Radiation Toleran
Activities in the LHC machine

Radiation 2 Electronics (R2E) Mitigation Project

PH/ESE Seminar, April 19th 2011

M. Brugger on behalf of the R2E Project

!!! Many Thanks To Everybody !!!

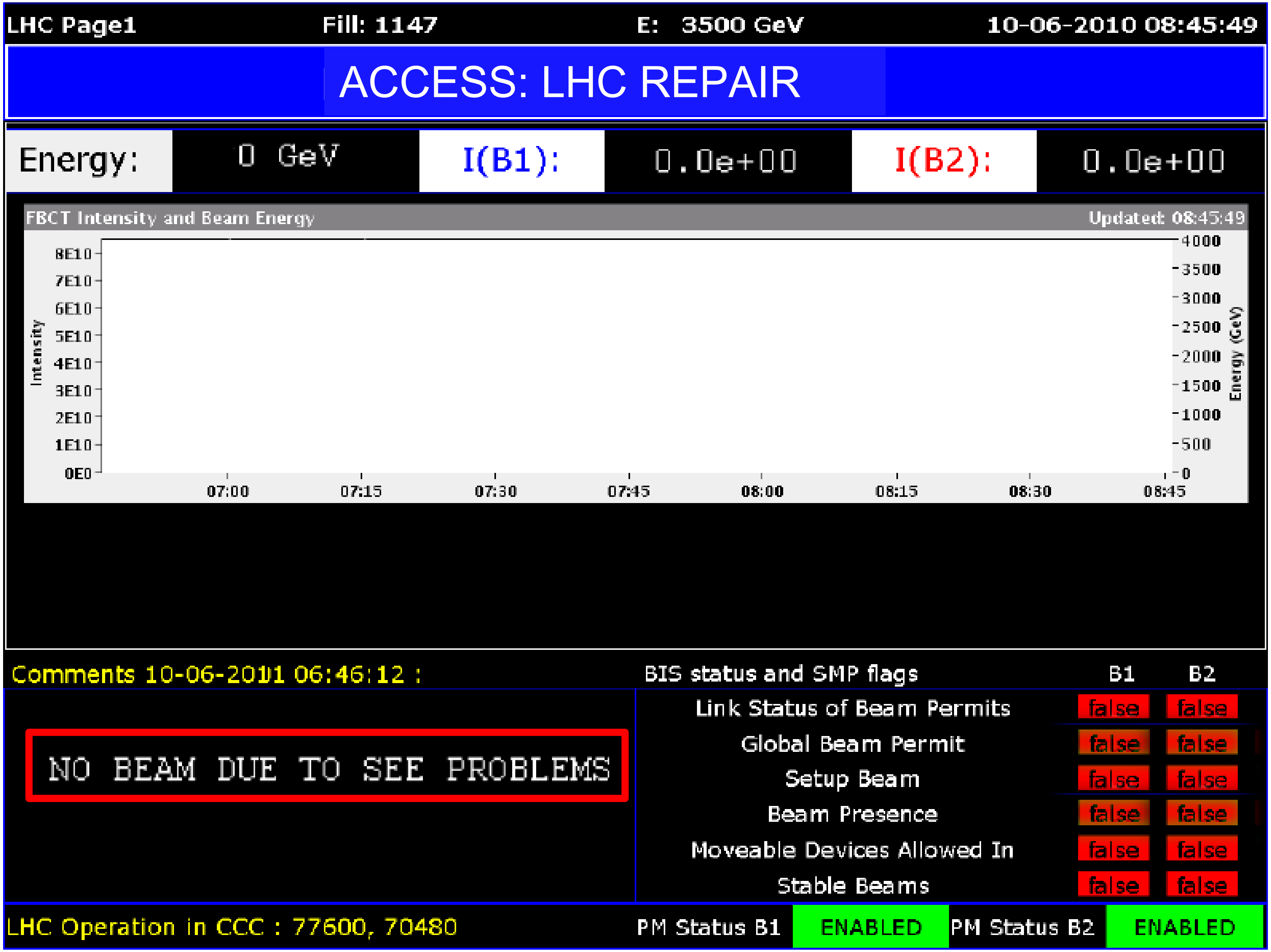
www.cern.ch/r2e

Overview

- A brief history of time… (The Challenge)
- LHC radiation fields & related monitoring
- Predictions based on Monte-Carlo codes and respective benchmarking
- Commercial equipment/systems and challenges (impossibilities)
- Test facilities and installations
- Mitigation approach
- Lessons learned (*e.g.*, the endeavor of an equipment inventory)

- **… picked a selection of results (thanks to many people!!!)**

What's to Be Avoided



To Put the Challenge in the Correct Perspective

LHC Construction Phase

Experiments:

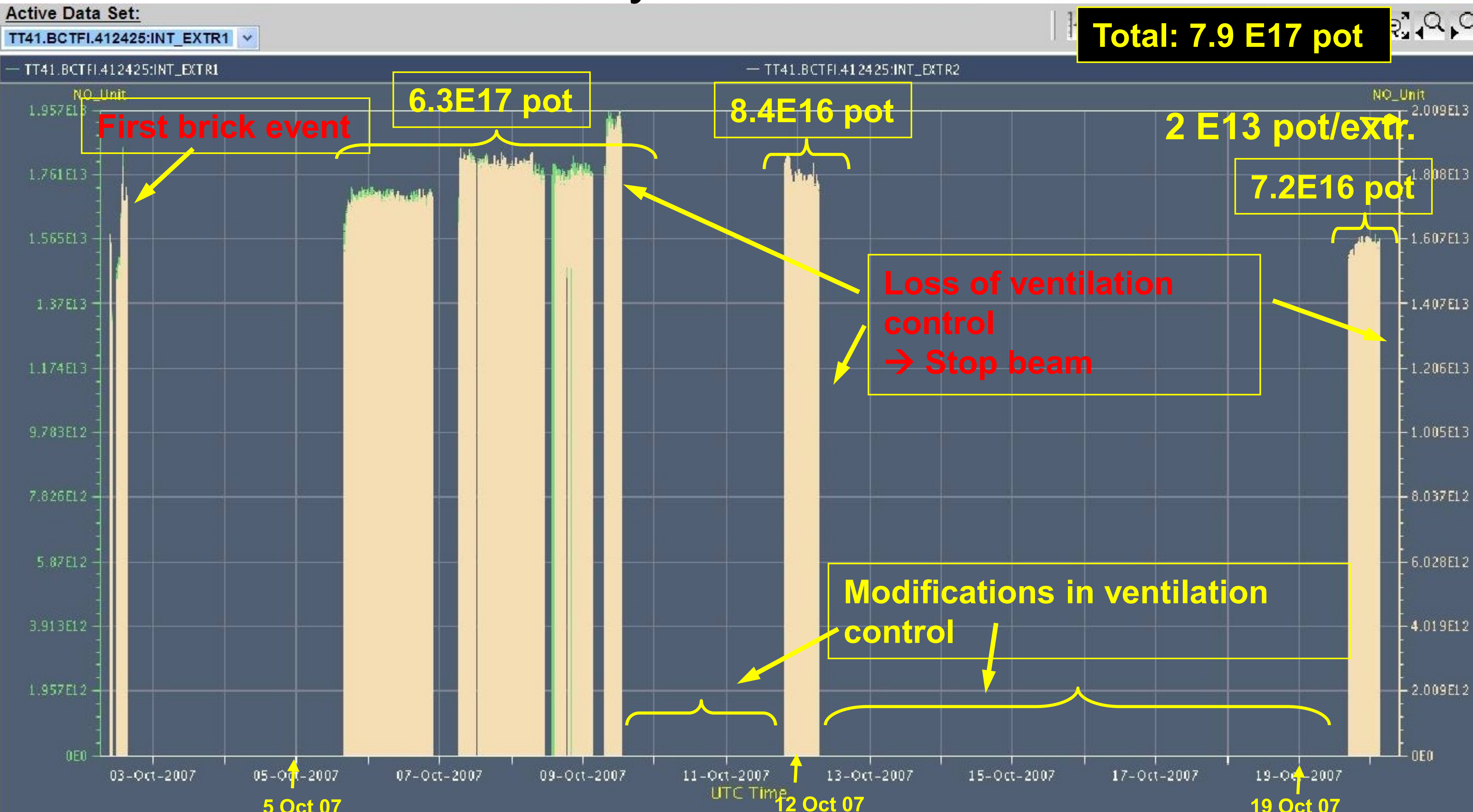
- “Rigorous” **design constraints** for electronics installed in the experimental cavern
- **Controlled approach:** design reviews, tests,…
- **Policy** and ‘**Police**’ available from early on

Machine:

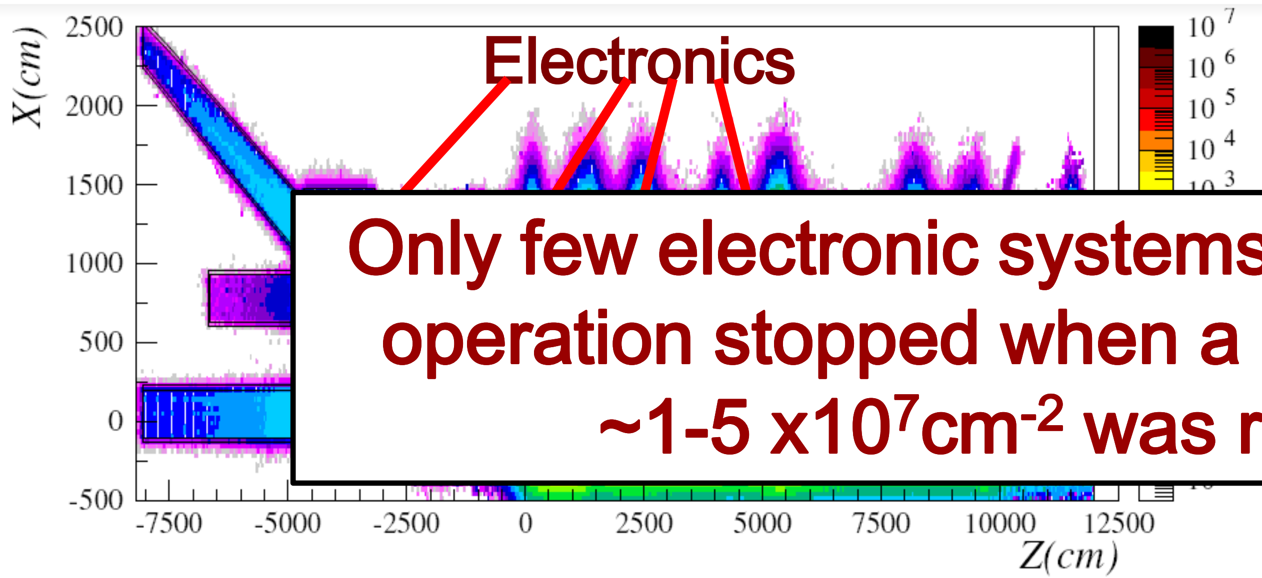
- **Similar approach for tunnel equipment** (*e.g.*, QPS, 60A power converters, Cryogenics, Beam-Instrumentation) – still with some shortcuts (some already discovered)
- **Little (no) design criteria** (limitations) for the remaining equipment (assumed to be ‘save’),
- No ‘Police’ and ‘Gendarmerie’ with very limited resources

The CNGS "Discovery"

CNGS Physics Run 2007

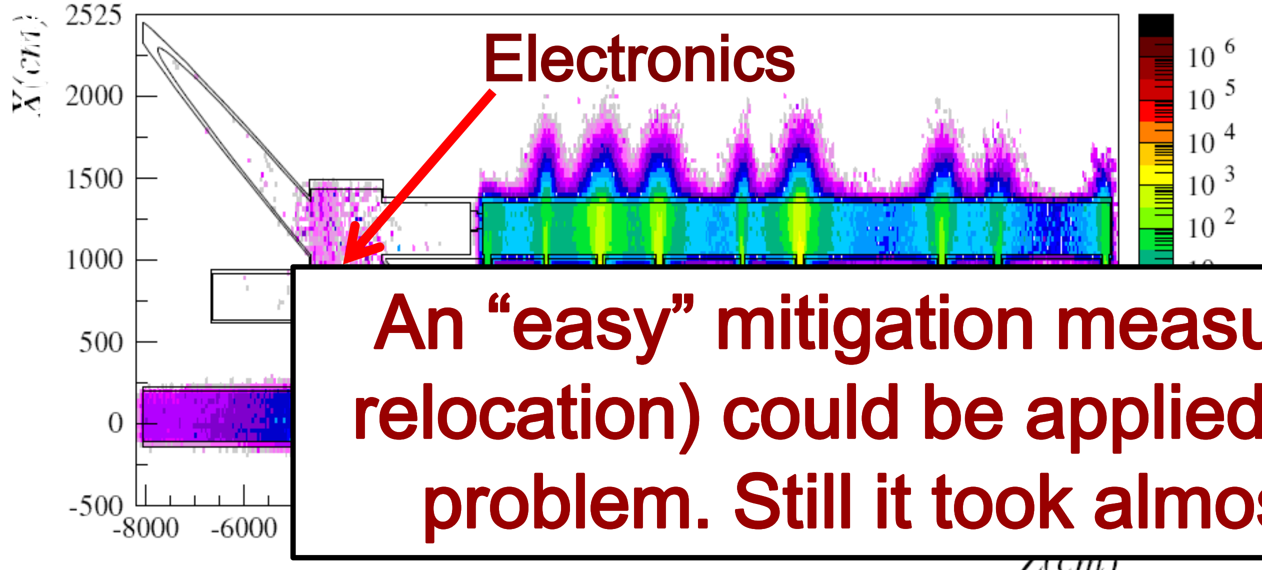


Issue: Solved By Heavy Shielding



- 2007 Layout before shielding

Only few electronic systems were exposed, operation stopped when a fluence of only ~1-5 x10^7cm^{-2} was reached!



- 2008 Layout – after installation of new shielding

An "easy" mitigation measure (shielding + relocation) could be applied and solved the problem. Still it took almost half a year!

Dose in Gray for a nominal CNGS year (4.5x10^{19} pot)

Time-Scale So Far…

- **CNGS Incident** -> It's Radiation (SEEs) !!!
- **Task-Force** to look at LHC Issues (**ups…**)
- **Solution for CNGS** (Study, Implementation)
- **Radiation To Electronics (R2E) Study Group**
- **Short-Term Actions (Safety 1st Priority)**
- **Full Analysis of LHC Areas** (Calculations,…)
- **R2E School** and **Getting 'Mobilized'**
- **Medium-Term Actions**
  (Focus on what can be done)
- **Power-Converter Review**
- **R2E-Workshop** & **Strategy**
- First **Long-Term Draft** and List of Options
- **R2E Mitigation Project**
- **xMasBreak Actions**

2007

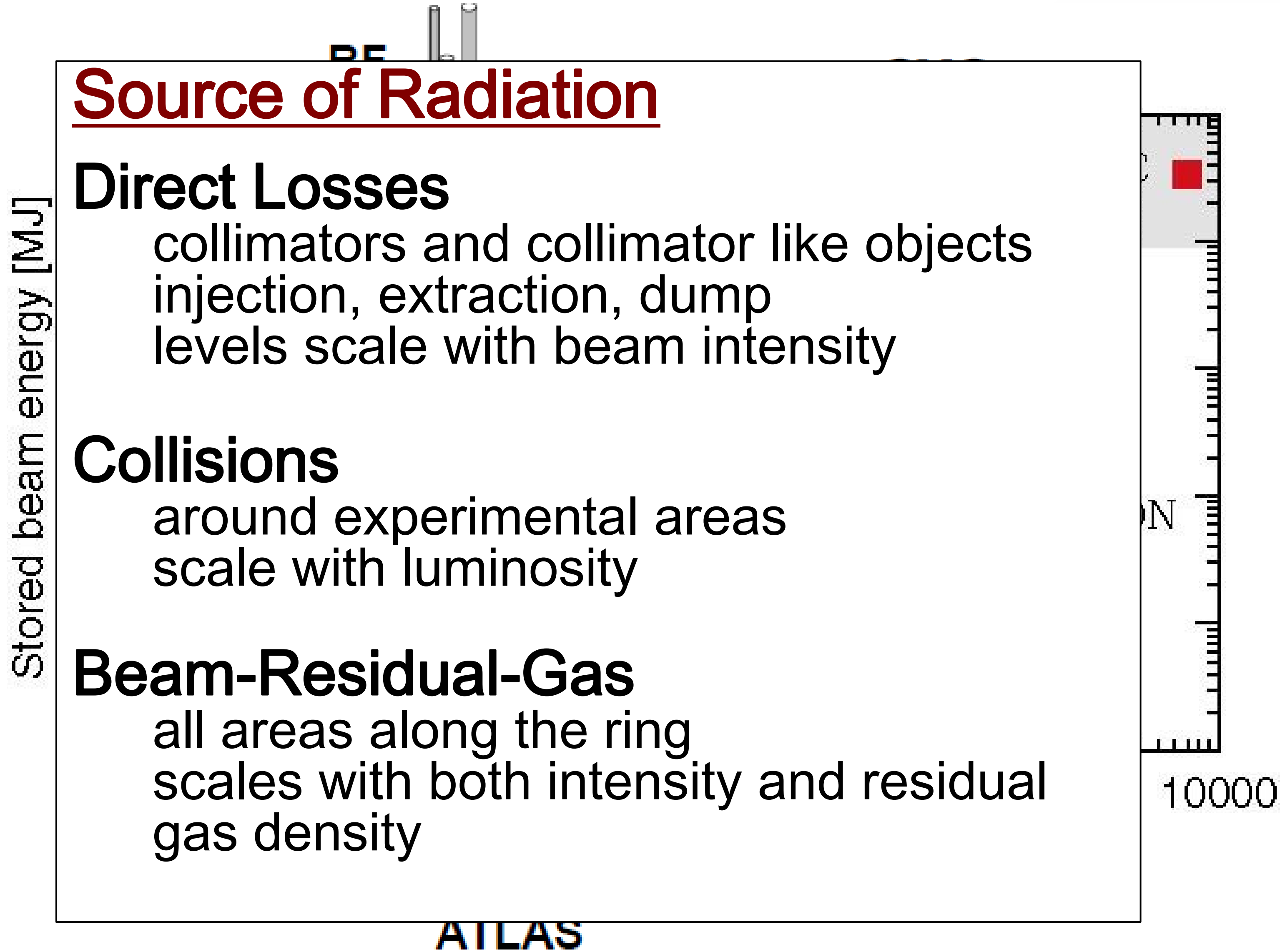
2008

2009

2010

2011

The LHC & 'Radiation Areas'



Source of Radiation

Direct Losses

- collimators and collimator like objects
- injection, extraction, dump
- levels scale with beam intensity

Collisions

- around experimental areas
- scale with luminosity

Beam-Residual-Gas

- all areas along the ring
- scales with both intensity and residual gas density

What Are the “Issues”? – Typical Shielding

Point 2

PX24 wall

inner triplet

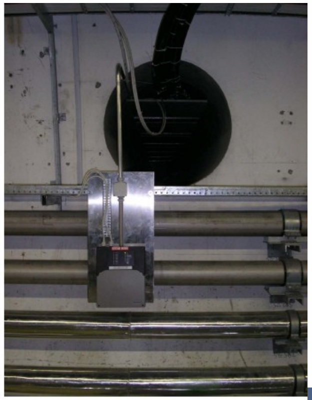
Point 3

!!!

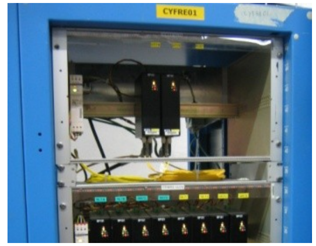
AND MANY MORE …

!!!

Point 6



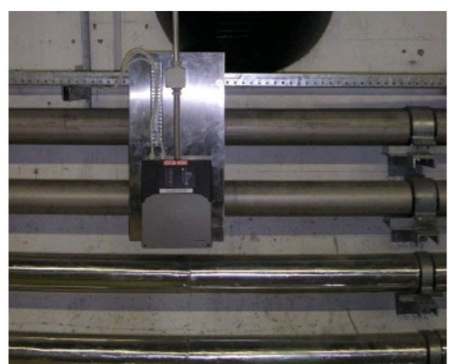
What Are the “Issues”? – Electronics



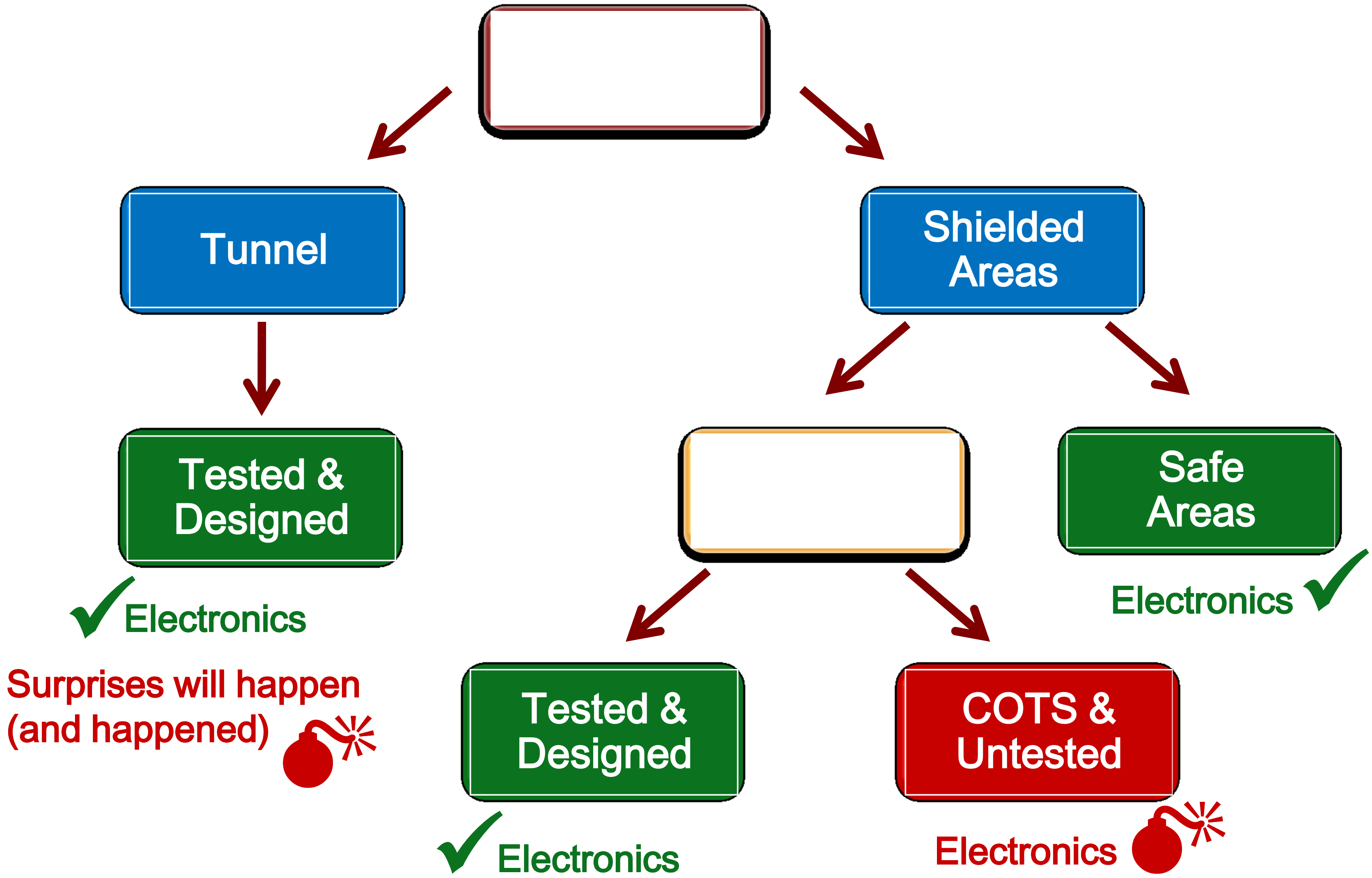
!!!

AND MANY MORE …

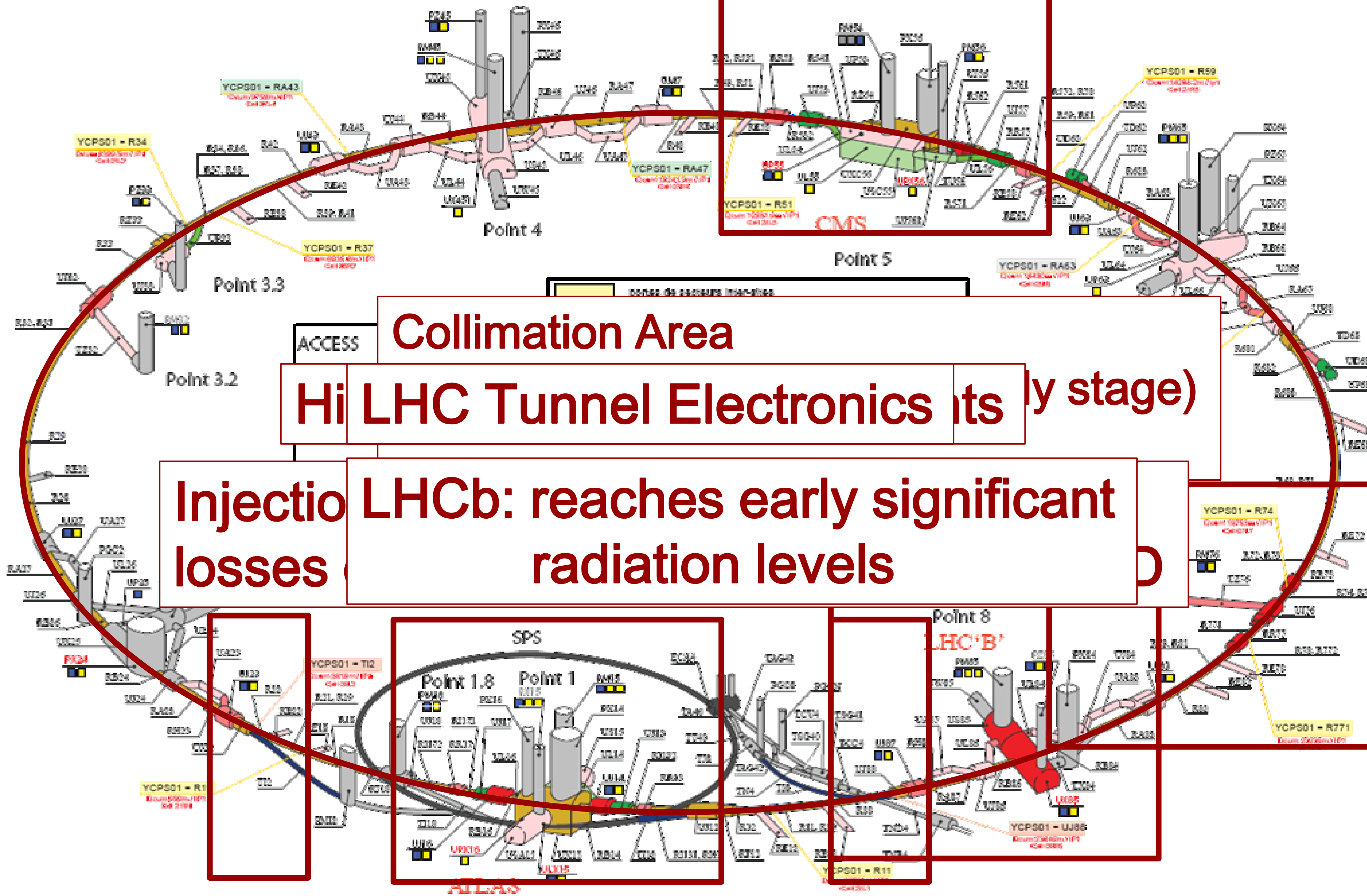
!!!



The LHC Challenge



Critical Area Overview (LHC Machine)



Collimation Area

ly stage)

Hi

LHC Tunnel Electronics

ts

Injectio

losses

LHCb: reaches early significant radiation levels

D

A “Simple” Calculation

- **17 Critical Areas**, *let’s say 15!*
- **10-30 Racks** in each area, *let’s say 20!*
- **1-4 Crates** in each rack, *let’s say 2 sensitive!*
- **10-100 Components** per rack, *let’s say 20 critical!*

-> **~12000 critical components**

(equipment inventory: ~10000 components/system)

- av. device/system **failure cross section: $1x10^{-8}cm^2$**
- av. **radiation levels (nominal): $1x10^8cm^{-2}y^{-1}$**

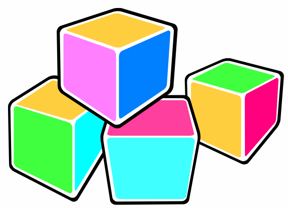
-> 12000 failures per nominal year (MTBF ~1h)

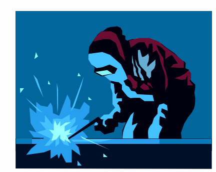
The Mitigation Strategy (R2Ebok)

A "Simple Recipe" to have no Radiation Issues:

- *1* Hand(Cook)book of **Radiation Damage on Electronics**
- *1000l* of **Radiation Levels & Environment** (calculations, measurements, operation)

- *100t* of **Electronics** (Inventory, Failure Modes)
- *1 full bag* of detailed values of their **radiation sensitivity**
- *1000t* of **shielding**
- *2y* of **relocation**
- *4y* of **new developments**
- *a trifle* of **money & people**



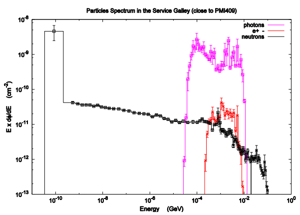


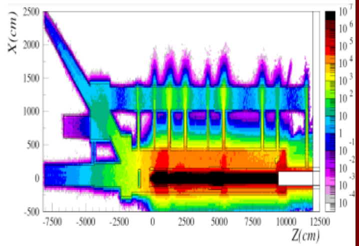
Putting it all together, leaving it for a couple of years,
A dish to be served hot…

The LHC
Radiation Environment

nuclear cascade

h > 20 MeV





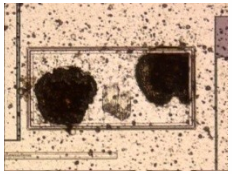
Radiation Field

h, e,.. > 100 KeV

EM cascade

radiation damage in semiconductors

Single Events

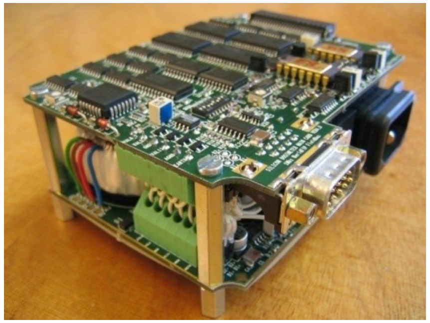


Effect in the Device

Displacement

Dose

Radiation Monitor



SEU counter

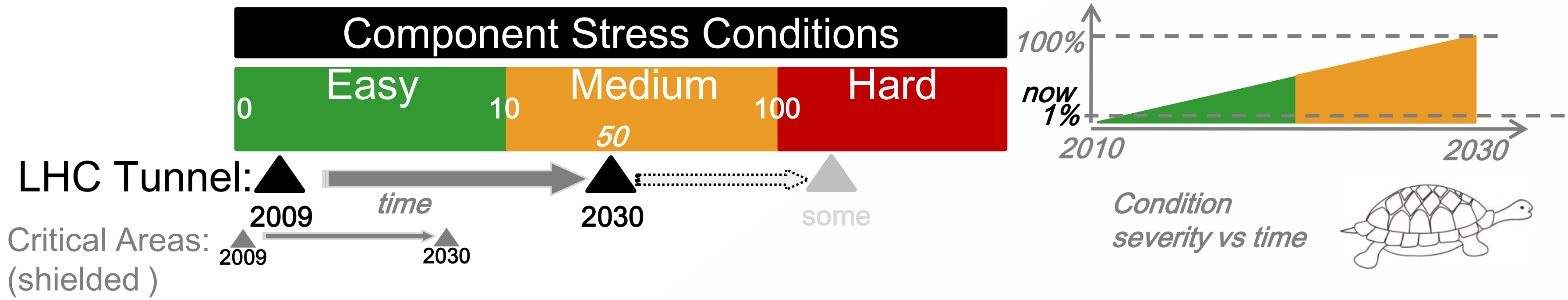
Measurement

PIN Diodes

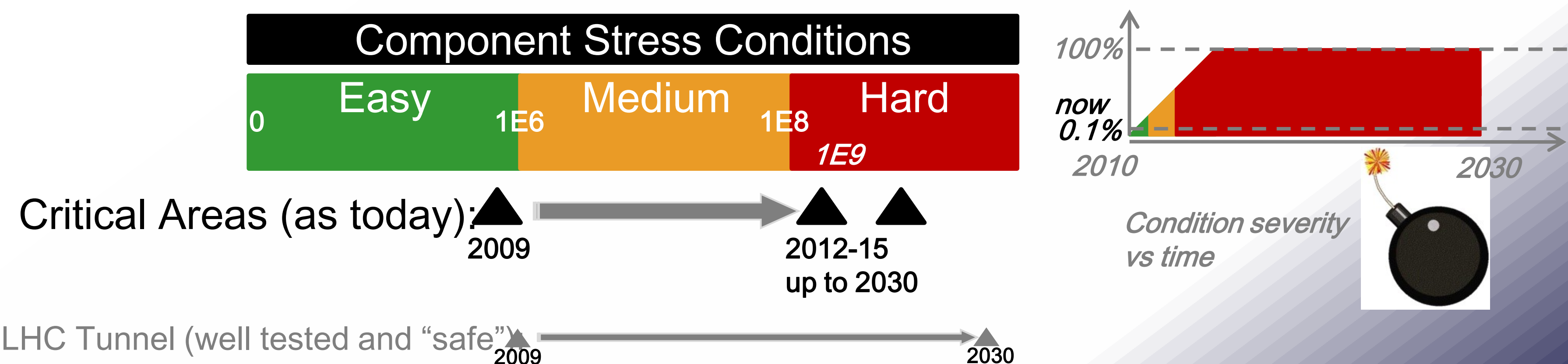
Radfet

Radiation Issues - Effects

- **Total Ionizing Dose (TID) + Displacement Damage (DD)** *Thanks to Y. Thurel*
  - ☺ **Cumulative effect** (Effect will be seen after given time, giving some freedom to react)
  - ☺ **Low stress level** (50 Gy max in 2030 when "standard component" can survive 20-30 Gy)



- **Single Event Effects [SEE]**
  - ☹ **Stochastic Effect** ("Events scale with number of affected components")
  - ☹ **Very High stress level** (Failures observed <$1x10^{7}cm^{-2}$)

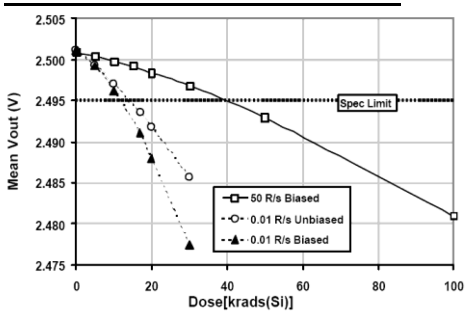


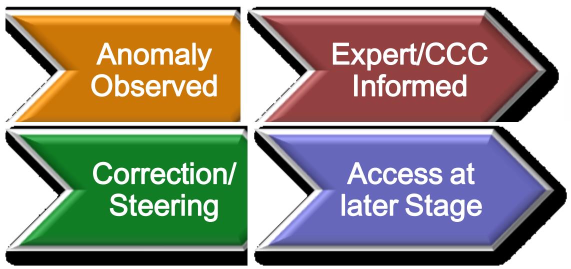
Radiation Issues – Failure Observation

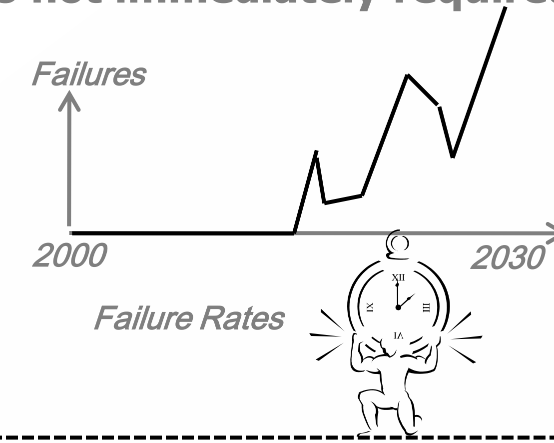
Thanks to Y. Thurel

- **TID + Displacement Damage**
  - ☺ **Devices get slowly out of tolerance (final failure can often be anticipated; access not immediately required)**
  - ☺ **No 'early' failures (due to radiation)**

Possible Scenario:

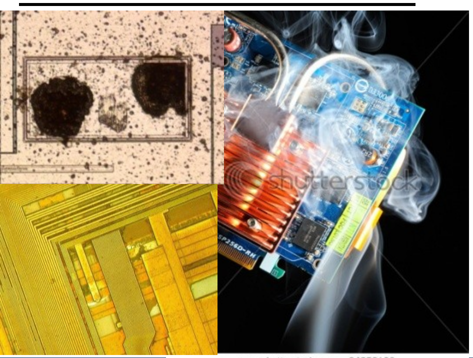


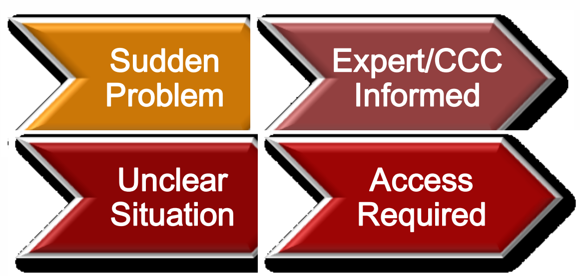


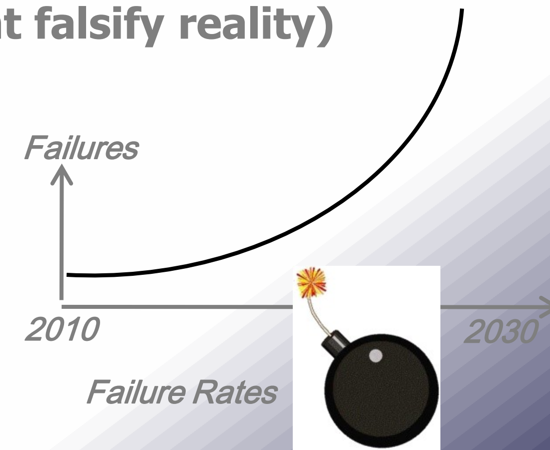


- **Single Event Effects**
  - ☹ **Failures will appear and rapidly increase in frequency (destructive failures possible; access often required)**
  - ☹ **'Early Operation ' problem (observation might falsify reality)**

Possible Scenario:

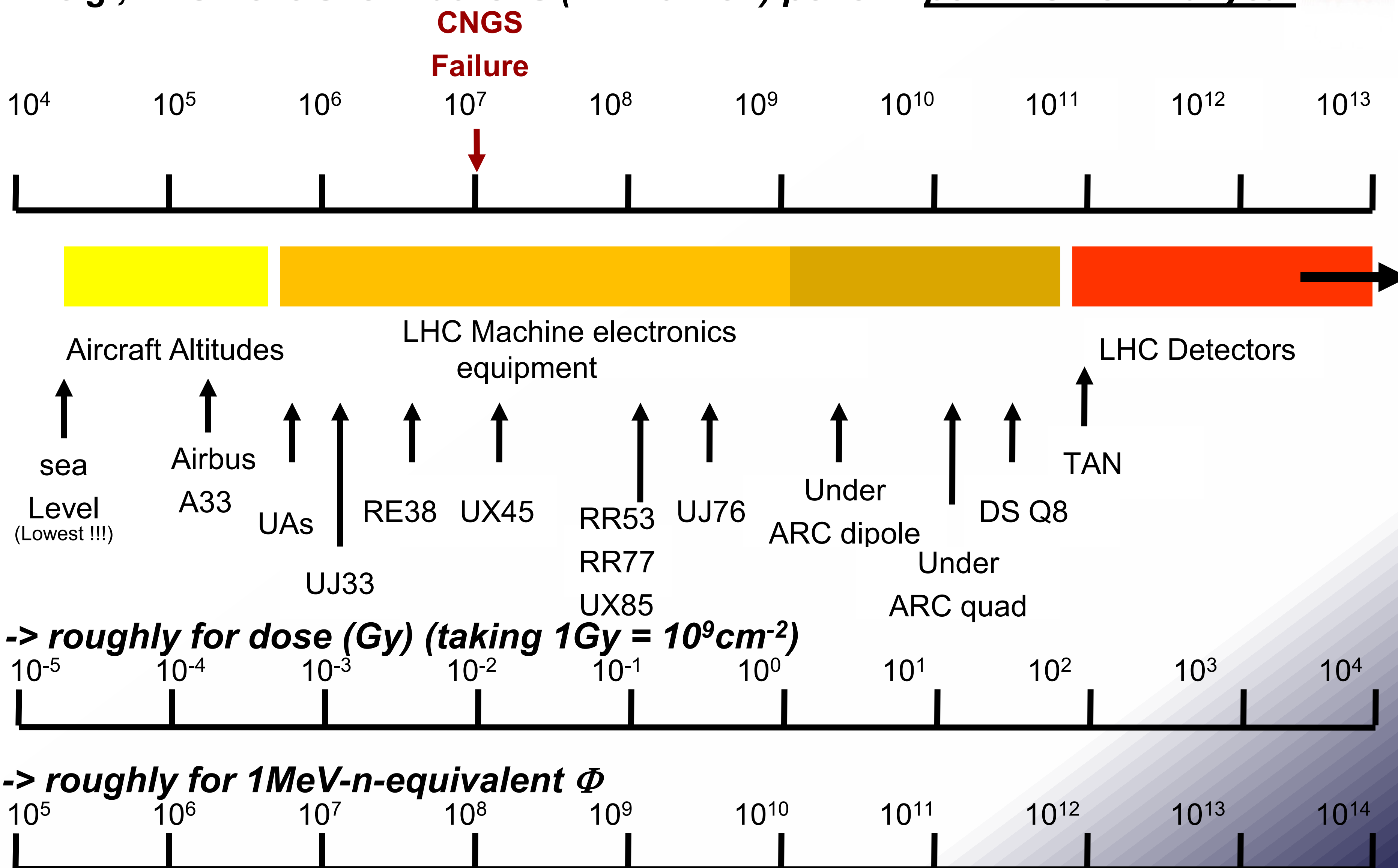






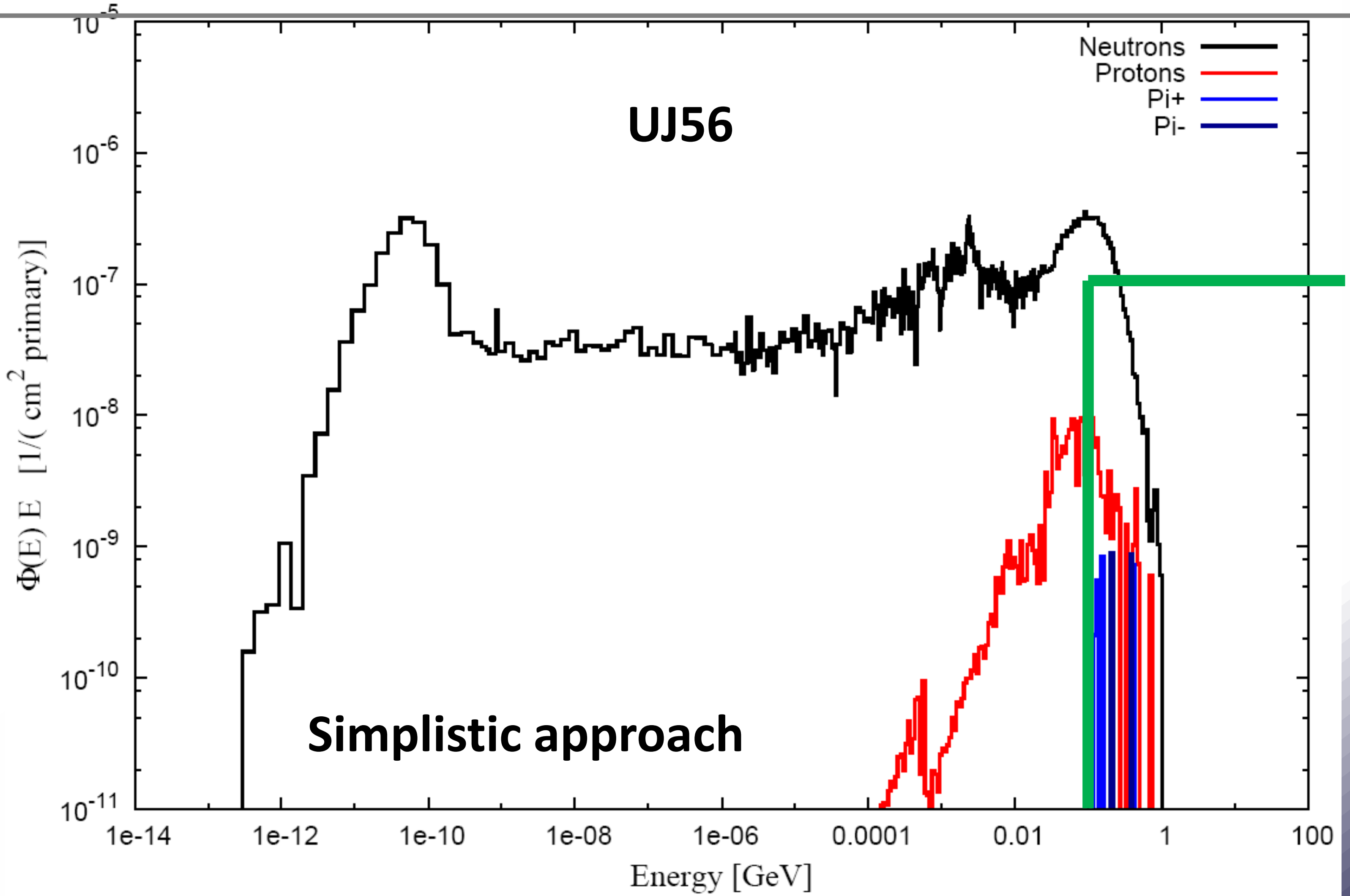
LHC High-Energy Hadron Fluences

e.g., LHC-Levels for Hadrons (E > 20 MeV) per cm² <u>per LHC nominal year</u>



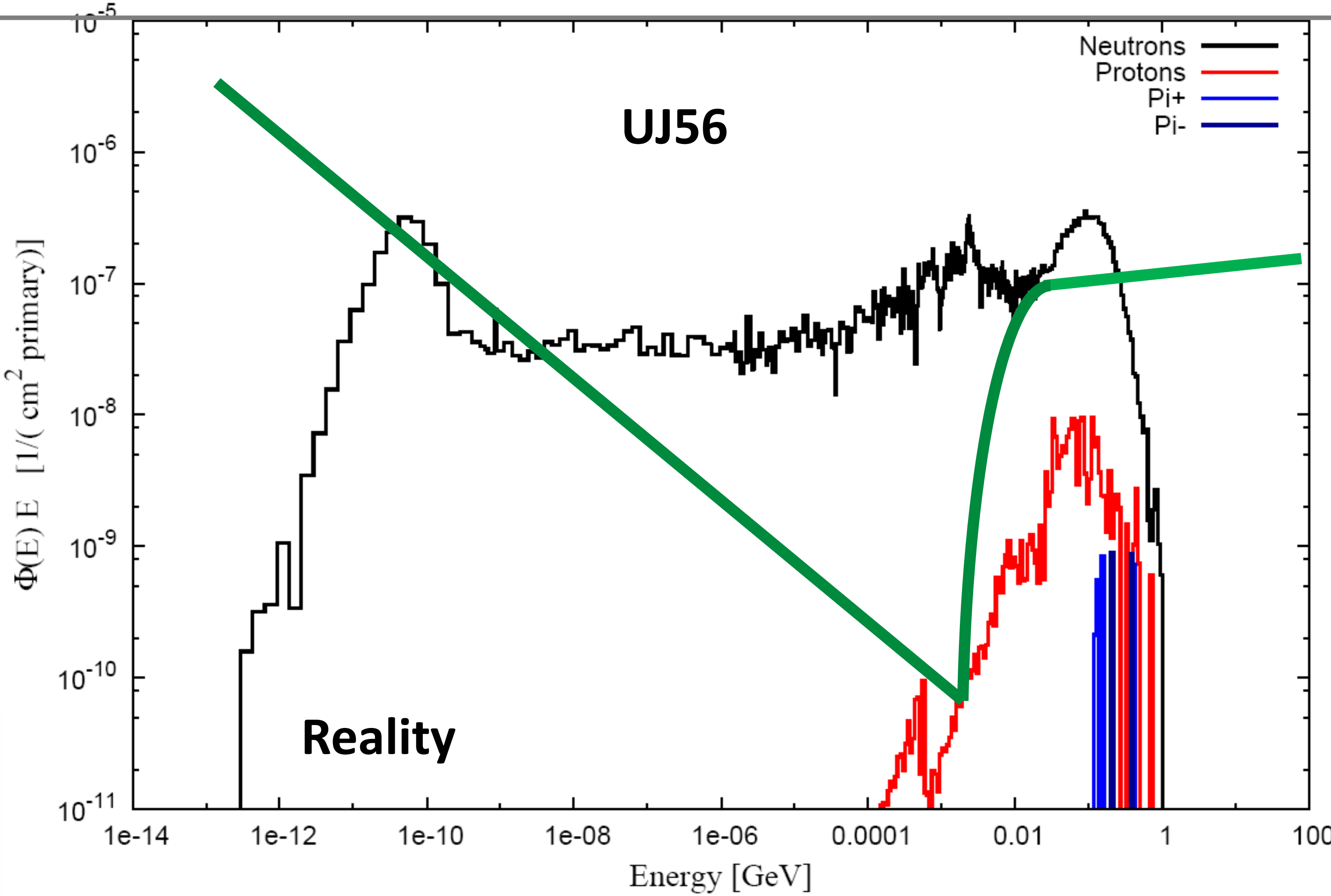
Radiation field and device sensitivity

$$\#SEU = \Sigma(\sigma_{HEH} \cdot \Phi_{HEH})$$



Radiation field and device sensitivity

$$\#SEU = \sum(\sigma_{Th.\,n.} \cdot \Phi_{Th.\,n.}) + \sum(\sigma_{5-20MeV\_n} \cdot \Phi_{5-20MeV\_n}) + \sum(\sigma_{HEH} \cdot \Phi_{HEH})$$



The Risk of Low-Energy Neutrons

❑Having a look in literature

DEVICE SEU CROSS SECTIONS, FROM THERMAL AND HIGH ENERGY NEUTRONS, CURRENT MEASUREMENTS

Part	Type	Vendor	DC/ Feat Size	Hi E SEU X-Sec, cm²/bit§	Therm SEU X-Sec, cm²/bit	Ratio-SEU, Therm/ Hi E
S-1	SRAM	VS-1	0446/0.15μ	2.1×10^{-14}	3.3×10^{-16}	1.6×10^{-2}
S-2	SRAM	VS-1	0446/0.15μ	7.9×10^{-15}	1.7×10^{-19}	2.2×10^{-5}
D-1	DRAM	VD-1	0446/0.15μ	6.4×10^{-17}*	1.3×10^{-15}	20
D-2	DRAM	VD-1	0422/0.13μ	2.95×10^{-16}*	1.18×10^{-16}	0.4
P-1	μprocess	VP-1	0240/0.18μ	1.5×10^{-14}	2.2×10^{-17}	1.5×10^{-3}
P-2	μcont.	VP-2	0439/0.13μ	1.02×10^{-3}†	1.68×10^{-5}†	1.7×10^{-2}
P-3	μcont.	VP-2	0532/0.15μ	6.99×10^{-4}†	6.03×10^{-6}†	8.6×10^{-3}
P-4	μcont.	VP-2	0341/0.18μ	1.54×10^{-4}†	1.34×10^{-5}†	8.7×10^{-2}
P-5	μprocess	VP-3	0311/0.18μ	1.3×10^{-15}	No upsets	0

† In units of Upset/dev-hr ;
* No actual upset detected; cross section based on 1 assumed upset
§ E> 10 MeV

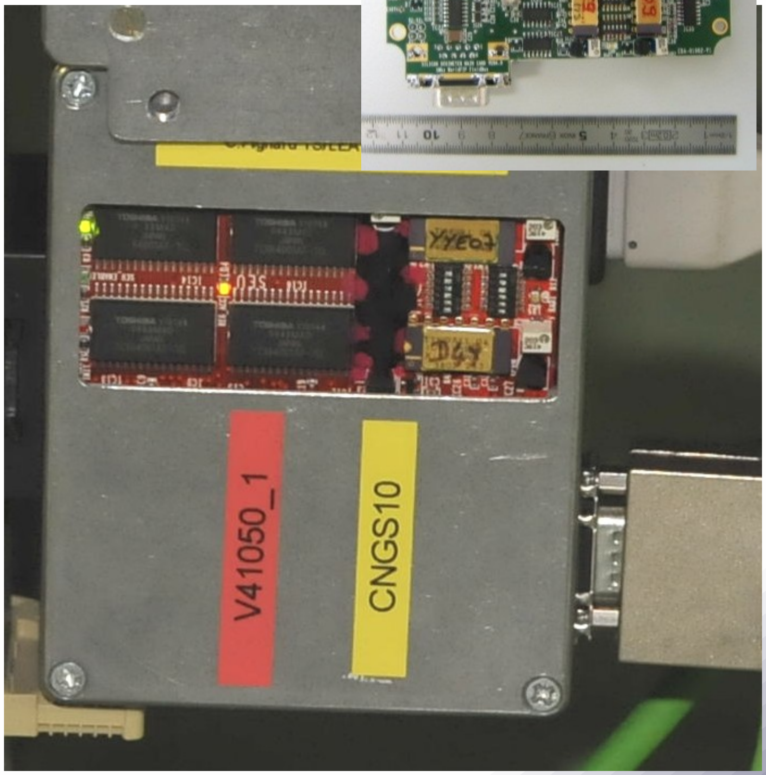
IEEE Trans. on Nucl. Sci., Vol 5, p. 3587-3595

❑Sensitivity ranges over four order of magnitudes

- ❑Some: similar or larger xSection
- ❑Others: a factor of 10-100 or further below

RadMon System in the LHC

- Used for monitoring of radiation close to installed electronic systems
- 3 types of sensors:
  - RadFets (NMRC) for TID
  - PIN diodes for 1MeV n eq.
  - SRAMs for high-E hadron fluence (SEEs)



- System of ~400 online radiation monitors
- Many calibration campaigns recently focusing on the memory and its thermal neutron response and intermediate energy (few MeV) neutrons

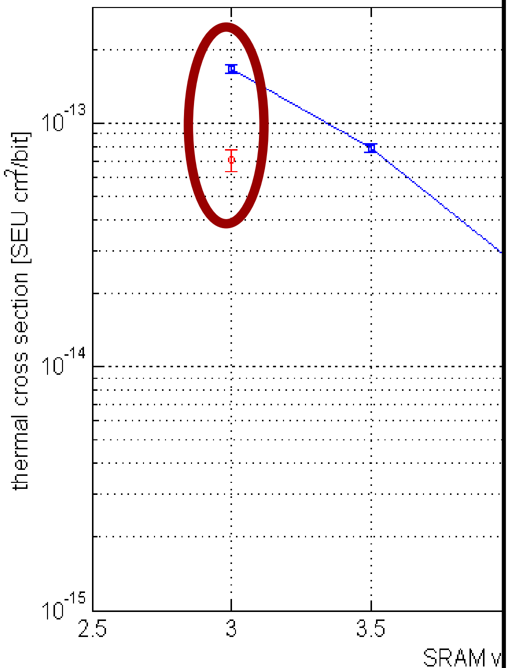
Additional Useful Monitoring

- LHC **Beam-Loss Monitoring System** (BLM)
- **Radiation-Protection Monitoring** (RAMSES)
  - Induced Radiation Monitors (PMIs)
  - Prompt Radiation Monitors (PATs)
- **Passive Monitoring** (installed for R2E and RP Purposes)
  - TLDs in and close to critical areas
  - Early monitoring (prior RadMon lower sensitivity)
  - Good idea about thermal neutron contribution
- **LHC Intensity & Luminosity** Monitoring
- Any other information which can be used…

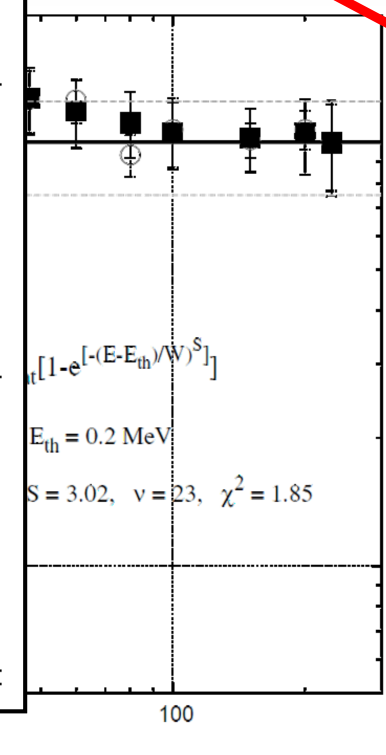
RadMon Calibration

© D. Kramer

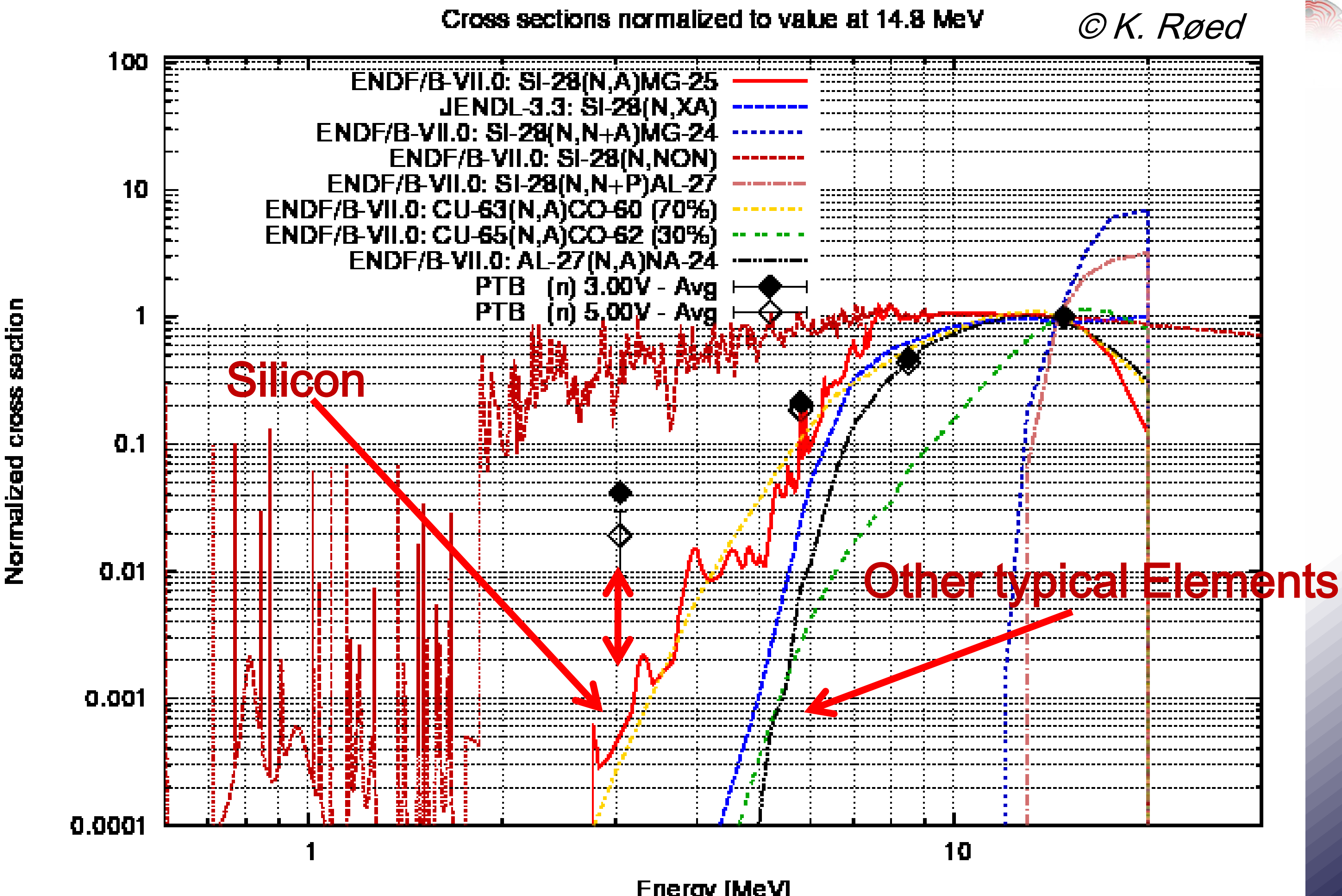
© K. Røed



ID	σ_{SEU} 5V (Err) $[cm^2/bit]$	σ_{SEU} 3V (Err) $[cm^2/bit]$
B1_A	$2.9 \cdot 10^{-14}$ (0.4)	$7.1 \cdot 10^{-14}$ (0.8)
B1_B	$2.1 \cdot 10^{-14}$ (0.3)	$5.6 \cdot 10^{-14}$ (0.6)
B1_C	$3.7 \cdot 10^{-14}$ (0.5)	$8.8 \cdot 10^{-14}$ (1.0)
B1_D	$3.1 \cdot 10^{-14}$ (0.4)	-
Average	$3.0 \cdot 10^{-14}$ (0.4)	$7.2 \cdot 10^{-14}$ (0.5)
B2_A 2	$2.2 \cdot 10^{-14}$ (0.3)	-
B2_B 3	$2.0 \cdot 10^{-14}$ (0.3)	-
B2_C 5	$2.4 \cdot 10^{-14}$ (0.3)	-
B2_D 6	$2.5 \cdot 10^{-14}$ (0.3)	-
Average	$2.3 \cdot 10^{-14}$ (0.3)	-



It's not only Silicon



CERF Benchmark

Location	RadMon [Error]	FLUKA [Error]	Ratio (R/F)
Pos1	3.77×10^{-4} [20.0%]	$4.17 \times 10^{--4}$ [5.1%]	0.90
Pos2	5.76×10^{-4} [20.0%]	5.76×10^{-4} [4.6%]	1.00
Pos3	1.99×10^{-3} [20.0%]	1.97×10^{-3} [2.8%]	1.04
Pos4	1.75×10^{-3} [20.0%]	1.71×10^{-3} [3.4%]	1.02
Pos5	1.53×10^{-3} [20.0%]	1.67×10^{-3} [3.2%]	0.92
Pos6	2.19×10^{-3} [20.0%]	2.19×10^{-3} [2.9%]	1.00

CNRAD Test Area "Benchmark"

Location	RadMon [Error]	FLUKA [Error]	Ratio (R/F)
TSG45	1.9×10^{-7} [20.0%]	2.1×10^{-7} [5.7%]	0.9
TSG46	2.0×10^{-8} [20.0%]	1.9×10^{-8} [6.8%]	1.05

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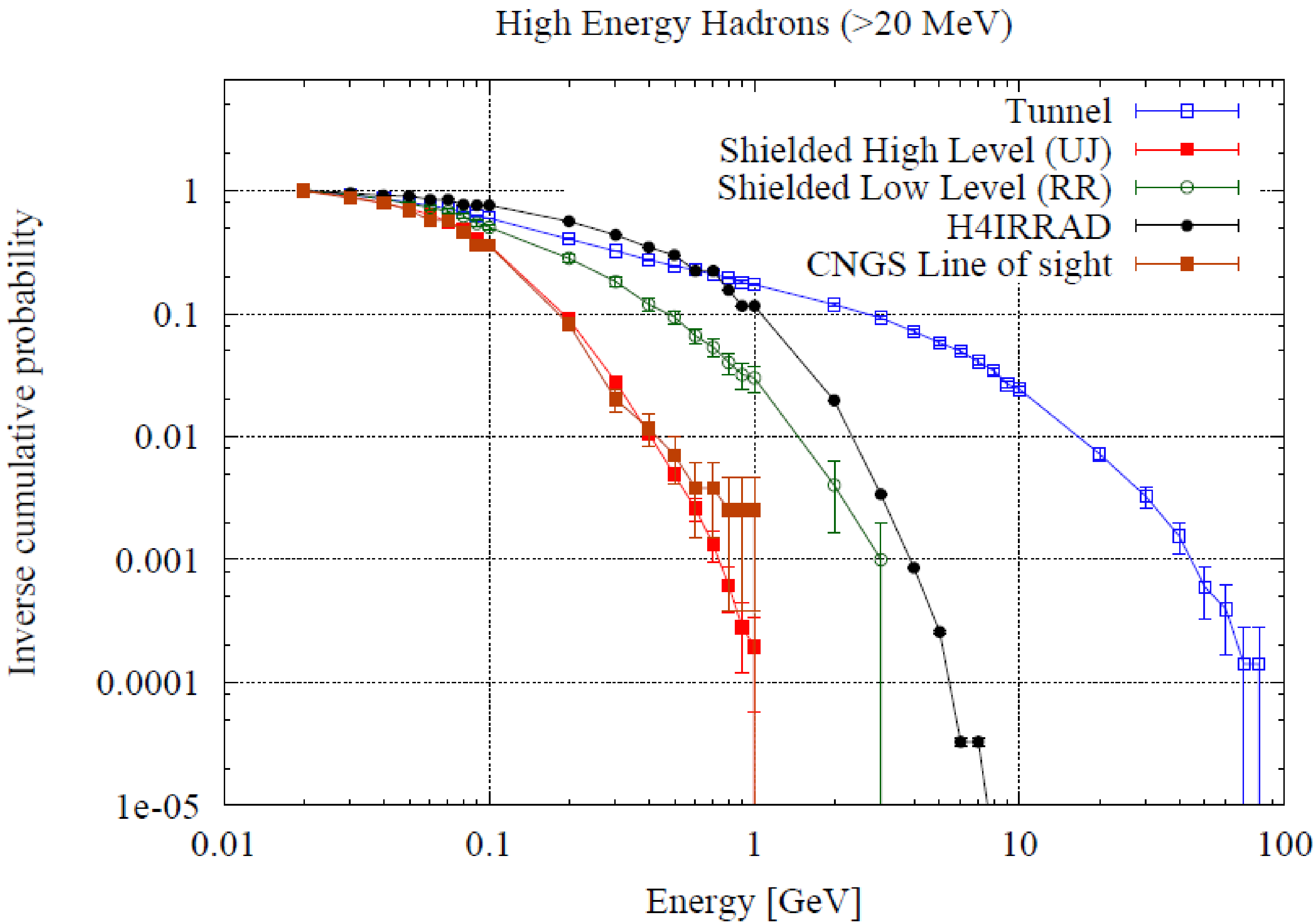
Radiation Test Requirements:

- Is PSI testing (combined with CNRAD) sufficient?



Radiation Levels & Our Confidence in Their Prediction

(strong efforts from the FLUKA Team

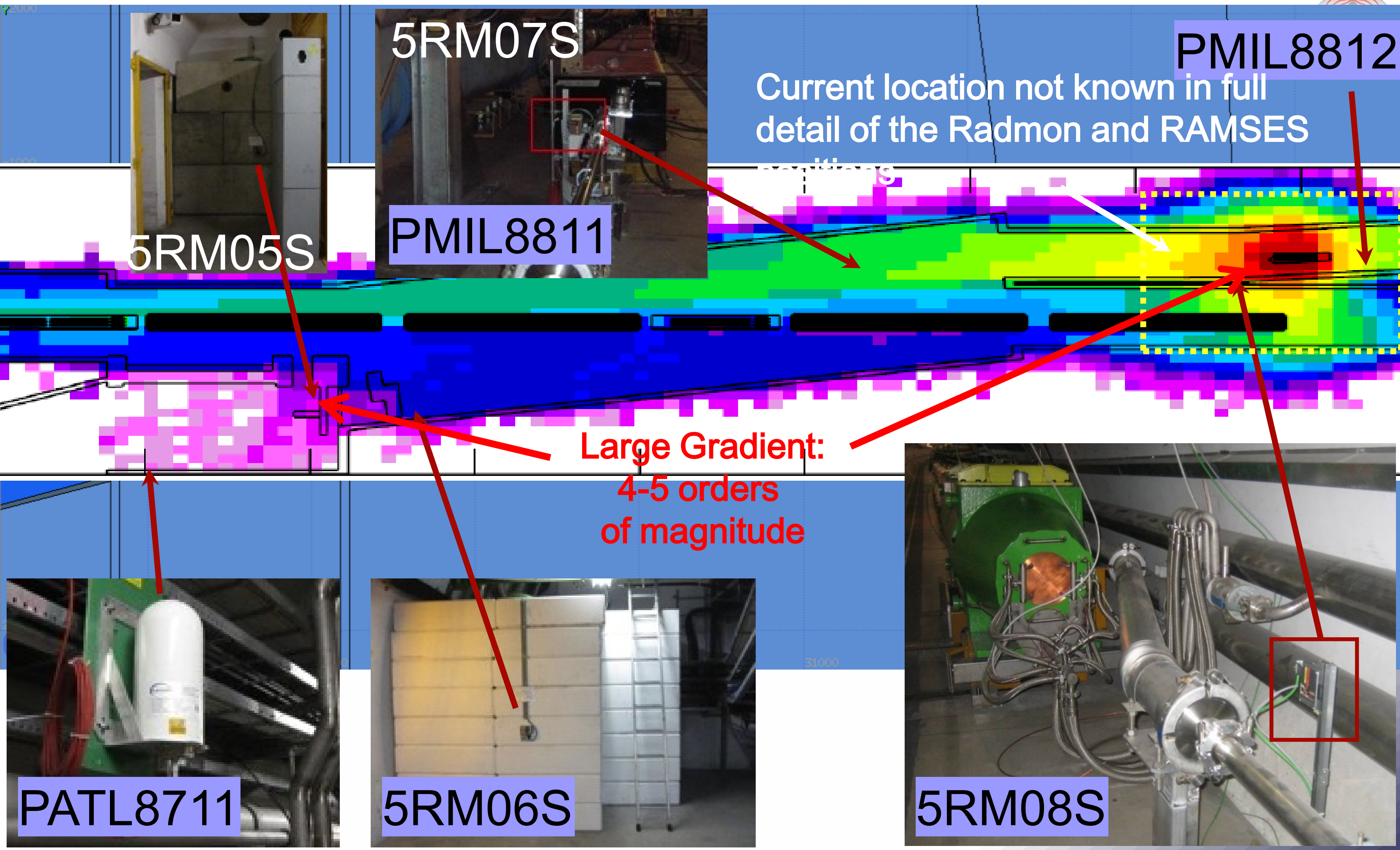
Confidence: FLUKA Calculations

Location	Monitors	Source	Agreement	Comments
CERF, CNGS, ...	RadMon, RAMSES, TLDs	Beam on target	Within 10-20%	Benchmark setup
TI2/8	RadMon	Controlled loss on TED and TCDI	Within 30%	Source term well controlled
UX/US85	RadMon, RAMSES	LHCb collissions	Within 30-50%	Detector update required
IR7/UJ76/RR77	RadMon	Losses on Collimators	Mostly within a factor of two	Very sensitive on loss distribution
IR1/5	RadMon	Collisions	Within a factor of 2-3	Only QUALITATIVE check

Uncertainty: Dominated by the source term and the considered details!

IP8/TI8 Radiation Detectors

© V. Boccone



TED Loss: RadMon Downstream

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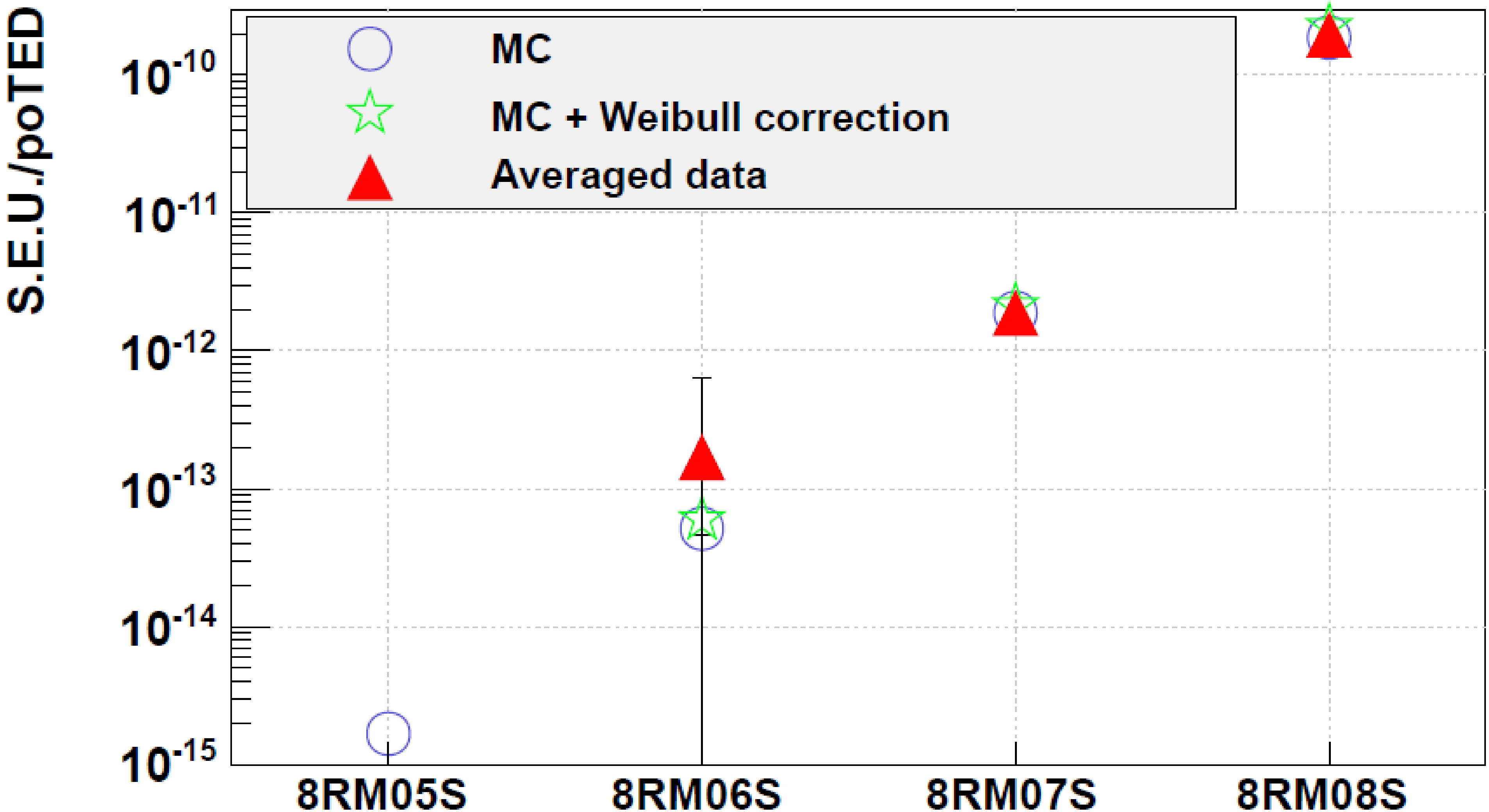
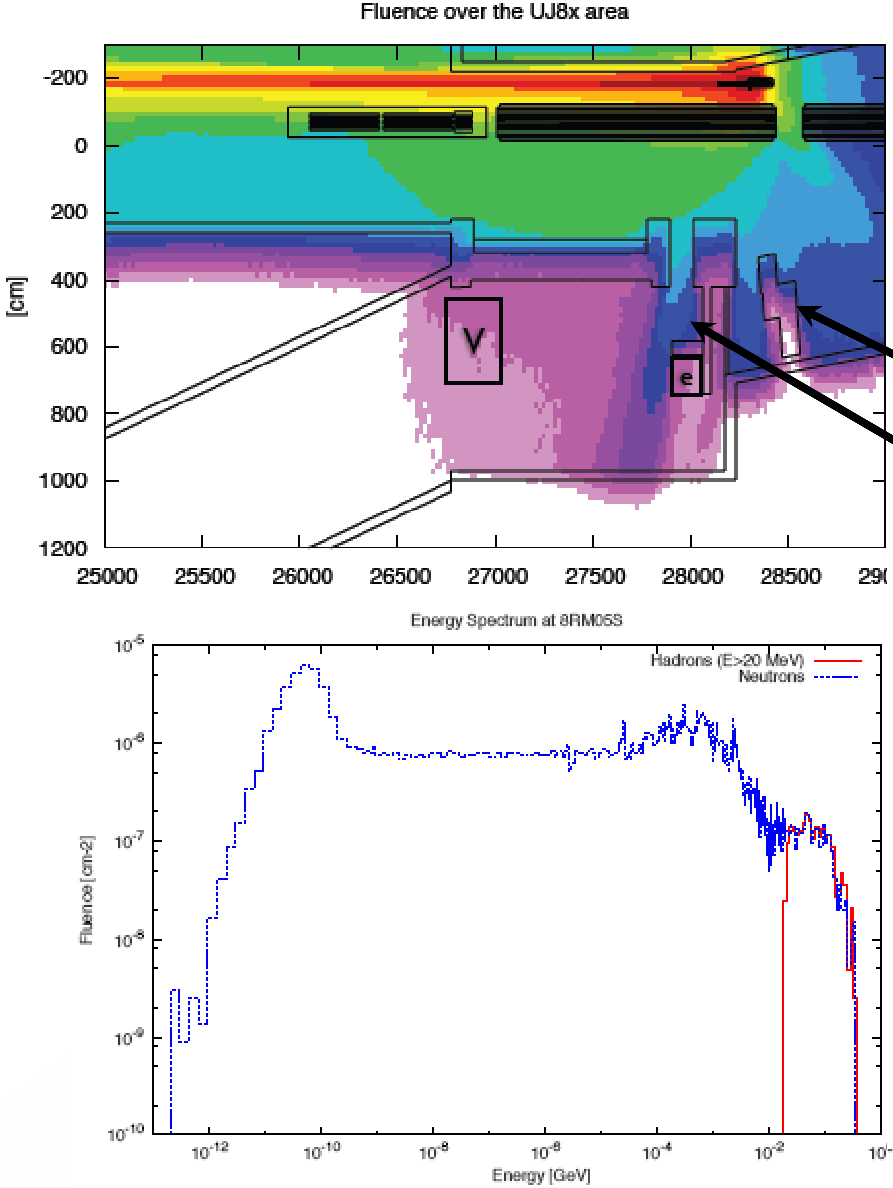
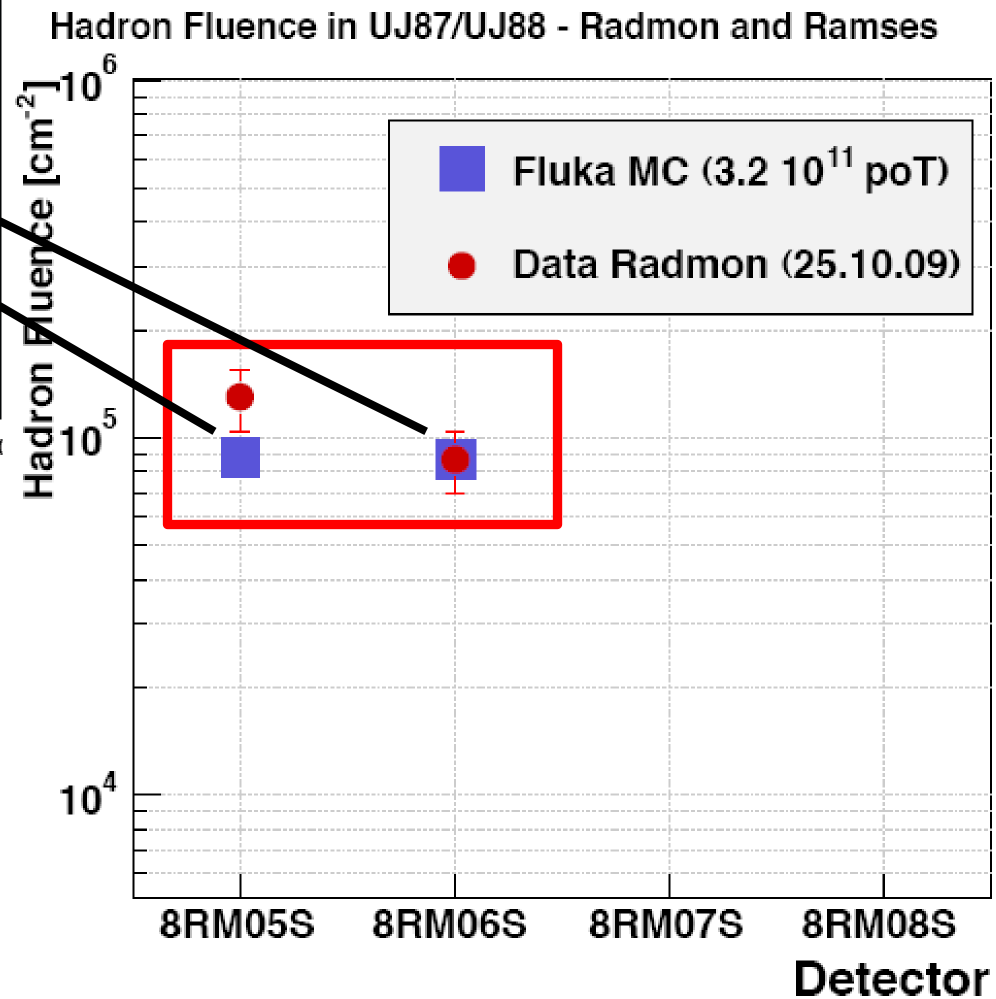


UJ87: Loss on TCDIH.87904

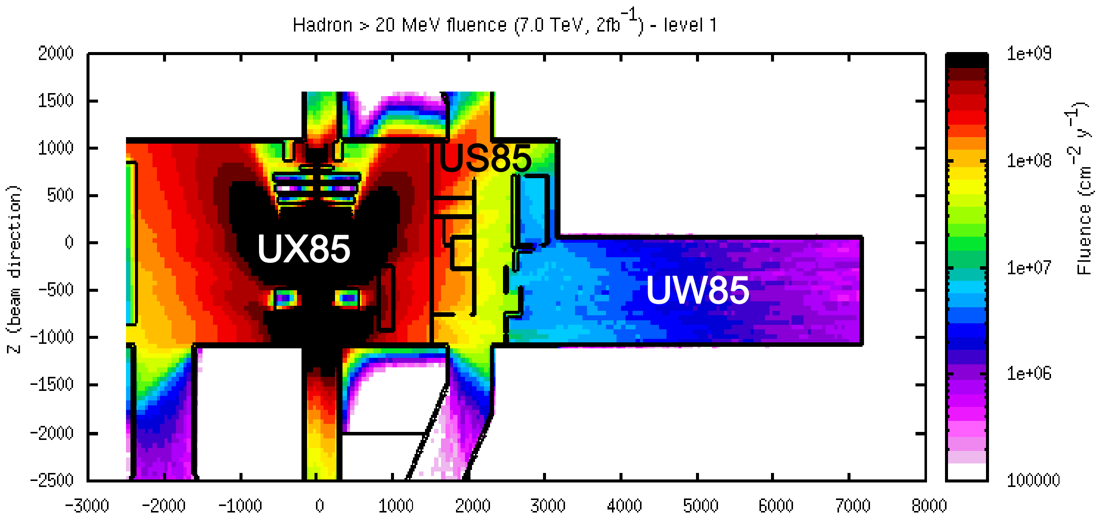
© V. Boccone





Point-8 Application Benchmark

© M. Calviani



FLUKA/RAMSES benchmark

Detector	Measured dose (μSv/h) @10.6MHz	Ratio (meas/simu)
PMI8501 (UX85)	24.0	1.1
PMI8511 (UX85)	120.0	0.8
PAT8511 (US85)	36.7	0.6

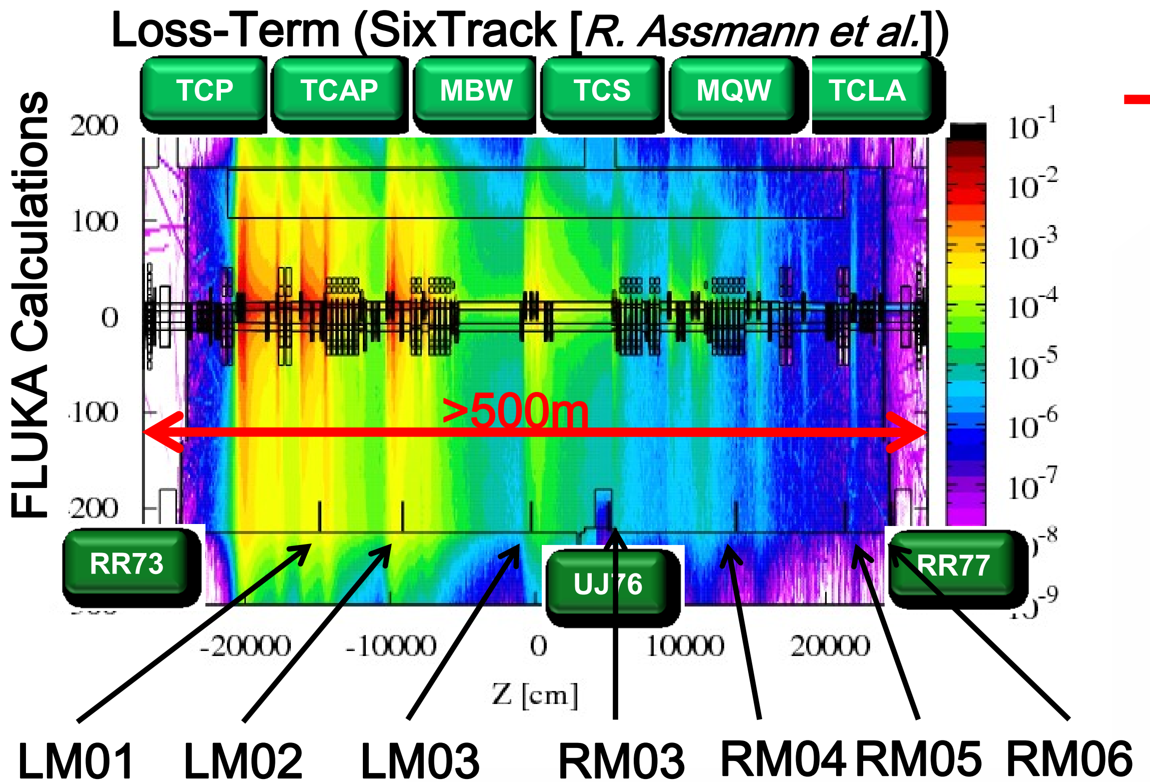
FLUKA/RadMon benchmark

Detector	Ratio (FLUKA exp/measure)
8LE10S	1.6
8LE07S	2.0
8LE04S	1.6
8LE08S	2.2

FLUKA Simulations provide high energy hadron fluence, dose and 1 MeV Si equivalent in the LHCb cavern according to the Phase-2 shielding implementation proposed in the R2E Project

- Very good agreement with PMIs and PATs RAMSES detectors
- RadMons set at 3V more difficult (at low count rates)
- Significant uncertainties to be considered (thermal neutron contribution, detector geometry, etc…)
- Uncertainty at least a factor of 2

IR7 FLUKA Application Benchmark



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→ Assumptions

↓

Normalisation

RadMon	Dcum	Rth	SEU (3V) Measured	Beam contribution	SEU (FLUKA) Expected	Error [%] Stat. only	Exp./Mes.
6L7.7**LM03**S	19846	5	14401	**B1**	15015	3	**1.04**
5L7.7**LM02**S	19904	3	5253	**B1**	9765	3	**1.86**
4L7.7**LM01**S	19991	5	2689	**B1+B2**	3116	6	**1.16**
4R7.7**RM03**S	20045	3	950	**B1+B2**	401	6	**0.42**
5R7.7**RM04**S	20133	5	18727	**B2**	13032	4	**0.70**
6R7.7**RM05**S	20208	31	303	**B2**	962	8	**3.17**
RR77.7**RM06**S	20241	1	13	**B1+B2**	17	22	**1.33**

Summary (Protons)		
In	6.02E+15	
Dumped	5.82E+15	96.70%
Lost in Machine	1.99E+14	3.30%
Of Lost protons		
Collisions	2.33E+13	11.73%
Elsewhere	1.76E+14	88.27%

BLM ratio IR7 / IR3	**Ratio**	**% Loss in IR7**
TCSG.A6L7.B1 / TCSG.5L3.B1	3.1	**76**
TCSG.A6R7.B2 / TCSG.5R3.B2	5.6	**85**

Radiation Levels 2010

- Source terms, operational conditions as well as monitor readings have to be carefully evaluated

Tracking/BeamGas/etc. → FLUKA Predictions → Operation Assumptions → Rad-Level Estimate → Monitor Readings → Calibration Assumptions → Final Values

Threshold of monitors is ~10^6!

(lower values only by 'trick' [big uncertainties!])

VERY GOOD AGREEMENT (given the underlying uncertainties)

	FLUKA & Operation		MEASUREMENTs	
	2010 using 2009 estimations	2010 with actual operation	2010 with RadMON (FLUKA r)	2010 with RadMON (TLD r)
UJ14 UJ16	2.5E+06	1.3E+06	1.6E+05	1.1E+06
RR13 RR17	5.0E+05	2.5E+05	1.0E+05	6.2E+05
UJ56	2.5E+06	1.3E+06	2.1E+05	
RR53 RR57	5.0E+05	2.5E+05	1.0E+05	6.2E+05
UJ76	6.9E+06	1.1E+06	5.9E+05	2.1E+06
RR73 RR77	3.4E+06	5.7E+05	2.1E+05	3.1E+06
UX85b	1.0E+07	1.3E+07	4.8E+07	1.0E+07
US85	5.0E+06	6.3E+06	3.6E+06	2.9E+06

2010/2011/20

	FLUKA & Operation		ME
	2010 using 2009 estimations	2010 with actual operation	2010 Radi (FLU
UJ14 UJ16	2.5E+06	1.3E+06	1.6E
RR13 RR17	5.0E+05	2.5E+05	1.0E
UJ56	2.5E+06	1.3E+06	2.1E
RR53 RR57	5.0E+05	2.5E+05	1.0E
UJ76	6.9E+06	1.1E+06	5.9E
RR73 RR77	3.4E+06	5.7E+05	2.1E
UX85b	1.0E+07	1.3E+07	4.8E
US85	5.0E+06	6.3E+06	3.6E

!!! Amazing !!! Close t

Electronics & Radiation Sensitivity

Equipment Groups Performing Tests

Detailed Tests (Past & Present) [mostly tunnel equipment]:

- **Cryogenics Equipment:** problems found and corrected (tests ongoing)
- **Interlock Controllers:** hard design of tunnel card, worries with control
- **Beam-Loss Monitoring:** tunnel equipment seems working fine
- **Beam-Position Monitoring:** failure xSection known -> acceptable
- **Quench-Protection System:** hard design, problem with ISO150
- **WorldFip:** radiation tolerant design, improvements performed
- **Power Converters:** very complex, see next slides
- **Survey Equipment:** thorough design
- **Current-Lead Heaters:** problems identified

Check of commercial equipment in critical shielded areas (Recently)

- Numerous systems tested, see quick overview later

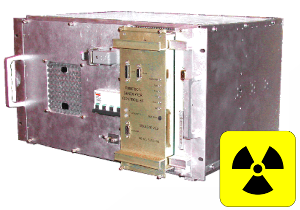
LHC POWER CONVERTERs

© V. Montabonnet, Y. Thurel

- Minimize the number of converter types:
  - Only the LHC60A-08V was specified for a radioactive environment !
  - 3 other converter types are part now of the radioactive sensitive areas!

LHC60A-08V
4-Quadrant

752 Units



Units : Quantity in all machine (UA, RR, UJ, tunnel)

LHC120A-10V
4-Quadrant

300 Units

LHC600A-10V
4-Quadrant

400 Units

LHC4..6kA-08V
1-Quadrant

200 Units

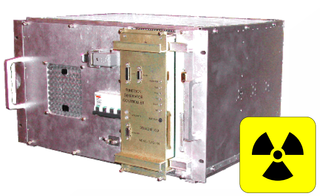
LHC POWER CONVERTER STRATEGY

© V. Montabonnet, Y. Thurel

- Separate out the subsystems that are acceptable by industry
- Place development and production contracts



- Design and build prototypes of remaining subsystems. Place production contracts



- Assume system integration responsibility
- Integration and test at CERN before installation
- Only equipment installed directly in the tunnel was tested

PCs: What was tested and where?

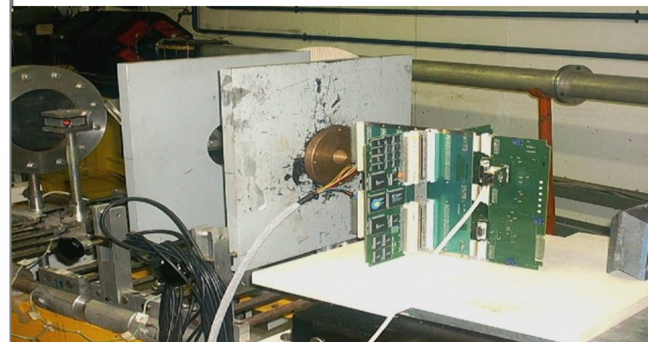
© Y. Thurel, Q. King

LHC60A-08V

FGC

PSUs

LOUVAIN (2003 - FGCs)

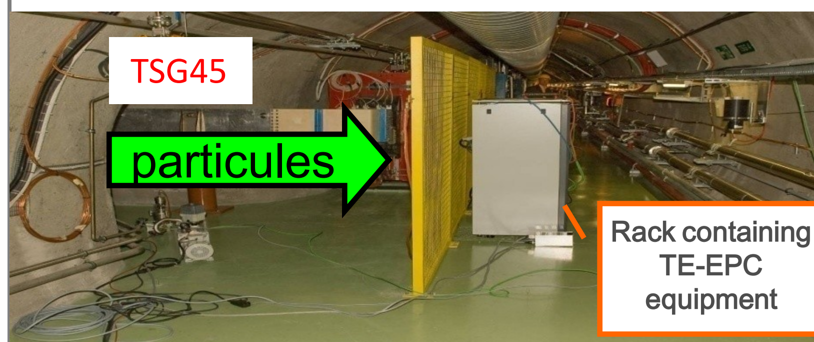


60 MeV proton components tests

PROSPERO (2009 - FGCs)

1MeV neutron displacement damage tests

CNGS (2008..2009 – FGCs, 60A, PSUs)

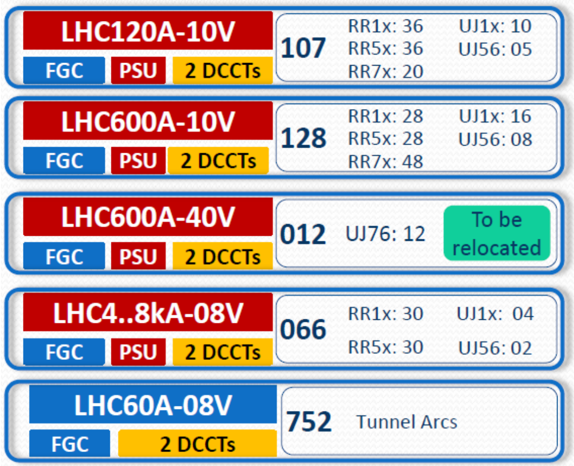


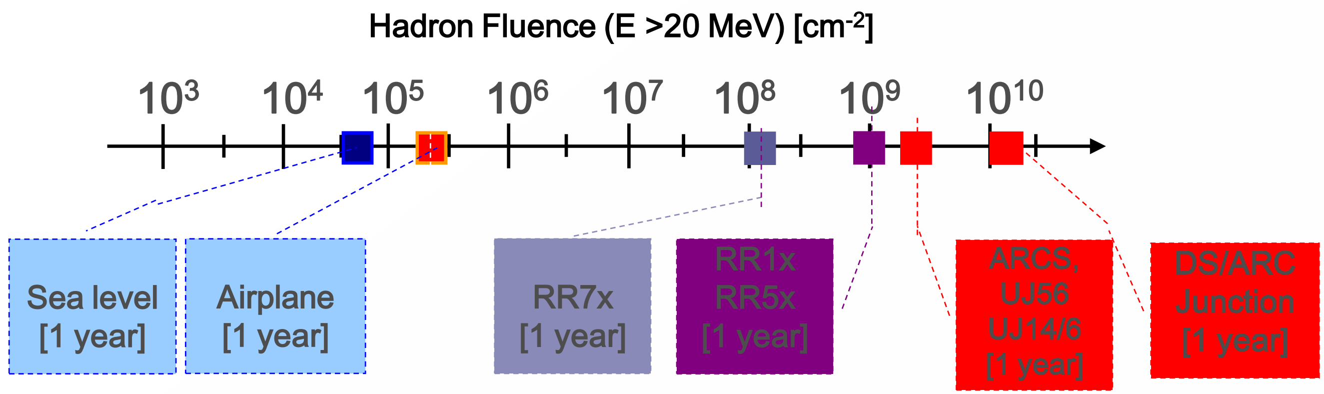
LHC-Environnement System Test

What was not tested

© Y. Thurel, Q. King

- All non 60A-Power-Converters





  - Consisting of a multitude of different components (partly high-power) (details available through dedicated review:)

- Latches, Burnout's at higher energies (until recently @ CNRAD)
- Thermal Neutrons
- Total dose using Gammas
  - With the exception of some WorldFIP components, for the Power-Converters components were never checked for TID

CNGS Radiation Test Area

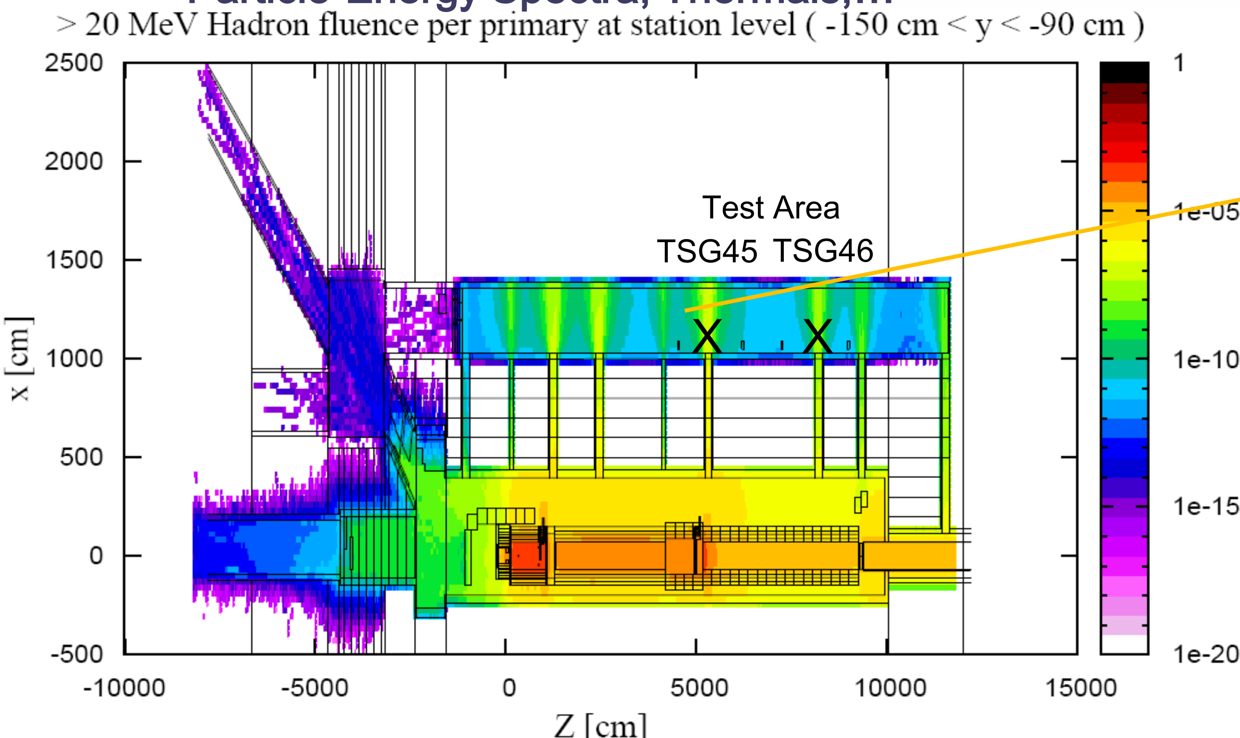
Mixed radiation fields similar to the ones expected in LHC

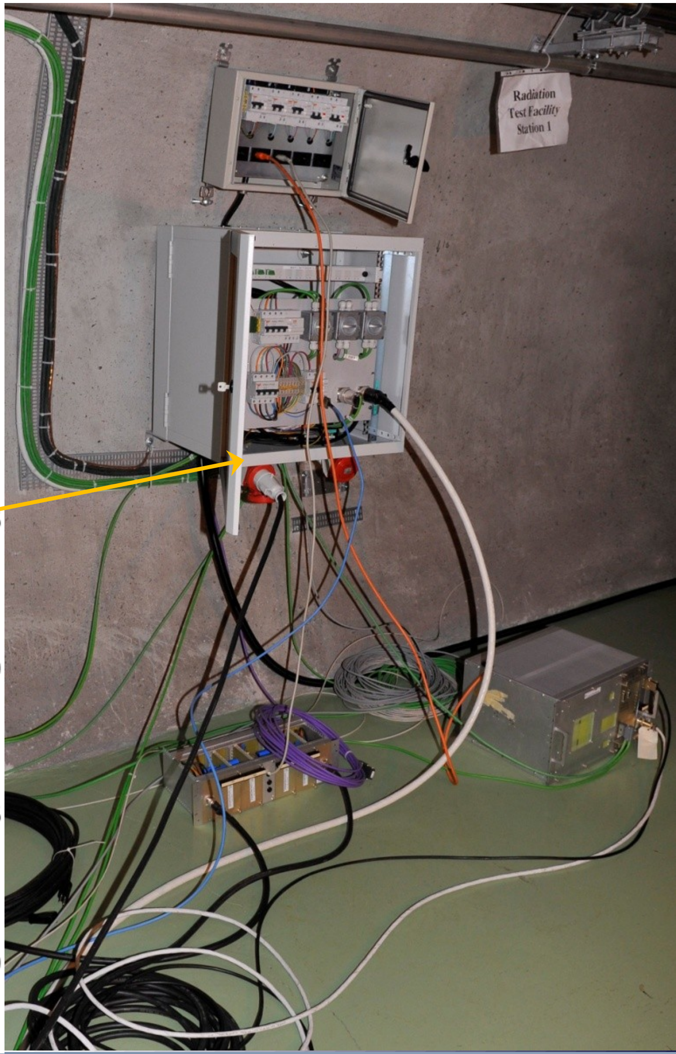
Extensive Monitoring:

- RadMons
- Compared to BLMs
- +GoldFoils, TLDs,…

Detailed FLUKA Simulations for:

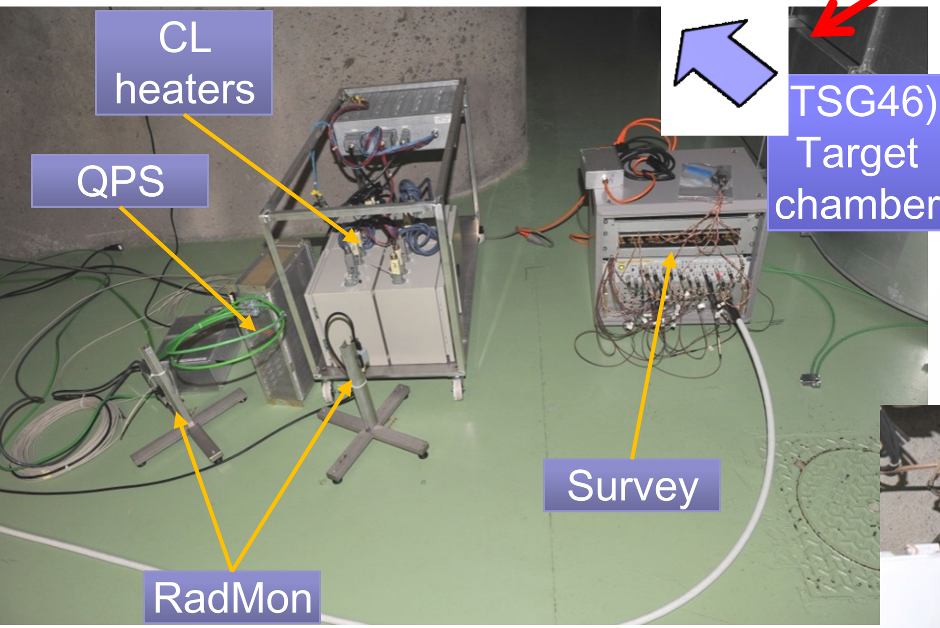
- TID (air), Hadron>20MeV fluence
- 1MeV neutron-equivalent fluence
- Particle-Energy Spectra, Thermals,…



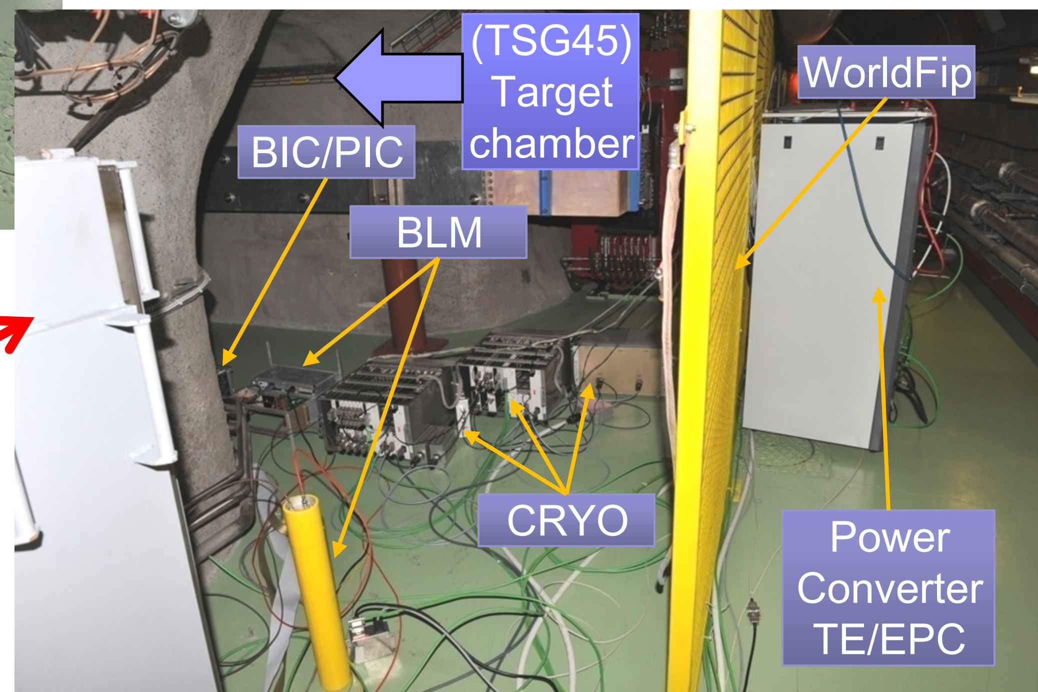


2009 CNGS Tests (Examples)

Test Area in TSG46:
~ 3 Gy (SiO_2)/week
~ $2x10^{10}$(>20MeV) cm^{-2}/week



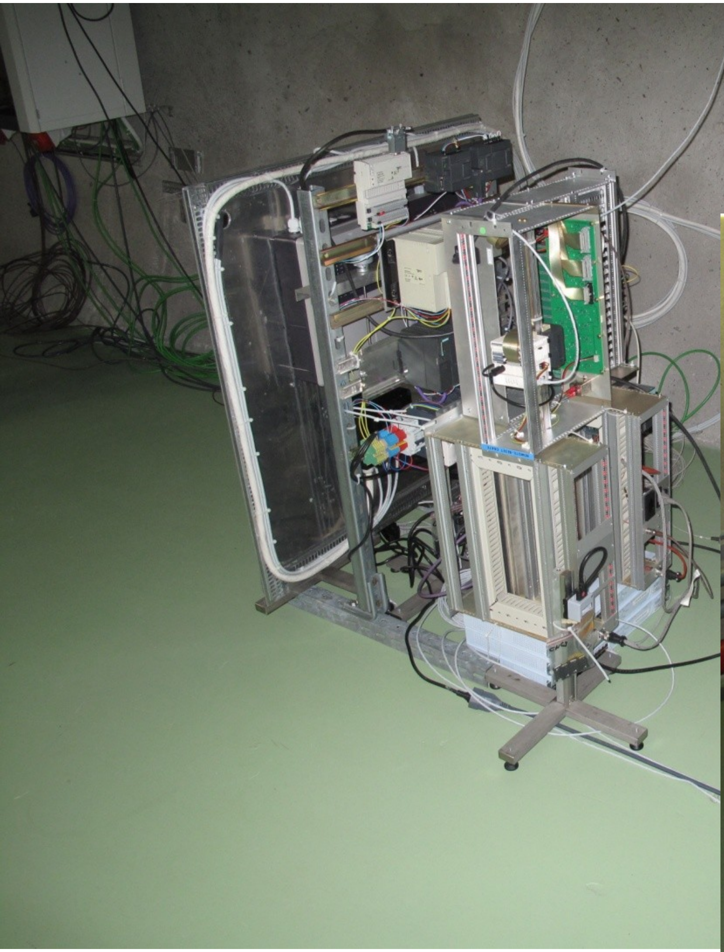
30 Gy are expected in the LHC Arcs Locations (PCs) in ~3-4 nominal years (~5-10Gy/y)

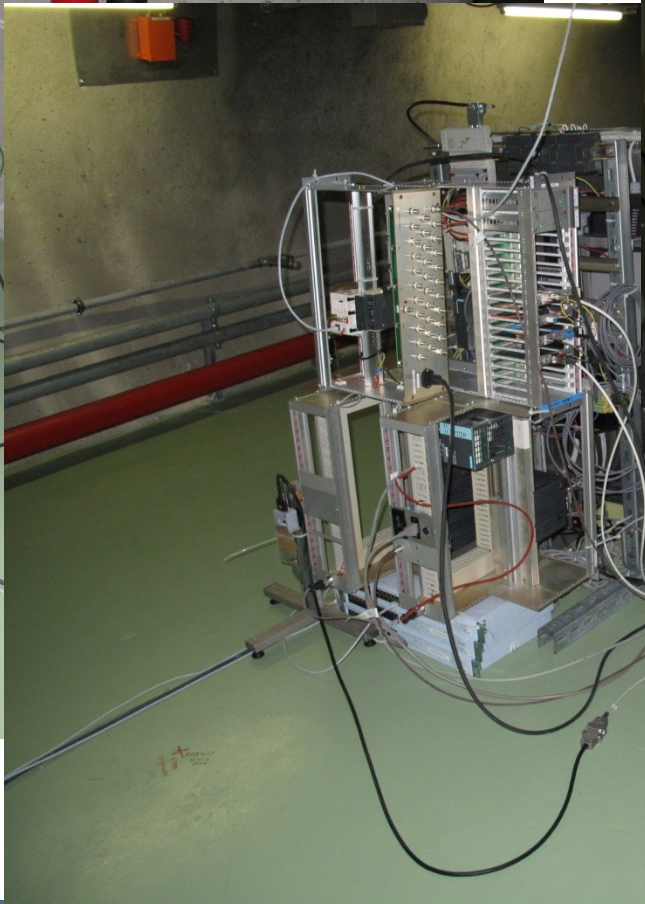


Test Area in TSG45 :
~ 30 Gy (SiO_2)/week
~ 2 10^{11}(>20MeV) cm^{-2}/week

2010 Test Challenge

- CNRAD, some pictures: The ‘Tower of Pisa’





Equipments: CNRAD Update

Tested Equipment:

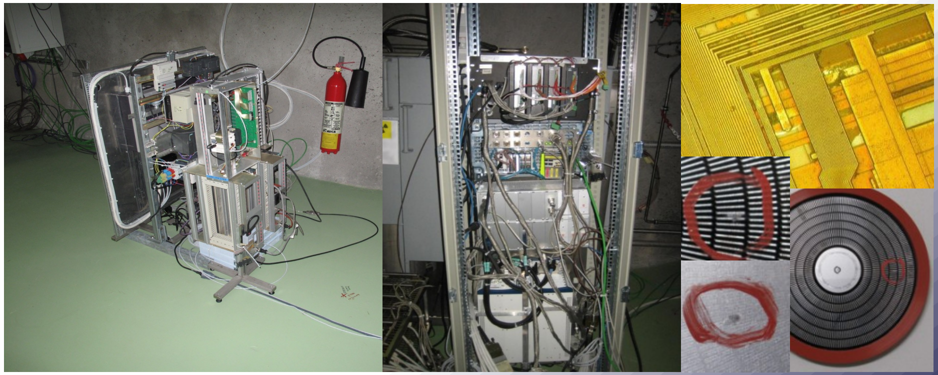
Failure xSection:

- **PLC-S7-200 (CV)** [profibus lost, reset needed]: 1.8×10^{-7} cm^2 → ~200 failures in a nominal year in UJ14/16
- **24V DC Power Supply (CV)** [burned]: 1.1×10^{-8} cm^2
- **PLC-S7-300 (CV)** [blocked, reset needed]: 7.8×10^{-8} cm^2
- **PLC-Schneider (CV)** [PS burned]: 1.1×10^{-7} cm^2
- **WIC Rack** [beam dump and access]: PLC S7-300 + FM352-5 Siemens: 1.1×10^{-7} cm^2
- **Fire Detectors ASD** [power cycle]: 1.0×10^{-9} cm^2
- **Ethernet Switch** [blocked, reset needed]:

  …

"Reset Req.": 1 every 10^{7}-10^{10}cm^{-2}

"Damaged": 1 every 10^{8}-10^{11}cm^{-2}



Uncertainty: up to one order of magnitude (but both directions!)

© D. Kramer

Possible SEE Failures Observed in 2010

CONFIRMED or very LIKELY

WIC crate failure in TI8
Observed in 2009
Known problem with moderate x-section

QPS Tunnel Card Failures
(2x in 9L7 [ions], 2x in 8R8 [inj.], + others)
ISO150 -> permanent PM trigger
SEE confirmed (EMC has same effect)

QPS tunnel Card Failures
in 9R7 & 9L7
uFip communication lost (2x)
SEE confirmed (seen in CNRAD)

CRYO tunnel card SEE in 8L2
1 Fault in uFip
(as observed in CNRAD 2010)
SEE confirmed

TE/EPC power supply burnout in UA87
Same effect observed in CNRAD
SEE is very likely the cause
(Streaming through Maze)

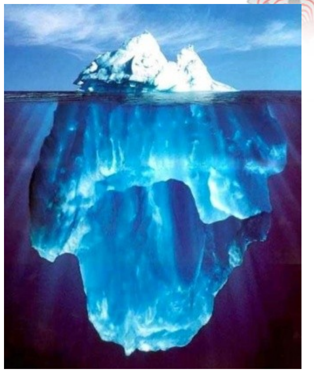
NOT CONFIRMED (unlikely)

VAC power supply burn out
In UA23 between maze and duct
(TDI losses + TCDI losses)
SEE rather unlikely

~~**PXI power supply burnout in UJ16**~~
~~To be confirmed by producer~~
~~(comparison with CNRAD burnouts)~~
~~SEE unlikely (early 2010 operation)~~

What's Coming Next?

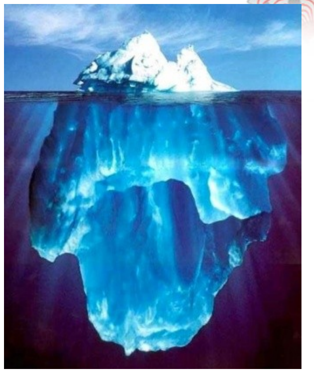
Single Event 2010 Review



– **Levels in the machine**
  - Only **10^5-**10^8 cm^{-2} “measured” around (**UJ, RR**, Tunnel) equipments
  - Only ~0.1% of nominal integrated luminosity, up to 2% of peak luminosity, ~1% of nominal lost beam, “no” scrubbing (yet)

– **What is good?**
  - Simulations correctly verified in many pla
    (controlled tests & standard operation)
  - Not too many failures occurred

Single Event 2010 Review

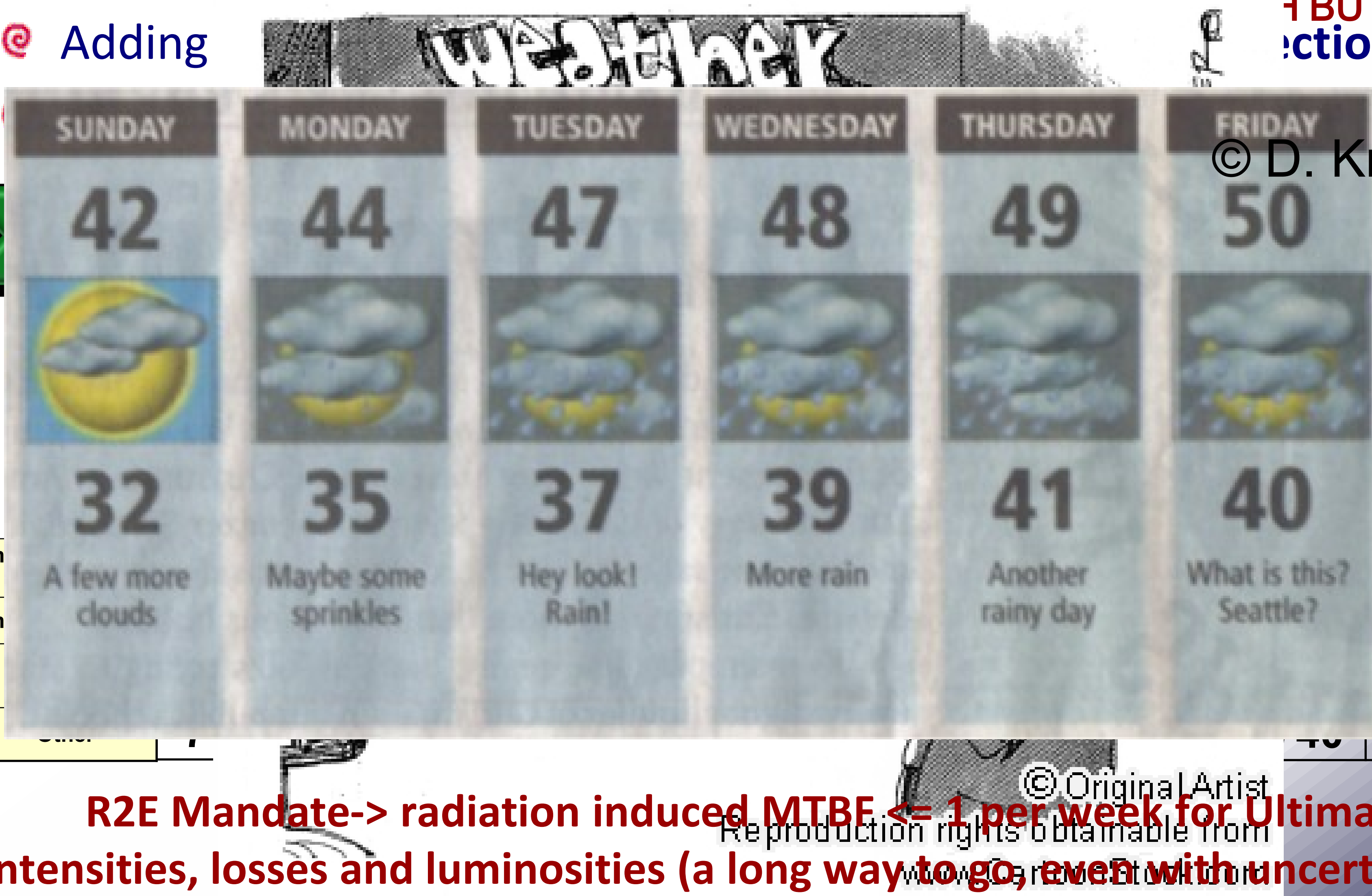


- **What is worrying?**
  - Critical areas: previsions beginning of 2010 expected quite some events in critical areas (several candidate/s, within error margins)
  - Tunnel: 5-10 SEE events already seen in 2010 causing Machine Stop (mostly mitigated)
  - *"we are already wrong"* … in the bad direction
- **What can make things worse**
  - equipments can be more sensitive (most is untested)?
  - we didn't see "critical" levels (mostly < $1x10^6$)
  - losses can also be higher than expected (*e.g.*, electron cloud, injection losses, life-time for ions)

Failure Rates 2011/2012++

- For 201… July)
- Adding … …H BUT OK …ections

Failures Rates



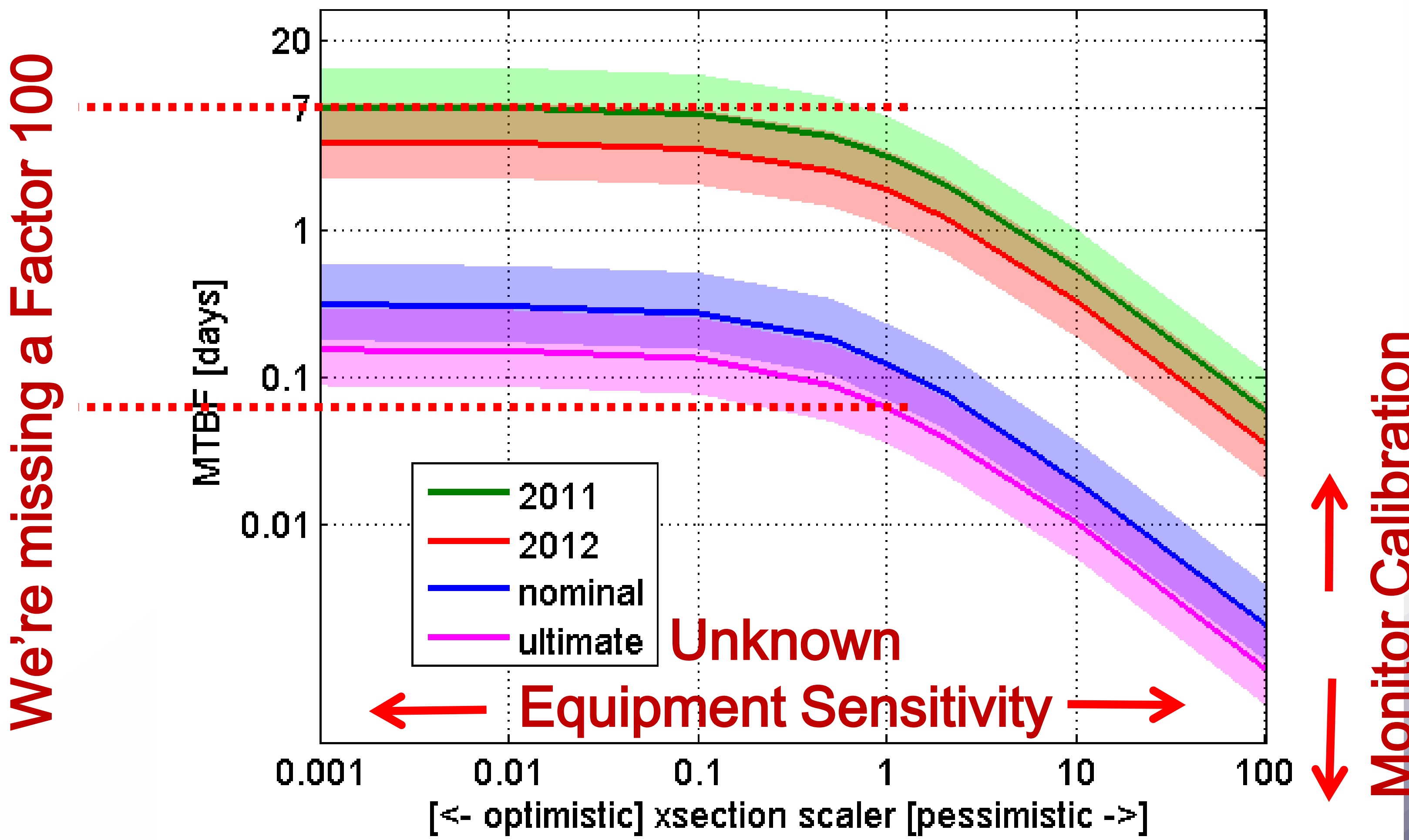
	…inal
	…TBF [days]
im…	0.14
im…	0.8
	0.5
	0.5

R2E Mandate-> radiation induced MTBF <= 1 per week for Ultimate Intensities, losses and luminosities (a long way to go, even with uncertainties)

Failure Rates 2010/2011/2012++

Sensitivity analysis based on failure xSections © D. Kramer

- **Uncertainties**: LHC operation & machine behavior, radi



What Did We Do?
What Can We Do?
…and How?

R2E Global Strategy

Panic

Struggling

Study Phase (2008-2010)
Calculations, Early Actions, Strategy

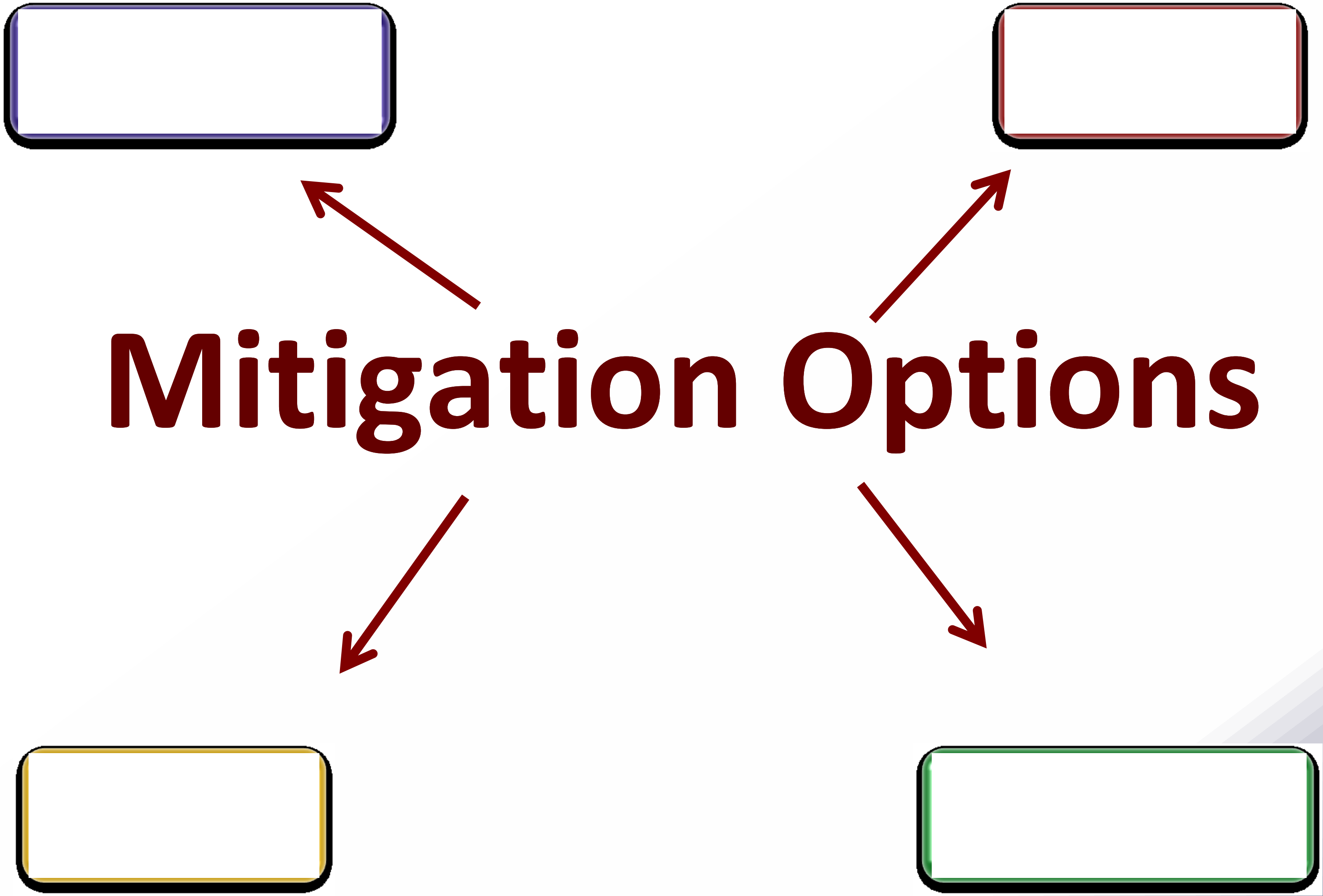
Project Proposal (2010)
Testing, Evaluation, Mitigation Plan

R2E Mitigation Project (2011-2016)

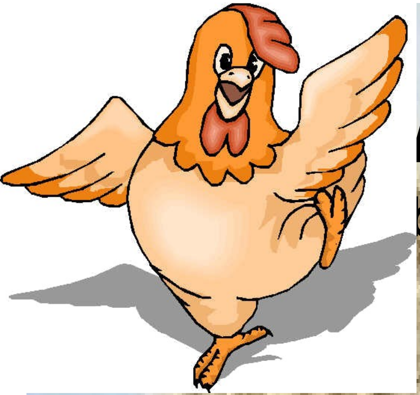
Evaluation

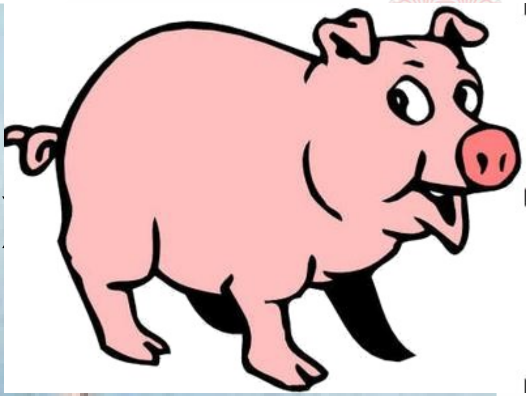
Resources

Medium Term	R&D For Long-Term	Evaluation	Long-Term
<u>Shielding & Relocation</u> P1, P5, P7, P8 (+ small items) <u>Collimation</u> Betatron in IR3	<u>Power-Converters</u> Rad-Tol Solution <u>SCLs</u> Horizontal/ Vertical Links	<u>Monitoring</u> Analysis, Calibration <u>Testing</u> Component & System Tests	<u>Combination</u> Relocation Rad-Tol Equipment SCLs (Civil Engineering)


Mitigation Options

The Perfect Solution



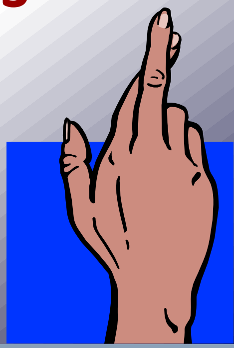


We keep on looking …

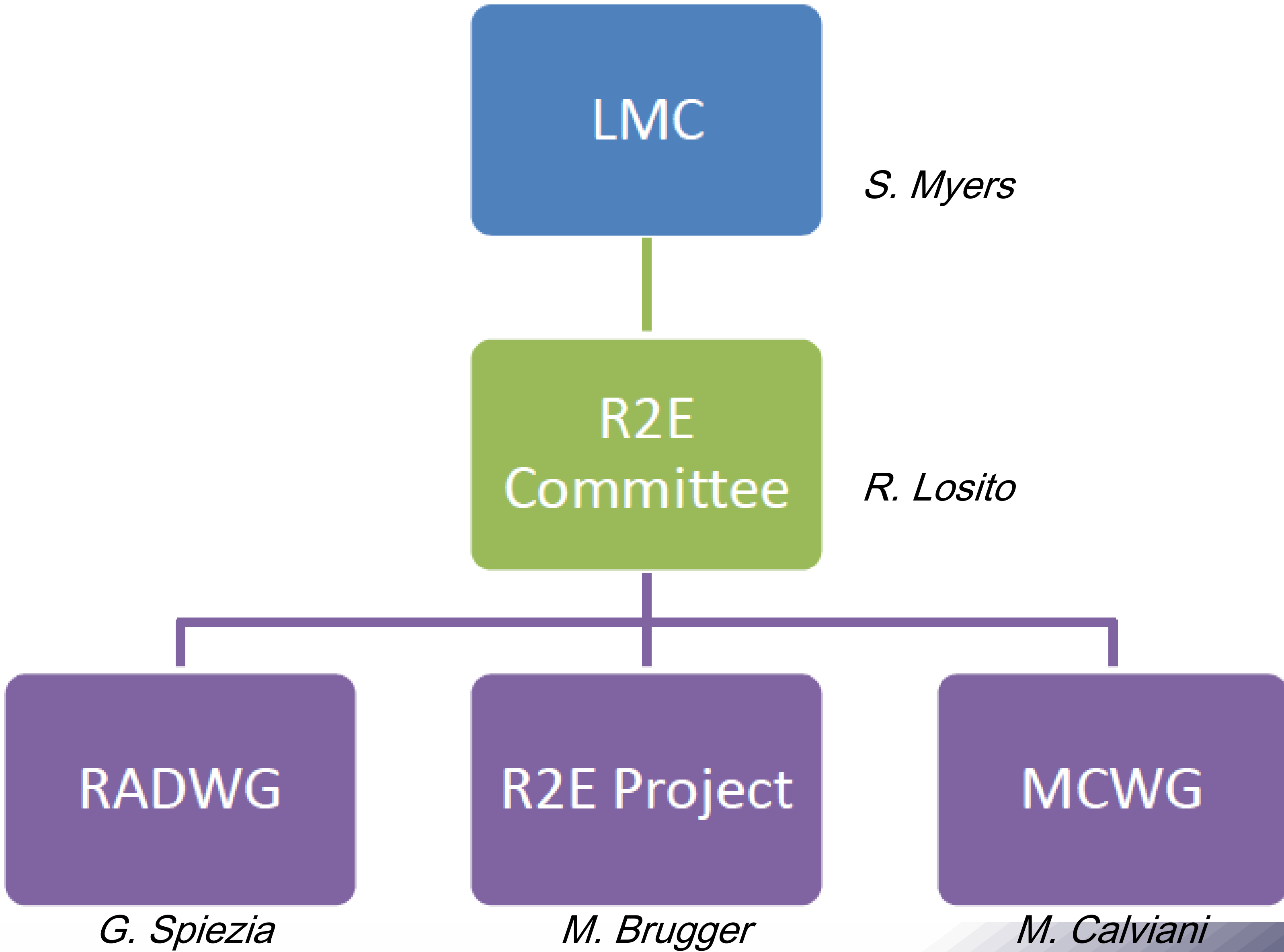
(but we already know that it's expensive ...)

R2E Approach

- **Constraints & Mandate:**
  - Minimize **(Avoid) any risk** of radiation induced failure to electronics
  - Foresee a **mitigation plan** fitting in the planned shutdown periods
  - **Optimize** with respect to planning and costs
- **Strategy:**
  - **Monitor** and benchmark to refine actions and planning
  - Prepare **"Patch-Solutions"** where available (not many left!)
  - **Shield** and Envisage/Prepare/Perform **Relocations**
  - Study/Pursue Major **Long-Term Solutions** (R&D for SCLs and Rad-Tol PCs, CE as backup)
  - … cross fingers, review, optimize, cross fingers…

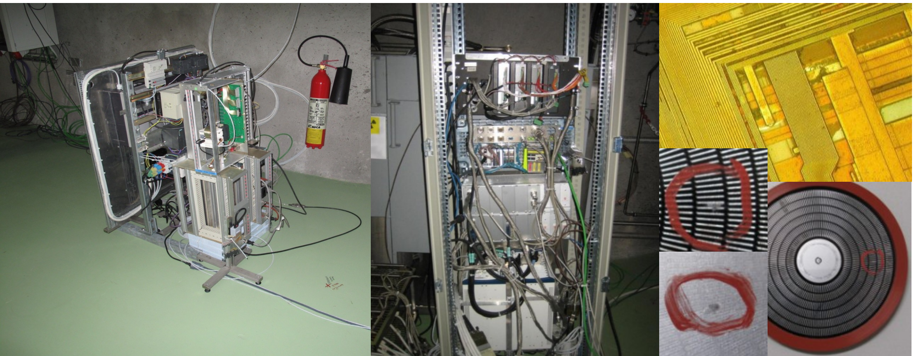


The LHC R2E Structure

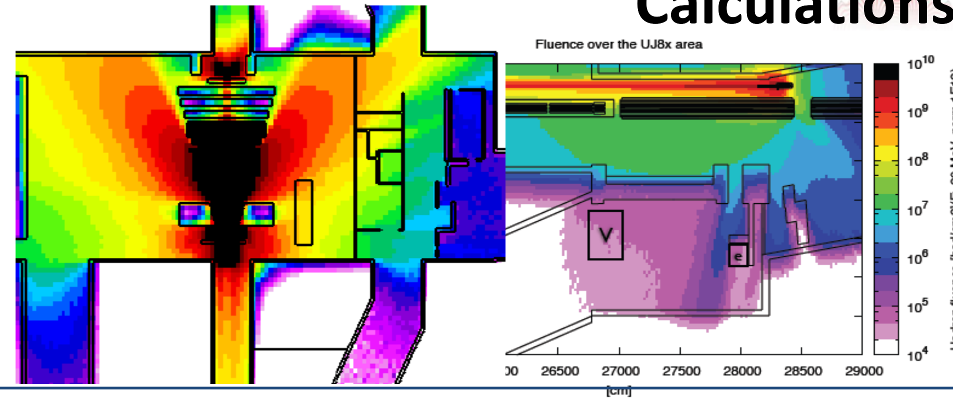


R2E Mitigation Project Building Blocks

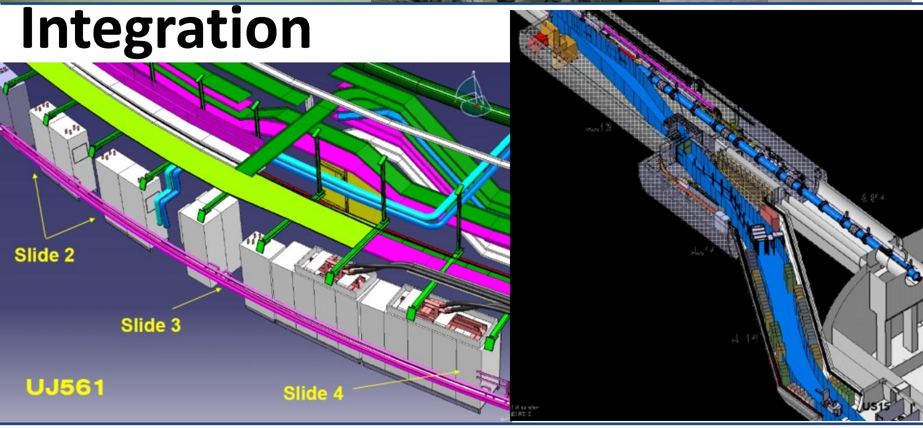
Radiation Tests



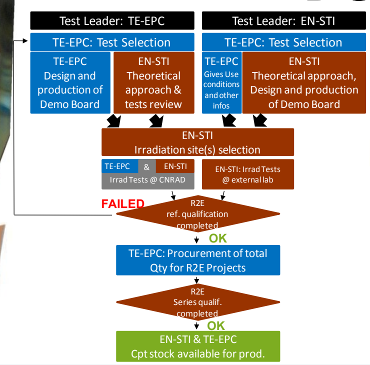
Calculations

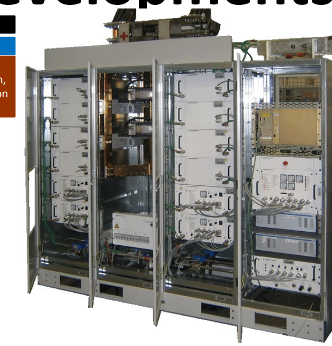


Integration

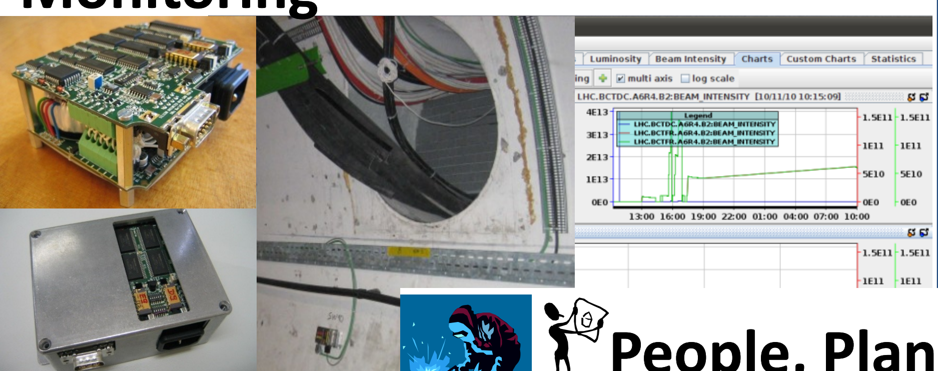


Developments

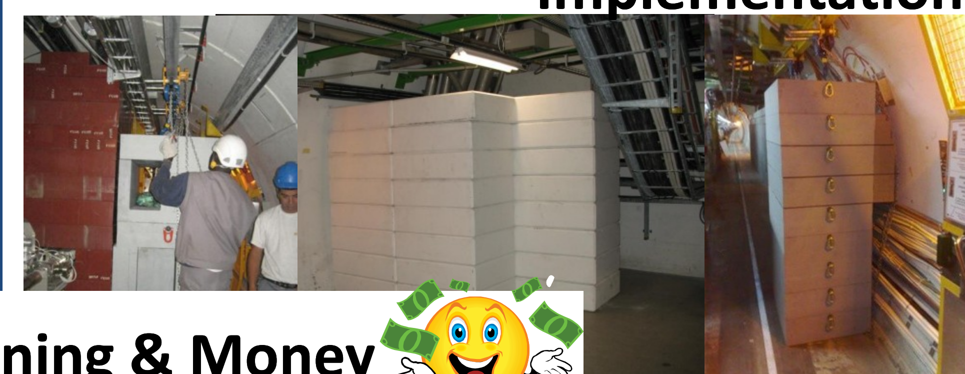




Monitoring

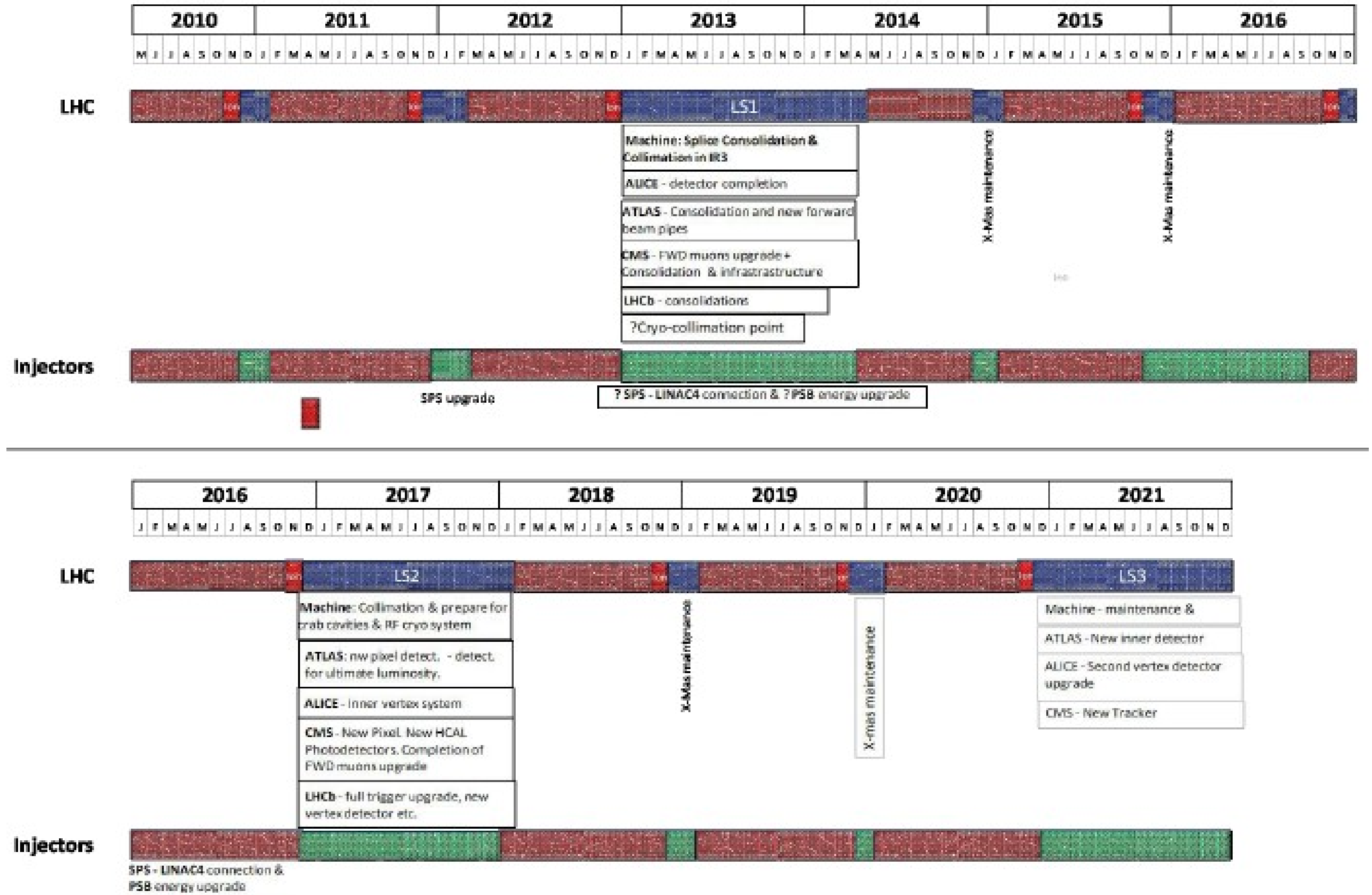


Implementation



People, Planning & Money

The Challenge of Planning



R2E Mitigation Project Plan

LHC	Shutdown	Mitigation Actions	Purpose(s)
I <=10% L <=1% E = 1/2 *2010*	2010 2011	• Fire/ODH Control Racks + EN/EL RTUs • Preparations for long shutdown (Anticipate)	R2E Safety & Patch
I <=30% L <=15% E ~= 1/2 *2011* I <=50% L <=25% E ~= 1/2 *2012*	2013	• Relocation US85 + Shielding • Shielding: UJ14/16/56 (23/87) • Relocation UJ76 (remaining) • Fire Detectors (UJ14/16/56/76,RR13/17/53/57) • Shielding: RR13/17/53/57 (mid/long-term)? • Relocation P1 (UJ14/16) • Relocation P5 (UJ56) (Anticipate) • Betatron Collimation @ Point-3 (???)	R2E Time Gain R2E Long-Term LHC Performance
I <=100% L <=100% E = 1 *2014 ->*	2017	OR lorizontal SCLs for RRs @P7 OR 'ert. (or Hor.) SCLs for RRs at P1/5 ??? OR :adiation Tolerant Power-Converter :ivil Engineering – New Caverns • Additional shielding upgrades where required • Tunnel equipment upgrades (if needed)	R2E Long-Term LHC Long-Term
I >=100% L >=100% E = 1 ???	???	• Vertical SCLs (LHC Upgrade UJs @P1/5, R2E only @P1) • Additional shielding (*e.g.*, RA/UA ducts, TI2/8, UJ/UA Junctions) • Further radiation tolerant equipment	LHC Upgrade R2E Long-Term

R&D

- Hor. SCLs — Development — X
- Rad-Tol Power-Converter — Development — X
- Vert. SCLs I — Development — X
- Vert. SCLs II (high-curr.) — X
- Design Reviews

R2E Project Organisation

Monitoring
Monitoring & Calculations WG:
MC Calculations
Monitoring & Benchmarking
Radiation Levels in Critical Areas

M. Calviani

Integration & Implementation
LHC Planning:
Shielding
Relocation
Coordination

A.L. Perrot

Radiation Testing
Radiation-WG:
Failure Analysis
Radiation Tests
Patch Solutions & New Developments
Radiation Policy

G. Spiezia

Civil Engineering
Pre-Studies
Impact on Long-Term

J. Osborne

Project Support
LHC Operation
Planning
Safety

S. Weisz, K. Foraz
M. Pojer, S. Roesler
C. Jach

EN | TE | BE | PH | GS | DGS | DG | FP

GS/SE
BE/BI
DG/PRJ
BE/OP
DGS/RP
DGS/SEE
TE/EPC
TE/CRG
TE/MSC
BE/CO
FP/PI
BE/ABP
PH/DT

R2E Mitigation Project
M. Brugger

Power Converters
Radiation Tolerant Power-Converter WG:
R&D & Concept Development
Testing
(Procurement)

Y. Thurel

Super Conducting Links
SCLs -WG:
R&D & Tests
Hor. SCLs
Vert. SCLs
(Procurement)

A. Ballarino

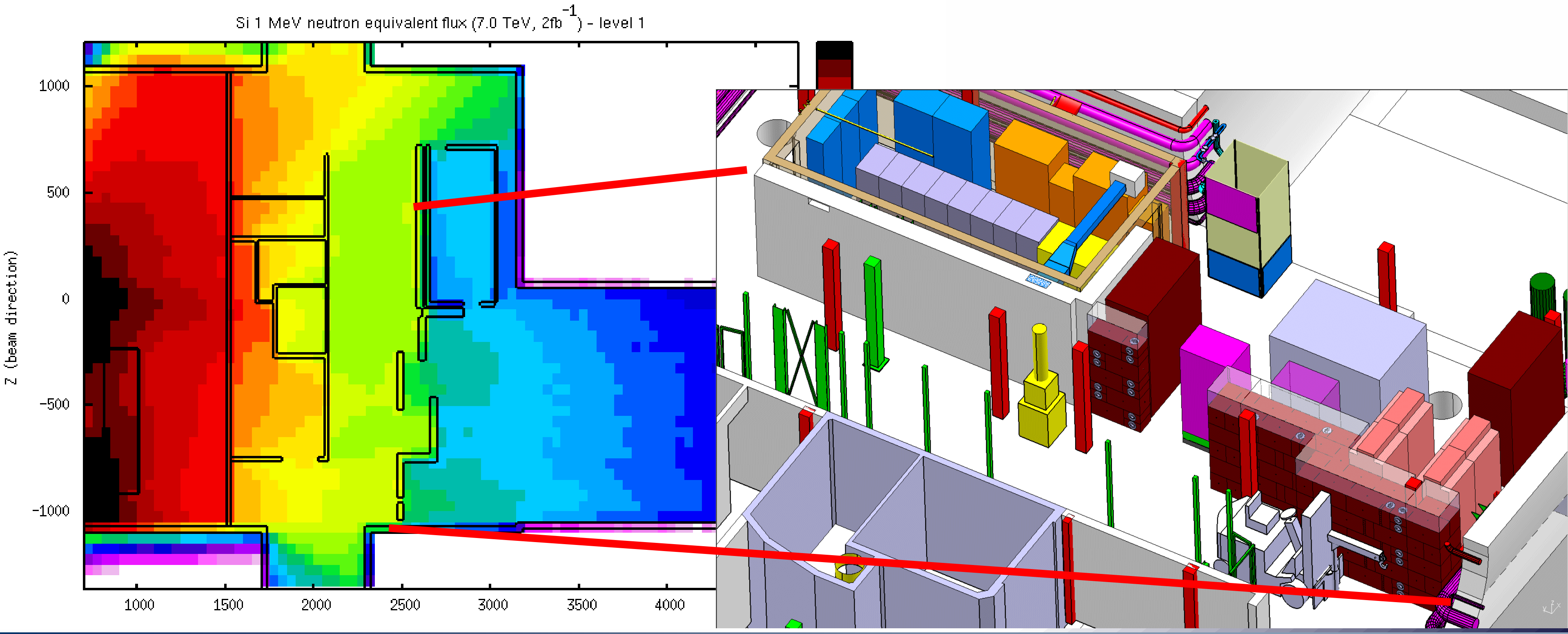
Collimation
Collimation-WG:
Betatron @ Point-3

R. Assmann

Test Facilities
H4IRRAD &
PS East-Area Facility

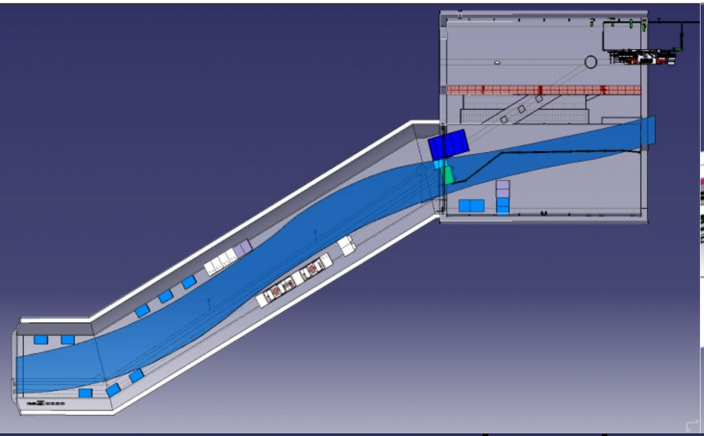
M. Calviani, M. Moll

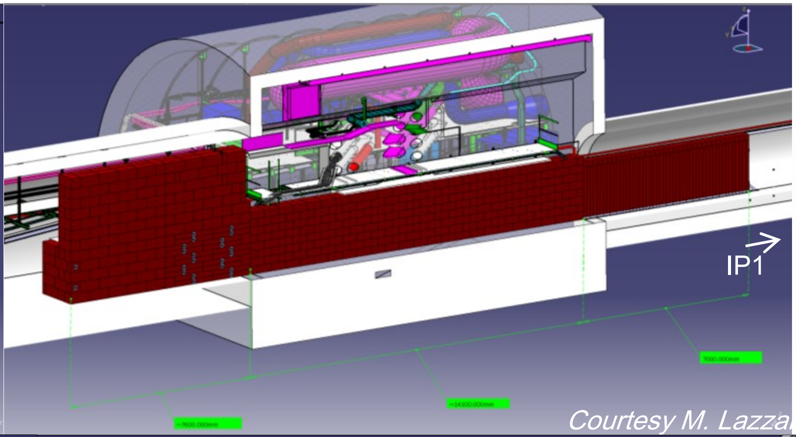
- Each shielding design and all questionable relocation areas have to be **carefully simulated**
- **Iterations are required** in many cases
- **Details are important**
- Key input to **benchmarks & radiation field** characterization



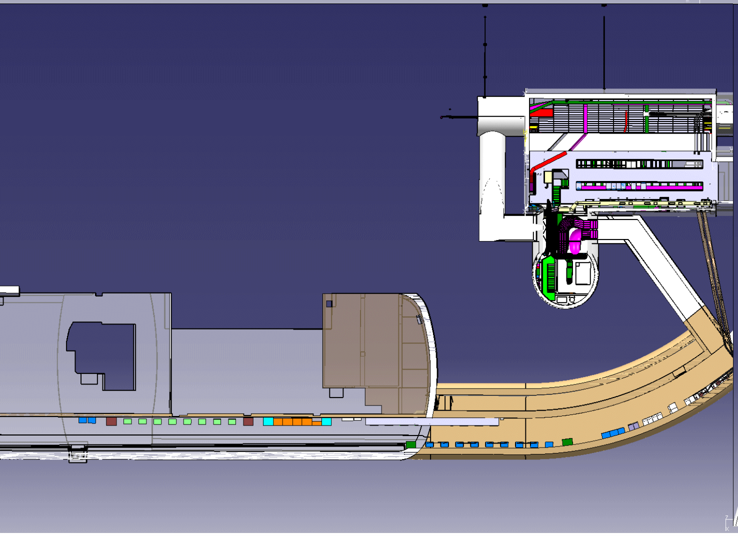
Integration & Implementation

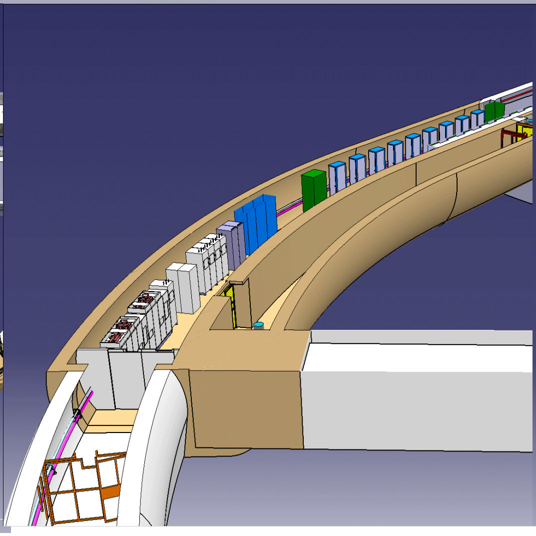
- Shielding & Relocation @ 12 underground areas

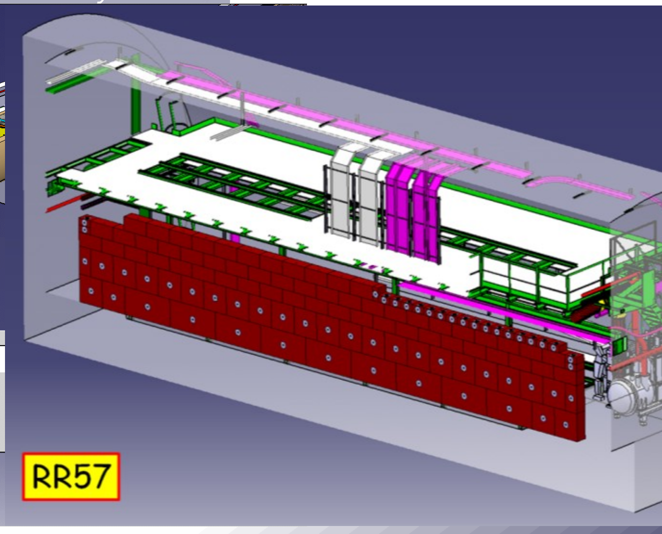




© A.L. Perrot
ICL Team
+ groups!







- 15 Groups, 4 Points, Parallel Activities, Short Time

Power-Converter R&D

- TE-EPC Planning for Rad Tolerant Converter Project

© Y. Thurel

Project	2011	★0 2012	★1 2013	★2 2014	2015	2016
R2E-FGClite	Design, component Choice	Prototype, demo test	Pre-series Rad Tests	Production/ installation	Installation →	
R2E-Rad-DIM	Design, component Choice	Pre-series Rad Tests	Production/ installation	Prod Installation	Installation →	
			Prod →			
HC120A-10V Rad-Tol	Risk Analysis on existing converters Rad test	Modification of existing part or total redesign.	Pre-series Rad Tests	Production	Production, Recep. Tests &	Tunnel Install Commissioning
H600A-10V Rad-Tol	Pre-Design Technical Study, Solution & Principles	Mechanical, prototype, demo board	Pre-series Rad Tests	Production	Production, Recep. Tests &	Tunnel Install Commissioning
-LHC4-6-8kA-08V Rad-Tol	Pre-Design Technical Study, Solution & Principles	Mechanical, prototype, demo board	Pre-series Rad Tests	Production	Production, Recep. Tests &	Tunnel Install Commissioning
				Prod →		
Rad-Tol Analogue Studies	Component Selection, Component testing, bibliography, theoritical analyze...		Testing of demo board, critical fctions			

★x Int/Ext Review **Stop** / **Go**

Radiation Testing

© Y. Thurel

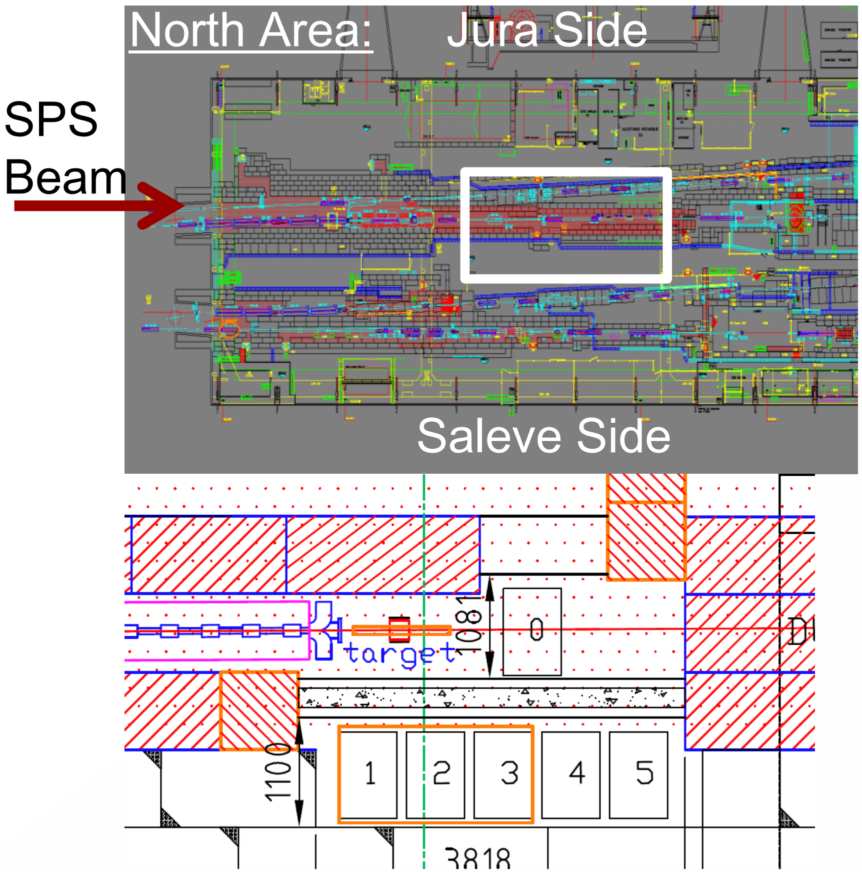
Family	Nb ref. [±50%]	Nature	Complexity	Test Leader*
Anti-fuse FGPA, Flash FPGA	4	Digital	High	EPC / STI
CPLD / EPLD	5	Digital	High	EPC / STI
Hig				
16-				
RS4				
Osc				
Op				
Pov				
DC-				
AC-				
IGE				
Lov				
Op				
Dio				
Lin				
Cur				
Spe				
Far				

- PC R&D is dominant, but there are other tests present and future (RadMon, EN/EL, GTOs,…)
- Enormous amount of components & tests
- Available test facilities: PSI, CNRAD, H4IRRAD (in construction)
- Radiation test requirements and conditions have to be carefully reviewed

New Facilities

Extensive and **complex radiation test campaigns** exceed our current test possibilities (CNRAD, PSI) – Important to think ahead!

- **H4IRRAD (2011)**



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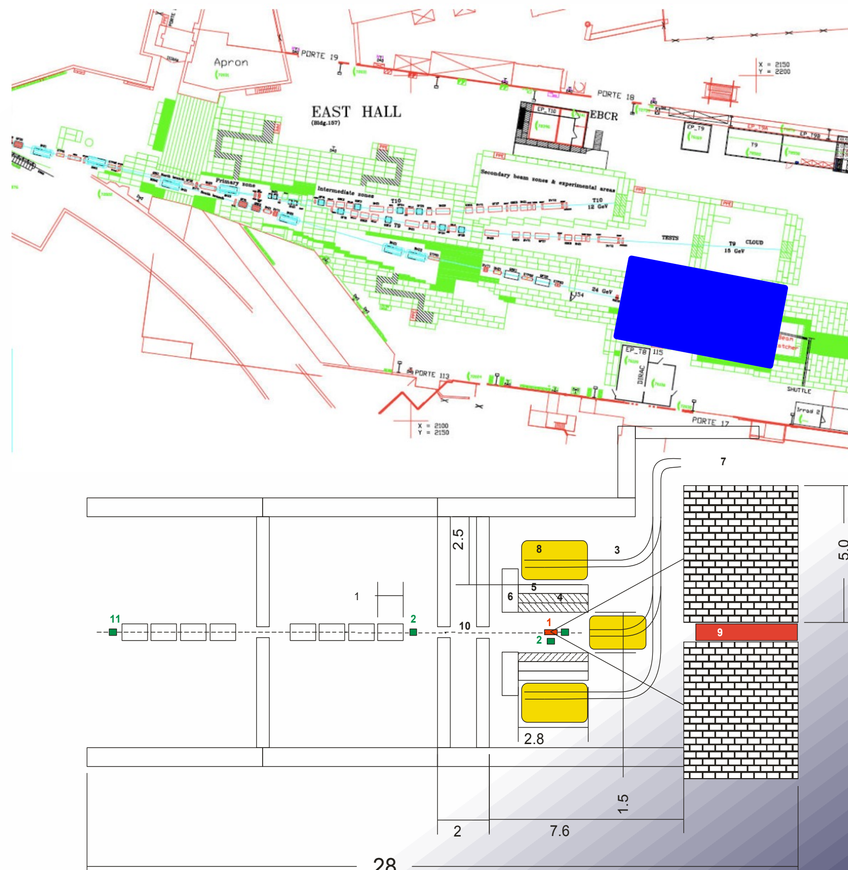
- **PS-EastArea (2013?)**



© L. Gatignon, M. Moll, M. Glaser *et al.*

Radiation Tests: Places and 2011 Plans

CERN:

- CNRAD (Mar-Nov 2011)
  - Tests on Power converters, QPS equipment, Cryogenics
- H4IRRAD (start May)
  - Tests on Power Converters, EN/EL equipment and GTOs

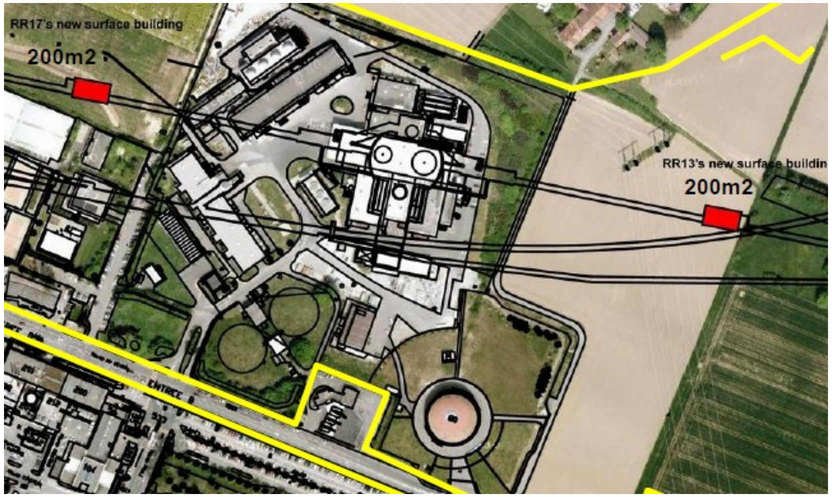
Outside CERN:

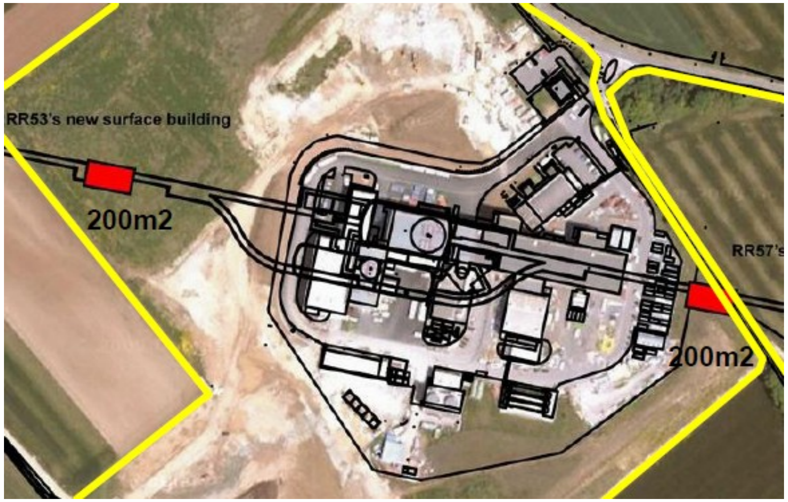
- PSI - Villigen (2011)
  - Agreement with PSI to get 1 weekend test per month;
  - Test of Amplifier, ADC buffers, and ADC for the PC redesign;
  - Continue calibration of the RADMONs.
- CEA – Valduc (Feb 2011)
  - Calibration of PinDiodes (RADMON) for the Displacement Damage measurements.
- TRIGA– Rome (or Prague facility) (2011)
  - RADMON memory calibration with a thermal neutron beam.

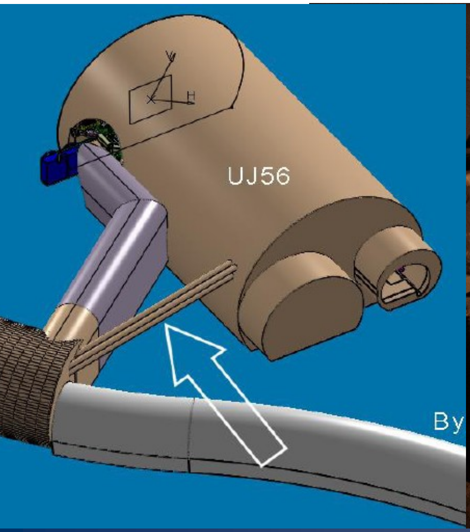
Civil Engineering

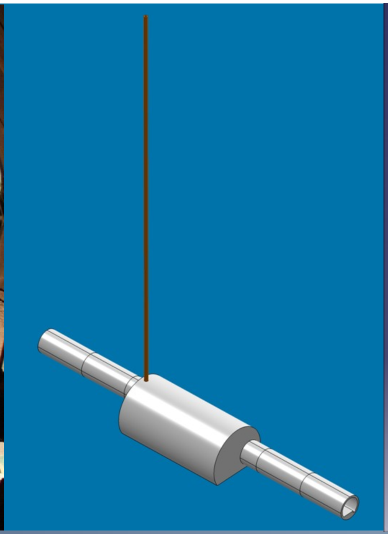
© J. Osborne

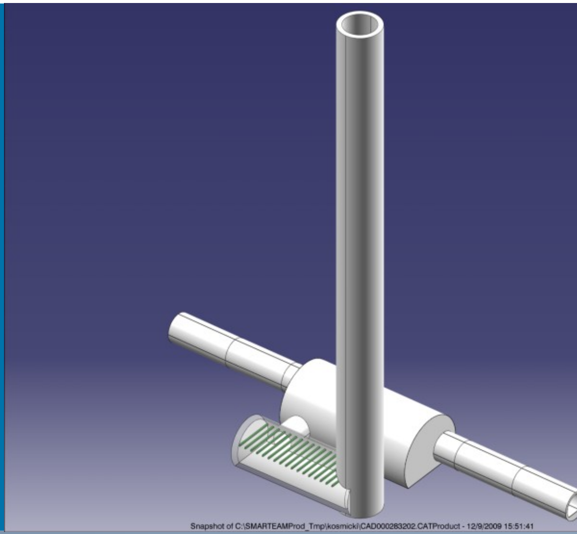
- Relocation/shielding purposes (*e.g.* long ducts in Point-5)
- Pre-Studies for long-term solution & final procurement (SCLs, Caverns)





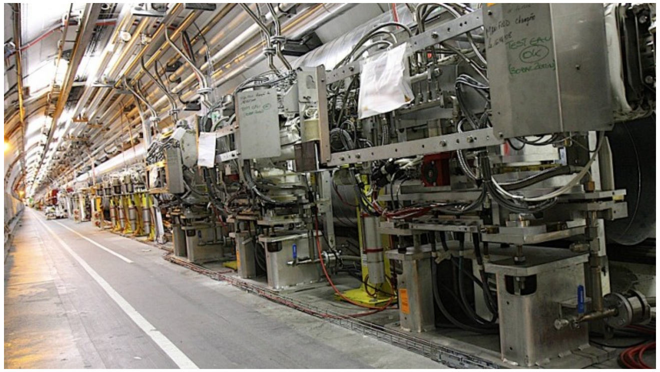




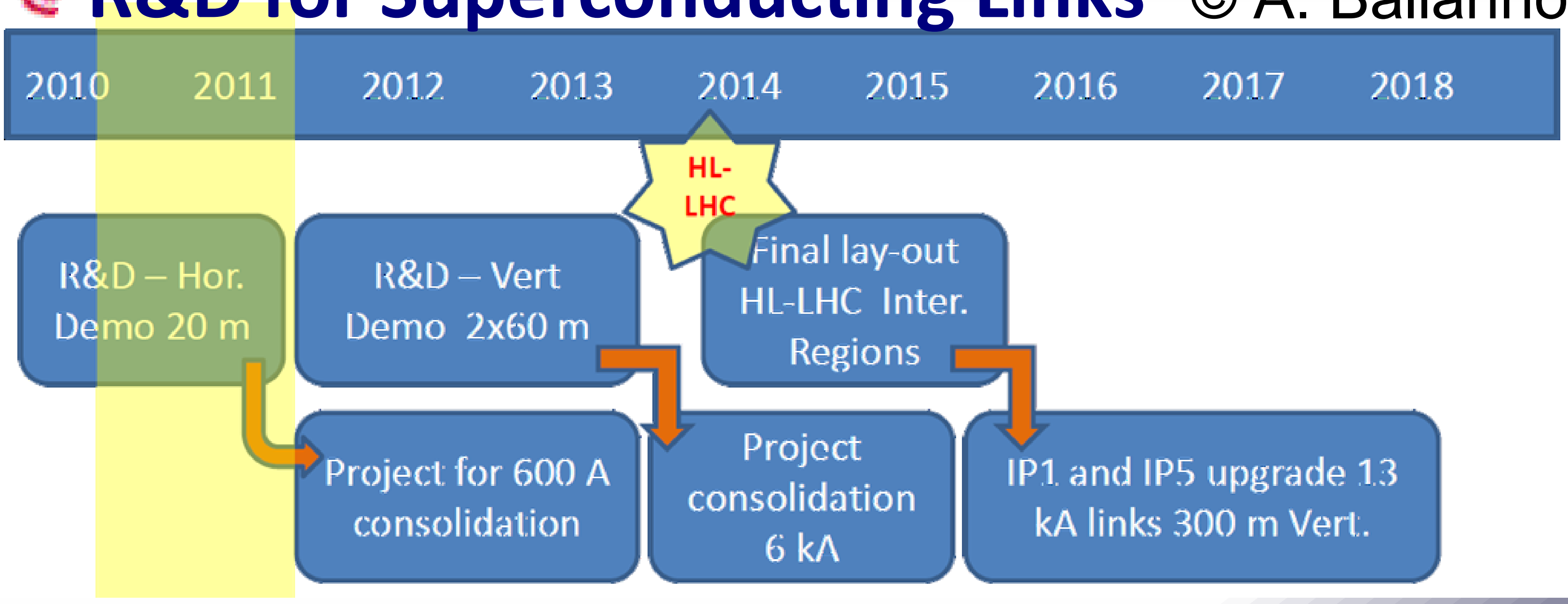


Linked Activities

- **Betatron Collimation in IR3** © R. Assmann *et al.*
  - Low radiation levels in IR7
  - Might be possible to reach nominal performance at 7TeV
  - (faster setup)



- **R&D for Superconducting Links** © A. Ballarino *et al.*



2011: What We Will Do…

- Preparation of **shielding & relocation** measures
- 2011 experience together with detailed monitoring & scheduled radiation tests (full power-converters) will allow us a **further optimization** step
- **Monitoring** and preparation of **patch solutions**

Current Goals:

- **Anticipate problems** whenever possible
- Aim to be **ready for 2012** shutdown in any case
- **Optimize the long-term solution**
  (Review in November)

Remarks
&
Lesson's Learned

A Few Things We Will ‘Remember’

- The detailed study of the **radiation environment** is of utmost important (early simulations, measurements) -> review of possible radiation effects *(we still have a certain doubt about SEL/SEBs and our test possibilities!)*
- All **equipment must be checked** prior installation *(it took us two years to get the inventory roughly complete)*
- A **clear policy** (+ police) would help, but…
- Well defined **time boundaries** are required (for development, tests, procurrement, tests, installation) *(constraints still change constantly)*
- A good **radiation tolerant development** requires: time, knowledge, time, experience, time, money, time… *(we are again in a bit of a hurry)*
- Communication and knowledge exchange is a key ingredient…

Remark 0

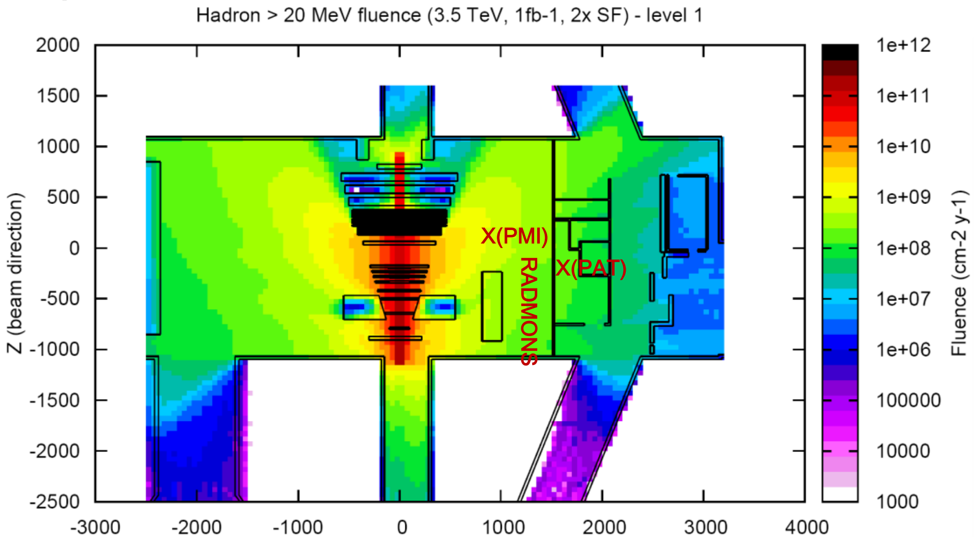
- In all our estimates and predictions **we try being as 'accurate' as possible (conservative but fairly close to reality)**, thus uncertainties strictly apply in all directions
  - **NO BIG SAFETY MARGINS LEFT**
- **Safety factors (except unknowns!) usually used** in the field of SEE estimates are **in the order of 10-100** and more (depending on the application: space missions, airplanes,…)

This we can't do (afford) at the LHC, even after the mitigation actions are applied

Remark 1

- Uncertainties go in both directions, thus as we try to be 'as accurate as possible', it's **not necessarily conservative**!
  - Example: LHCb (UX/US85: early measurements versus 'expectation'):

Updated FLUKA Simulations, 'old' detector



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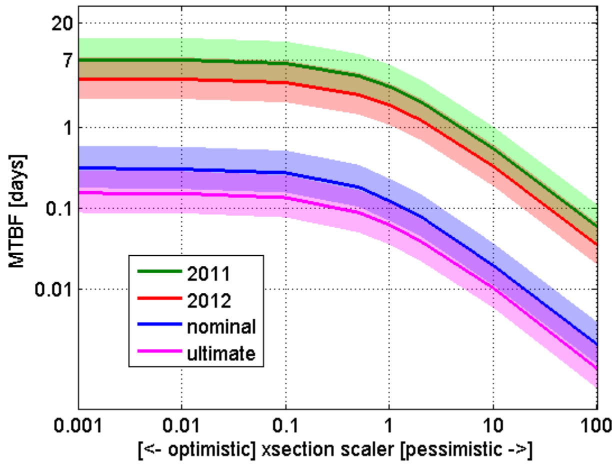
- PMI sees up to 30μSv/h at a luminosity of $10^{31}cm^{-2}s^{-1}$ (expected: 10μSv/h)
- PAT sees a few μSv/h (expected: less than one)
- RadMons: see equivalent counts, however less statistics (expected: first count only)

- **Reason:** old detector geometry and magnetic field (**in work!**)
- Other areas: low-energy neutrons not to be forgotten! (then our estimates would be even less conservative)

Remark 2

- In our estimations, **we have to be 'wrong' by a factor of ~100-1000 (only in one direction)** in order to reach acceptable SEE induced failure rates for the LHC (if nothing is done)!

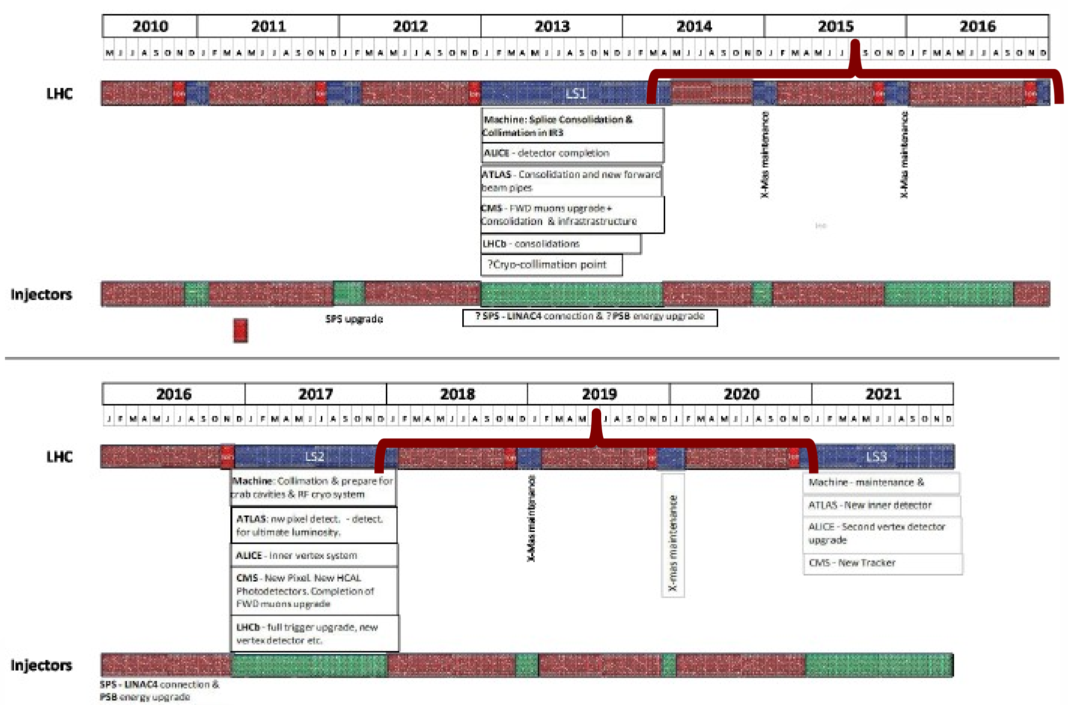


We're looking for a MTBF of 150-300h what concerns 'acceptable' SEE induced problems (tunnel equipment not included!)

- **All test results we get, all the analysis** from the available early monitoring (some shown today), **make this impossible**
- **SEE induced problems happened already** (WIC in injection line, QPS, Power-Converter, Cryogenics, µFip)

Remark 3

- Seeking maximum LHC performance, **we're bound to fit all R2E related work in the shutdown planning**. Operational periods between long shut-downs will be challenging and require the possibility to react in case of problems



Needed:

- preparation of patch-solutions (equipment level)
- radiation tolerant developments (R&D for power converters)
- strong RadWG & collaborations within CERN
- radiation test possibilities at CERN

The Summary & Credits

Conclusions

- A **“Hitchhiker's Guide“** through LHC R2E activities
- **Radiation environment** is known in a fairly accurate way, still some question-marks exist
- **Mitigation measures** focus on existing equipment (mostly based on commercial components and systems)
- **Tunnel equipment** (radiation tolerant design) needs to be followed, including new developments
- Important **radiation test requirements** (especially for the challenging project of radiation tolerant power-converters)
- This and next year will be crucial to optimize the **mitigation strategy and actions** (time & effort)

- **Knowledge (and effort) exchange is crucial**

!!! Thank You !!!

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Phili … Oliver
Brur … o
Calv … ni,
Fred … adine

And I'm sure we missed some…

Conan, Jean-pierre Corso, Gloria Corti, Pierre Dahlen, Knud Dahlerup-petersen, Ali Day, Julien De Freitas,
Claude Dehavay, Bernd Dehning, Emmanuelle Delachenal, Frederic Delsaux, Reiner Denz, Luca Di,
Mathieu Donze, Nuno Dos Santos, Pascal Droux, Laurent Ducimetiere, Dorothee Duret, Francois Duval,
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Vincent Froidbise, Sylvain Fume … e Gayet, Alain Gharib, Sylvain
Girod, Giancarlo Golluccio, Paul … usiou, Silvia Grau, Edda
Gschwendtner, Jean-claude Gu … rty, Sonia Infante, Cezary Jach,
Geraldine Jean, Michael Jeckel, … hodri Jones, Jean-michel Jouanigot,
John Jowett, Tjitske Kehrer, Qu … t, Luisella Lari, Isabelle Laugier,
Michael Lazzaroni, Naour Le, El … Losito, Betty Magnin, Antonio Marin,
Christophe Martin, Alessandro M … lessio Mereghetti, Christophe
Claude Mitifiot, Michael Moll, Va … oceo, Yvon Muttoni, Steve Myers,
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Michel Pangallo, John Pederser … ernandez, Paul Peronnard, Anne-
laure Perrot, Thomas Petterssor … regory Pigny, Mario Pinheiro, Serge
Pittet, Mirko Pojer, Nicole Polivk … ie Rasmussen, Hubert Reymond,
Daniel Ricci, Ketil Roeed, Stefa … , Christian Saint-jal, Eric Sallaz,
Rudiger Schmidt, Viliam Senaj, … l Sierra, Florian Sonnemann,
Sebastien Sonnerat, Giovanni S … hornton, Yves Thurel, Ralf Trant,
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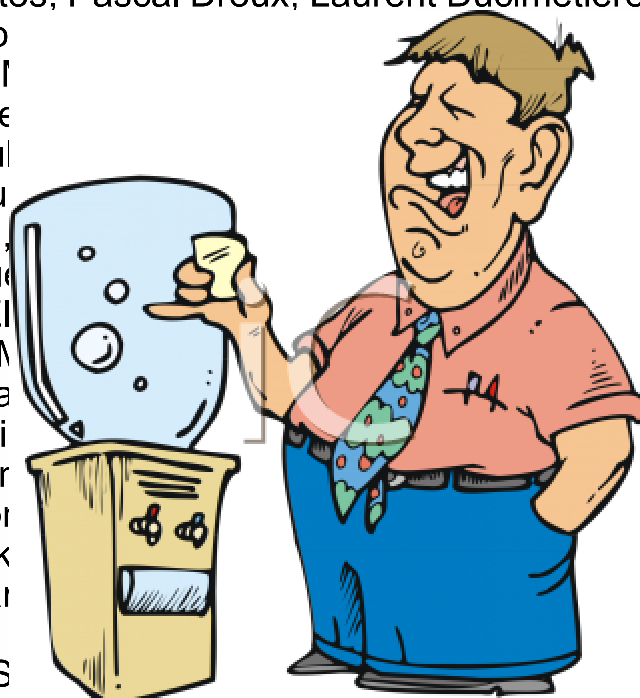
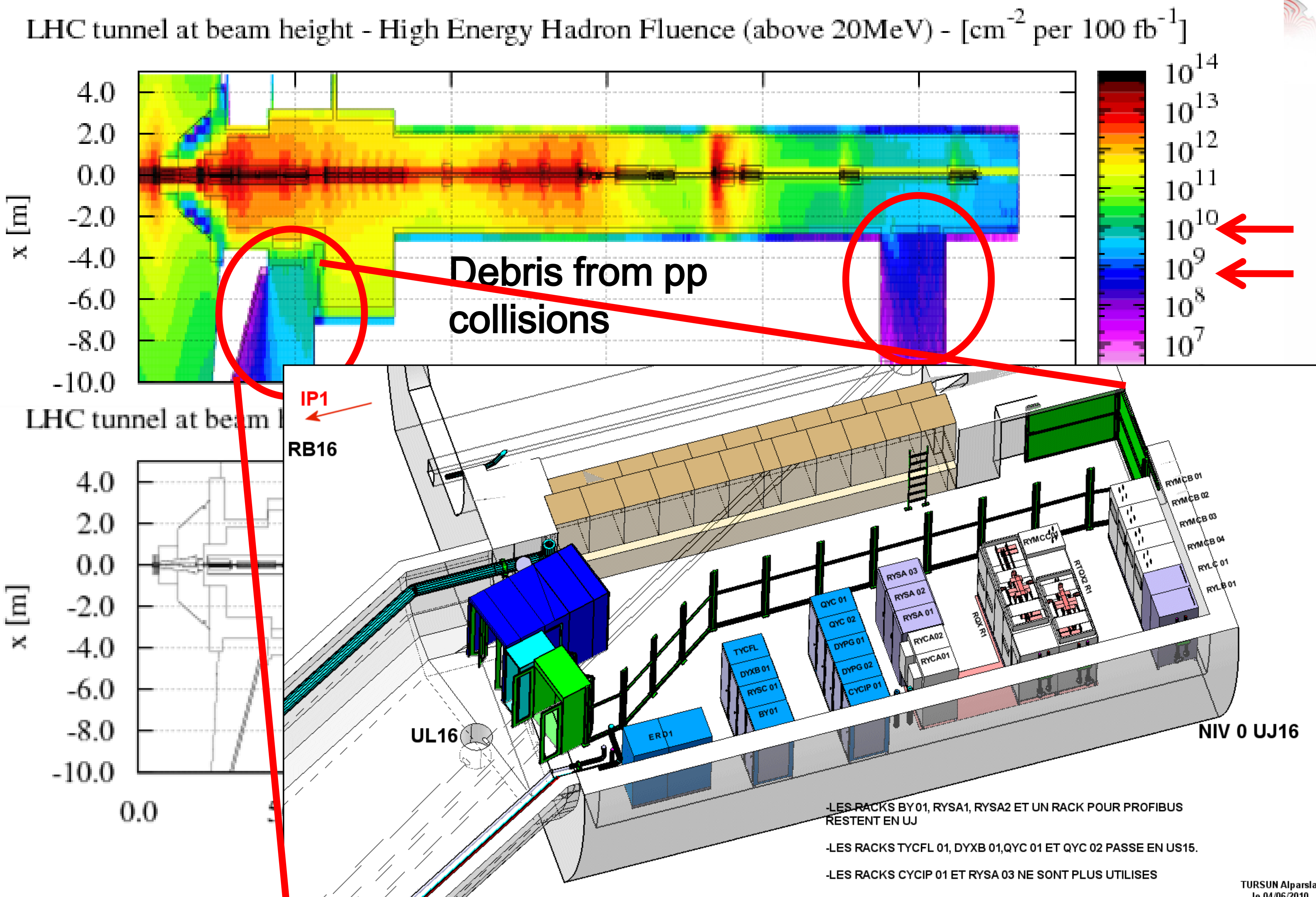
Markus Zerlauth,

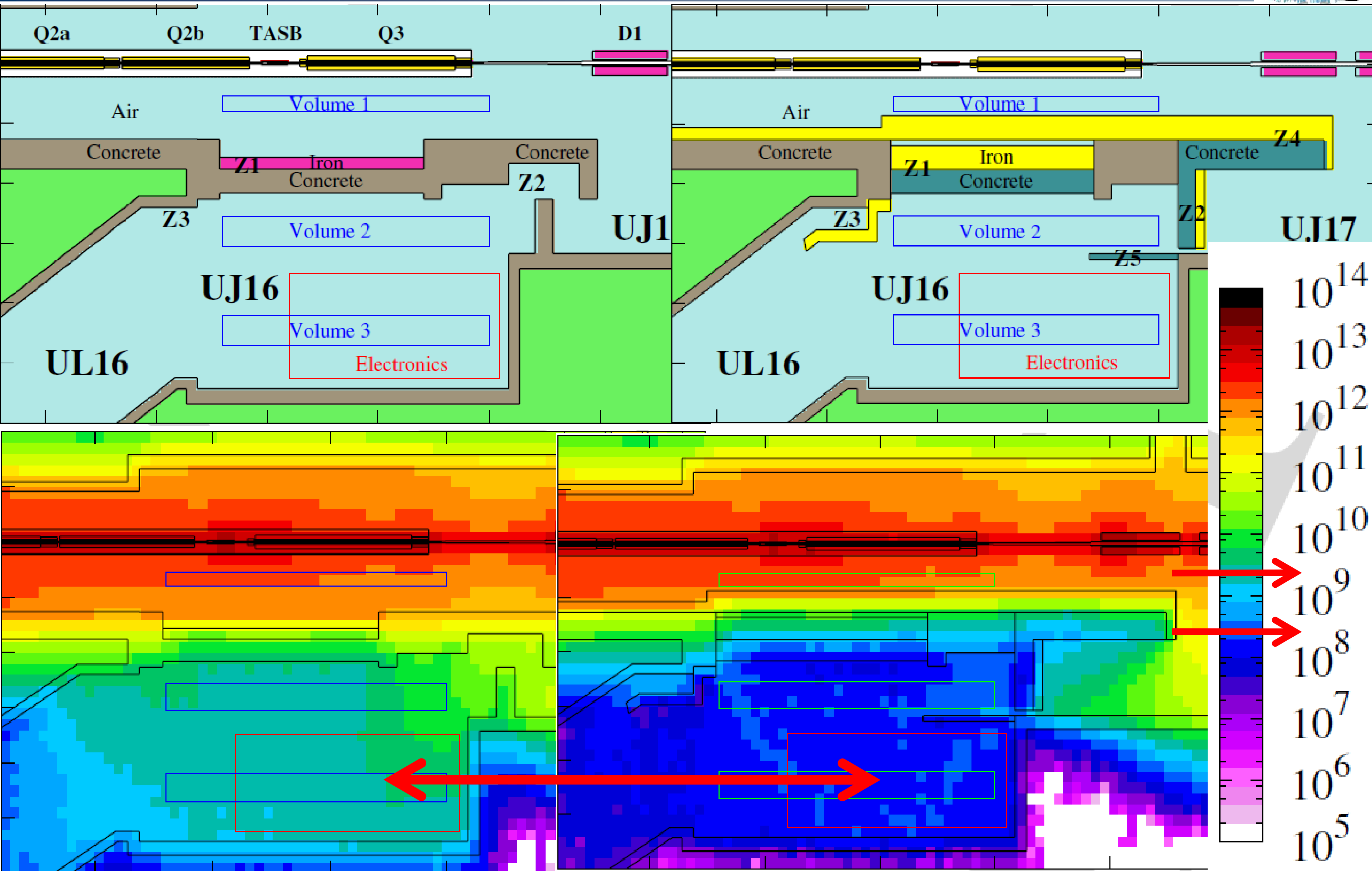


Backup

Shielding & Relocation (*e.g.*, ATLAS)



Shielding



Q2a
Q2b
TASB
Q3
D1
Air
Volume 1
Concrete
Z1
Iron
Concrete
Concrete
Z2
Z3
Volume 2
UJ1
UJ16
Volume 3
Electronics
UL16
Air
Volume 1
Concrete
Z1
Iron
Concrete
Concrete
Z4
Z2
Z3
Volume 2
Z5
UJ17
UJ16
Volume 3
Electronics
UL16
10^{14}
10^{13}
10^{12}
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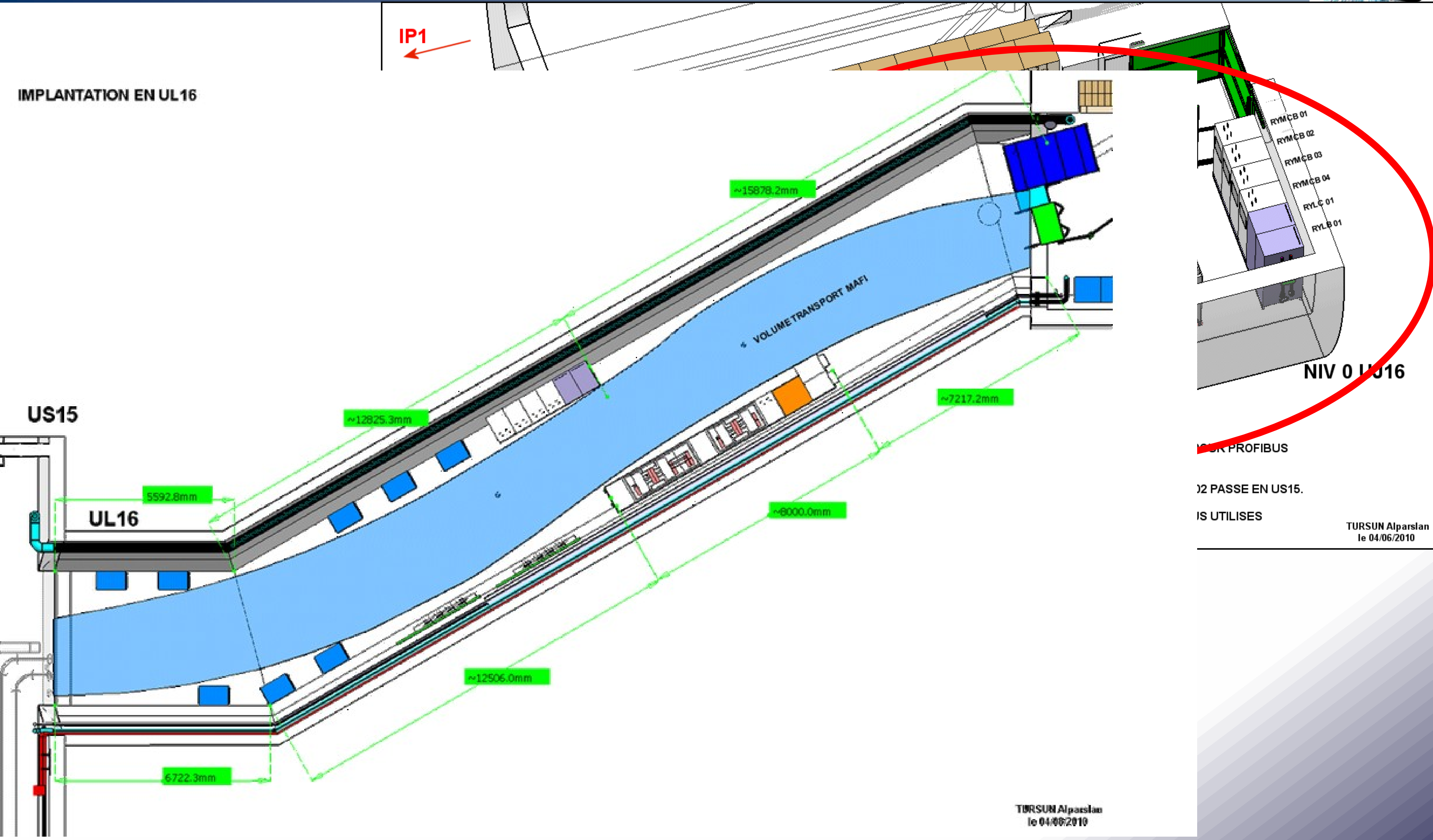
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}

Relocation


IP1
IMPLANTATION EN UL16
US15
UL16
~15878.2mm
~12825.3mm
5592.8mm
6722.3mm
~12506.0mm
~8000.0mm
~7217.2mm
VOLUME TRANSPORT MAFI
RYMCB 01
RYMCB 02
RYMCB 03
RYMCB 04
RYLC 01
RYLB 01
NIV 0 UJ16
PROFIBUS
02 PASSE EN US15.
IS UTILISES
TURSUN Alparslan
le 04/06/2010

Failure Rate Estimate

Failure Rate Approach

(1) Use the 'Aging' Radiation Level

LHC Point	Area(s)	High-Energy Hadron Fluence [cm-2/y] 2010	2011	2013	2014	Nominal	Ultimate	Thermal Ratio	Action Priority
Point 1	UJ14 UJ16	2.5E+06	2.5E+07	3.0E+08	7.0E+08	2.5E+09	5.0E+09	200.0	2
	RR13 RR17	5.0E+05	5.0E+06	6.0E+07	1.4E+08	5.0E+08	1.0E+09	10.0	3
	UPS14 UPS16	5.0E+05	5.0E+06	6.0E+07	1.4E+08	5.0E+08	1.0E+09	2 (guess)	4
Point 3	UJ33	2.2E+04	1.9E+05	5.3E+05	5.7E+05	1.3E+06	1.4E+06	3 (guess)	4
	UJ/RE32	2.3E+06	2.2E+06	1.9E+07	6.7E+07	2.5E+08	3.7E+08	50 (guess)	3
	RE38	4.6E+05	4.4E+05	3.7E+06	1.3E+07	5.0E+07	7.5E+07	20 (guess)	3
Point 4	UX45	2.3E+05	2.2E+05	1.9E+06	6.7E+06	2.5E+07	3.7E+07	50 (guess)	4
Point 5	UJ56	2.5E+06	2.5E+07	3.0E+08	7.0E+08	2.5E+09	5.0E+09	2.0	2
	RR53 RR57	5.0E+05	5.0E+06	6.0E+07	1.4E+08	5.0E+08	1.0E+09	10.0	3
	UPS54 UPS46	5.0E+05	5.0E+06	6.0E+07	1.4E+08	5.0E+08	1.0E+09	2 (guess)	4
Point 6	UA63 UA67 (next to TCDQ)	8.6E+04	1.7E+05	9.3E+05	1.0E+06	5.0E+06	5.7E+06	50-400 (guess)	1

(2) Check for each equipment in each area

		number of devices					
device type		120A	120A	120A	600A	4-6/8kA (inner Tr)	4-6/8kA (oth)
LHC Point	Area(s)	immediate dump and access	scheduled access	other	immediate dump and access	immediate dump and access	immediate dump and access
Point 1	UJ14 UJ16	10			16	4	
	RR13 RR17		36		28		30
	UPS14 UPS16						
Point 3	UJ33			10	70		
	UJ/RE32						
Point 5	UJ56	5			8	2	
	RR53 RR57		36		28		30
	UPS54 UPS46						
Point 6	UJ76				12		
	RR73 RR77			20	48		
Point 8	UX85b						
	US85						
	UW85						
TI2	UJ23			8			
TI8	UJ87			8			

(3) Apply the expected failure cross section

	LHC60A-08V	LHC120A-10V	LHC600A-10V	LHC4-6-8kA-08V	Inner-Triplet
Type	RPLA	RPLB	RPMB	RPH	RPxx
Cross Section	[1E-10..1E-11] /cm²	[5E-9..1E-11] /cm²	[5E-8..5E-9] /cm²	[5E-8..5E-9] /cm²	[2E-8..1E-9] /cm²
Hypothesis & Comments *(DCCTs being excluded since redundant and low risk)*	• power part relatively safe, with some SEGR on some Power MosFets • FGC cross section @ 1E-11 is correct	Not Rad Tested • power part relatively safe, with some SEGR on some Power MosFets • Converter more complex than 60A (more components) • CPLD in Digital control board only 1x CPLD, then not adding too high extra failure • FGC cross section @ 1E-11 is correct	Not Rad Tested • power part relatively safe, with some SEGR on some Power MosFets • 5x CPLD in Digital control board only 1x CPLD, not adding too high extra failure • FGC cross section @ 1E-11 is correct • 3x DC-DCs unknown • AC-DC unknown but high AC voltage range •48x Power Mosfets used in 4QLS	Not Rad Tested • power part relatively safe, with some SEGR on some Power MosFets • 8x CPLD in Digital control board only 1x CPLD, adding extra failure • FGC cross section @ 1E-11 is correct • 1 DC-DC • no AC-DC	Not Rad Tested • power part relatively safe, with some SEGR on some Power MosFets • 8x CPLD in Digital control board only 1x CPLD, adding extra failure • FGC cross section @ 1E-11 is correct • no AC-DC • Sigma delta + 1 CPLD • Additional Thyristor + 1 DCDC
Risk factor *(DCCTs being excluded since redundant and low risk)*	No High Risk. Well tested in CNGS.	No high Risk since CERN Design, and very few critical or unknown components. A security hole remains on current lead protection (CPLD based).	High Risk since some unknown integrated devices: 5x CPLD + 1x AC-DC + 3x DC-DC in power part.	High Risk since some unknown integrated devices + 8x CPLD + 1x DC-DC in power part	High Risk since some unknown integrated devices + 8x CPLD 1x DC-DC in power part + Inner-Triplet additional components with DC-DC or CPLD
Rad Status	Well tested.	Converter not Tested under radiation. Estimation provided assuming no unexpected very high sensitive device included in unknown / untested parts, which would completely change the situation.			

(4) Result: failures per equipment/area

		FAILURES PER YEAR EXPECTED IN 2011					
device type		120A	120A	120A	600A	4-6/8kA (inner Tr)	4-6/8kA (oth)
LHC Point	Area(s)	immediate dump and access	scheduled access	other	immediate dump and access	immediate dump and access	immediate dump and access
Point 1	UJ14 UJ16	1	0	0	20	10	0
	RR13 RR17	0	1	0	7	0	8
	UPS14 UPS16	0	0	0	0	0	0
Point 3	UJ33	0	0	0	1	0	0
	UJ/RE32	0	0	0	0	0	0
Point 5	UJ56	1	0	0	10	5	0
	RR53 RR57	0	1	0	7	0	8
	UPS54 UPS46	0	0	0	0	0	0
Point 6	UJ76	0	0	0	8	0	0
	RR73 RR77	0	0	1	16	0	0
Point 8	UX85b	0	0	0	0	0	0
	US85	0	0	0	0	0	0
	UW85	0	0	0	0	0	0
TI2	UJ23	0	0	0	0	0	0
TI8	UJ87	0	0	0	0	0	0

2011 Estimation

Failure Mode	EXPECTED FAILURES PER YEAR - LHC ALCOVES																
	CV	Pconv Opt	Pconv Pess	CRYO	BPWIC	Fire/ODH	QPS	CL heaters	IT	VAC	SURVEY	Collim	EN/EL	TIMING	REM RESET	BI	RP
immediate dump and access	1	29	544	13	35		14		4			0.2	0.6				
immediate dump				9	3							7	0.3	0.0			
Scheduled access	8	0.0	15	0.0		13		0.4		9			3		0.9		
other	3	0.0	9	8							0.0	12	1.3			0.1	5

Optimistic		Pessimistic		Guess/Tested
SUM	MTBF [days]	SUM	MTBF [days]	Ratio
98	4	614	1	2.7
19	19	19	19	0.02
35	10	50	7	0.6
30	12	39	9	0.4

2012 Estimation

Failure Mode	EXPECTED FAILURES PER YEAR - LHC ALCOVES																
	CV	Pconv Opt	Pconv Pess	CRYO	BPWIC	Fire/ODH	QPS	CL heaters	IT	VAC	SURVEY	Collim	EN/EL	TIMING	REM RESET	BI	RP
immediate dump and access	2	48	912	22	60		24		8			0.4	1.1				
immediate dump				14	5							12	0.7	0.0			
Scheduled access	14	0.1	26	0.0		22		0.7		16			5		1.6		
other	7	0.0	16	14							0.0	21	2.4			0.2	8

Optimistic		Pessimistic		Guess/Tested
SUM	MTBF [days]	SUM	MTBF [days]	Ratio
166	2.2	1031	0.35	2.6
33	11	33	11	0.02
60	6	86	4	0.5
52	7	68	5	0.5

Relocation and Shielding Improvements

NOMINAL OPERATION	No Changes	Additional Shielding	+ relocation
UJ14 UJ16	1666	17	8
RR13 RR17	376	75	75
UJ33	1	1	1
UJ/RE32	3	3	3
UJ56	265	265	0
RR53 RR57	376	75	75
UA63 UA67	4	4	4
UJ76	85	85	0
RR73 RR77	166	33	33
UX85b	8	8	0
US85	25	25	0
UW85	2	2	2
UJ23	0	0	0
UJ87	0	0	0
SUM	2977	594	201
MTBF [d]	0.12	0.61	1.82

Most systems (QPS,MKS etc) excluded from UA63/7 list as duct shielding can be added if necessary

Only few equipments included in UW85 list

Power converters 120A in UJ23/87 classified as “other” SEE => no DUMP

Nominal Estimation (After Shielding & Relocation)

Failure Mode	EXPECTED FAILURES PER NOMINAL YEAR - LHC ALCOVES																
	CV	Pconv Opt	Pconv Pess	CRYO	BPWIC	Fire/ODH	QPS	CL heaters	IT	VAC	SURVEY	Collim	EN/EL	TIMING	REM RESET	BI	RP
immediate dump and access	2	108	2001	3	0		60		3			0.1	0.0				
immediate dump				20	0							2	0.0	0.0			
Scheduled access	39	0.2	90	0.0		9		1.6		0			2		0.0		
other	21	0.1	64	2							0.0	4	2.4			0.3	0

Failure Mode	Optimistic	
	SUM	MTBF [days]
immediate dump and access	176	2.1
immediate dump	22	17
Scheduled access	52	7.0
other	29	13

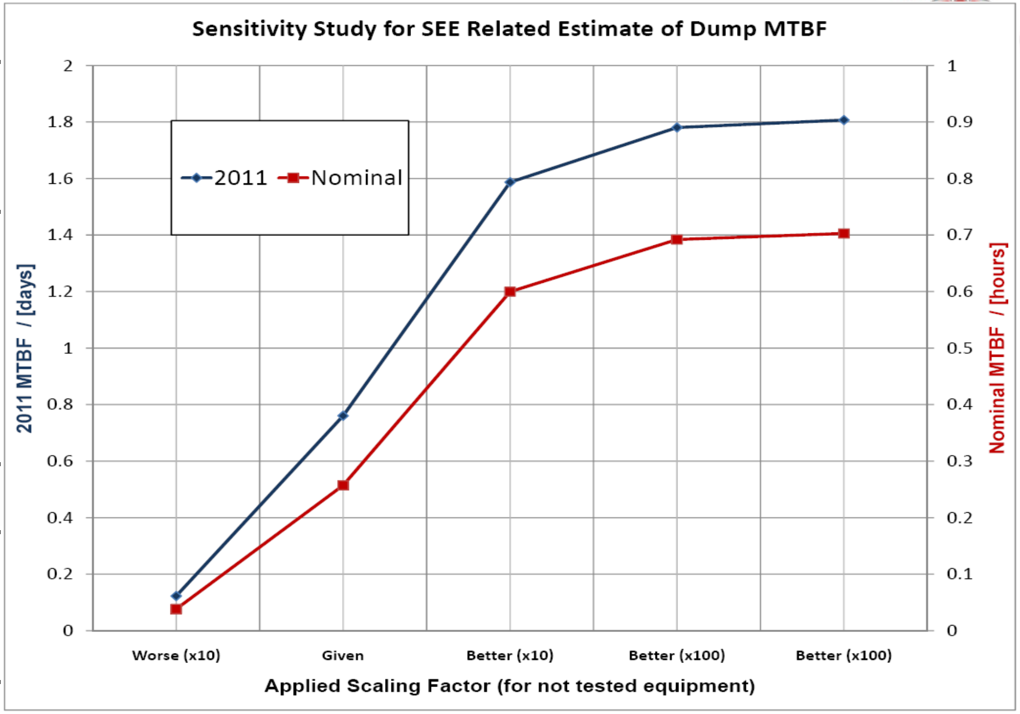
Expected SEE Failure Rates (status 08/10)

2011 LHC Operation:

Failure Mode	Failure Estimate		Confidence (Tested vs. Assumed)
	SUM	MTBF [days]	Ratio
Immediate Dump and Access	332	1	0.06
Immediate Dump	146	2	7
Scheduled Access	133	3	0.4
Other	104	3	1

Nominal LHC Operation:

Failure Mode	Failure Estimate		Confidence (Tested vs. Assumed)
	SUM	MTBF [hours]	Ratio
Immediate Dump and Access	24709	0.3	0.03
Immediate Dump	7500	1.0	9
Scheduled Access	4210	1.2	1
Other	4682	1.4	4

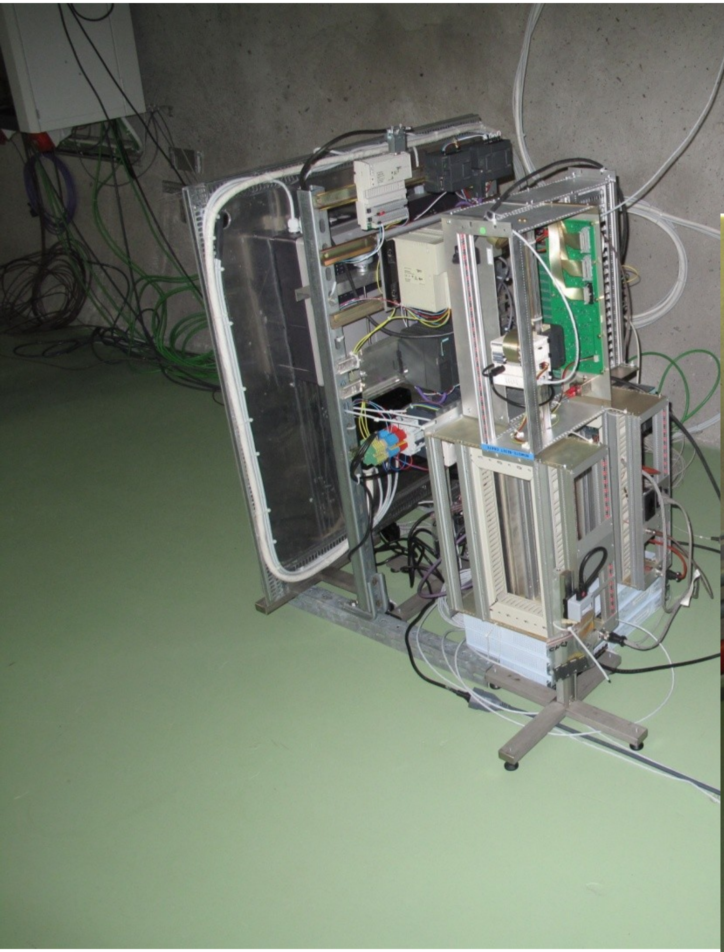


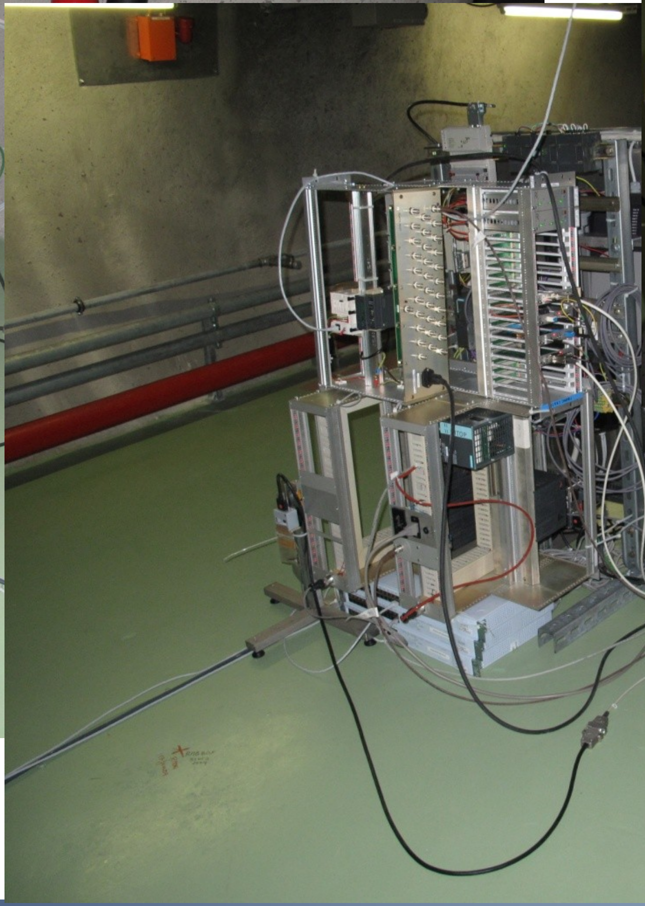
- **Best possible estimate today**
- **Uncertainties:** LHC operation & machine behavior, radiation levels, equipment sensitivities **-> see next slides**
- **2011 will be at the edge (and above)** and possibly show first limitations
- In order **not to have problems** with nominal LHC operation we would have to be **wrong by a factor 500-1000 !**

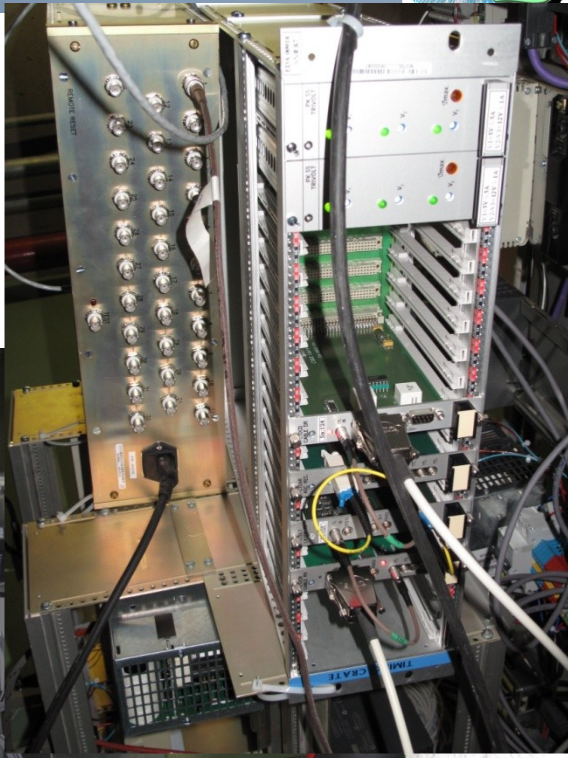
Radiation Tests

'Only' a selection could be tested!

- CNRAD, some pictures: The 'Tower of Pisa'







Radiation Tests in 2011

CERN:

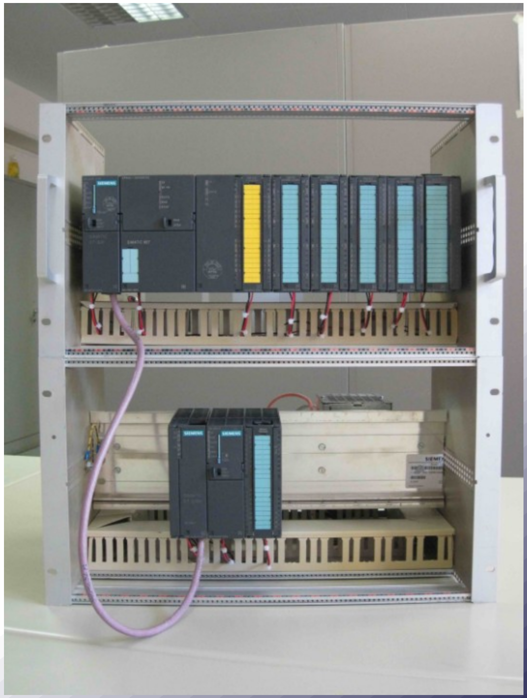
- **CNRAD (Mar-Nov 2011)**
  - Tests on Power converters, QPS equipment, Cryogenics
- **H4IRRAD (start May)**
  - Tests on Power Converters and EN/EL equipment.

Outside CERN:

- **PSI - Villigen (2011)**
  - Agreement with PSI to get 1 weekend test per month;
  - Test of Amplifier, ADC buffers, and ADC for the PC redesign;
  - Continue calibration of the RADMONs.
- **CEA – Valduc (Feb 2011)**
  - Calibration of PinDiodes (RADMON) for the Displacement Damage measurements.
- **TRIGA– Rome (or Prague facility) (2011)**
  - RADMON memory calibration with a thermal neutron beam.

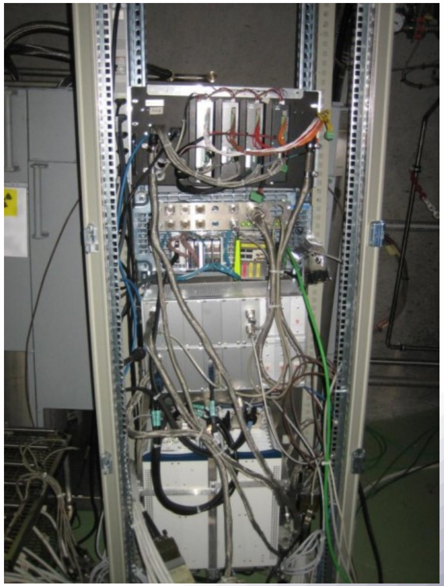
What Equipment is/was Tested

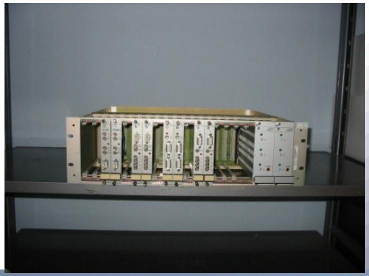
- **Cooling and Ventilation (H. Jena)**
  - Siemens S7-300, S7-200
  - Schneider Telemecanique Premium
- **Warm Interlock Rack (P. Dahlen)**
  - PLC 315F 2 DP, Ethernet controller
  - 24 DI safety input modules, 2 x DO Relay modules, 2 x 32 DO modules
  - IM153.1 - ET 200M
  - Boolean Processor - FM 352-5
- **Ethernet (E. Sallaz)**
  - Three Ethernet Switches
  - 3Com 4400



What Equipment is/was Tested

- **Fire Detectors (S. Grau and Team)**
  - 4 Detectors (different types)
- **Collimation (G. Spiezia and Team)**
  - Full Rack with Drivers, I/O RIO
  - National Instruments PXI MDC + PRS (ADC, DAC, FPGA card, power supply)
  - Europa crate (custom electronic for LVDTs and Resolvers excitation/acquisition, power supply)
- **Timing & Remote Reset (R. Chery)**



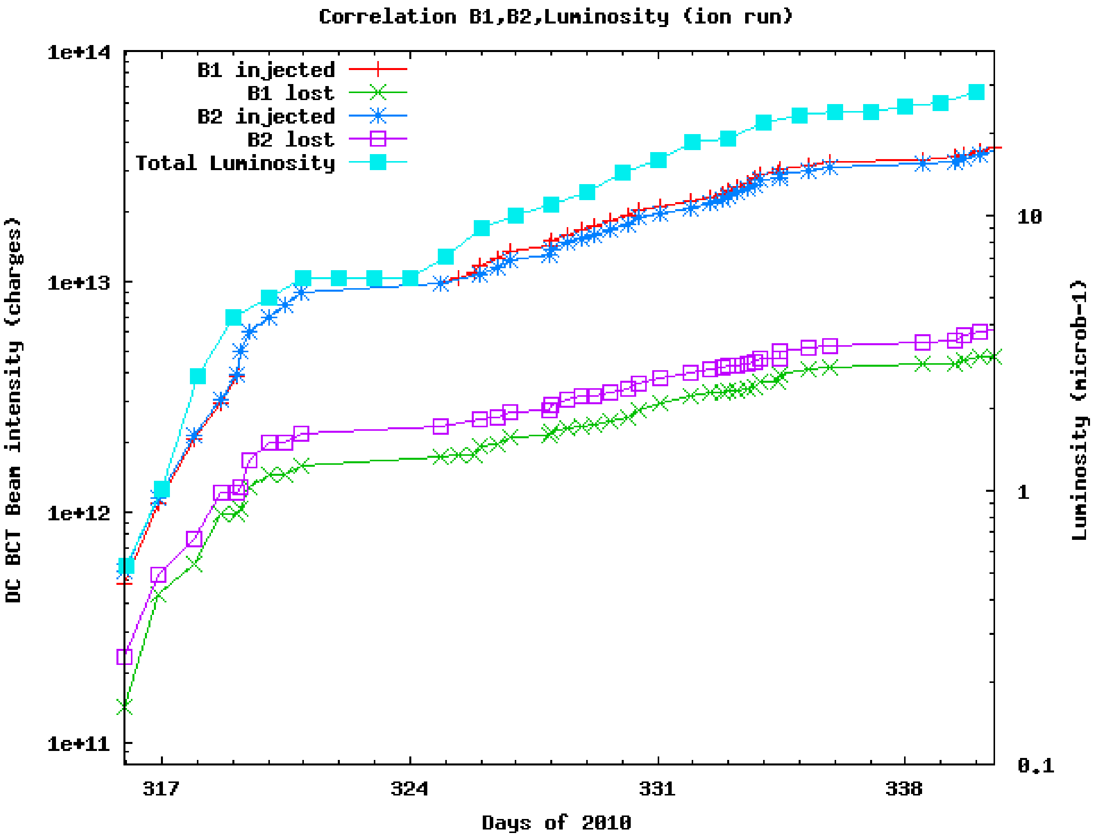


Benchmarks

Operation & Normalisation

Summary (Protons)		
In	6.02E+15	
Dumped	5.82E+15	96.70%
Lost in Machine	1.99E+14	3.30%
Of Lost protons		
Collisions	2.33E+13	11.73%
Elsewhere	1.76E+14	88.27%

Summary (Ions)		
In	7.46E+13	
Dumped	6.36E+13	85.25%
Lost in Machine	1.10E+13	14.75%
Of Lost protons		
Collisions	3.77E+10	0.34%
Elsewhere	1.10E+13	99.66%

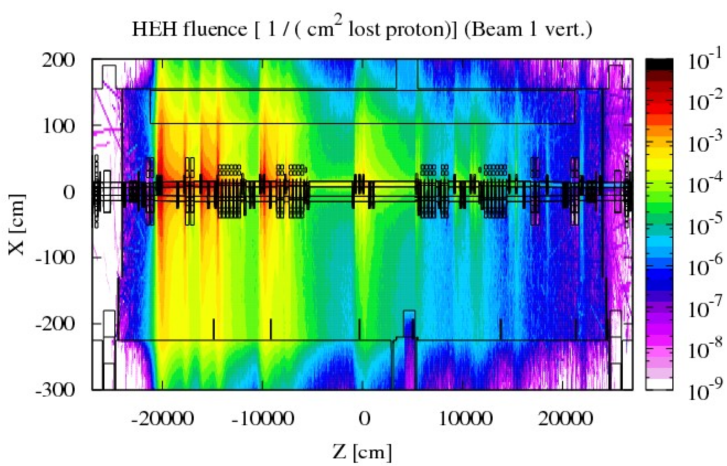


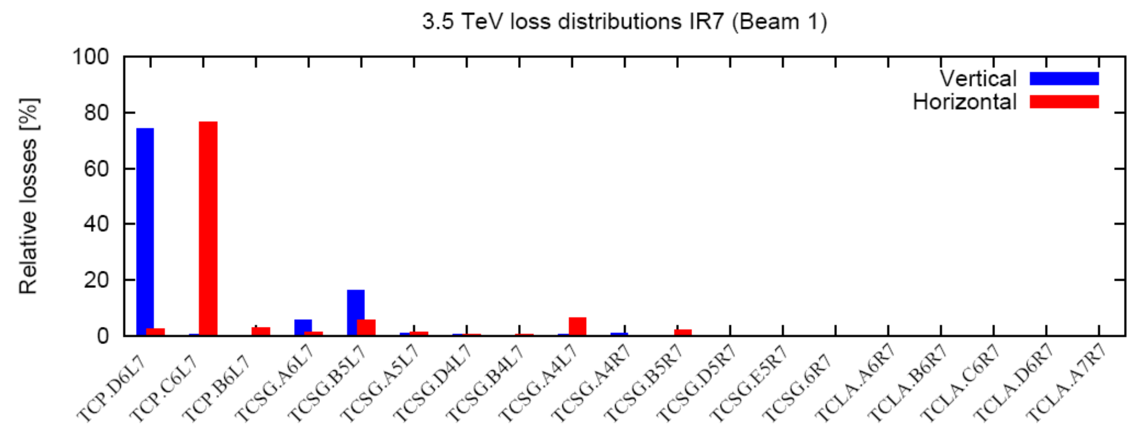
IR7 Benchmark - Loss Scenario 2010

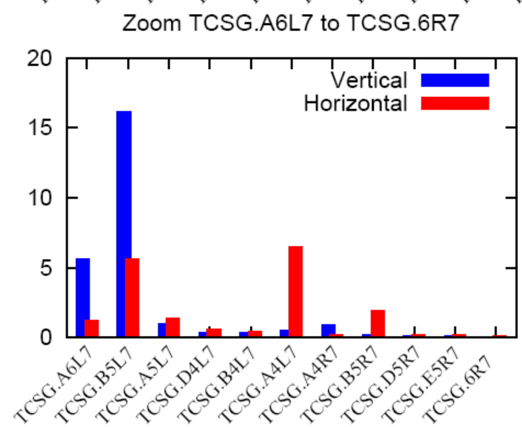
Summary (Protons B1)		
In	3.53E+15	
Dumped	3.44E+15	97.26%
Lost in Machine	9.67E+13	2.74%
Of Lost protons B1		
Collisions	1.17E+13	12.07%
Elsewhere	**8.50E+13**	87.93%

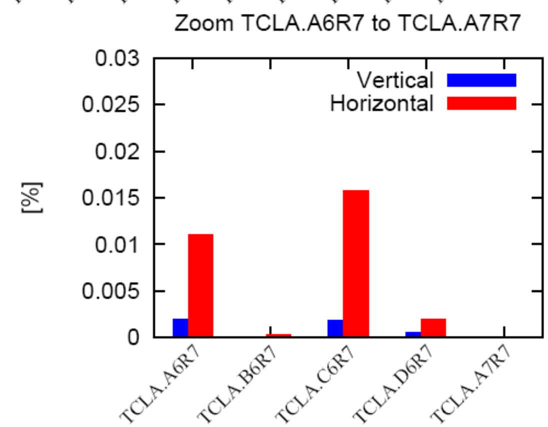
Summary (Protons B2)		
In	2.49E+15	
Dumped	2.38E+15	95.89%
Lost in Machine	1.02E+14	4.11%
Of Lost protons B1		
Collisions	1.17E+13	11.42%
Elsewhere	**9.05E+13**	88.58%

BLM ratio IR7 / IR3	**Ratio**	**% Loss in IR7**
TCSG.A6L7.B1 / TCSG.5L3.B1	3.1	**76**
TCSG.A6R7.B2 / TCSG.5R3.B2	5.6	**85**

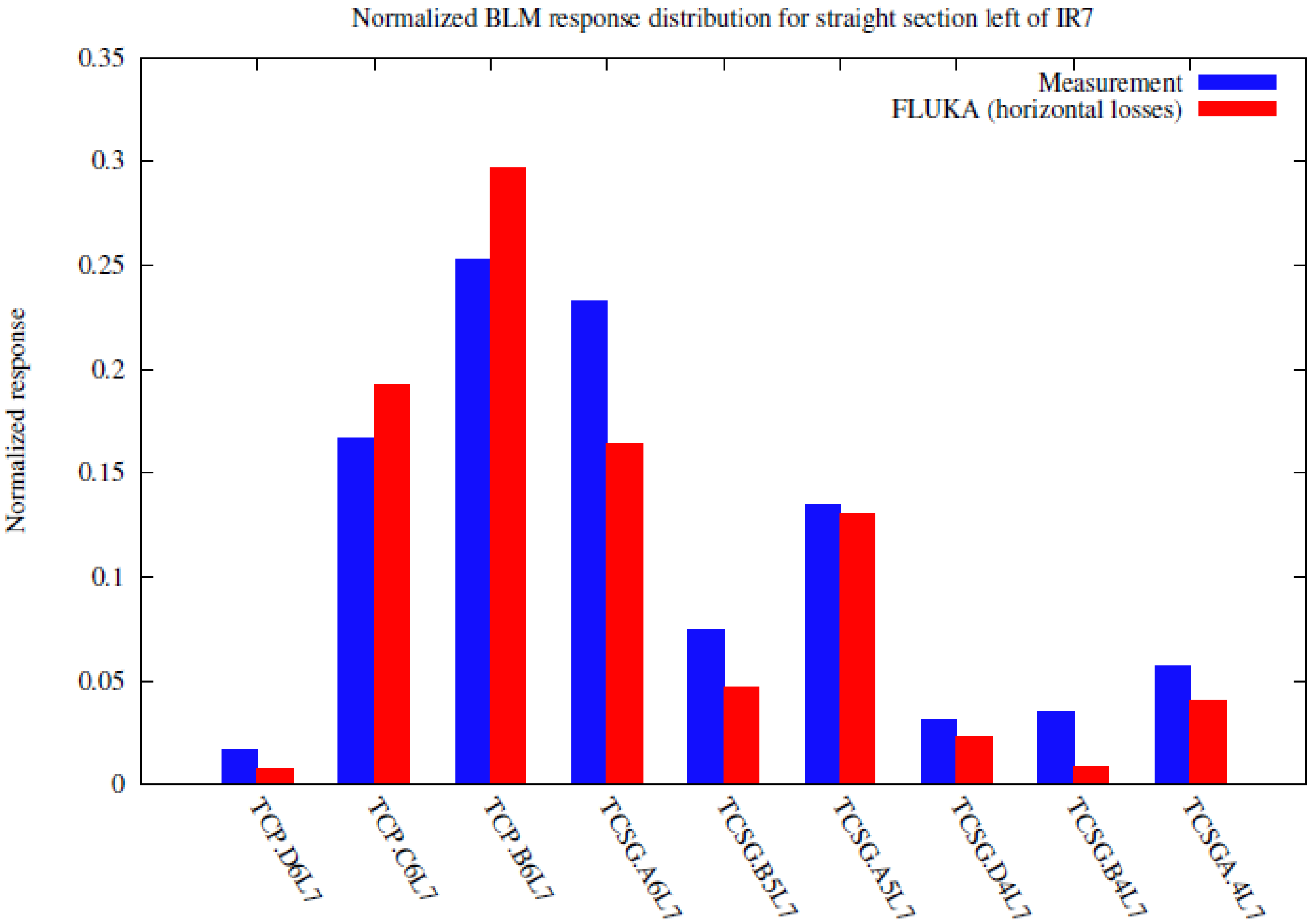






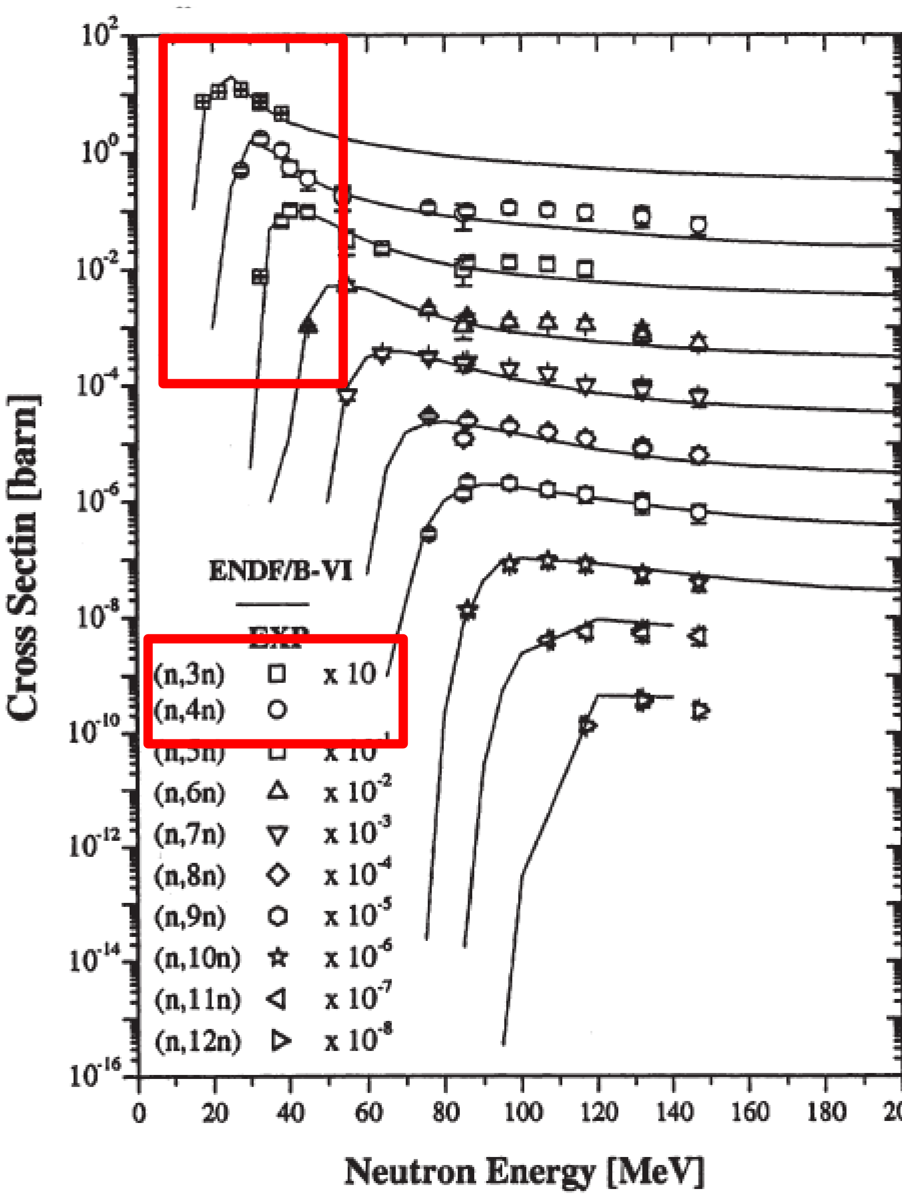


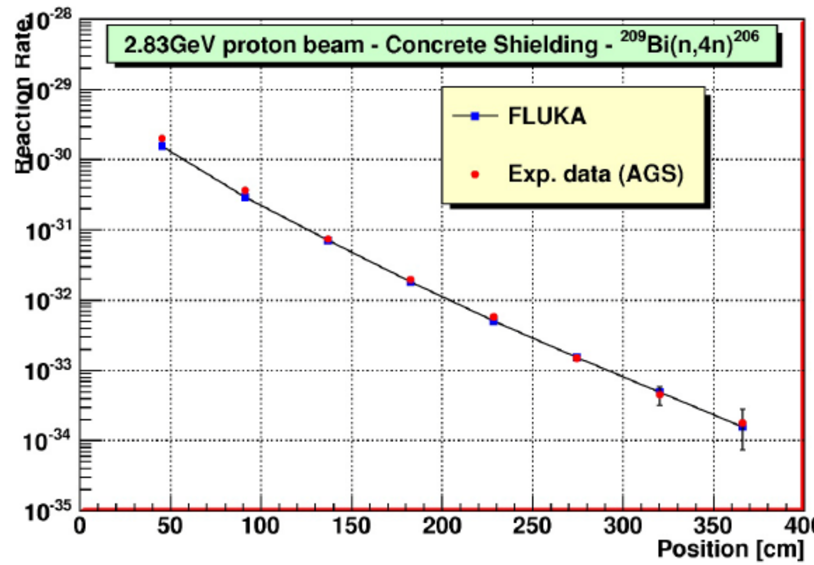
IR7 Benchmark - Loss Scenario 2010

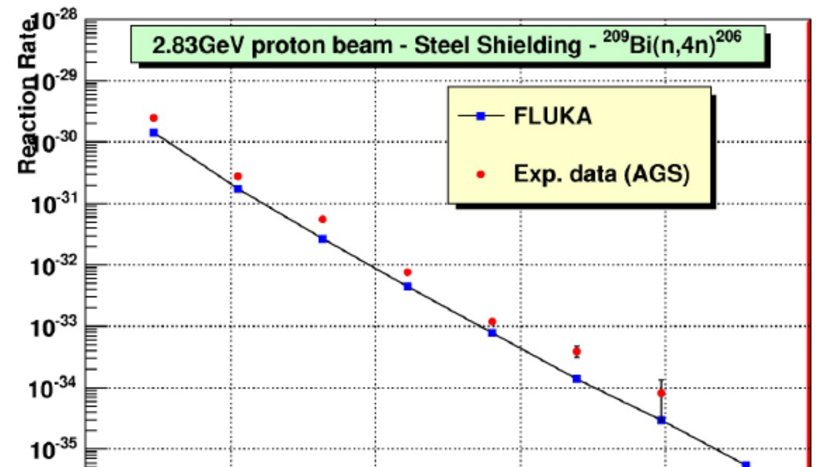


Shielding Benchmark:

© C. Adorisio, S. Roesler





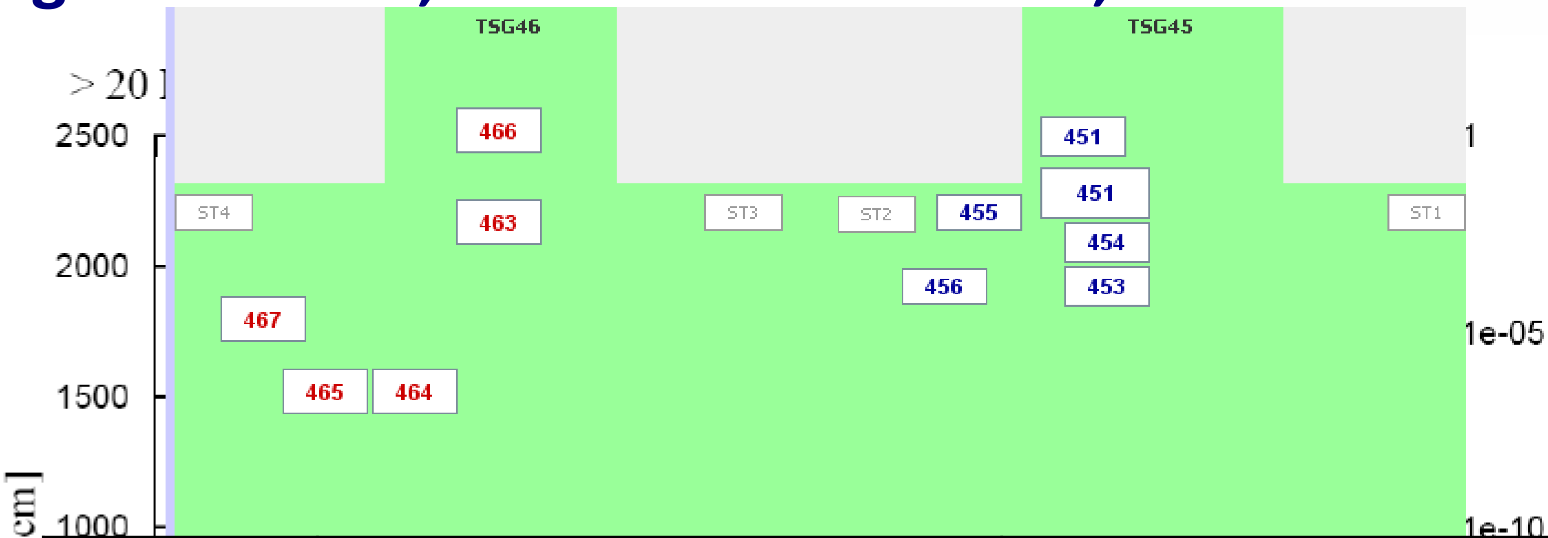


T. Nakamura, Journal of Nuclear and Radiochemical Sciences, Vol. 4, No.2, pp. R15-R24, 2003

RadMon/FLUKA @ CNRAD

© D. Kramer, K. Roeed

- **Very Complex Geometry**
- **Large Distances, ‘unknown’ materials, …**



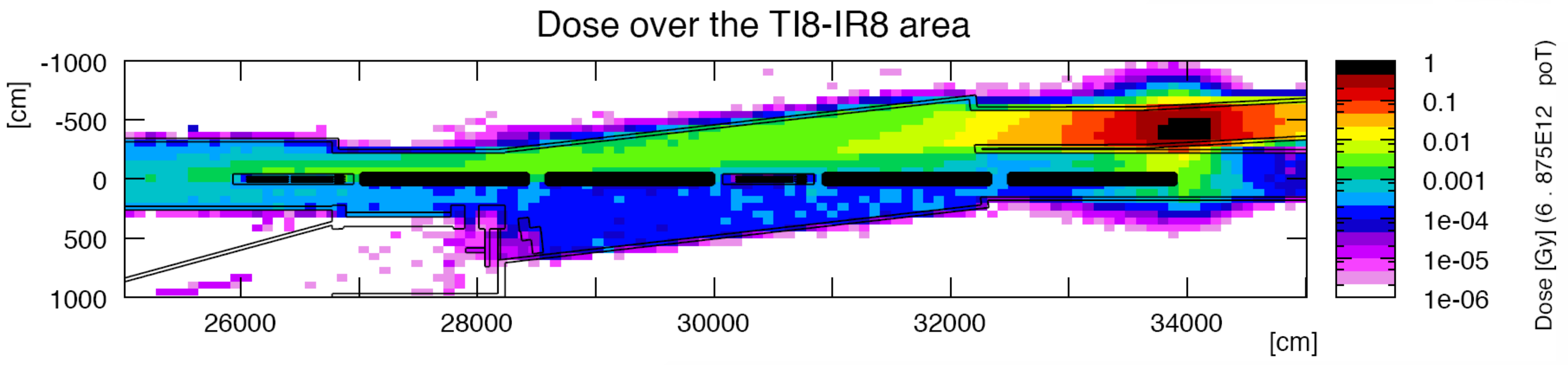
Area	High energy hadron fluence			Dose		
	RadMon [cm^{-2}/pot]	Fluka [cm^{-2}/pot]	Fluka/ RadMon	RadMon [Gy(Si)/pot]	Fluka [Gy(Air)/pot]	Fluka/ RadMon
455	4.3e-9	3.2e-9	0.74	1.4e-18	1.9e-18	1.36
456	1.8e-9	9.2e-10	0.50	7.4e-19	1.1e-18	1.48
467	3.7e-10	3.0e-10	0.81	1.2e-19	2.0e-19	1.67
463	1.7e-8	1.9e-8	1.12	3.3e-18	3.9e-18	1.18
451	1.8e-7	2.1e-7	1.17	2.8e-17	4.2e-17	1.50

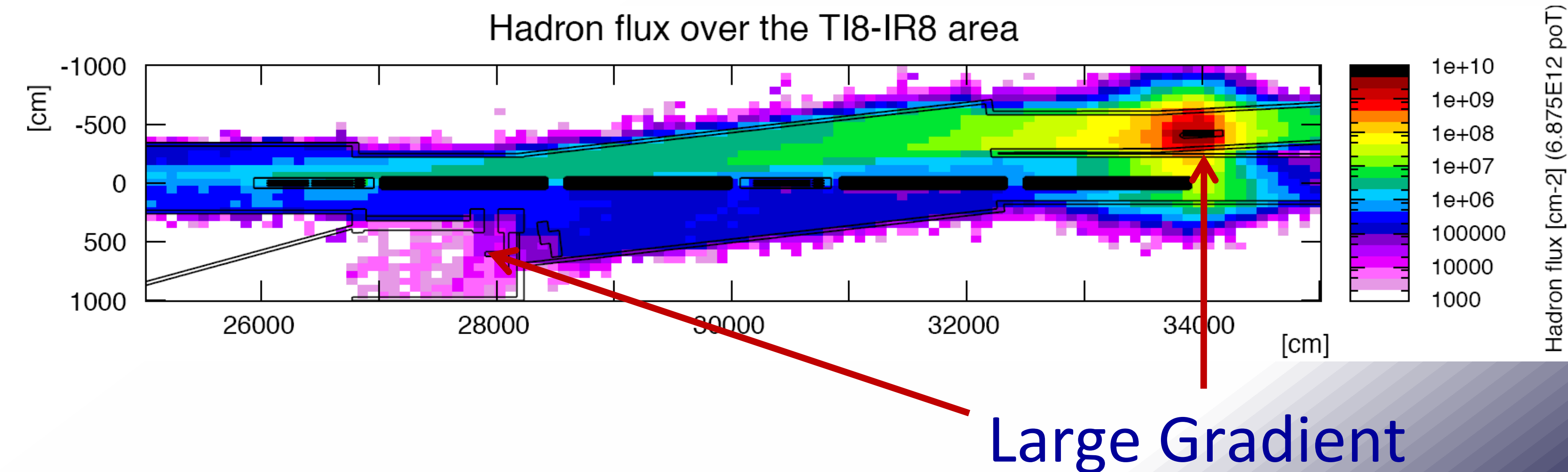
off-axis (rows 455, 456, 467)

line-of-sight to TSG4 (rows 463, 451)

Benchmark Simulations for TI2/8

© V. Boccone

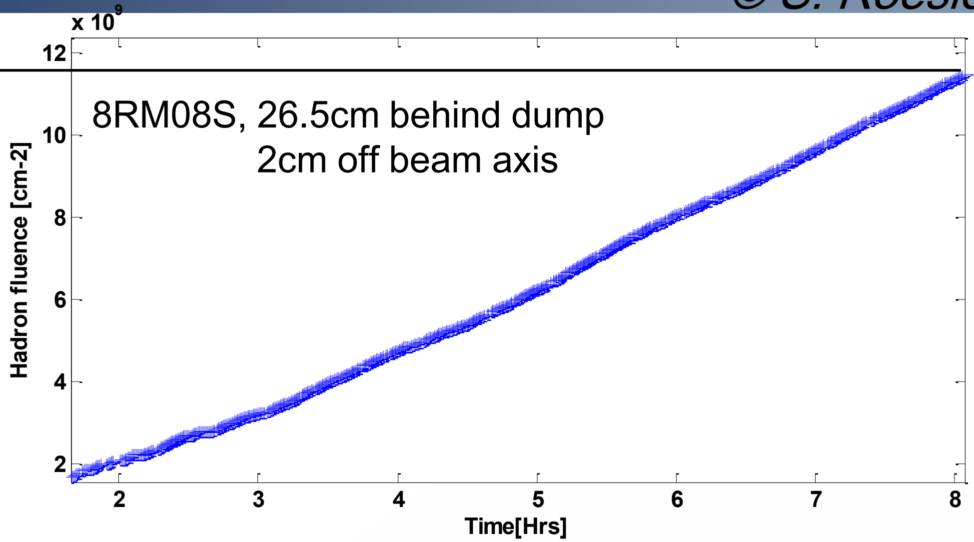




Injection: TED – High-E Fluence

© S. Roesler

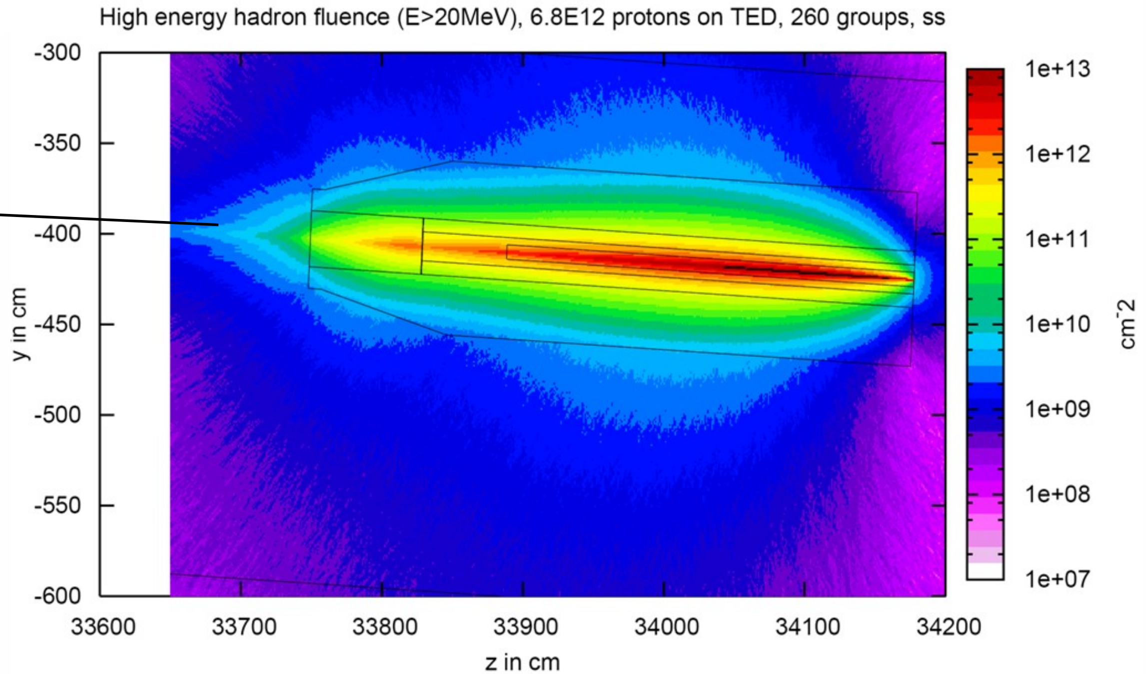
RADMON
1.2×10^{10} cm^{-2}



FLUKA
0.96×10^{10} cm^{-2} ± 3.2%
(scoring in a volume of 2 x 2 x 2cm^3)

- protons: 9.8%
- neutrons: 34.1%
- pos. pions: 21.9%
- neg.pions: 22.4%
- others: 11.8%

(1.03×10^{10} cm^{-2} ± 3.2%
scoring in a volume of 5 x 5 x 5cm^3)



Injection: TED – 1MeV N-Equiv.

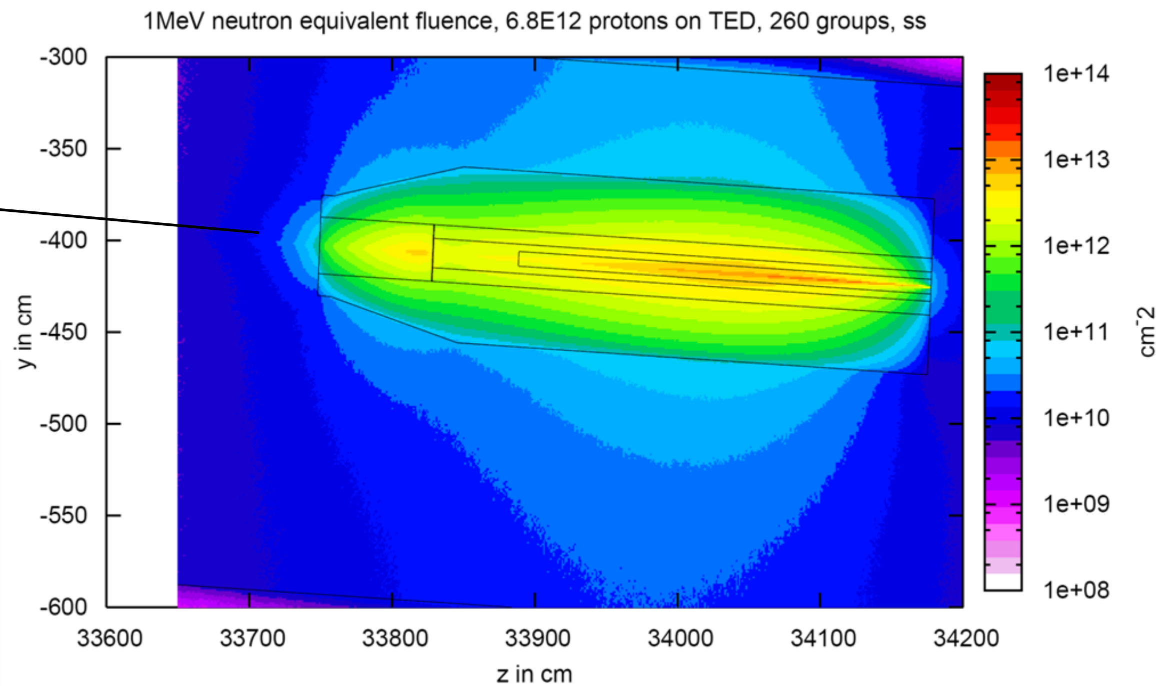
© S. Roesler

RADMON
2×10^{10} cm^{-2}

FLUKA
2.1×10^{10} cm^{-2} ± 2.5%
(scoring in a volume of 2 x 2 x 2cm^3)

protons:	4.6%
neutrons:	81.6%
pos. pions:	5.3%
neg.pions:	5.6%
others:	2.9%

(2.25×10^{10} cm^{-2} ± 1.8%
scoring in a volume of 5 x 5 x 5cm^3)

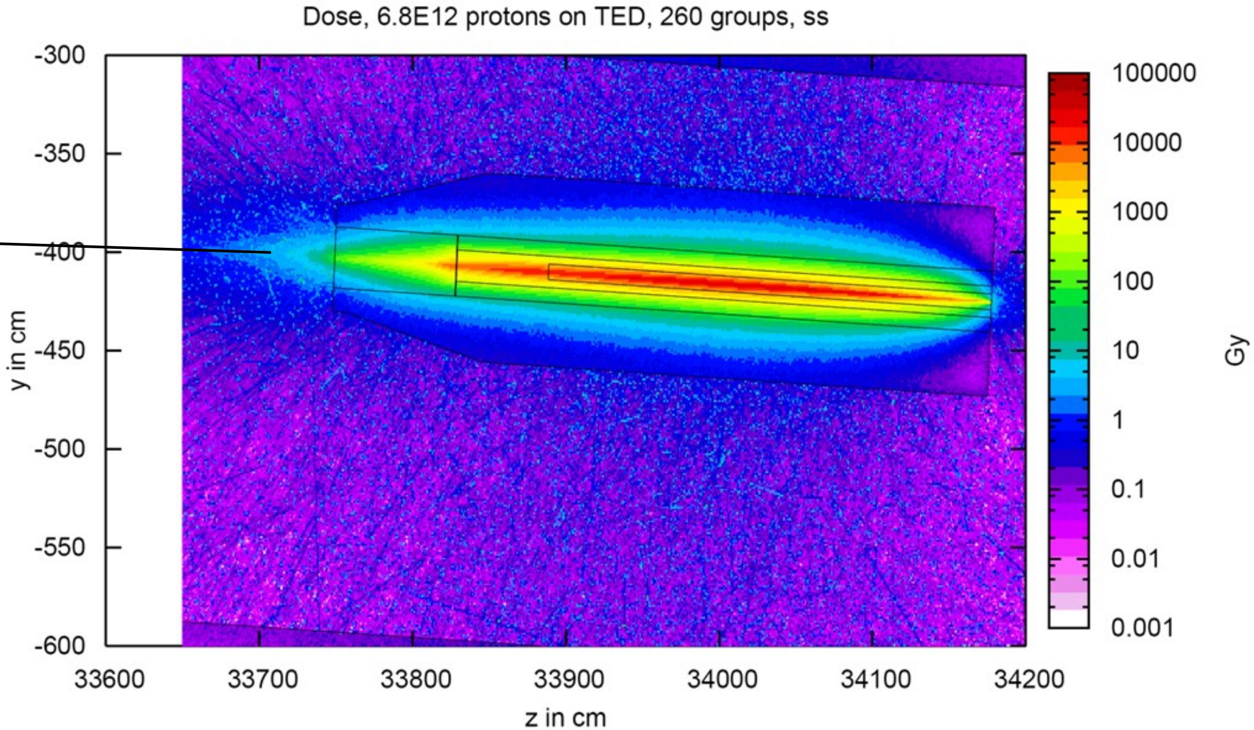


Injection: TED - Dose

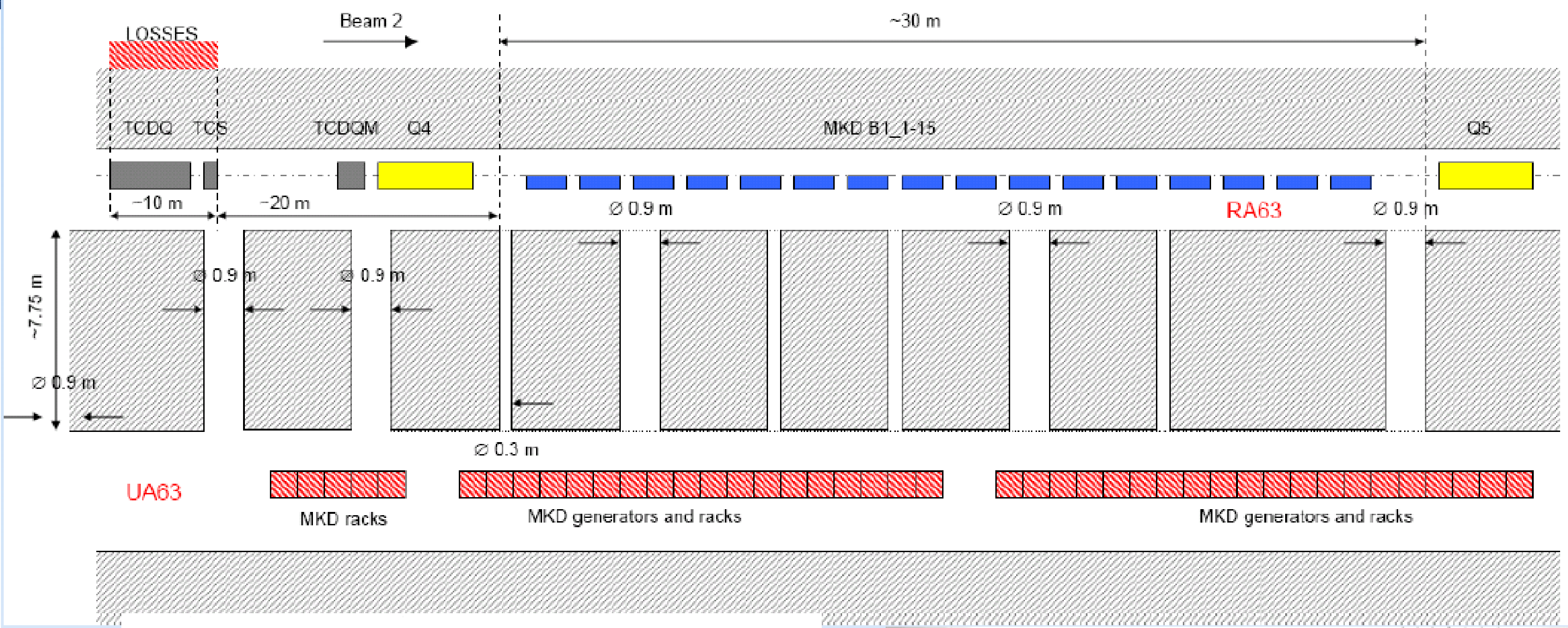
© S. Roesler

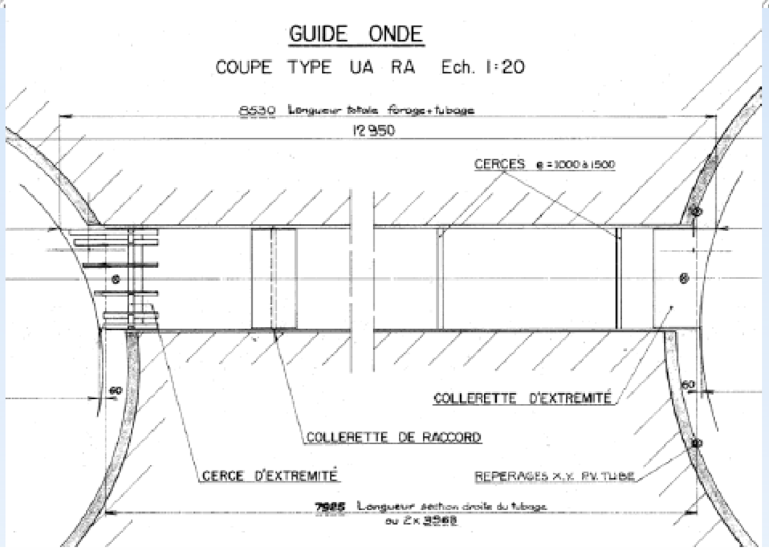
RADMON
4.73 Gy (Si)

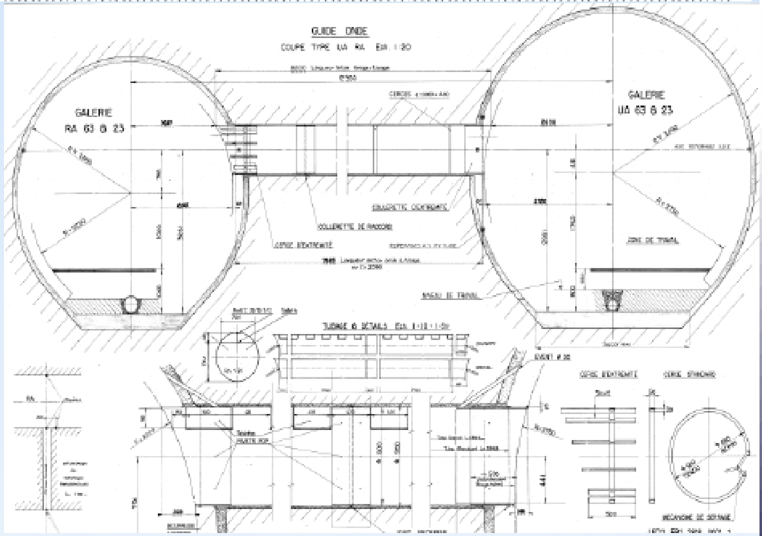
FLUKA
5.0 Gy (air) ± 10%
(scoring in a volume of 5 x 5 x 5cm³



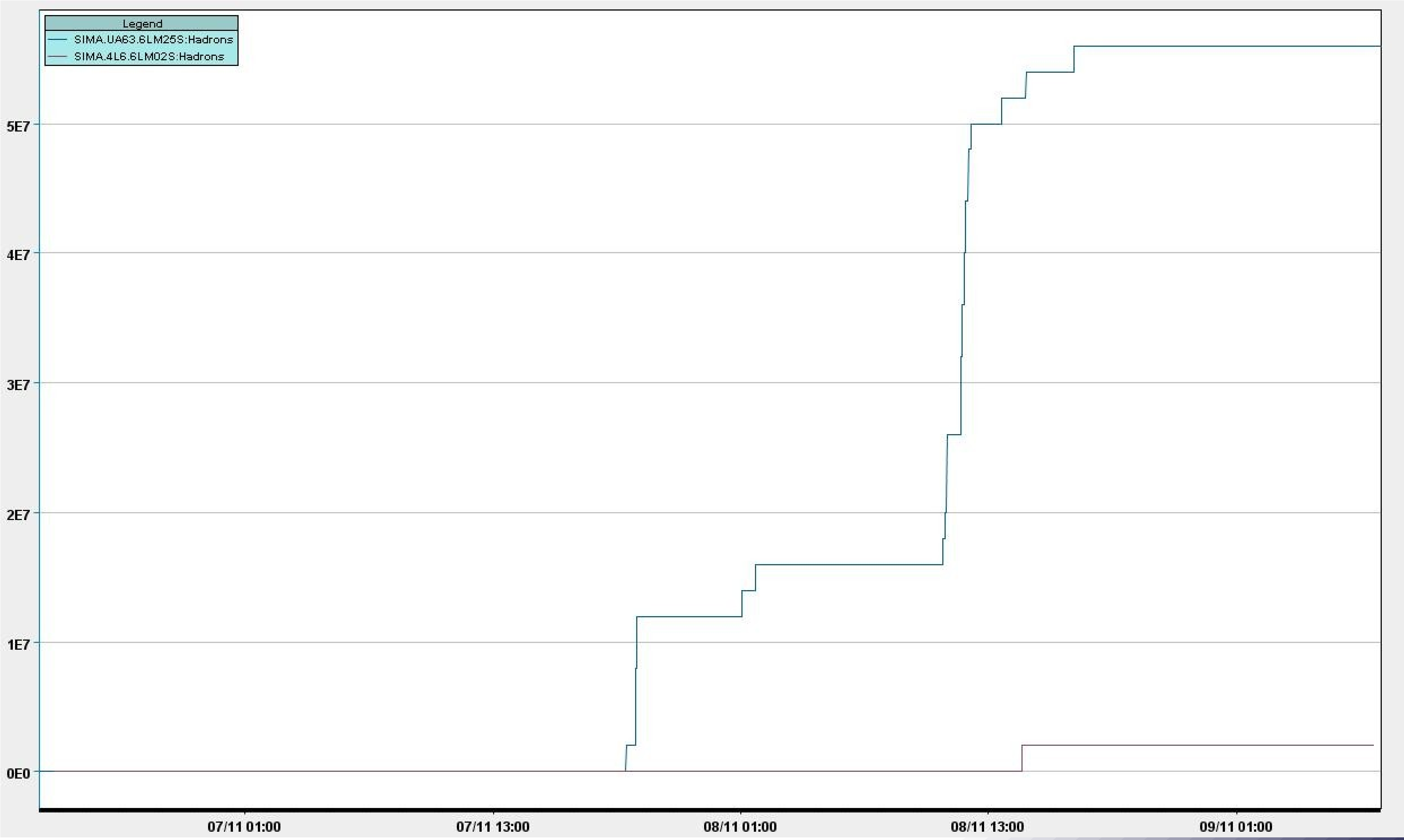
TCDQ Losses 07-09.11.2009



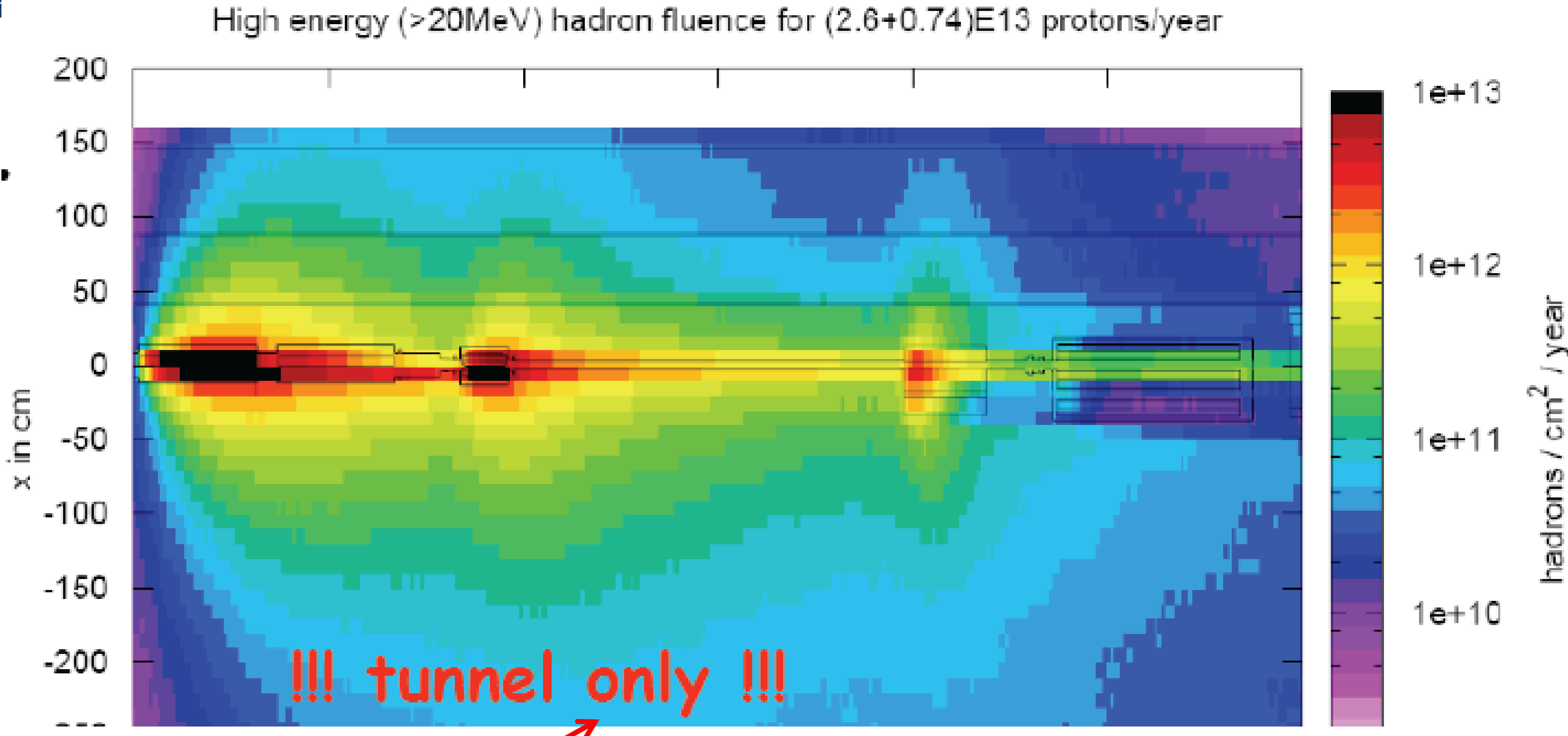




TCDQ Losses 07-09.11.2009



TCDQ Losses 07-09.11.2009

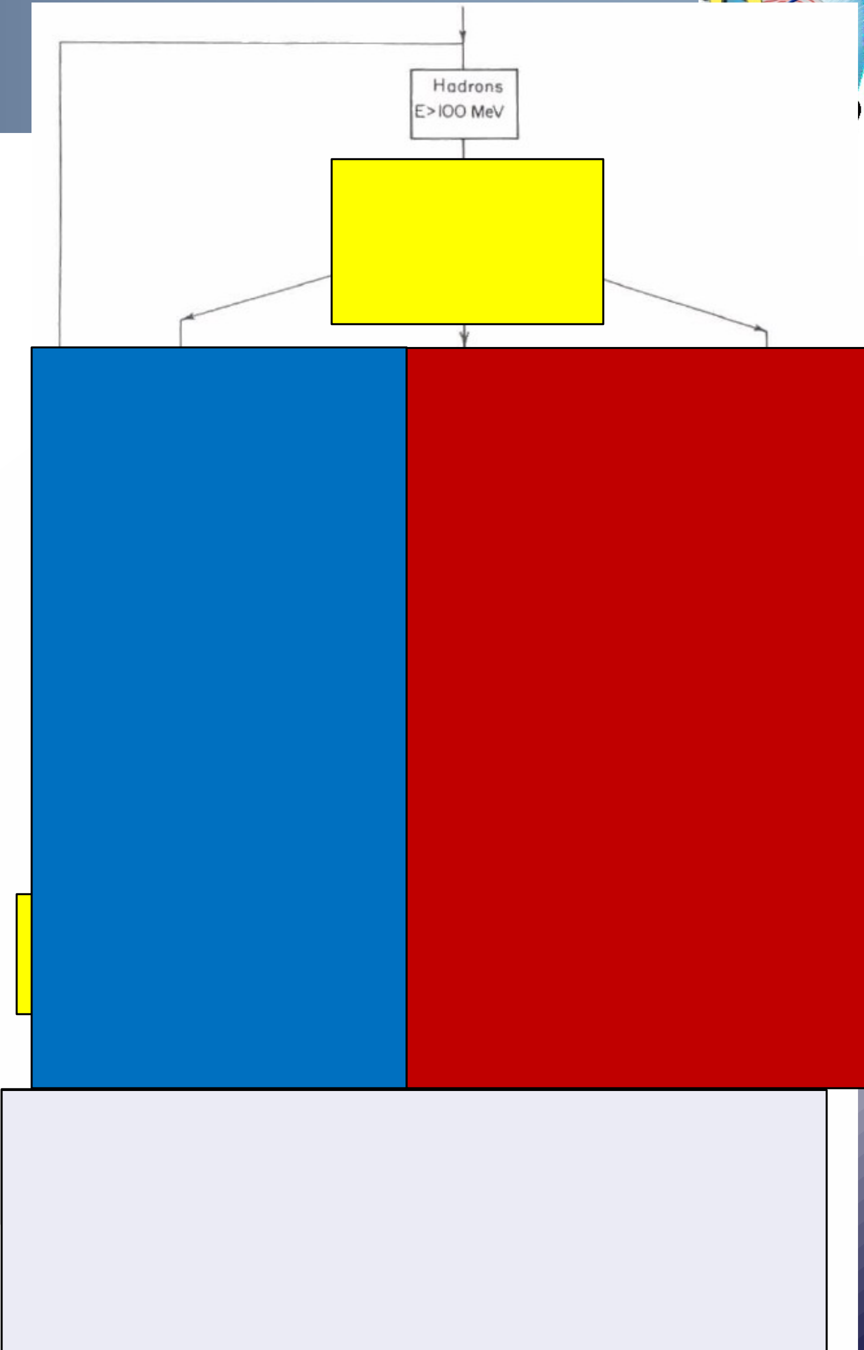


- ~3×10^{10} cm^{-2} high-E hadrons for 7TeV and 2.6×10^{13}
- rough scaling: ~2×10^{9} cm^{-2} at 450GeV
- this results in ~4×10^{5} per 5×10^{9} shot
- We had about 50 (full) shots on the TCDQ -> ~2×10^{7} expected
- 5.6×10^{7} measured at the tunnel location (~30counts!)
- In the UA, the monitor is set to 3V (factor of 10 more sensitive) -> nothing measured -> confirms the expected attenuation factor of ~1000

FLUKA

Physics Overview

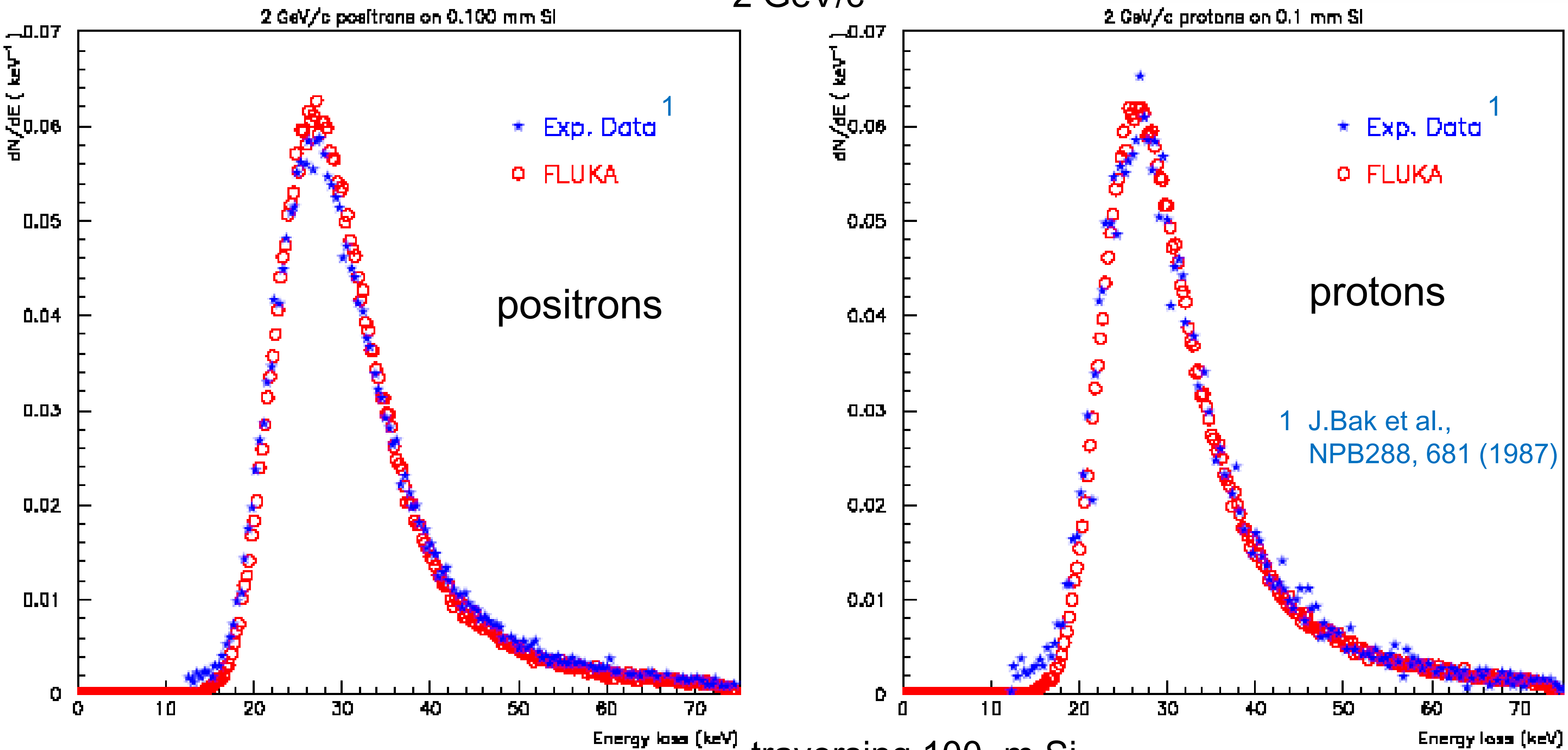
- Nuclear Interaction
- Hadronic Cascade
- Electro-Magnetic Cascade



Ionization (Positrons/Protons)

ionization fluctuations

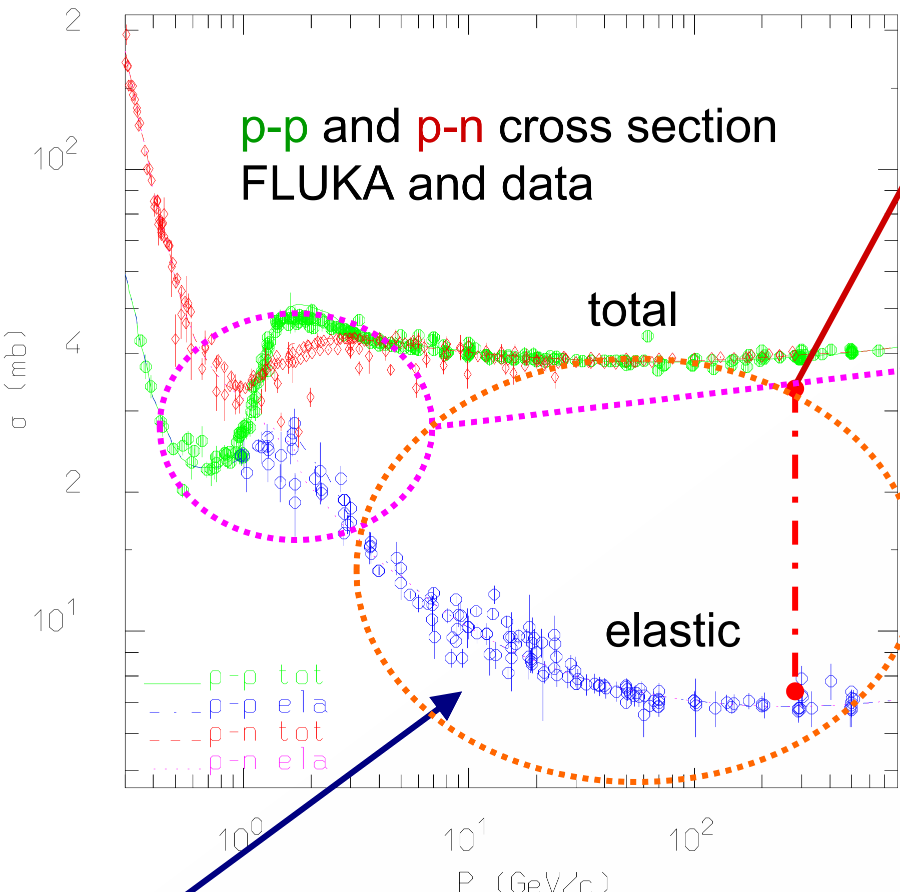
2 GeV/c



traversing 100μm Si

stochastic nature of the energy loss in collisions with the electrons of the material
=> range straggling

Hadron-Nucleon Interaction



Particle production interactions: two kinds of models

Those based on "resonance" production and decays, cover the energy range up to 3–5 GeV

Those based on quark/parton string models, which provide reliable results up to several tens of TeV

Elastic, charge exchange and strangeness exchange reactions

- $N_1 + N_2 \rightarrow N_1' + N_2' + \pi$ threshold at 290 MeV, important above 700 MeV
- $\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV
- *anti-N + N* opens at rest !

Hadron-Nucleus Interactions

P E A N U T

Target nucleus description (density, Fermi motion, etc)

↓

Glauber-Gribov cascade with formation zone

↓

Generalized IntraNuclear cascade

↓

Preequilibrium stage
with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

↓

Evaporation/Fragmentation/Fission model

↓

γ deexcitation

t (s)

10^{-23}

10^{-22}

10^{-20}

10^{-16}

R2E Scoring in FLUKA

- All important quantities to estimate risks of damage to electronics can be directly scored in FLUKA :

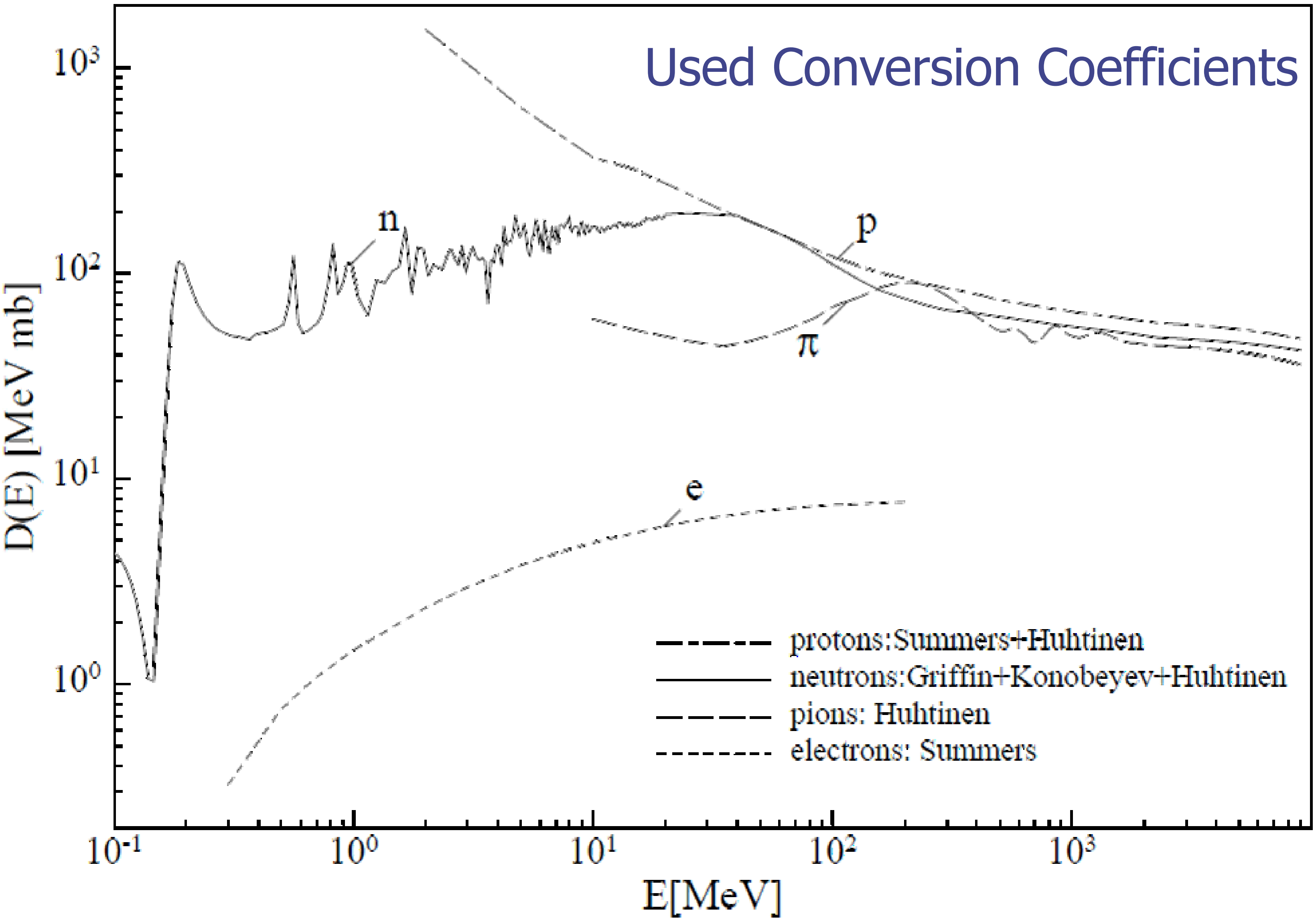
Cumulative damage:

- Energy deposition (total dose) by scoring DOSE with any 'energy deposition like estimator' (*e.g.*, USRBIN)
- Si Lattice displacement (1-MeV neutron equivalent particle fluxes) with any 'fluence like estimator' (*e.g.*, USRTRACK)

Stochastic failures (SEU):

- "high" energy hadron fluences ("E>20 MeV") with any 'fluence like estimator' (*e.g.*, USRTRACK)
  (**the option of special threshold functions [user defined] is currently in development and will be included in the next release together with the scoring related to the "damage by thermal neutrons"**)

1MeV Neutron Equivalent



Related Scoring (FLUKA)

DOSE total absorbed dose in (obviously...) GeV/g!

SI1MEVNE Silicon 1 MeV-neutron equivalent fluence

HADGT20M Hadrons fluence with energy > 20 MeV

- **USRTRACK** scores average $d\Phi/dE$ (differential fluence) in a given region (SI1MEVNE HADGT20M or any particle type)
- **USRBDX** scores for the same quantities average $d^2\Phi/dEd\Omega$ (double-differential fluence or current) on a given surface (between two regions)
- **USRBIN** scores the spatial distribution either of deposited dose, or fluence (1MeV or 20MeV) in a regular mesh (cylindrical or Cartesian) described by the user
- **USRBIN** also scores the same quantites on a region basis
- **USRDUMP** allows for an event-by-event analysis

- Theses **scoring options** together with **the analysis of particle energy spectra** allows a detailed study in order to select best possible locations for electronics or efficiently design shielding implementations