Commissioning of the Control System for the LHC Beam Dump Kicker Systems

for a safe operation with beam

Etienne Carlier, Alain Antoine, Christophe Chanavat, Brennan Goddard, Verena Kain, Nicolas Magnin, Jan Uythoven, Nicolas Voumard

(CERN, Geneva)

With significant contributions from Controls and Operation groups.
Thanks for their support.

Outline

- LHC Beam Dump System
- Kicker Systems
- Commissioning
- Open issues
- Summary

LHC Beam Dump System
The challenge

The function of the LHC beam dumping system is to **fast extract** the **circulating beam** in a **low-loss way** from each ring of the collider and to **transport it** to an **external absorber** with the **appropriate beam dilution** in order to not overheat the absorber material.

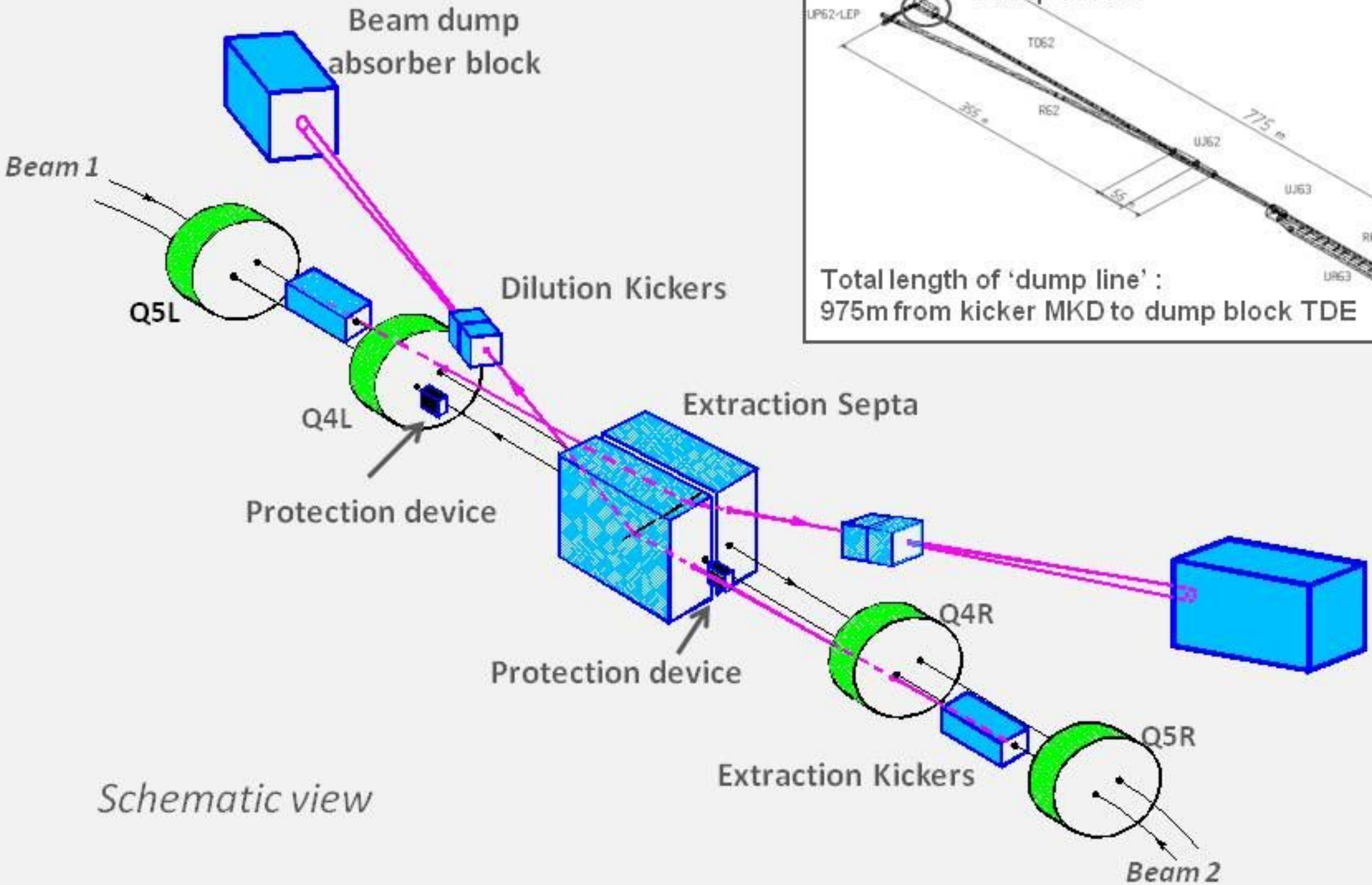
Is not just to dispose of the LHC beam…

…but to dispose of it

- **quickly** (within a few turns, i.e. 100-200 μs)
- **safely** (with an extremely low probability of dangerous failures)
- **robustly** (insensitive to expected machine/system failures)
- **cleanly** (with low distributed/uncontrolled losses)
- **efficiently** (without inducing extra machine down time, i.e. quenches)
- **repetitively** (re-usable dump block and protection devices)

LHC Beam Dump System

Overview



Schematic view

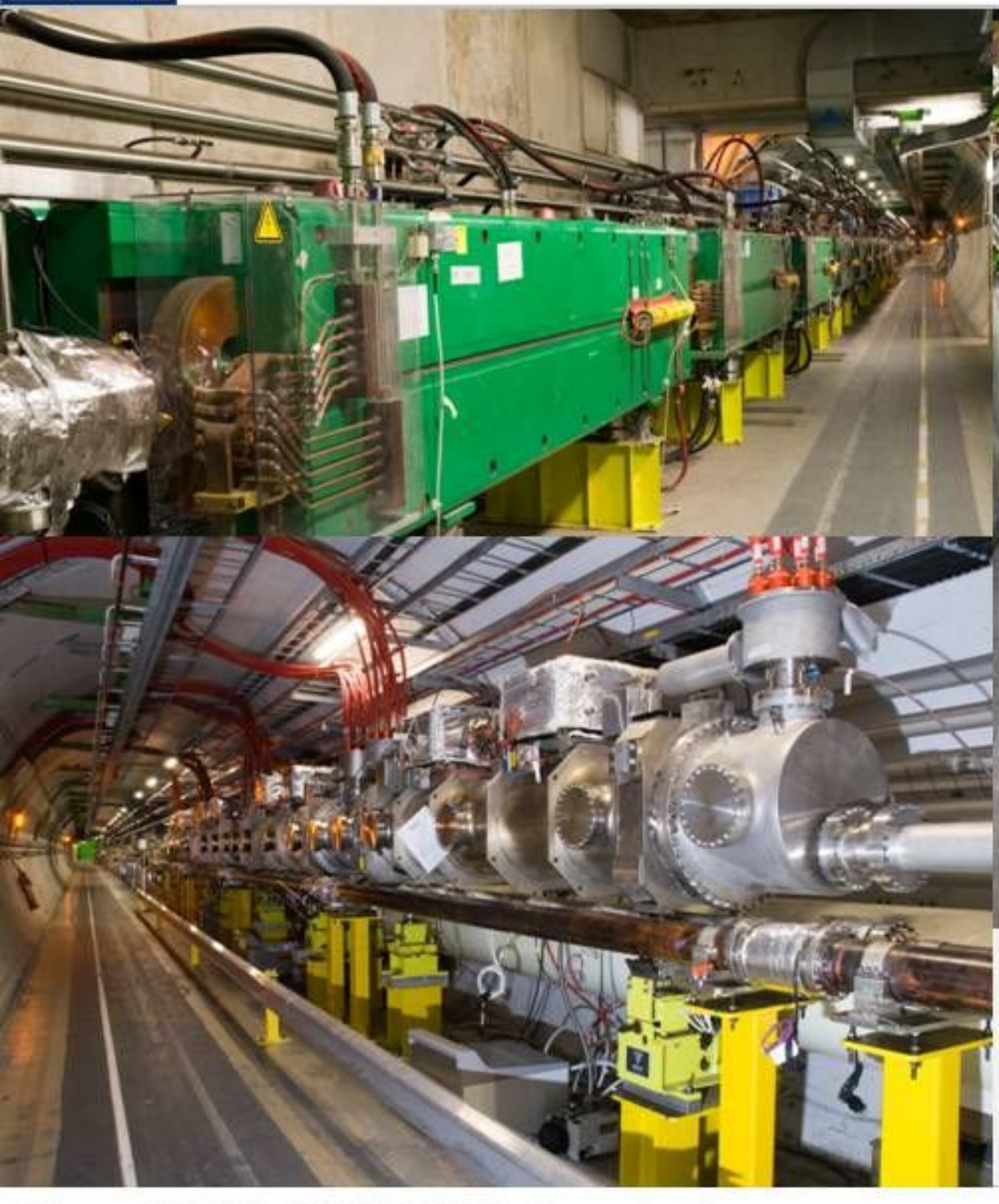
LHC Beam Dump System

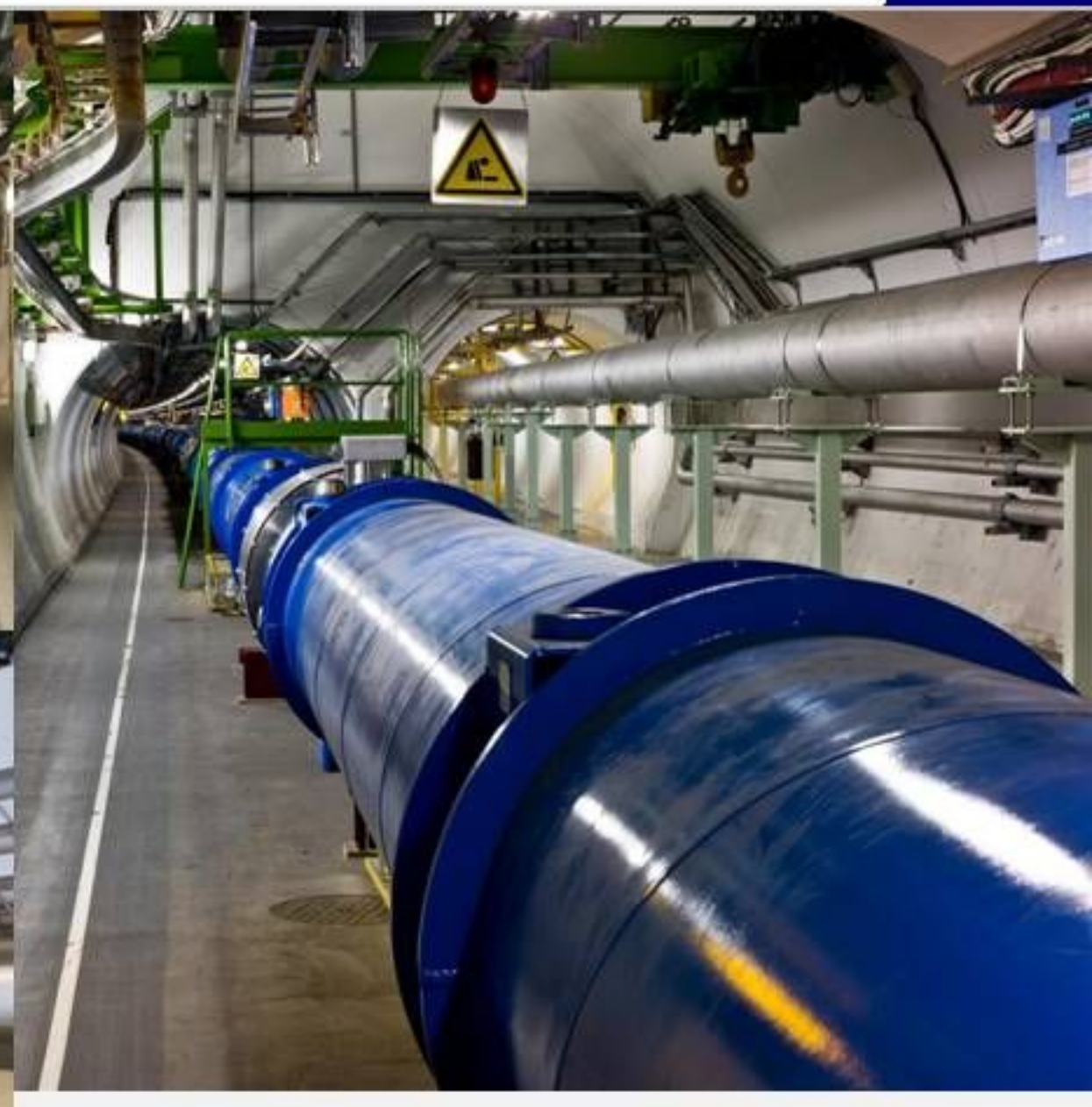
Pictures

Extraction kicker magnets and
their high voltage generators

LHC Beam Dumping System

Pictures





Extraction septa,
dilution kicker magnets and
beginning of extraction line

LHC Beam Dump System

Pictures

Extraction line and
beam dump

LHC Beam Dump System
Interdependencies

Operation
Sequencers, Application software, Fixed Display…

Machine Protection
Beam permit
Injection permit

Timing
Inject & dump,
Circulate & dump

Power Converter
Beam Energy

Beam Dumping System
State, Strength & Timing

Post-mortem
XPOC - IPOC

Revolution frequency
Particle free gap

Controls
Data logging, Data archiving, Alarms, Communication framework

Beam Instrumentation
Extraction trajectory monitors & losses

Beam Instrumentation
Dumped beam Profile, Beam bunch structure

Services
Electrical distribution, Cooling & ventilation, Vacuum

Availability and reliability of each interdependency is essential for the safe dumping of the beam and for the analysis of its correct execution.

LHC Beam Dump System

Kickers

Kicker Systems

Kickers = Fast Pulsed Magnets

Ready / Not Ready

99,99999% of the time

Continuous surveillance

Ready if no fault condition exist.
Synchronous self-trigger in case of internal fault

Redundant fail-safe protection

Pulsing

0.00001% of the time

Post operational check

Prevent to re-pulsed in case of fault during the last pulse

Redundant fault-tolerant protection

To achieve safe operation of the LHC kicker systems, the safety-relevant parts of the protection and control devices must continuously function correctly during their mission time, and, when a fault or failure occurs, the system must be brought automatically into a safe condition, i.e. perform a correct beam dumping action.

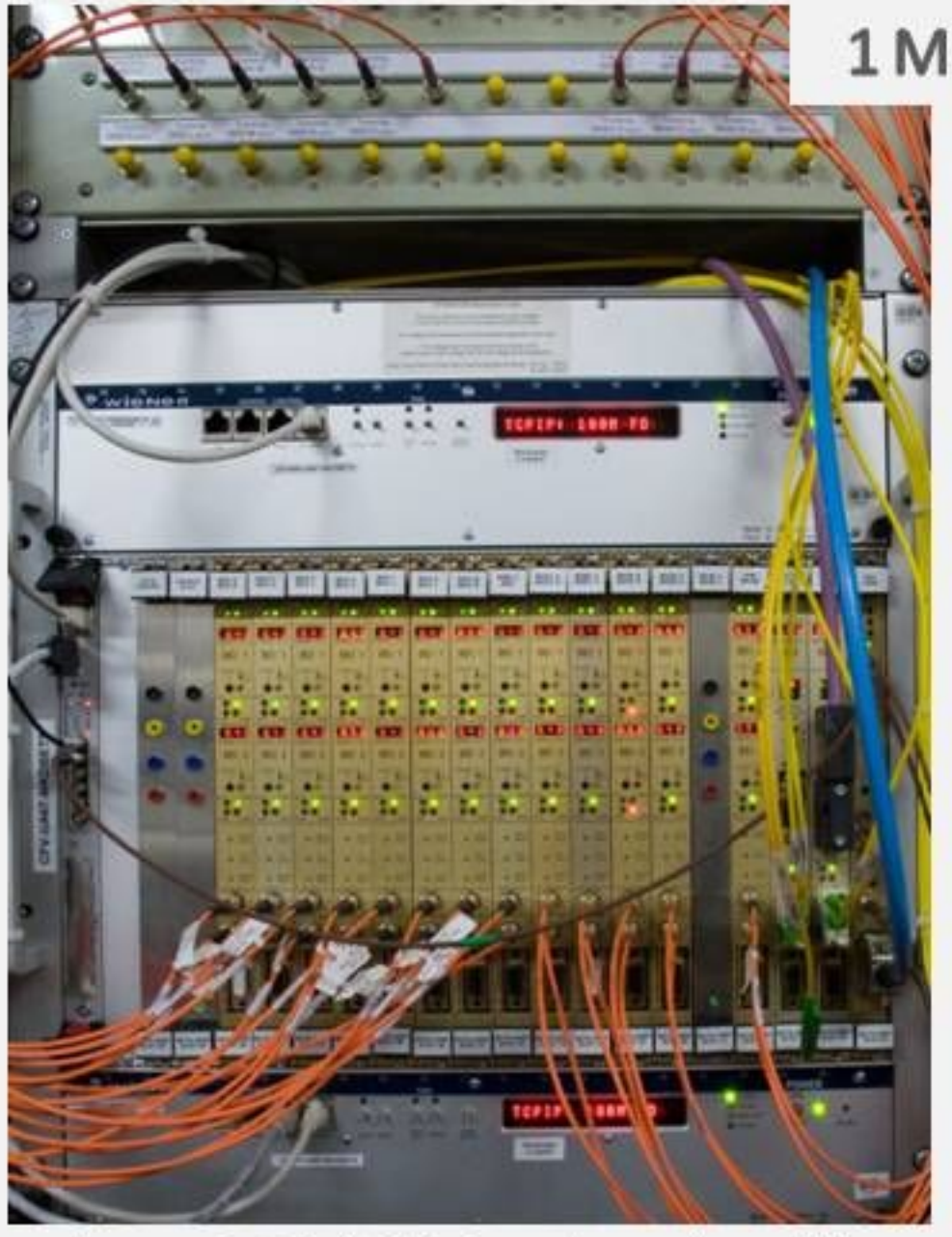
Kicker Systems

Ready state - Surveillance

100 Hz

Fail-safe SIEMENS SIMATIC S7-F Programmable Logic Controllers

1 MHz



LynxOS VME front-ends with dedicated hardware including specific embedded software

Kicker Systems

Pulsing State - Post Operation Checks

Post Operation Checks verify the correct execution of the last dump action

Important components in reliability of the overall system
Particularly for detecting faults in redundant fault-tolerant circuits

"Feed-forward protection"

- **Equipment level → Internal Post Operation Check (IPOC)**
  - How performed the different kicker systems during the dumping process?
  - Executed at the front-end layer

- **System level → External Post Operation Check (XPOC)** → TUP021
  - What happened during the dumping process with the beam?
  - Executed at the server and application layers within the LHC Post-Mortem system

Kicker Control

Internal Post Operation Checks (IPOC)

Verification that the beam dump hardware operated correctly during the last dump action

- **Check**
  - Kicker magnet current waveforms
  - Reception of dump requests
  - Correct event sequence
  - Event synchronisation
  - Distribution of trigger pulses
  - Distribution of re-trigger pulses
  - Status of re-trigger sensors
  - …

Linux cPCI & NI PXI-5122
14bit/100Ms/s digitisers

Kicker Systems

External Post Operation Checks (XPOC)

Verification of the correct execution of the last beam dump action by analyzing and correlating hardware signals from equipment and beam measurements

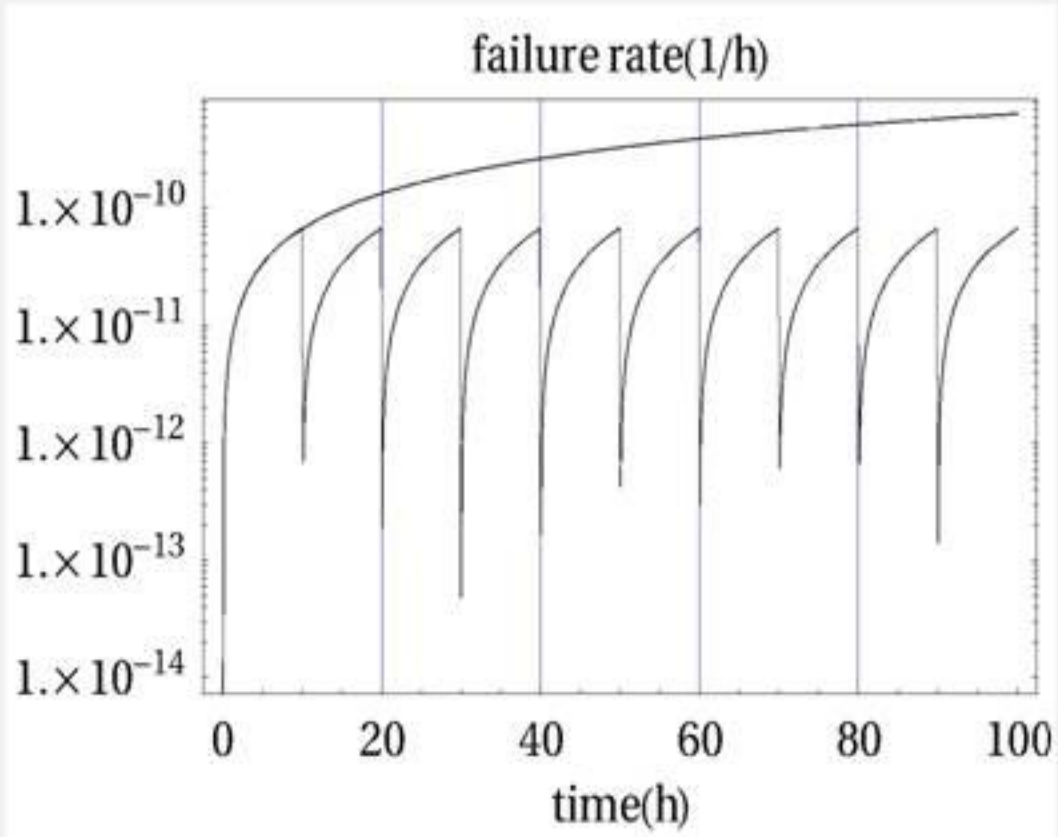
- **Fully redundant analysis to the IPOC**
  - Individual references and tighter tolerance limits
- **Acquisition and analysis of beam measurements and instrumentation during dump execution**
  - Impact position and shape of the swept beam on the absorber block
  - Synchronisation with the particle free gap
  - Losses in the extraction channels
  - Dumped beam intensity
  - Beam energy
  - Vacuum pressure in extraction channel
- **Full archiving of each dump action**
  - Detection of long term degradation

Commissioning – Objective 1

As-good-as-New

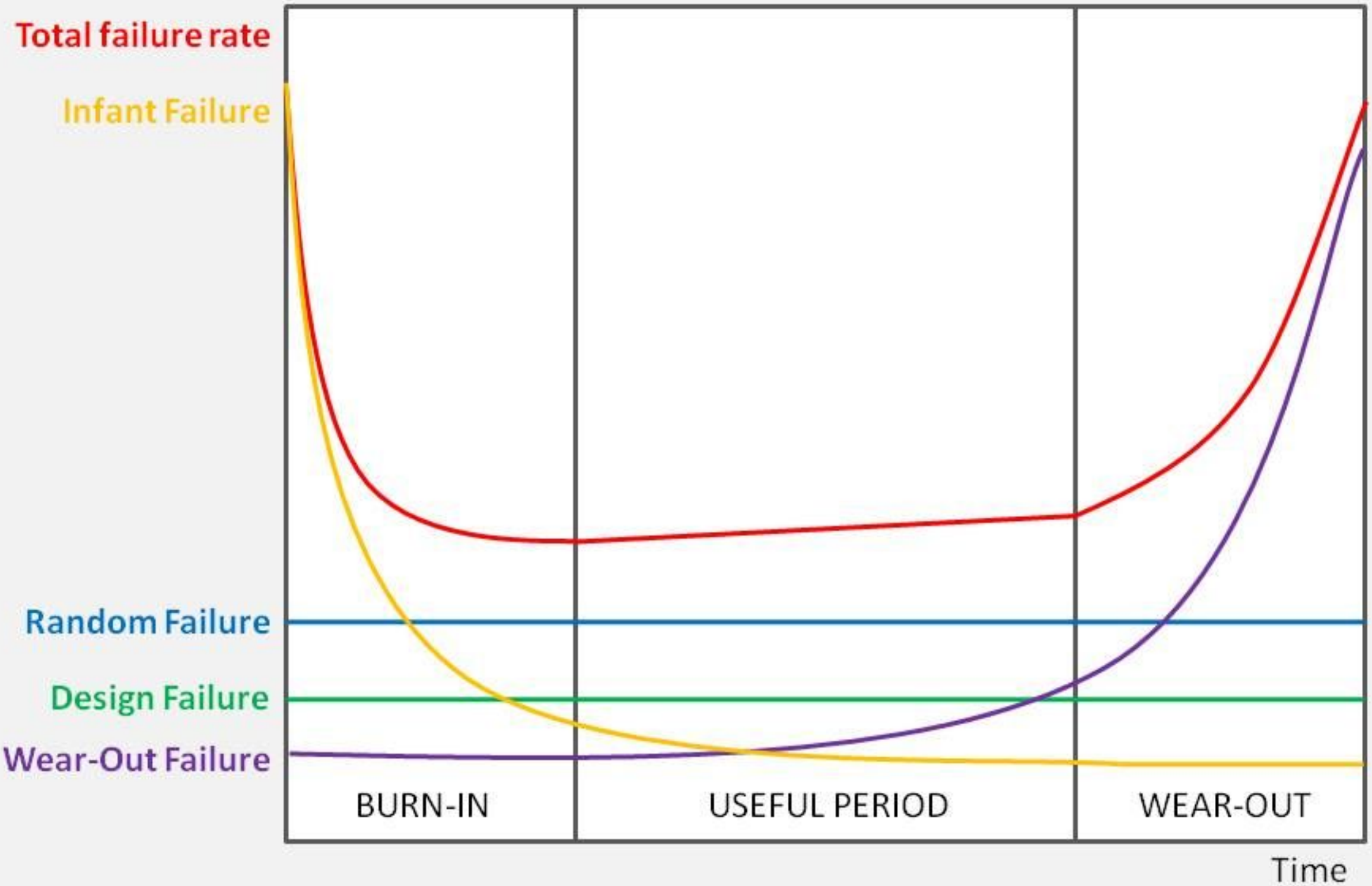
Each dump action is used for validation of the beam dump system and authorisation of a new beam dump (Self test).

- After every dump request, IPOC & XPOC data are checked and correlated.
- If no discordance is found between the 2 systems, beam will be allowed in the LHC with a system which is assumed to be "As-good-as-New".
- Implementation of strict rules for system re-arming and error acknowledgment through Role Based Access (RBAC) protection system. → TUP020
- Application of re-commissioning procedures after any intervention.
- Execution of validation dump after "period" without pulsing.



Commissioning – Objective 2

As-low-as-possible failure rate at “start for physics”



Commissioning
Strategy

Failure	Strategy
Design	• RAMS (Reliability, Availability, Maintainability and Safety) • FMECA (Failure Mode, Effect and Criticality Analysis) • **Reviews**
Infant	• Individual system test (from production QAP up to acceptance tests) • Calibration run • **Reliability runs** • **Dry runs**
Random	• Fail-Safe system surveillance • Internal Post Operational Check • External Post Operational Check
Wear-out	• External Post Operational Check

Commissioning
Reviews

- **LHC Machine Protection Review (April 2005)**
  - Full session dedicated to the beam dumping system

  Outcome:
  - *Recommendation to organise detailed reviews of most critical systems (Beam Interlock System, Beam Dumping System, Beam Loss Monitor System).*

- **LHC Beam Dump System – Technical Audit (January 2008)**
  - All LBDS subsystems reviewed in detail (SCSS, BETS, TSDS, FAAS, IPOC, XPOC…)
  - Purpose was to confirm critical parts, to understand function of those parts, to validate their design

  Outcome:
  - *"Design and implementation of the LHC Beam Dumping System is sound, complete, straight-forward and in particular, conform to the requirement of a high inherent level of safety, reliability and availability"*
  - *Establishment of a set of recommendations for the different sub-systems reviewed*
  - *Ask for clarification of interface definitions between LBDS and Beam Interlock System and between LBDS and Radio Frequency system*
  - *Recommendation for parallel peer-reviews for VHDL and PLC code*

Commissioning
Reviews

- **LHC Beam Dump System – Technical Audit Follow-up (June 2009)**
  - Review of the progress made in the implementation of the audit recommendations

  Outcome:
  - *"Reliability runs have impressively shown the proper functioning of XPOC and IPOC"*
  - *60% of the recommendations of the initial audit have been implemented. Remaining 40% are pending implementation during 2009*
  - *Recommendation to perform full review of FPGA code and to deploy FPGA test benches*
  - *Reassess the recommendation to perform peer-reviews of the PLC code*

- **Technical Review of the Trigger Synchronisation Unit of the LHC Beam Dumping System (On-going)**
  - The validation of the correct implementation of the functional requirements,
  - The verification of the pre-series performance,
  - The identification of possible hardware and/or software anomalies,
  - The recommendation of possible improvements,
  - The proposal of guidelines of possible maintenance procedures for the embedded software.

Commissioning
Reliability run

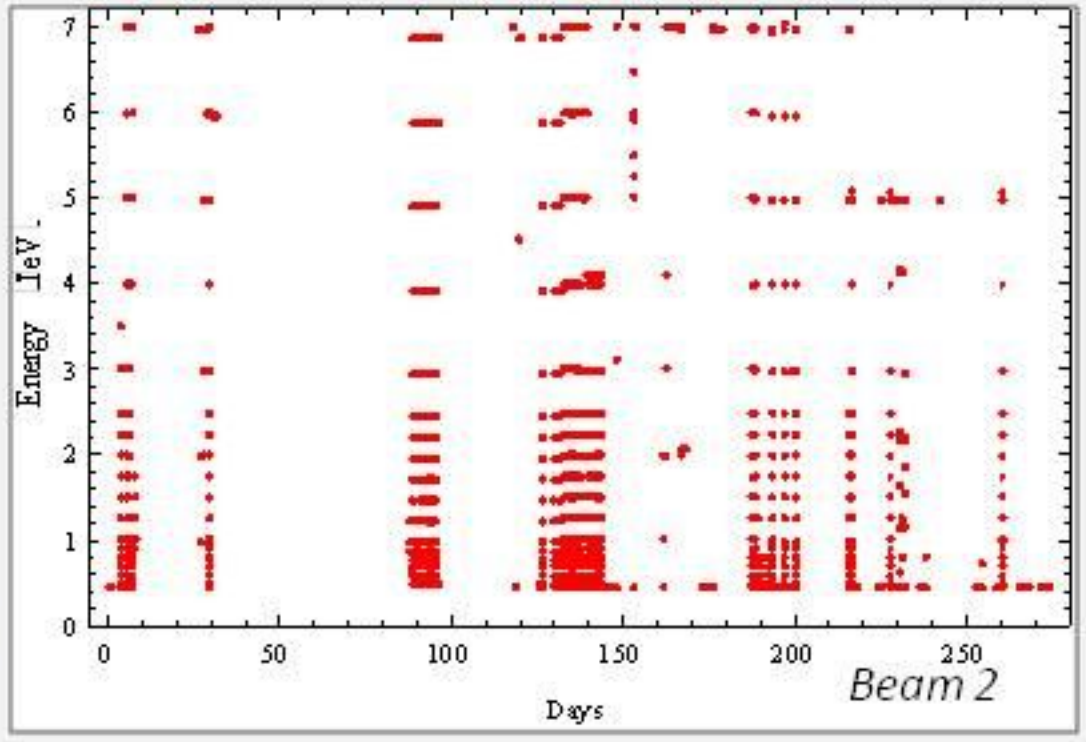
Objectives

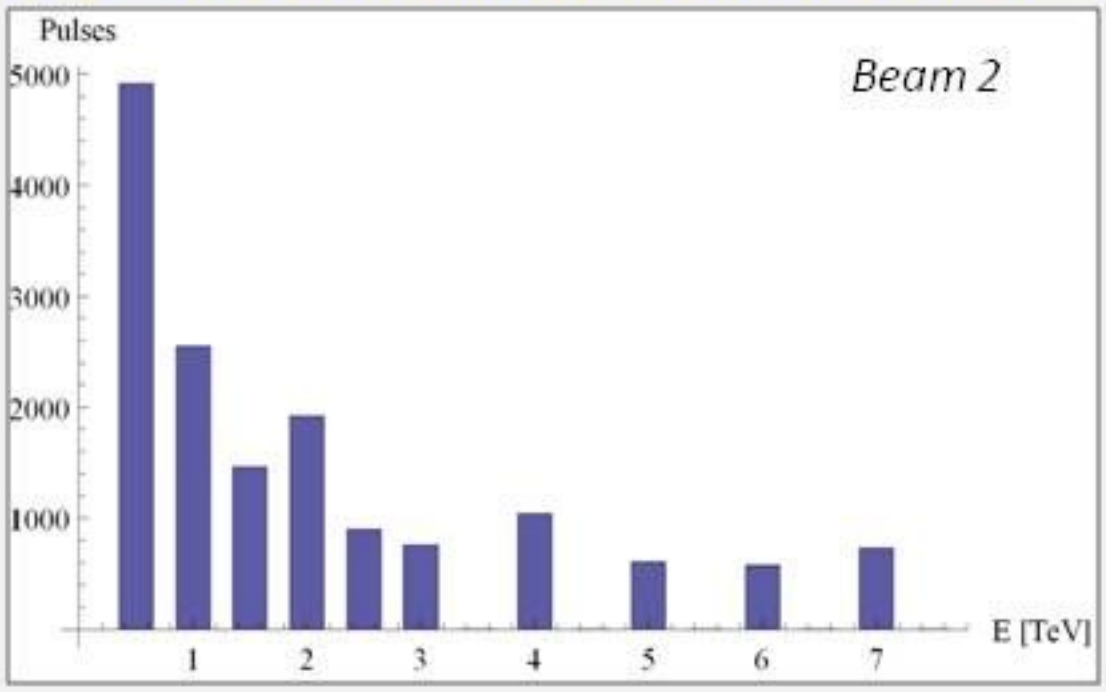
- Validation of FMECA and RAMS studies
- Pass the burn-in period
- Validation of IPOC & XPOC analyses

741'057 magnet pulses analysed with IPOC and XPOC systems

- Some hardware problems discovered

No critical failures which would have resulted in a non-acceptable beam dump even if redundancy would not be there

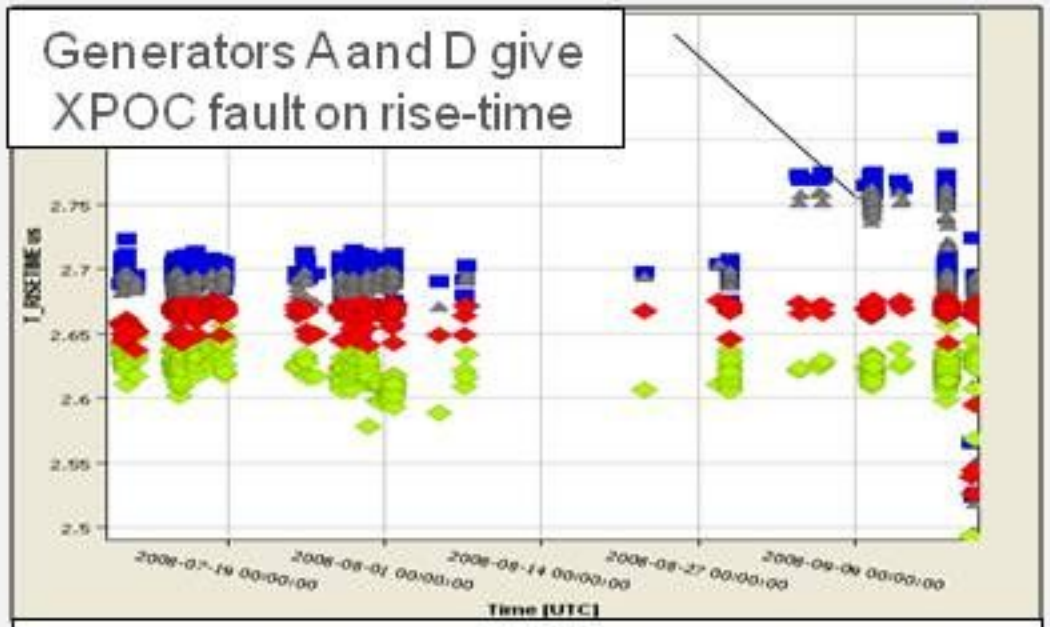




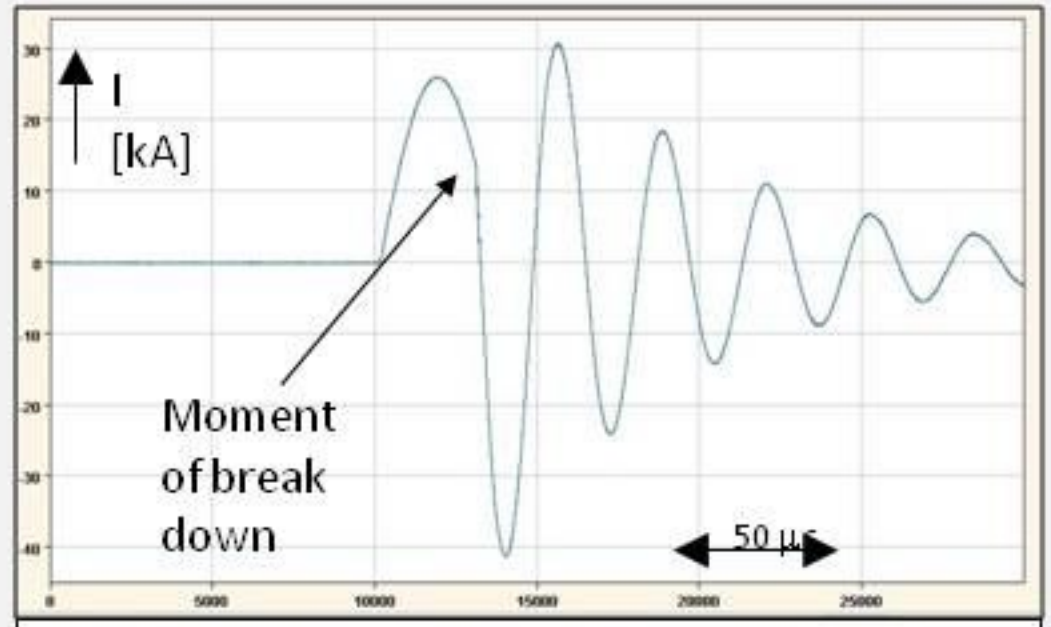
	Beam 1	Beam 2
# Pulses	23'534	15'469
Time considered	10.5 months	9.1 months
Continuous running (p <13 h)	2.7 months	1.7 months

Data from 8/11/07 to 19/09/08

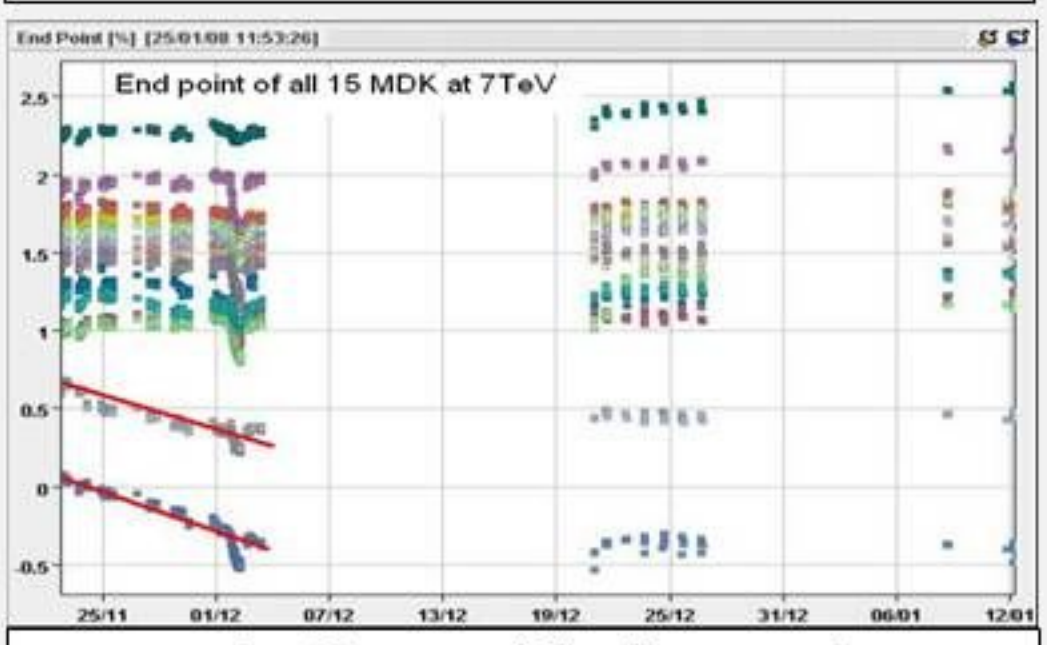
Commissioning
Reliability run



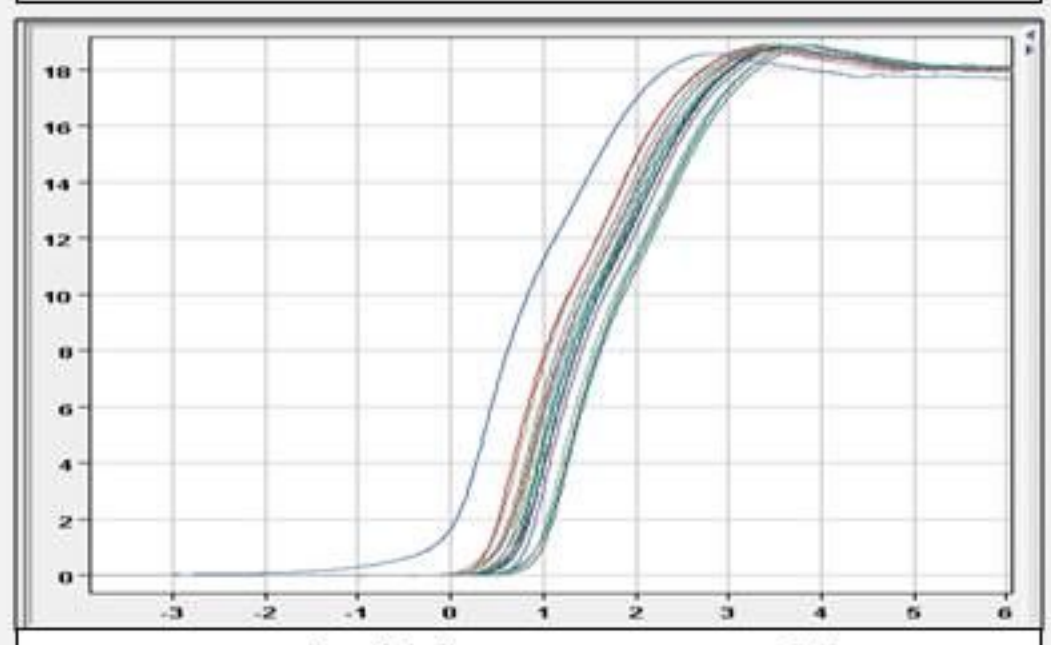
Power trigger cables badly connected



Dilution kicker magnet flashover



Burn-in effect on self healing capacitors



Extraction kicker spontaneous firing

All failures were detected by IPOC/XPOC diagnostics

Commissioning

Dry runs

- **Integration of LBDS control within accelerator control system**
  - Test complete system under operational conditions
  - Check software stability
  - Validation of new software release deployment technique
- **Individual test of all the system interdependencies**
  - Hardware and software
- **Prepare to commission to nominal cycle**
  - Remote operation from the control room
    - Test of the complete system under operational conditions
  - Test & validation of application programs
    - Sequencer
    - Fixed displays
    - Operator & Expert applications
    - Management of critical settings
    - RBAC roles and rules
    - Analogue signal acquisition & viewer

→ WEP099

  - Training of operation crews
    - Feedback on API and GUI
- **Run LHC nominal cycles with all systems (i.e. including LBDS) with LHC Sequencer.**

→ THC003

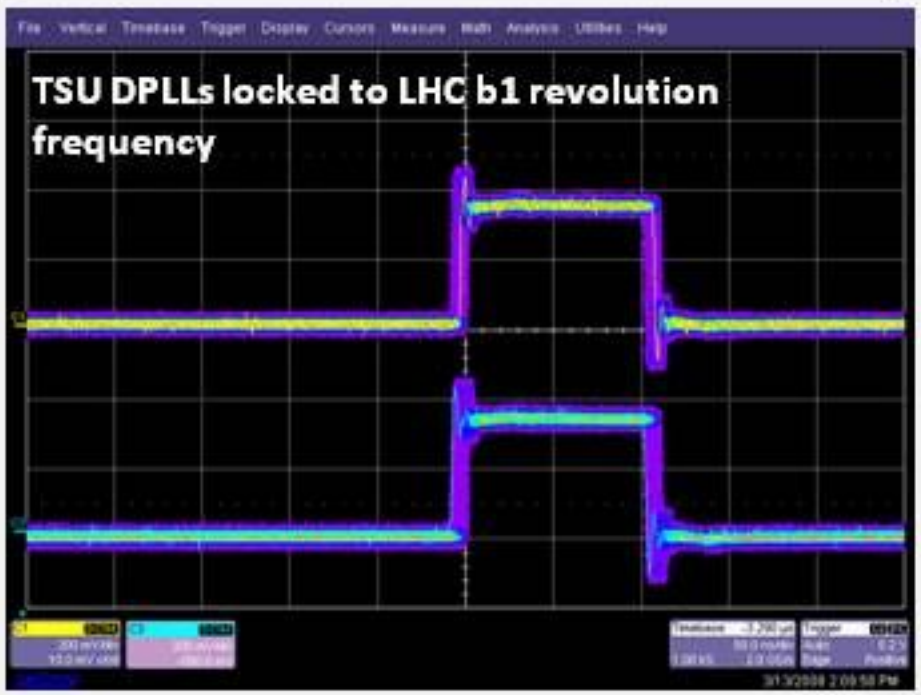
Commissioning
With Beam

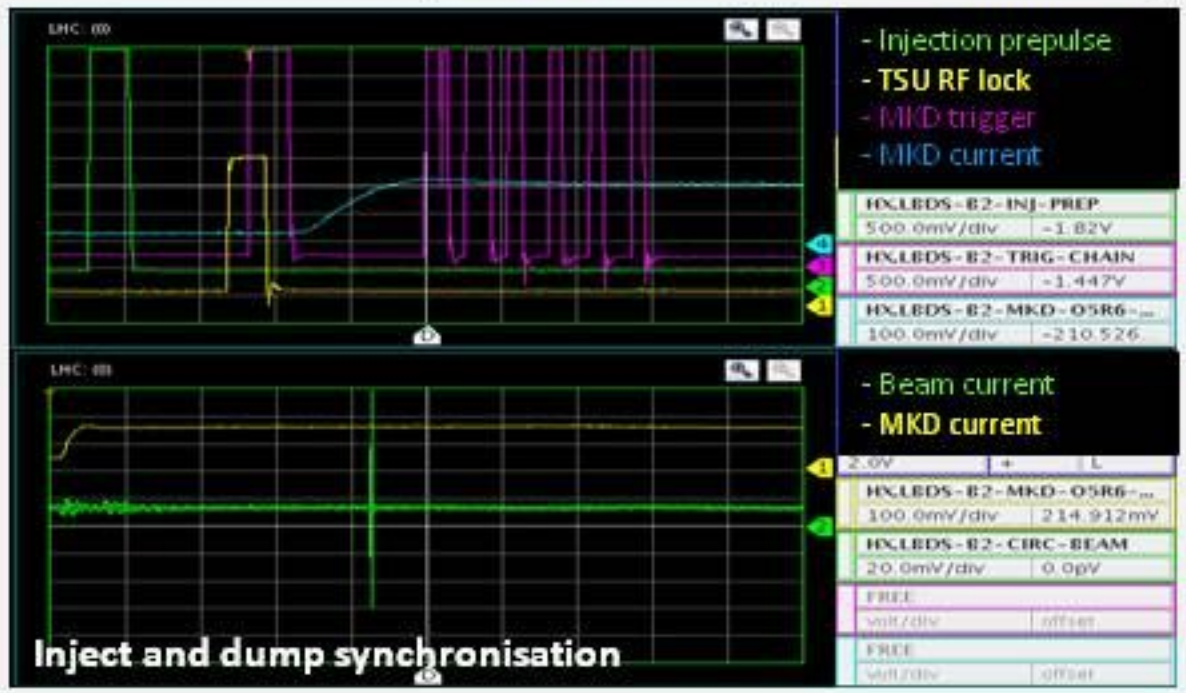
Check that the expected performance is obtained over the complete operational range

- **Boot-strapping of the complete system with beam**
  - Test and commissioning of the instrumentation with beam
  - Steering of the trajectories to optimise available aperture
  - Fine tuning of kicker timing and synchronisation
- **Validation of the XPOC analysis for beam measurement signals**
  - Tune interlock thresholds
  - Generation of reference settings
- **Test expected failure modes with safe beam intensity**
  - Missing extraction kicker
  - Asynchronous dump
  - …

Commissioning
With beam

	Beam 1	Beam 2
Inject and dump setup	OK	OK
Circulate and dump setup	To do	OK
Dump region aperture	To do	Started (some phases)
Detailed kicker synchronisation	To do	To do
Extraction element strengths	Started (corrected MSD)	Started (corrected MSD)
Beam instrumentation checks	Started	Started
Interlocks (BPMSA, TCDQ, ...)	To do	To do
Sweep waveform measurement	To do	To do (parasitic looks OK)
Dump protection systems setup	To do	To do
PM and XPOC	Started	Started
Tracking tests	Started (2 sectors only)	Started (2 sectors only)
Abort gap keeper	Started	Started





Open Issues

- **Missing version management and code modification tracking tools within SIEMENS STEP7 software development framework**
- **High sensitivity to accelerator control framework at application and front-end software levels**
  - Software interdependencies
- **Lack of remote low-level diagnostic for the redundant fault-tolerant systems**
  - Lost of vital information by shaping the signal instead of acquiring the true signal
- **Maintenance, test and re-validation of software**
  - Application, front-end, embedded and PLC levels
- **Missing automated procedure for re-validation of the complete system after hardware and/or software modifications without jeopardising the reliability of the complete system**

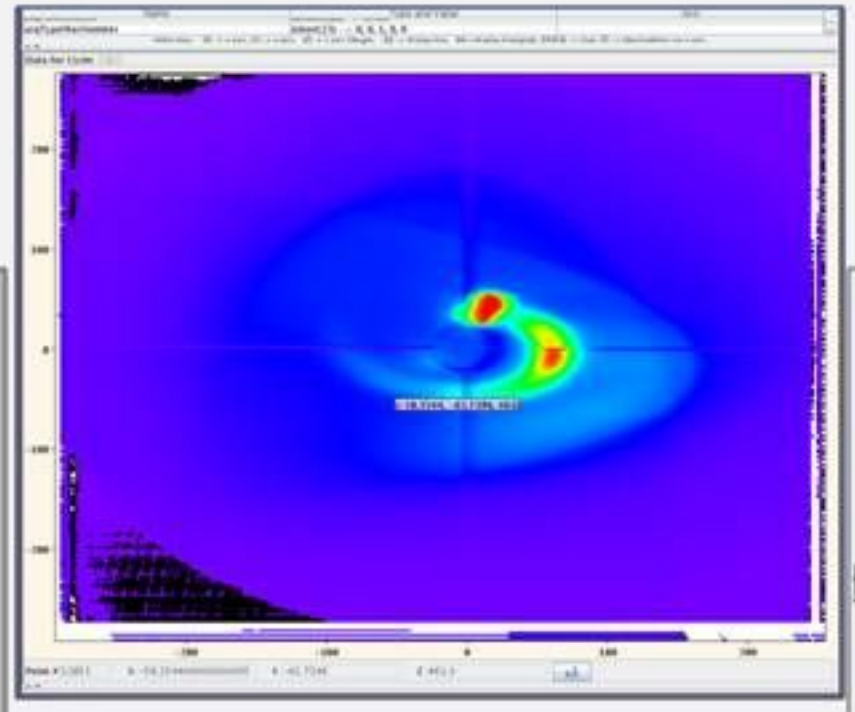
General awareness of the system criticality / safety is important.

Necessity to obtain (beam) time after an intervention or if something in the system is not 100% understood.

Summary

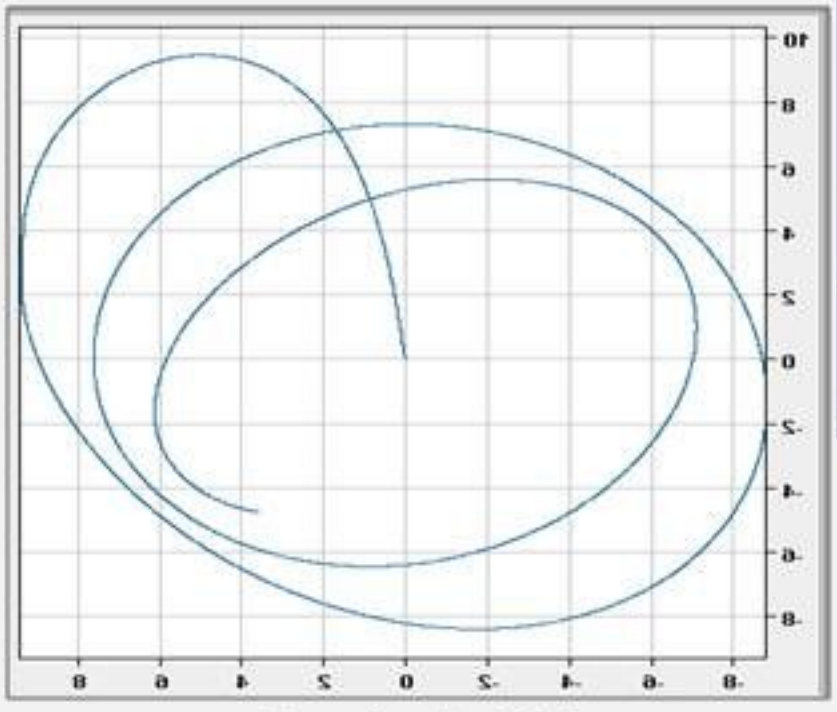
- **Highly reliable control architecture inherent to design choices**
  - Fail-safe systems with continuous surveillance when in *Ready* state
  - Fault-tolerant and redundant systems with post operational checks when in *Pulse* state
- **Software tools mature enough to start commissioning with beam under safe conditions**
  - Reviews
  - Reliability runs
  - Dry runs
- **XPOC and IPOC have successfully shown their usefulness**
  - Capture of instabilities and fast transients
  - Detection of early performance degradation
- **Maintenance remains an issues**
  - Introduction of systematic failures
  - Software interdependencies

Beam sweep image on beam dump screen



IPOC

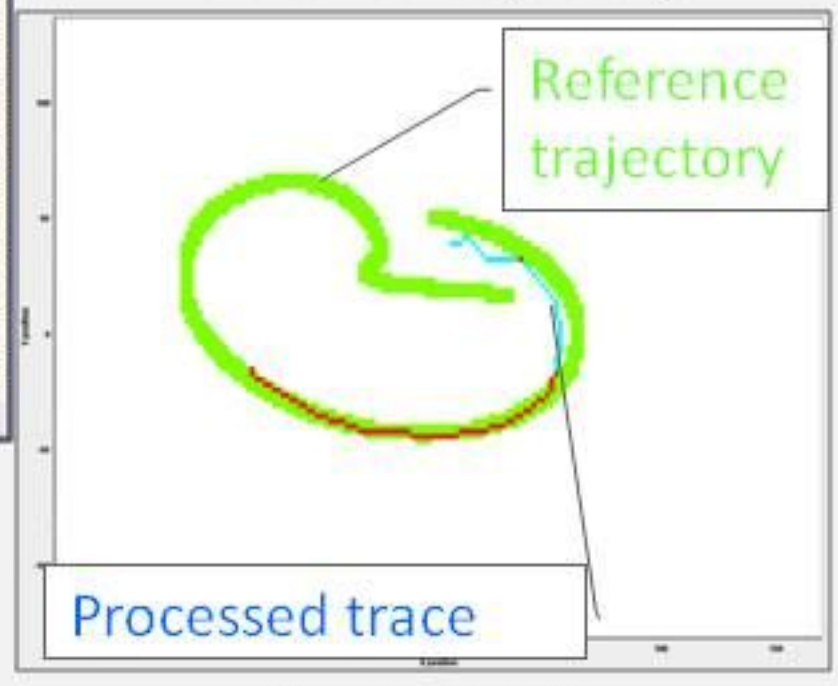
Sum kicker magnet current



Analysis OK

XPOC

Dumped beam trajectory Vs Reference trajectory



Analysis OK

As-Good-as-New

Looking forward to new dumps soon…

Fin