Lessons learned from LHC

- LHC Specifics and compromises coming from building the LHC machine in the old LEP tunnel

- **With input from many LHC experts!**

- **Special thanks to:**
  G. Arduini, P. Collier, E. Jensen, R. Jones, M. Lamont, R. DeMaria, B. Goddard, S. Redaelli, L. Rossi, R. Schmidt, R. Thomas, J. Wenninger, F. Zimmermann

- Important lessons learned from the LHC installation

- Important lessons learned from the LHC operation

1) LHC Specifics coming from the old LEP tunnel

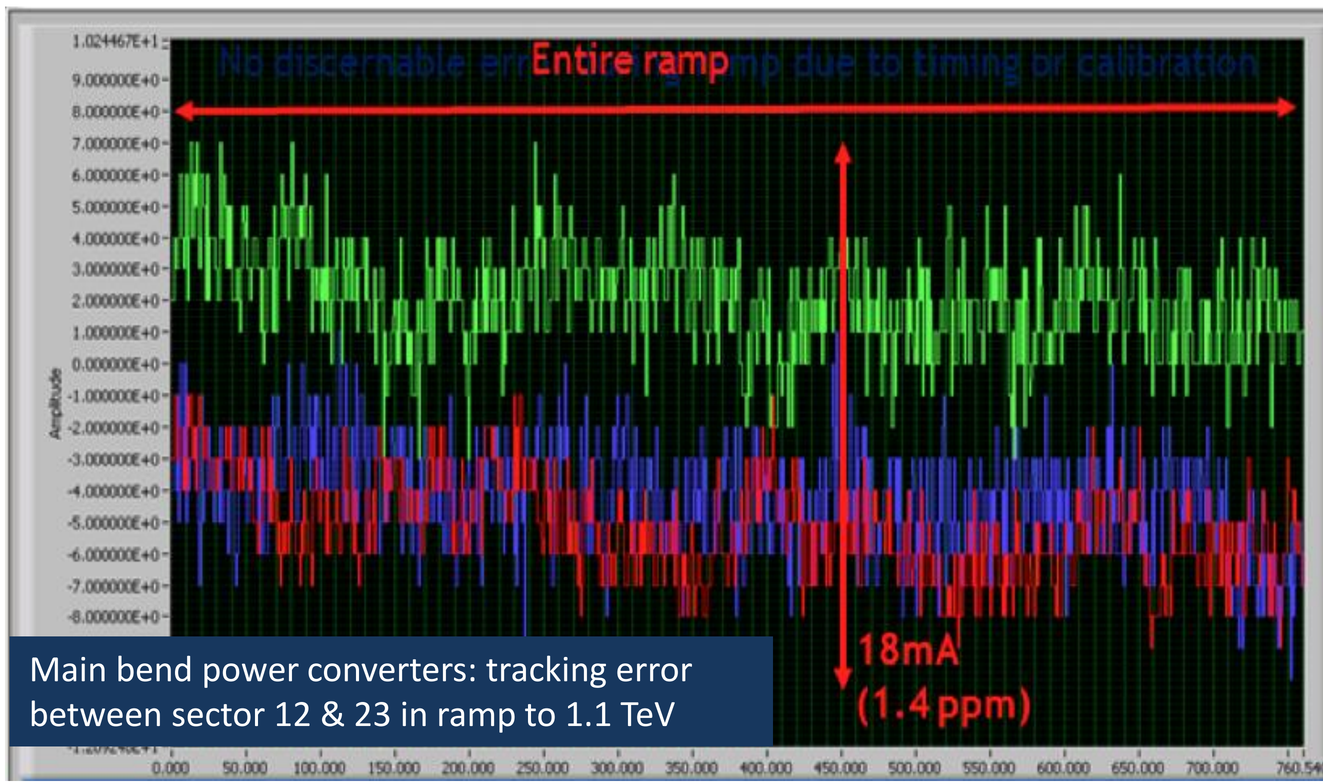
- Dispersion Suppressor: geometry defined by LEP FODO cell
  ➔ requires quadrupole tuning for dispersion matching

- Combined experimental Interaction and Injection Regions
  ➔ Implying risk of beam loss and detector damage
  ➔ Implying additional constraints and elements for optics matching and machine protection (e.g. TCLIs and 90^o to TDI)

- R2E and components in the tunnel: ➔ limited underground space for installation of sensitive components (e.g. PC)
  ➔ Installation of equipment in the tunnel (e.g. QPS & CO PC)
  ➔ R2E and machine availability and efficiency!!!
  ➔ Super Conducting Link and new cavern for HL-LHC

2) LHC specific design choices

- Powering in 8 separate Sectors (stored EM energy ≈ 1GJ):
  - ➔ ppm Power Converter tracking; matching between sectors, Machine Protection and Energy Tracking
  - ➔ Excellent performance of the LHC PCs, ppm level!!!



Main bend power converters: tracking error between sector 12 & 23 in ramp to 1.1 TeV

2) LHC specific design choices

- Common triplet for both beams & debris leaving the IR:
  → Heat load inside the triplet and D1
  → warm D1 and efficient triplet cooling (heat exchanger)
    → Machine protection issues with warm magnets
    (fast time constants!)

- Anti-symmetric optics design: → driven by goal to facilitate simultaneous optics matching for Beam1 & Beam2
  → Dispersion is not anti-symmetric → matching routines
    → Should be reassessed for FCC (e.g. flat beams etc.)

- Series powering of Beam1 and Beam2 quadrupoles:
  → limits flexibility of different phase advances between Beam1 & Beam2 → could be reassessed for FCC (e.g. ATS?)

2) LHC specific design choices

- Power Converter Noise at locations with $\beta > 4$km

  ➔ triplet powering layout (in series for intrinsic compensation)

  ➔ HL-LHC follows a different approach for current baseline implying even tighter tolerances for the PC

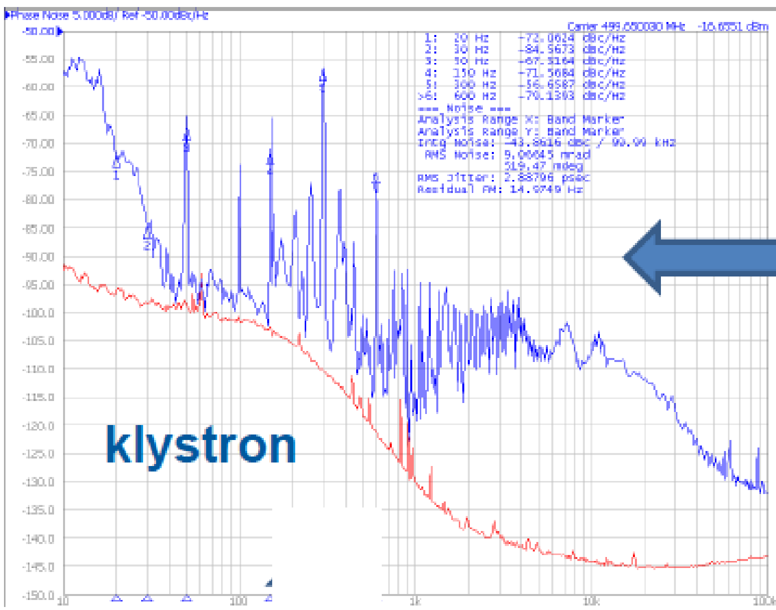
  (but might come back to series powering)

- Klystron driven super conducting RF

3) Worries from previous Experiences

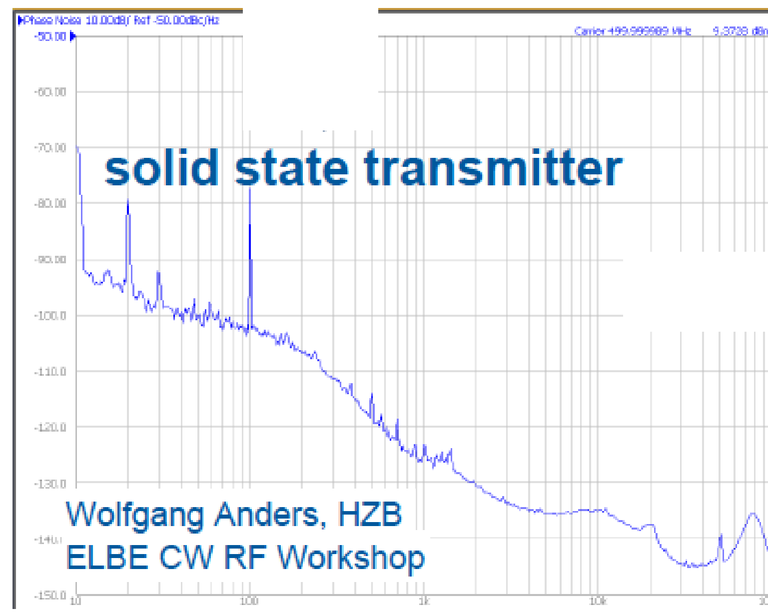
Klystron driven SC RF and noise:

→ Excellent experience from LHC!



Noise spectrum of klystron transmitters

without loops

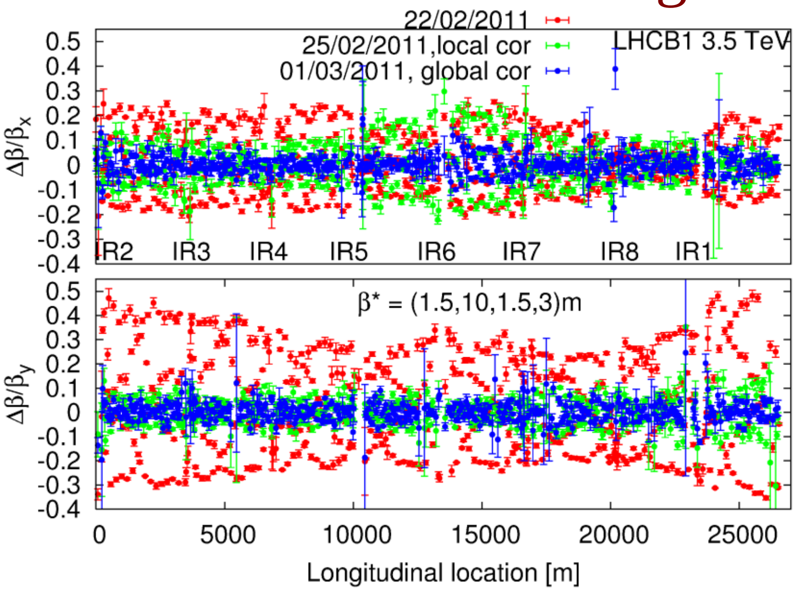


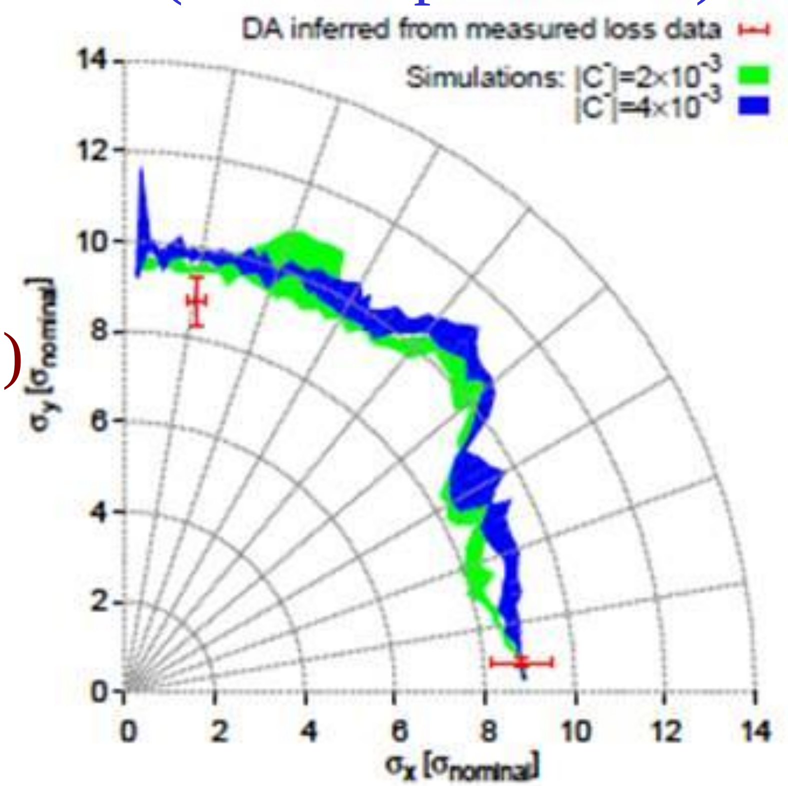
3) Worries from previous Experiences

Field Quality and Dynamic Aperture (factor 2 prediction)

➔ Excellent DA thanks to sorting and manet quality!

➔ Excellent Agreement for LHC (No noise from PC and RF? Excellent knowledge of optic?)





Profiting of development of distributed computing for long term tracking simulations (e.g. LHC@Home)

3) Worries from previous Experiences

- Electron cloud: appeared late on the LHC design table
  ➔ Could not be incorporated by redesign of beam screen
  ➔ Surface conditioning (beam scrubbing) as primary mitigation

- Emittance blow-up: ➔ was a big worry for BI and lead to careful estimates for measurements in the LHC
  ➔ great performance in the machine (noise?) and BBQ

- Beam-Beam limit: limits suggested by SppS, Tevatron and HERA
  ➔ achieved higher than expected beam-beam parameters during RunI (no RF noise?)

4) Lessons Learned from Installation

- Sorting during installation:
  - ➔ Was initially judged difficult due to small sample number (≈10)
  - ➔ Problem with cryogenic supply line (QRL) provided unique opportunity:

    Ended up with almost 1000 magnets stored on CERN site before installation

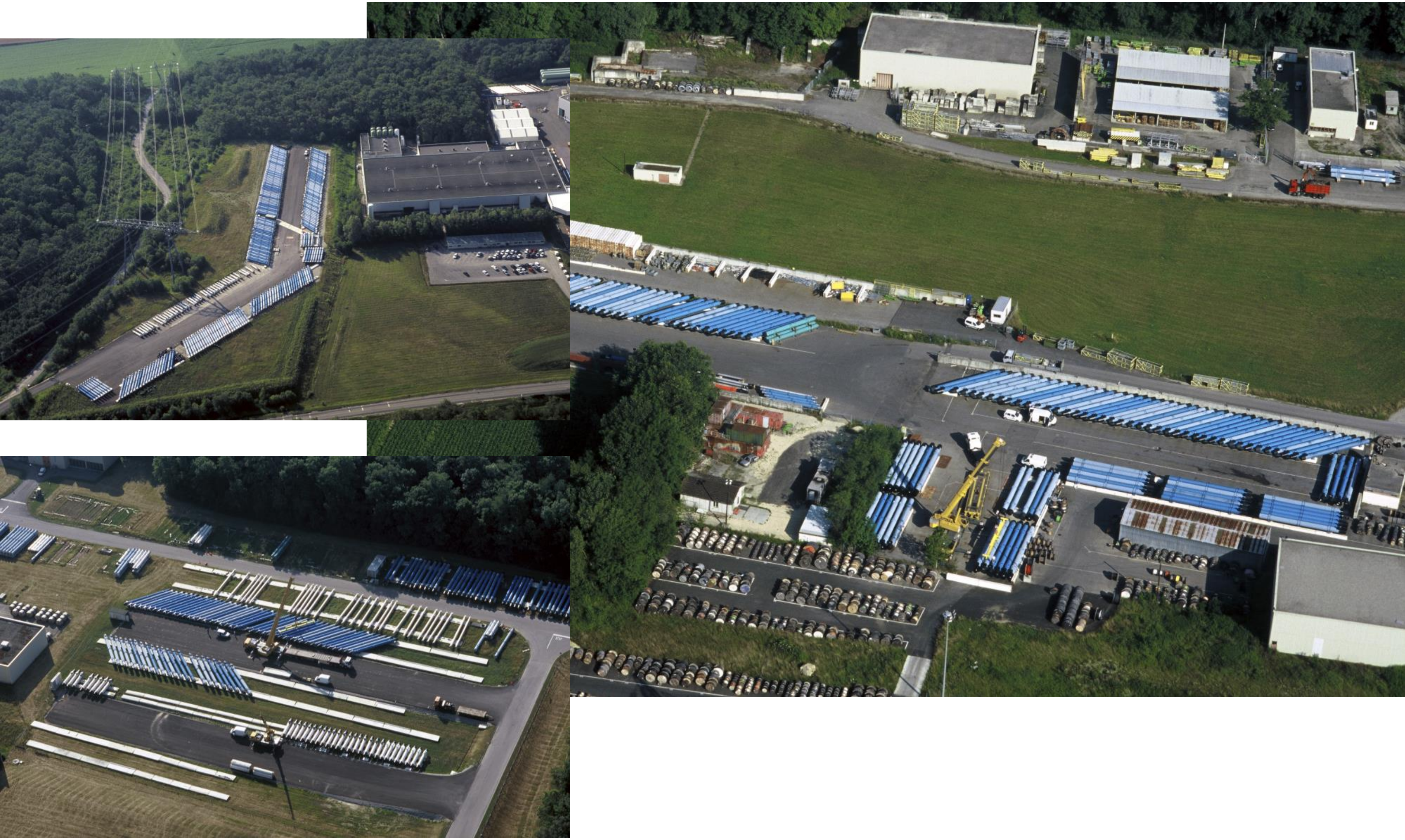
  - ➔ Allowed sorting by geometry and Field Quality

    LHC operation clearly benefits from this!

  - ➔ Requires significant space on site!!!!!
  - ➔ Requires sufficient capacity for cryostating and testing

4) Lessons Learned from Installation

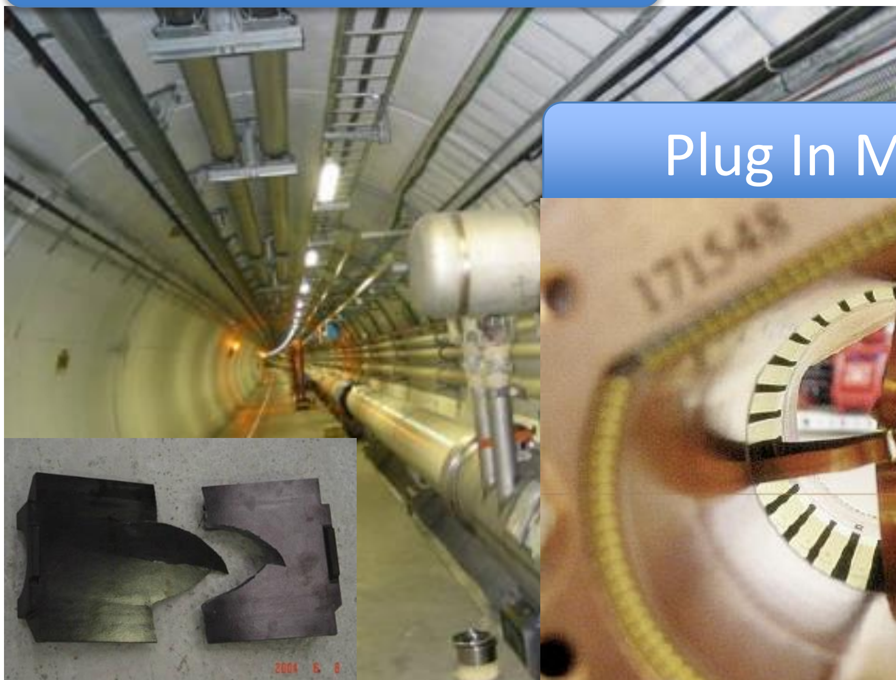
- Storing & cryostating magnets for sorting:



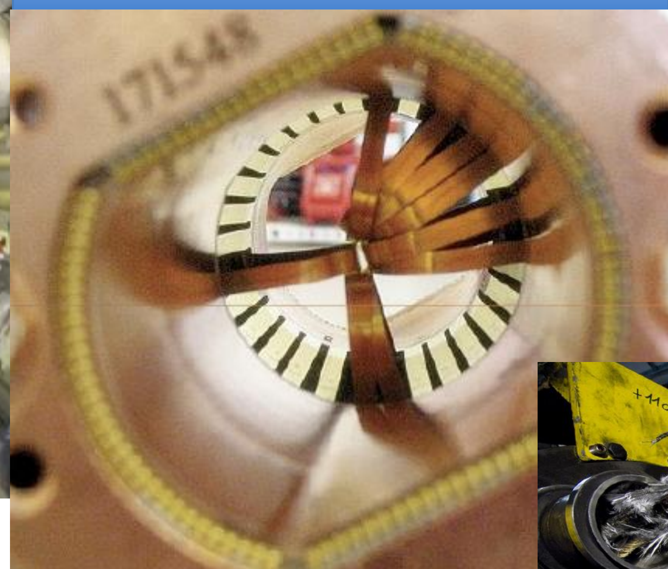
4) Lessons Learned from Installation

Ability to tackle problems:

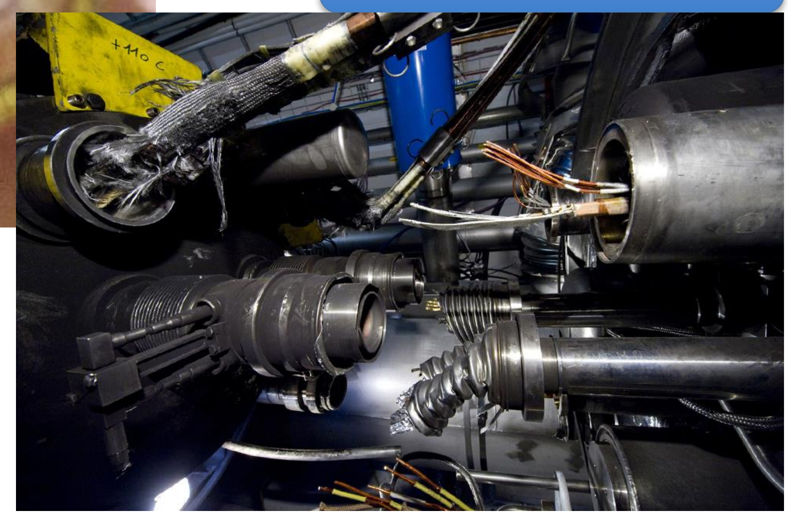
Cryogenic supply line



Plug In Modules



The incident



Superconducting Magnets and Circuits Consolidation (SMACC)

Monumental effort

- Over 350 persons involved
- Including preparation: ~1,000,000 working hours
- No serious accidents!

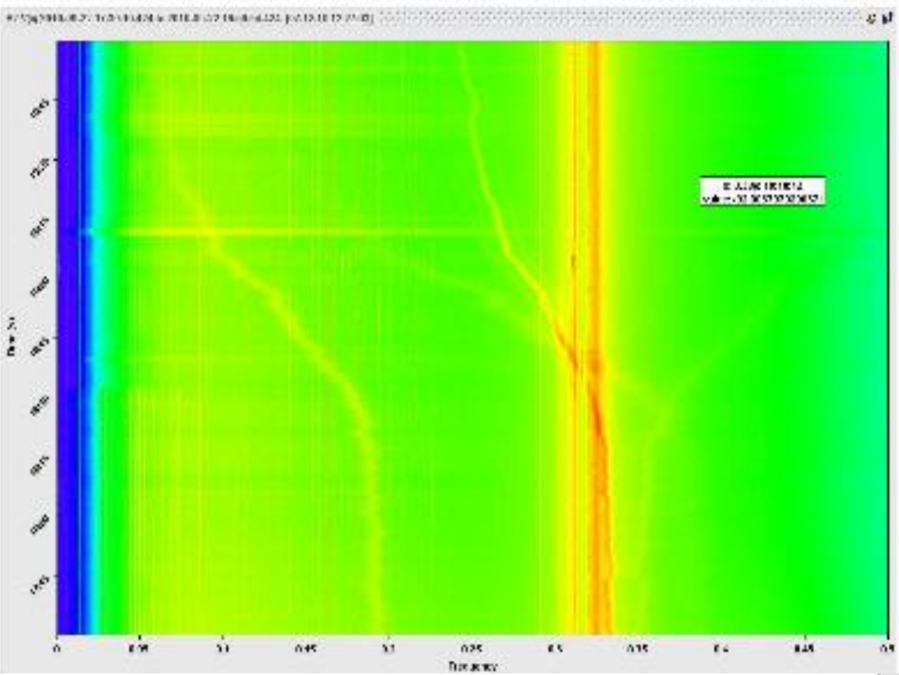
Jean-Philippe Tock

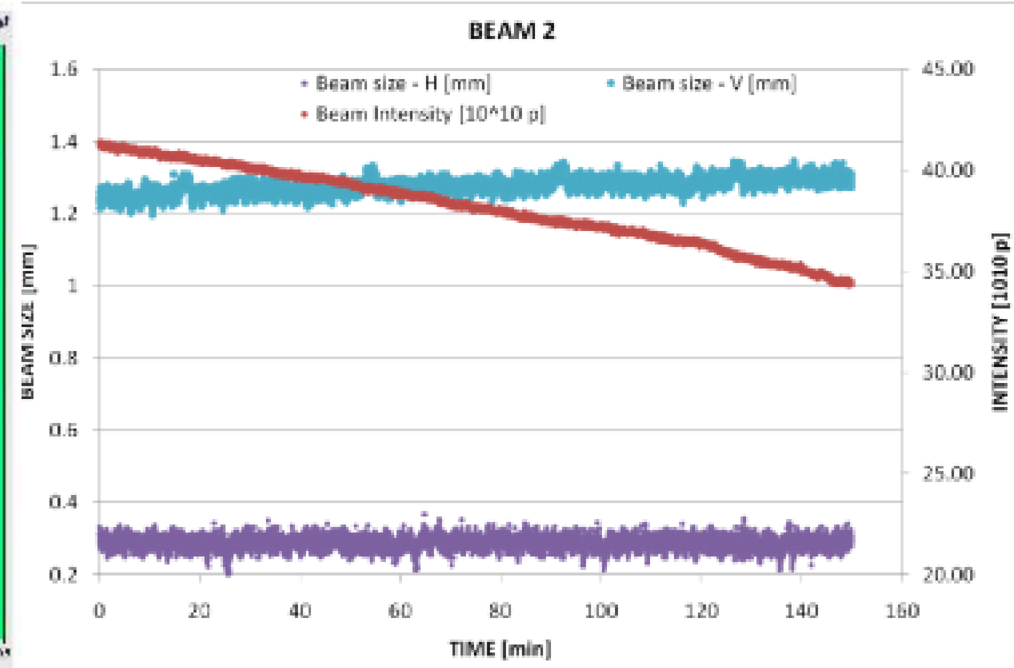
Collaborations with NTUA (Athens), WUT (Wroclaw) and support of DUBNA

SMACC project : Closure of the last interconnection – 18.06.2014
Activity led by A Musso (TE-MSC)

5) Lessons Learned from Commissioning & Run I

- Beam lifetime: ➔ initially expected to be rather poor, leading to estimates of intensity limitations (≈ 20%)
  ➔ spikes and short dips do remain a concern though!!!



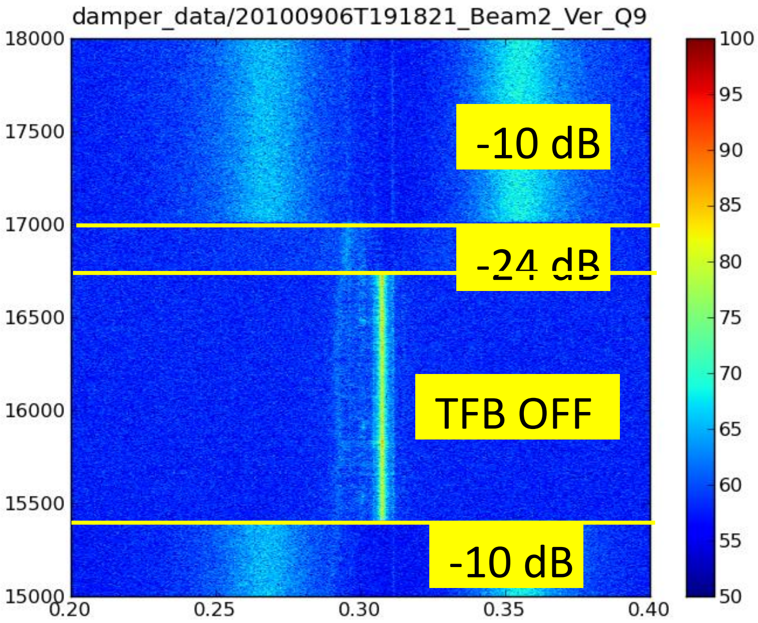


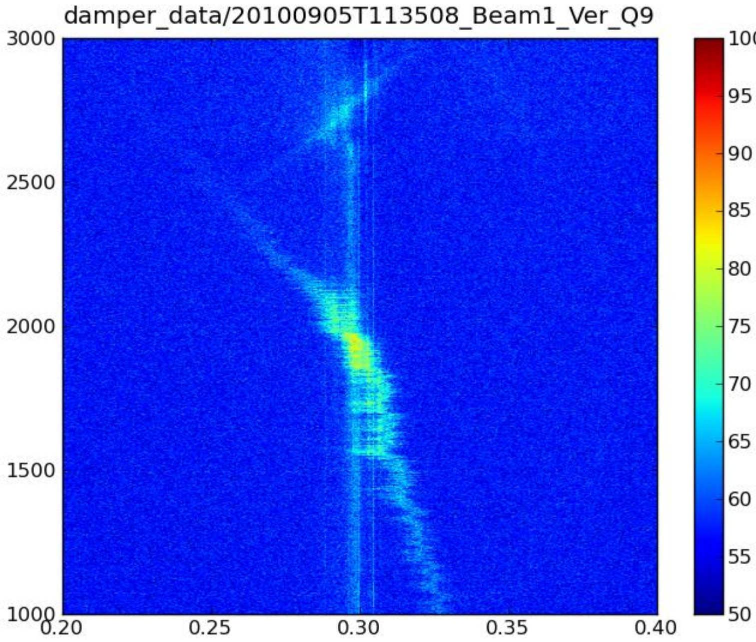
- Noise sources: ➔ ‘hump’ raised concerns initially!
  ➔ But the effect disappeared after first year of operation
  ➔ But origin has still not been fully understood!

5) Lessons Learned from Commissioning & Run I

Importance of powerful Beam Instrumentation:

e.g. fast and efficient commissioning in 2010,
could see the hump and compensate with damper





Machine Protection & range in beam intensities:

- ➔ interlock @ dump and BPM gain
- ➔ Commissioning with ‘safe beam’ versus ‘nominal’
- ➔ collimation hierarchy and orbit stability

5) Lessons Learned from Commissioning & Run I

- Importance of powerful, flexible and mature injector complex

Bunch spacing	Protons per bunch	Norm. emittance H&V

Later options feature:

-8b4e as e-cloud mitigation

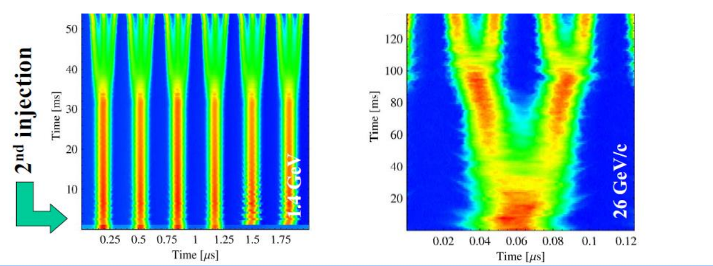
-Bunchlet scheme for enhanced scrubbing

-BCMS as low emittance option

-80 bunch injection scheme to SPS

e:

- I_b^2
- lower total intensity
- less of an electron cloud challenge



→ Each bunch from the Booster divided by 6 → 6 × 3 × 2 × 2 = 72

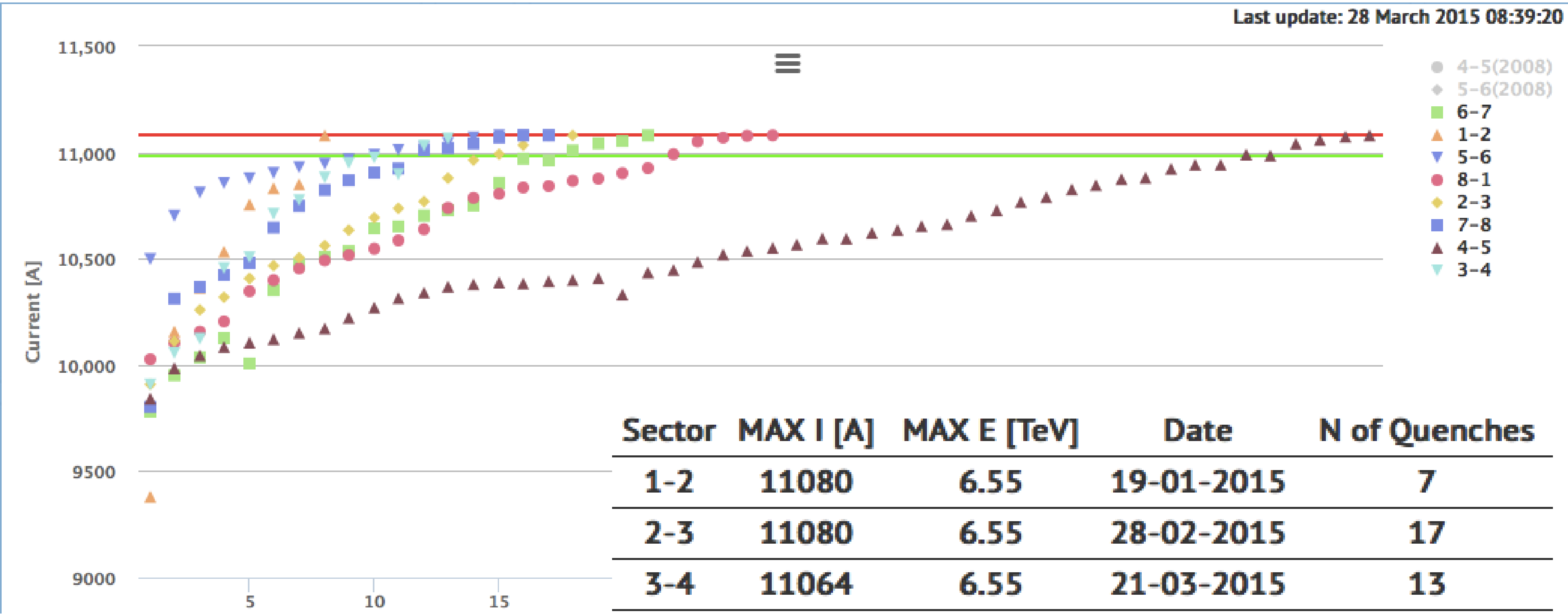
5) Lessons Learned from Commissioning & Run I

- Time needed for cryogenic maintenance:
  - ➔ Ca. 1 year for full maintenance (incl warm-up and cool-down)
    - ➔ new running paradigm
      - ➔ 3y operation + long shutdown

- Definition of ‘good’ magnets during production:
  - ➔ LHC: reward for fast training to ‘ultimate’ current
  - ➔ Turned out NOT to be correlated to ‘de-training
    - ➔ impact on maximum ‘efficient’ energy 7 TeV -> 6.5 TeV
    - ➔ impact on devising optimum running schedule

5) Lessons Learned from Commissioning & Run I

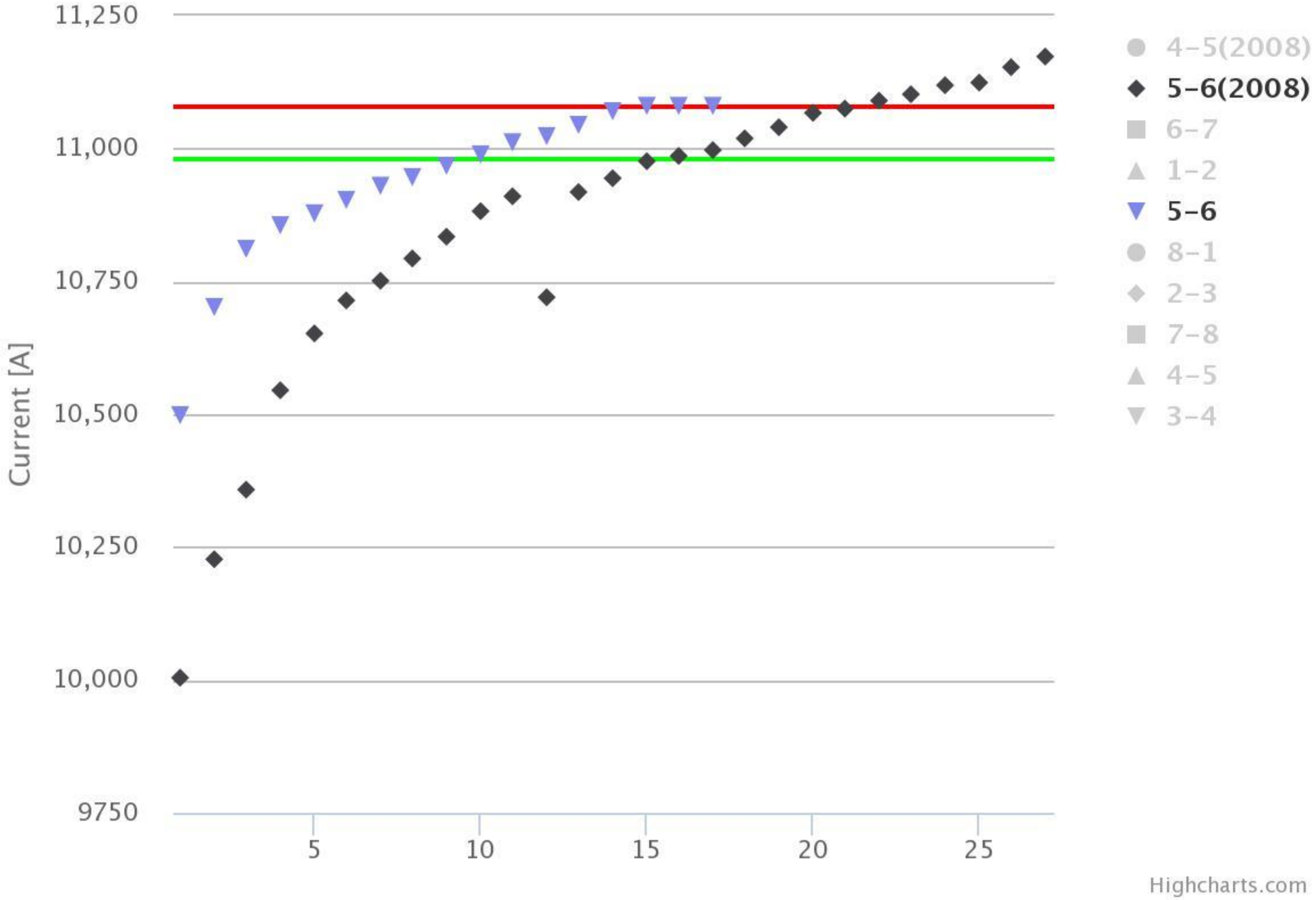
Long training to 'nominal' in tunnel:



Sector	MAX I [A]	MAX E [TeV]	Date	N of Quenches
1-2	11080	6.55	19-01-2015	7
2-3	11080	6.55	28-02-2015	17
3-4	11064	6.55	21-03-2015	13
4-5	11080	6.55	28-03-2015	49
5-6	11080	6.55	08-02-2015	16
6-7	11080	6.55	10-12-2014	20
7-8	11080	6.55	12-03-2015	16
8-1	11080	6.55	22-02-2015	25

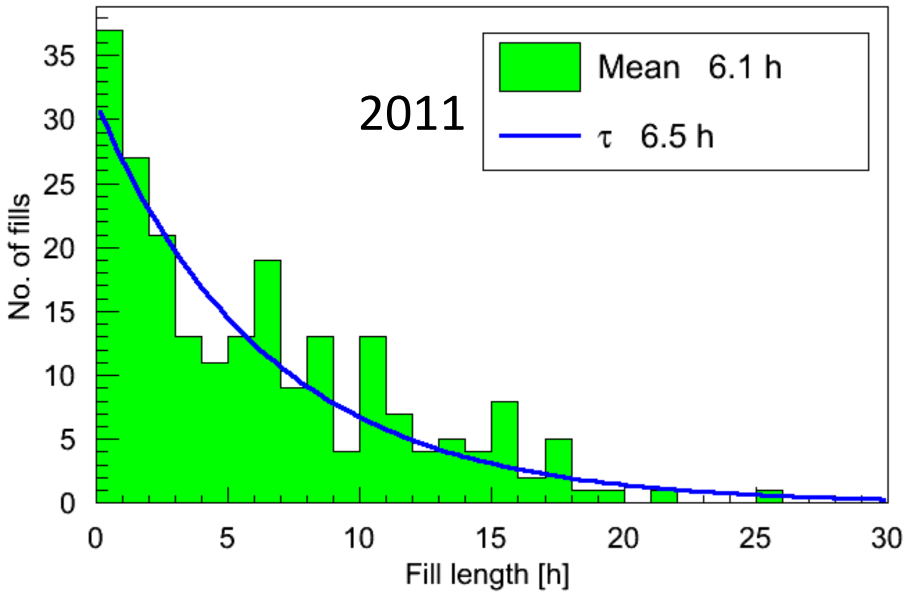
5) Lessons Learned from Commissioning & Run I

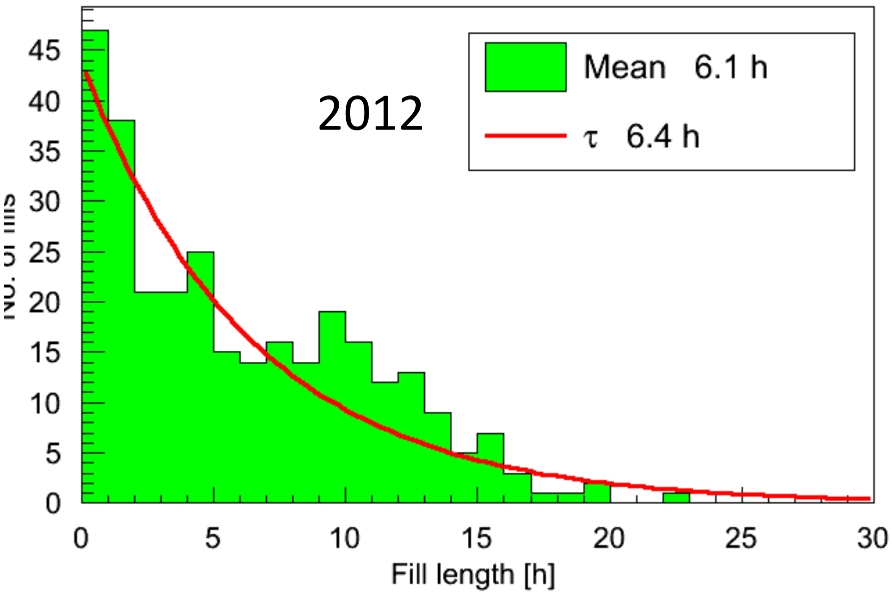
- Detraining after long shut down:



5) Lessons Learned from Commissioning & Run I

- Machine efficiency: e.g. UFO's, R2E and loss spikes
  ➔ beam aborts due to very small beam losses ➔ Margins!!!
  ➔ only 30% of all fills have been terminated by operators!



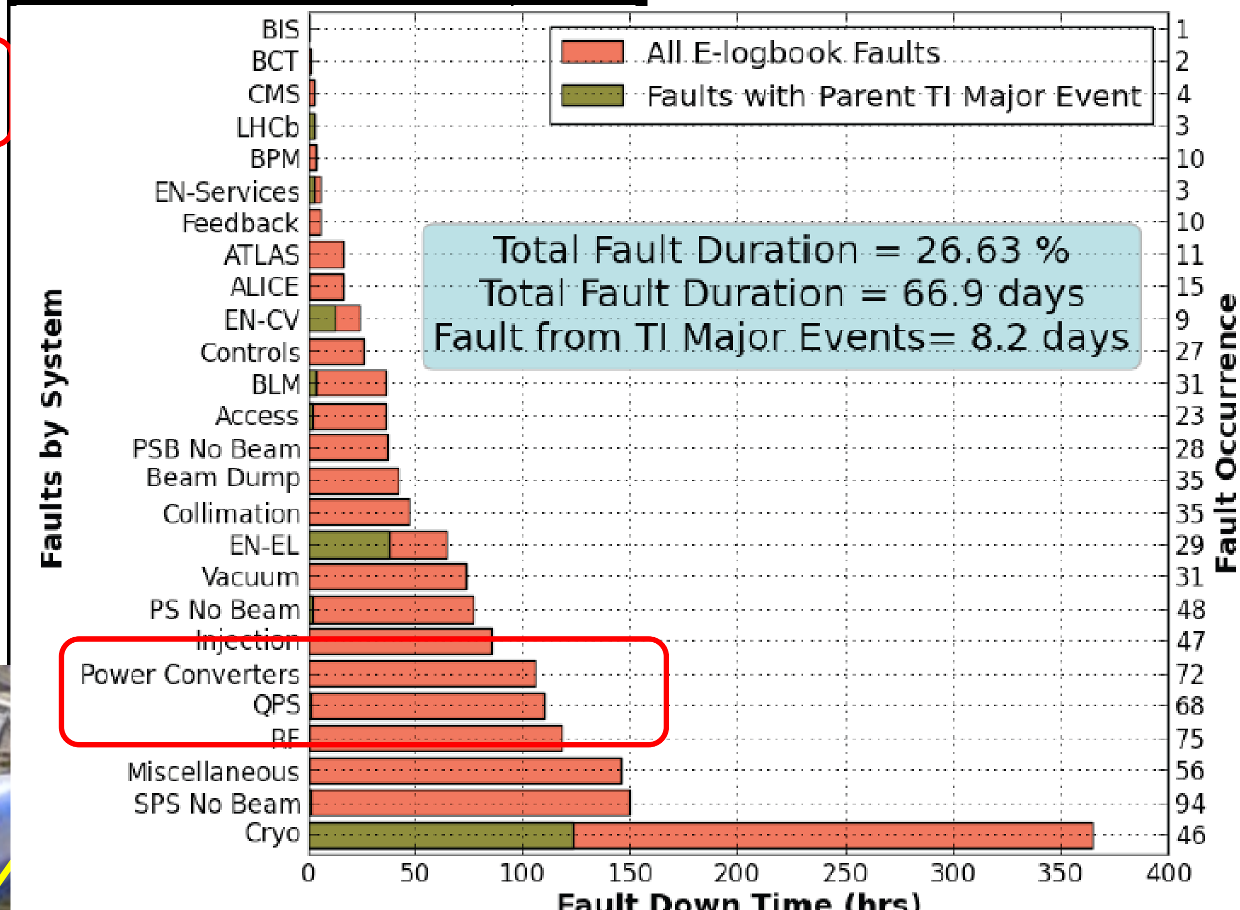


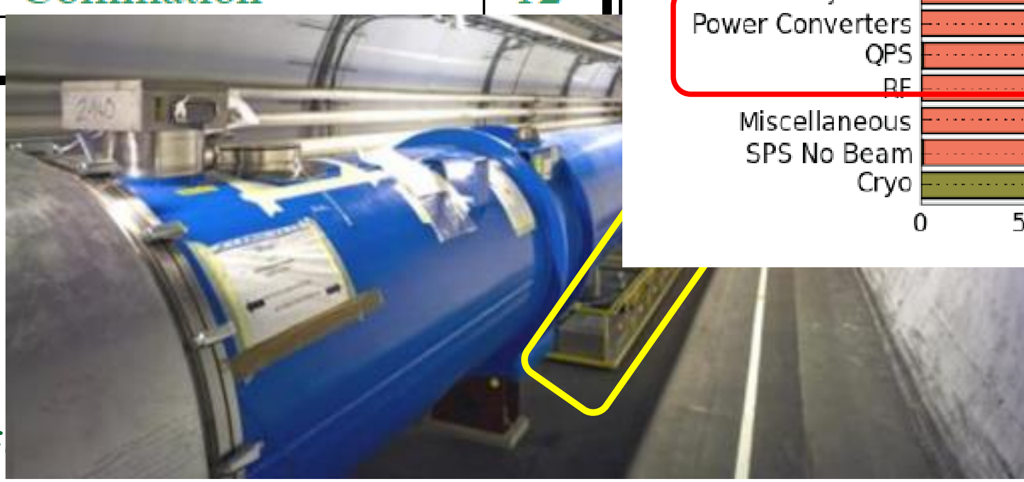
➔ Optimum fill length and machine efficiency

5) Intervention rate & time: R2E

Dump Cause	#
Beam: Losses	58
Quench Protection	56
Power Converter	35
Electrical Supply	26
RF + Damper	23
Feedback	19
BLM	18
Vacuum	17
Beam: Losses (UFO)	15
Cryogenics	14
Collimation	12

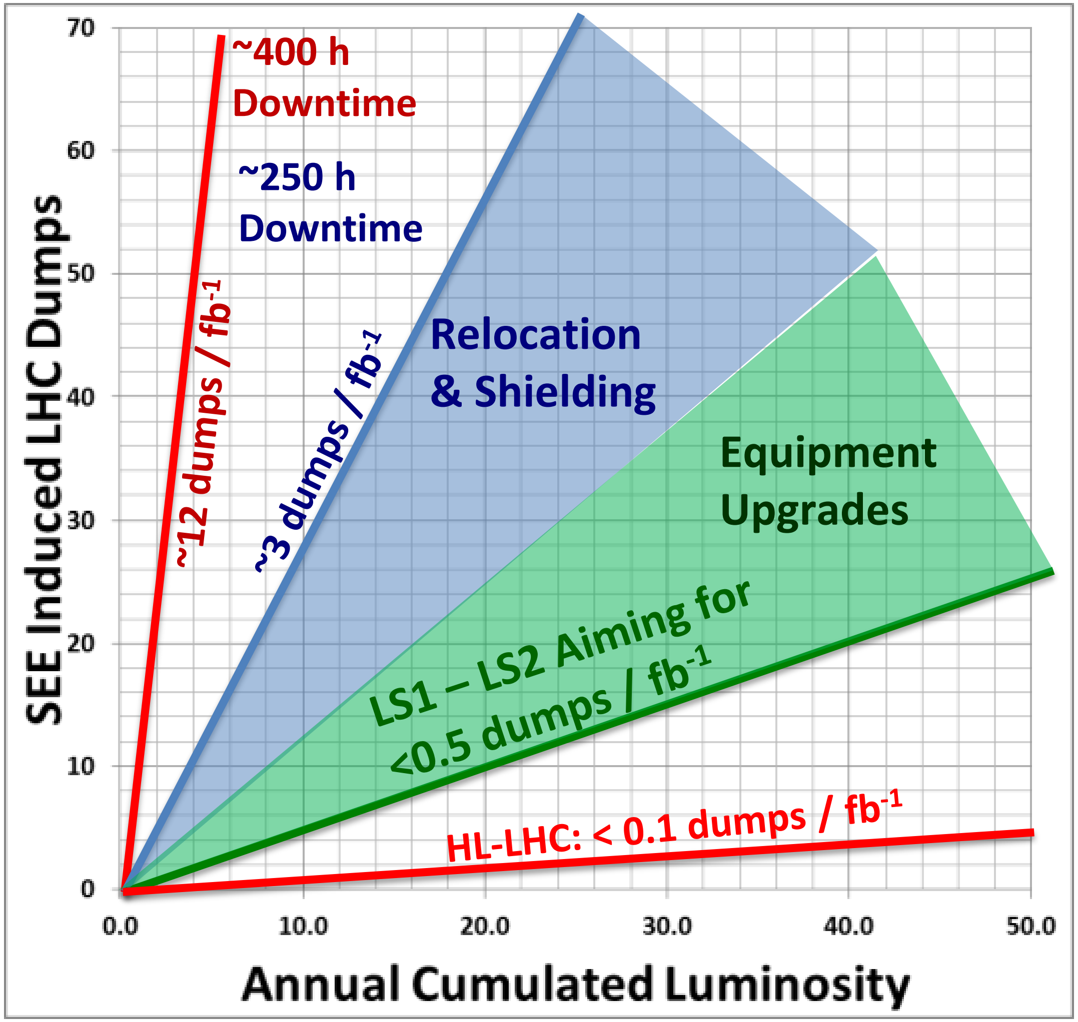
Dump Cause	#





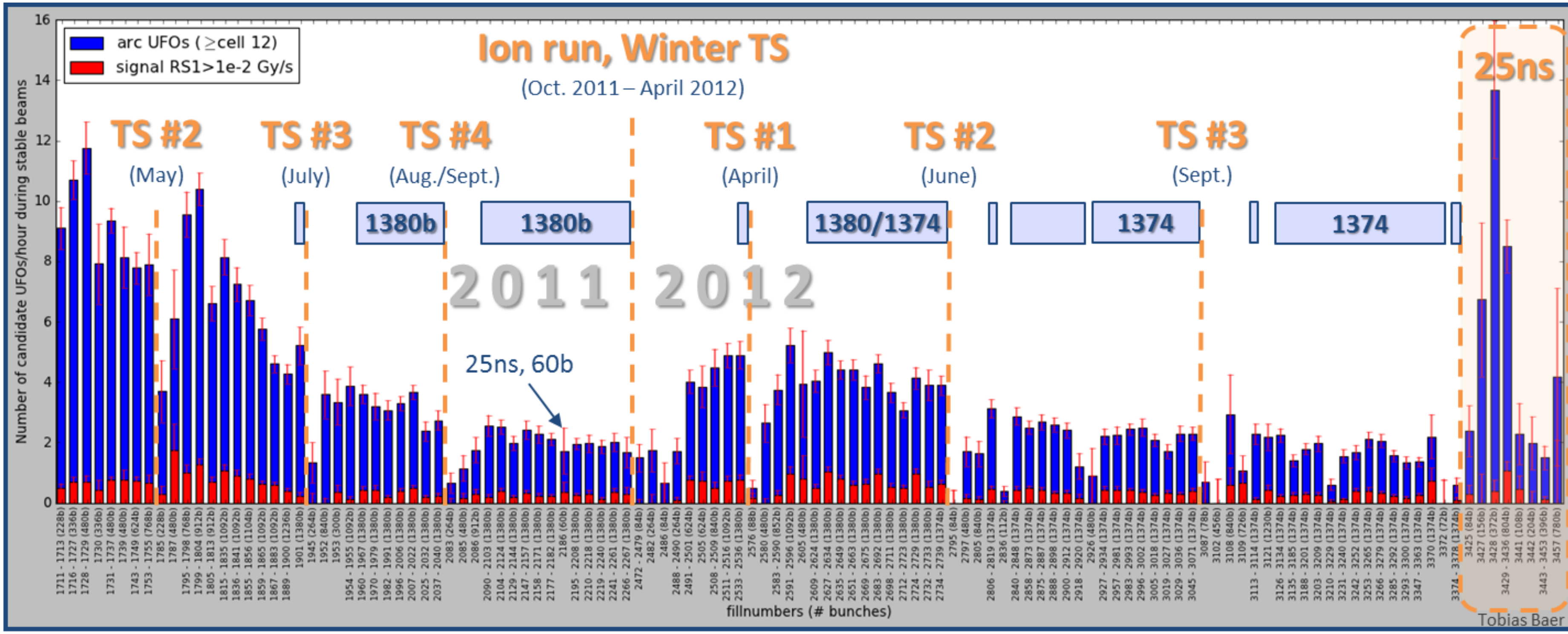
New paradigme: remove as much as possible from the tunnel

5) R2E SEU Failure Analysis - Actions



- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding
- **LS1 (2013/2014)**
  - Relocation of power converters
- **LS1 – LS2:**
  - Equipment Upgrades
- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations

5) ARC UFO rate:



2011: Decrease from **≈10 UFOs/hour** to **≈2 UFOs/hour.**

2012: Initially, about **2.5 times higher** UFO rate than in2011: scaling with Energy?

UFO rate decreases since then. Up to **10 times** increased UFO rate with **25ns.**

Extrapolation to 7 TeV: ***91 UFO related beam dumps***(*based on 2011: 112 dumps*)*!!!*

➔ *scrubbing and BLM threshold and position optimization after LS1*

5) Lessons Learned from Commissioning & Run I

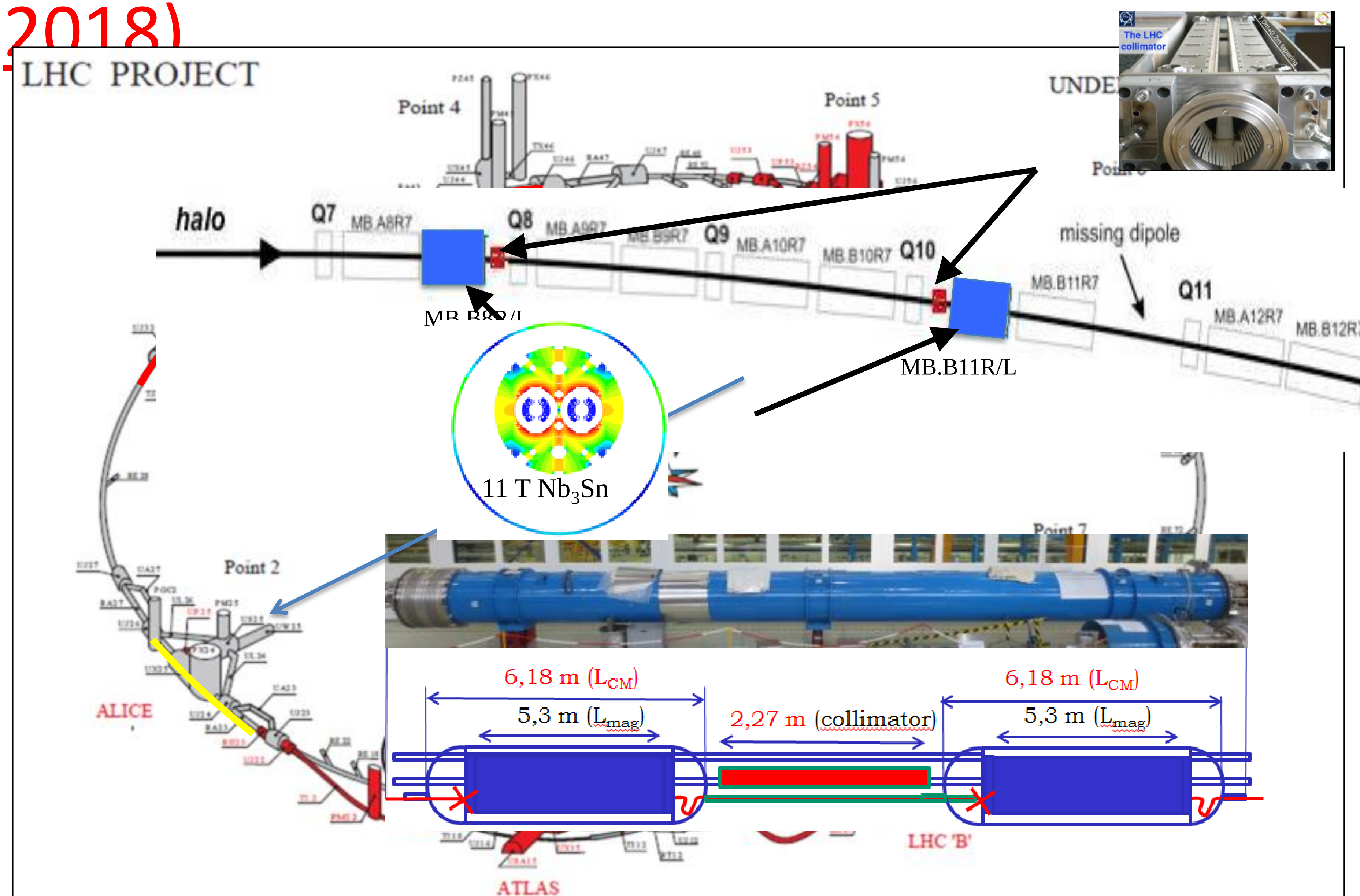
- Snap back and dynamic effects under control thanks to detailed magnet measurements (no need for reference magnets)
  ➔ LHC achieved very good machine reproducibility and stability!

- Machine reproducibility is key for high efficiency of the cleaning insertions and for Machine Protection

- Losses in the Dispersion Suppressor:
  ➔ Integrate already @ design stage collimators into the dispersion suppressor

Reserve Transparencies

DS collimators – 11 T Dipole (LS2 - 2018)



Issues 3/4: Two Types of Beam Aborts…

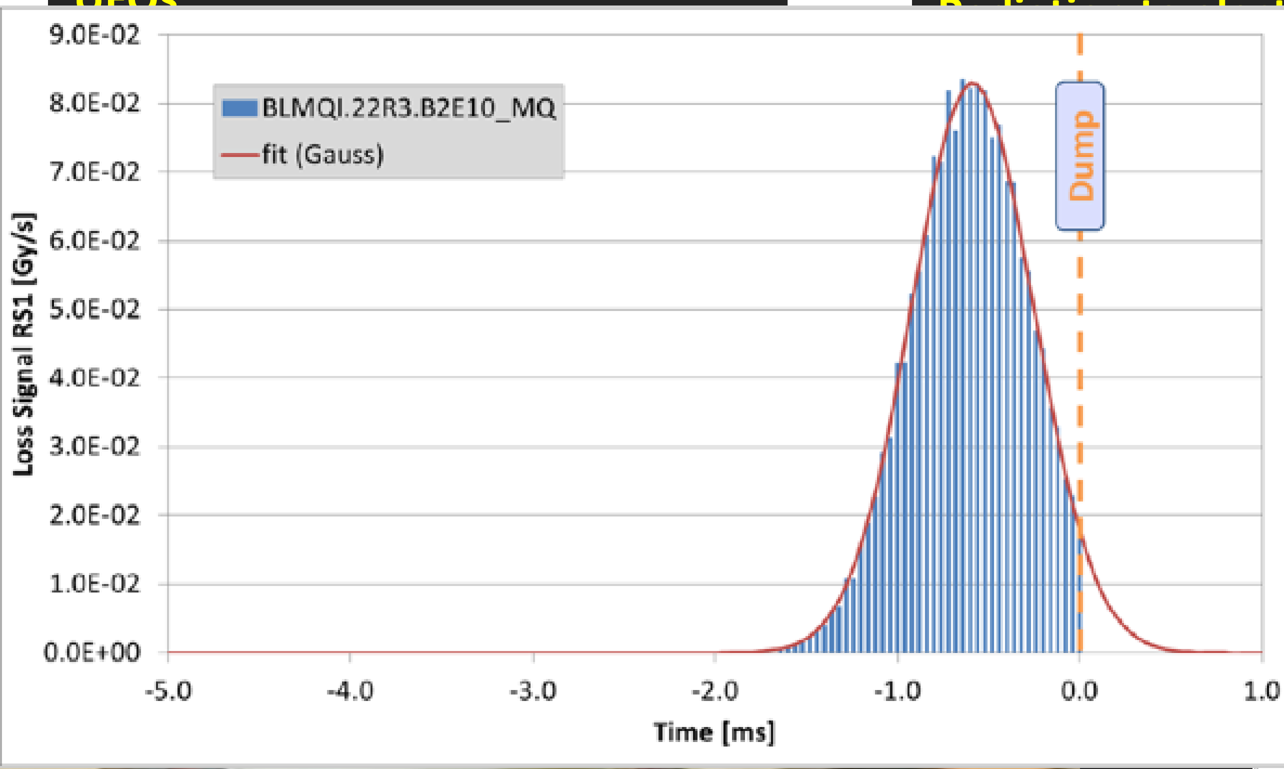
UFOs

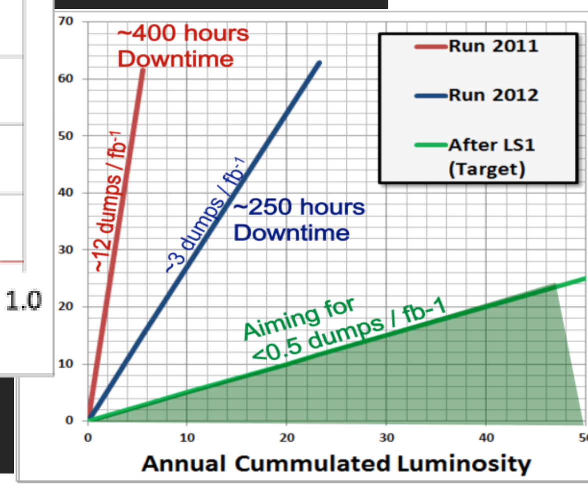
ronics

am of mitigation

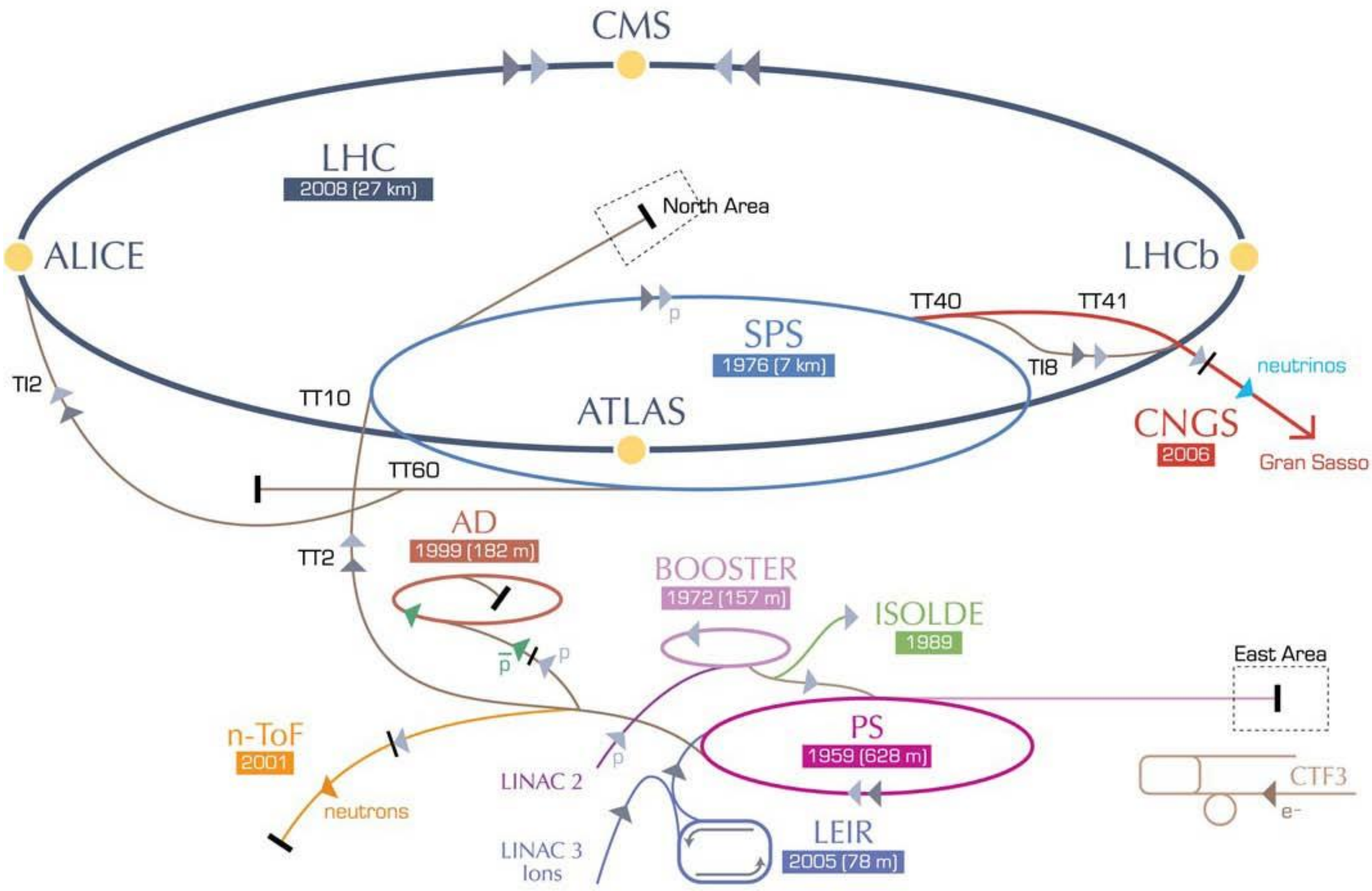
ing, relocation…)

rate down from

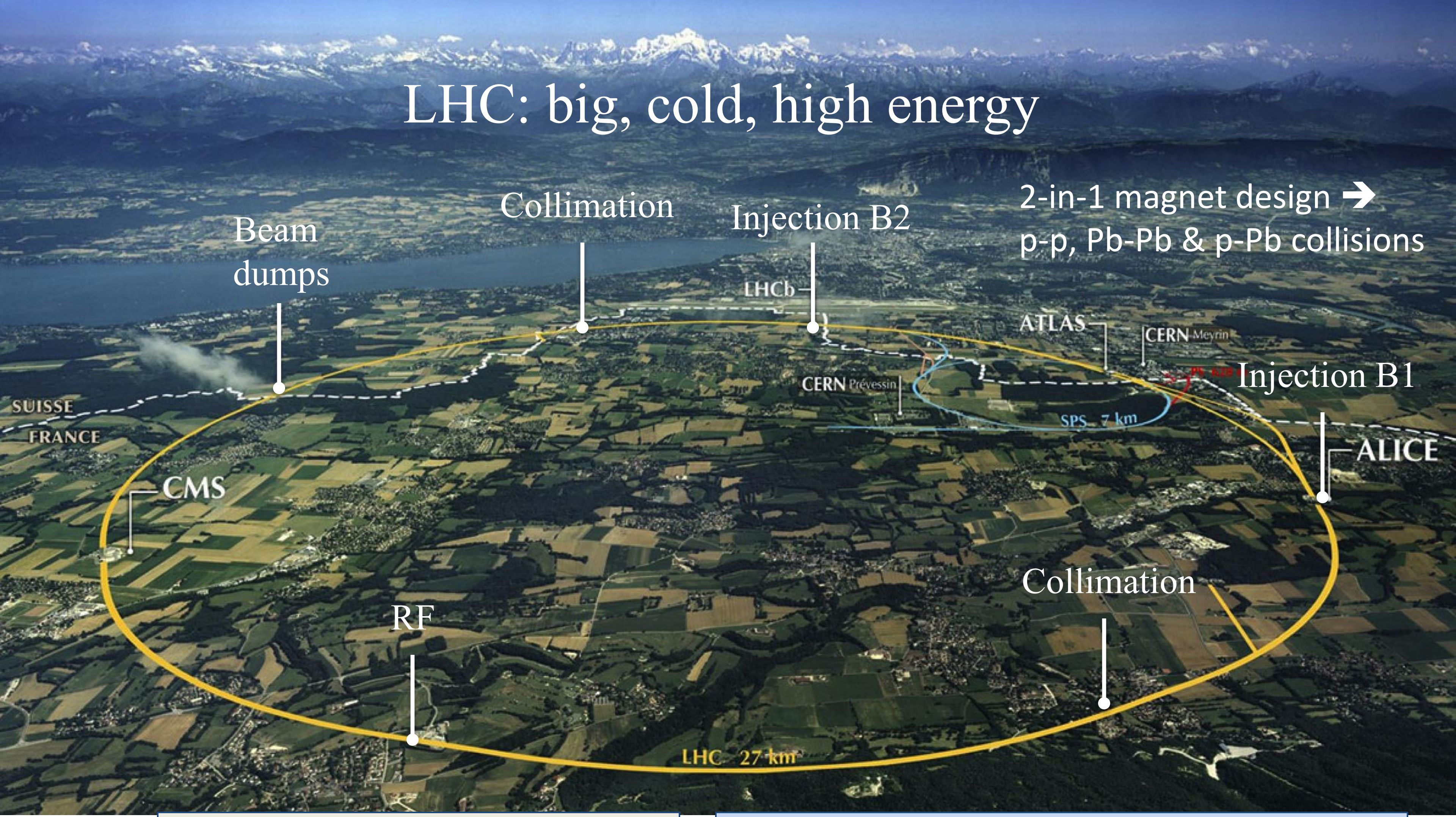




LHC Complex Overview



LHC: big, cold, high energy



1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
4000 Beam loss monitors

150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
370 MJ design and > 500 MJ for HL-LHC!
450 MJ magnetic energy per sector at 4 TeV
➔ ≈ 10 GJ total @ 7 TeV