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Conceptual Design of SC Magnets of FFHR2m1 with CIC Conductors on the Engineering Base for ITER.

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1. Introduction
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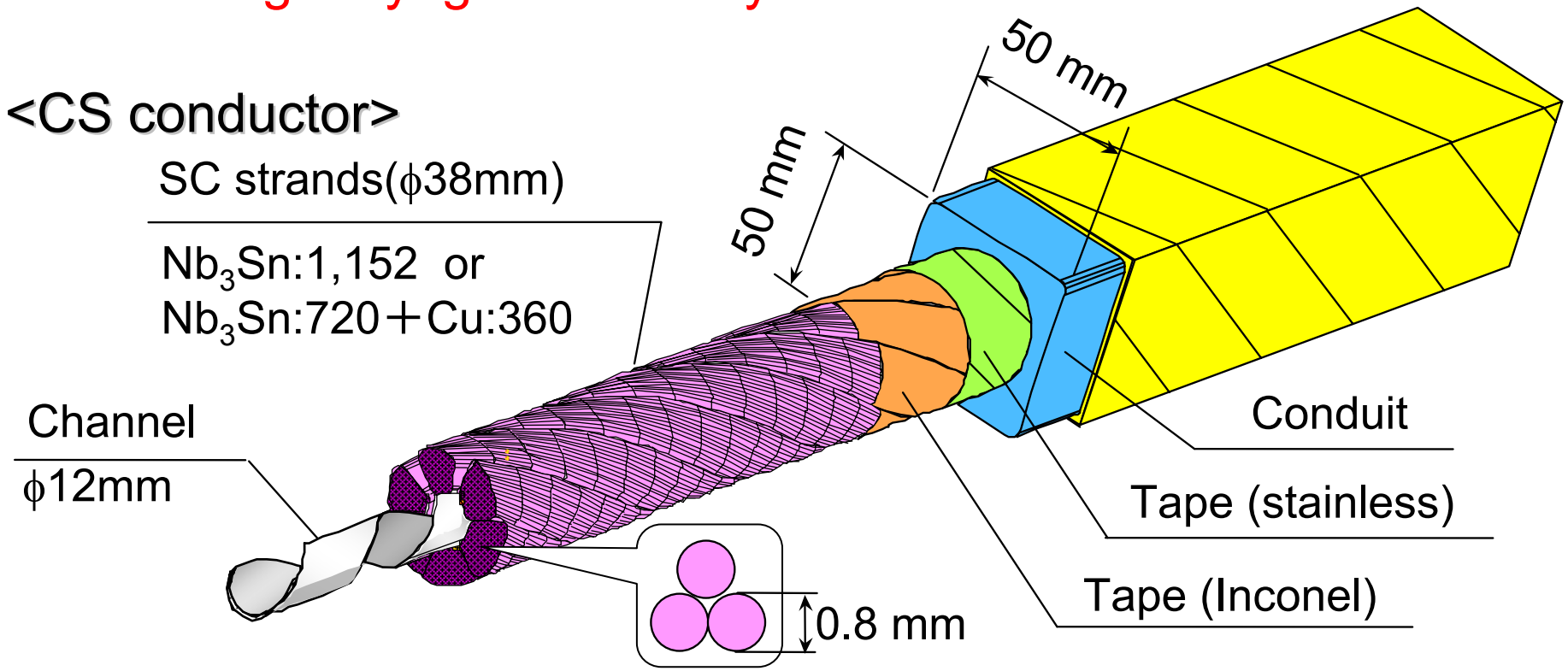
4. Summary

Background

(1) Fusion magnets need high mechanical strength, high reliability, and low cost.

(2) CIC (Cable-in-conduit) conductors have been developed for large pulse coils, and adopted for ITER magnets.

(3) CIC conductors : large current up to 100 kA, high strength, and high cryogenic stability.



Objectives

CIC conductors will not be the best for magnets of a helical reactor that is operated with a constant current.

(1) Circulation pumps are needed, because CIC conductors should be cooled by forced flow.

(2) Quick discharge with an external dump resistor is indispensable for the coil protection. It induce high voltage.

However, technology related to CIC conductors will be strongly improved through the construction of ITER especially in a cost and in the winding technique.

Then, we study the helical winding with CIC conductors on the engineering base of ITER <u>as a conventional option</u>.

Design Criteria for HC with CICC

<Design Criteria for CIC Conductor [Spec. of ITER-TF coil]>

・Max. length of cooling path	< 1000 m	[780 m]
・Current	< 100 kA	[68 kA]
・Max. field	< 13 T	[11.8 T]
・SC current density	< 300 A/mm^2	[273 A/mm^2]
・Coil current density	< 30 A/mm^2	[20.3 A/mm^2]
・SC material	Nb_3Al (*1) for HC	[Nb_3Sn]
	NbTi for PC (Poloidal coil)	

(*1) React & Wind method can be adopted by managing strain during winding within about 0.5%.

Parameters of Heliotron-type Reactor

Items			FFHR2m1	FFHR2m2	FFHR2	LHD
Polarity / Field period	l / m		2/10	2/10	2/10	2 / 10
Coil pitch parameter			1.15	1.25	1.15	1.25
Coil major radius	R_c	m	14.0	17.3	10.0	3.9
Plasma major radius	R_p	m	14.0	16.0	10.0	3.75
Plasma radius	a_p	m	1.73	2.80	1.20	0.61
Plasma volume	V_p	m^3	831	2475	284	27.5
Magnetic field	B_0	T	6.18	4.43	10.0	4
Max. field on coils		T	13.3	13.0	13.0	9.2
Magnetic energy		GJ	120	142	147	7.85
Coil current density	j	MA/m^2	26.6	32.8	25.0	53
Min. Blanket space		m	1.20	1.10	0.70	0.12
Electron density	$ne(0)$	10^{19} m^{-3}	26.7	33.5	16.3	1.64
Temperature	$Ti(0)$	keV	15.6	15.6	18.7	
H factor of ISS95			1.96	1.8	1.9	
Average beta	$< \beta >$		2.84	3.56	4.06	
Fusion power (*1)	P_F	GW	1.90	3.00	3.00	
Neutron wall load		MW/m^2	1.50	2.37	1.31	

(*1) A heating efficiency is0.9, density fraction of He and O are 2% and 0.5%.
Density profile and temperature profile are parabolic.

Concept to Adopt CICC for HC

<Features of Helical coil of FFHR2m1 compared to ITER-TF>

(a) Large magnet-motive force: 43.3 MA => OK

(b) Large magnetic energy: 120-130 GJ => OK

(c) Long coil center line: 134 m => 5 times longer

(d) Fairly high coil current density: 25-30 A/mm^2 => OK?

<Concept to adopt CIC conductor for HC>

(1) To reduce a turn number with a large conductor

(2) To shorten the cooling length with <u>five parallel winding</u>

=> <u>Layer winding</u> will be needed.

HC with CICC for FFHR2m1

		FFHR2m1-HC	ITER-TF
Bmax	T	13	11.8
Magnetic energy	GJ	120	41
Max length for cooling	m	804.6	780.0
Conductor current	kA	90.1	68.0
Number of parallel winding		5	1
Current density (winding)	A/mm^2	26.59	20.33
Cross-sectional area per turn	mm^2	58.2*58.2	59.2*56.5
Cu ratio of strand		1	1
Non-Cu current density	A/mm^2	300.0	273.4
Ratio of Cu strands (area)		0.330	0.360
Central tube diameter	mm	9.21	8.00
Void fraction		0.34	0.34
Cable outer diameter	mm	46.28	40.2
Conduit outer diameter	mm	49.4	43.4
Number of coils		2	18
Total length of conductor	km	128.7	82.2
Total weight of SC strands	ton	619.7	351.2
Total weight of Cu strands	ton	339.9	131.5
Total weight of winding	ton	2696.5	1831.4
Weight of coil cases	ton	1770.2	4288.6
Total weight of coils	ton	4466.6	6120.0

PCs with CICC for FFHR2m1

		FFHR2m1-OV	FFHR2m1-IV	ITER-PF3
Radius of coils	m	18.1	10	11.97
Length of coil center line	m	113.7	62.8	75.2
Bmax	T	7.4	6.2	4
Coil current	MA	22.53	11.62	8.46
Number of turns per coil		392	200	188
Number of layers		28	20	16
Number of turns per layer		14	10	11.75
Number of parallel winding		2	1	1
Max length for cooling	m	796.1	628.3	883.8
Conductor current	kA	57.5	58.1	45
Current density (winding)	A/mm^2	9.31	9.08	15.26
SC Strands		NbTi	NbTi	NbTi
Cu ratio of strand		3.0	3.0	1.0
Non-Cu current density	A/mm^2	200	300	229.9
Central tube diameter	mm	12.0	12.0	12.0
Void fraction		0.34	0.34	0.34
Cable outer diameter	mm	48.80	40.68	34.5
Number of coils		2	2	1
Total length of conductor	km	89.161	25.133	14.14
Total weight of SC strands	ton	841.2	159.8	41.4
Total weight of coils	ton	3686.4	1124.8	258.2

How to Wind Parallel?

Two types of winding structures for CIC conductor.

(1) Thick Jacket

high strength

high stress in insulators, Large force for winding

(2) Internal plate (Radial plate)

Relatively small force for winding

Relatively low stress in insulators

but, internal plates are complicated and expensive.

=> Manufacturing technology will be improved through ITER-TF construction.

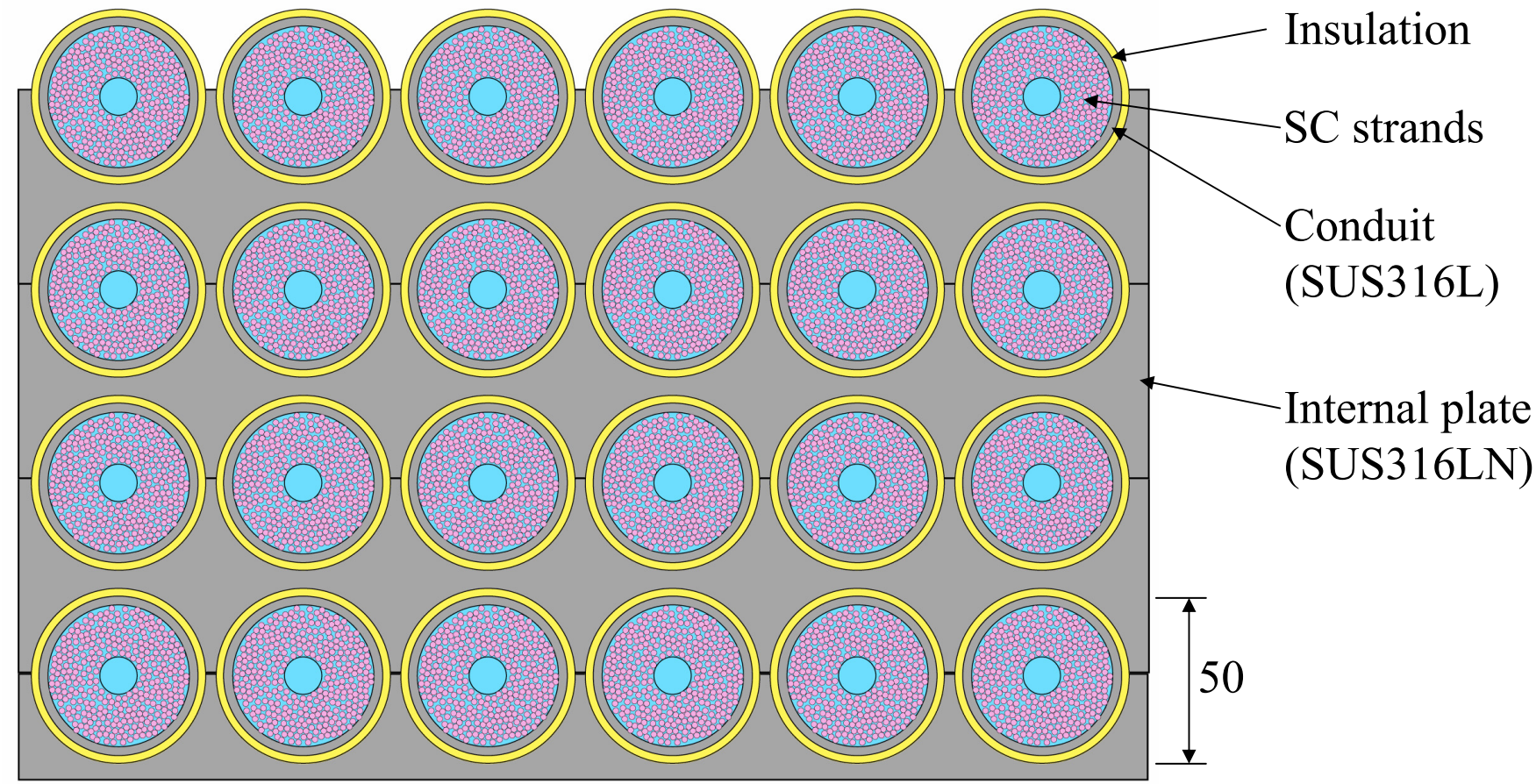
Internal plates with grooves are suite for parallel winding, because CIC Conductors are just put in the groove.

Concept of HC Winding with CICC

(1) Five parallel layer winding by React & Wind method

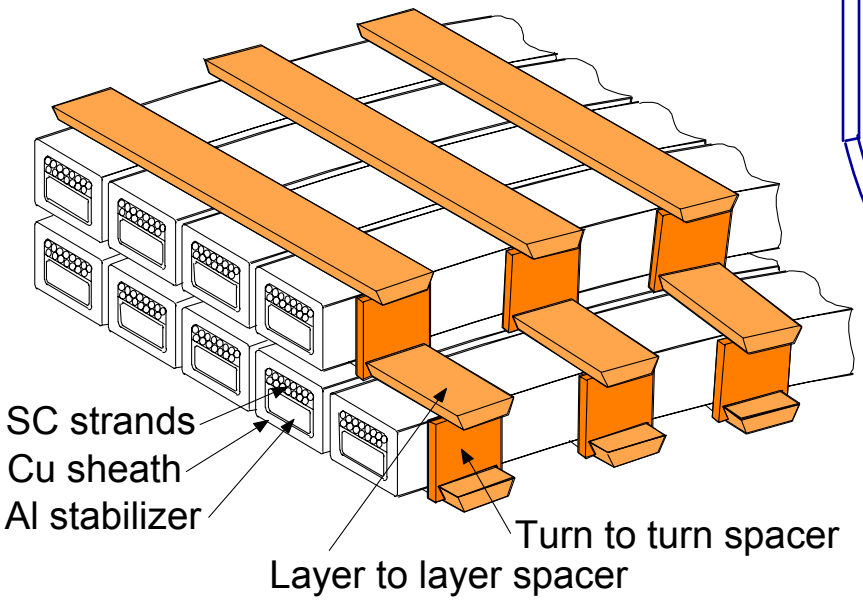
(2) Winding guides are grooved in the internal plates. The half pitch (180 deg in poloidal) sectors are weld each other on site.

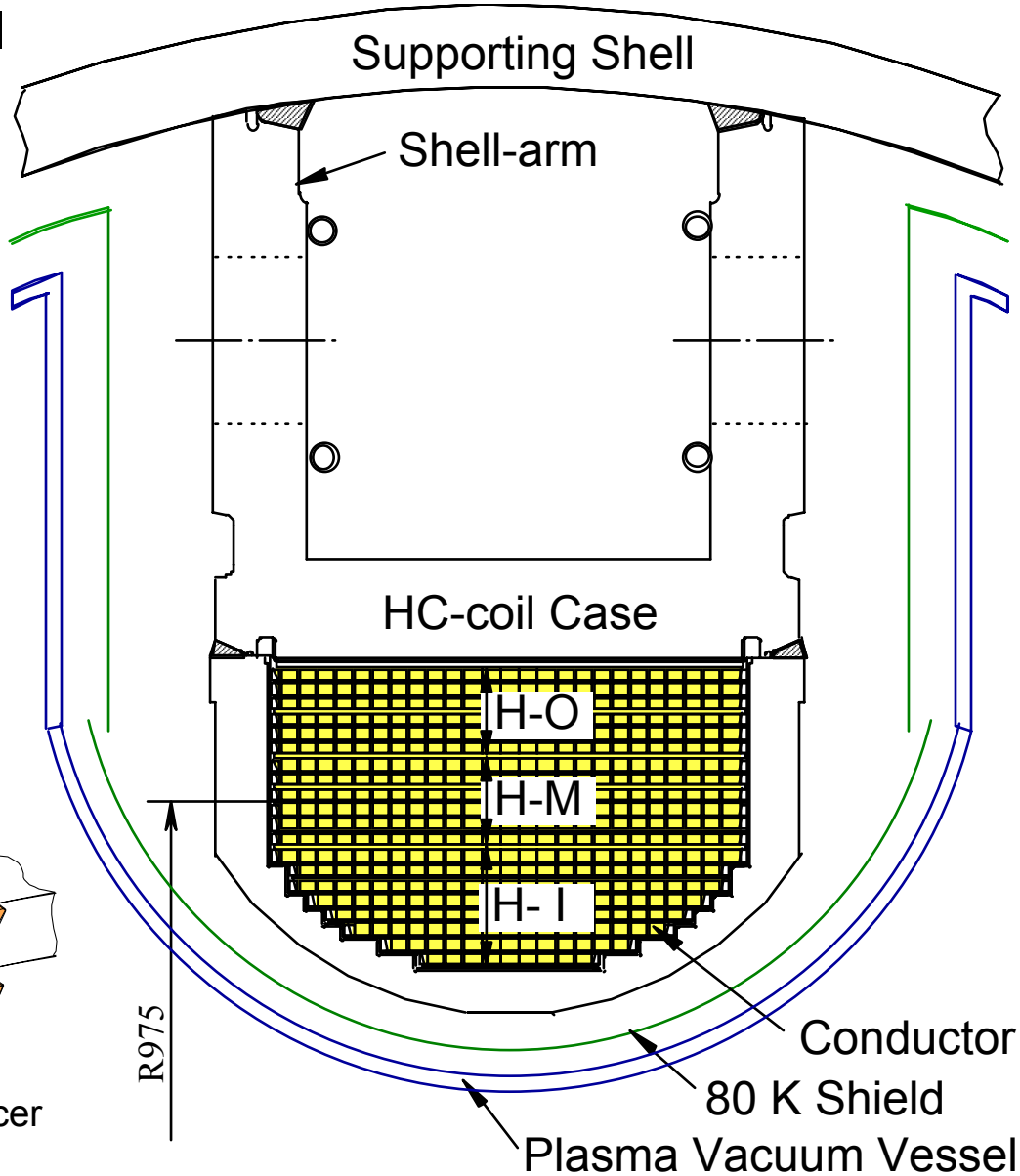
(3) CIC conductors are wound into the groove with insulation.



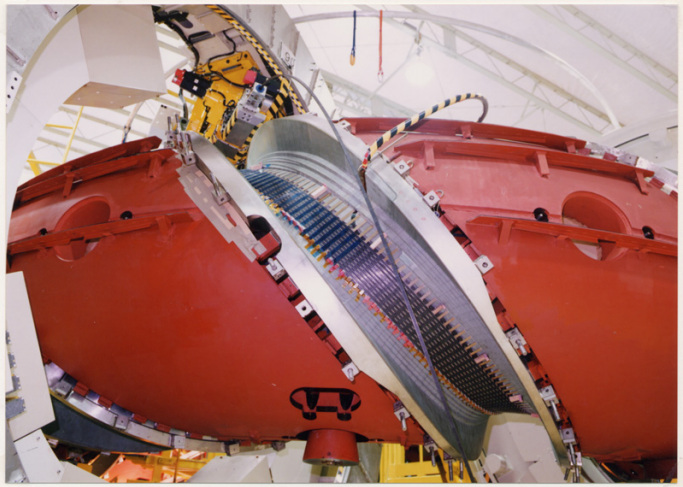
Manufacture of Helical Coil for LHD

(1) Upper and lower half pitch coil cases are machined, and weld each other on site.
(2) Conductors were wound on the coil case.
(3) Top covers of coil case were machined by sectors of 120 deg in poloidal, and welded on site.

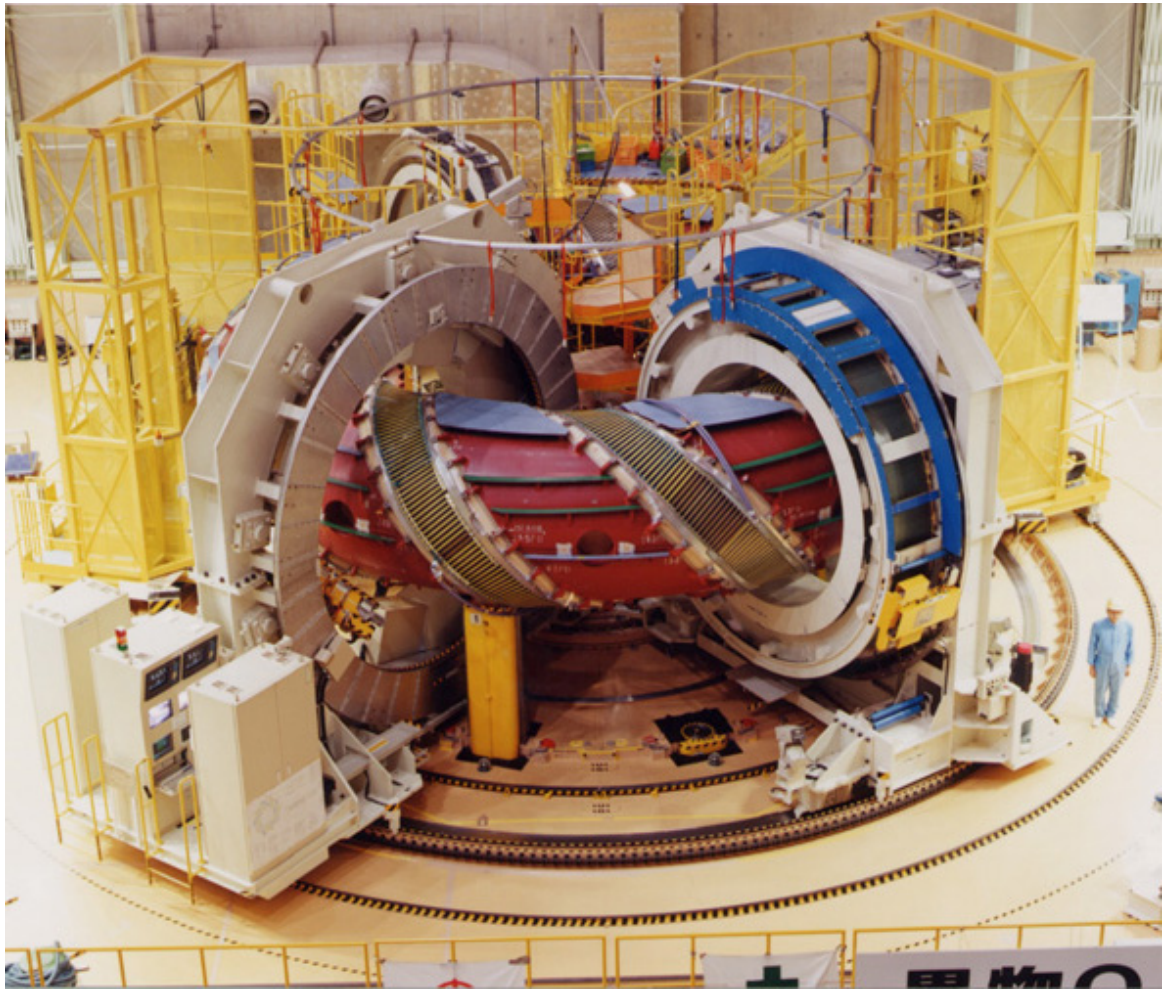


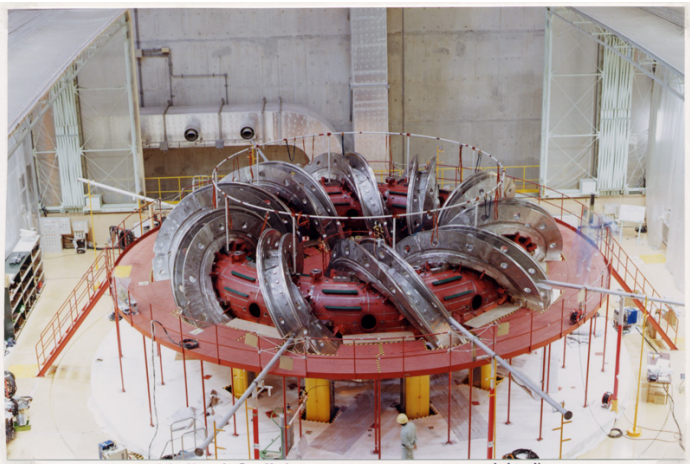


Helical Coil Winding of LHD



Shaping Head of Winding Machine





Helical Coil (top covers were welded)

Summary

(1) CIC conductors can be adopted for large helical windings by adopting layer winding and parallel winding method. This design is expected to be a conventional option which can be realized by small extension from ITER technology.

(2) React & Wind method is preferred for a large magnets. Nb_3Al is a candidate for the helical coil because of its good tolerance against mechanical strain.

(3) Future works are

structural analysis considering the rigidity of the winding area with CICCs and internal plates,
and design of winding method including joints and feeders.