R2E Developments for PIC and BIS in HL-LHC

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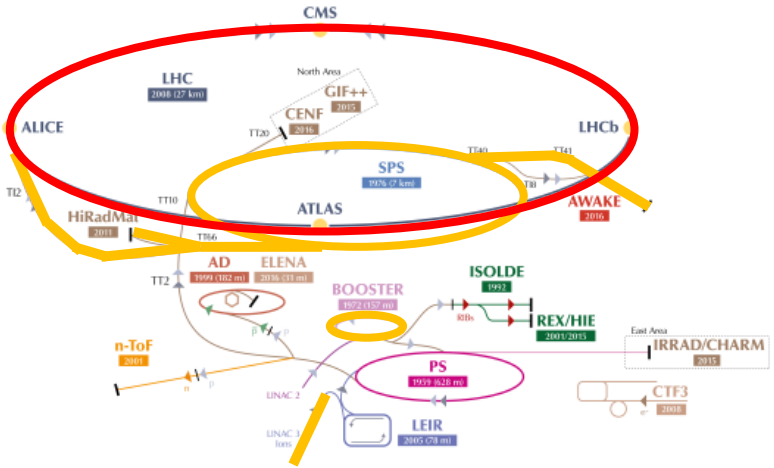
Outline

- Beam Interlock Controller developments
  - R2E
  - Linking of beam permit loops
- Power Interlock Controller developments
  - Relocation
  - Protection against erratic CLIQ triggering

The Beam Interlock System User Interface: CIBU

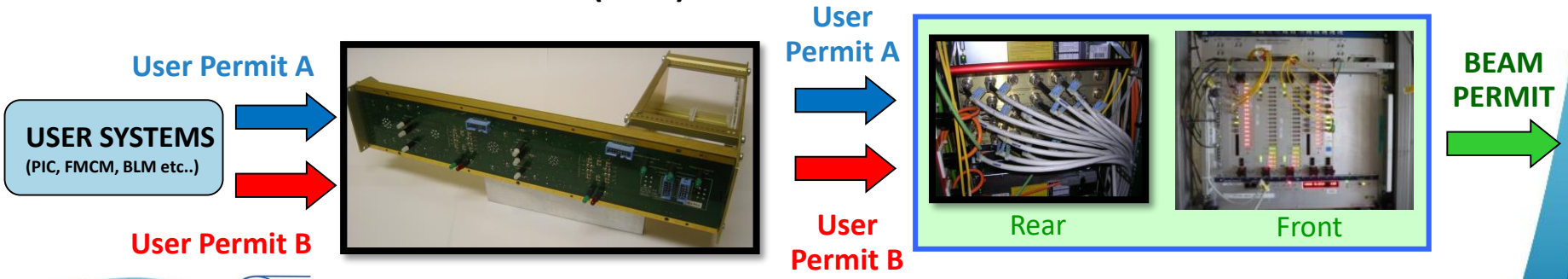


CIBU: Unique BISv2 User Interface system

- **LHC : ~150** CIBUs
  - **12 CIBU Units** installed in **RR areas**: points 1,5 and 7
- **SPS and Injectors**: **~350**

User Interface (CIBU)

Beam Interlock Controller

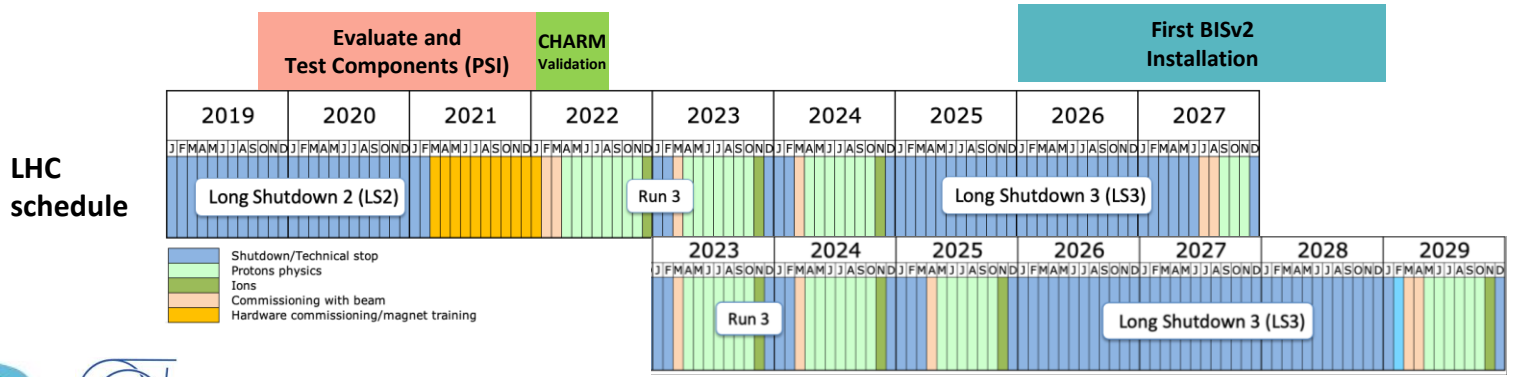


Planning and Strategy

- **BIS v2**: first installation planned during **LS3**
- **CIBU spares BISv1 running low**
  - CIBUv1 components hard to find
  - CIBUv2 design to be compatible with **BIS v1**
  - **Strategy discussed with R2E:** the CIBU is the **unique interface for any User to be connected to the LHC-BIS**

    → Design a Rad-Tol CIBUv2 targeting the **RR** areas (worst-case scenario)

- Development of **ONE CIBUv2 design**:
  - **COTS** from available databases (RadWG, ESA…)
  - **Tests** carried out at **PSI** (BE-CEM) to qualify components. LOTs recorded for system production
  - System **fully validated** in **CHARM**, April-May 2022.



R2E: Radiation Levels and Validation

	Annual ($360\ fb^{-1}$) HL-LHC radiation levels			
	TID [Gy]	HEH [cm^{-2}]	Th. neut. [cm^{-2}]	1MeVn-eq [cm^{-2}]
RR13-17-53-57 Lo	15	$1 \cdot 10^{10}\ cm^{-2}$	$9 \cdot 10^{10}\ cm^{-2}$	$7 \cdot 10^{10}\ cm^{-2}$
RR13-17-53-57 L1	25	$1.4 \cdot 10^{10}\ cm^{-2}$	$1.2 \cdot 10^{11}\ cm^{-2}$	$7 \cdot 10^{10}\ cm^{-2}$

- **HL-LHC Radiation level specification: EDMS 2302154**
- **Hi-Lumi, RR** (L1) **ultimate** scenario: **4000 fb^{-1}**
  - **TID = ~280 Gy**
  - **HEH total fluence = ~1.6 x10^{11} cm^{-2} total**
  - **1MeVn-eq fluence = ~ 8 x10^{11} cm^{-2}**

- **CRITICAL** and **MONITORING** COTS components selected and evaluated
- CIBUv2 RHA Project Validation, **RHAPV: EDMS** 2679251
- CIBUv2 Full **CRITICAL** circuit **qualified, EDMS** 2415099
- **Separate evaluation** of the Power Supply unit (**CIBD**) components (TRACO 5V, Voltage Regulator).

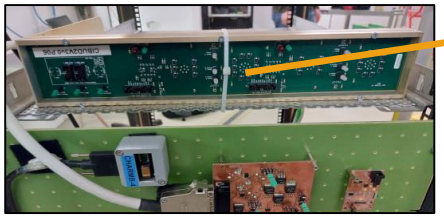
CHARM Validation - April 2022

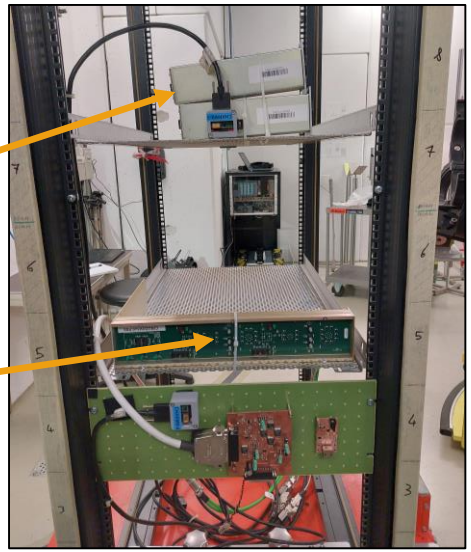
- Two test runs, **one week irradiation** each.
- **CHARM Settings**: position **R13**, CuOOOO.
- First Run: **one** CIBUv2 unit and **two CIBDs**
- Second Run: **one** CIBUv2 unit and **one CIBD**

CHARM April 2022 Test Campaign setup

CIBU Power Supply unit (**CIBD**)

CIBUv2





CIBU CHARM Test Results

	Requested for Hi-Lumi ultimate scenario	Achieved in CHARM
TID [Gy]	~280 Gy	**383** Gy
HEH fluence [cm^{-2}]	~1.6×10^{11}	**~1.57×10^{12}**
1MeVn-eq fluence [cm^{-2}]	~8×10^{11}	**~3.3×10^{12}**

CIBU

- **2x CIBU** tested, each one in a separate irradiation run
- **No degradation** of the **CIBU critical path** over **TID** up to at least **~383 Gy**
- **No evidence of SEL** nor any destructive **SEE** up to a fluence of **~1.57e12 cm-2 HEH** and **~3.3e12 cm-2 1MeVeqn, within Hi-Lumi targets**
- ~27 **SETs** occurring on the USER PERMIT lines observed
  - Assuming **12 CIBU units** in the RRs, the worst-case estimated # **false-dumps** per year is **~1.2**
  - Transients had a **duration < 2µs** → **all can be filtered** at the level of the BIC

CIBD (CIBU power supply)

- **Total of 3x CIBD** units **tested**
- In the worst-case: **failure at 217 Gy** and **~7e11 cm^{-2}** of **HEH** fluence → Considering ~24 CIBD units in operation, if required they can be 'rotated' during a Long Shutdown
- LT3083 Voltage Regulator: does **not survive power cycles** → to be replaced by a new candidate (suggested by R2E)

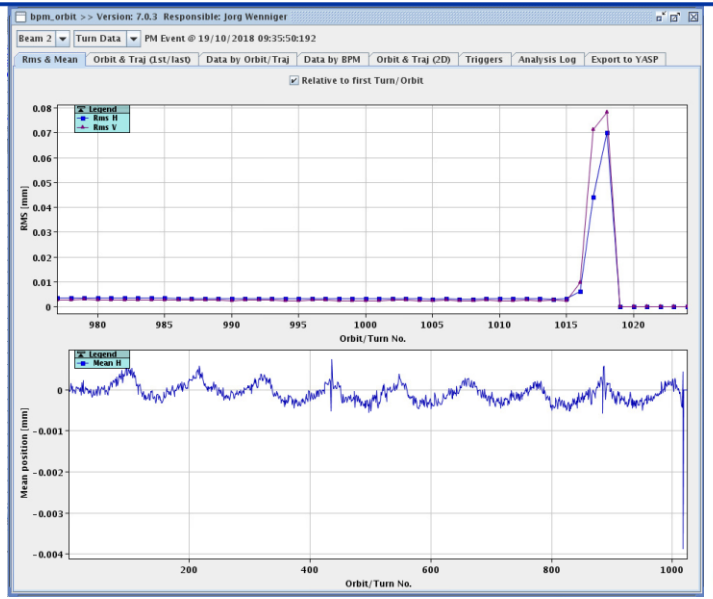
Details of the test results are reported in EDMS 2768960

Linking the beam permit loops for HL-LHC

Motivation

- Extraction of one beam causes a missing beam-beam kick in the other beam, i.e. an **ultra fast orbit offset**, leading to beam losses
- With BIS1 delays, the loss of beam-beam kick can be present for **up to 3 turns**
- For HL-LHC the beam-beam kick is reaching critical levels, risking to cause damage in the collimation system, if beams are **not dumped swiftly** after each other

Beam beam kick	LHC run 2	HL-LHC
Amplitude	~0.5 sigma	~1.6 sigma
Losses	Not critical	1st turn: 380kJ 2nd turn: 1.29MJ



Beam Position Monitor: Post-mortem analysis of beam dump 19/10/2018

Requirements

- There shall be **no more than one turn delay** between the two beam dumps
- **Reliable linking** of the two beam permits required for high intensity operation, **done in hardware**, independent of the origin of the beam dump request

References:

- BIS-V2 Workshop: indico.cern.ch/event/751827/
- B. Lindstrom et al., Fast failures in the LHC and the future high luminosity LHC, Physical review accelerators and beams 23, 081001, 2020

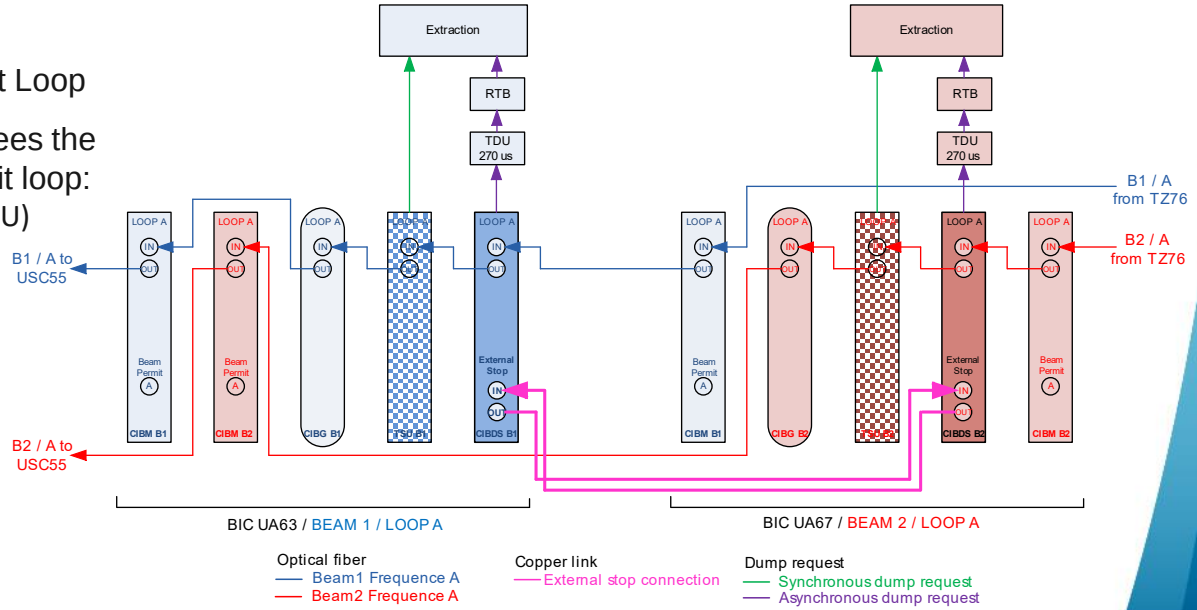
Proposed Linking Solution

BIS2 implementation - latency

- Link mode implemented in the CIBDS. The CIBDS handles the redundant link from the BIS to the LBDS re-triggering lines. BIS1 currently uses the CIBG (beam permit loop generator) to implement the link mode
- The CIBDS can open the Beam Permit Loop
- The order of BIS components guarantees the lowest latency to open the beam permit loop: (CIBG -> CIBM -> … -> CIBM -> CIBDS -> TSU)

=> Less than one turn delay between the two beam dumps

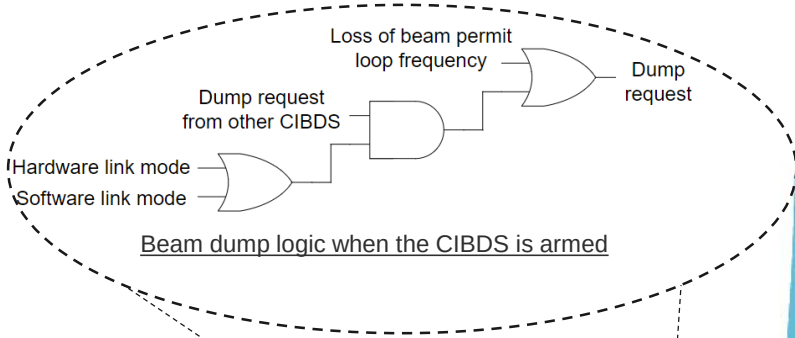
Only loop A is shown.
The same layout applies for loop B.

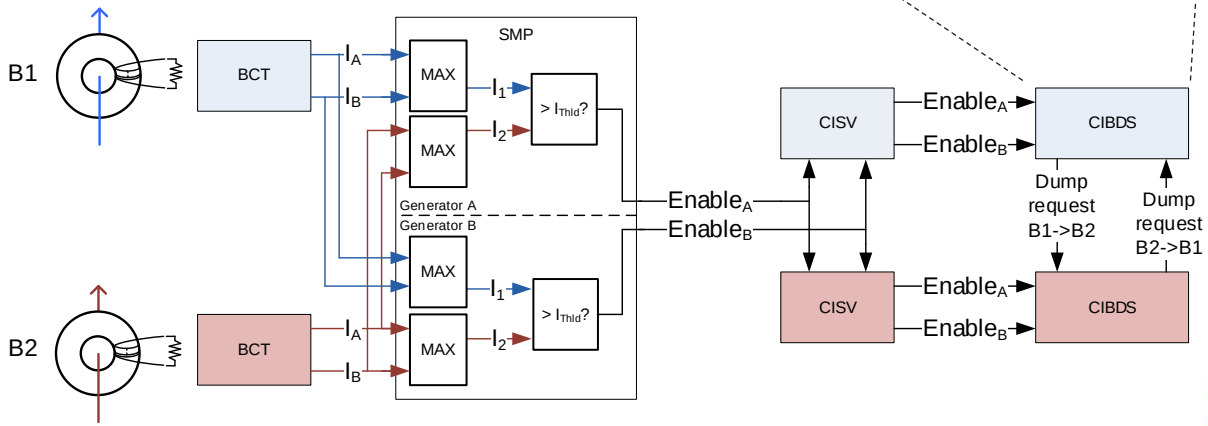


Linking depending on Safe Machine Parameters

BIS2 implementation - enforcing link mode

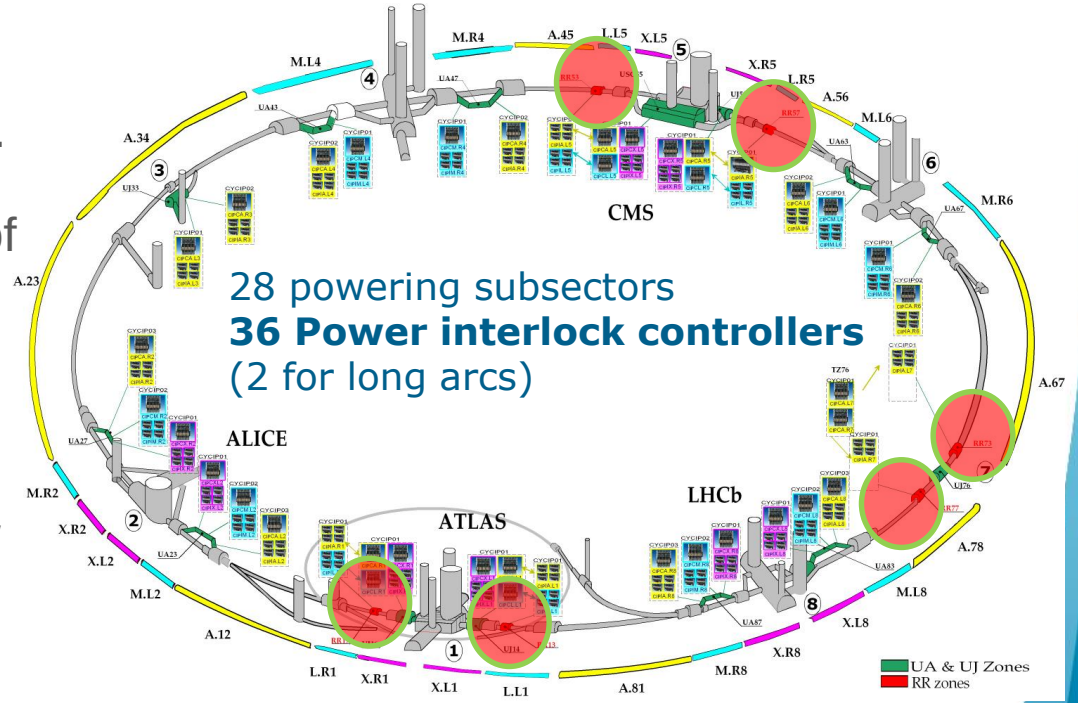
- The link mode can be enabled/disabled below a safe beam limit (software link mode flag)
- Above the safe beam limit, the linking will be enforced by the SMP system (hardware link mode flag)
- The safe beam limit is based on beam intensity and is provided by the **Safe Machine Parameter**





The Power Interlock Controller (PIC)

- Ensures the correct powering conditions for the superconducting magnet circuits.
- Requests a beam dump via the Beam Interlock System in case of failure of a connected circuits.
- **10 out of 36 PICs are in a radioactive environment, namely the RRs at point 1, 5 and 7**.
- HL-LHC: Implementation of new CLIQ systems at point 1 and 5 and requirements on PIC.

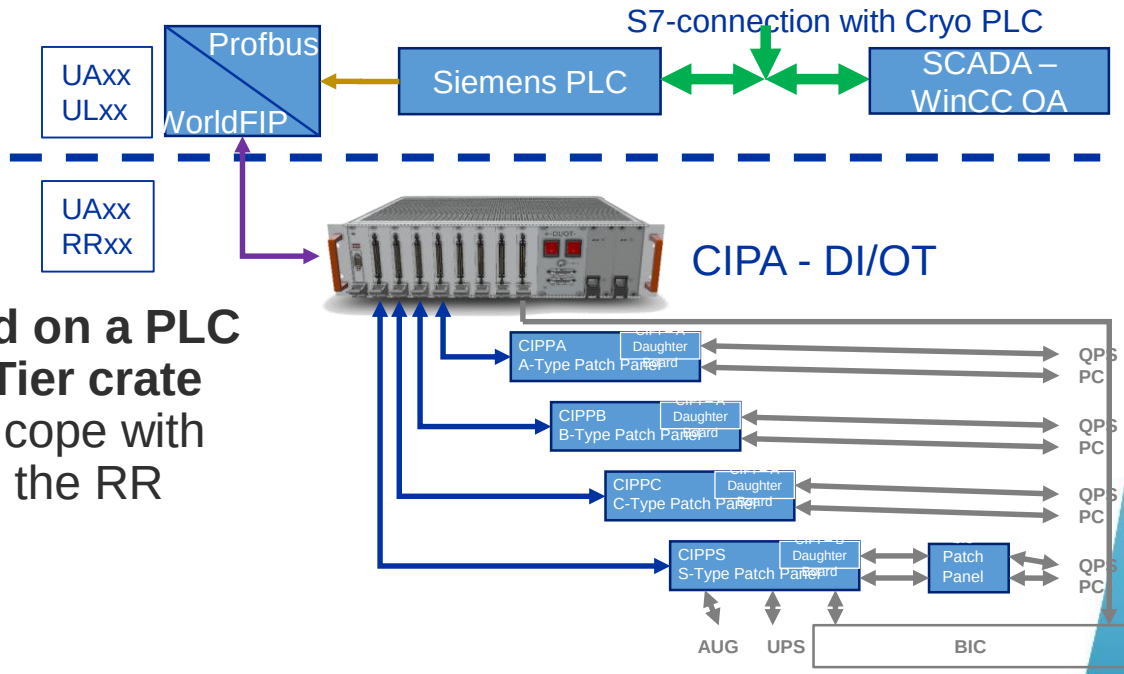


Motivation for a Second Generation PIC

- 36 PIC hybrid CPLD/PLC-based systems were installed in 2006 and in operation since 2007. They have demonstrated a high availability and reliability with no interlocking failure recorded.
- An upgrade is necessary to provide a long-term reliable operation for the HL-LHC era:
  - Assure compatibility with HL-LHC protection requirements, both in terms of system architecture and reliability.
  - Extend the lifespan of the PIC systems beyond 2037 by addressing the obsolescence of critical components in the system design.
  - Implement a technical solution to deal with the estimated increase in radiation in the RR areas induced by the HL-LHC beams.
  - Address the shortcomings observed during initial LHC operation and further improve diagnostics of the system and its connected client systems
- PICv2 installation is planned for LS3.

PICv2 Design Option I: DI/OT Based

Estimated Annual HL-LHC radiation levels	TID [Gy]	HEH [cm^{-2}]
RR13, RR17, RR53, RR57 (L1)	25	$1.4.10^{10}$
RR73, RR77 (L1)	4	2.10^{9}

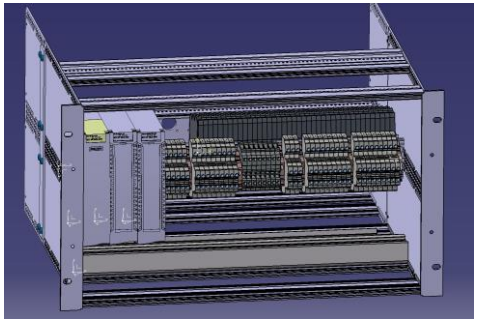
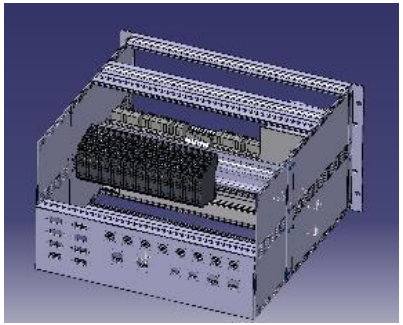
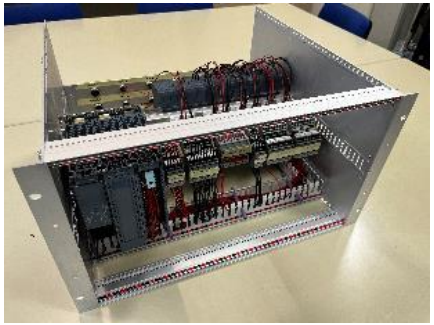
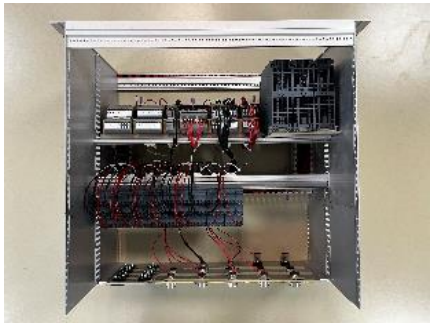


New control architecture based on a PLC connected to a Distributed IO Tier crate (DI/OT) designed by BE-CEM to cope with the increase in radiation levels in the RR zones (L1) estimated at EDMS 2302154.

PICv2 Design Option II: Relocation

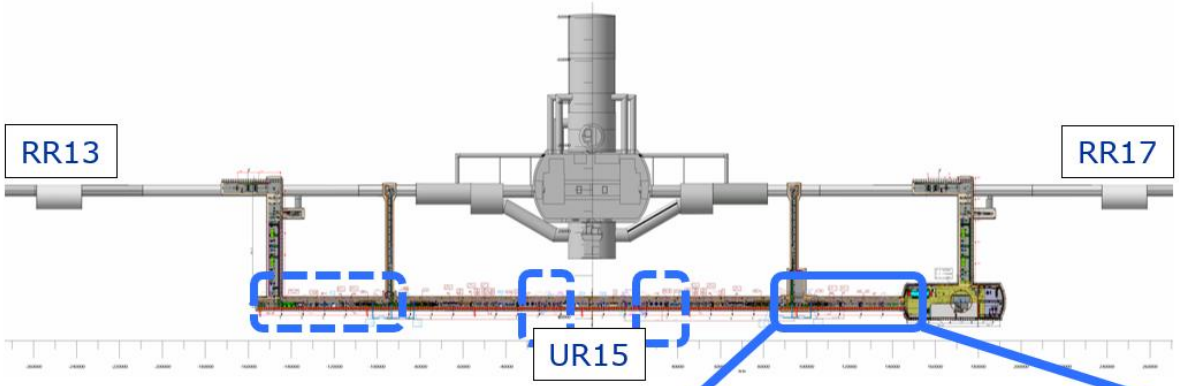
Relocation of the PIC electronics out of the RRs to the new UR galleries at points 1 and 5 using a new full industrial control architecture based on PLCs with high speed capability for the Beam dump function.

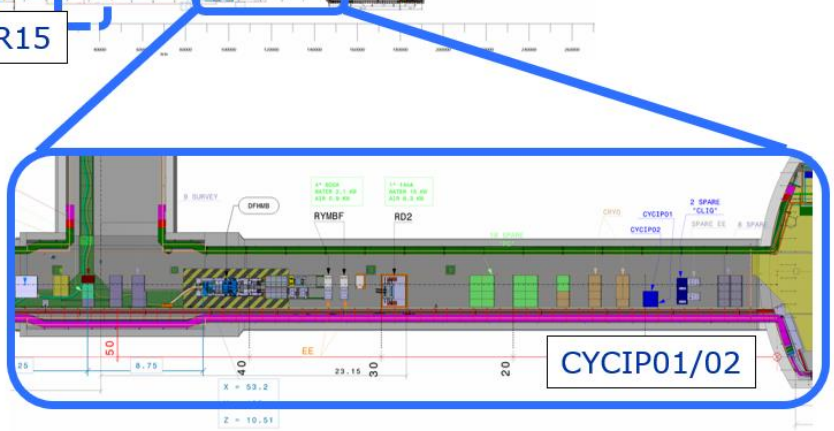
At point 7, electronics will be relocated in TZ76 in the current PIC racks (an additional rack will maybe be necessary).

- **Relocation option supported (Internal review of the ECR in MPE).**
- **A full industrial prototype is designed and will be put into service at the String facility**

Relocation of PIC for HL-LHC





New NE100 cables to be pulled from the RRs to the URs (or TZ76)

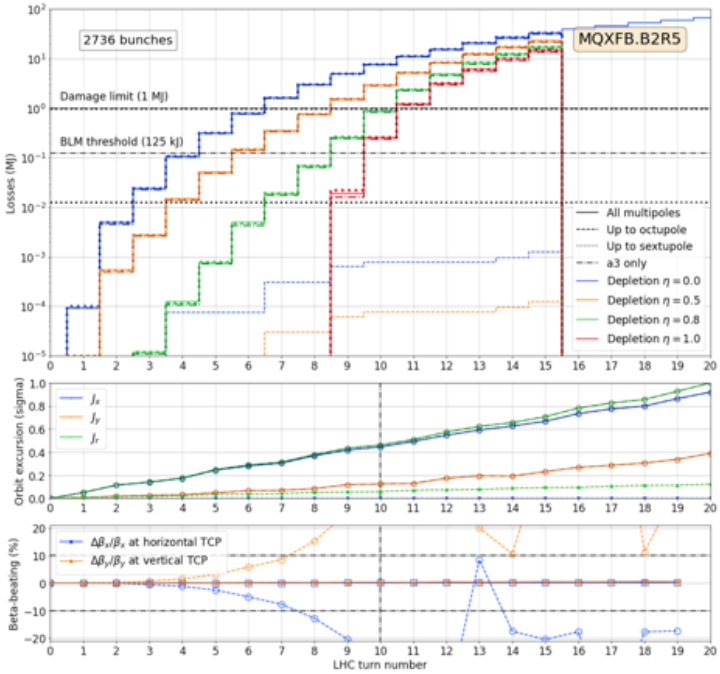
- **Budget ~320 KCHF**
- **Compensated by reduced costs of hardware and no development costs for electronics hardware design**

PIC requirements from CLIQ

Studies updated by C. Hernalsteens, see his presentation this afternoon.

- CLIQ is a new method for protecting superconducting magnets after a sudden transition to the normal state. Alternative or complement to classical quench heaters.
- Besides significant advantages of this technology, the use of CLIQ for the protection of the HL-LHC triplets will introduce a new, fast failure mode for the beams in the LHC in case of a spurious discharge of one unit.
- Critical loss level reached after 5 turns (450 us)

Onset to damage margin	450 µs
Propagation via BIS from P1 to P6	- 100 µs
LBDS synchro.	- 89 µs
Extraction	- 89 µs
Allowed interlock reaction time	**= 170 µs**

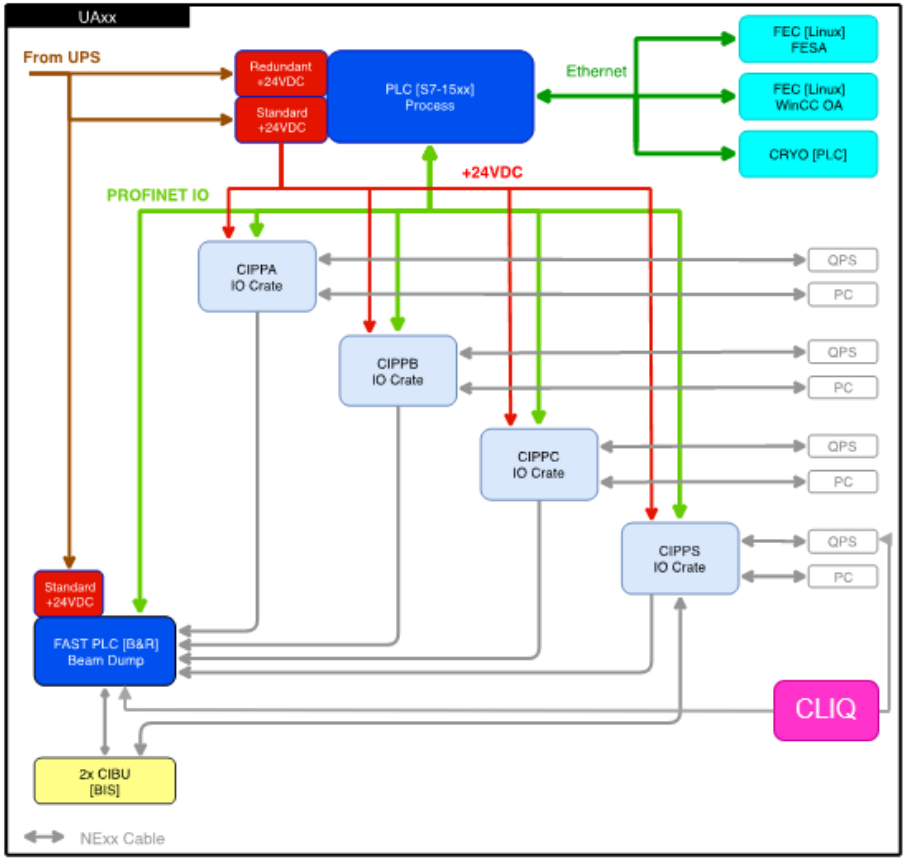


Losses due to **orbit offsets** induced by a discharge (Simulation)

B. Lindstrom, *et al.*, Phys. Rev. Accel. Beams **23**

A fast PIC for CLIQ

- CLIQ will be connected to the PIC through two paths:
  - The existing QUENCH loop to request a beam dump as well as ensure proper removal of power converter supply permission.
  - A dedicated link to ensure a fast redundant beam dump request.
- Current status:
  - A prototype based on a Siemens S7-1500 PLC in redundancy with a reACTION Technology B&R PLC is designed and will be validated at the IT-String.
- Choice of PLC modules:
  - The choice of the fast industrial PLC solution is not yet definitive and will be discussed through the CTTB.



Conclusions

- The new BIS2 User Interface (CIBU) will withstand the radiation levels as expected in the HL-LHC RR regions
  - Full system validation at CHARM succeeded
  - Foresee a production of about 20 units
- The linking of the B1 and B2 Beam Permit Loops of the BIS2 will be done in hardware at the level of the CIBDS
  - Guaranteed delay < 1 turn between the two beams being dumped
- PICv2 will be installed out of the RRs in IP1, 5 and 7
  - Rather long NE100 cables (about 250 m) will be pulled
  - No special radiation tolerant hardware development is foreseen
- PICv2 will have a dedicated link to the CLIQ system to have a fast beam dump request in case of a CLIQ erratic triggering