VLT
Virtual Laboratory for Technology
For Fusion Energy Science

The ITER CS Magnet System

Timothy A. Antaya
MIT Plasma Science and Fusion Center

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

16th ANS Topical Meeting on the Technology of Fusion Energy

Madison, Wisconsin
September 15, 2004

The University of Wisconsin-Madison
Applied Superconductivity Center

Contents

- What is ITER?
- US participation in ITER: the packages...
- Why do the CS?
- CS Magnet Supply Scope
- CS Magnet Engineering Baseline 2004
- Preproduction Risk Mitigation and Engineering Issues
- US CS Industrial Supply Plan
- Present Status

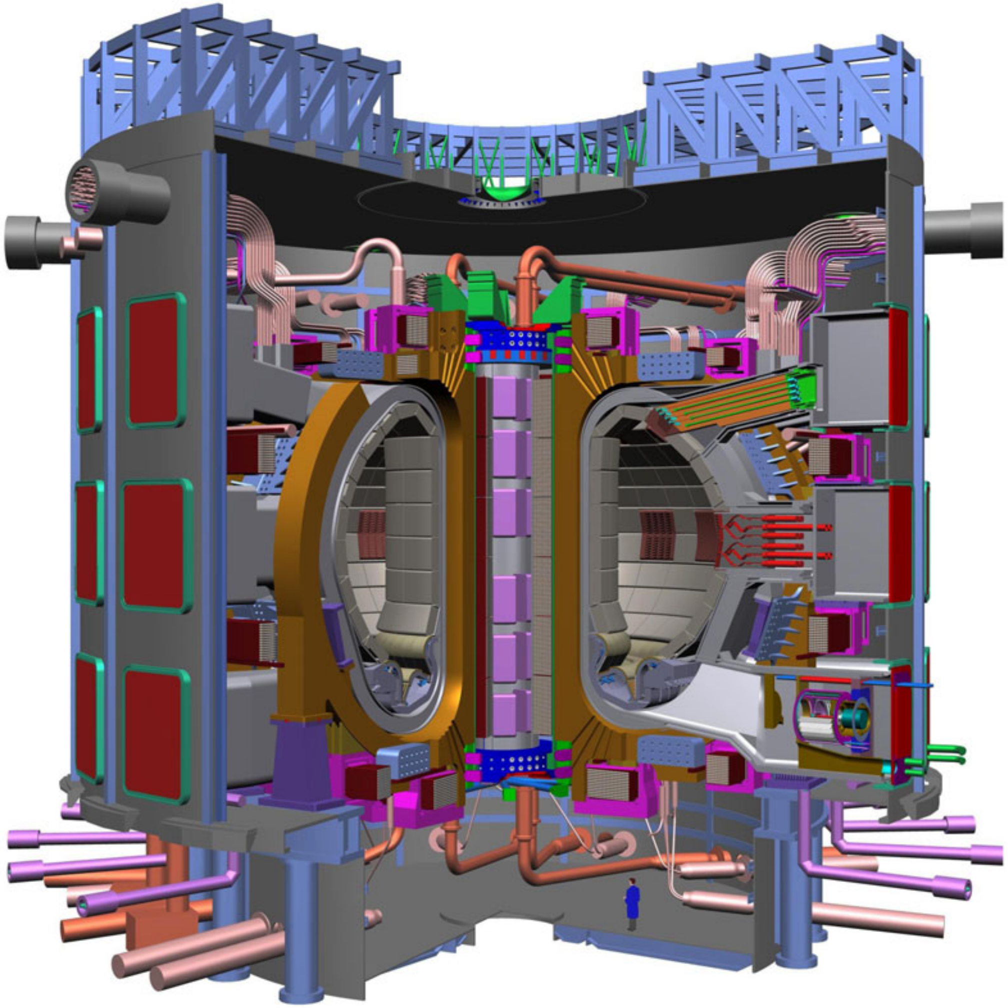
Present effort under auspices of VLT

- Minervini (P.I.)/Antaya (co-P.I.) at MIT direct the DOE VLT Magnet Technology for Magnetic Fusion Program
- 2003- We were asked by Sauthoff and Baker to:
  - assess alternative scenarios for ITER CS Magnet Supply
  - support of the US - ITER negotiations as needed
- 2004- our support now includes:
  - ITER task agreements to assist in closing out the CS design
  - Risk assessment and mitigation
  - Visiting engineers assigned to ITER in NAKA
- Present effort includes support from many individuals and organizations; Key individual contributors include Nicolai Martovetsky (LLNL), Jun Feng, Phillip Michael and Joel Schultz (MIT)

Get the real story tomorrow:

- Plenary III – The ITER Project, Wednesday, September 15
  - ITER Status- P.Barabaschi, ITER International Team
  - US ITER Project Activities- N. Sauthoff, US ITER Project Manager
  - Relation of US VLT Program to ITER- C.Baker, Director, VLT

What is ITER?

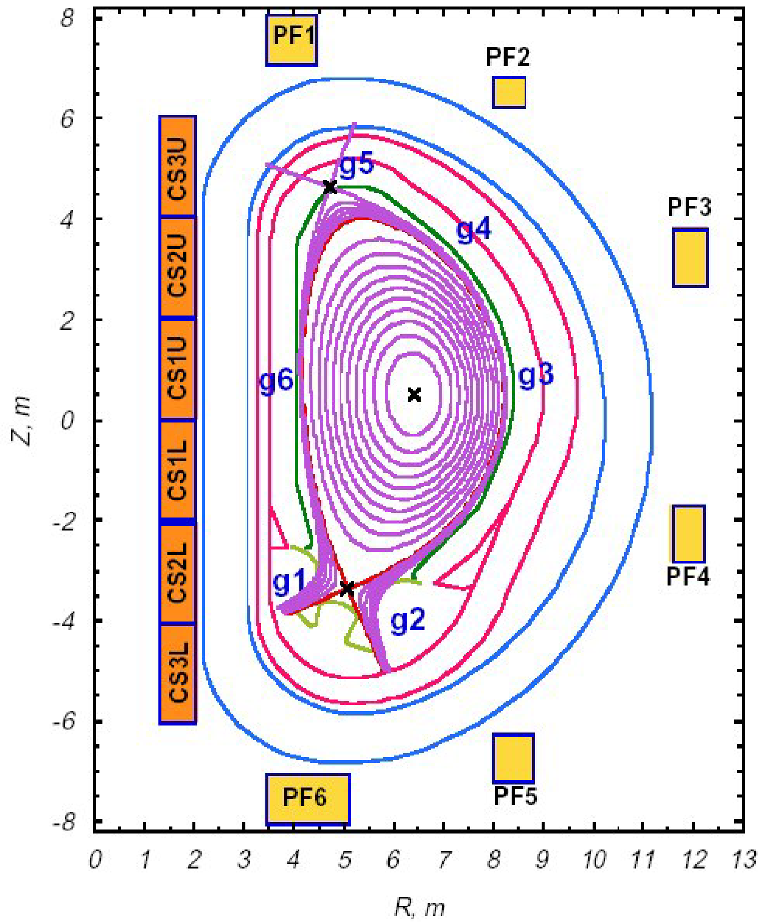


ITER is a single poloidal null diverted tokamak

Burning Plasma Mission (FDR 2001 baseline):

- Plasma
  - Q>10 extended inductive burn of 300-500s
  - Q>5 steady state with non-inductive current drive
- Engineering
  - demonstration and integration of required fusion technologies
  - test future reactor components
  - test tritium breeding for >0.5MW/m^2 neutron wall load

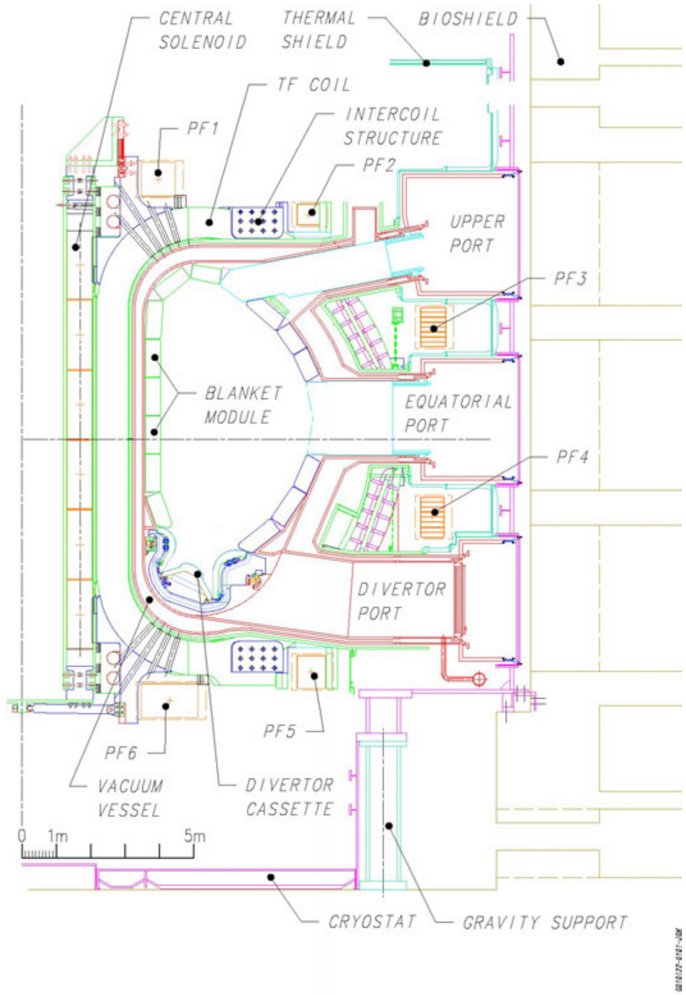
For a system costing 50% of the 1998 ITER EDA design



ITER Tokamak Core Systems

- Magnets and Vessel Dominate the Core Structures
- They also dominate the machine core capital costs: 52% and 15% respectively
- Magnet Systems are also a significant overall capital cost (26%)
- With plant building they critical path systems

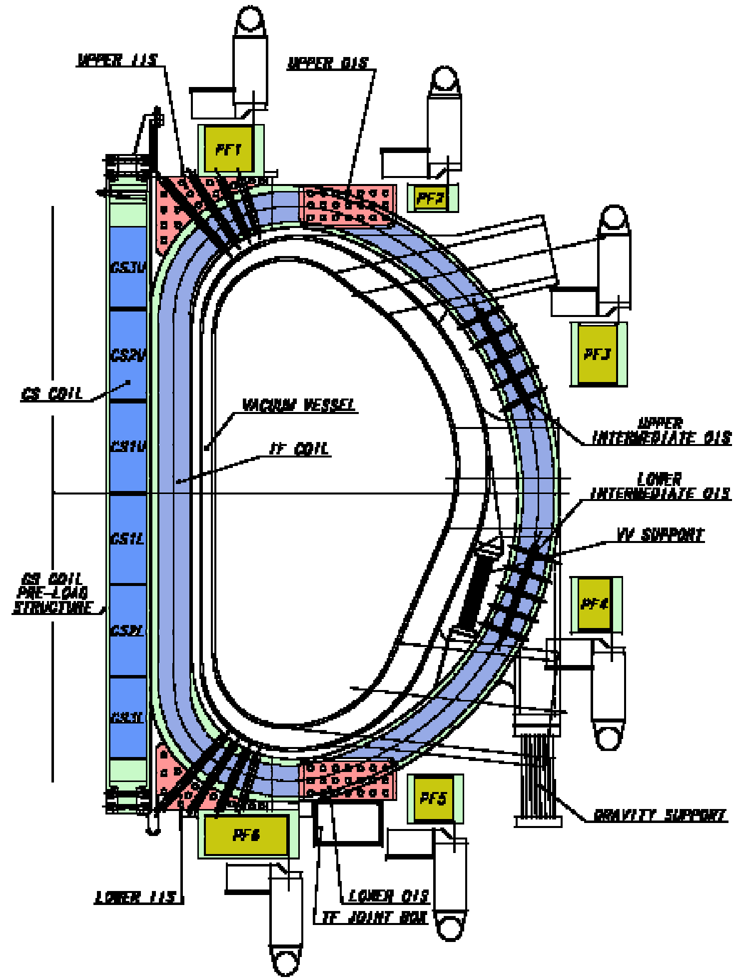
∴ ITER Participants will all have to contribute to the magnet system supply, and most magnet systems start early



ITER Magnet System Consists of 6 *Split Packages*

1. TF Coils
   a. Prototype + 9
   b. 9
2. Magnet Structures
   a. 10 TF cases
   b. 9 TF cases
   c. PF + CC + CS + Gravity supports
3. PF and Correction Coils
   a. P1 and P6
   b. P2-3-4-5
   c. CC
4. Central Solenoid
   a. Proto + 3 + installation
   b. 3
5. Feeders
   a. cryostat ...
   b. sensors ...
6. Conductor
   a. TF
   b. CS
   c. PF

- Significant portion of ITER direct cost is to be provide as such In-kind 'Package' contributions
- ITER and Participant Teams have established a value for each package



ITER Magnet System- Key Features

- High Fields, Long Inductive Burn and SS operation make the magnets superconducting in ITER
- TF System:
  - 18 cased coils: 14 m high x 9 m wide, 290 tonnes each
  - assembled TF serves as integrated structural load path for all magnets and vacuum vessel
- CS System:
  - 6 independently excited, hoop force self-supporting modules
  - axial loads both inward and outward require preload structure
  - 15m high x 4m diameter system weighs 840 tonnes
- TF and CS use brittle, wind & react Nb_3Sn conductor
  - TF: maximum possible field, inboard leg heating, forces
  - CS: high field, large flux swing, stability

ITER Magnet System- Key Features (cont'd)

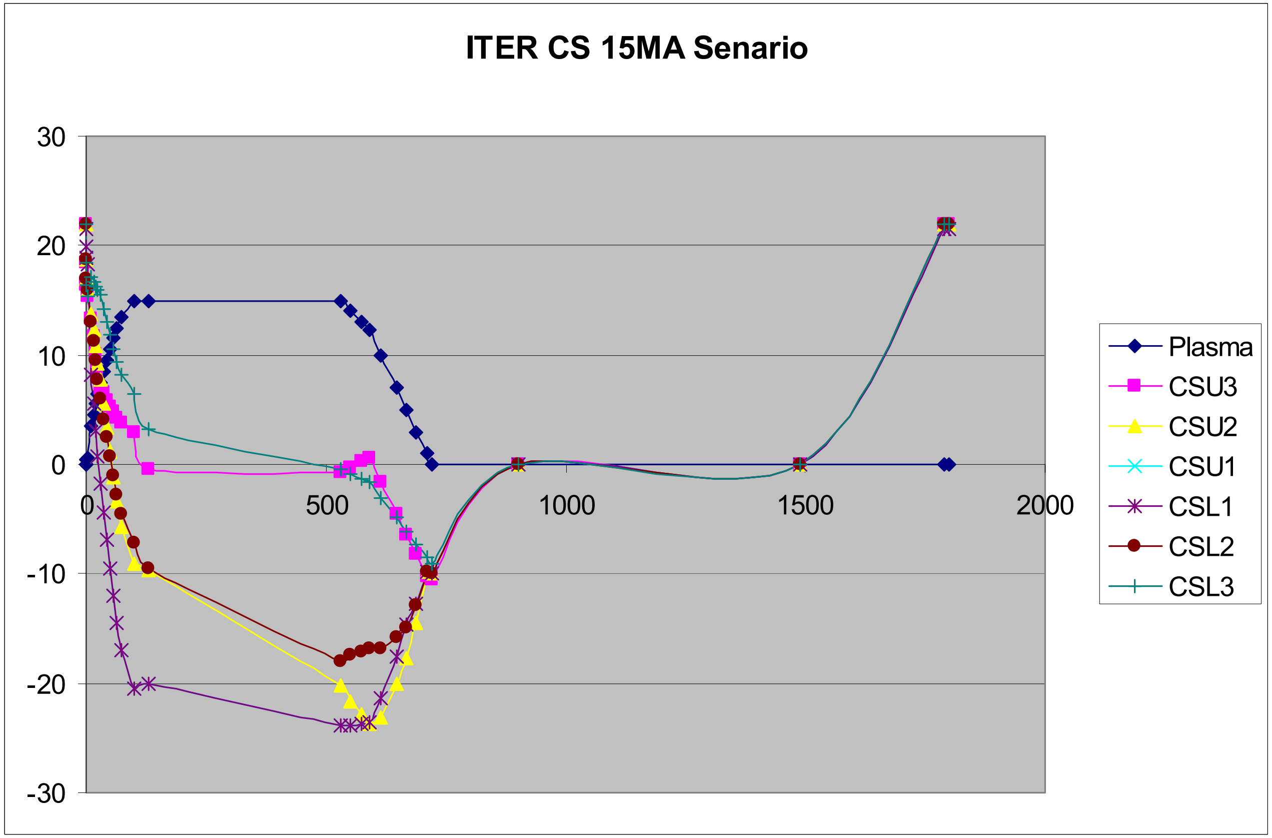
- Wind and react Nb3Sn conductors have special engineering challenges
  - all bending and forming must occur before heat treatment
  - conductor components and techniques (e.g. welding) must be compatible with long (~200 h) heat treatment cycles at ~650 C
  - heat treatment must occur before the addition of temperature sensitive components- insulation and sensors
- PF (6) and Correction Coils (18) use NbTi conductor
  - significantly lower peak fields and heating allow NbTi
  - wind and react process is avoided reducing cost
  - PF5 and PF6 are trapped and need to be replaceable in situ
  - PF3-4 are very large: 24 m diameter and ~600 tonnes each

US Proposed Magnet Contribution

- Package 4a (3 +1 CS Modules and final assembly) and 57% of Package 6b (CS Conductor)

- Why?
  - Combination of programmatic "Value" ratings- (#1) contributions enabling BP research, (#2) key fusion technologies with US industrial role, (#3) high tech non-fusion specific technologies
  - Prior Experience- US participated in successful CSMC Task during the EDA
  - In-kind value-
    - the US would be a ~10% partner in ITER
    - the CS leaves room for other important contributions
- Also: few external interfaces and tooling largely at the single module level

CS Enabling Role in Burning Plasma Research

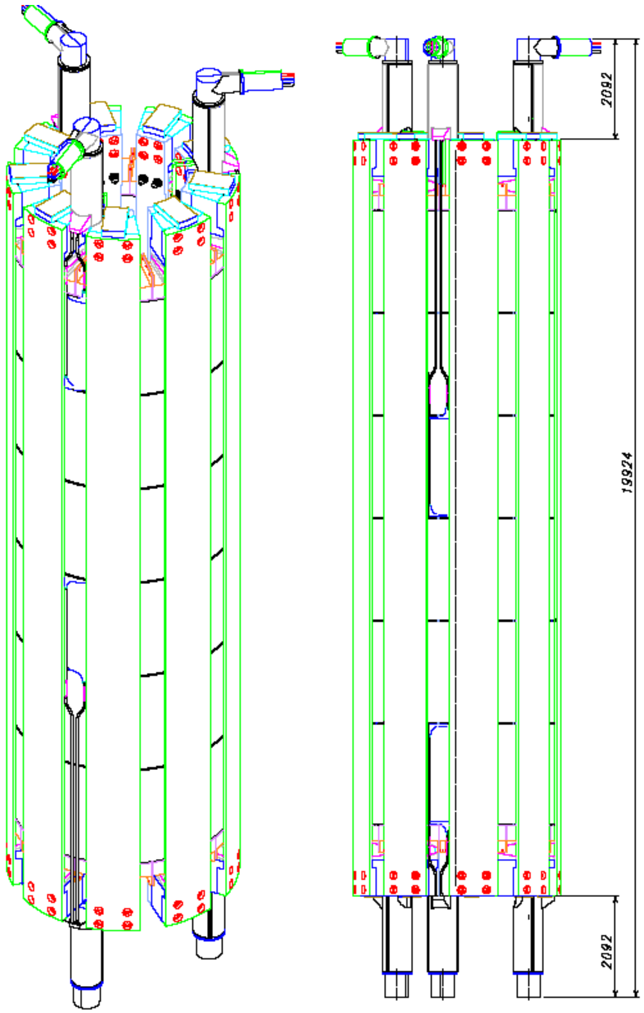


Proposed CS Supply- details

- Package 4a
  - final manufacturing design including tooling
  - CS fabrication facilities
  - fabrication of 1 spare and three production CS modules
  - coordination of US module fabrication with the Package 4b supplier (probably Japan; possibly also the US)
  - Factory assembly of the CS using ITER supplied sensors, joints and preload structure
  - Final assembly and acceptance testing at ITER site
- Package 6b
  - Supply of dummy conductor for process qualification
  - Supply of production conductor for 4 modules

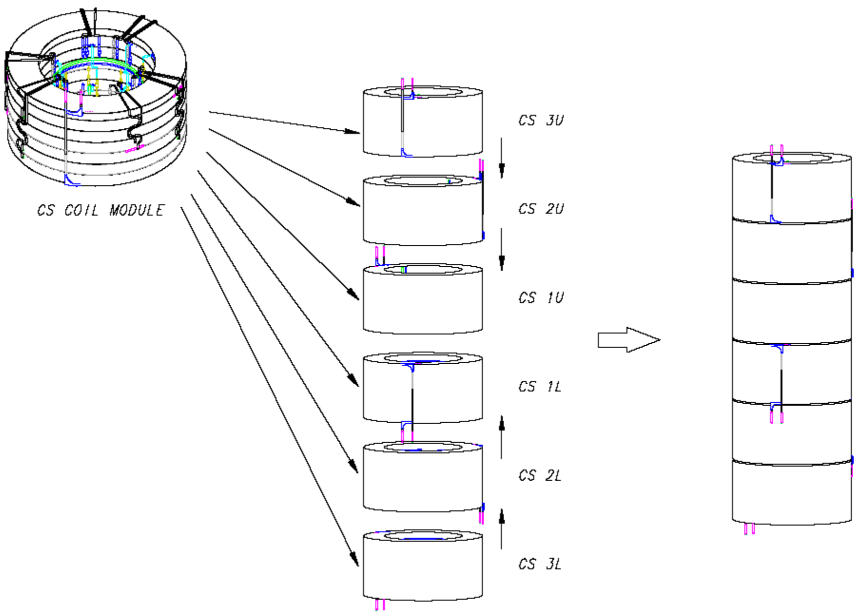
ITER CS 2004 Engineering Baseline

ITER CS Magnet System Assembly



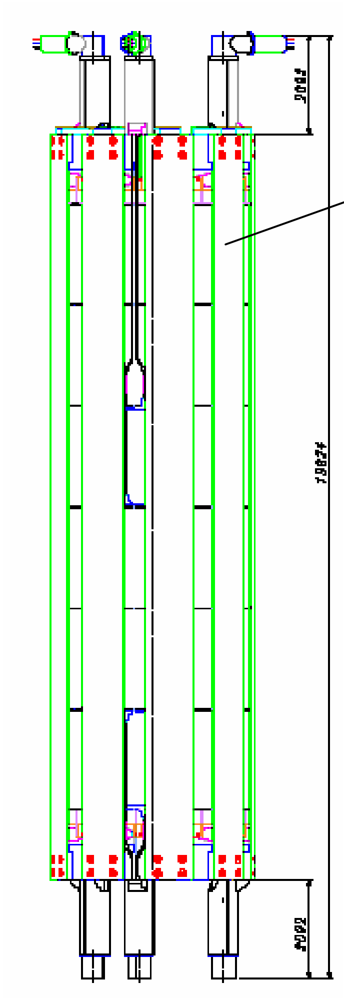
- CS Assembly includes:
  - 6 identical modules
  - Composite inter coil spacer Structures
  - Axial pre-compression system
  - Sets of axial upper and lower current and cryogen feeders
- CS main interface is the TF System:
  - CS mounts off the upper TF coil cases
  - TF in board sets the radial build constraint of CS but not the load path for electromagnetic forces

Package 4: Central Solenoid Module Supply

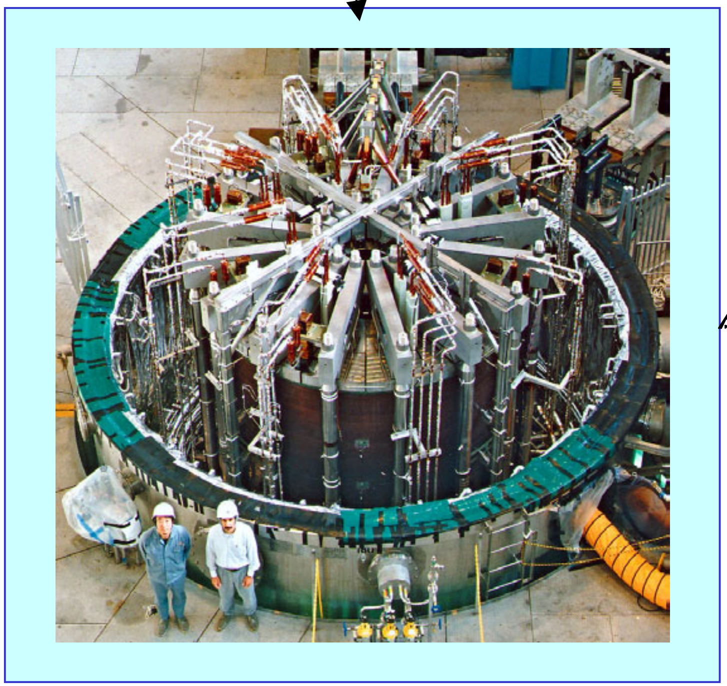


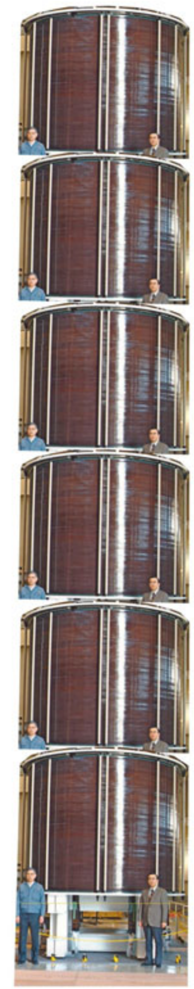
- Module, tooling and process manufacturing designs are in package scope
- Module Fabrication:
  - All 6 modules are identical
  - 60° module indexing at assembly
  - Each Module:
    - ~5900m of conductor
    - 1 quad [4 layer] and 6 hexa [6 layer] pancakes
  - In line butt joints between pancakes
  - He stubs and local coil leads included in scope

CS Magnet System Scale



Each Module is slightly larger than the complete CS Model Coil





ITER Central Solenoid Model Coil Test

Test Program Objectives:

- Perform model coil demonstration tests under ITER operating conditions
  - DC operation to 13T, 46 kA and 640 MJ (inner + outer)
  - Pulsed operation to simulate the ITER scenario for the CS
  - 0.6 T/s to 13T
- Characterization of the performance of the conductors and joints
  - AC losses, current sharing temperature, quench properties
- Characterization of the Mechanical, Thermal and hydraulic behaviors
  - no instabilities observed
- Limited lifetime testing with more than 10,000 cycles for the inserts
  - 1.2 T/s to 13T for the Nb3Sn insert
- Test of insert coils using all likely conductor types

All of these objectives were completed successfully

US Participation in the CSMC (1992-2002)

Inner Module
(US)

- Conductor- IGC, Teledyne Wah Chang
- Cabling- BIW
- Conduit Material- Inco Alloys
- Inner Module Fab- Lockheed Martin, MIT, LLNL
    - Winding
    - heat treatment (Wall Colmonoy)
    - insulation, impregnation, assembly, joints
    - Tooling, development programs, vendor supervision, inspection and testing, training
- SC Buses and Structures- Lockheed Martin
- Testing Program Support at NAKA- MIT, LLNL

(L-M core group now at General Atomics)

Package 6b: Central Solenoid Conductor

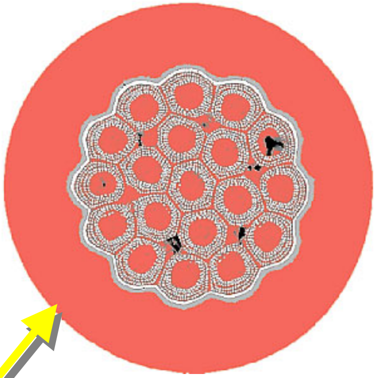
ITER selected JK2LB as Jacket Material

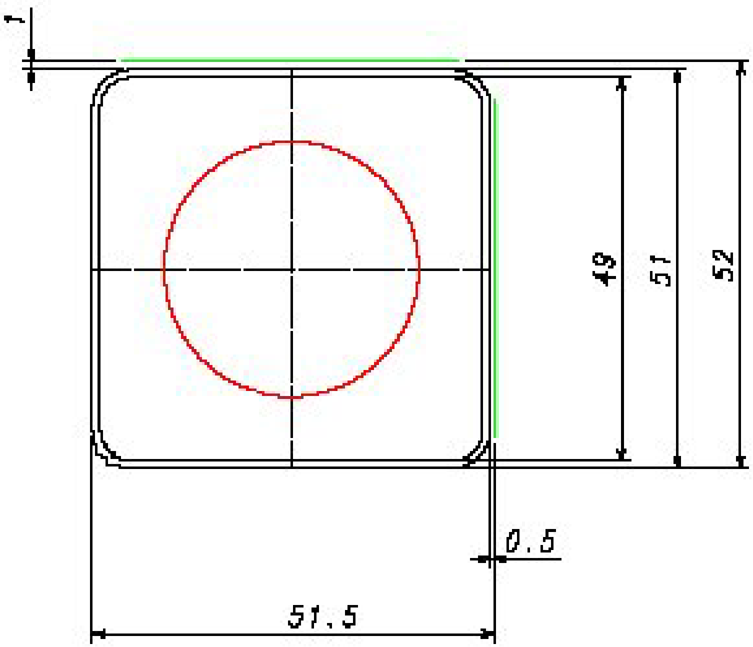
Procurement consists of:

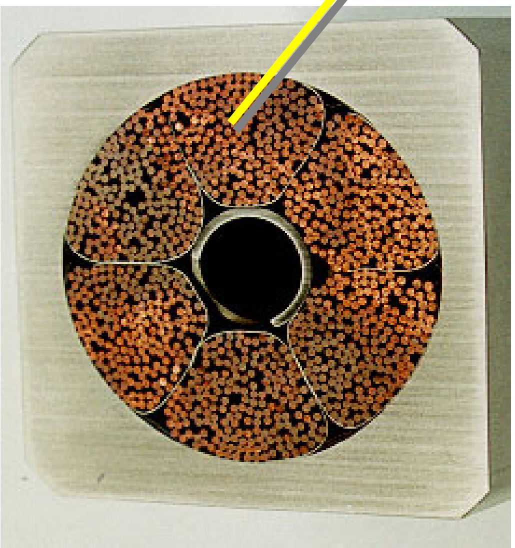
- Nb_3Sn superconducting strand
- Pure copper strands
- Multi-stage cable including wraps and central spiral
- Jacket
  - Extruded segments 4-8m long
  - Butt welded/inspected
  - Cable inserted and compacted

Strand

(0.81 mm diameter)







CICC

(50 mm x 50mm)

CSMC Test Results also drive Post-FDR Design Changes

Results for CSMC and TFMC suggest cyclic transverse forces on the cable have reduced the ultimate superconductor performance

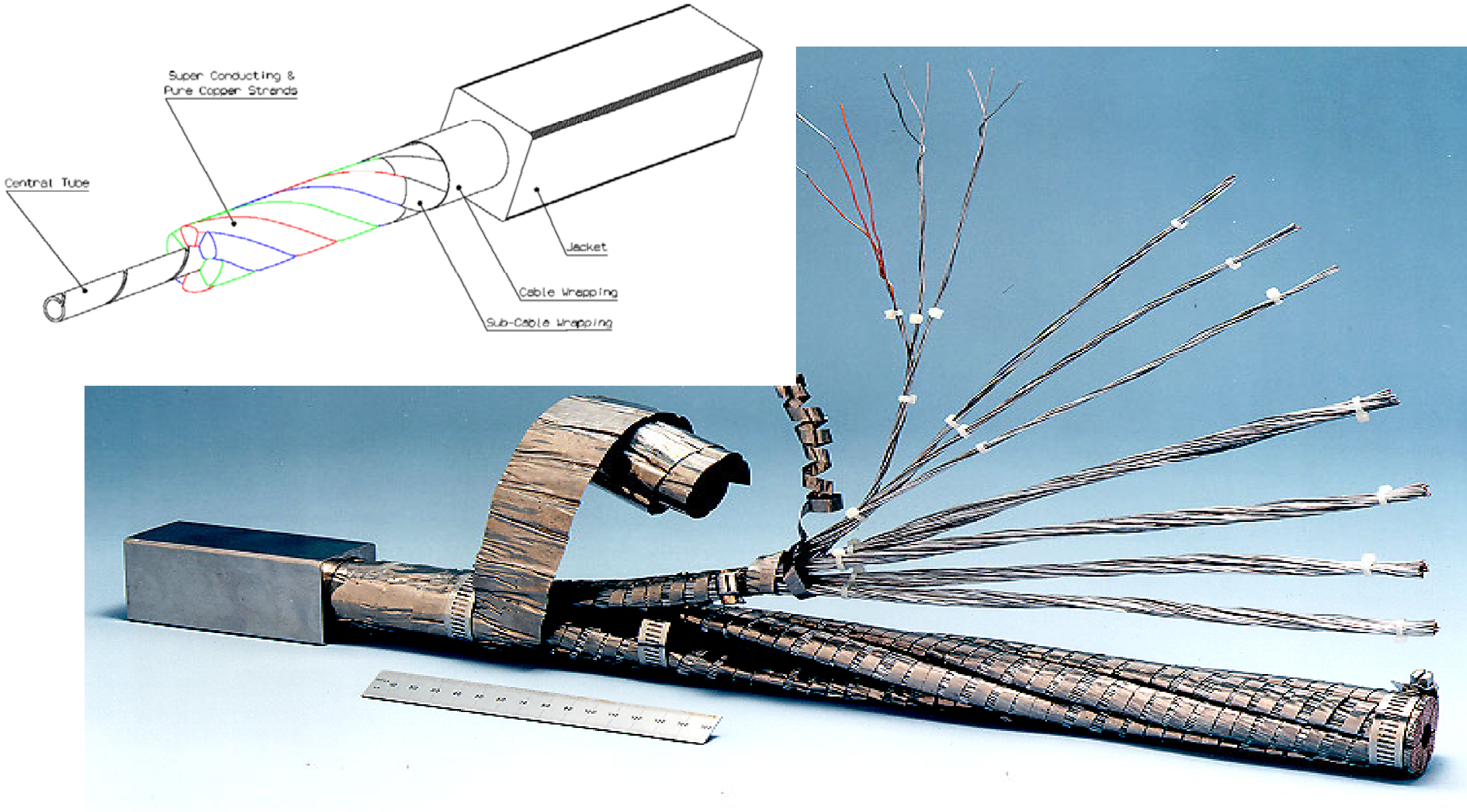
Adjustments:

- Temperature margin needs to be increased
- Drop low Coefficient of Expansion (COE) jacket alloys (Incoloy and Ti) in favor of mis-matched modified stainless steels for more initial compression.

Result:

- Both require increasing the **amount** of superconductor in winding pack and/or J_c of superconductor
- Keep ~same cable space so changes don't require major redesign of windings and structure:
  - Increase strand J_c
  - Increase number of strands
  - Increase cable compaction
  - Decrease copper fraction in strand

Central Solenoid Integrated Conductor



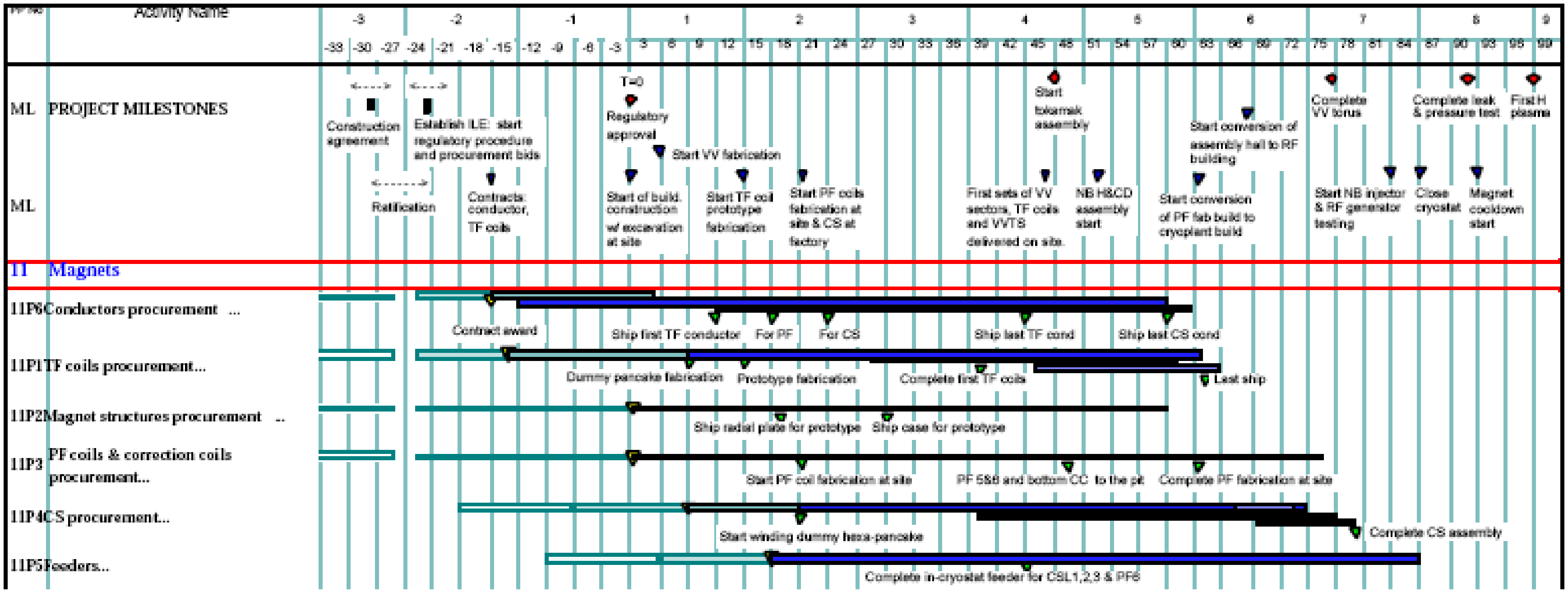
Package 4a: CS Final Assembly and Test Scope

- Final Assembly Main Tasks
  - Assembly and Preload of the CS Stack
  - Assembly of the CS Supports
  - Final Connections for the bus, headers and instrumentation
  - Implementation of the final acceptance tests
- ITER Furnished Materials/Services
  - Space for assembly at ITER Site in an area of the Assembly Hall having overhead crane access
  - Structure (from DDD 1.1 PP 2)
  - Feeders (from DDD 1.1 PP 5)
  - Work Platform (from DDD 2.2 PP 1)
  - CS Lifting tool [not shown] (from DDD 2.2 PP 2)
  - CS Module Testing (from DD 1.1 PP 4)

US CS Industrial Supply Plan

- Deliverables have been established
- We will examine here milestones, key resources needed and production plan

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

The University of Wisconsin-Madison
Applied Superconductivity Center

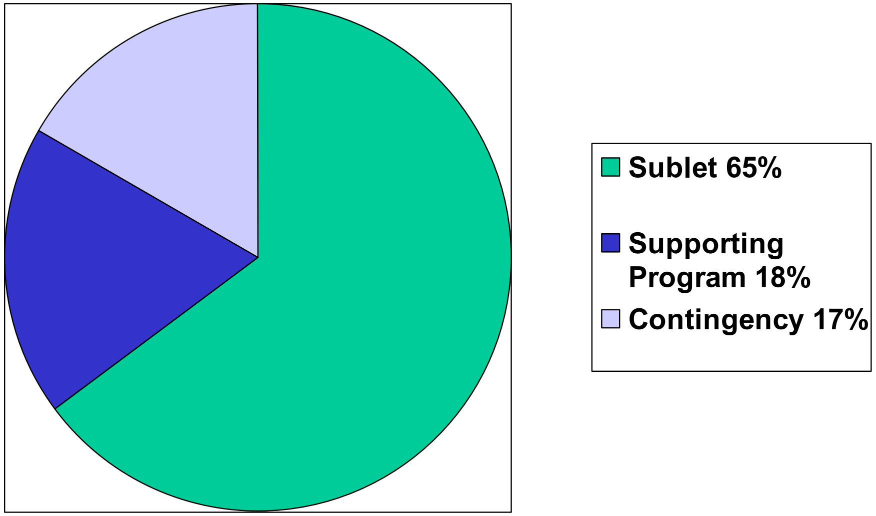
ITER CS Milestones
June 2006 Start

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

4 Module vs. 7 Module Supply Cost

- Conductor- largest cost item, largely becomes a commodity purchase in either case- ~70 tons module
- Fabrication includes about $12M in tooling and seven module fabrication costs only 20% more than 4 module fabrication
- Programmatic risk embedded in the first module production
- Modules 5-7 total supply costs are only 40% of the cost of the 1-4

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



Programmatic 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 Contracting
  - How? Perform needed preproduction implementation 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 then fixed baseline

Comparison of Present CS With 2001 FDR

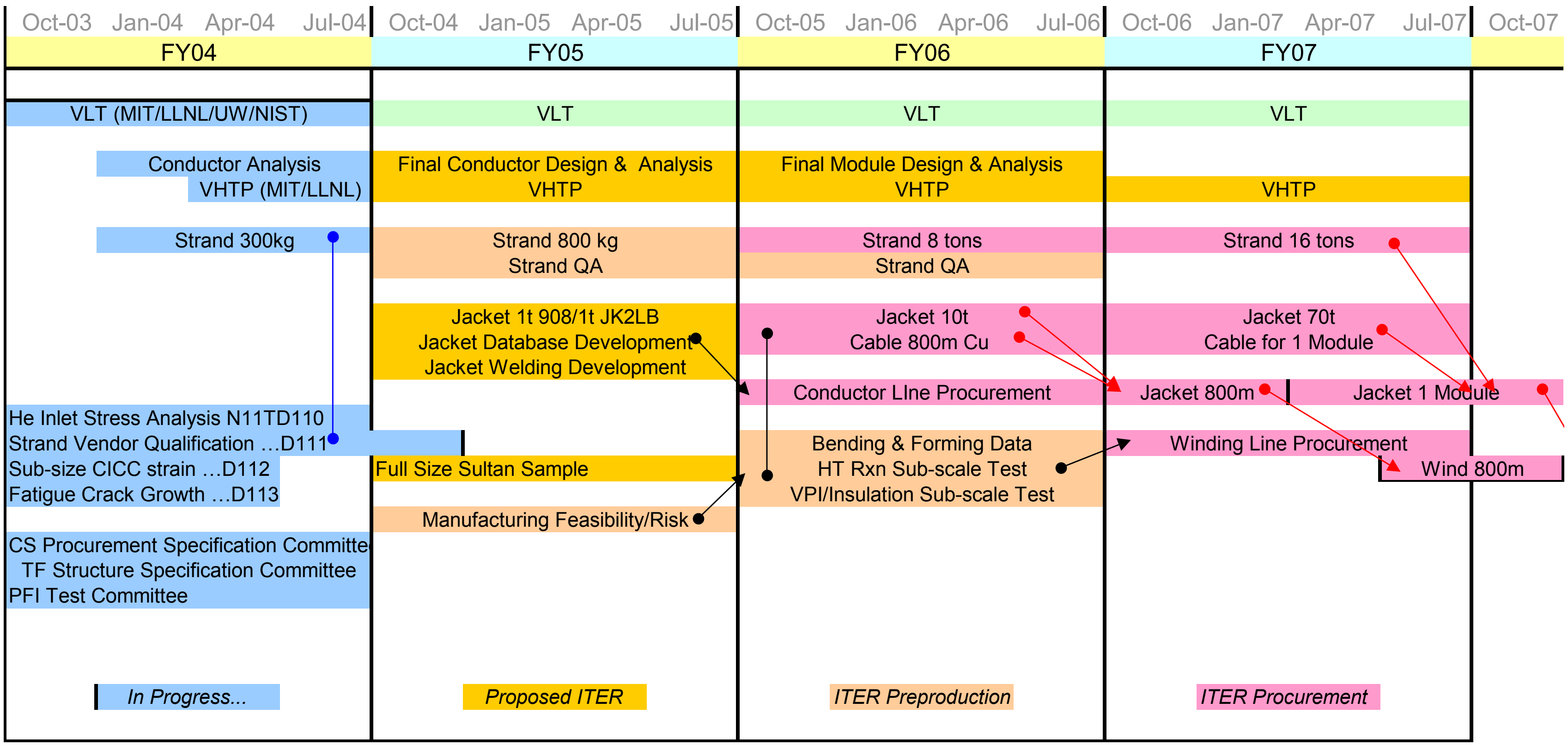
FDR	Present Design
Continuous Solenoid ~12m Tall	Segmented Solenoid 6 Modules
Bucked by TF Coils Conductor in Compression	Free-Standing Solenoid Conductor in Tension
Layer Winding 4-In-Hand/Series Connected	Pancake Winding 6 Hexa-Pancakes and 1 Quad-Pancake Separate Power Supplies
Lap or Butt Joints	Butt Joints
Incoloy Alloy 908 Jacket SS was an option (2 Grades - 45 mm square and 49 mm square)	JK2LB Stainless Steel Jacket 49 mm x 49 mm
Nb_3Sn Strand 650 A/mm² J_c CSC Ratio - 1.5:1	Nb_3Sn Strand > 700 or 800 A/mm² J_c CSC Ratio - 1.0:1
2 K Temperature Margin	< 1 K Temperature Margin

CS 2004 Baseline Technical Issues

1. Jacket Fatigue Crack Growth - Modified Stainless Steels (JK2LB)
2. Failure to detect a quench
3. Insulation in tension and shear in self-supporting modules
4. Butt joint performance
5. Cable transverse strain and conductor performance

- These are all *Performance Risk Issues* so early supply tasks are focused on mitigation.

Coil Winding Ramp-up for June 2006 Start



The University of Wisconsin-Madison
Applied Superconductivity Center

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

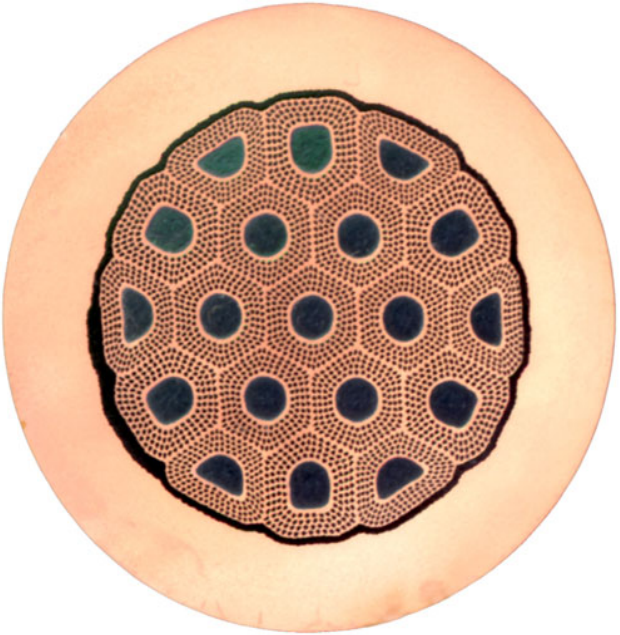
6. Members of Committees for:
   - CS Procurement Specification
   - TF Structure Specification
   - PF Coils Specification
   - PF Insert Coil Test Committee

For a CS 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

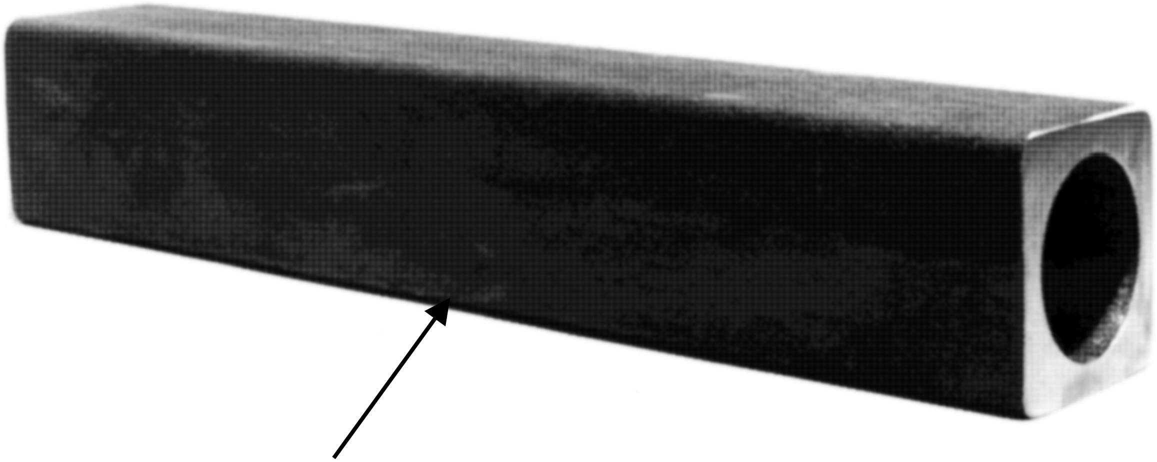
FY04	**300 kg**
FY05	**800 – 1000 kg**
FY06	**8 tons**
FY07	**16 tons (16 + 8 = 24 tons, enough for 1st module)**



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

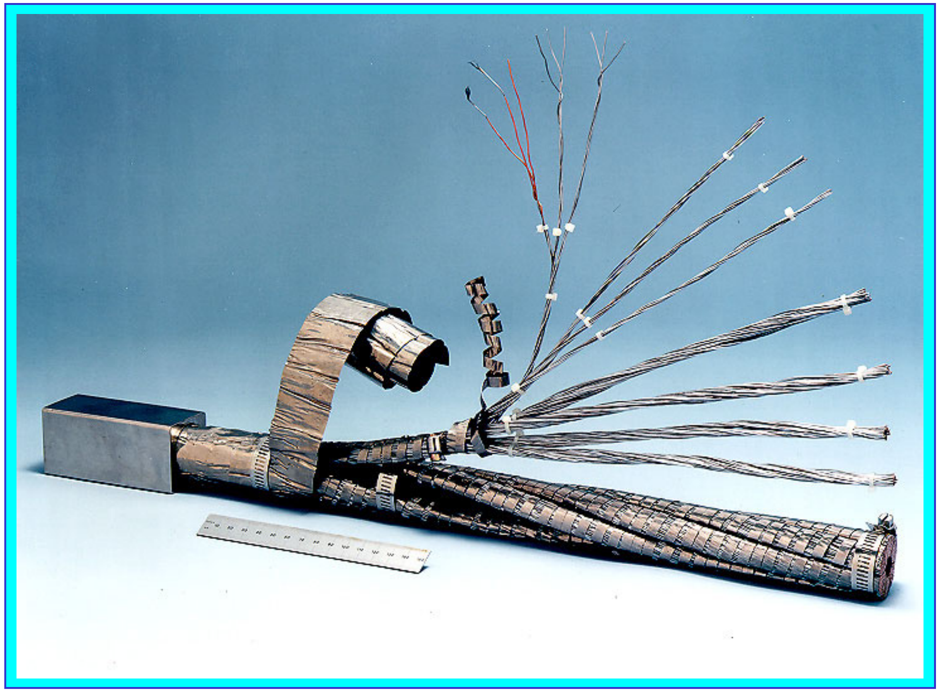
Trepanned extrusion billets

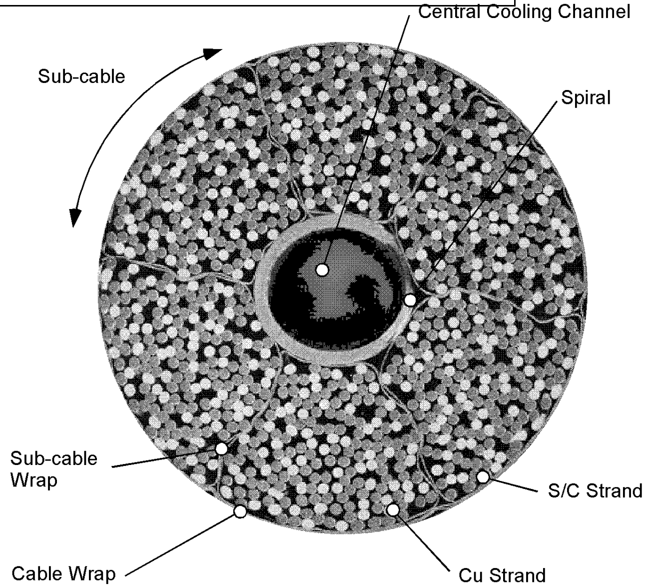


Extruded jacket section ~50mm x 50mm x5000 mm

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:

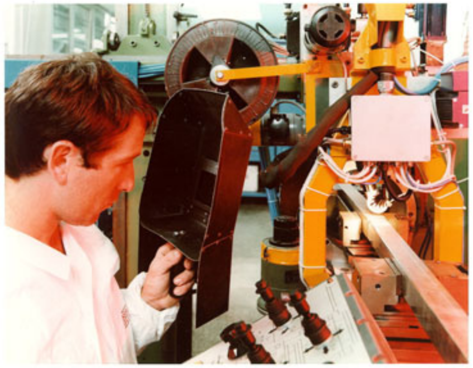
Copper Cable	881m + 2 * 1.2m	= 883.4 m
SC Cable Hexa Pancake	881m + 2 * 1.2m (specimen)	= 883.4 m
SC Cable Quad Pancake	579m + 2 * 1.2m (specimen)	= 581.4 m

The University of Wisconsin-Madison
Applied Superconductivity Center

Conductor Line
First Production Hardware Needed FY06

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

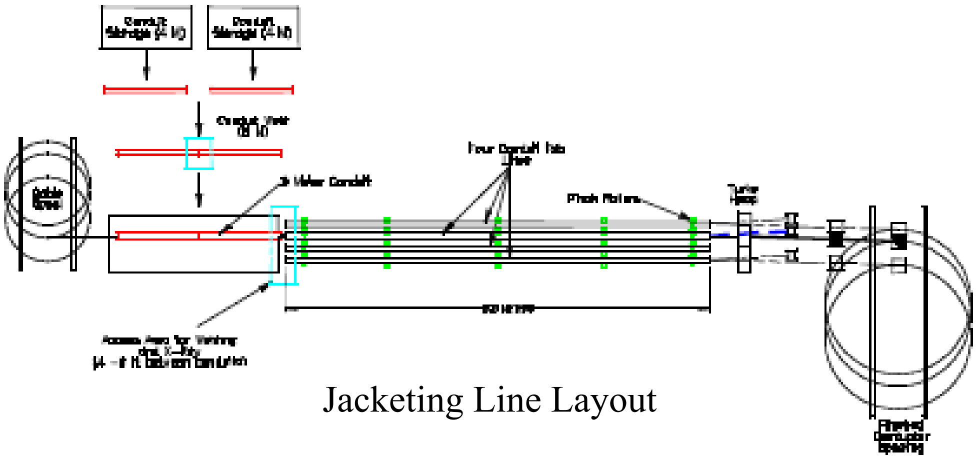
CS module Unit length is 800m- 4x CSMC length



Orbital welding is a critical operation

Butt weld x-ray inspection

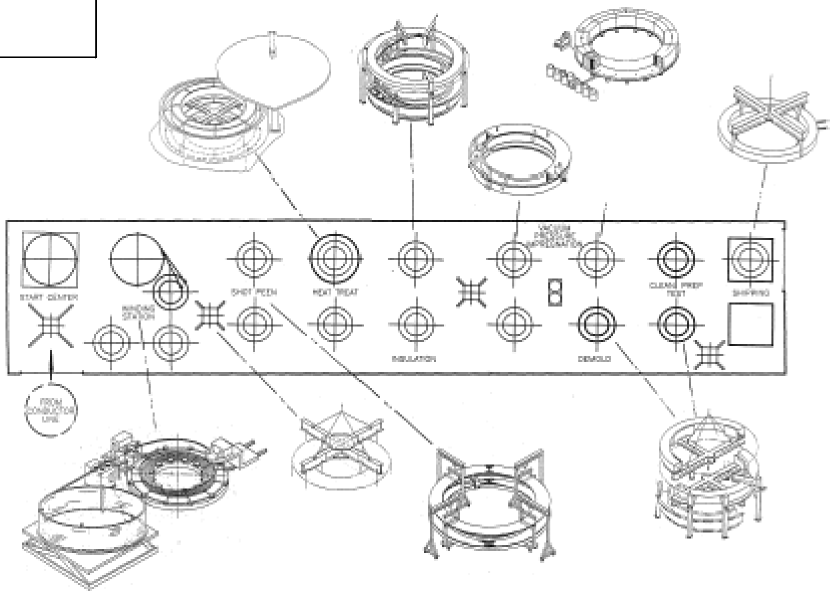
Reduction to final shape



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



Summary

- Most ITER Systems are supplied as In-kind Contributions
- Each Home Team will have a ‘portfolio’ of such packages
- The talks in this session represent most of the proposed US in-kind contributions)
- One such proposed US contribution is part or all of the CS magnet System
- We have prepared a WBS based, bottoms up plan for US industrial supply of the CS
- Overall risks are moderate but we address risk mitigation in the early years with key preproduction efforts
- U/Lab role over the life of the program is Sub-contract Technical management- no large development program is required or planned
- Within present constraints, we are working independently some areas, and with ITER and Japan in others, to prepare the CS magnet system for fabrication, in support of the evolving US Burning Plasma Program