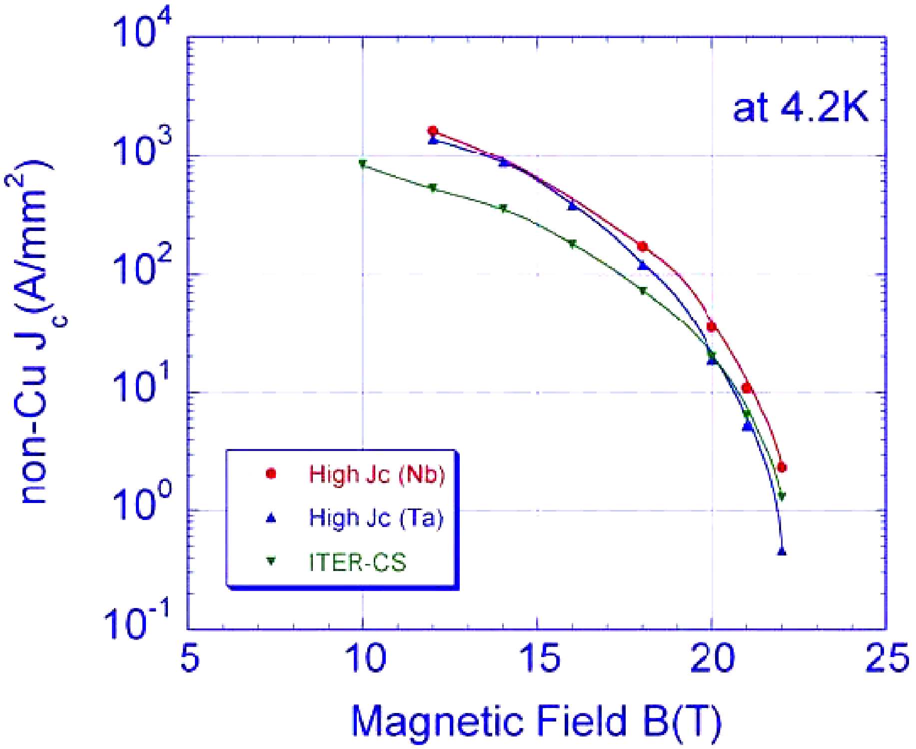
MF Nb3Sn—Internal Sn



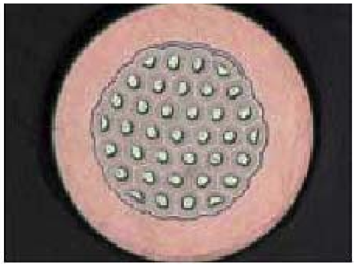


Courtesy of Shahin Pourrahimi (Superconducting Systems, Inc., Waltham)

MF Nb3Sn—Internal Sn



Nb barrier



Ta barrier

Diffusion Barrier: Nb or Ta
Wire diameter: 1.0 mm
Cu/non-Cu ratio: 1.3
Number of modules: 37
 # filaments: 20,424
Filament diameter: 2.6 μm

Courtesy of Kunishiko Egawa (Mitsubishi Electric, Sagami)

Scaling Law for Nb-Ti $J_c(B_{max}, T_{op})$

$$J_c = J_0\left(1-\frac{B_{\max}}{B_{c2_0M}}\right)\left(1-\frac{T_{op}}{T_c(B_{\max})}\right)$$

$$T_c\left(B_{\max}\right) = T_{c0M}\cdot\left(1-\frac{B_{\max}}{B_{c2_0M}}\right)$$

where B_{c2_oM}=15 T; T_{c0M} =9.3 K; J_0= 0.73×10^{10}A/m^2

*Scaling Law for Nb3Sn $J_c(B_{max}, T_{op}, \varepsilon_{tot})$**

$$J_c\left(B_{\max}, T_{op}, \varepsilon_{tot}\right) = \frac{J_{c1}\left(B_{\max}, T_{op}, \varepsilon_{tot}\right)}{1 + \dfrac{J_{c1}\left(B_{\max}, T_{op}, \varepsilon_{tot}\right)}{J_0\left(T_{op}\right)}}$$

$$T_c\left(B_{\max}, \varepsilon_{tot}\right) = T_{c0}\left(\varepsilon_{tot}\right) \cdot \left(1 - \frac{B_{\max}}{B_{c2_0 M}}\right)$$

L.T. Summers, M.W. Guinan, J.R. Miller, and P.A. Hahn, "A model for the prediction of Nb_3Sn critical current as a function of field, temperature, strain, and radiation damage," IEEE Trans. Mag. 27, 2041 (1991).

$$J_{c1}\left(B_{\max},T_{op},\varepsilon_{tot}\right)=C_0\left(B_{c2}\left(T_{op},\varepsilon_{tot}\right)\right)^{-1/2}\left(1-t^2\right)^2 b^{-1/2}(1-b)^2$$

$$B_{c2}\left(T_{op},\varepsilon_{tot}\right)=B_{c2_0}\left(\varepsilon_{tot}\right)\left(1-t^2\right)\left(1-\frac{t}{3}\right)$$

$$J_0\left(T_{op}\right)=J_{c0}\left(1-t^2\right)^2$$

$$b=\frac{B_{\max}}{B_{c2}\left(T_{op},\varepsilon_{tot}\right)}$$

$$t=\frac{T_{op}}{T_{c0}\left(\varepsilon_{tot}\right)}$$

$$T_{c0}\left(\varepsilon_{tot}\right)=T_{c0M}\left(1-\alpha\left|\varepsilon_{tot}\right|^{1.7}\right)^{1/3}$$

$$B_{c2_0}\left(\varepsilon_{tot}\right)=B_{c2_0M}\left(1-\alpha\left|\varepsilon_{tot}\right|^{1.7}\right)$$

(α=900 for $\varepsilon_{tot}<0$; α=1250 for $\varepsilon_{tot}>0$)

Nb_3Sn material constant values

Binary Nb_3Sn: B_{c2_oM}=24 T; T_{c0M} =16 K; C_0=2.22×10^{10} $AT^{1/2}$ m^2

High Performance Ternary Nb_3Sn :

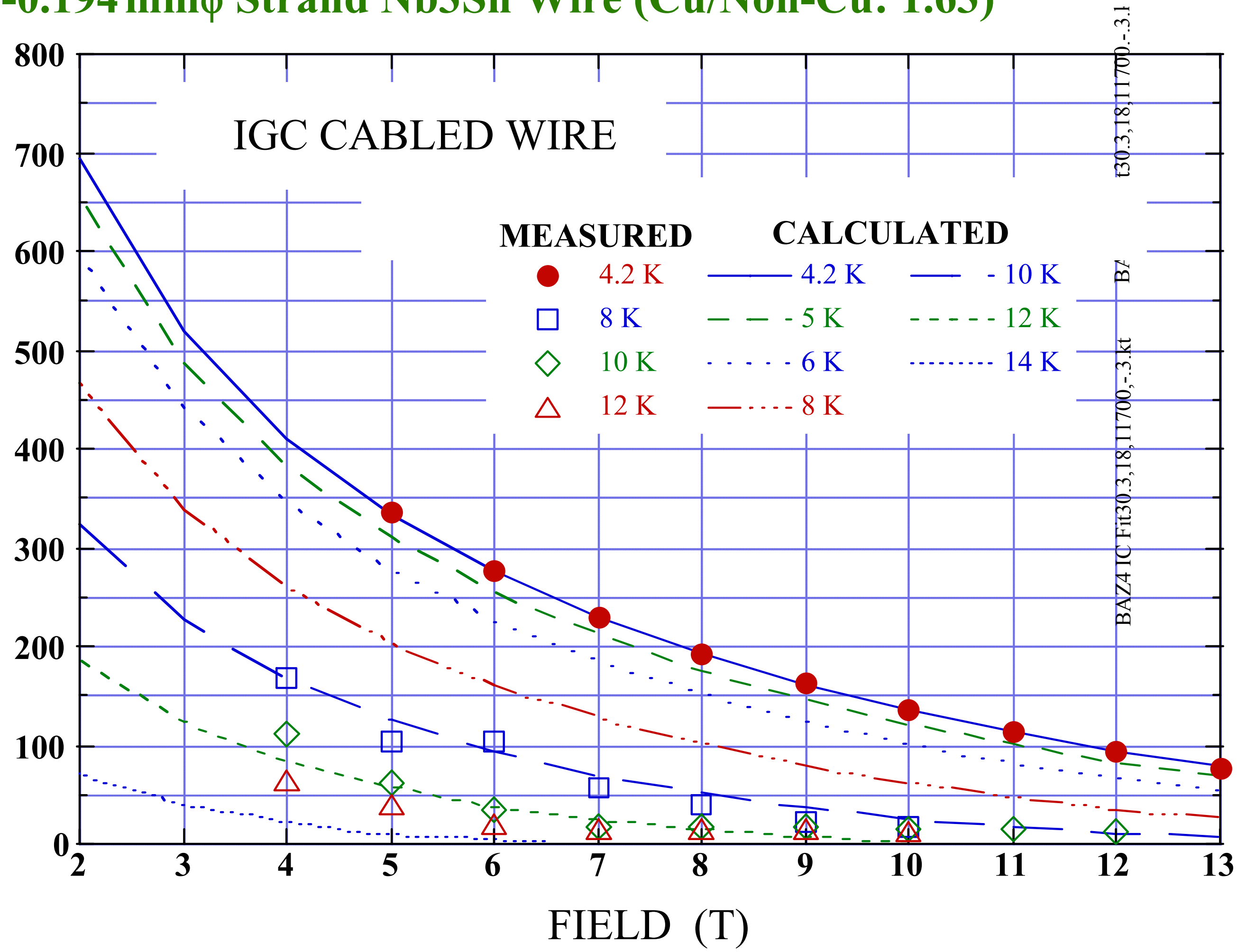
B_{c2_oM}=28 T; T_{c0M} =18 K; C_0=1.16×10^{10} $AT^{1/2}m^2$; J_o= 3.3554×10^{10}A/m^2

Low Performance Ternary Nb_3Sn :

B_{c2_oM}=28 T; T_{c0M} =18 K; C_0=0.9064×10^{10} $AT^{1/2}m^2$; J_o= 3.3554×10^{10}A/m^2

An Example of Application of the Nb_3Sn Scaling-Law

IGC 6-0.194 mmϕ Strand Nb3Sn Wire (Cu/Non-Cu: 1.63)



$C_0 = 1.17\text{x}10^{10}$ A $T^{0.5}$ m^{-2} , and $\varepsilon = -0.3\%$.

Courtesy of Makoto Takayasu (MIT/PSFC)

Thermal Shrinkage Differentials

	Young's Modulus @293 K (GPa)	Young's Modulus @4.2 K (GPa)	Thermal Shrinkage ($\times 10^{-3}$ m/m)	Density (kg/m^3)
Titanium	115	130	1.5	4400
Low Carbon Steel	200		2.0	
Stainless Steel (304/316)	200	210	2.9	7800
Copper (OFHC)	130	140	3.1	8900
Aluminum Alloy	70	80	4.2	2800
Nb-Ti Cables w. Polyimide Insulation[a)]	6	9-11	~5	
Resin-Impregnated Nb_3Sn Cables[a)]	30	45	3.5–4	

[a)] Upon loading @80 MPa; depends on cable and insulation parameters.

Courtesy of Joel H. Schultz (PSFC/MIT)

Physical properties of austenitic stainless steels

Stainless steel & temperature [K]	Density [kg/m^3]	Young's Modulus [GPa]	Poisson's ratio	Thermal conductivity [W/m-K]	Mean thermal expansion [K^{-1} 10^{-6}]	Specific heat [J/kg-K]	Electrical resistivity [μΩ-m]
AISI 304							
295	7,860	200	0.29	14.7	15.8	480	70.4
77		214	0.278	7.9	13.0		51.4
4		210	0.279	0.28	10.2	1.9	49.6
AISI 316							
295	7,970	195	0.294	14.7	15.8	480	75.0
77		209	0.283	7.9	13.0	190	56.6
4		208	0.282	0.28	10.2	1.9	53.9

Yield Stress & Ultimate Strength for Structural Materials

Material	Yield Stress [MPa]			Ultimate Strength [MPa]		
	RT	77K	4K	RT	77K	4K
316LN Annealed	310	607	815	552	1069	1362
304L Annealed	400	460	550	660	1500	1660
Incoloy 908 Mill Annealed	1075	1189	1227	1433	1664	1892
Incoloy 908 20% Cold Worked	1279		1489	1499		1903
Cu 20% Cold Worked	270	300	330	280	380	450
INVAR 15% Cold Worked	650	950	1150	650	1050	1200
6061-T6 Al	300	360	380	330	440	550
Inconel 718	1080	1280	1370	1310	1640	1850
Ti-6Al-4V	890	1420	1700	960	1500	1770

Mechanical Properties of Al Alloys

Alloy	Temperature	Yield Strength	Tensile Strength	Elongation	Modulus
	K	MPa	MPa	%	GPa
7075-T6	295	502	589	16.9	63.2
	76	589	714	15.8	73.2
	4	648	810	10.1	74.4
7475-T761	295	460	515	17.1	66.3
	76	549	636	17.3	75.3
	4	572	739	15.1	76.4
2219-T87	295	397	475	12.6	67.8
	76	484	597	13.5	76.5
	4	539	711	12.4	77.9
2090-T8E41	295	488	528	12.1	74.0
	76	551	640	10.8	76.9
	4	614	727	9.9	84.1