CERN

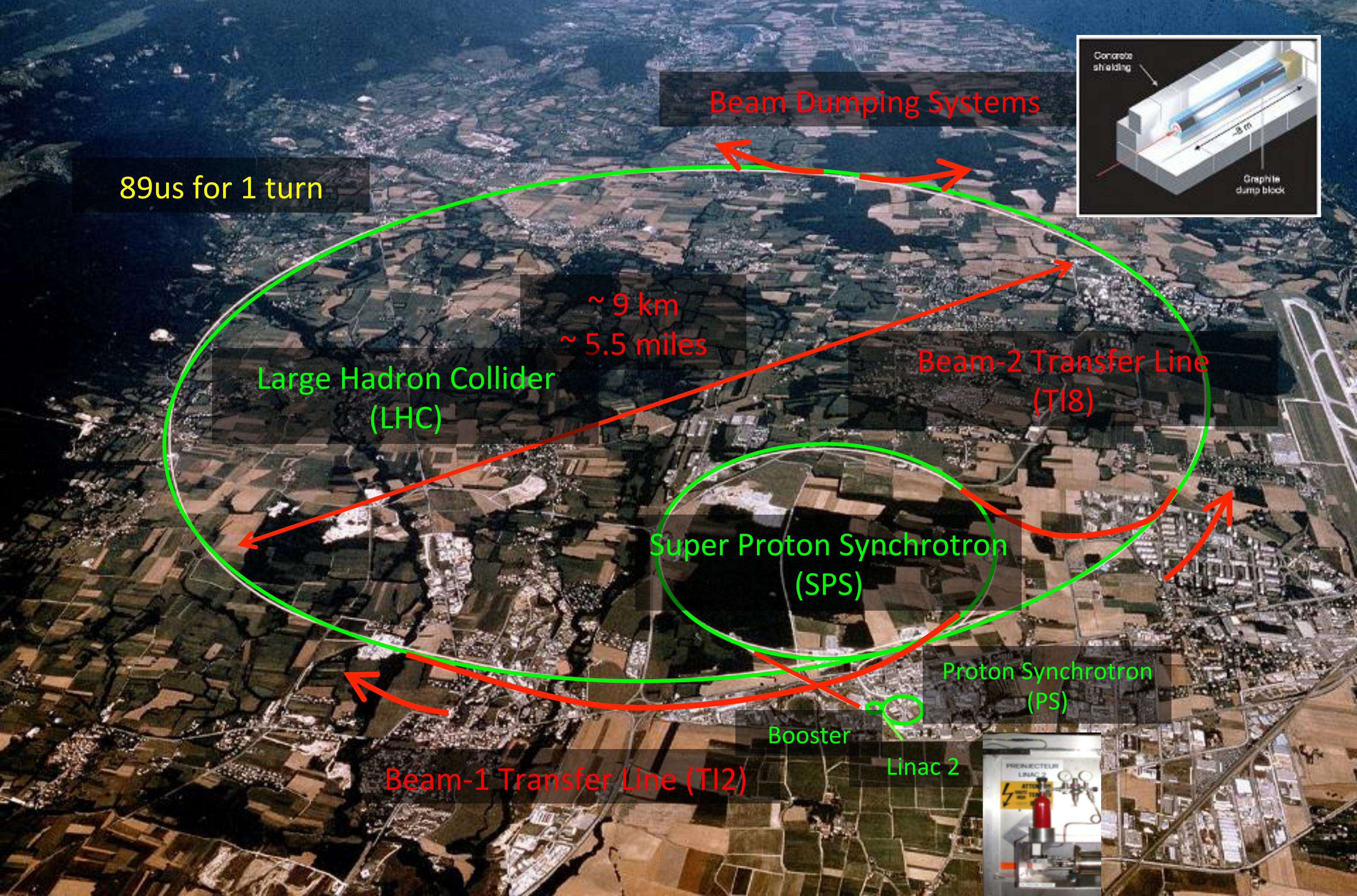
LHC Machine Protection and Fast Interlock Systems

M.Zerlauth on behalf of all CERN colleagues concerned with MP

Outline

- LHC layout
- Energies at stake and protection functions
- LHC Machine Protection and reaction times
- LHC Beam Interlock System
- Fast failure detection
- Dependability of Interlock Systems
- LINAC 4 protection
- Conclusions

Acceleration of particles in the CERN complex

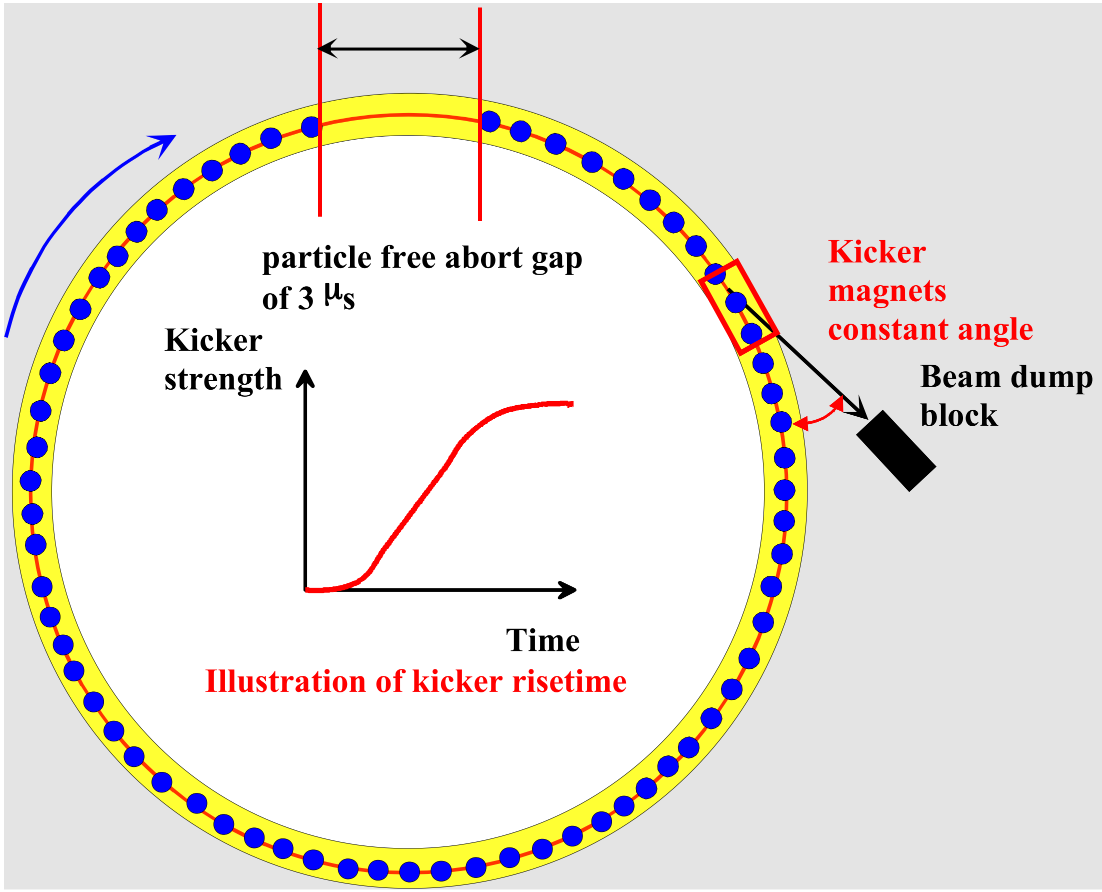


Removing the beams from LHC

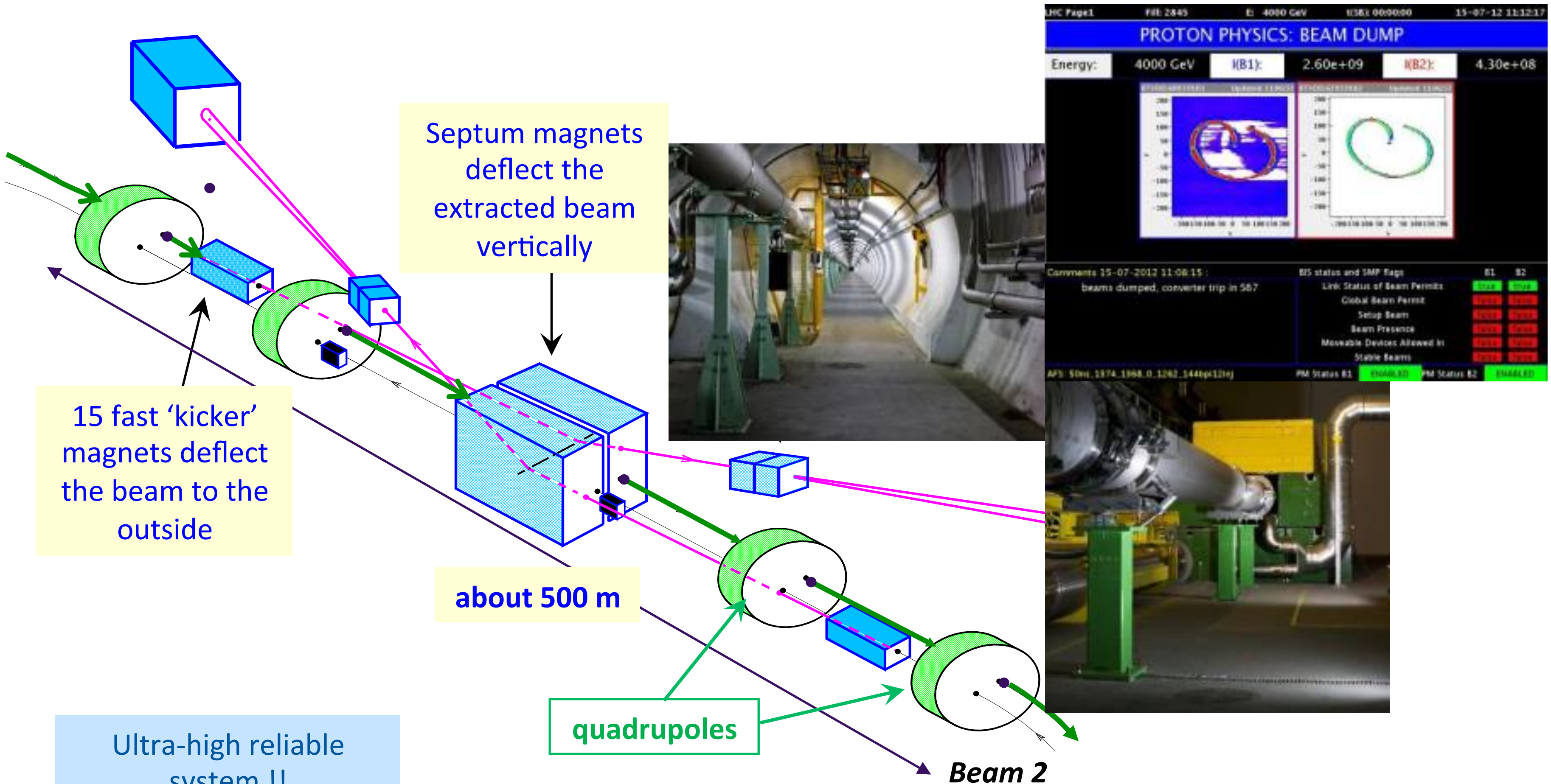
Single beam dump system in point 6

Kicker activation synchronized with particle free gap

Gap needs to be free of particles (losses during dump)

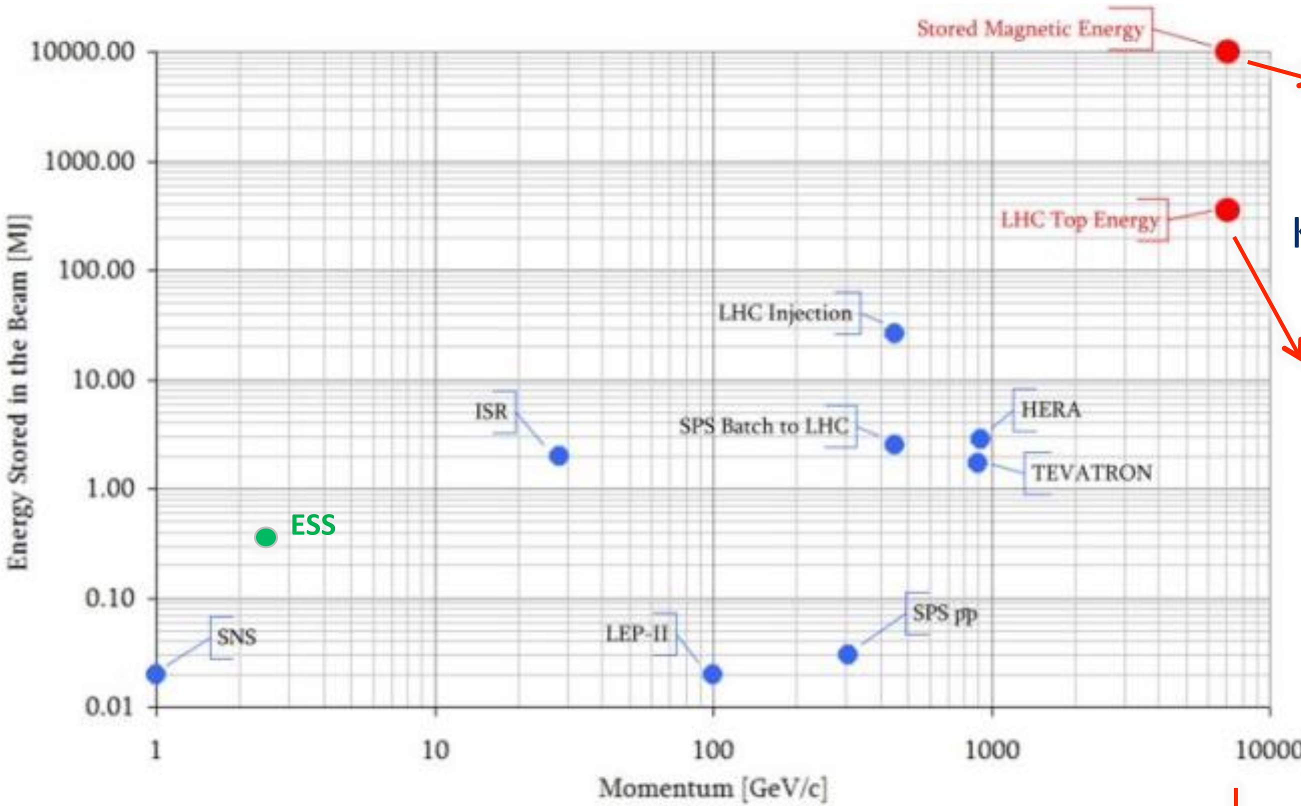


LHC beam dumping system



Ultra-high reliable system !!

Energies at stake



Kinetic Energy of Charles the Gaulle at 50 km/h ≈ 9 GJ

Kinetic Energy of 200m long TGV at 155 km/h ≈ 360 MJ

Energy of single proton ~ flying mosquito (1μJ)

10^{10}

Protection functions

Beam Protection:	Beam Energy →	Beam Dump

100x energy of TEVATRON

0.000005% of beam lost into a magnet = quench

0.005% beam lost into magnet = damage

Failure in protection – complete loss of LHC is possible

Powering Protection:	Magnet Energy →	Emergency Discharge

10-20x energy per magnet of TEVATRON

magnet quenched = hours downtime

many magnets quenched = days downtime

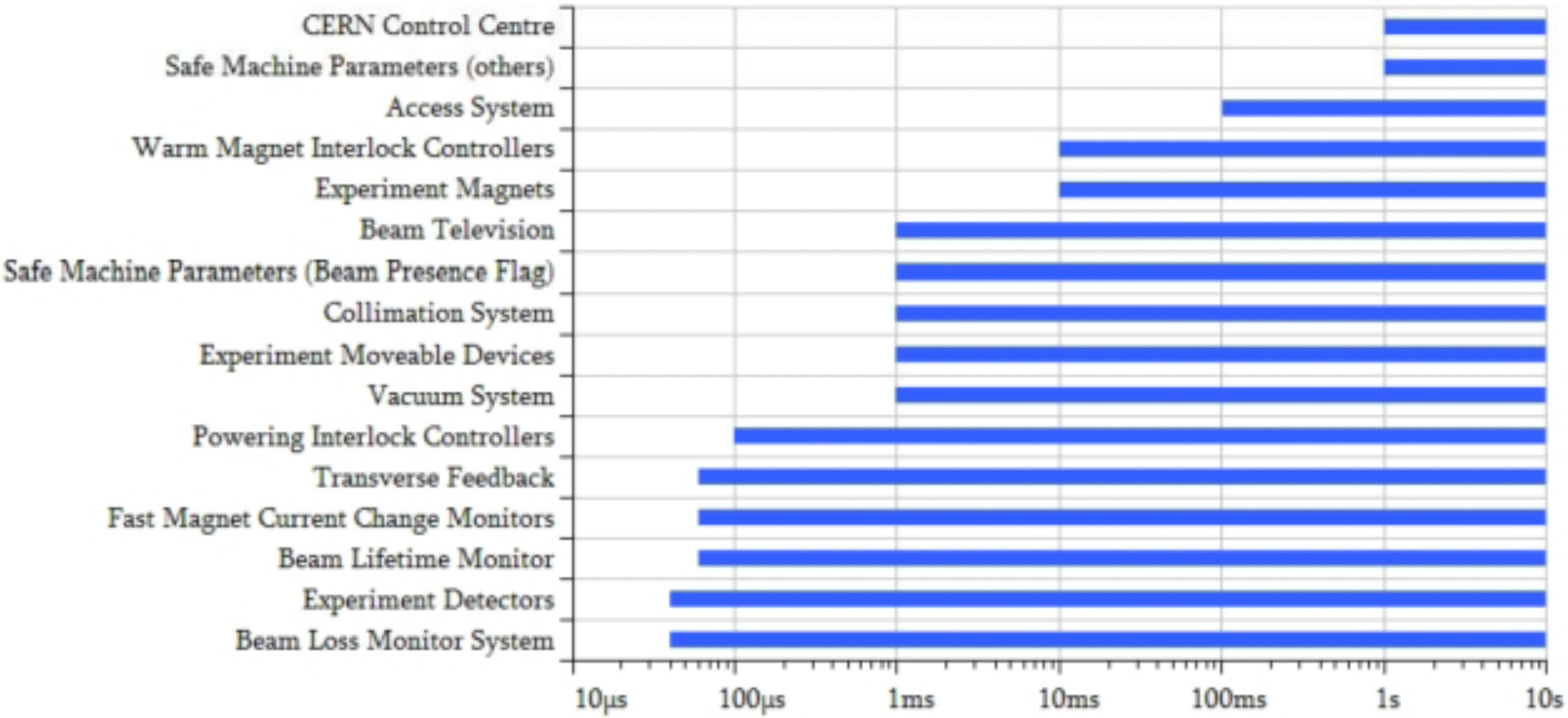
magnet damaged = $1 million, months downtime

many magnets damaged = many millions, many months downtime (few spares)

Failures and their mitigation

- Three classes of failures need to be considered
  - Ultra Fast failures (single beam passage during e.g. beam transfer, injection,...): protection with passive elements and absorbers
  - Fast failures (few LHC turns following UFOs, certain fast powering failures,...): Protection with BLMs and dedicated protection systems
  - 'Slow' failures (powering failures, feedback, RF,..): Protection through equipment monitoring, ...

Failure detection time @ LHC

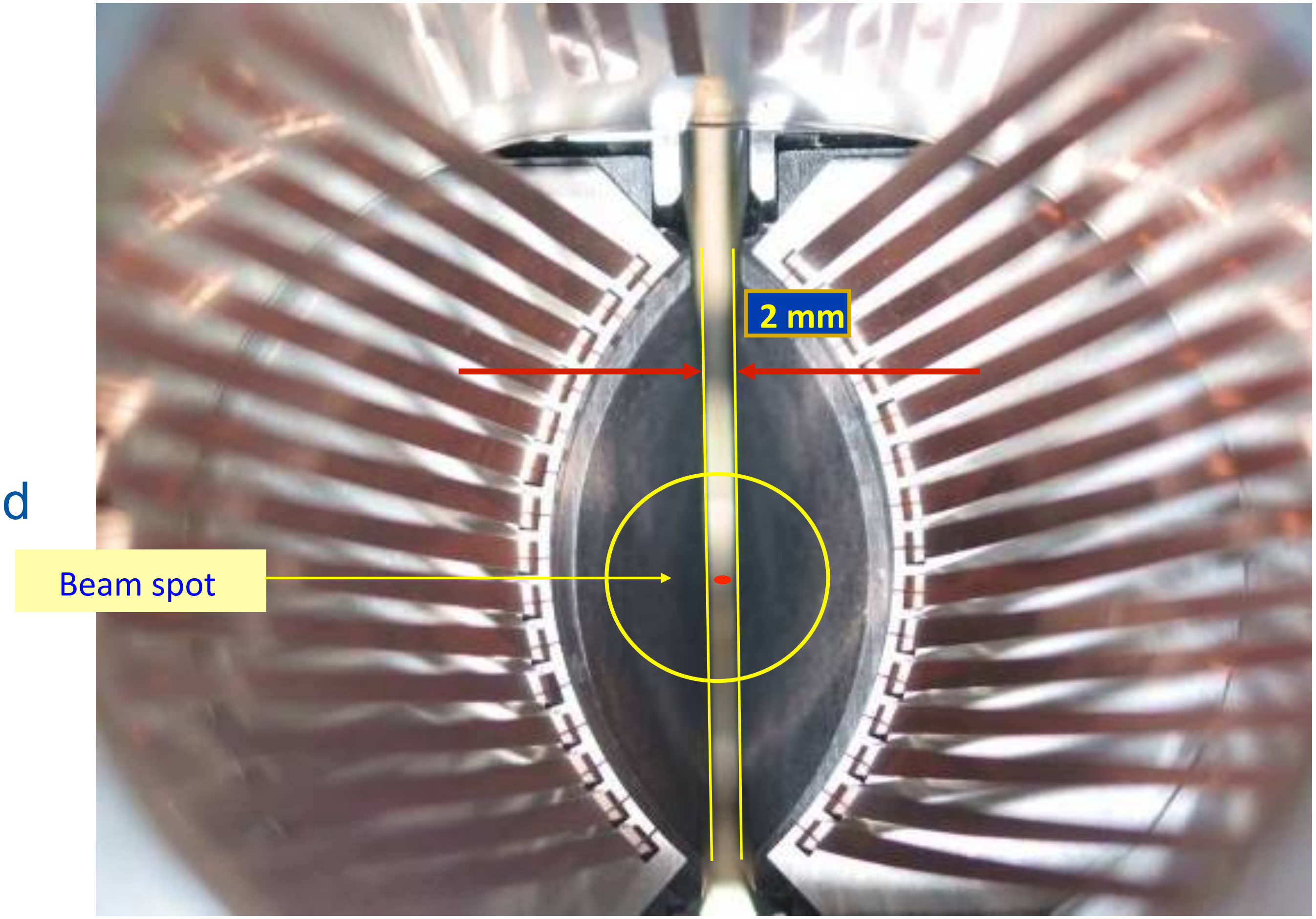


best failure detection time = 40 us = half turn

LHC collimators

View of a two sided collimator

About 100 collimators installed all around the LHC



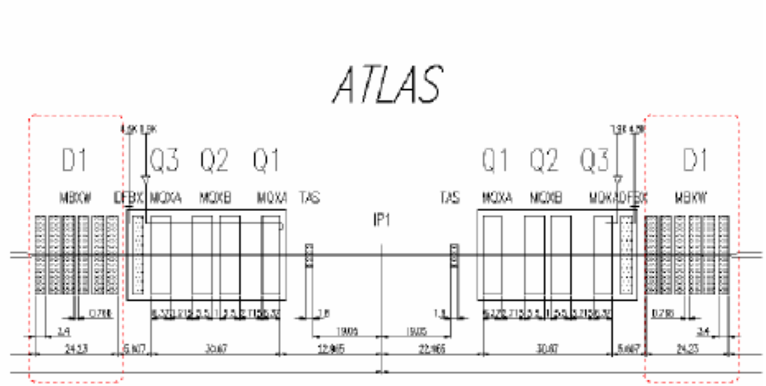
Fast(est) equipment failure in LHC

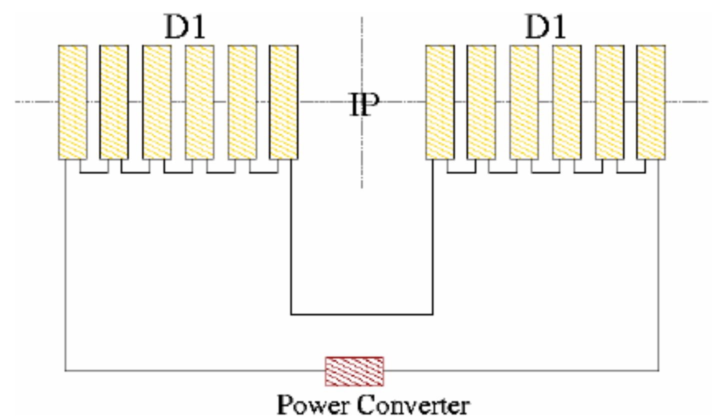
- Separation dipoles **D1** in **IR1** and **IR5**: normal conducting: 12 modules **powered in series**
- **βx > 2000m**
- power converter failure:

$$B(t) = B_0 \cdot e^{-\frac{t}{\tau}}$$

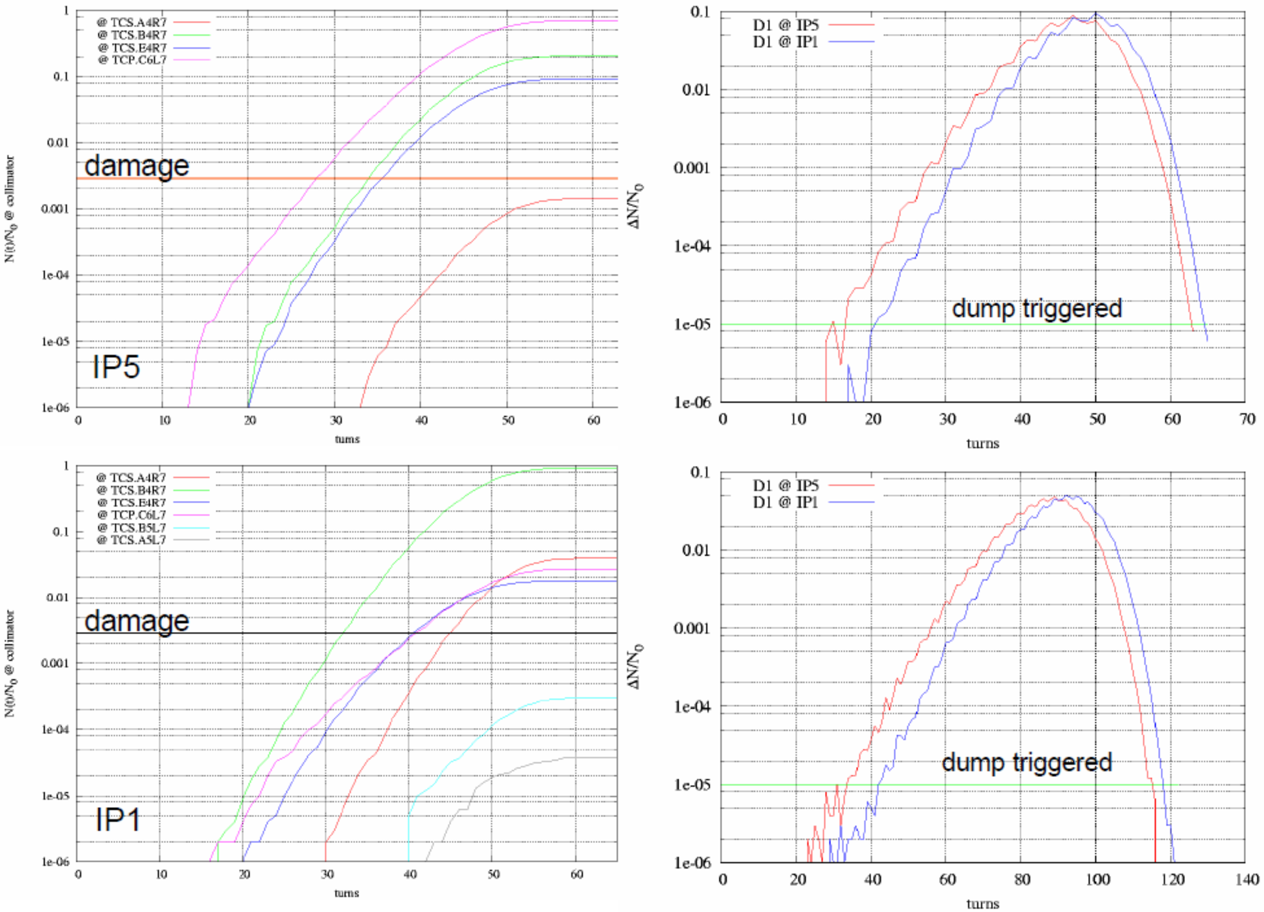
- time constant for D1

$$\tau = \frac{L}{R} \qquad \tau = 2.53s$$



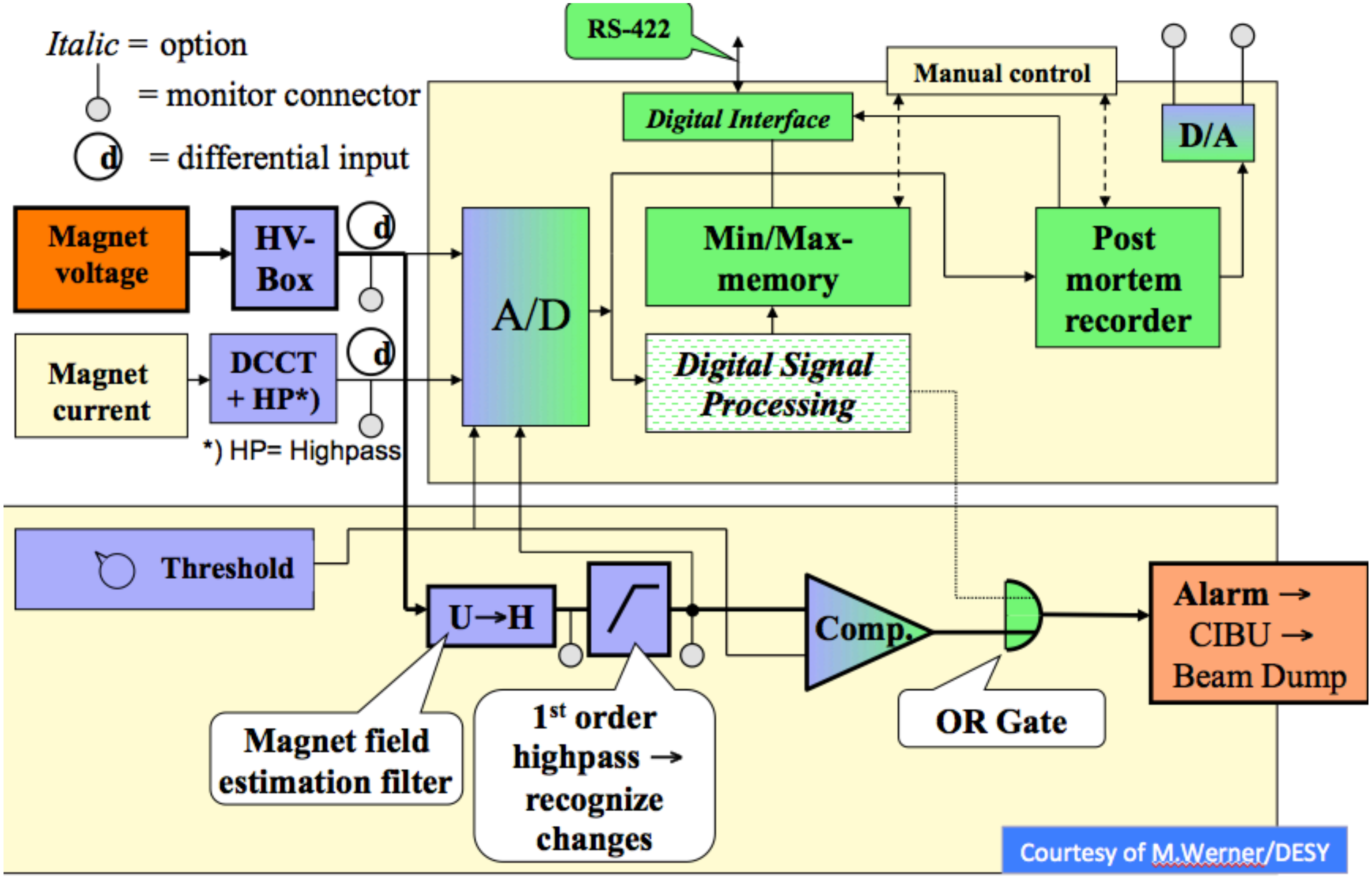


Studies of Fast(est) LHC failures



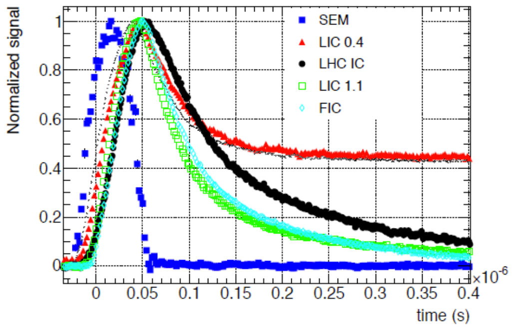
Courtesy of V.Kain

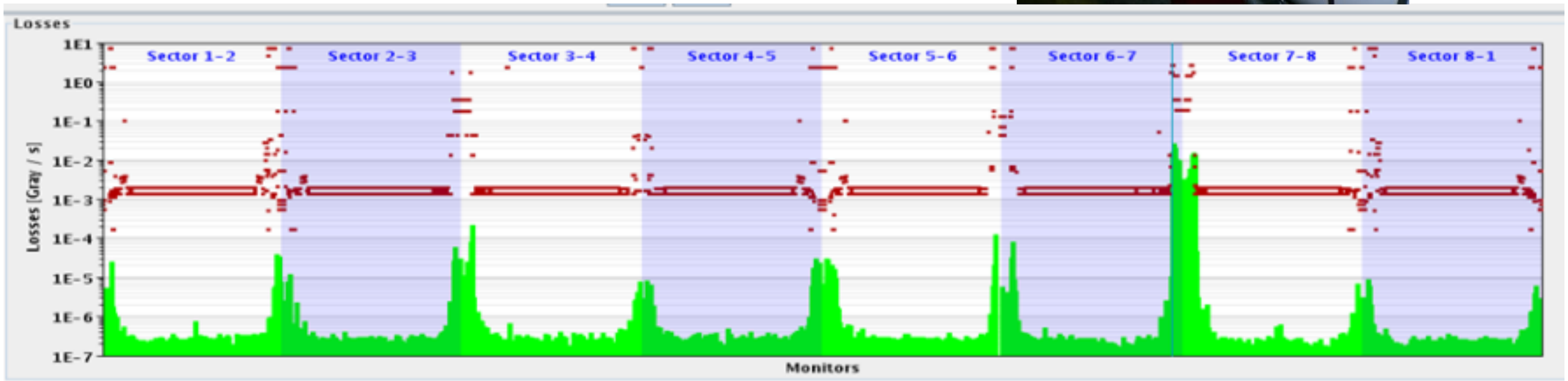
FMCM schematics



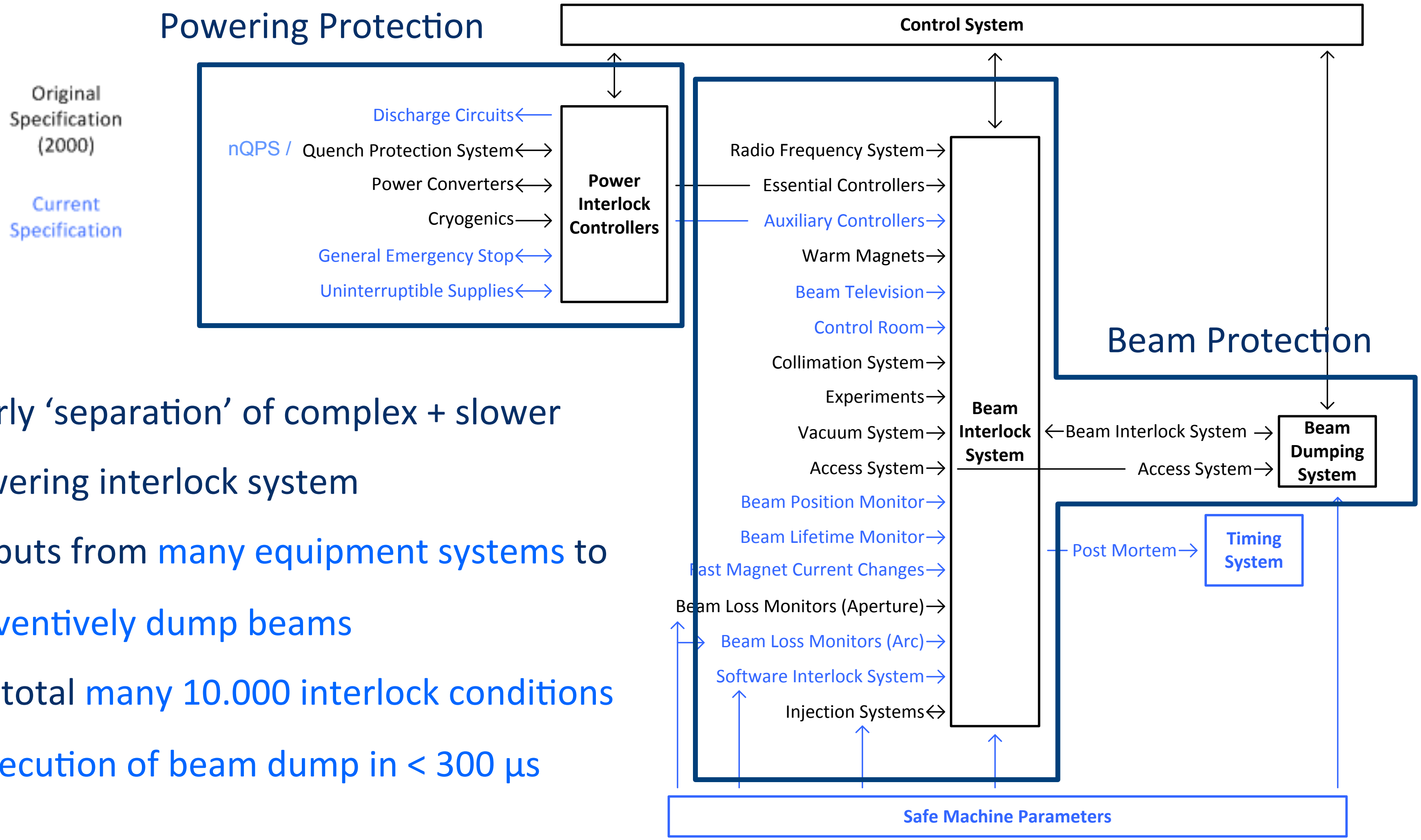
LHC beam loss monitors

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





LHC Machine Protection Architecture



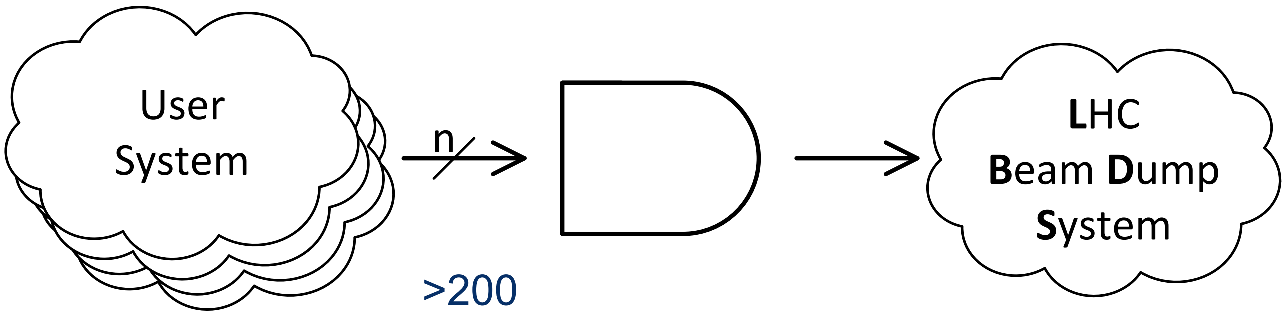
- Early ‘separation’ of complex + slower powering interlock system
- Inputs from many equipment systems to preventively dump beams
- In total many 10.000 interlock conditions
- Execution of beam dump in < 300 μs

Beam Interlock System

Generic for all of CERN's beam related machine protection…

LHC Ring, SPS Ring, SPS Extraction, LHC Injection, Linac 4, Booster…

transmit beam abort request from user systems to beam dump:



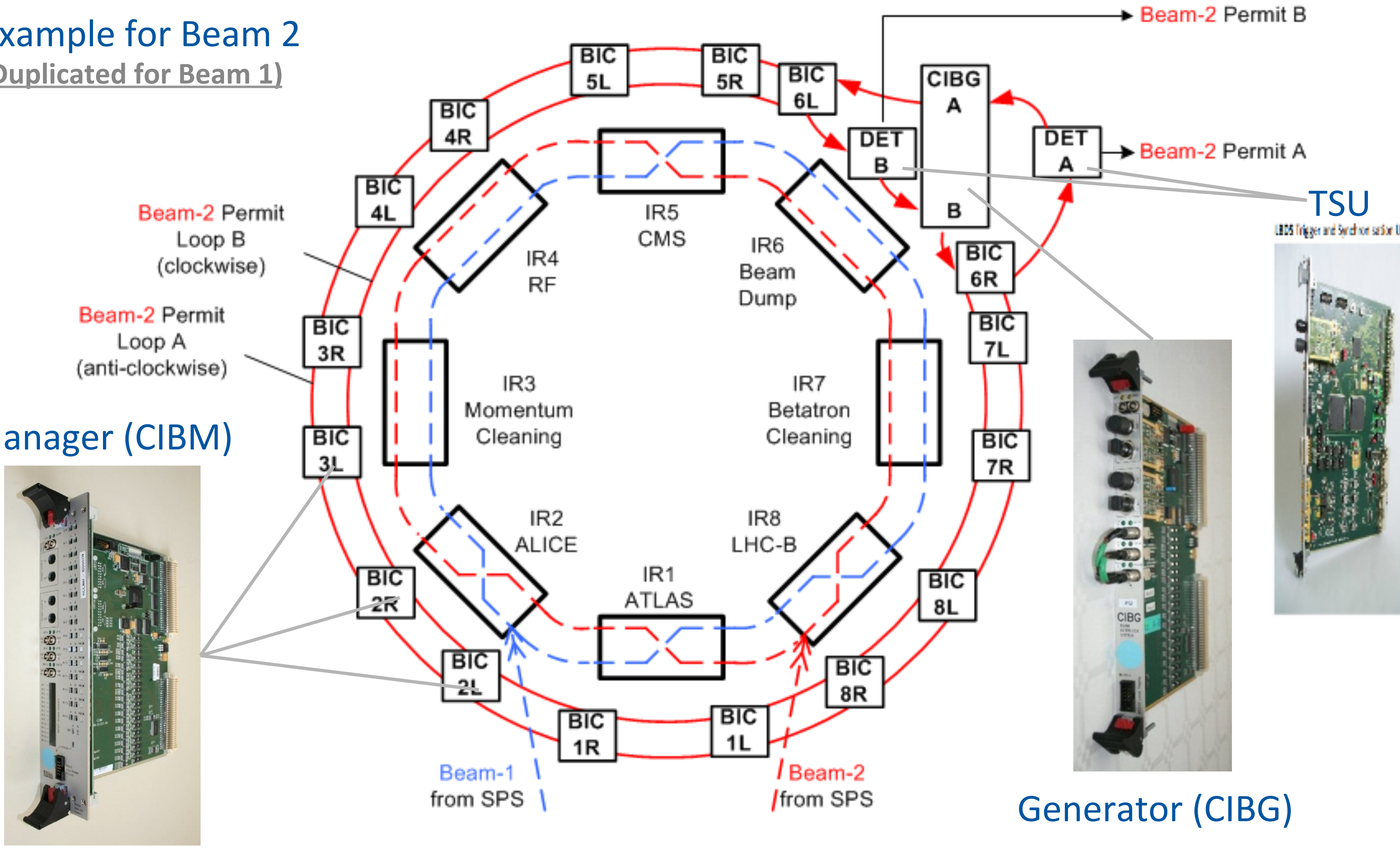
•fast •safe •reliable •available •flexible

200us over 27km   equivalent SIL3   <1% downtime

Beam Interlock System

Example for Beam 2

(Duplicated for Beam 1)

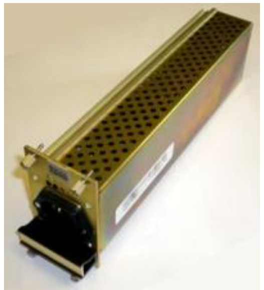


TSU

Manager (CIBM)

Generator (CIBG)

Beam Interlock System

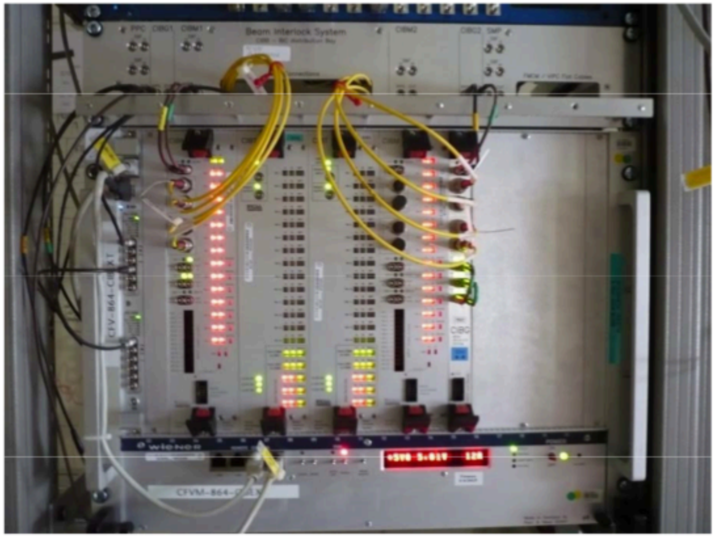


Tailor made design which took ~ 10 man-years to engineer

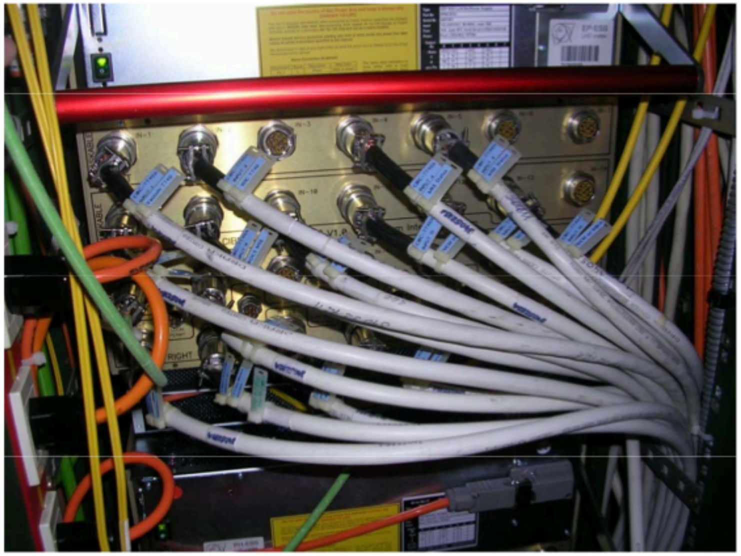
Beam Interlock System

User Interface

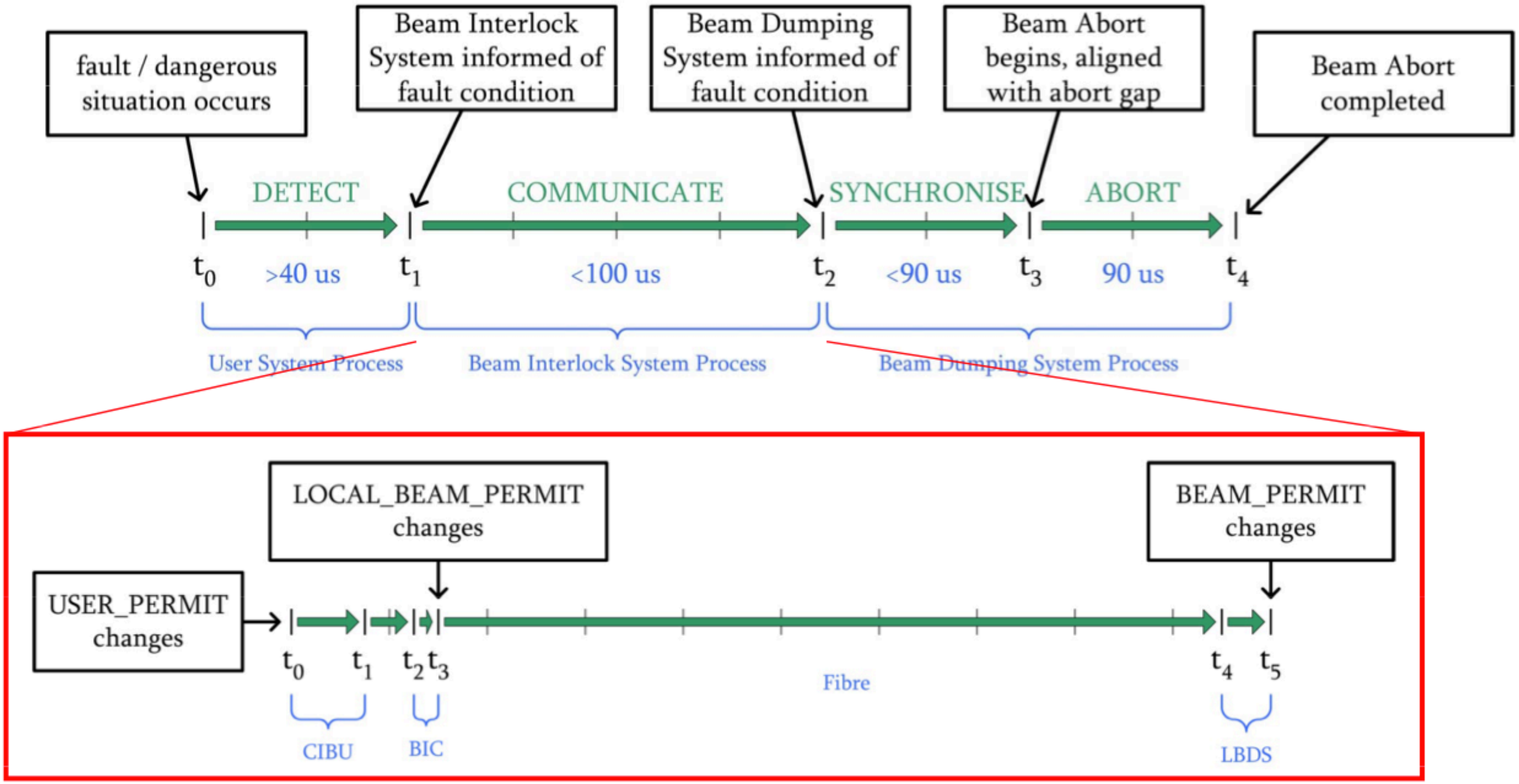
BIC (Front)



BIC (Rear)



Beam Interlock System



How to predict reliability…

…for a ‘non-complex’ system ?

FMECA

Failure Modes, Effects and Criticality Analysis

In what way can the system fail?...

...and what happens because of that?...

...and just how much of a problem does this cause?

FMECA cycle

FMECA starts at the Component Level of a system

Break a large system into blocks, defining smaller, manageable sub-systems

⇩

get subsystem schematics, component list, and understand what it does

MIL-HDBK-338 ⇩ MIL-HDBK-217

get MTBF of each component on the list, derive P_{FAIL}(mission)

MIL-HDBK-338 ⇩ FMD-97

derive failure modes and failure mode ratios for each component

⇩

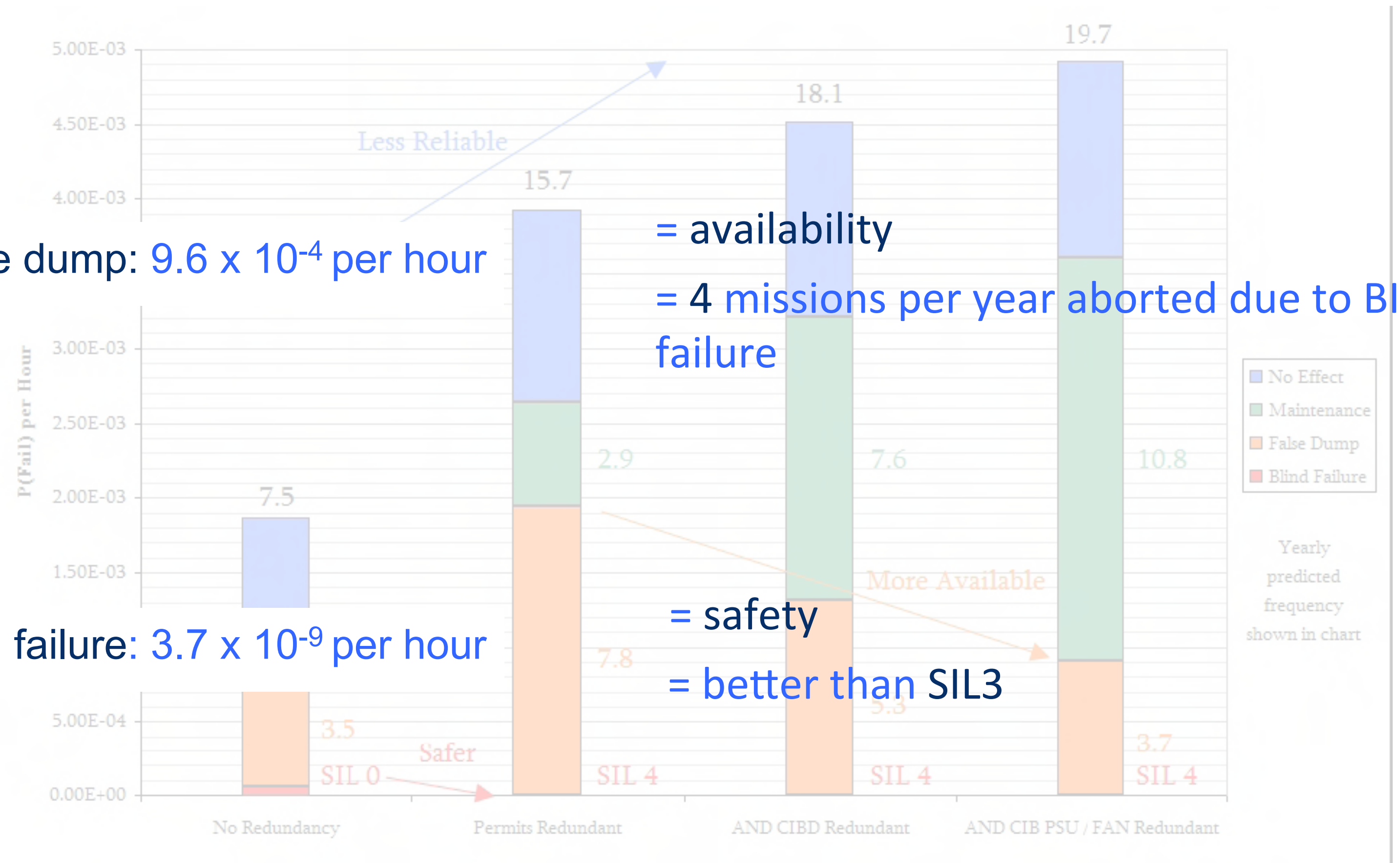
explain the effect of each failure mode on both the subsystem and system

⇩

determine the probability of each failure mode happening. Draw conclusions.

Dependability vs. Configuration

for all parts combined P(fail) =



false dump: 9.6×10^{-4} per hour

= availability

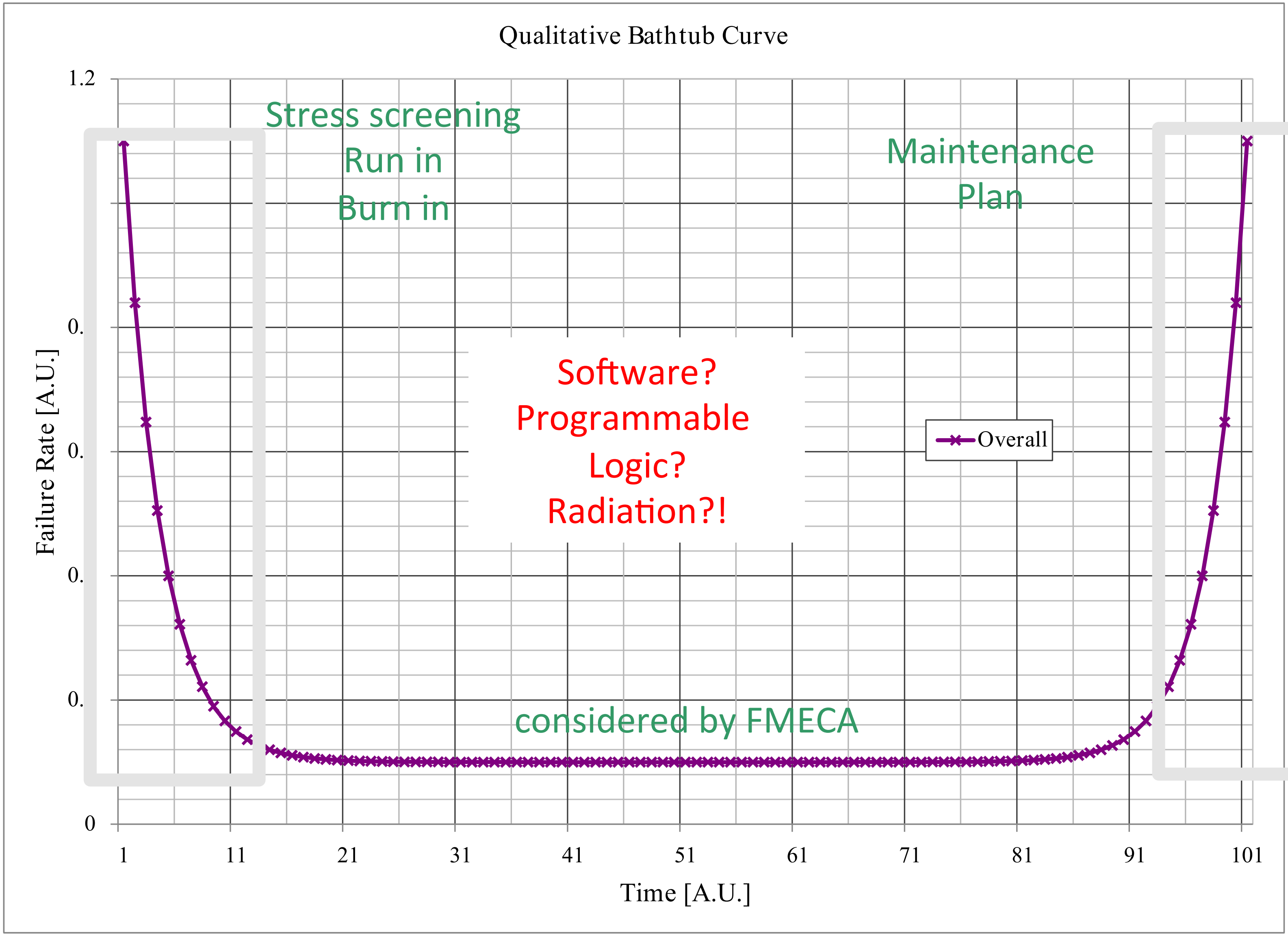
= 4 missions per year aborted due to BIS failure

blind failure: 3.7×10^{-9} per hour

= safety

= better than SIL3

Areas Outside FMECA Scope



Our experience…

<1k lines for a non-complex system… Software / programmable logic…

FMECA = lots of work = pessimistic

Manufacturer predicted MTBF witchcraft it seems…

Failure rate too low to validate FMECA - wear out will begin

Typical failures of BIS do not stop operation

Lose availability with multiple failures (Murphy's Law)

e.g. installation not quite correct AND
User system not exactly as expected AND
Software not configured correctly AND
Something simple fails =

Difficult to diagnose but Easy to fix

System does as specified, but the specification wasn't complete

It does what we expected, but we didn't quite expect that

What to do for complex systems?

<1k lines for a non-complex system… with many components…

Beam Interlock System

FMECA

>80k lines for a complex system … with few components …

Safe Machine Parameters

More likely to be systematic..
Random failures insignificant…
= formalisation …

Review…
Test…
Observe…
Repeat…

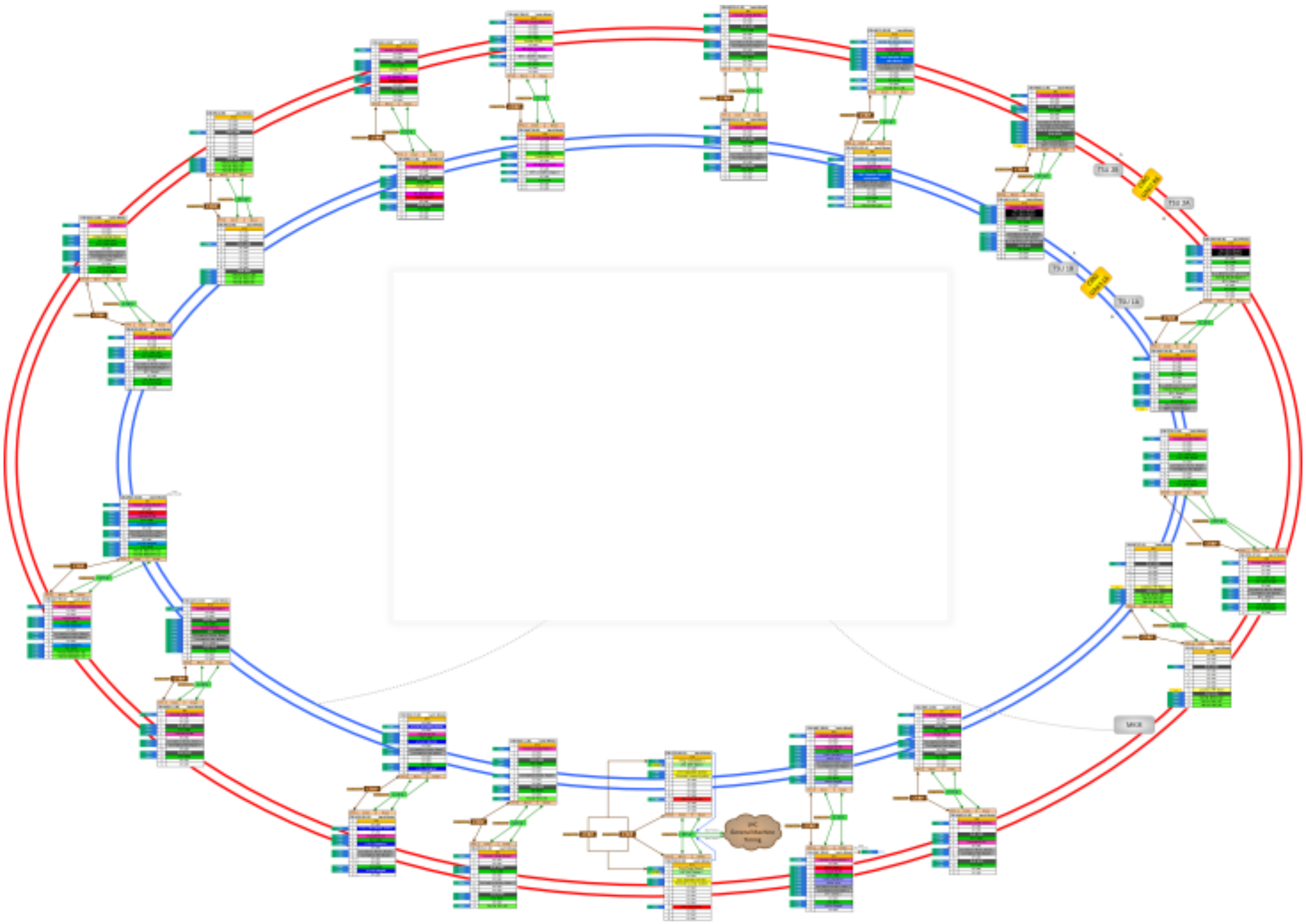
>>1k lines for a complex system … with many components …

Function Generator Controller Lite

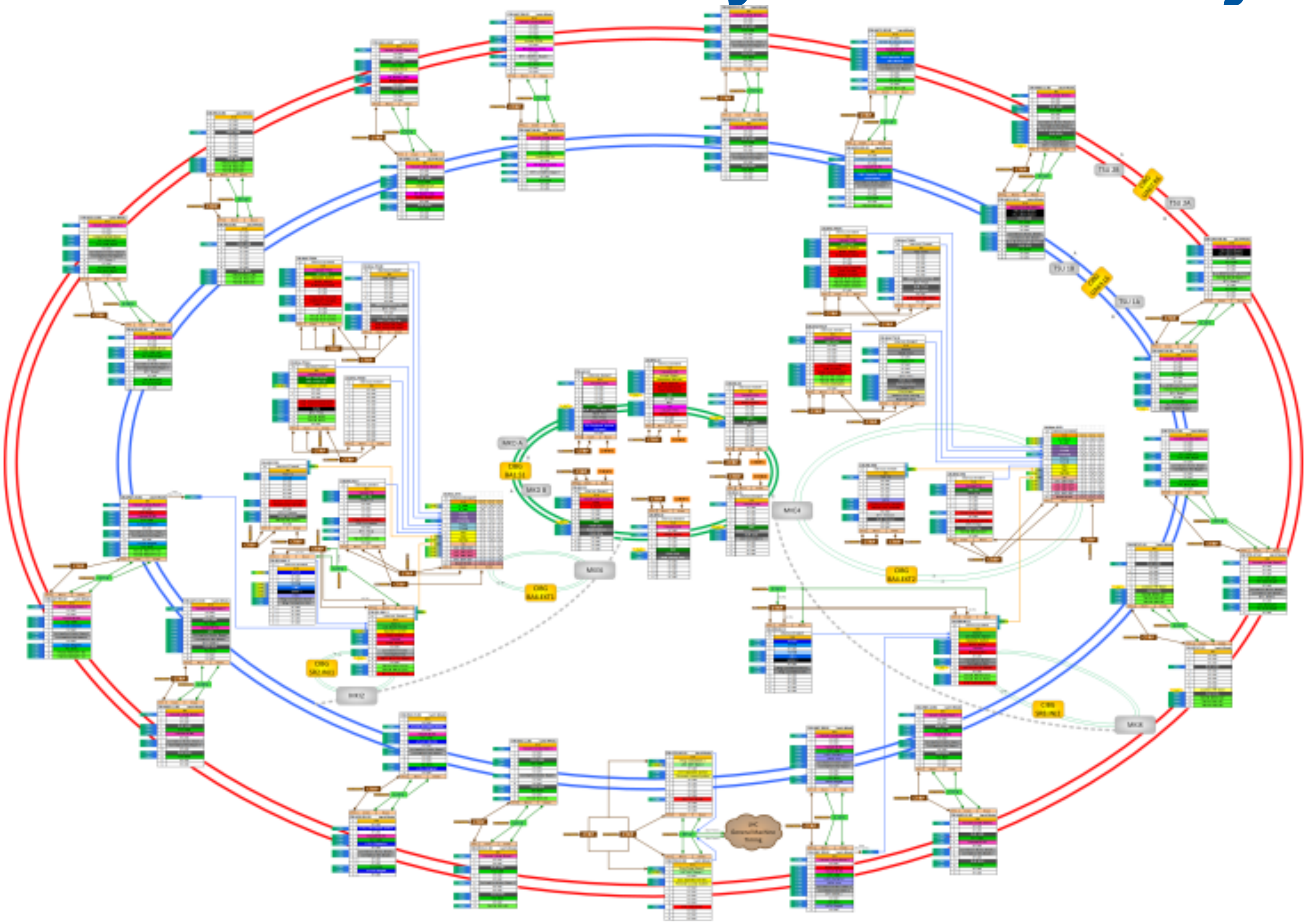
FMECA + Formalisation + Safety Life-cycle?

Fast interlocks for different architectures of accelerators…

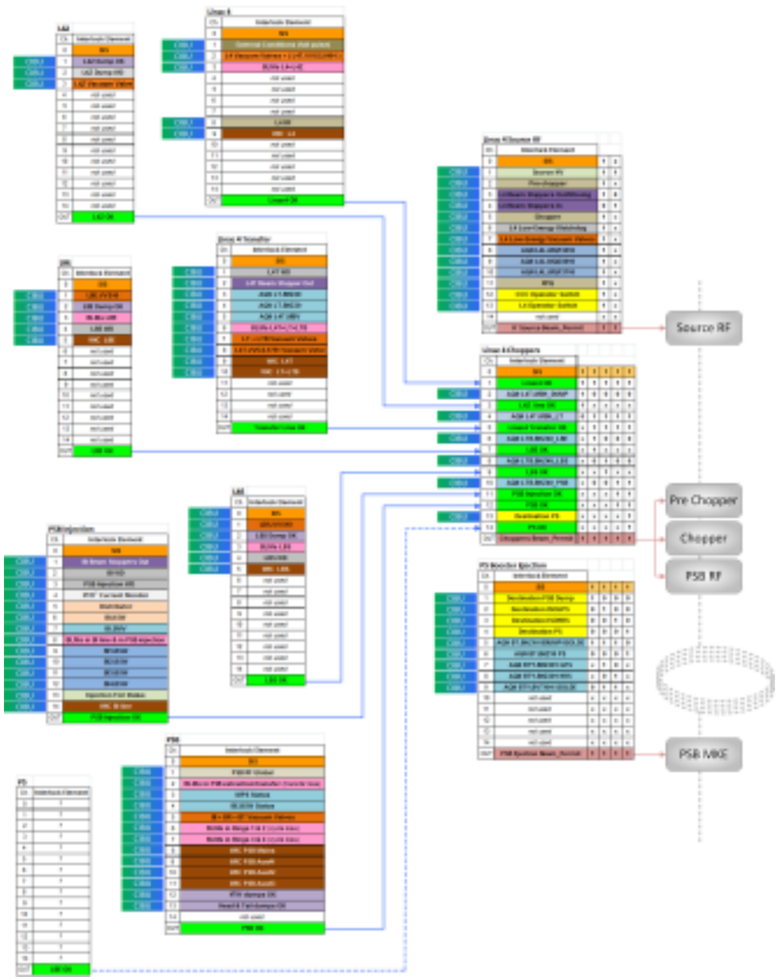
Beam Interlock System LHC + SPS



Beam Interlock System + Inj



Beam Interlocks for LINAC 4



- For SPS extraction / LHC injection and LINAC 4 protection, BIC systems are daisy-chained
- in LINAC 4:
  - One interlock master for RF High-voltage
  - Second master to interlock pre-chopper and chopper as a function of following LINAC state (fast interlock during pulse possible)
  - (fast) controllers to summarize interlocks from different beam lines -> For reasons of flexibility, I/Os and speed PLC might have been better option

Conclusions

- Fast interlocks systems mostly tailored designs, requiring substantial development + maintenance efforts
  - only justified in case of (very) specific needs?!
  - Very good record of operation with e.g. beam interlock, BLM, FMCM systems,… so far
- PLC solutions offer very mature & flexible technical solutions, compliance with many industrial standards and development/ testing tools that considerably facilitating design process
  - Excellent operational record (experience limited to single vendor)
- Separation of slow/fast controls proven very useful, certainly would have no doubt to make same PLC choice for slow controls

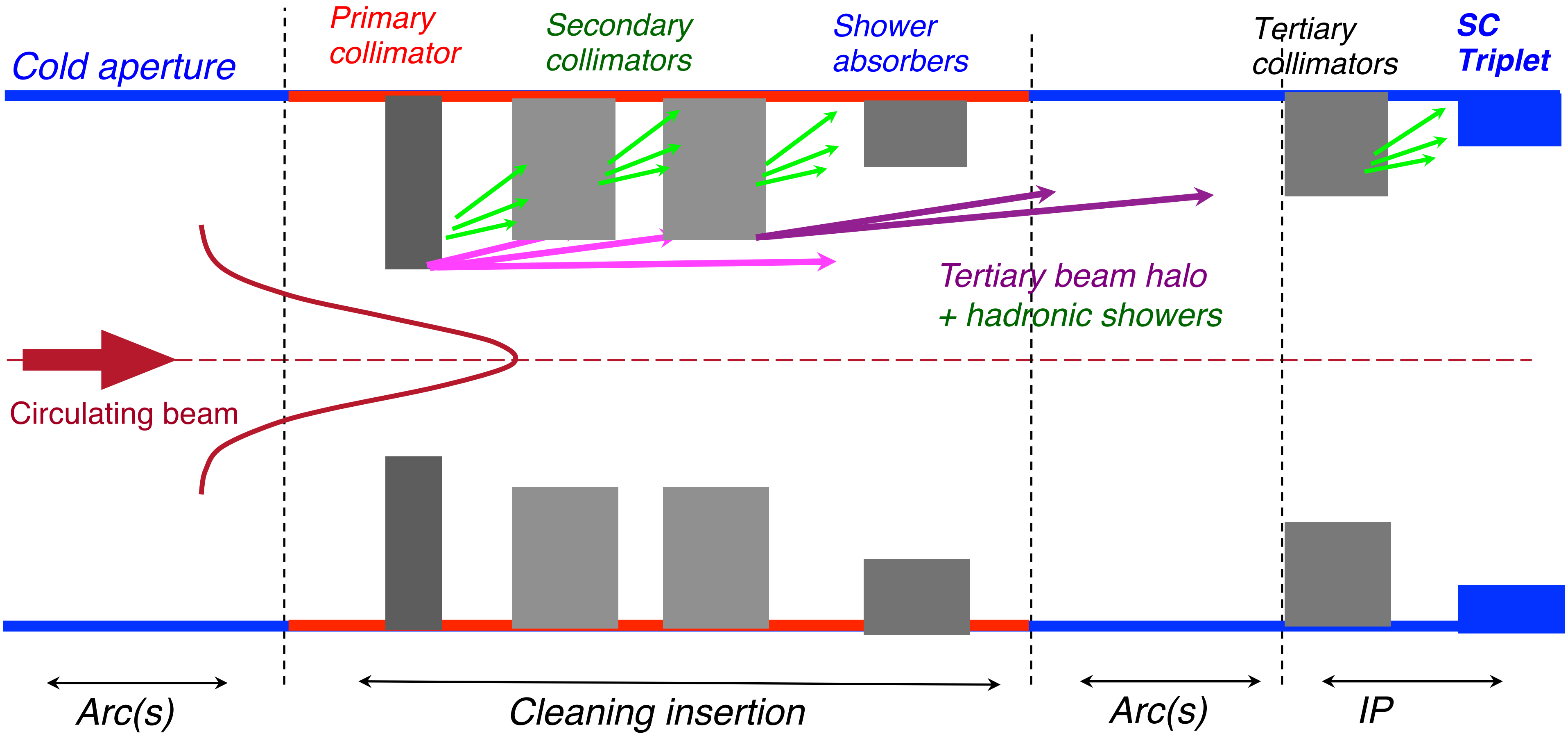
Fin

Thanks a lot for your attention!

www.cern.ch

LHC collimators

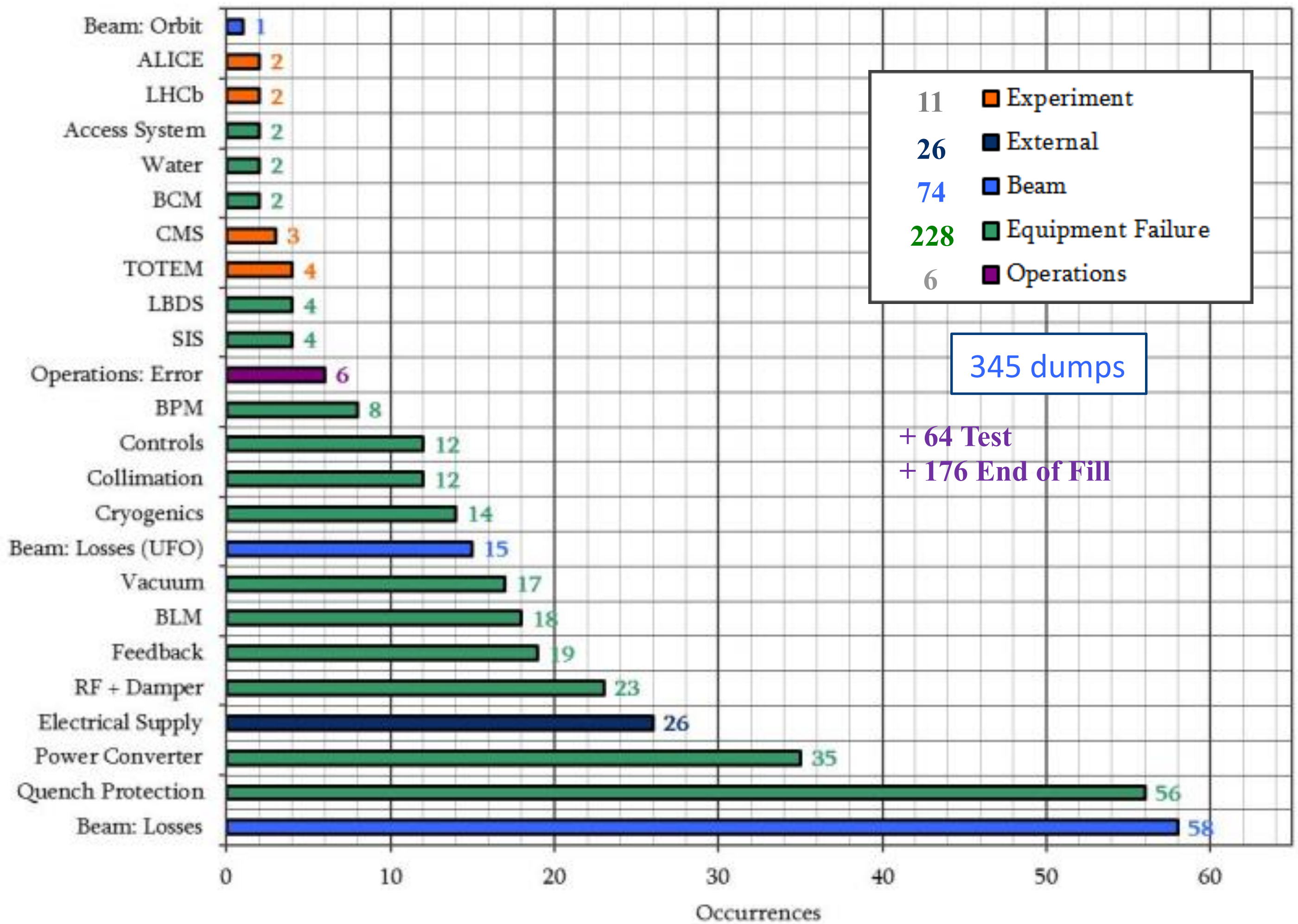
- Machine elements (especially 'cold' elements like magnets, cavities, …) need to be protected from impacts of high energy particles



Pro’s and Con’s of

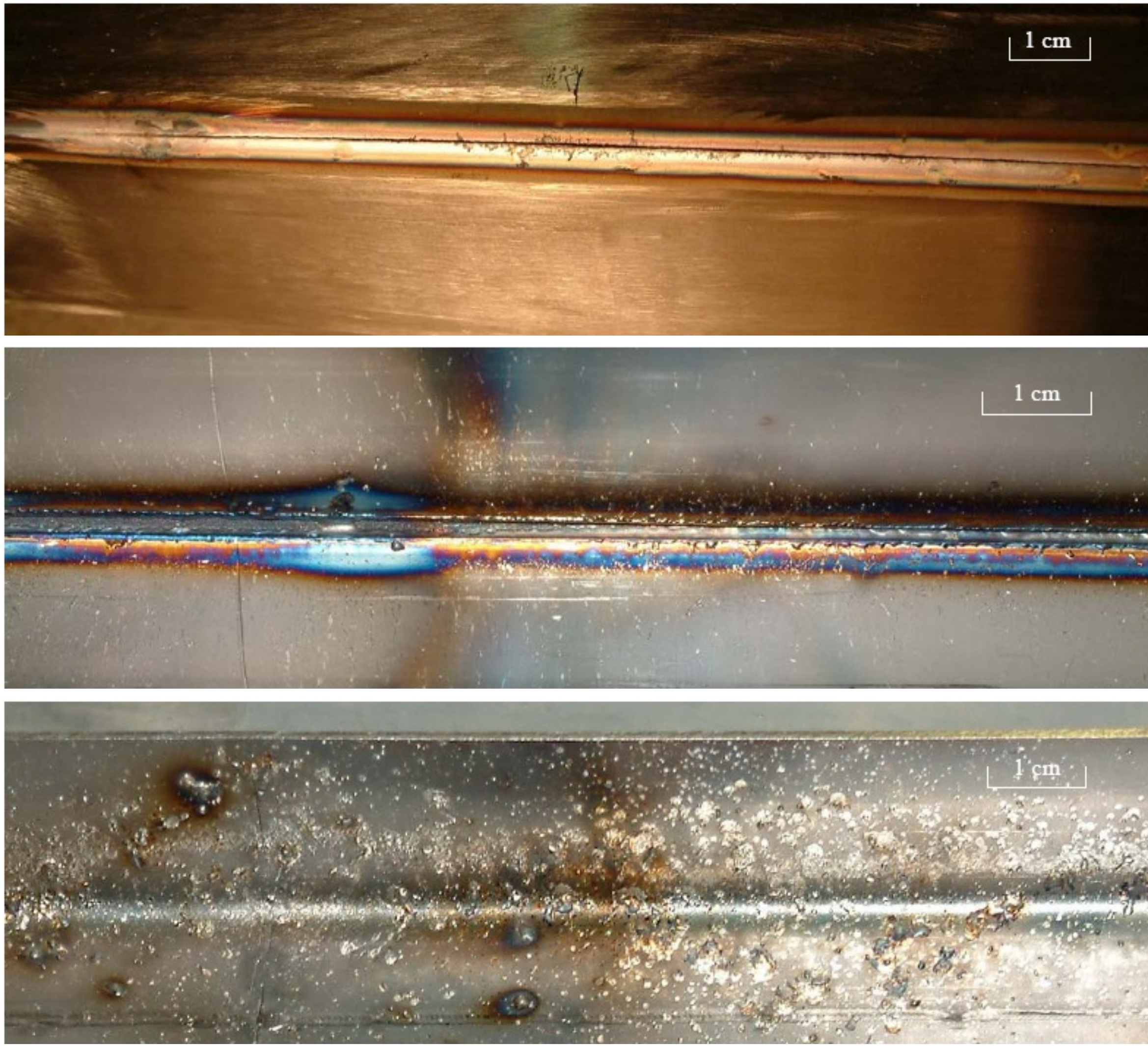
PLC based	Criteria	Fast Interlocks (Tailor made)
>=1ms (some 10us with Fast modules)	Reaction Time	µs
SIL 3 equivalent possible	Dependability	FMECA
Few I/O modules qualified for ~ 100 Gy, avoid for CPU	Radiation	Requires design effort and radiation testing
Level 4 of IEC 61000	EMC	Design effort
Many tools and solutions available, profiting from > market	Development effort	>>
	Testing	

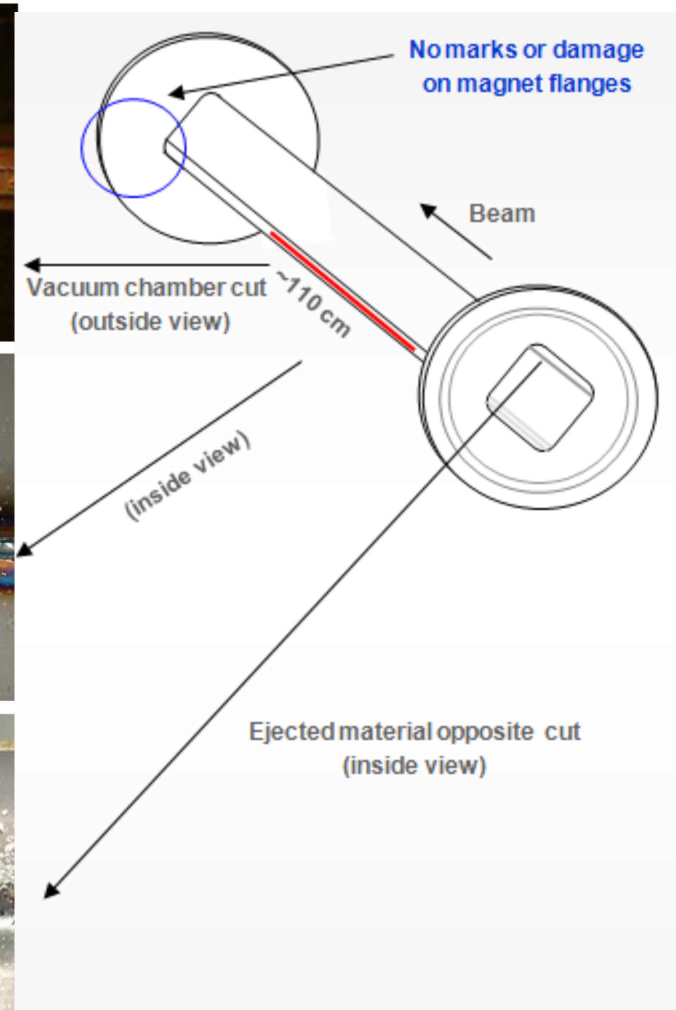
Beam dumps from 4 TeV in 2012



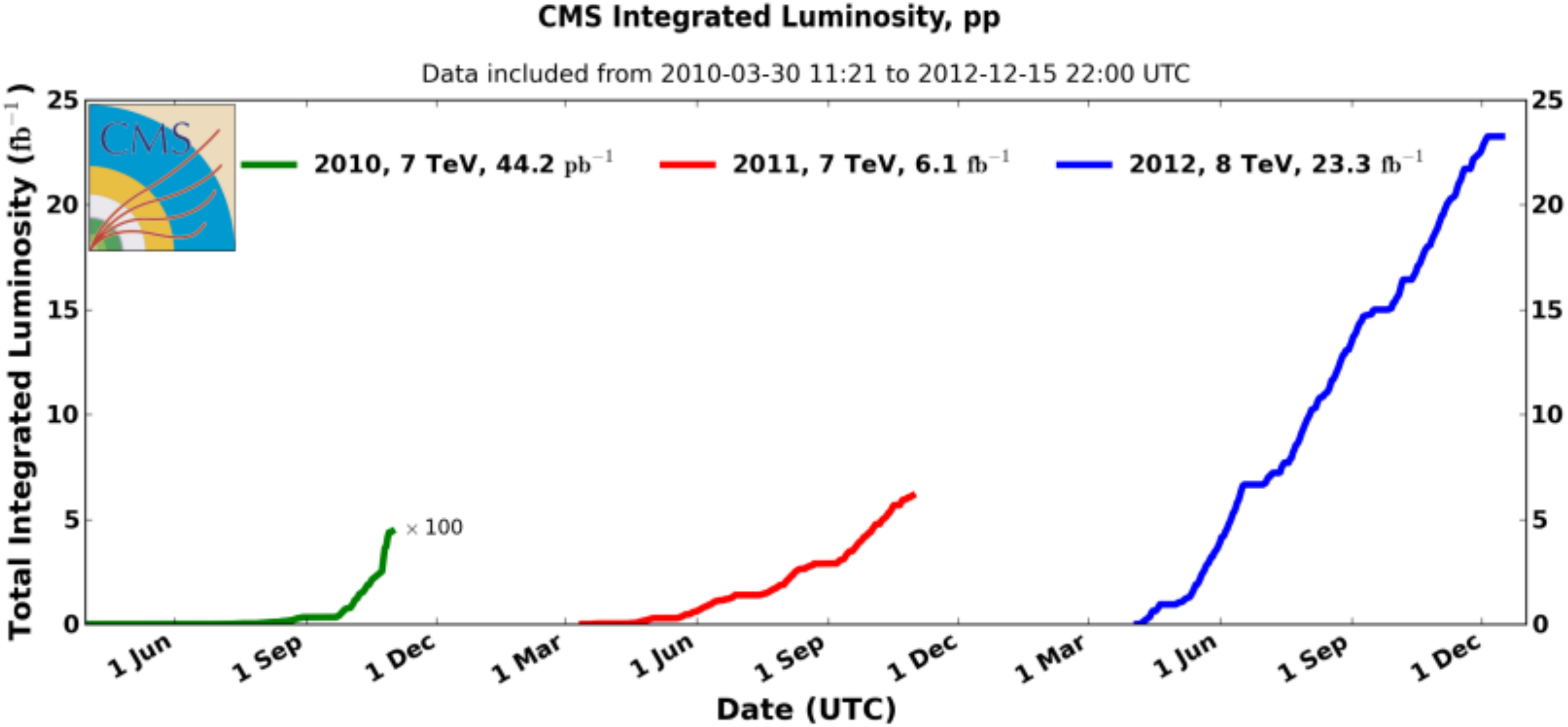
APPENDIX

Extraction event in TT40 in fall 2004





Integrated Luminosity

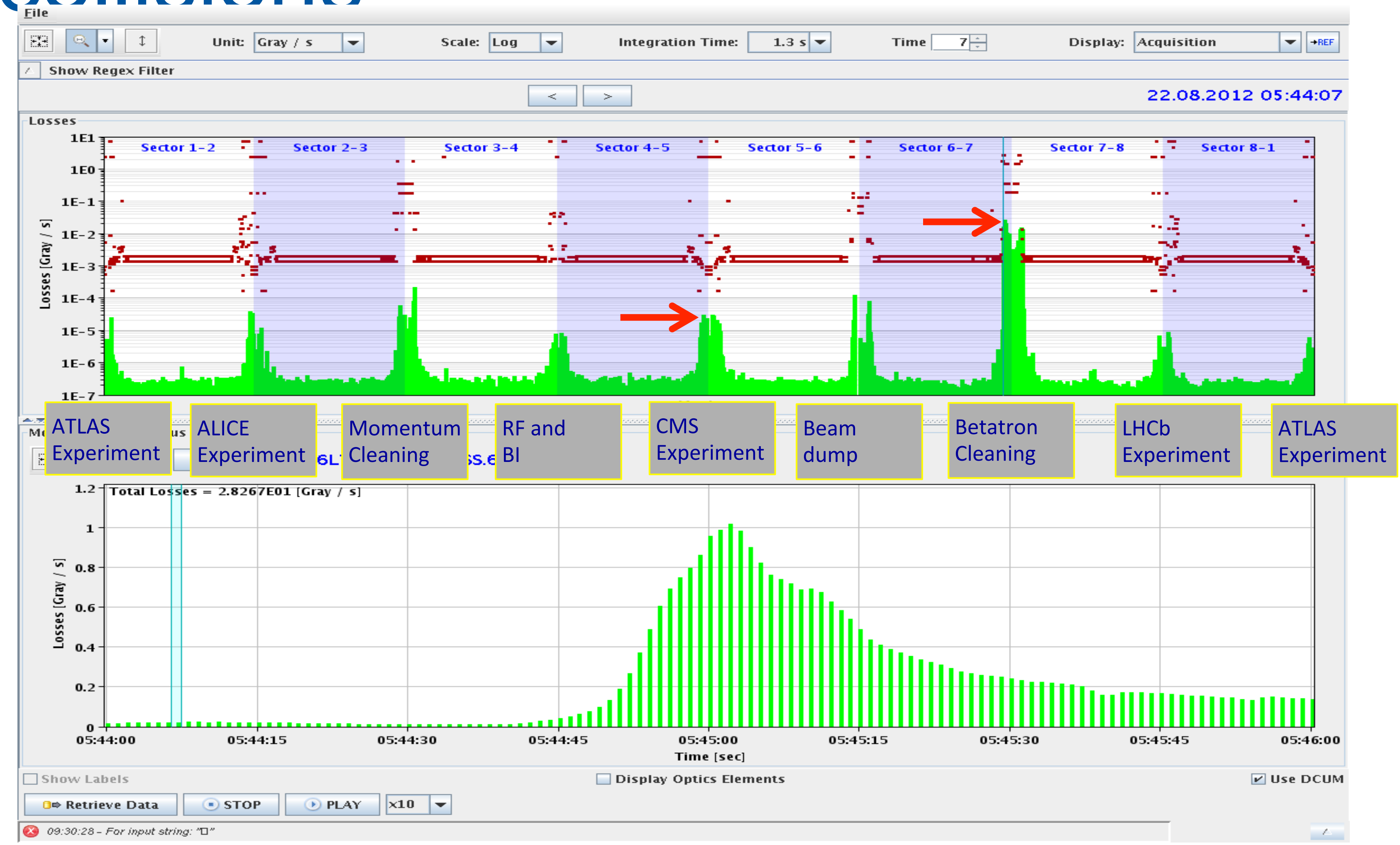


LHC Performance end 2012

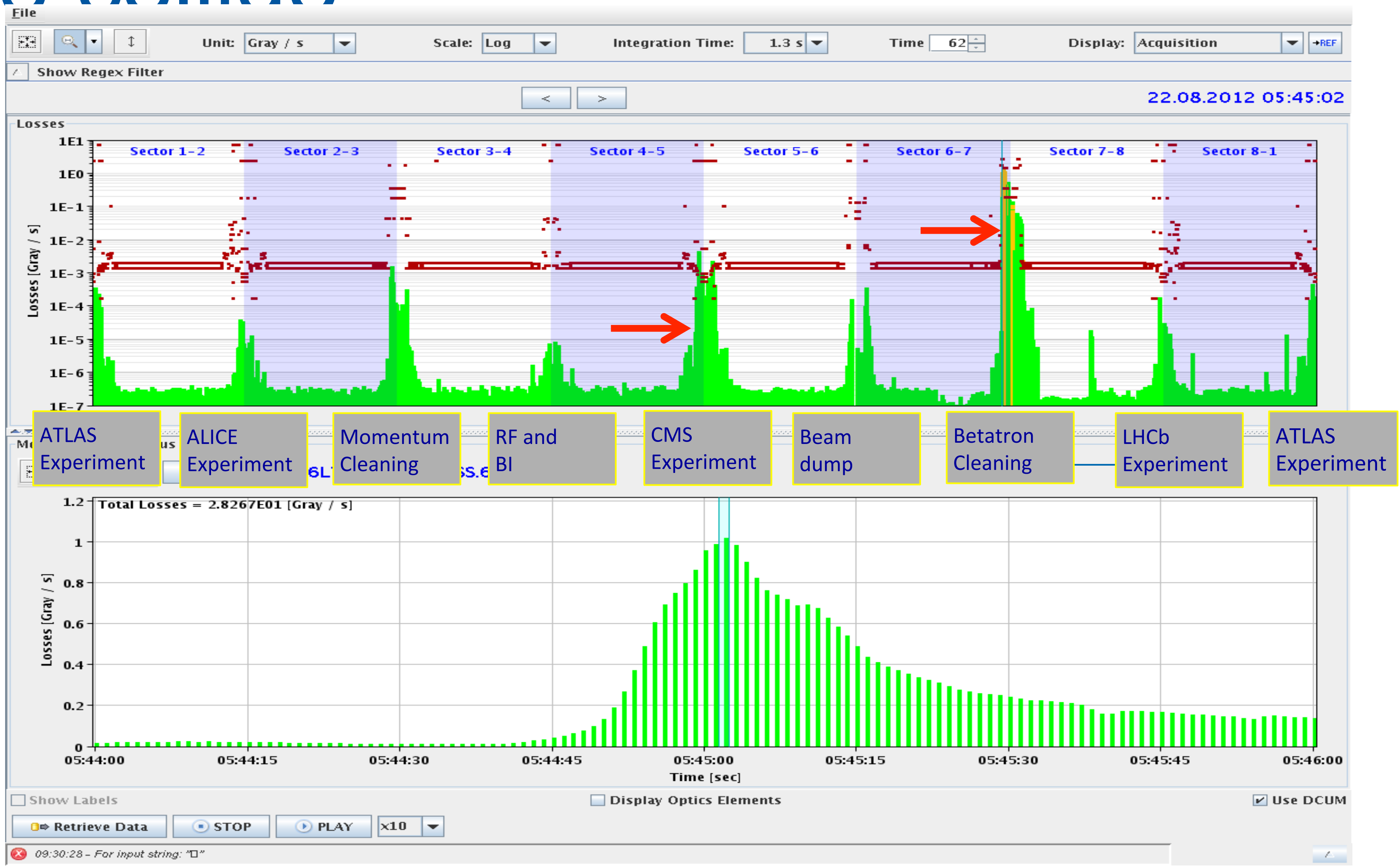
77% of design luminosity:
- 4/7 design energy
- nominal bunch intensity++
- ~70% nominal emittance
- beta* = 0.6 m (design 0.55 m)
- half nominal number of bunches

Max. luminosity in one fill	237 pb^{-1}
Max. luminosity delivered in 7 days	1350 pb^{-1}
Longest time in stable beams (2012)	22.8 hours
Longest time in stable beams for 7 days	91.8 hours (55%)
Fastest turnaround	2 hours 7 minutes

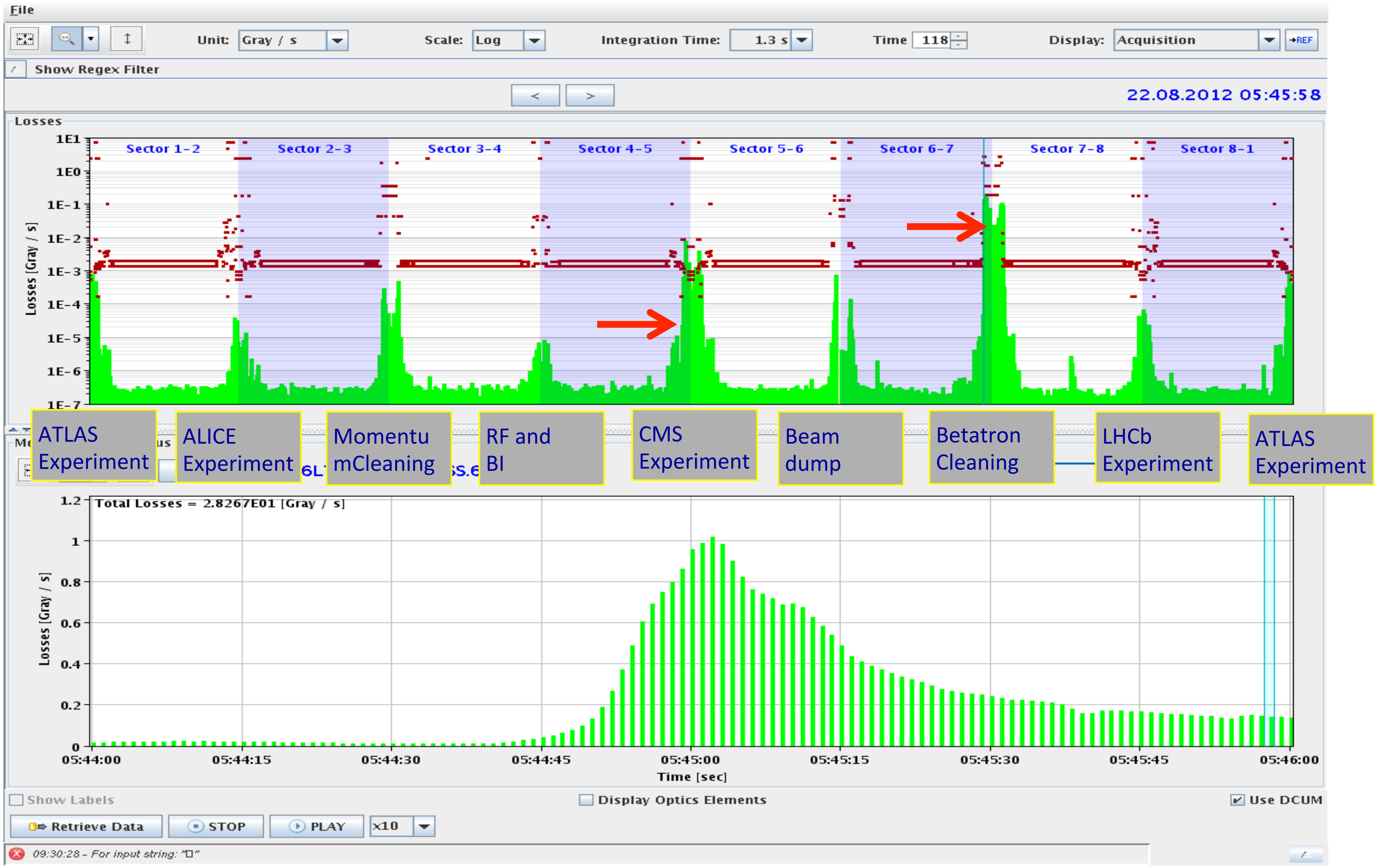
LHC cycle – Losses before collisions



LHC cycle – Losses when starting to collide



LHC cycle – Losses after bringing into collisions



What do the experiments want?

High Energy

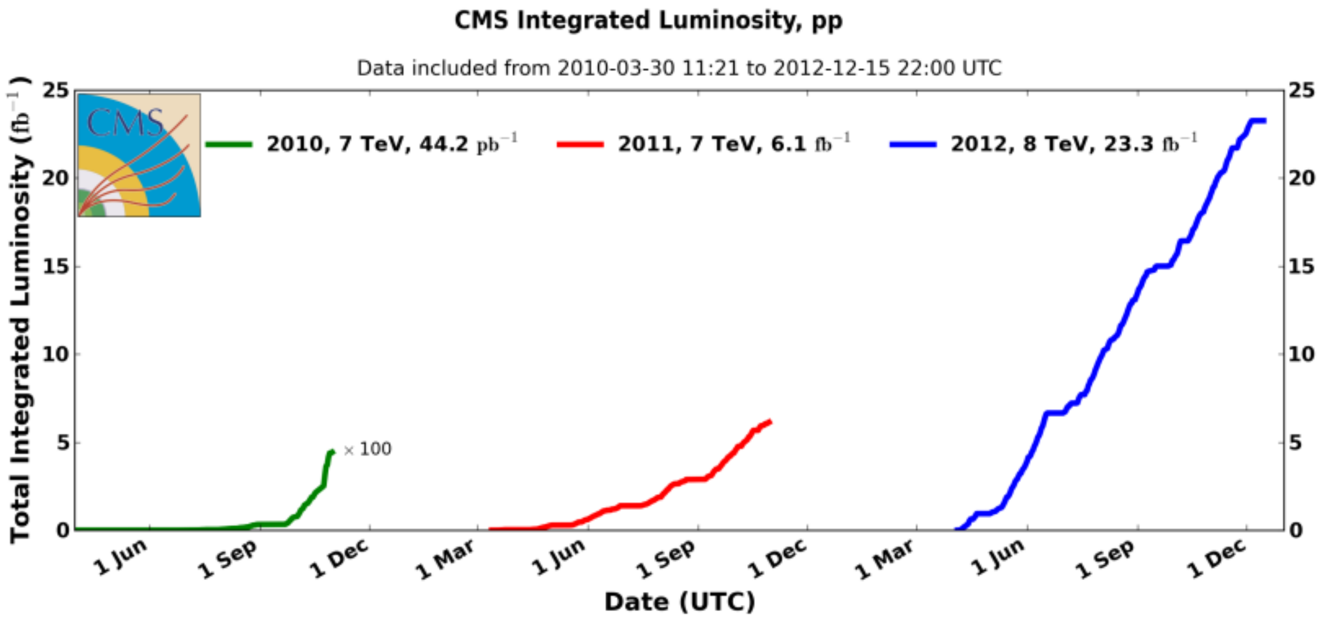
B = Magnetic field
ρ = Radius
p = Momentum
e = Charge

$$B\rho = \frac{p}{e}$$

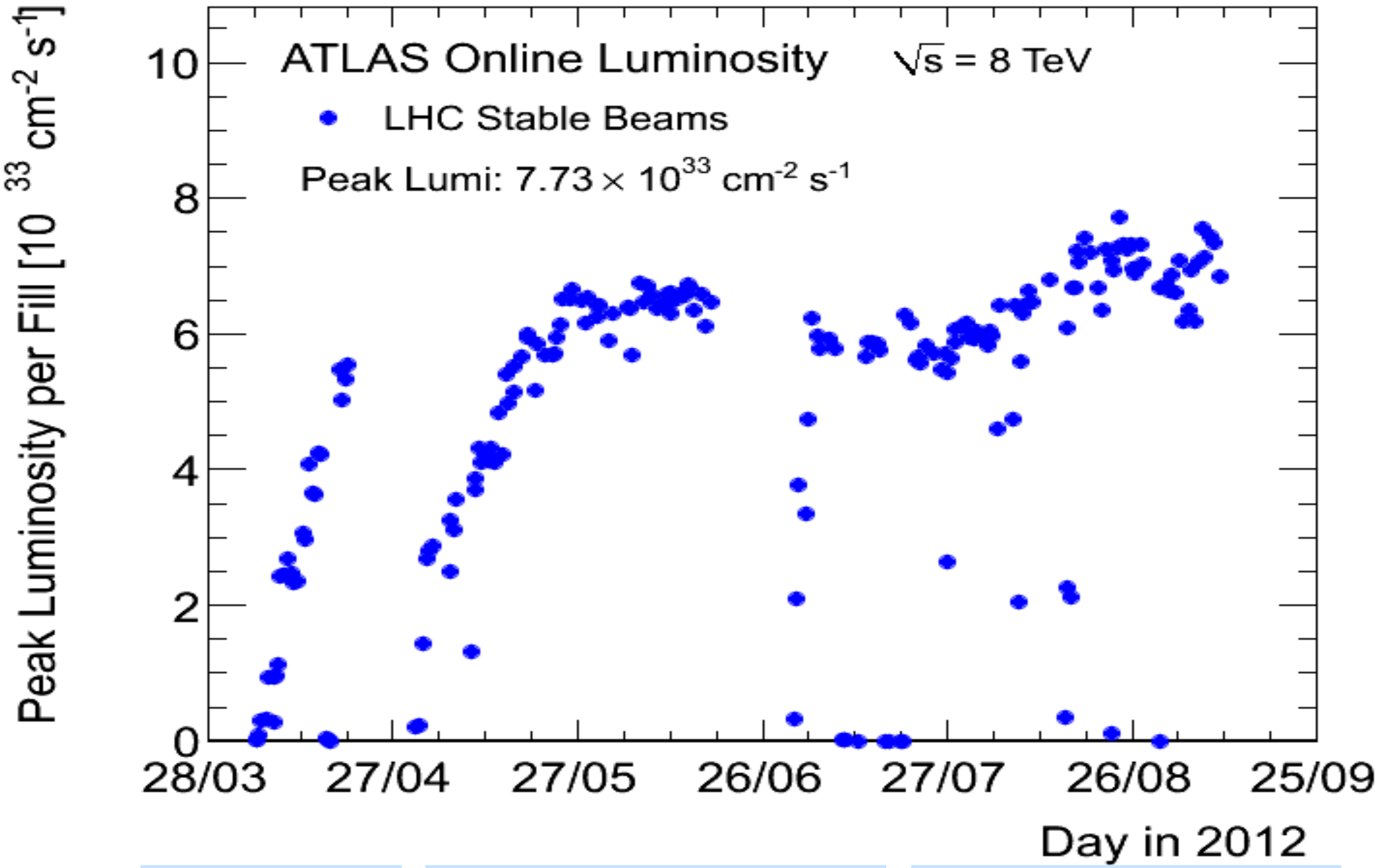
High Luminosity

$$\mathcal{L} = \frac{N^2 n_b f_{\mathrm{rev}}}{4\pi\sigma_x\sigma_y} F$$

N = Number of particle
n_b = Number of bunches
f_{rev} = Revolution Frequency
$\sigma_{x,y}$ = Beam size
F = Geometric Factor



Peak luminosity evolution during 2012



Start-up phase for machine protection

Recovering from technical stop and increase - approaching limits

Recovering from technical stop, approaching limits, changing parameters

The LHC story so far…

1994 – 2002 – 2005 – 2007 – 2008 – 2009 – 2010 – 2011 – 2012 – 2013 – 2014

LEP

Install magnets

Repair

3.5 TeV

4 TeV

Upgrade

>6.5 TeV

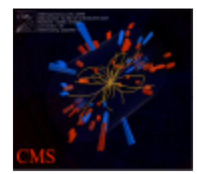
LHC project approved

September 10th first circulating beam

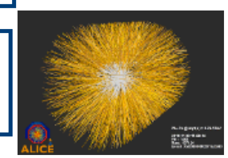
September 18th first lesson learned

November 20th second startup

March 30th First collisions at 3.5 TeV

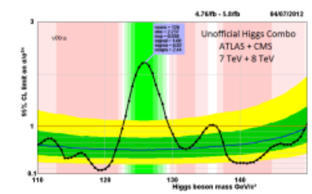


November Ions



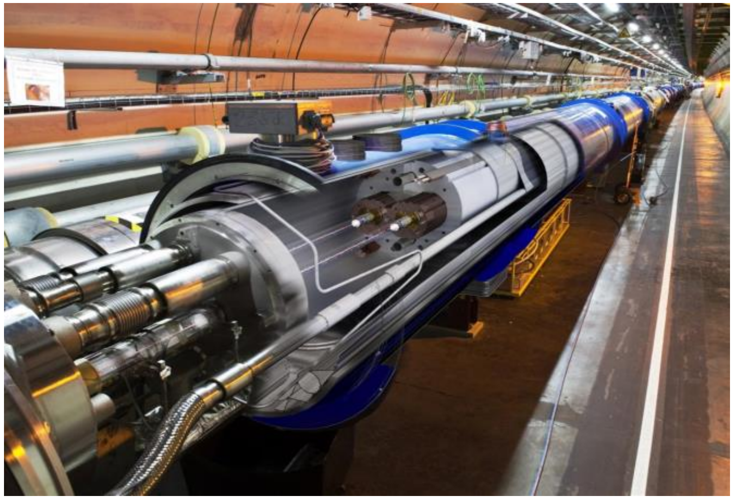
June 28th 1380 bunches

July 4th Higgs discovery



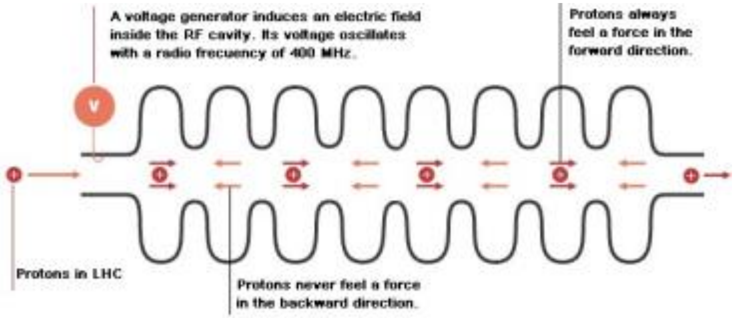
LHC magnets + protection

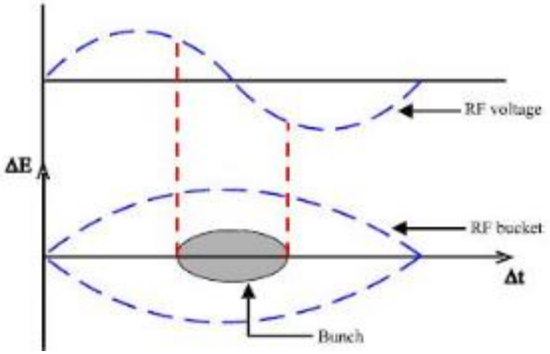
- 19km of ring composed of 1232 superconducting dipoles magnets, 8.3T (7TeV), 15m, 1.9K
- 392 superconducting quadrupole magnets (focusing of beams)
- 8000 higher order corrector magnets for steering, corrections,…
- Sophisticated Quench protection system



Presentation of A.Siemko

RF cavities





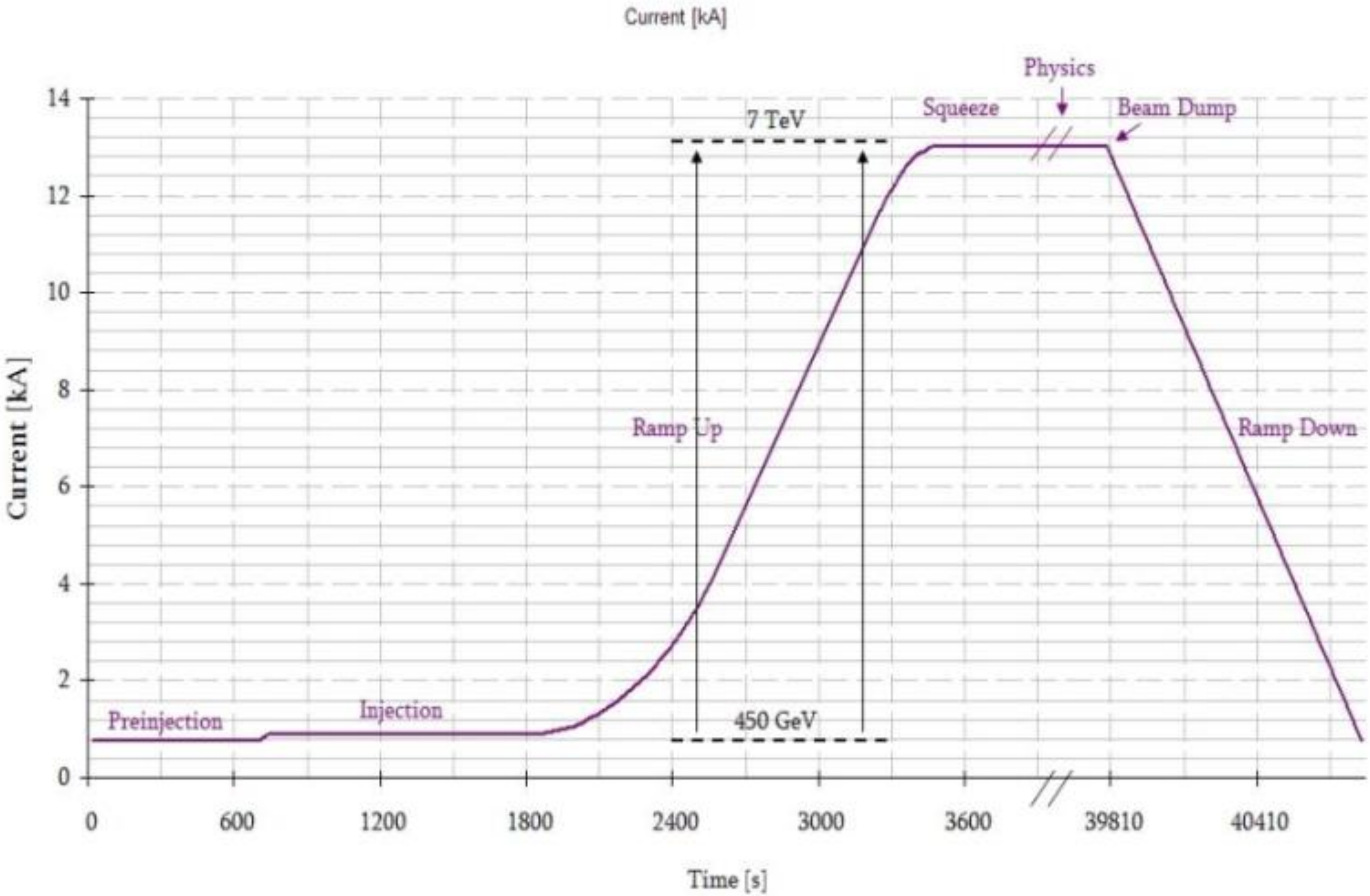
- For acceleration particles have to be in right phase with RF voltage
→ LHC can only accelerate particle ‘bunches’

Operation - CERN Control Centre

Yearly schedule

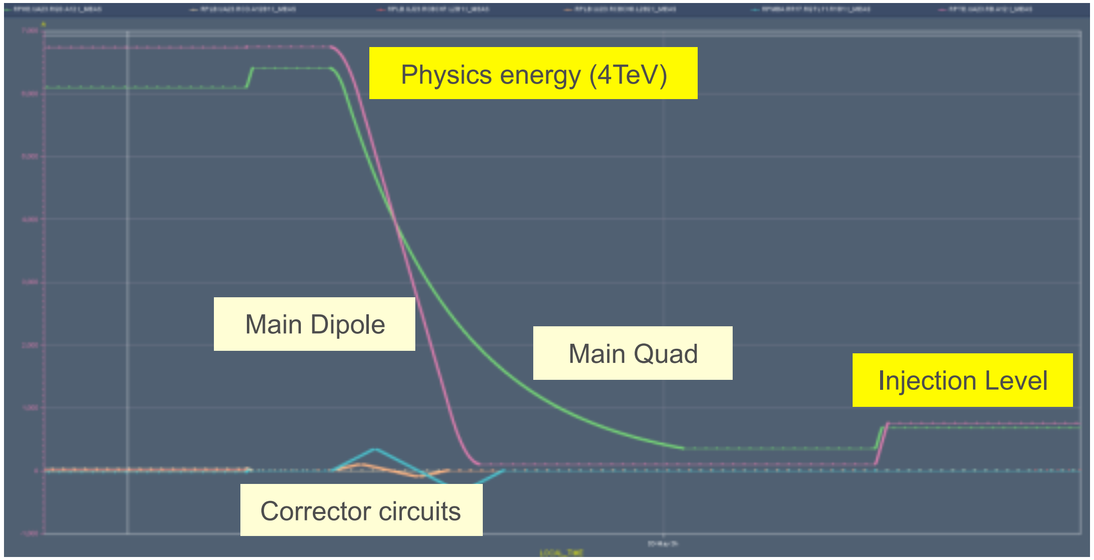
- Operation crews in CCC on 24/7 basis
- Typical operational year includes
    - Technical stop over Christmas
    - Hardware commissioning
    - Cold checkout / beam commissioning
    - Production runs
    - Special Physic runs (high beta, VdM scans, …)
    - Machine Developments

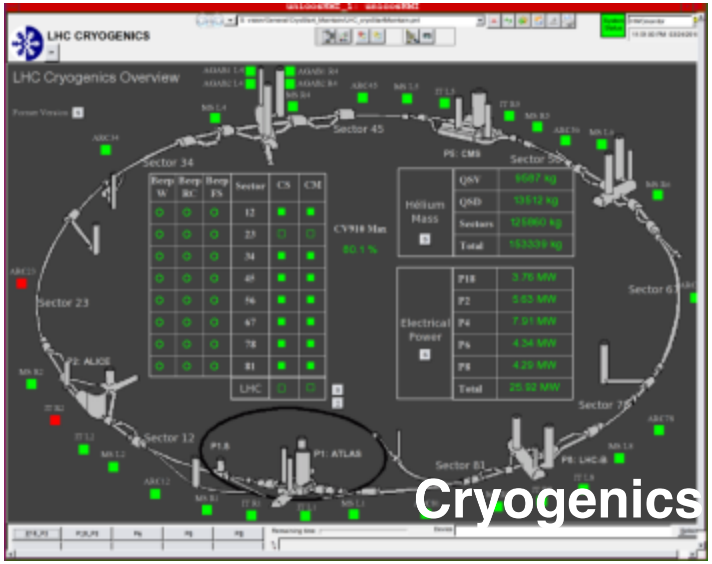
LHC cycle


Current [kA]
Physics
Squeeze
Beam Dump
7 TeV
14
12
10
8
6
4
2
0
Current [kA]
Ramp Up
Ramp Down
Preinjection
Injection
450 GeV
0
600
1200
1800
2400
3000
3600
39810
40410
Time [s]

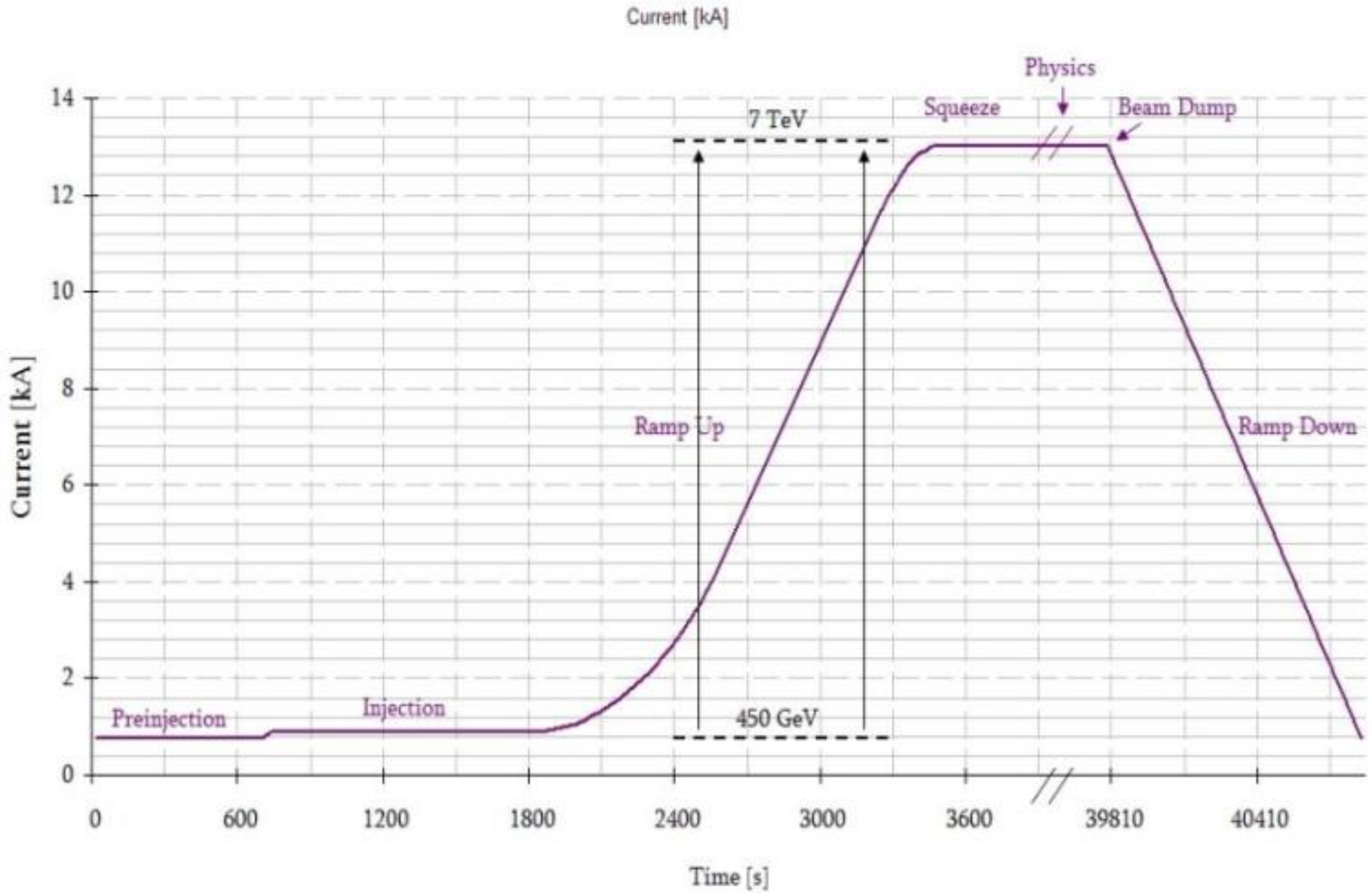
LHC cycle – Preparing for injection

- Machine to injection energy (450GeV)
- Precycling of magnets
- Preparation/verification of equipment systems (RF, BI, Cryo, Access…)
- Preparation of beams in injector complex



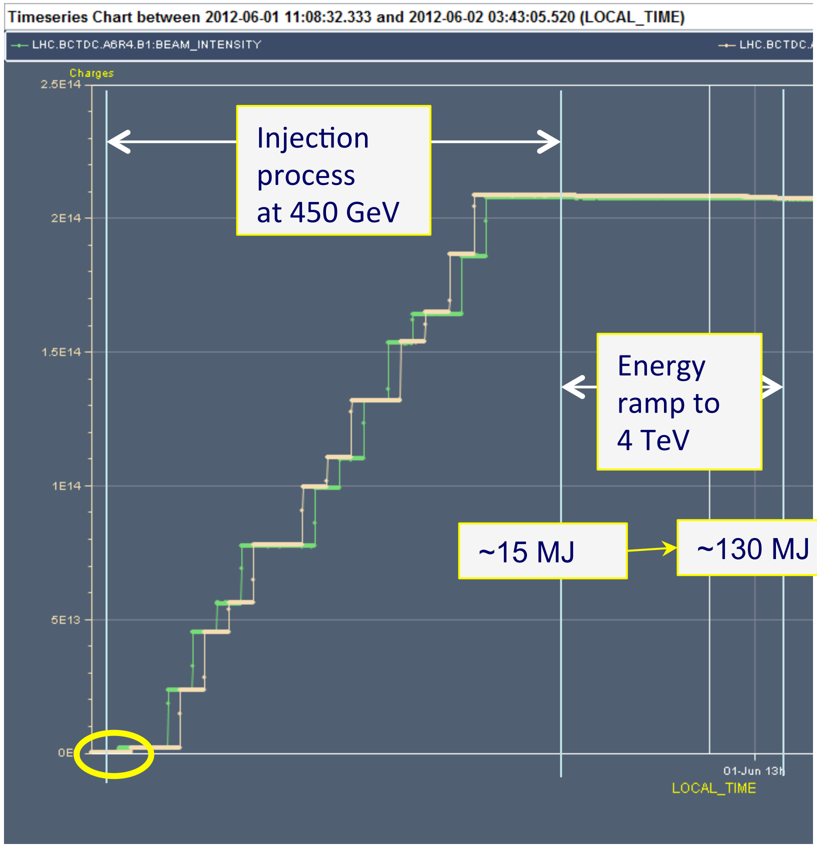


LHC cycle – Injection of beams



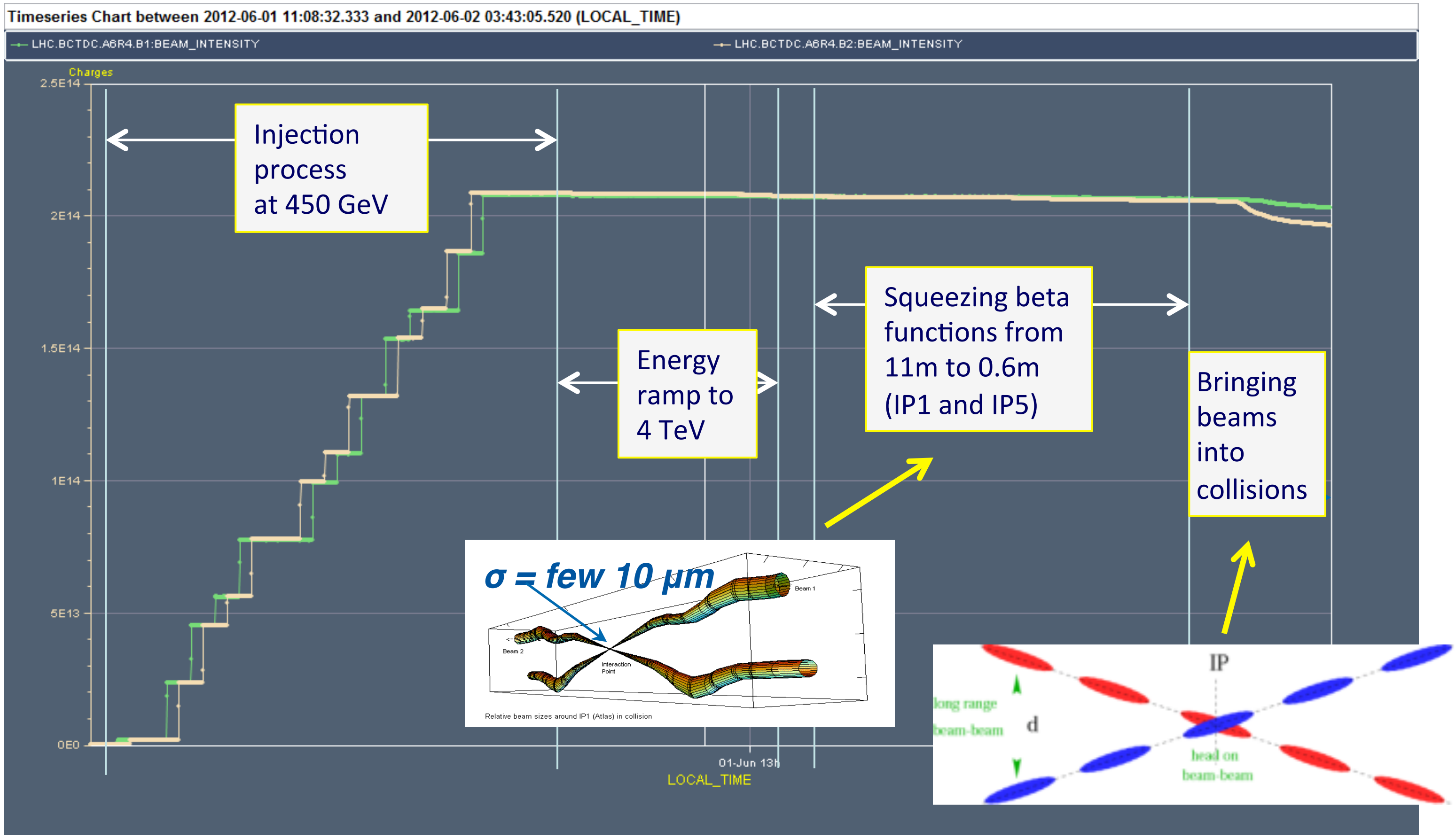
LHC cycle – Injection of beams

- Inject beams, starting with very small pilot beam
- Then steps of 144/288b
- Verification of beam parameters (position, dimensions, profiles, tune,…)
- Followed by energy ramp (Magnets + RF in parallel)

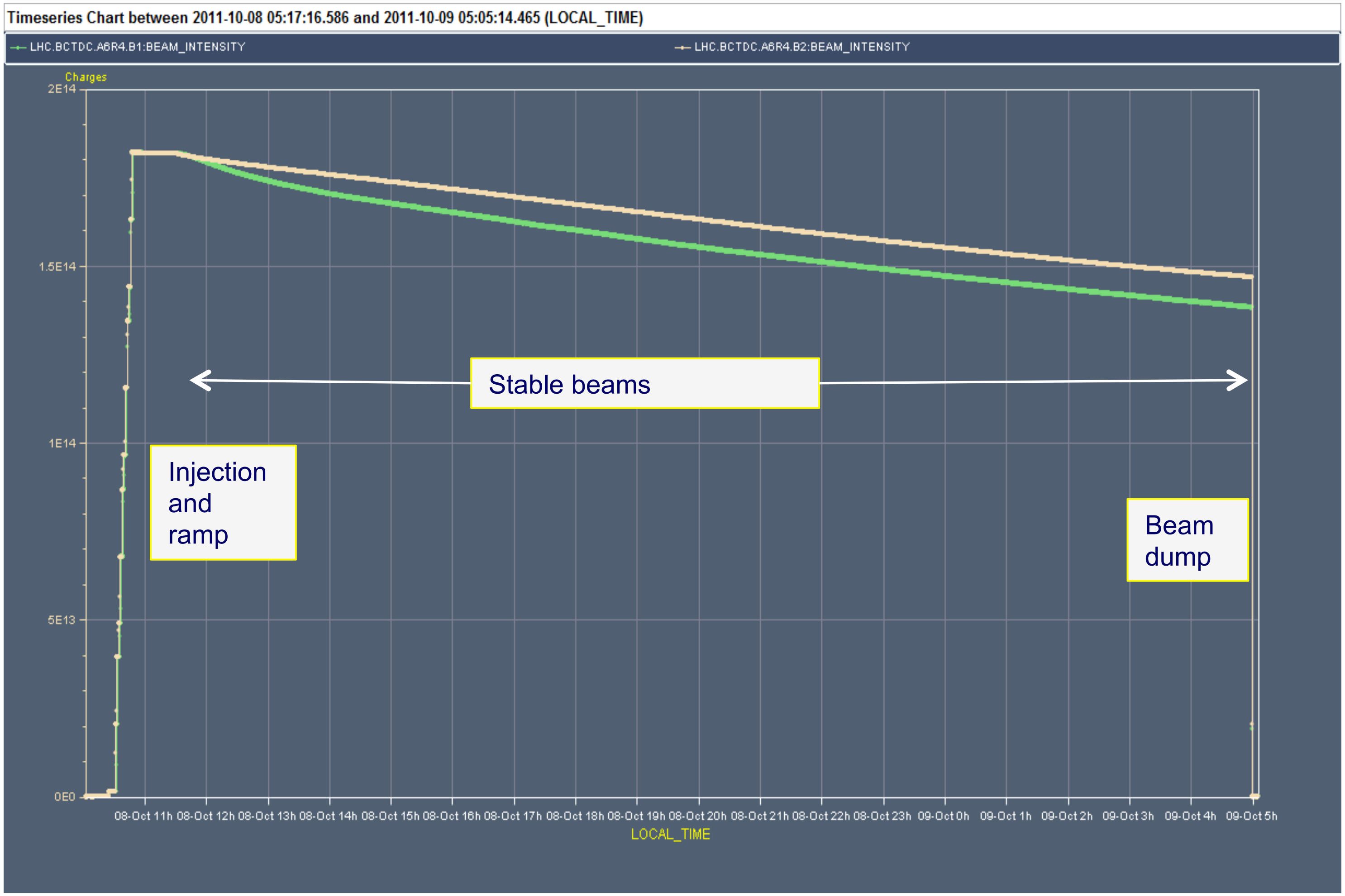



Beam Position

LHC cycle – Squeeze and Collide



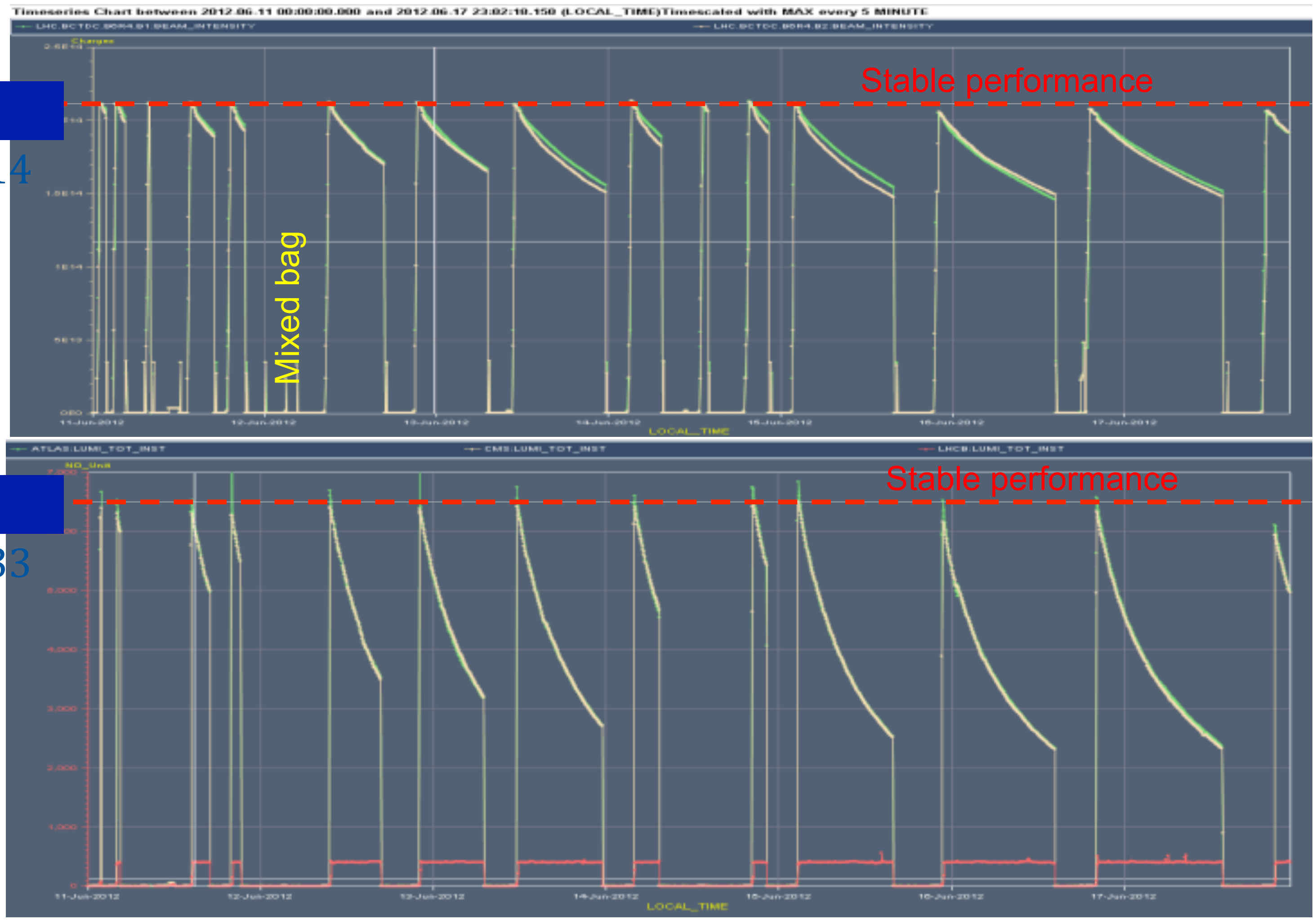
LHC cycle – Stable Beams



Beam Intensity and Luminosity, 11-18/6/2012

2×10^{14}

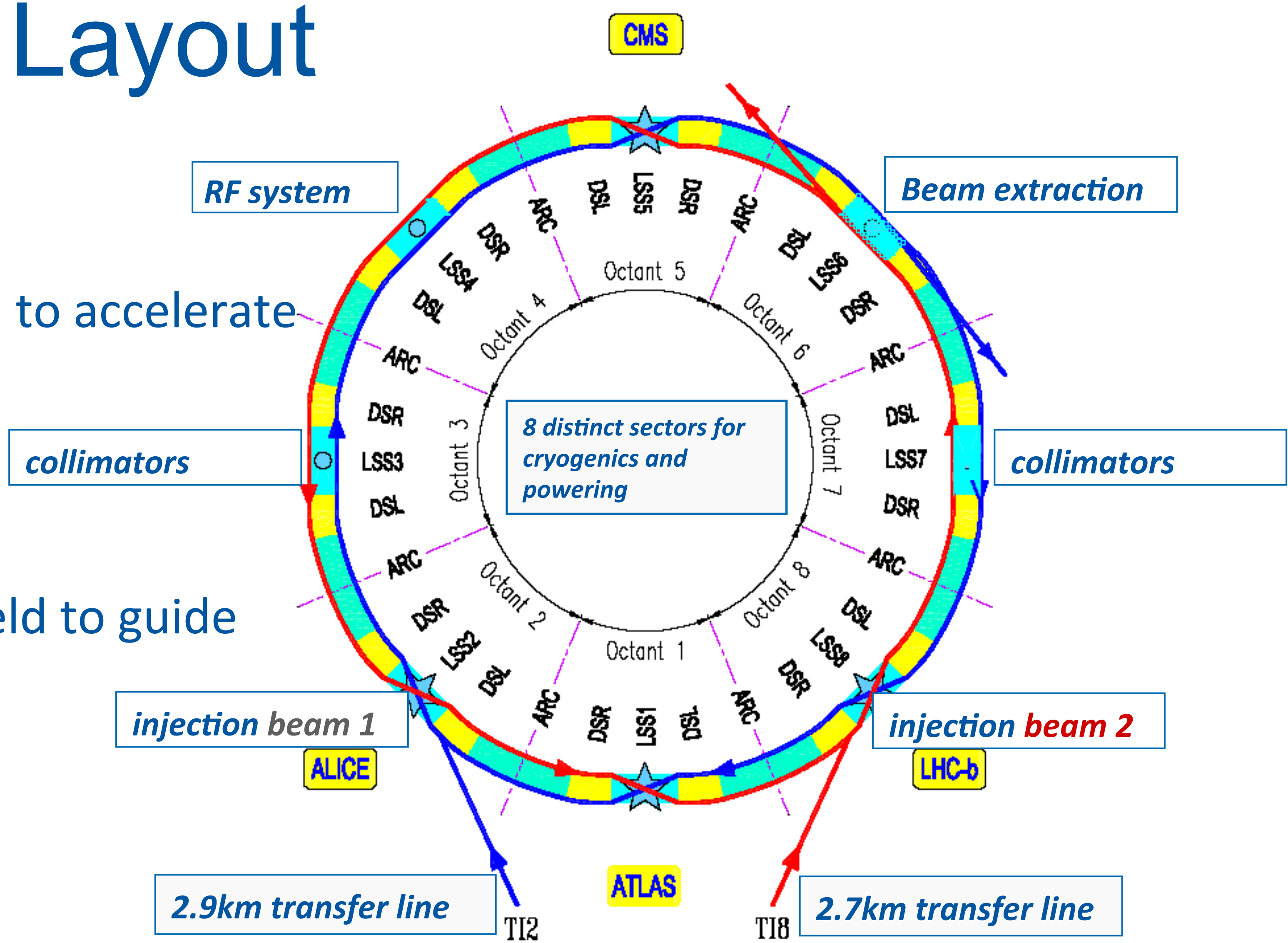
6×10^{33}



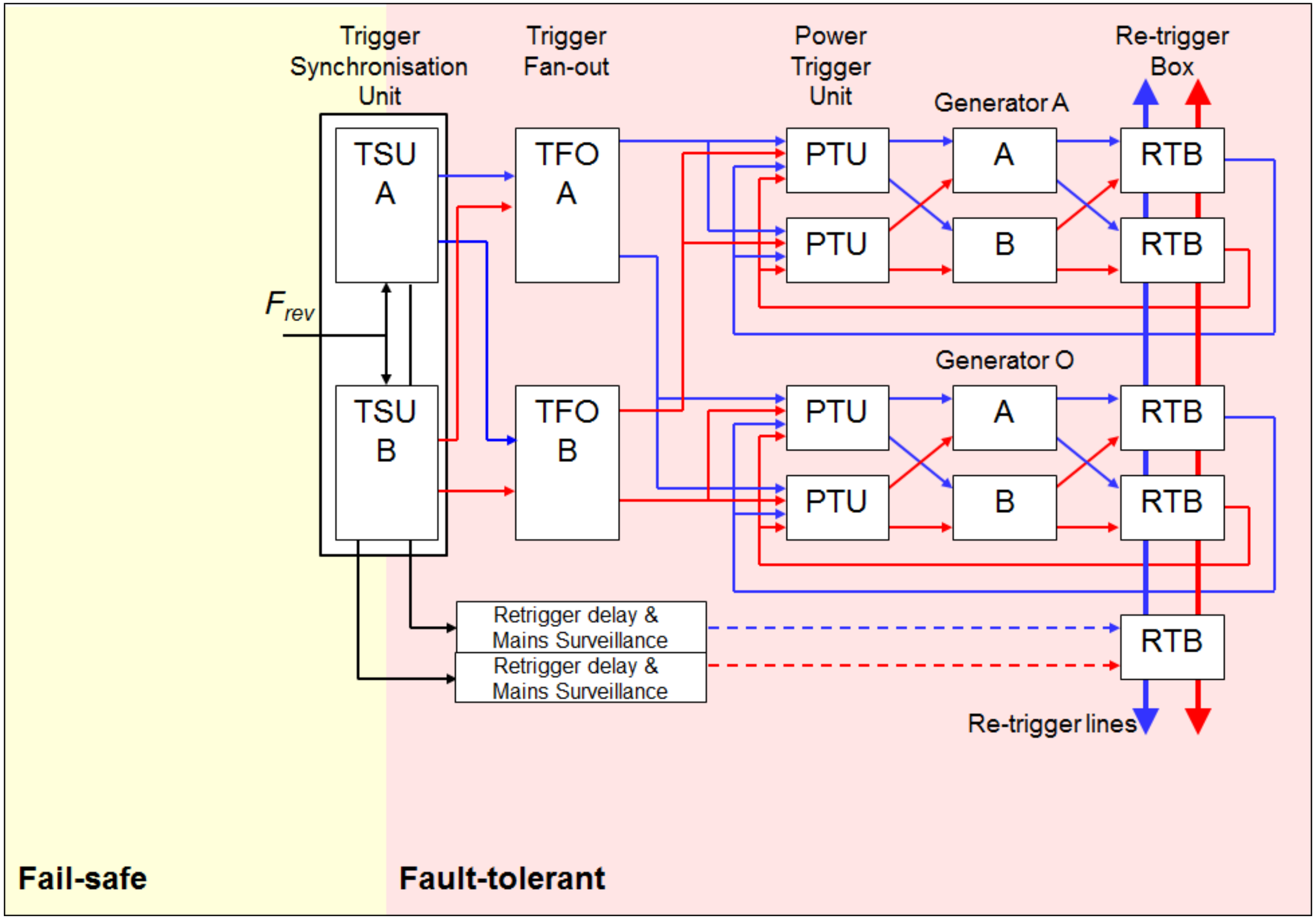
LHC Layout

Electric field to accelerate the beam

Magnetic field to guide the beam

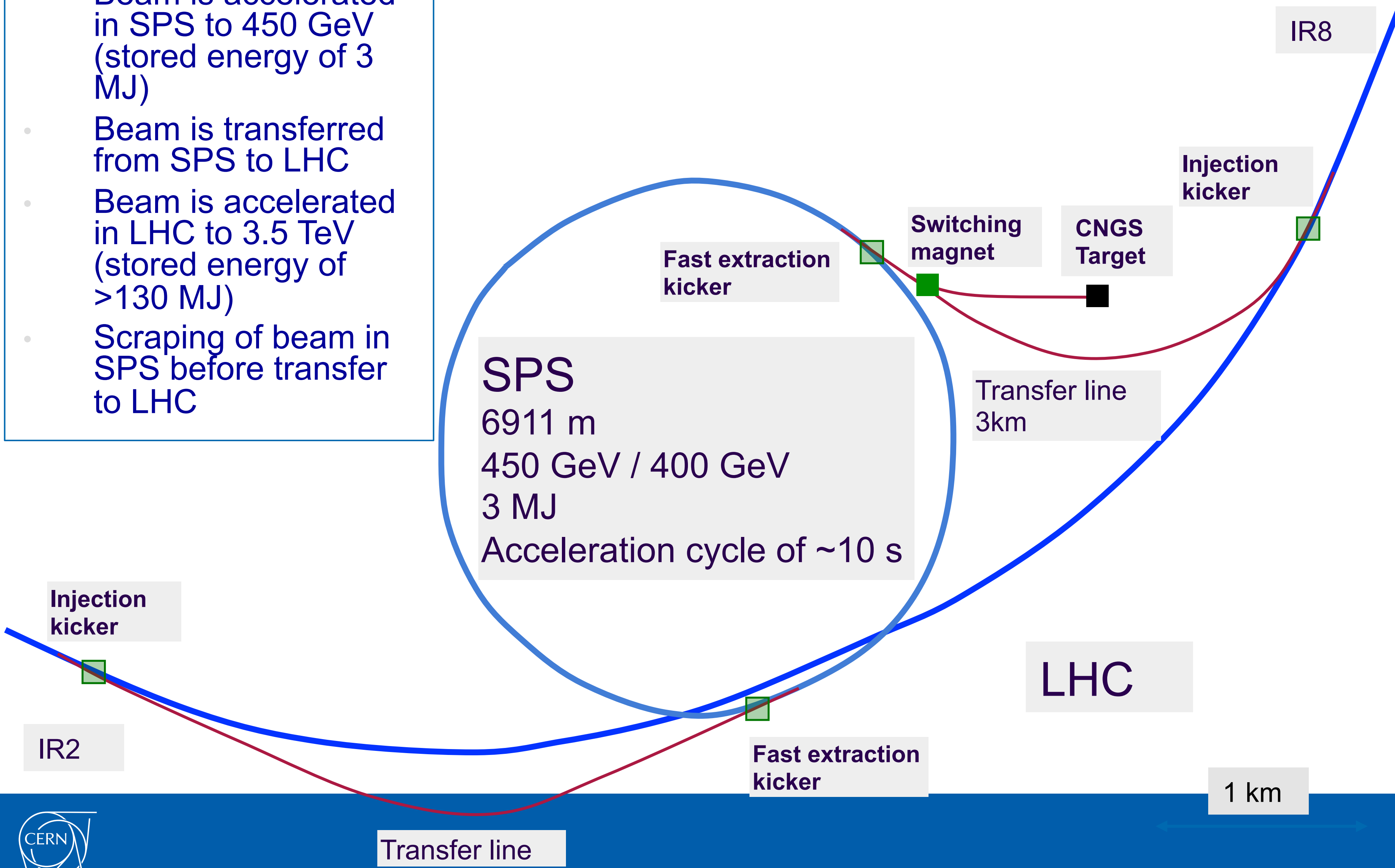


LBDS and Trigger Synchronisation Unit

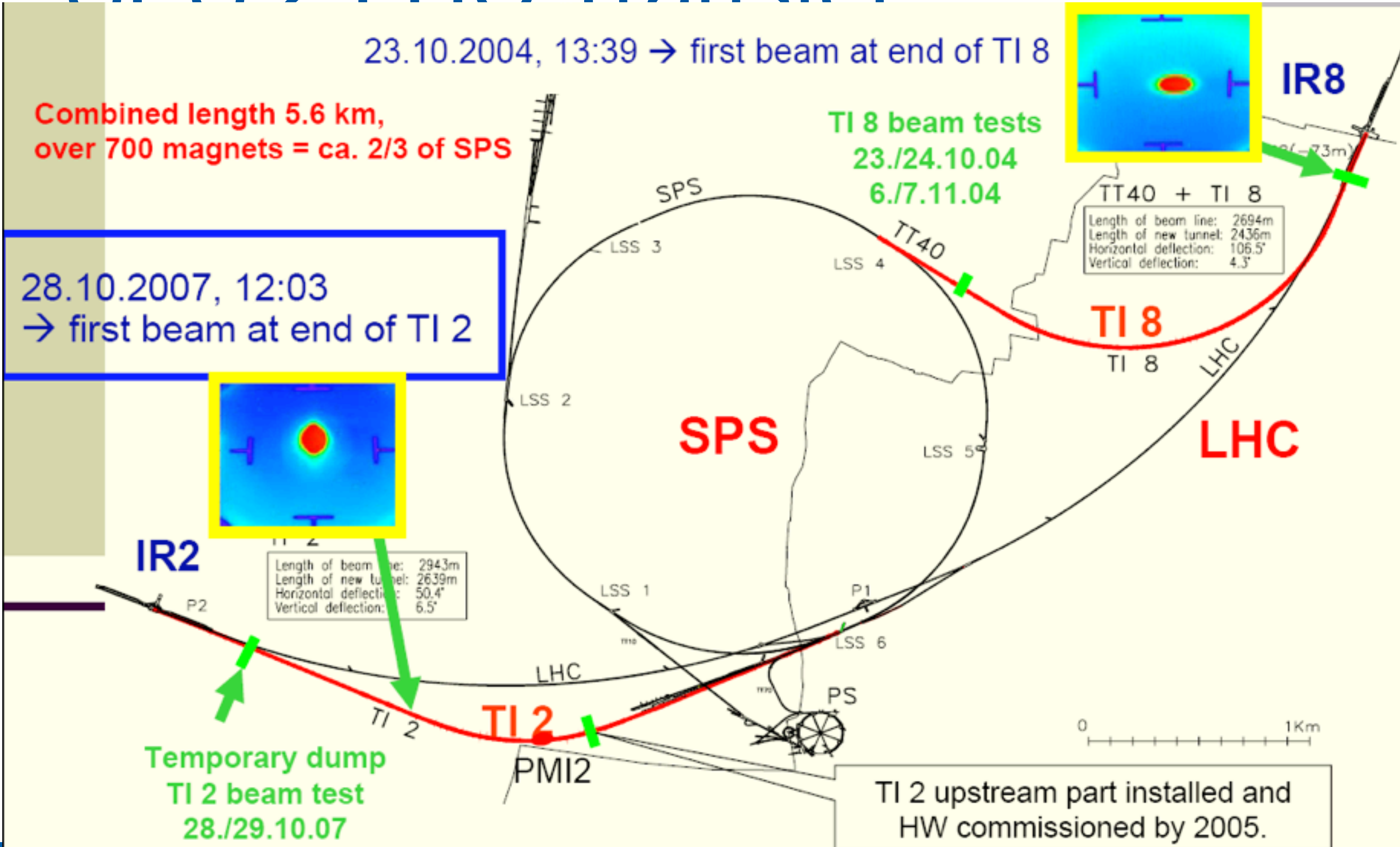


SPS, transfer line and LHC

- Beam is accelerated in SPS to 450 GeV (stored energy of 3 MJ)
- Beam is transferred from SPS to LHC
- Beam is accelerated in LHC to 3.5 TeV (stored energy of >130 MJ)
- Scraping of beam in SPS before transfer to LHC

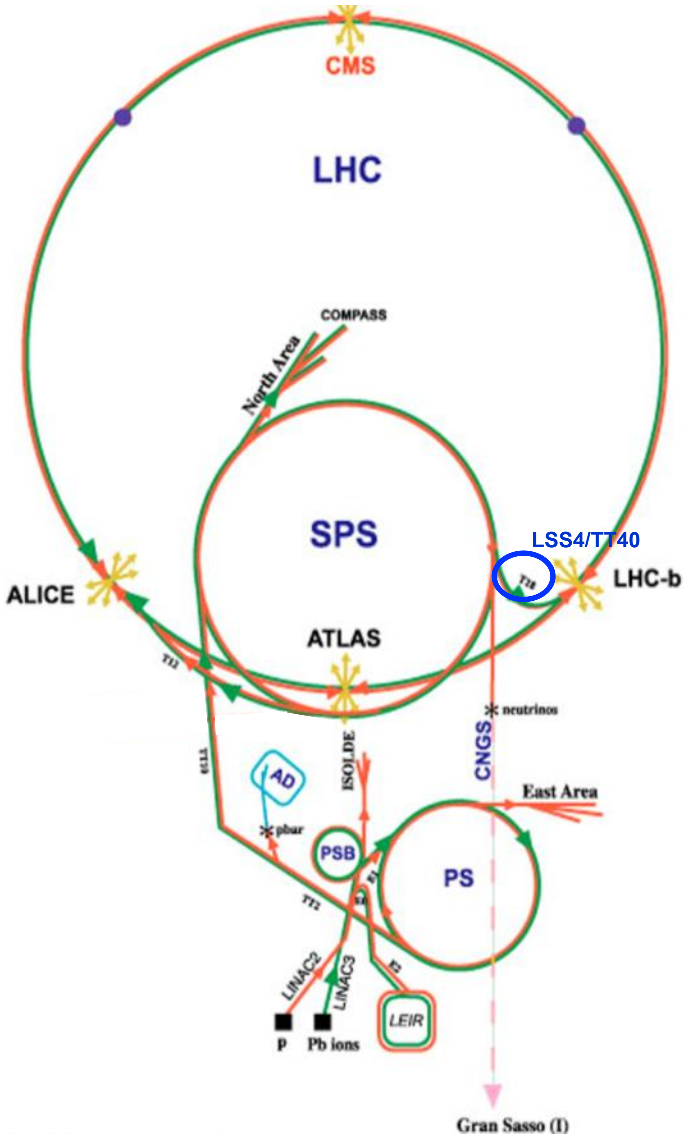


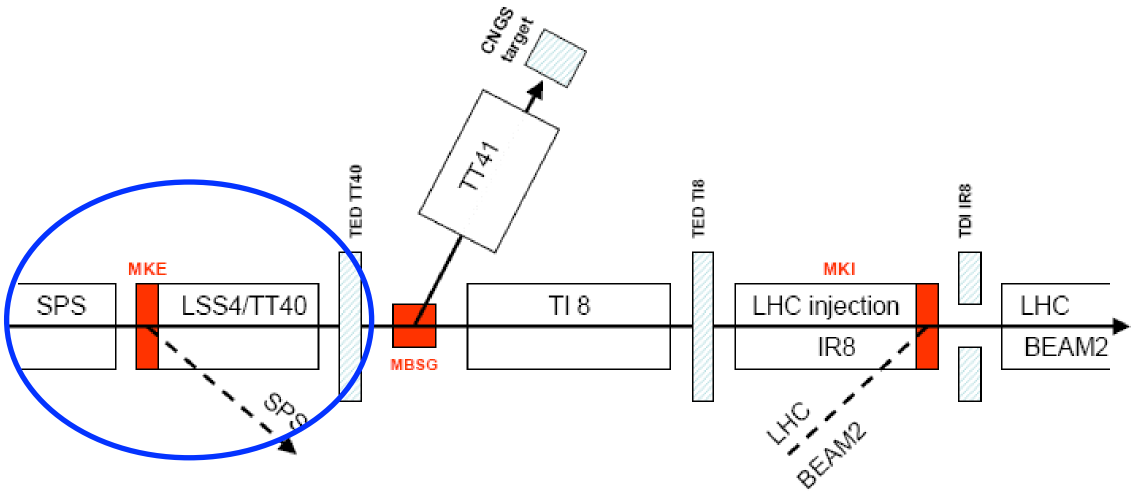
SPS 2 LHC Transfer

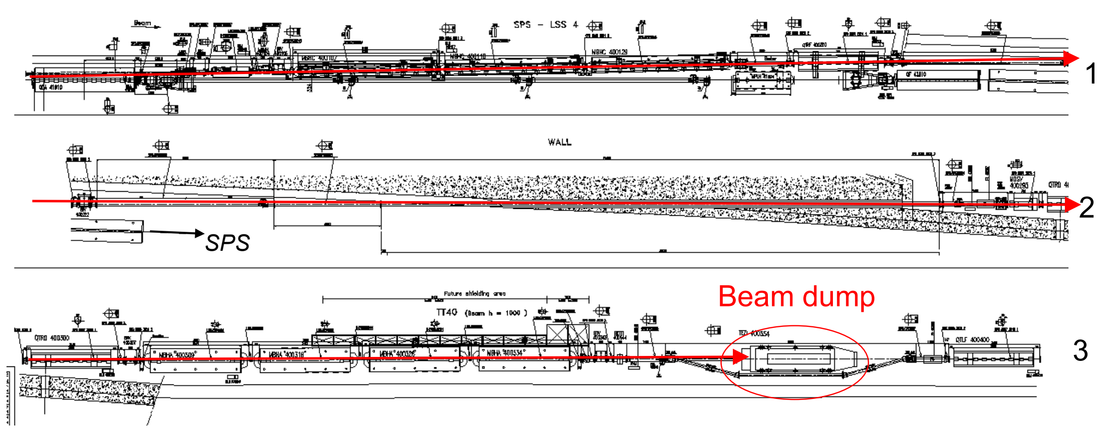


- Large amount of energy stored in the beams
- Injecting beams, performing the energy ramp and bringing the beams into collisions …. without quenching or even damaging accelerator and experiments
- Dumping 130 MJ beam without quenching magnets
- Detecting all failures that could lead to uncontrolled beam losses
- Avoiding beam losses, in particular in the superconducting magnets
  - Magnet quench limits when 10^{-8}-10^{-7} of beam hits magnet at 7 TeV
  - Beam cleaning (Betatron and momentum cleaning) is vital during operation
  - Collimator position depends on energy and on beta function at collision point
- Radiation, in particular in experimental areas from beam collisions
  - Single event upset in the tunnel electronics

Extraction event in TT40 in fall 2004







First 100m of TT40 transfer line (to movable beam dump)