Equipment Faults Detection Sequence

Bruno PUCCIO

Workshop on Machine Protection, focusing on Linear Accelerator complexes

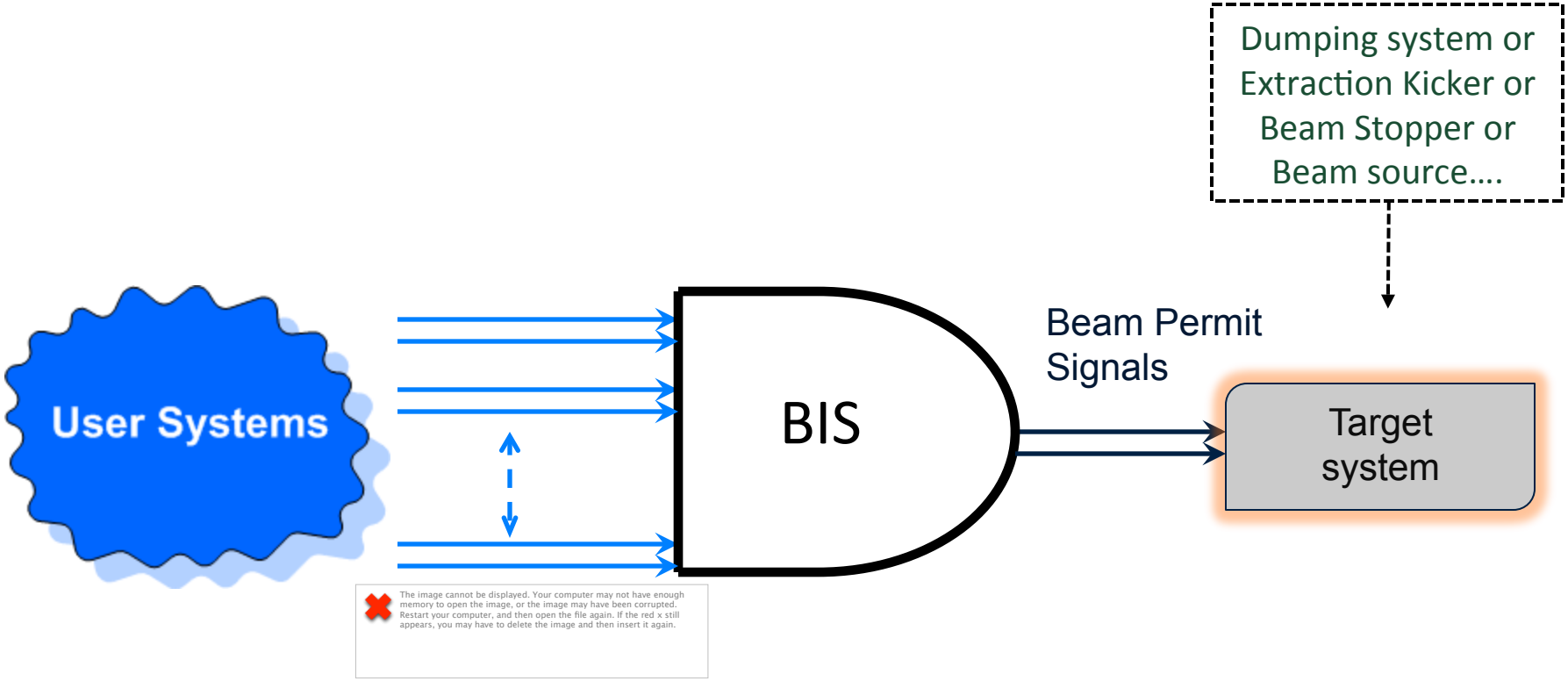
6-8 June 2012

With contributions of Benjamin Todd, Ivàn Romera & Markus Zerlauth

Outline

- Beam Interlock System overview
- BIS & Timing Sequences
- Post-Mortem system
- Summary

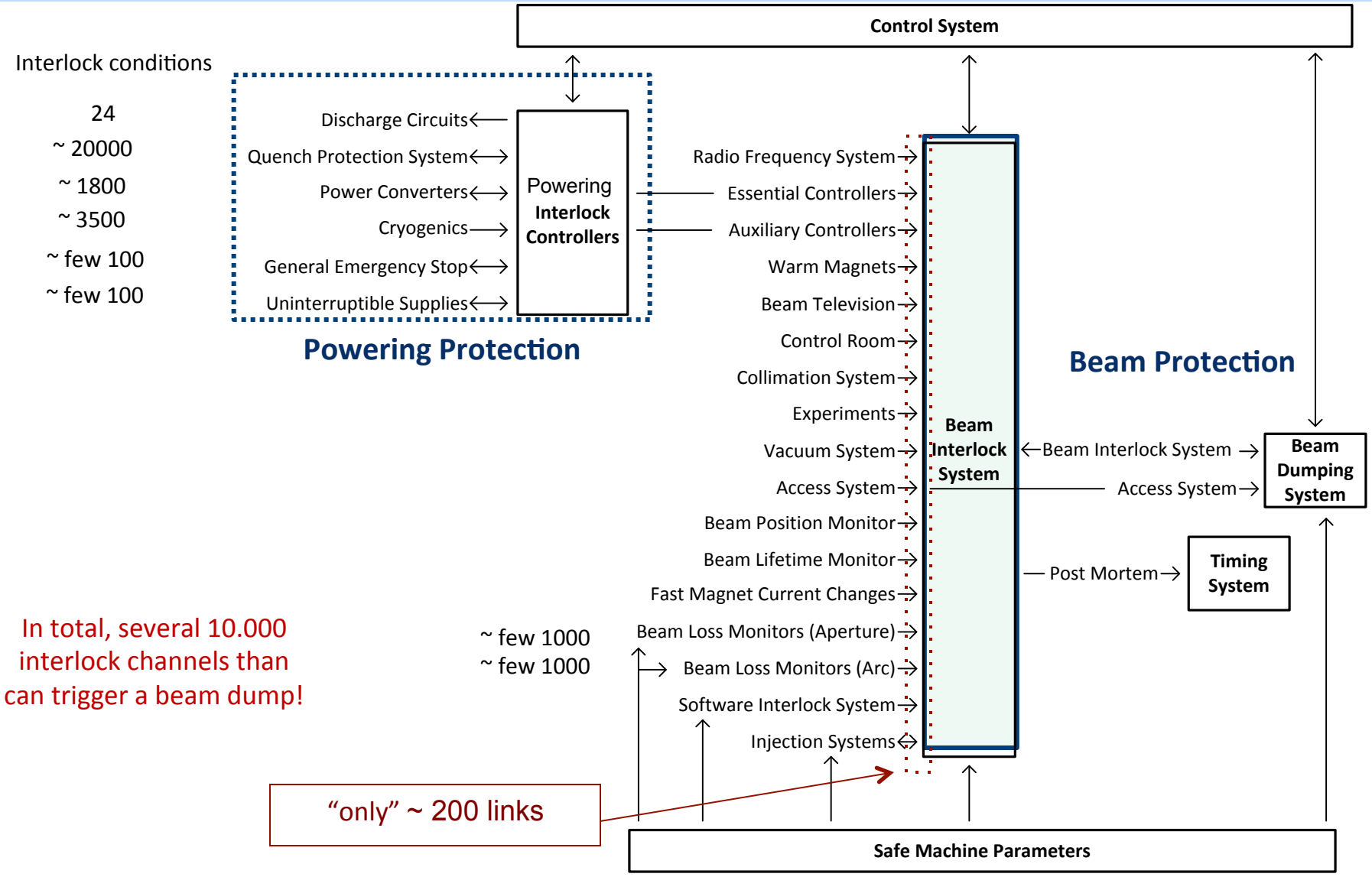
Beam Interlock System Function



Σ(User Permit = “TRUE”) => Beam Operation is allowed

IF one User Permit = “FALSE” => Beam Operation is stopped

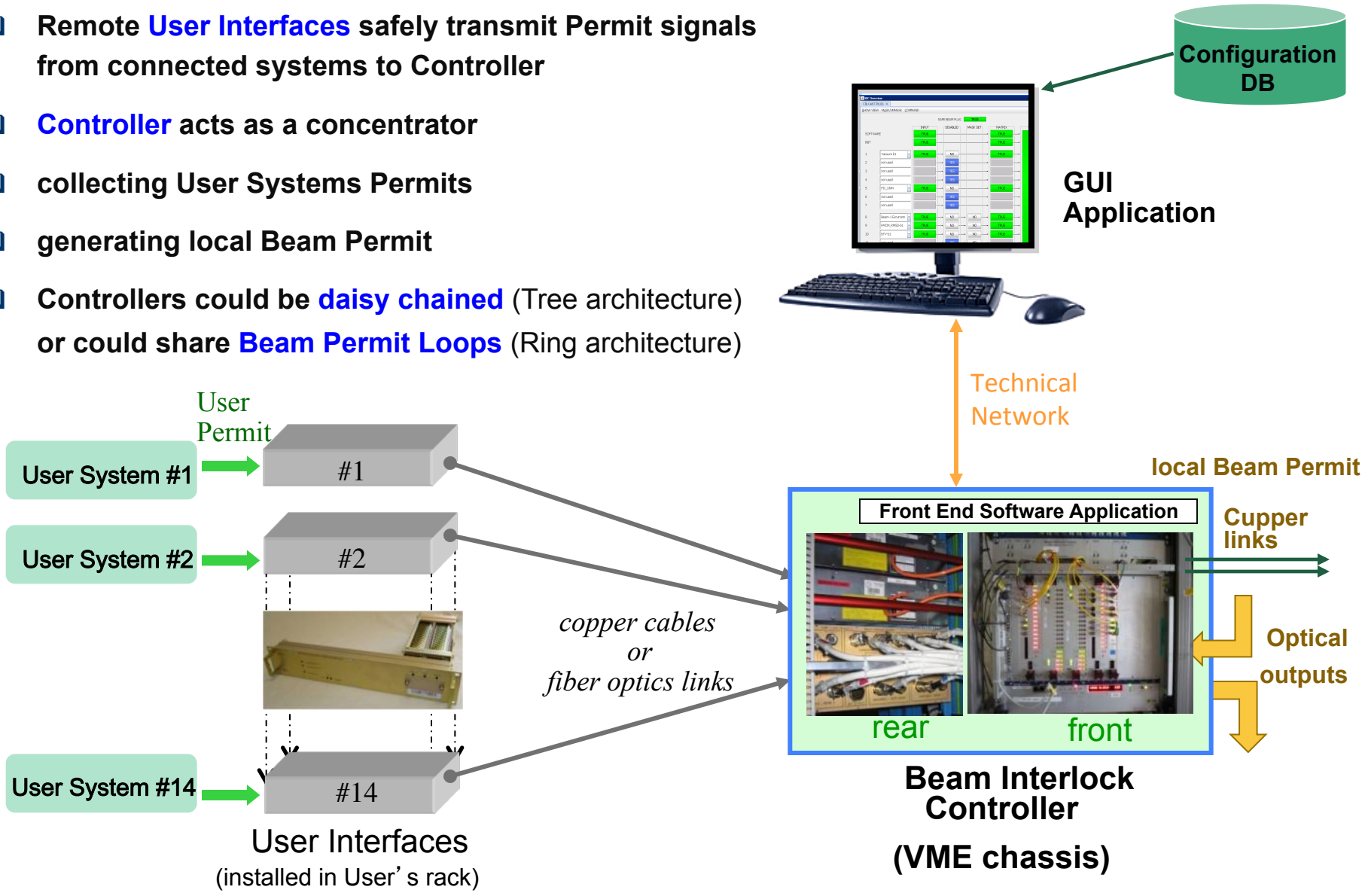
BIS = Core of LHC Machine Protection



Courtesy of B.TODD

BIS Overview

- Remote **User Interfaces** safely transmit Permit signals from connected systems to Controller
- **Controller** acts as a concentrator
- collecting User Systems Permits
- generating local Beam Permit
- Controllers could be **daisy chained** (Tree architecture) or could share **Beam Permit Loops** (Ring architecture)



LHC Beam Permit Loops

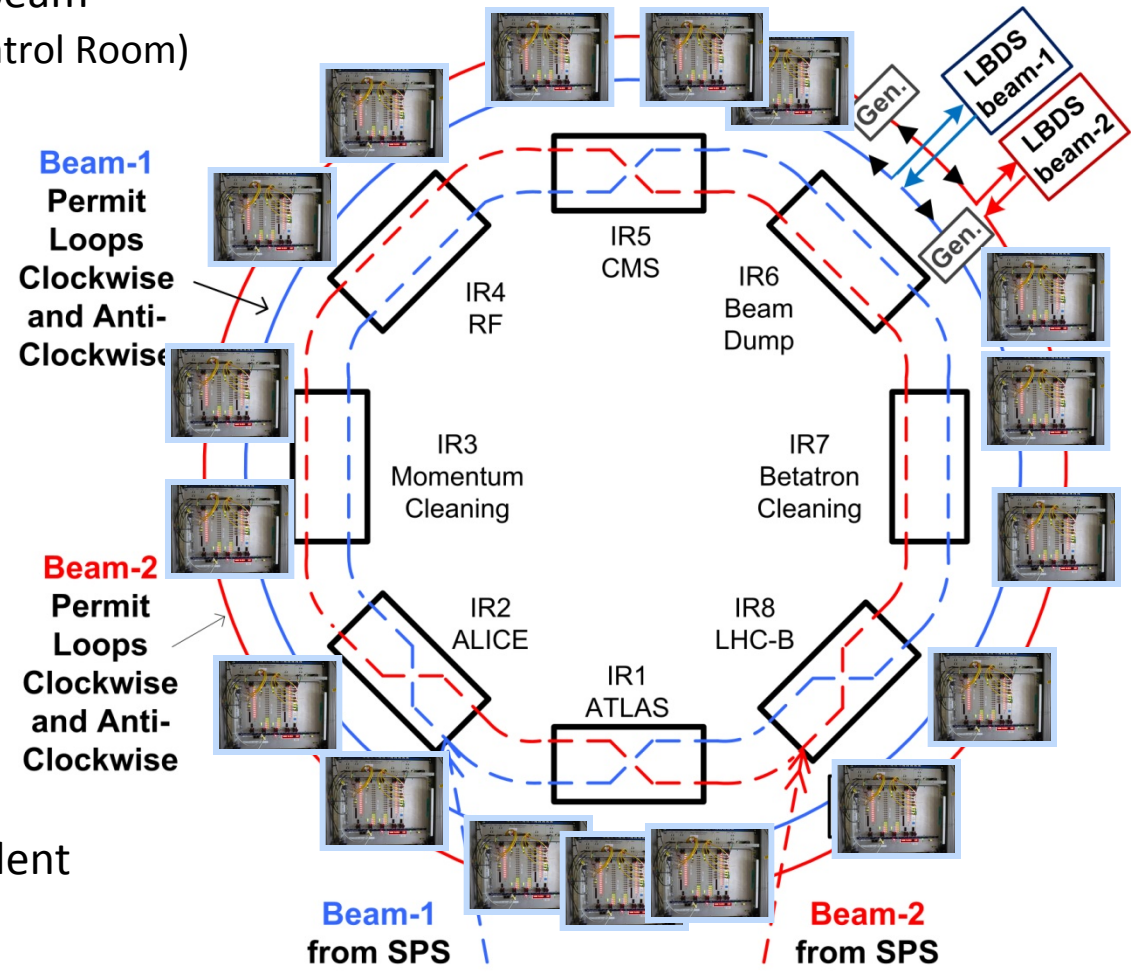
17 Beam Interlock Controllers per beam
(2 per Insertion Region (IR) + 1 near Control Room)

4 fibre-optic channels:
1 clockwise & 1 anticlockwise
for **each** beam

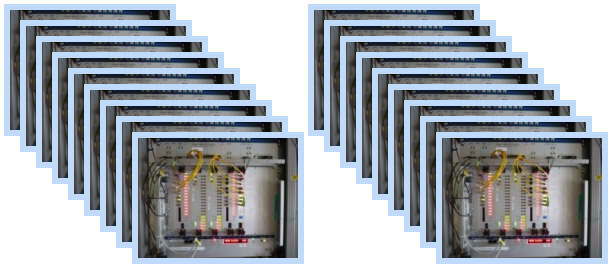
Square wave generated at IR6:
Signal can be **cut** and **monitored** by any Controller

When any of the four signals are absent at IR6, **BEAM DUMP!**

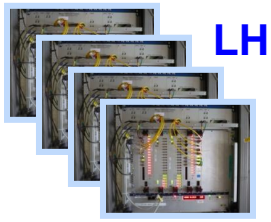
Beam-1 / Beam-2 loops are independent but they can be linked (or unlinked)



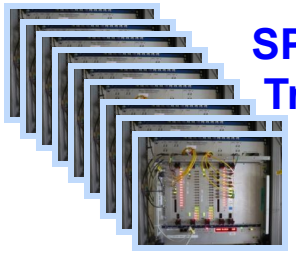
Beam Interlock Systems currently in Operation



LHC ring
(2 x 17 controllers)



LHC Injection regions
(4 c.)

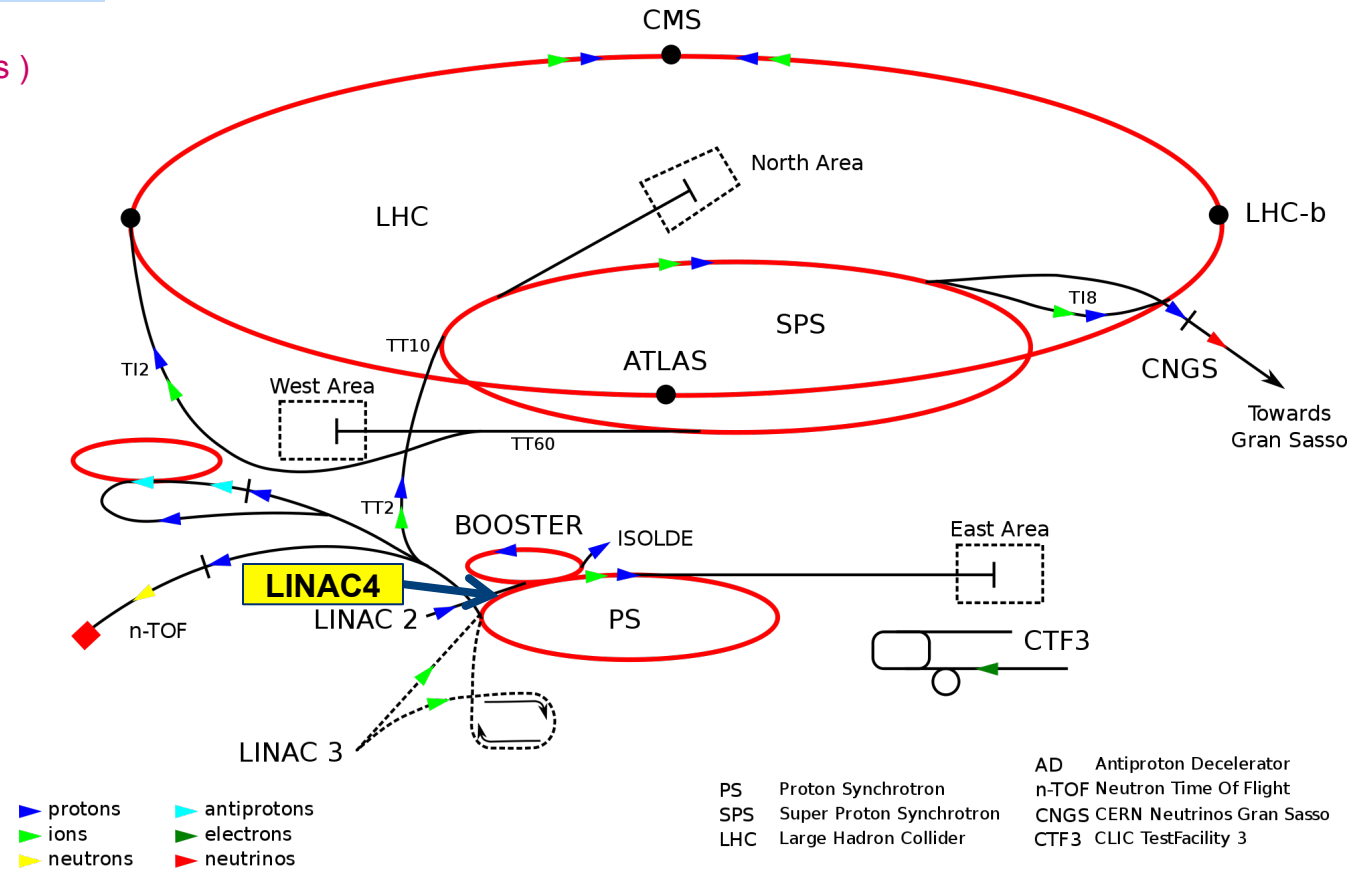


SPS to LHC Transfer lines
(14 c.)

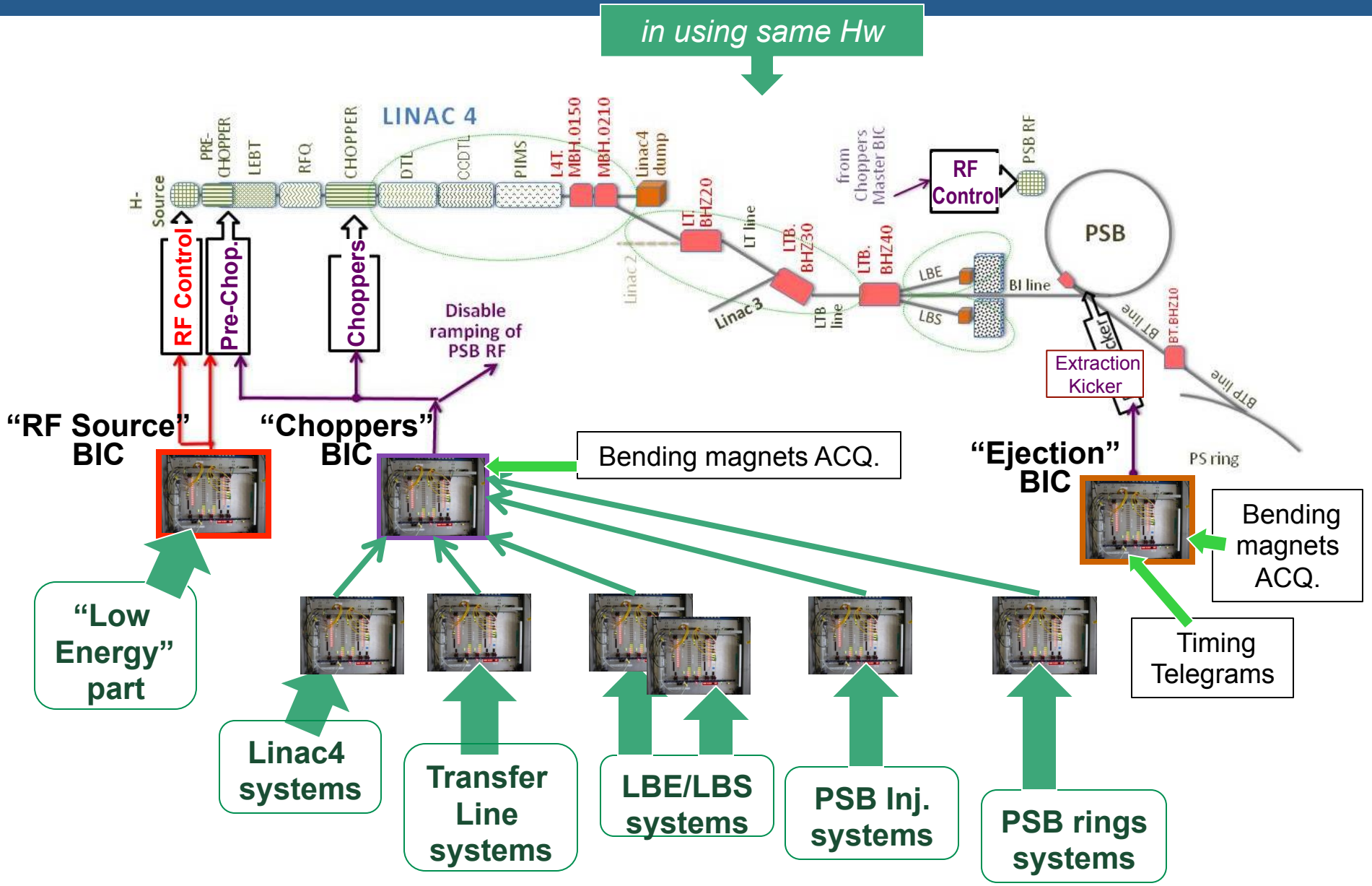
SPS ring
(since 2006)
(6 c.)

50 Controllers in total

~ 370 connected systems



2013: BIS deployment to new Linac4 (and to Booster)



BIS Performance

(1/3)

Fail Safe concept:

Must go to fail safe state whatever the failure

Safe: (Safety Integrity Level 3 was used as a guideline).

Must react with a probability of unsafe failure of less than 10^{-7} per hour and,
Beam abort less than 1% of missions due to internal failure
(2 to 4 failures per year).

Reliable: (whole design studied using Military and Failure Modes Handbooks)

Results from the LHC analysis are:

P (false beam dump) per hour = 9.1×10^{-4}

P (missed beam dump) per hour = 3.3×10^{-9}

Available:

Uninterruptable Powering (UPS)
Redundant Power Supply for Controller (i.e. VME crate)
Redundant Power Supply for Remote User Interface

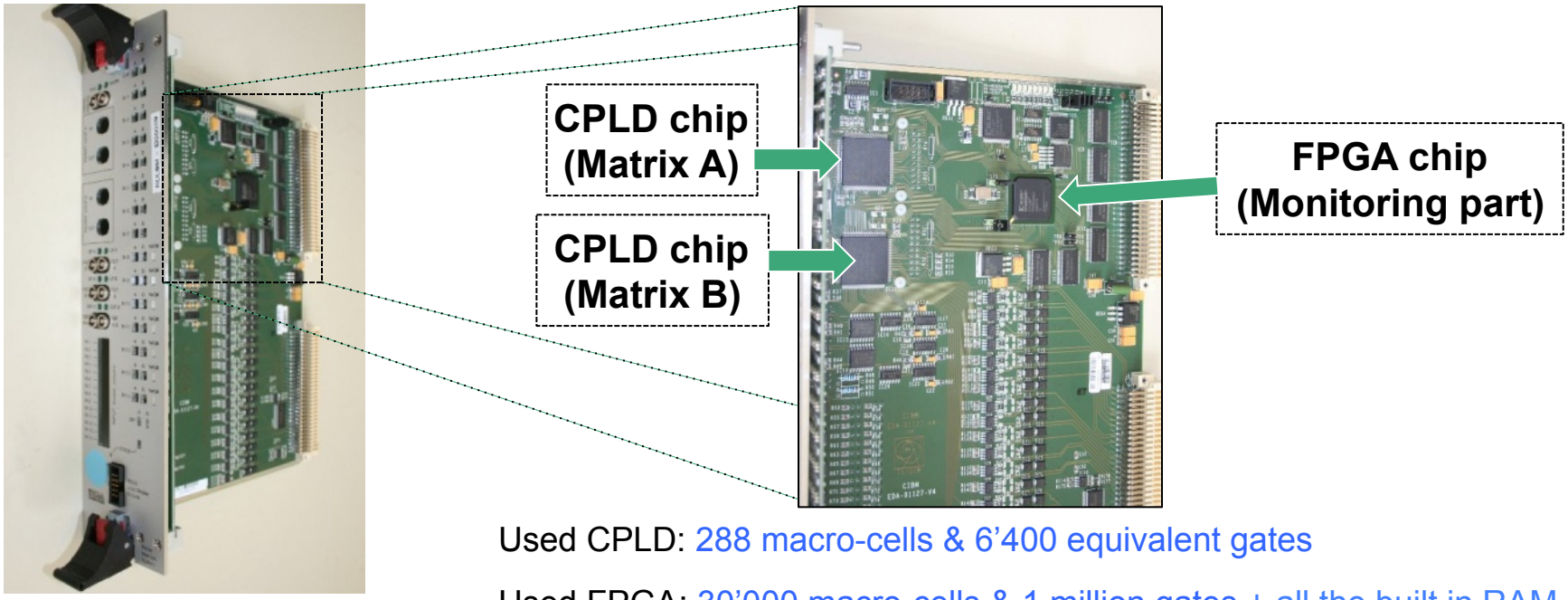
BIS Performance

Critical process in Hardware:

- functionality into 2 redundant matrices
- VHDL code written by different engineers following same specification.

Critical / Non-Critical separation:

- Critical functionality always separated from non-critical.
- Monitoring elements fully independent of the two redundant safety channels.



Manager board

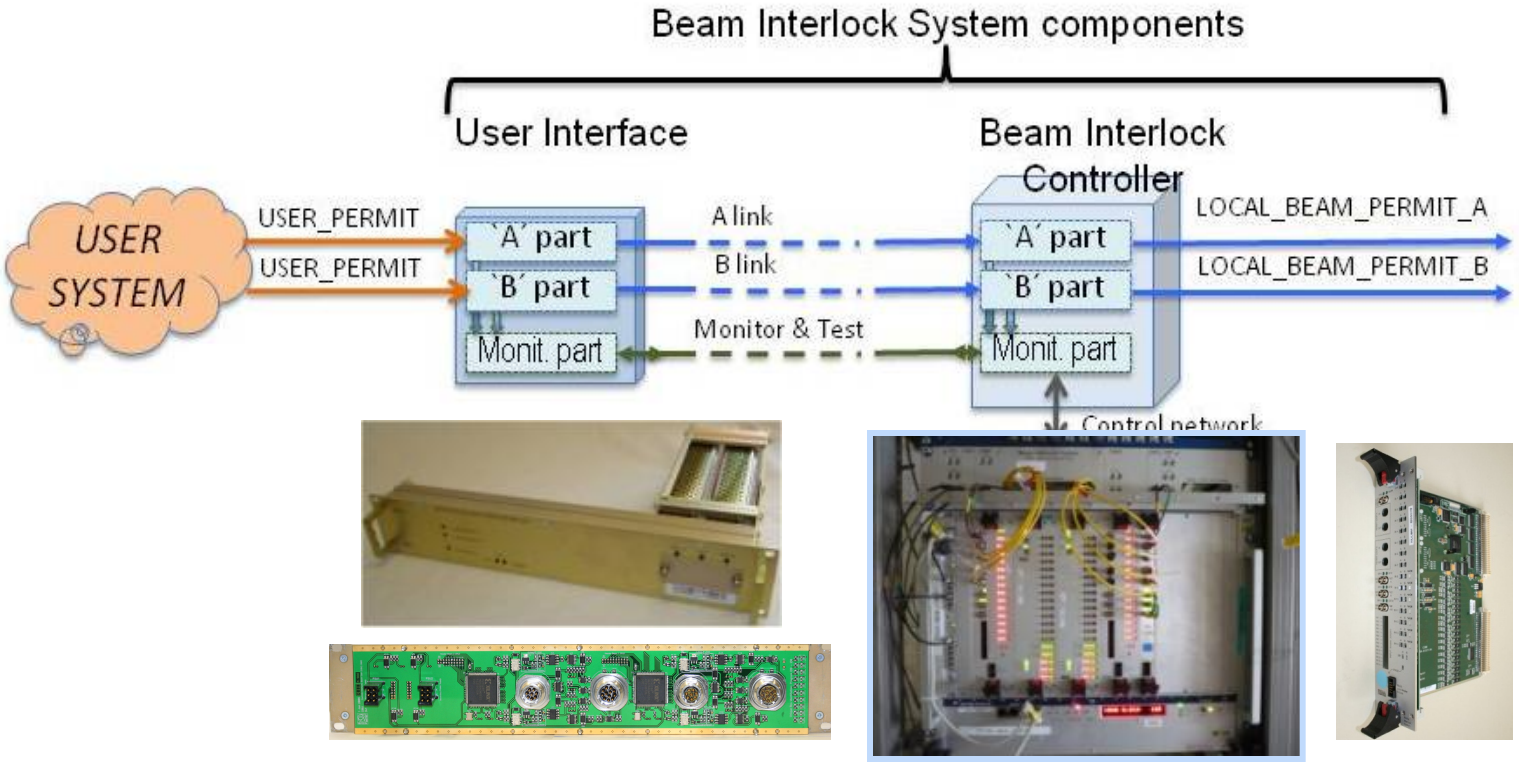
Used CPLD: 288 macro-cells & 6'400 equivalent gates

Used FPGA: 30'000 macro-cells & 1 million gates + all the built in RAM ,etc.

CPLD: Complex Programmable Logic Device FPGA: Field Programmable Gate Array

BIS Performance

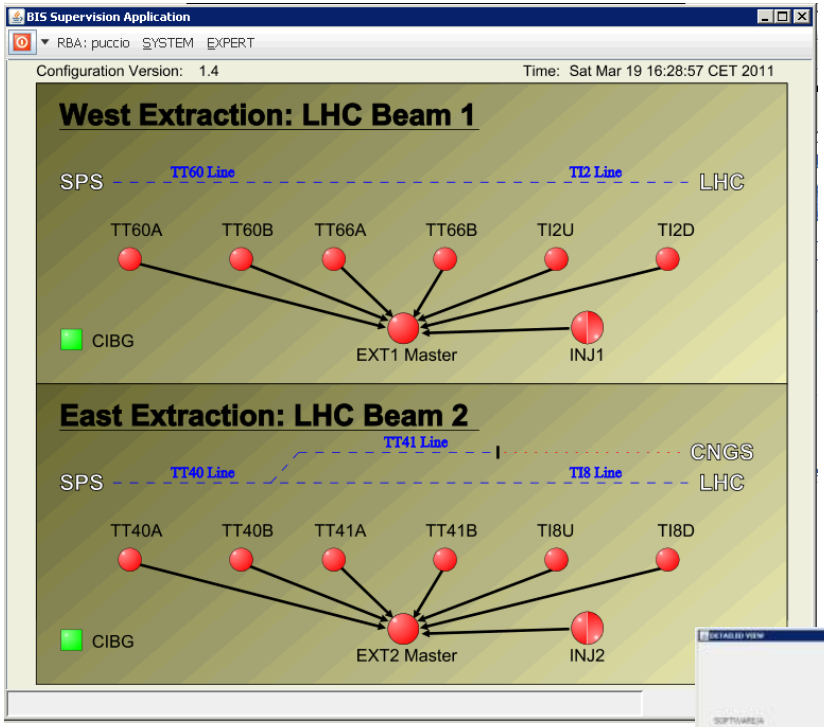
100% Online Test Coverage: Can be easily tested from end-to-end in a safe manner => recovered "good as new"

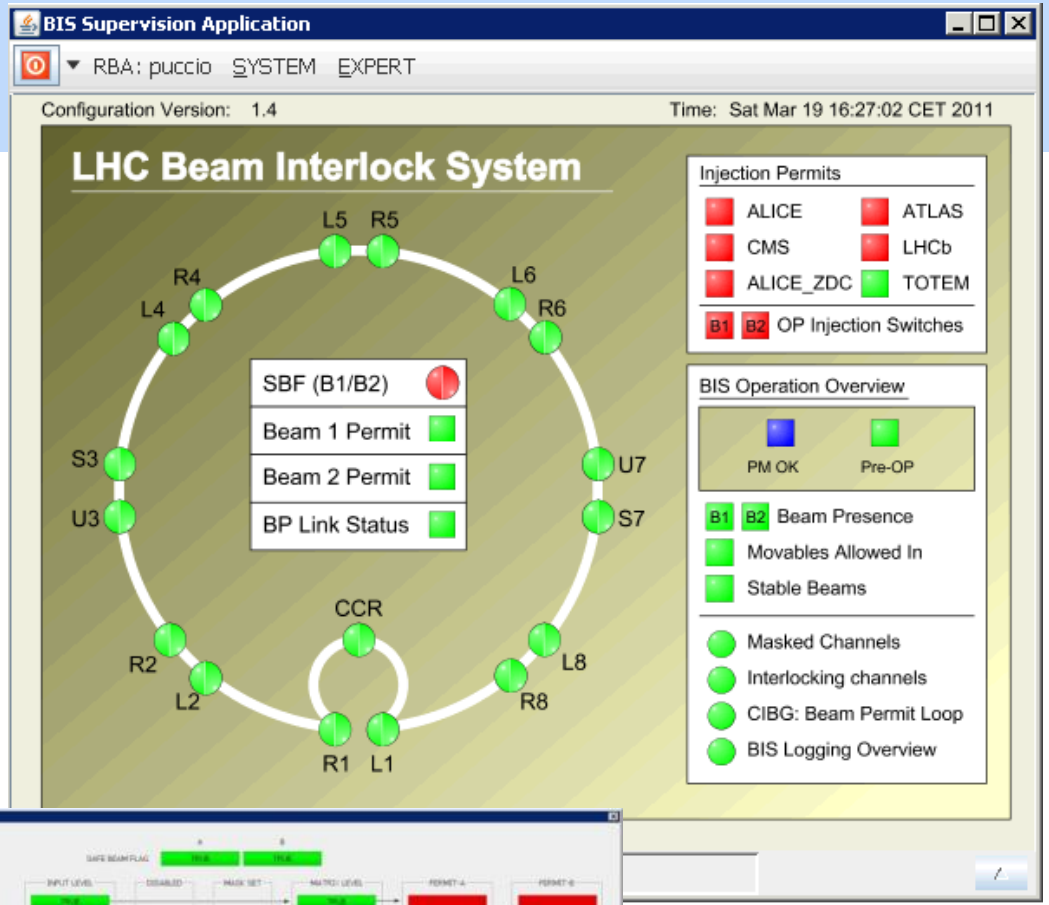


Fast: ~20µS reaction time from *User Permit* change detection to the corresponding *Local Beam Permit* change

Modular: **(** "Tree" or "Ring" topology) **&** (daisy chain of BIC to BIC possible)

Control Room GUIs



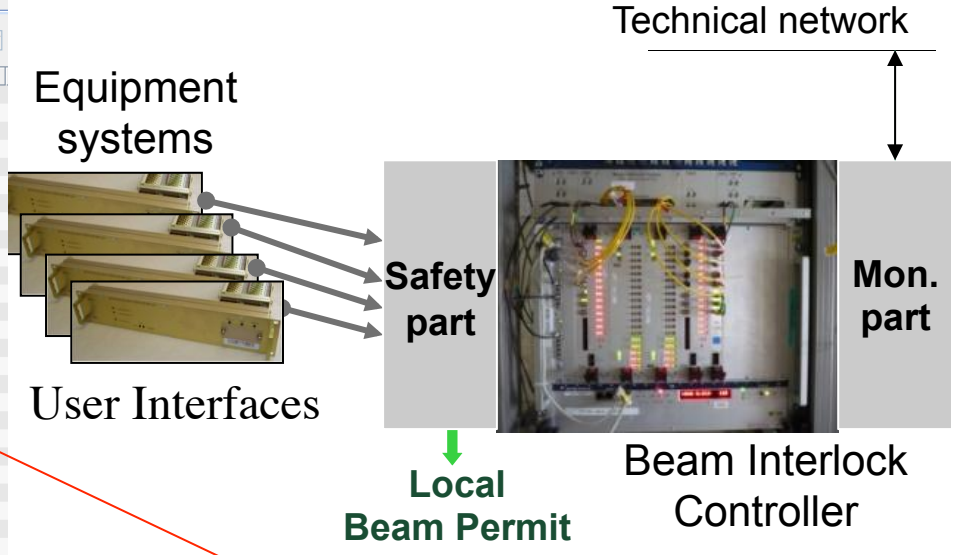


History Buffer

History Buffer | Memory Map

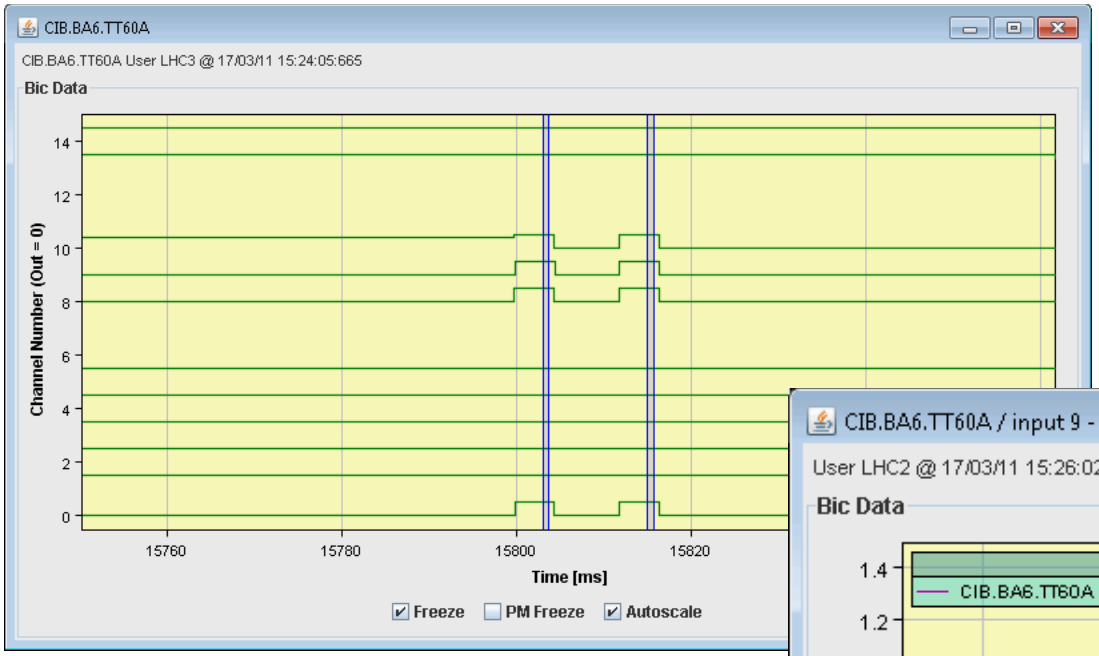
FILTER: OPERATOR | Logging | ☑ USE SNAPSHOT

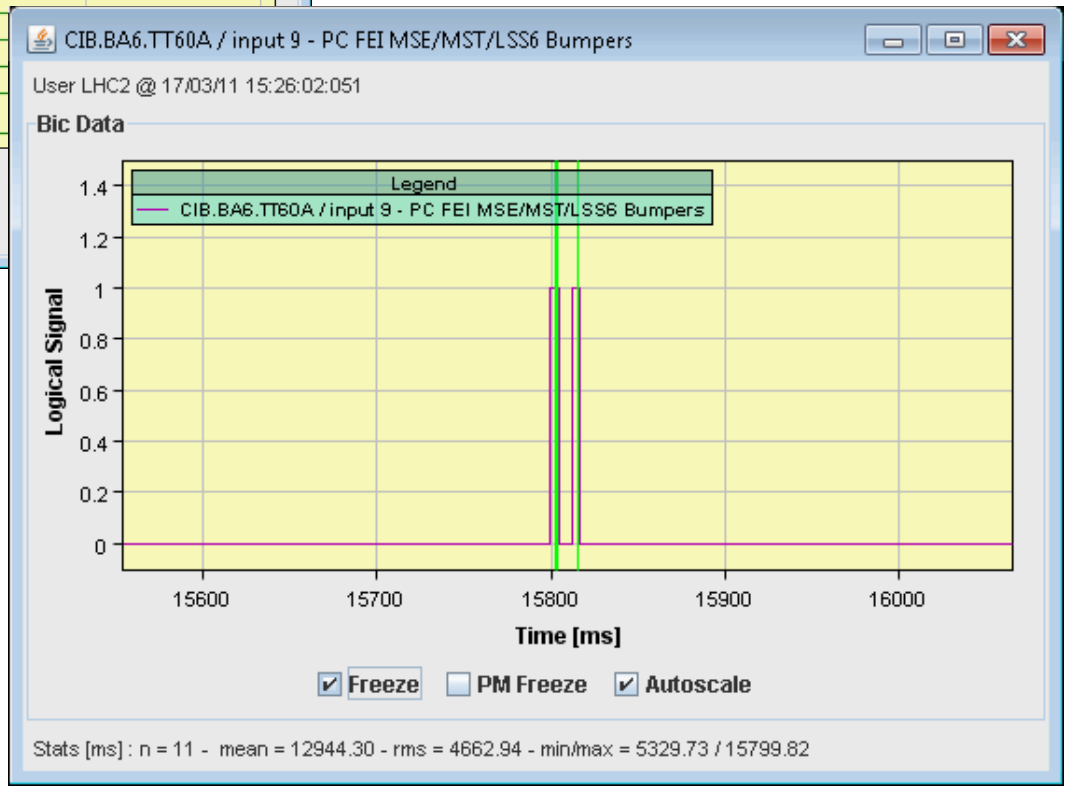
PERMIT	TIMESTAMP	DEVICE	DESCRIPTION
	2012-06-06 16:02:06.152292	CIB.BA6.TT60A	USER PERMIT: Ch 8(TT60 Converters currents): B T -> F
	2012-06-06 16:02:06.152291	CIB.BA6.TT60A	USER PERMIT: Ch 8(TT60 Converters currents): A T -> F
	2012-06-06 16:02:06.15228	CIB.BA6.TT60A	LOCAL PERMIT: B T -> F
	2012-06-06 16:02:06.15228	CIB.BA6.TT60A	LOCAL PERMIT: A T -> F
	2012-06-06 16:02:06.152278	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): B T -> F
	2012-06-06 16:02:06.152278	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): A T -> F
	2012-06-06 16:02:06.151002	CIB.BA6.TT60A	MARKER: 2 us
	2012-06-06 16:02:06.147781	CIB.BA6.TT60A	LOCAL PERMIT: B F -> T
	2012-06-06 16:02:06.147781	CIB.BA6.TT60A	LOCAL PERMIT: A F -> T
	2012-06-06 16:02:06.14778	CIB.BA6.TT60A	USER PERMIT: Ch 10(MBB current): B F -> T
	2012-06-06 16:02:06.14778	CIB.BA6.TT60A	USER PERMIT: Ch 10(MBB current): A F -> T
	2012-06-06 16:02:06.14773	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): B F -> T
	2012-06-06 16:02:06.14773	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): A F -> T
	2012-06-06 16:02:06.147724	CIB.BA6.TT60A	USER PERMIT: Ch 8(TT60 Converters currents): B F -> T
	2012-06-06 16:02:06.147724	CIB.BA6.TT60A	USER PERMIT: Ch 8(TT60 Converters currents): A F -> T
	2012-06-06 16:02:06.140292	CIB.BA6.TT60A	USER PERMIT: Ch 8(TT60 Converters currents): B T -> F
	2012-06-06 16:02:06.140291	CIB.BA6.TT60A	USER PERMIT: Ch 8(TT60 Converters currents): A T -> F
	2012-06-06 16:02:06.140278	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): B T -> F
	[illegible]	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): A T -> F
	2012-06-06 16:02:06.140231	CIB.BA6.TT60A	LOCAL PERMIT: B T -> F
	2012-06-06 16:02:06.140231	CIB.BA6.TT60A	LOCAL PERMIT: A T -> F
	2012-06-06 16:02:06.140229	CIB.BA6.TT60A	USER PERMIT: Ch 10(MBB current): A T -> F
	2012-06-06 16:02:06.140228	CIB.BA6.TT60A	USER PERMIT: Ch 10(MBB current): B T -> F
	2012-06-06 16:02:06.135737	CIB.BA6.TT60A	LOCAL PERMIT: B F -> T
	2012-06-06 16:02:06.135737	CIB.BA6.TT60A	LOCAL PERMIT: A F -> T
	[illegible]	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): B F -> T
	2012-06-06 16:02:06.135736	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): A F -> T
	2012-06-06 16:02:06.135734	CIB.BA6.TT60A	USER PERMIT: Ch 8(TT60 Converters currents): B F -> T
	2012-06-06 16:02:06.135734	CIB.BA6.TT60A	USER PERMIT: Ch 8(TT60 Converters currents): A F -> T
	2012-06-06 16:02:06.135703	CIB.BA6.TT60A	USER PERMIT: Ch 10(MBB current): B F -> T
	2012-06-06 16:02:06.135703	CIB.BA6.TT60A	USER PERMIT: Ch 10(MBB current): A F -> T
	2012-06-06 16:02:05.825663	CIB.BA6.TT60A	USER PERMIT: Ch 14(FMCM_MST6177M): B F -> T
	2012-06-06 16:02:05.825663	CIB.BA6.TT60A	USER PERMIT: Ch 14(FMCM_MST6177M): A F -> T
	2012-06-06 16:02:05.800256	CIB.BA6.TT60A	USER PERMIT: Ch 13(FMCM_MSE6183M): B F -> T
	2012-06-06 16:02:05.800256	CIB.BA6.TT60A	USER PERMIT: Ch 13(FMCM_MSE6183M): A F -> T
	2012-06-06 16:02:05.238001	CIB.BA6.TT60A	SAFE BEAM FLAG: B F -> T
	2012-06-06 16:02:05.238001	CIB.BA6.TT60A	SAFE BEAM FLAG: A F -> T
	2012-06-06 16:01:47.388	CIB.BA6.TT60A	SAFE BEAM FLAG: A T -> F



	2012-06-06 16:02:06.15228	CIB.BA6.TT60A	LOCAL PERMIT: B T -> F
	2012-06-06 16:02:06.15228	CIB.BA6.TT60A	LOCAL PERMIT: A T -> F
	2012-06-06 16:02:06.152278	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): B T -> F
	2012-06-06 16:02:06.152278	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): A T -> F
	2012-06-06 16:02:06.151002	CIB.BA6.TT60A	MARKER: 2 us
	2012-06-06 16:02:06.147781	CIB.BA6.TT60A	LOCAL PERMIT: B F -> T
	2012-06-06 16:02:06.147781	CIB.BA6.TT60A	LOCAL PERMIT: A F -> T

Timing views extracted from history buffer





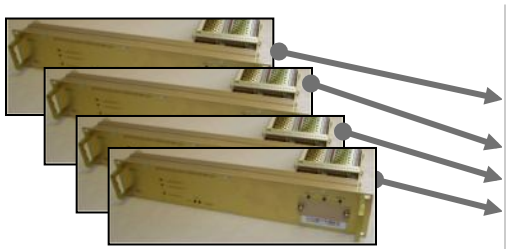
Courtesy of J. Wenninger

External signal(s) logged in history buffer

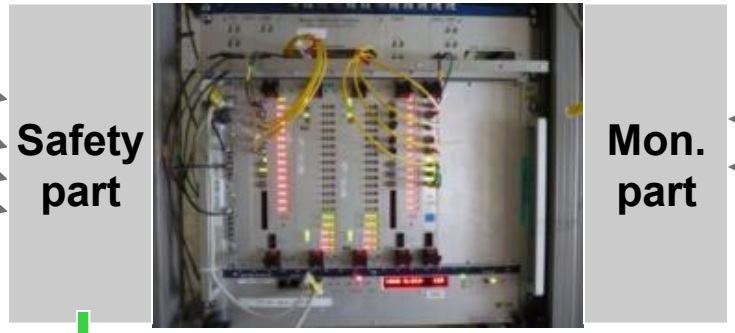
Equipment systems

Beam Interlock Controller

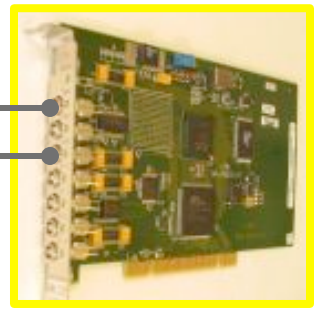
Timing Receiver card



User Interfaces



Local Beam Permit

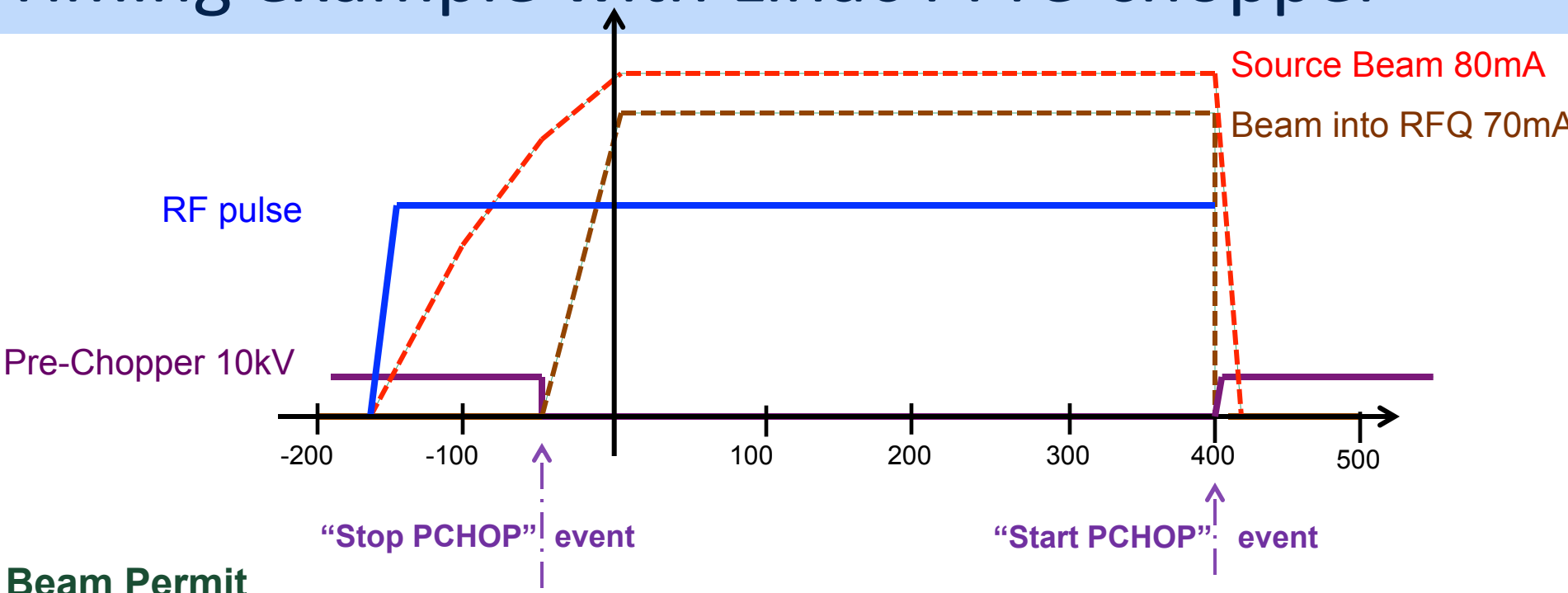


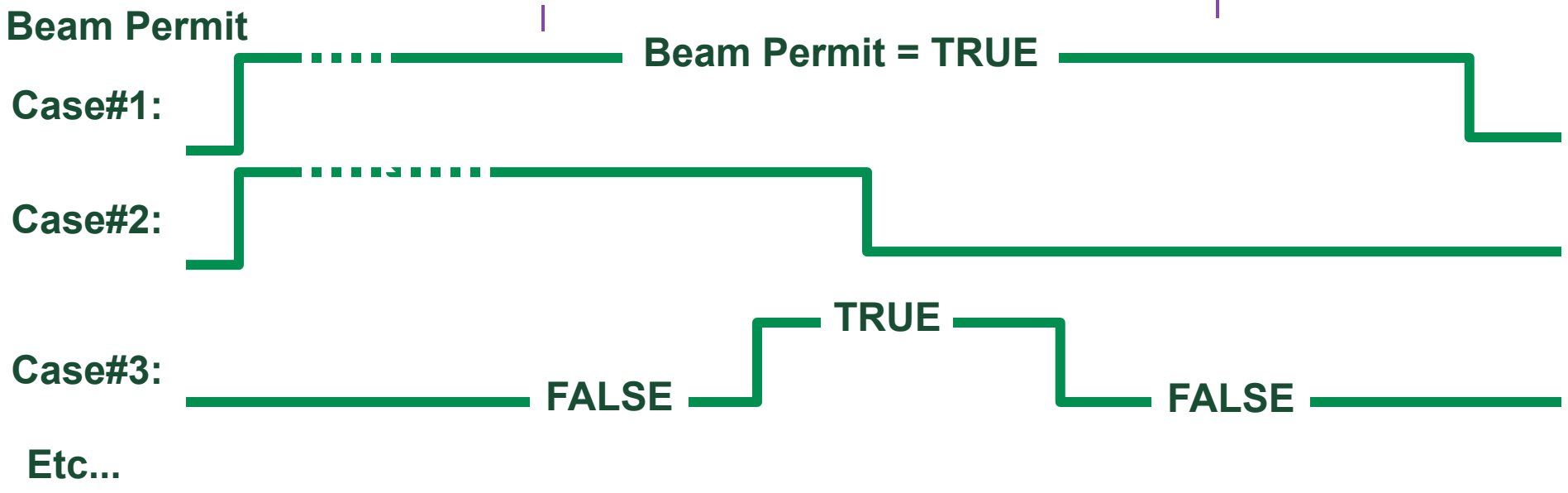
External signals can be connected to BIC Front-panel

	2012-06-06 16:02:06.15228	CIB.BA6.TT60A	LOCAL PERMIT: B T -> F
	2012-06-06 16:02:06.15228	CIB.BA6.TT60A	LOCAL PERMIT: A T -> F
	2012-06-06 16:02:06.152278	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): B T -> F
	2012-06-06 16:02:06.152278	CIB.BA6.TT60A	USER PERMIT: Ch 9(MSE/MST currents): A T -> F
	2012-06-06 16:02:06.151002	CIB.BA6.TT60A	MARKER: ← SPS Extraction event
	2012-06-06 16:02:06.147781	CIB.BA6.TT60A	LOCAL PERMIT: B F -> T
	2012-06-06 16:02:06.147781	CIB.BA6.TT60A	LOCAL PERMIT: A F -> T

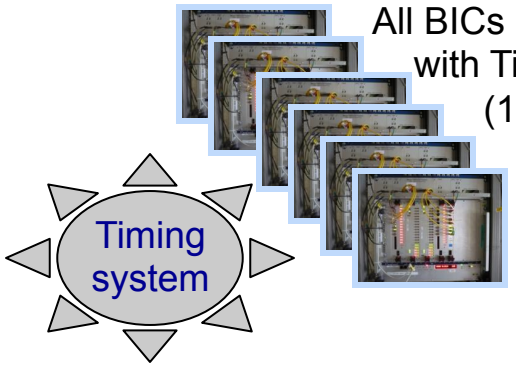
extracted from the SPS Extraction BIC's history buffer

Timing example with Linac4 Pre-chopper

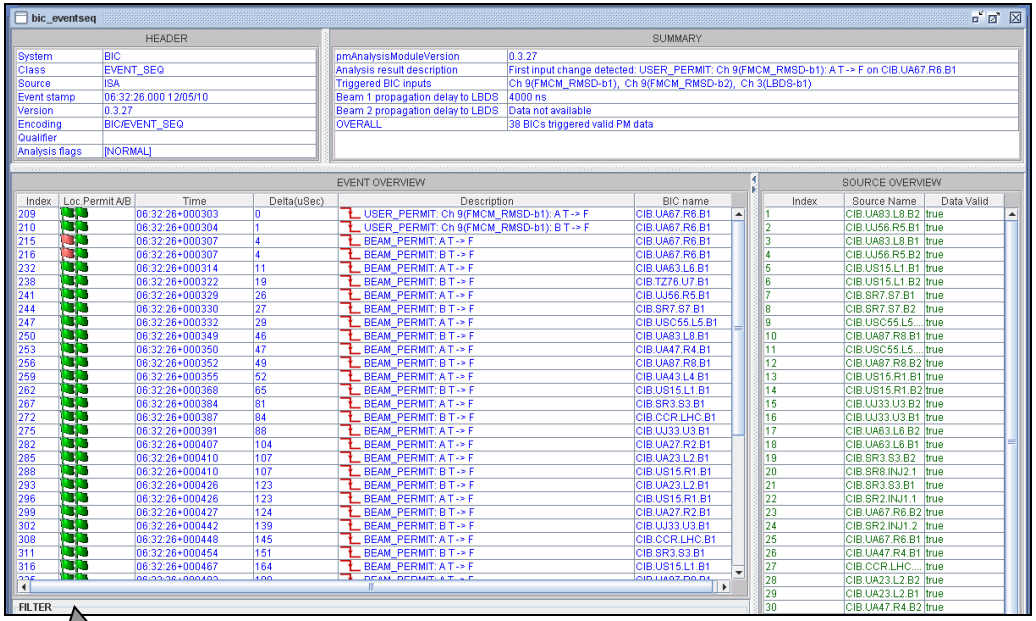


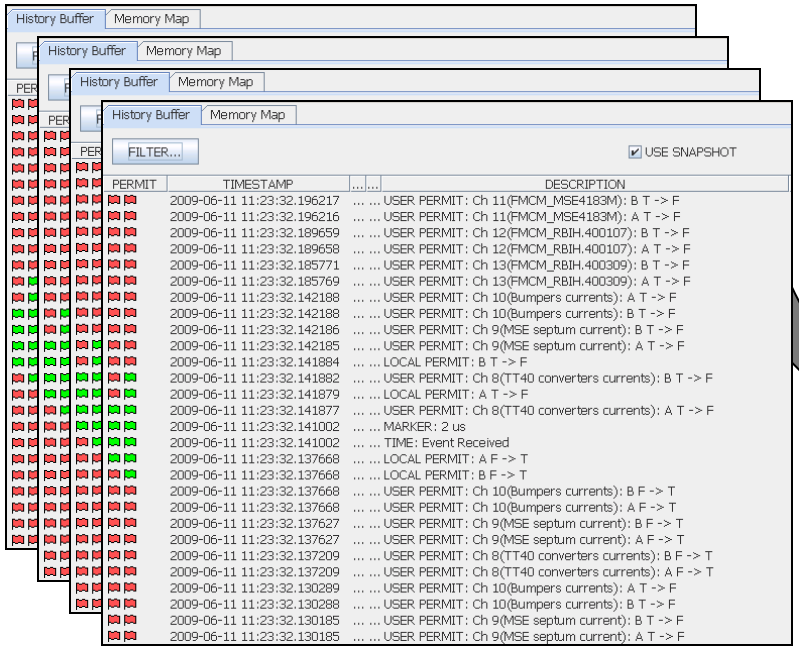


BIS = key element of Post-Mortem analysis



All BICs synchronised with Timing System (1µS accuracy)





History Buffers

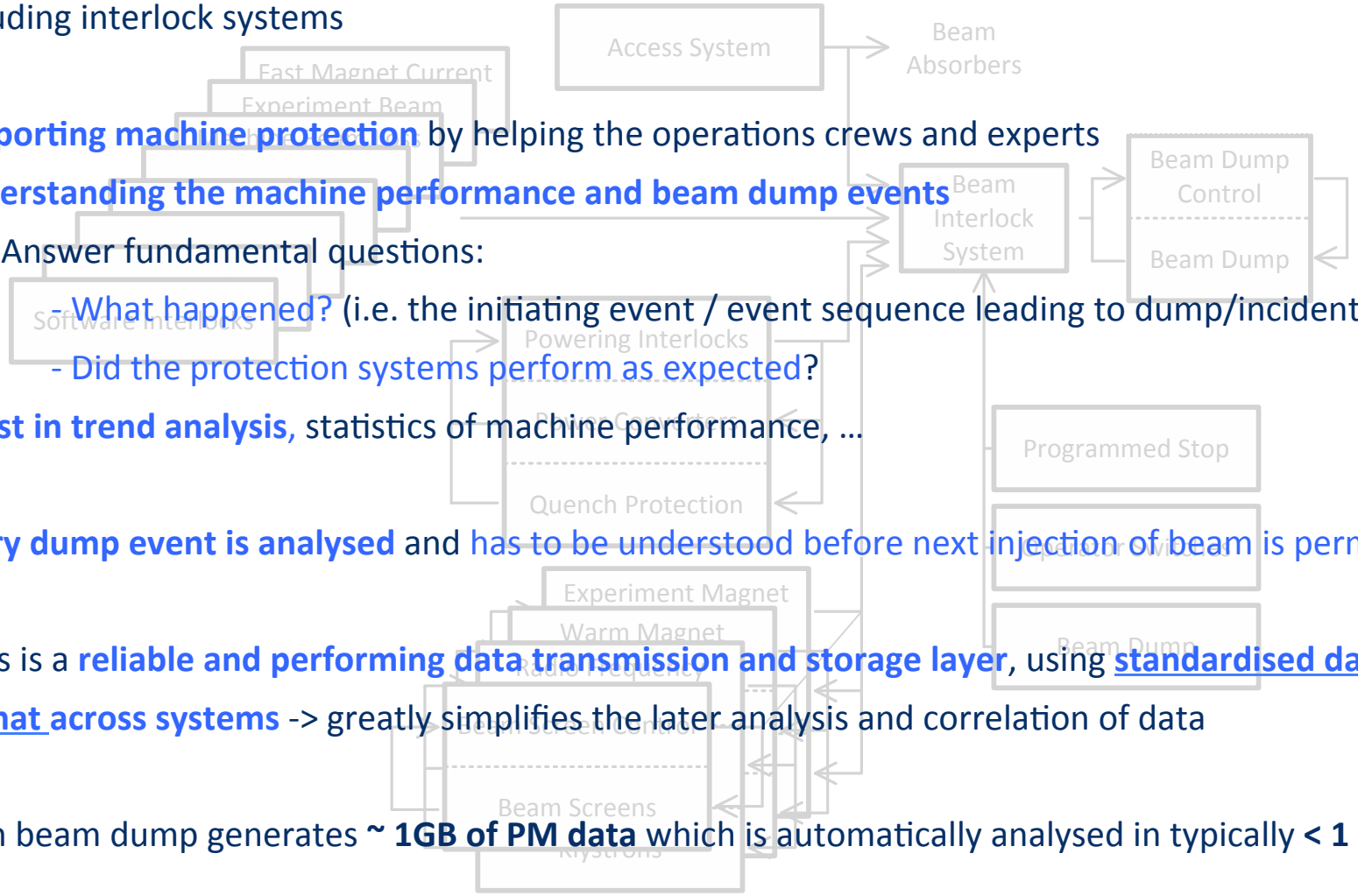
Thanks to different gathered HBs:

=> Identify of source of beam dump

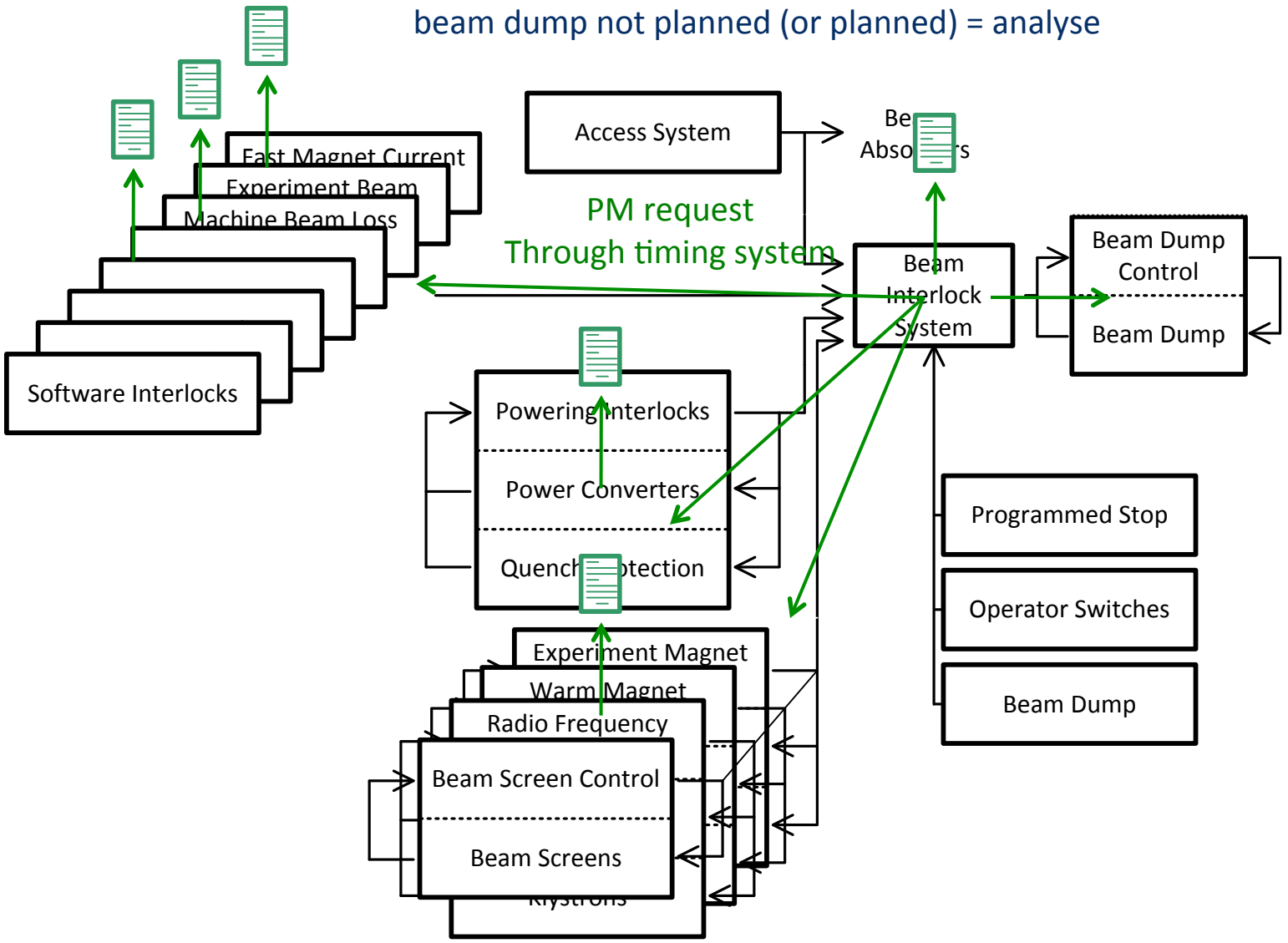
=> Reconstruct sequence of events that has led to the beam dump

Post-Mortem system

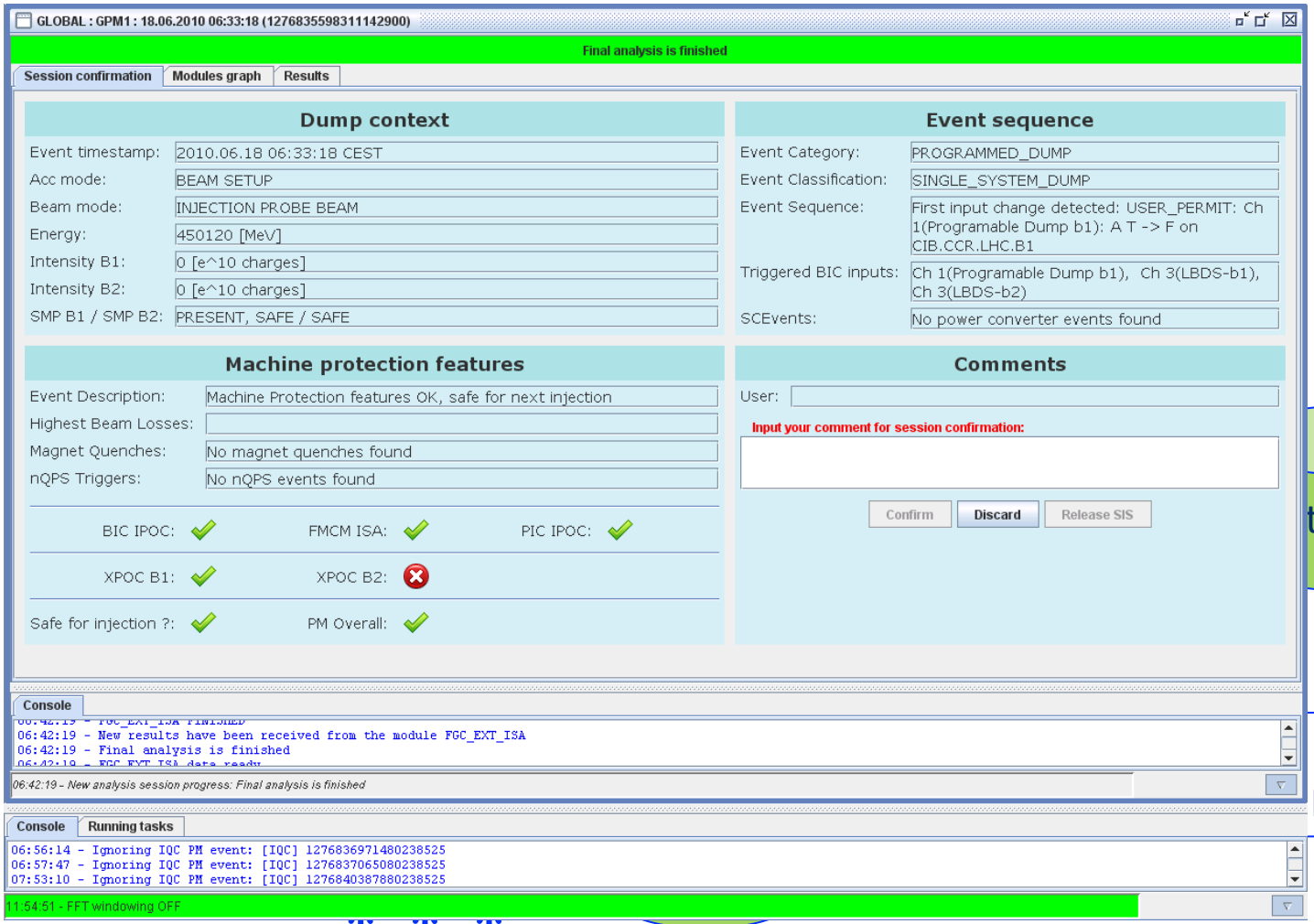
- **Automated post-operational analysis** of transient data recordings from LHC equipment systems, including interlock systems
- **Supporting machine protection** by helping the operations crews and experts
- **Understanding the machine performance and beam dump events**
- and Answer fundamental questions:
  - What happened? (i.e. the initiating event / event sequence leading to dump/incident)
  - Did the protection systems perform as expected?
- **Assist in trend analysis**, statistics of machine performance, …
- **Every dump event is analysed** and has to be understood before next injection of beam is permitted
- Basis is a **reliable and performing data transmission and storage layer**, using **standardised data format across systems** -> greatly simplifies the later analysis and correlation of data
- Each beam dump generates **~ 1GB of PM data** which is automatically analysed in typically **< 1 min**



Post-Mortem layout



PM Server Architecture

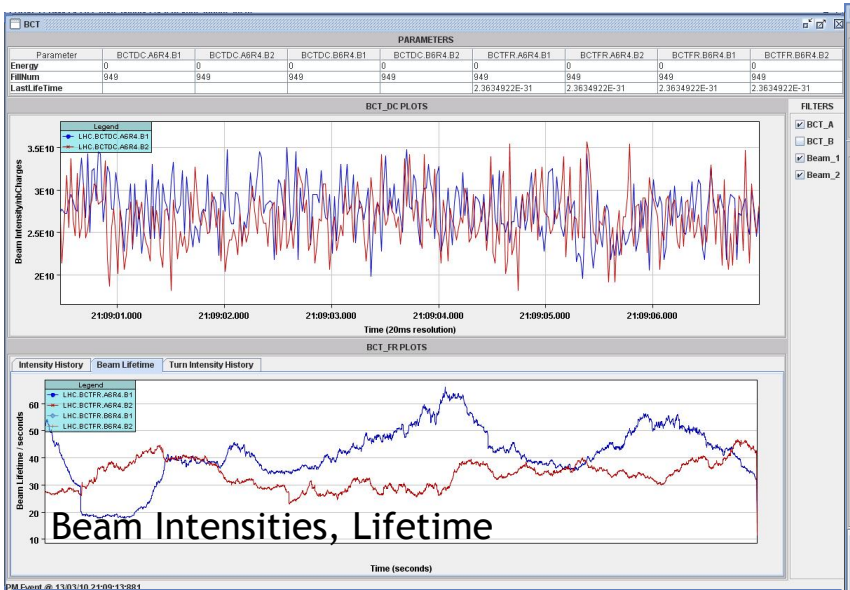


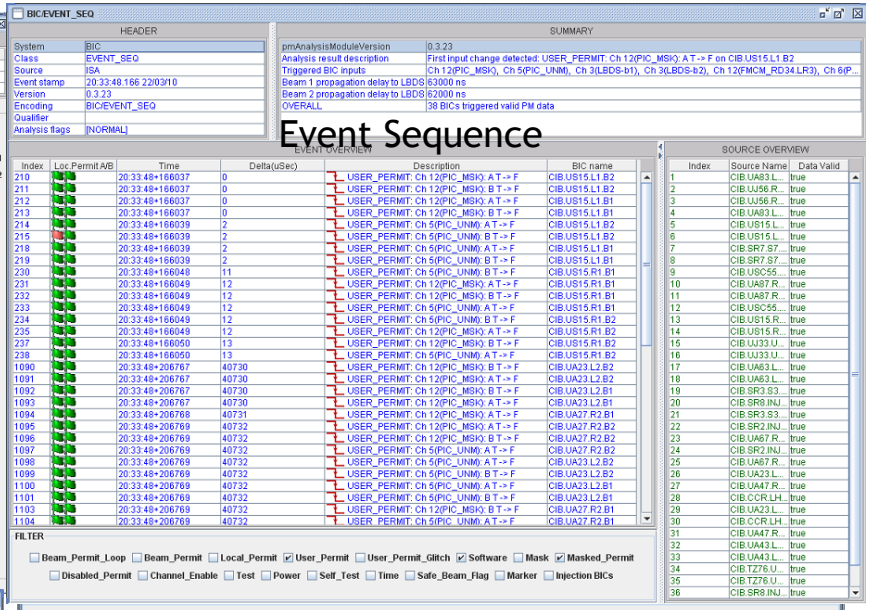
tabase

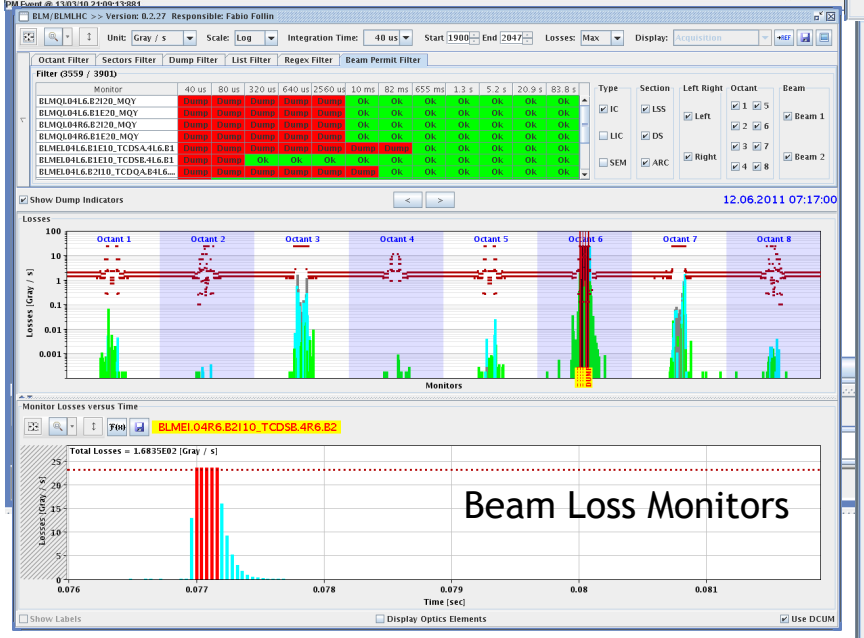
LHC Logging

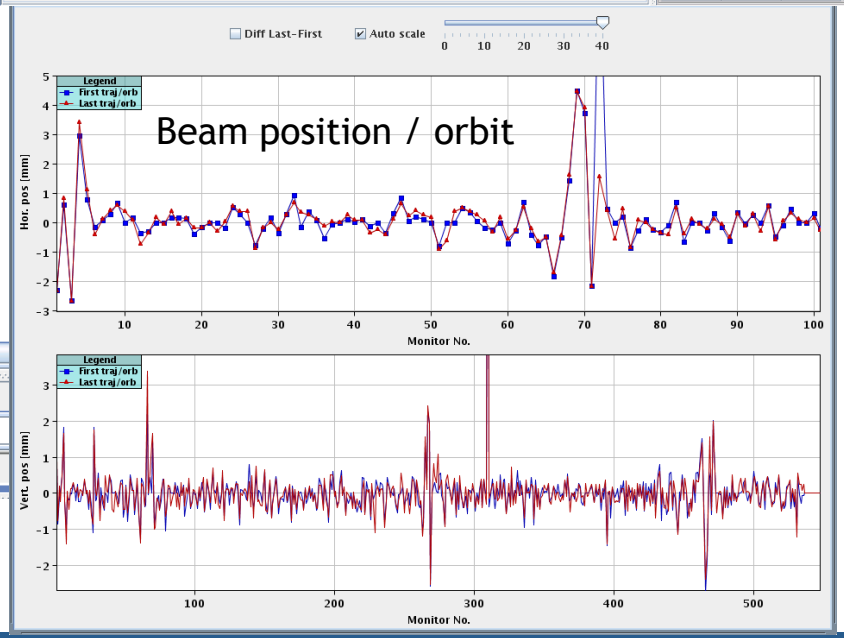
PM buffers

Analysis of global events…









An example of event sequence

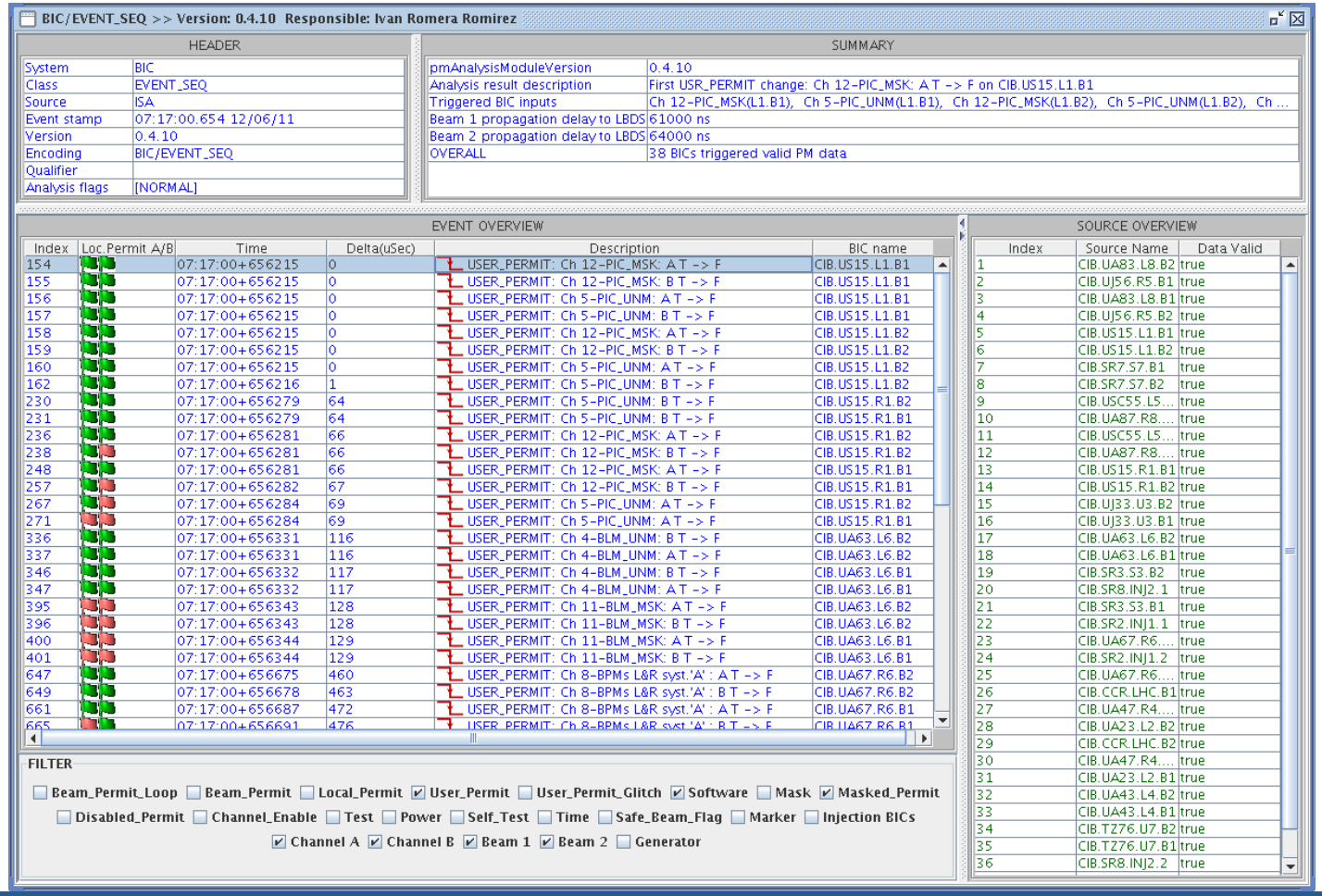
Event Timestamp: **12-JUN-11 07.17.00.656290 AM**

Beam Energy: **3500040**

Mps Expert Comment : **Quench of RD2.L1 magnet**

(+ due to suspected imbalance as well RQ4 some 17 sec. after the dump…

Dump clean.



Triggered BIS Inputs:

Ch 12-PIC_MSK(L1.B1),
Ch 5-PIC_UNM(L1.B1),
Ch 12-PIC_MSK(L1.B2),
Ch 5-PIC_UNM(L1.B2),
Ch 5-PIC_UNM(R1.B2),
Ch 5-PIC_UNM(R1.B1),
Ch 12-PIC_MSK(R1.B2),
Ch 12-PIC_MSK(R1.B1),
Ch 4-BLM_UNM(L6.B2),
Ch 4-BLM_UNM(L6.B1),
Ch 11-BLM_MSK(L6.B2),
Ch 11-BLM_MSK(L6.B1),
Ch 8-BPMs L&R syst.'A' (R6.B2),
Ch 8-BPMs L&R syst.'A' (R6.B1),
Ch 10-BPMs L&R syst.'B' (L6.B1)
Ch 10-BPMs L&R syst.'B' (L6.B2)
Ch 3-LBDS-b2(R6.B2),
Ch 3-LBDS-b1(L6.B1),
Ch 4-Vacuum b1b2(R1.B2),
Ch 4-Vacuum b1b2(R1.B1),
Ch 1-Vacuum b2(L1.B2),
Ch 1-Vacuum b1(L1.B1)

Summary

Beam Interlock System is by design: safe, reliable, fast, modular….

+ has embedded features for monitoring and testing interlock process,

Together with Timing system, Post-Mortem and GUI applications:

- Provide clear and useful information to Operation
- Minimize machine downtime

Thank you for your attention

Spare

BIS Feature

“Flexible”:

thanks to Input Masking

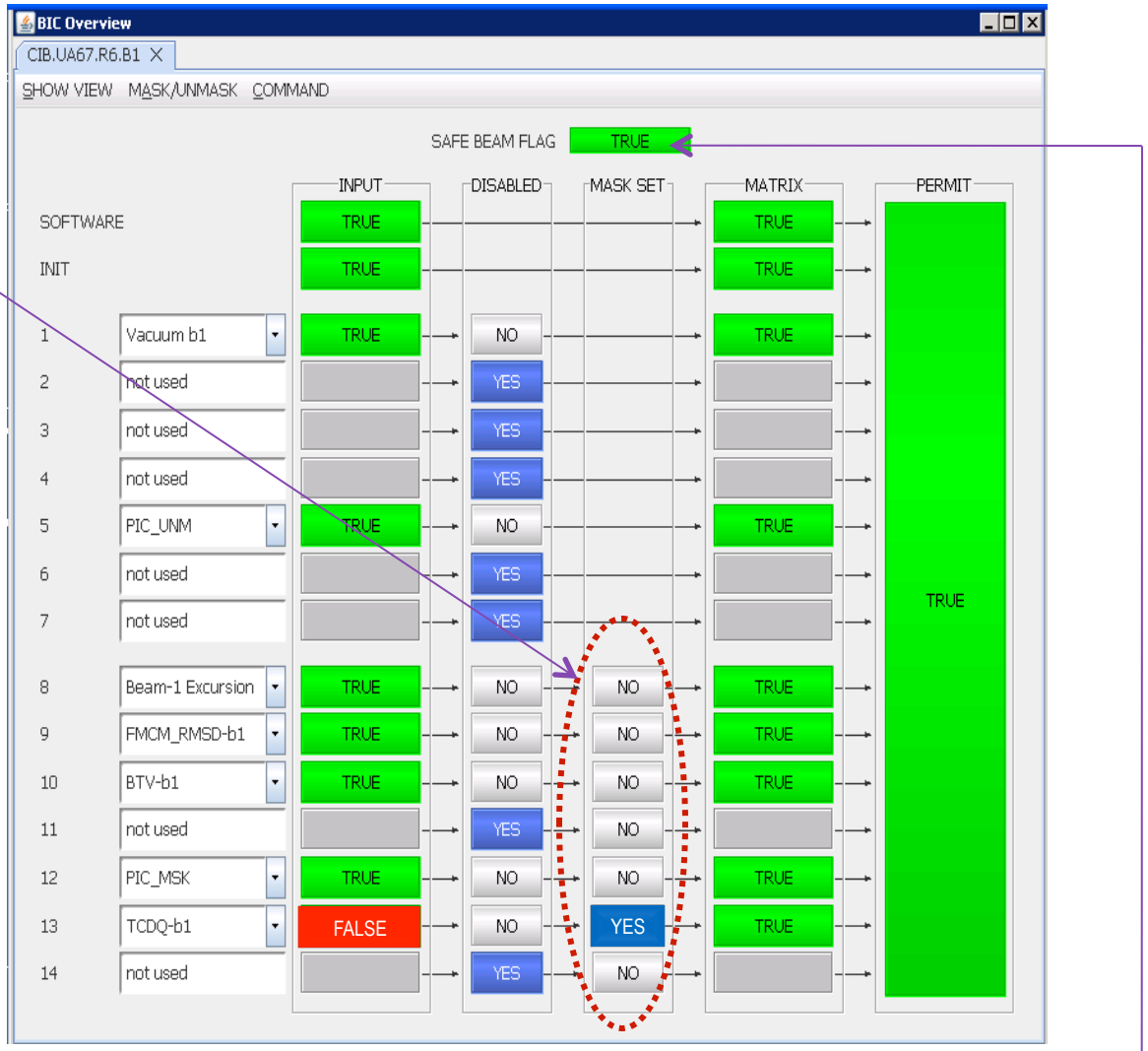
Within a fixed partition, half of *User Permit* signals could be remotely masked

Masking depends on an external condition:

the ***Setup Beam Flag***

- generated by a separate & dedicated system (Safe Machine Parameters)
- distributed by Timing

Masking automatically removed when ***Setup Beam Flag*** *= FALSE*



BIS User Systems: LHC Vs. Linac4

version of 01.08.2009

	User Systems	LHC ring L1	R1	L2	R2	U3	S3	L4	R4	L5	R5	L6	R6	U7	S7	L8	R8	CCR	Σ	INJ. b1	INJ. b2	Abbrev.
1	Collimation (Environmental Param.)		1 1	1 1	1 1	1 1				1 1	1 1	1 1		1 1		1 1	1 1		10 10	1	1	COLL_ENV
2	Collimation (Motor positions)	1 1	1 1	1 1	1 1	1 1				1 1	1 1	1 1		1 1		1 1	1 1		11 11	1	1	COLL_MOT
3	Vacuum system ("sector valves")	1 1		1 1	1 1	1 1		1 1	1 1	1 1		1 1	1 1	1 1		1 1	1 1		12 12			VAC
	Vacuum system ("X valves")		1	1	1						1					1	1		6	1	1	
4	PIC for essential circuits	1	1	1	1	2		1	1	1	1	1	1	2		1	1		16			PIC_UNM
	PIC for auxiliary circuits	1	1	1	1	2		1	1	1	1	1	1	2		1	1		16			PIC_MSK
5	BLM at aperture limitations	1		1			1	1		1		1			1	1			8			BLM_UNM
	BLM in arcs	1		1			1	1		1		1			1	1			8			BLM_MSK
6	Fast Magnet current Change Monitors	1			2		3				1		1 1		3				10	1	1	FM_xxxx
7	WIC (Warm Magnets Interlock)	1		1		1			1	1		1		1		1			8			WIC
8	Screens			1		1 1			1 1			1	1 1	1					4 5			BTV
9	RF & Transverse Damper							1 1	1 1										2 2			RF
10	Beam excursion (BPM)												1 1						1 1			BPM
11	LHC Beam Dumping System											1	1						1 1	1	1	LBDS
12	Beam Aperture Kicker							1 1											1 1			MKA
13	Injection Kickers				1												1		1 1	1	1	MKI
14	TCDQ											1 1							1 1			TCDQ
15	LHC Access Safety System						1		1									1	3			LASS
16	LHC Control Room (Operator Buttons)																	1	1	1	1	CCC
17	Programmed Beam Dump (via Timing)																	1	1			PROG
18	LHC Safe Machine Parameters																	1 1	1 1			SMP
19	Fast Beam current Change Monitors								1 1										1 1			FBCM
20	*ATLAS* (Detector part)		1																1	1	1	ATL_DET
21	*LHCF* (Detector part)		1																1			LHCF_DET
22	*ALICE* (Detector part)				1														1	1	1	ALI_DET
23	*CMS* (Detector part)										1								1	1	1	CMS_DET
24	*TOTEM* (Detector part)										1								1	1	1	TOT_DET
25	*LHCb* (Detector part)																1		1	1	1	LHCB_DET
26	*ATLAS* (Magnets)		1																1			ATL_MAG
27	*ALICE* (Magnets)				1														1			ALI_MAG
28	*CMS* (Magnets)										1								1			CMS_MAG
29	*LHCb* (Magnets)																1 1		1 1			LHCB_MAG
30	*ATLAS* (movable devices)		1 1																1 1			ATL_MOV
31	*TOTEM* (movable devices)										1 1								1 1			TOT_MOV
32	*LHCb* (movable devices)																1		1			LHCB_MOV
33	*ALICE-ZDC* (movable device)																		0 0	1		ALI_ZDC
34	*MSI* Convertor Sum Fault																		0 0	1	1	MSI_SUM
	User Systems	L1	R1	L2	R2	U3	S3	L4	R4	L5	R5	L6	R6	U7	S7	L8	R8	CCR		b1	b2	*Abbrev.*
	Individual beam connections (Unmaskable) max = 3,3	1 1	1 1	1 1	2 1	1 1	0 0	1 1	1 1	1 1	1 1	2 1	1 2	1 1	0 0	1 1	1 1	1 1	50 51 14 13			
	Both beams connections (Unmaskable) max = 4	3	4	4	3	3	1	2	2	3	4	3	1	3	1	4	4	2	87 215			connections
	Individual beam connections (Maskable) max = 3,3																					

SIS

- Source HV
- Pre-chopper
- L4 Beamstopper Out/Moving
- L4 Beamstopper In
- Chopper
- L4 Low-Energy WD
- No Inhibit (Operator)
- L4 Low-Energy Vacuum Valves
- AQN L4L.MQF3910
- AQN L4L.MQD4010
- AQN L4L.MQF4110

Low Energy part

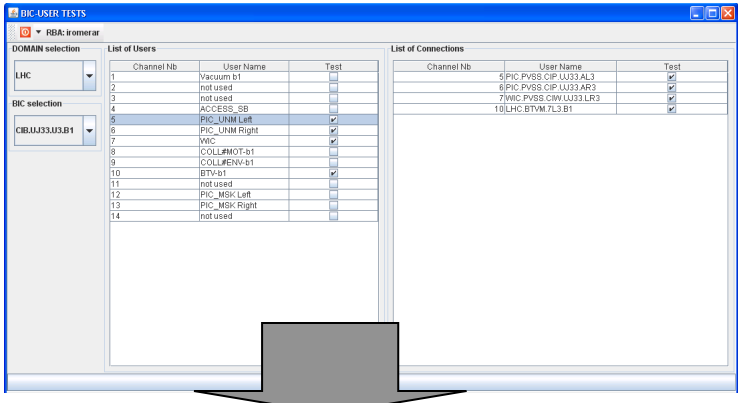
SIS

- Ex. Conditions (full pulse)
- L4 RF
- BLMs L4+TL (low loss)
- BLMs L4+TL (high loss)
- L4 WD before BHZ20 (high loss)
- L4 WD before BHZ20 (low loss)
- L4 Vacuum Valves + L4T.VVGS.0101

after Chopper

BIS: Operational Checks

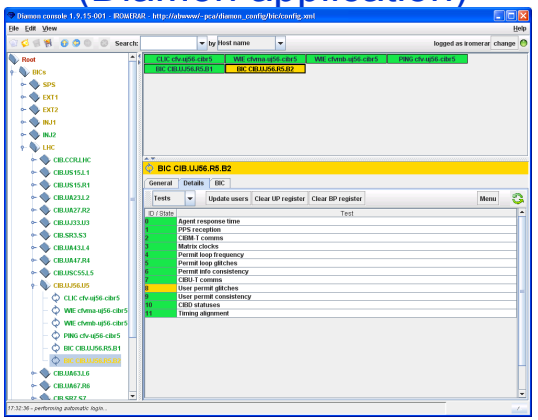
Pre-Operation checks (launched by Beam Sequencer)



configuration verification and integrity check

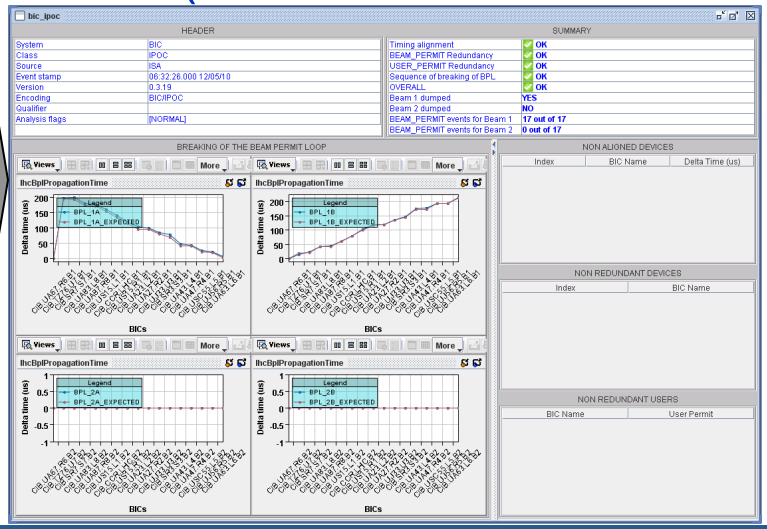
fault diagnosis and monitoring

During Operation
(DiaMon application)



response analysis

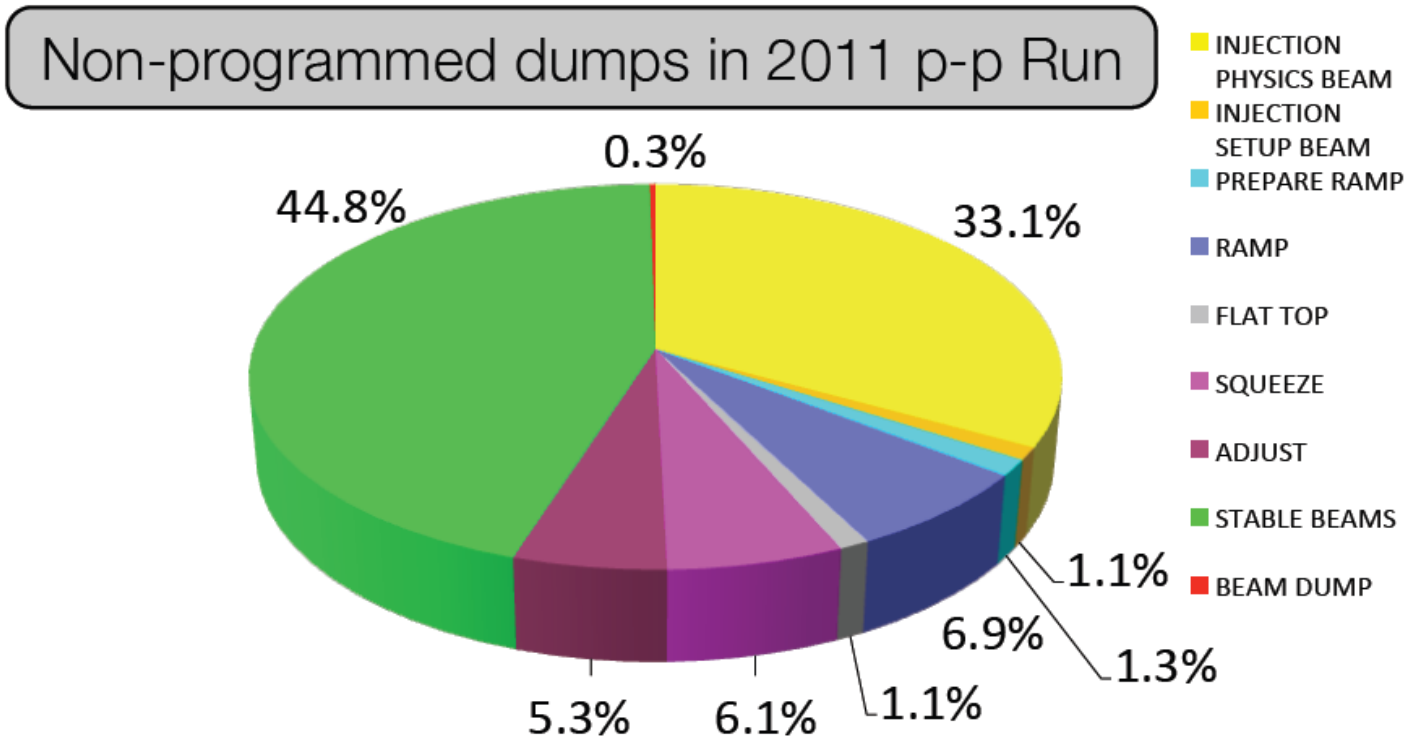
Post-Operation checks
(included in Post Mortem analysis)



In order to ensure that safety is not compromised, the verification is carried out in three stages

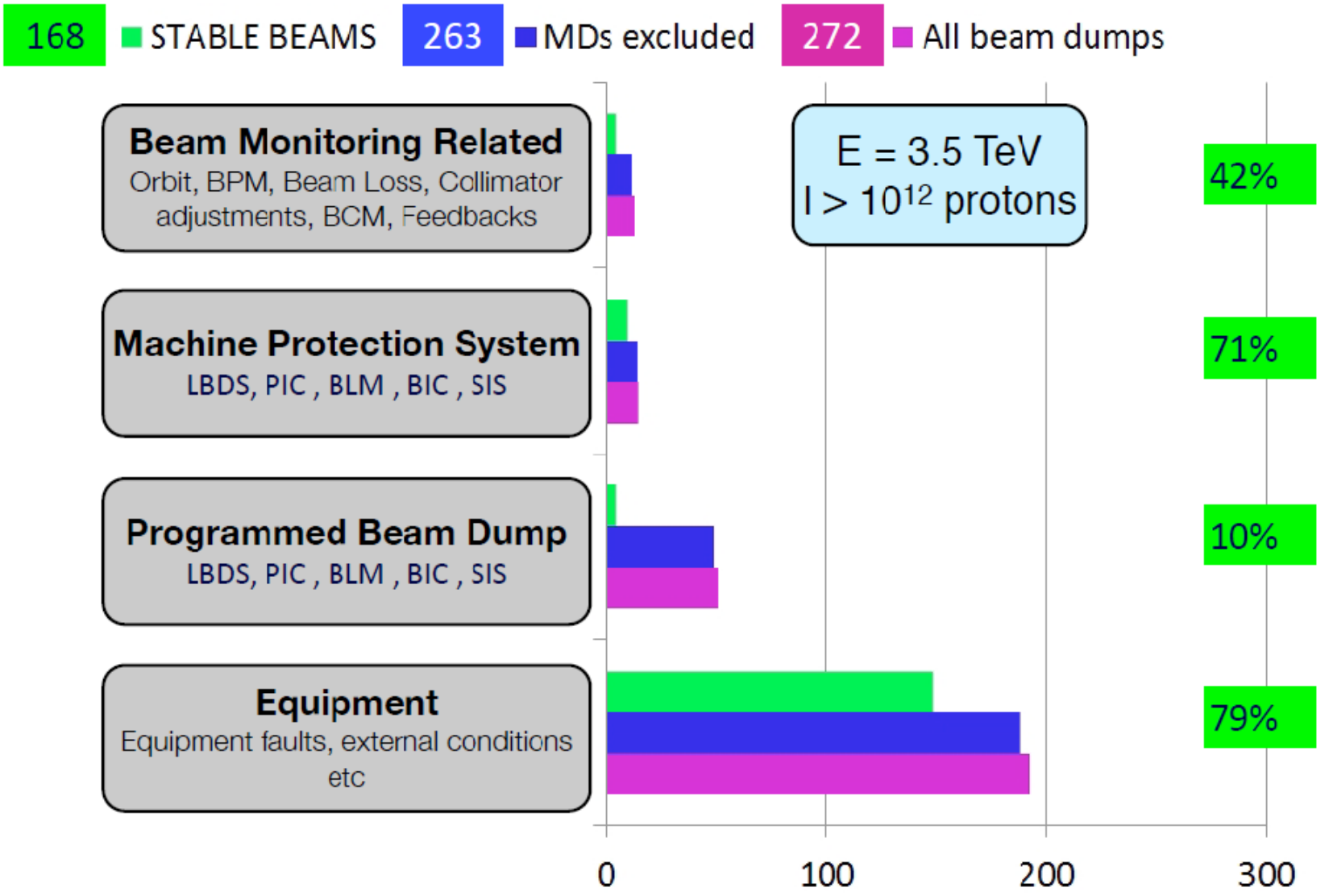
Beam Dumps in 2011 Proton Run

- Number of Beam Dumps in 2011 p-p Run: **482**
- Number of Non-Programmed Beam Dumps: **375 (78%)**
- Number of Non-Programmed Beam Dumps in Stable Beams: **168 (35%)**



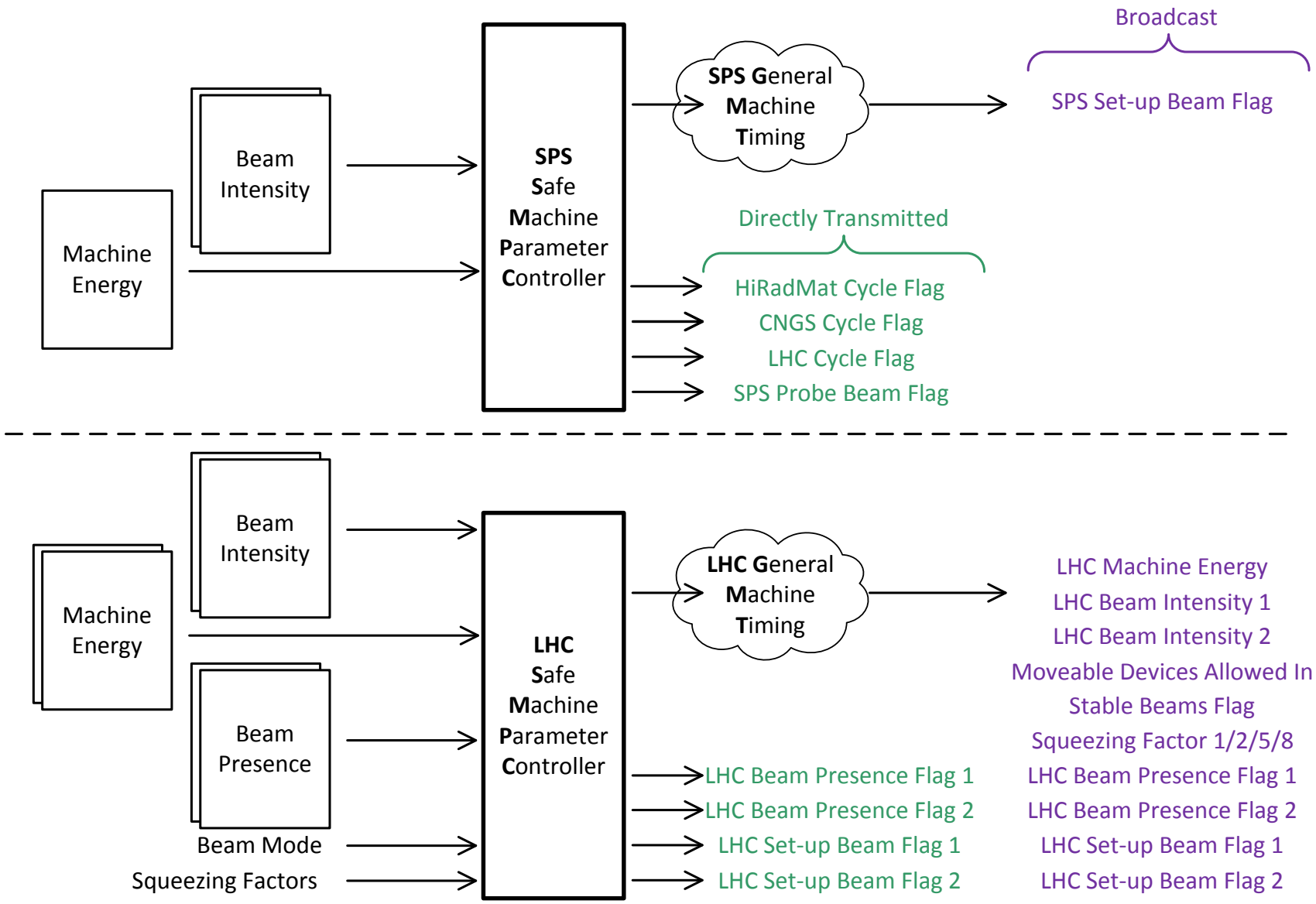
Courtesy of A. McPherson

2011 Proton Run: Beam Dump Causes



Courtesy of A. McPherson

Safe Machine Parameters Layout



Courtesy of B.TODD