ED PHENIICS

Understanding basic principles of particle accelerators

Zoom on the LHC

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THE LHC

Note: most slides from today lecture are taken from seminars and conference presentation by others. In particular: F. Zimmerman, M. Lamont,…

short LHC history

1983 *LEP Note 440* - S. Myers and W. Schnell propose twin-ring *pp* collider in LEP tunnel with 9-T dipoles

1991 CERN Council: LHC approval in principle

1992 EoI, LoI of experiments

1993 SSC termination

1994 CERN Council: LHC approval

1995-98 cooperation w.Japan,India,Russia,Canada,&US

2000 LEP completion

2006 last s.c. dipole delivered

2008 first beam

2010 first collisions at 3.5 TeV beam energy

2015 collisions at ~design energy (plan)

we are already late if we want to get a new machine by ~2040!

>30 years!

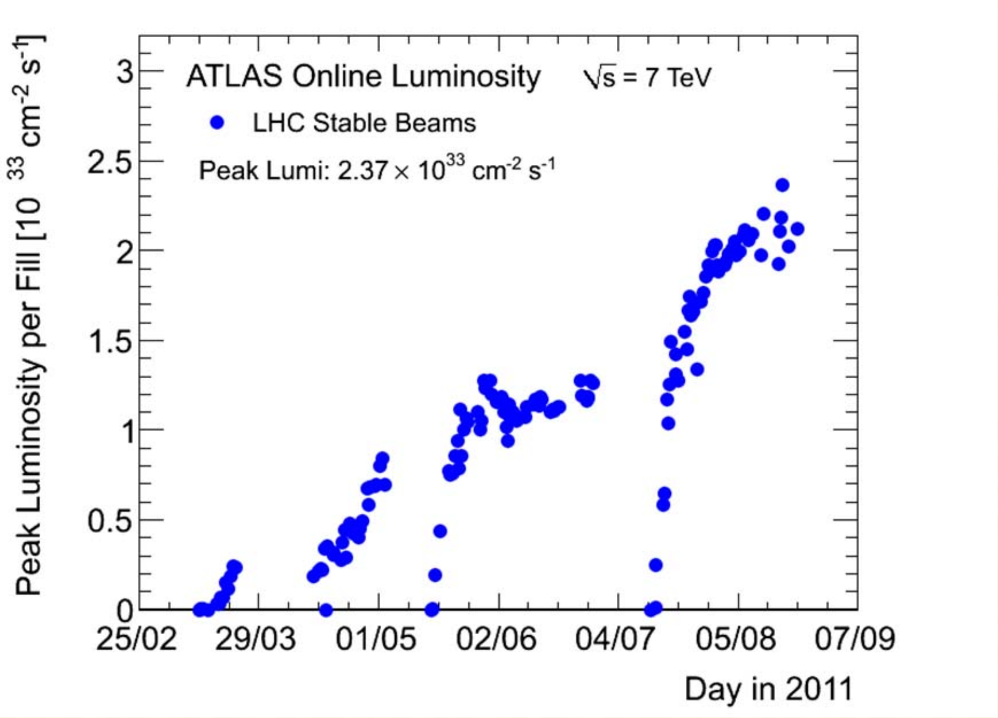
LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

A complex enterprise

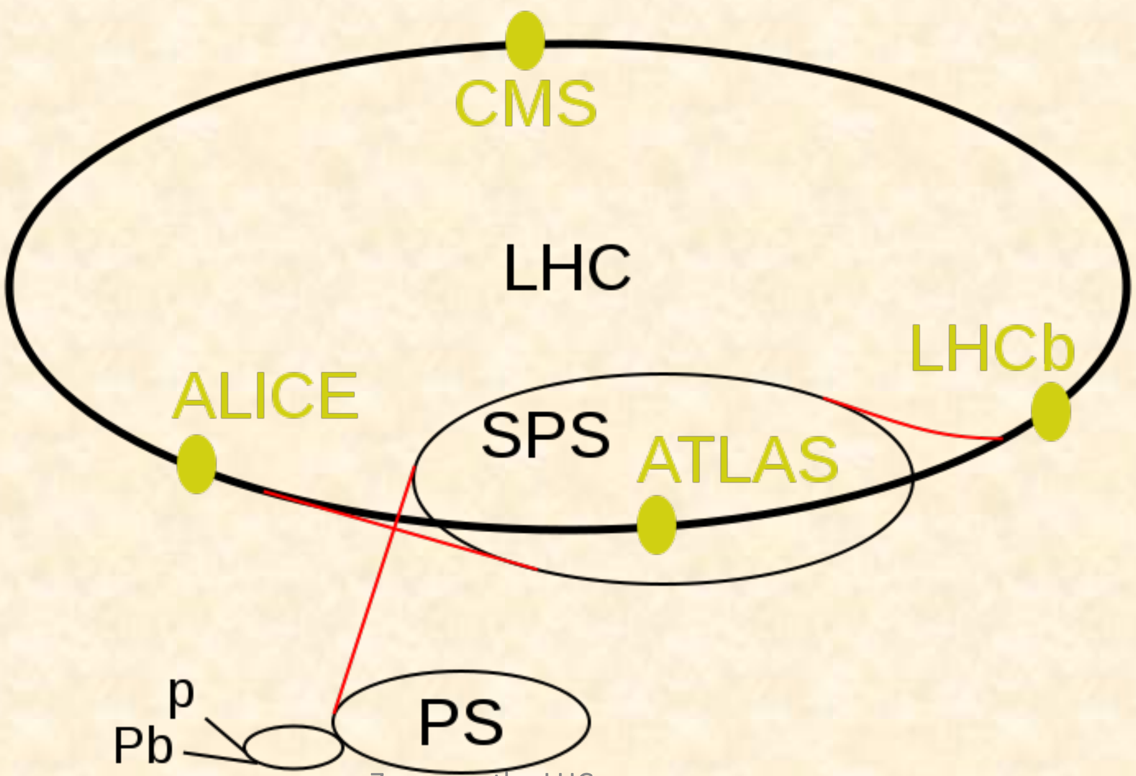
- Beyond the particle physics challenges associated with the construction of the detectors and the analysis of the data, building and operating the LHC machine was also an immense challenge involving a large number of skills.
- The machine has not yet reached its full potential and the engineers running it improve its performance all the time.



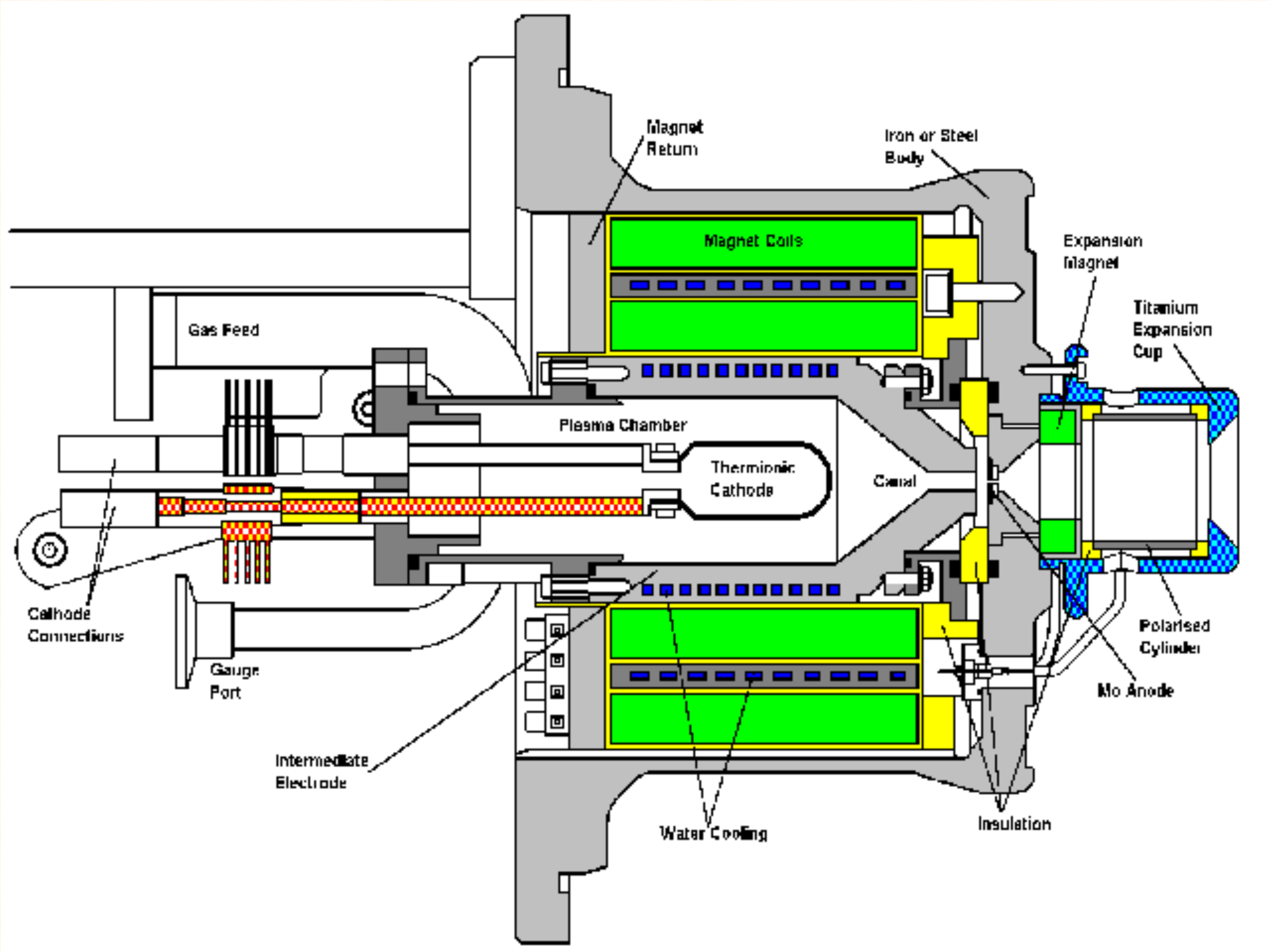
References: http://lhc.web.cern.ch/lhc/LHC-DesignReport.html and
« The LHC Machine, Lyndon Evans and Philip Bryant 2008 *JINST* **3** S08001 doi:10.1088/1748-0221/3/08/S08001 »

The injection chain

- Particles can not directly be produced and accelerated in the LHC, several preliminary steps are necessary.
- Let's follow a proton from the source to the collisions…

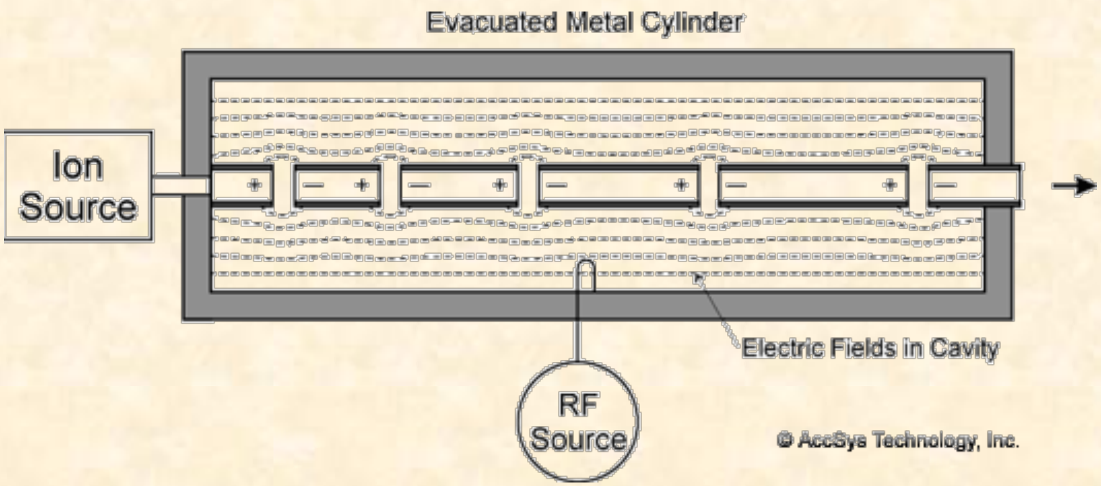


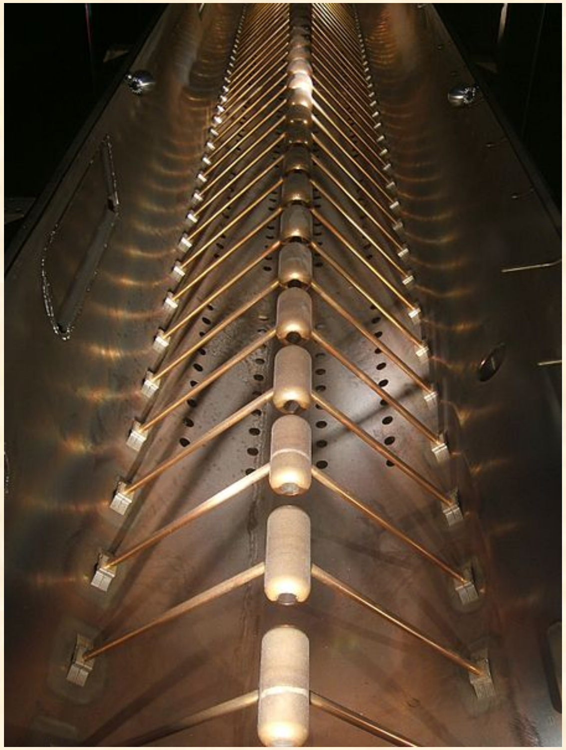
Proton source



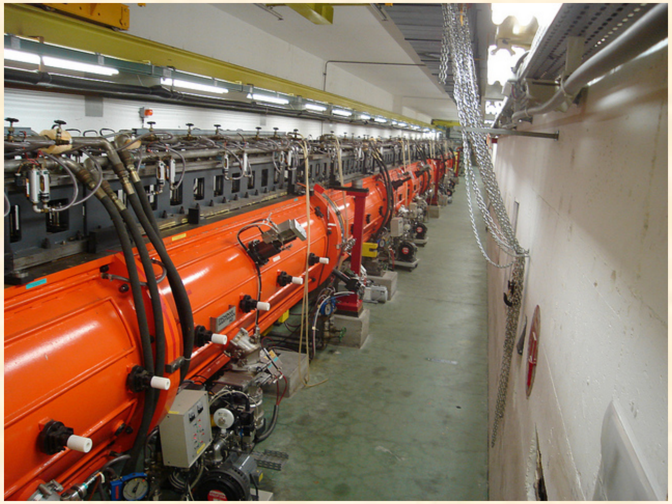
- Particles are extracted by ionisation of hydrogen as in a device called "Duoplasmotron Proton Ion source"

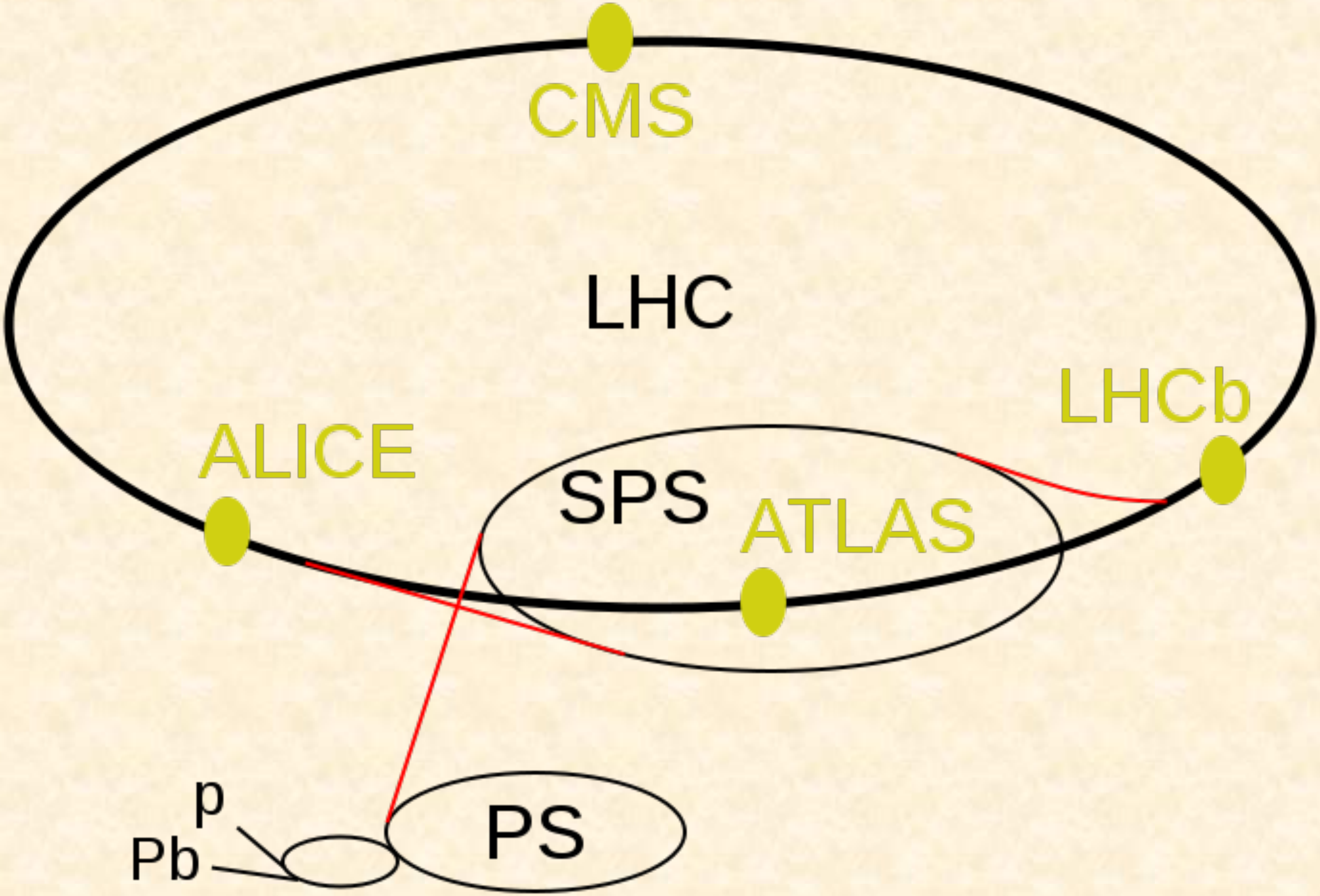
Linac





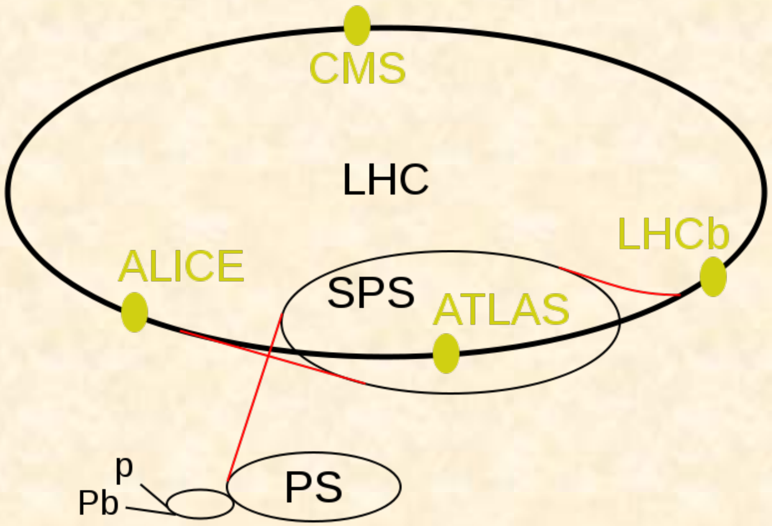
- After the source the protons are accelerated in a linac.
- As the protons gain speed they travel longer distance in a RF cycle and therefore the length of the tubes must be increased.
- At the end of the Linac the protons reach an energy of 50 MeV.

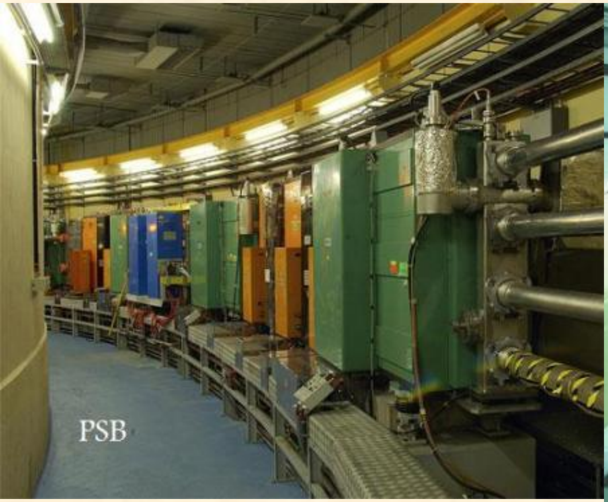



CMS
LHC
LHCb
ALICE
SPS
ATLAS
p
Pb
PS

Pre-acceleration rings

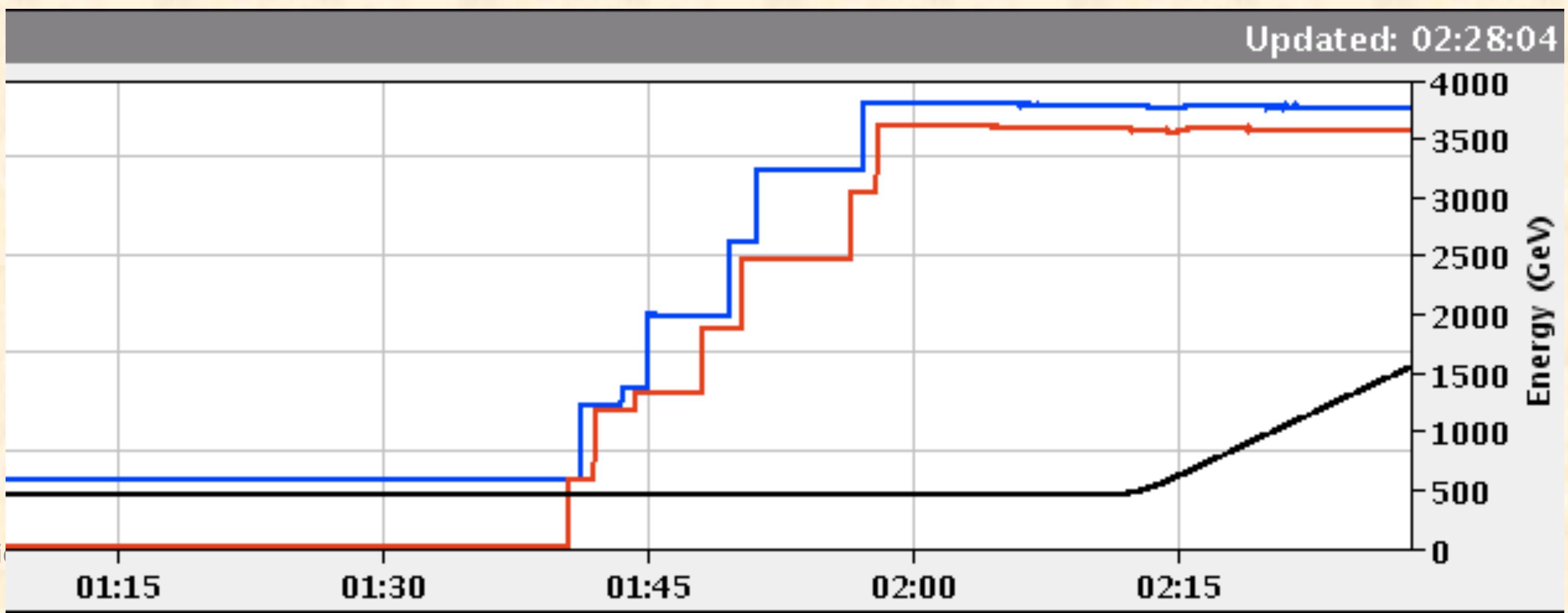
- At 50 MeV the energy of the protons is too low to be injected in the LHC.
- Several intermediate rings are necessary to bring their energy to the LHC injection energy.
- To save space the first of these rings, the PS booster is made of 4 rings stacked on to each other!
- All these rings use pulsed magnets which allow to change the beam configuration very quickly.
- The PS was built in 1959, the PSB in 1972 and the SPS in 1976.





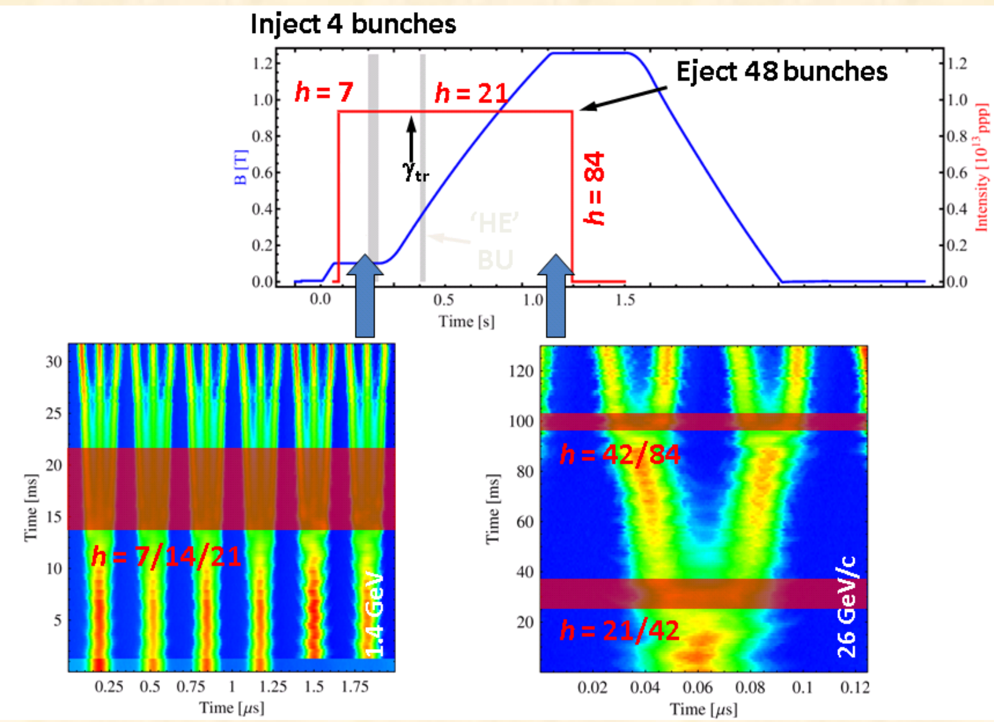
Why pre-acceleration rings?

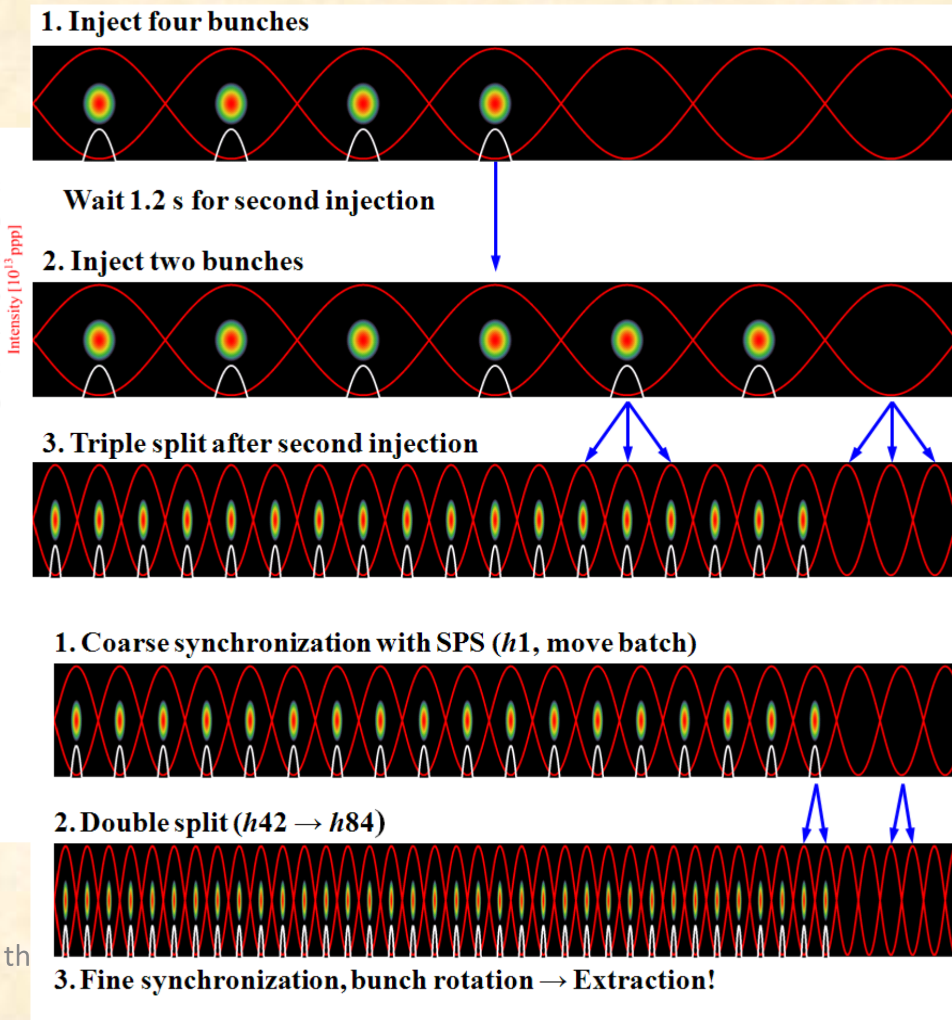
- In a synchrotron the strength of the magnets must be increased when the energy of the particles is increased.
- It is cheaper to have magnets (and power supplies) with a limited dynamic range.
- As the energy of the beam increases its emittance (and therefore its size) decreases.
  Early accelerators in the acceleration chain must have a wide aperture whereas the LHC has a small aperture (a bunch from the Linac would not fit in the LHC).



Protons bunch splitting

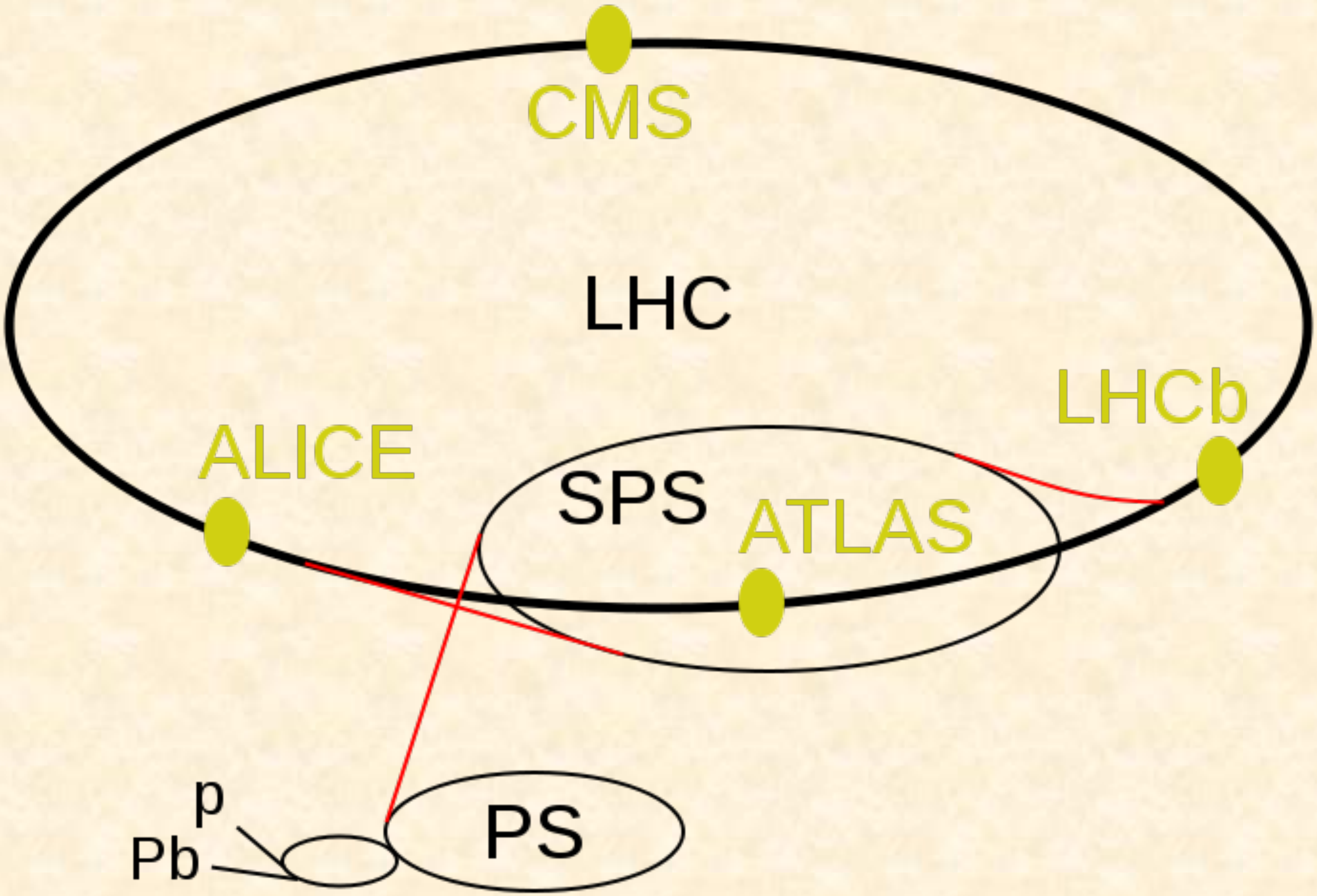
- Another purpose of the PS is to adapt the bunch structure from the Linac to the requirements of the LHC.
- The RF of the PS is used to split 8 proton bunches into 84 bunches!





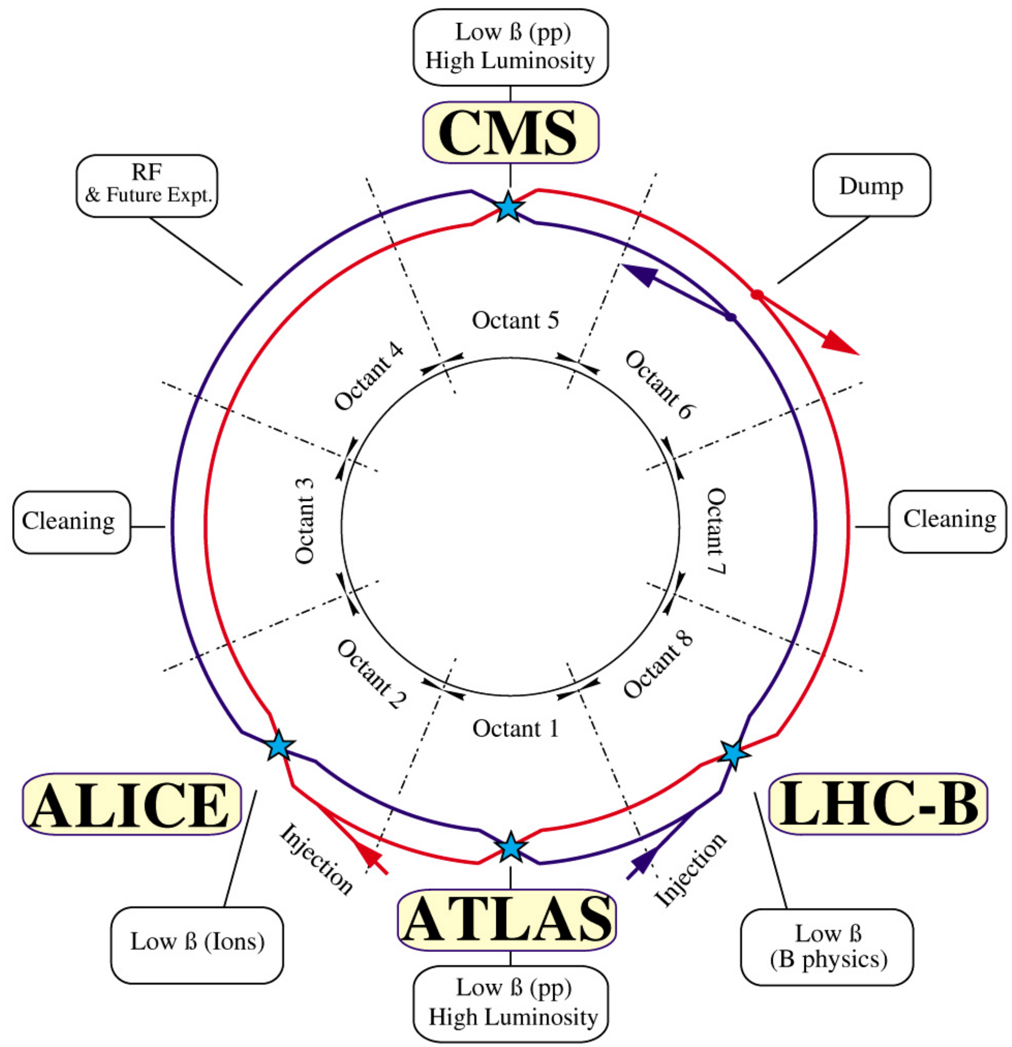
Multi turn extraction from the SPS

The LHC itself



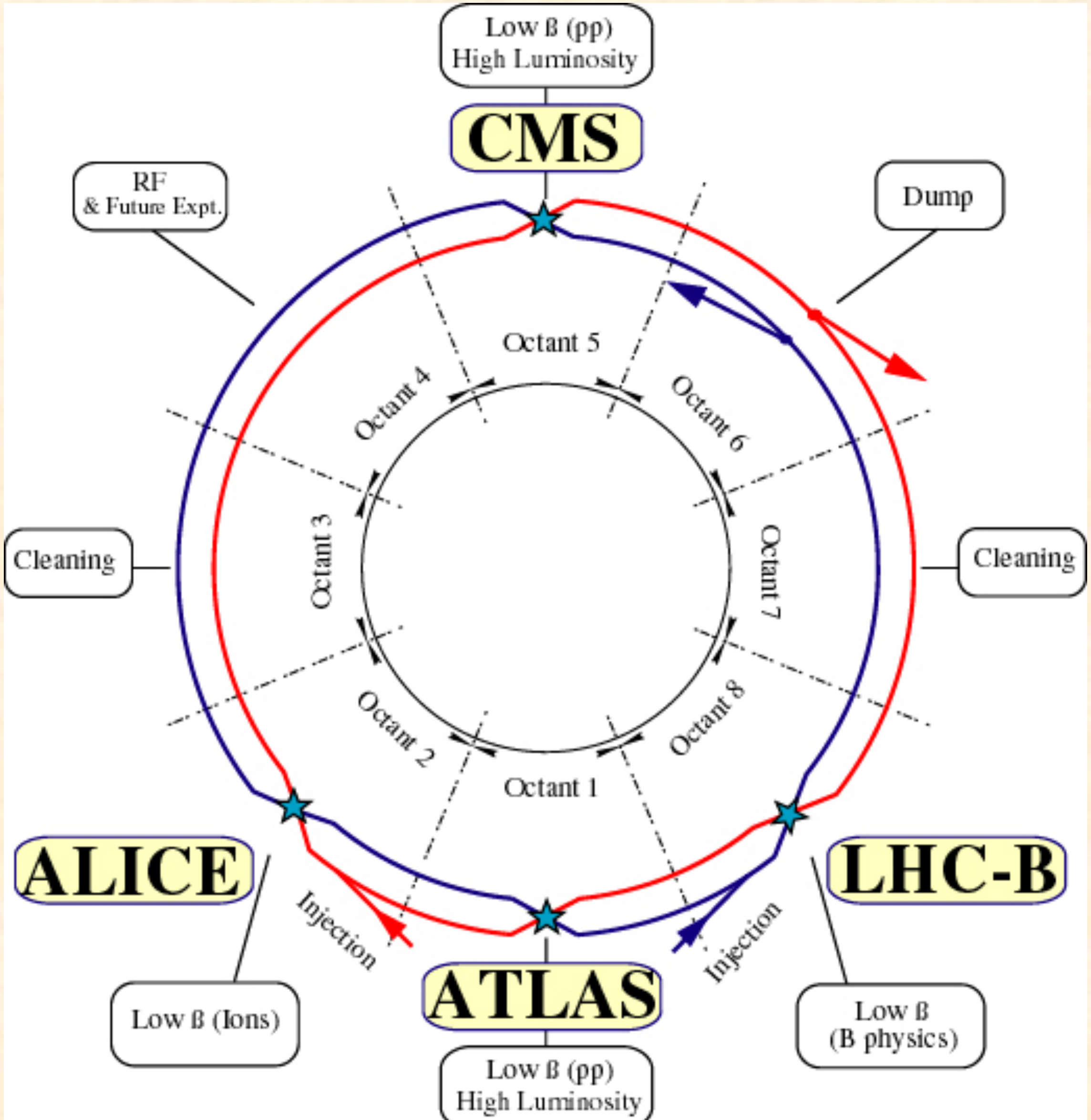
The LHC

- Circumference: 26659m
- Injection energy: 450 GeV
- 9300 magnets (1232 dipoles, 858 quadrupoles,…)
- Power consumption: 180MW



CERN AC _ EI2-4A_ V18/9/1997

LHC: highest energy *pp*, *AA*, and *pA* collider



design parameters

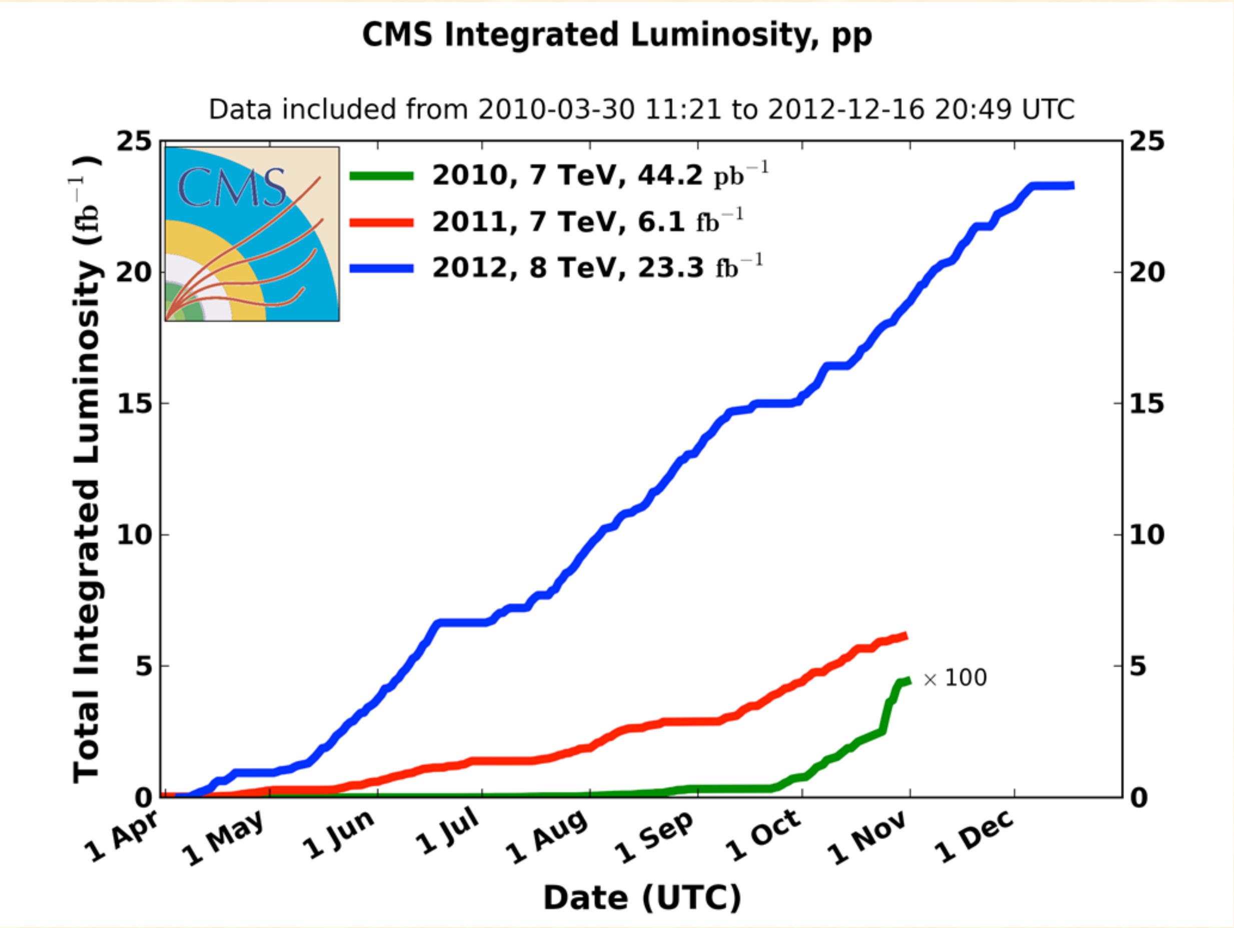
c.m. energy = 14 TeV (*p*)
luminosity $=10^{34}\ cm^{-2}s^{-1}$

1.15×10^{11} p/bunch
2808 bunches/beam

360 MJ/beam

$\gamma\varepsilon=3.75\ \mu m$
$\beta^*=0.55$ m
$\theta_c=285\ \mu rad$
$\sigma_z=7.55$ cm
$\sigma^*=16.6\mu m$

integrated *pp* luminosity 2010-12

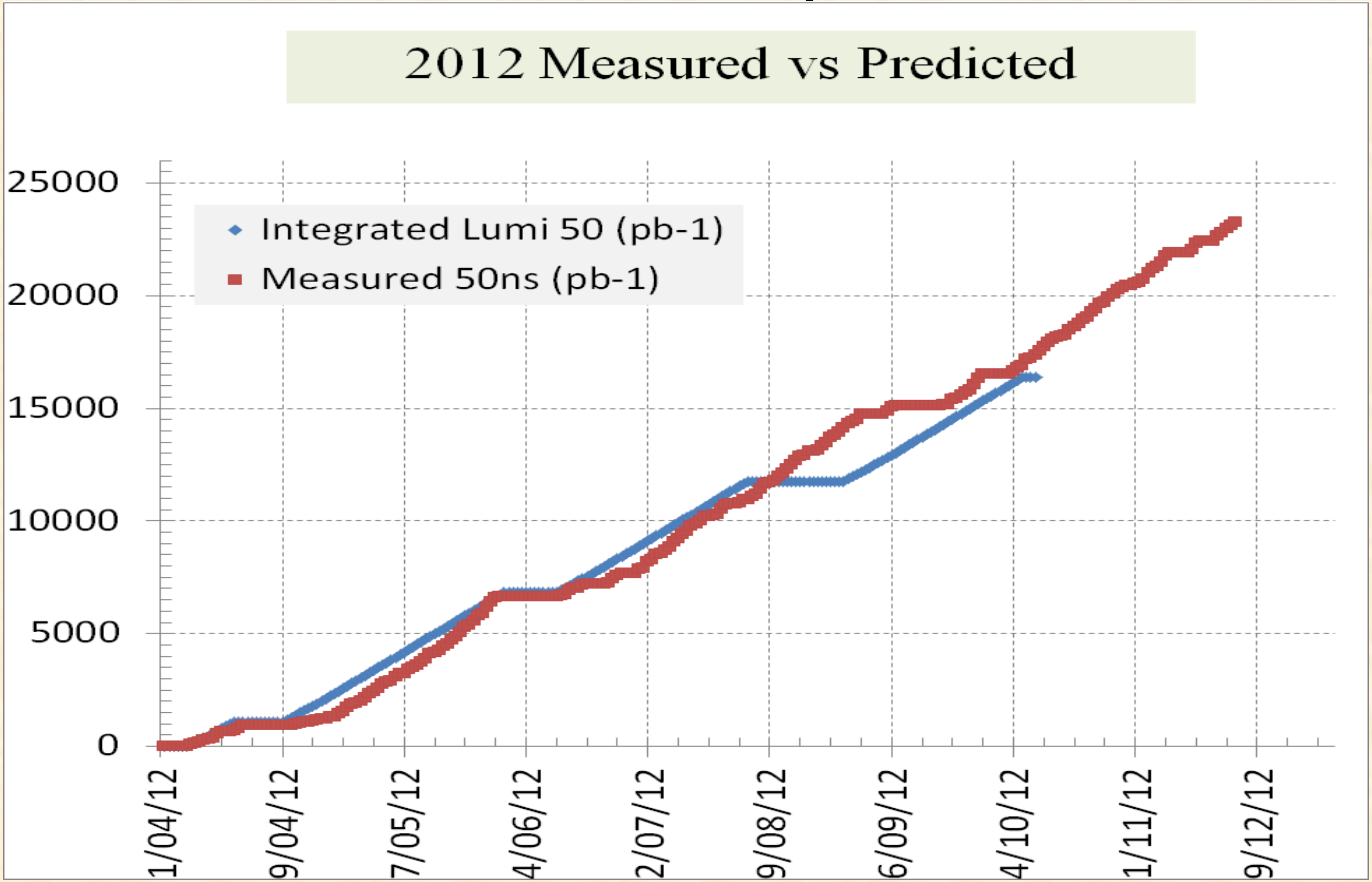


- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

M. Lamont, IPAC'13

Steve Myers, CMAC

reliable luminosity forecasts



peak performance through the years

	2010	2011	2012	Nominal
bunch spacing [ns]	150	50	50	25
no. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
max. **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
normalized **emittance** [mm-mrad]	~2.0	~2.4	~2.5	3.75
peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

>2x design when scaled to 7 TeV!

M. Lamont, IPAC'13

Quizz

- Suggest reasons to explain the limitations of the parameters in the table.

	2010	2011	2012	Nominal
bunch spacing [ns]	150	50	50	25
no. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
max. **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
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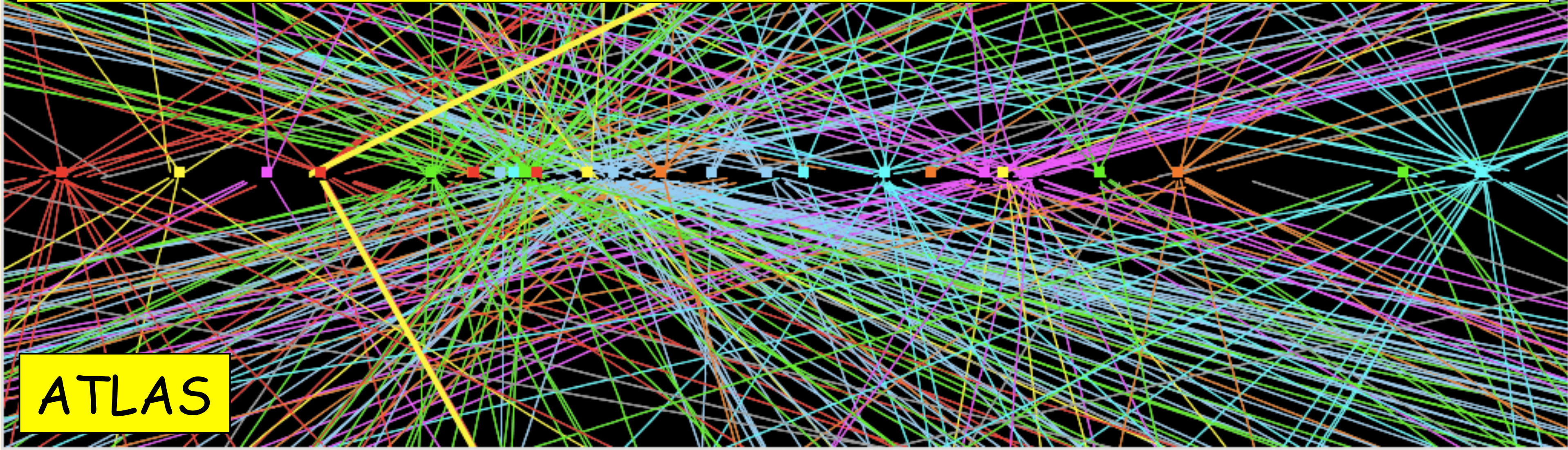
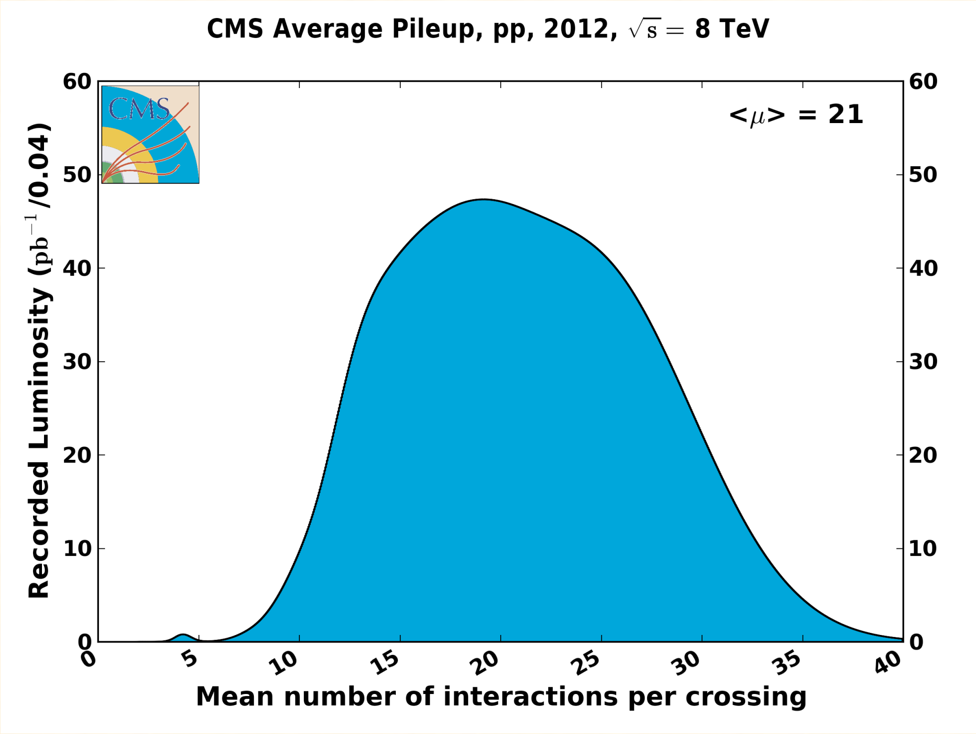
Answer

- Bunch spacing: if the bunches are too close they affect each other with their wake.
- Beta: if the bunches are too small, internal effects (space charge, IBS,…) can destroy the bunches…
- Intensity: It is difficult to accumulate charge in a bunch. Losses all along the injection chain must be well controlled.

Z→ μμ event from 2012 data with 25 reconstructed vertices

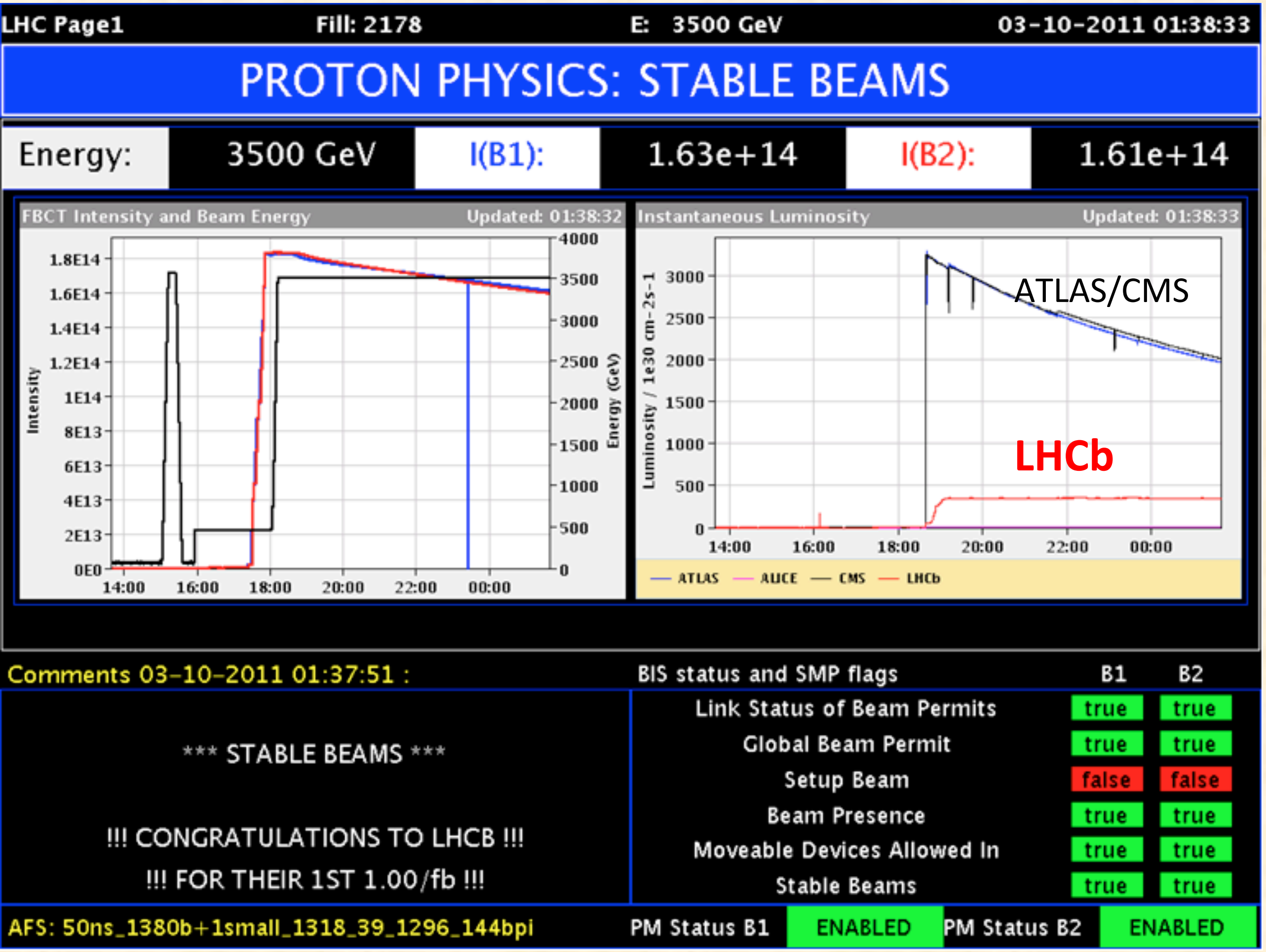




pile up
will increase
at higher energy
→
experiments
request
25 ns
operation
in 2015

M. Lamont, IPAC'13

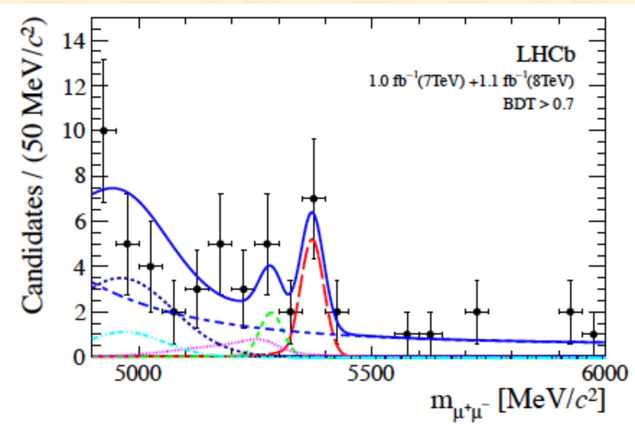
LHCb



luminosity levelling at around 4e32 $cm^{-2}s^{-1}$ via transverse separation (with a tilted crossing angle)

not completely trivial!

first evidence for the decay $B_s \rightarrow \mu^+ \mu^-$



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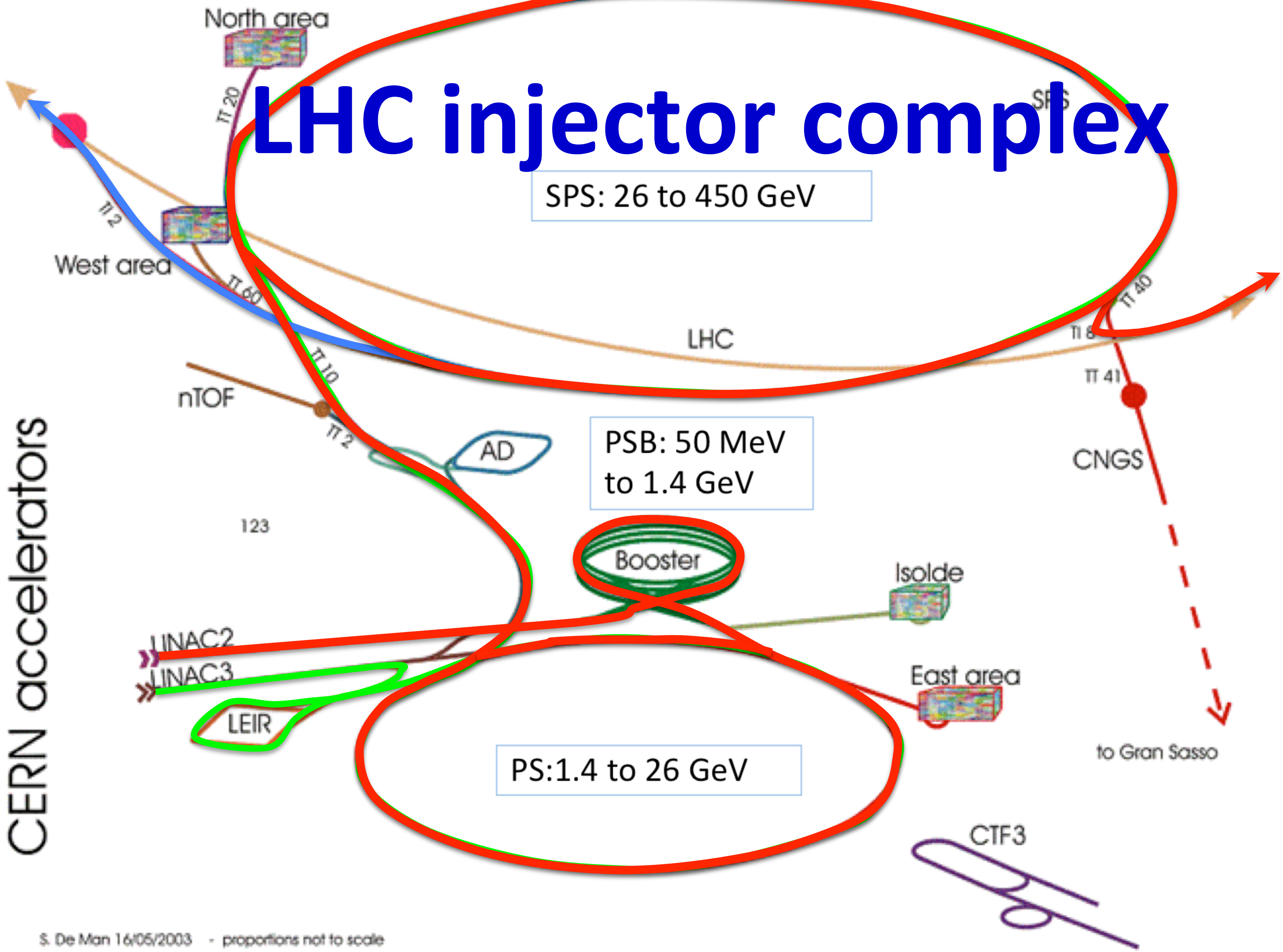
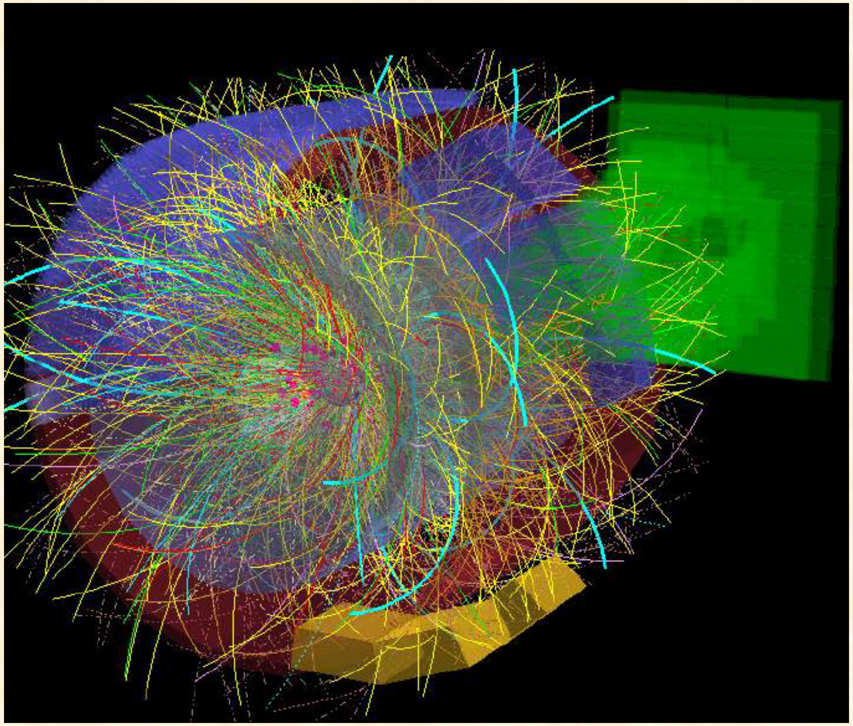
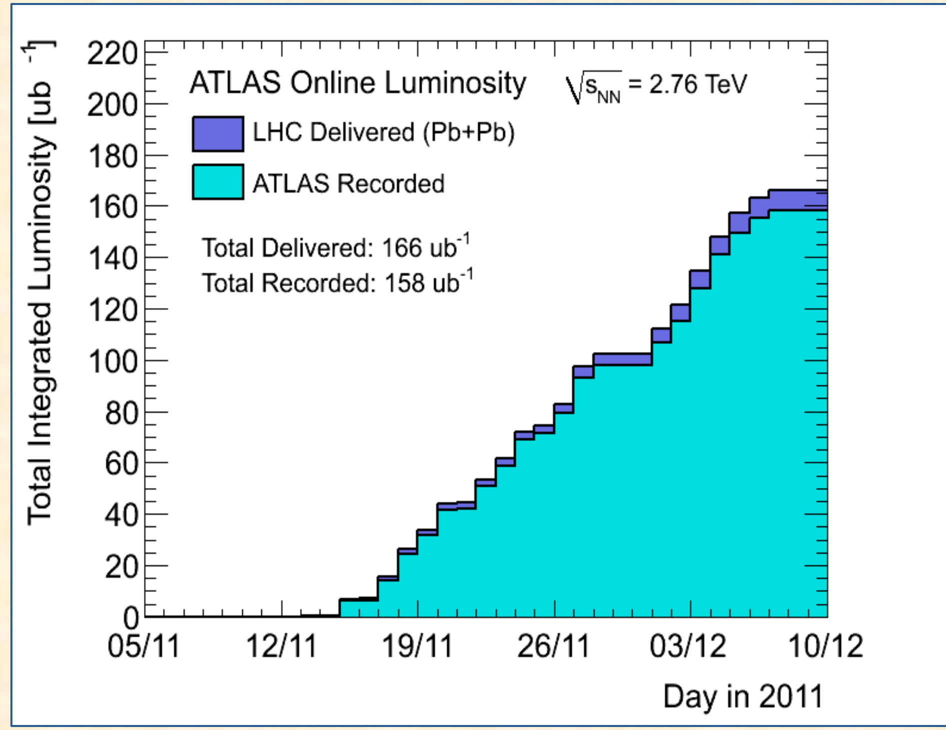
LHC injector complex



M. Lamont

Pb-Pb

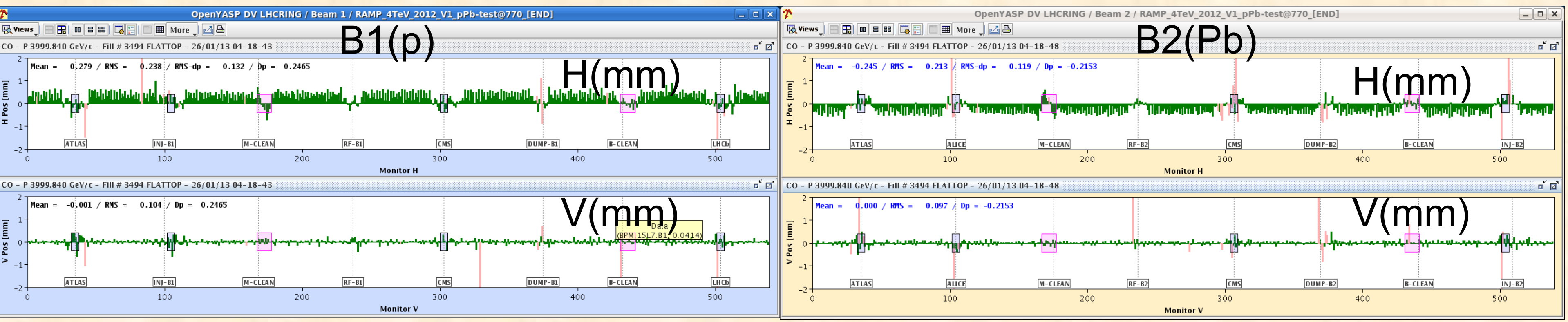




- good performance from the injectors - bunch intensity and emittance
- preparation, Lorentz' law: impressively quick switch from protons to ions
- peak luminosity around 5 x 10^{26} $cm^{-2}s^{-1}$ at 3.5*Z* TeV (2011) – nearly twice design when scaled to 6.5*Z* TeV

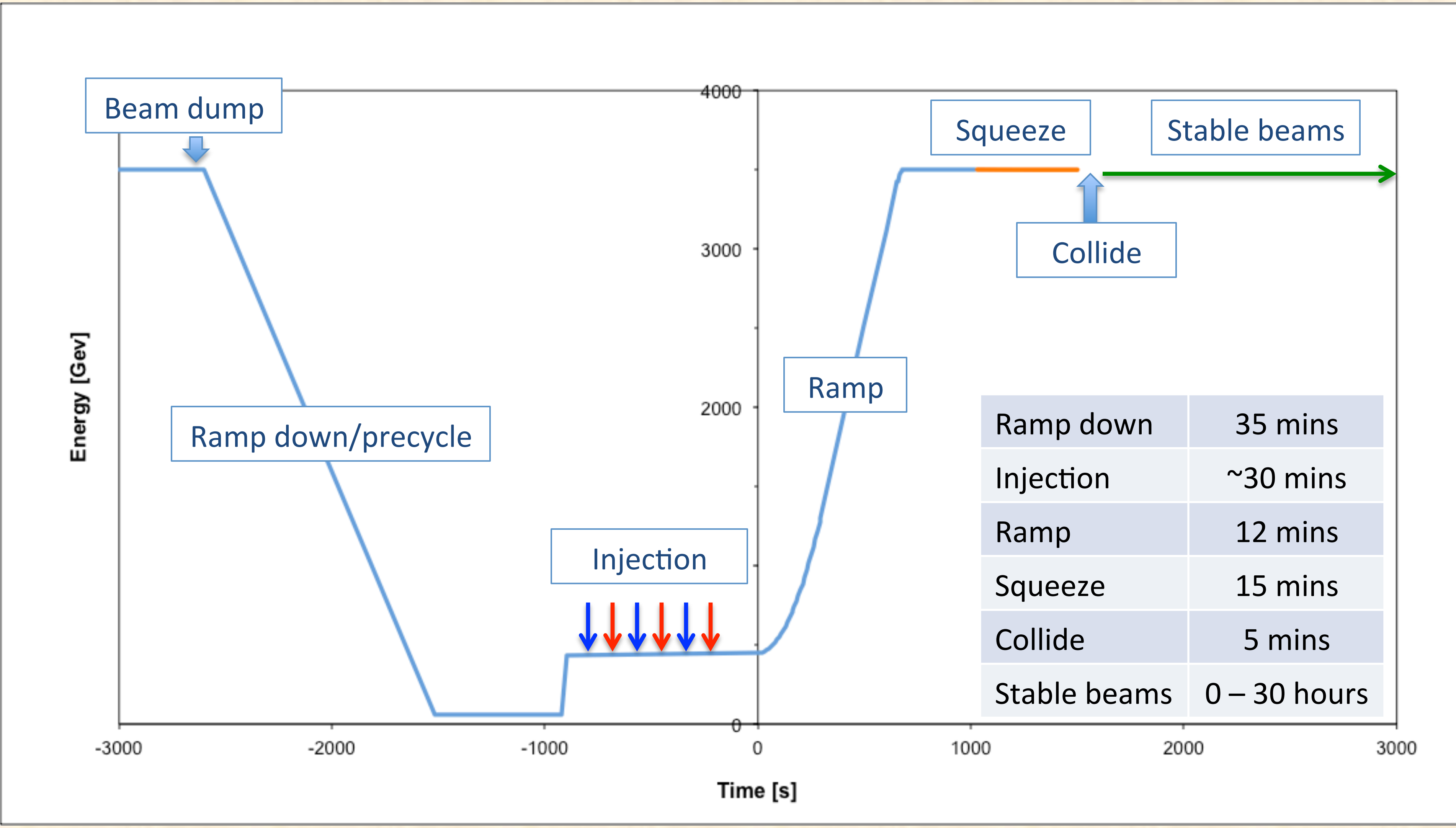
proton-lead

- beautiful result in early 2013
- final integrated luminosity above experiments’ request of 30 nb^{-1}
- injectors: average number of ions per bunch was ~1.4×10^8 at start of stable beams, i.e. around twice the nominal intensity



beam orbits at top energy with RF frequencies locked to Beam 1

operational cycle

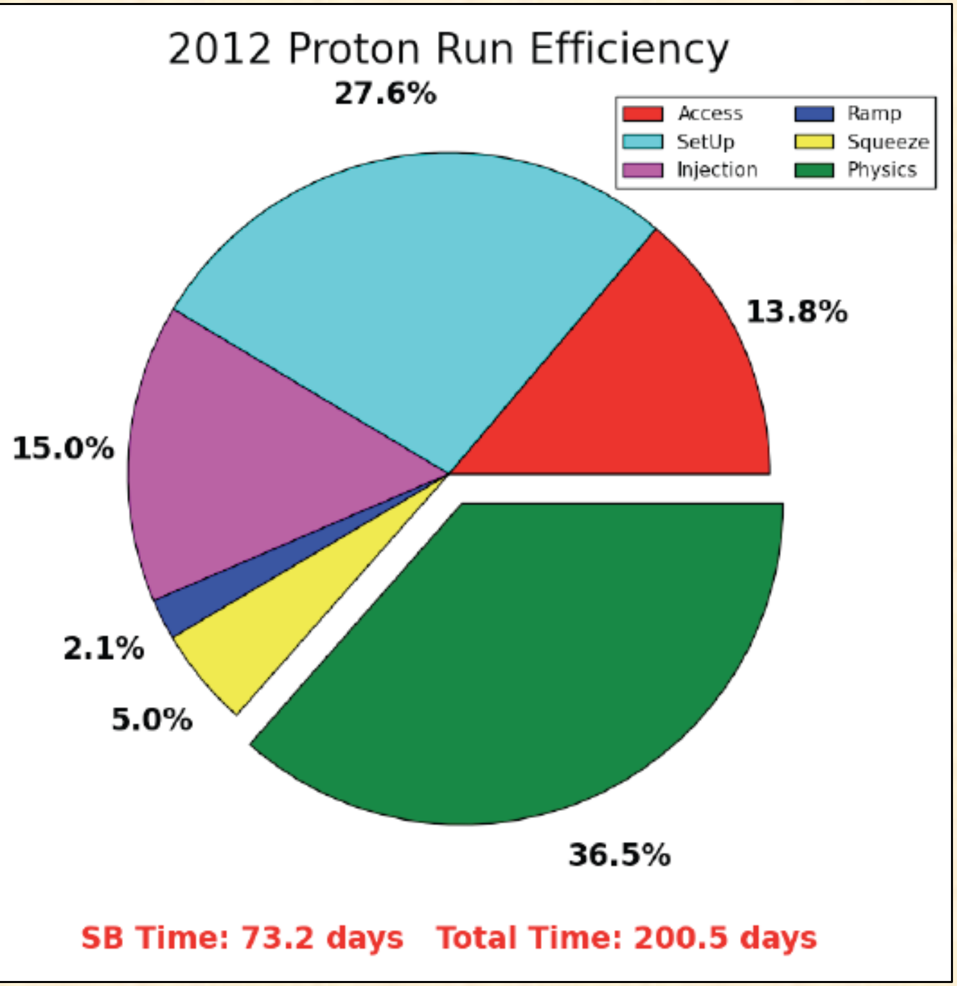


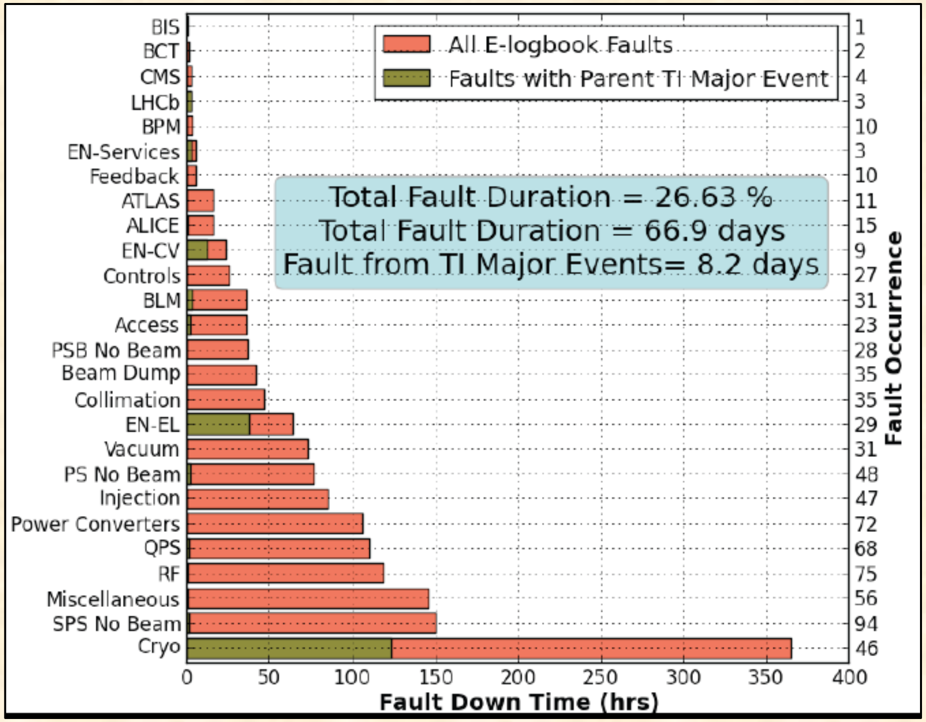
Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

turn around 2 to 3 hours on a good day

availability

- “There are a lot of things that can go wrong – it’s always a battle”
- Pretty good availability considering the complexity and principles of operation





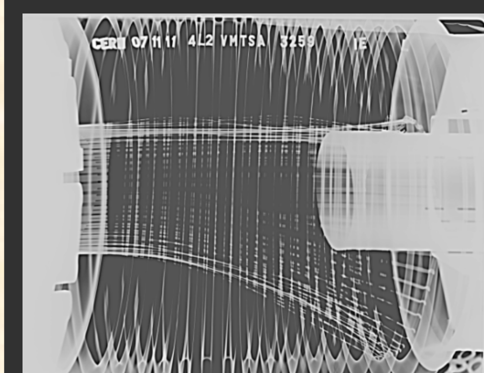
Cryogenics availability in 2012: 93.7%

M. Lamont, IPAC’13

some issues in 2011-12 operation

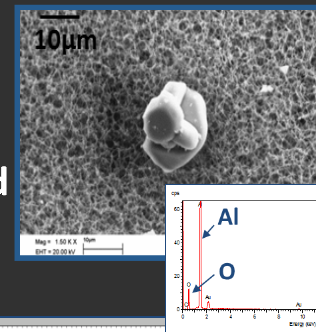
Beam induced heating

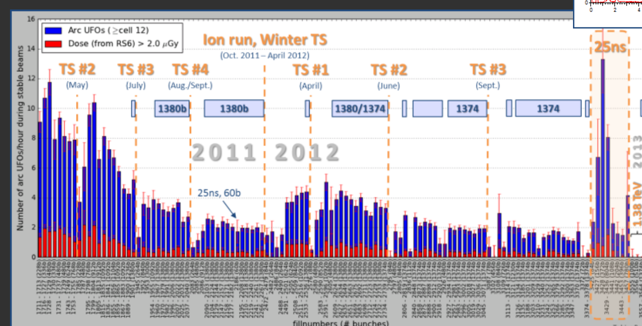
- Local non-conformities (design, installation)
  - injection protection devices
  - sync. Light mirrors
  - vacuum assemblies

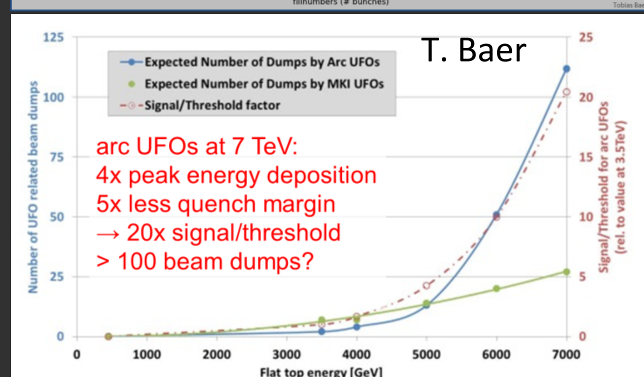


UFOs

- 20 dumps in 2012
- time scale 50-200 μs
- conditioning observed
- worry about 6.5 TeV and 25 ns spacing

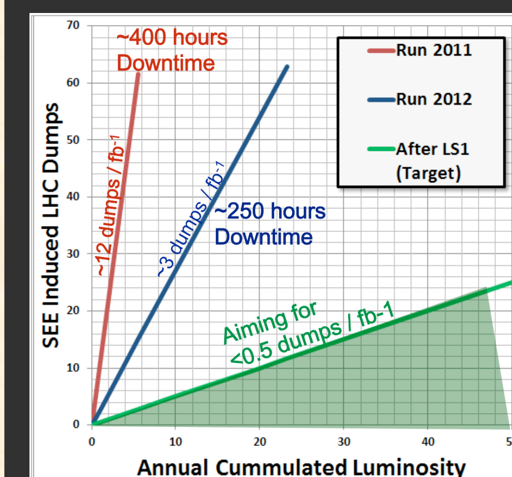






Radiation to electronics

- concerted program of mitigation measures (shielding, relocation…)
- premature dump rate down from 12/ fb^{-1} in 2011 to 3/ fb^{-1} in 2012



“All Clear” for LHC UFOs?

UK closed UFO desk after 50yrs and no 'potential threat'

Jun 21, 2013

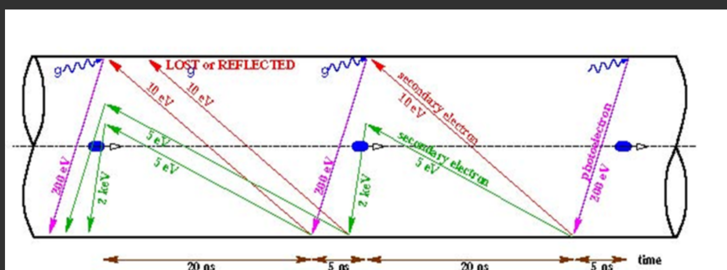
The British government finally shut down a special unit investigating UFO sightings after more than 50 years as it was a drain on resources and not a single report ever revealed " a potential threat to the United Kingdom," newly released government files showed Friday.

phys.org

another issue in 2011-12 operation

Electron cloud

- **beam induced multipactoring process, depending on secondary emission yield**
- **LHC strategy based on surface conditioning (scrubbing runs)**
- **worry about 25 ns (more conditioning needed) and 6.5 TeV (photoelectrons)**



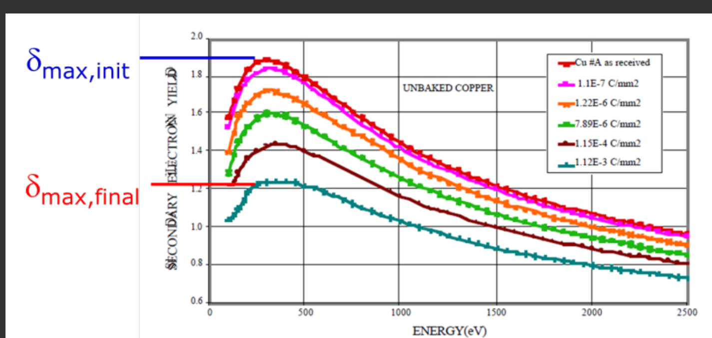
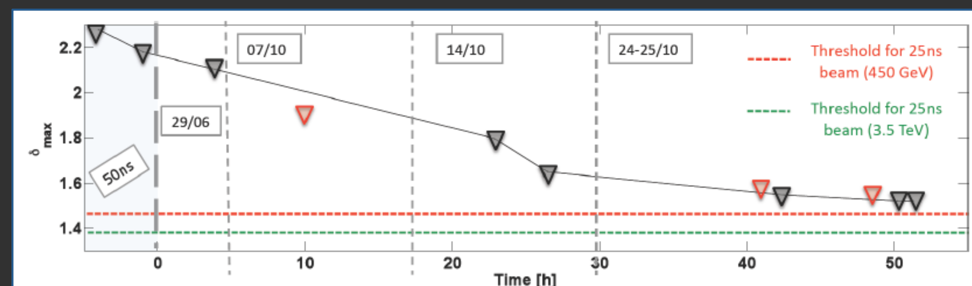
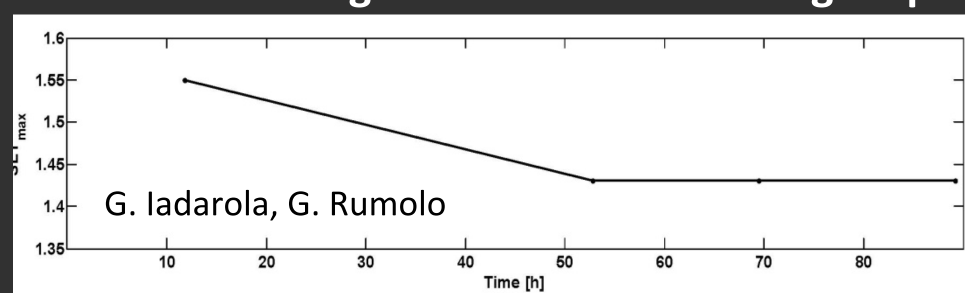


Figure 12: Variation of the S.E.Y. of copper with the incident electron dose

25-ns scrubbing in 2011 – decrease of SEY

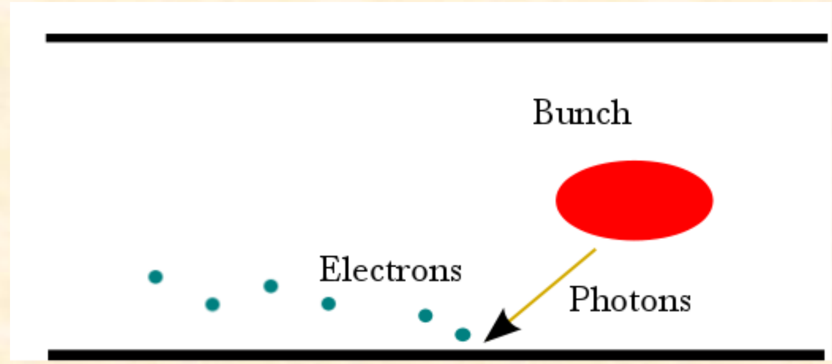


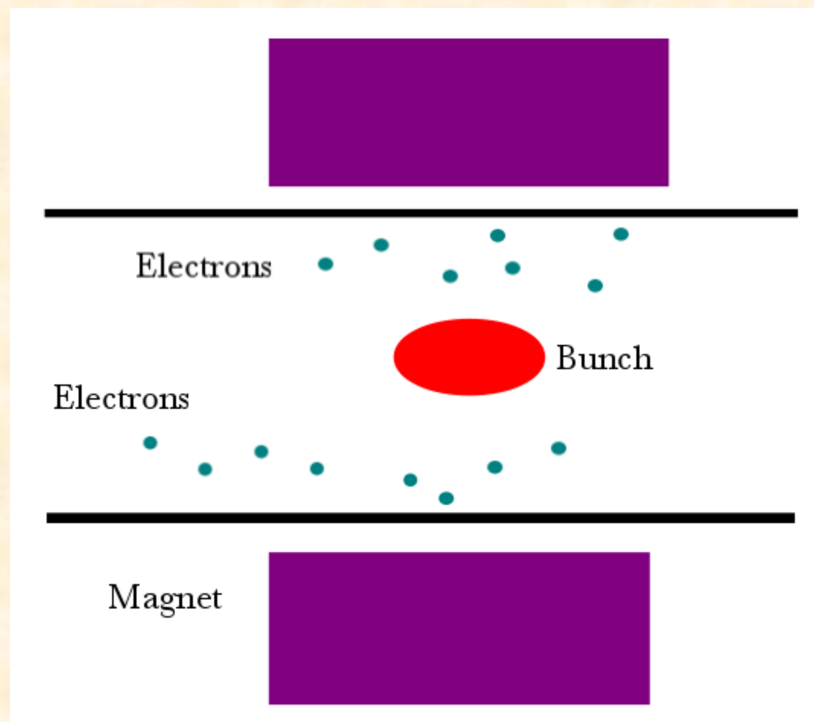
25-ns scrubbing in 2012 – conditioning stop?



Electron cloud effect

- Radiation from a bunch can extract electrons (and ions) from the beam pipe and from residual gas in the vacuum.
- These electrons fall back and get re-absorbed with a certain time constant.
- However if the bunch frequency is too high these electrons (and ions) will accumulate in the beam pipe and shield the beam from the magnetic elements.
- Special coatings, beam pipe geometries and bunch repetition patterns can mitigate this problem to some extent.
- This is one of the main limitations to increasing the





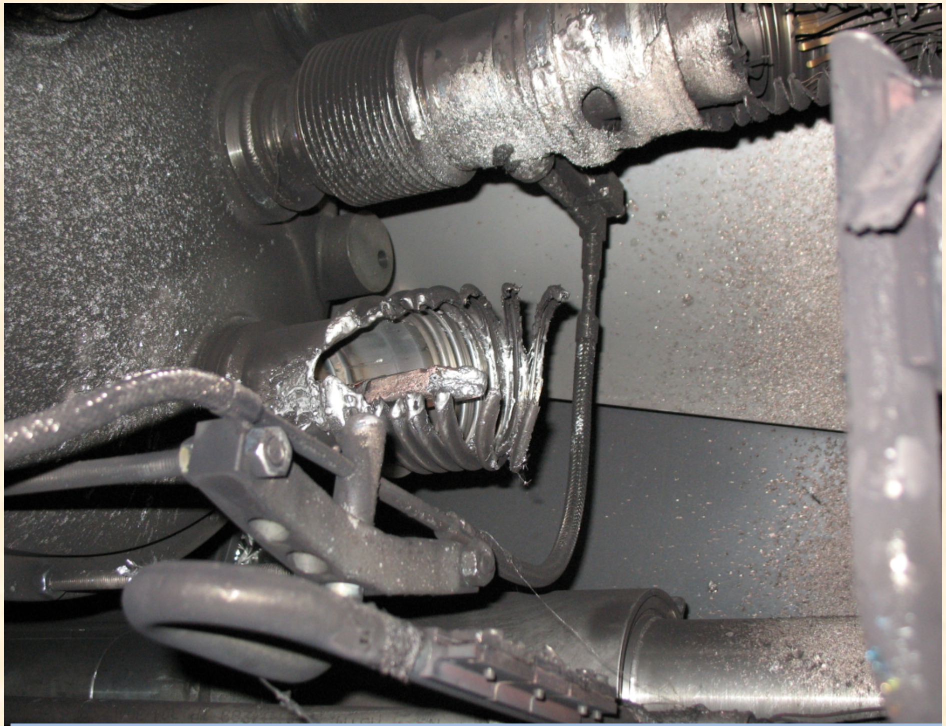
Long Shutdown 1 - motivation

after 2008 incident partial consolidation & related problem of imperfect *Cu* stabilizer continuity discovered

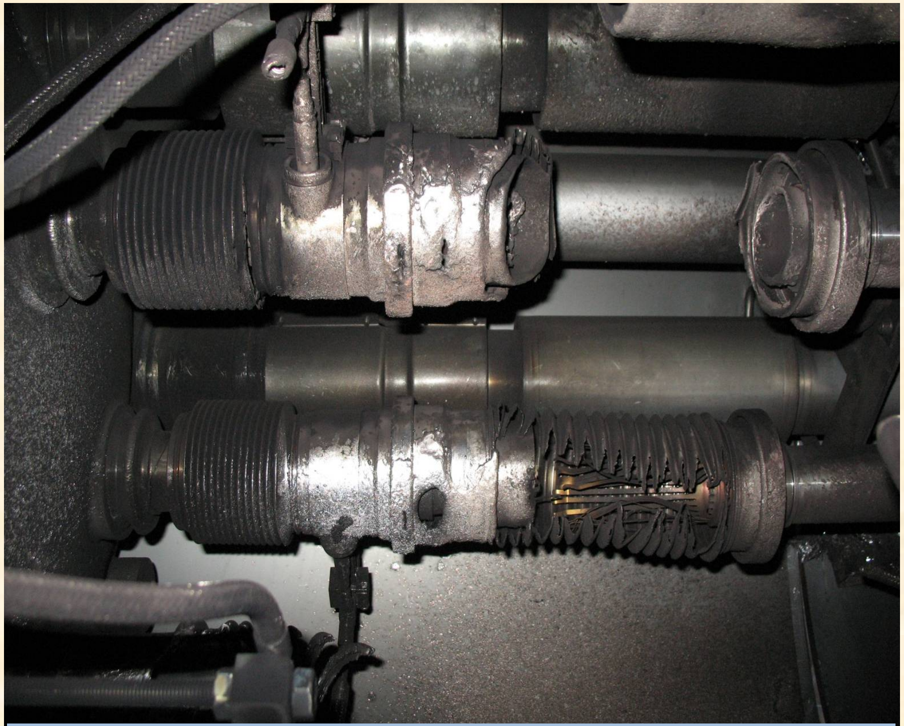
in 2010-12 LHC operated at 7 & 8 TeV c.m. beam energy to avoid any risk

presently: Long Shutdown 1 (LS1) ~2 yr to prepare LHC for 13-14 TeV c.m., detector upgrades in parallel

2008 “incident”



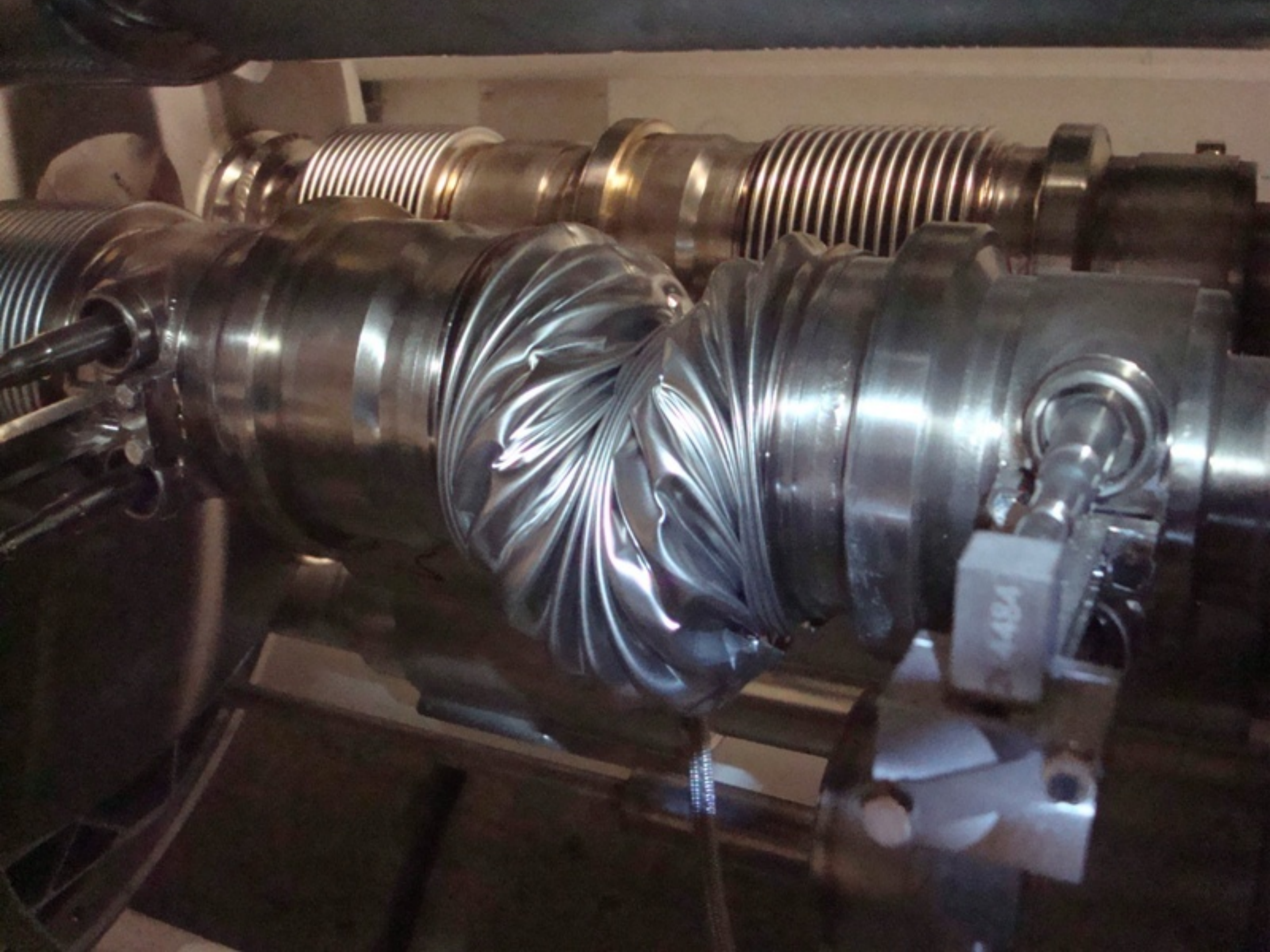
A faulty bus-bar (SC splice) in a magnet interconnect failed, leading to an electric arc which dissipated some 275 MJ



This burnt through beam vacuum and cryogenic lines, rapidly releasing ~2 tons of liquid helium into the vacuum enclosure

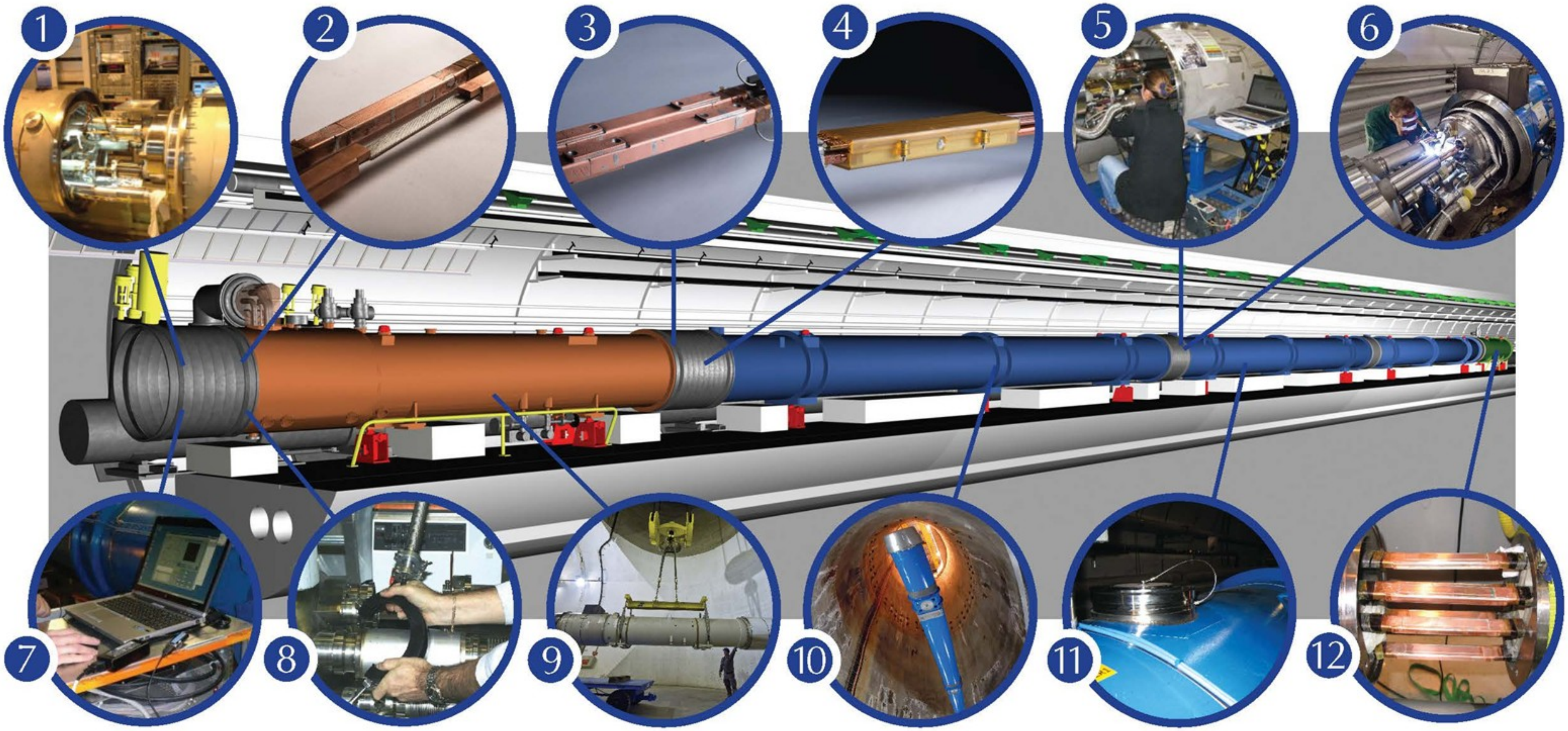
R. Veness


VELAN
QV



The main 2013-14 LHC consolidations

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines

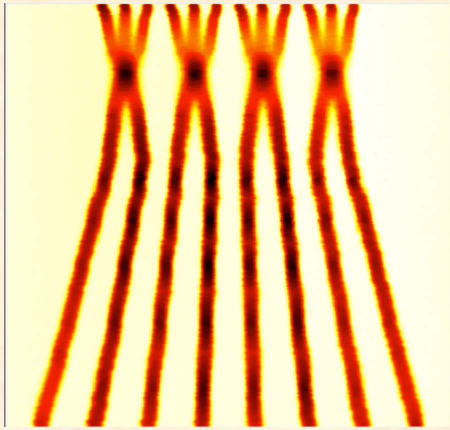


7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 4 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

2015 – post LS1

- energy: 6.5 TeV (magnet retraining)
- bunch spacing: 25 ns
  - pile-up considerations
- injectors potentially able to offer nominal intensity with even lower emittance

BCMS = Batch Compression and Merging and Splitting



	Number of bunches	Ib LHC FT[1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns low emit	2520	1.15	1.9	**1.7e34**	52	~45

expected maximum luminosity from inner triplet heat load (collisions debris) 1.7×10^{34} $cm^{-2}s^{-1}$ ±20%

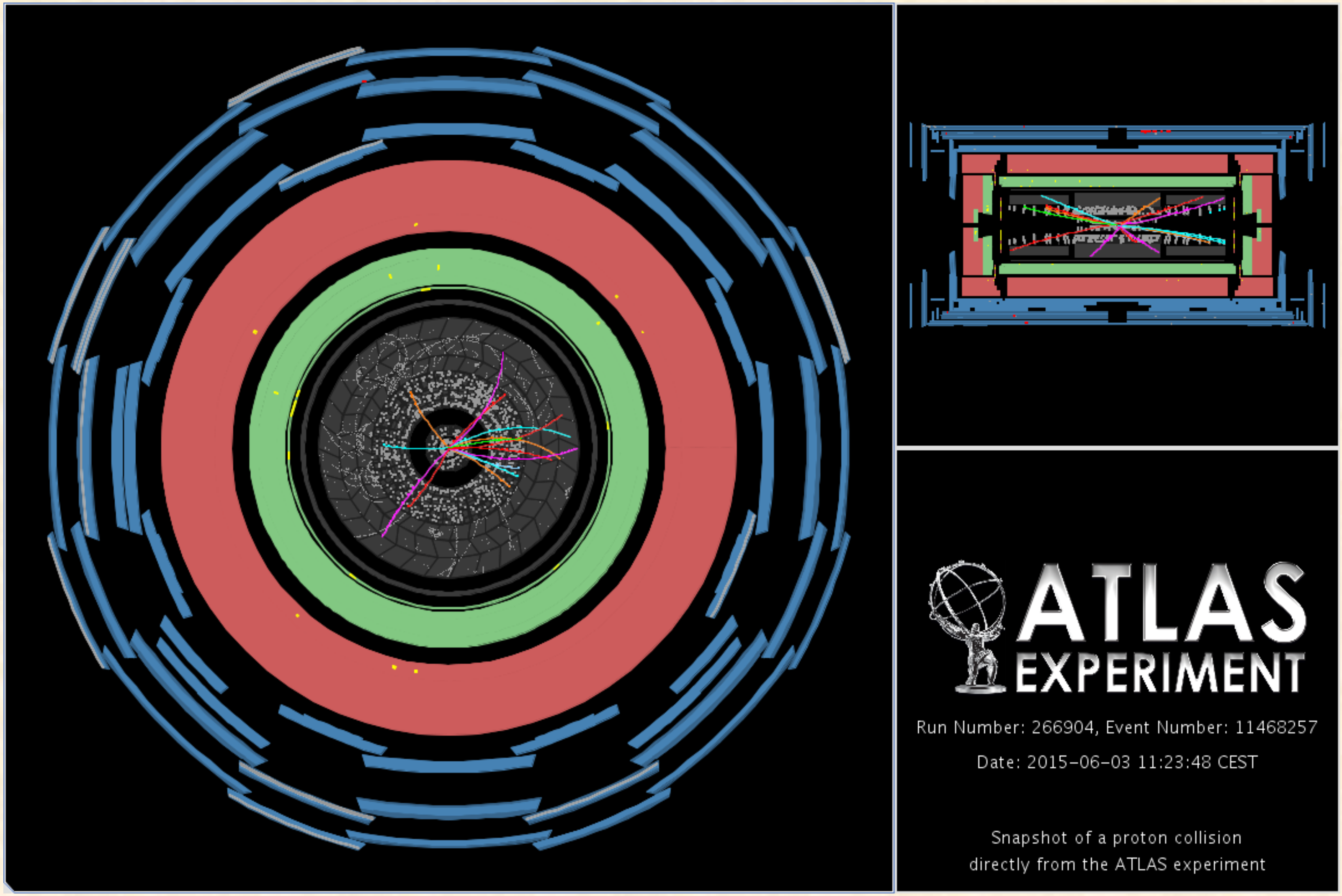
uncertainties for 2015:

- electron cloud
- UFOs

both get more difficult at 25 ns &
at higher energy

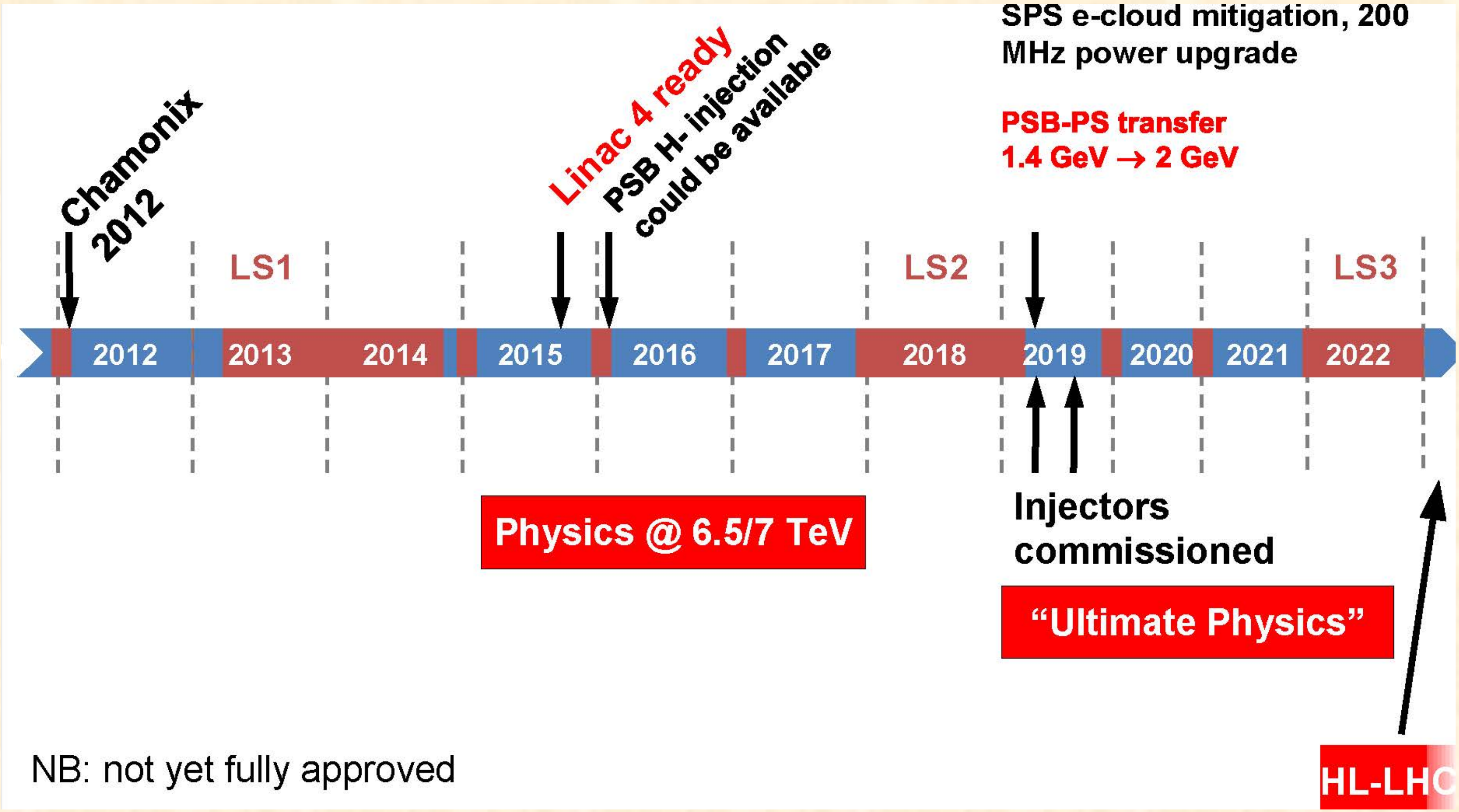
- energy (limited by retraining)

And yesterday…



The first physics events of run 2 were recorded!

example LHC time line – next ten years



Ralph Steinhagen, ICHEP2012

Linac4 (160 MeV H^- instead of 50-MeV p)

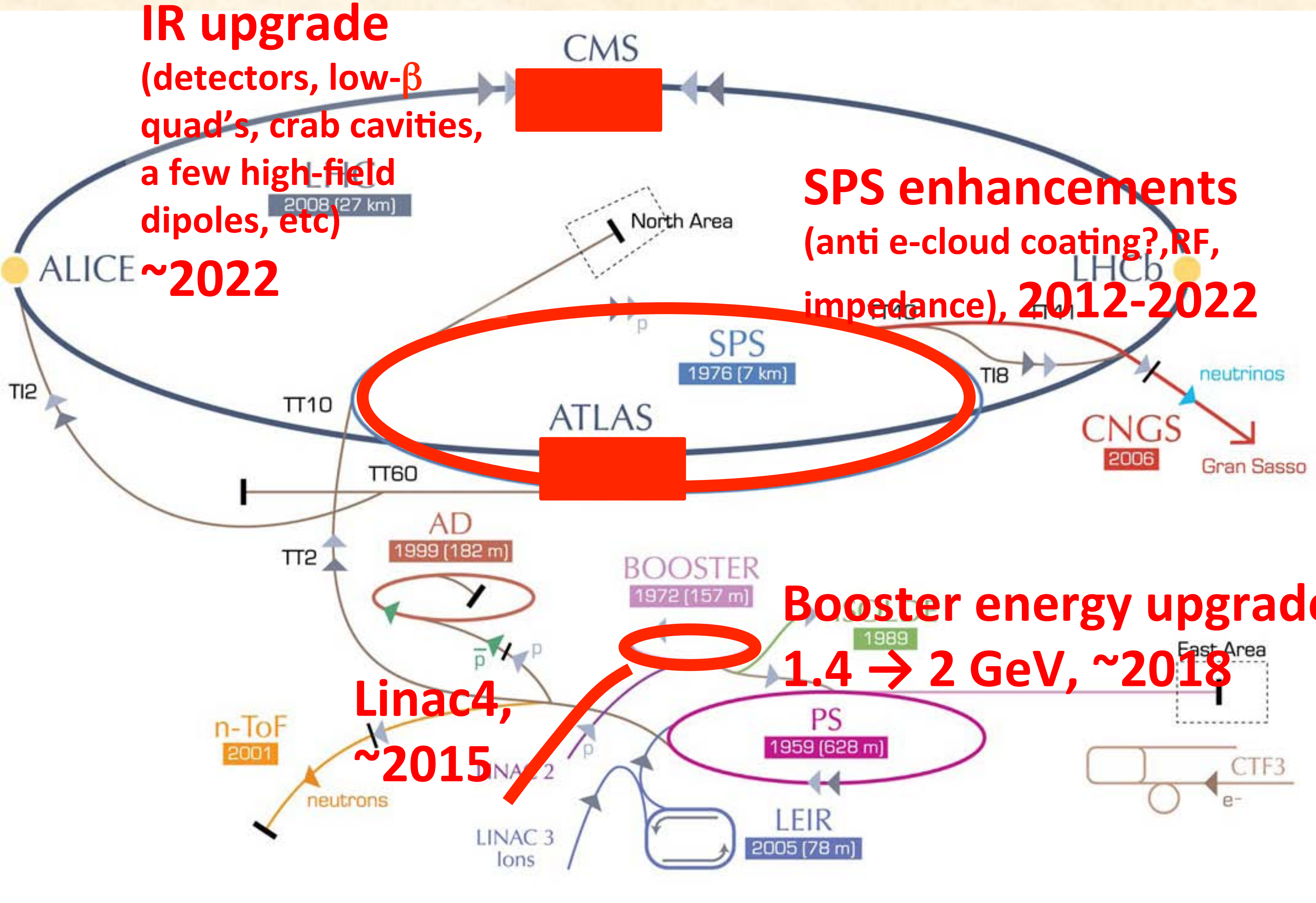
Linac4 could double the beam brightness injected into the booster, but there may be other bottlenecks downstream (e.g. PS injection)

LHC luminosity forecast

~30/fb at 3.5 & 4 TeV	**2012 DONE**
~400/fb at 6.5-7 TeV	**2021 goal (?)**
~3000/fb at 7 TeV	**2035 goal (??)**

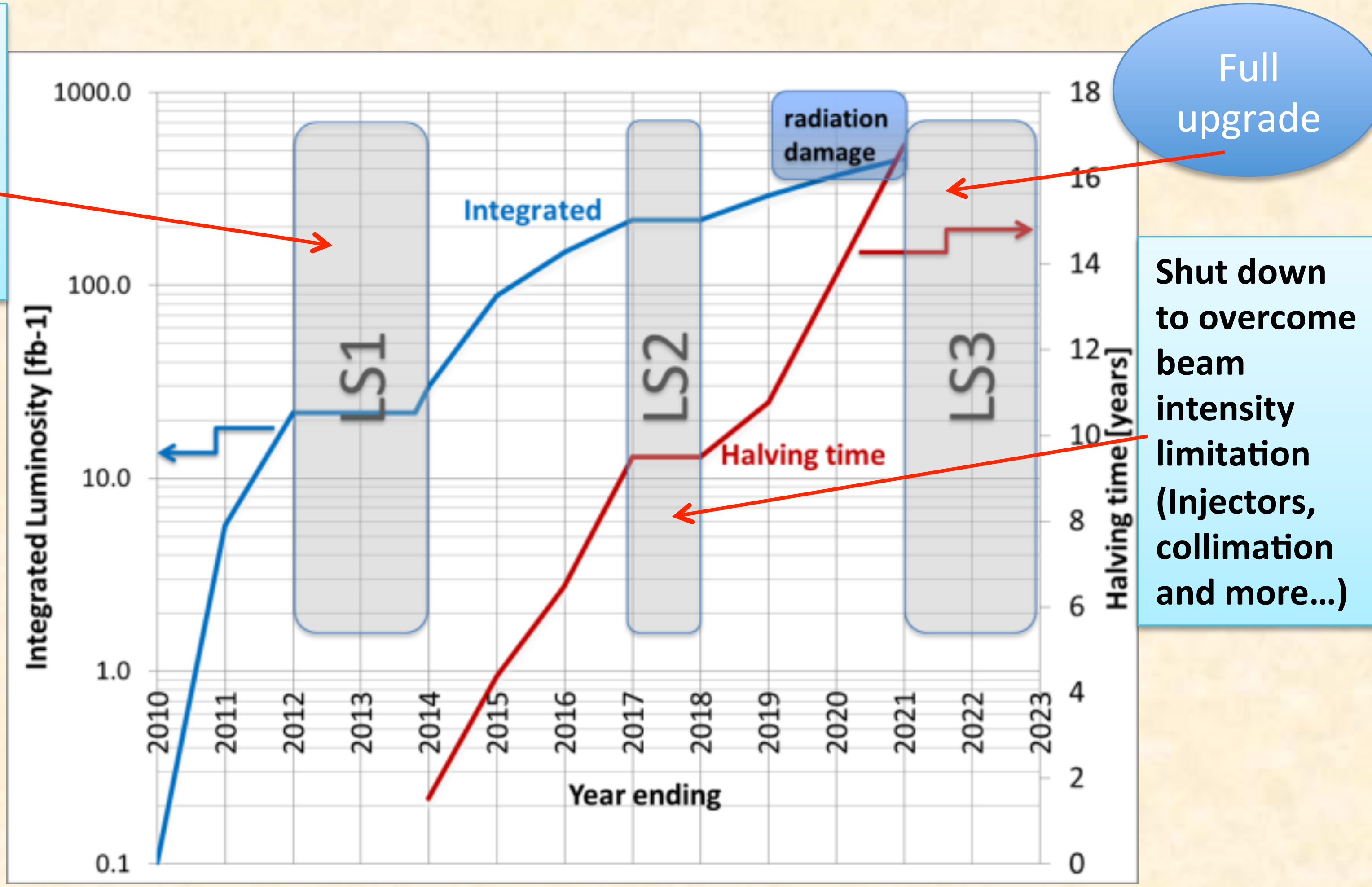
to obtain 3000/fb by 2035
*we need the **HL-LHC***

HL-LHC – modifications



(HL-)LHC Time Line

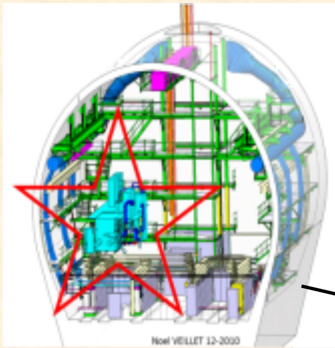
Shut down for interconnects to overcome energy limitation (LHC incident of Sept. 2008) and R2E



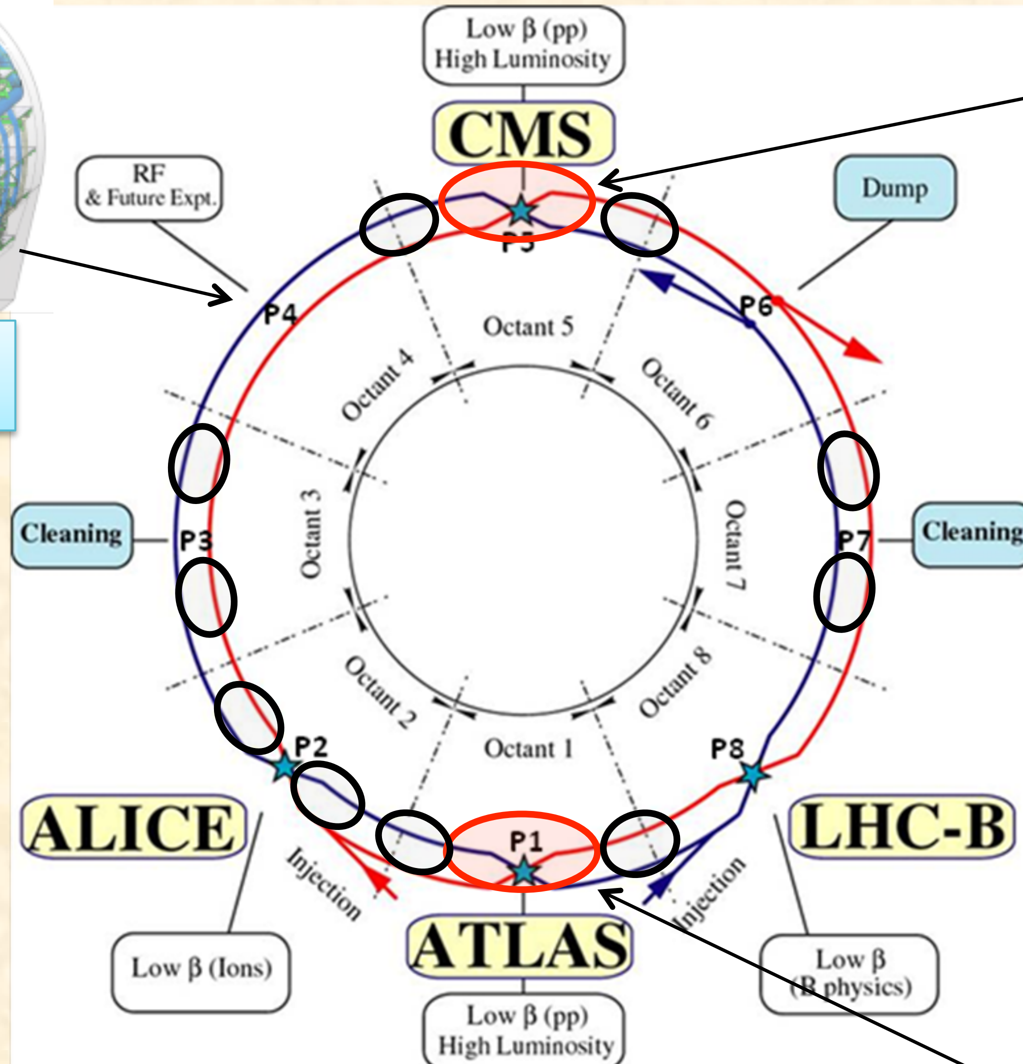
Shut down to overcome beam intensity limitation (Injectors, collimation and more…)

two reasons for HL-LHC: performance & consolidation

in LHC: 1.2 km of new equipment …



6.5 kW@4.5K cryoplant



2 x 18 kW @4.5K cryoplants for IRs

HL-LHC Official Beam Parameters

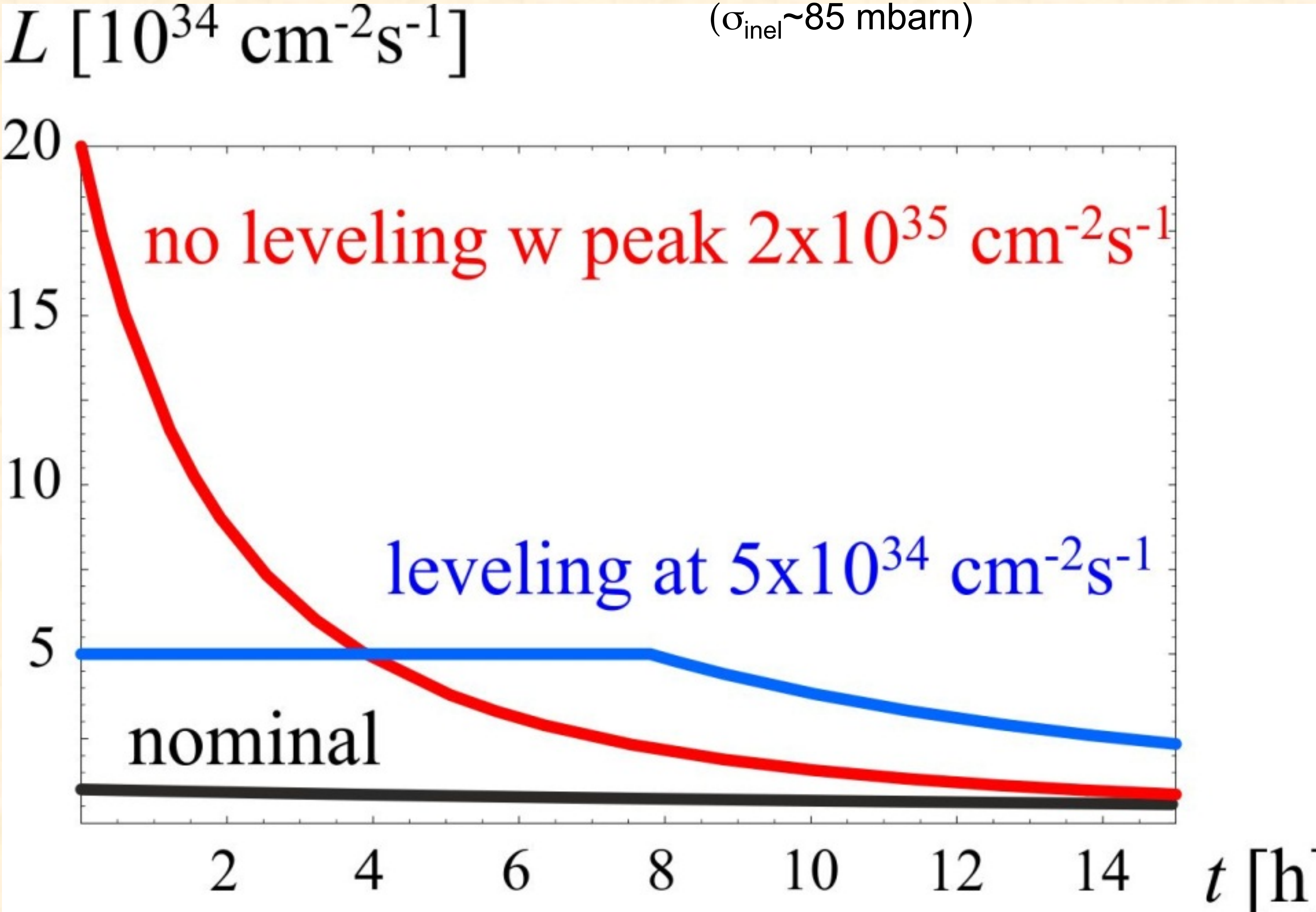
Parameter	nominal	25ns	50ns		
N	1.15E+11	**2.2E+11**	**3.5E+11**		
n_b	2808	2808	1404		
beam current [A]	0.58	**1.12**	**0.89**		
x-ing angle [μrad]	300	590	590		
beam separation [σ]	10	12.5	11.4		
β^* [m]	0.55	**0.15**	**0.15**		
ε_n [μm]	3.75	2.5	3.0		
ε_L [eVs]	2.51	2.5	2.5		
energy spread	1.20E-04	1.20E-04	1.20E-04		
bunch length [m]	7.50E-02	7.50E-02	7.50E-02		
IBS horizontal [h]	106	**20.0**	**20.7**		
IBS longitudinal [h]	60	**15.8**	**13.2**		
Piwinski parameter	0.68	**3.1**	**2.9**		
geom. reduction	0.83	**0.35**	**0.33**		
beam-beam / IP	3.10E-03	**3.9E-03**	**5.0E-03**		
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**		
Virtual Luminosity	$1.2\ 10^{34}$	**$21\ 10^{34}$**	**$26\ 10^{34}$**		
Events / crossing (peak & leveled L	27	**210**	**475**	**140**	**140**

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

(Leveled to $5\ 10^{34}\ cm^{-2}\ s^{-1}$ and $2.5\ 10^{34}\ cm^{-2}\ s^{-1}$)

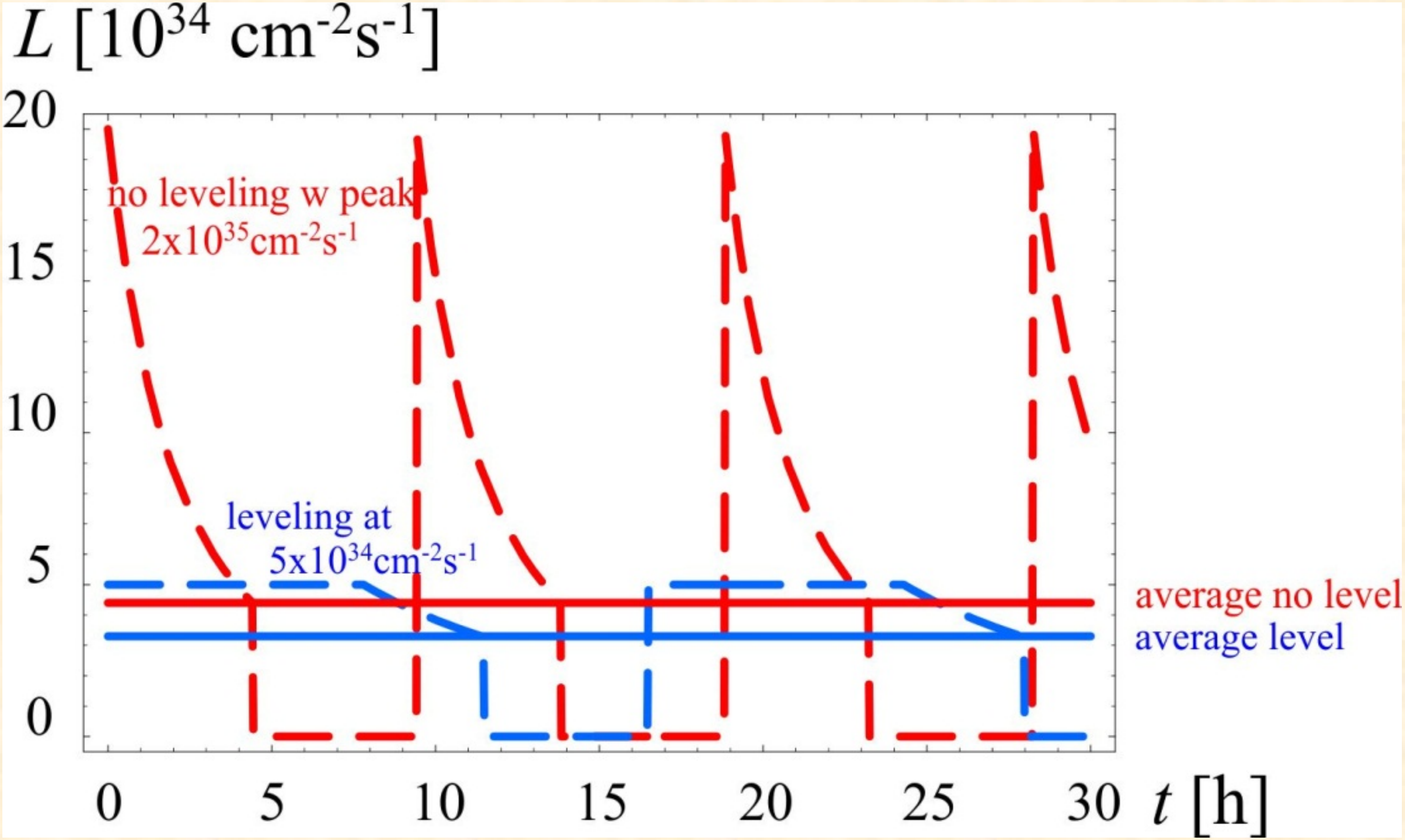
luminosity leveling at the HL-LHC

example: maximum pile up 140 (σ_{inel}~85 mbarn)



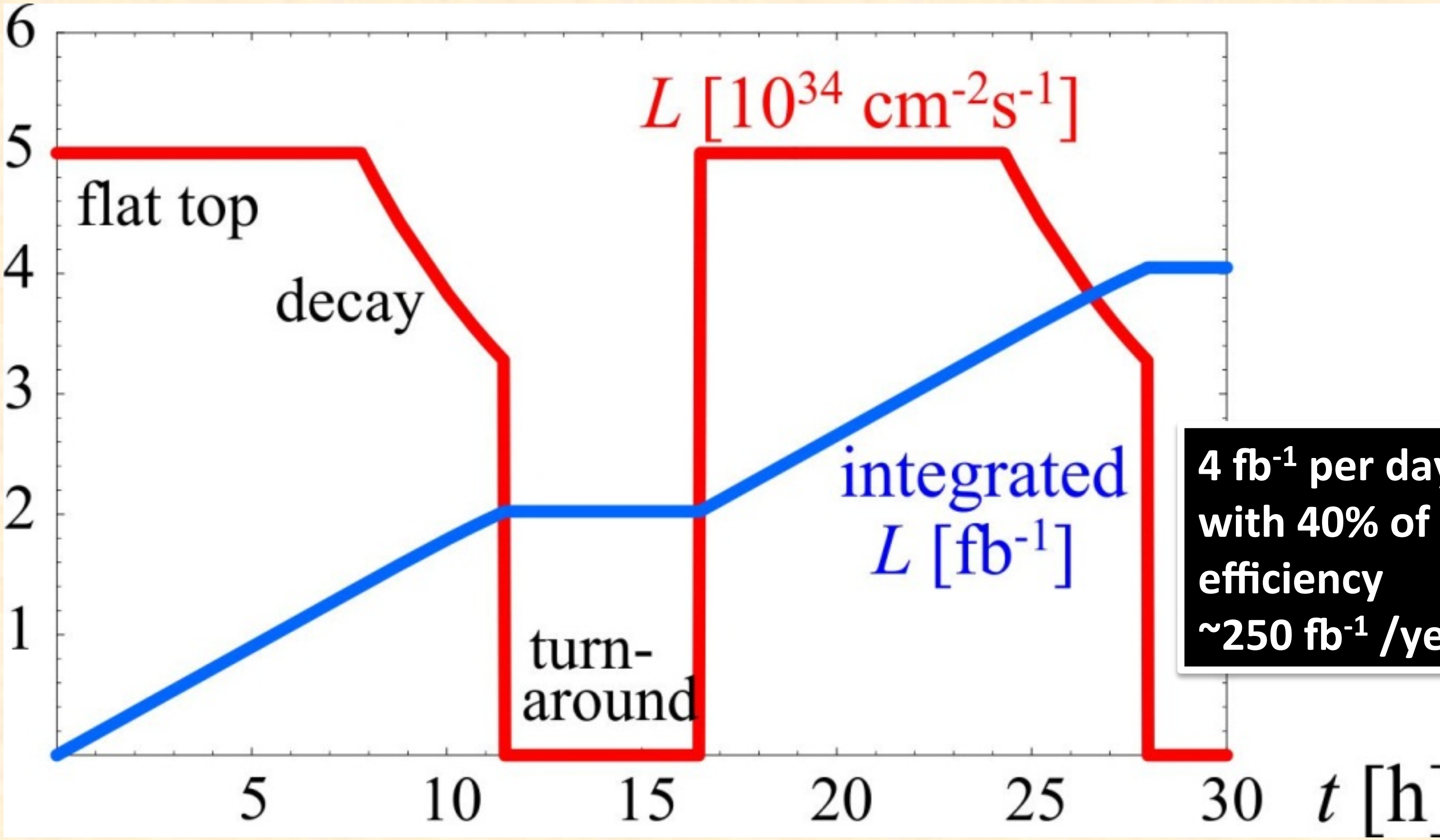
luminosity leveling at the HL-LHC

example: maximum pile up 140



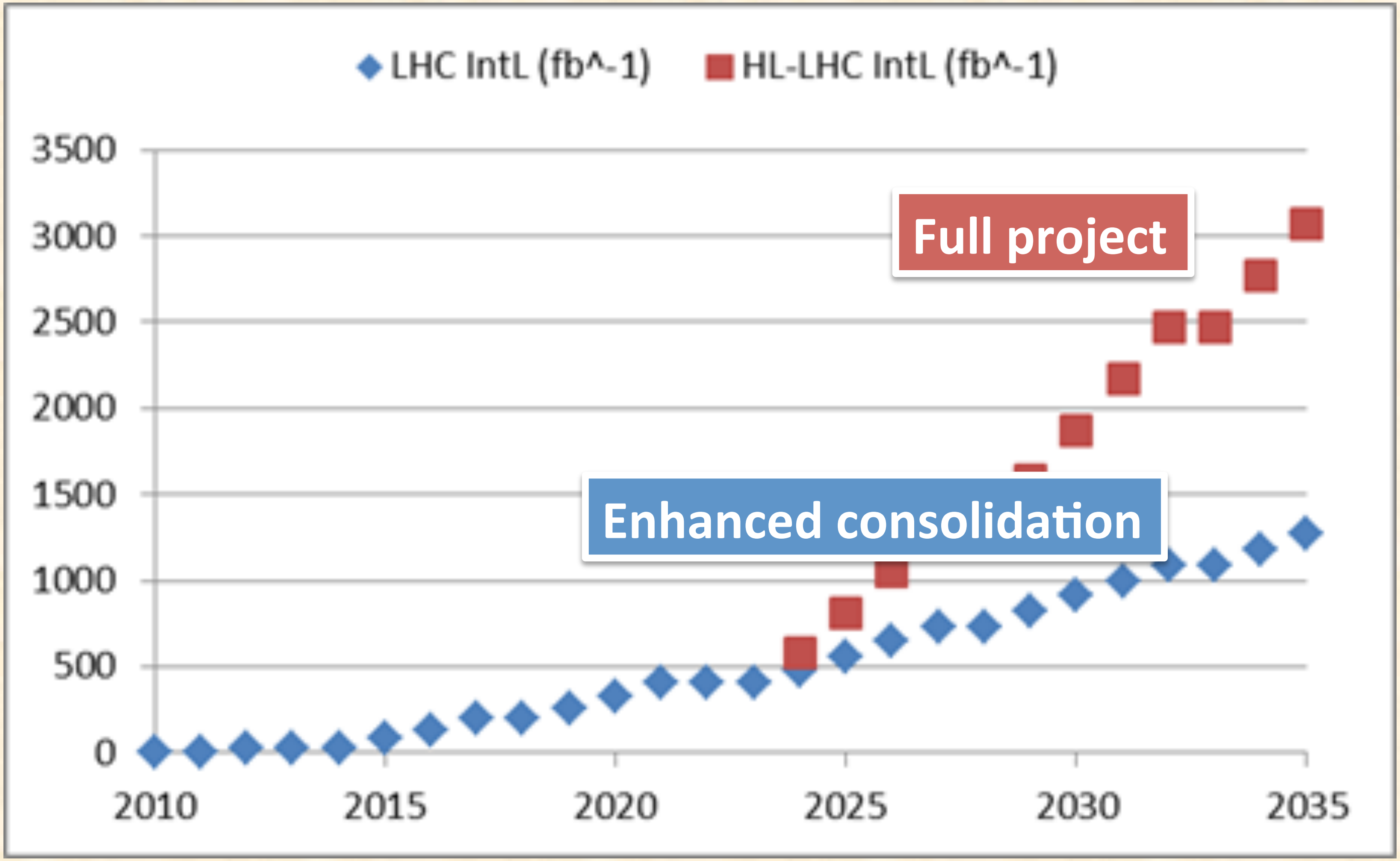
luminosity & integrated luminosity during 30 h at the HL-LHC

example: maximum pile up 140



4 fb^{-1} per day, with 40% of efficiency ~250 fb^{-1} /year

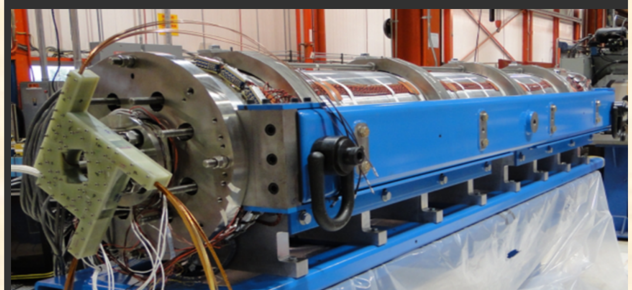
final goal : 3000 fb^{-1} by 2030's…



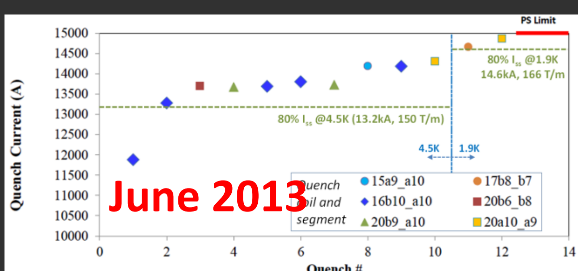
some HL-LHC ingredients

new final quadrupoles

- Nb_3Sn instead of Nb-Ti
- larger aperture allowing smaller β*



LQS03 (90 mm ap., 3.7 m long): **208 T/m**@4.6 K, **210 T/m**@1.9 K

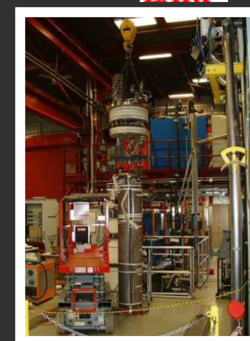


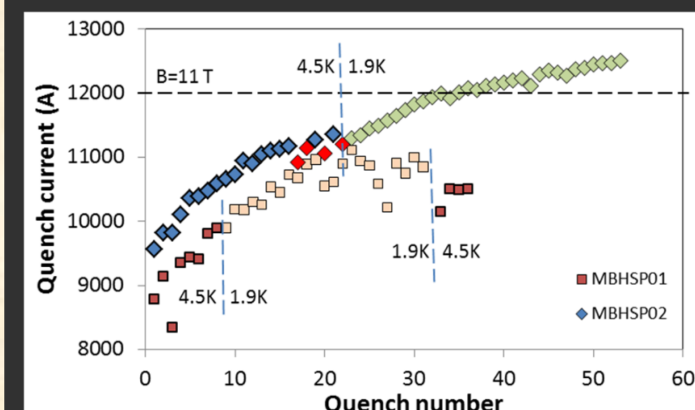
HQ02a (120 mm, 1.5 m long): **150 T/m**@4.6 K, **170 T/m**@1.9 K

Goal: 150 mm ap, 140 T/m

11-T dipoles for dispersion suppressors

- Nb_3Sn instead of Nb-Ti
- provide space for extra collimators catching off-energy protons or ions at ALICE, collimator sections, ATLAS & CMS





1-m model tested in April 2014, B_{nom}=11 T achieved!

Next: 2-m single bore, then 2-in-1

SC link

- move radiation sensitive power converters away from machine
- first prototype, 20 m – 20 kA, under test at CERN!

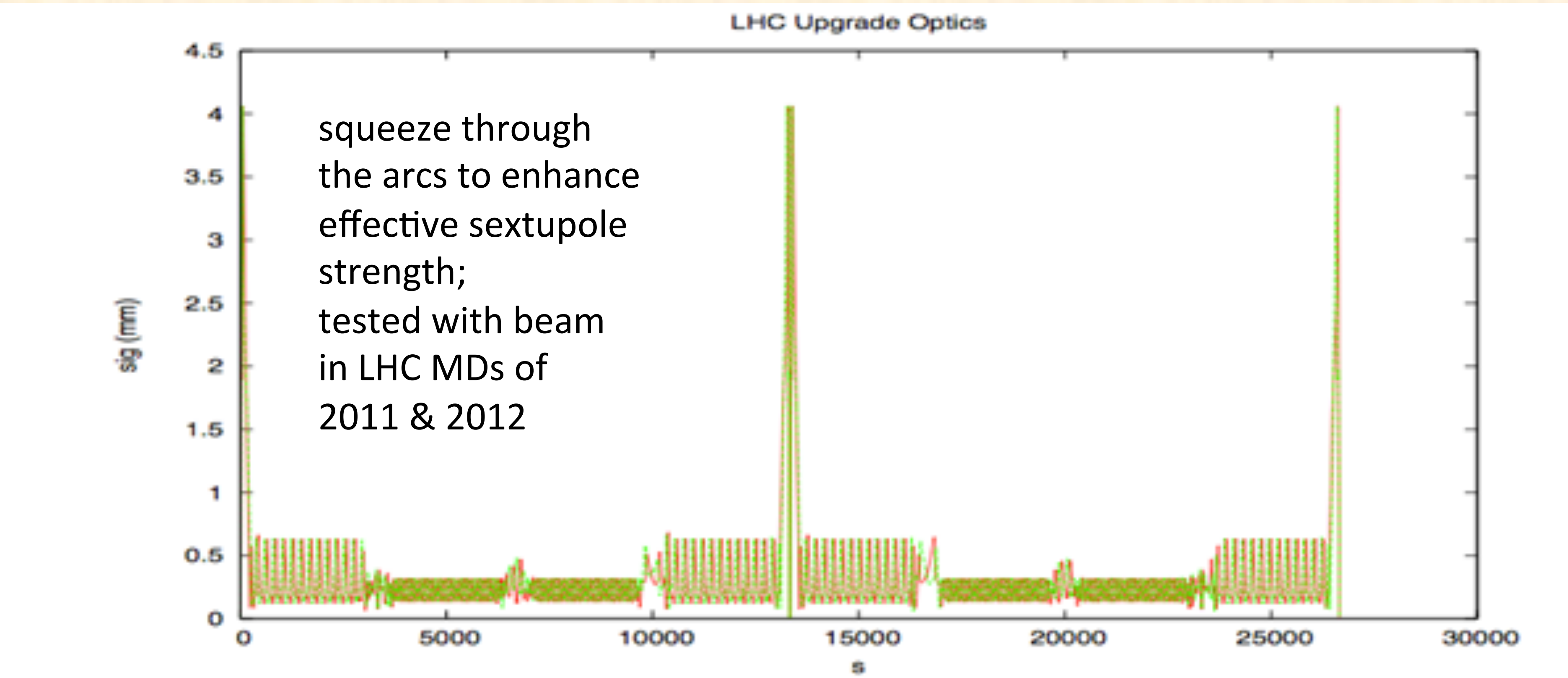
- also of interest for electrical power distribution

tests of novel MgB_2 and *HTS* (YBCO and *BSCCO*) cables

HL-LHC optics

S. Fartoukh

Achromatic Telescopic Squeeze (ATS), «fully proven»
MDs (β^* = 15 cm «easy», room for β^* ~ 10-12 cm)



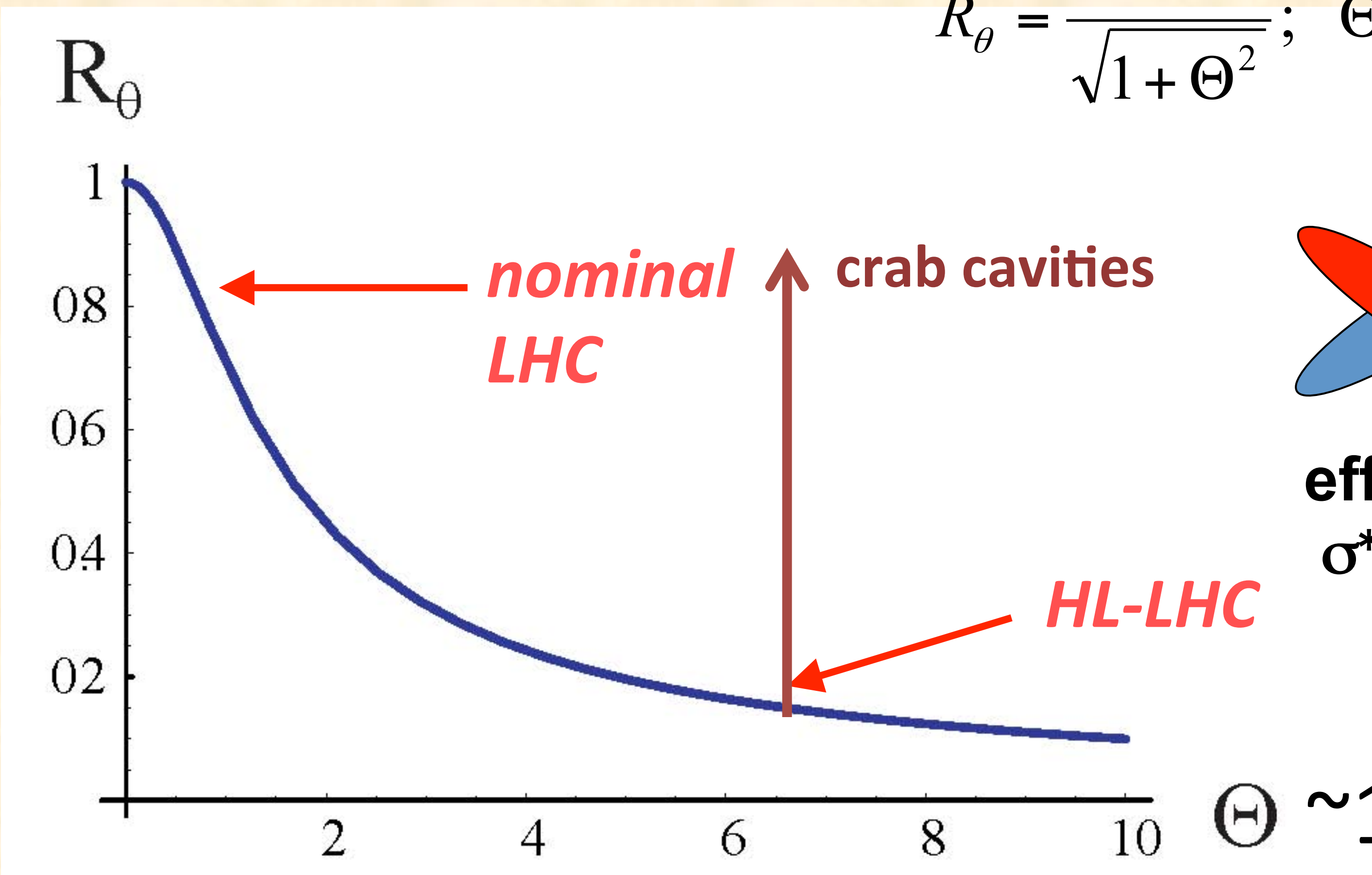
typical ATS collision optics with IR1 & IR5 squeezed down to β^*=10 cm

luminosity reduction due to crossing angle is more pronounced at smaller β^*

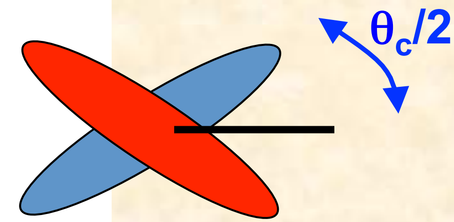
"Piwinski angle"

luminosity reduction factor

$$R_\theta = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$



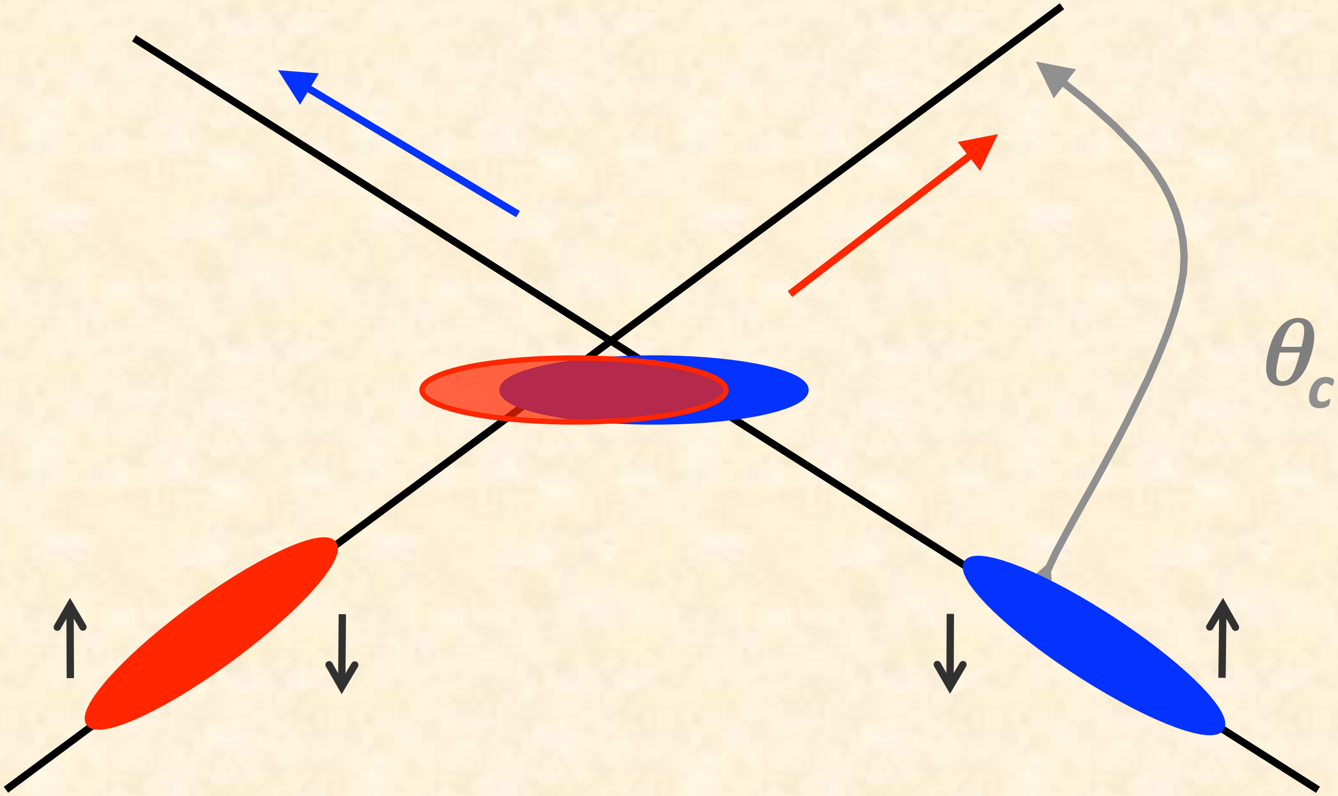
Θ ~$1/\beta^*$



eff. beam size:

$\sigma^*_{x,\mathrm{eff}} \approx \sigma_x^*/R_\theta$

schematic of crab crossing

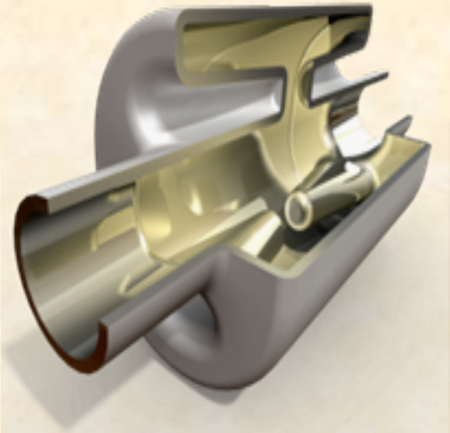


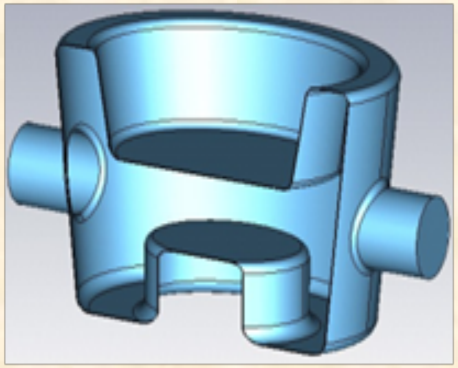
- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, used in operation at KEKB since 2007

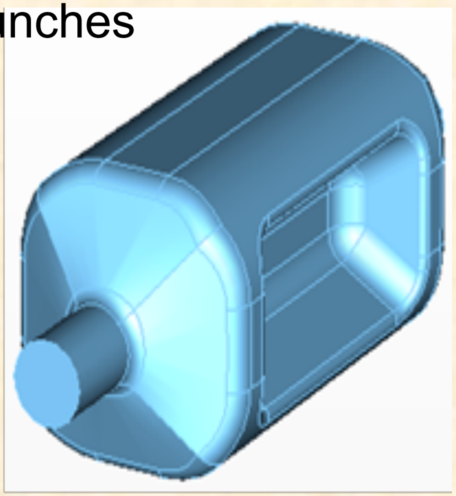
until recently plan was to vary crab cavity voltage for leveling, but this would change size of luminous region & is disliked by experiments (instead leveling by β^* or offset?)

HL-LHC needs compact crab cavities

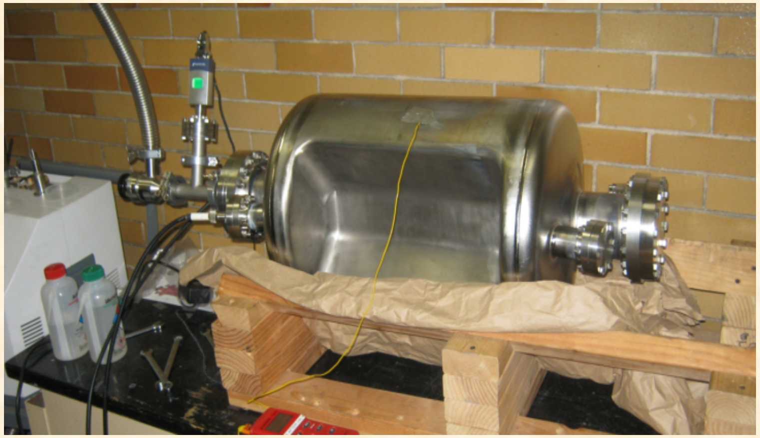
only 19 cm beam separation, but long bunches





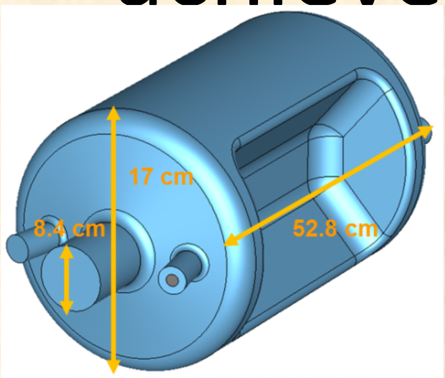


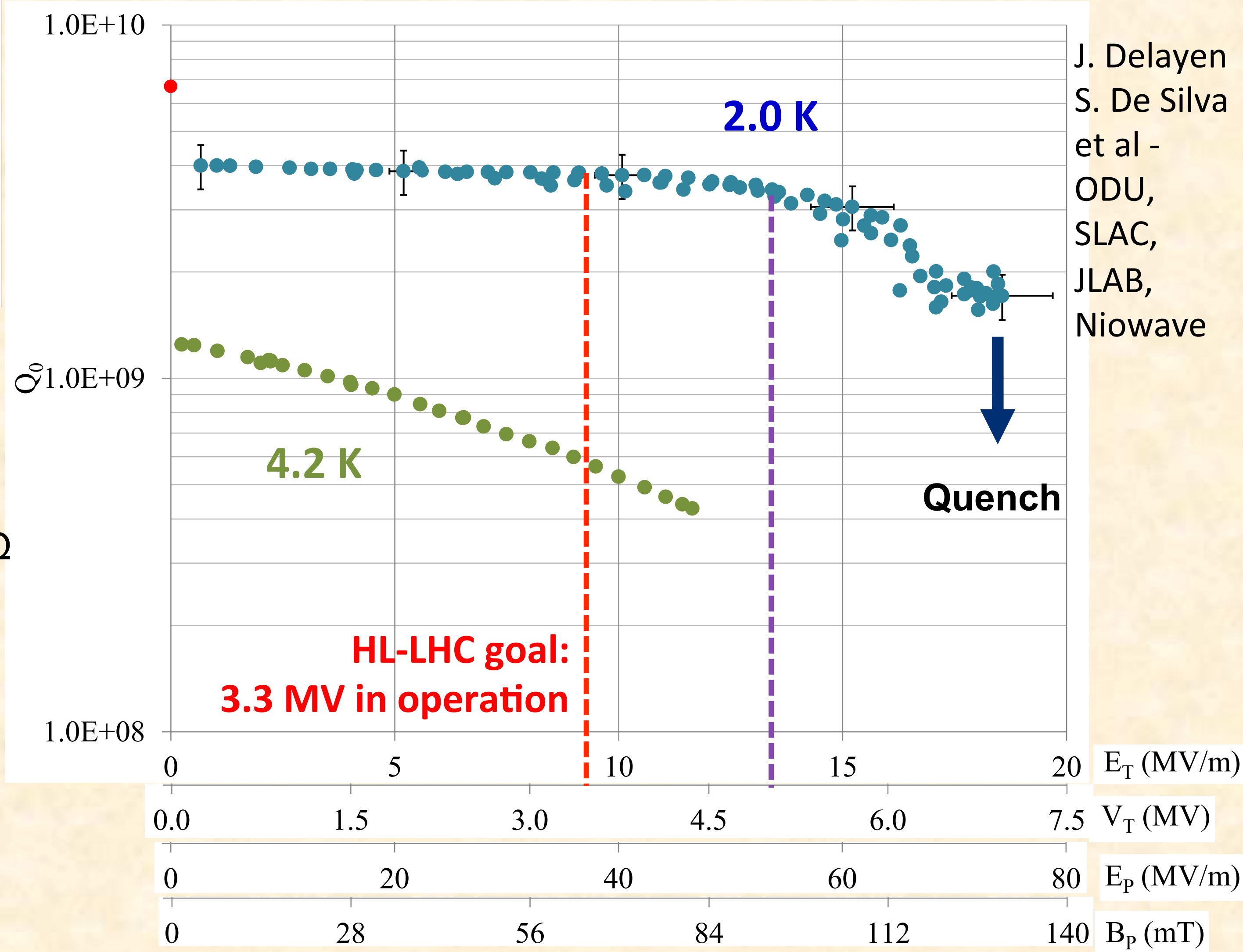
Final down-selected compact cavity designs for the LHC upgrade: 4-rod cavity design by Cockcroft I. & JLAB (left), $\lambda/4$ TEM cavity by BNL (centre), and double-ridge $\lambda/2$ TEM cavity by SLAC & ODU (right).



Prototype compact *Nb-Ti* crab cavities for the LHC: 4-rod cavity (left) and double-ridge cavity (right).

breaking news – PoP double-ridge cavity achieved 7 MV deflecting voltage cw





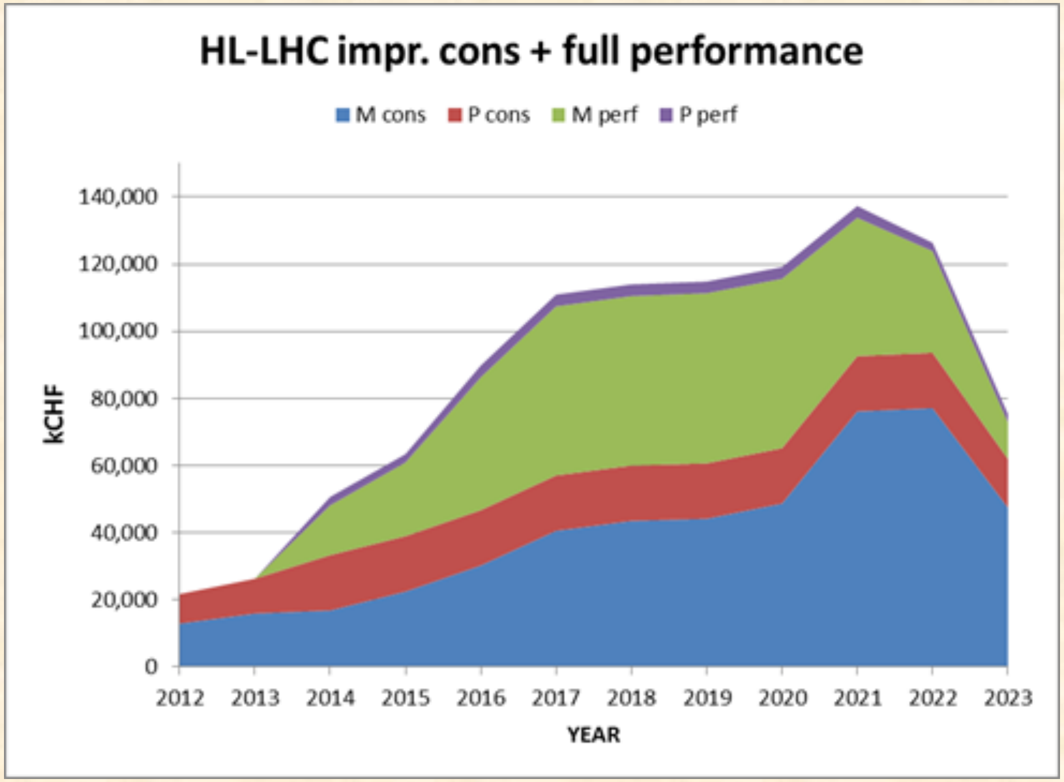
J. Delayen
S. De Silva
et al -
ODU,
SLAC,
JLAB,
Niowave

- Expected
  $Q_0 = 6.7\times10^9$
  - At R_S = 22 nΩ
  - And R_{res} = 20 nΩ
- Achieved
  $Q_0 = 4.0\times10^9$
- Achieved fields
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT

better than required!

J. Delayen, LARP CM20

HL-LHC preliminary budget estimate



	Improving Consolidation	Full performance	Total HL-LHC
Mat. (MCHF)	476	360	836
Pers. (MCHF)	182	31	213
Pers. (FTE-y)	910	160	1070
TOT (MCHF)	658	391	1,049

RLIUP 2013
“Review of LHC and injector upgrade plans”
CERN, 29-31 October 2013

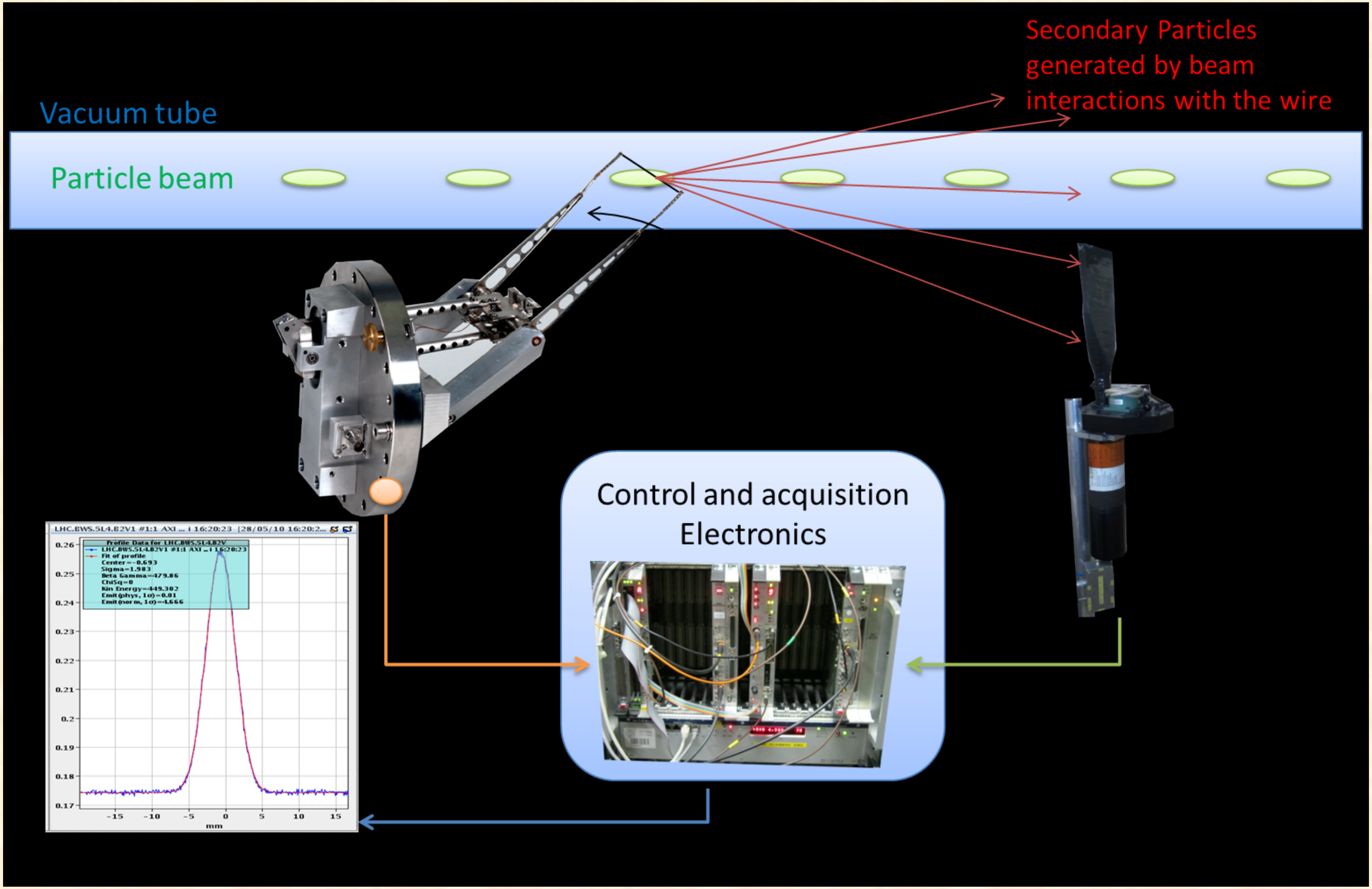
3 scenarios	PICs Performance Improving Consolidations	US1 Upgrade Scenario 1	US2 Upgrade Scenario 2
		+HHRF?+DS collimators?	+crab cavities, e-lens,…
integrated luminosity by 2035	**1000-1200 /fb**	**2000/fb**	**3000/fb**

physics needs & motivation?; also, reasons to go >3000/fb?

(most slides courtesy of Dr Rhodri Jones)

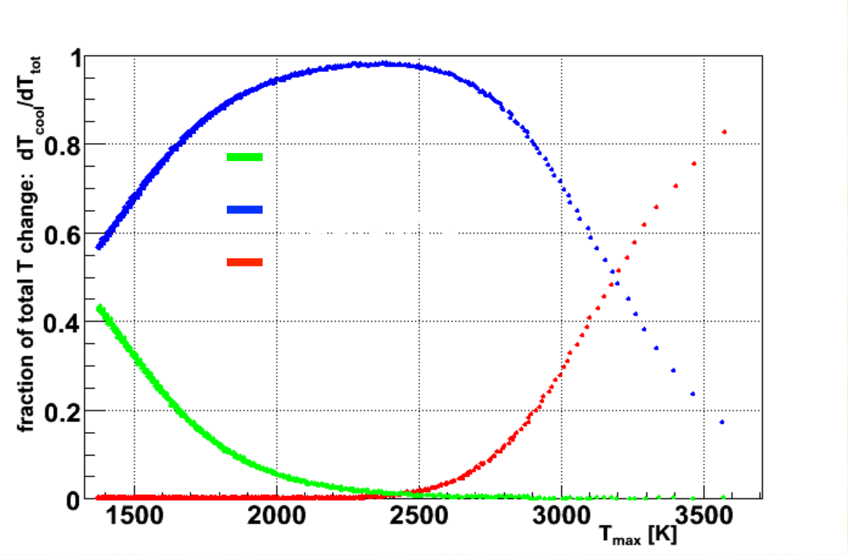
LHC BEAM INSTRUMENTATION

Beam Profile Monitoring using Wire-Scanners



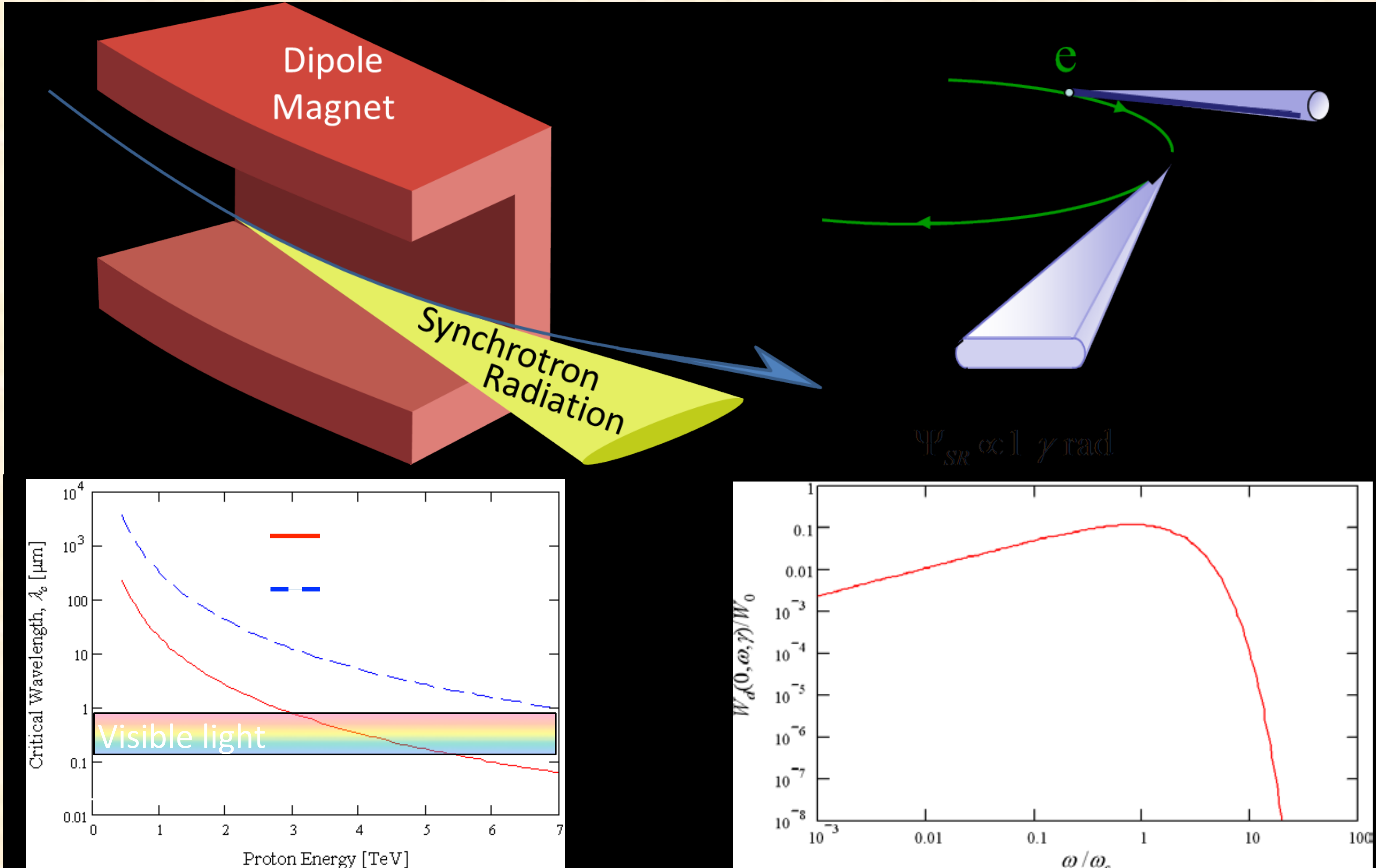
Limitation of WireScanners

- Wire Breakage – why?
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by proton beam
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling
    - Radiative
    - Conductive
    - Thermionic
    - Sublimation
- Wire Choice
  - 33μm Carbon
    - Good mechanical properties
    - Sublimates at 3915K



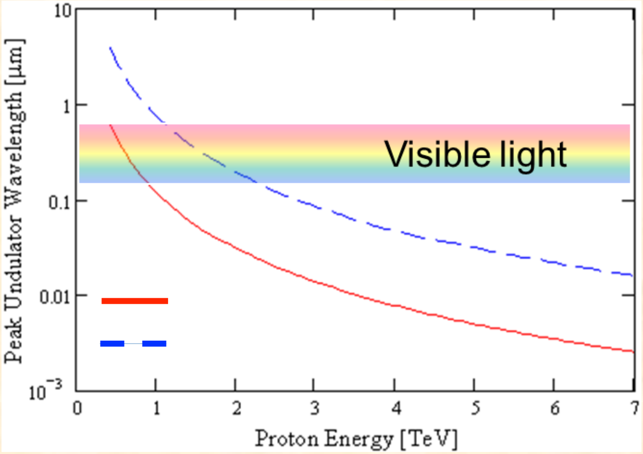
  - Typical scan lasts 1 ms & total cooling time constant ~10-15 ms
    - Cooling during measurement negligible

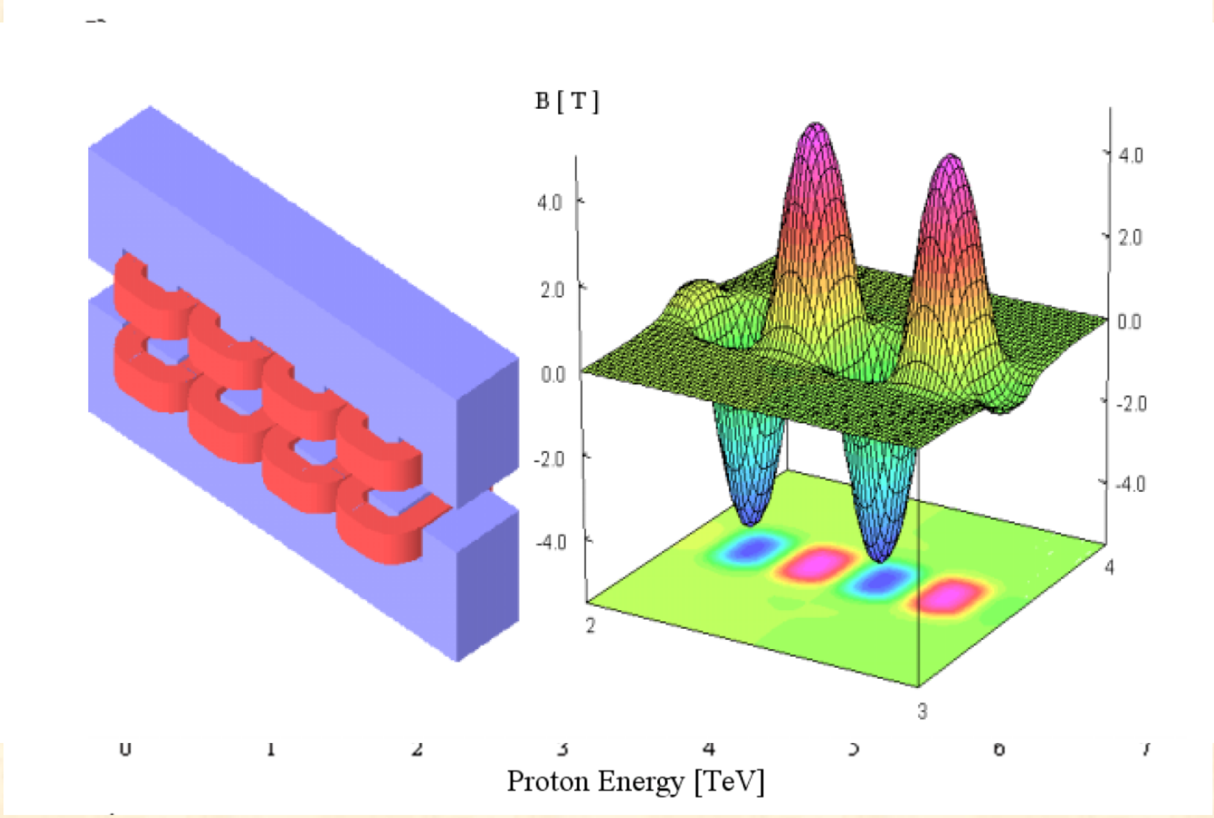
Synchrotron Light in the LHC

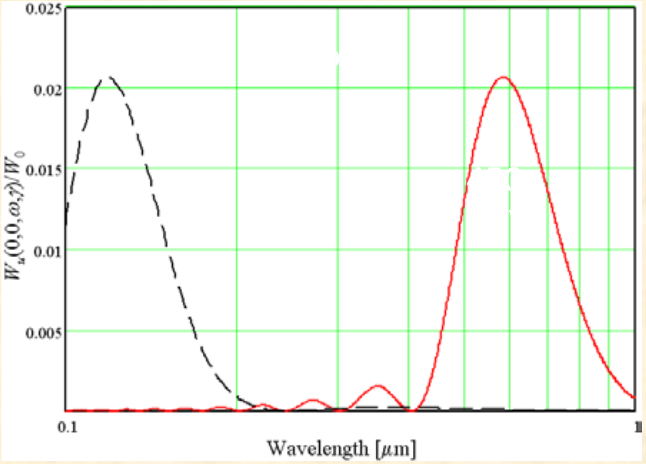


Synchrotron Light in the LHC

- At LHC injection energy
  - Visible emission from D3 dipole very low
  - Short superconducting undulator added
  - 2 periods of length 28cm with B field of 5 T

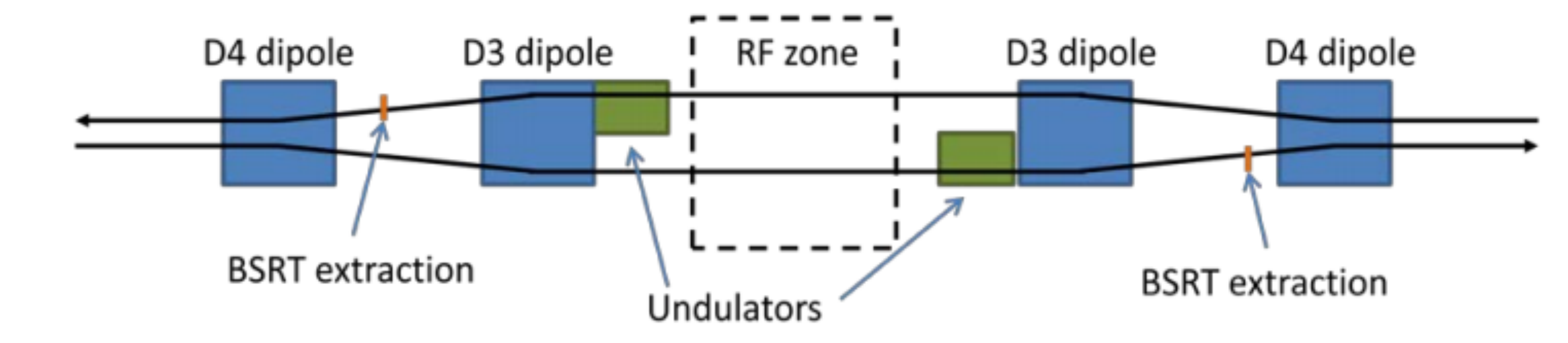






Synchrotron Light in the LHC

- Beam Synchrotron Radiation Telescope
  - BSRT located in Point 4 of the LHC



Synchrotron Light in the LHC

- Beam Synchrotron Radiation Telescope

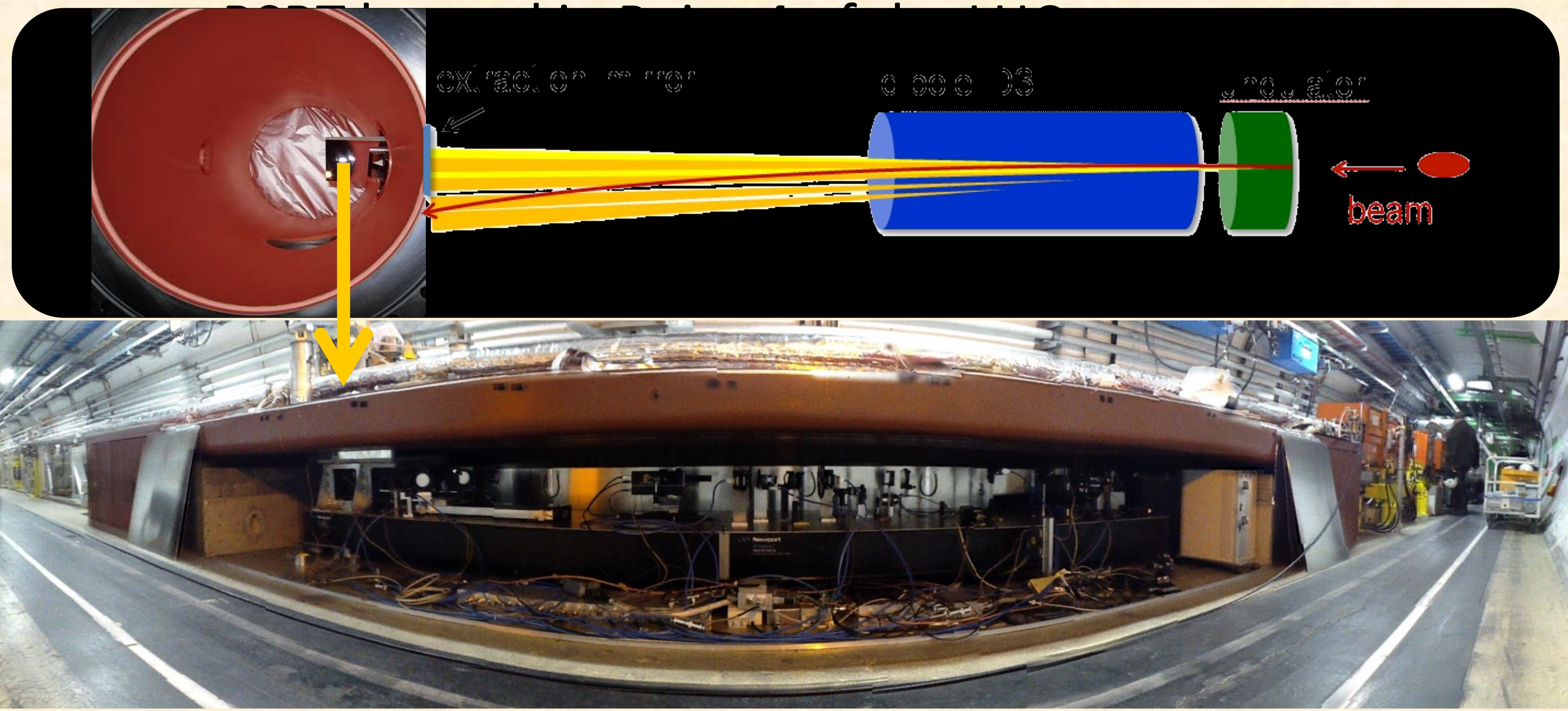


Image Acquisition in the LHC

- Using a gated intensified camera

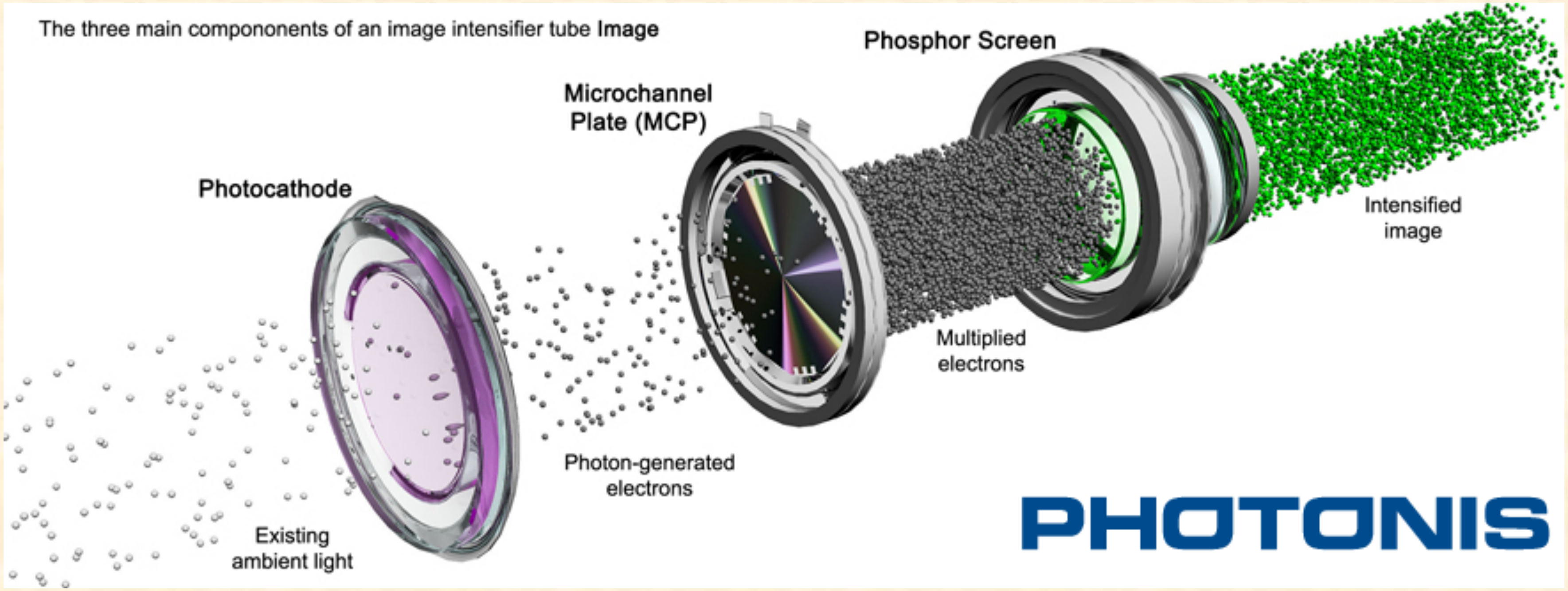
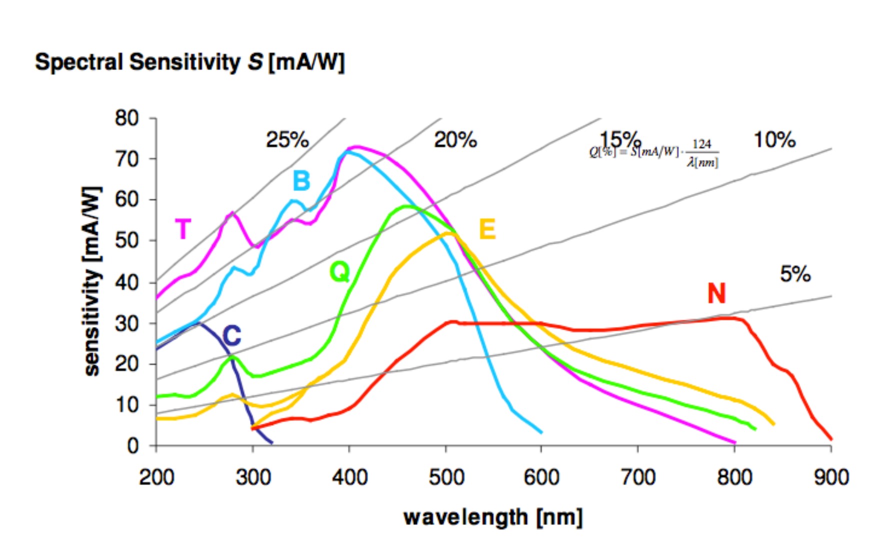


Image Acquisition in the LHC

- Proxitronic gated intensified camera
  - Intensifier max trigger rate : 200 Hz (~55 LHC turns)
  - Intensifier min gating : 25ns (1 LHC bucket)
- Present max acquisition rate is 10Hz
  - On paper 10 bunches per second but slower to get statistics

<u>Photocathode response</u>

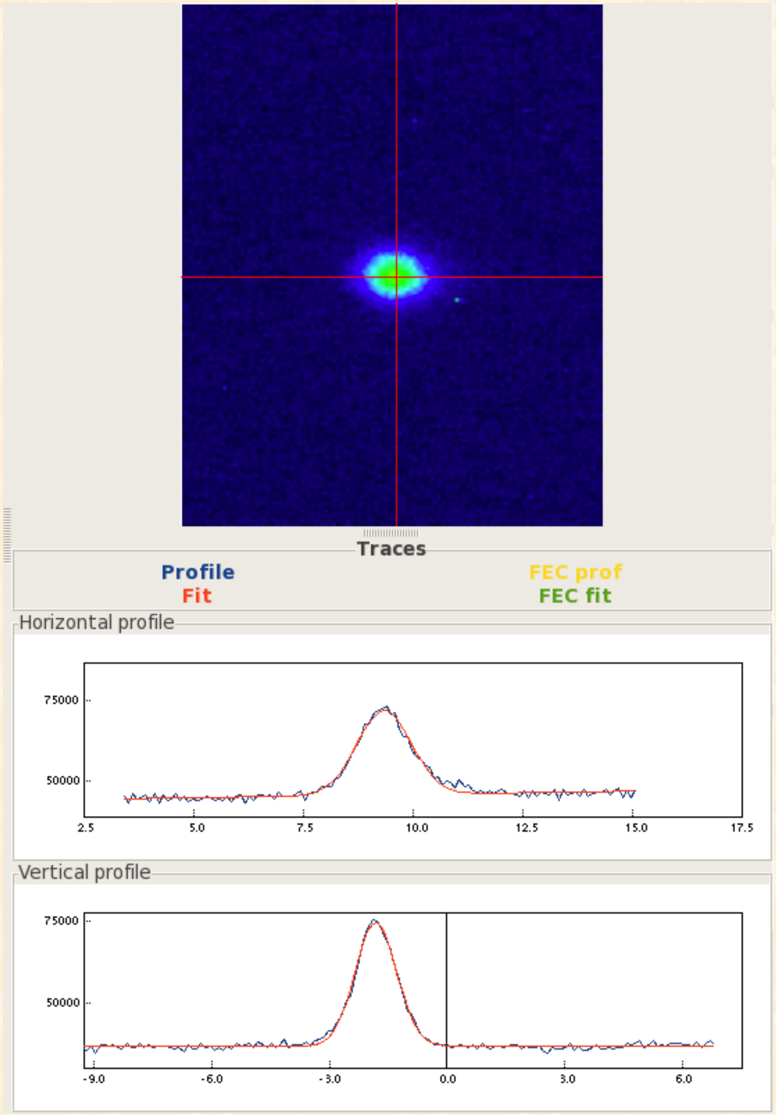
- cameras equipped with **N type** during Run I
- Will be equipped with **T type** for Run II



- Overall system sensitivity
  - Enough light to see
    - single proton pilot bunch (5e9p) on a single turn at injection (450GeV)
    - ~20 Ion Pb bunches at injection, averaged over 4 turns

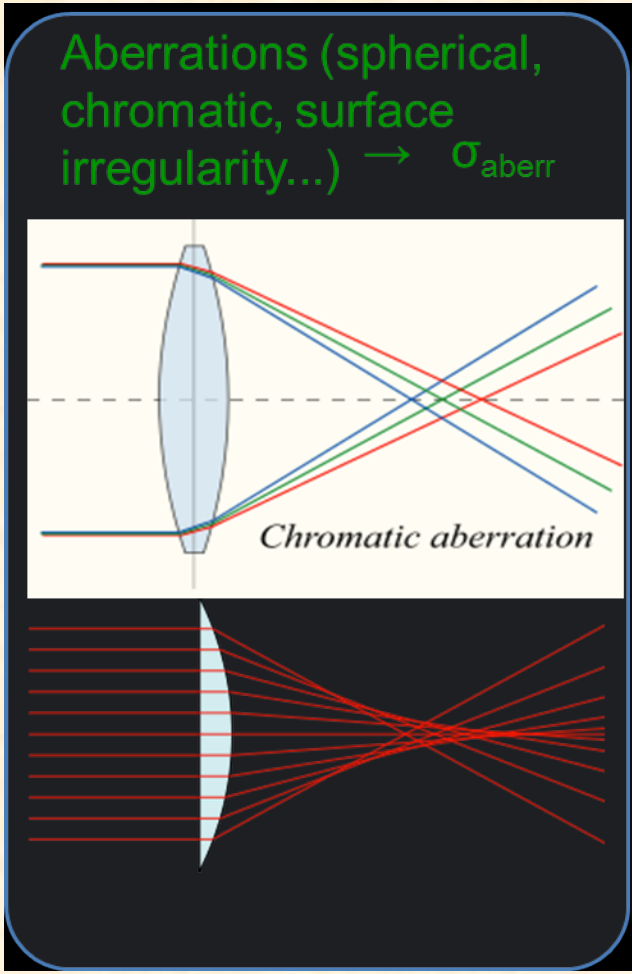
Proton Image Example

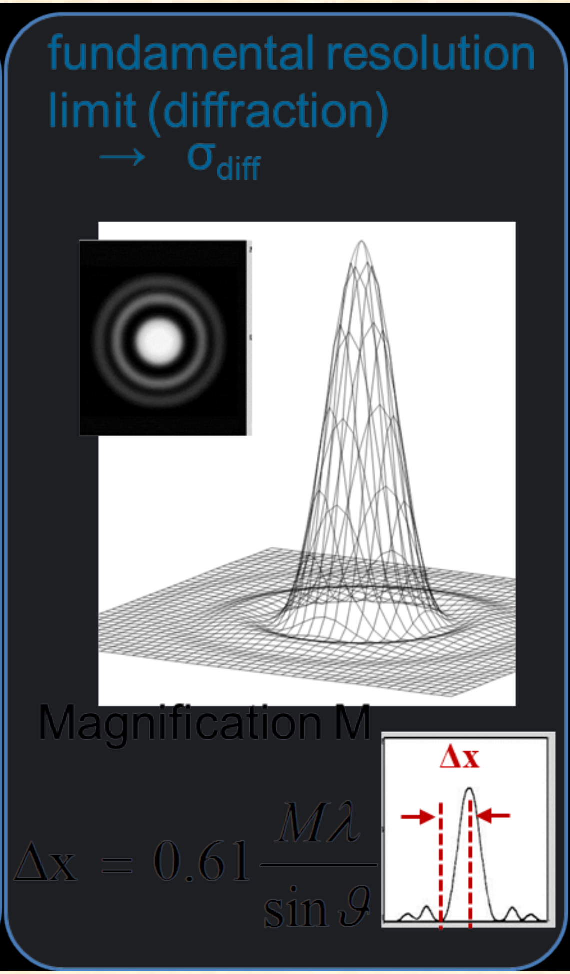
- Beam
  - Single bunch ~1.1e11p @ 3.5 TeV
- Acquistion
  - Accumulated over 4 turns at 200Hz

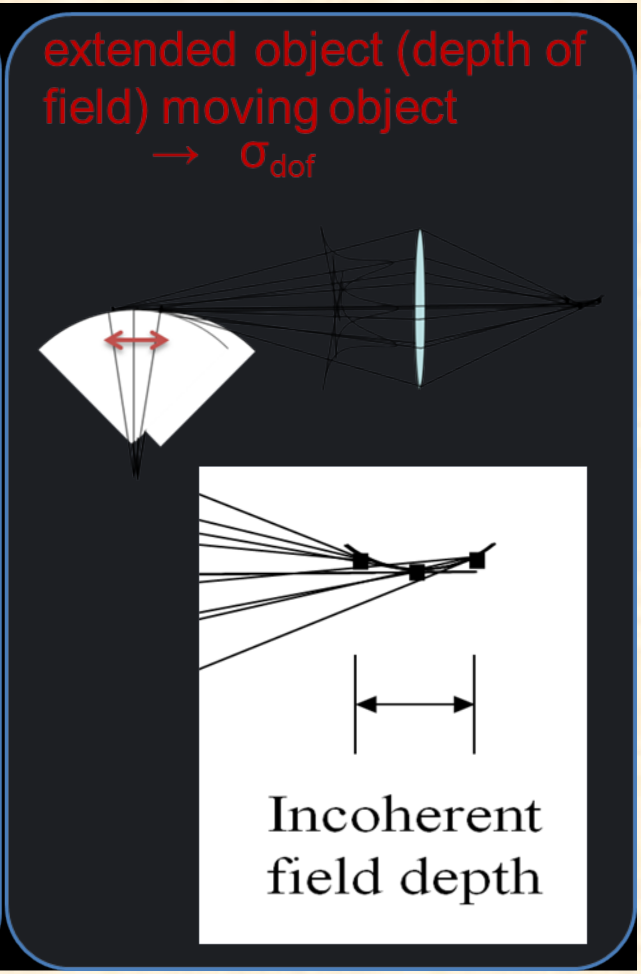


Beam Size Measurement with Synchrotron Light

- Imaging Resolution



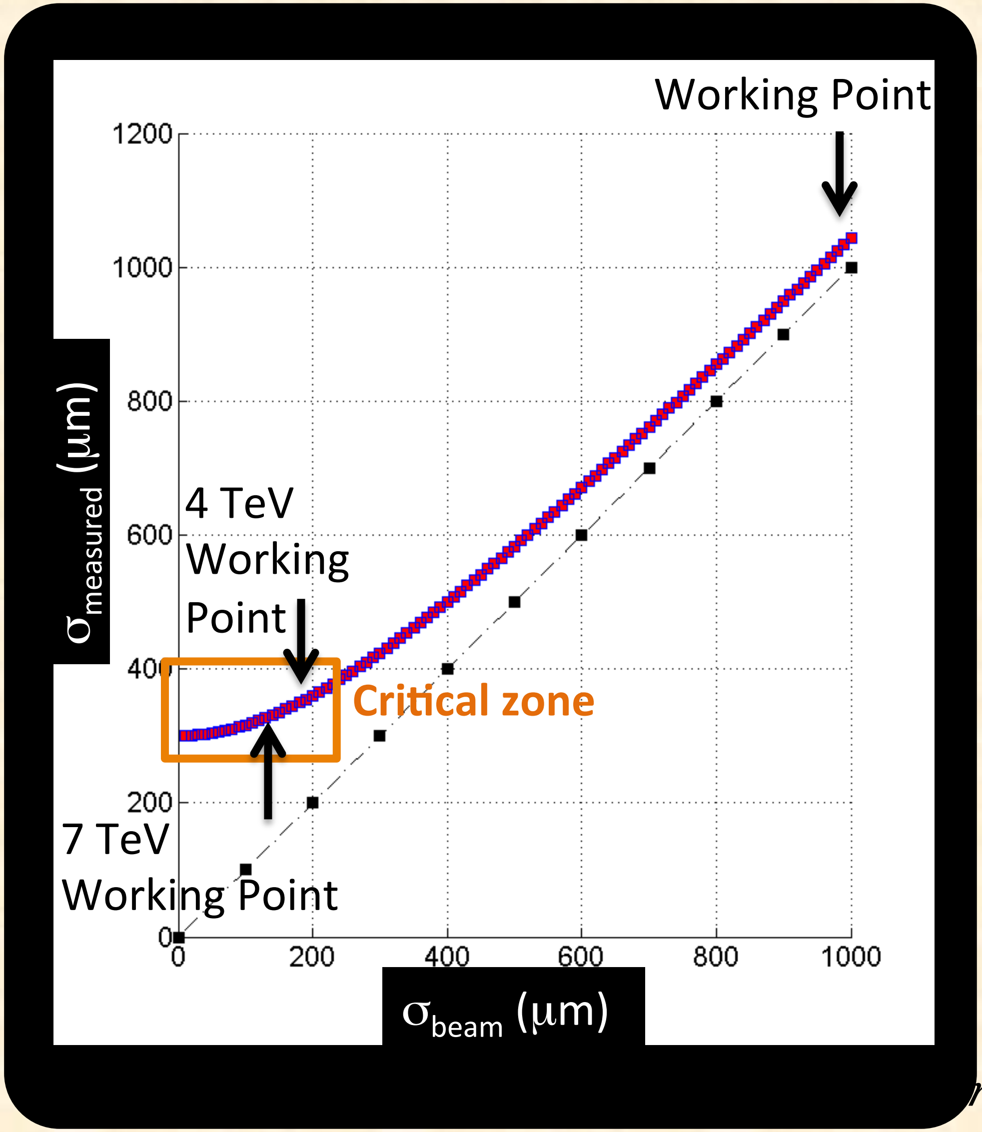




Synchrotron light limitations in the LHC

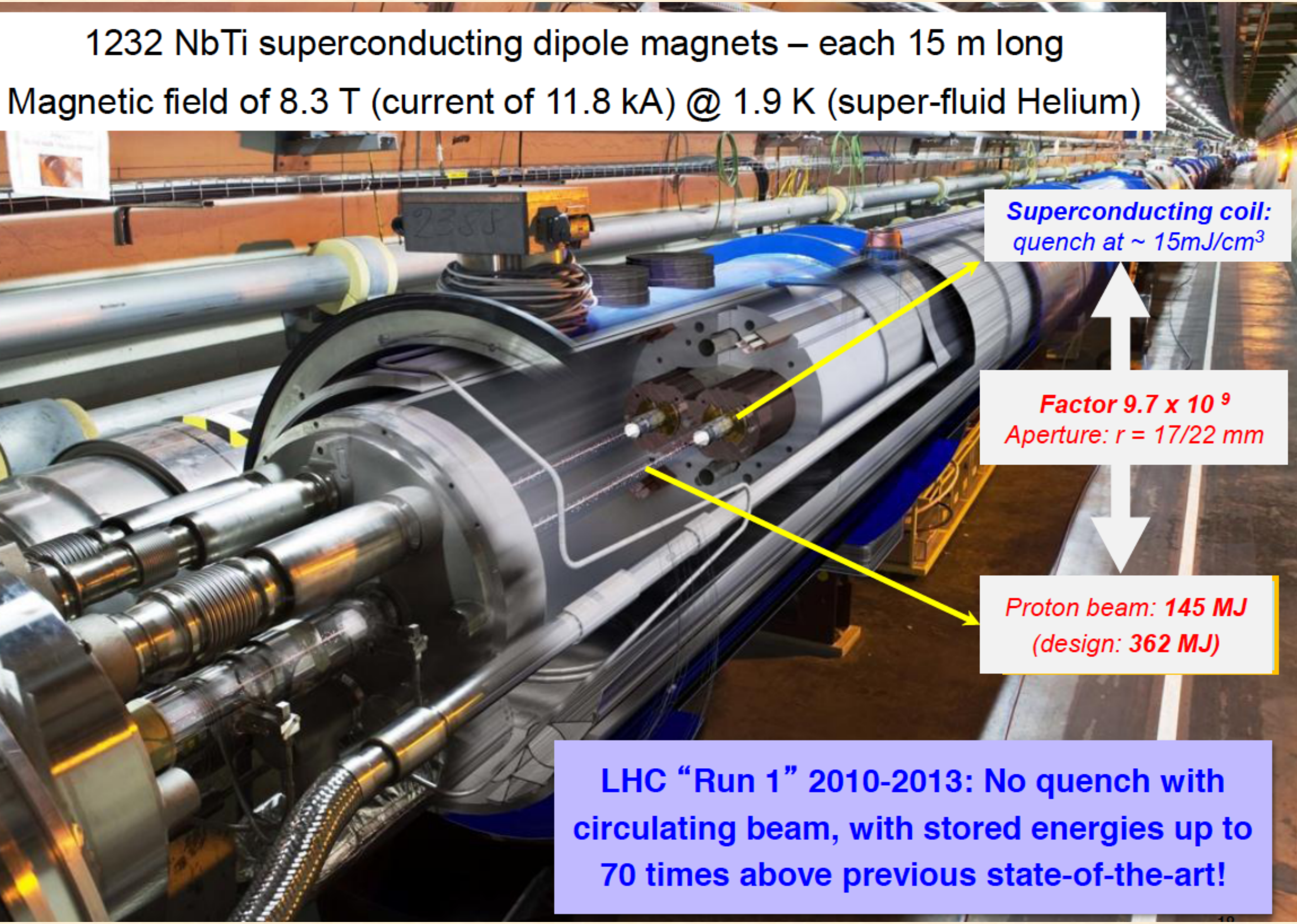
- $\sigma_{correction}$
  - Difficult to model accurately & simulate
  - Therefore experimentally measured ,knowing the real beams size
    - WireScanner cross calibration

- Size measured has to be de-covoluted by a correction factor to obtain the real size
  - For LHC correction factor is of same order as real beam size

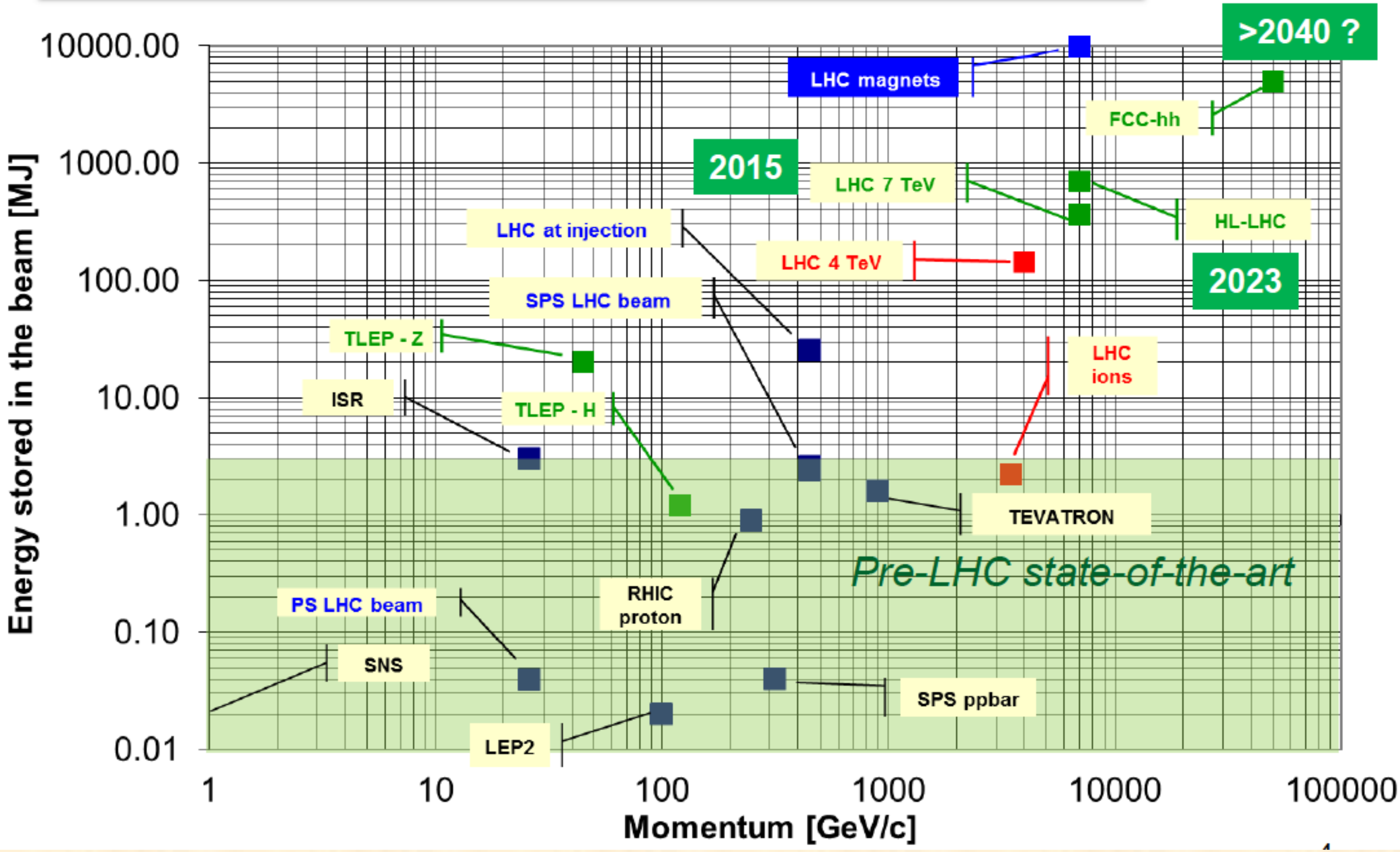


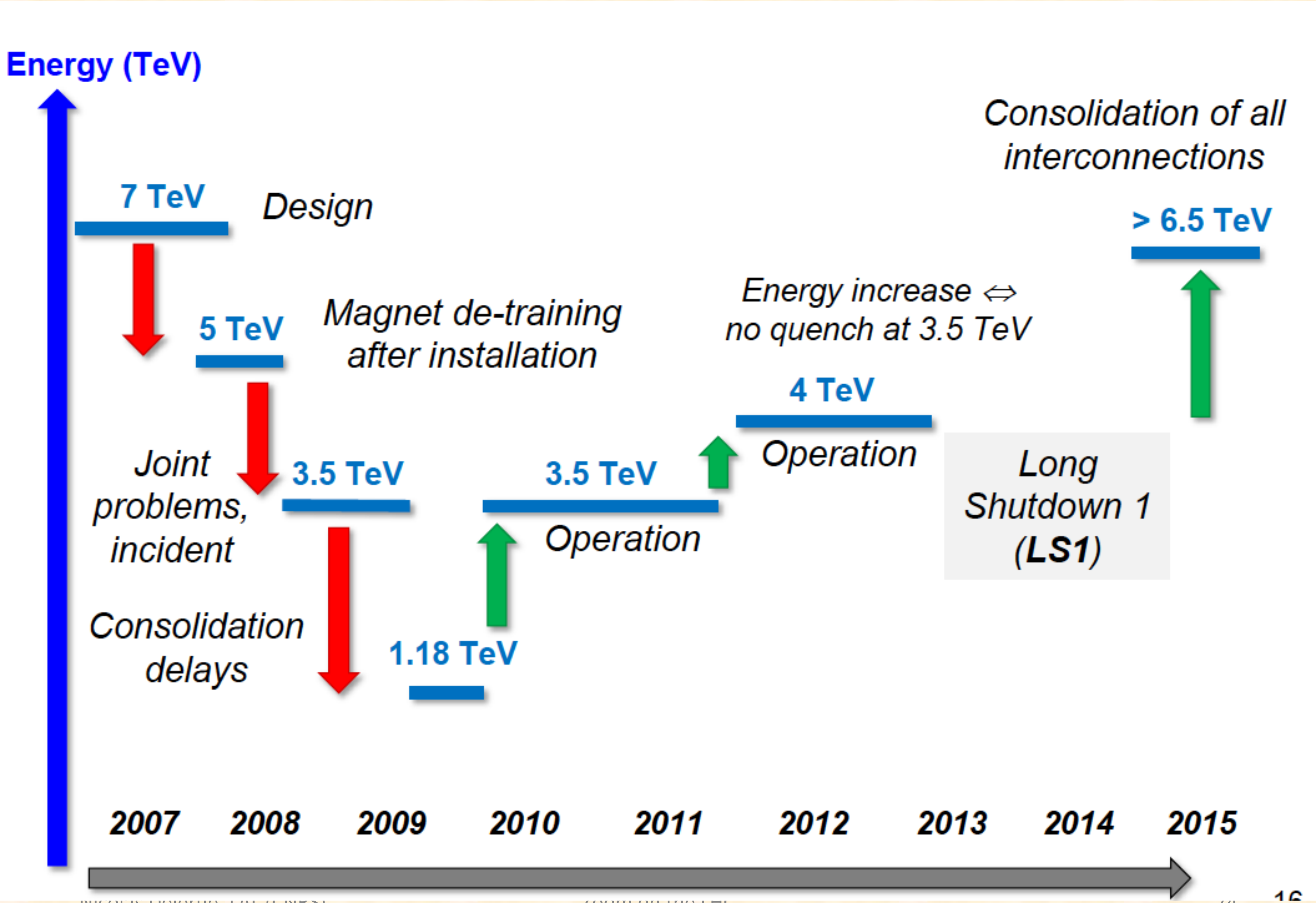
(most slides courtesy of Dr Rhodri Jones and J. Wenninger)

MACHINE PROTECTION AND BEAM LOSS MONITORS

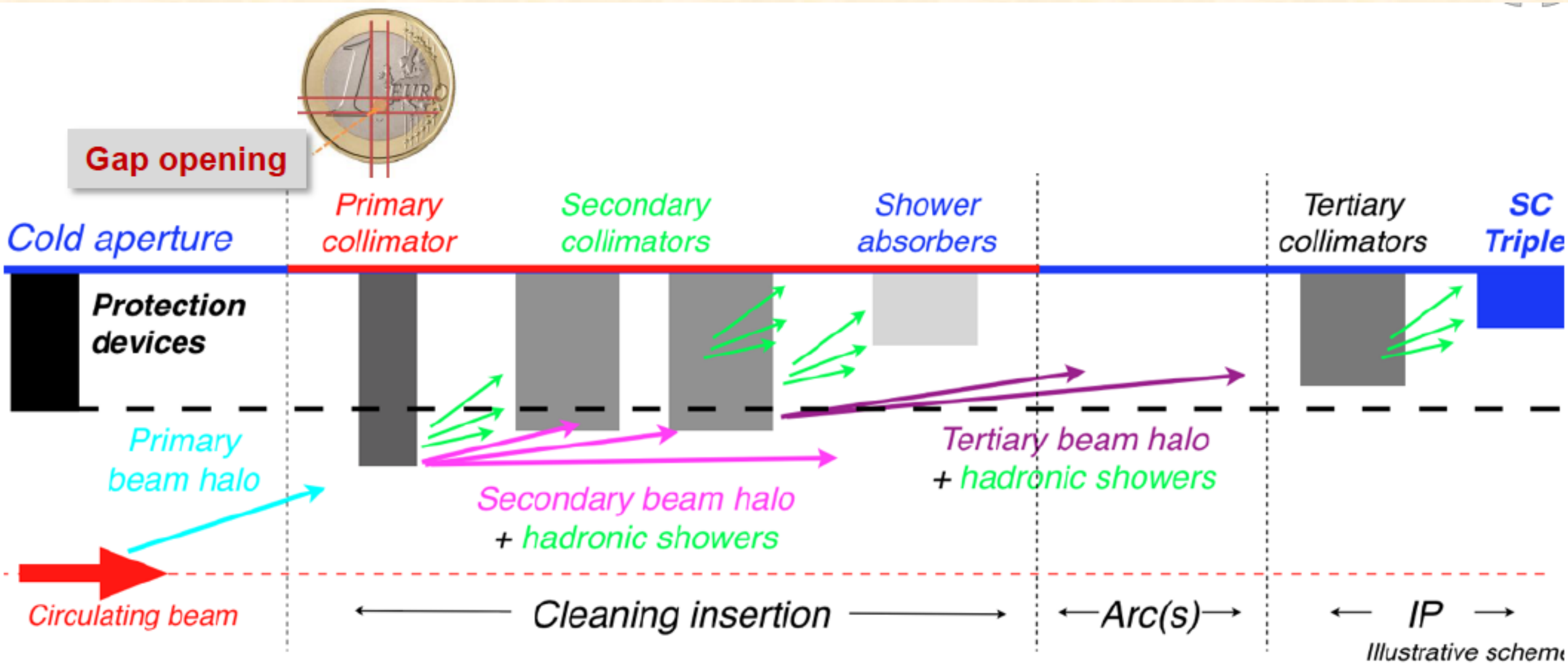

1232 NbTi superconducting dipole magnets – each 15 m long
Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)
Superconducting coil:
quench at ~ 15mJ/cm³
Factor 9.7 x 10 ⁹
Aperture: r = 17/22 mm
Proton beam: 145 MJ
(design: 362 MJ)
LHC "Run 1" 2010-2013: No quench with circulating beam, with stored energies up to 70 times above previous state-of-the-art!

LHC pushes the stored energy from few MJs to > 100 MJs




Energy (TeV)
Consolidation of all interconnections
7 TeV
Design
> 6.5 TeV
Energy increase ⇔ no quench at 3.5 TeV
5 TeV
Magnet de-training after installation
4 TeV
Operation
Joint problems, incident
3.5 TeV
3.5 TeV
Operation
Long Shutdown 1 (**LS1**)
Consolidation delays
1.18 TeV
2007
2008
2009
2010
2011
2012
2013
2014
2015
16

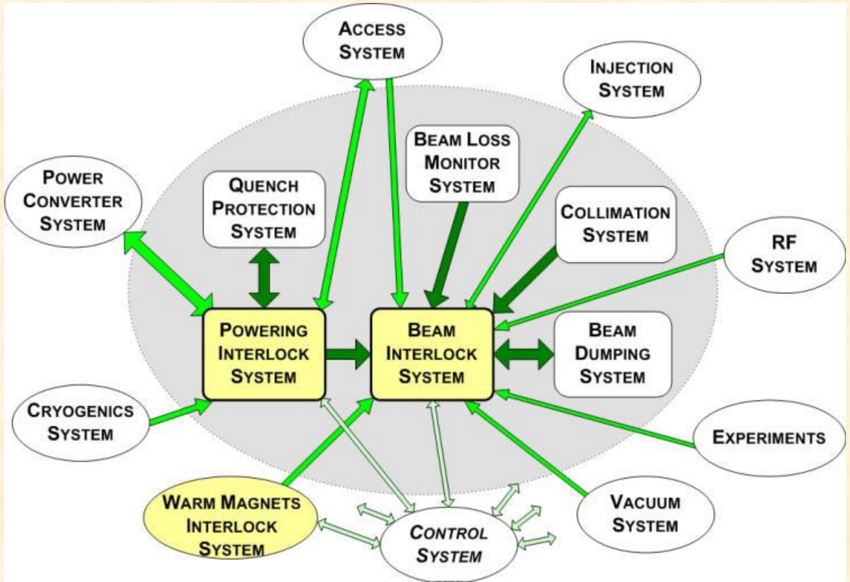
Collimation system



- To be able to absorb the energy of the 7 TeV proton, the LHC requires a multi-stage collimation system – primary, secondary, tertiary.
- The system worked perfectly so far – thanks to excellent beam stabilization and machine reproducibility – only one full collimation setup / year.
  - ~99.99% of the protons that were lost from the beam were intercepted.

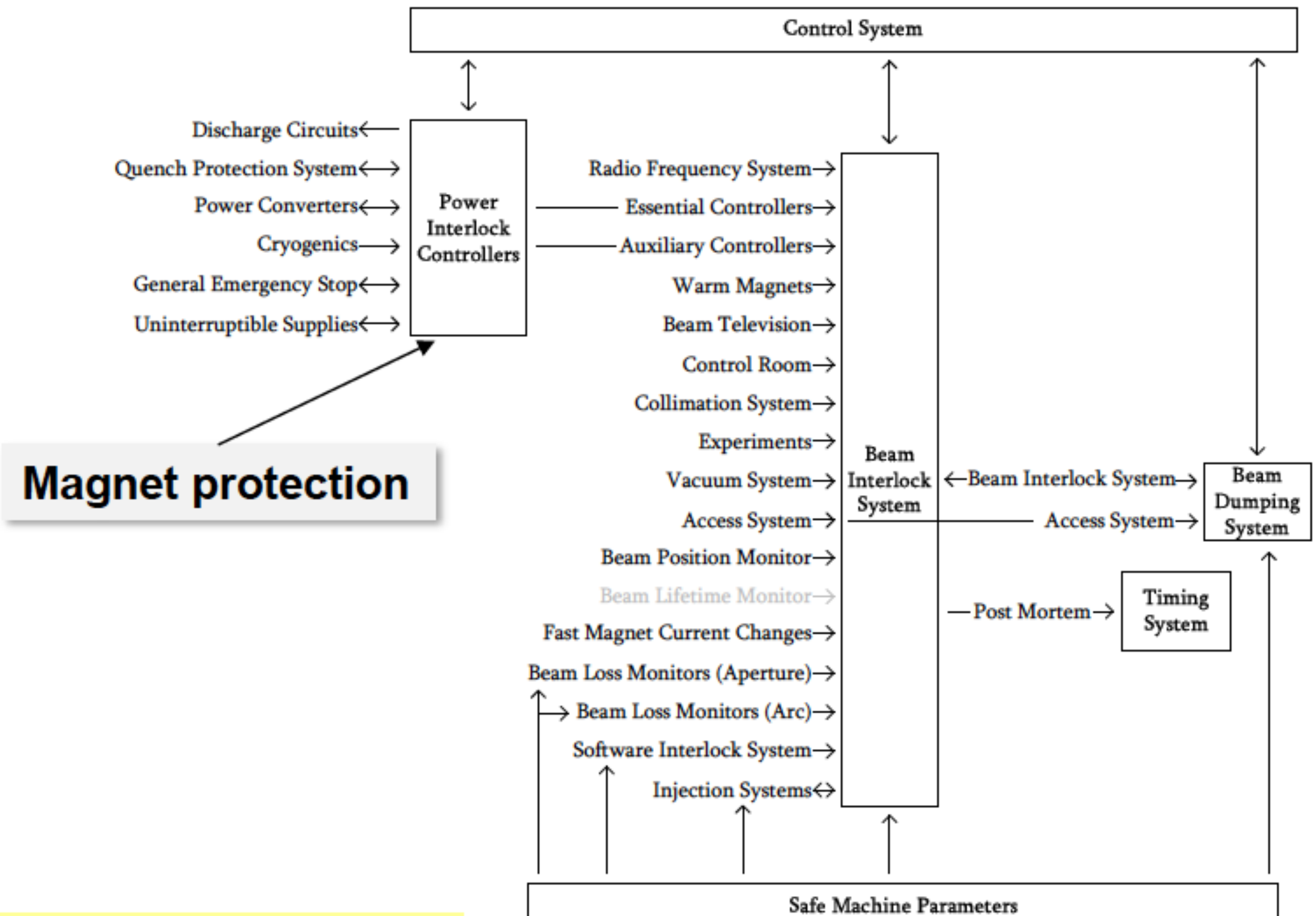
Machine protection system

- The LHC beams carry the same amount of energy than a jumbo plane at take-off!
- If a beam is sent on the beam pipe accidentally it could make serious damages!
- A complex “machine protection system” is used to monitor the machine at all time and prevent injection or dump the beam if a fault is detected.
- A system of flags and permits is used to prevent any situation that might led to significant damages.



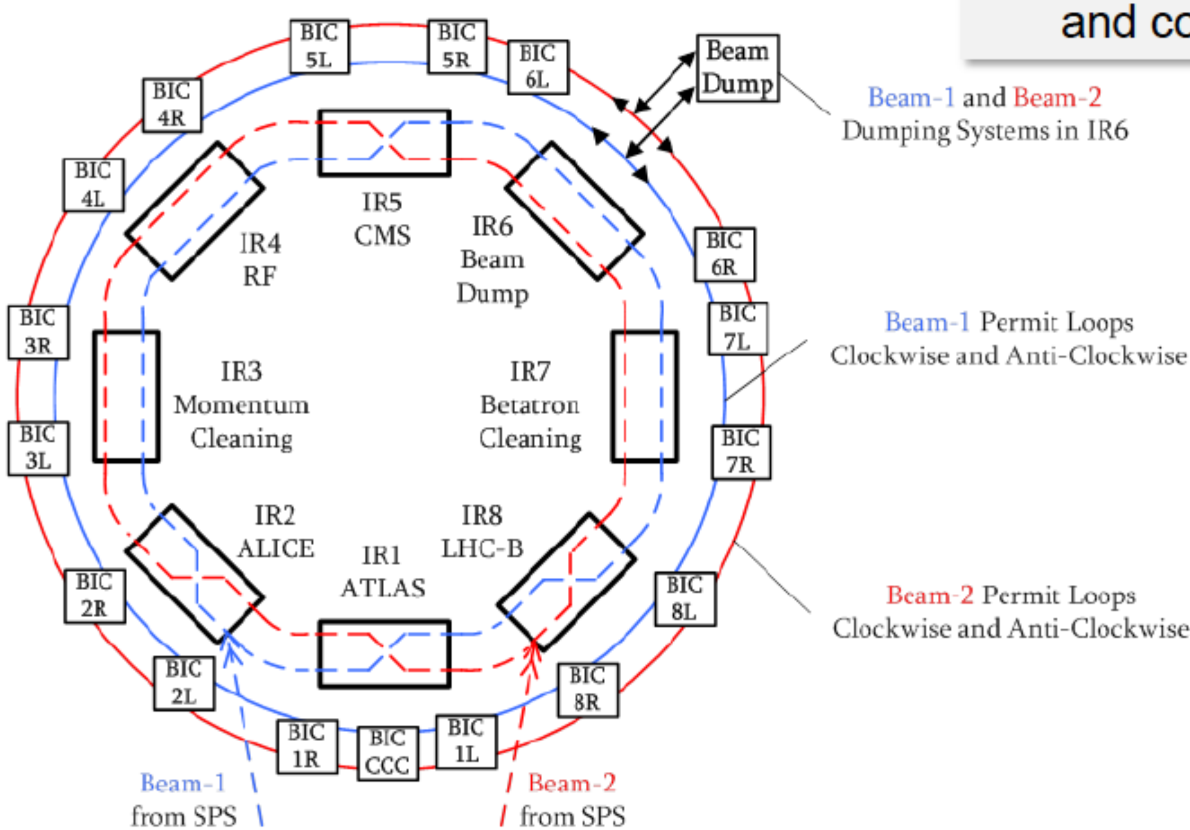
MPS

- The LHC beam interlock system (BIS) has 189 inputs from client systems (including injection).
- Behind each input that can be many individual tests / interlocks.



Beam permit

see lecture by R. Schmidt



Loop signal propagation in clockwise and counter-clockwise directions

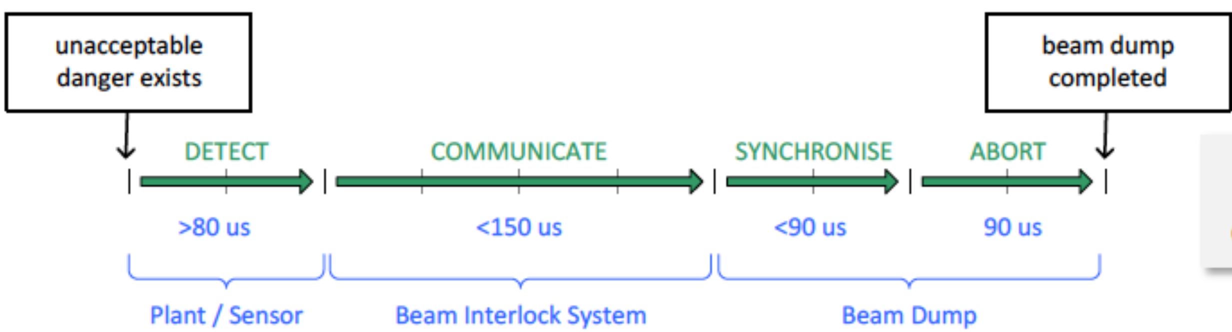
4 beam permit loops

2 permit loops / beam

Direct link to LHC injection and SPS extraction

→ no beam permit

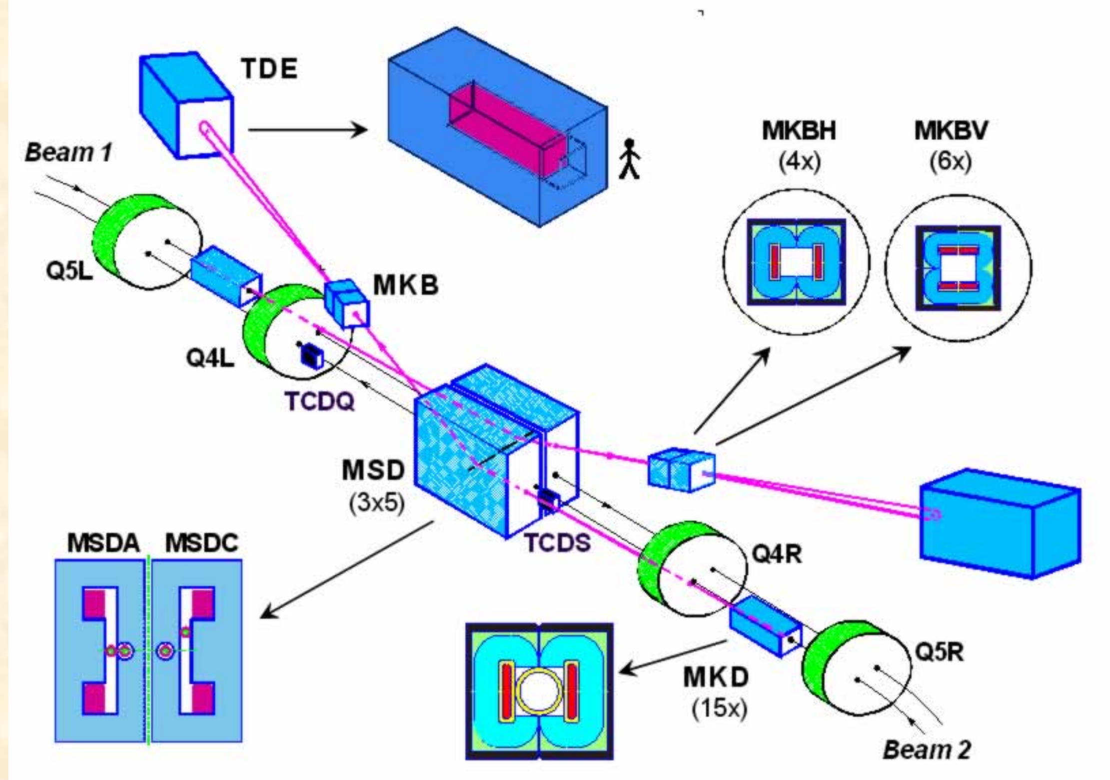
→ no injection/extraction

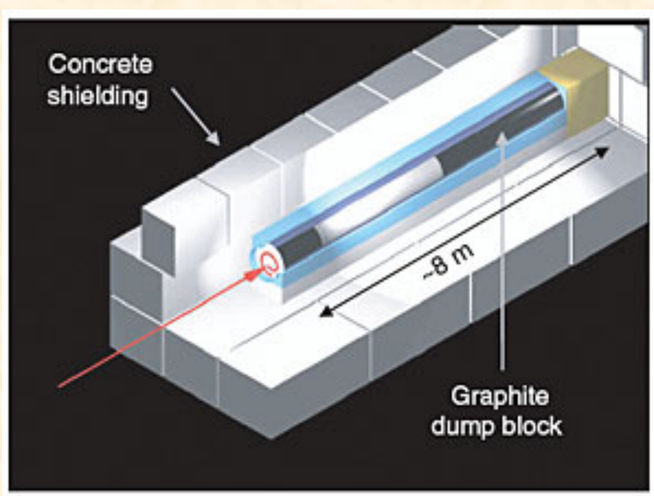


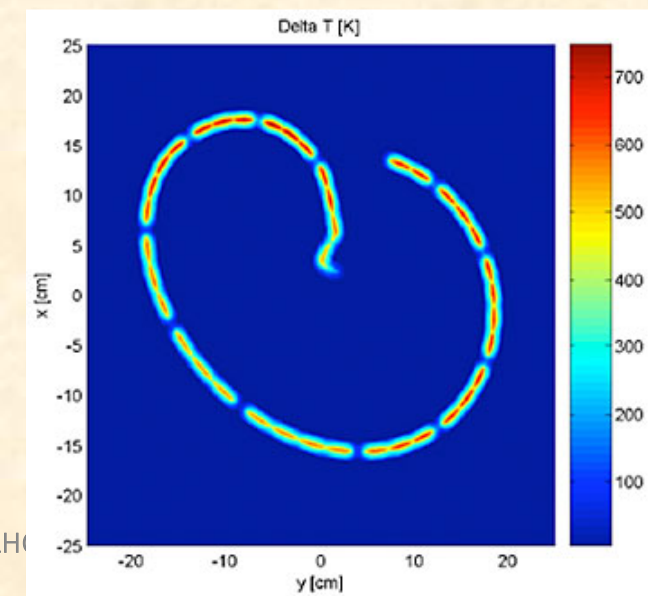
At the LHC the dump delay can reach ~3 turns – ~300 μs

How to get rid of the beams?

- With so much energy stored in the beams they have to be disposed of with care.
- A special area “dumps” has been designated and instrumented for this purpose.
- All the energy can not be disposed of on a single point.

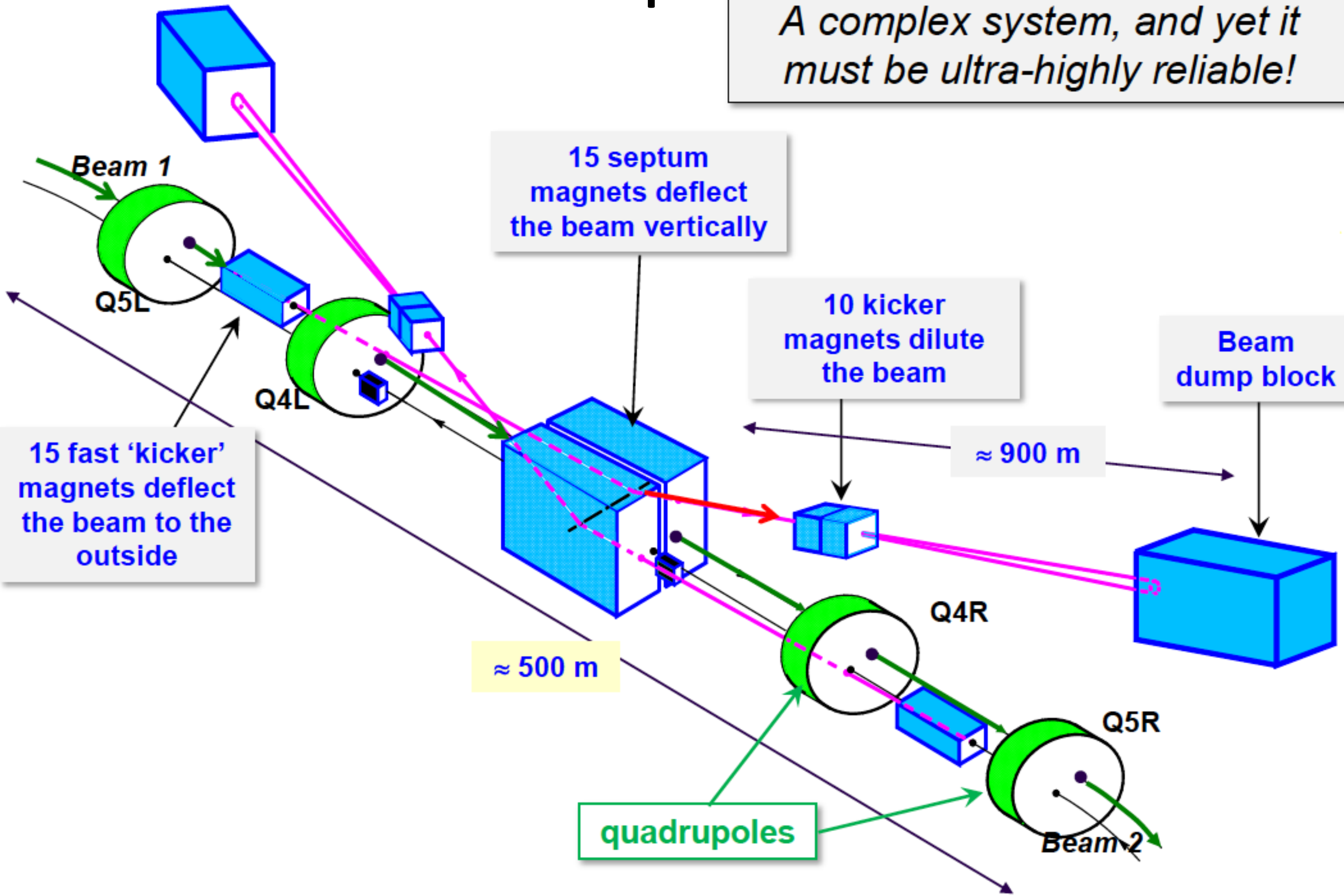


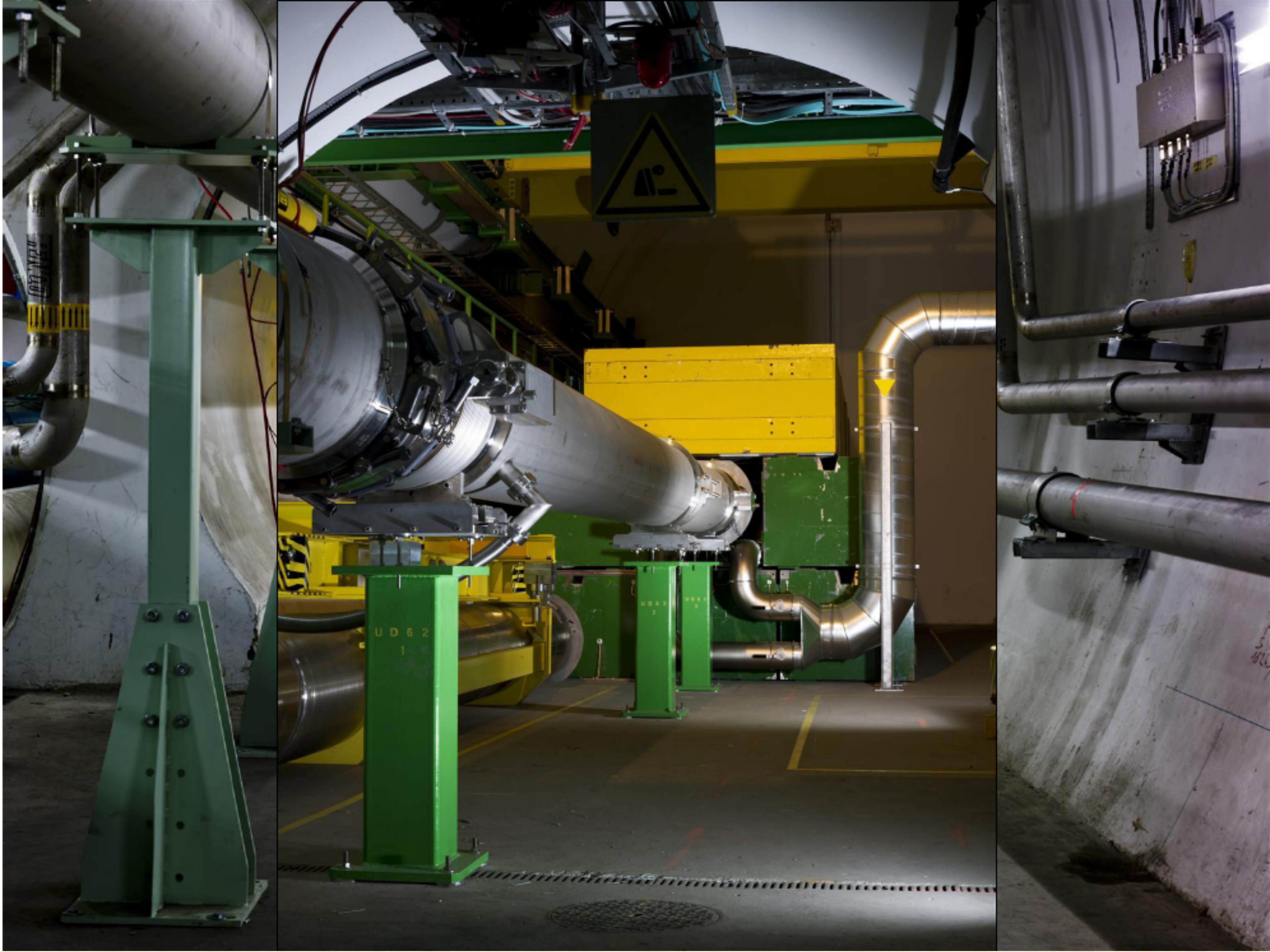




LHC beam dump

A complex system, and yet it must be ultra-highly reliable!

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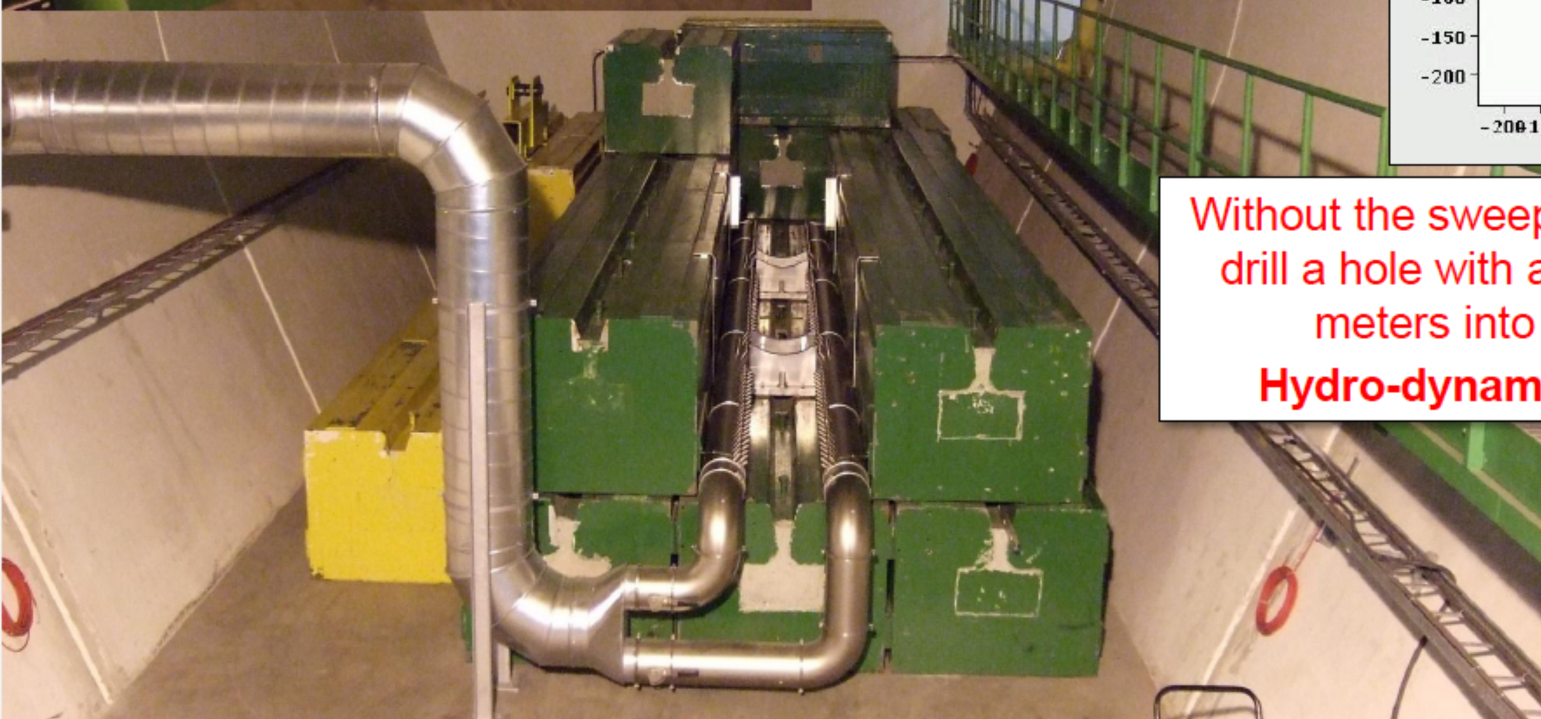
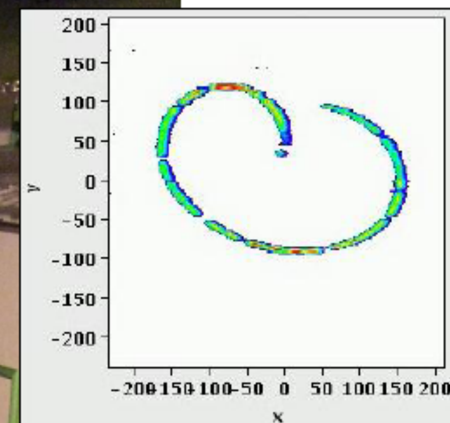


The dump block is the only LHC element capable of absorbing the nominal beam.

The beam is swept over dump surface to lower the power density.



Without the sweep the beam could drill a hole with a depth of a few meters into the block !

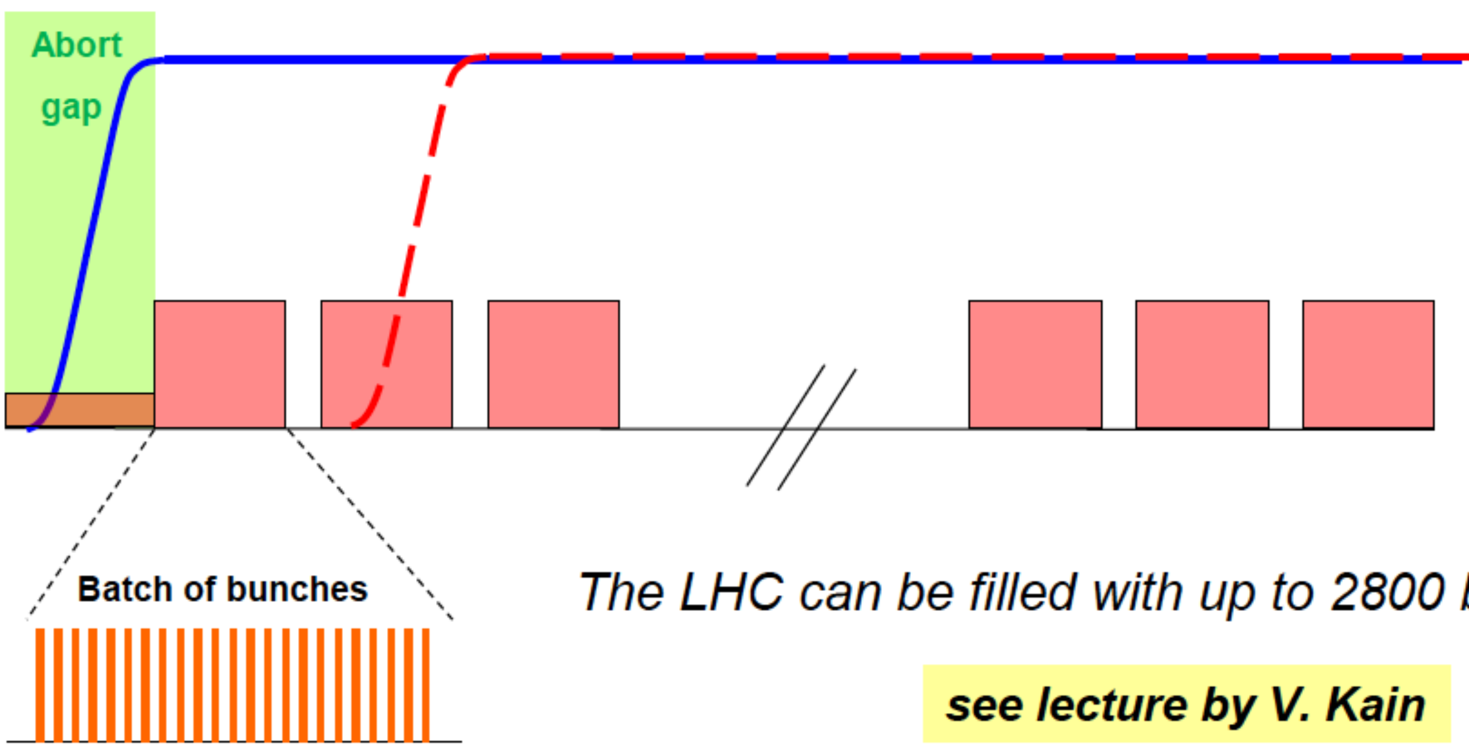
Hydro-dynamic tunnelling

25

Beam dump synchronisation

- The beam dump must be accurately synchronized to the **beam abort gap** to avoid spreading beam across the aperture during the kicker rise-time.
- The 3 μs long **beam abort gap** must be … free of beam !
- Possible failure modes:
  - The abort gap fills with beams (RF fault, debunching, injection error),
  - The kicker synchronization fails,
  - A kicker fires spontaneously (not synchronized).

Asynchronous dump failure



The LHC can be filled with up to 2800 bunches

see lecture by V. Kain

LHC incident on September 19th 2008

- Last commissioning step of one out of the 8 main dipole electrical circuit in sector 34 : ramp to 9.3kA (5.5 TeV).
- At 8.7kA an electrical fault developed in the **dipole bus bar** located in the interconnection between quadrupole Q24.R3 and the neighboring dipole.

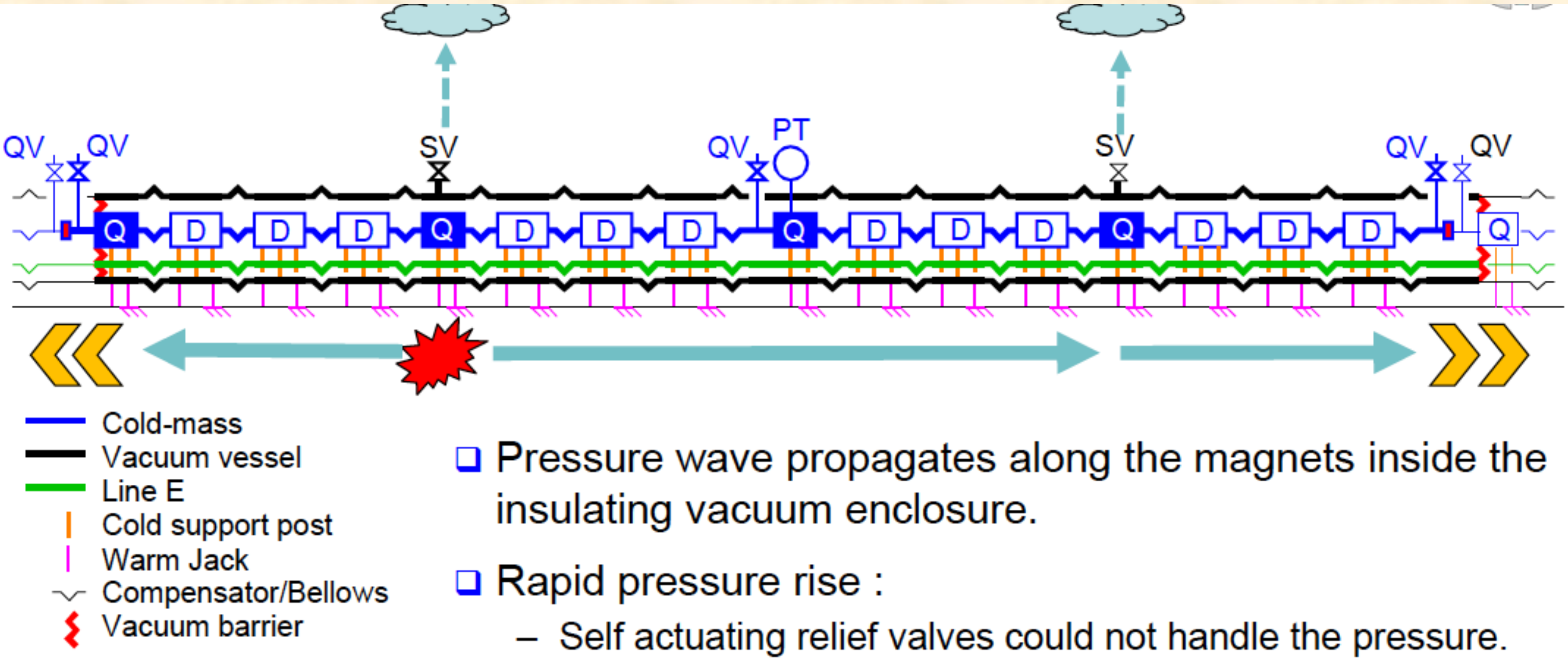
  Later correlated to a local resistance of ~220 nΩ – nominal value 0.35 nΩ.
- An electrical arc developed which punctured the helium enclosure.

  Secondary arcs developed along the arc.

  Around 400 MJ from a total of 600 MJ stored in the circuit were dissipated in the cold-mass and in electrical arcs.
- Large amounts of Helium were released into the insulating vacuum.

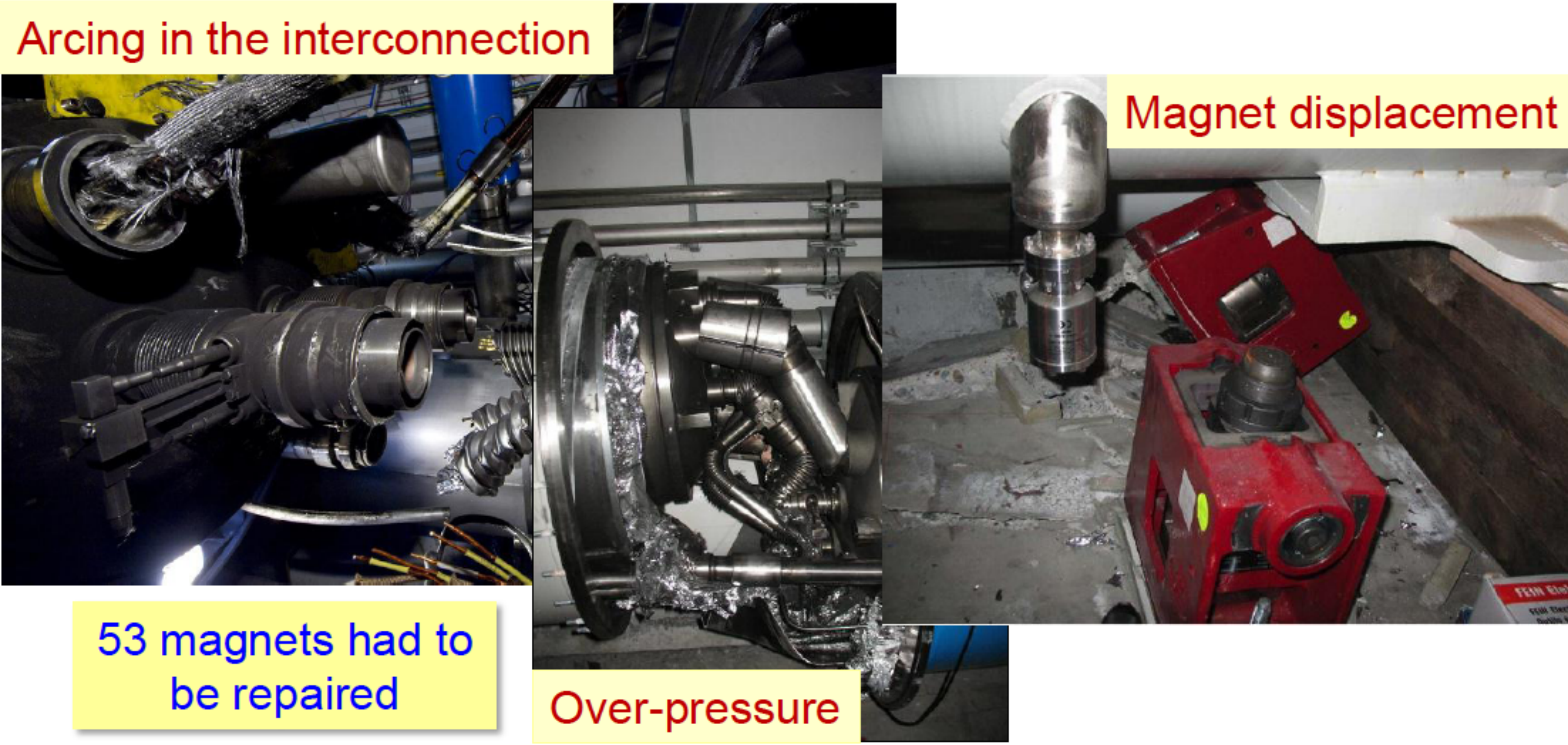
  In total 6 tons of He were released.

This incident involved magnet powering, but no beam!



- Pressure wave propagates along the magnets inside the insulating vacuum enclosure.
- Rapid pressure rise :
  - Self actuating relief valves could not handle the pressure. *designed for 2 kg He/s, incident ~ 20 kg/s.*
  - Large forces exerted on the vacuum barriers (every 2 cells). *designed for a pressure of 1.5 bar, incident ~ 8 bar.*
  - Several quadrupoles displaced by up to ~50 cm.
  - Connections to the cryogenic line damaged in some places.
  - Beam vacuum to atmospheric pressure.

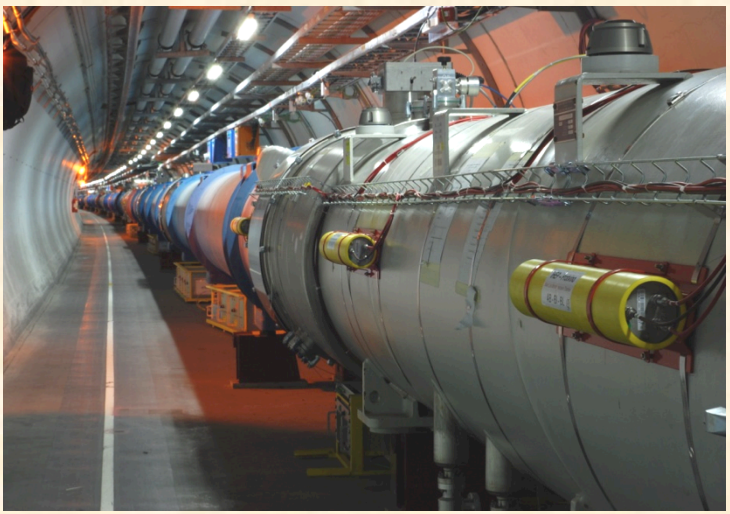
The Helium pressure wave damaged ~600 m of LHC, polluting the beam vacuum over more than 2 km.

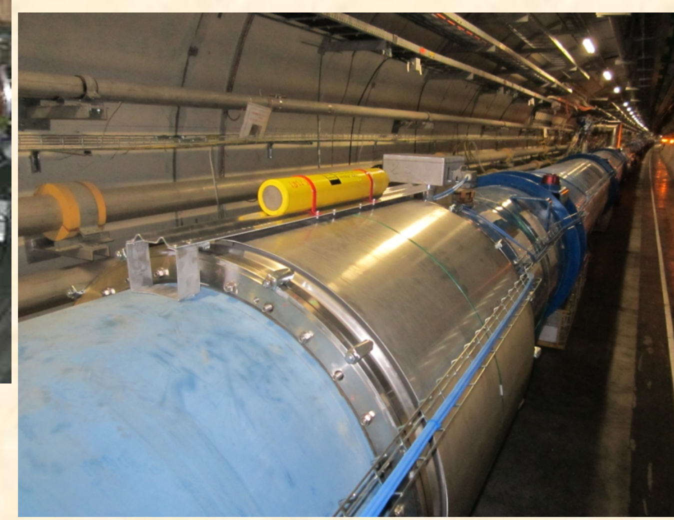


53 magnets had to be repaired

Beam Loss Detection

- Role of a Beam Loss Monitor (BLM) system:
  - Protect the machine from damage
  - Dump the beam to avoid magnet quenches (for SC magnets)
  - Diagnostic tool to improve the performance of the accelerator



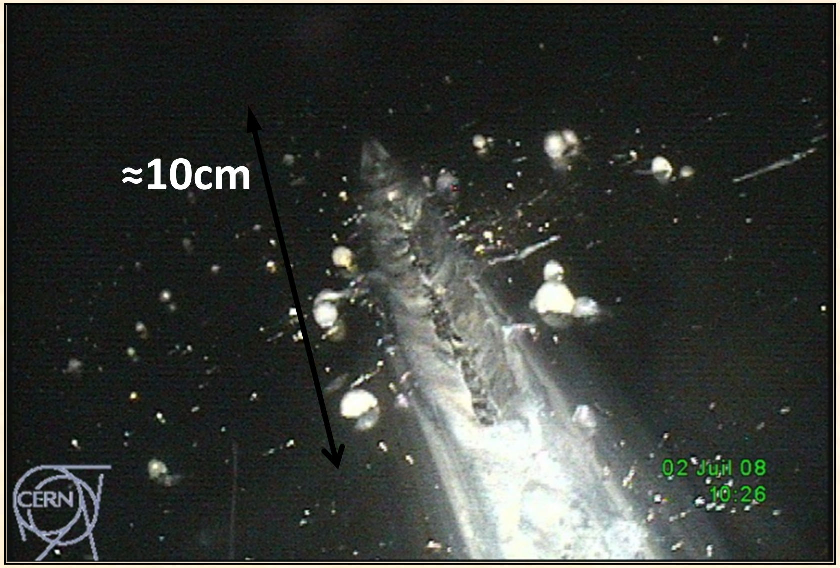


Machine Protection

- Failure in protection
  - loss of complete LHC is possible
- Magnet damage
  - months of downtime & significant cost
- Magnet quench
  - hours of downtime

Stored Energy	
Beam 7 TeV	2 x 362 MJ
2011 Beam 3.5 TeV	above 2 x 100 MJ
Magnets 7 TeV	10 GJ

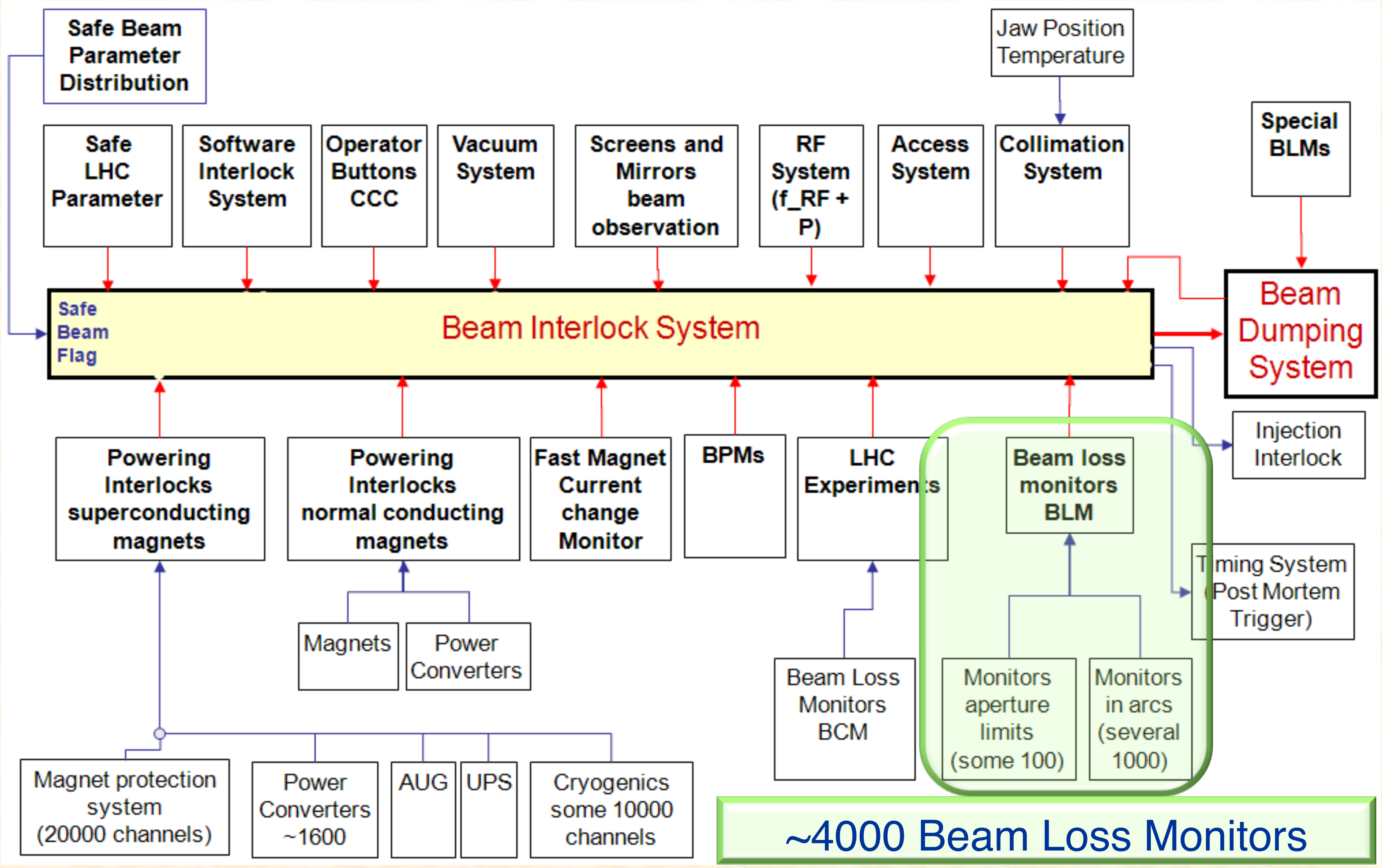
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3



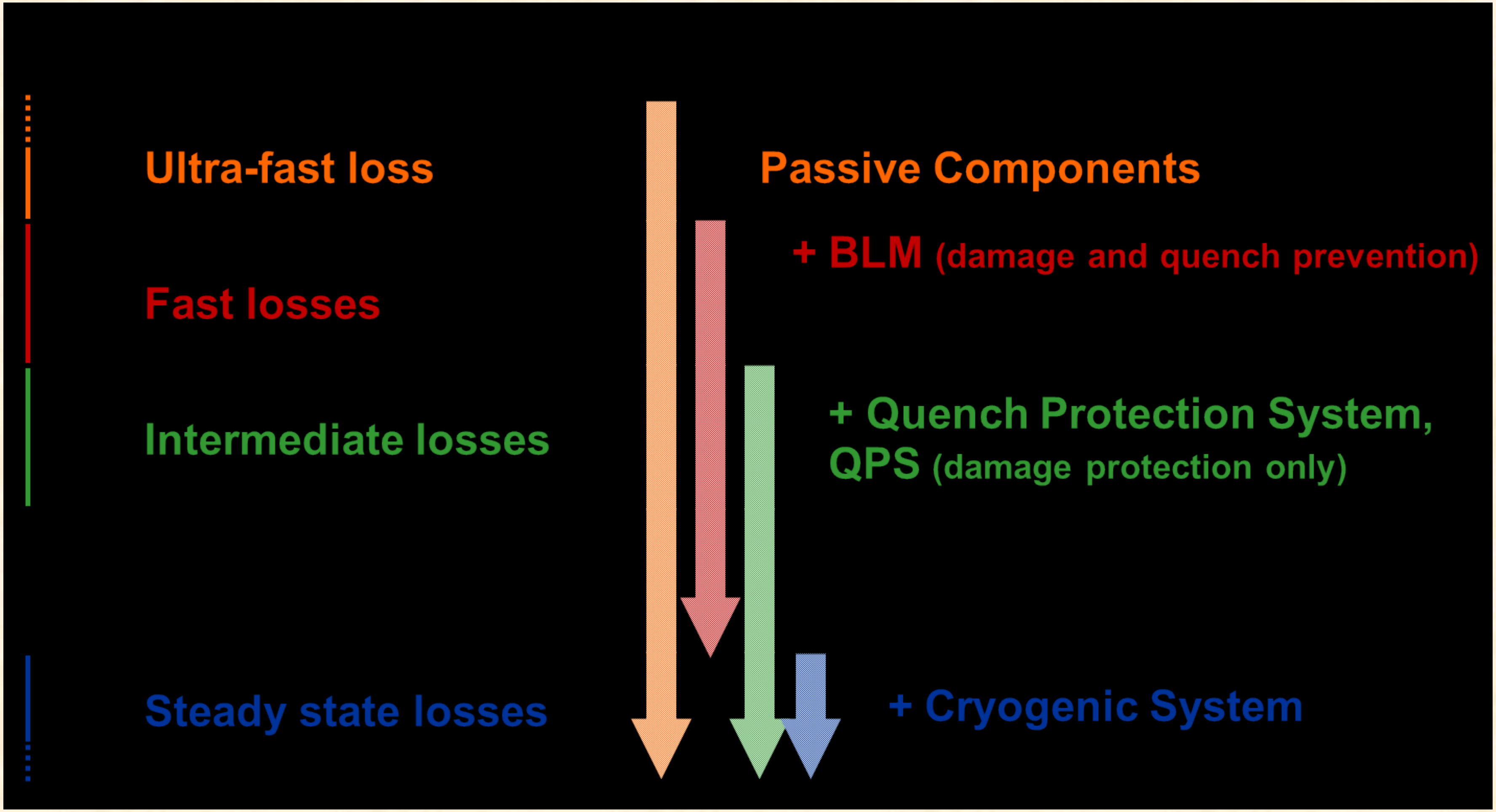
- SPS incident
  - June 2008
  - 2 MJ beam lost at 400GeV

The LHC Machine Protection System

- Over 20,000 channels from ~250 user input connections



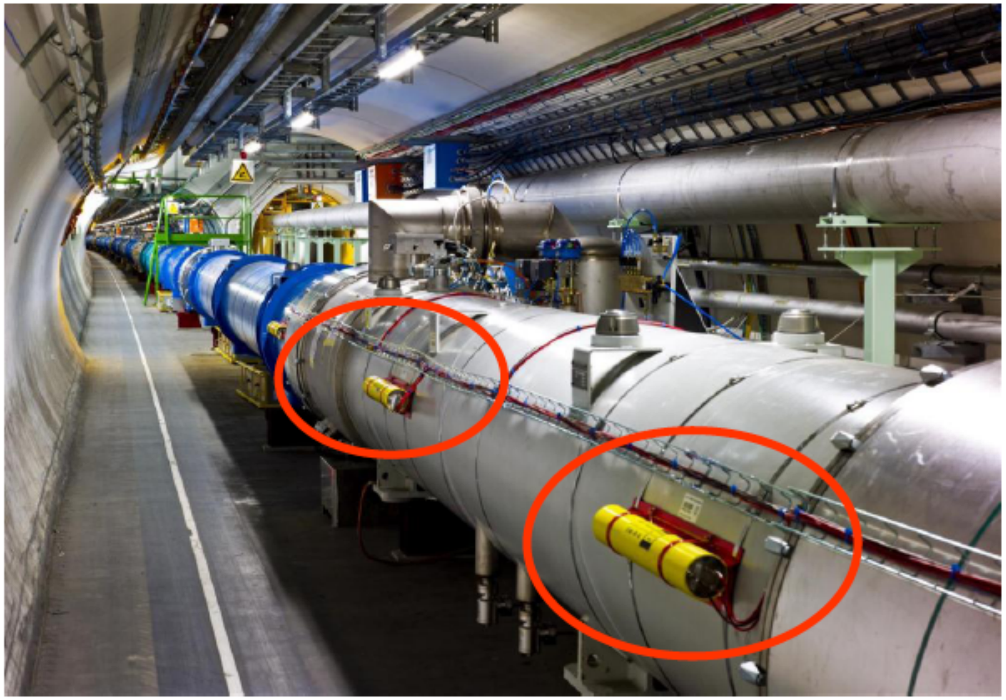
Beam Loss Durations

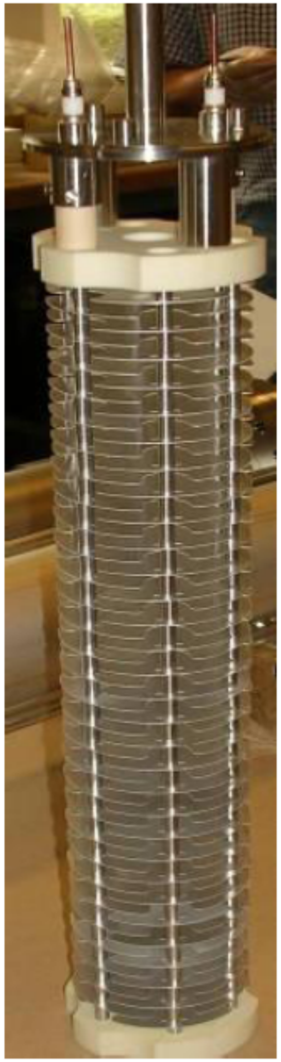


- LHC BLM System
  - Main system to prevent magnet damage from multi-turn beam losses
  - Only system to prevent magnet quench

Beam loss monitoring

- Ionization chambers are used to detect beam losses:
  - Very fast reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- ~**3600** chambers (BLMS) are distributed over the LHC to detect beam losses and trigger a beam abort !
- BLMs are good for almost all failures as long as they last ~ a few turns (few 0.1 ms) or more !





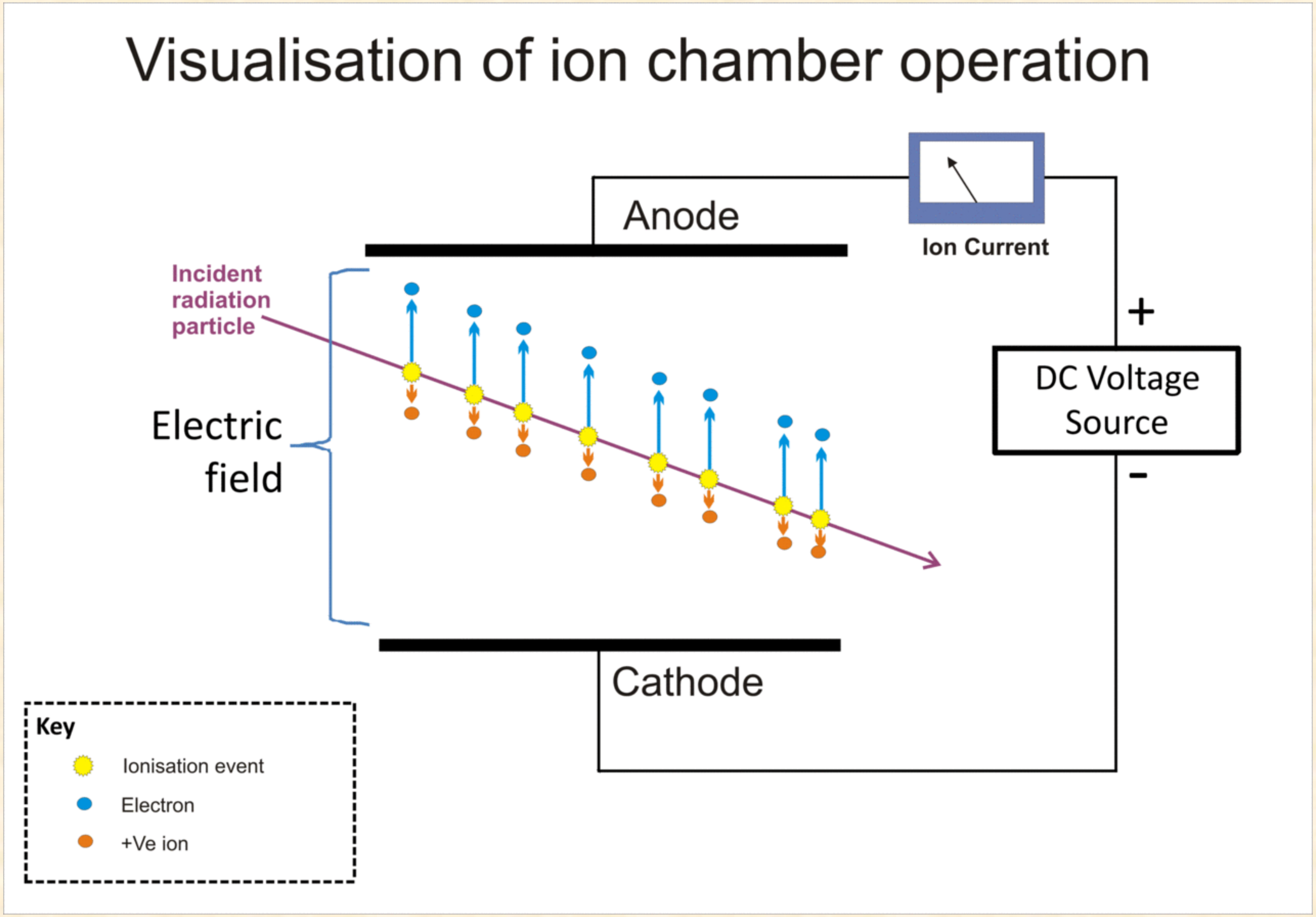
BLM System Challenges

- Design Specifications
  - Reliability
    - tolerable failure rate 10^{-7} per hour per channel $\Rightarrow$ 10^{-3} magnets lost per year (assuming 100 dangerous losses per year)
    - Implies
      - Reliable components, radiation tolerant electronics
      - Redundancy, voting
      - Monitoring of availability and drift of channels
  - Less than 2 false dumps per month (operation efficiency)
  - High dynamic range 10^{13}
  - Fast (1 turn, 89 μs) trigger generation for dump signal
  - Quench level determination with uncertainty of factor 2
    - Extensive simulations and measurements
    - Threshold values a function of loss duration and beam energy

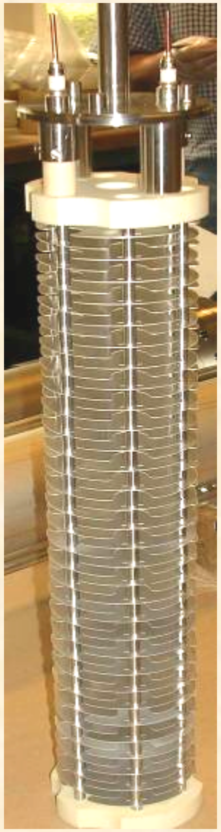
Loss Scenarios in the LHC

- Orbit bumps or combination of orbit bump & fast perturbation
  - Much of the LHC controlled automatically with feedbacks
- Leakage from collimation regions
  - Debris reach cold magnets in dispersion suppressors
- Luminosity debris
  - mainly for inner triplets
- Injection losses
- Unidentified Falling Objects (UFOs)
  - anywhere around the ring (more on this later)
- Ion losses
  - Secondary ion beam with different charge / mass ratio
  - Around experiments: Bound-free pair production at the IPs
  - Around collimation regions: nuclear processes in primary collimator
  - Highly localised in dispersion suppressors

Detection Principle for main LHC BLMs

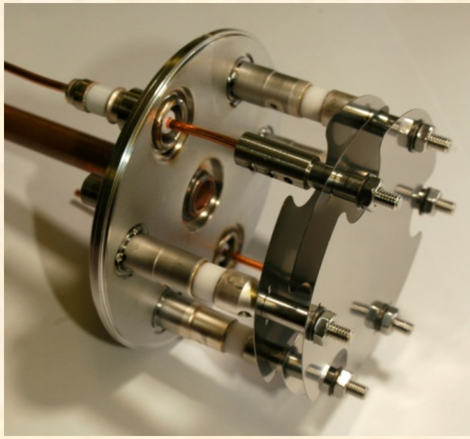


The LHC BLM System



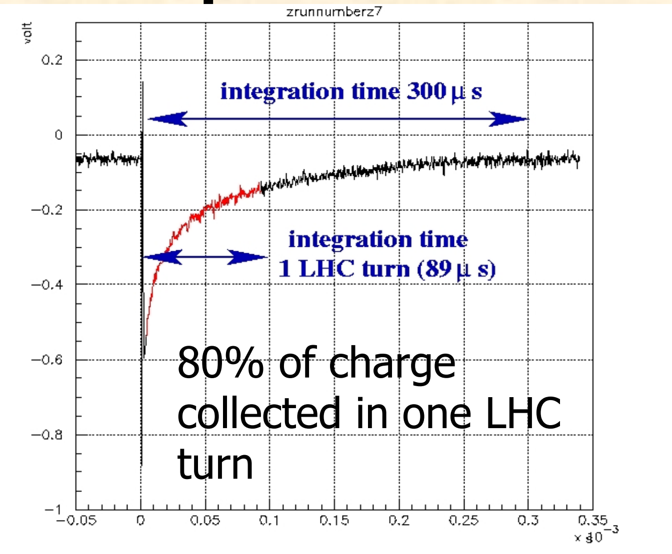
- Ionisation chamber
  - ~3600 installed
  - Gas filled with many metallic electrodes & kV bias
    - Length 50 cm
    - Sensitive volume 1.5 litre N_2 gas filled at 1.1 bar
  - Speed limited by ion collection time
  - Dynamic range of up to 10^9
    - Limited by leakage current through ceramic & saturation

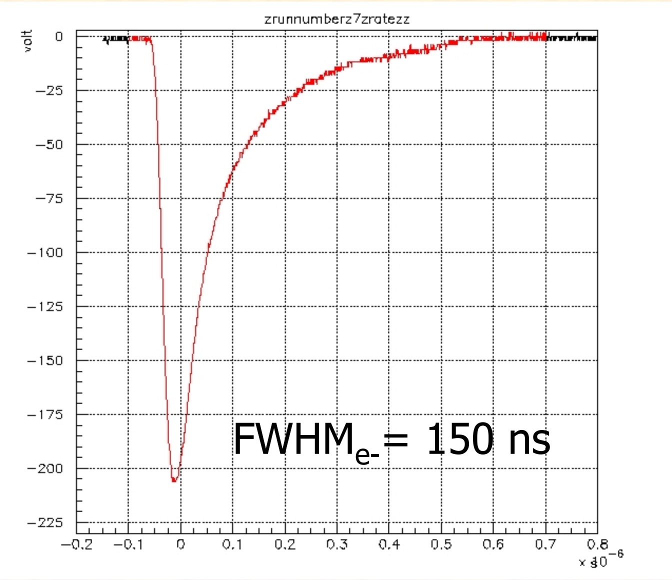
- Secondary emission monitor
  - ~300 installed
  - Vacuum filled, few electrodes & kV bias
    - Length 10 cm
    - pressure < 10^{-7} bar
  - Complements ionisation chamber
    - ~70,000 times smaller gain



Ionisation Chamber Response

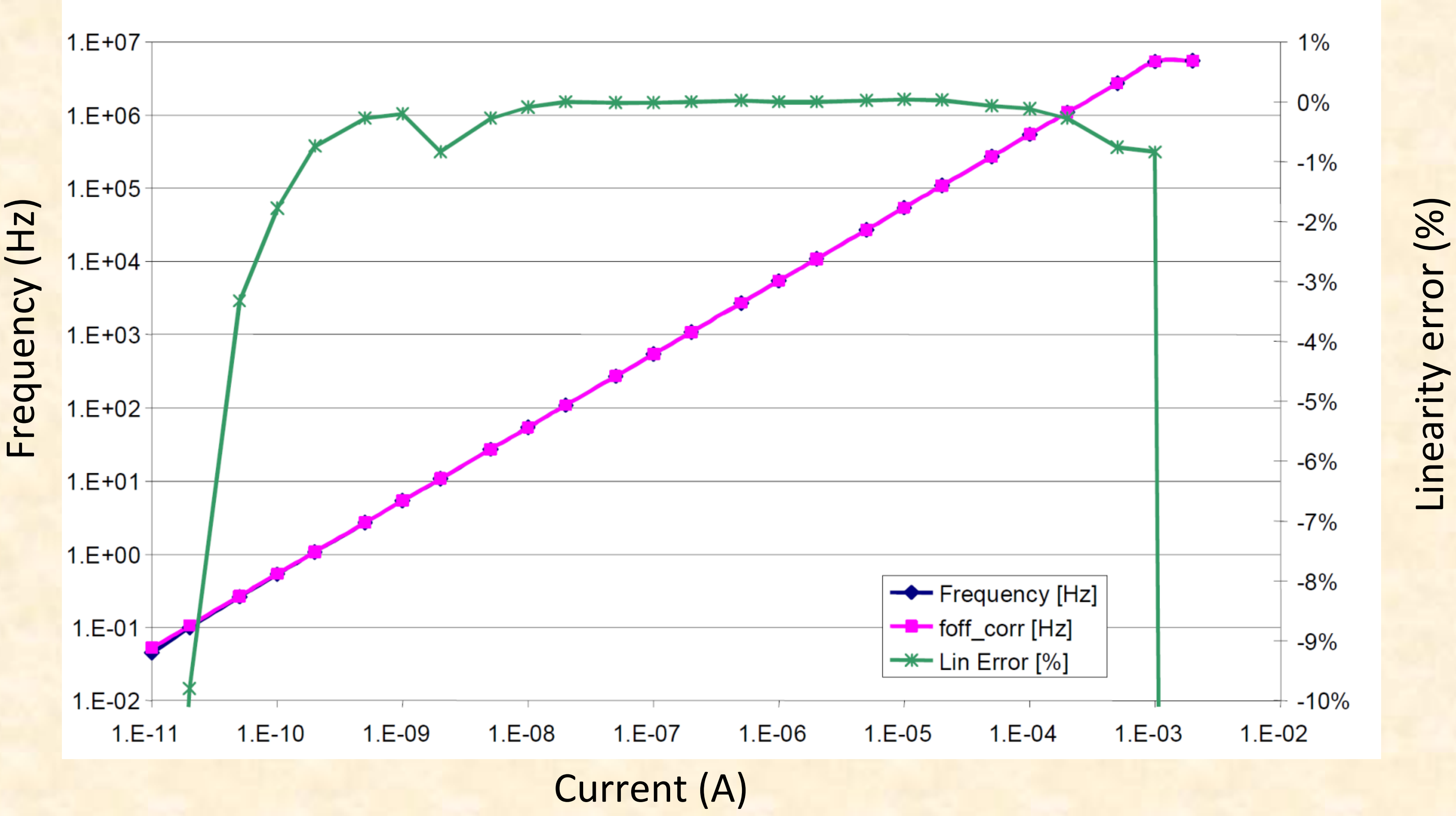
- Sensitivity 54 μC/Gy
- Time response
  - Electron collection 150 ns
  - Ion collection time 80 % at 89 μs
- Absolute calibration +- 30%
- Dynamic (linear range)
  - minimum current < 1 pA
  - maximum current 10 mA
- Radiation tolerance
  - Gain variation:
    - 30 kGy $\Delta\sigma/\sigma$ < 0.01
    - 100 MGy $\Delta\sigma/\sigma$ < 0.05
  - OK for 30 years of operation



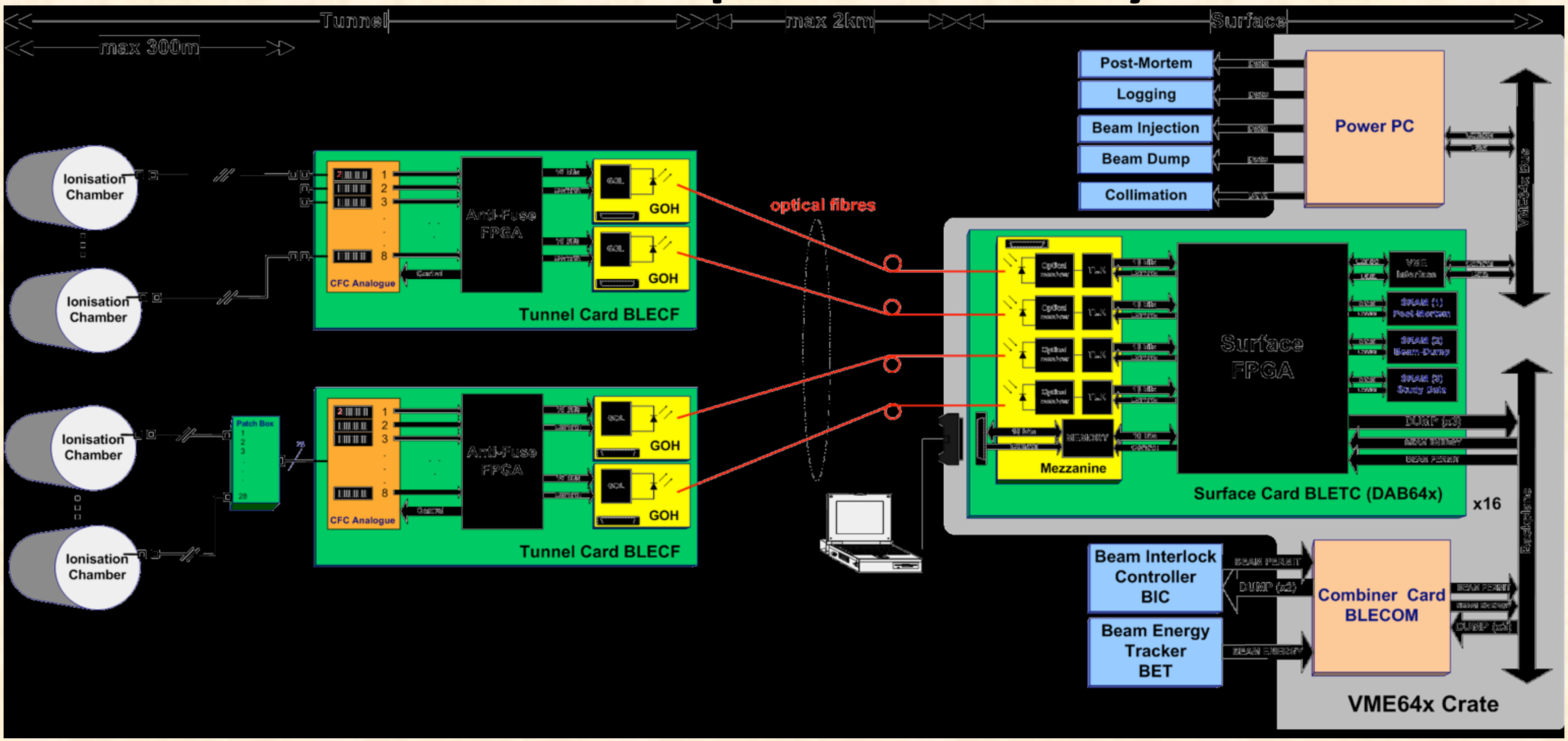


BLM System Electronics

- Linearity
  - Measures currents from tens of pA to 1mA
    - Corresponding frequency from few tenths of a Hz to a few MHz
    - Linearity better than 5%



The BLM Acquisition System



Tunnel electronics (Radiation Hard)

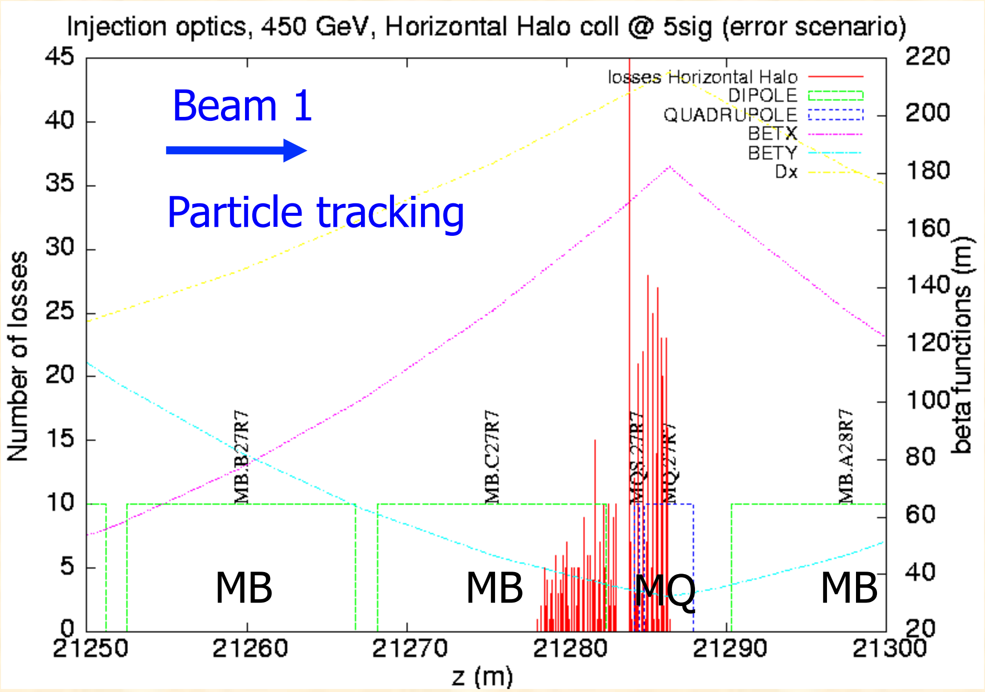
- Current to Frequency Converters (CFCs)
- Analogue to Digital Converters (ADCs)
- Gigabit Optical Links

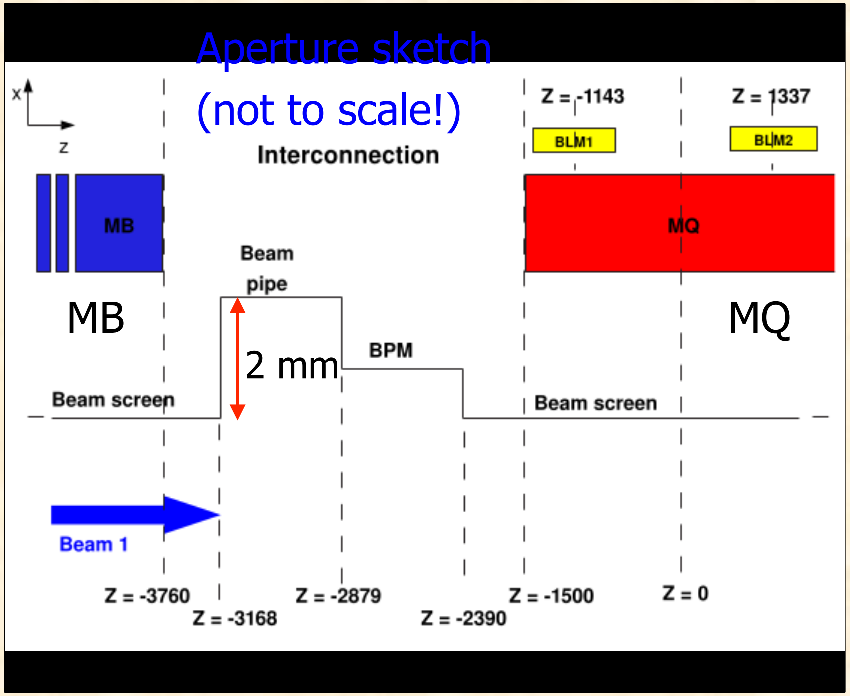
Surface electronics

- Gigabit Optical Receiver
- FPGA for data processing
- SRAM memory for temporary storage
- Non volatile RAM for system settings

Determining Thresholds via Simulations

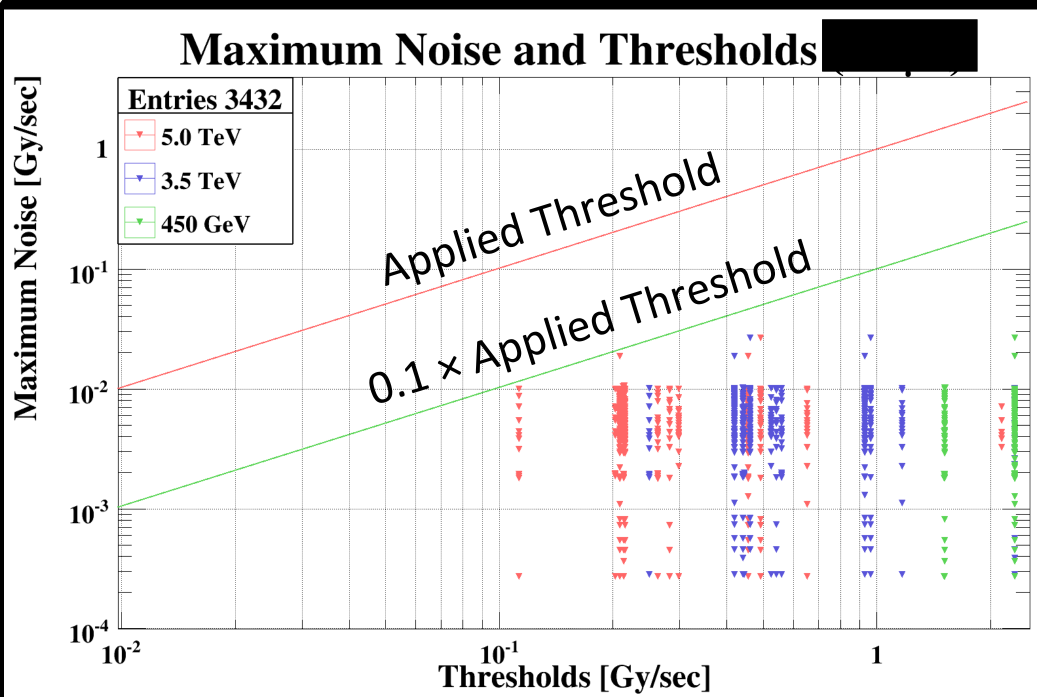
- Particle tracking to determine most likely loss locations
  - Any aperture reduction concentrates location of particle impacts
  - Localises losses at high beta values & reduced aperture
    - Quadrupoles, where orbit deviation and beam size is largest

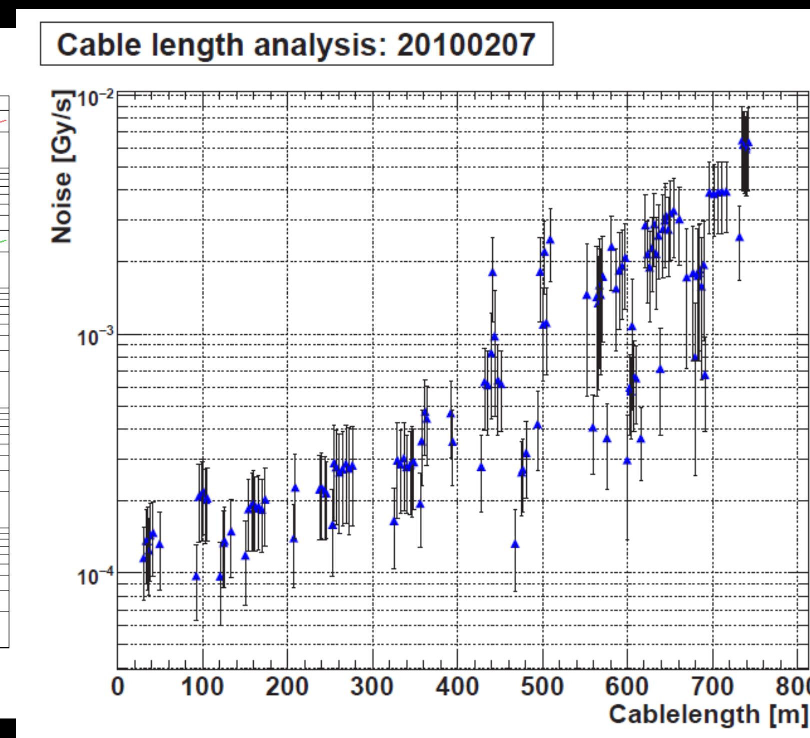




Thresholds Compared to Noise Levels

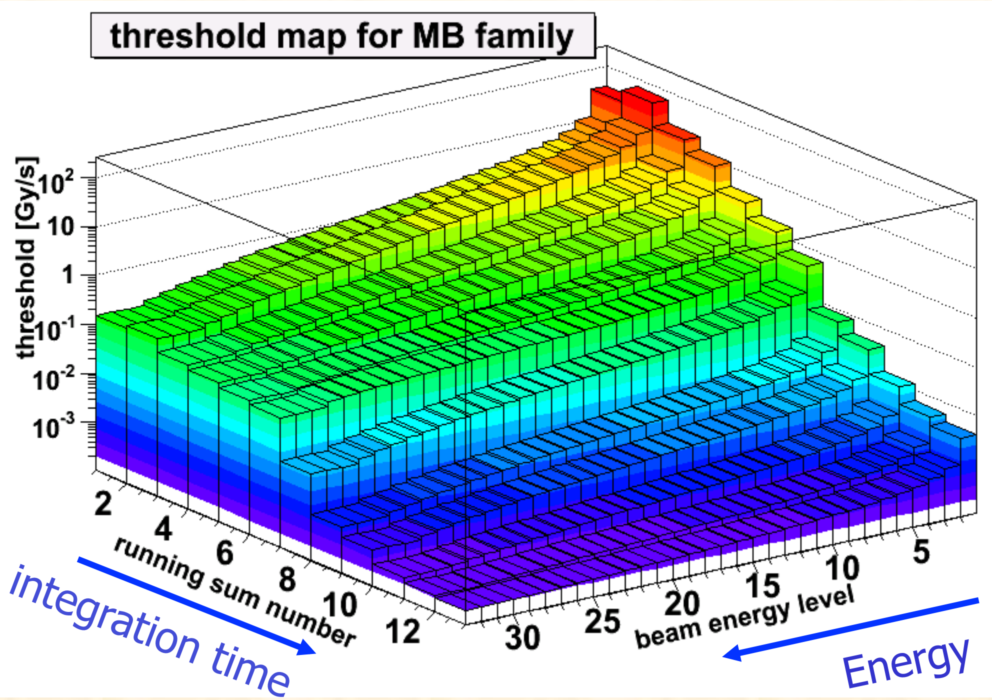
- Are the thresholds safely above the noise levels?
  - YES up to 5TeV but noise proportional to cable length
    - Better cable installed in LS1 to allow operation up to 7TeV
  - RadHard ASIC being developed for HL-LHC
    - Would allow mounting front-end electronics near BLM

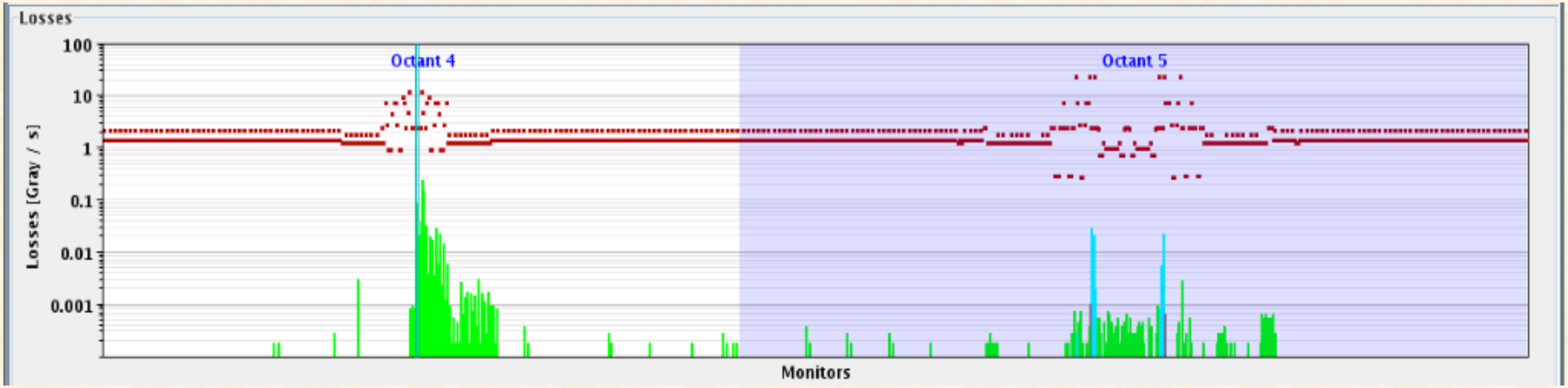




Threshold Management

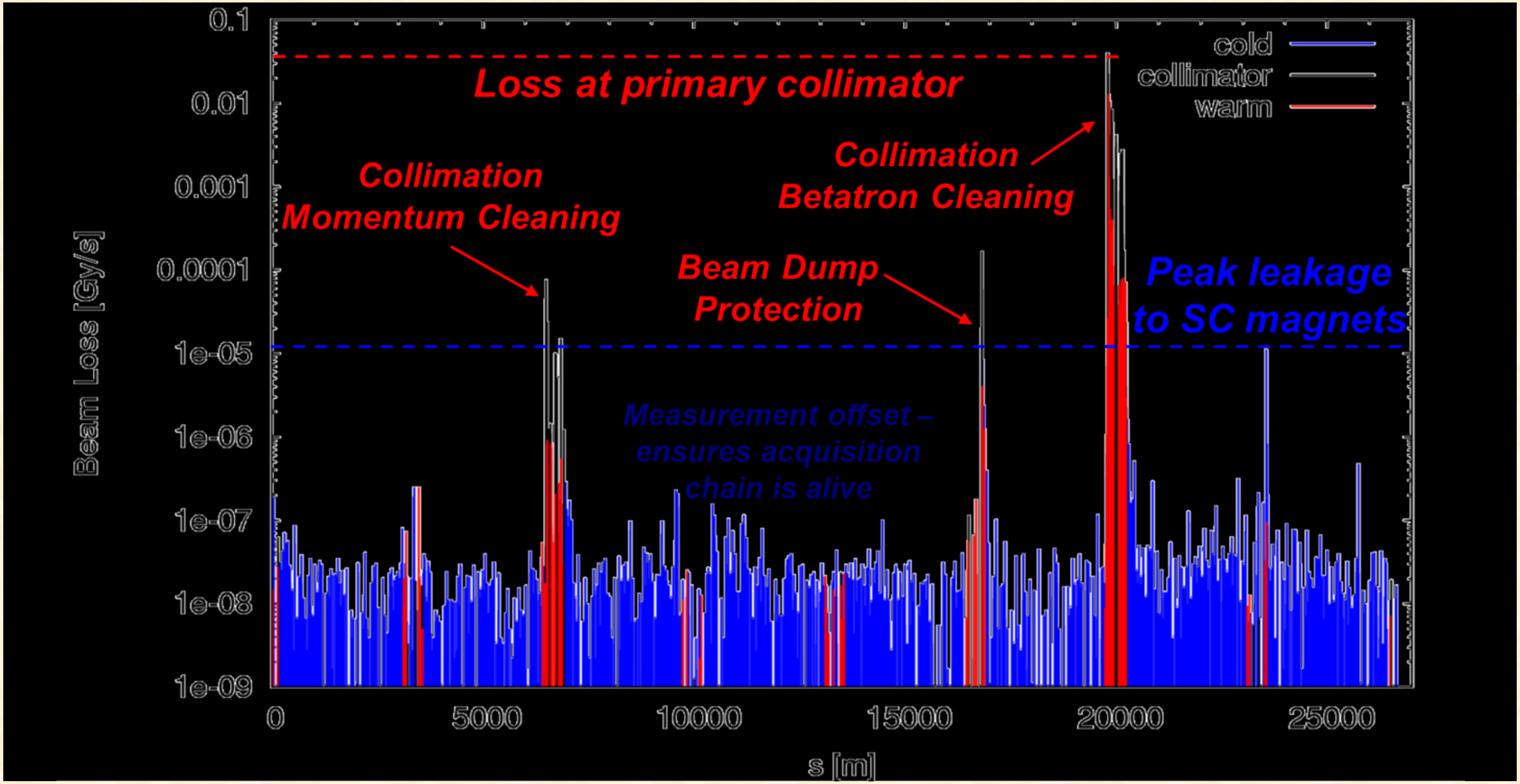
- Beam abort thresholds
  - 12 integration intervals
    - from 40µs to 84s
  - 32 energy levels
  - Managed by family
- Each monitor will abort beam if:
  - One of the 12 integration intervals is over threshold
  - Internal test fails





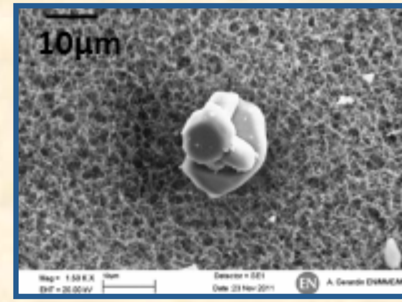
BLM Functionality – Collimator Verification

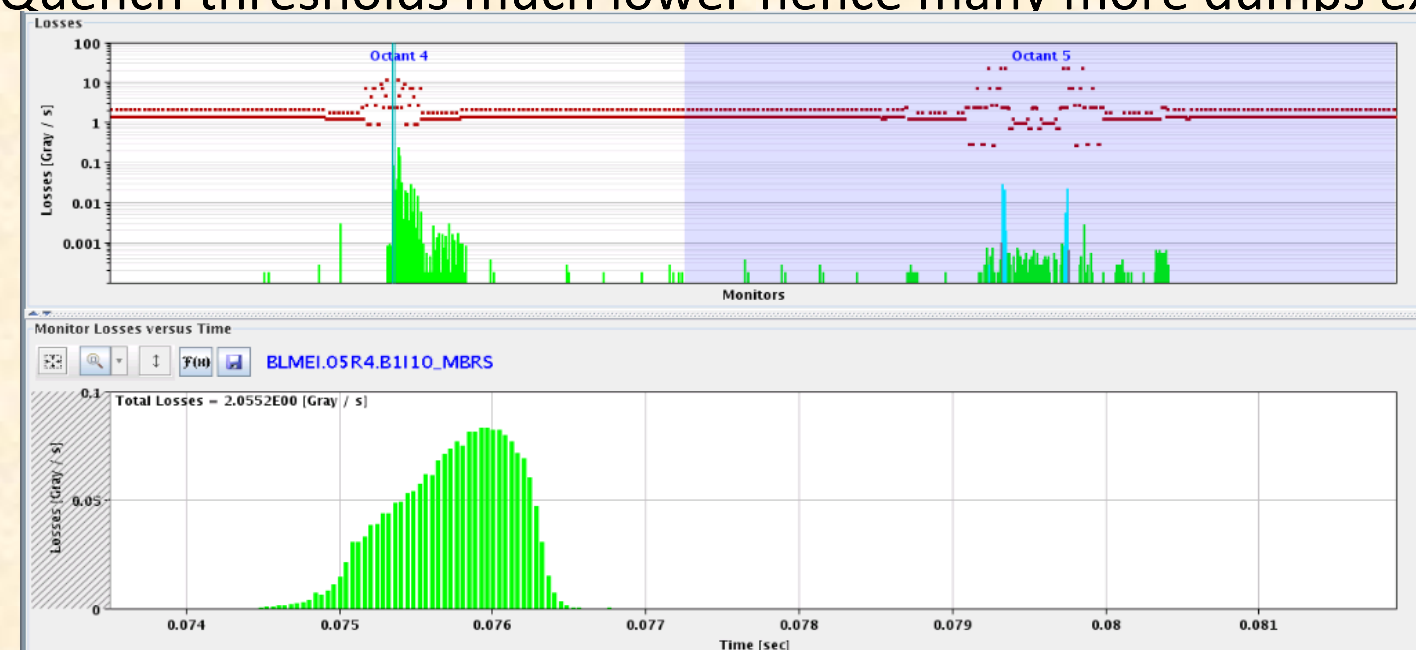
- BLM system used both for setting-up and qualifying
- Beam cleaning efficiencies ≥ 99.98% ~ as designed



Observing Fast Losses

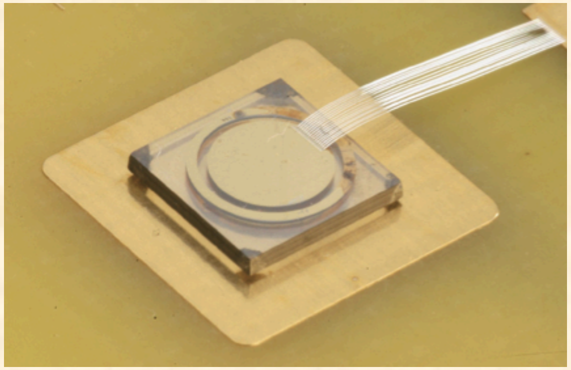
- Dealing with Unidentified Falling Objects (UFOs)
- In 2012:
  - 20 beam dumps due to (Un)identified Falling Objects
    - 14 dumps at 4TeV, 3 during ramp, 3 at 450GeV
  - ~17,000 candidate UFOs below BLM thresholds
- At 6.5 – 7 TeV
  - Quench thresholds much lower hence many more dumps expected

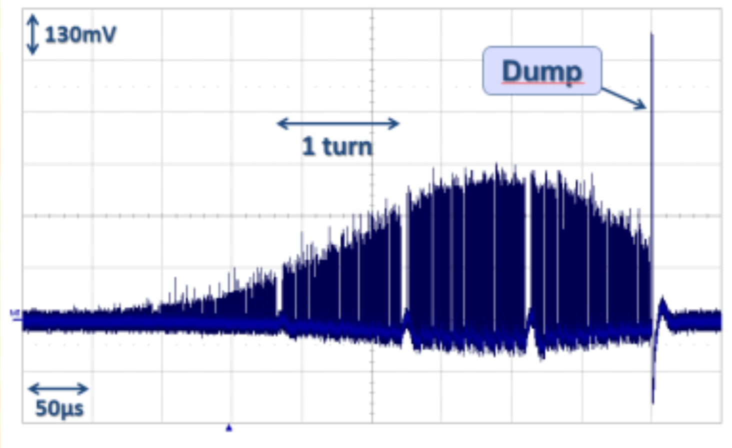


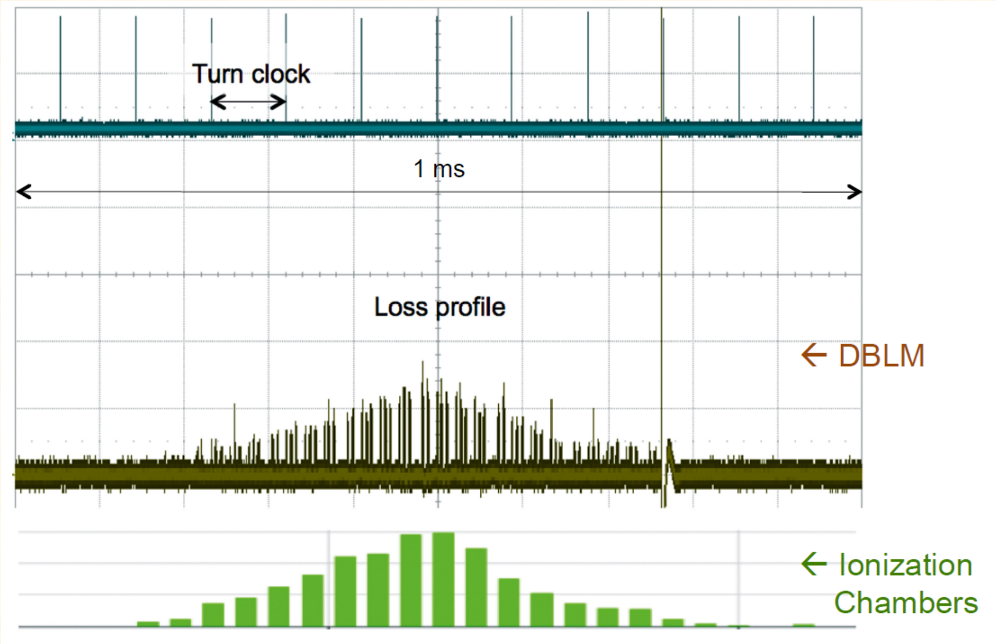


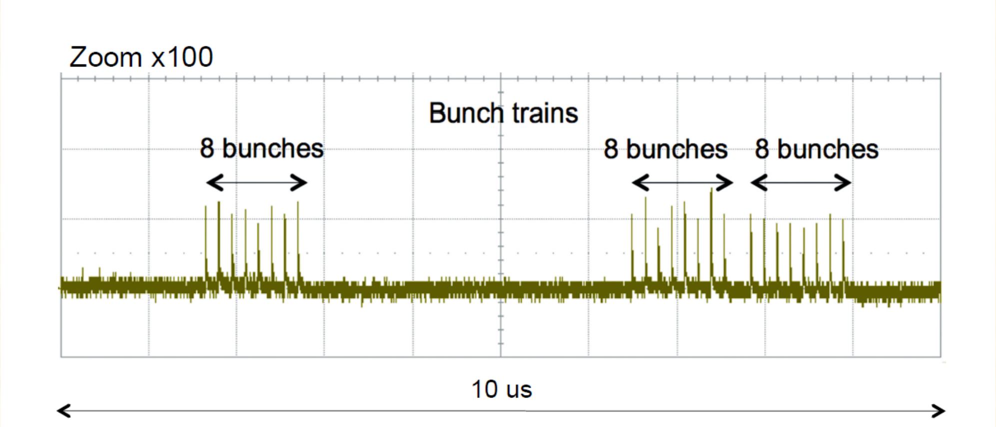
Observing Fast Losses

- Diamond Detectors
  - Fast & sensitive
  - Used in LHC to distinguish bunch by bunch losses



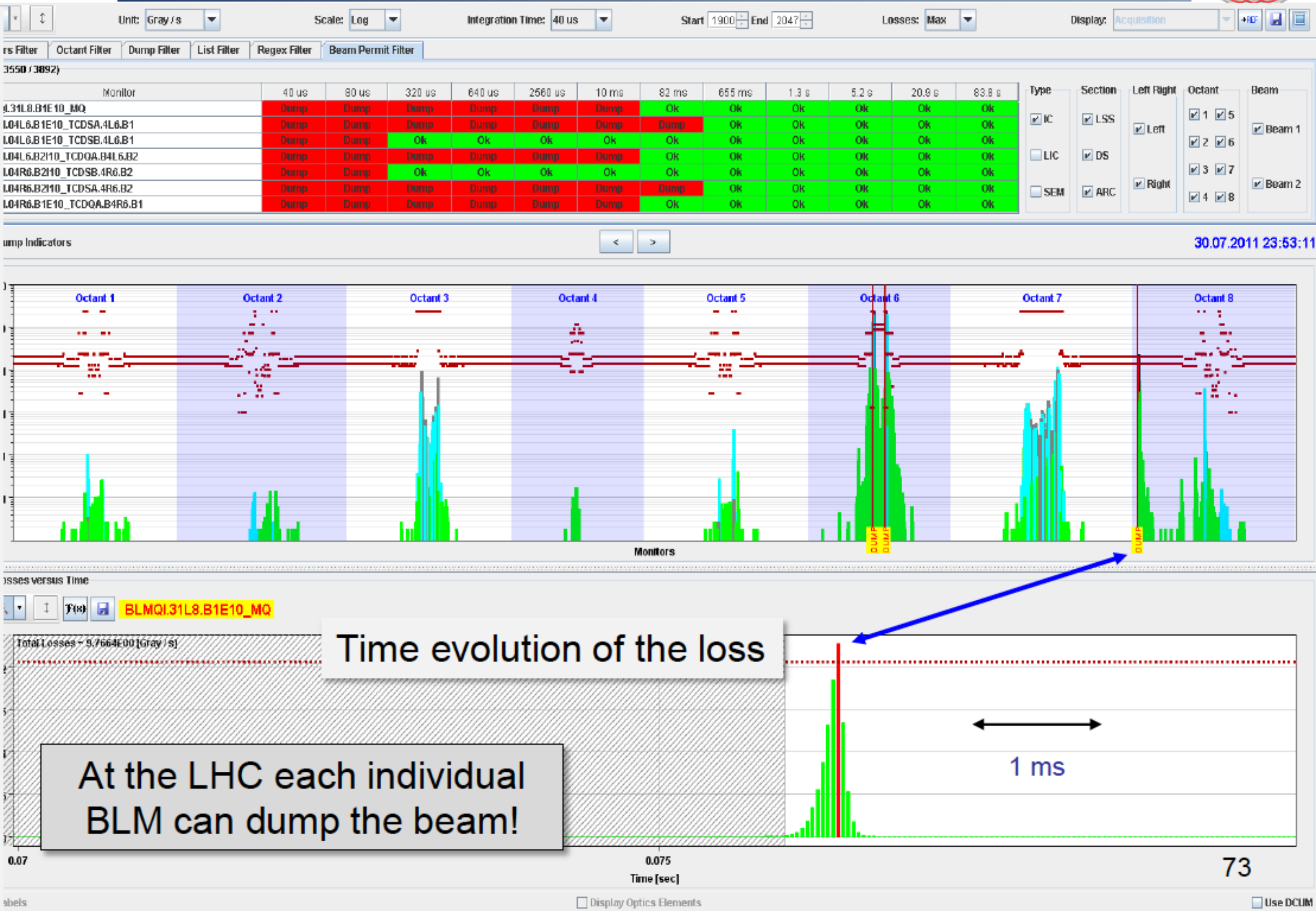






Courtesy of E. Griesmayer

Accidental beam loss



Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
l.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
L04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
L04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
L04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
L04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
L04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
L04R6.B1E10_TCDQA.B4R6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok

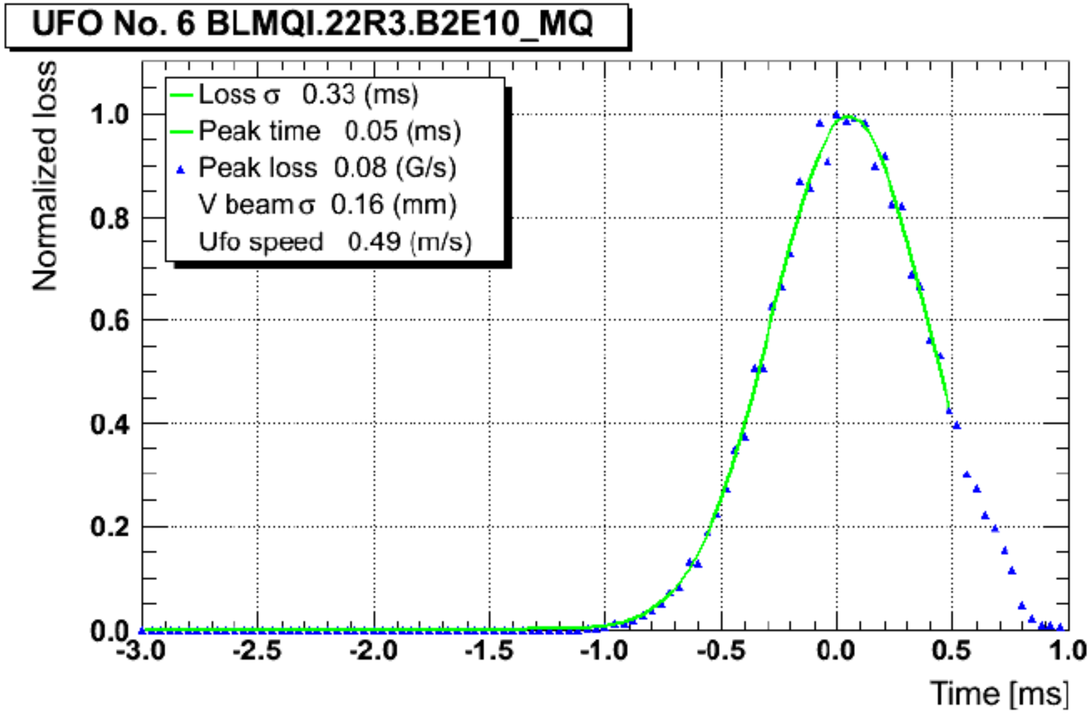
At the LHC each individual BLM can dump the beam!

Surprise, surprise !

- Very fast beam loss events (~ ms) mainly in supercondcting regions have been **THE SURPRISE** of LHC operation – nicknamed UFOs*.
  - *~20 dumps by such UFO-type events every year (2010-2012).*

- The signals are consistent with small (10's μm diameter) dust particles 'entering' the beam.

Time evolution of a UFO-type loss

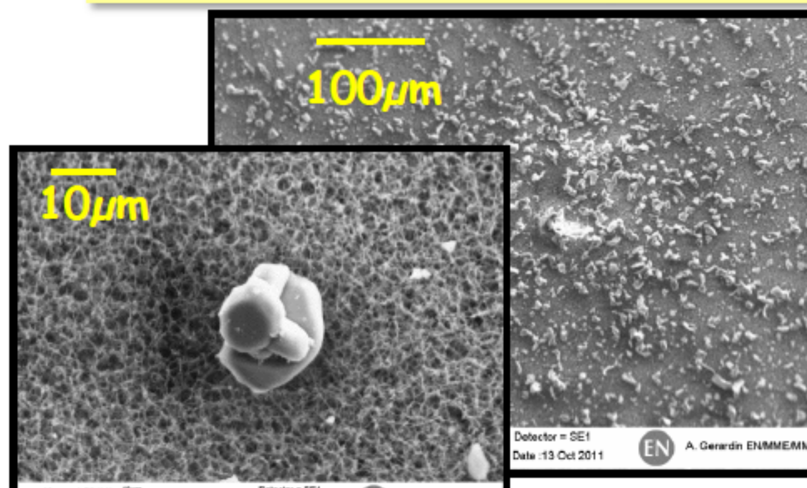


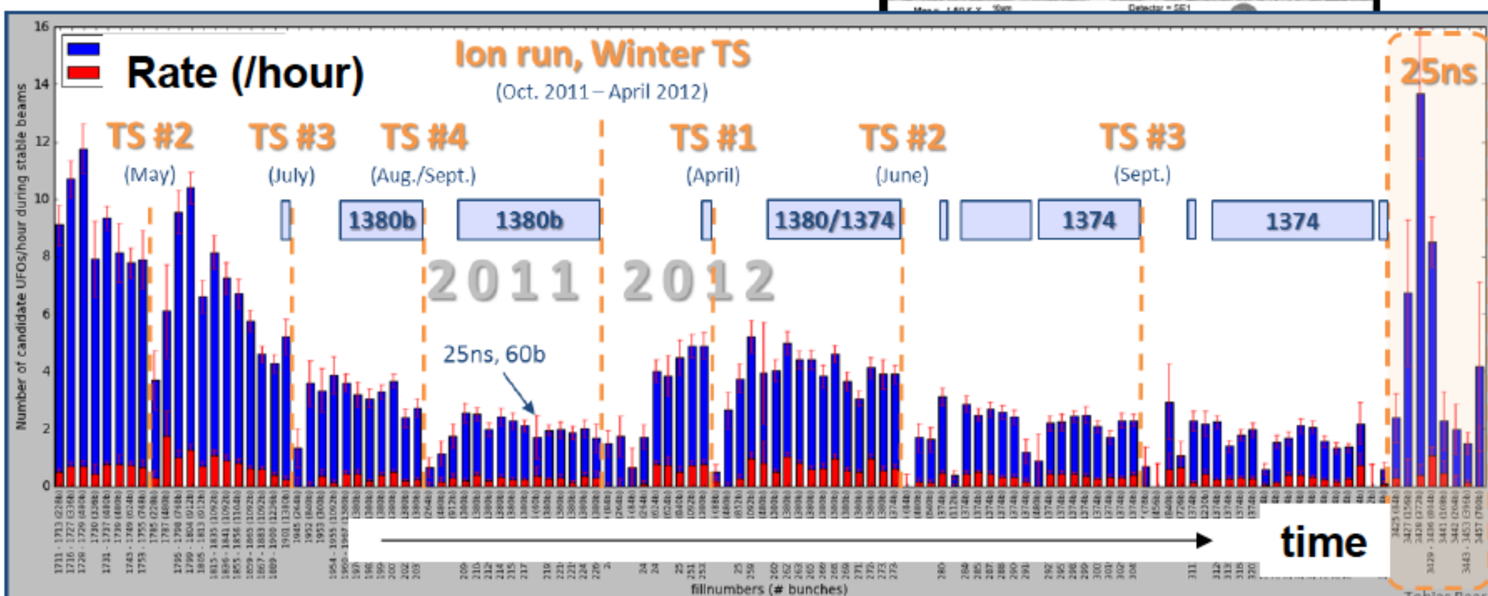
***:Unidentified Falling Object, acronym borrowed from nuclear fusion community**

UFO monitoring

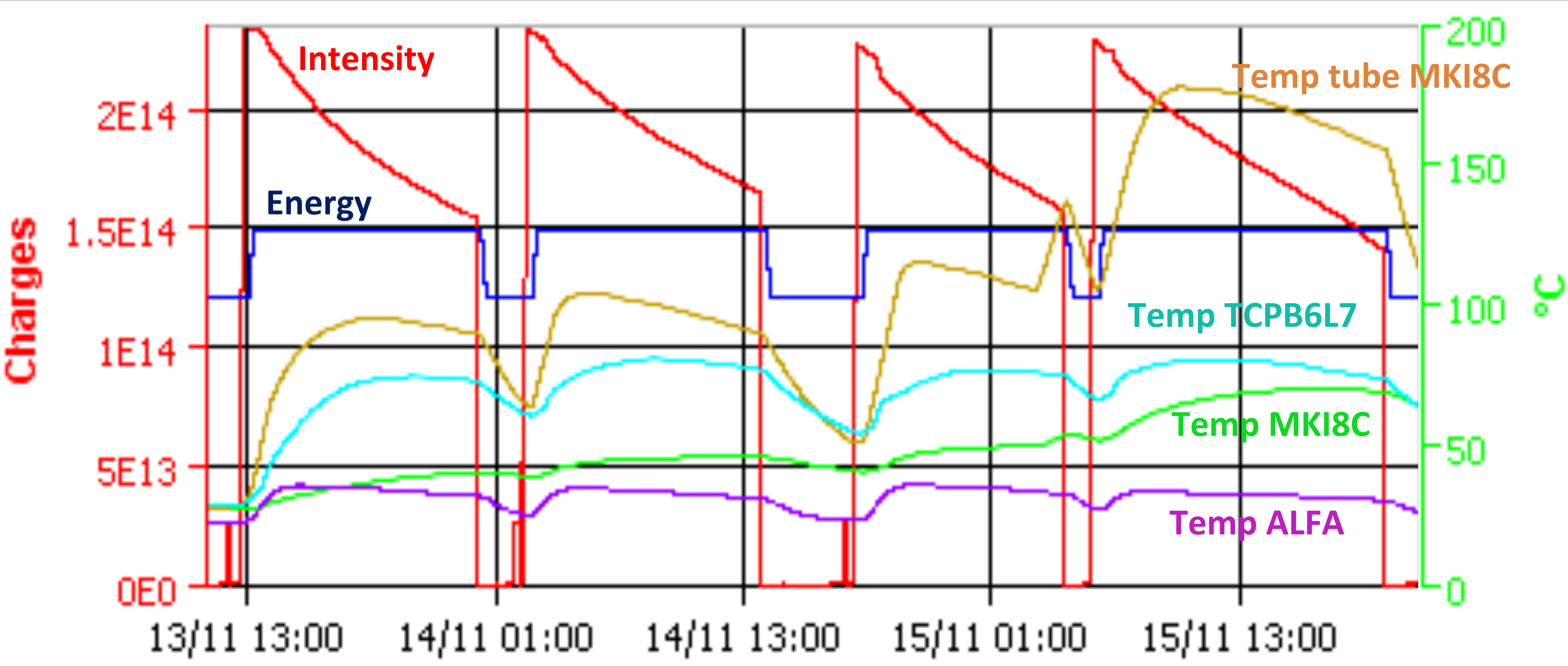
- Monitoring of UFO-like loss events was initiated. *The vast majority of events lead to losses below dump threshold.*
- For LHC injection kickers UFOs could be traced to Al oxide dust → cleaning campaign during the long shutdown.
- There is **conditioning** with beam:
  - The (non-dumping) UFO-rate drops from ~10/hour to ~2/hour over a year.

In the injection kickers UFOs were traced to Al oxide particles.





Beam induced RF heating?



→ Example of temperature increase for kicker, collimator, detector during 4 LHC fills in mid Nov 2012

→ Temperature increase believed to be due to the interaction of beam induced wake fields with the surrounding → also referred to as "RF heating"

→ Temperature increase in LHC devices can cause several issues (damage, delays, dumps)

→ Other sources of heating of beam surrounding : synchrotron light, beam losses, electron cloud (not addressed during this talk)

18 typical LHC days

Intensity B1

Intensity B2

Luminosity

Energy

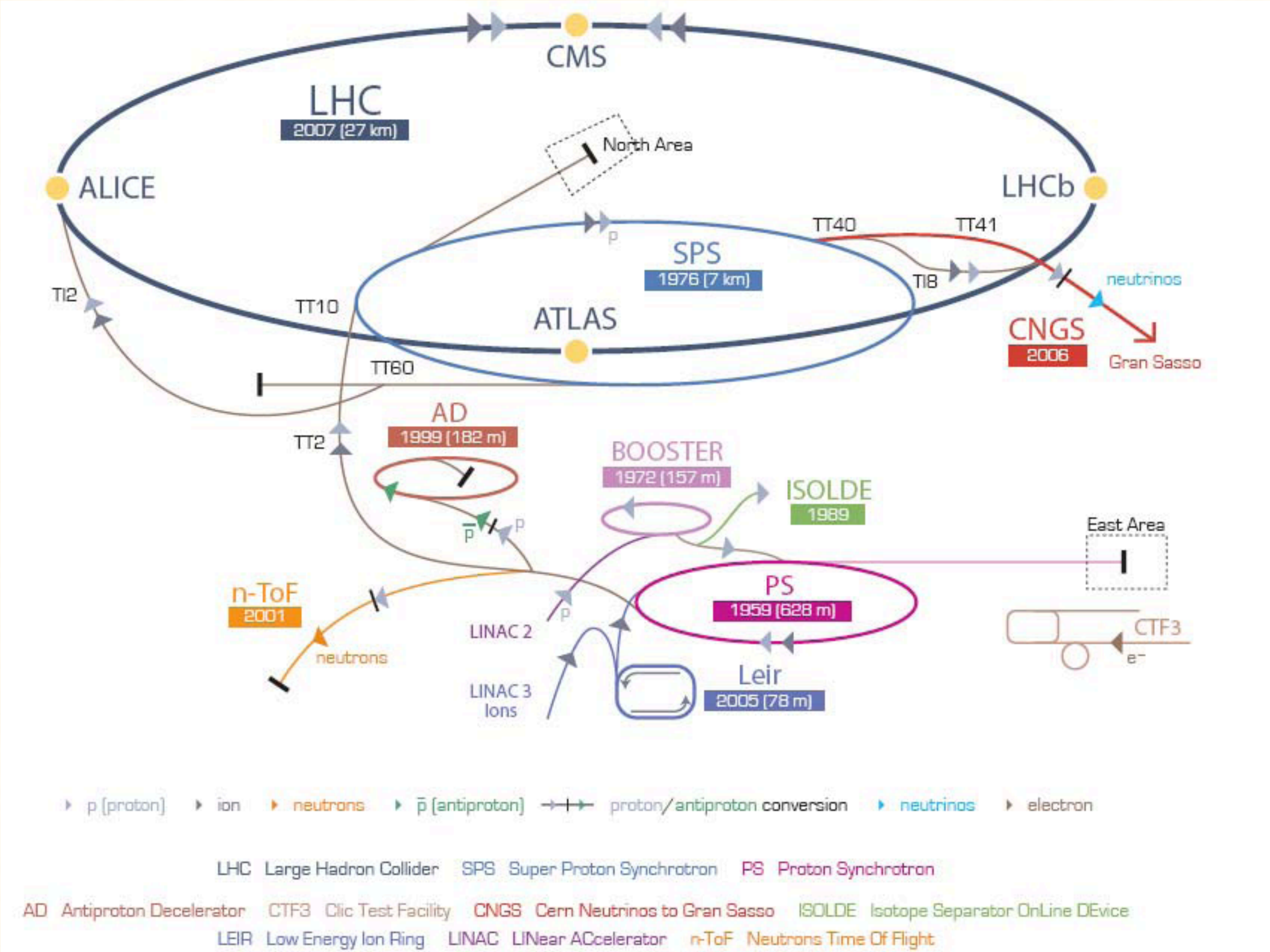
Luminosity lifetime ~ 10 h

Summary

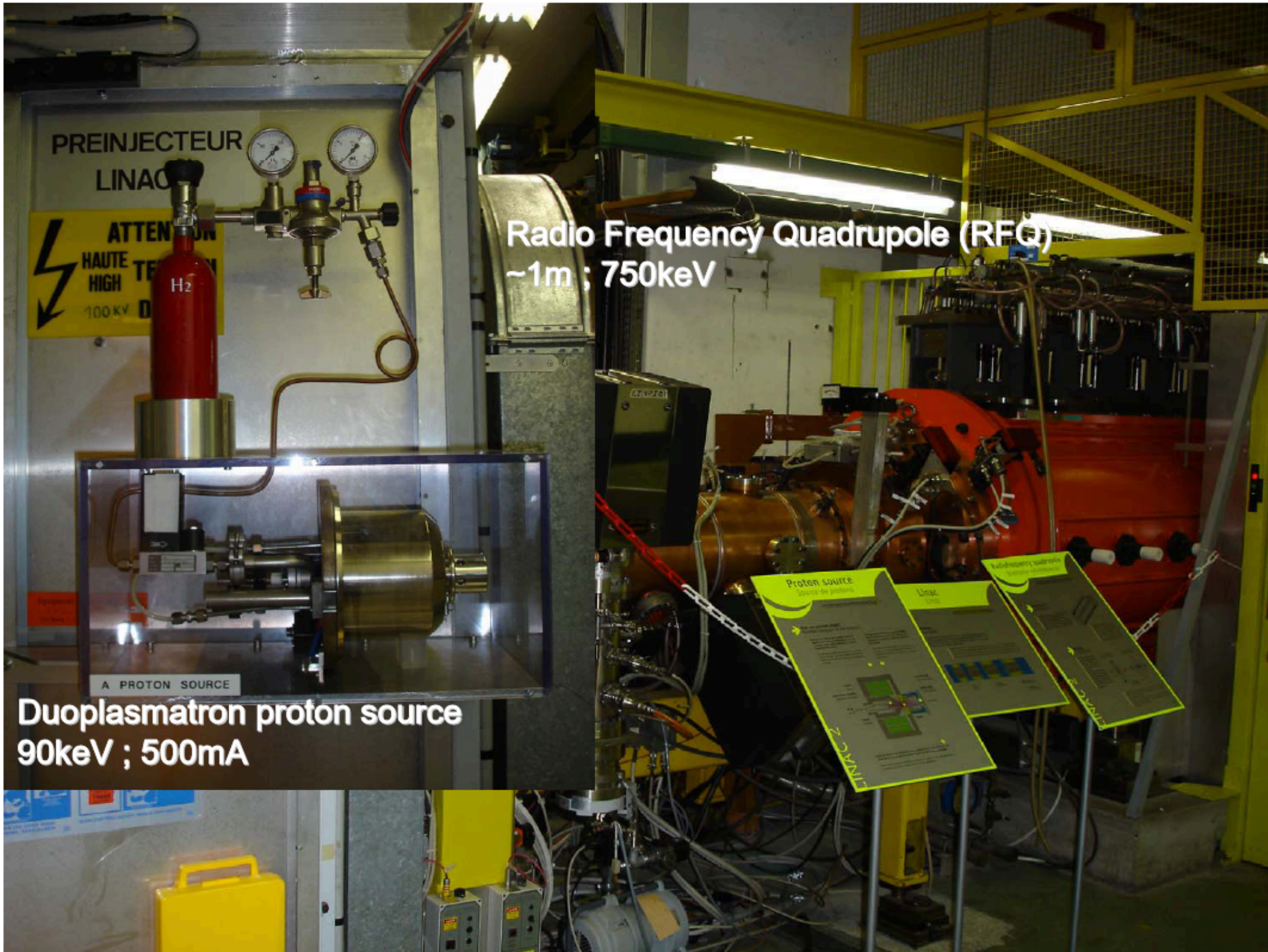
- The LHC is a very complex machine.
- The energy stored in the LHC could destroy it in a single turn.
- Its operation must balance availability for HEP and safety.
- All known effects had been correctly anticipated however some unexpected phenomena were discovered.
- Run 1 has been a success…
- … and run 2 started yesterday!

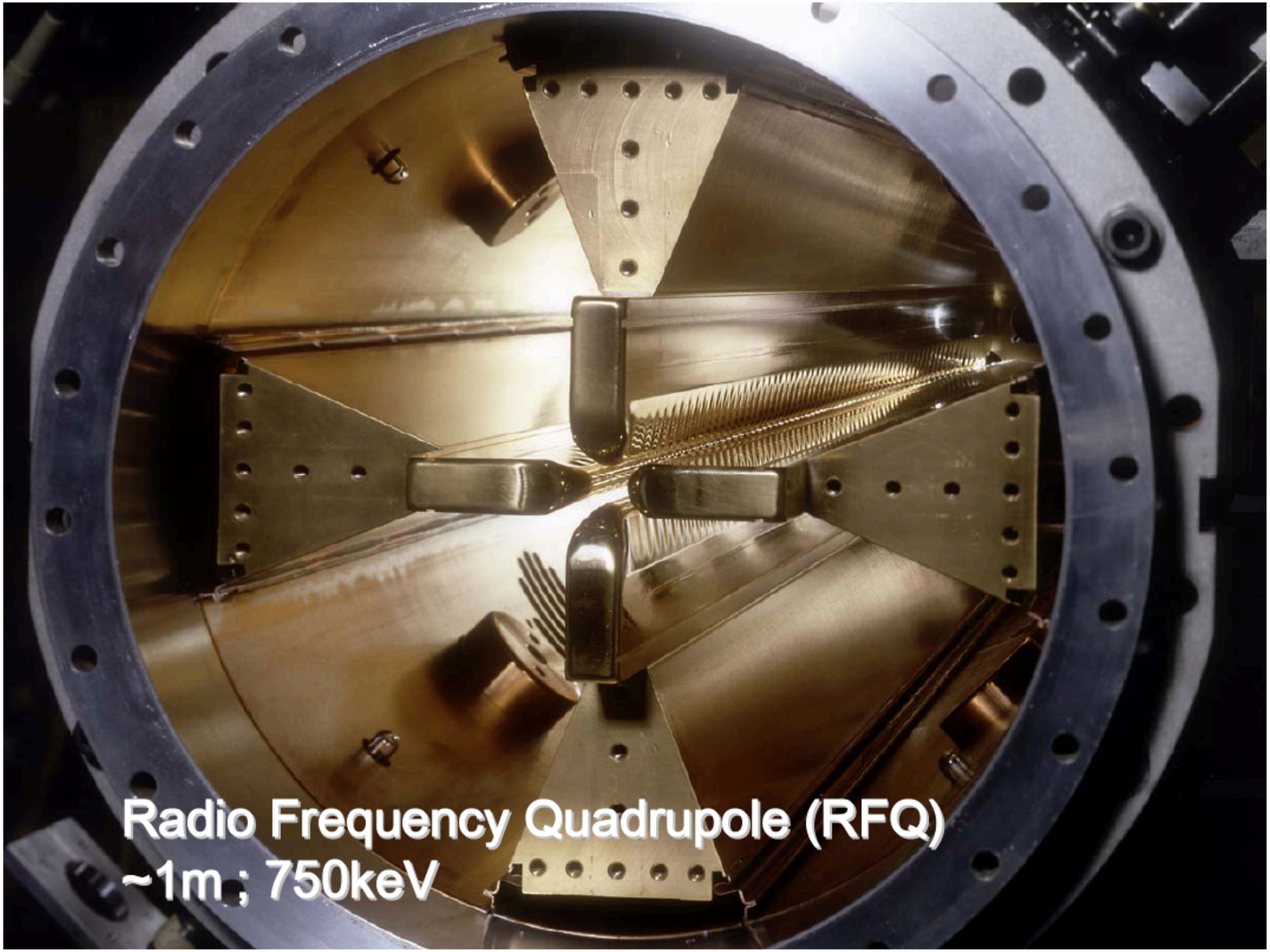
THE JOURNEY OF A PROTON FROM THE SOURCE TO THE LHC

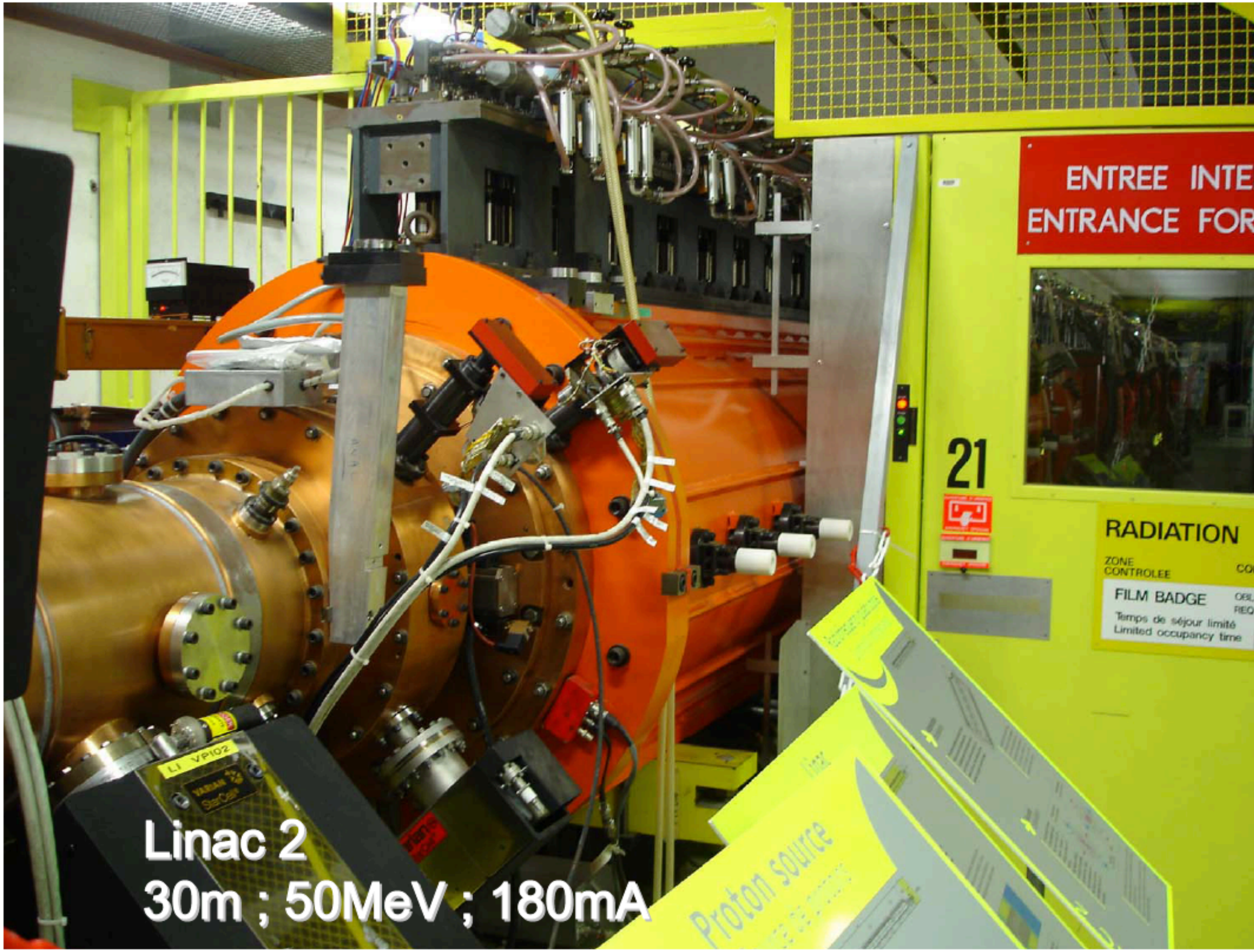
(Courtesy of D.Manglunki - BE/OP/CERN)

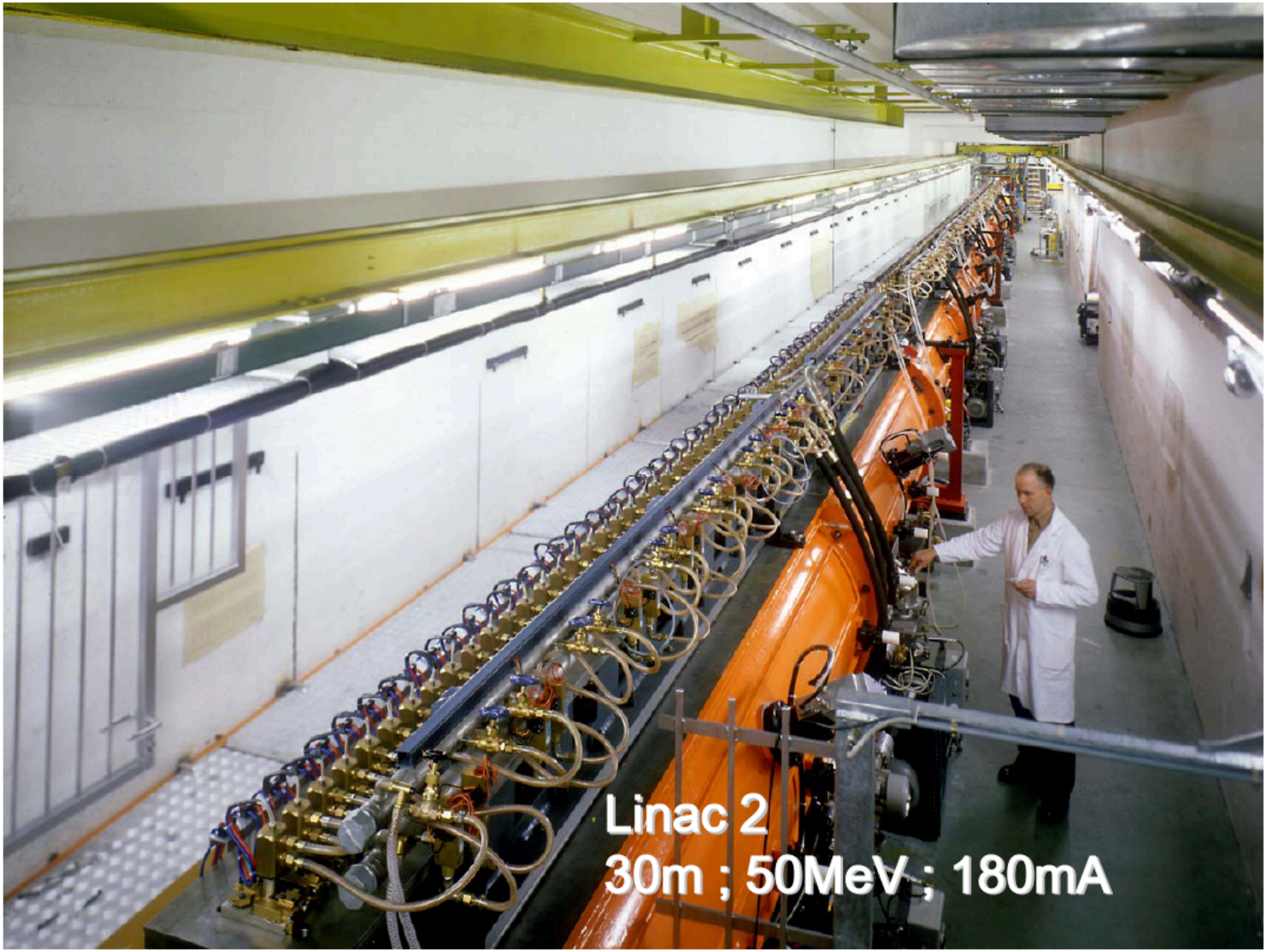


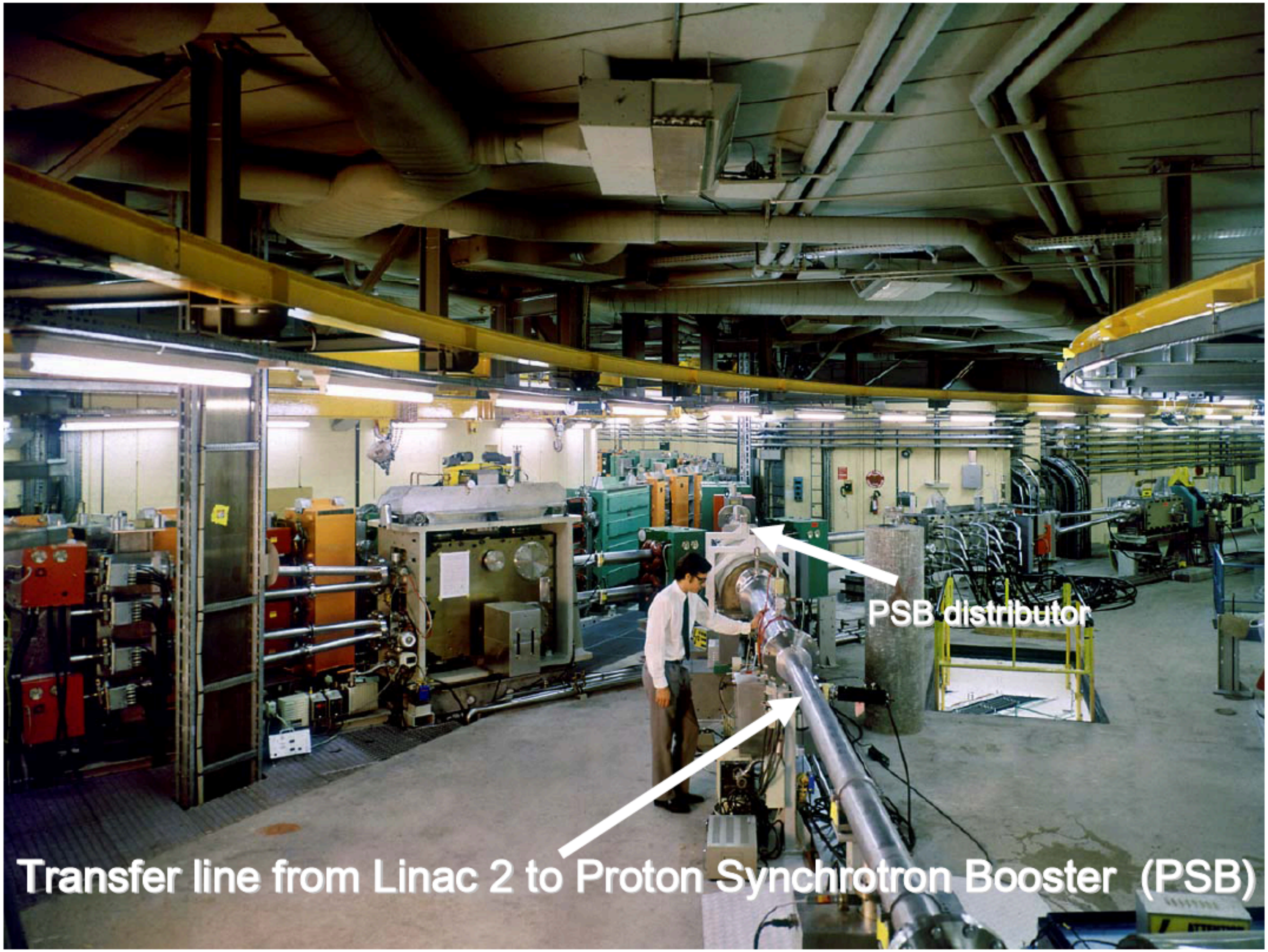
CMS
LHC
2007 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
LINAC 2
CTF3
e⁻
neutrons
Leir
2005 (78 m)
LINAC 3
Ions
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
AD Antiproton Decelerator
CTF3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso
ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight

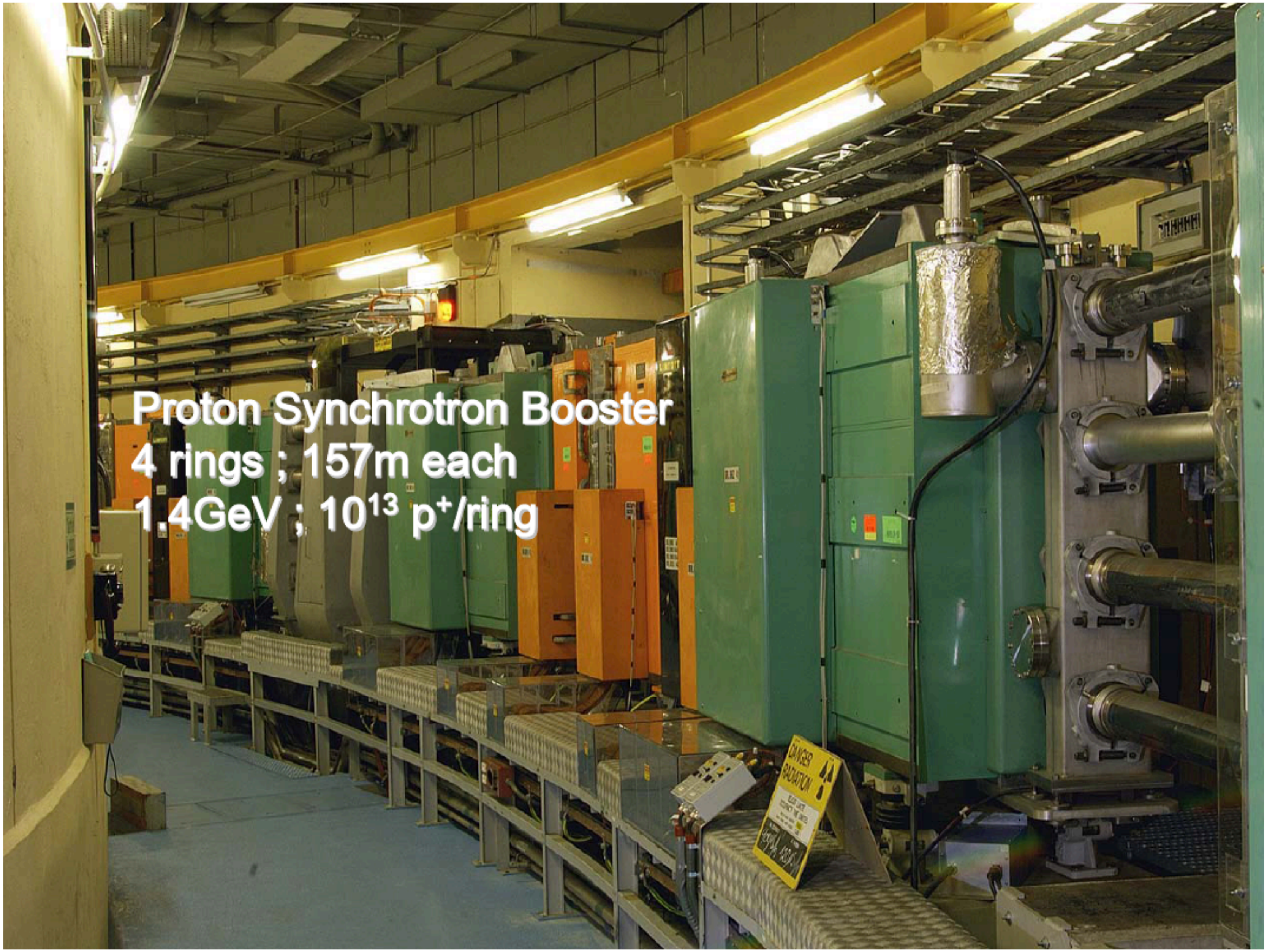

Radio Frequency Quadrupole (RFQ)
~1m ; 750keV
PREINJECTEUR
A PROTON SOURCE
Proton source
Linac
Duoplasmatron proton source
90keV ; 500mA

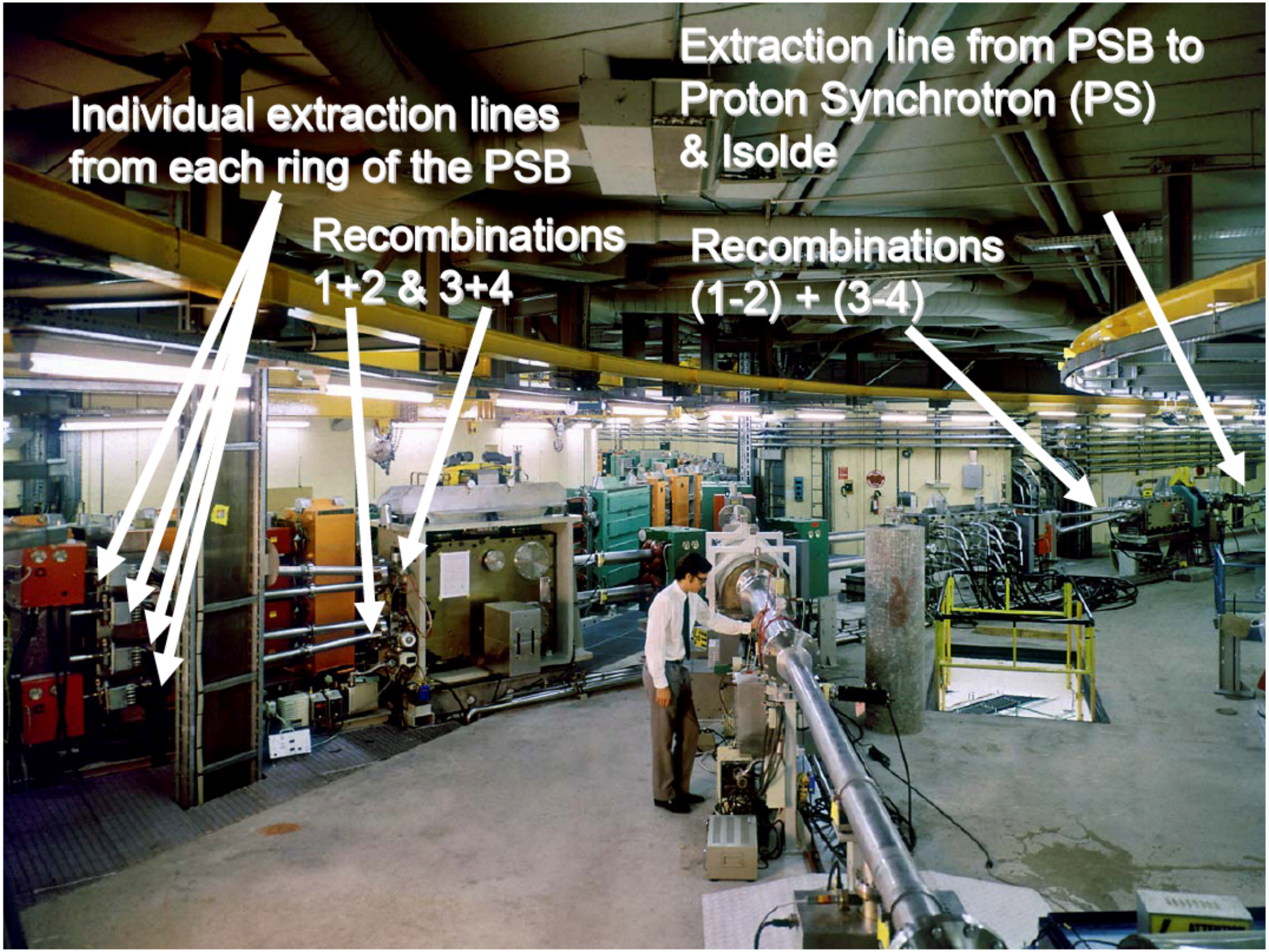

Radio Frequency Quadrupole (RFQ)
~1m ; 750keV

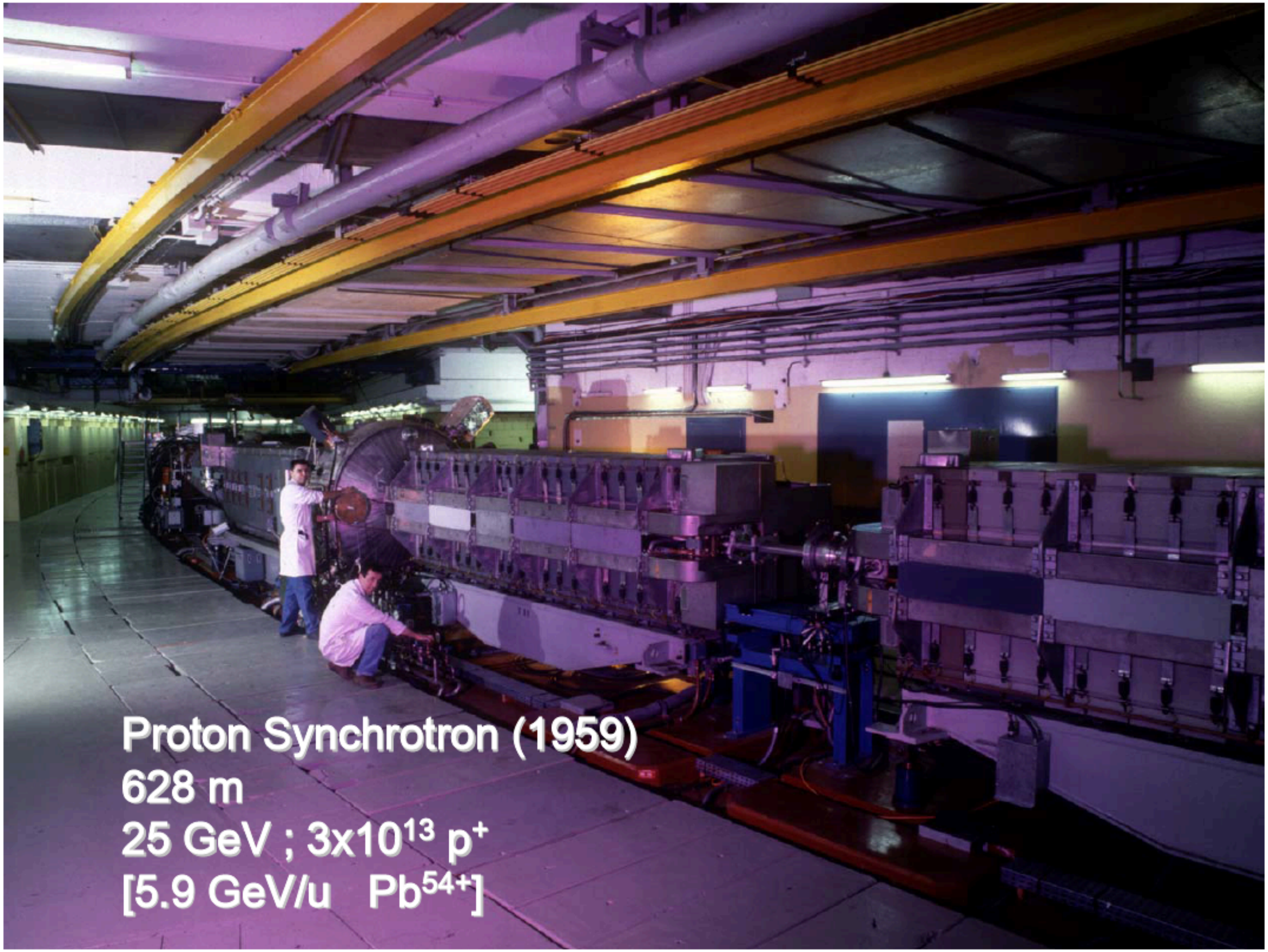

Linac 2
30m ; 50MeV ; 180mA
21
RADIATION
ZONE CONTROLEE
FILM BADGE
Temps de séjour limité
Limited occupancy time
Proton source
LI VP102
VARIAN

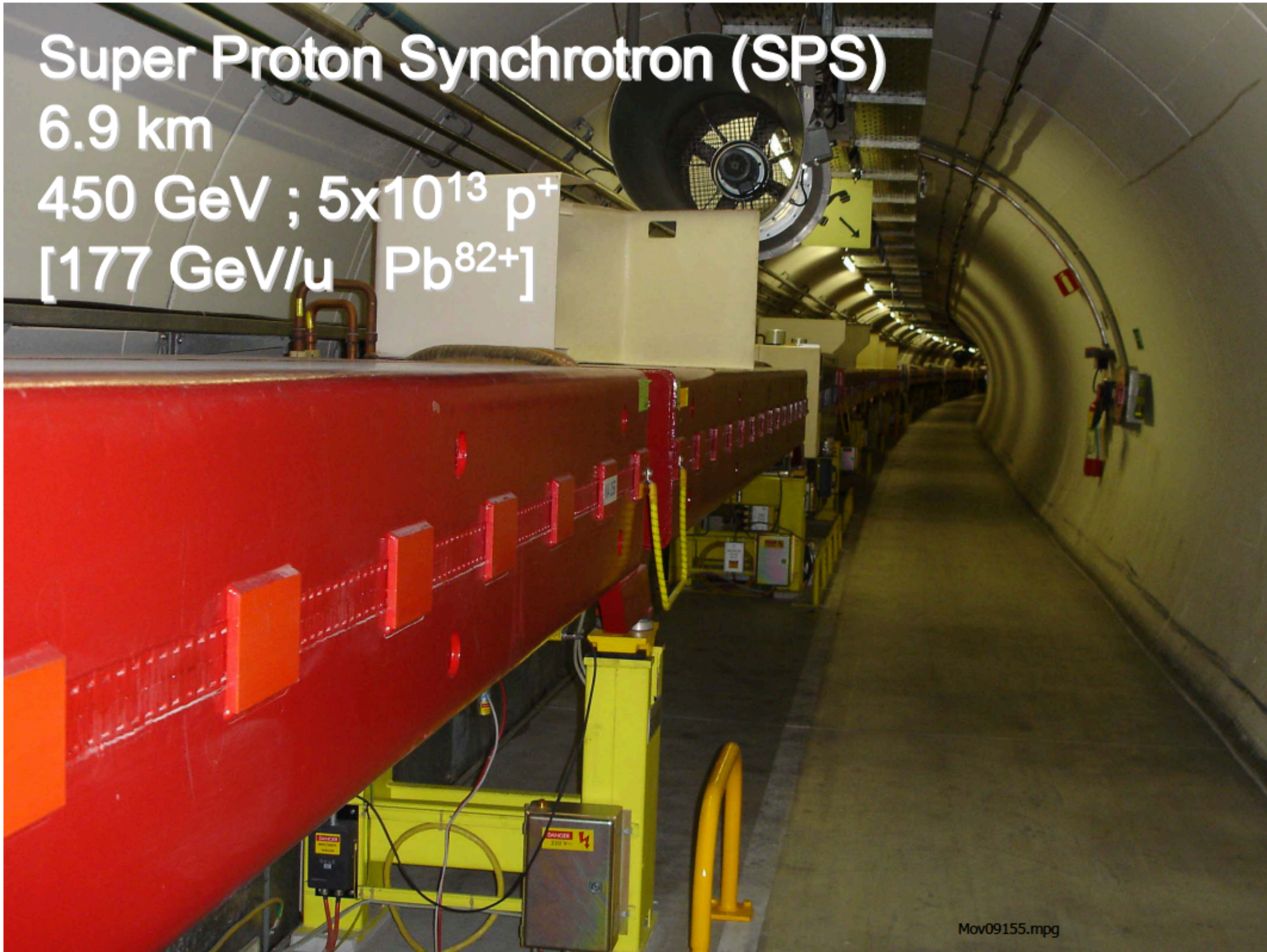

Linac 2
30m ; 50MeV ; 180mA


PSB distributor
Transfer line from Linac 2 to Proton Synchrotron Booster (PSB)

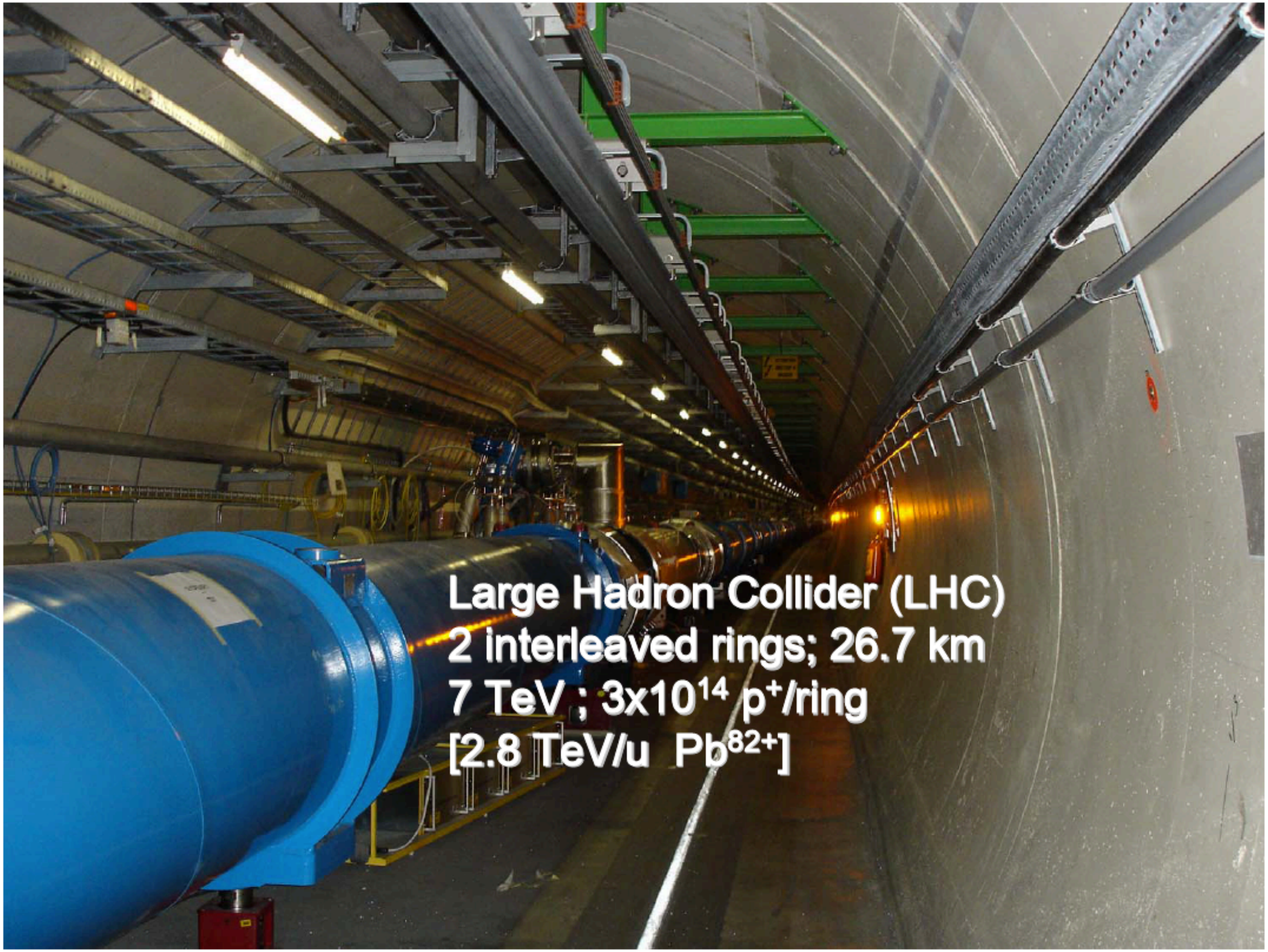

Proton Synchrotron Booster
4 rings ; 157m each
1.4GeV ; 10^{13} p^+/ring
DANGER
RADIATION


Extraction line from PSB to Proton Synchrotron (PS) & Isolde
Individual extraction lines from each ring of the PSB
Recombinations 1+2 & 3+4
Recombinations (1-2) + (3-4)


Proton Synchrotron (1959)
628 m
25 GeV ; 3x10^{13} p^+
[5.9 GeV/u Pb^{54+}]


Super Proton Synchrotron (SPS)
6.9 km
450 GeV ; $5x10^{13}$ p^+
[177 GeV/u Pb^{82+}]
Mov09155.mpg

TI8 counter-clockwise transfer line from SPS to LHC


Large Hadron Collider (LHC)
2 interleaved rings; 26.7 km
7 TeV ; 3x10^{14} p^{+}/ring
[2.8 TeV/u Pb^{82+}]