VLT
Virtual Laboratory for Technology
For Fusion Energy Science

Magnet Technology

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MIT Plasma Science and Fusion Center

On Behalf of Magnets Program Participants:
LLNL, UW, MIT

VLT Program Advisory Committee Meeting

University of California, San Diego
San Diego, CA
March 2, 2003

MIT PSFC

The University of Wisconsin-Madison
Applied Superconductivity Center

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Magnet Technology Mission

Support of MFE and IFE Programs

Reduce the size and cost of superconducting magnets by higher fields, current densities, stress levels and operating temperatures. Develop high critical temperature superconductors. Develop improved conductors and components for a Burning Plasma Experiment and advanced magnet concepts to achieve better physics performance. Develop cost effective design and fabrication techniques for IFE-HIF focusing magnets.

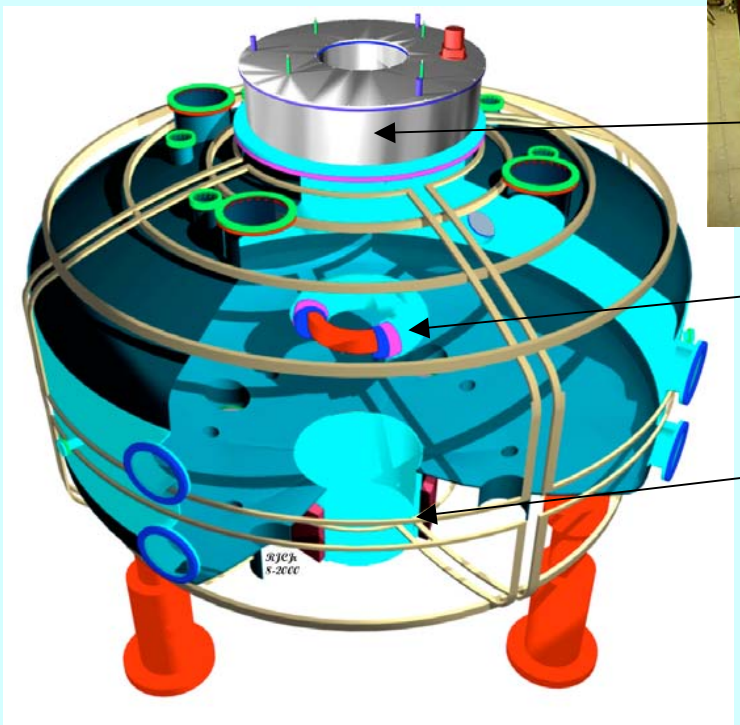
- **Support of LDX**
  - **Low and High Temperature superconducting magnet design, fabrication and testing**
- **Support of IFE-HIFD**
  - **HCX magnet and cryostat design, fabrication and test**
- **Support of Next Step Options**
  - **FIRE and ITER magnets**
- **Basic R&D**
  - **Superconductors and magnet insulation and structural materials**
  - **Education and training of students**

Magnet Technology

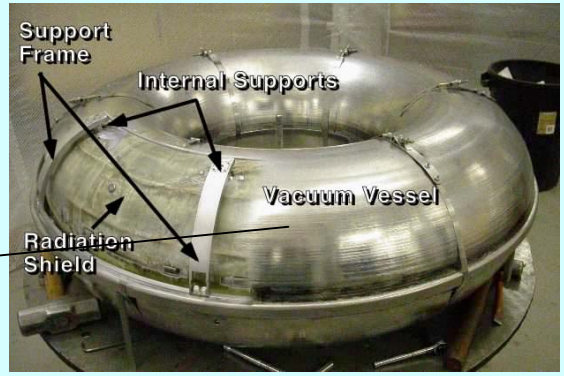
FY03/04 Technical Highlights

- Magnet program contributes important technology to alternate concepts like LDX
- Final assembly nearing completion

Levitation coil acceptance tested and installed on VV. (HTS magnet)



Floating coil assembly just before closing out cryostat. (Nb_3Sn magnet)



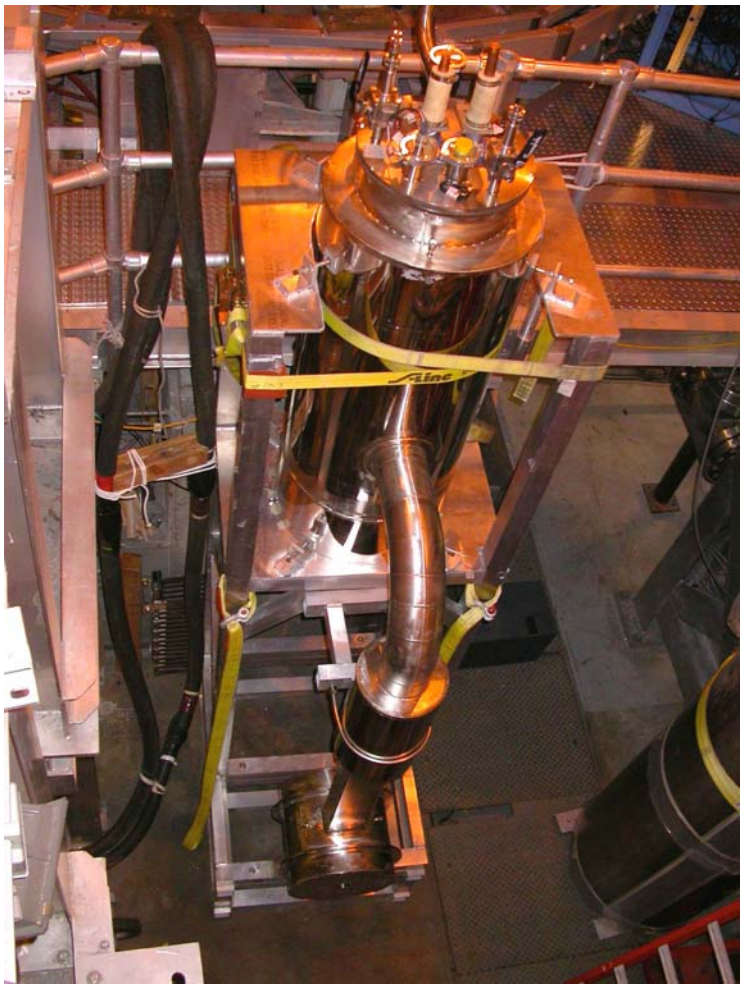
Charging Coil installed and acceptance testing completed. (NbTi magnet designed and fabricated at Sintez, St. Petersburg, Russia)

Magnet Technology

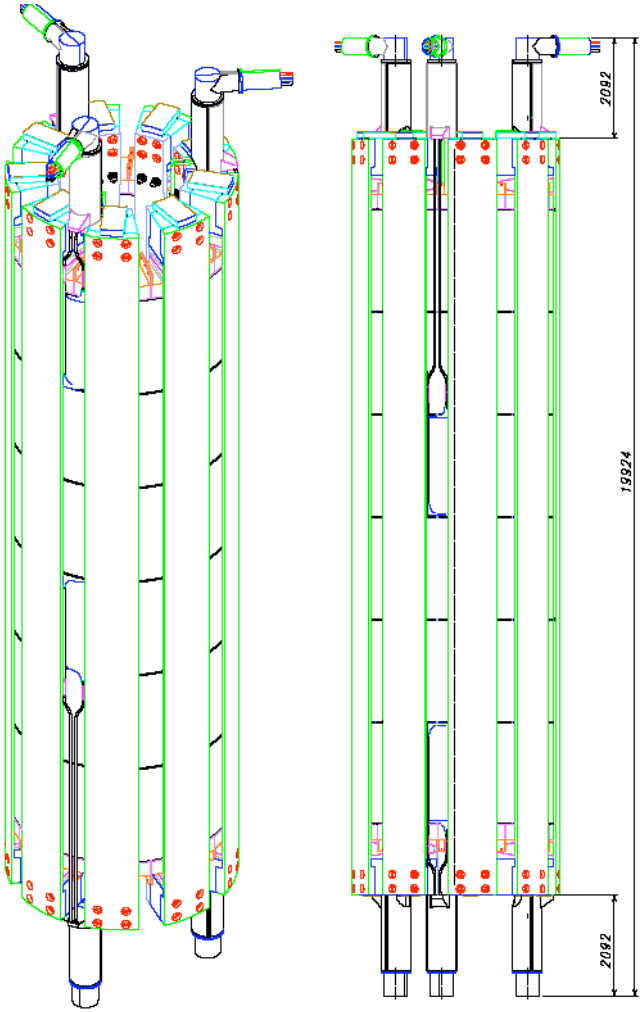
FY03/04 Technical Highlights

Successful collaboration by LBNL, LLNL, and MIT in the design, fabrication and testing of quadrupole focusing magnets and dual quad, warm-bore cryostat for the HCX for the IFE-HIFD program.

- Cryostat fabricated by CVIP in Emmaus, PA
- Coils made by LLNL
- Cryostat designed by LLNL/fabrication followed by MIT
- System tested by MIT.

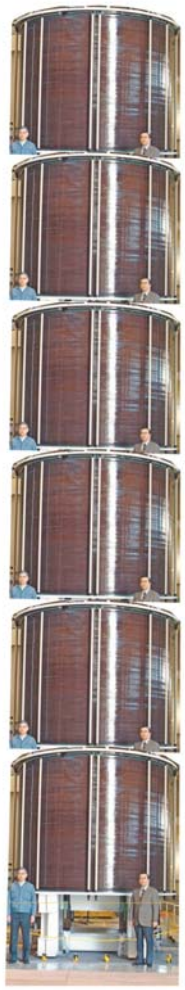


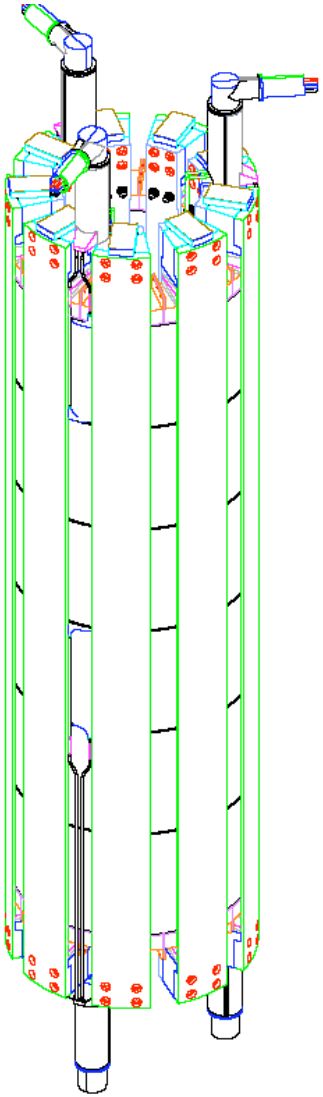
ITER CS Scope of Supply

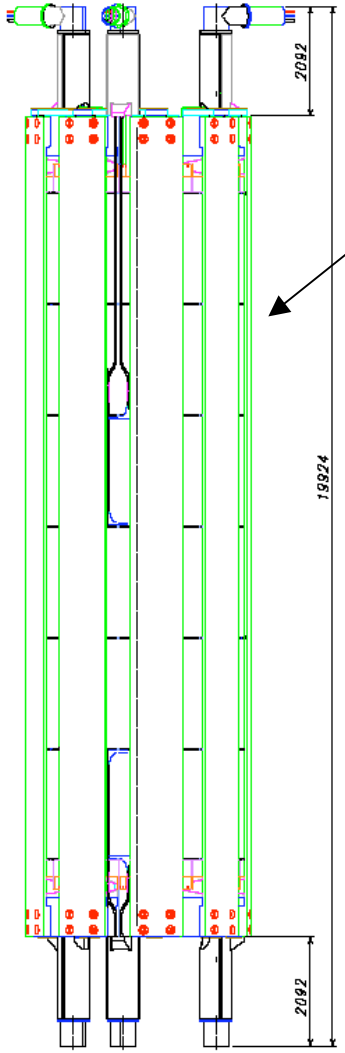


- CS Assembly includes:
  - 6 identical modules
  - Composite inter coil spacer Structures
  - Axial pre-compression system
  - Sets of axial upper and lower current and cryogen feeders
- CS main interface is the TF System:
  - CS mounts off the upper TF coil cases
  - TF sets the radial build constraint of CS

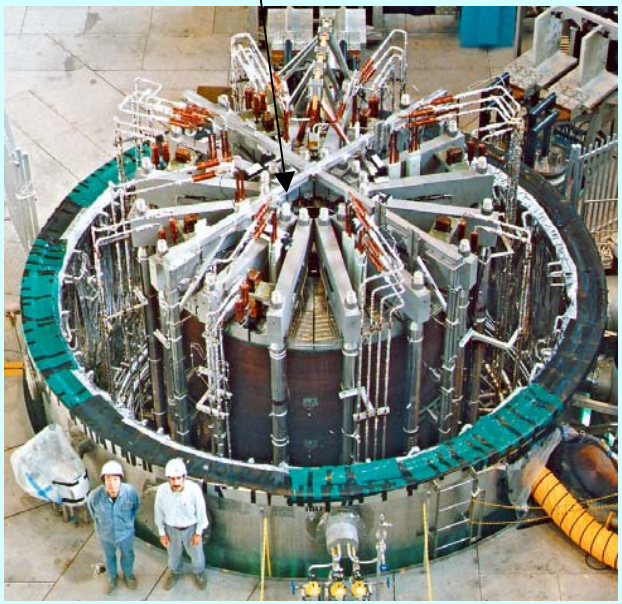
CS Coil is Composed of 6 Pancake Wound Modules



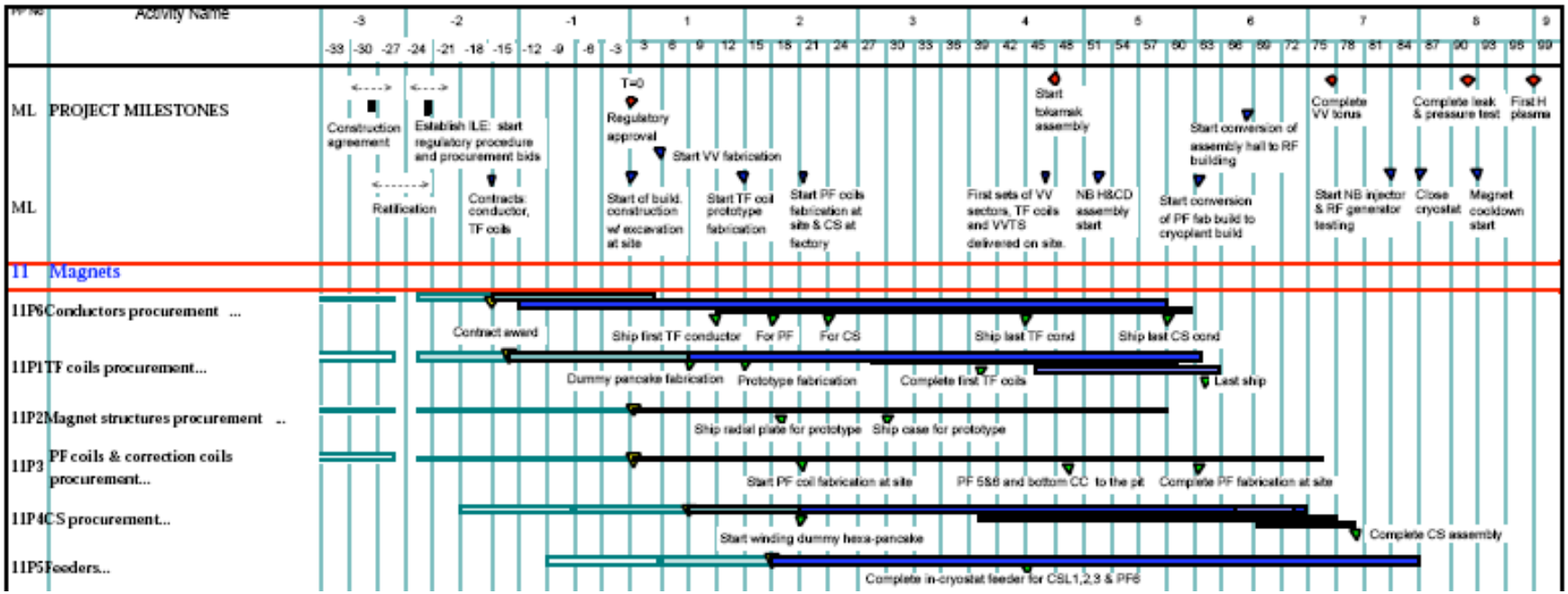




Each Module is slightly larger than the complete CS Model Coil



ITER Baseline Schedule For Magnets



Year -2: First Conductor Contracts Awarded

Year 0: CS Procurement Effort Must Start

Year +2: First CS Conductor Shipment

Year +4: CS Assembly Starts

Year +6: CS Manufacturing Complete; Assembly Complete

Year +7: CS Assembly Complete

Year +8: Magnet System Energized

ITER CS Milestones

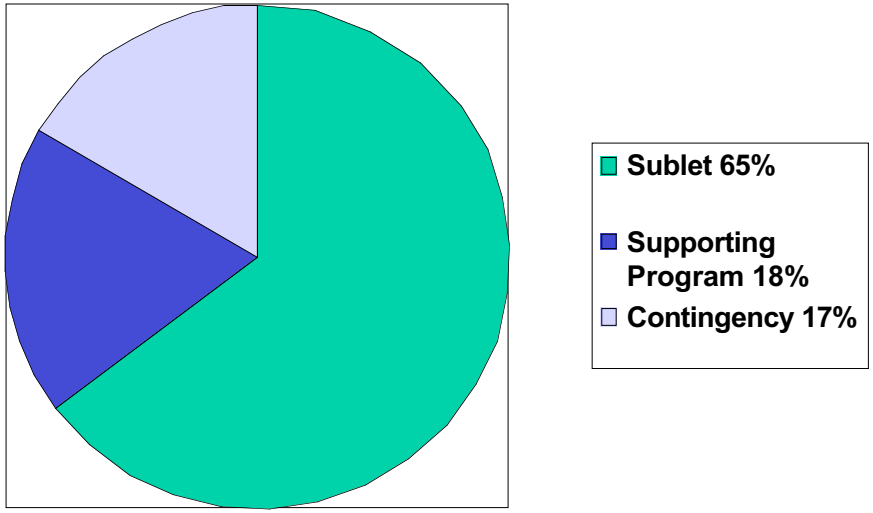
June 2006 Start

		ITER MILESTONE	US CS FABRICATION MILESTONE (aligned to ITER CS Assembly Complete mi	
6/1/2003	-3			FY04
9/1/2003				
12/1/2003				
3/1/2004				
6/1/2004	-2	PT CS Preproduction Start		FY05
9/1/2004				
12/1/2004				
3/1/2005				
6/1/2005	-1	PT CS Procurement Start	CS Vendor Contract Start	FY06
9/1/2005				
12/1/2005				
3/1/2006				
6/1/2006	1	T=0 ITER START	Fabricate Dummy Hexapancake Conductor	
9/1/2006			Module 1 Conductor Start	
12/1/2006		CS Vendor Start		FY07
3/1/2007			CS Fabrication Line Complete	
6/1/2007	2			
9/1/2007			Module 1 Fabrication Start	
12/1/2007		Dummy Hexapancake Start		FY08
3/1/2008		CS Conductor Procurement Start		
6/1/2008	3		Conductor Fabrication Complete	
9/1/2008			Start Module 2	
12/1/2008				FY09
3/1/2009			Module 1 Complete	
6/1/2009	4	CS Module Shipment Starts		
9/1/2009			Module 1 Cold Test	
12/1/2009				FY10
3/1/2010				
6/1/2010	5			
9/1/2010				
12/1/2010				FY11
3/1/2011				
6/1/2011	6	CS Module Fabrication Complete		
9/1/2011			CS Assembly Start	
12/1/2011		CS Cold Testing Start	Module 7 Complete	FY12
3/1/2012				
6/1/2012	7	CS Cold testing Complete	Module 7 Cold Test Complete	
9/1/2012		CS Shipment Complete		
12/1/2012		CS Assembly Complete	CS Assembly Complete	FY13
3/1/2013		CS Installation in Cryostat		
6/1/2013	8			
9/1/2013		Integrated Core Commissioning Start		
12/1/2013				FY14
3/1/2014				
6/1/2014	9			
9/1/2014		Magnet Testing Complete		
12/1/2014				FY15
3/1/2015				
6/1/2015				

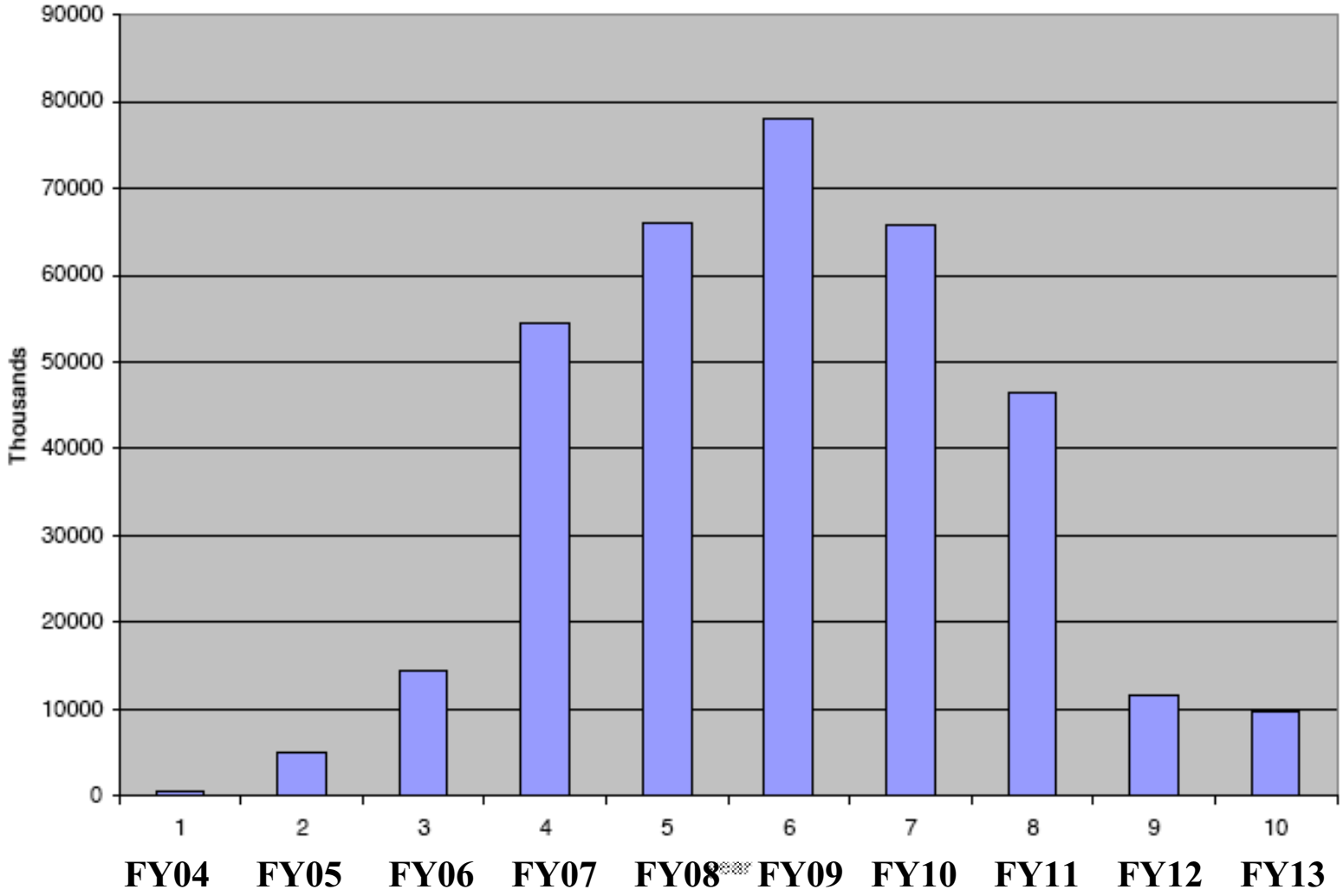
4 Module vs. 7 Module Supply Cost

	Conductor ($M)	Fabrication ($M)	Total ($M)	Cost Per Module
4 Module Supply	163.1	78.4	241.5	~60M
7 Module Supply	260.3	91.8	352.1	~50M

- **4 Module Breakdown**
- **7 Module distribution is similar**



Budget Profile for 7 Module Supply
ITER CS



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Present ITER Task Agreements
(Magnets)

1. N 11 TD 110 FU: Qualification of industrial suppliers of Nb3Sn strands with increased value of Jc. (ITA 11-18-UA)

2. N 11 TD 111 FU: Stress Analysis of the Helium Inlet Regions (ITA 11-20)

3. N 11 TD 112 FU: Conductor Performance and Design Criteria (ITA 11-22)

4. N 11 TD 113 FU: CS Jacket Weld Defect Assessment (ITA 11-23)

5. VHTP– begins March 04
   N. Martovetsky/LLNL and P. Michael/MIT part time assignment in Naka

6. Members of Committees for:
   - CS Procurement Specification
   - TF Structure Specification
   - PF Coils Specification
   - PF Insert Coil Test Committee

VLT Budget

	FY05 VLT CBR Base ($K)
MIT	1,804
LLNL	318
UW	106
NIST	20
Total	2,248

ITER Technical Issues with Fundamental Base Program Relevance

1. Jacket Fatigue Crack Growth - Modified Stainless Steels
2. Failure to detect a quench
3. Insulation in tension and shear
4. Butt joint performance
5. Cable transverse strain and conductor performance

- These are all *Performance Risk Issues* so early tasks are focused on mitigation.
- Although work will be done to address specific ITER-relevant design issues, the knowledge basis and experience will directly relate to the base program work and capabilities.
- ITER offers the advantage of making large quantities of components and resources available to address technical issues on a scale which could not be done under the modest base program budgets.

Proposed FY05 Tasks Details
(VLT CBR Funding)

Task	Description	Milestones	Institution/($K)				Total ($K)
			MIT	UW	NIST	LLNL	
1	Strand development						
	Procurement-oversight	continuous	160				160
	Strand acceptance measurements/QA	continuous	160	28			188
	Fundamental characterization			28	20		48
2	CS Jacket Material						0
	Fundamental metallurgical characterization		80				80
	Properties database development (tensile, fracture, fatigue)	Decision on jacket alloy 3/05	160				160
3	CS winding specifications and procurement package development	Package complete 9/05	96				96
4	CS conductor specifications and procurement package development	Package complete 9/05	160				160
5	CS performance analysis including pulse scenario, AC losses, heat removal and thermal-hydraulic, and longitudinal/ transverse stress.	Analyses competed 6/05	160				160
6	CS design criteria	Report 6/05	80			85	165
7	CS structural analysis	Report 6/05	160				160
8	Full-size butt-joint development	Prototype joint developed 9/05				148	148
9	Full-size US CICC samples testing in SULTAN and data analysis	Sample Fab Completed 9/05Ship to SULTAN 10/05	64			85	149
10	Preparation of PTF for reactivation	Facility ready 9/05	160				160
11	Supporting small scale lab experiments and measurements - transverse bending and compression		160				160
12	Graduate Student Research (strands, cables, jacket properties)		204	50			254
	Total (Staff)		1600	56	20	318	1994
	Total Budget ($K)		1804	106	20	318	2248

	$K	%
Base	702	31%
ITER Specific	1,238	55%
For ITER w/ base understanding	309	14%
Total	2,249	100%

Color Code:

- **Blue indicates fundamental base research**
- **Red indicates primarily ITER specific work**
- **Green indicates done for ITER but with contributions to fundamental understanding**

Proposed FY05 Tasks Details

(ITER Funding)

	VLT Base
MIT	1,804
LLNL	318
UW	106
NIST	20
Total	2,248

	ITER Personnel, Travel and M&S	ITER Industry	Contingency	Comments	Institution
Strand Vendor		800		~0.8-1.0 tons strand total from 3 vendors	
Strand Follow/QA/Characterize	150			Includes UW and NIST testing effort additional to VLT	NIST, UW, MIT
Jacket Extrusion	100	150		1 ton JK2LB + 1 ton I908	MIT
Material Database	300			Includes 1 FTE and costs for sample preparation (Base Metal & Weld), heat treatment, test costs and test equipment	MIT
Welding Development	50	100		Industry Subcontract for orbital welding devleopment, process control and QA	MIT
Manufacturing Feasibility	200	200		Detailed manufacturing process, QC and tooling assessment wrt ITER CS spec.s and requirements	MIT, LLNL
Full-Size CICC/SULTAN	95	155		Includes sample fabrication and cost of initial cabling development. Uses strand/jacket from industrial development	MIT, LLNL Testing personnel costs/travel covered under VLT budget
VHTP Personnel	200			0.5 Michael (MIT) + 0.5 FTE Martovetsky (LLNL). Remainder of their salaries covered under VLT Base	MIT, LLNL
VHTP Travel	100			2 People/1 FTE fulltime in Naka	MIT, LLNL
Design/ Analysis	500			2 FTE	MIT
ITER Sub Total	1,695	1,405		**3,100**	
Total (VLT + ITER)	3,943	1,405			
Grand Total	**5,348**				

Notes:
- **No Escalation**
- **No overheads on industry contracts**

FTEs
- **VLT ~6**
- **ITER~5**
- **Total:11**

Proposed FY05 Tasks Details
(VLT CBR Funding + 10%)

Additional Task:

- **NIST upgrade capability to test I_c (B,T,ε) simultaneously in a single apparatus**
  - **Would be the only facility in the US**
  - **Would enhance fundamental strand characterization**
  - **Cost $190K/year for 3 years**

- **Add funding for graduate student ~ $45 K**

Proposed FY06 Tasks Details

(VLT CBR Funding)

Task	Description	Milestones	Institution/($K)				Total ($K)
			MIT	UW	NIST	LLNL	
1	Superconductor development						
	Fundamental Nb3Sn Strain (Simultaneous Jc(B,T,e)		32		20		52
	Advanced HTS for fusion applications (e.g. MgB2)	Prototype short length 9/06	64	56			120
2	Jacket Material						
	Low Cycle Fatigue	Completed 3/06	128				128
	Reduced SAGBO Alloy Development	Sample heats 6/06	128				128
3	Advanced quench detection sensor development	Samples for dummy cable 12/05	128				128
4	Embedded quench sensor electromagnetic analysis	Report 3/06	128				128
5	Coupled structural-thermal analysis of winding pack component properties and tolerance variations	Report 6/06	160				160
6	Winding pack tension and shear detailed stress analysis	Report 6/06	80				80
7	Transient electrodynamic analysis voltage/peak field for normal and off-normal events	Report 6/06	80				80
8	Full-size butt-joint development	Prototype Joint Sample 6/06				148	148
9	Full-size US CICC samples testing in SULTAN and data analysis	Sample Fab Completed 9/05Ship to SULTAN 10/05	32			85	117
10	Full-size US CICC samples testing in PTF and data analysis	Facility ready 9/05	320			85	405
11	Supporting small scale lab experiments and measurements - transverse bending and compression standard test rig		320				320
12	Graduate Student Research (strands, cables, jacket properties)		204	50			254
	Total (Staff)		1,600	56	20	318	2,248
	Total Budget ($K)		1,804	106	20	318	2,248

	$K	%
Base	1,002	45%
ITER Specific	468	21%
For ITER w/ base understanding	778	35%
Total	2,248	100%

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Proposed FY06 Tasks Details

(ITER Funding)

	VLT Base
MIT	1,804
LLNL	318
UW	106
NIST	20
Total	2,248

	ITER Personnel, Travel and M&S	ITER Industry	Contingency	Comments	Institution
Strand Vendor		5,440	1,088	~8 tons strand total from 3 vendors	
Strand Follow/QA/Characterize	220	100		Additonal NIST and Industrial Testing	NIST, UW, MIT
Cable Development	120	1,200	271	Cu conductor- Hexapancake Cable length; 10m SC Cable	MIT
Jacket Extrusion	120	650	158	Production lot: 900 m - hexapancake length + 100m	MIT
CICC Bending and Forming Characterization	150	150			MIT
Welding Process Development + QA	50	100		Orbital welding and inspection	MIT
HT Process & QA Devel	150	150		2 section welded jacket full HT with extracted strand testing and jacket mech eval	MIT
Insulation/VPI Process and QA	80	120			MIT
Full-Size CICC and Butt-Joint Samples Tested in PTF and SULTAN	100	200		Includes sample fabrication and cost of initial cabling development. Uses strand/jacket from industrial development	MIT, LLNL Testing personnel costs/travel covered under VLT budget
VHTP Personnel	200			2 FTE- complete final CS PT specs, & plan with ITER	MIT, LLNL
VHTP Travel	100			2 People/1 FTE fulltime in Naka	MIT, LLNL
Design/ Analysis	500			2 FTE- support all process and testing	MIT, LLNL
CS Conductor Integration Line Design and Tooling Procurement	250	4,441	962		MIT
Sub-Contract travel	100				
ITER Sub Total	2,140	12,551	2,478		
Total ITER				**17,169**	
Total (Base + ITER)	4,388	12,551	2,478		
Grand Total				**19,417**	

Notes:
- **No Escalation**
- **No overheads on industry contracts**

FTEs
- **VLT ~6**
- **ITER~8**
- **Total:14**

The University of Wisconsin-Madison
Applied Superconductivity Center

Proposed FY06 Tasks Details

(VLT CBR Funding)

Task	Description	Milestones	Institution/($K)				Total ($K)
			MIT	UW	NIST	LLNL	
1	Superconductor development						
	Fundamental Nb3Sn Strain (Simultaneous Jc(B,T,e)		32		20		52
	Advanced HTS for fusion applications (e.g. MgB2)	Prototype short length 9/06	64	56			120
2	Jacket Material						
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9	Full-size US CICC samples testing in SULTAN and data analysis	Sample Fab Completed 9/05Ship to SULTAN 10/05	32			85	117
10	Full-size US CICC samples testing in PTF and data analysis	Facility ready 9/05	320			85	405
11	Supporting small scale lab experiments and measurements - transverse bending and compression standard test rig		320				320
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	Total (Staff)		1,600	56	20	318	2,248
	Total Budget ($K)		1,804	106	20	318	2,248

	$K	%
Base	1,002	50%
ITER Specific	228	11%
For ITER w/ base understanding	778	39%
Total	2,008	100%

- Eliminate Tasks 5 and 6
- This is equivalent to ~ 1 FTE
- Shift tasks to ITER budget and slightly reduce one of the major procurements

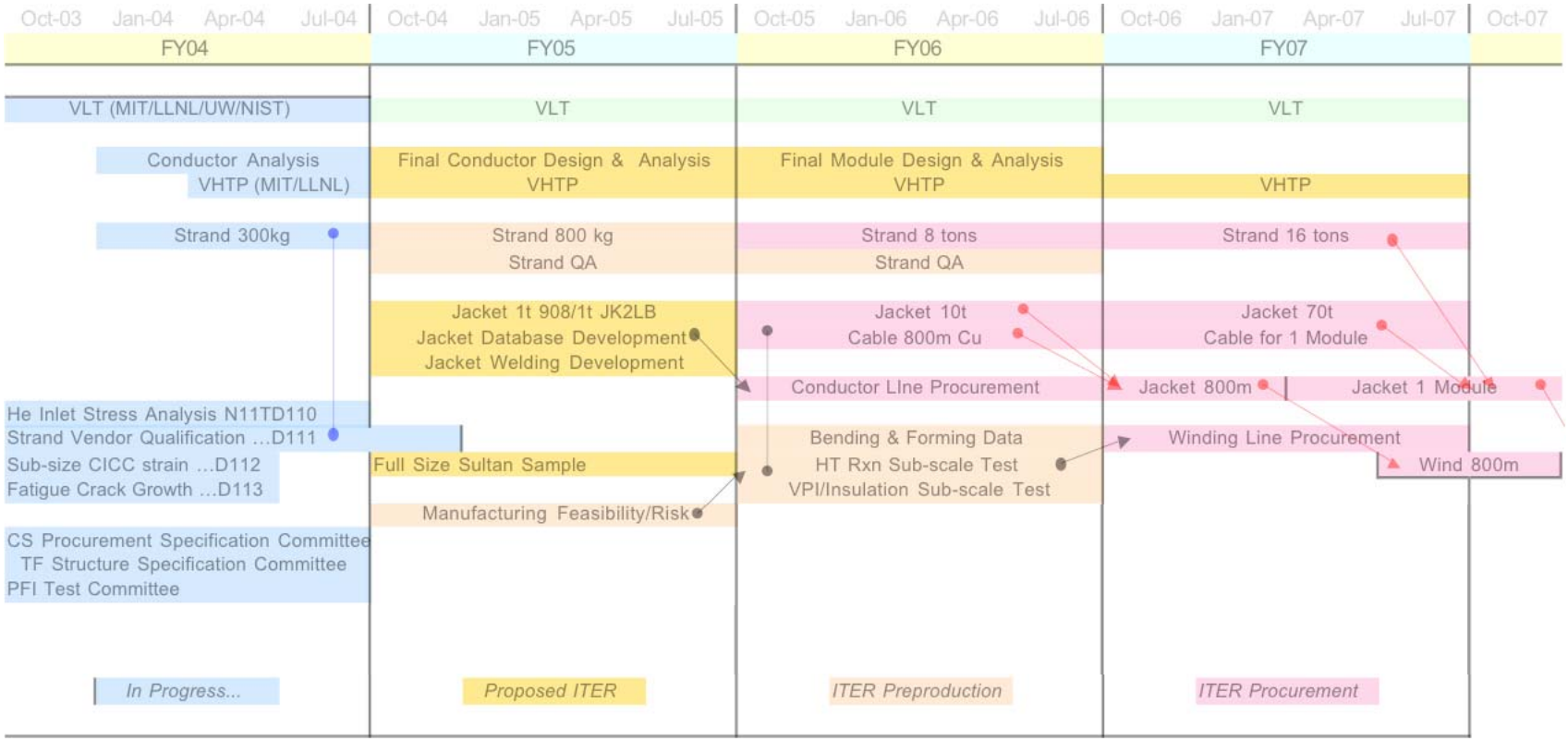
Proposed FY06 Tasks Details
(VLT CBR Funding + 10%)

Additional Task:

- **Increase funding for development of MgB_2 high temperature superconductor ($120K)**

- **Add funding for advanced sensor development (e.g. fiberoptic quench/temperature sensor ($120K)**

Coil Winding Ramp-up



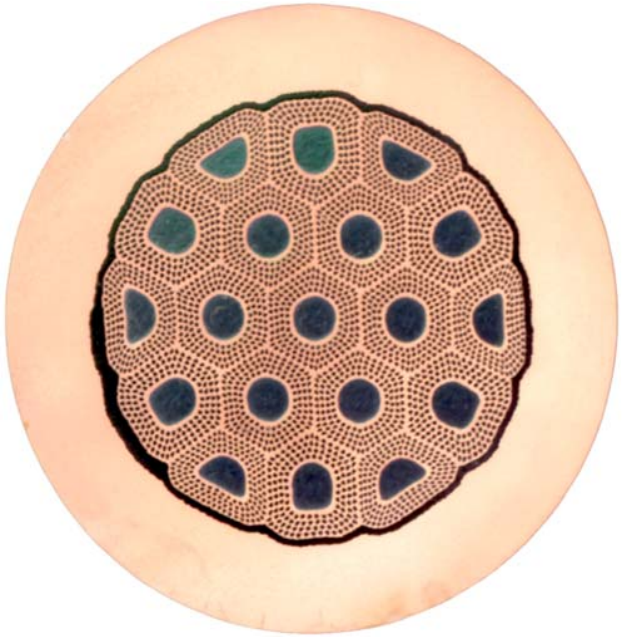
ITER June 2006 Start

CS Near Term Production Requirements

FY06	CS Conductor Line Fabrication CS Module and Winding Tooling Final Design CS Hexa-pancake Dummy Cable and Jacket Sections Fabrication
FY07	CS Hexa-pancake Dummy Conductor Fabrication CS Winding Machine Fabrication CS Module 1 Conductor Fabrication
FY08	CS Hexa-pancake Dummy Winding Module-1 Winding CS Module Assembly Tooling Fabrication

Strand Production Ramp-up

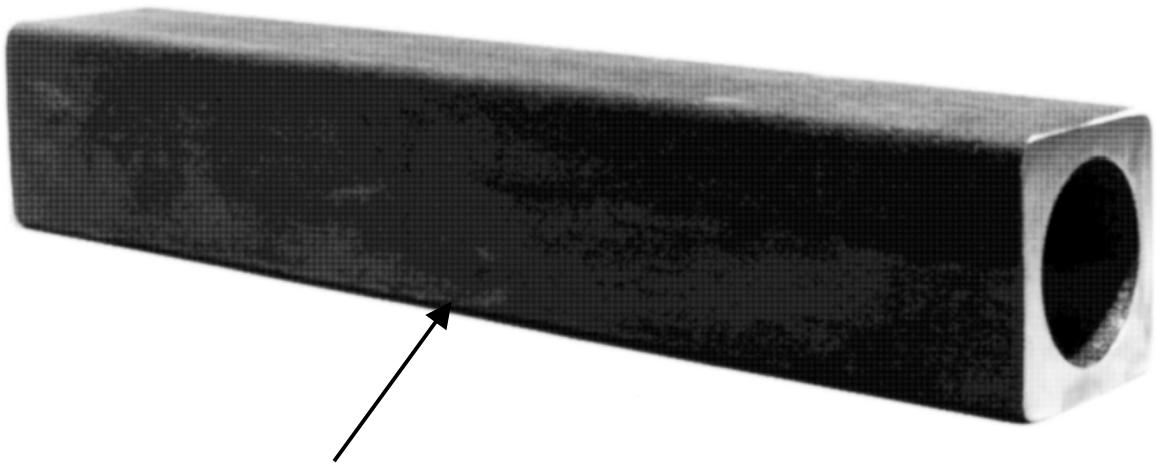
FY04	**300 kg**
FY05	**800 – 1000 kg**
FY06	**8 tons**
FY07	**16 tons (16 + 8 = 24 tons, enough for 1st module)**



Jacket Production Ramp-up

FY04	JK2LB test sample analysis
FY05	1 ton each Incoloy 908 & JK2LB
FY06	10 tons - 800 m for dummy winding + 100 m for bending, forming, pre-production tasks
FY07	70 tons (5600 m), enough for 1 module

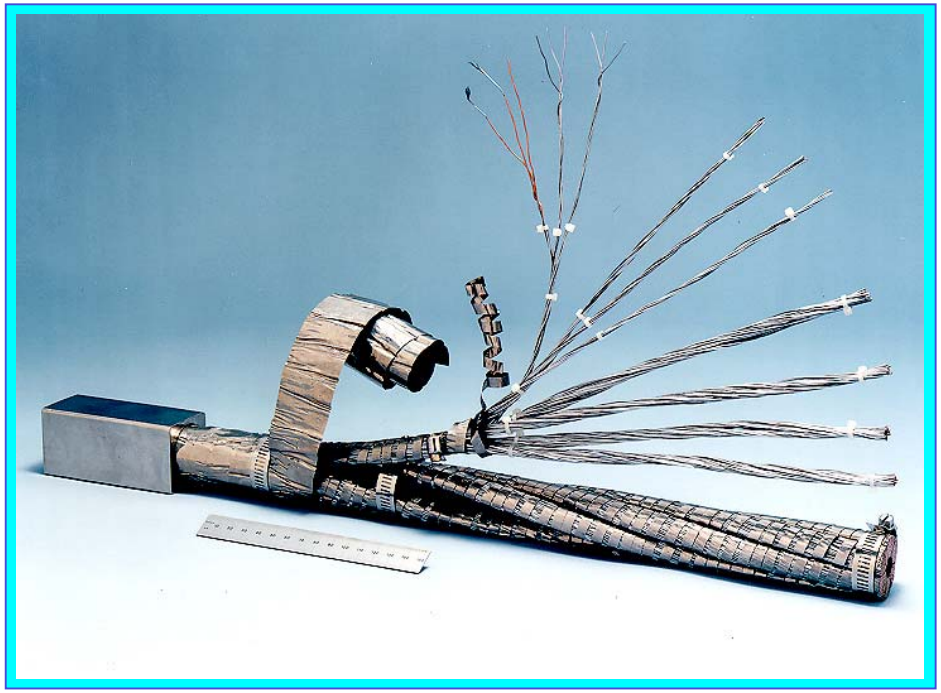
Trepanned extrusion billets

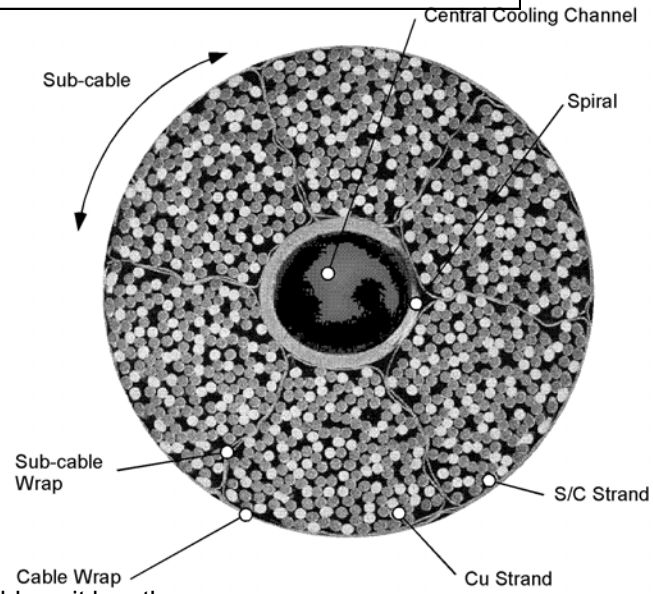


Extruded jacket section ~50mm x 50mm x5000 mm

Cable Production Ramp-up

FY04	**Cable parameter design**
FY05	**30 m cable for SULTAN/PTF Sample**
FY06	**Dummy Hexa-pancake cable, 880 m, copper strand**
FY07	**1 module, 5600 m, superconducting strand**





CS Cable unit lengths:

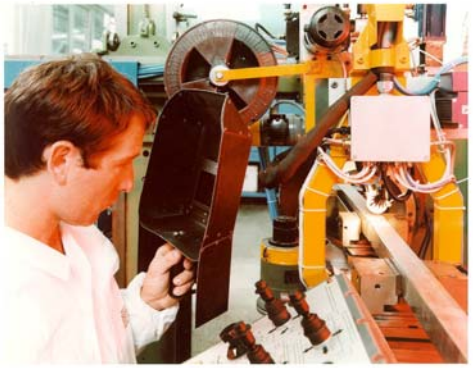
Copper Cable	881m + 2 * 1.2m	= 883.4 m
SC Cable Hexa Pancake	881m + 2 * 1.2m (specimen)	= 883.4 m
SC Cable Quad Pancake	579m + 2 * 1.2m (specimen)	= 581.4 m

Conductor Line

First Production Hardware Needed FY06

Selected images from the CSMC inner module conductor jacketing operation at Ansaldo (1997)

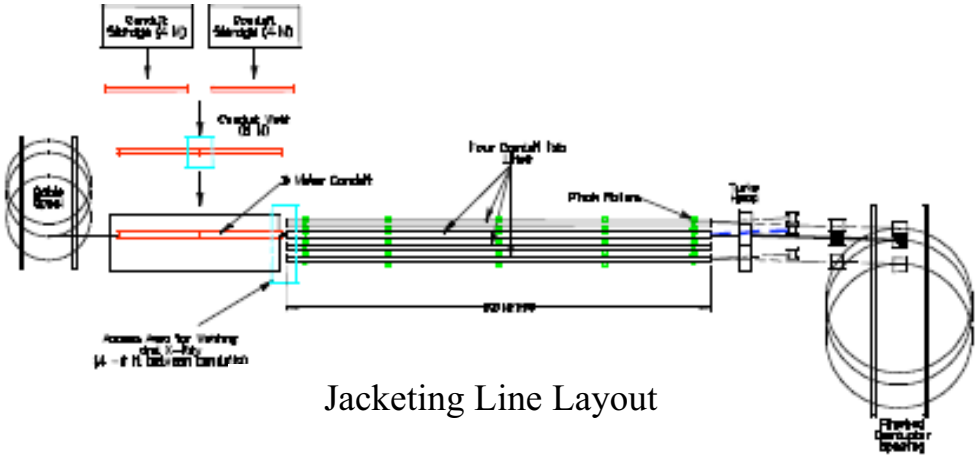
CS module Unit length is 800m- 4x CSMC length



Orbital welding is a critical operation

Butt weld x-ray inspection

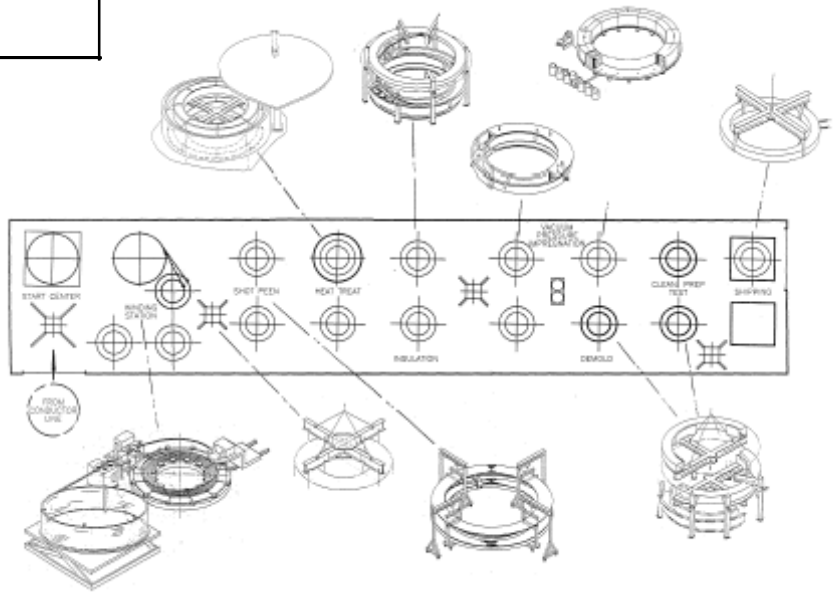
Reduction to final shape



Jacketing Line Layout

Coil Winding Ramp-up

FY04	Cable parameter design
FY05	Full-size SULTAN/PTF Sample Test and Characterization
FY06	Conduit Bending Characterization
FY07	Hexa-pancake Dummy Winding
FY08	Start Module-1 Fabrication



Issues/Concerns

- Risk mitigation occurs in the early years
- 2/3 of the CS Supply will be Industrial Contracts
  - Aim- eliminate need for significant Vendor Cost Plus Fixed/Incentive Fee Production Contracting
  - How? Perform needed development work ahead of procurements in a phased manner:
    - Critical Design Confirmative Analyses (structural, thermal hydraulic, fatigue)
    - Materials Characterization & Performance (e.g. jacket, strand)
    - Process/Tooling Development (HT, bending, welding)
    - Critical Component Testing
- Requires early confirmation or change of evolving ITER CS design

Summary

- Work scope for US contribution-in-kind of ITER CS is defined
- Good cost basis has been estimated
- VLT magnet program personnel have been integrating into ITER tasks
- In FY05 much of the VLT base program has ITER focus
  - required to mitigate cost/performance/schedule risks
- In FY06 ramp-up of ITER construction funding allows reestablishment of fundamental focus of VLT base tasks.