



**EUROPEAN  
SPALLATION  
SOURCE**



# Experience with and plans for Machine protection system at ESS

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# Agenda



- 1 Context MP-SoS
  - 2 MP-SoS Verification Overview & Strategy
  - 3 Challenges
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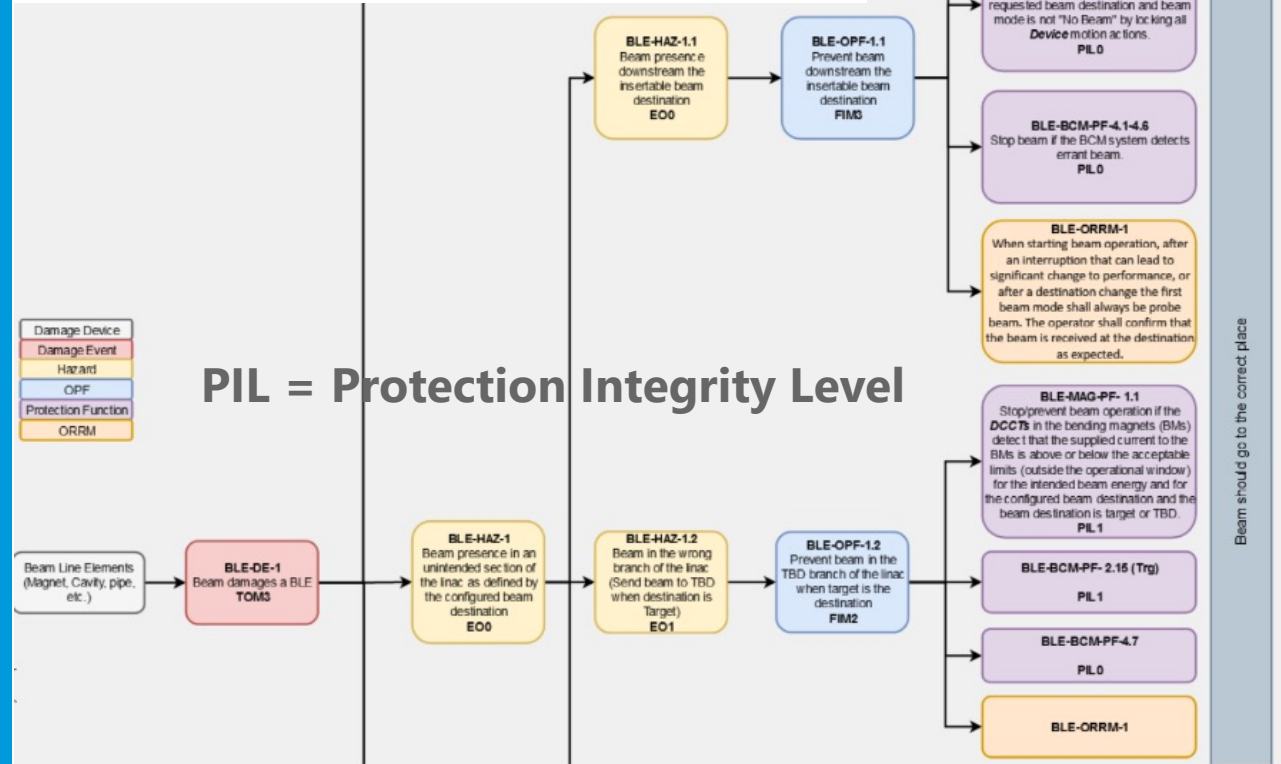


# Context Machine Protection Analysis

## Protection Functions (ESS-1089062)

Table 5: Protection Integrity Level compared to Safety Integrity Level

PIL	SIL (IEC 61508)	Required PFH	Required PFD
PIL0	N/A	$\leq 1 * 10^{-4}$	$\leq 1$
PIL1	SIL1	$\leq 1 * 10^{-5}$	$\leq 1 * 10^{-1}$
PIL2	SIL2	$\leq 1 * 10^{-6}$	$\leq 1 * 10^{-2}$
PIL3	SIL3	$\leq 1 * 10^{-7}$	$\leq 1 * 10^{-3}$
N/A	SIL4	$\leq 1 * 10^{-8}$	$\leq 1 * 10^{-4}$



PIL = Protection Integrity Level

- Damage Device
- Damage Event
- Hazard
- OPF
- Protection Function
- ORRM

### 9.5.1. BLE-FBIS-PF-1.1 – 1.6 (Beam Mode and Beam Destination monitoring)

PF ID	BLE-FBIS-PF-1.1-1.6		
PF Type	Global		
Description	Stop/prevent beam operation if FBIS detects that a system's configured Beam Mode and/or Beam Destination is different to the one distributed by the timing system and system is required for the current destination.		
Linked OPF	BLE-OPF-4	Linked Hazard	BLE-HAZ-4
Sensor / Input	Timing system		
Logic	FBIS		
Actuator	Beam Stop Actuator Systems		
PIL Requirement	PIL2	Timing Requirement	500 ms
Comments	FBIS-PF-1.1 (MPSID) FBIS-PF-1.2 (MPSMag) FBIS-PF-1.3 (MPSVac) FBIS-PF-1.4 (BCM) FBIS-PF-1.5 (MPSTrg) FBIS-PF-1.6 (FIST)		

PF ID	BLE-ID-PF-1.1 – 1.6		
PF Type	Global		
Description	Stop/prevent beam operation if <i>Device</i> position switch "Position In" is not actuated when <i>Device</i> is the requested beam destination and beam mode is other than "No Beam".		
Linked OPF	BLE-OPF-1.1	Linked Hazard	BLE-HAZ-1.1
Sensor / Input	Timing system <i>Device</i> position switch "Position In"		
Logic	MPSID FBIS		
Actuator	Beam stop actuators		
PIL Requirement	PIL 2	Timing Requirement	300 ms
Comments	<i>Device</i> = 1. FCLEBT (LEBT-010:PBI-FC-001) 2. FCMEBT (MEBT-010:PBI-FC-001) 3. FC1DTL (DTL-020:PBI-FC-001) 4. FC2DTL (DTL-050:PBI-FC-001) 5. IBSSPK (Spk-010LWU:ID-IBS-001) 6. IBSMBL (MBL-060LWU:ID-IBS-001)		

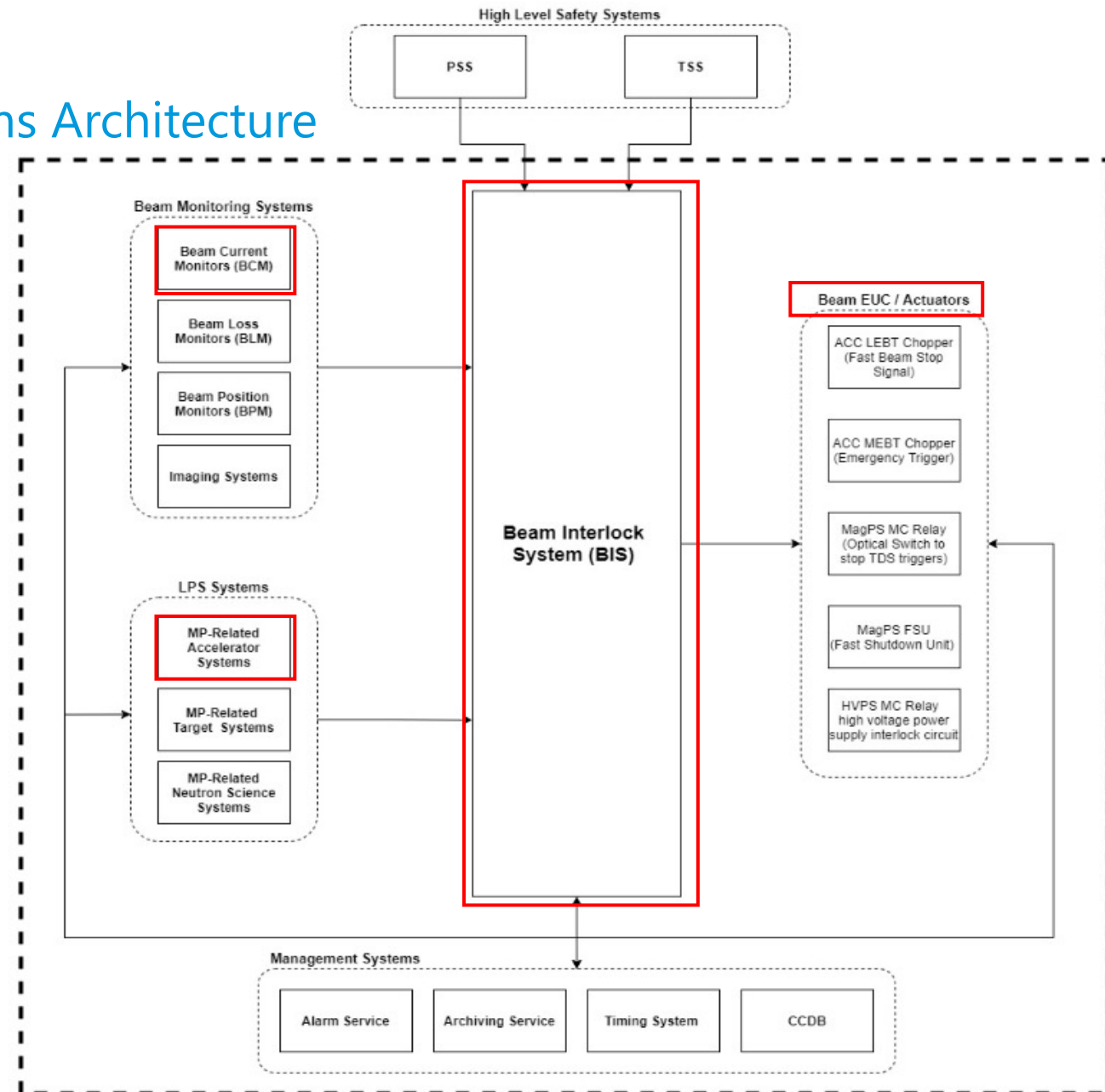
# Context MP-SoS

## Machine Protection Systems of Systems Architecture

### 5 Classes of Systems in MP-SoS (ESS-0057251)

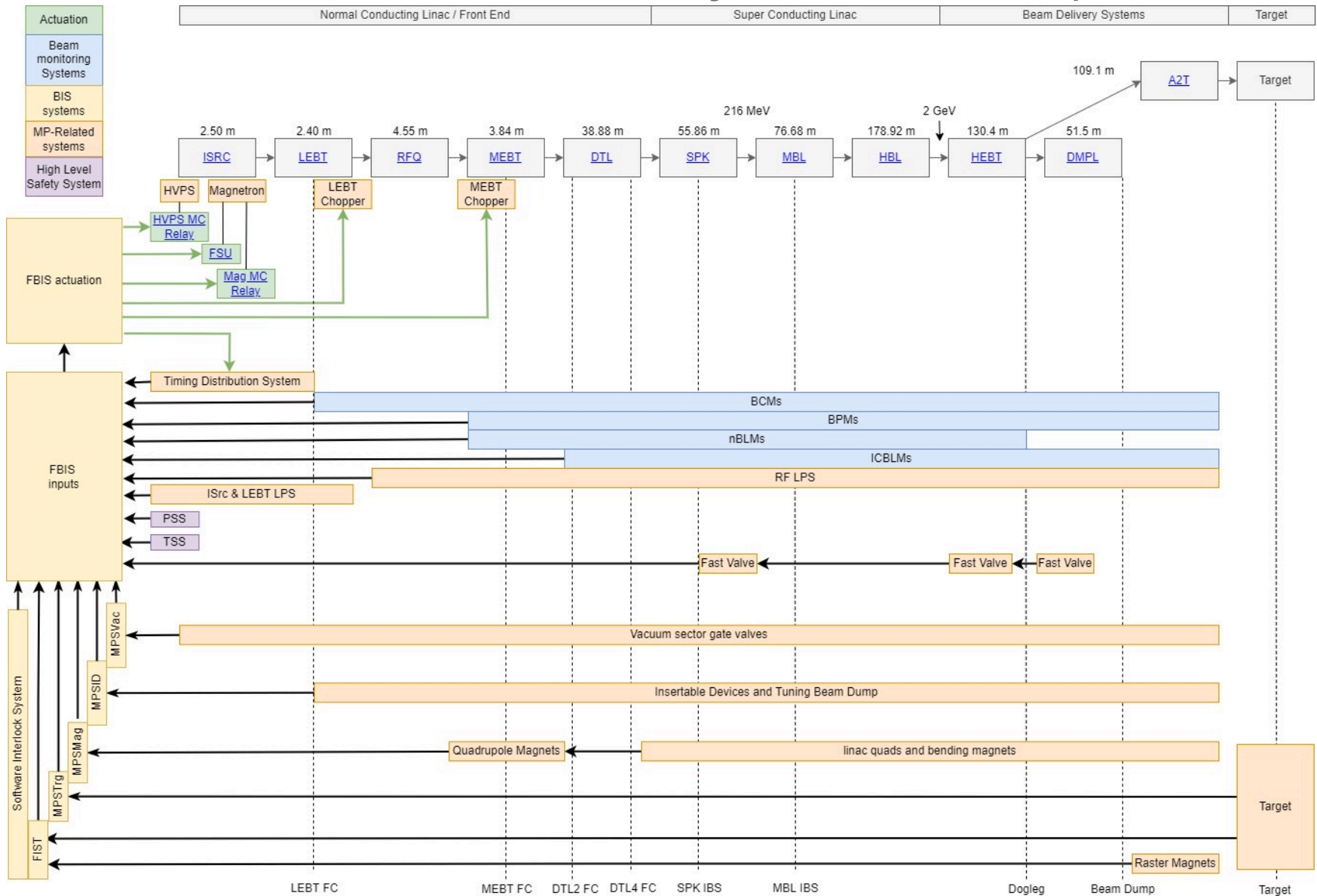
- Local MP-related systems (Accelerator and Target)
- MP-related proton beam monitoring systems;
- Beam Interlock System (BIS);
- MP-related beam switch-off actuation systems;
- MP-related management systems.

**MP-SOS**





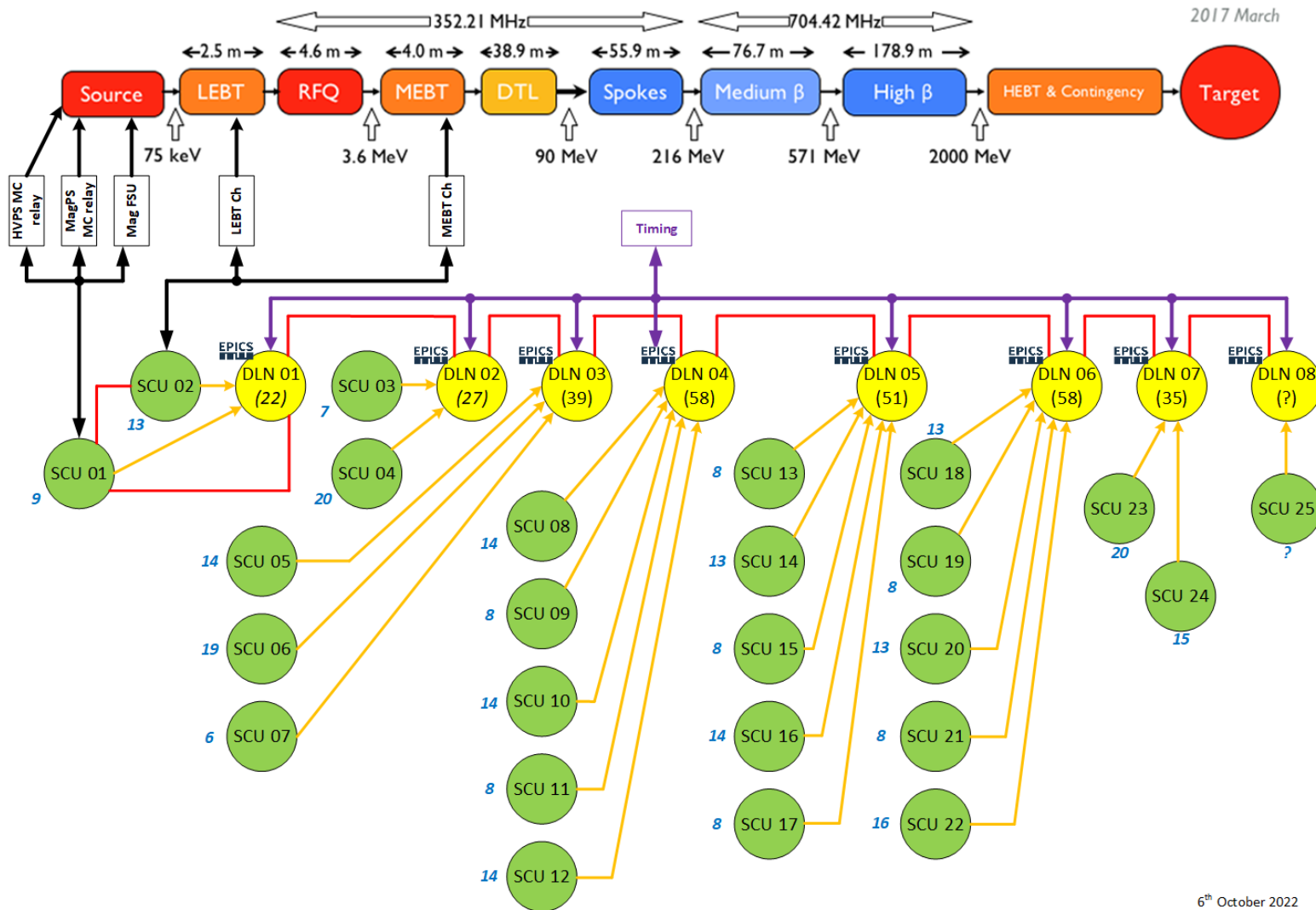
# Context MP-SoS Full System Scope



# Context MP-SoS *Fast Beam Interlock System*

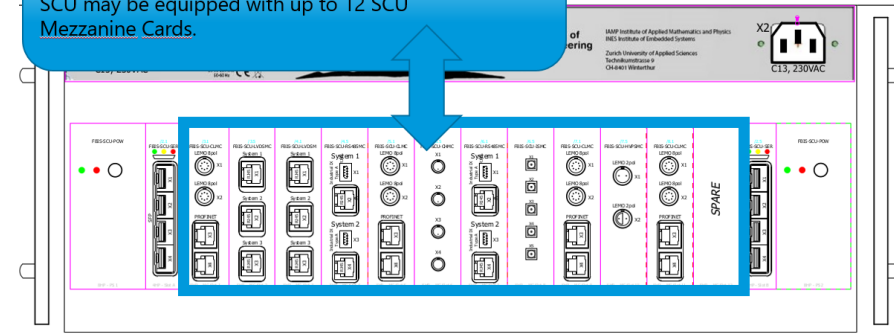


## Layout and scope of the Fast Beam Interlock System (FBIS)

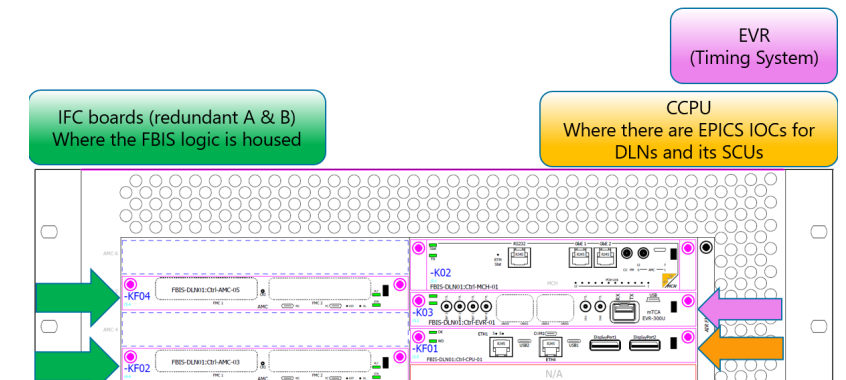


### SCU hw Signal Conversion Unit

The SCU Mezzanine Cards host the physical interfaces to Sensor and Actuation Systems. Different types of Mezzanine Cards exist. One SCU may be equipped with up to 12 SCU Mezzanine Cards.



### DLN hw Decision Logic Node







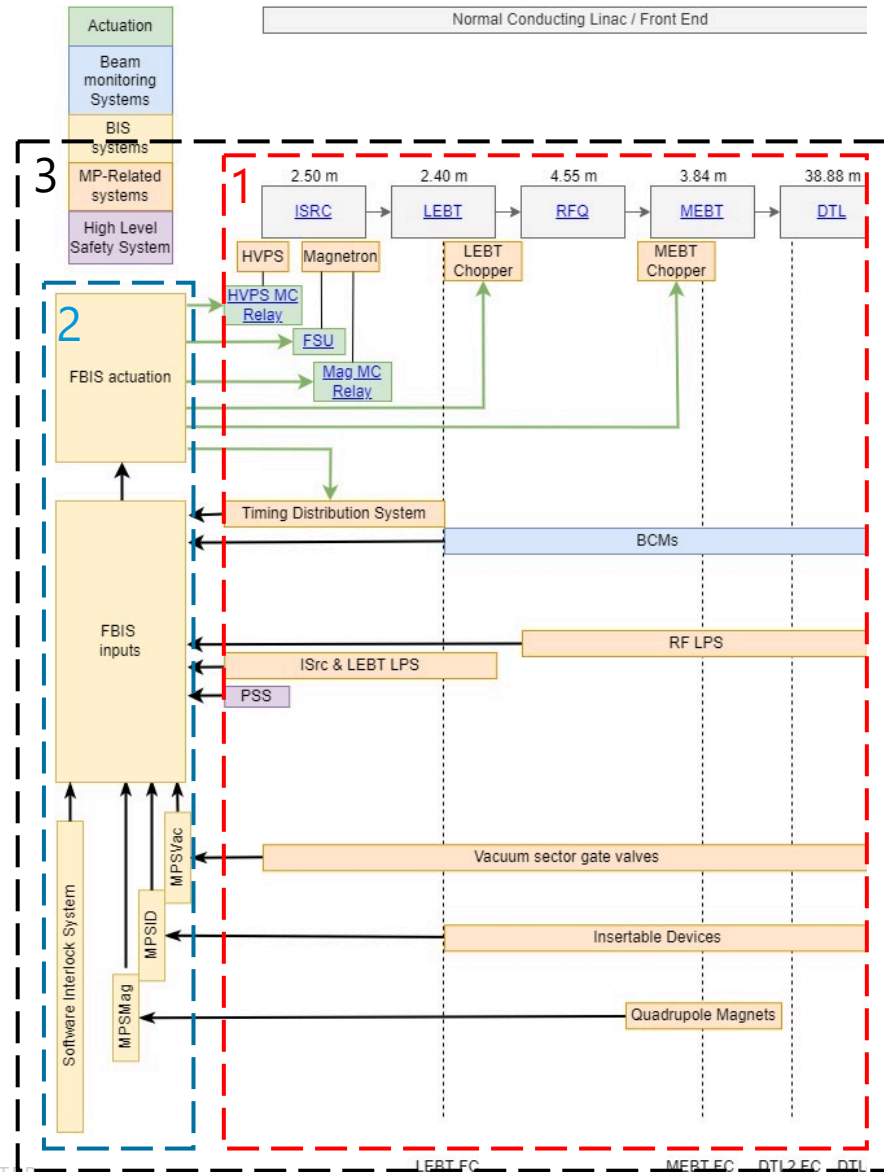


# Verification Overview & Strategy

1. **Interfacing System verification specifications are reviewed by MP team against MP requirements, performed by system owners.**
2. **Beam Interlock systems are verified from interface for all systems in both simulation and production environment.**
3. **Subset of Protection Functions are tested in Final Integration Test, to test full chain protection functions and reaction times etc.**

- 2**
- BIS Systems Site Integration Testing (SIT)**
- MPSVac SIT Report (ESS-3271566)
  - MPSMag SIT Report (ESS-3271572)
  - MPSID SIT Report (ESS-3271573)
  - FBIS SIT Report (ESS-3532799)

- 3**
- Final Integration Testing (FIT)**
- MP-SoS NCL Final Integration Test Report ESS-3728373



- 1**
- Actuator Systems – Test Reports**
- Magnetron (ESS-3244791)
  - High Voltage Power Supply (ESS-3244790)
  - MEPT Chopper (ESS-3069798)
  - LEPT Chopper (ESS-3491849)
- Beam Current Monitors - Test Reports**
- MEPT BCM 02 - ESS-3523885
  - MEPT BCM 01 - ESS-3523880
  - RFQ BCM 01 - ESS-3523883
  - LEPT BCM 01 - ESS-3175492
  - ISRC BCM 01 - ESS-3523879
- RFLPS RF-LPS System- Test Reports**
- RFQ RFLPS ESS-4017667 –
  - MEPT 1,2,3 ESS-4017668, ESS-4017668, ESS-401766
  - DTL 1 ESS-401766
- Slow LPS – Test Reports**
- Ion Source PLC (ESS-3432635 )
  - Vacuum Interlock System (ESS-3260648, ESS-3260650, ESS-3179273)
  - Quadrupole Systems (11 x Quads) (Spec ESS-3069799)
  - ID LPS Systems (up to 16 devices)
    - ESS-3209965 (rev 2) - LEPT FC
    - ESS-3213286 (rev 2) - MEPT FC



# MP-SoS Final Integration Testing

## Overview of MP-SoS Final Integration testing (Full Chain / Beam Testing)

### **Test case 1 (Beam Disabled, verify mode change sequences, procedures and verify correct limits are set)**

- Configuration Check – Cycle through all Proton Beam Modes, using operational procedure for changing modes and verify BCM thresholds values.  
Configuration Mismatch – Create Beam Mode mismatch and check operational procedures
- Configuration Check – Cycle through all Proton Beam Destinations, using operational procedure for changing Proton Beam Destination and verify motion function of destinations.

### **Test case 2 (Beam Disabled, verify full chain PFs, diagnostics and operational procedures)**

- Scenario 1: Full Chain Tests for Magnet, Vacuum, ID, RFLPS, BCM includes timing check and Procedural elements

### **Test case 3 (Beam Disabled, using waveform generator to test threshold values of BCMs)**

- Scenario 1, 2, 3: Verify interlock function when BCM detects Beam Mode limits are exceeded
- Scenario 4, 5, 6: Verify that BCM Interlocks if Beam is detected downstream of Proton Beam Destination
- Scenario 7: Verify that BCM for ISrc ACCT Interlocks if beam is detected when in Plasma Conditioning Mode (Waveform Generator)

### **Test case 4 (Beam Enabled, BCM differential tests, and actuator tests)**

- Scenario 1, 2, 3: Verify that BCM Interlocks if BCM Differential limit is exceeded between 2 BCMs Phase A (With Beam)
- Scenario 4: Machine Protection actuator testing for Magnetron
- Scenario 5: Machine Protection Actuator Testing for Choppers

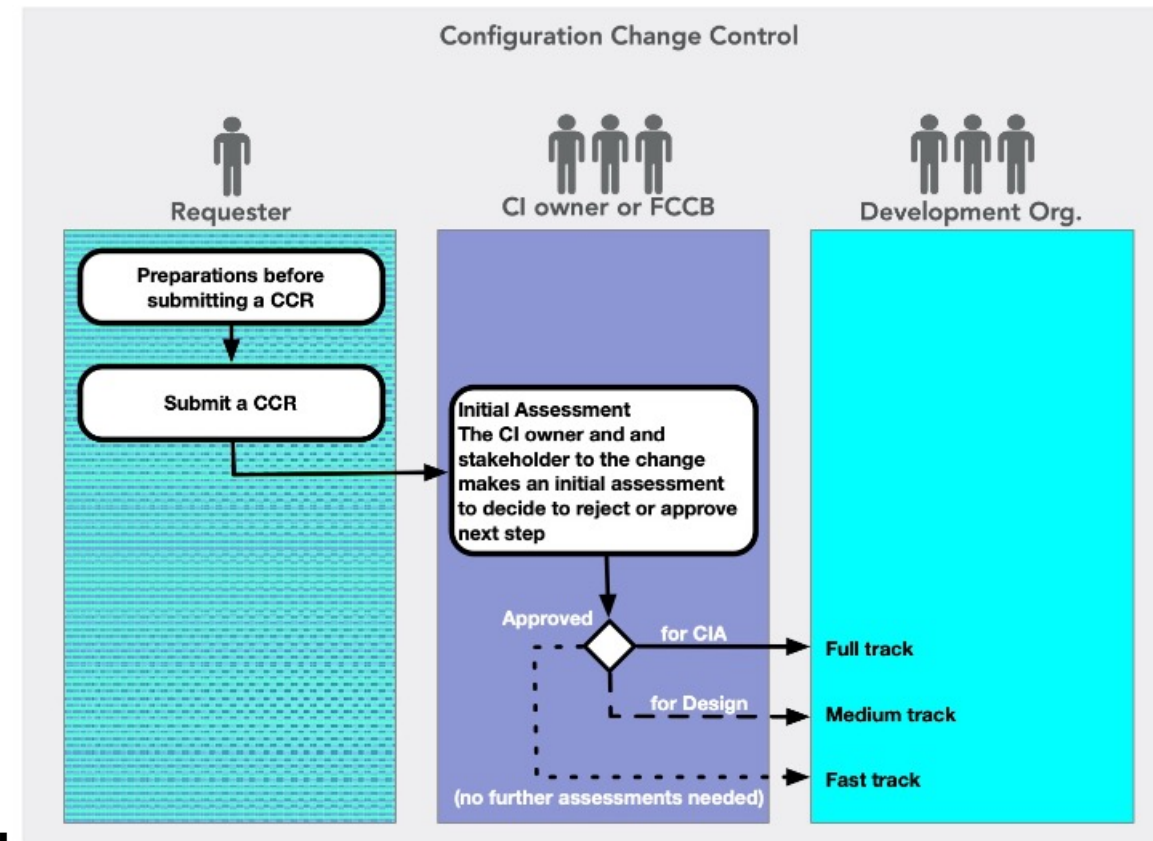
# Challenges



## ESS Facility Configuration Management based on documentation.

L2	ESS Facility				
L3	ACC*	Target Station	NSS	Buildings	Site and INFR
L4	ISRC+LEBT RFQ MEBT DTL SPK MBL HBL HEBT DMPL A2T ACC PSS TS2 <i>TS2 Timing Distribution</i> <i>TS2 PSS</i> <small>CIDLs in <i>italics</i> relate to sub CIs. VACUUM, RFS, WTRC and CNPW will be included as a sub-item in each of the relevant Accelerator sub CIDLs. *Includes shielding walls (temporary, chicane etc)</small>	Active Cells Facility <b>Cooling &amp; Utility Plant</b> Casks Assembly Neutron Beam Extraction Systems Target Systems <i>PSV OCS</i> Target Safety System TS PSS Fluid distribution TS Electrical Proton Beam Monitoring Systems Shielding and Confinement MRP PBW TS HVAC Target Test Stands	BEER BIFROST C-SPEC DREAM ESTIA FREIA HEIMDAL LoKI MAGIC MIRACLES NMX ODIN SKADI T-REX VESPA RML Test Beamline NSS Bunker	B01 E01 B02 E02 D01 E03 D02 E04 D03 E05 D04 F01 D05 F03 D06 F04 D07 G01 D08 G02 H01 G04 H05 H06 H09 H10	REMS ACCP ACC CDS TMCP TMCP CDS TICP TS2 CDS IT BIS Timing Distribution System Technical Network <i>ICS Computing Infrastructure</i> Control Rooms Phase Reference Line Process Electrical Control & Monitoring Fire Safety Systems Transport HVAC Physical Protection

<https://confluence.ess.lu.se/display/EIS/Configuration+Management+for+ESS+Facility>



CI = Configuration Item

CIDL = Configuration Item Documentation List

CCR = Configuration Change Request

**CCR process only relevant if changes affect documents!**



# Examples

## Changes to Configuration.

**CCR: ESS-3732221:**

*Temporary hardware masking of the MEBT Chopper feedback to FBIS until SRR2*

**CCR: ESS-4089190 Rev 1**

*Removing the MEBT chopper as beam stop actuator until SRR3*

**CCR: ESS-3528829**

*(Scope Change) Beam instrumentation systems in initial NCL phase - Beam Current Monitors*

**CCR: ESS-3481590**

*(Scope Change) Beam Instrumentation systems in initial NCL phases - insertable devices*

**CCR: ESS-4123454**

*Additional allowed beam modes in MPSID for DTL1 FC*

**CCR: ESS-4099584**

*Removing security cable between the FSU and the magnetron PS*

**CCR: ESS-#####**

*Update MEBT Chopper PCB Interface for DTL04 conditioning*

**CCR: ESS-4224098**

*Sector gate valves need to be temporarily masked for an initial phase of SCL conditioning and operation.*

**CCR: ESS-3999230**

*change of the allowed voltage range (on the HV platform) for beam extraction*



# Challenges

## Non Conformities (PIL = Protection Integrity Level of Protection Function)

- **Non Conformity: 10225 = MEBT Chopper not operational as beam stop actuator**

*Since the MEBT chopper is not operational as beam stop actuator, PIL 1 can not be reached for the fast protection function (less than 3 us). see "ACT COMB 5 - LEBT, MEBT CHOPPER" in "ESS-2755165 - PIL Report for Actuation Systems"*

- **Non Conformity: 10222 = LEBT cooling not compliant with PIL 1 requirement**

*sensors below are not compliant with MP-MC-REQ-2 (ESS-0151690)*

*ACC.E02.W01.E01.BF011 (FIS-XXX) LEBT FC, ACC.E02.W01.E01.BF003 (FIS-XXX) LEBT EMU 1*

*ACC.E02.W01.E01.BF010 (FIS-XXX) LEBT EMU 2*

- **Non Conformity: 10226 = FBIS is not compliant with PIL 2 requirement**

- **Non Conformity: 10220 = BCM system not compliant with PIL 2 requirement**



# Challenges

## Managing operational limits

### [NSOI-204](#)

*Temporarily Increase Threshold on Errant Beam Detection for DTL1 BCM from 3mA to 5mA*

### [NSOI-208](#)

*Temporary Mask Interlock Function for DTL1 BCM Max Allowed Beam Current*

### [NSOI-205](#)

*Temporary Mask DTL1 BCM Errant Beam Interlock Function*

### [NSOI-163](#)

*Interlock Masking for Ion Source repeller voltage, LEBT repeller voltage*

### [NSOI-171](#)

*Mask LEBT Collimator Thermocouple Interlock*

### [NSOI-191](#)

*Permanently Change LEBT Repeller Threshold*

## 9. APPENDIX A: DESCRIPTION OF RESPONSIBILITIES DURING THE INTERLOCK CHANGE REQUEST PROCESS

More detailed responsibilities for roles as:

### Change Requester (CHR):

- To generate the mask or change request using the "Interlock Mask Request" or "Interlock Change Request" **JIRA task** as shown in APPENDIX B and attaching it to the appropriate Mask/Change request in the **logbook**.
- To request the **SO, SL and MSC<sup>S</sup> and MPSoSC** (if required) to review, comment and approve the request under the created **JIRA task**.
- To be responsible for clearly describing the interlock and the method of mask or change to the **SO and SL and MSC<sup>S</sup>**.
- To ensure the interlock is masked or changed after the required actions are taken.
- To ensure that **SLs** have been notified about the change. By adding them to the **JIRA task** (as watchers).
- **To ensure that masking is removed** (in coordination with **SO**) due time.

### System Owner (SO):

- **To have a clear understanding of the mask or change and why the mask or change is being applied.**
- To perform a risk assessment, which documents the consequences and risks in case the interlock is changed. To document this in the **JIRA task**.
- To ensure the interlock mask or change is implemented after the required actions are taken.
- To ensure that masking is removed (in coordination with **CHR**) due time.

### Machine Section Coordinator (MSC):

- **To have a clear understanding of the mask or change and why the mask or change is being applied.**
- To perform a risk assessment **along with the organisational panel to their choice**, which documents the consequences and risks in case the interlock is changed. To document this in the **JIRA task**.
- To ensure that masking is removed (in coordination with **CHR**) due time.

### Shift Leader (SL) /Machine Section Coordinator:

- To ensure that the change request is completed satisfactorily and that the correct **SOs** have provided requested information and are notified.





Thanks,  
Questions?



# Supporting Slides

## Beam Modes and Destination



Table 1: Allowed combinations of beam destinations and beam modes for NCL commissioning to DTL4

Beam modes vs Destinations	No Beam	Conditioning	Probe	Fast commissioning	RF test	Stability test	Slow commissioning	Fast tuning	Slow tuning	Long pulse verification	Shielding verification	Production
ISrc	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	TBD	Y
LEBT FC (LEBT-010:PBI-FC-001)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	TBD	Y
MEBT FC (MEBT-010:PBI-FC-001)	Y	Y	Y	Y	Y	TBD	Y	Y	Y	N	TBD	N
DTL1 FC (<21 MeV) (DTL-010:PBI-FC-001 is the same device as DTL-020:PBI-FC-001)	Y	Y	Y	Y	Y	TBD	Y	Y	TBD	N	TBD	N
DTL2 FC (20.4-40.1 MeV) (DTL-020:PBI-FC-001)	Y	Y	Y	Y	Y	TBD	TBD	TBD	TBD	N	TBD	N
DTL4 FC (38-76 MeV) (DTL-040:PBI-FC-001)	Y	Y	Y	Y	Y	TBD	TBD	TBD	TBD	N	TBD	N

Table 3: List of the defined Proton Beam Modes

Name	Max Beam Parameter			Description
	I [mA]	T [μs]	f [Hz]	
No Beam	0	0	0	No Proton Beam
Conditioning	0	0	0	Plasma production, magnetron allowed but no extraction HV
Probe	6	5	1	First proton beam to be send through a section; non-damaging even in the case of total proton beam loss (even repeated); used to verify that machine configuration is not grossly incorrect
Fast commissioning	6	5	14	Limited proton beam loading; used for fast scans to rapidly determine/verify RF setpoints
RF Test	6	50	1	To perform an initial RF test with a longer pulse
Stability Test	6	50	14	To be used mostly for proton beam stability test
Slow Commissioning	62.5	5	1	Very short pulse planned to be used during Normal Conducting Linac commissioning. It would allow installation of the rest of the Linac in parallel to Beam Commissioning.
Fast tuning	62.5	5	14	Limited proton beam loading; used for fast scans to rapidly determine/verify RF setpoints and measure proton beam profiles with wire scanners.



# Supporting Slides

## Beam Modes and BCM Limits

Table 4: ACCTs threshold for the Probe beam

Beam Mode : Probe			
ID : 20			
ACCT name	Upper Threshold (mA)	Max Pulse Length ( $\mu$ s)	Max Repetition rate (Hz)
ISrc	Disabled	Disabled	1.000001 <sup>2</sup>
LEBT	$6+0.3^3*6+0.1^4*6 = 8.4$	$5+40^5+1^6 = 46$	
RFQ	6.6	46	
MEBT1	6.6	6	
MEBT2	6.6	6	
DTL1	6.6	6	
DTL2	6.6	6	
DTL3	6.6	6	
DTL4	6.6	6	
DTL5	6.6	6	

Table 5: ACCTs threshold for the Fast commissioning mode

Beam Mode : Fast commissioning			
ID : 30			
ACCT name	Upper Threshold (mA)	Max Pulse Length ( $\mu$ s)	Max Repetition rate (Hz)
ISrc	Disabled	Disabled	14.000196
LEBT	8.4	46	
RFQ	6.6	46	
MEBT1	6.6	6	
MEBT2	6.6	6	
DTL1	6.6	6	
DTL2	6.6	6	
DTL3	6.6	6	
DTL4	6.6	6	
DTL5	6.6	6	

Beam Mode : Slow Commissioning

Beam Mode : Slow Commissioning			
ID : 60			
ACCT name	Upper Threshold (mA)	Max Pulse Length ( $\mu$ s)	Max Repetition rate (Hz)
ISrc	Disabled	Disabled	1.000001
LEBT	$62.5+62.5*0.3+62.5*0.1 = 87.5$	$5+40+2^7+1 = 48$	
RFQ	68.75	48	
MEBT1	68.75	8	
MEBT2	68.75	8	
DTL1	68.75	8	
DTL2	68.75	8	
DTL3	68.75	8	
DTL4	68.75	8	
DTL5	68.75	8	

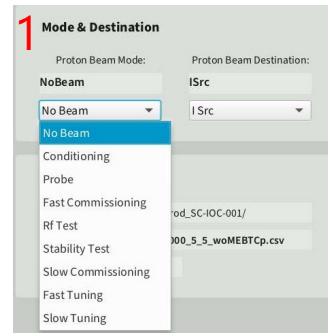
ESS-2169873 - BCM Look Up Table for Beam Mode Consistency Checks during the ESS Normal Conducting Linac Commissioning

# Supporting Slides

## Changing Beam Modes and Destination

1. Operator selects a predefined configuration from OPIs. Can only change when Beam is Stopped

( Requested Beam Mode (BM) and Beam Destination (BD)

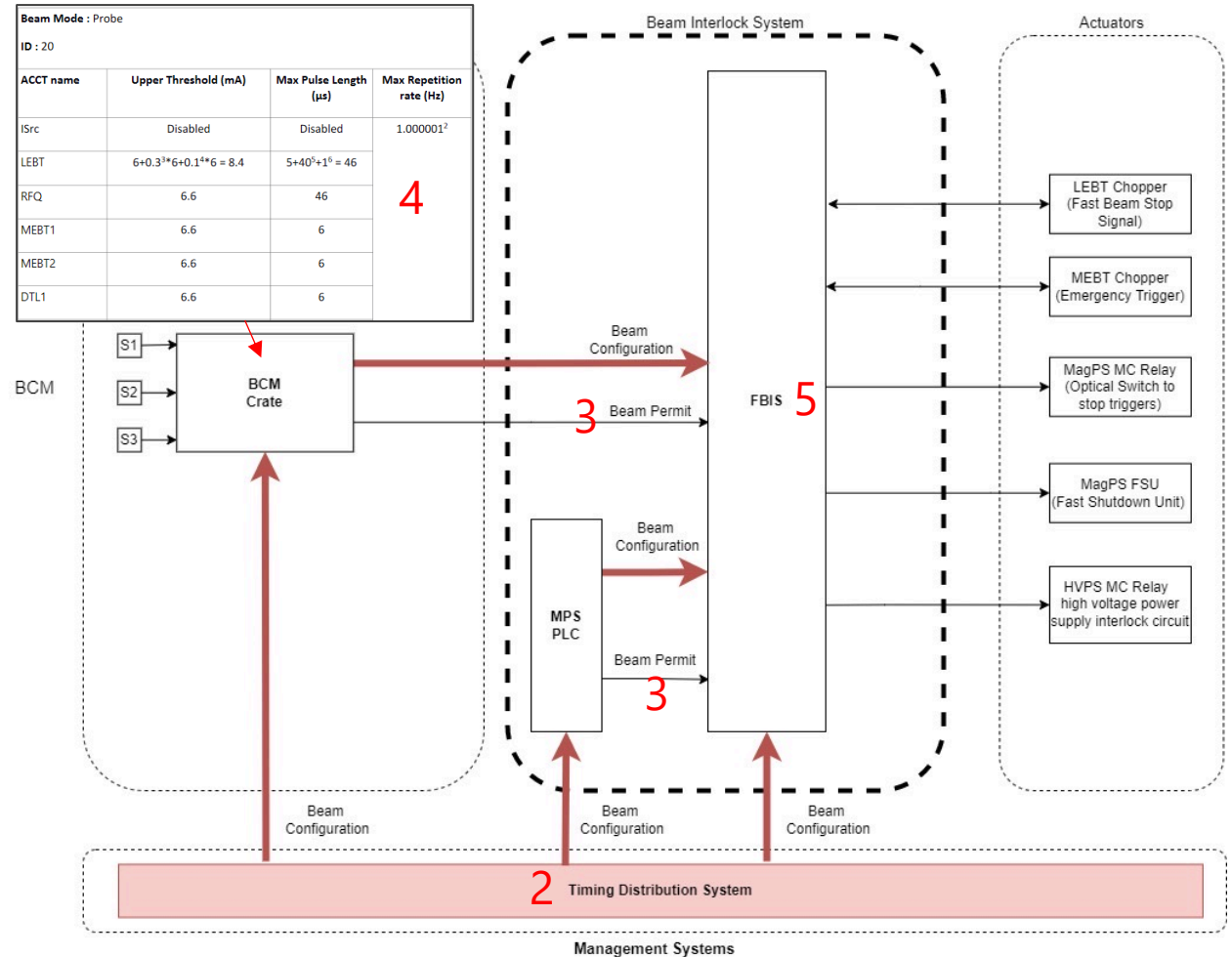


2. TDS Distributes the new "requested" configuration to all systems

3. BIS Systems check status of all input systems relevant for destination. PLCs Send Configured Mode & Destination to FBIS. (All upstream devices, all actuators)

4. BCM system updates thresholds for ACCTs based on new "requested" configuration (Hardcoded). Sends Configured Mode & Destination to FBIS and removes Beam Permit if Beam is outside the limits, (Values are based on look up tables)

5. FBIS Checks all systems have correct Configuration or inhibits beam, and that all Beam Permits are OK for Destination or Interlocks beam.



# Supporting Slides

## Protection Functions

