Nb_3Sn Superconducting Magnet Fabrication & Test Program

based on KSTAR and ITER experience & lessons-learned

November 28, 2024

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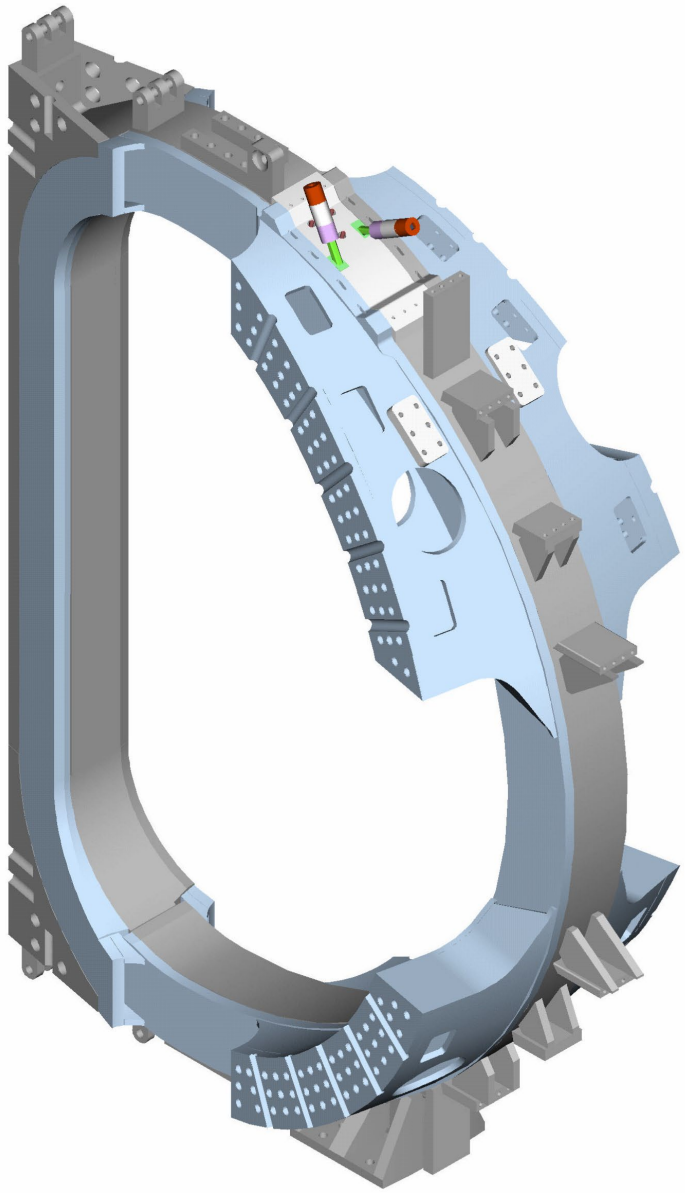
with Contributions from the KSTAR Construction Team including Dr. J.S. Bak, Dr. Y.K. Oh, Dr. C.H. Choi, Dr. H.Y. Yang, Dr. Y.M. Park, Dr. K.R. Park, Dr. K. Kim

& ITER Organization, JA-DA, and EU-DA



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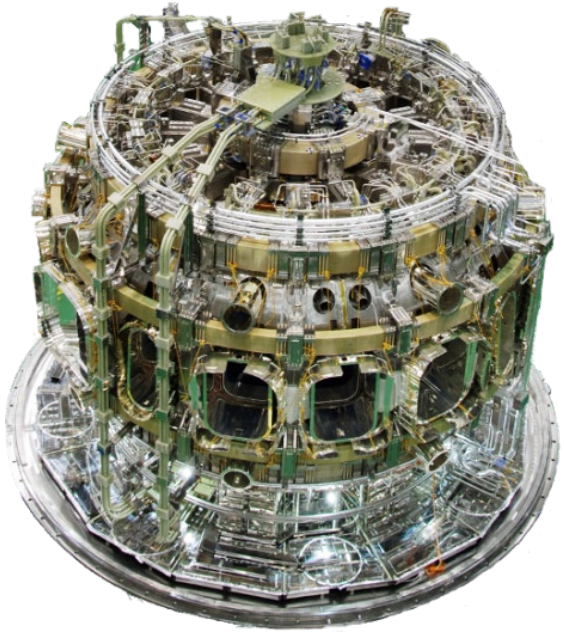
Well-known Controversial Question :

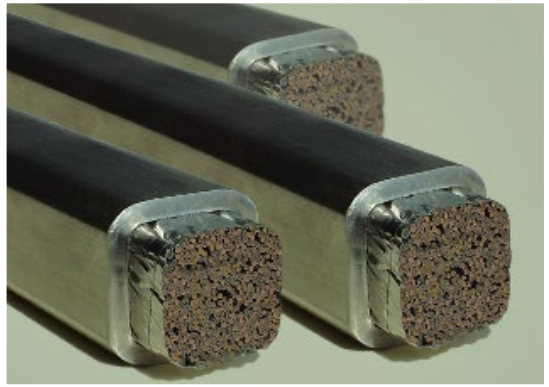
How to qualify Nb_3Sn SC magnet system performance without "full power (?) cold test" of all TF Coils?

For commercial Fusion Plant using SC Magnet (LTS or HTS), the success of QA/QC process without full cold testing for qualification is detrimental to achieve goal!

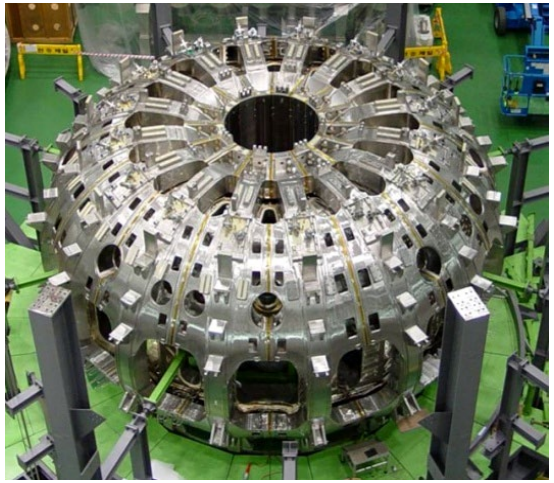
KSTAR Nb_3Sn SC Magnet System

- Superconducting Magnet System adopting Nb_3Sn both in 16 TF coils and in 8 CS / 2 PF(Divertor) coils. (4 PF Ring coils: NbTi)
- Each TF coils was encased in SS316LN structure and was assembled with accurate tolerance control. (Minimum possible Low-n Field Error)
- Central Solenoid was assembled in pre-loading structure by CS Shell Plate heating and Wedge adjusting.
- Electric insulation of coils are using pre-impregnated glass-fiber overwrapping and electric breakers on Helium lines. (Risk Management: Robust Electrical Insulation (Paschen) and Helium Leak Prevention)

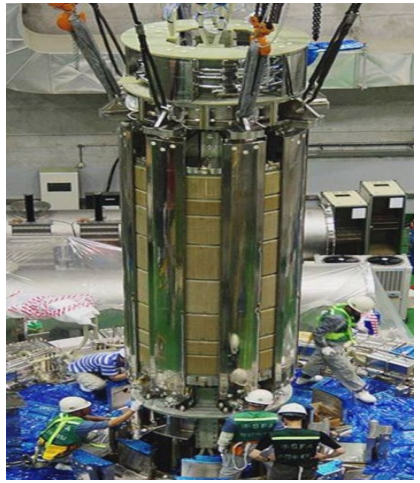




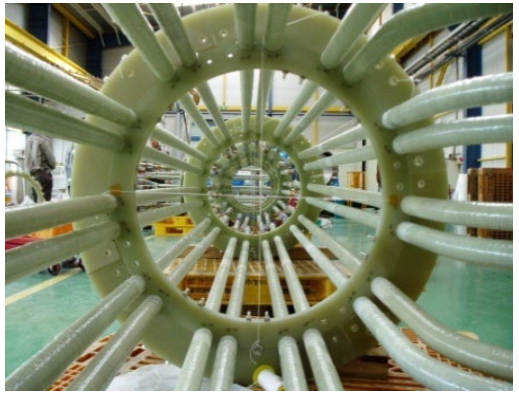
Nb3Sn Conductor & Incoloy908 Jacket



TF Magnet Assembly



CS under Installation



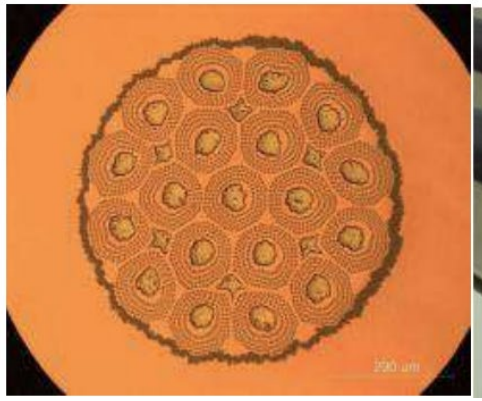
SC buslines with GFRP insulation

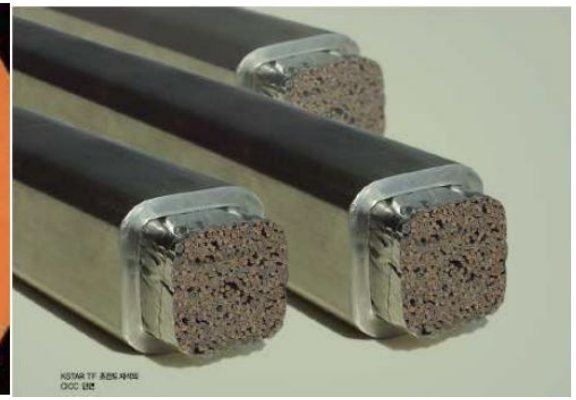
Electric breaker

Nb_3Sn SC Strand & CIC-Cable Quality Management

Item	Contents
SC Type	Nb_3Sn : PF1~5, NbTi : PF6~7
Dia. Of Strand	0.78mm
No. of SC Strand	240
No. of Cu Strand	120
Cabling Pattern	3×4×5×6
Jacket Material	Incoloy908 : PF1~5, 316LN : PF6~7
Dim. Of Jacket	22.3×22.3 mm²

Item	Contents
SC Type	Nb_3Sn
Dia. Of Strand	0.78mm
No. of SC Strand	324
No. of Cu Strand	162
Cabling Pattern	3×3×3×3×6
Jacket Material	Incoloy908
Dim. Of Jacket	25.65×25.65 mm²





From left to right: Lee Jun-Seg (Nexans Korea), Guido Roveta(I.C.A.S), Antonio Della Corte (I.C.A.S), Kwon Myeun (NFRI), Han Il-Young (Nexans Korea), Park Soo Hyeon (NFRI), Jung Ki Jung (NFRI), Lee Hyeon Gon (NFRI), Ahn Hee-Jae (NFRI).

CICC : Sultan Test

Nb_3Sn SC Coil Heat-Treatment Quality Management

- Locate position-representation samples of **Nb_3Sn strands around the coil during heat treatment**
- **Performance test of the stand samples** according to standard procedure (Jc at 4.2 K, 12 T & AC loss)
- In-direct but highly accurate measurement to assess the effect of **heat treatment "history"**

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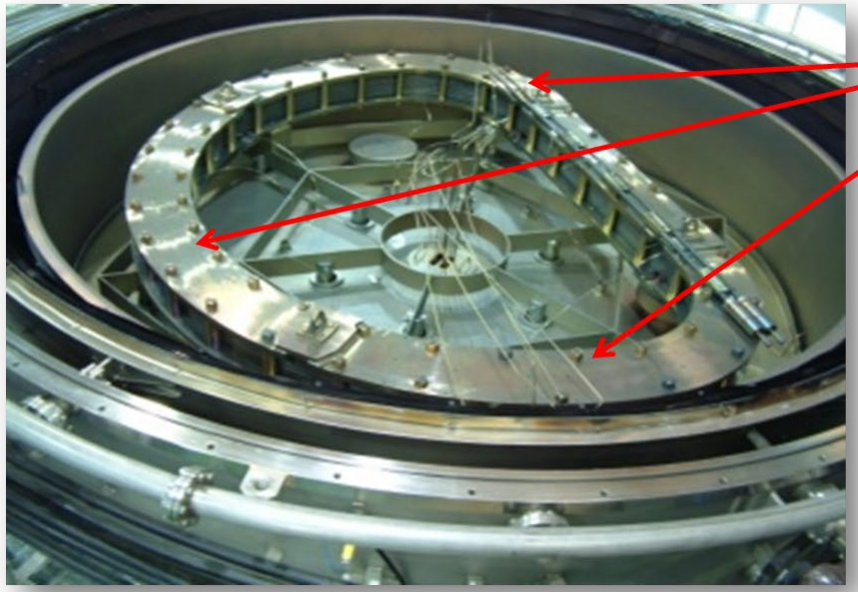
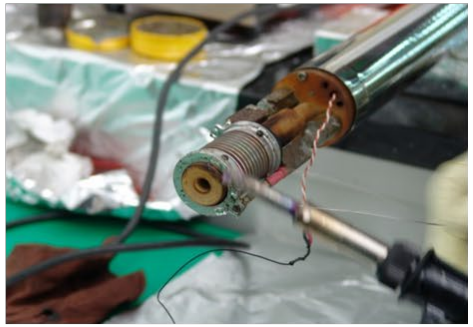
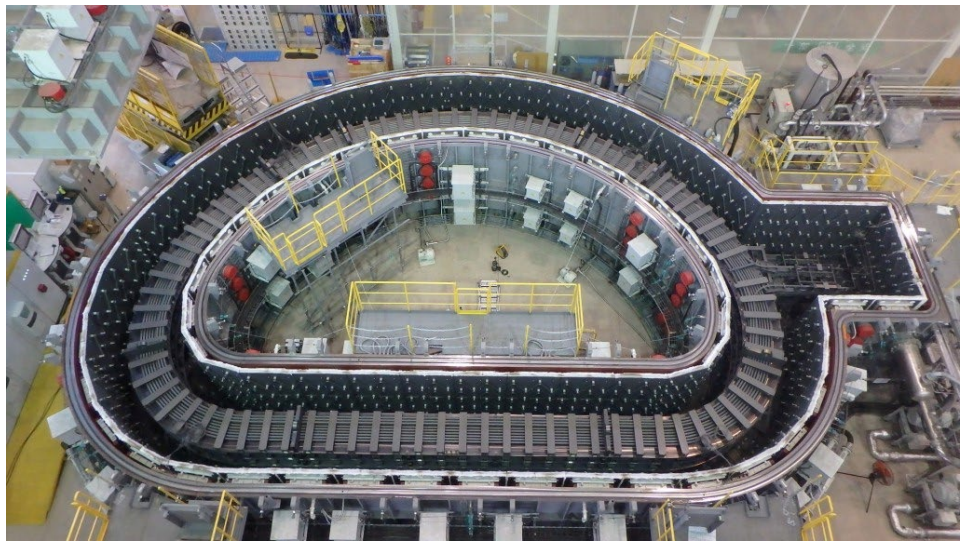
Specific Issue on "Wind & React" Process of Nb3Sn Coils







ITER TF Inert-Gas Environment Furnace

Strand samples (from specific TF coil) placed around TF coil during heat treatment (KSTAR Vacuum Furnace)

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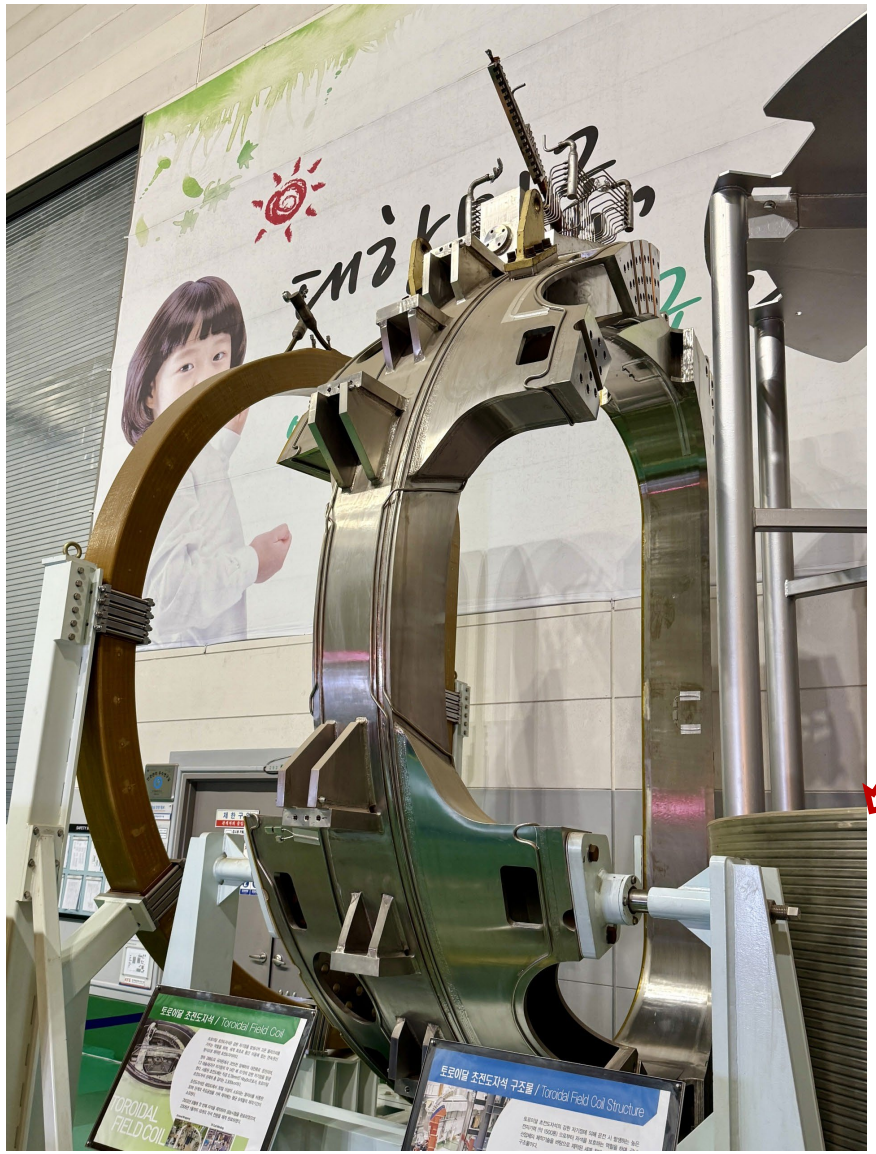
KSTAR Nb_3Sn TF Coil and Structure (TF00 Proto-type for Test)



Real CICC Cable
(Risk Management)

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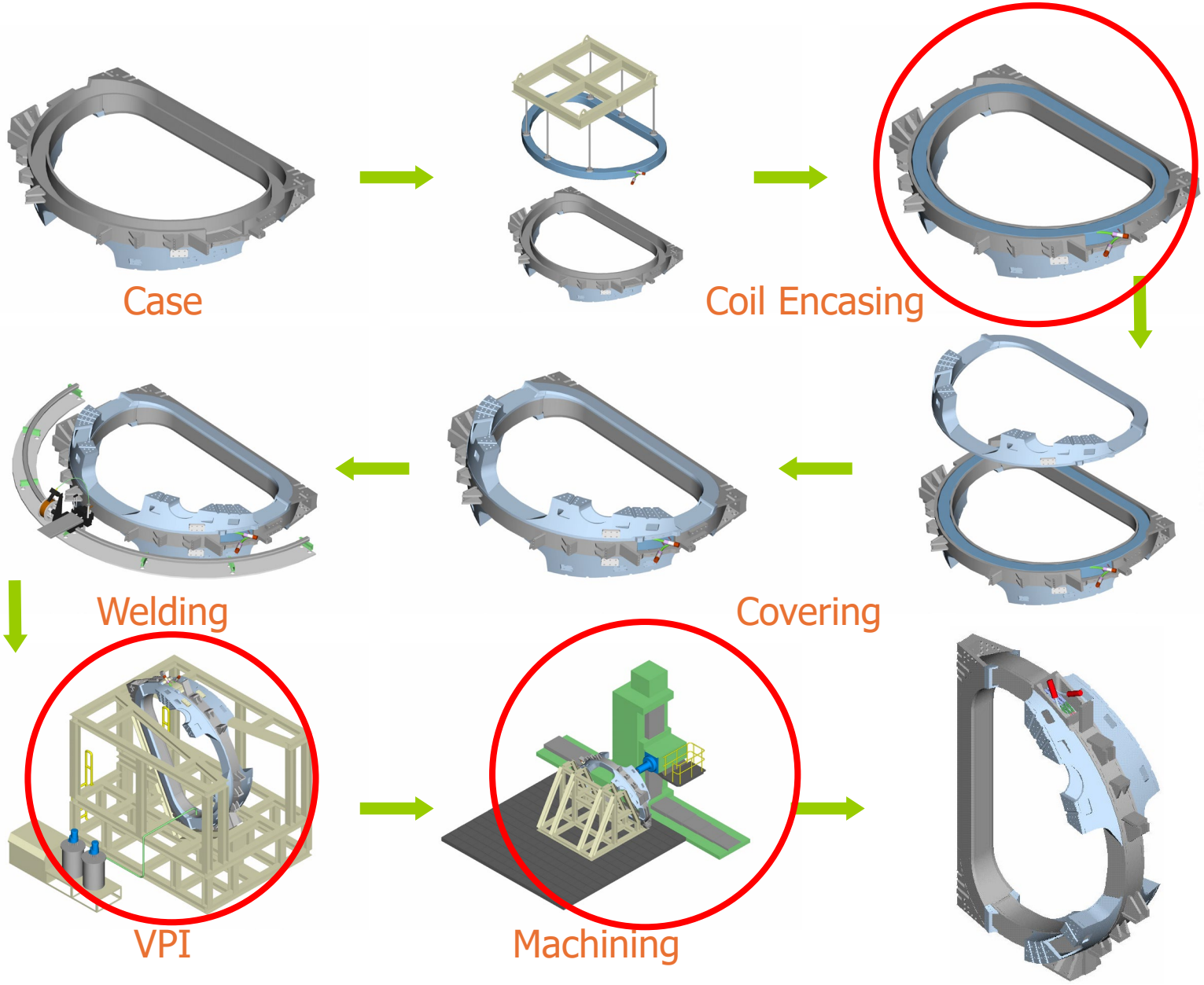
KSTAR TF Coil encasing to Structure (Low-n Field Error Control)



Field Perturbations

Ripple

- Physics goal: beam ion loss <5% due to stochastic ripple diffusion and ripple trapping.
- 16 Toroidal Field coils with D-shape, edge ripple 0.13%

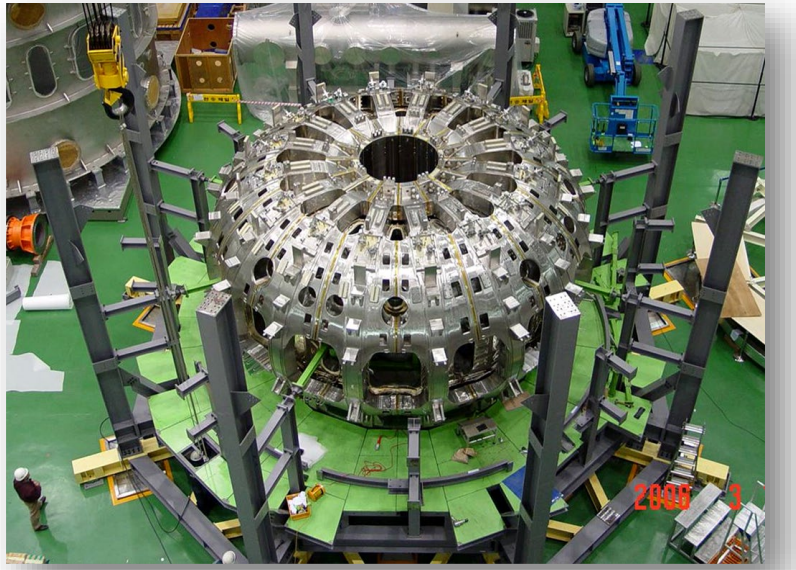
Field Errors

The definition of $\delta B_{r_{m,n}}$ is:

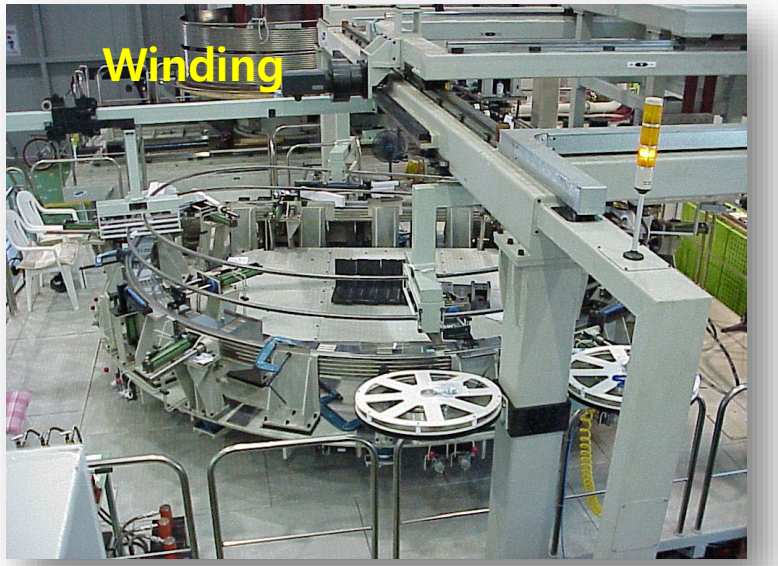
$$\delta B_{r_{m,n}} = \frac{1}{2\pi^2}\int_0^{2\pi}\int_0^{2\pi} \hat{r}\cdot\vec{B}e^{i(n\phi-m\theta)}d\theta d\phi$$

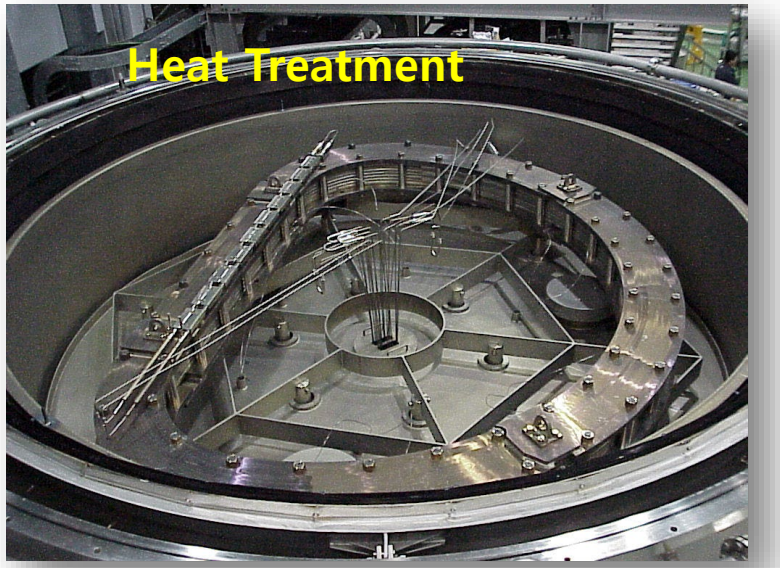
$$\left|\frac{\delta B_{r_{2,1}}}{B_0}\right| < 1\times10^{-4} \qquad \left|\frac{\delta B_{r_{4,2}}}{B_0}\right| < 2\times10^{-4}$$

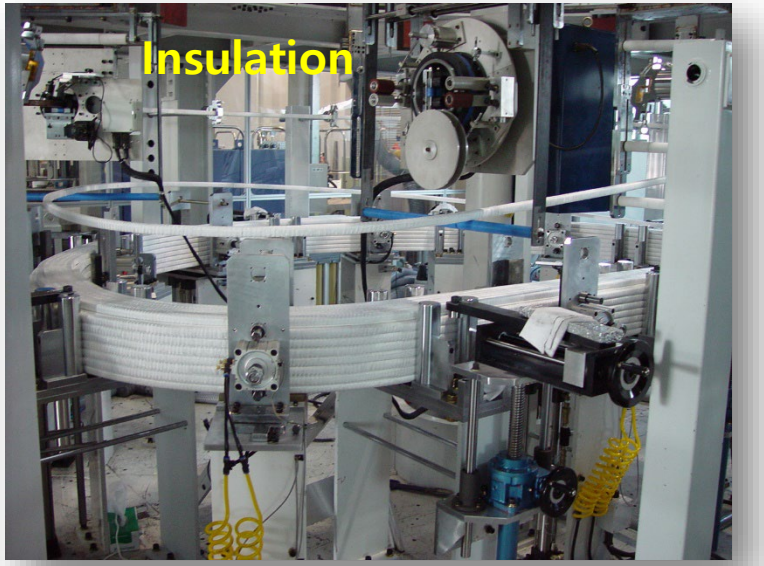
$$\left|\frac{\delta B_{r_{m,1}}}{B_0}\right| < 2\times10^{-4};\ m = 1,3,4 \qquad \left|\frac{\delta B_{r_{m,2}}}{B_0}\right| < 4\times10^{-4};\ m = 3,5$$

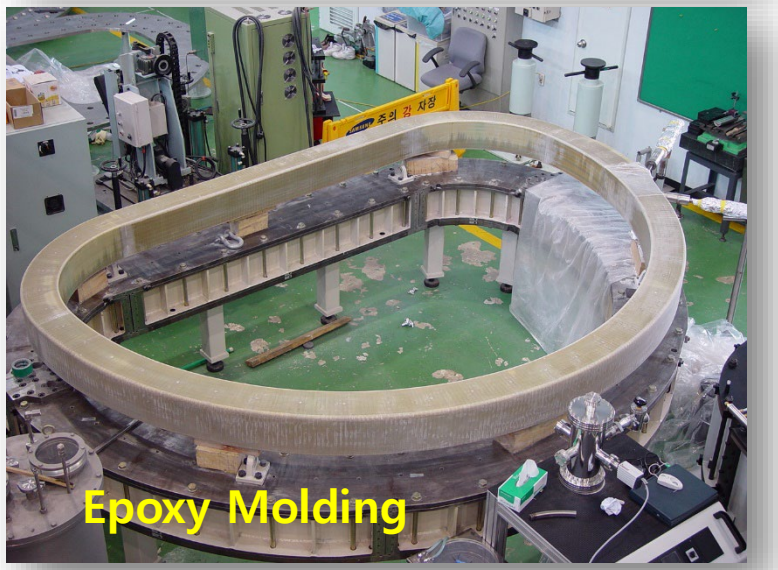


KSTAR Nb_3Sn TF Magnet (Samsung, Kiswire, Doosan, SFA …)

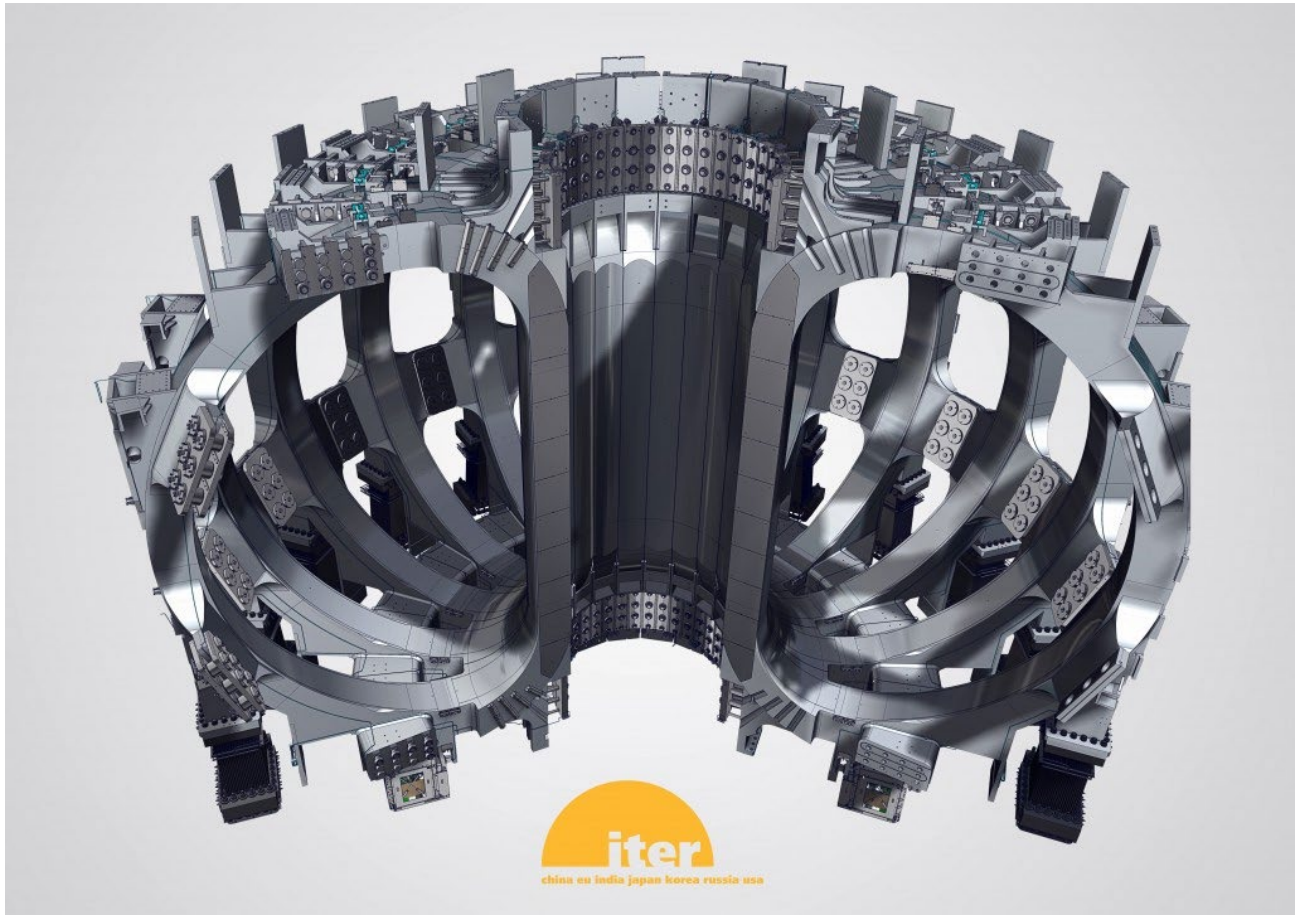


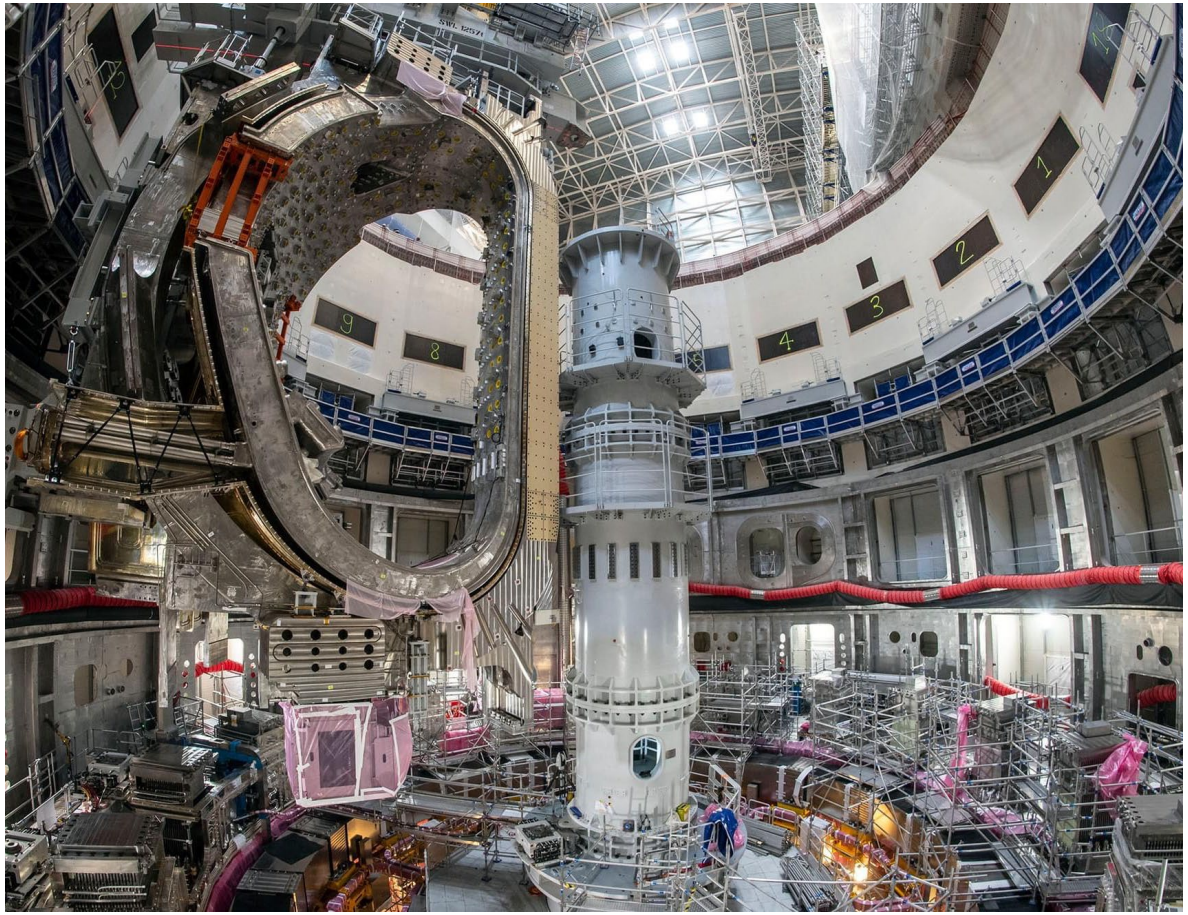




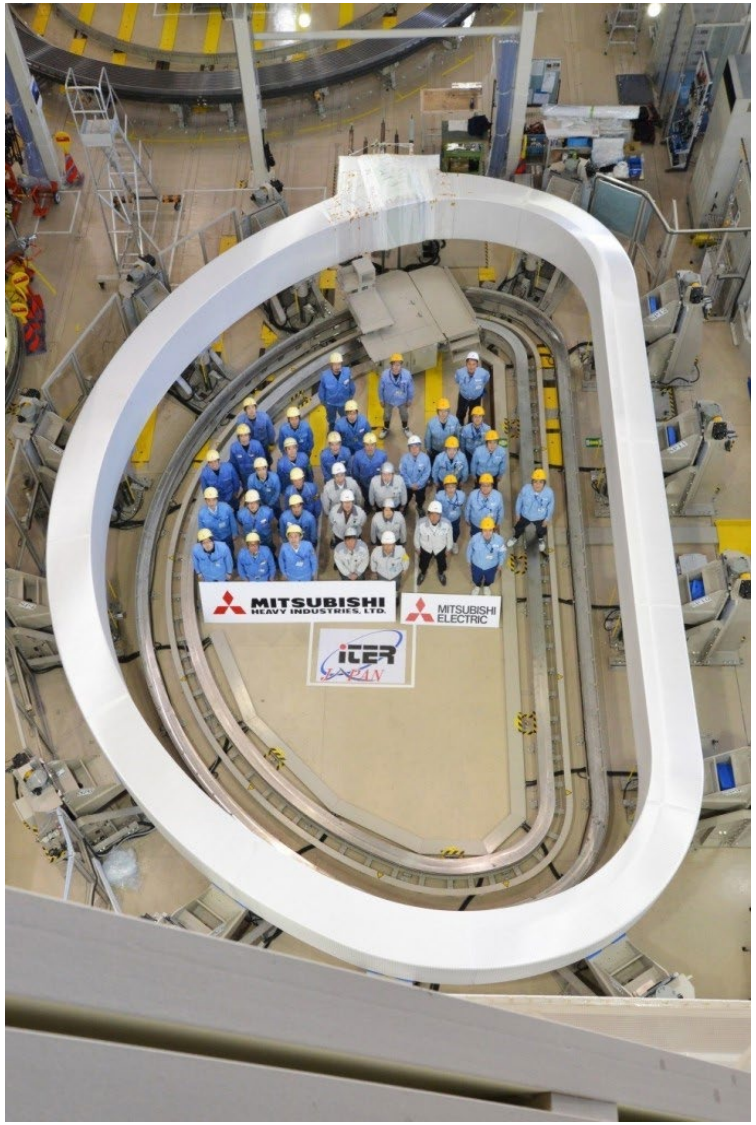


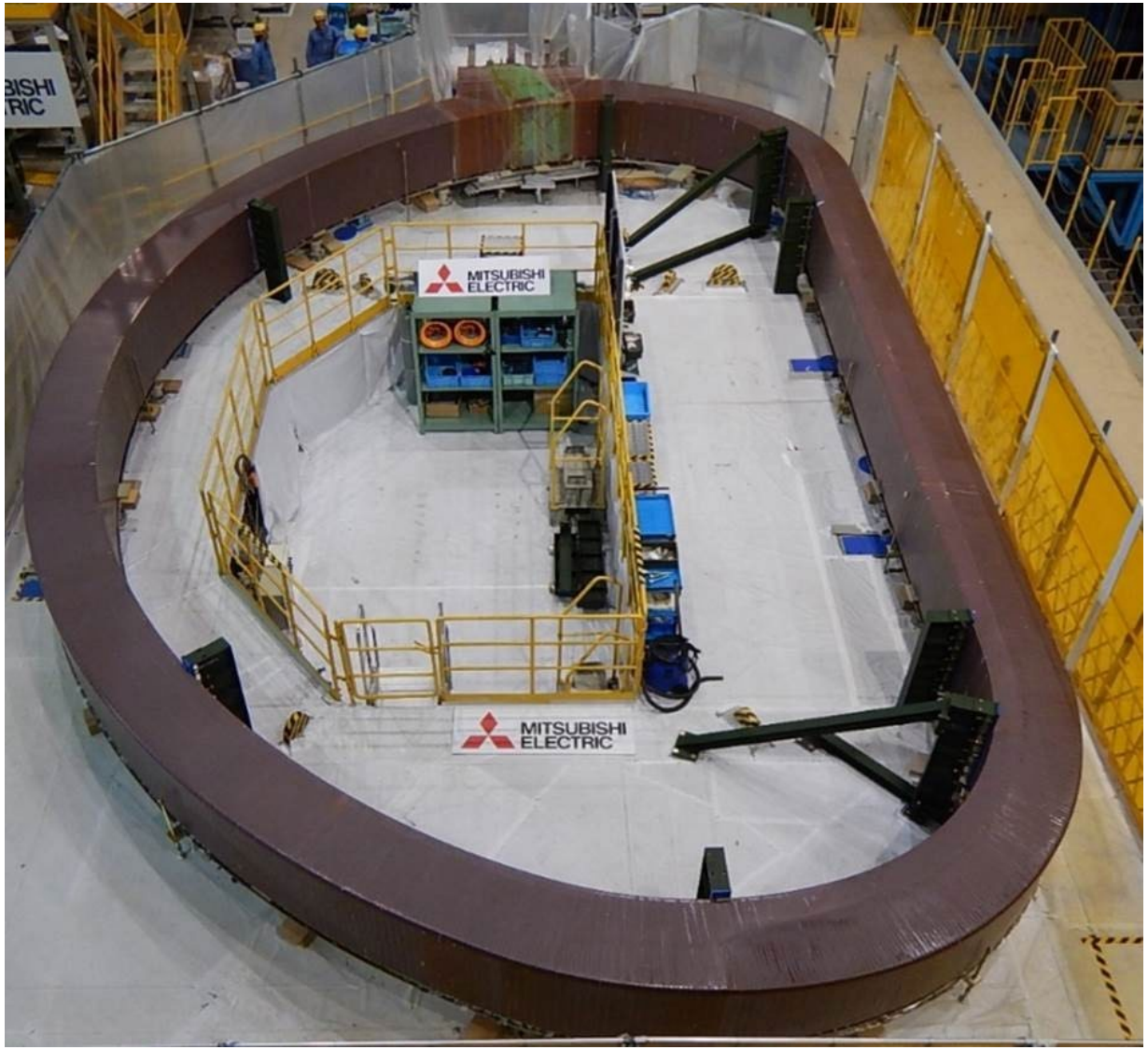
ITER Nb_3Sn Magnet Fabrication





ITER Nb_3Sn TF Winding Pack (JA : Mitsubishi & Toshiba)





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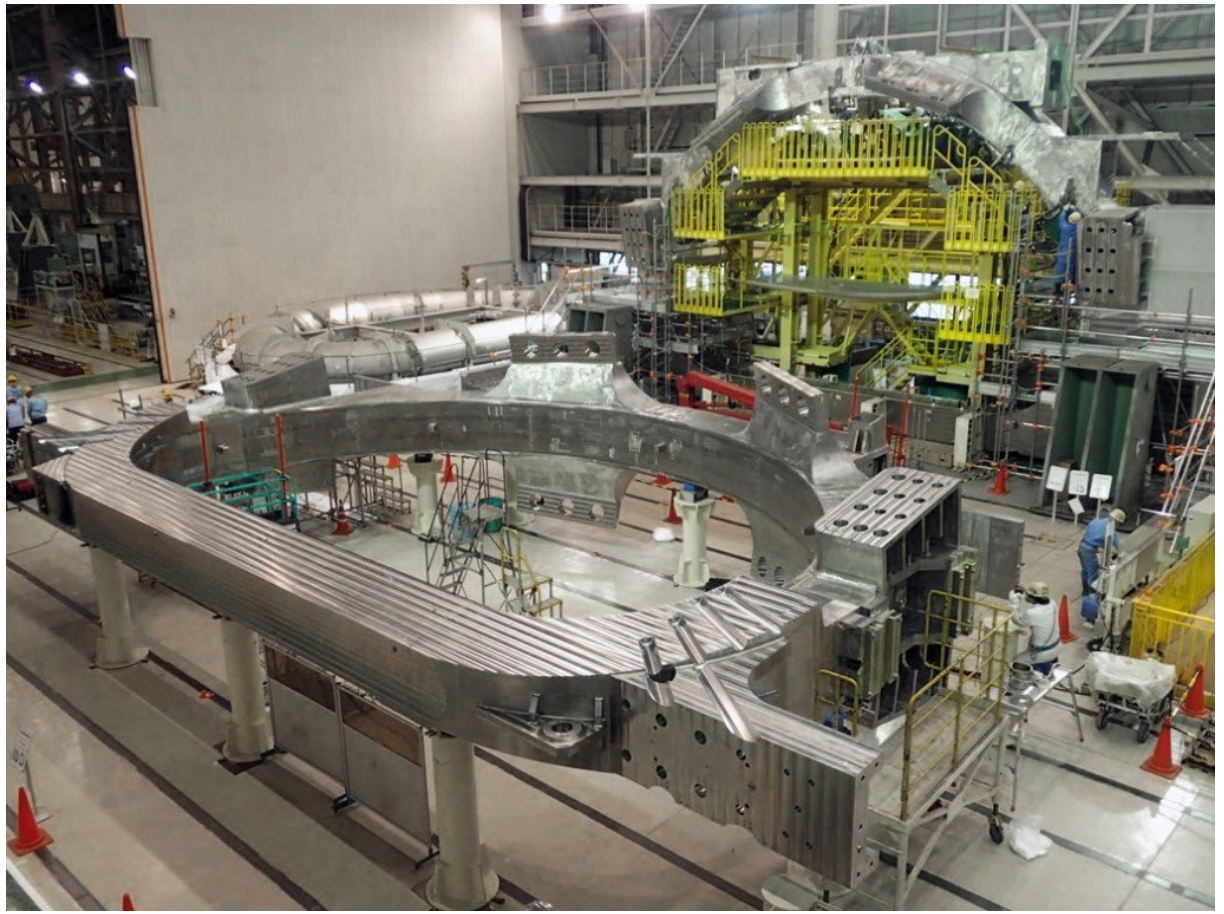
ITER Nb_3Sn TF Vertical Insertion (JA: Mitsubishi & Toshiba)



How to “harmonize” with EU Horizontally Inserted TF? Low-n Error?

ITER Nb_3Sn TF Cold Integrity Testing (JA : Mitsubishi & Toshiba)

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ITER Nb_3Sn TF Winding Pack (EU : ASG Consortium)

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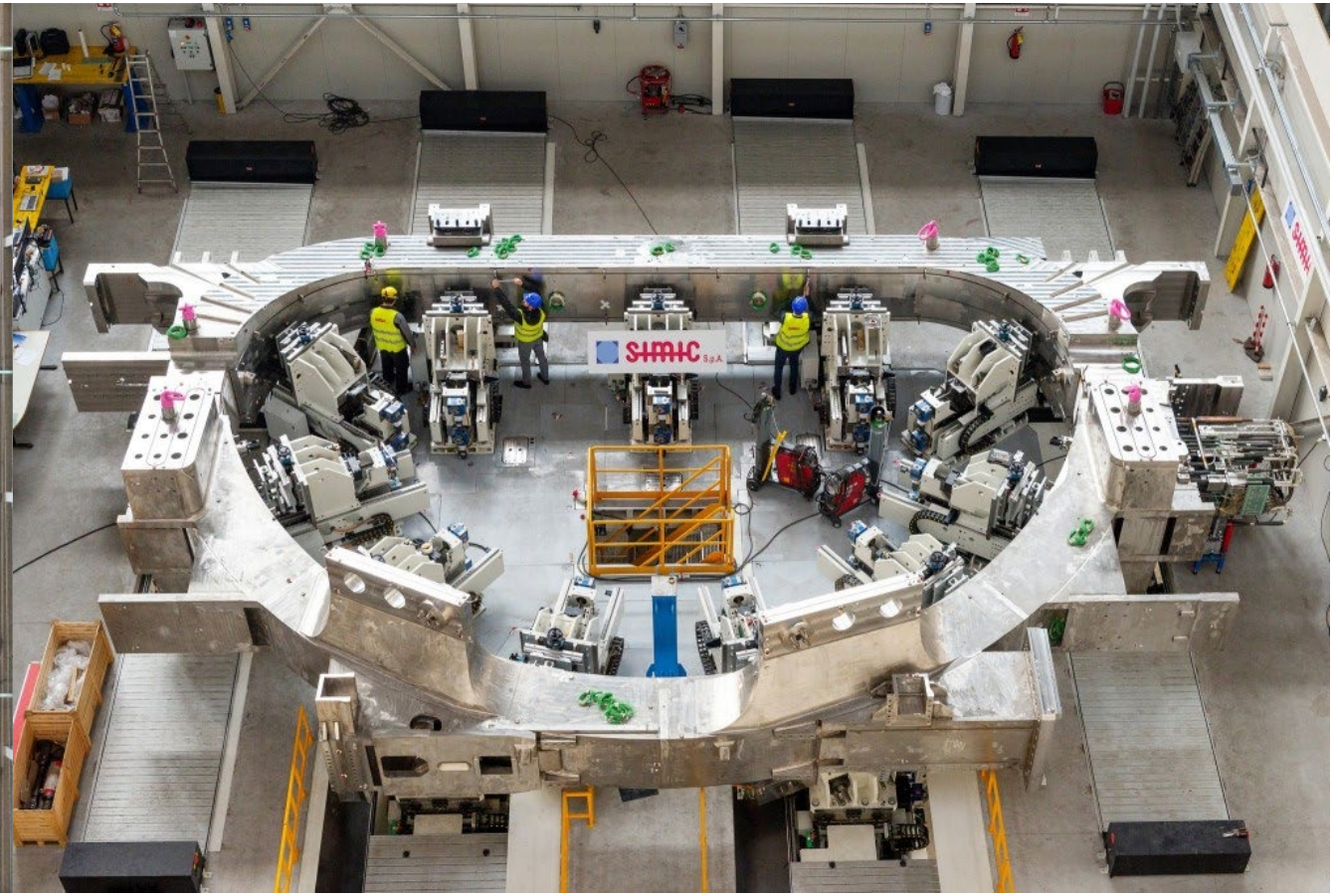
ITER Nb_3Sn TF Horizontal Insertion (EU : SIMIC)



How to “harmonize” with JA Vertically Inserted TF? Low-n Error Field?

ITER Nb_3Sn TF Magnet Completion (EU : SIMIC)

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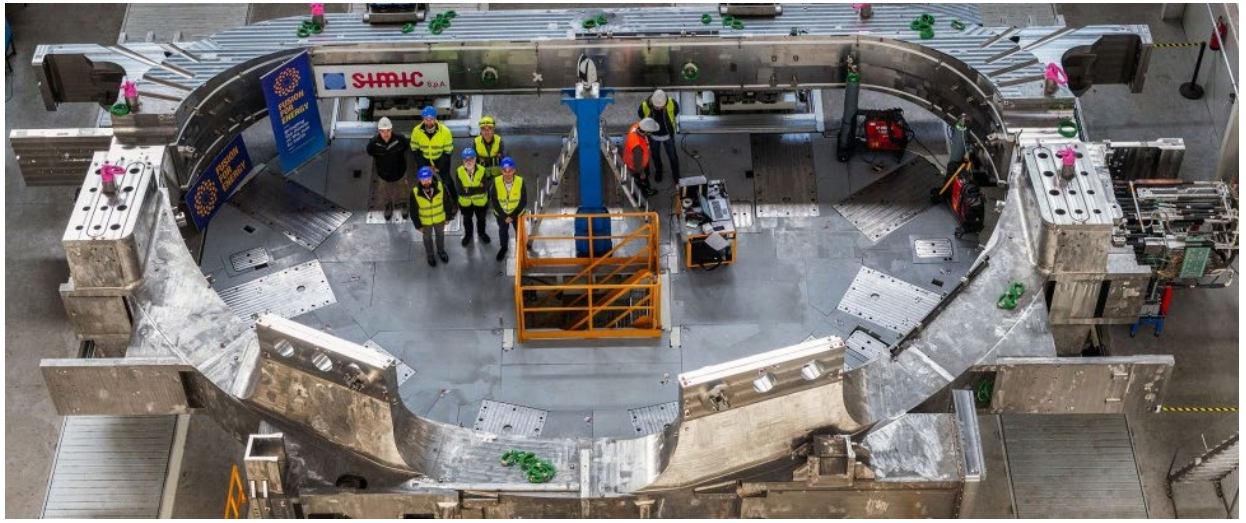
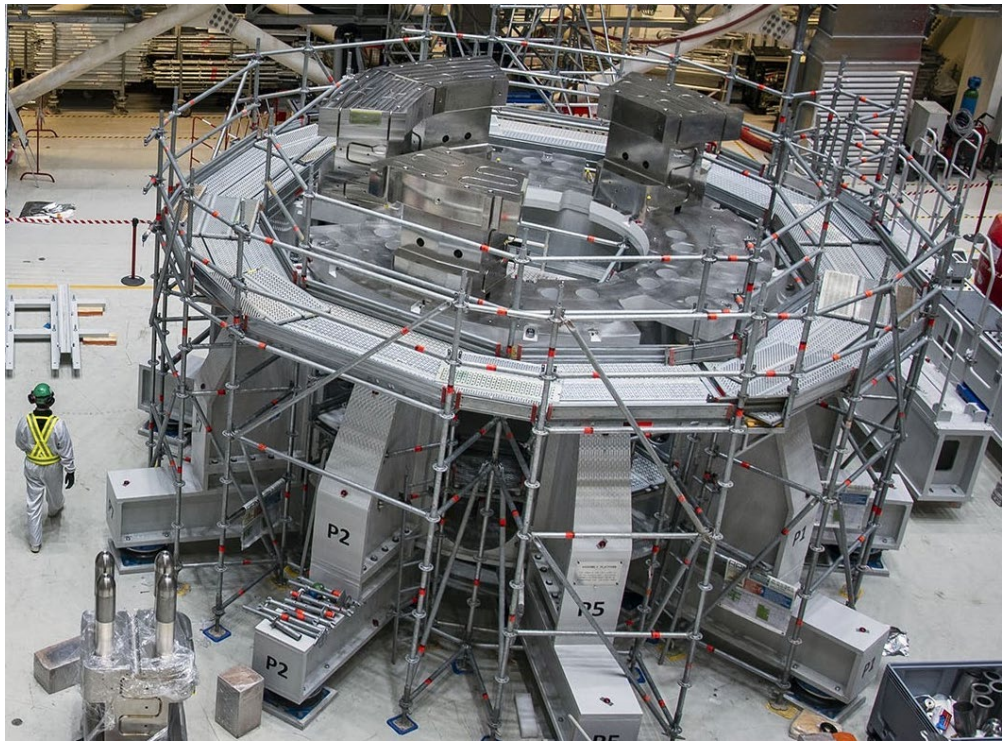


TF Cold Integrity Testing

ITER SC Solenoid Manufacturing (AC Nb_3Sn Magnet)

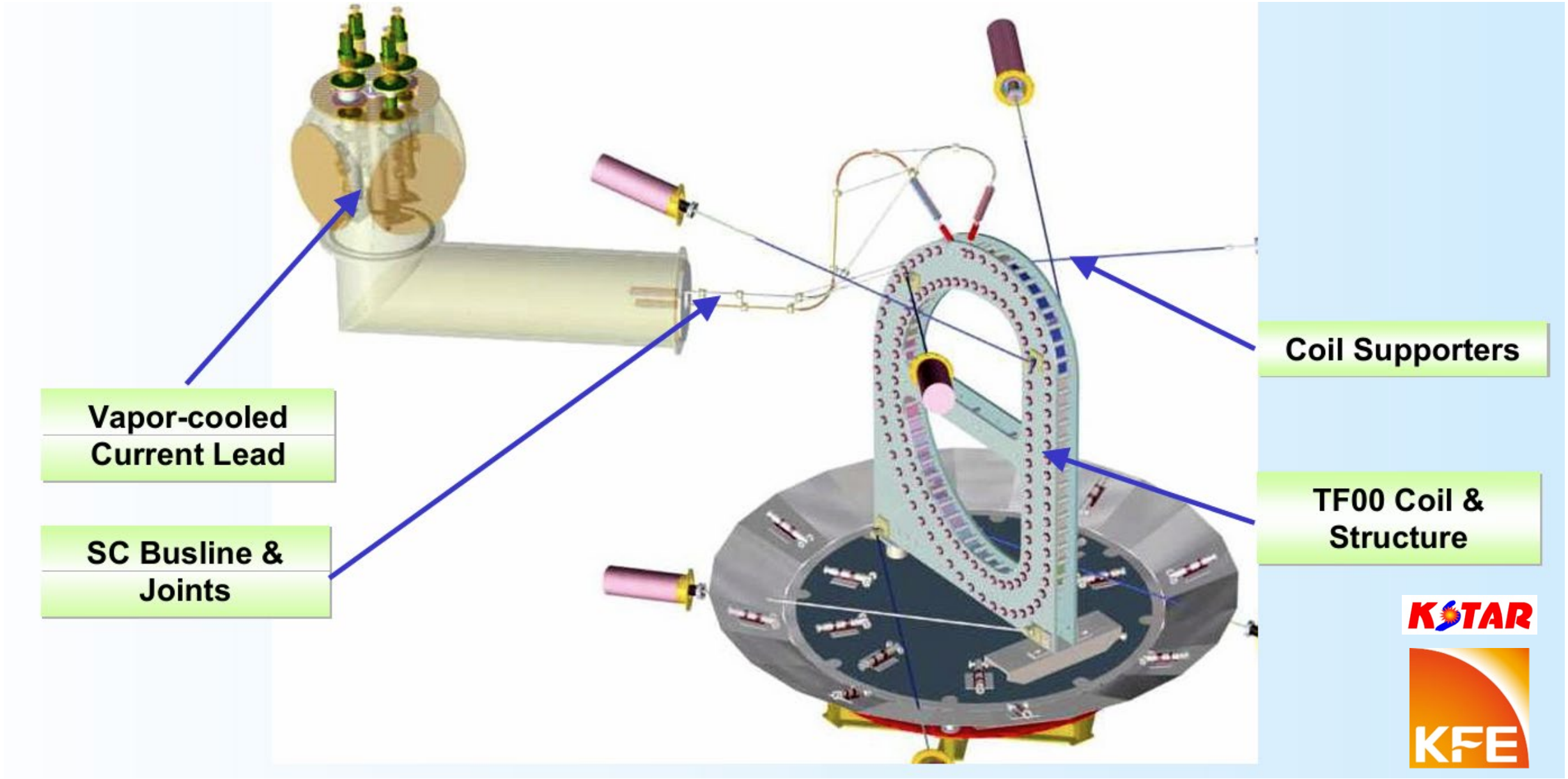


Central Solenoid Superconducting Magnets (US)

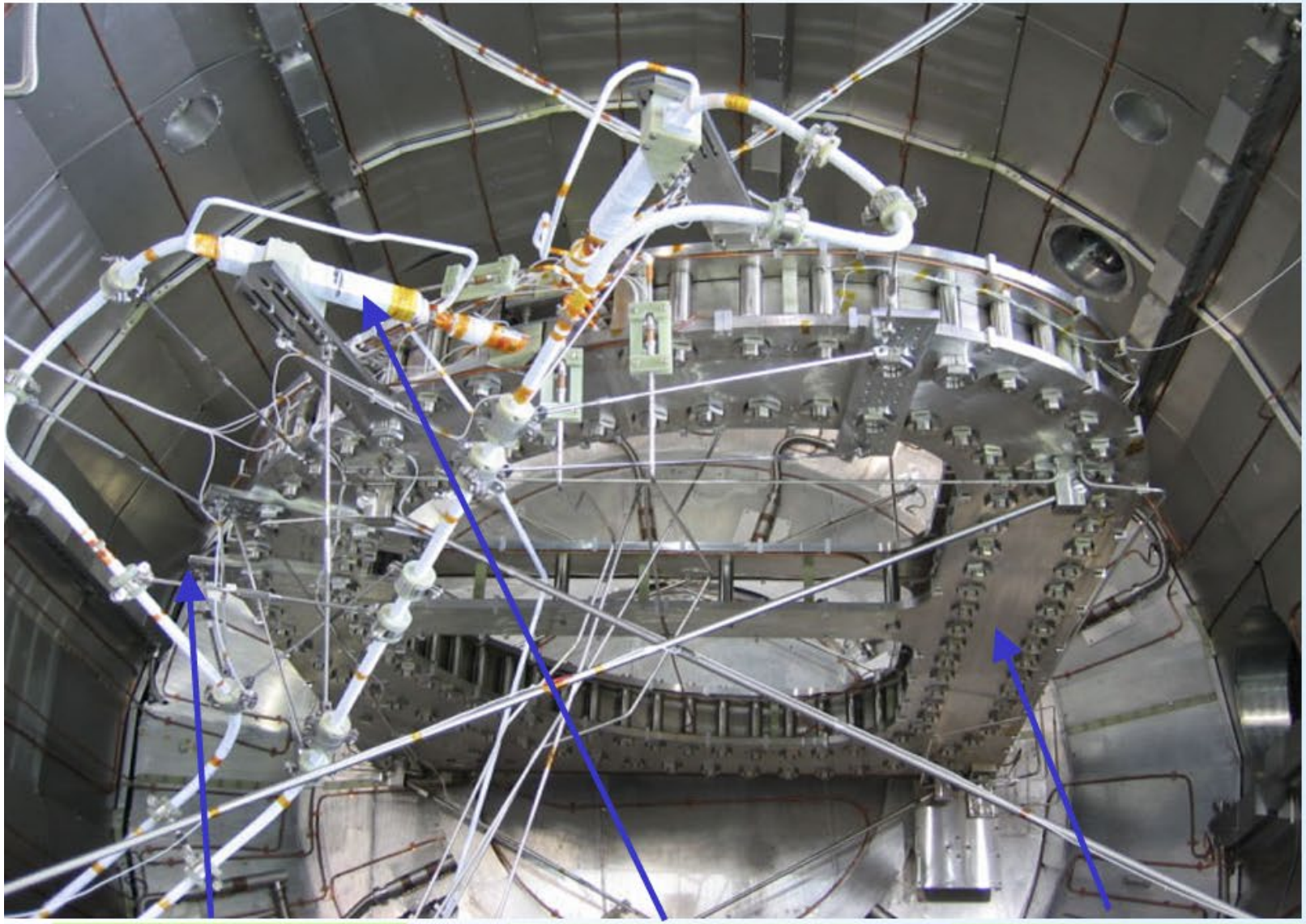
Nb_3Sn SC Magnet Cold Test

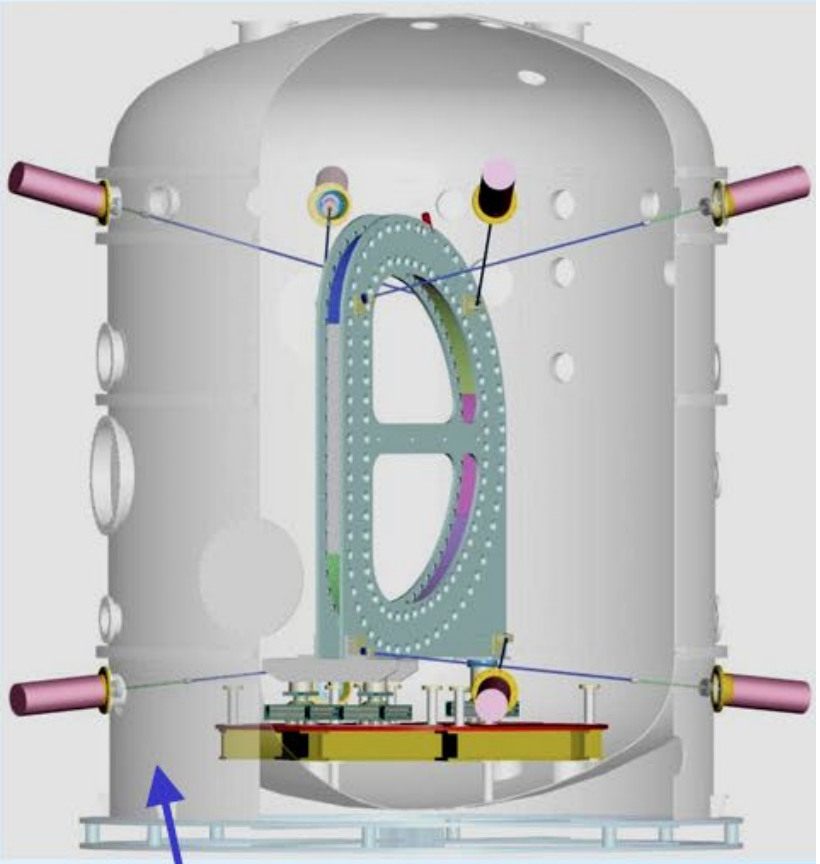
Why to do? & How to do?

KSTAR Nb_3Sn TF Coil Cold Test Program (using TF00 Proto-type)



KSTAR Nb_3Sn TF Coil Cold Test Configuration





SC Busline

Joints

Coil & Structure

Vacuum Cryostat

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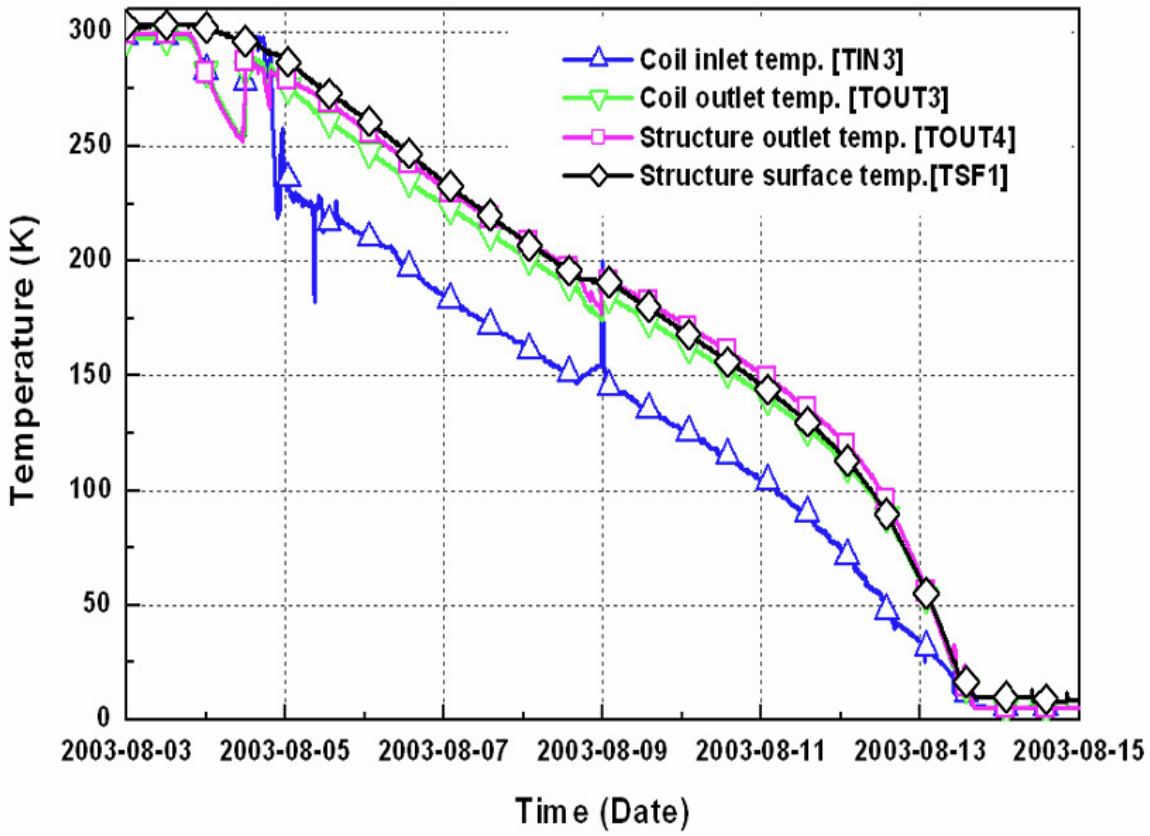
KSTAR Nb_3Sn TF Coil Cold Test (Cool-down & Thermal Load)

- Cool-down in 9 days
- RRR > 200 (requirement > 100)
- SC Phase transition @ 18 K
- No helium leak @ 5 K, 6 bar

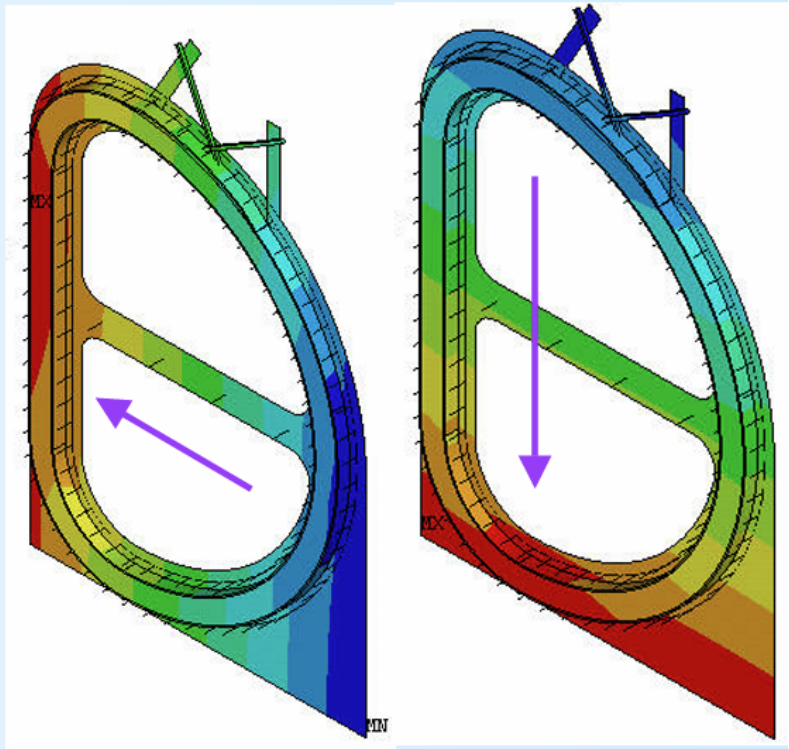
Temperature History during Cool-down



Thermal Contraction by Cool-down

Horizontal
(- 9.3 mm)

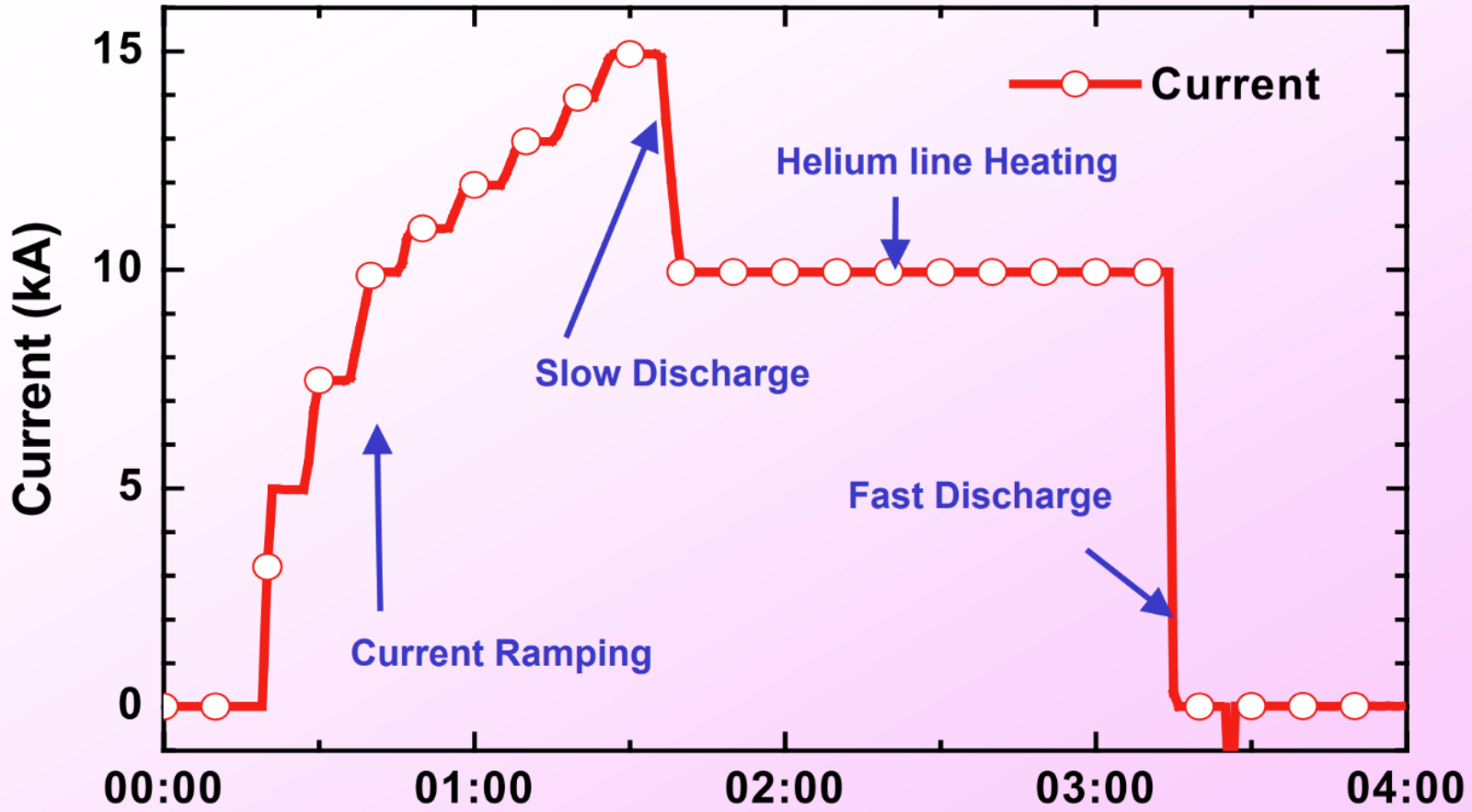
Vertical
(-13.3 mm)



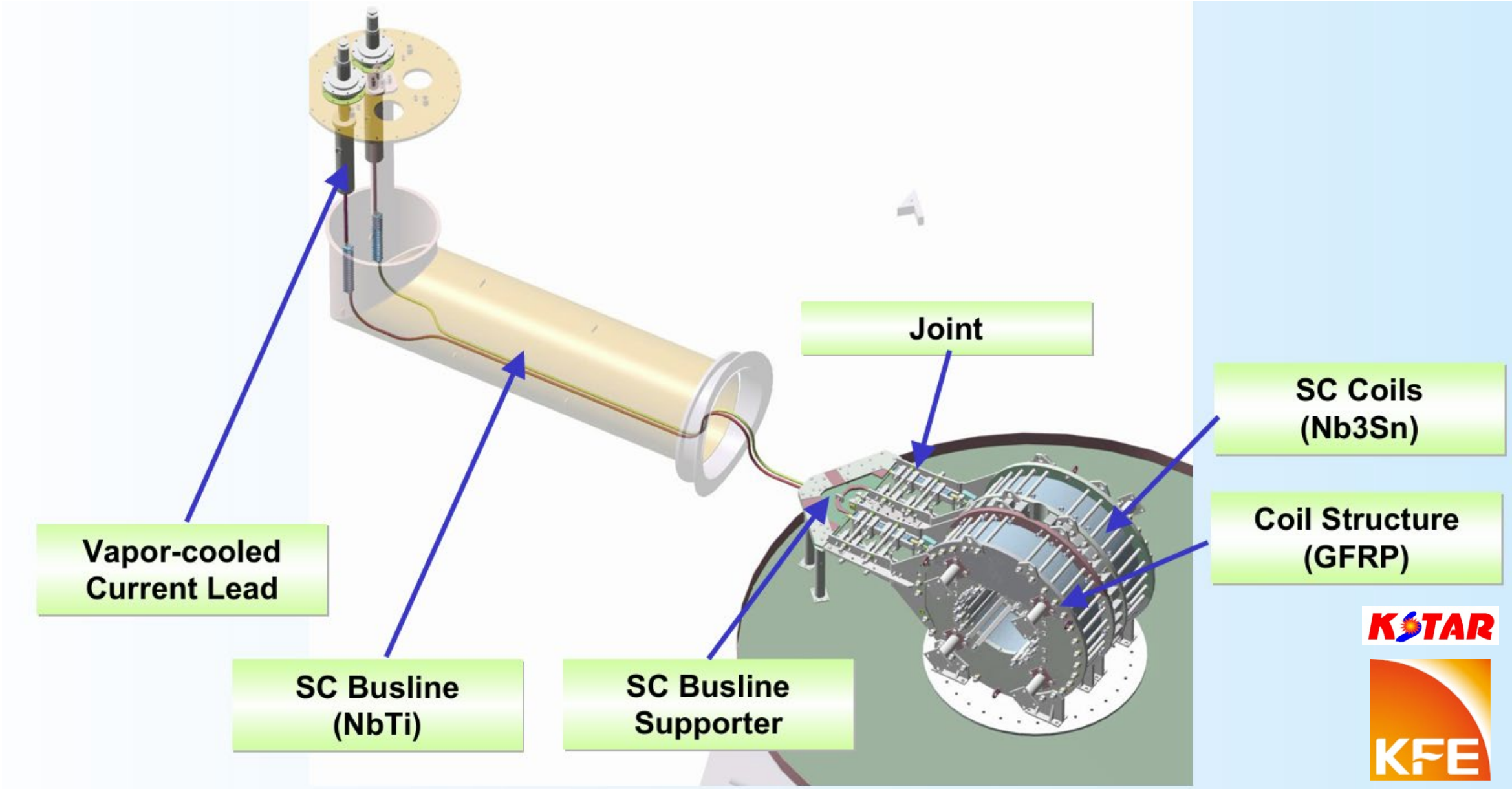
KSTAR Nb_3Sn TF Coil Cold Test (Current Excitation Test)

- Current Charge in step up to 15 kA
- Slow discharge to 10 kA
- Heating on helium inlet at 10 kA
- Fast discharge, τ_dump ~ 3 sec

Full Current or What Current Range Test (?)
Single Coil Self Field + Additional Background Field (?)
TF Magnet System vs. Single TF Coil : Different EM Load!
Joint Resistance Measurement (KSTAR Single-wind Coil)



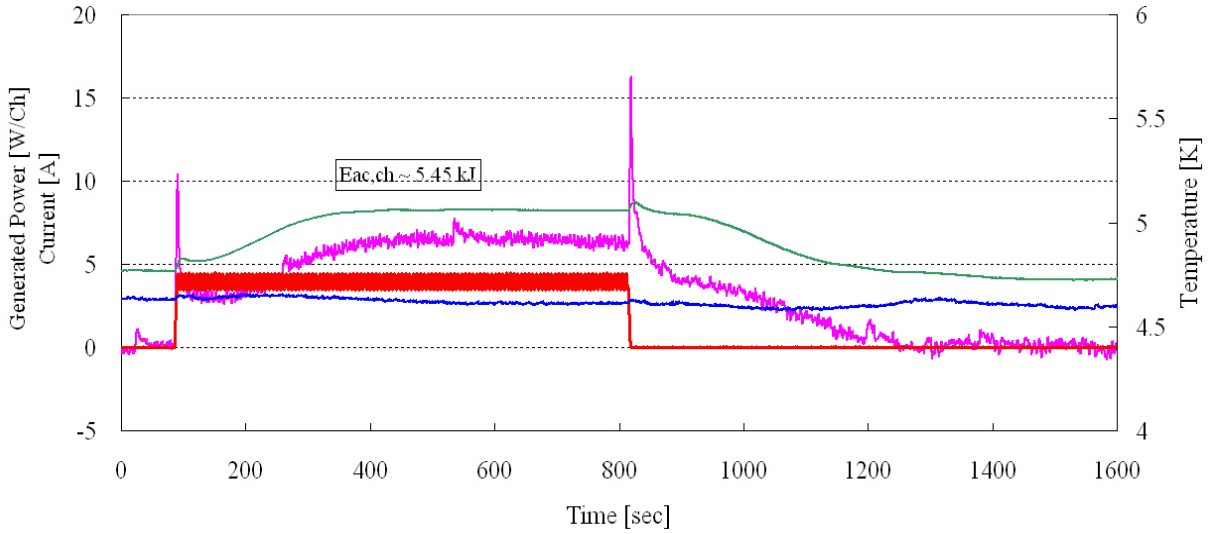
KSTAR Nb_3Sn CS Model Coil Cold Test Program (Split Coil)



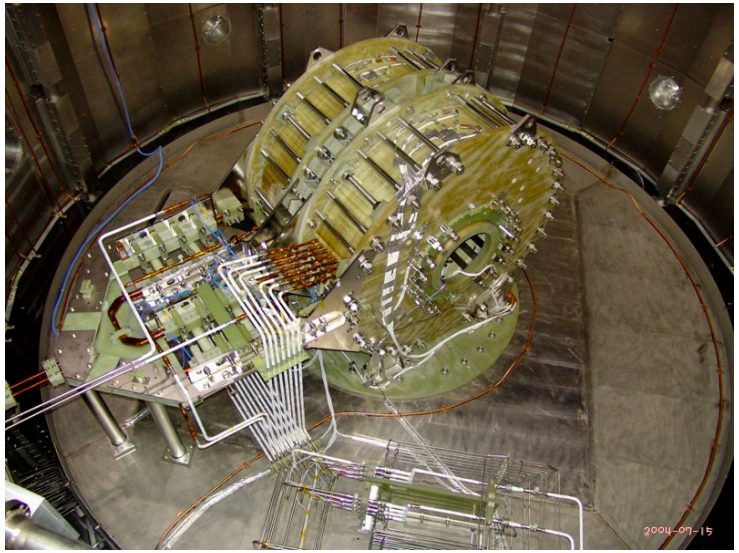
KSTAR Nb_3Sn CS Model Coil Cold Test Configuration

Originally conceived as "Background Field" Split-Magnet

- **CS Model Coils with Nb_3Sn conductor was tested at cryogenic temperature to measure the AC loss as well as the dc performance.**
  - DC charging: 25 kA, 10.6 T
  - AC charging: 10 kA (dI/dt=2 kA/s)
  - AC loss measurement under various waveform
  - (coupling loss coefficient : nτ measured)



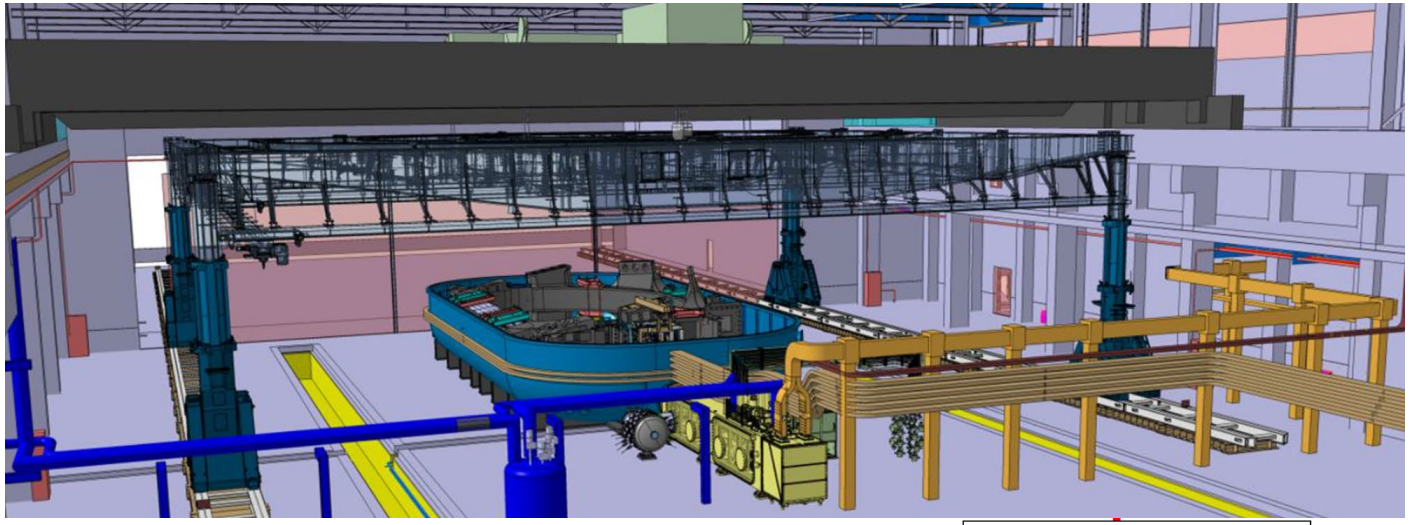
Sinusoidal waveform to measure AC loss

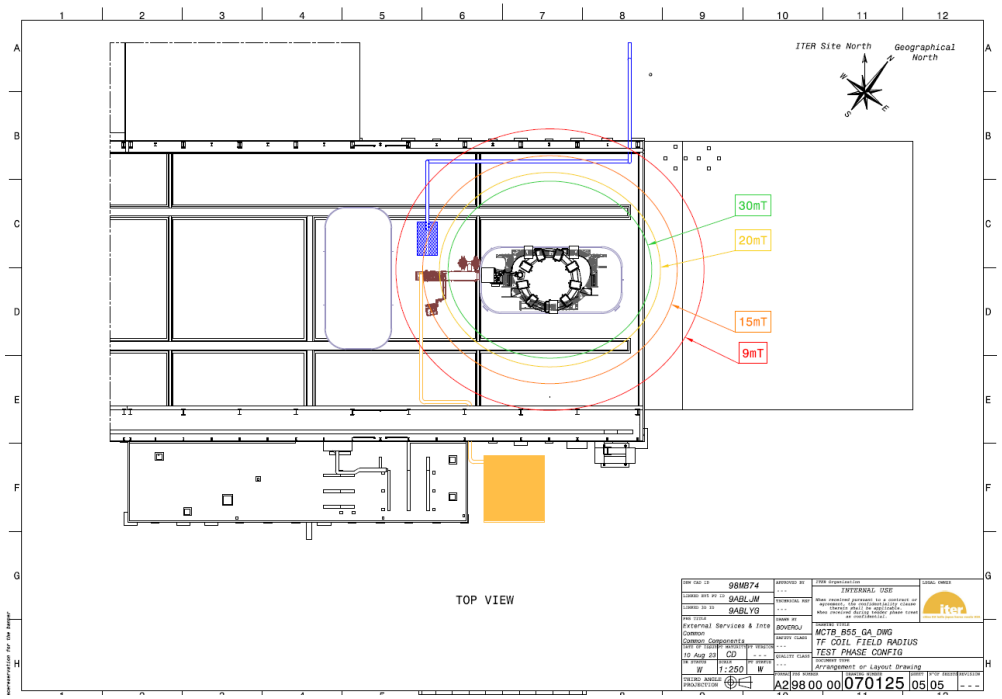


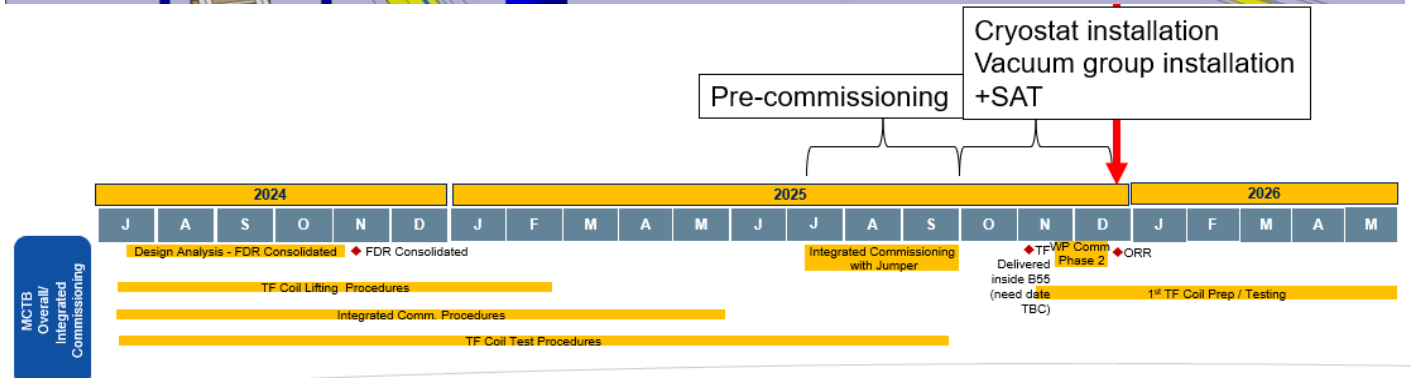
Pair of CS Model Coils in Testing

ITER “On-going” Nb_3Sn TF Coil Cold Test Program

- Testing will be on **as many TF coils as possible** (1 (spare) or 18 : Selection Rule(?))
- One test sequence is expected to last **6 months / TF coil** (18 TF Coils : 9-year Effort)
- **PF1** will also be tested later, to verify its performance in pulsed plasma conditions, and its size is compatible with a common test cryostat. (PF6 is Critical: Not-removable)







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Personal View on THE Issue :

Test should be based on Risk Management and Quality Assurance Program of the Project.

NOT by Worries!

(Need to study origin of W7-X and JT-60SA Magnet Issues)

- **Why and what to measure at what current range?**

(Field and Load conditions are different! Joints(?))

- **How many TF Coils to test with what logic?**

(What Temperature? How long years to test? What to gain?)

Key is Magnet Fabrication Quality Management Process!

(Strands, CICC, Winding Pack, Single Coil, Encasing, Final Machining)