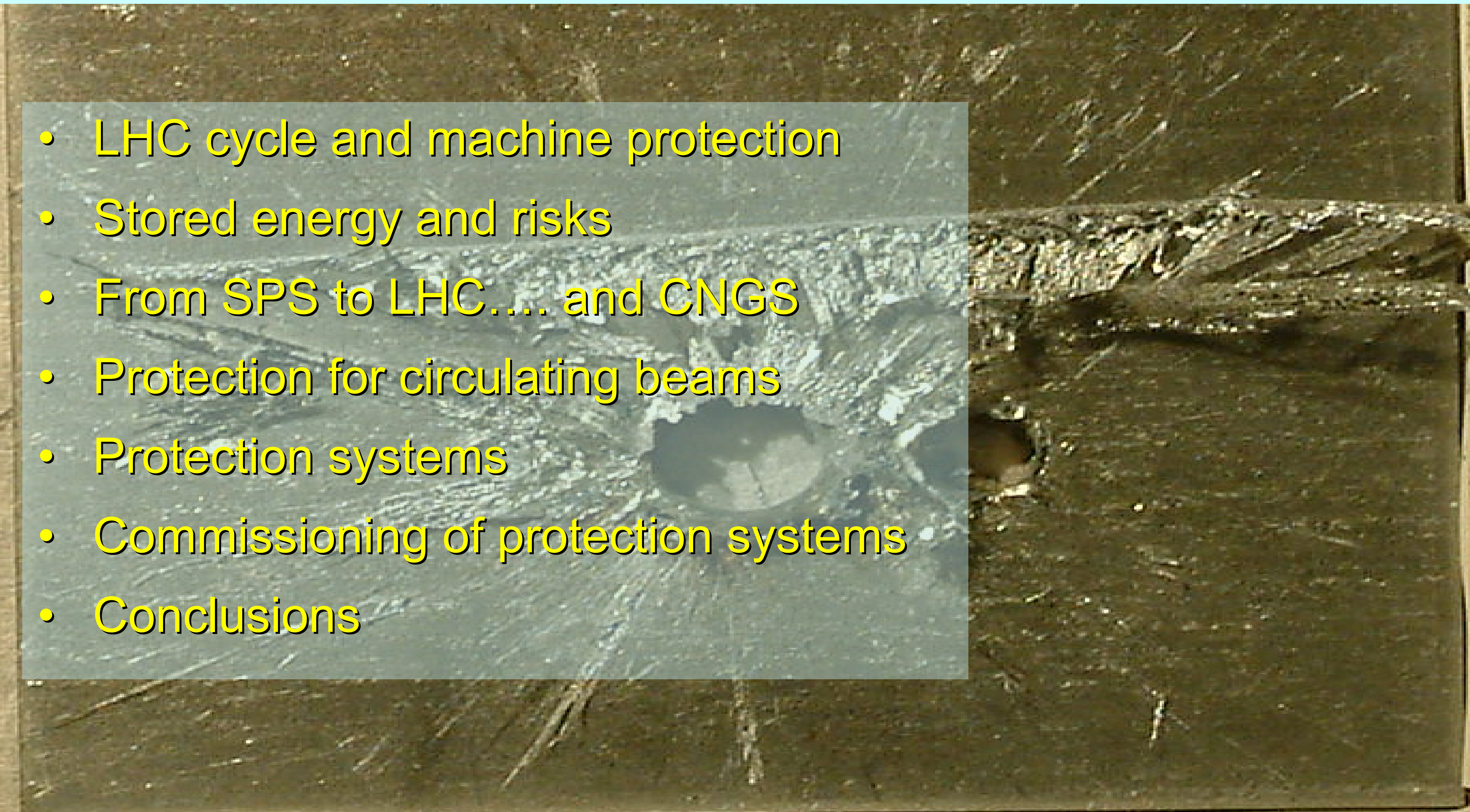
LHC Machine Protection

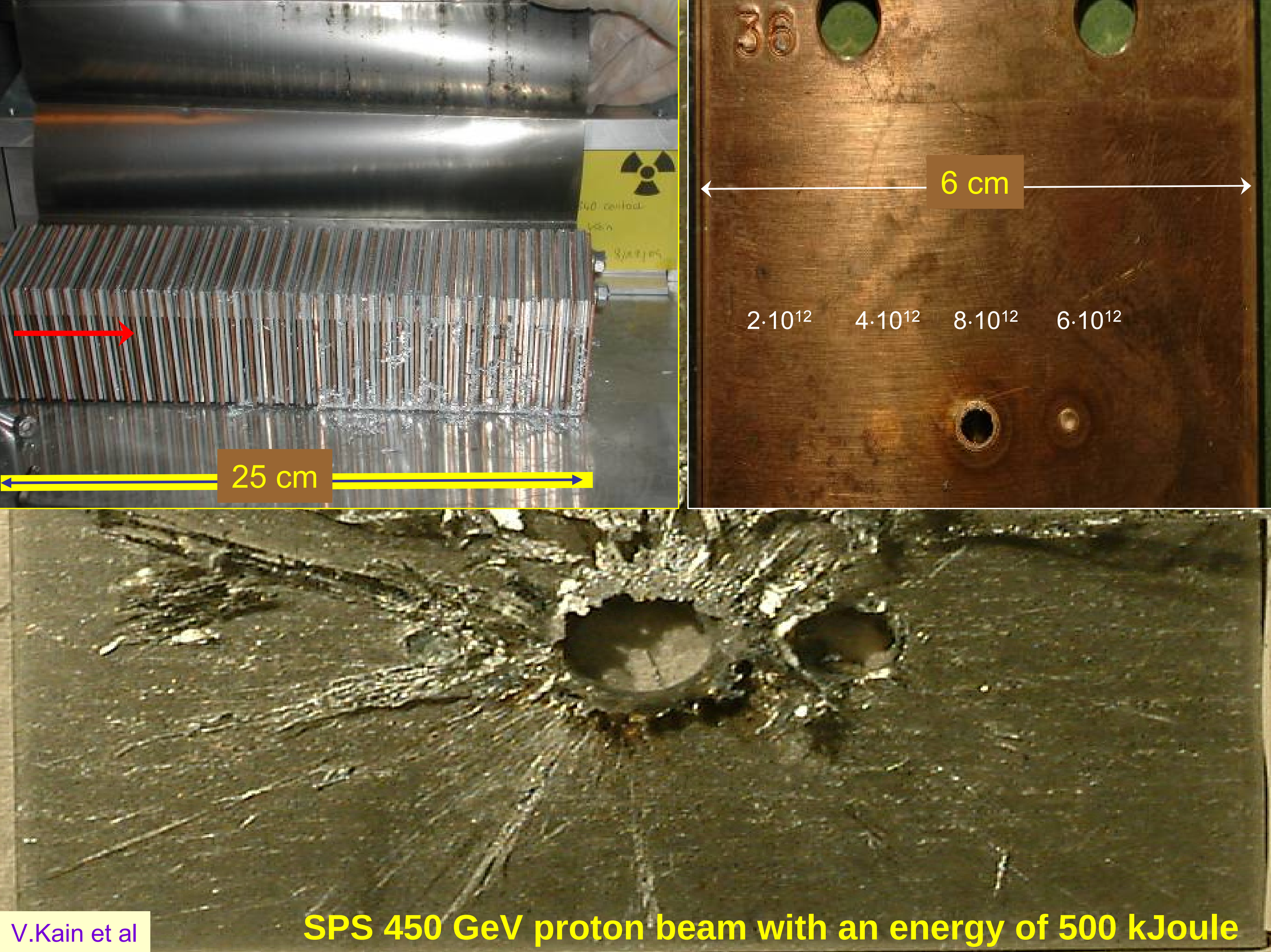
Rüdiger Schmidt

R.Assmann, E.Carlier, B.Dehning, R.Denz, B.Goddard, E.B.Holzer, V.Kain, B.Puccio, B.Todd, J.Uythoven, J.Wenninger, M.Zerlauth

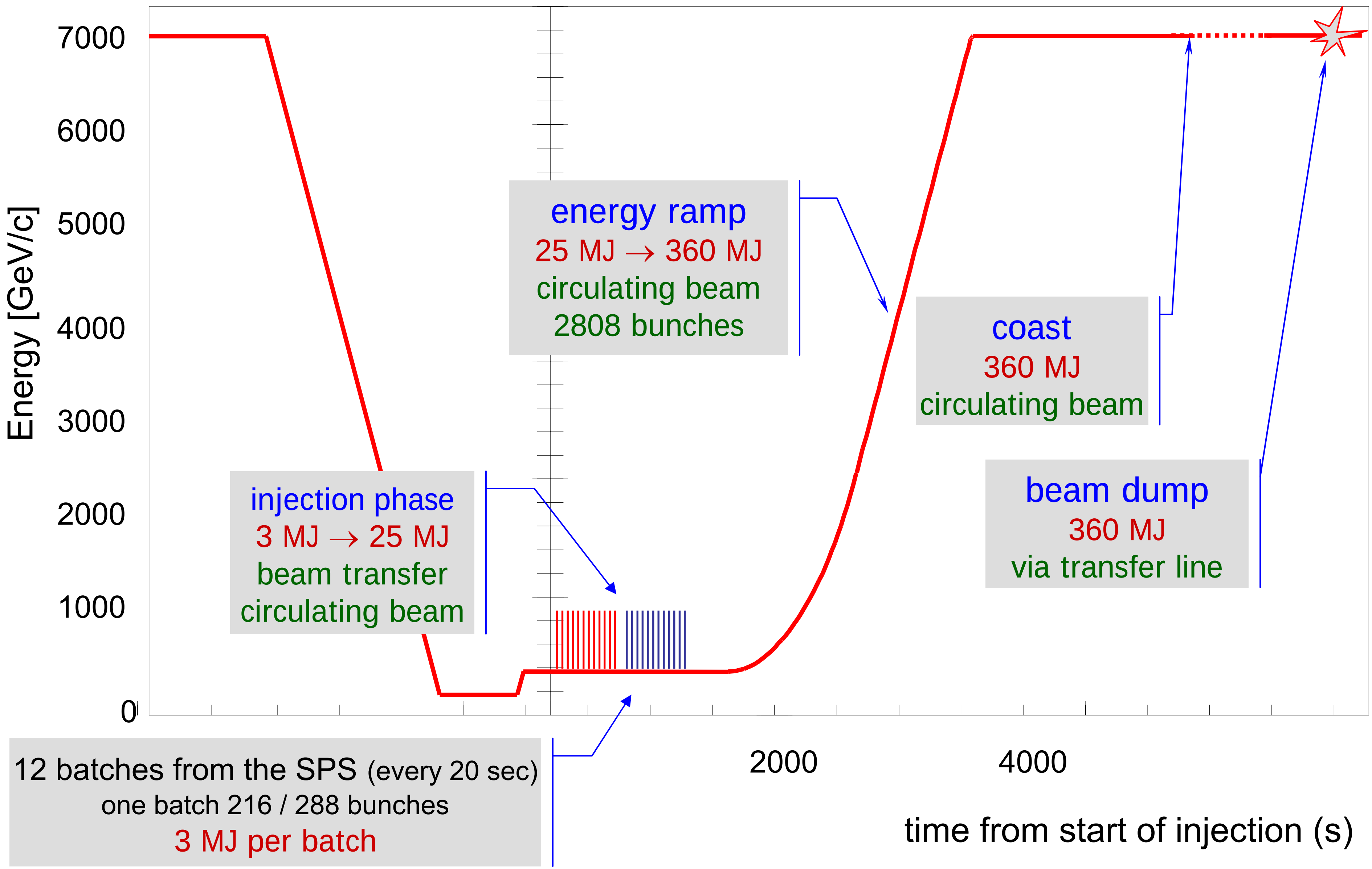
PAC June 2007



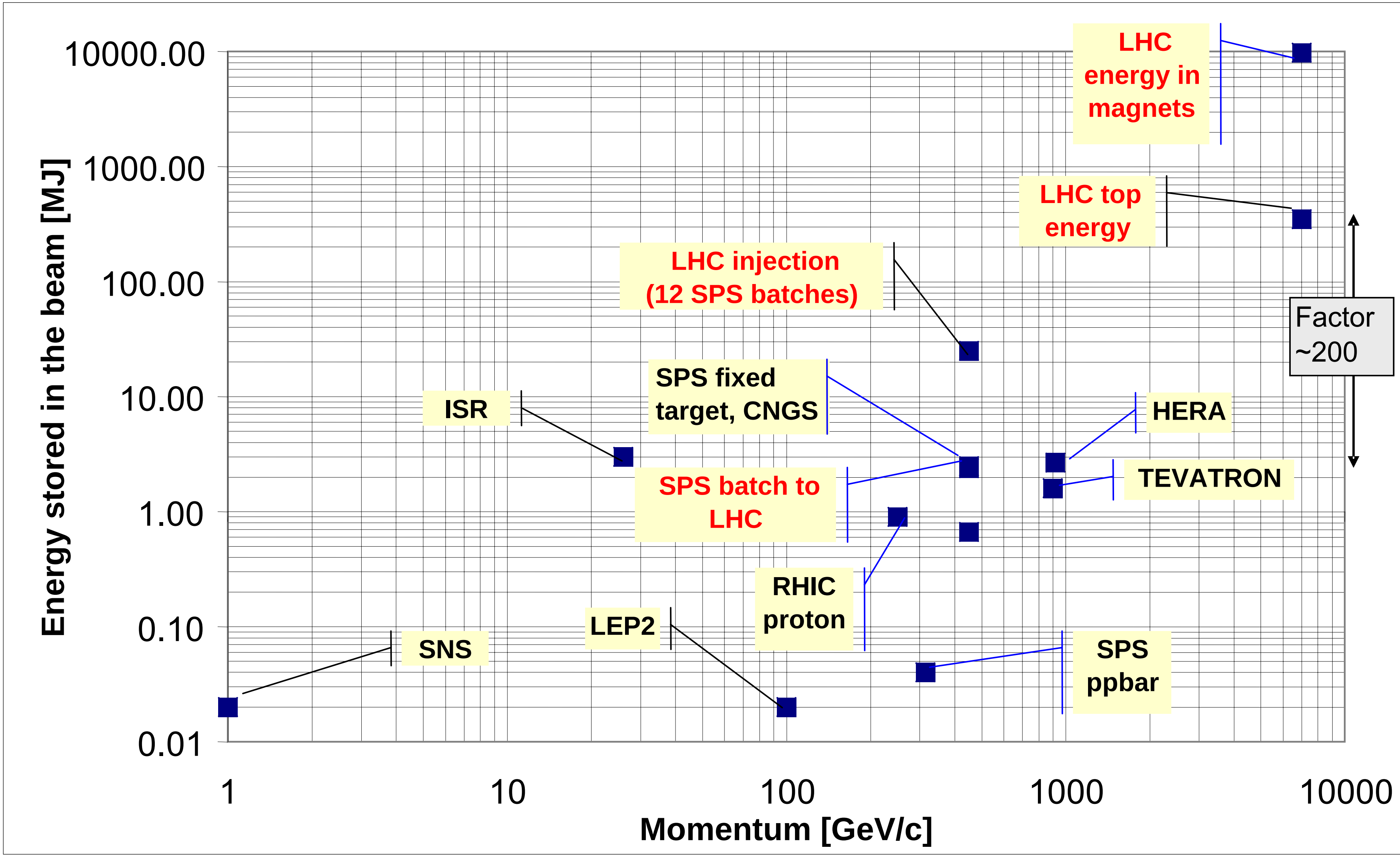
- LHC cycle and machine protection
- Stored energy and risks
- From SPS to LHC…. and CNGS
- Protection for circulating beams
- Protection systems
- Commissioning of protection systems
- Conclusions


25 cm
36
6 cm
2·10^12
4·10^12
8·10^12
6·10^12
V.Kain et al
SPS 450 GeV proton beam with an energy of 500 kJoule

LHC operational cycle and stored beam energy

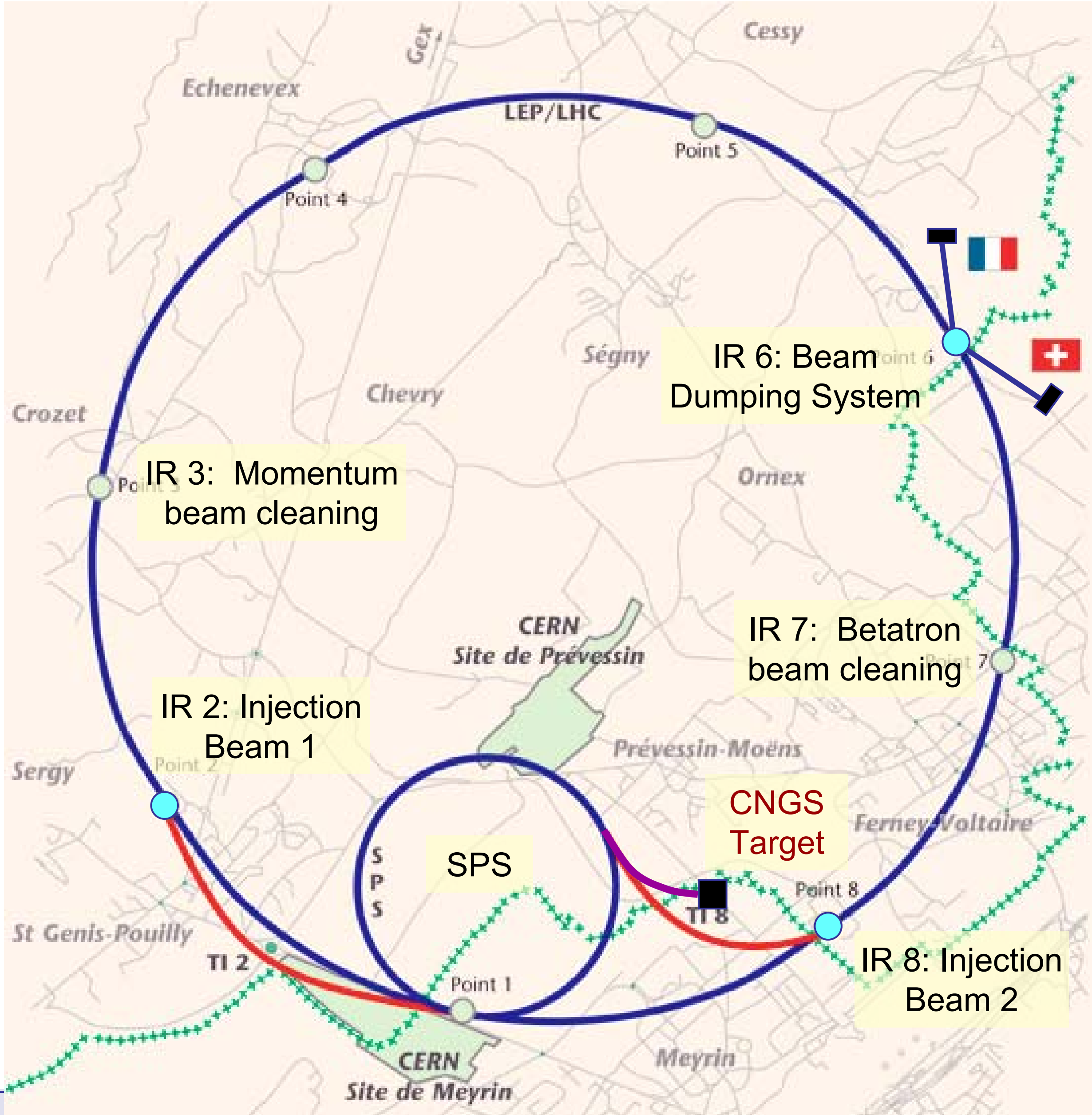


Livingston type plot: Energy stored magnets and beam



based on graph from R.Assmann

Machine protection for LHC and injector



- Safe acceleration of beam in SPS
- Safe transfer of beam to LHC via TI2 and TI8
- Safe injection of beam into LHC
- Safe storage and acceleration of beam in LHC
- Always dumping beams into the beam dump blocks, at end of fill or after failure

Safe transmission of beam to CNGS

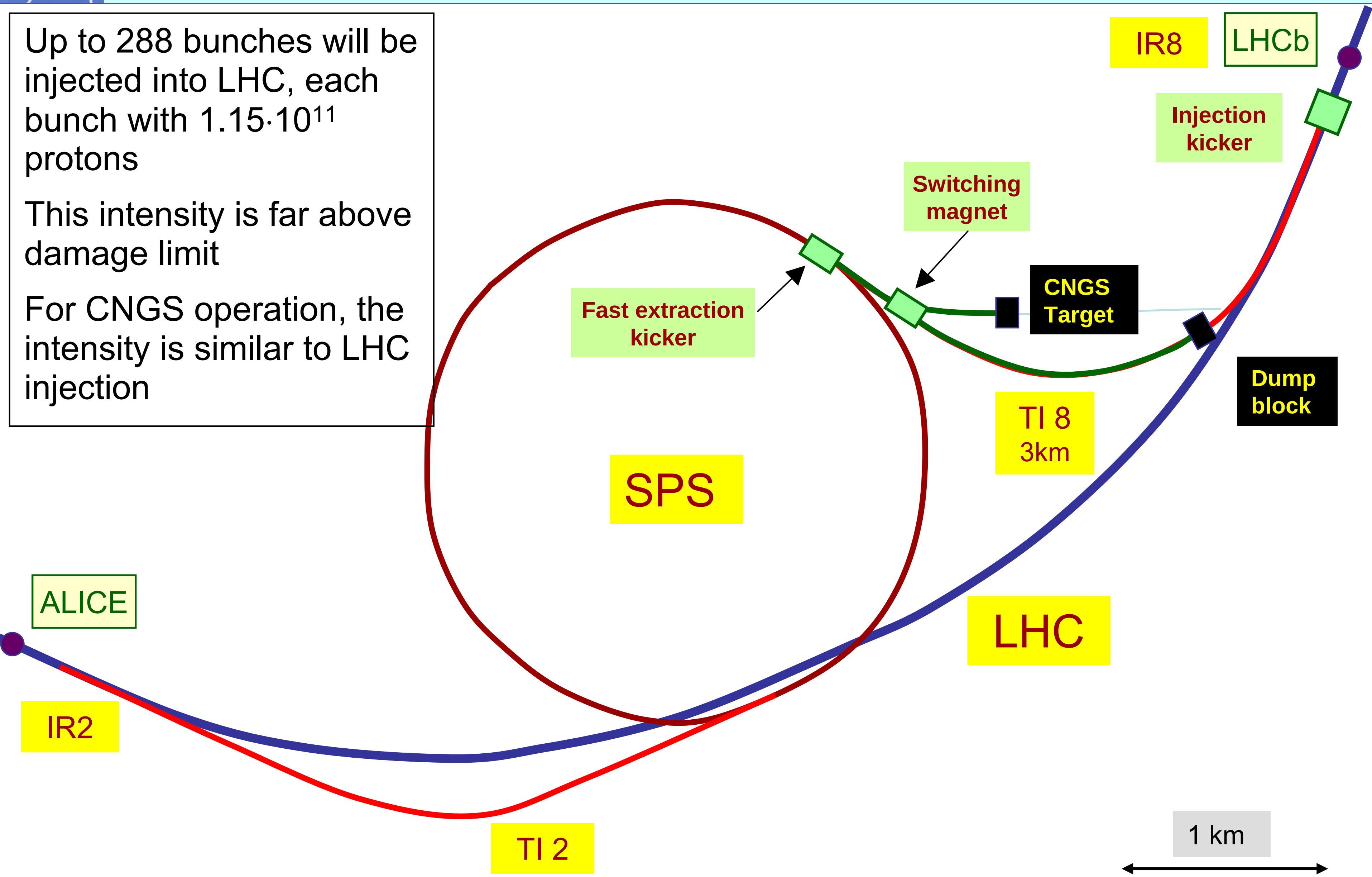
talk on CNGS by M.Meddahi

SPS, transfer line, LHC Injection and CNGS

Up to 288 bunches will be injected into LHC, each bunch with $1.15 \cdot 10^{11}$ protons

This intensity is far above damage limit

For CNGS operation, the intensity is similar to LHC injection



Protection for beam transfer after SPS extraction

- After extraction the trajectory is determined by the magnet fields: safe beam transfer and injection relies on correct settings
  - orbit bump around extraction point in SPS during extraction with tight tolerances
  - correct magnet currents (slow pulsing magnets, fast pulsing magnets)
  - position of vacuum valves, beam screens,… must all be OUT
  - LHC or CNGS must be ready to accept beam
- Verifying correct settings just before extraction and injection

“**Extraction Permit**” is **required to extract beam from SPS**

“**Injection Permit**“ to **inject beam into LHC**

- The kicker must fire at the correct time with the correct strength
- Collimators and beam absorbers in SPS, transfer line and LHC injection region must be positioned correctly to protect from misfiring

Beam interlocks systems for SPS and CNGS

CNGS experiment
Beam Permit = YES

Switching magnet in CNGS position
Beam Permit = YES

CNGS pulsing elements
Beam Permit = YES →
Beam Permit = NO →

CNGS permit
NO → YES → NO
1ms

Transfer line and SPS pulsing elements + BPMs
Beam Permit = YES →
Beam Permit = NO →

Transfer line static elements
Beam Permit = YES

SPS extraction permit
NO → YES → NO

- CNGS beam interlock system
- SPS extraction interlock system
- SPS beam interlock system

Beam interlocks systems for SPS and LHC

LHC ring
Beam Permit = YES

LHC static injection elements
Beam Permit = YES

LHC pulsing injection elements
Beam Permit = YES →
Beam Permit = NO →

LHC injection permit
NO → YES → NO
1ms

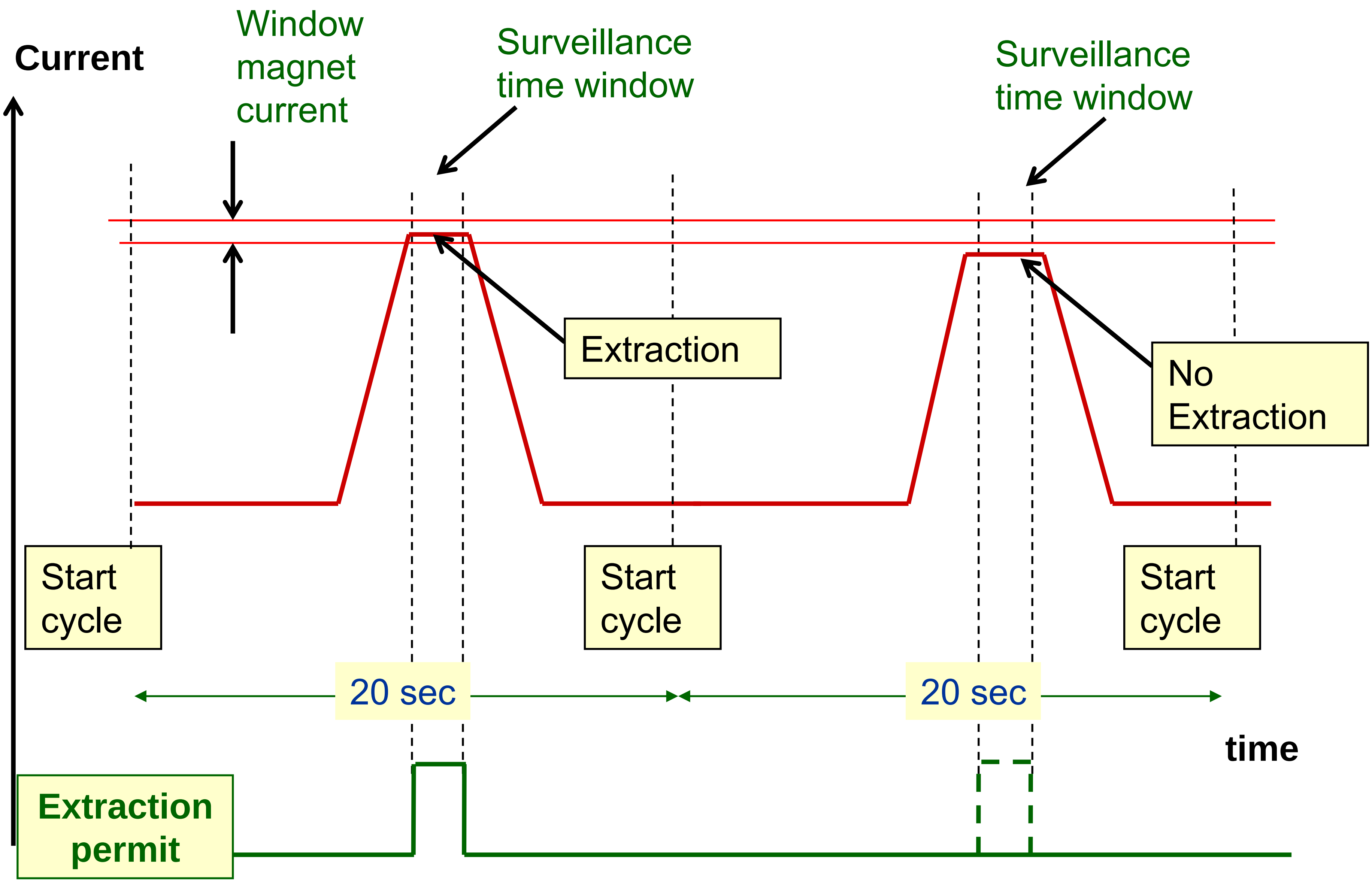
Transfer line and SPS pulsing elements + BPMs
Beam Permit = YES →
Beam Permit = NO →

Transfer line static elements
Beam Permit = YES

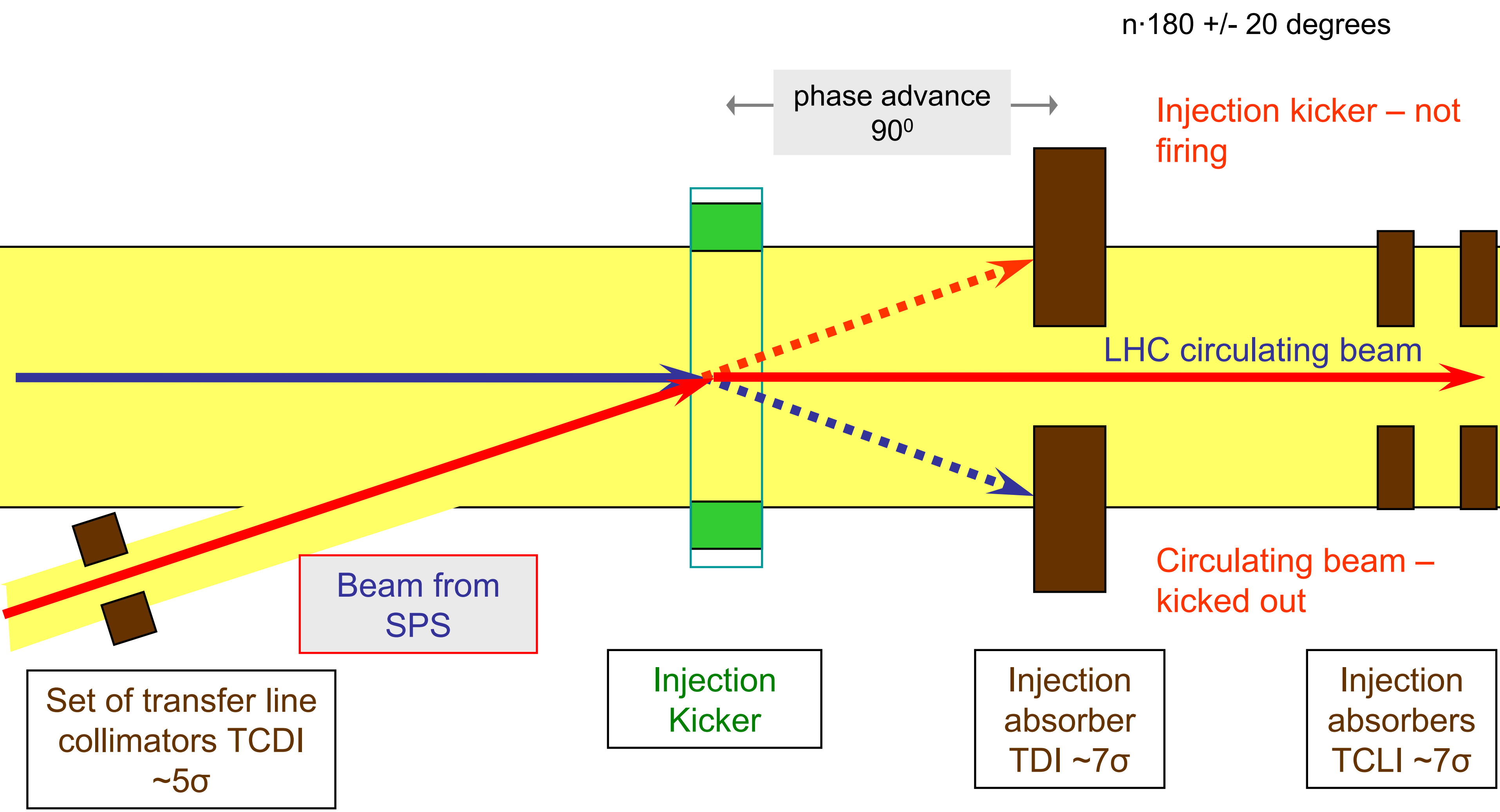
SPS extraction permit
NO → YES → NO

- LHC beam interlock system
- LHC injection interlock system
- SPS extraction interlock system

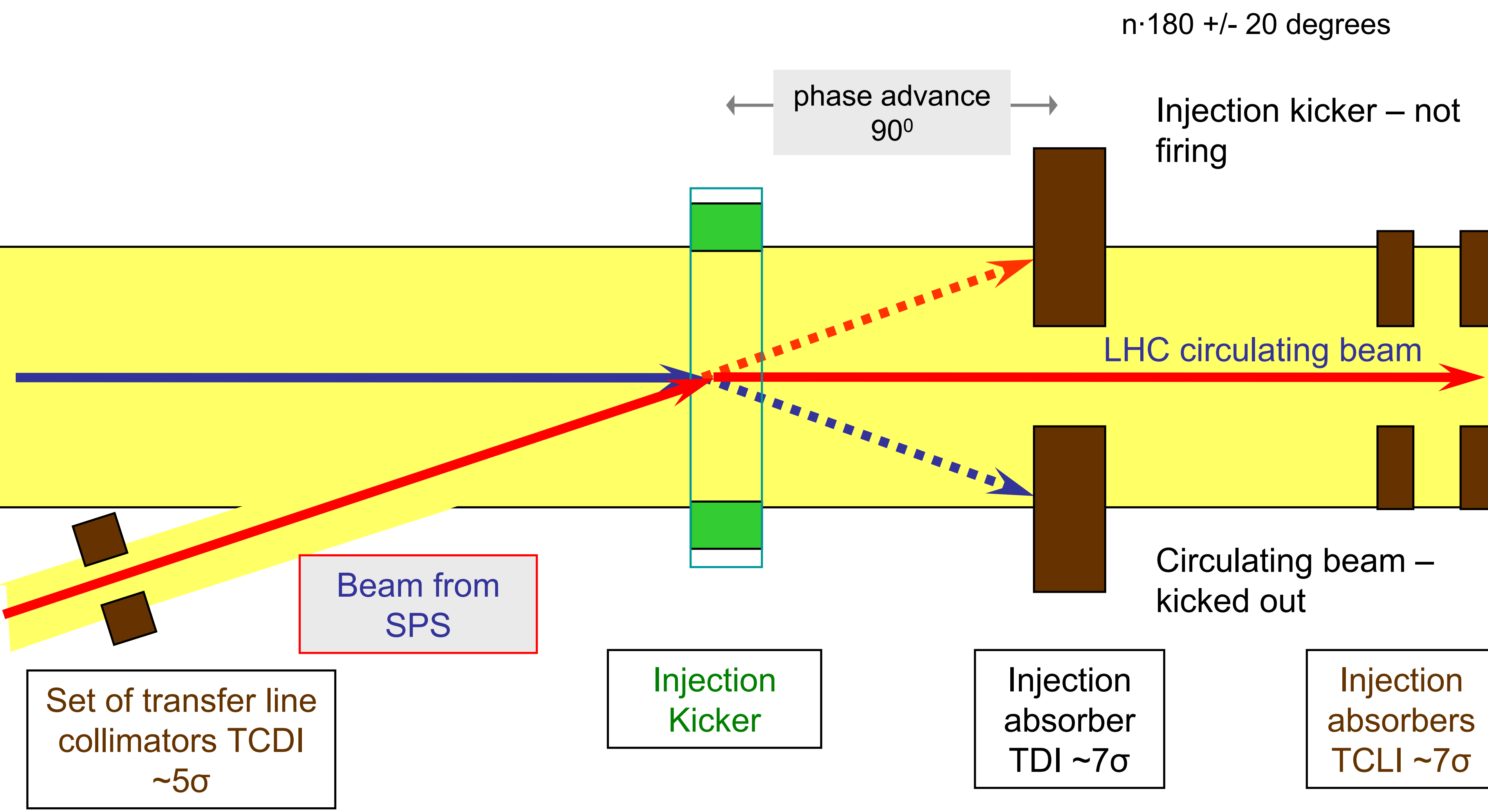
Interlocks for pulsing elements



Example for beam absorber: protection at injection in case of extraction or injection kicker misfiring



Replacing low intensity beam by a full batch



Only when beam is circulating in the LHC, injection of high intensity beam is permitted

Circulating beams and failures

- The number of possible failures that could drive the beam unstable is huge
  - **failures** of the **powering system** (magnet quench, power converter trip, thunderstorm, …)
  - an **object touches the beam** (vacuum valve, collimator, experimental detector, …)
  - **operational failure** (operator, controls, timing, …)
  - beam **instability**
  - others
- The beams must always be extracted into beam dump blocks
- How fast to extract the beams?
  - **Single turn failures** by kicker magnets => **beam absorbers**
  - Few failures lead to very fast beam losses (**some turns to some milliseconds**), e.g. after a trip of some normal conducting magnets
  - Most failures lead to beam losses with a time constant of **5 ms or** much **more** (magnet quenches, powering failures, ….)

Strategy for machine protection

• Definition of LHC aperture by collimators.	**Beam Cleaning System**
• Early detection of failures for equipment acting on beams generates dump request, possibly before the beam is affected.	**Quench detection and Powering Interlocks** **Fast Magnet Current change Monitor**
• Active monitoring of the beams detects abnormal beam conditions and generates beam dump requests down to a single machine turn.	**Beam Loss Monitors** Other Beam Monitors
• Reliable transmission of beam dump requests to beam dumping system. Active signal required for operation, absence of signal is considered as beam dump request and injection inhibit.	**Beam Interlock System**
• Reliable operation of beam dumping system for dump requests or internal faults, safely extract the beams onto the external dump blocks.	**Beam Dumping System**
• Passive protection by beam absorbers and collimators for specific failure cases.	**Beam Absorbers**

LHC aperture

Machine aperture in units of beam sigma (σ), including alignment errors and other tolerances.

Injection

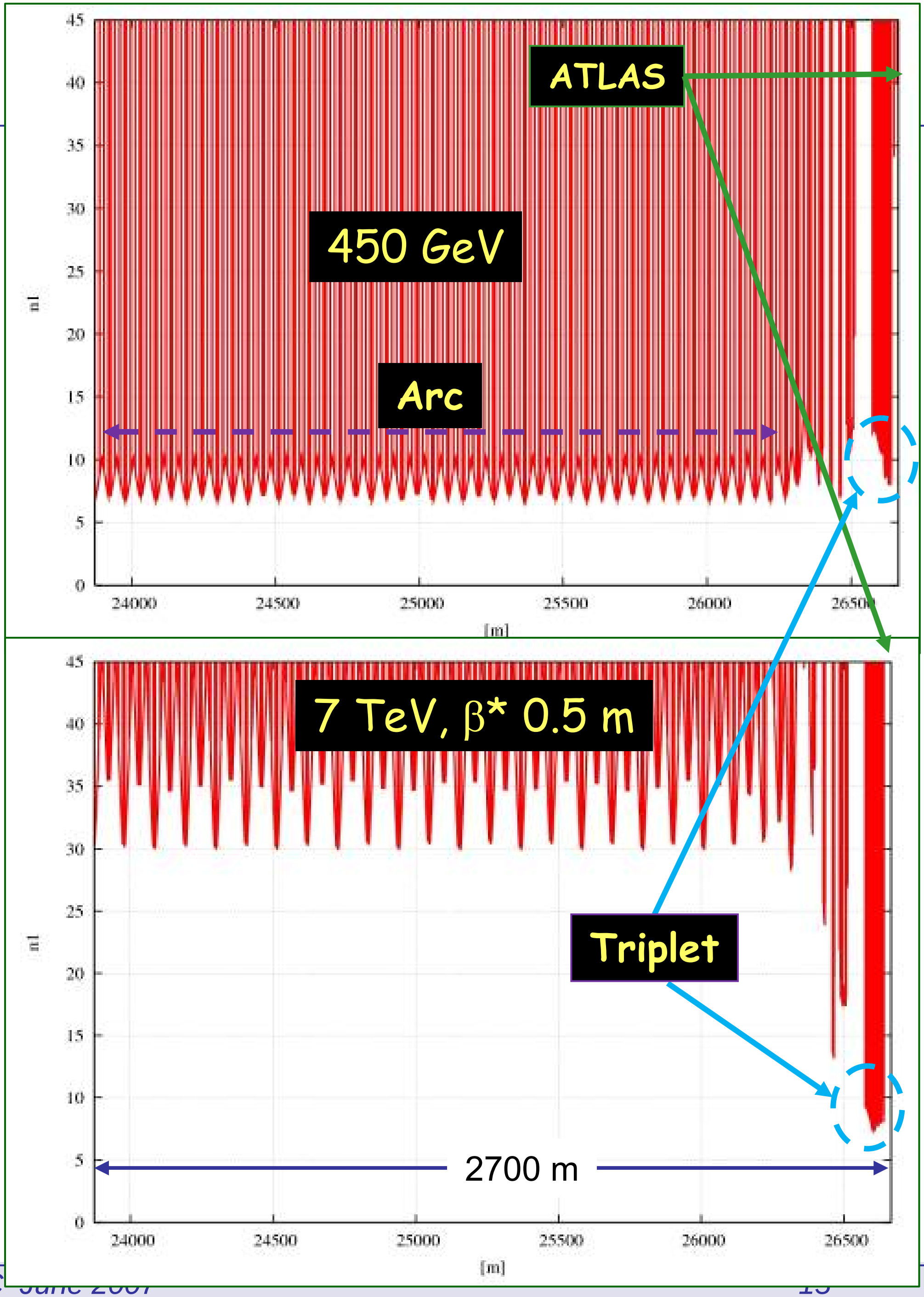
- Aperture limit is the LHC ARCs (~7-8 σ)
- The triplet magnets in front of ATLAS/CMS are slightly behind the ARC (~ 8-9 σ)

→ **Collimators @ ~5-6** σ !

Collisions, squeeze to β^* 0.55 m

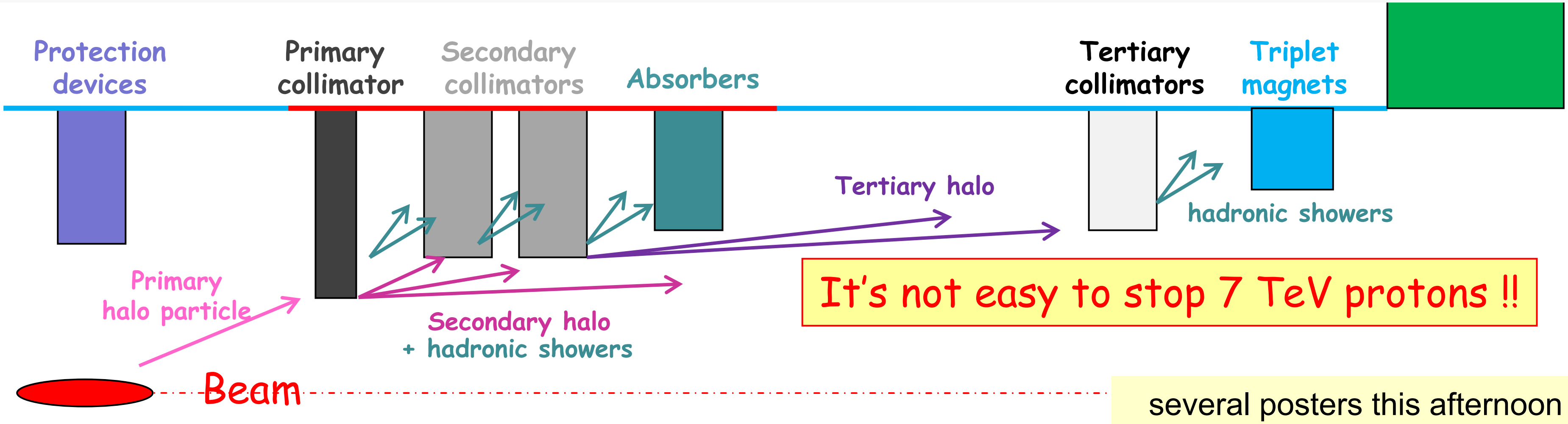
- Aperture limit is given by the triplet magnets in front of ATLAS/CMS ~ 8σ

→ **Collimators @ ~6** σ !



Beam collimation

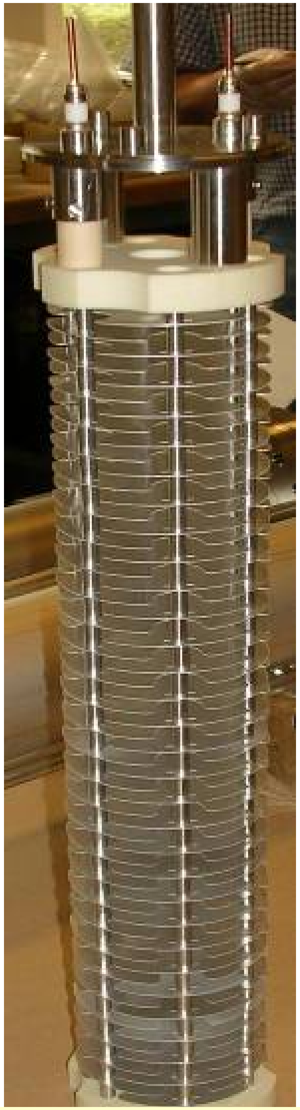
- **Multi-stage beam cleaning** (collimation) system to protect sensitive LHC magnets from beam induced quenches and damage
- Halo particles are first scattered by the primary collimator (closest to beam)
- The scattered particles (forming the secondary halo) are absorbed by the secondary collimators, or scattered to form the tertiary halo.
- Monitors detect abnormal beam losses and provide a beam dump request
- More than 100 collimators jaws are needed for the nominal LHC beam.
- Primary and secondary collimators made of Carbon to survive beam impact !
- The collimators must be very precisely adjusted (< 0.1 mm) to guarantee a high efficiency above 99.9% at nominal intensities.



several posters this afternoon

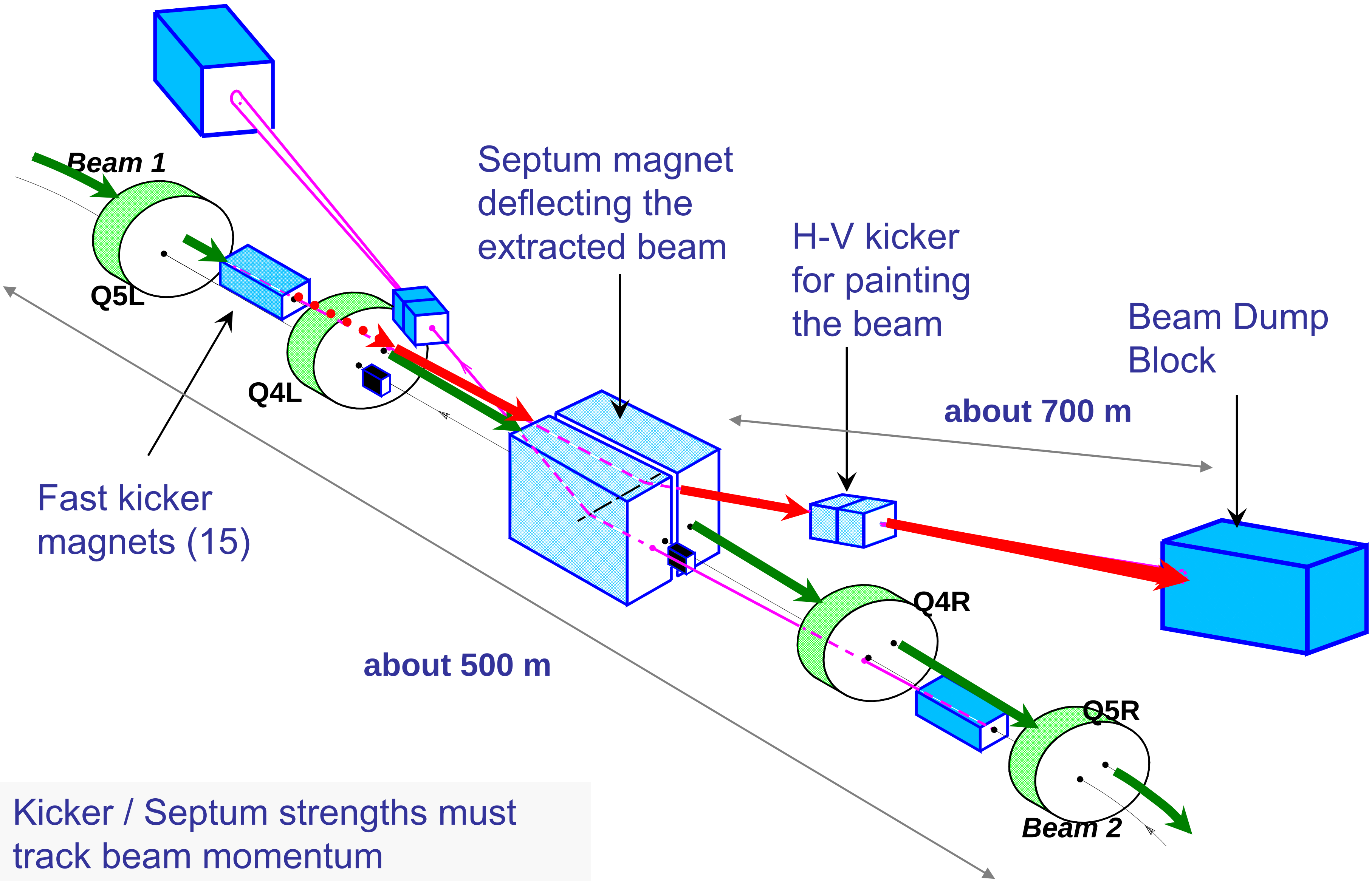
Beam Loss Monitors

- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 ms)
  - Very large dynamic range (> 10^6)
- There are ~3600 chambers distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !



FRPMN071/72 LHC Beam Loss Measurement System

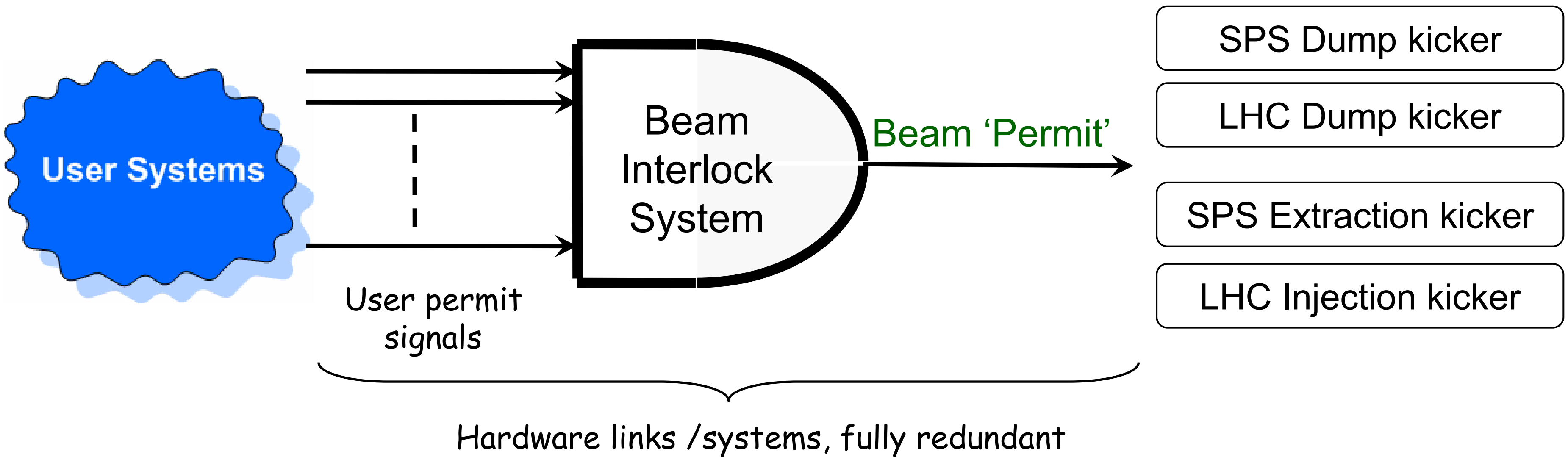
Schematic layout of beam dumping system in IR6



Kicker / Septum strengths must track beam momentum

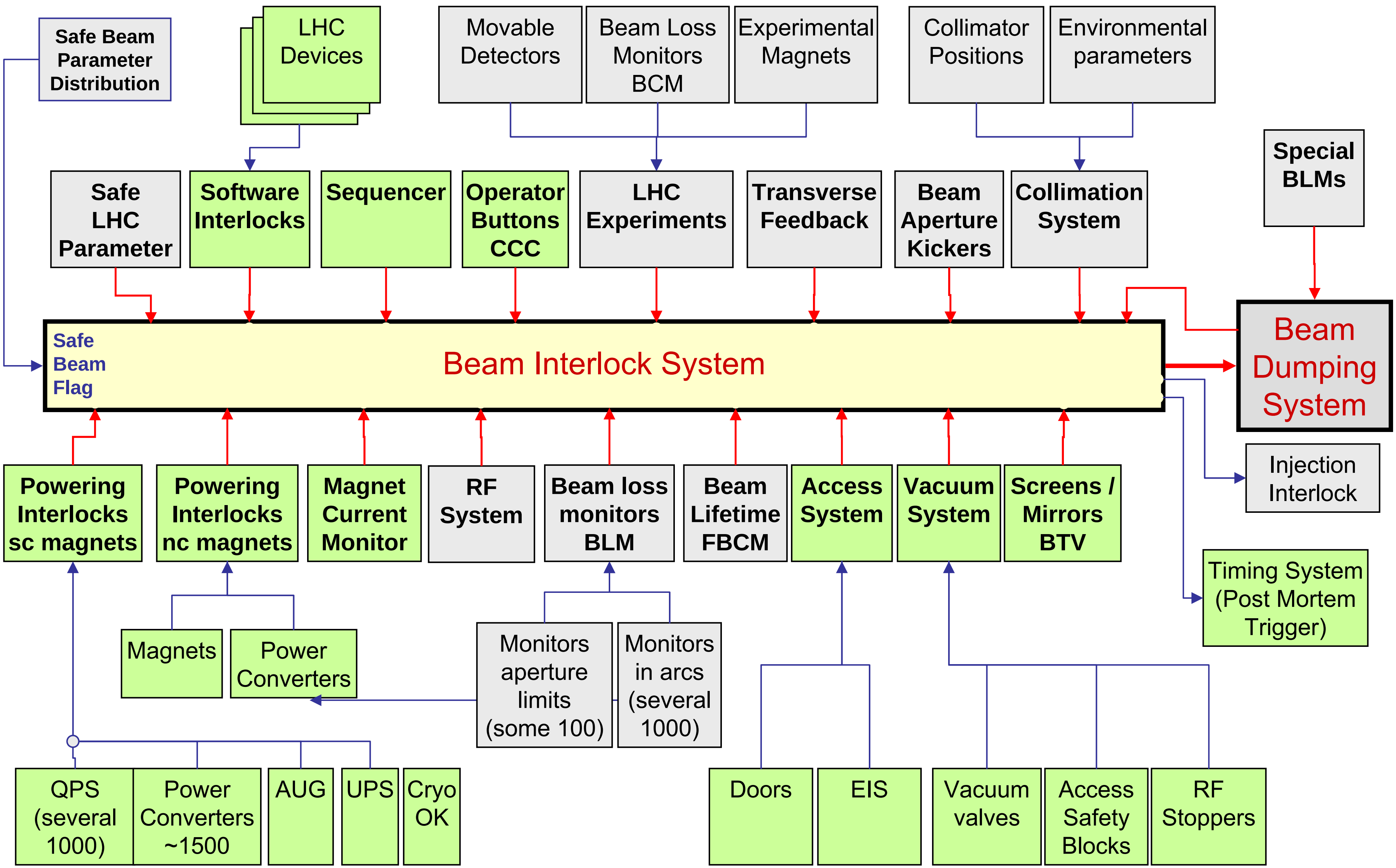
Beam Dumping System: dump block taking shape

Principle of Beam Interlock Systems



- '**User systems**' can detect failures and send hardwired signal to beam interlock system
- Each user system provides a status signal, the **user permit** signal.
- The beam interlock system combines the user permits and produces the **beam permit**
- The **beam permit** is a hardwired signal that is provided to the dump kicker and to the injection or extraction kickers :
- SPS ring: absence of beam permit → dump triggered !
- LHC ring: absence of beam permit → dump triggered !
- LHC injection: absence of beam permit → no injection !
- SPS extraction: absence of beam permit → no extraction !

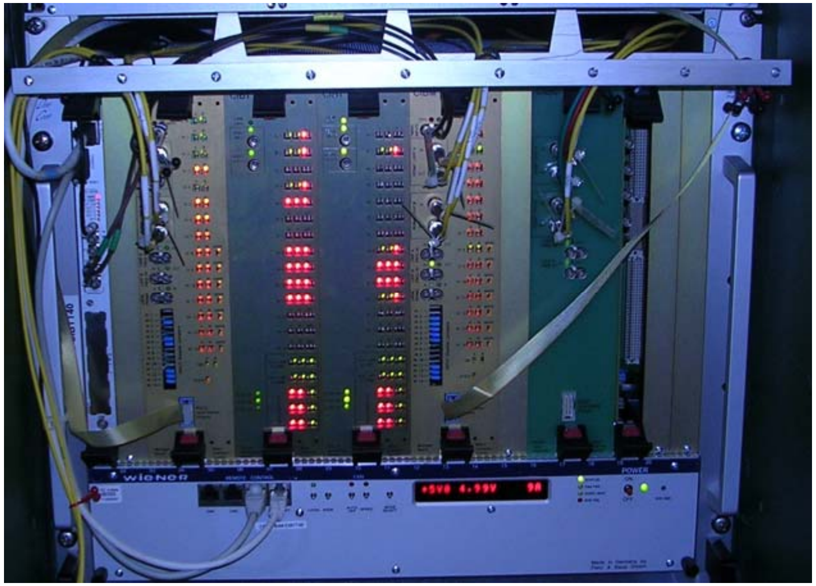
Systems detecting failures and LHC Beam Interlocks



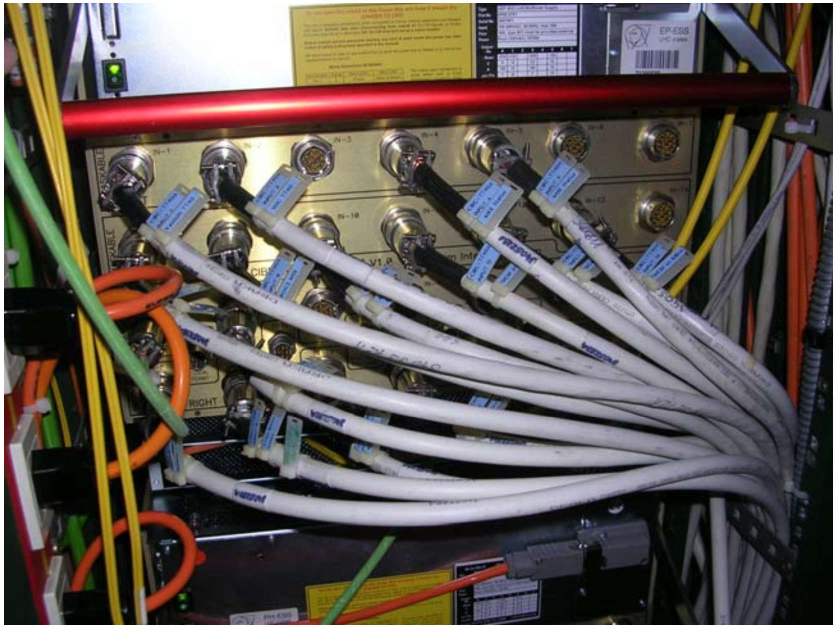
Beam Interlock System hardware

User Interface

BIC (Front) TT40



BIC (Rear) TT40



Commissioning has started

Applications of Machine Protection systems to LHC injectors, in particular for SPS and fast extraction from SPS to CNGS / LHC

- Fast Magnet Current change Monitoring (FMCM)
- Beam Interlock Systems with same design as for LHC
  - CNGS and transfer line (towards LHC!) extraction interlocking
  - SPS ring interlock in 2007
  - Safe Beam Flag for CNGS operation
- Interlock system for normal conducting magnets (LEIR, LHC)
- Software Interlock System
- Energy tracking system for beam dump (SPS)

LHC Hardware Commissioning

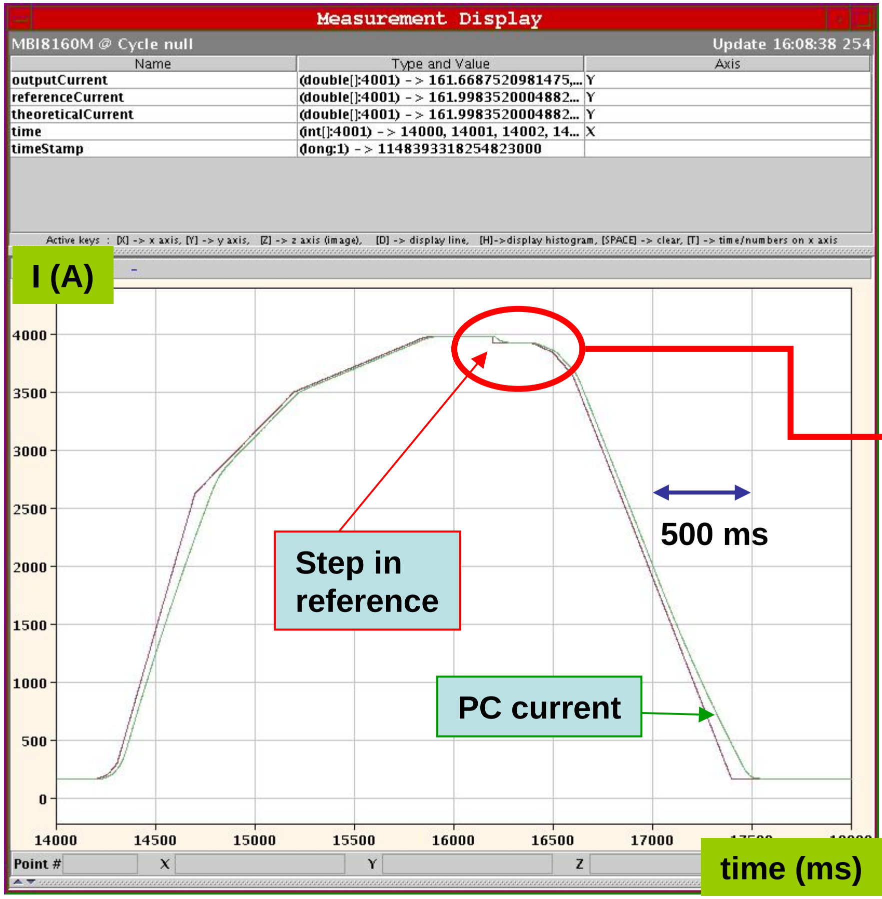
– Experience of equipment for machine protection with the powering of the first LHC sector

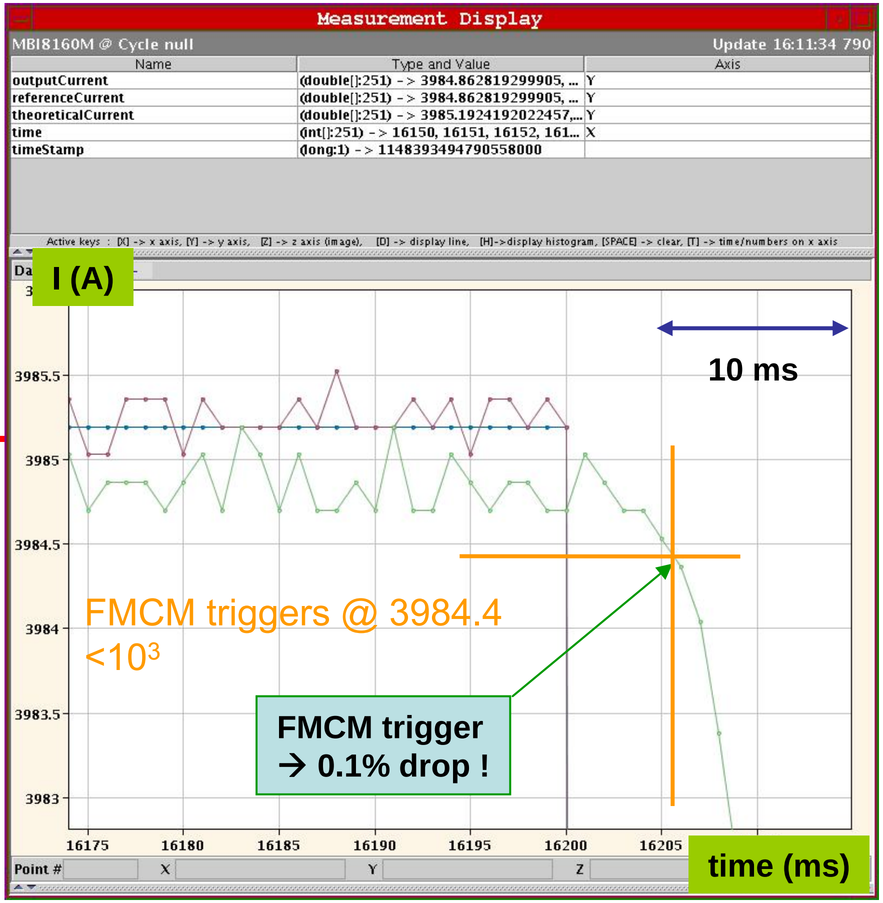
Commissioning of the LHC Technical System, Friday (R.Saban et al.)

Fast Magnet Current change Monitors

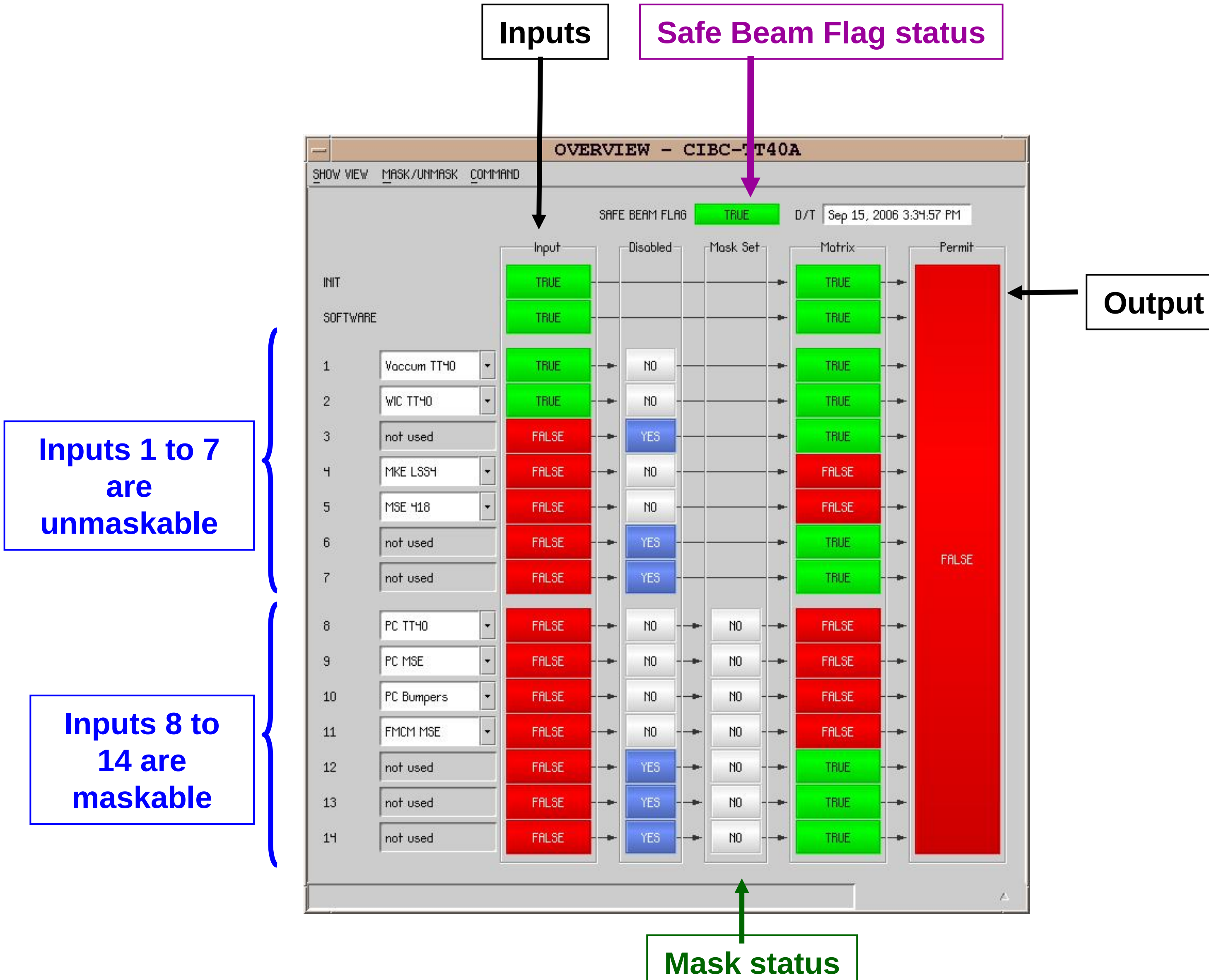
(DESY development + CERN adaptation)

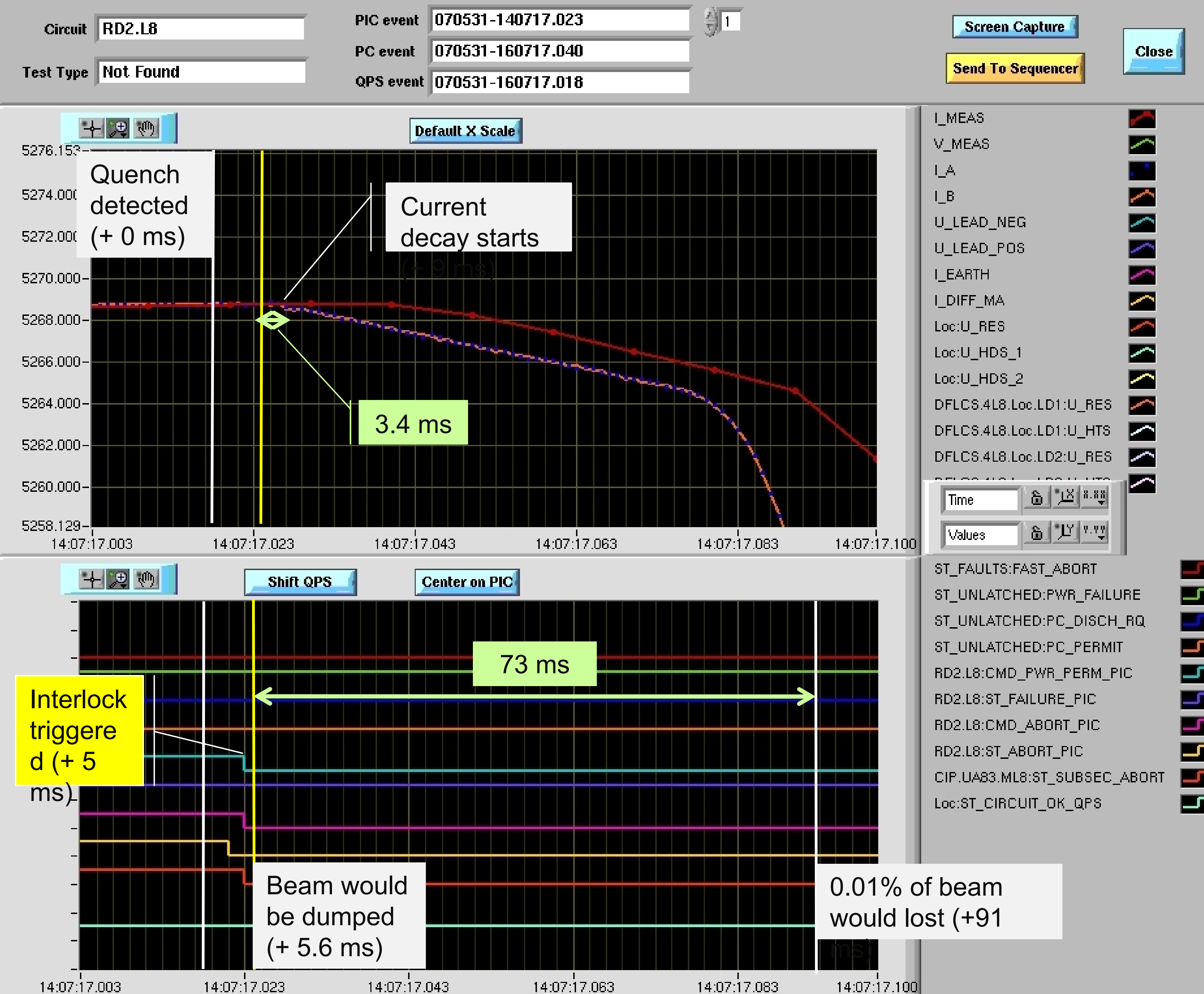
- 3 FMCMs are installed on septum magnet and dipole magnets
- Tested using steep reference changes to trigger FMCM. The trigger threshold and the magnet current (resolution one ms)
- Beam tests confirmed these results





SPS Extraction towards to LHC
Using SPS Extraction BIS





Circuit RD2.L8
Test Type Not Found
PIC event 070531-140717.023
PC event 070531-160717.040
QPS event 070531-160717.018
Screen Capture
Send To Sequencer
Close
Default X Scale
Quench detected (+ 0 ms)
Current decay starts
3.4 ms
5276.153
5274.000
5272.000
5270.000
5268.000
5266.000
5264.000
5262.000
5260.000
5258.129
14:07:17.003
14:07:17.023
14:07:17.043
14:07:17.063
14:07:17.083
14:07:17.100
I_MEAS
V_MEAS
I_A
I_B
U_LEAD_NEG
U_LEAD_POS
I_EARTH
I_DIFF_MA
Loc:U_RES
Loc:U_HDS_1
Loc:U_HDS_2
DFLCS.4L8.Loc.LD1:U_RES
DFLCS.4L8.Loc.LD1:U_HTS
DFLCS.4L8.Loc.LD2:U_RES
Time
Values
Shift QPS
Center on PIC
73 ms
Interlock triggered (+ 5 ms)
Beam would be dumped (+ 5.6 ms)
0.01% of beam would lost (+91 ms)
ST_FAULTS:FAST_ABORT
ST_UNLATCHED:PWR_FAILURE
ST_UNLATCHED:PC_DISCH_RQ
ST_UNLATCHED:PC_PERMIT
RD2.L8:CMD_PWR_PERM_PIC
RD2.L8:ST_FAILURE_PIC
RD2.L8:CMD_ABORT_PIC
RD2.L8:ST_ABORT_PIC
CIP.UA83.ML8:ST_SUBSEC_ABORT
Loc:ST_CIRCUIT_OK_QPS

Machine Protection and Controls

- **Software Interlock Systems (SIS)** provides additional protection for complex but also less critical conditions:
  - **Became operational for the 2007 SPS run**
  - For example surveillance of magnet currents at injection and during collisions to avoid certain failures (local bumps) that would reduce the aperture
  - The reaction time of those systems will be at the level of a few seconds.
  - The systems rely entirely on the machine technical network, databases, etc – clearly not as safe as HW systems !
- **Sequencer:** program to execute defined procedures
  - Sequencer for hardware commissioning operational
  - Sequencer for beam commissioning in progress
- **Logging and PM systems**: recording of data – continuous logging and for transients (beam dump, quench, …)
  - Has been successfully used during powering tests

Conclusions

- **Machine protection** for LHC **starts at the SPS**, since beam extracted from SPS towards LHC has already substantial damage potential.
- There is **no single system for LHC machine protection**, safe operation relies on **several core systems**, beam interlocks, beam dumping system, beam loss monitors, collimators and beam absorbers.
- For many sub-systems **commissioning or testing started**, during **LHC hardware commissioning**, during **CNGS operation** and **SPS operation.**
- This allows **validating hardware design choices** and **gaining experience** with commissioning and operation of systems identical/similar to those to be used in LHC.
- Most **commissioning procedures** can be done **BEFORE beam operation**, during Hardware Commissioning and "Cold check out"
- **Commissioning** of LHC with **low intensity beams**, slowly increasing the intensity to nominal, bringing up all machine protection systems

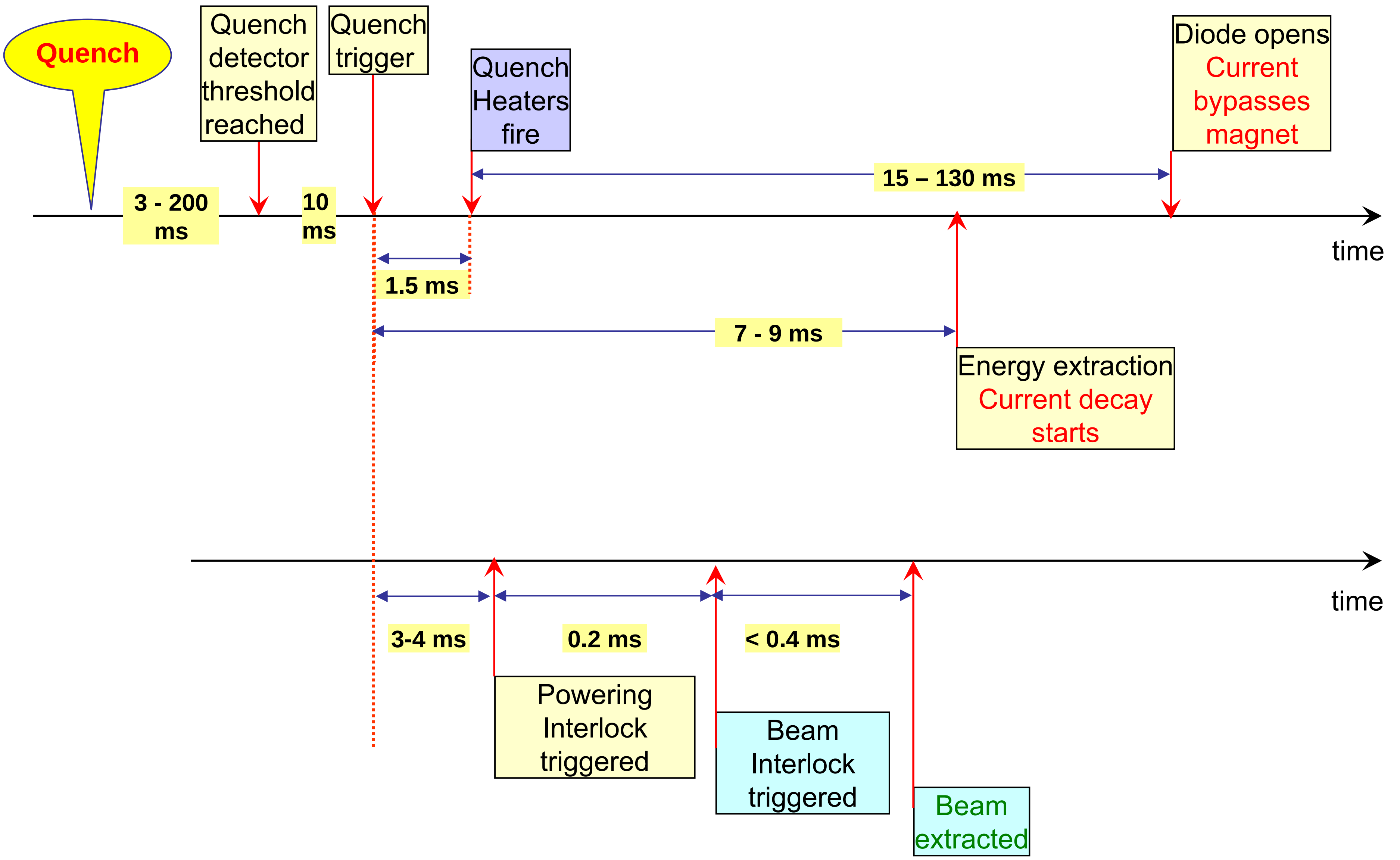
Acknowledgements

LHC Machine Protection reflects the complexity of the LHC accelerator.

Many colleagues contributed to LHC Machine Protection. We like to thank them and are very grateful for their contributions.

Reserve slides

Quench detection and beam dump trigger



press release

CERN announces new start-up schedule for world's most powerful particle accelerator

Geneva, 22 June 2007. Speaking at the 142nd session of the CERN[1] Council today, the Organization's Director General Robert Aymar announced that the Large Hadron Collider (LHC) will start up in May 2008, taking the first steps towards studying physics at a new high-energy frontier. A low-energy run originally scheduled for this year has been dropped as the result of a number of minor delays accumulated over the final months of LHC installation and commissioning, coupled with the failure in March of a pressure test in one of the machine's components.

The LHC is a scientific instrument of unprecedented complexity, and at 27 kilometres in circumference, the world's largest superconducting installation. Cooling the first sector of the machine to a temperature of 1.9 K (-271.3°C), colder than outer space, began earlier this year and has provided an important learning process. The first sector cool down has taken longer than scheduled, but has allowed the LHC's operations team to iron out teething troubles and gain experience that will be applied to the machine's seven remaining sectors. Now cold, tests on powering up the sector have begun and the cool down of a second sector will soon be underway.

In March, a magnet assembly known as the inner triplet, provided to CERN as part of the contribution of the US to the LHC project, failed a pressure test. A repair has been identified and is currently being implemented.

"The low-energy run at the end of this year was extremely tight due to a number of small delays, but the inner triplet problem now makes it impossible," said LHC Project Leader Lyn Evans. "We'll be starting up for physics in May 2008, as always foreseen, and will commission the machine to full energy in one go."

The new schedule foresees successively cooling and powering each of the LHC's sectors in turn this year. Throughout the winter, hardware commissioning will continue, allowing the LHC to be ready for high-energy running by the time CERN's accelerators are switched on in the spring. Commissioning a new particle accelerator is a complex task. Beams will be injected at low energy and low intensity to give the operations team experience in driving the new machine. Intensity and energy will then slowly be increased.

"There's no big red button when you're starting up a new accelerator," said Evans, "but we aim to be seeing high energy collisions by the summer."

Installation of the large and equally innovative apparatus for experiments at this new and unique facility will continue at the same time. This huge effort will be completed on a schedule consistent with that of the accelerator.

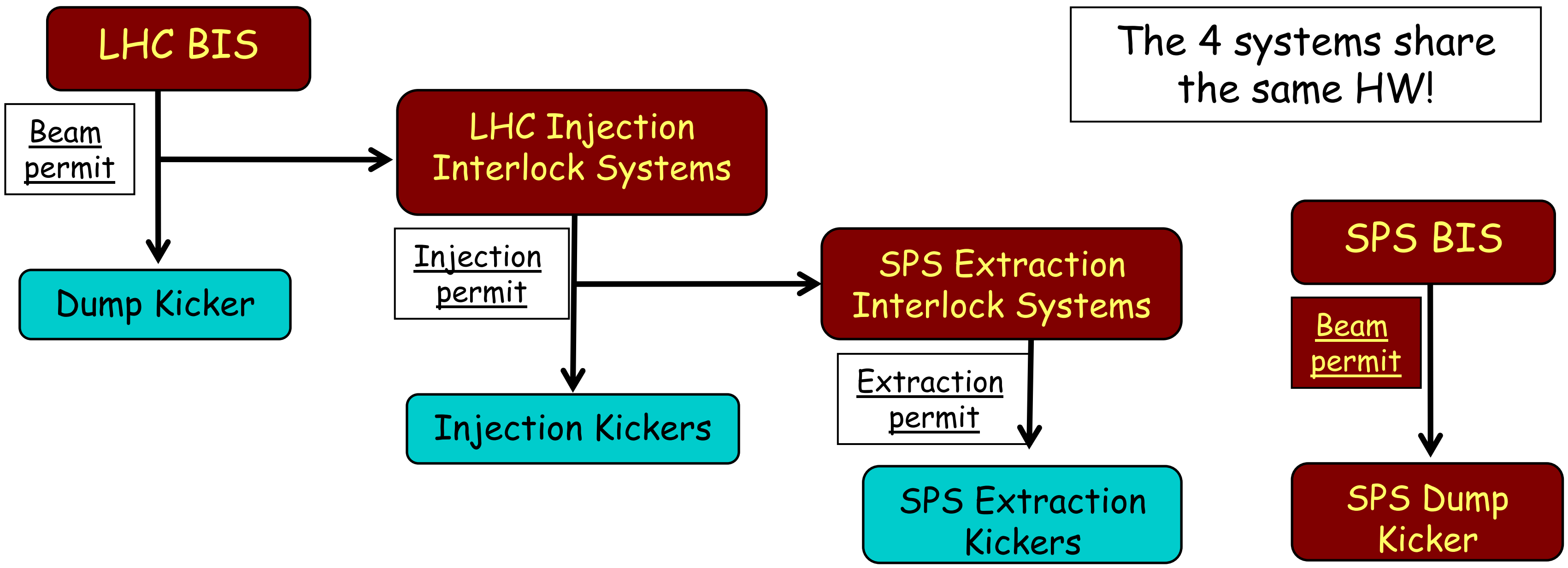
In another important development, the CERN Council agreed to increase CERN's funding over the years 2008-2011 as an important first step towards implementing the decisions Council made in July 2006 for a European strategy for particle physics.

"This is an important vote for the future of particle physics in Europe," said CERN Director General Robert Aymar, "it allows us to consolidate the laboratory's infrastructure, prepare for future upgrades of the LHC and to re-launch a programme of R&D for the long-term future."

The LHC relies on a chain of particle accelerators, the oldest of which was constructed in the 1950s. Their successful operation is essential to the smooth running of the LHC. These additional resources will be used to consolidate CERN's infrastructure, and build on it for the future.

Beam interlocks systems for SPS and CNGS

Several distinct interlock systems play a role for protection during LHC and CNGS operation:



- The LHC BIS acts primarily on the LHC circulating beam (dump kicker)
- The LHC Injection Interlock Systems (IR2 & IR8) acts on the injection kicker (Surveillance of injection elements in the LHC ring)
- The SPS Extraction Interlock Systems acts on the extraction kicker (Surveillance of the transfer lines and the extraction elements of the SPS

Conditions for stored beam in LHC

- Nothing blocks the aperture (vacuum valves, beam screens, experimental detectors, etc.)
- Magnets powering must be adequate and without fault
  - correct magnet currents
- Collimators and beam absorbers should be correctly positioned
  - at all times collimators limit the aperture – particles lost first on collimators
- Monitors detecting failures redundantly and providing Beam Permit
  - monitors detecting hardware failures
  - monitors detecting beam parameters outside specification (beam loss, …)
  - must be ready during the fill at any time
- Beam interlock system receiving all signals and triggers the beam dump in case of failure
- The beam dumping system should be ready to extract the beam at any moment
  - safe extraction of beam to the beam dump blocks
  - beam absorbers in extraction region should be correctly positioned

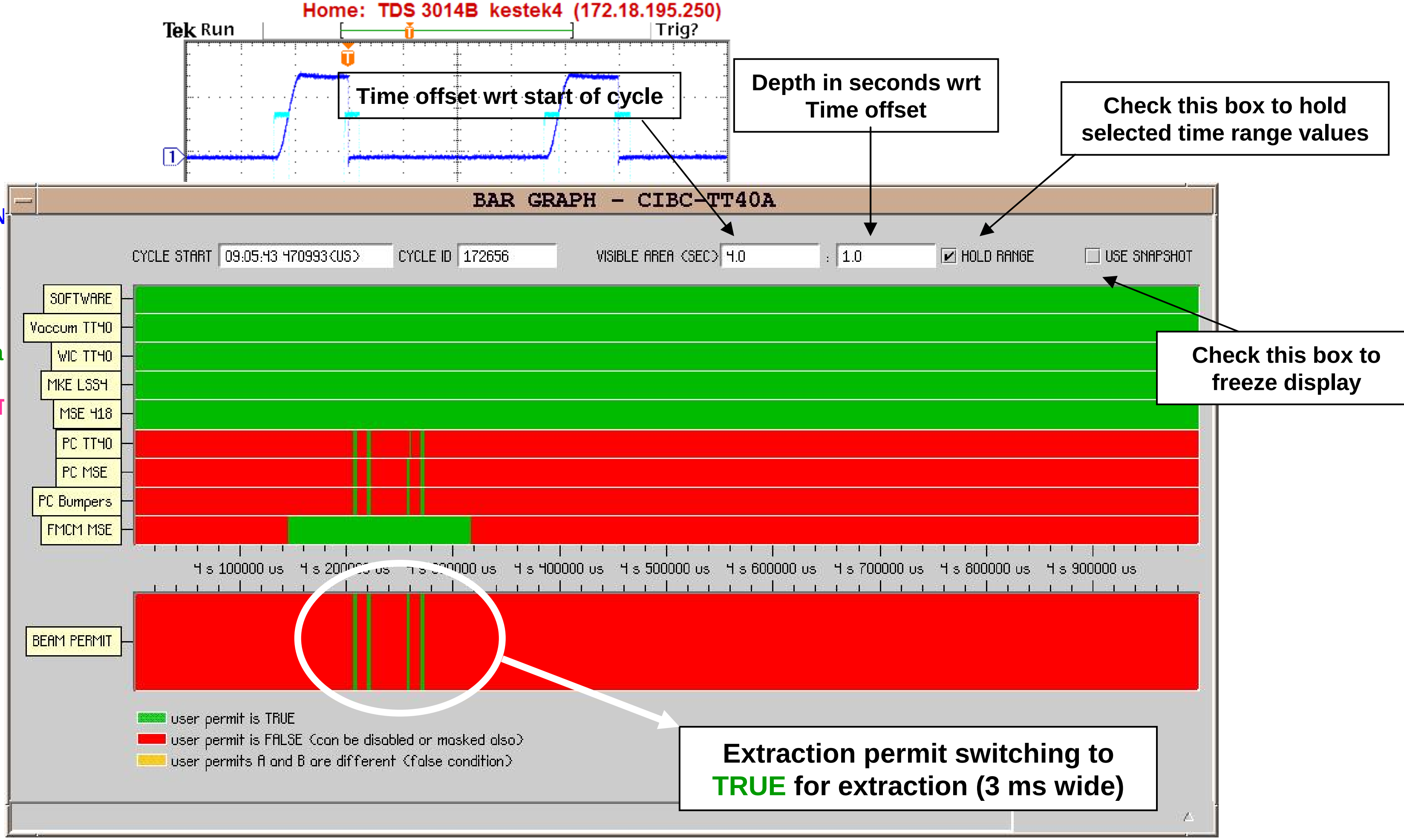
Strategy for machine protection

- Redundancy in the protection system such that failures may be detected by more than just a single system.
- Very high safety and reliability standards that are applied in the design of the core protection systems.

BIS information

Timing of kicker, BIC permit and BETS:

- PFN
- BIC
- Bea
- BET



SPS experiment: Beam damage at 450 GeV

to benchmark simulations

Controlled SPS experiment

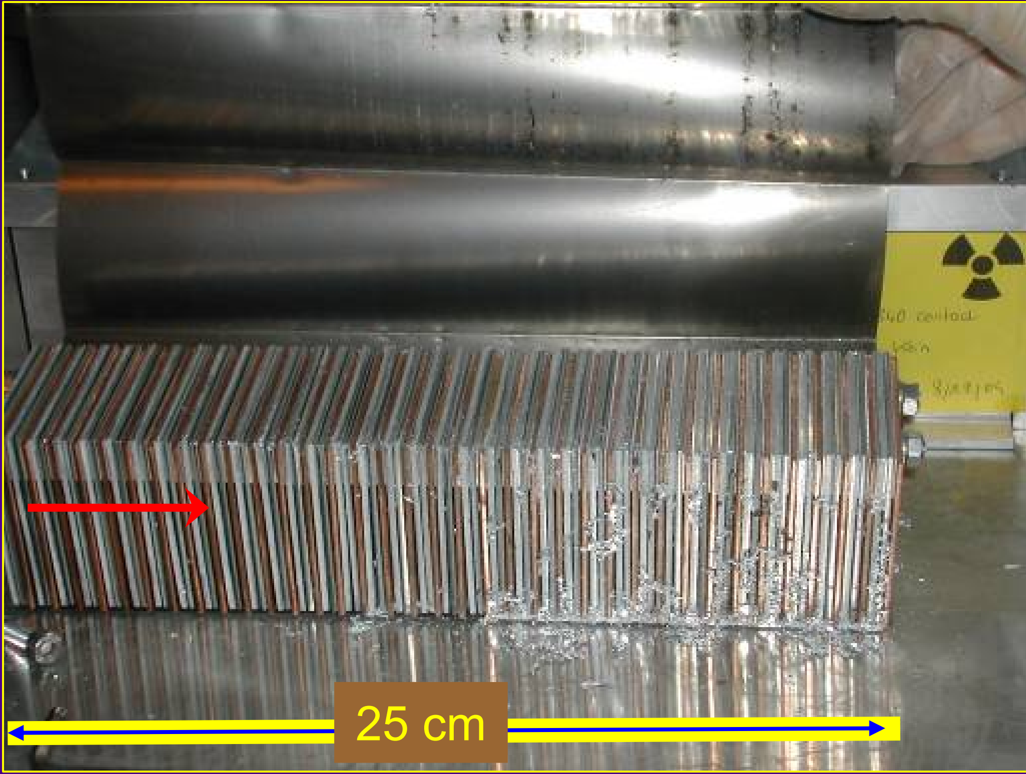
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

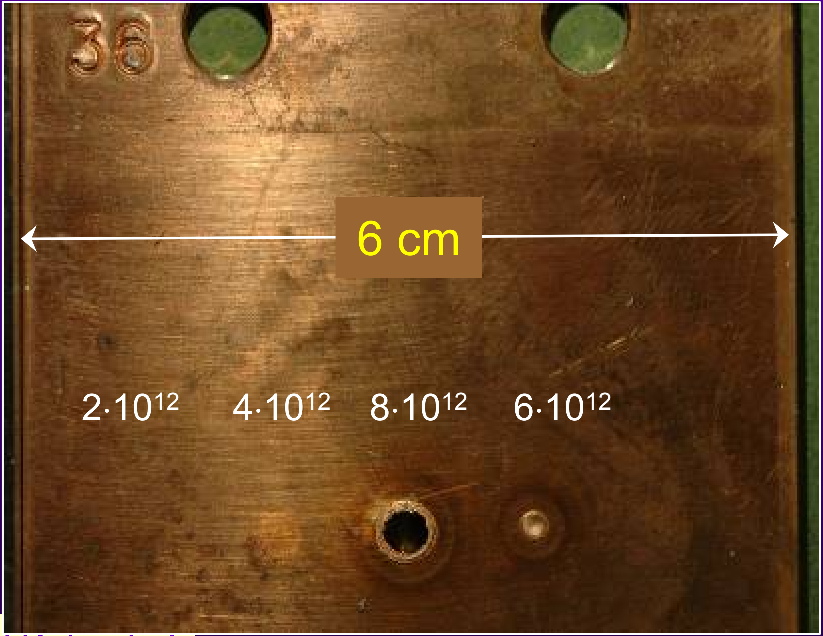
above damage limit for copper

- $2 \cdot 10^{12}$ protons

below damage limit for copper

stainless steel no damage





0.1 % of the full LHC beams

V.Kain et al

Machine Protection during all phases of operation

- The LHC is the first accelerator with the intensity of the injected beam already far above threshold for damage, protection during the injection process is mandatory
- At 7 TeV, fast beam loss with an intensity of about 5% of one single “nominal bunch” could damage equipment (e.g. superconducting coils)
- The only component that can stand a loss of the full beam is the beam dump block - all other components would be damaged
- The LHC beams must ALWAYS be extracted into the beam dump blocks
  - at the end of a fill
  - in case of failure
- During powering, about 10 GJ is stored in the superconducting magnets, quench protection and powering interlocks must be operational long before starting beam operation – started already