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Extra budget: Towards the RAMI analysis of the DEMO magnet system

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R. Bonifetto[1], D. Carloni[2], N. Mantel[2], L. Savoldi[3]

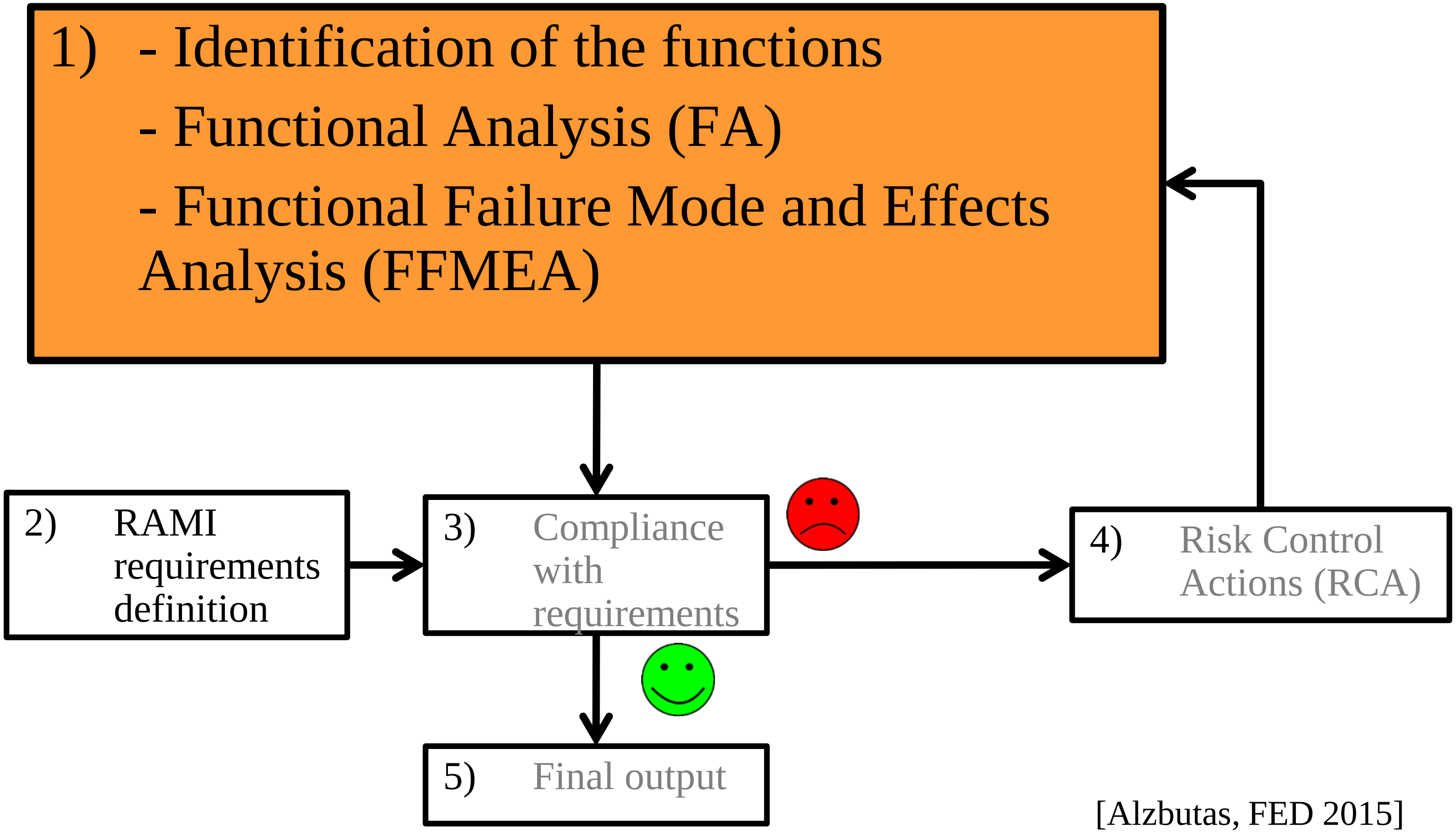
[1] nemo Group, Dipartimento Energia, Politecnico di Torino, Italy
[2] Culham Centre for Fusion Energy, Culham Science Centre, UK
[3] Dipartimento Energia «Galileo Ferraris», Politecnico di Torino, Italy

EUROfusion

Outline

- RAMI methodology applied to DEMO magnet system
- Functional analysis: sample outcomes
- FFMEA: sample outcomes
- Conclusions and perspective

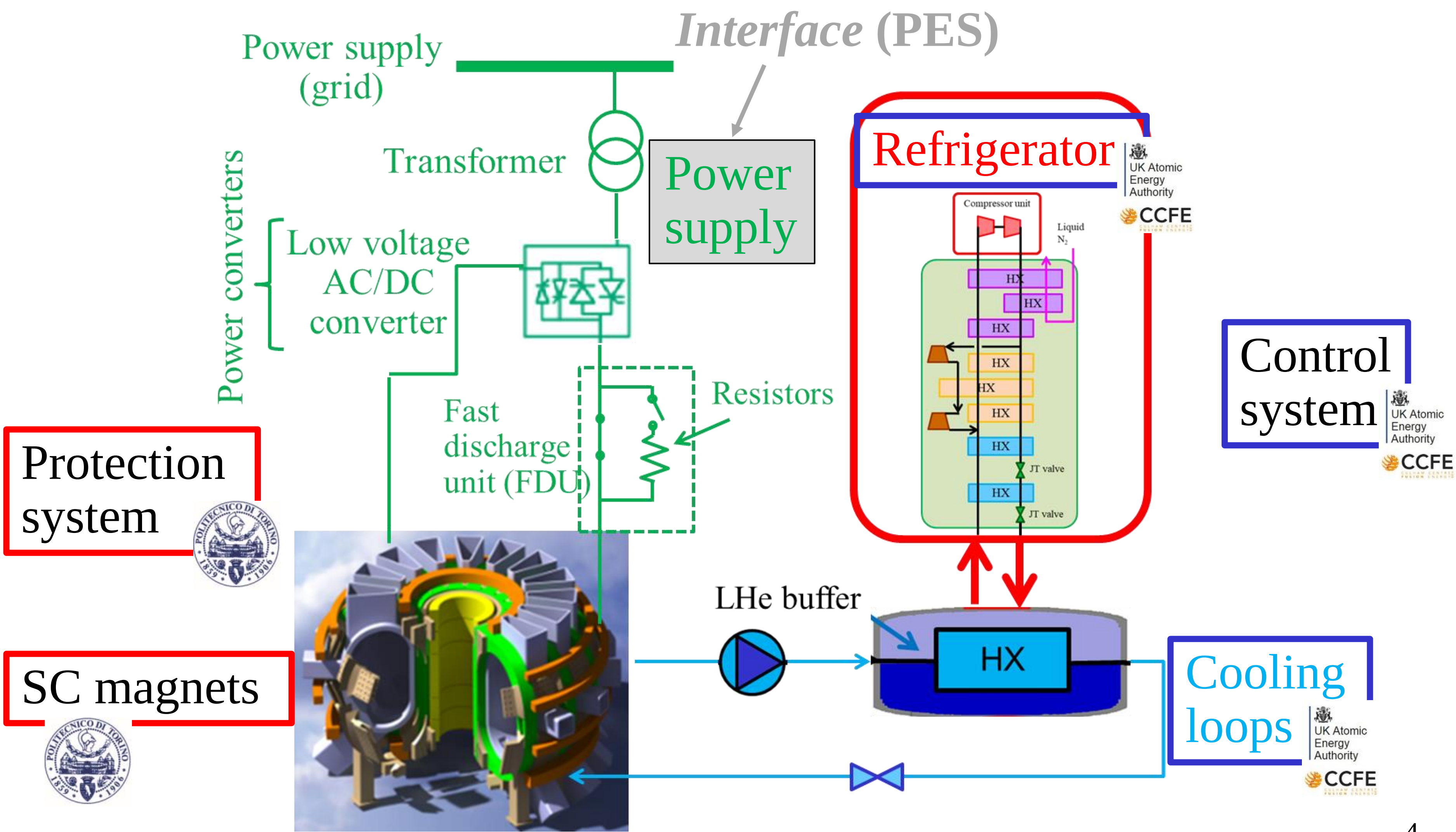
Reliability, Availability, Maintainability and Inspectability (RAMI) analysis



[Alzbutas, FED 2015]

[N. Taylor, General safety principles, EFDA_D_2LJVZ7, 2016]

Domain of the analysis within DEMO magnet system



Ongoing activities at PoliTo and CCFE

1) Magnets and Cryoplant and Cryodistribution (2019) & Protection and Control systems (2020):
   a. Functional Analysis (FA)
   b. FFMEA for the operating condition into consideration

2) Definition of the RAMI requirements for the EU DEMO magnet system

3) RAMI requirement verification for the magnets: reliability and availability quantification

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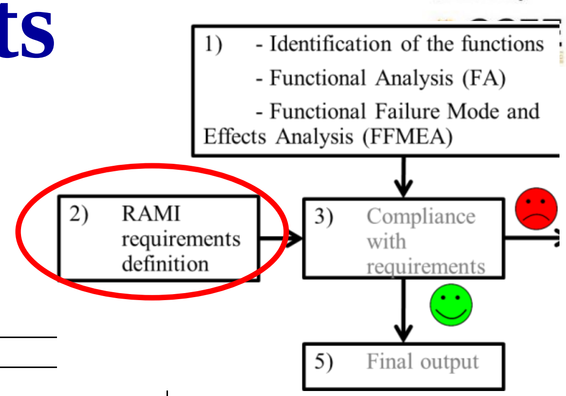
DEMO requirements



- Definition of the RAMI requirements for the EU DEMO magnet system, from
  - C. Bachmann, "Plant Description Document," EFDA_D_2KVWQZ v1.3, July 2018.

	ITER	DEMO
Availability	Experimental campaigns. Long dwell time, outages for maintenance, component replacements.	High availability

5.2.1 Requirements

Functional	• The TF system shall generate a toroidal magnetic field with a toroidal ripple of less than 0.6% (not considering ferromagnetic inserts)

  - J. Johnston, "DEMO Plant Safety Requirements Document (PSRD)," EFDA_D_2MKFDY v3.1, March 2017.
  - L. Morici, "Magnet System Requirement Document (SRD) & Load Specifications (LS)," EFDA_D_2NEKRG v1.0, June 10, 2019.
  - "DEMO Power Plant Requirements -PRD- document," EFDA_D_2MG7RD v3.5, July 5, 2019

De-Risk Future Fusion Power Plant	
PRD_06	DEMO shall demonstrate the reliable operation of the plasma including a low number of required unplanned maintenance intervals to repair damaged components due to failures triggered by off-normal plasma events
Performance	
PRD_10	The duration of *flat top* shall be at least 2h
Maintain Operation	
PRD_17	The DEMO plant shall be designed such that its availability can be extrapolated to a commercial FPP, which operates as a base load that achieves an availability of 60-90%.

FFMEA strategy

Select an **operational mode** of the system

↓

Functional analysis: identify the process (and associated safety/protection) **functions**

↓

Systematically **identify all the relevant failure modes** of each subsystem, together with the corresponding causes and consequences

↓

Process function	Associated safety / protection function	PBS components	Failure	Cause	Failure consequence	Detection	Prevention action	Mitigation action

How can the failure be (easily) detected?

Some affecting the design phase!

Outcomes

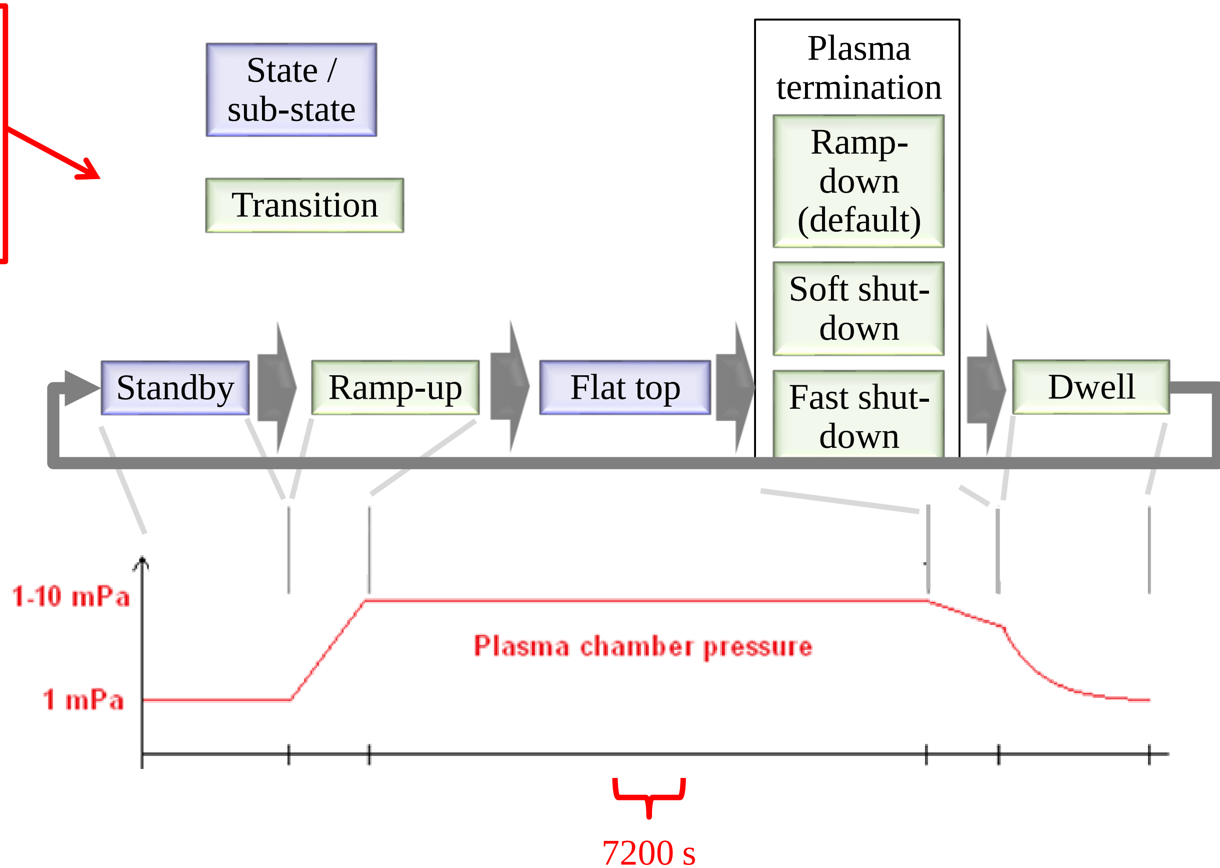
Point out the **critical components** (they need more attention during the design)

- Provide a list of IEs leading to scenarios that may compromise the magnets safety and availability
- Select the Postulated IEs (**PIEs**): most challenging consequences

2018 activity

Selection of the operation mode

- Plasma Operation
  - Dwell sub-state
  - Standby sub-state
  - Pulse sub-state
  - Terminate pulse state
- Testing & Conditioning
- Scheduled Maintenance
  - In-vessel maintenance
  - In-cryostat maintenance
  - Ex-vessel maintenance
- Failed mode (unscheduled maintenance)



[Bachmann, DEMO Plant Description Document, EFDA_D_2KVWQZ, 2018]

Other operational modes to be addressed in FP9

DEMO magnets functional analysis

- FA of the DEMO magnets

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Cryo-distribution:
ITER Documents (2010)

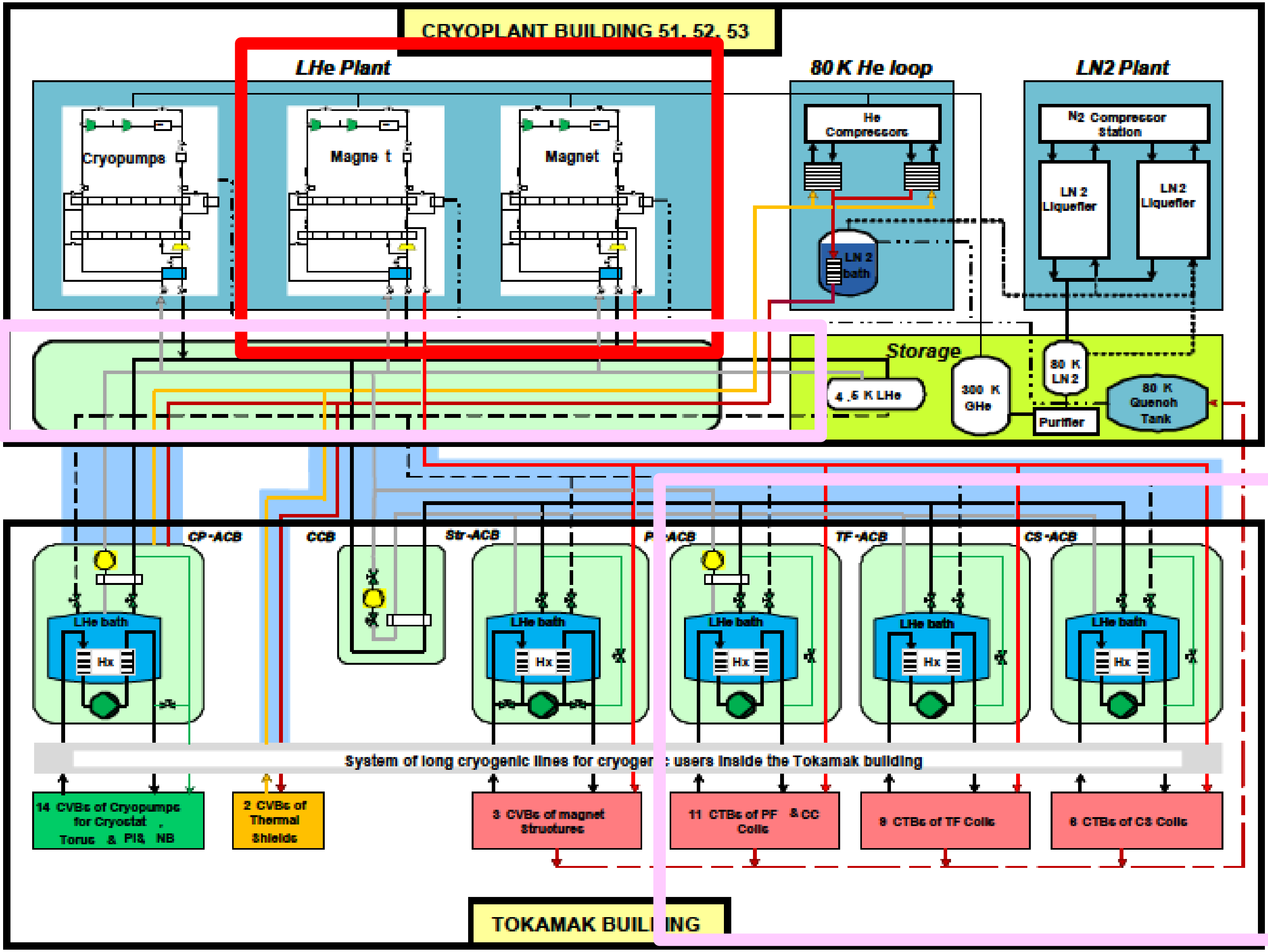
- DDD 34 - Design
- SRD 34 – Functions and Requirements
- Functional analyses for Cryoplant
- Functional analyses for Cryodistribution
- Summary of the Cryogenic System (PBS 34) functional analysis
- RAMI for the CP ACB

…but not the full RAMI for the PBS 34☹

NEW here for DEMO: more attention to

- Confinement (especially T), involving all the barriers
- Availability

ITER Cryo-distribution FA (2010)



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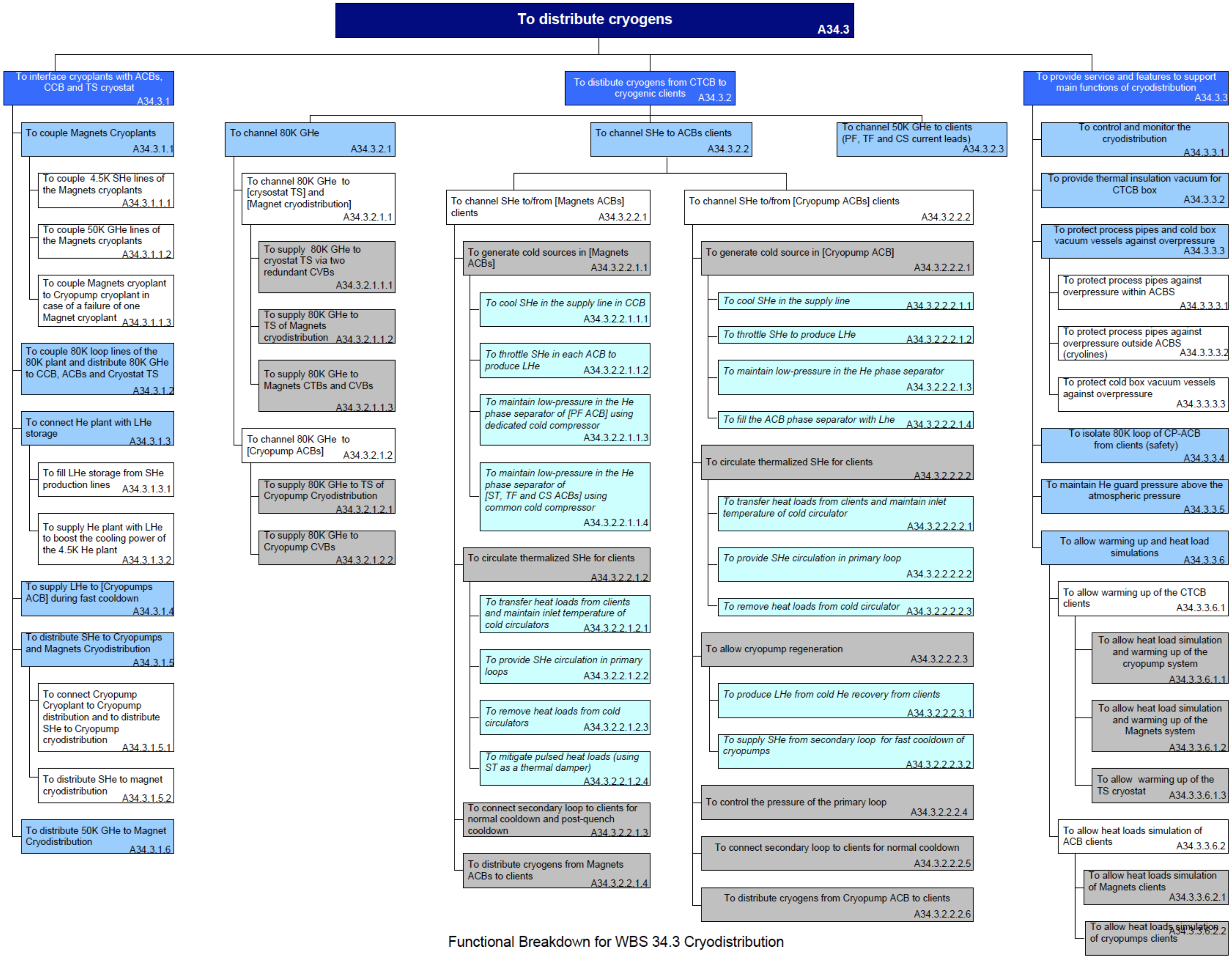
ITER Cryo-distribution FA (2010)



Functional Breakdown for WBS 34.3 Cryodistribution

DEMO Cryo-distribution Process Functions

- 1. **To provide cryogen to the cryogenic users**
  - **1.1. To supply helium**
  - **1.2. To distribute cryogen to the magnets**
  - **1.3. To recover cryogen from the magnets**
  - **1.4. To distribute cryogen to the current leads**
  - **1.5. To recover GHe from the current leads**
  - **1.6. To Monitor cryogenic systems**
  - **1.7. To ensure all the different operation modes and the transient between 2 modes**

DEMO Cryo-distribution Process Functions

- 1. **To provide cryogen to the cryogenic users**

- **1.2. To distribute cryogen to the magnets**
- 1.2.1.To supply LHe bath
- 1.2.1.1. To liquify GHe
- 1.2.1.2. To extract vapor from the He bath
- 1.2.1.3. To keep and preserve leek tightness
- 1.2.1.3.1. To connect cryo-equipment and lines
- 1.2.1.3.2. To prevent vibrations and stresses
- 1.2.1.4. To Overcome pressure drop for requested flow
- 1.2.1.5. To Thermally Insulate cryogenic loop
- 1.2.1.6. To allow monitoring from CODAC of LHe bath parameters
- 1.2.1.7. To record parameters
- 1.2.1.8. To compare real parameters condition to expected condition
- 1.2.1.9. Regulate LHe flow
- 1.2.1.10. To open/close cryogen channel
- 1.2.1.11. To increase/reduce cryogen flow to required conditions
- 1.2.2.To provide SHe at nominal conditions
- 1.2.2.1. To compress SHe at nominal pressure
- 1.2.2.2. To Cool down SHe at nominal temperature
- 1.2.2.3. To provide heat sink to the SHe
- 1.2.2.4. To Circulate a nominal SHe mass flow
- 1.2.2.5. To keep and preserve leek tightness
- 1.2.2.5.1. To connect cryo-equipment and lines
- 1.2.2.5.2. To prevent vibrations and stresses (IP)
- 1.2.2.6. Overcome pressure drop for requested flow
- 1.2.2.7. To Thermally Insulate cryogenic loop
- 1.2.2.8. To allow monitoring from CODAC of SHe parameters
- 1.2.2.9. To record parameters
- 1.2.2.10. To compare real parameters condition to expected condition
- 1.2.2.11. Regulate SHe flow
- 1.2.2.12. To open/close cryogen channel
- 1.2.2.13. To increase/reduce cryogen flow to required conditions
- 1.2.3.To smooth the pulsed heat load from the plasma
- 1.2.3.1 To distribute the cryogen
- 1.2.3.2 To thermally isolate the magnet

FFMEA (Cryo-distribution)

- Process Functions and
- Associated I & S functions

- Type of failure
- Cause
- Failure Consequences

- Detection
- Prevention
- Mitigation

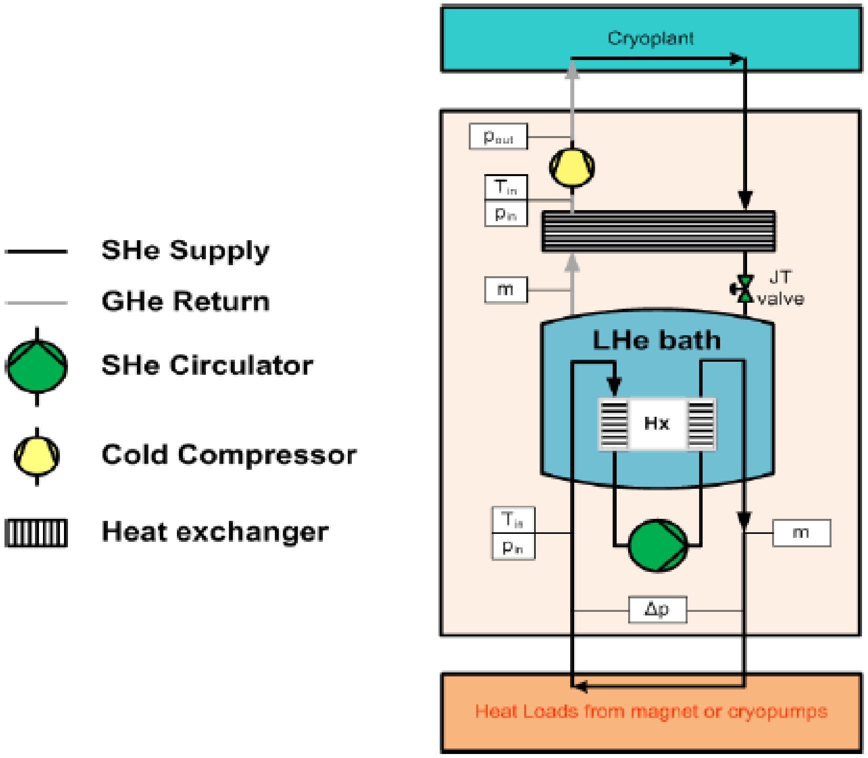
Process Function	Associated Protection/Safety Functions	PBS components	Type of Failure	Cause	Failure consequences	Detection	Preventive actions	Mitigative Actions
1. To provide cryogen to the cryogenic users	To prevent abnormal operation in process systems To ensure Safety							
1.1. To supply helium								
1.1.1. To supply LHe to the magnets								
1.1.1.1.1. To supply LHe@4K	To prevent abnormal operation in process systems	TBD	Loss of He supply	Compressor failure/malfunctioning Loss of Power Supply	unavailability of the cold boxes	Loss of He flow, Liquid Bath temperature	Monitoring, Maintenance	Stop of the plant, repair
1.1.2. To supply GHe to the current leads								
1.1.1.1.2. Supply He @50K	To prevent abnormal operation in process systems	TBD	Loss of He supply	Compressor failure/malfunctioning Loss of Power Supply	unavailability of the cold boxes	Loss of He flow, Liquid Bath temperature	Monitoring, Maintenance	Stop of the plant, repair
1.1.3. To supply He to the users during warm-up @300K		TBD	Loss of He supply	Hot Helium supply malfunctioning Loss of Power Supply	Slow-down of the warm-up operations	Loss of He flow	Monitoring, Maintenance	None
1.2. To distribute cryogen to the magnets	To protect integrity of cryogenic systems To protect the integrity of the distribution system To confine at all process levels fluids and gases							
1.2.1. To supply LHe bath								
1.2.1.1. To liquify GHe		TBD	Loss of cryo heat sink	HXs malfunctioning	Ovrepressurization of the CB	High pressure in the CB	Inspection/Maintenance	Stop and repair
1.2.1.2. To extract vapor from the He bath		TBD	Loss of gas flow	Compressor failure/malfunctioning Loss of Power Supply	Ovrepressurization of the CB	High pressure in the CB	Inspection/Maintenance	Stop and repair
1.2.1.3. To keep and preserve leek tightness	To withstand the cryogenic system kinetic pressure	TBD						
1.2.1.3.1. To connect cryo-equipment and	To retain structural integrity of pressure control system or expansion volumes of cryogenic loops	TBD	Loss of fluid	line leak/rupture	Loss of cryogen fluid	Pressurization of the environment	Inspection/Maintenance On-line Leak Detection	Isolation of the faulted line
1.2.1.3.2. To prevent vibrations and stresses		TBD	Loss of piping/equipment geometry	undue vibrations/stresses	Loss of leak-thightness Equipment/piping rupture	High vibration of piping/equipment	Inspection/Maintenance	Stop of the affected line Repair
1.2.1.4. Overcome pressure drop for requested	To monitor parameters of equipment of the cryogenic systems To perform automatic actions to reduce discrepancies and mitigate	TBD	Loss of flow	Compressor trip/malfunctioning	Loss of cryognic flow Faulted line quench	Low flow Low pressure	Design Monitoring Maintenace	Repair Replacement
1.2.1.5. To Thermally Insulate cryogenic loop		TBD	Loss of vacuum	Leak from piping/equipment Loss of Power Supply	Pressurization of the vacuum system	P of the vacuum system	Design	Repair Replacement
1.2.1.6. To allow monitoring from CODAC of LHe bath parameters	To monitor parameters of equipment of the cryogenic systems	TBD	Loss of signals	Instrumentation malfunctioning/failure	Possible abnormal operation	Error signal	Maintenace	Replacement
1.2.1.7. To record parameters		TBD	Loss of parameters recording	Cable malfunctioning/ruptur	None	Error signal	Maintenace	Replacement
1.2.1.8. To compare real parameters condition to expected condition	To monitor parameters of equipment of the cryogenic systems	TBD	Loss of signals	Instrumentation malfunctioning/failure	Possible abnormal operation	Error signal	Maintenace	Replacement
1.2.1.9. Regulate LHe flow		TBD	Loss of regulation	Equipment malfunctio	Abnormal He supply	Error signal	Maintenace	Replacement

FFMEA (Cryo-distribution)

Formula Bar Process Function	Associated Protection/Safety Functions	PBS components	Type of Failure	Cause	Failure consequences	Detection	Preventive actions	Mitigative Actions
1.2. To distribute cryogen to the magnets	To protect integrity of cryogenic systems To protect the integrity of the distribution system To confine at all process levels fluids and gases							
1.2.1. To supply LHe bath								
1.2.1.1. To liquify GHe		TBD	Loss of cryo heat sink	HXs malfunctioning/loss of vacuum	Overpressurization of the CB	High pressure in the CB	Inspection/Maintenance	Stop and repair
1.2.1.2. To extract vapor from the He bath		TBD	Loss of gas flow	Compressor failure/ malfunctioning Loss of Power Supply	Overpressurization of the CB	High pressure in the CB	Inspection/Maintenance	Stop and repair
1.2.1.3. To keep and preserve leek tightness	To withstand the cryogenic system kinetic pressure loads	TBD						
1.2.1.3.1. To connect cryo-equipment and lines	To retain structural integrity of pressure control system or expansion volumes of cryogenic loops	TBD	Loss of fluid	line leak/rupture	Loss of cryogen fluid	Pressurization of the environment	Inspection/Maintenance On-line Leak Detection	Isolation of the faulted line
1.2.1.3.2. To prevent vibrations and stresses		TBD	Loss of piping/equipment geometry	undue vibrations/stresses	Loss of leak-thightness Equipment/piping rupture	High vibration of piping/equipment	Inspection/Maintenance	Stop of the affected line Repair
1.2.1.4. Overcome pressure drop for requested flow	To monitor parameters of equipment of the cryogenic systems To perform automatic actions to reduce discrepancies and mitigate negative effects	TBD	Loss of flow	Compressor trip/malfunctioning	Loss of cryognic flow Faulted line quench	Low flow Low pressure	Design Monitoring Maintenace	Repair Replacement

2019 Components

- **Cryolines**
  - leakage/rupture
  - Clogging
- **Valves**
  - malfunctioning
- **SHe Circulator**
  - Several failure modes
  - Loss of power supply
- **Cold Compressor**
  - Several failure modes
  - Loss of power supply
- **HX**
  - Plug
  - Leakage
  - Rupture



Conclusions and perspective

- Methodology for RAMI of the DEMO magnet system has been described
- For plasma operation mode:
  - Functional analysis for cryoplant/cryodistribution and magnets
  - Preliminary FFMEA for cryoplant/cryodistribution and magnets
- Main outcome in 2 keywords: **repairability(replaceability) + redundancy** + ***more to come in 2020+***
- **2020 TS**: for magnets control (CCFE) and protection (PoliTo) systems, in plasma operation mode
  - Functional analysis
  - FFMEA

Next Step

- Review and approval of the FA
- From functions to components
  - Update of failure modes
  - Definition of MTTR for each component
- Reliability and Availability ranking (6 levels)
- Inspectability and Level of Confidence

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6 levels Ranking

Reliability		Maintainability	
Potential failure frequency	**Potential failure effect**	**Mean time to Repair (MTTR)**	**Maintainability Access require**
1. Very Low→ MTTF>2000Y	1. No effect on plant output	1. MTTR>1h	1. No access restriction
2. Low →200Y<MTTF<2000Y	2. Reduced plant output	2. 1h<MTTR<1day	2. Breach of Bio shield
3. Moderate →20Y<MTTF<200Y	3. No plant output controlled shut down	3. 1day<MTTR< 1 week	3. Breach of Cryostat
4. High →2Y<MTTF<20Y	4. No plant output uncontrolled shut down	4. 1 week <MTTR< 2 months	4. Breach of NB Vacuum
5. Very High →10 Weeks<MTTF<2 Years		5. 2 months<MTTR<1 year	5. Breach of Tokamak Vacuum
6. Frequent→ MTTF<10 Weeks		6. 1year<MTTR	

[2019, RFX-CCFE, RAMI evaluation of the modular beam source in comparison to the ITER-like beam source]

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6 levels Ranking

Inspectability	Level of confidence	
Possibility of Fault detection	**System readiness level**	**Reliability estimation based on**
1. Continuous monitoring (preventative)	1. Mock-up demonstrating the element performance for the operational environment	1. Data based on system in the operating environment
2. Detection when failure occur	2. Mock-up demonstrating the critical functions of the element in a relevant environment	2. Data based on system in different operating environment
3. Detection during Dwell	3. Component and/or breadboard critical function verification in relevant environment	3. Databased on similar system in similar environment
4. Detection during STM	4. Component and/or breadboard functional verification in laboratory environment	4. Data based on similar system in different operating environment
5. Detection during LTM	5. Analytical and experimental critical function and/or characteristic proof-of-concept	5. Analytical and experimental critical function and/or characteristic proof-of-concept
6. Impossible	6. Technology concept and/or application formulated	

Thank you for your attention!

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Backup slides

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IFMIF Reliability Database (2012)

- Data selected for RAMI assessments in IFMIF
- Carlos Tapia, JavierDies, JavierAbal, Angel Ibarra, José M.Arroyo
- Fusion Energy Engineering Laboratory,Barcelona,Spain
- CIEMAT, Madrid,Spain

IFMIF Reliability Database (2012)

Data selected for RAMI ass
Carlos Tapia, JavierDies, JavierAbal,
Fusion EnergyEngineeringLabo
CIEMAT, Madri

Component	Comp	Failure Mode	FM	CODE	Failure rate (1/h)	MTTR (h)
High Voltage Power Supply	VS	cable failure	G	VSG	3.00E-07	2
High Voltage Power Supply	VS	Sparks	K	VSK	3.30E-05	1
High voltage power wires 1m	H1	Short circuit	S	H1S	7.10E-07	5
Hoses 1m	S1	Water Leakage	L	S1L	1.40E-07	4
Hoses 2m	S2	Rupture	R	S2R	4.00E-07	4
HVAC	HV	All failure mode	G	HVG	4.29E-07	3
HWR Cavities	HW	Deformation	G	HWG	1.00E-08	24
Insulators	IN	All failure mode	G	ING	1.00E-08	1
Ion pumps (Vacuum)	IO	Fail to operate	O	IOO	3.90E-05	10
Ion Trap	IT	External Leakage	X	ITX	5.00E-07	3
Lifter	LI	All failure mode	G	LIG	1.00E-05	24
Linux PC	PC	Software	S	PCS	1.71E-05	1
Linux PC	PC	Hardware	H	PCH	3.60E-06	1
LiPb capsule creep	LP	All failure mode	G	LPG	3.93E-08	10
Liquid He connector	LC	Leakage	G	LCG	1.45E-08	10
Liquid Helium feedthrough	LH	Leakage	H	LHH	5.30E-06	12
Liquid Helium feedthrough	LH	Vacuum Leakage	L	LHL	1.00E-07	2
Liquid Helium pipes 1m	L1	External Leakage	G	L1G	5.00E-07	5
Liquid Helium welds	LW	Leakage	G	LWG	1.43E-08	2

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DEMO Cryo-distribution Process Functions

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- 1.1.1.To supply LHe to the magnets
- 1.1.1.1.1. To supply LHe@4K
- 1.1.2.To supply GHe to the current leads
- 1.1.1.1.2. To Supply He @50K
- 1.1.3. To supply He to the users during warm-up @300K
- **1.2. To distribute cryogen to the magnets**
- 1.2.1.To supply LHe bath
- 1.2.1.1. To liquify GHe
- 1.2.1.2. To extract vapor from the He bath
- 1.2.1.3. To keep and preserve leek tightness
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- 1.2.1.3.2. To prevent vibrations and stresses
- 1.2.1.4. To Overcome pressure drop for requested flow
- 1.2.1.5. To Thermally Insulate cryogenic loop
- 1.2.1.6. To allow monitoring from CODAC of LHe bath parameters
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- 1.2.2.3. To provide heat sink to the SHe
- 1.2.2.4. To Circulate a nominal SHe mass flow
- 1.2.2.5. To keep and preserve leek tightness
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- 1.2.2.5.2. To prevent vibrations and stresses (IP)
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- 1.2.3.To smooth the pulsed heat load from the plasma
- 1.2.3.1 To distribute the cryogen
- 1.2.3.2 To thermally isolate the magnet
- **1.3. To recover cryogen from the magnets**
- **1.4. To distribute cryogen to the current leads**
- **1.5. To recover GHe from the current leads**
- 1.5.1. To Circulate GHe
- 1.5.1.1. To keep and preserve leek tightness
- 1.5.1.2. To connect cryo-equipment and lines
- 1.5.1.3. To Thermally Insulate cryogenic loop
- 1.5.1.4. To Overcome pressure drop for requested flow
- 1.5.1.5. To Monitor GHe flow
- 1.5.1.6. To record flow
- 1.5.1.7. To compare real flow condition to expected flow condition
- 1.5.1.8. To Regulate GHe flow
- 1.5.1.9. To open/close cryogen channel
- 1.5.1.10. To increase/reduce cryogen flow to required conditions
- **1.6. To Monitor cryogenic systems**
- 1.6.1.To Monitor cryogen
- 1.6.2.To Monitor cryogen flow rate
- 1.6.3.To Monitor cryogen temperature
- 1.6.4.To Monitor cryogen pressure
- 1.6.5.To Monitor cryogenic loop component parameters
- 1.6.6.To Monitor insulation of the cold boxes
- 1.6.7.To Monitor Vibration
- 1.6.8.To Monitoring Oil impurity
- **1.7. To ensure all the different operation modes and the transient between 2 modes.**
- 1.7.1.To Cool down
- 1.7.2.To Warm up
- 1.7.3.To cope with Plasma scenario
- 1.7.4.To cope with other modes