Design of the ITER Magnets to Provide Plasma Operational Flexibility

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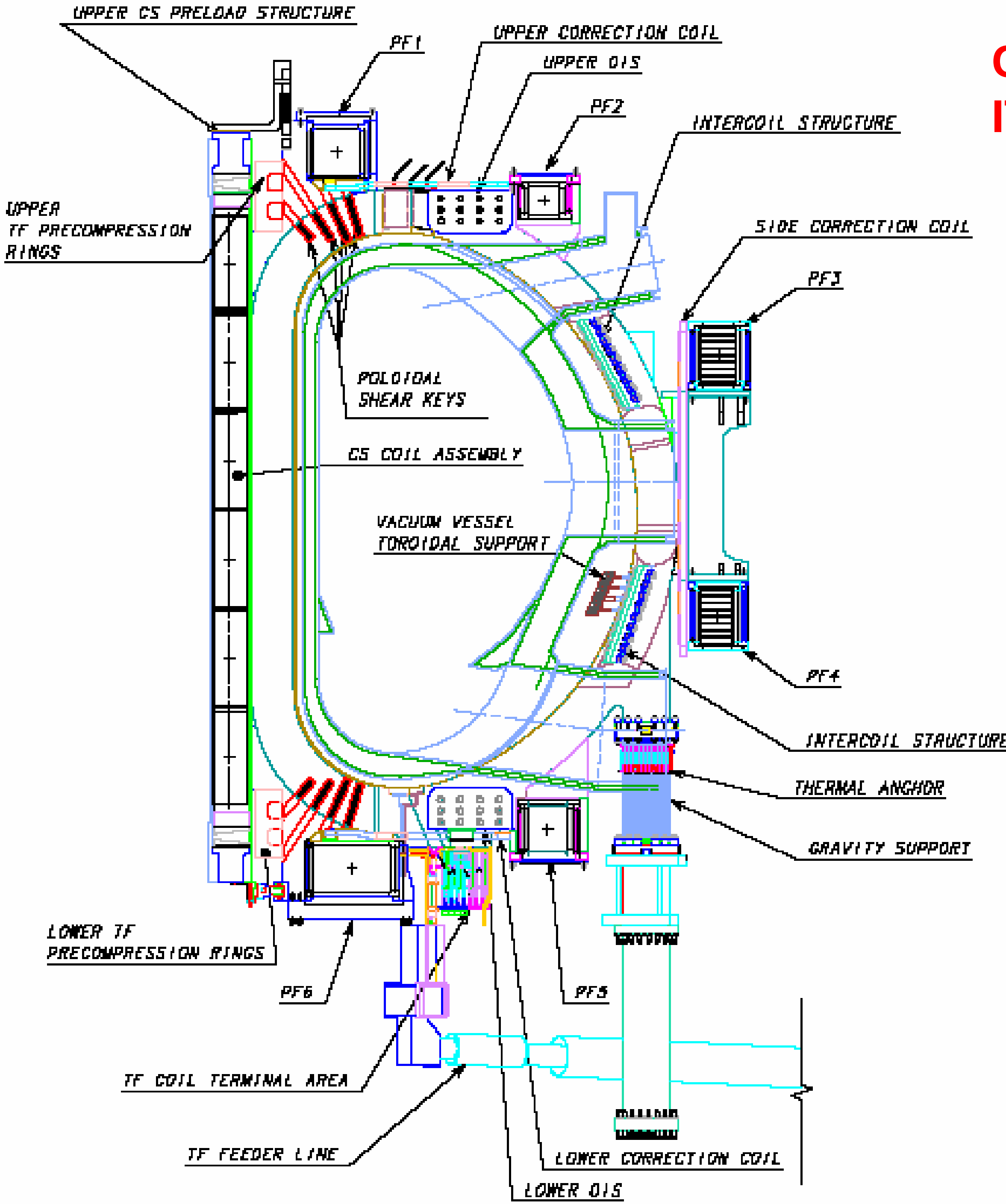
(with slide contributions from J. Minervini, P. Lee, I. Rodin, P. Bruzzone)

Cross-section of ITER magnets



Developments since 2001 (ITER Final Design Report)

Problems in 2001……..

- **Design in 2001 had a significant number of open options eg**
  - **3 conductor/layouts for the CS, 2 for the TF**
  - **2 concepts for the TF structures**
- **Preparation of manufacturing specifications made difficult due to design uncertainty.**

………………………..Solutions in 2004

- **Detailed investigations, negotiations with the ITER partners**
  ➔ single agreed reference design.
- **Detailed design and analysis (mostly in the inner poloidal key region, in the TF cooling and nuclear shielding and the CCs)**
  ➔ FLEXIBILITY to operate with a range of plasmas and cover uncertainties (in control, nuclear heating, plasma parameters)
- **No change to the cost or overall machine parameters**

Limited time for talk➔ pick out 4 examples in more detail

Main Work Areas

Design improvements to improve functionality

- Inner Poloidal Keys
- Outer OIS (friction joint)
- Central solenoid layout

Response to R&D results

- Nb_3Sn conductor

Optimisation to reduce costs

- TF Case fabrication route
- Coil and structure cooling

Definition of Critical Components for Manufacturing

- Correction coils

➔ select 4 limited examples for presentation

Structural Design of TF Coil Case

- 3 Material classes to minimise weight of high strength high cost steel

- Segmentation to improve fit of winding in case, easier closure welds

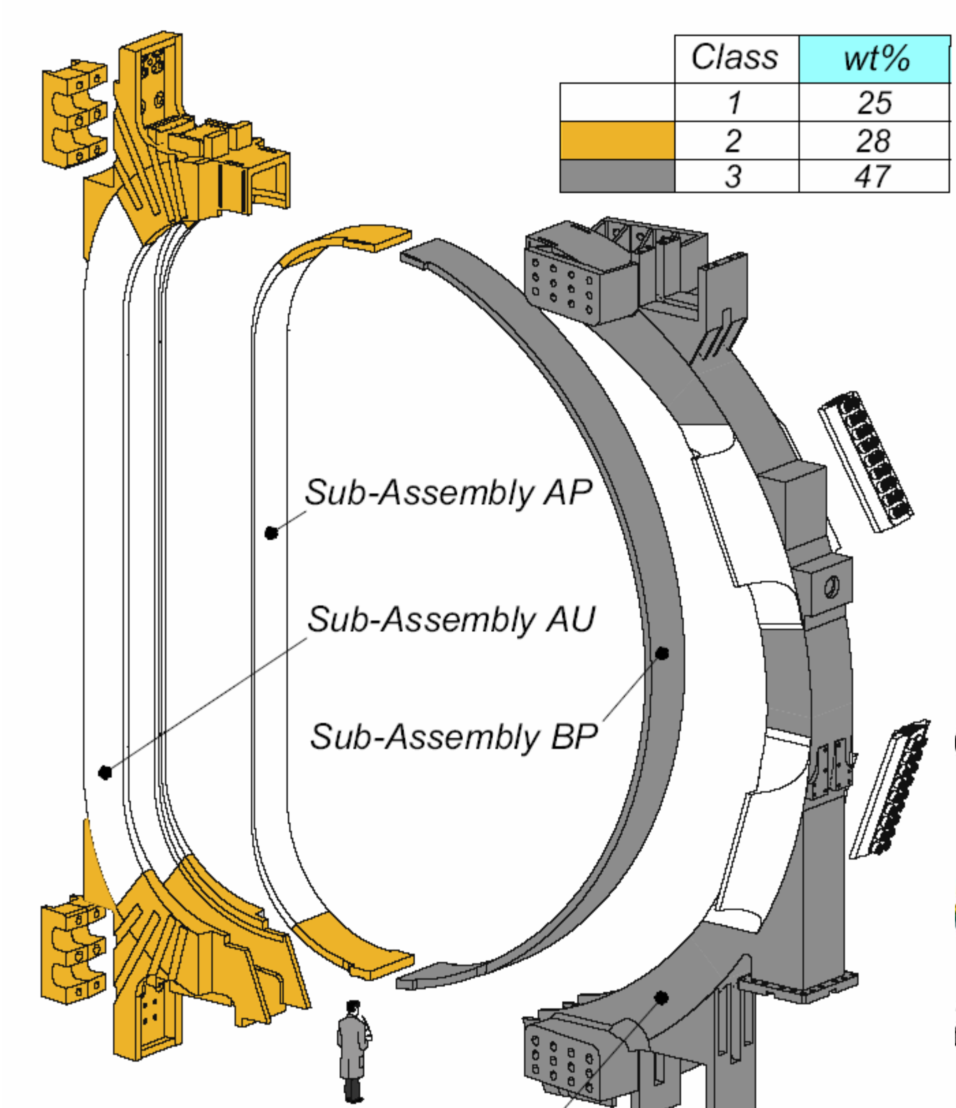
- Optimisation of poloidal key ways to distribute loads evenly

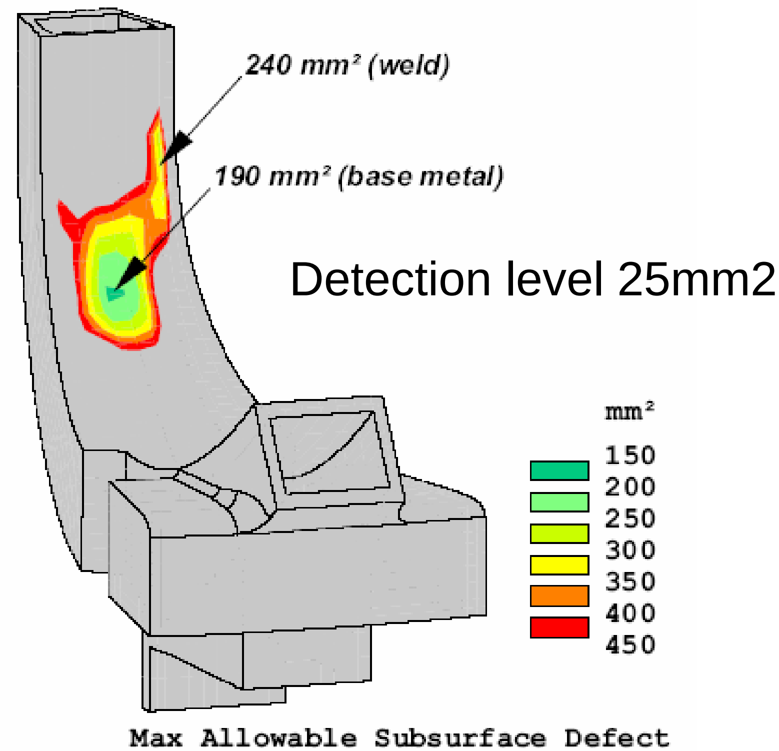
- Structural design to include defects and fatigue (ASME XI procedures) SN and initial defect limits
  - Keyways typical of SN limit
  - Case typical of defect limit

- Leave margin for effect of tolerances and misalignments

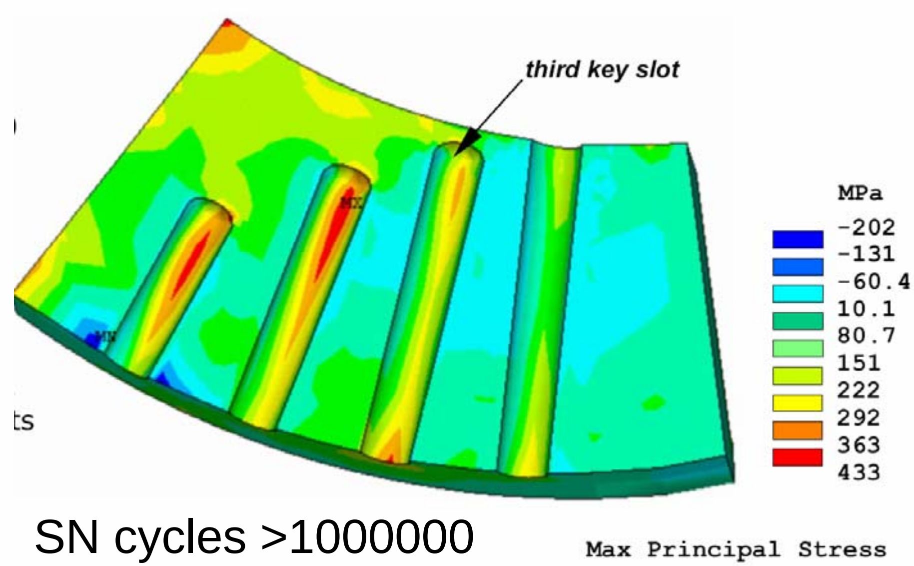
TF Coil Case and Inner Key Region

	Class	wt%
(white)	1	25
(orange)	2	28
(grey)	3	47





Detection level 25mm2



SN cycles >1000000

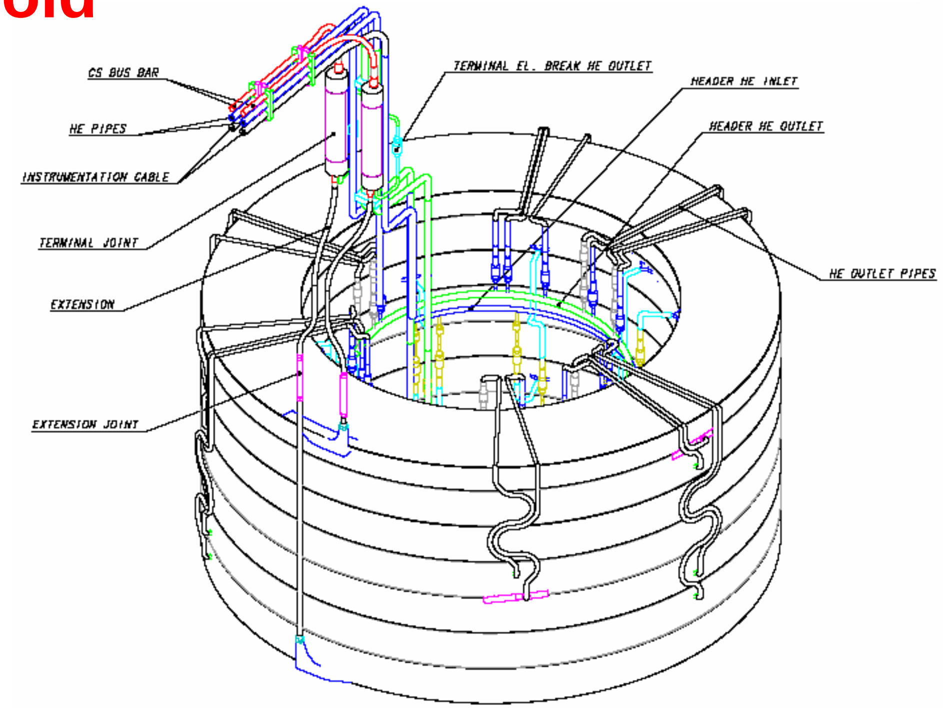
Flux Optimisation of the Central Solenoid

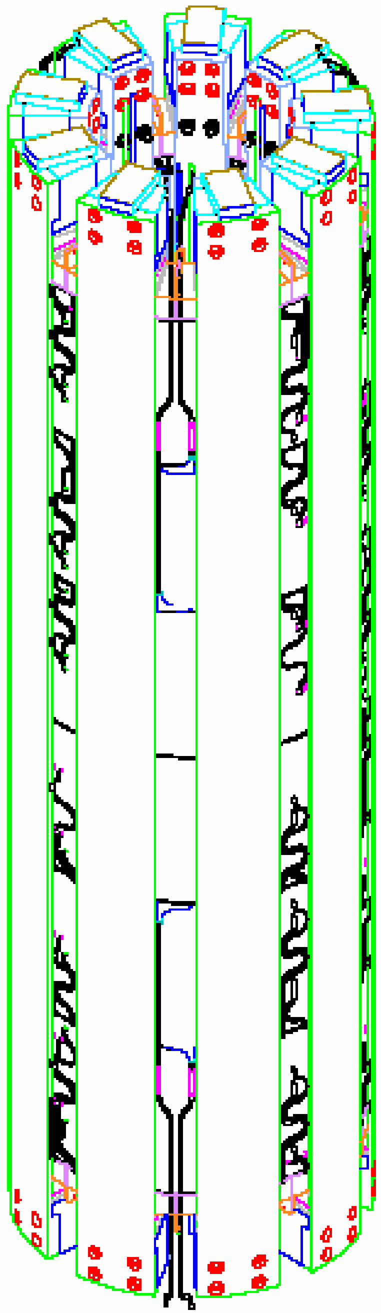
- **Central solenoid has conflicting requirements**
  - **Flux generation to drive plasma**
  - **Minimum space to shrink machine size**
  - **Shaping function for outer part (uniform current density not possible)**

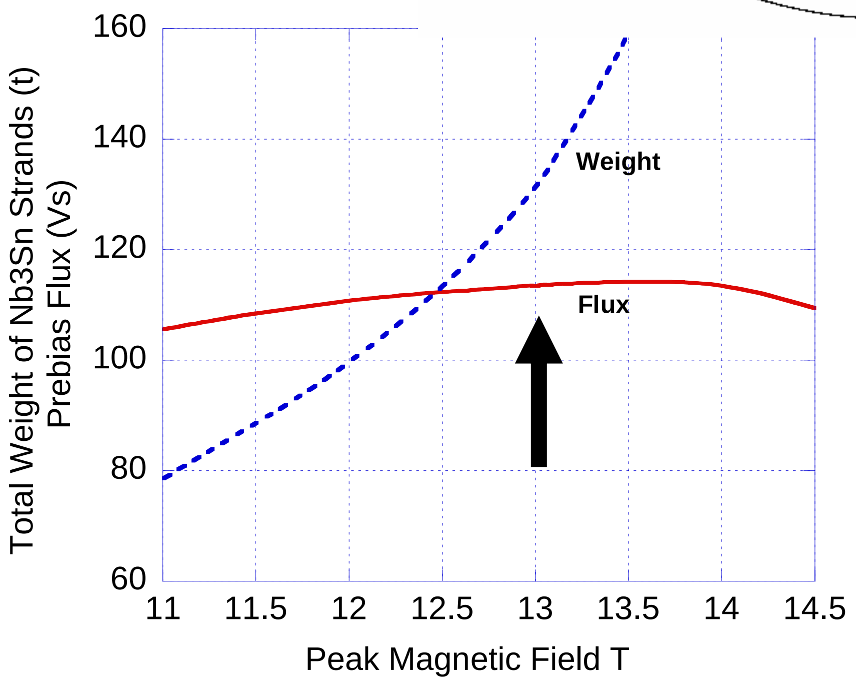
- **Shaping function has large impact**
  - **➔vertical support structure to hold CS together**
  - **➔Independent current supplies to modules**

- **CS has been adjusted to lower field (13.5T➔ 13T) since FDR2001**
  - **Lower thickness (lower stress, less Nb3Sn) allows same flux, lower cost**
  - **Integration of outer current feeders and vertical support, less radial space**
  - **Cooling brought into inner bore**
  - **Identical modules in stack for redundancy (1 spare for all)**

Central Solenoid







- Modular layout
- Cooling in inner bore
- Outer flanges and feeders
- Field optimised for flux

Redesign of TF Conductor

- Improvements in strand performance since 1994 (model coils)

➔ ITER action in 2002 to re-assess industrial availability

All 6 ITER PTs now in pre-qualification action for strand supply

- Confirmed that strand specification can be increased at least to ITER proposed values

- Assessment of ITER model coils showed conductor performance less than expected, also evidence of performance drop of s/c dependent on ‘transverse load’ (BI force)

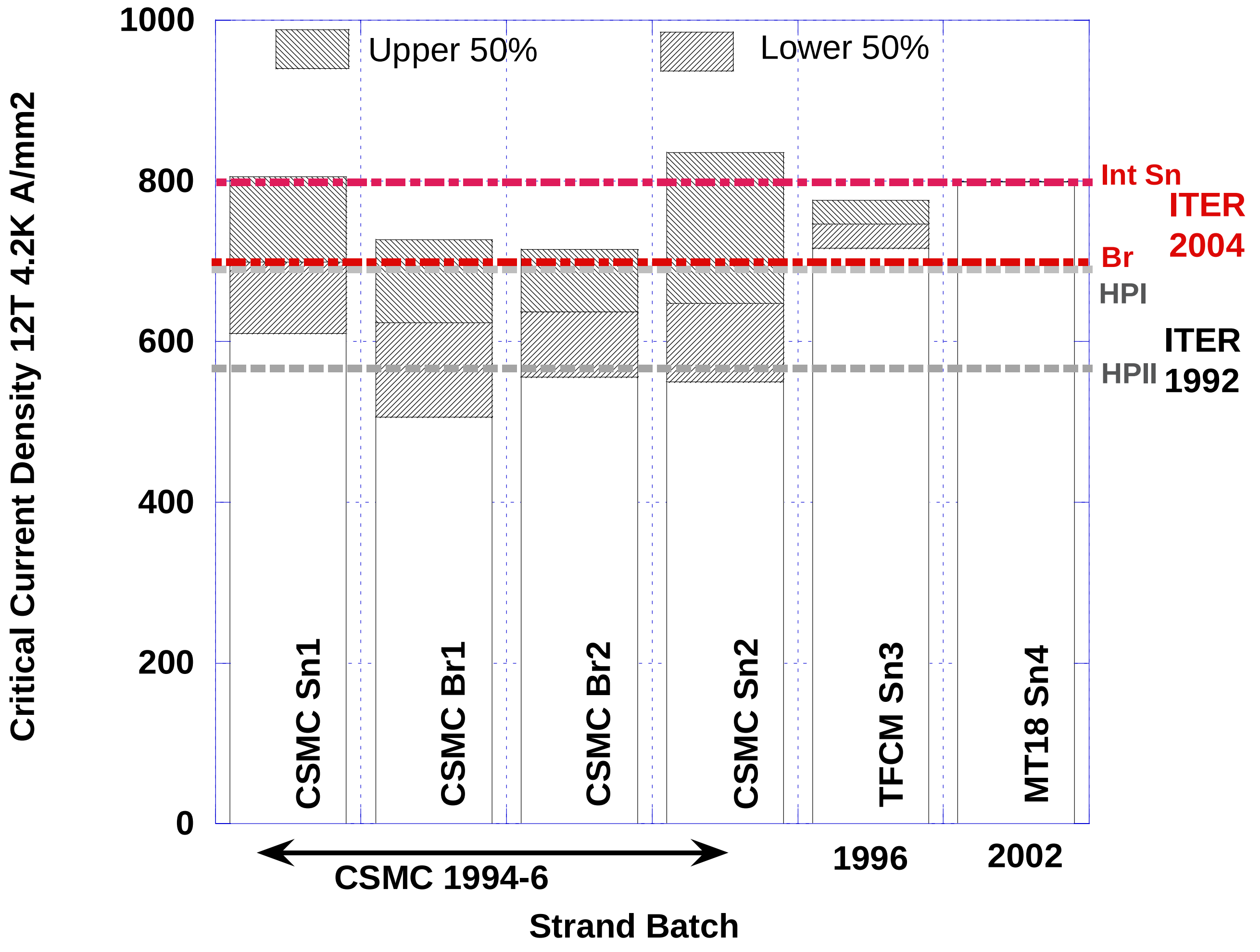
- Caused by local bending of strands, current degradation of strain sensitive Nb_3Sn and in some cases local filament fracture

Correction by

- decreased void fraction to improve strand support
- steel jacket to give overall compression, reduce number of filaments going into tension
- high performance strand to increase margins to allow for degradation
- Limit currents (and BI forces) in individual strands

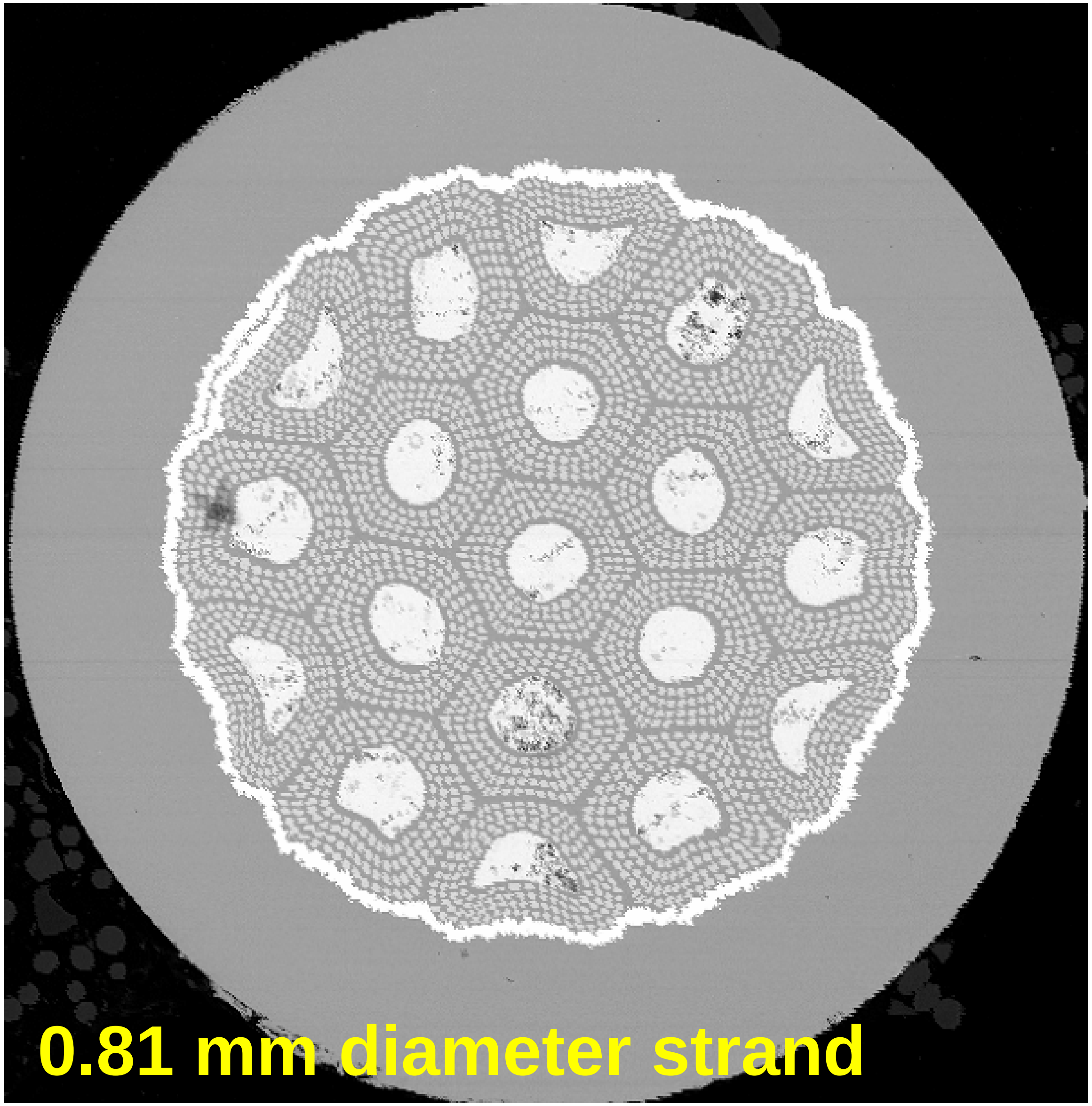
Published Range of Strand Performance for ITER 1994-2004

lowest-mean (weight averaged)-maximum jc



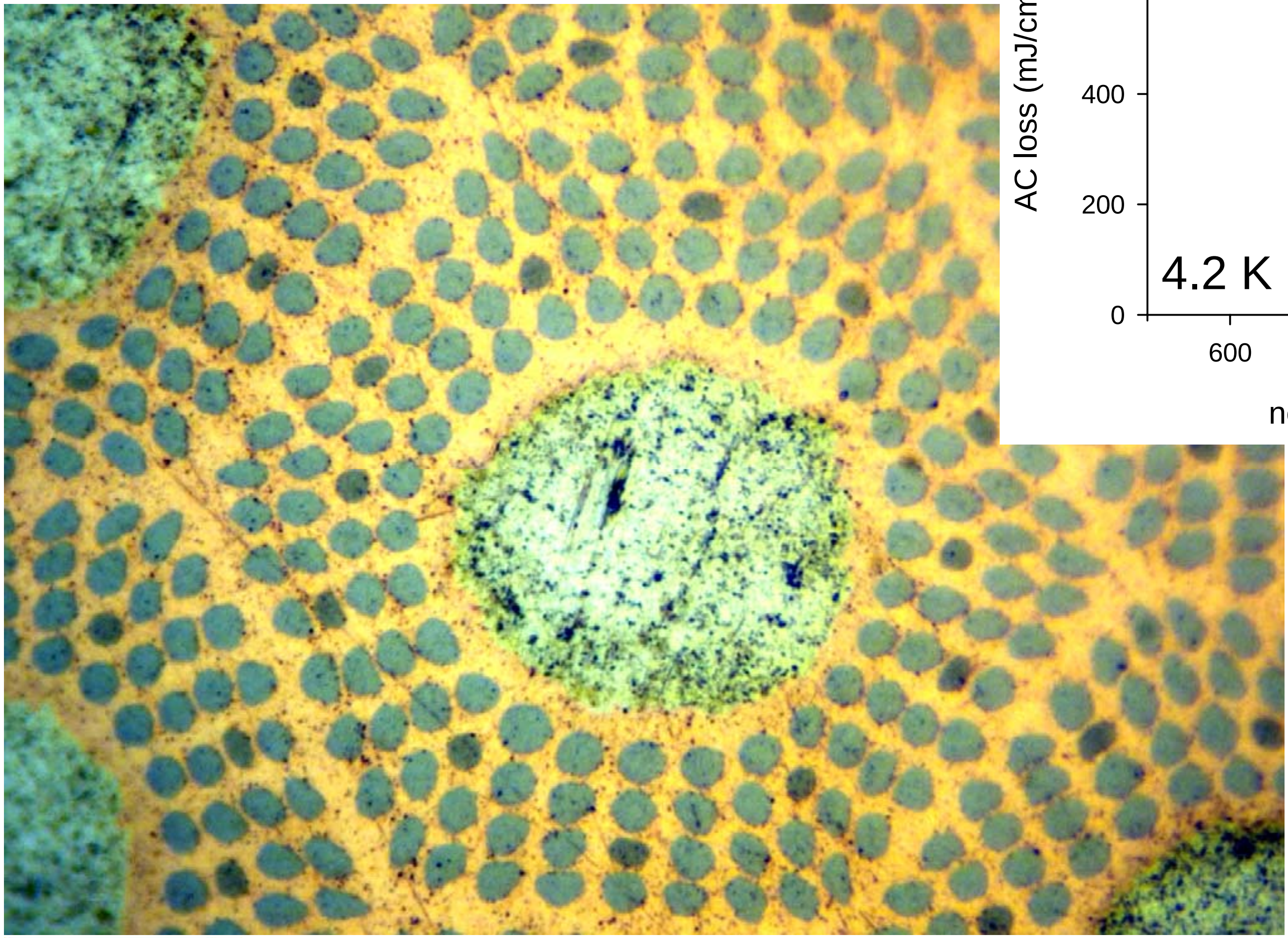
Oxford Instruments (US strand contract)

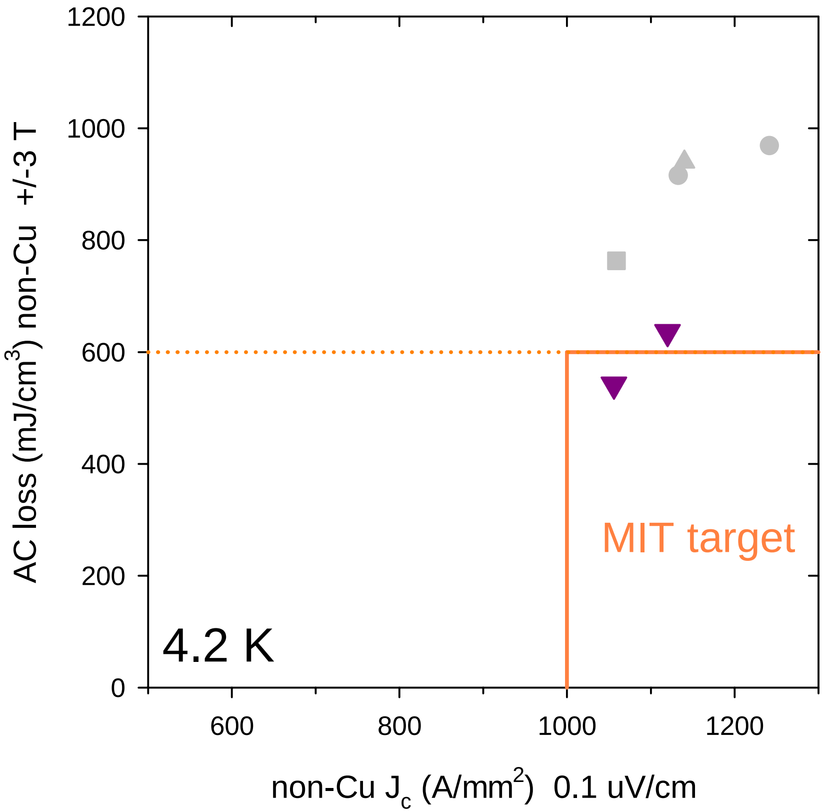
- 19 subelements
- single Ta barrier
- Cu:non-Cu = 1
- billet size ~35 kg
    - ➢ 3 billets are expected to fill 100 kg requirement
- Production billets would be larger (60 kg+)



Nb-47Ti rods as Ti source

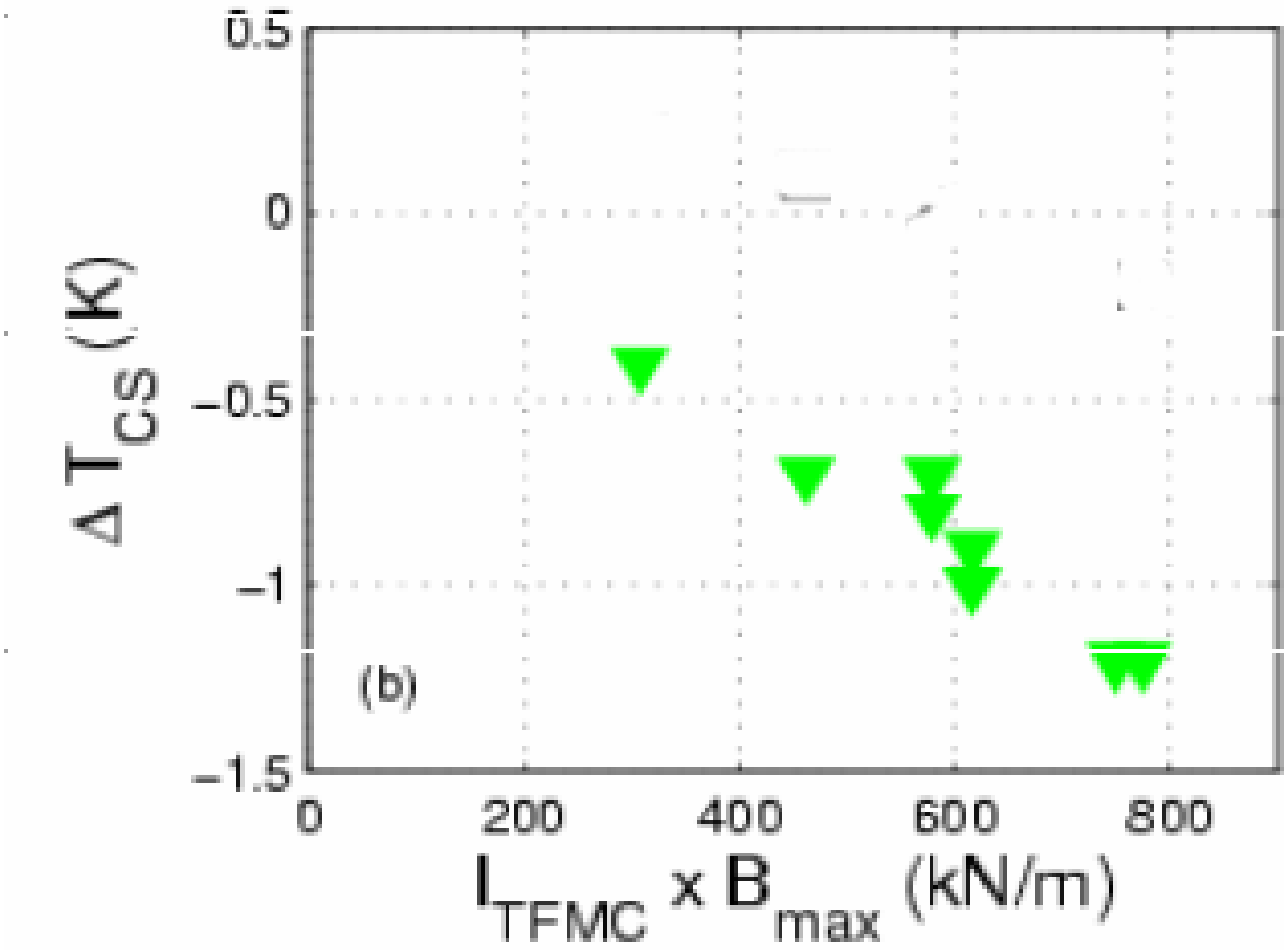
- ➢ New OST patent (pending) process
- ➢ No Sn-Ti: costs less, eliminates Ti_6Sn_5 intermetallic particle problem



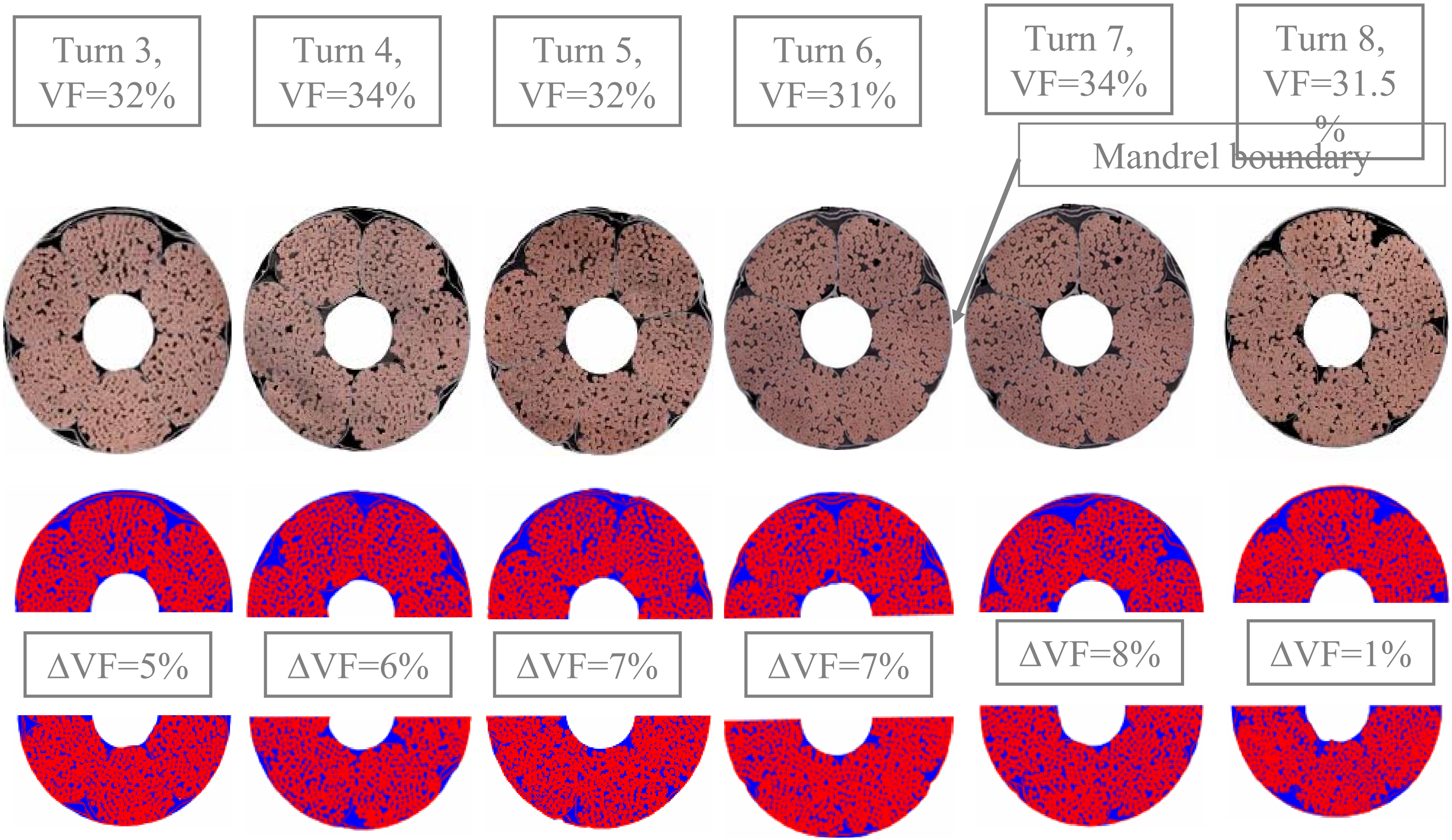


- ➢ Design nearly reaches MIT target, well above ITER spec

Assessment of TFMC Results – Current Sharing Temperature Relative to ‘Expected’ Value, against Local Magnetic Load BI



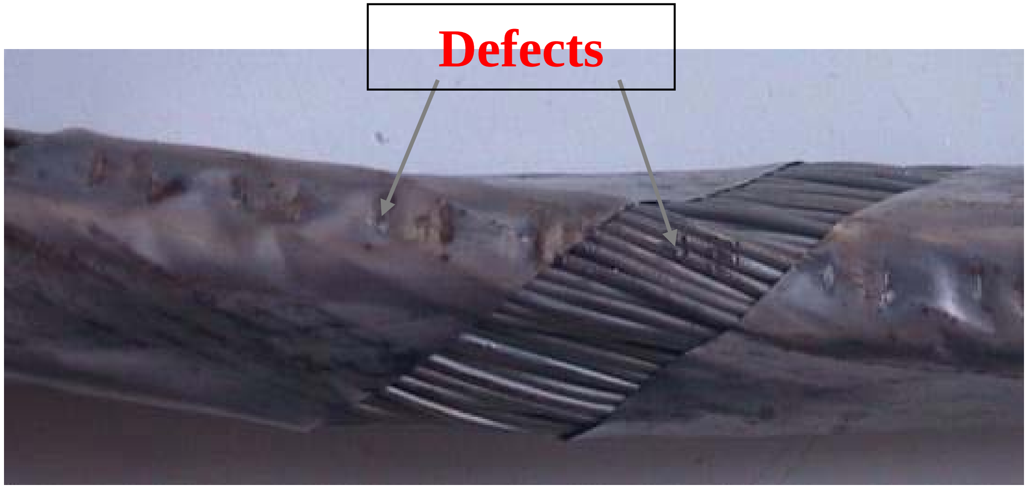
Sectioning of the TF Insert Conductor (Ti jckt) After Operation



Cable compressed permanently to one side

(I Rodin, Efremov Lab)

TFI Cable Before and After Operation



The mean number of the defects per 1 m of length of last stage subcable is 223:

- 172 are placed in the wraping zone;

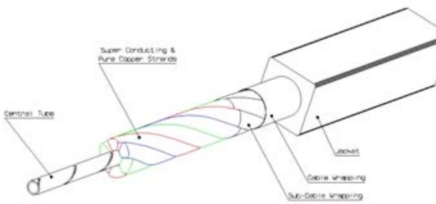
-51 are placed on the strands directly

1&2 Last stage subcables before the heat-treatment and test

3 -Last stage subcable after the heat-treatment and test

4. Ti spiral before the heat-treatment and test

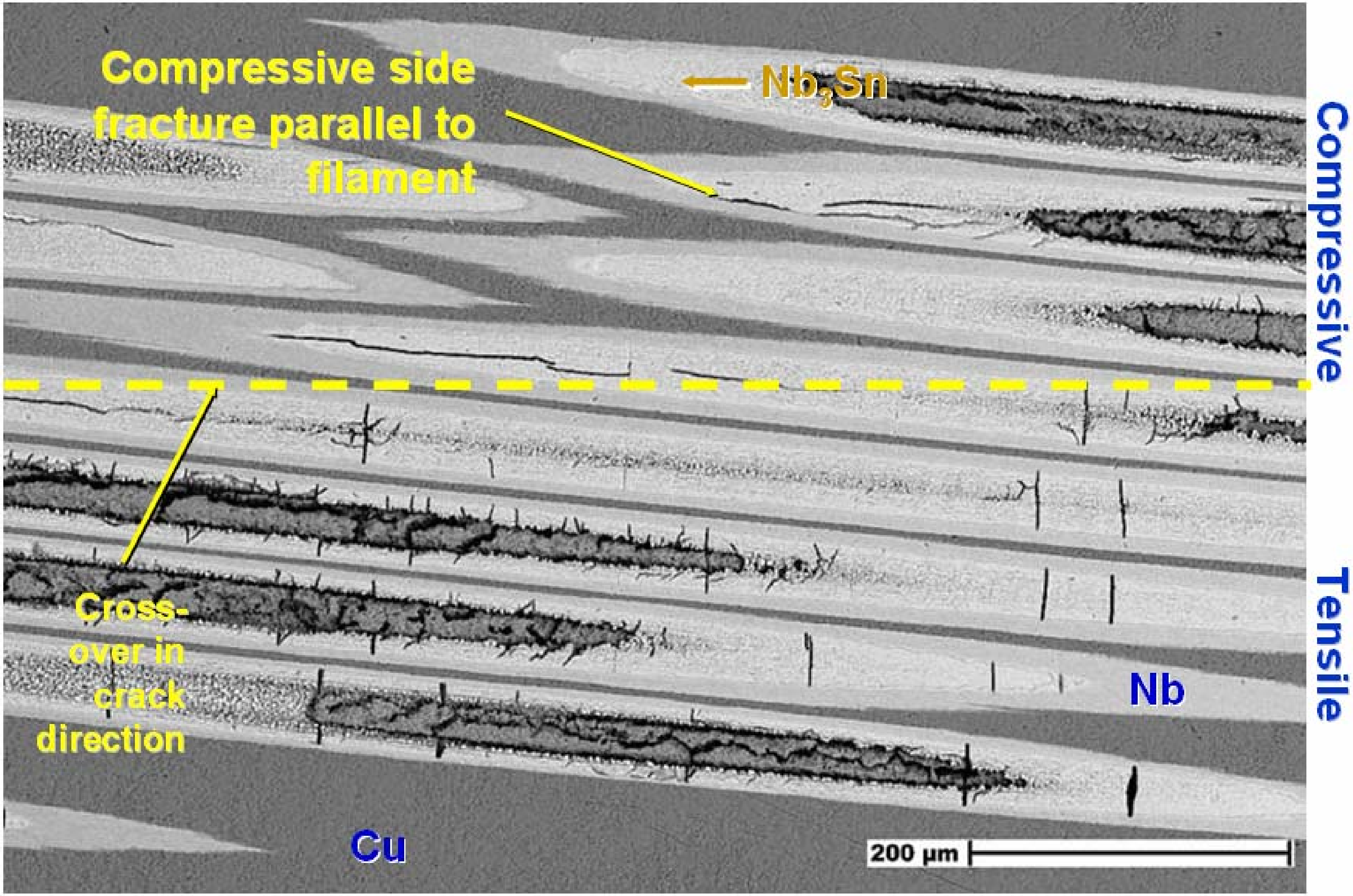
In operation strands pressed into central cooling channel



Sectioning of a strand after 0.6% bending

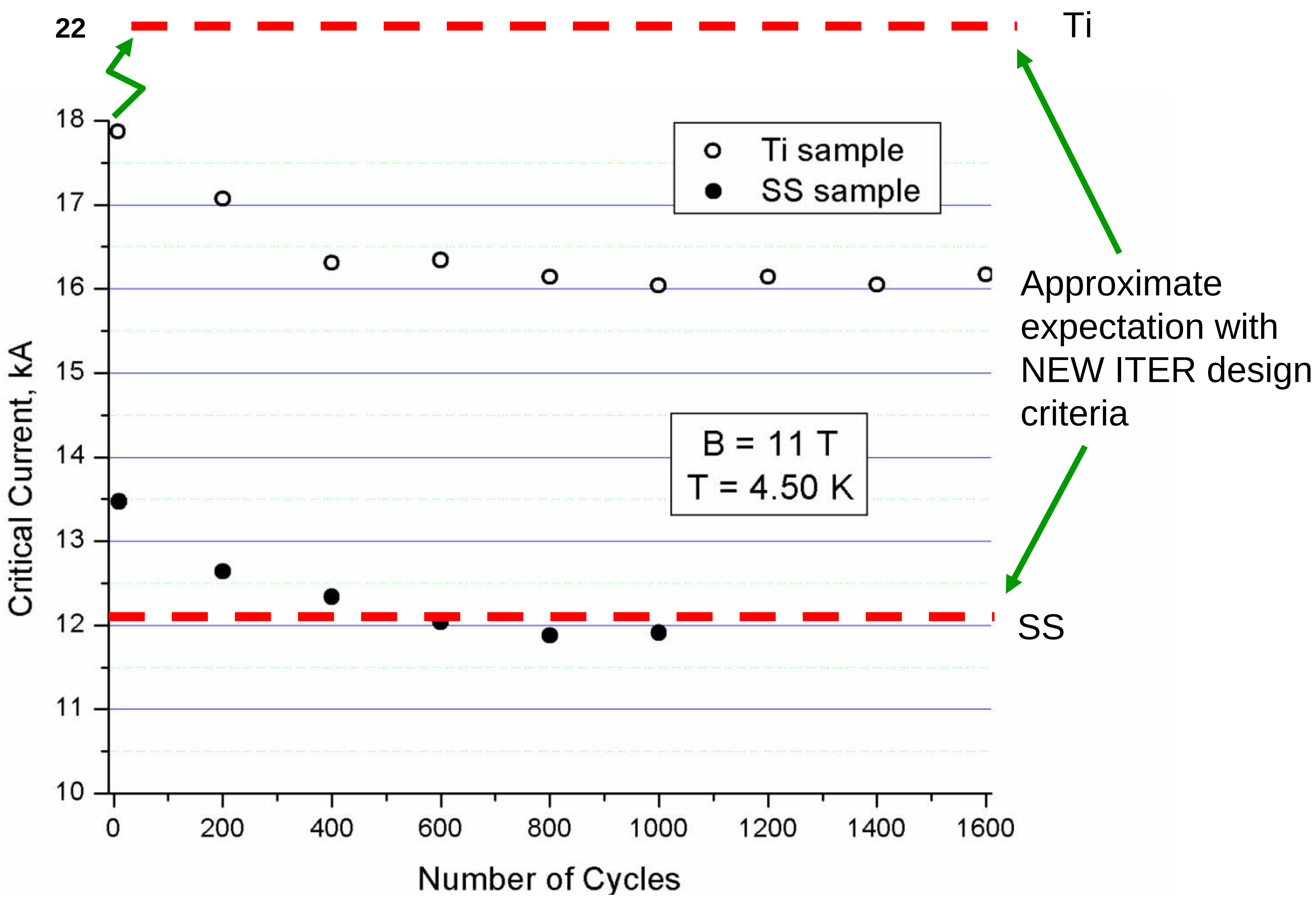
(University of Wisconsin, P.Lee)

PIT Powder-in-tube Nb(Ta) at 0.6%



Nb3Sn Behaviour in Conductors

Sultan short sample test of Steel and Ti jacket, identical cable 1/6 ITER scale



Coil cooling optimisation and cryoplant control

ITER thermal load variable ➔ primary cooling circuit buffers cryoplant

- **Cryoplant heat load smoothed by buffering heat in coils**

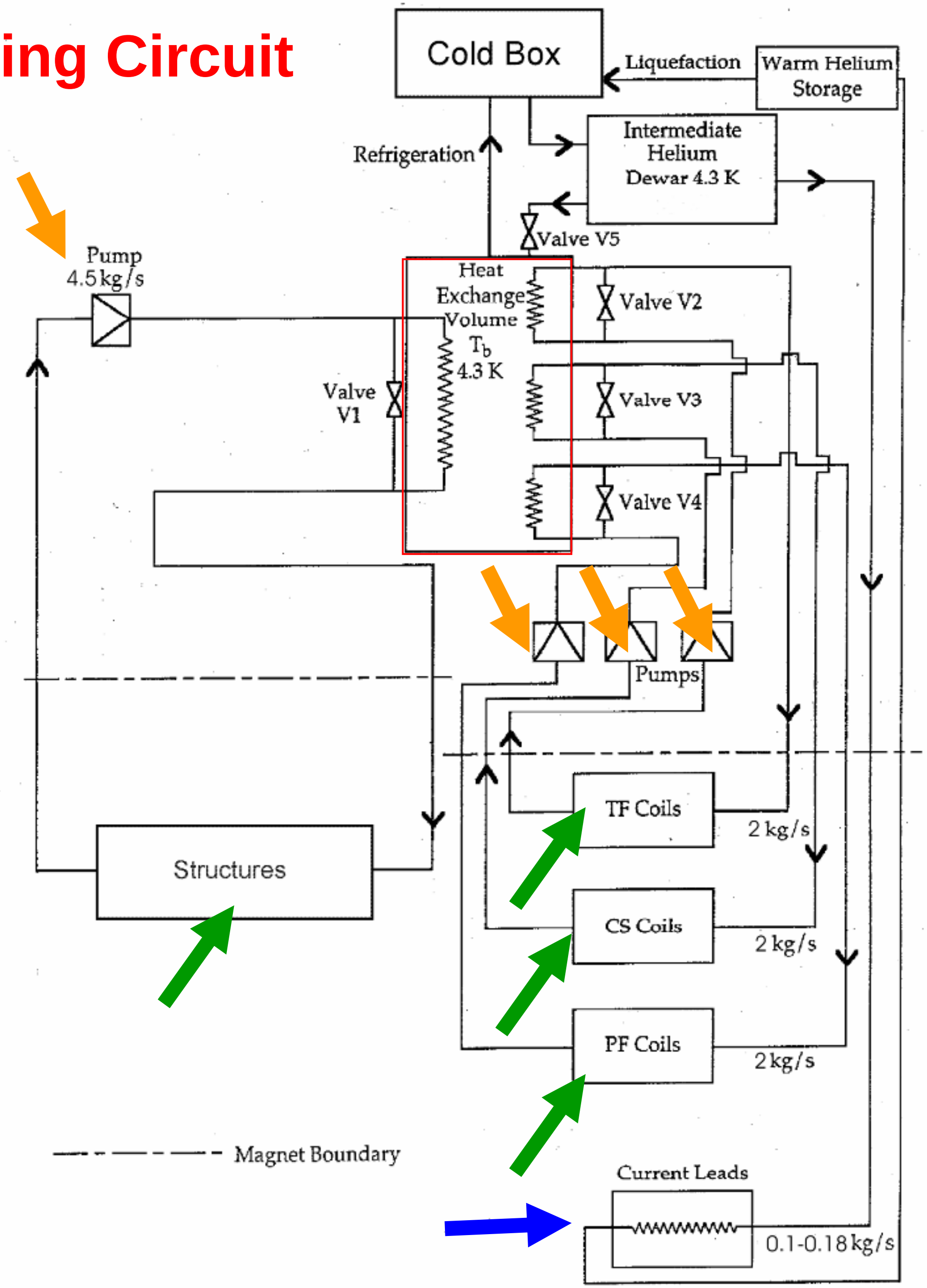
➔limits on pulse rate of ITER especially in H operation when loads may be unexpected (ie disruptions, control)
➔Pulse schedule needs to be planned to match cryoplant

- **Two conflicting requirements**
  - **Thermal loads (operating cost) depend on pump power, current leads**
  - **Conductor design (construction cost) depends on AC losses, nuclear heating**

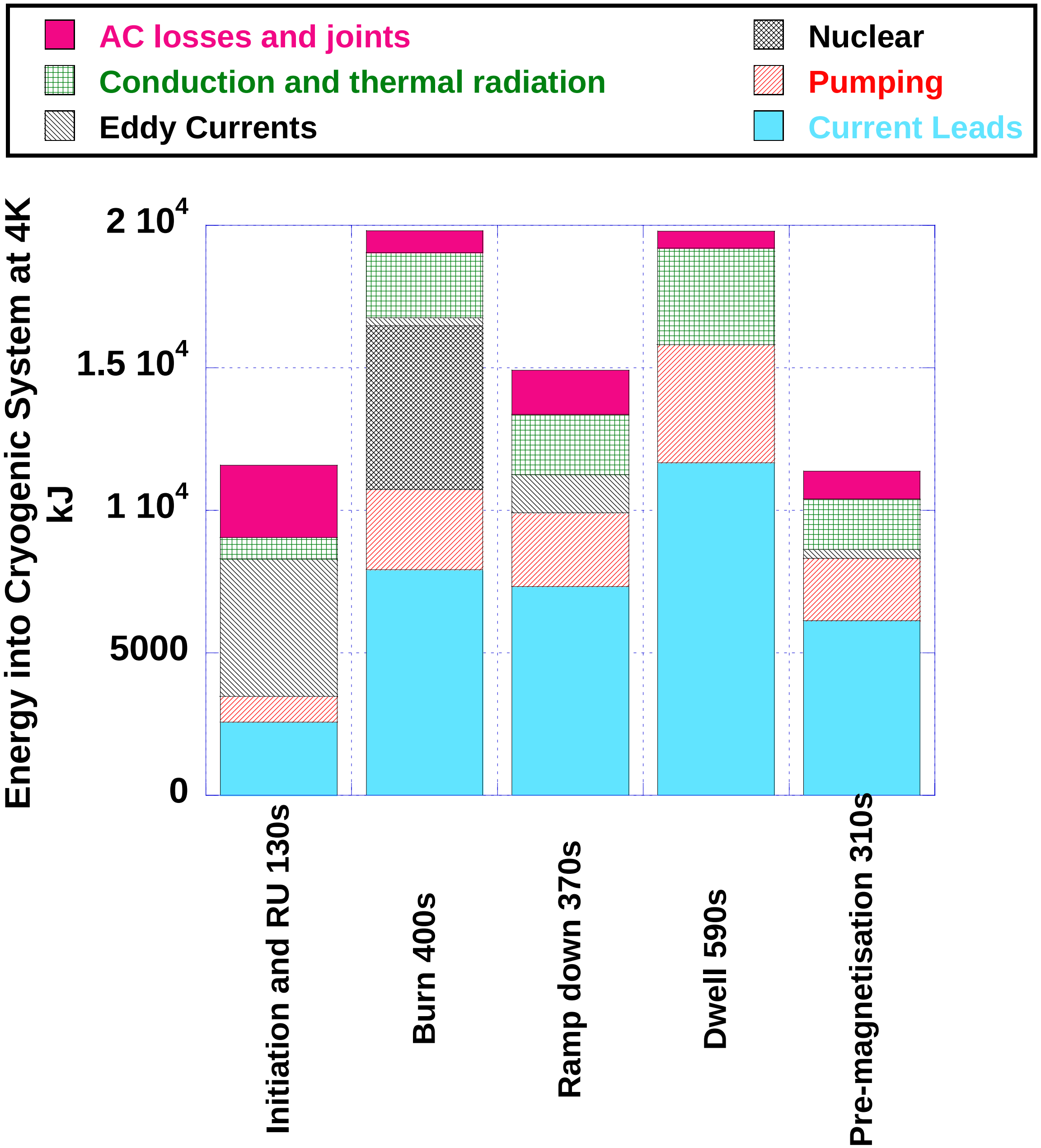
Higher pump loads ➔ less superconductor, lower construction cost

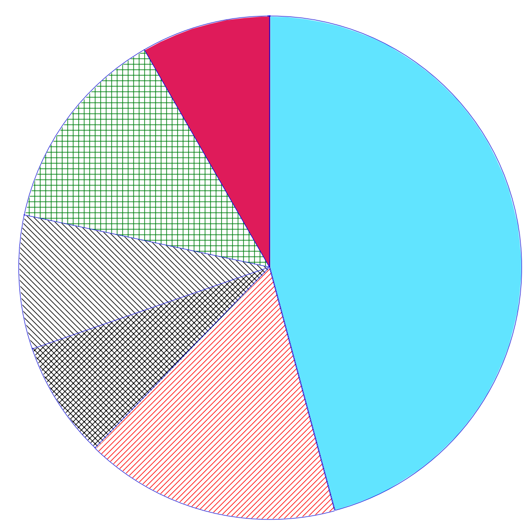
- **Design optimisation of conductor with**
  - **Central cooling channel to reduce pressure drop (and pump power)**
  - **Minimum length cooling channels compatible with winding**
  - **Optimised He inlets (low pressure drop)**

Magnet Primary Cooling Circuit



Contributions to Cryoplant Load and Distribution Over 1800s Reference Pulse with 500MW nuclear power (current leads He consumption converted to Joules with 1l/hr=6W)





SUMMARY OF NUCLEAR HEAT LOADS AND FLEXIBILITY OF COOLING

	Normal Operation (allow 33% margin on nuclear heat)	Operation with 100% Excess Nuclear Heat
Total nuclear heat (during burn) kW	13.9	18
Mass flow rate in TF thermal screen/ winding kg/s	4.5 / 2	6 / 3
TF pump heating power, 70% efficiency, kW, thermal screen /winding	1.0 /2.6	2.2 /5.6
Pulse rate to maintain constant average heat load	1 every 30 mins	1 every 45 mins

Uncertainty in nuclear heating (due to nuclear data and blanket assembly gaps)
➔ Margin (up to 100% uncertainty) by adjusting pulse rate of 2/hour

Conclusions ---- FAQs

Are there basic questions over the feasibility and performance of the magnets?
No

Is R&D needed before magnet construction can start
Yes
We do not fully understand reasons for strand-in-cable degradation
➔Must qualify conductor BEFORE fabrication by short sample test (and do supporting R&D to improve understanding)
➔Need industrial input for optimisation of structure fabrication
➔Need industrial development on insulation, precompression rings

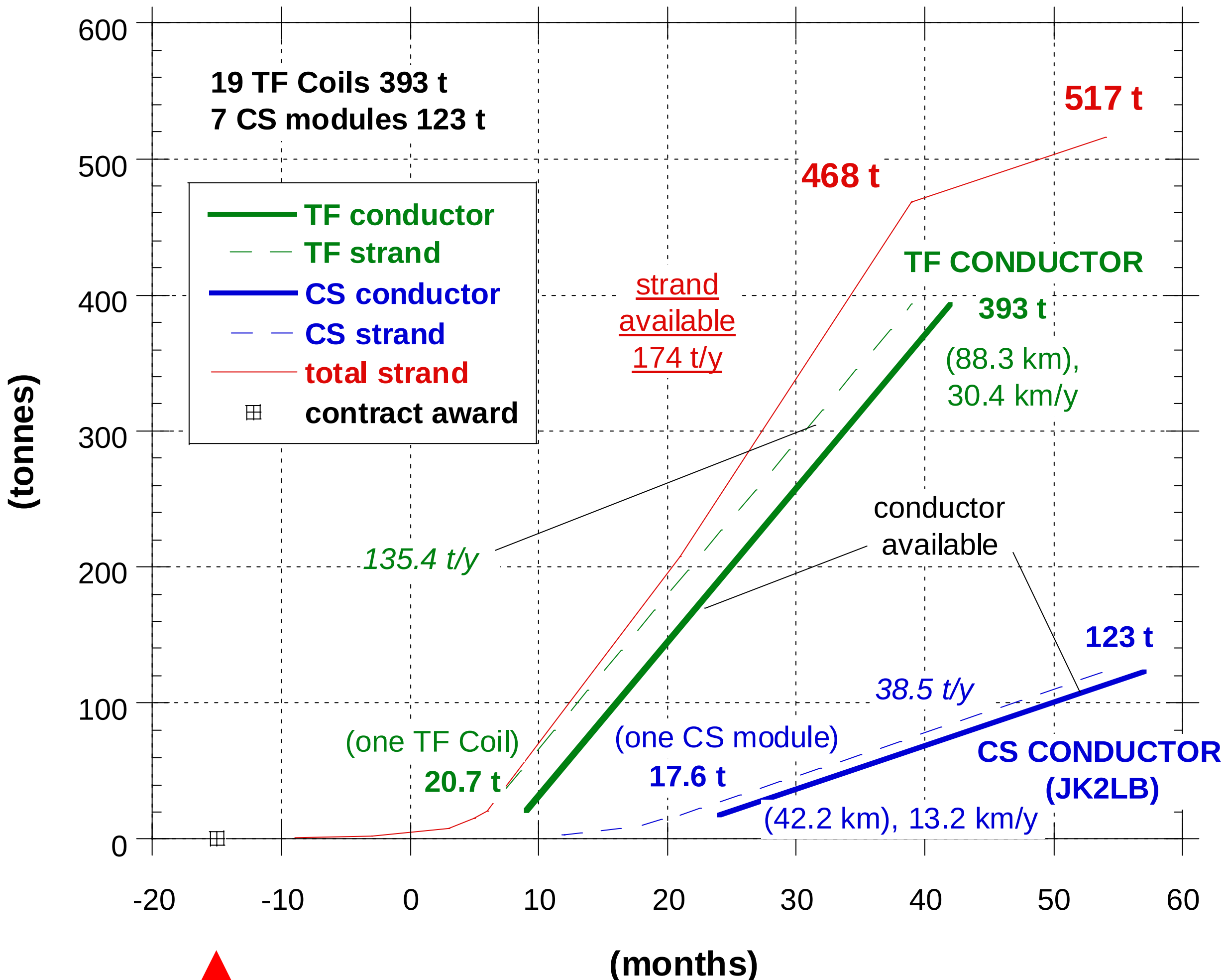
What else has to be done before PTs can start to place procurement contracts
Lots of supporting design and analysis (FE stresses, cooling simulation etc)
We must avoid design iterations once PTs start procurement…too many interfaces to control
No major design changes but adjustments within individual components

What is the soonest procurement (orders for Nb3Sn strand) could start
After qualification tests on conductor samples…Probably Nov 2005

What is limiting progress on the magnet design
Effort available to IT to work on main issues

ITER Magnet Construction

Time Schedule for Strand



Possible Nov 2005