Bringing a Nuclear Quality Approach to Superconducting Magnets

Special Session “Lesson Learned”

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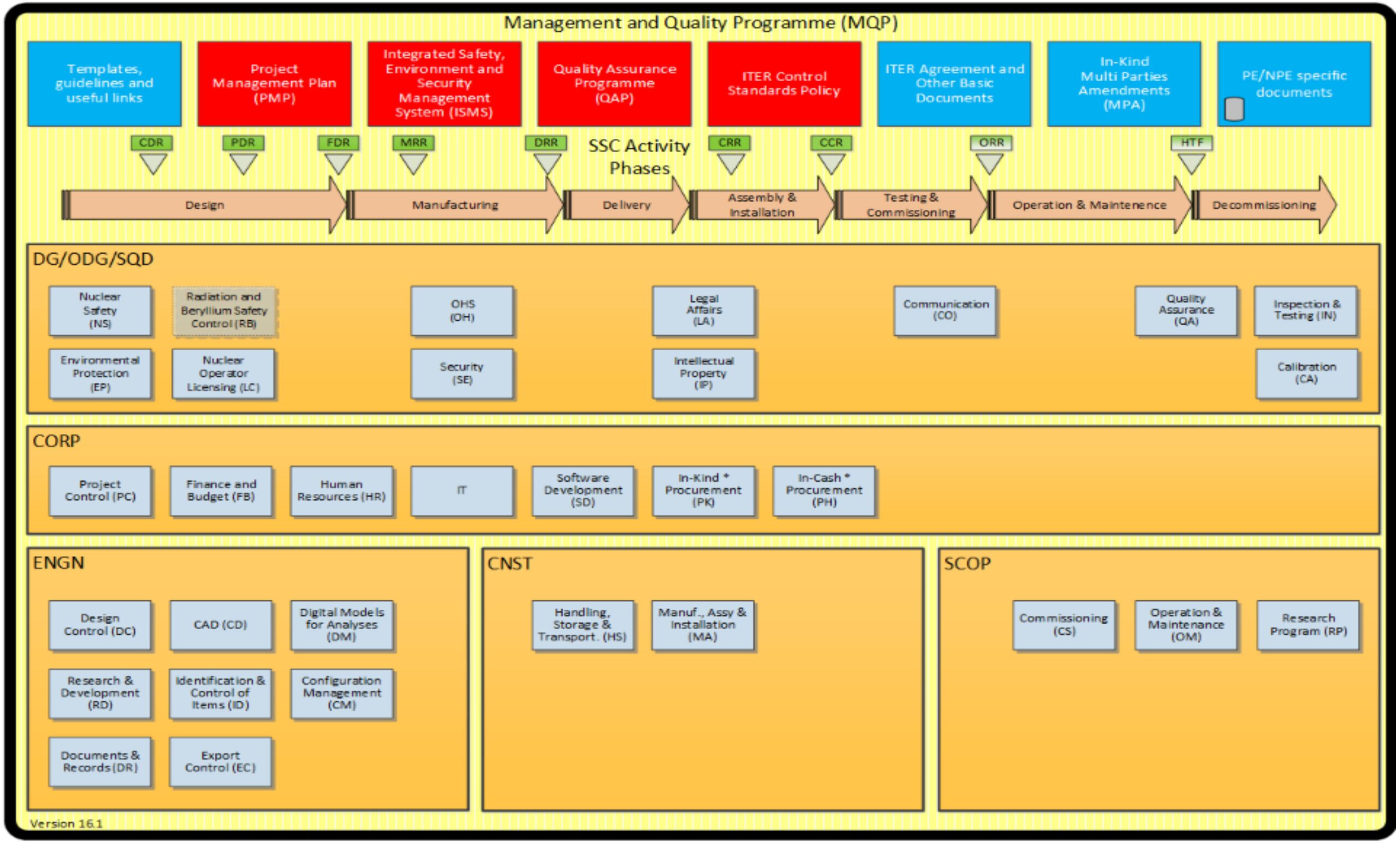
ITER Organization, France

Outline

- Overview of quality approach to ITER superconducting magnets
  - What is the nuclear quality approach/integrated approach in ITER
  - Methods and techniques for quality assurance in ITER Superconducting Magnets
- Status, Current and future challenge for Superconducting magnet QC programme
  - Challenge
  - Superconducting magnet QC programme
  - Some examples mostly happened in sensitive quality areas such as insulation, He leaks, welding, and in deviations from special process control
- Lessons learned and advances in science and technology to meet challenges

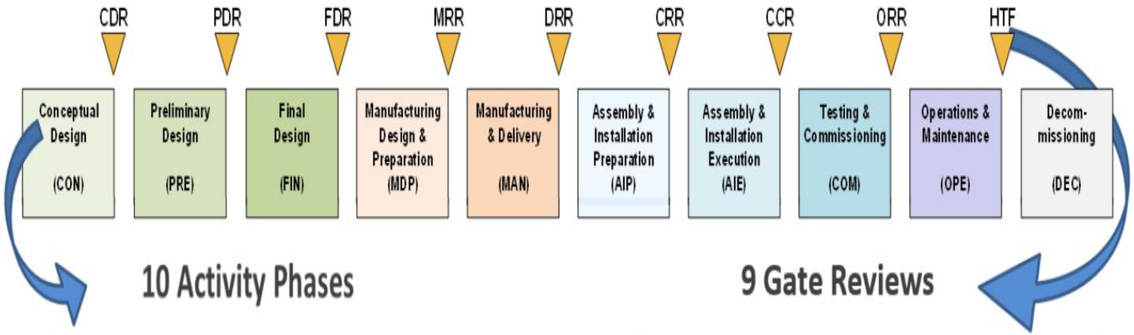
ITER Quality Assurance Program

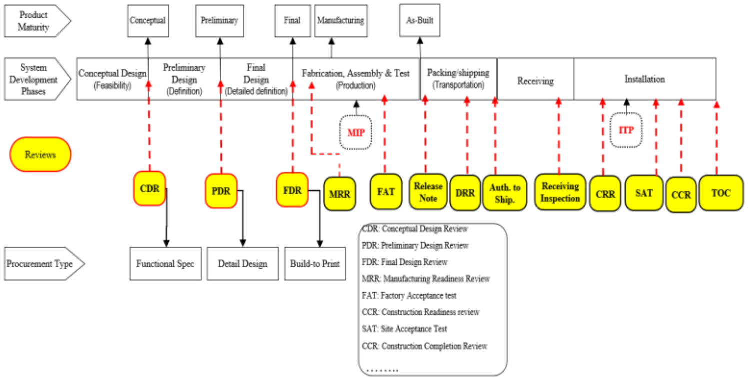


Integrated Quality Approach Superconducting Magnets covers a very wide range of manufacturing, assembly and operational items, weighted by impact;

A series of mature quality assurance and traceable quality control methods during ITER manufacturing and assembly.

Gate reviews and control points for technical/quality control during the whole lifecycle





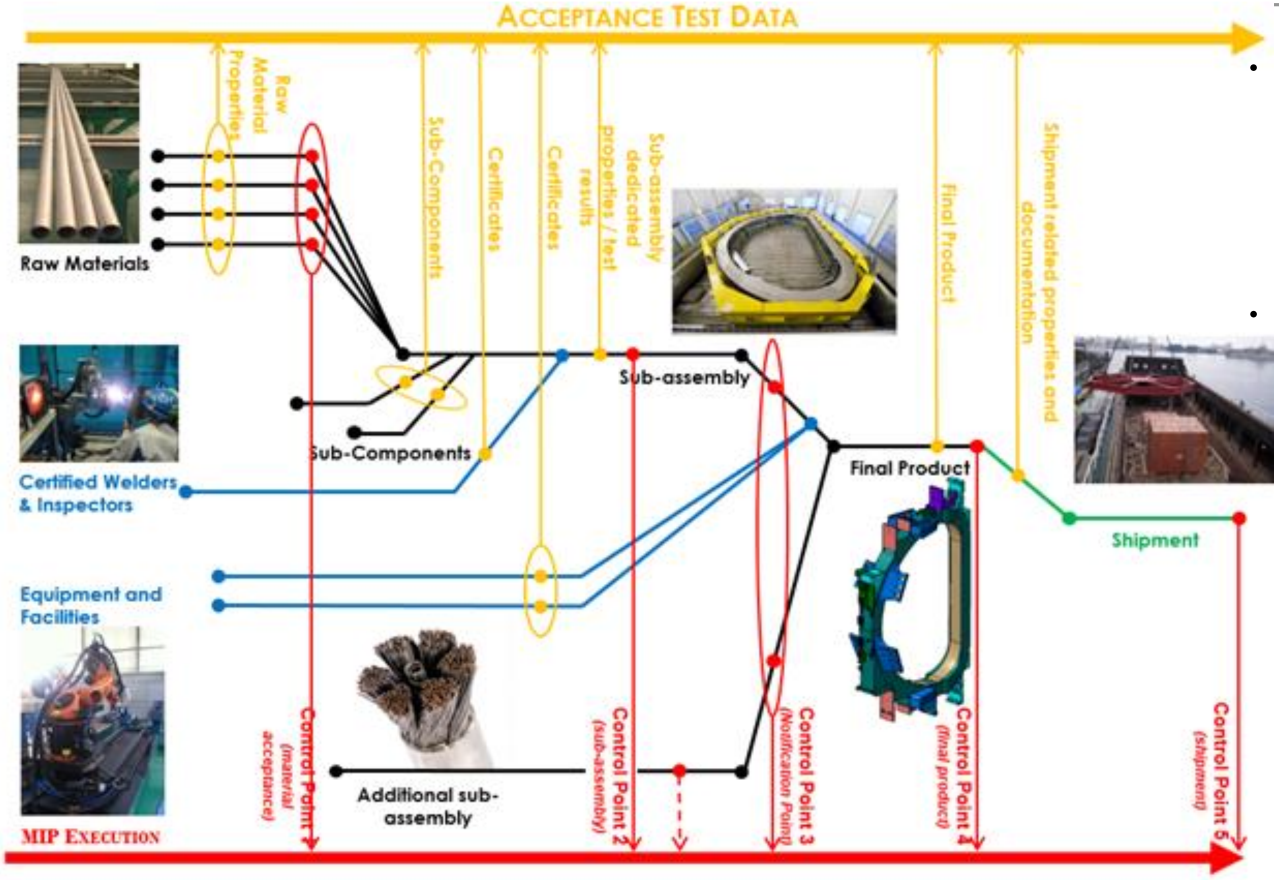
CON	Conceptual Design
PRE	Preliminary Design
FIN	Final Design
MDP	Manufacturing Design & Preparation
MAN	Manufacturing & Delivery
AIP	Assembly & Installation Preparation
AIE	Assembly & Installation Execution
COM	Testing & Commissioning
OPE	Operation & Maintenance
DEC	Decommissioning

CDR	Conceptual Design Review
PDR	Preliminary Design Review
FDR	Final Design Review
MRR	Manufacturing Readiness Review
DRR	Delivery Readiness Review
CRR	Construction Readiness Review
CCR	Construction Completion Review
ORR	Operation Readiness Review
HTF	Handover to France

Full List of Panel experts / representatives	Participation
Review Chair (Chairperson)	M
IO-Nuclear Operator [SQD]	M
IO/QA representative (QARO) [SQD/QMD]	M
IO/Health and Safety [SQD/SHS]	M
IO/Design Integration (SIRO(5)) [ENGN/CIO/PFI]	M
IO/Assembly&Installation [CNST/CMO]	O (M for FDR)
IO/Operations [SCOP/SCOD/OPD]	M
IO/Science [SCOP/SCOD/SCD]	O
IO/Maintenance [SCOP/SCOD/OPD]	O
IO/Main Interfacing System Representatives	O
IO/I&C [SCOP/SCOD/CD]	O
Other Technical Experts (1)	O
Concerned DA (2)	M (4)
CEA expert (3)	O

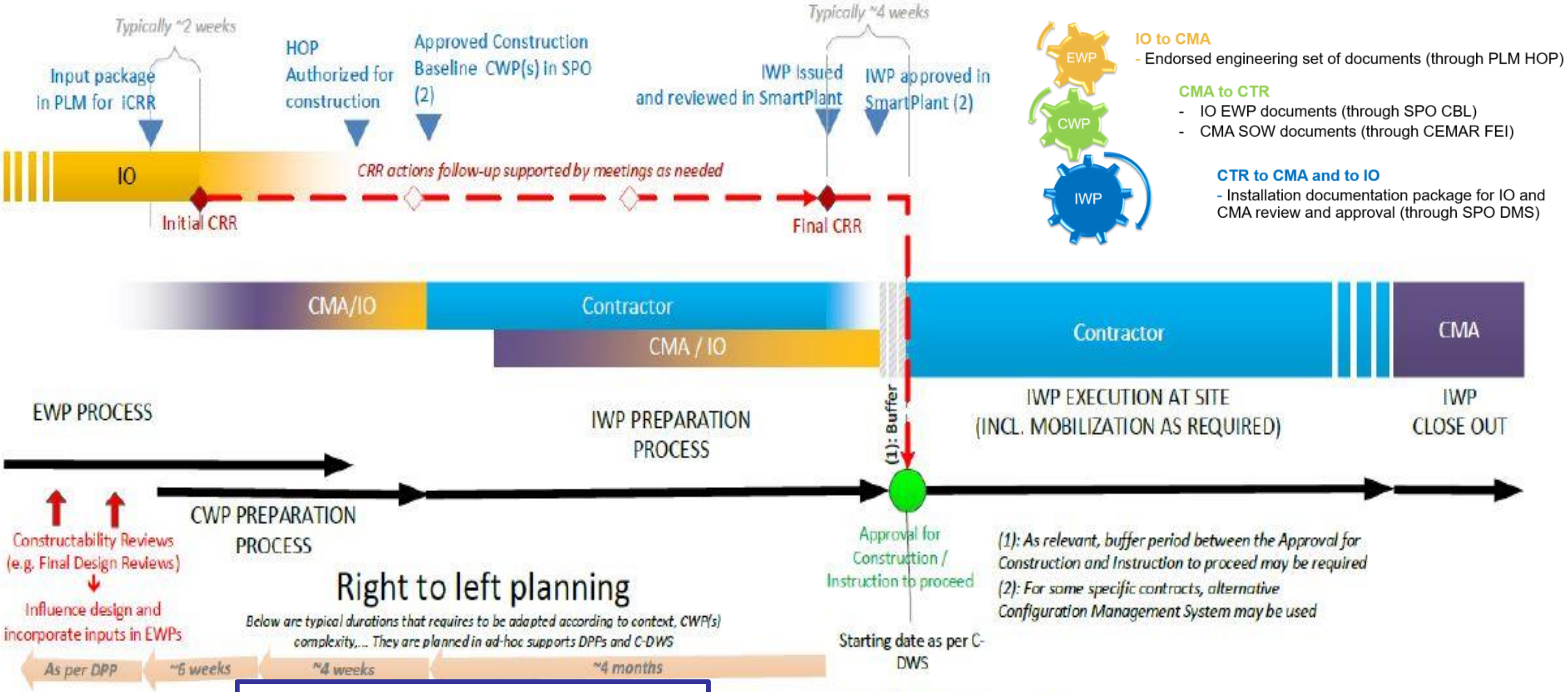
M *= Mandatory participation*
O *= Optional participation*

Implementation of manufacturing database in ITER conductor coil production



- In order to be compliant with the defined requirements and/or technical requirements, ITER developed a manufacturing database to monitor the progress of activities and control the quality during procurement control.
- With the implementation of the conductor database, during the 4 years of the conductor production period, the ITER Organisation (IO) has cleared ~6900 control points for the strand lots, and ~27 000 critical measurements are well monitored and qualified. It covered the production for 600 t of Nb3Sn strands for the TF and CS coils, while it needed around 275 t of Nb–Ti strands for the PF and CC and bus bar conductors.

Assembly and Installation quality and documentation Process Control

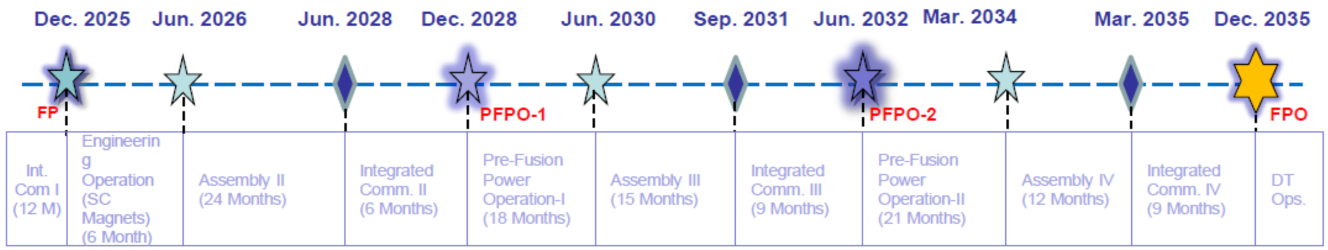


Engineering Work Package (EWP)
Construction Work Package (CWP)
Installation Work Package (IWP)

EWP-CWP-IWP Life Cycle

Licensing Future for MAGNETS

Timeline(Theoretical)



FP & EC priorities for magnet control.

Evaluation of FP/EC data magnet technical characteristics without plasma Iterate on control models.

Evaluation of magnet behaviour with plasma. Real impact of VS control and disruptions. Iterate on control models

Nuclear licensing

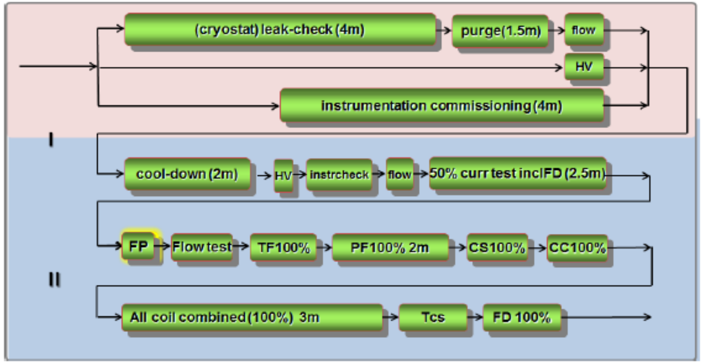
- The control of commissioning activities and verification functions until the hand over of Superconducting Magnets for operation.
- Typical impacted operational items are Reliability, Field Quality and Error Fields, Magnetic Forces and Stresses, Degradation and Training, Cryogenic Stability, Quench and Protection, Instrumentation and Measurement Techniques.

Modelling for Commissioning

- Instrumentation and its Interface to Control;
- Cool down control with model;
- Quench detection modelling and thresholds

Bottom Up Schedule from Magnets : 'integrated' commissioning as developed by magnets

- 5 months pre-FP after cooldown
- 12 months engineering commissioning post-FP (11 months without CC)



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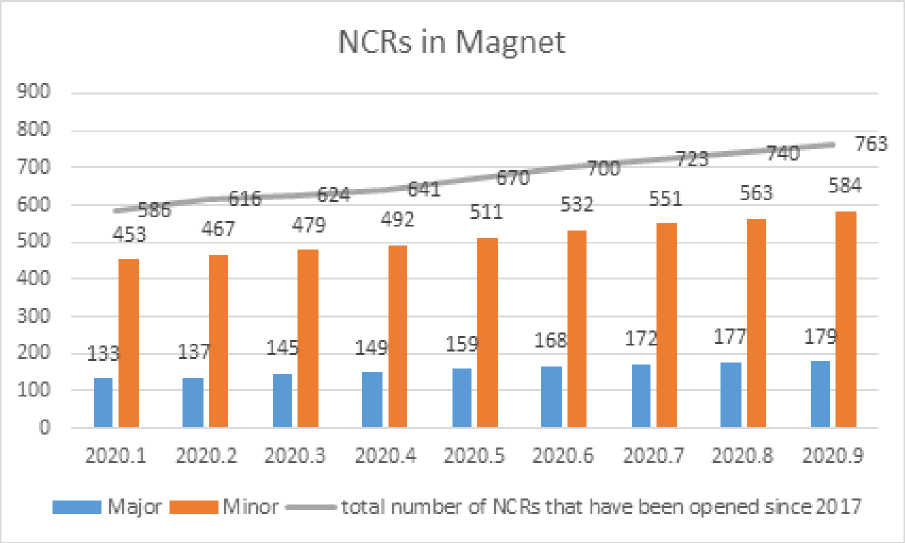
Statistics on NCRs for superconducting magnets happened in sensitive quality areas

- ❖ ITER non-conformances on-line database to almost all suppliers, implemented in December 2018.
- ❖ Statistics of NCRs for magnets since 2017
  - 763 NCRs, 584 major NCRs mostly happened in sensitive quality areas such as insulation, He leaks, welding, and special process control.



❖ **ITER NCR database statistics of NCRs shown superconducting magnet faults are typically in four areas:**

(1) **TF degrada**tion, from Sultan sample tests, problem of the SC cable design qualification;

(2) **Weld defects** in He pipes and in structural (like coils terminal service box);

(3) **Electrical problems** are mostly with the HV insulation like HV wires and pipe exits;

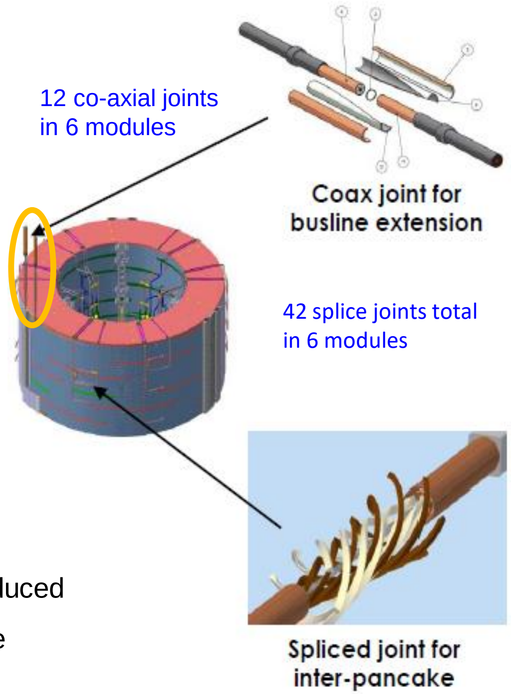
(4) Many many **NCRs on tolerances** (probably most of all).

- ❖ Some examples to demonstrate the basic inspection and test needs
  - E.g,Weld inspection，HV quench detection wires inspection, early consideration could save lots of time in manufacturing.

Example 1: qualification on CS coaxial joint NCRs

During manufacturing qualification:

- ❖ Coaxial busbar joint : 2 joints per module
- ❖ Coaxial joint using intermediate crimp / solder / SC layer
- ❖ Persistent difficulties to achieve qualification of joint
- ❖ Required resistance 4nOhm, range achieved 15-80nOhm
- ❖ Manufacturing work continued in parallel
- ❖ Result now is 4 modules to be repaired (joint partial formed), 3 modules to be corrected (joints not yet formed)



Lessons for Construction: What went wrong

- ❖ Missing qualification
- ❖ Lack of Production Proof Sample
- ❖ Technology developed by one could not be reproduced
- ❖ Success orientated strategy without plan for failure

Qualification in construction for CS coaxial joint

- Qualified Procedure
- Qualification by SULTAN test: Resistance < 4.1nΩ @ I=40kA, B=4T, T=4.2K
- Training to get qualified operators

Disassembly and re-assembly of indium joint

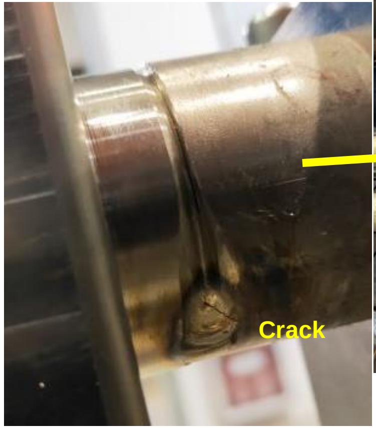
Qualified procedure transferred to TAC1 contractor by series of training

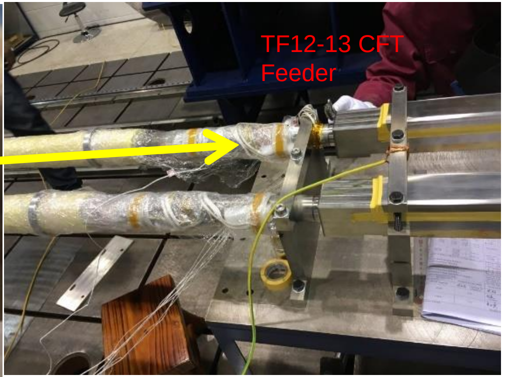
Example 2: Crack of TF12/13 CFT Busbar

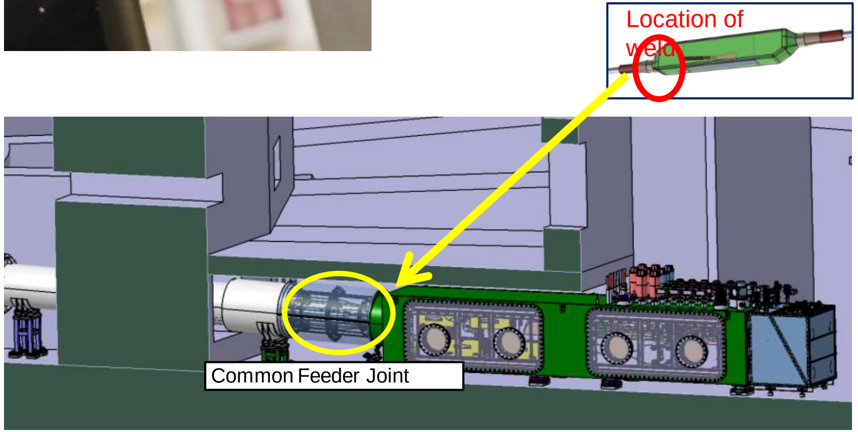
- ❖ Superconducting strand of internal conductor partially melted due to weld over penetration
- ❖ Copper contamination of the weld bead induced hot cracking.
- ❖ Root cracks by subsequent welding passes.

Lessons for construction

- ❖ Inadequate weld procedure , QC records of these welds in MMD or IDM references + inadequate welder training;
- ❖ Missing qualification
- ❖ Misuse of Production Proof Sample







Example 3: Insulation related NCR statistics and commonalities

- 8 out of 21 NCRs are majors, Systems affected include TF09, TF12, CS1L, PF6 & CC.

❖ Findings:

- ***11 for HV ground Insulation failure*** has been a common feature of FAT tests, from 2 (at least) of these related to hand wrapping of Polyimide tape the ground insulation (TF09 ,TF12, CS1L)
- ***8 for Wire extraction*** focus on design, Procedure qualification and worker qualification are the key points.. (TF12, TF03, CS1L)
- ***2 for Mockup manufacturing issues*** on the qualified procedures to be revised. (TF09 ,TF12, PF6, CC)

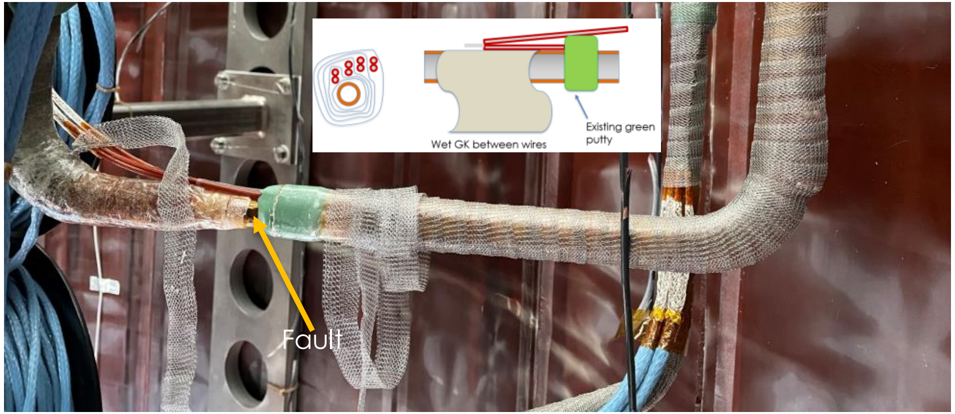
Event	Severity	Root cause
TF08 Paschen test failure	Minor	Damage of the DP1 RP in shaving off process of surplus resin after DP impregnation
TF12 DC Hi-pot failure	Major	Cracks at 3 wire extractions from feedthrough
TF12 Paschen test failure	Major	Gap inside the wire feedthroughs from resin flow down
	Major	Electron path created along the HV wire after cold tests coming from a lack of good bonding
	Minor	Deterioration of the DP5 RP insulation due to mistakenly grinding after DP impregnation
TF09 Paschen test failure	Major	Damages in the wire insulation possibly during handling
TF03 Paschen test failure	Minor	HV wire insulation damage
CS Module 1 Hi-pot test failure	Major	Neat resin was cracked above one HV wire leading to crack the wire
VLF Hi-pot test failure	Major	HV wire manufacture defect not detected by the QC
BCC DC Hi-pot leakage current > 25 µA	Minor	Glass humidity too high
From IO DB for PF		
PF6 Paschen test failure	Major	Damages in the wire insulation possibly during handling

Event	Severity	Root cause
CS Mockup Paschen test failure	Minor	Trip of the hi-pot tester at 13kV, cracks at wire extractions
	Minor	Improperly applied Kapton insulation at L6, lack of operator training → common to PF6?
	Minor	Similar to #85 but at L8
	Minor	Void volumes between adjacent HV wires
	Minor	Weak insulation between the L3 HV wires and a small piece of GP mesh
	Minor	Similar to #85 but at L7
		Similar to #85 but at L13
		Similar to #85 but at L5
	Minor	Trip of the hi-pot tester at 13kV, weakened due to repeated connection/disconnections
	Minor	Trip at 11 kV during Paschen, local concentration of electric field on bolt head
	Major	Neat resin cracks at cool down plus transient effect from previous breakdown
PF6_DP9 Helium inlets insulation test before VPI	Minor	HV test (manufacturing, DC, turn-to-turn) not done before VPI
Tear of outer layers of WP Ground Insulation at TF12WP (JA01) (MHI)	Major	Lack of compression during WP impregnation.Weak bonding between the resin and kapton tape.

Example 3: Insulation related NCR statistics and commonalities

❖ Root Cause:

- ➢ Wires do not appear to be source of breakdown
- ➢ Not enough length to left of fault for another wire exit
- ➢ Repair by cutting wires and repairing with qualified process
- ➢ Route cables carefully back towards cable tray



❖ Quality Control process in Paschen Testing

- ➢ Reference for Acceptance of high voltage test
- ➢ A High Voltage Testing Plan (HVTP)
- ➢ Quality control and acceptance of applied voltage levels

❖ Lessons learned:

- ➢ The quality and quantity of the cameras are crucial in the efficiency of the failure identification. We will save time and reduce the risk of damage on series production if the Paschen are accurately instrumented.
- ➢ The grounding scheme at Hi-pot and Paschen tests can be a source of breakdown if not appropriate. This test grounding scheme shall be made clear and submitted to review.
- ➢ Qualification of the procedures and qualification of the workers are fundamental: our experience shows the HV insulation issues can be solved and much better avoided whether the right processes are performed the right way.

In deviations from special process control

Identification of special process

Quality Assurance Requirement from ASME NQA-1-2015: Quality Assurance Requirements for Nuclear Facility Applications

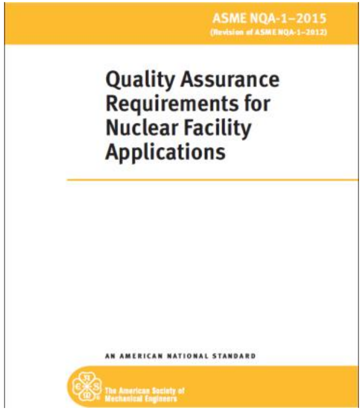
Special processes**:** a process, the results of which are highly dependent on the control of the process or the skill of the operators, or both, and in which the specified quality cannot be readily determined by inspection or test of the product.

- (*) e.g. process like welding, heat treating, coating, Some not-so obvious special processes may include mold making and wire crimping

ISO 9001:2008 clause 7.5.2 refers to special processes as

"processes requiring validation."

- For special processes not covered by existing codes and standards or where quality requirements specified exceed those of existing codes or standards, the necessary requirements for qualifications of personnel, procedures, or equipment shall be specified or referenced in procedures or instructions.



- Which processes must be validated;
- What the validation must demonstrate;
- The way to establish the validation process.

In deviations from special process control

- **Special process**
  - “Special processes” refer to processes that produce outputs which cannot be verified before being released to the customer. Deficiencies are noticed only during use.
  - These products require special attention during production to endure that they are free of defects.
  - Validating special processes is that the responsibility of quality assurance activity.
  - Validation means proving that a process is capable of meeting the specification.
  - Validation shall demonstrate the ability of these processes to achieve specified results.
- **The Validation includes**
  - **Approval of equipment Qualification of personnel**
  - **Process Qualification**
  - **Requirements for records.**
  - **Revalidation**

Special process control

❖ Requirements

Quality Assurance Requirement from ISO 19001:2015: Validation of processes /ASME NQA-1-2015

- ❖ Special processes shall be controlled by instructions, procedures, drawings, checklists, travelers, or other appropriate means.
- ❖ Special process instruction shall include or reference procedure, personnel, and equipment qualification requirements.
- ❖ Conditions necessary for accomplishment of the process shall be included. These conditions shall include proper equipment, controlled parameters of the process, specified environment and calibration requirement.

Technician applying insulation to an insulated break

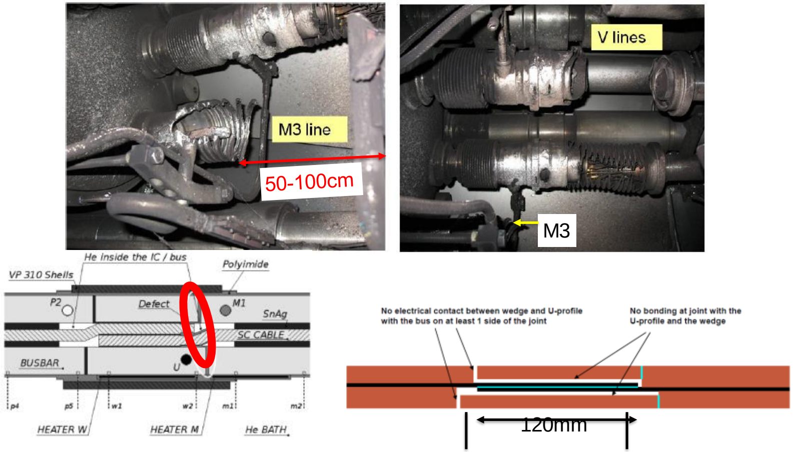
Conductor strands
after chrome striping

Conductor strands
Prior to chrome striping

❖ Construction examples are special (un-inspectable) welds, HV insulation, joint closure, HV wires lead outs, instrumentation, almost all CS stacking,…

Example： Special Process Failure in CERN LHC accident

The CERN LHC Incident 2008



Images courtesy of CERN

Lessons learnt:

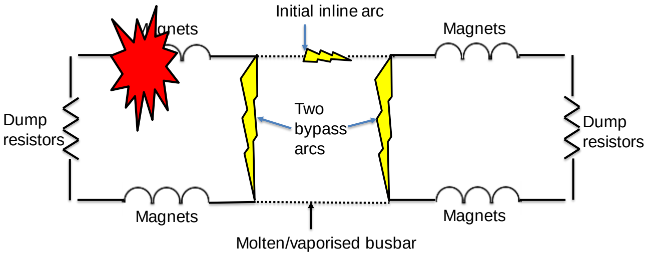
- The SP was the soldering process carried out by contractors using a tool provided by CERN
- Special scripts for the analysis of the production parameters were created by the LMF-QA team
- Systematic and rigorous verification of the data represented the first indicator of the quality of the LMF performance

Root cause:

- Incomplete soldering of a joint between 2 NbTi sc cables
- Exception point for Shunt soldering max temperature
- The soldering was carried out by a special heating tool (eddy current or microwave)
- Either qualification, training or process monitoring was inadequate

The CERN LHC Incident

- The initial arc had a power of ~2MW.



A localised arc became an explosion

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Lessons Lessoned: Advances in science and technology to meet challenges

- **Set up the quality policy for a nuclear environment and to have ensured the achievement of quality awareness training within the whole staff.**
- **Develop the mature quality control approach**
  - Reviews of manufacturing design (drawings, procedures)
  - Detailed definition of quality control programmes and demonstrations that they work
  - Rigorous implementation of QA culture behind QC to ensure proactive implementation and honest reporting
  - Independent verification of qualification tests
  - Independent verification of QC tests during manufacture
- **Safety is more important than schedule: everybody agrees but at the end of large projects (inevitable problem of budget and schedule) the pressure to take shortcuts is strong.**
- **Never spare on risk analysis (by competent people) and take mitigation measurements. Whatever might go wrong, it goes! What is important is to survive and limit damage (mitigation measurements).**
- **Diagnostics and measurements are key: but important is to select what really matters, to avoid to be overwhelmed by un-important Non-Conformities. QA effectiveness vs. paper QA.**

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Opening the way to a new energy future

Thank you for your attention!

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