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CERN, 11-15 May 2009

Quality control for electronics exposed to Radiation in the ATLAS experiment at CERN and in ITER

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ITER International Organization

Outline

- Radiation issues
- The ATLAS approach
  - ATLAS experiment
  - Radiation hardness assurance
  - Examples of radiation test results
  - Summary
- The ITER approach
  - ITER Project
  - Radiation hardness assurance

Radiation issues

2 families: cumulated effects, and instantaneous (single event effects)

Cumulated effects

- Total Ionizing Dose (TID)
  - Energy deposited in the electronics by radiation in the form of ionisation.
  - Unit: Gray (Gy), 1 Gy = 100 rad = 1 joule / kg.
  - Affects all electronics devices
- Non-Ionizing Energy Loss (NIEL)
  - Displacement damage, mainly due to hadrons (n, p, π, …)
  - Unit : particles / cm^2
  - Energy dependent → normalized to 1 MeV neutrons equivalent / cm^2.
  - Bipolar JT, LEDs, lasers, CCDs, optocouplers, photo-BJTs,… are affected
  - CMOS are not affected (majority carriers)

Radiation issues (2)

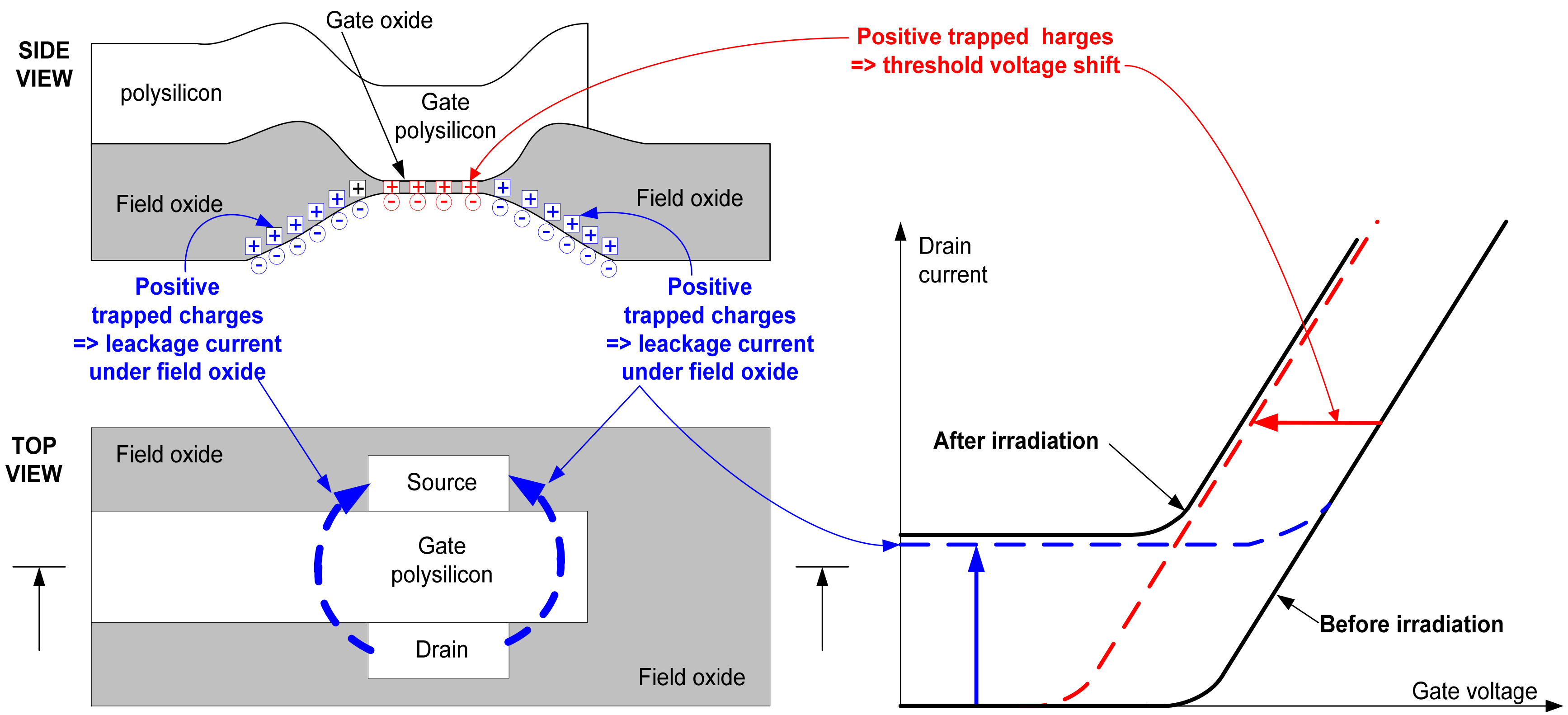
Single Event Effects (SEE)

- Destructive effects:
  - SEL (Single Event Latch-up)
  - SEB (Single Event Burnout
  - SEGR (Single Event Gate Rupture
  - …
- Transient effects: upsets
  - SEU : Single Event Upset (logic)
  - SET : Single Event Transient (linear)
- SEEs are *instantaneous* effect
  - May occur just after the beam is switched on

Radiation issues : TID (total ionizing dose)

- Mechanism : charge trapping in oxides and interfaces
  => threshold voltage (Vt) shift, leakage current, noise, …

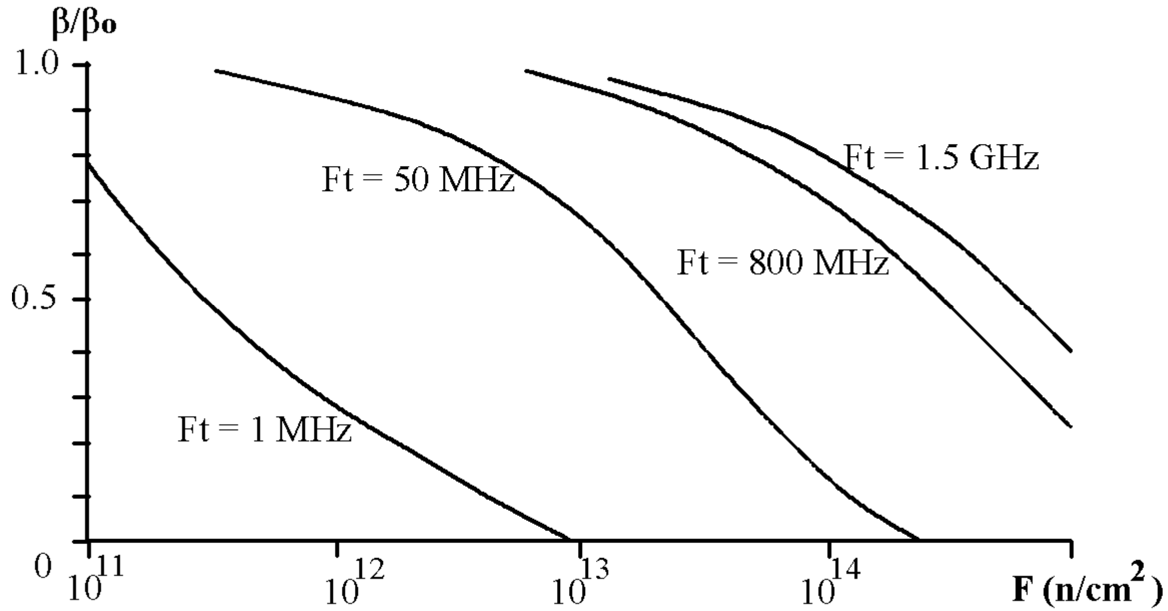
Example: leakage current and Vt shift induced in NMOS by total dose



Radiation issues : NIEL (Non-Ionizing Energy Loss)

- Mechanism : bulk defects in semiconductors
  => decrease of BJT gain β, noise, …
- Cumulated damage => delayed effect

Example: dependance of BJT gain decrease on base thickness



PRACTICAL CRITERION

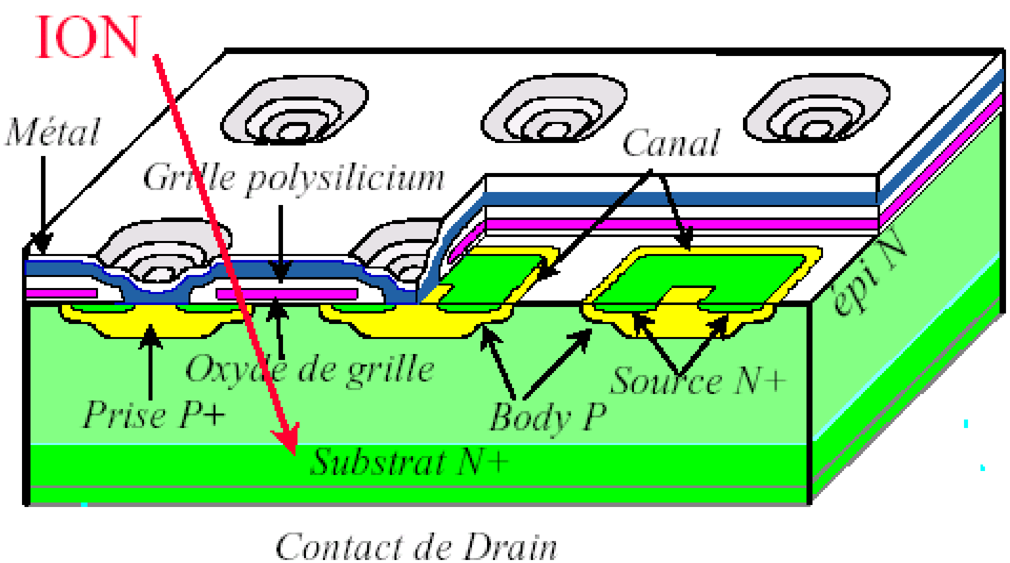
Rad-hard bipolars:
- **High Ft**
- **Thin base**

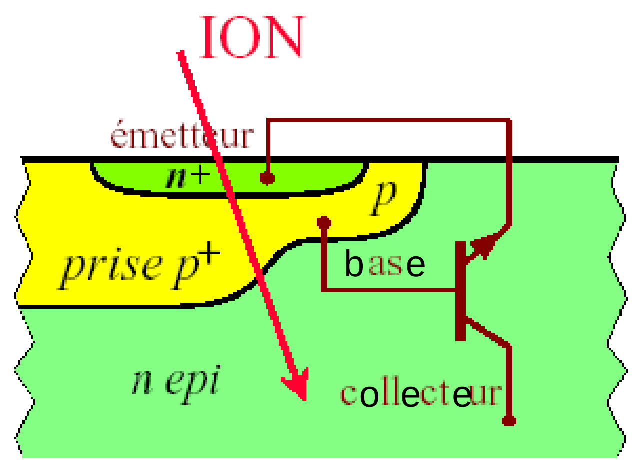
Non rad-hard bipolars:
- **low Ft**
- **Thick base**
 (latteral, power, phototransistors)

(lateral, power, phototransistors)

Radiation issues : SEE (Single Event Effects)

Example : Single Event Burnout





Power MOSFET (VDMOS) = 15000 cells in parallel

Triggering of the parasitic bipolar transistor ⟶ Burnout

LHC experiments

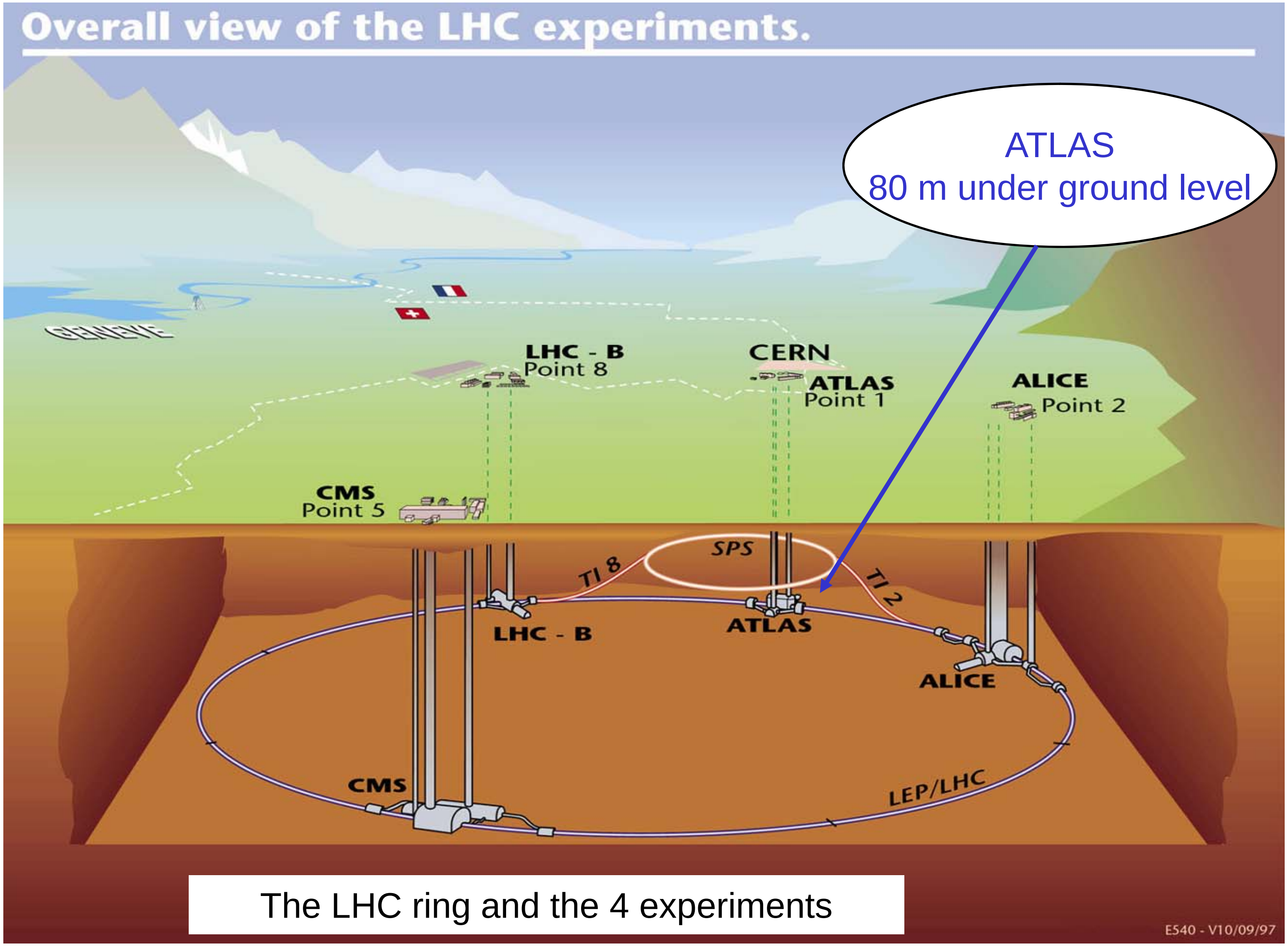
LHC beams

2 proton beams in opposite direction

Energy:
7 TeV – 7 TeV

Luminosity:
10^{34} p.cm^{-2}.s^{-1}

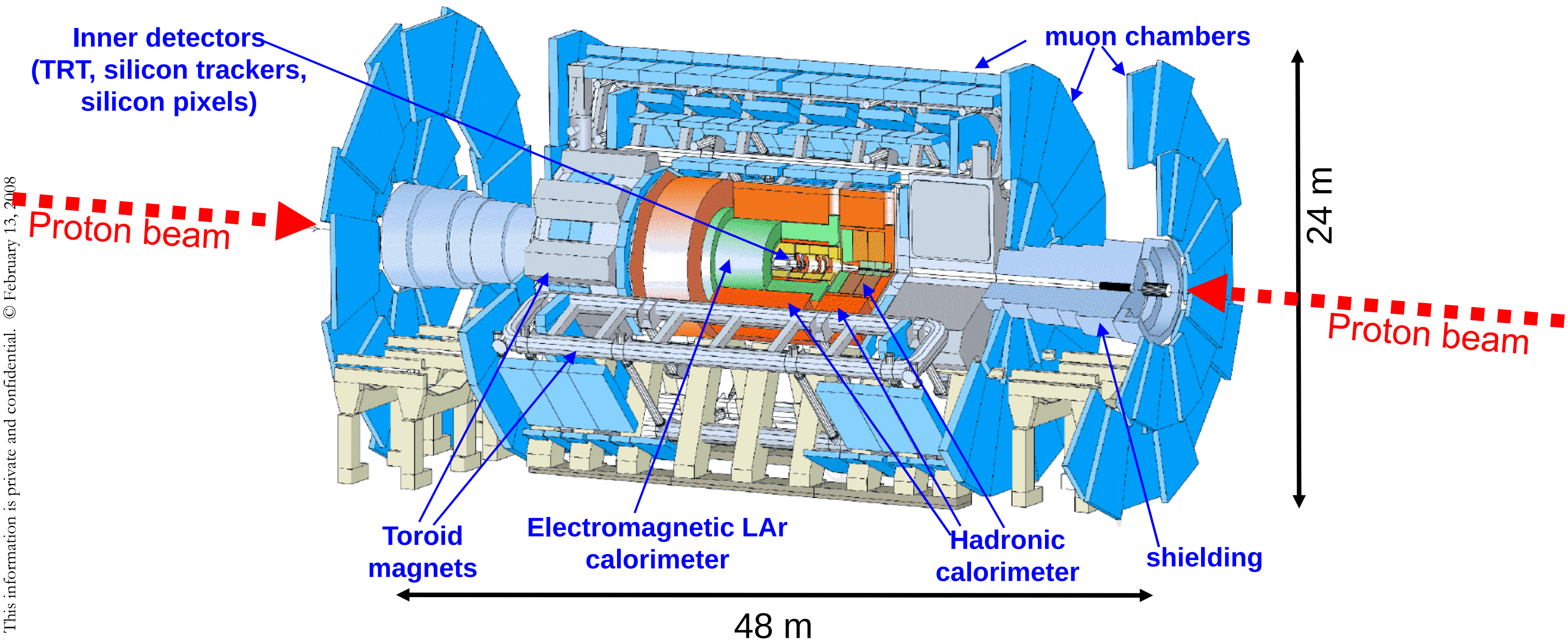
Repetition rate:
40 MHz



The LHC ring and the 4 experiments

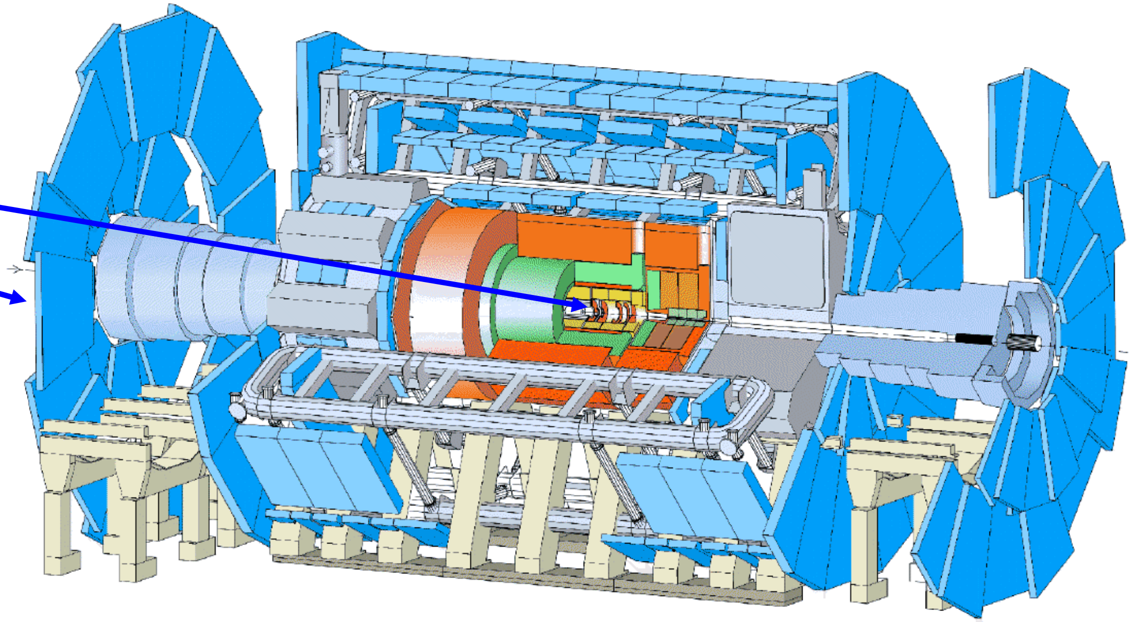
LHC experiment: ATLAS

- International collaboration, about 1900 people from ~150 institutions from 34 partner countries (incl. EU, US, Japan, Russia, Israel, Brazil, …)
- 300 millions Euros among which 75 millions Euros for electronics
- One of the two largest detector of the LHC experiments
- 15 main systems, each of them containing electronics



Radiation constraints (10 years)

- TID
  - 1 MGy (Pixels)
  - 2 Gy (Cavern)
- NIEL
  - 4.10^{14} n.cm^{-2} (Pixels)
  - 5.10^{10} n.cm^{-2} (Cavern)
- SEE
  - 4.10^{14} h.cm^{-2} (Pixels)
  - 1.10^{10} h.cm^{-2} (Cavern)
  - hadrons > 20 MeV



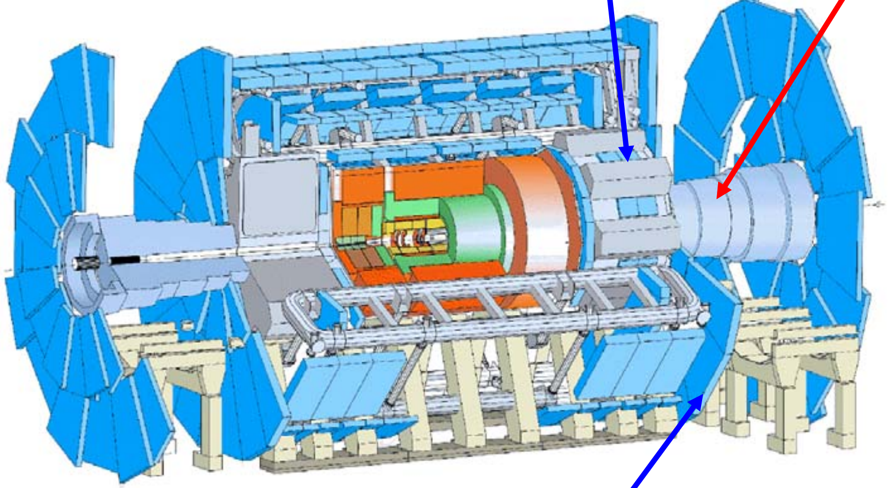
Simulations tools : FLUKA and G3-CALOR

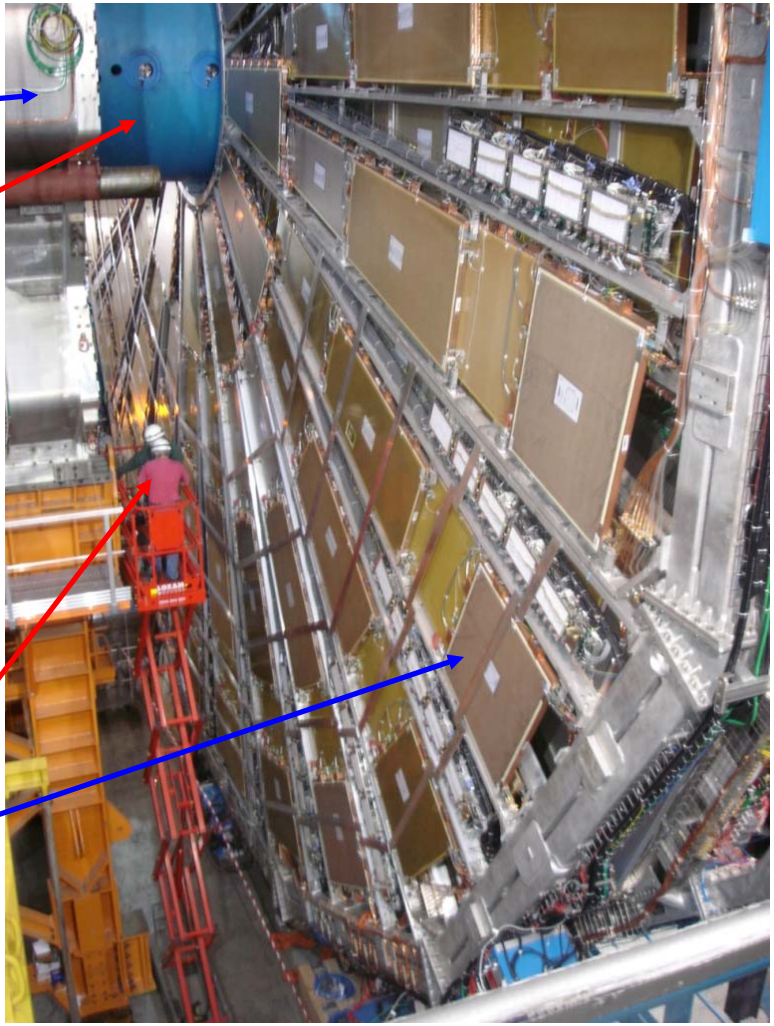
Front-end electronics (readout and pre-treatment) and some of the power supplies cannot be installed remotly (away from radiation), and cannot be shielded (it must be as transparent as possible to avoid shadows or parasitic images on particle detectors)

ATLAS systems

Toroidal magnets (supra)

shielding

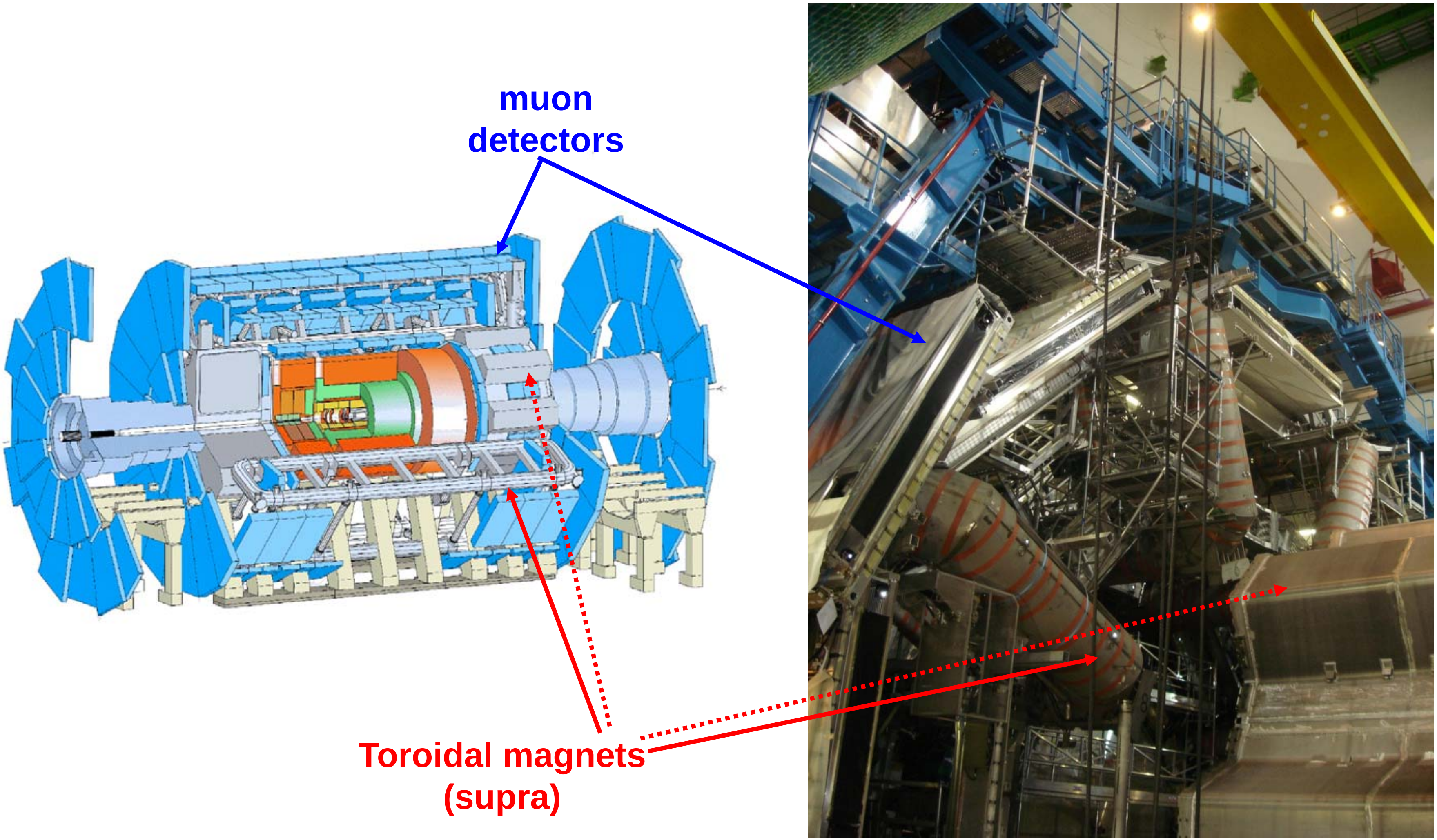




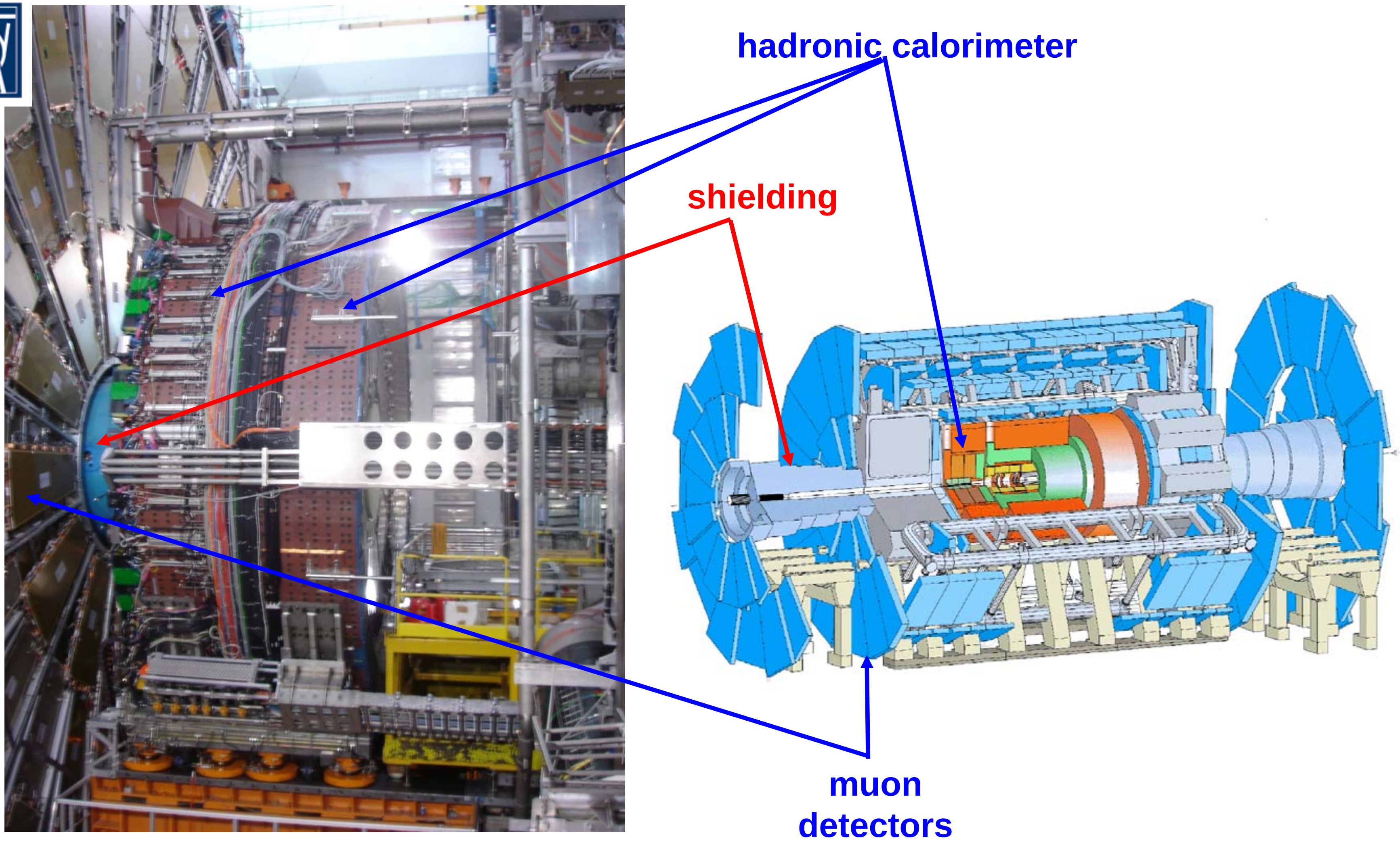
man

muon detectors

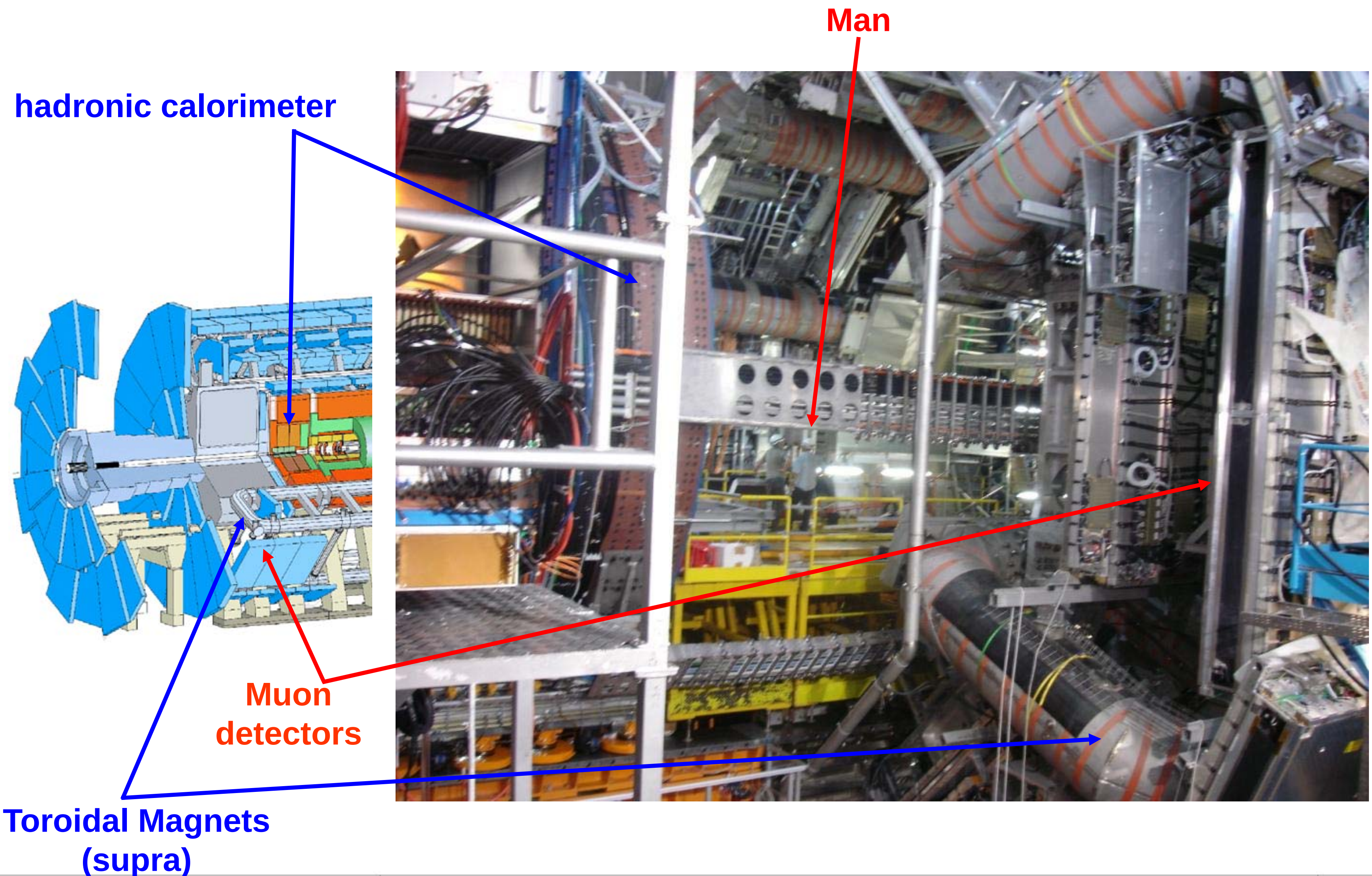
ATLAS systems



ATLAS systems



ATLAS systems



ATLAS policy on radiation tolerant electronics

- Goal: reliability of the experiment with respect to radiation
  - Estimated lifetime of components must cover foreseen lifetime of LHC experiments, or at least a large fraction of it.
  - Rates of transient or destructive SEE must be acceptable.
  - Safety systems must remain always functionnal.
- Mandatory for each sub-system of the experiment
  - Particular attention was paid to the identification of critical elements and to their possible failure modes.
- Coherent approach
  - Same rules for every system
- Based on recognized test methods
  - E.g. US-DOD MIL-STD-883E ; ESA SCC basic spec. No 22900 and 25100
- Simple, efficient and cost-effective

Main procedure

ATLAS project	ATLAS Policy on Radiation Tolerant Electronics				
ATLAS Project Document No.	*Institute Document No.*	*Created:*	Nov. 1997	*Page*	1 of 46
ATC-TE-QA-0001	EB-00-016	*Modified:*	21 July 2000	*Rev. No.*	2

ATLAS POLICY ON RADIATION TOLERANT ELECTRONICS

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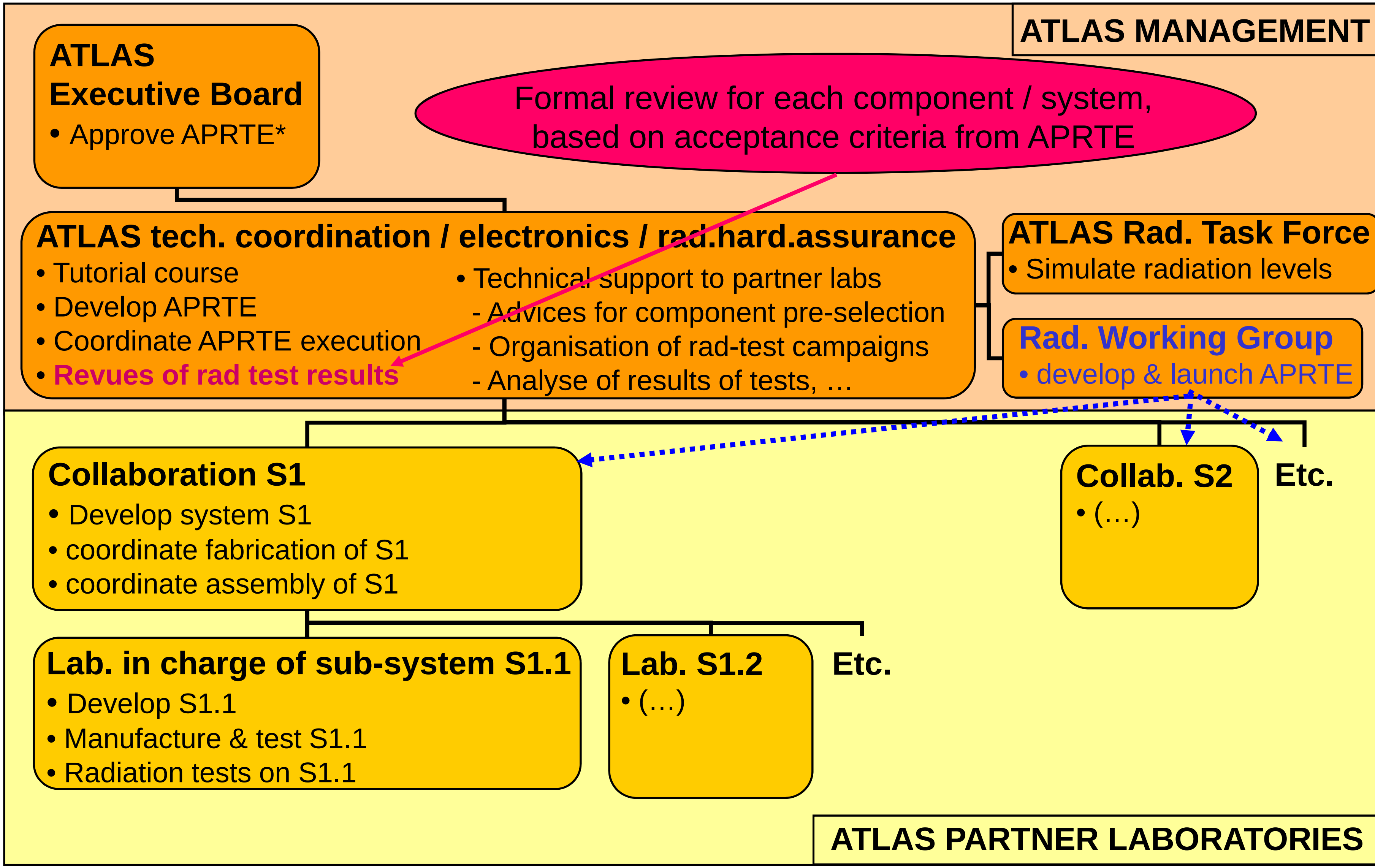
Distribution List

ATLAS Executive Board members;
ATLAS Electronics Co-ordinators;
ATLAS Radiation Hardness Assurance Working Group members.

Content:

- **Strategy for electronics procurement (ASICs, COTS)**
- **Radiation Tolerance Criteria**
- **Radiation Test Methods**
- **Lists of radiation facilities**
- **Standard test report form**
- **(…)**

Organisation



Tutorial course

- **To establish a basic knowledge on radiation effects on electronics**

- **Part 1 : Radiation effects on electronic components**
  - Radiation effects on materials (semiconductors, insulators, etc.)
  - Radiation units
  - Radiation effects on electronic devices

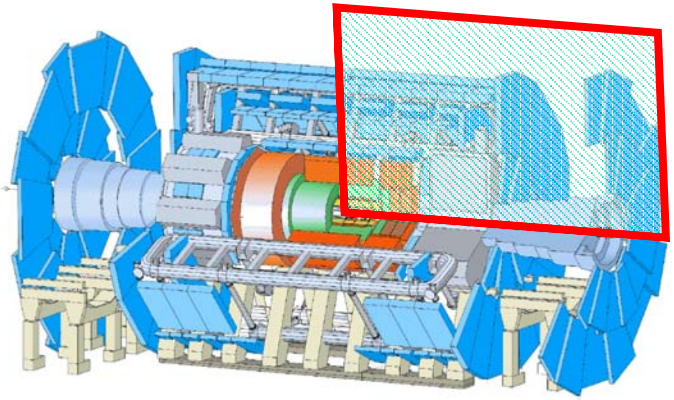
- **Part 2 : Radiation effects on electronic circuits**
  - Cumulated radiation effects on digital and analog circuits
  - Single event effects on digital and analogue circuits
  - Examples of mitigation technics

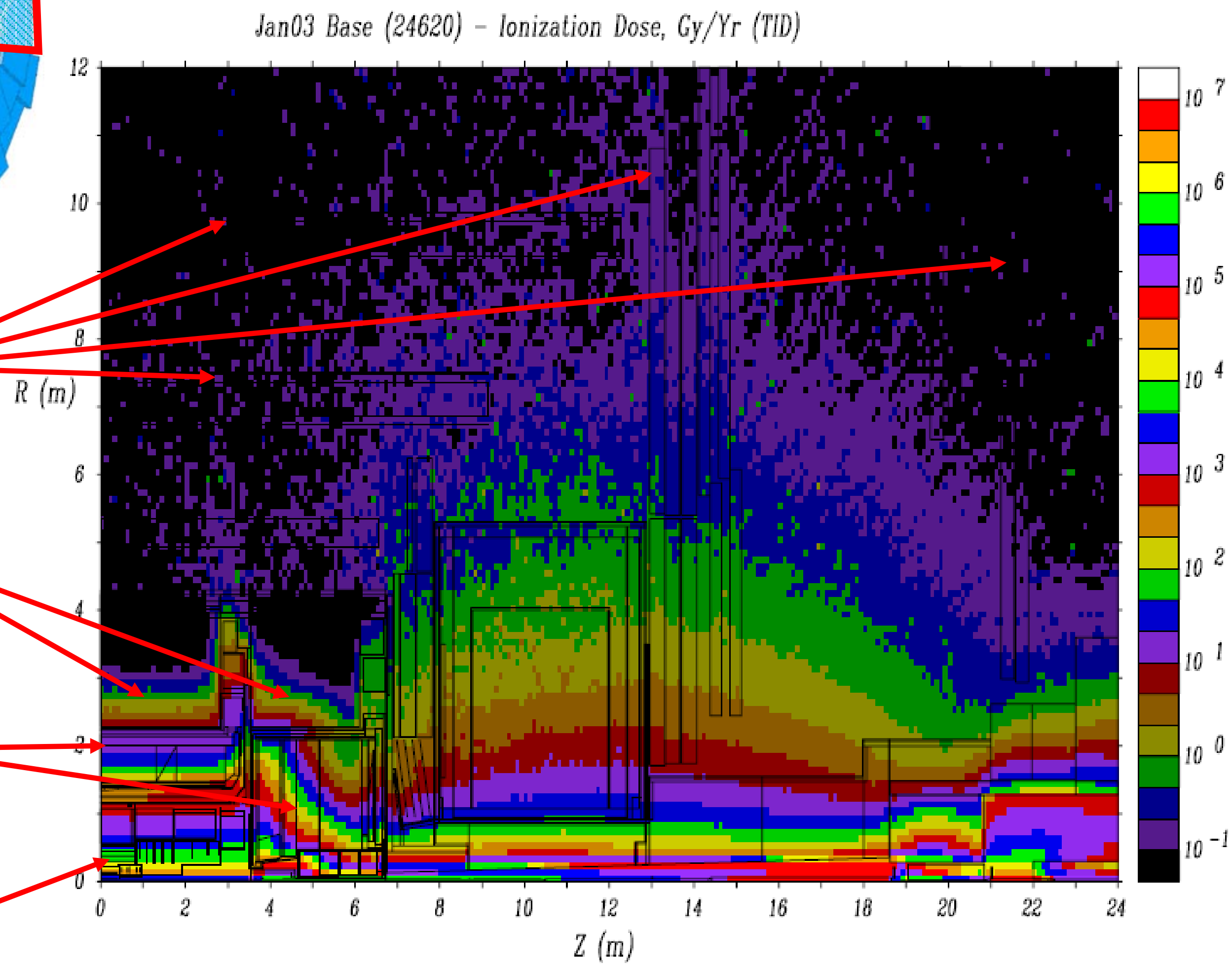
- **Course given in 2000 to the LHC partners at CERN**
  and to several ATLAS Partner Institutes

- **Updated version given in 2006 at JET to EFDA Associations :**
  - http://www.jet.efda.org/seminars/2006/060323dentan.pdf (part 1)
  - http://www.jet.efda.org/seminars/2006/060720dentan.pdf (part 2)

Radiation levels map

Example: Total Ionizing Dose





Radiation Tolerance Criteria

Table of raw simulated radiation levels

SYSTEM	SUB-SYSTEM	POSITION				RAW SIMULATED RADIATION LEVEL		
		Z min (cm)	Z max (cm)	R min (cm)	R max (cm)	SRL_{tid} ($Gy.10y^{-1}$)	SRL_{niel} (1 MeV $n.cm^{-2}.10y^{-1}$)	SRL_{see} (>20 MeV $h.cm^{-2}.10y^{-1}$)
TRT	barrel	79.0	79.0	56.0	107.3	1.59E+04	6.68E+13	2.99E+13
	end-cap	83.0	340.0	108.0	108.0	8.14E+03	6.92E+13	1.82E+13
LAR	barrel	300.0	350.0	290.0	340.0	4.87E+01	1.56E+12	7.67E+11
	end-cap	620.0	670.0	290.0	340.0	5.67E+00	1.45E+11	2.14E+10
TILE	HV micro	210.0	210.0	400.0	400.0	6.41E-01	4.35E+10	1.76E+09
	HV opto	200.0	200.0	400.0	400.0	8.80E-01	3.28E+10	1.27E+09
	Mother	275.0	275.0	410.0	410.0	2.54E+00	2.29E+11	5.66E+10
	Integrator	210.0	210.0	410.0	410.0	5.20E-01	3.70E+10	2.80E+09
	Adder	260.0	260.0	410.0	410.0	1.22E+00	1.40E+11	2.33E+10
	Digitiser PC	275.0	275.0	410.0	410.0	2.54E+00	2.29E+11	5.66E+10
	S-link & interface	150.0	150.0	410.0	410.0	2.25E-01	1.49E+10	6.32E+08
MUON CSC	Start CSC 1	717.7	717.7	89.4	89.4	5.16E+03	5.41E+12	1.12E+12
	End CSC 1	694.1	694.1	204.7	204.7	1.47E+01	1.03+E12	1.21E+11
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	2	1470.0	1480.0	680.0	1180.0	2.49E+00	1.42E+10	4.53E+09

Table of safety factors

SYSTEM	SUB-SYSTEM	SF_{sim}			SF_{ldr}				SF_{lot}		
SF applies on:		SRL_{tid}	SRL_{niel}	SRL_{see}	SRL_{tid} (a)	SRL_{tid} (b)	SRL_{niel}	SRL_{see}	All SRL (c), (d)	All SRL (e)	All SRL (f)
TRT	barrel	3.5	5	5	5	1.5	1	1	4	2	1
	end-cap	3.5	5	5	5	1.5	1	1	4	2	1
LAR	barrel	3.5	5	5	5	1.5	1	1	4	2	1
	end-cap	3.5	5	5	5	1.5	1	1	4	2	1
TILE	HV micro	3.5	5	5	5	1.5	1	1	4	2	1
	HV opto	3.5	5	5	5	1.5	1	1	4	2	1
	Mother	3.5	5	5	5	1.5	1	1	4	2	1
	Integrator	3.5	5	5	5	1.5	1	1	4	2	1
	Adder	3.5	5	5	5	1.5	1	1	4	2	1
	Digitiser PC	3.5	5	5	5	1.5	1	1	4	2	1
	-link & interface	3.5	5	5	5	1.5	1	1	4	2	1
MUON CSC	Start CSC 1	3.5	5	5	5	1.5	1	1	4	2	1
	End CSC 1	3.5	5	5	5	1.5	1	1	4	2	1
	Start CSC 2	3.5	5	5	5	1.5	1	1	4	2	1
	End CSC 2	3.5	5	5	5	1.5	1	1	4	2	1
	Start CSC 3	3.5	5	5	5	1.5	1	1	4	2	1
	End CSC 3	3.5	5	5	5	1.5	1	1	4	2	1
	Start CSC 4	3.5	5	5	5	1.5	1	1	4	2	1
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	End-cap 2	3.5	5	5	[illegible]	1.5	1	1	4	2	1
	End-cap 3	3.5	5	[illegible]	5	1.5	1	1	4	2	1

Simulated radiation levels:
- For each location;
- For each type of radiation (TID, NIEL, SEE)

Safety factors representing:
- Simulation inaccuracy;
- Low dose rate effects
- batch-to-batch variations

Radiation Tolerance Criteria
to be used for radiation tests

ATLAS electronics

COMPONENT TYPES	LOCATION	
	Inner detectors	Other areas
RADIATION HARD INTEGRATED CIRCUITS		
ASICs* - DMILL rad-hard technology - CMOS 0.25 μm + radiation-tolerant layout	Y	Y
STANDARD COMPONENTS QUALIFIED WITH RESPECT TO RADIATION		
optoelectronic devices (lasers, LEDs, optocouplers, optical fibers, …)	Y	Y
FPGAs (Fully Programmable Gate Arrays)		Y
COTS (Components Of The Shelf)		Y
Voltage regulators		Y
Power transistors		Y

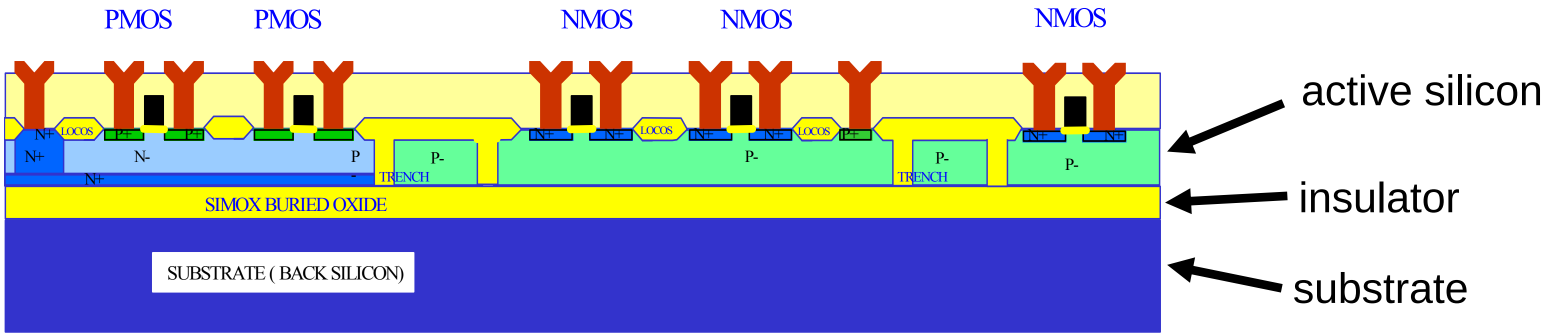
*** ASIC = Application Specific Integrated Circuit**

ATLAS electronics (2)

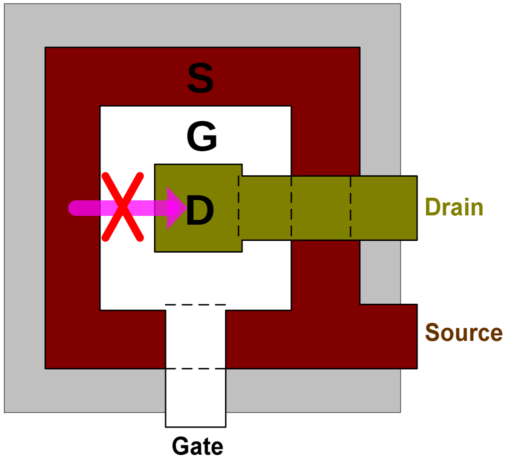
Location	Part name	Channel number	Function	Technology	RTC (Dose)	RTC (NIEL)	RTC (SEE)
5-20cm from Beam pipe	FEI-3	>30 M	Pixel Readout chip	Rad-Tol 0.25 um CMOS	30 Mrads	$5E14n/cm^2$	$5E14p/cm^2$
20-60cm from Beam pipe	ABCD	>7 M	Tracker Readout chip	DMILL BiCMOS	10 Mrads	$2E14n/cm^2$	$2E14p/cm^2$
1-2m from Beam Pipe	SCA	100K	Barrel Calorimeter	DMILL BiCMOS	300Krad	$4E13n/cm^2$	$8E12p/cm^2$
5-8m	AMT-3	100K	Muon Chambers	Commercial CMOS, SEU correction	Up to 50Krads	$2E13n/cm^2$	$2E12p/cm^2$
Cavern	COTS	-	Patch Panels	Commercial CMOS, Bipolar	14Krads	$1E12n/cm^2$	$2E11p/cm^2$

Technologies used for rad-hard ASICs

- DMILL CMOS-NPN-PJFET SOI technology (radiation-hard)
  - Developed by CEA and produced by ATMEL for LHC and other applications
  - > 10 Mrads and > 3.10^{14} n/cm^2 ; reduced SEE sensitivity



- 0.25 µm CMOS bulk technology (standard)
  - Thin gate oxide => almost no Vt shift
  - Radiation tolerant layout (closed gate structure, etc.) => no leakage current
  - > several 10 Mrads and > several 10^{14} n/cm^2 with radiation tolerant layout



Principle of closed gate structure

Procurement strategy

- Whenever possible:
  - Remove electronics from radiation and purchase standard electronics.
  - Otherwise, apply following strategy:

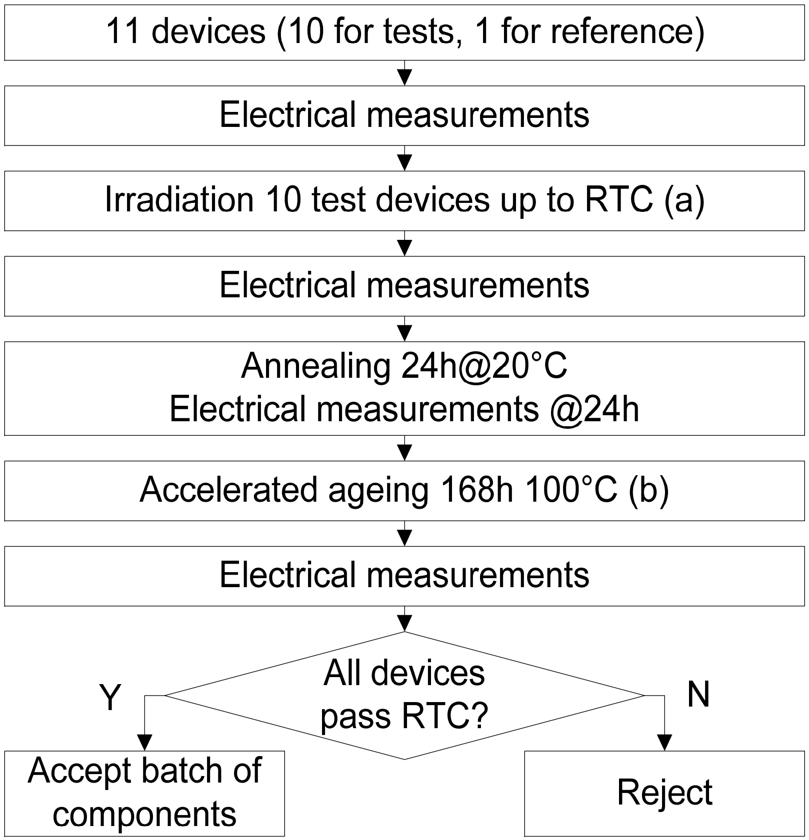
- Radiation tolerant COTS:
  1. Determine **radiation level** in the application (tables of simulated radiation levels)
  2. Calculate the **Radiation Tolerance Criteria** (using ATLAS safety factors)
  3. **Pre-select** generic components (radiation tests)
  4. **Purchase** batches of pre-selected generic components
  5. **Qualify** batches of components (radiation tests)

  - Radiation tests can be made on individual components or on boards
  - Special agreements with vendors may allow purchasing qualified batches only

- Radiation-hard ASICs:
  1. Determine the **radiation level** in the application
  2. Calculate the **Radiation Tolerance Criteria**
  3. **Select** a radiation hard technology (DMILL or CMOS 0.25 μm + rad-tol layout)
  4. **Develop** prototype ASIC and qualify the design (radiation test)
  5. **Qualify** batches of components (radiation tests)
  6. **Purchase** qualified batches

ATLAS standard radiation test methods

TID test method for qualification of batches of CMOS components



Radiation tests must be normalized:

- to be relevant ;
- to allow comparizons ;
- to allow predictions ;
- to allow sharing results.

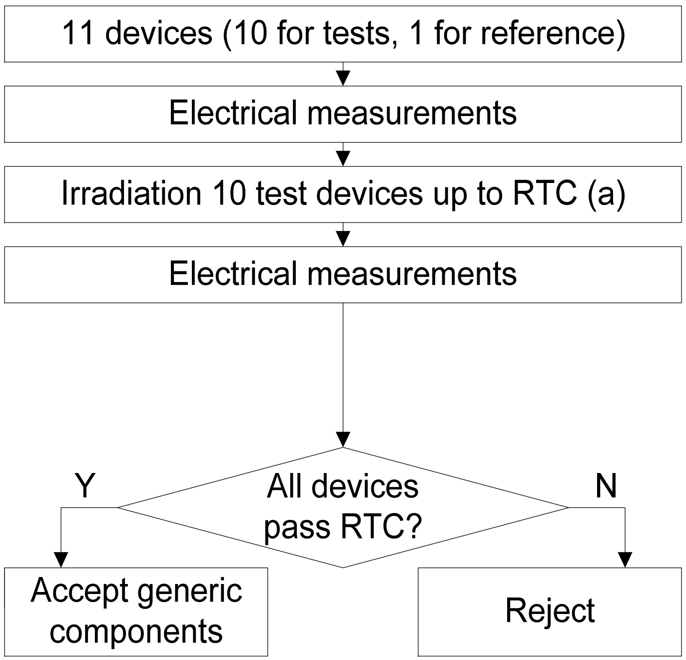
Only components passing Radiation Tolerance Criteria with normalized tests were installed in ATLAS

(a) RCT = Radiation Tolerance Criteria

(b) Alternatively, use appropriate safety factor and skip this step

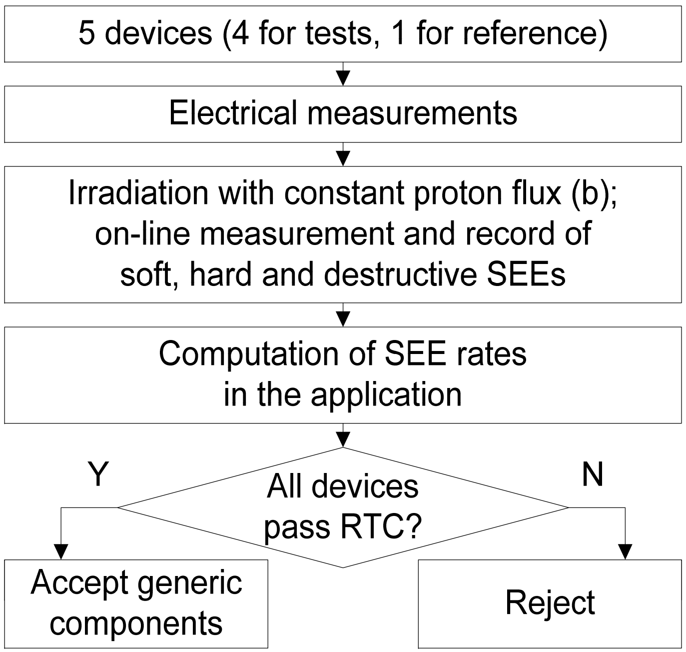
ATLAS standard radiation test methods (2)

NIEL test method for qualification of batches of components



(a) RCT = Radiation Tolerance Criteria

SEE test method for qualification of batches of components



(b) - 60 MeV < E < 200 MeV to seek soft SEEs
- 200 MeV < E < 500 MeV to seek hard or destructive SEEs

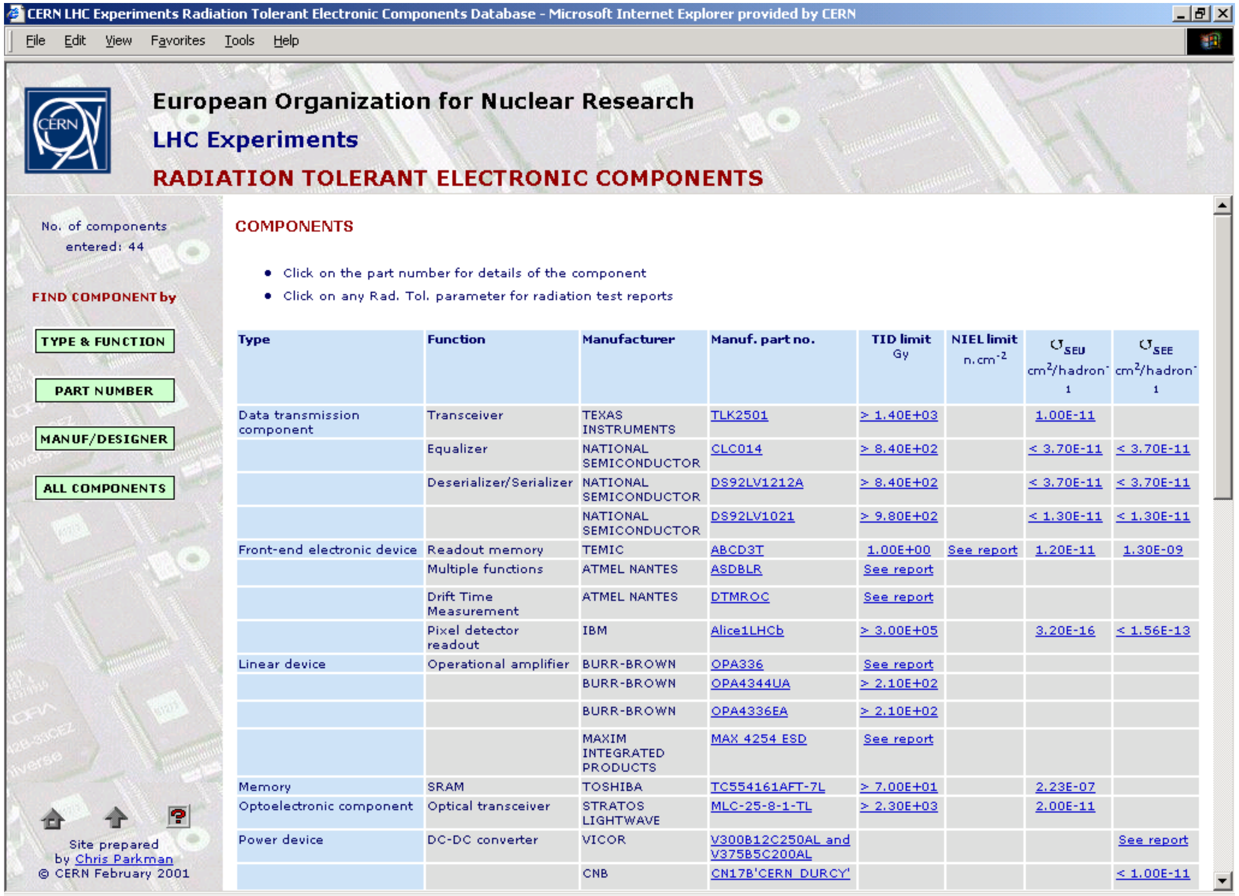
Recommended irradiation sources for tests

Test	Source	Normalized unit
TID	Gamma (^{60}Co) X-rays	Gray
NIEL	Neutrons (reactors)	1 MeV equivalent neutron / cm2
Soft SEE	Protons 60 to 200 MeV	Proton / cm2 / s
Hard SEEs	Protons 200 to 500 MeV	Proton / cm2 / s

- Radiation sources must be calibrated
- Radiation levels must be specified in normalized units

Radiation Tolerant Components Database

- Developed by ATLAS
- Accessible on internet.
- Standard test results recorded and shared by the four LHC experiments.
  => savings, efficiency improvement



CERN LHC Experiments Radiation Tolerant Electronic Components Database - Microsoft Internet Explorer provided by CERN

File Edit View Favorites Tools Help

European Organization for Nuclear Research

LHC Experiments

RADIATION TOLERANT ELECTRONIC COMPONENTS

No. of components entered: 44

FIND COMPONENT by

TYPE & FUNCTION

PART NUMBER

MANUF/DESIGNER

ALL COMPONENTS

Site prepared by Chris Parkman

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COMPONENTS

- Click on the part number for details of the component
- Click on any Rad. Tol. parameter for radiation test reports

Type	Function	Manufacturer	Manuf. part no.	TID limit Gy	NIEL limit n.cm^{-2}	σ_{SEU} cm^2/hadron^{-1}	σ_{SEE} cm^2/hadron^{-1}
Data transmission component	Transceiver	TEXAS INSTRUMENTS	TLK2501	> 1.40E+03		1.00E-11	
	Equalizer	NATIONAL SEMICONDUCTOR	CLC014	> 8.40E+02		< 3.70E-11	< 3.70E-11
	Deserializer/Serializer	NATIONAL SEMICONDUCTOR	DS92LV1212A	> 8.40E+02		< 3.70E-11	< 3.70E-11
		NATIONAL SEMICONDUCTOR	DS92LV1021	> 9.80E+02		< 1.30E-11	< 1.30E-11
Front-end electronic device	Readout memory	TEMIC	ABCD3T	1.00E+00	See report	1.20E-11	1.30E-09
	Multiple functions	ATMEL NANTES	ASDBLR	See report			
	Drift Time Measurement	ATMEL NANTES	DTMROC	See report			
	Pixel detector readout	IBM	Alice1LHCb	> 3.00E+05		3.20E-16	< 1.56E-13
Linear device	Operational amplifier	BURR-BROWN	OPA336	See report			
		BURR-BROWN	OPA4344UA	> 2.10E+02			
		BURR-BROWN	OPA4336EA	> 2.10E+02			
		MAXIM INTEGRATED PRODUCTS	MAX 4254 ESD	See report			
Memory	SRAM	TOSHIBA	TC554161AFT-7L	> 7.00E+01		2.23E-07	
Optoelectronic component	Optical transceiver	STRATOS LIGHTWAVE	MLC-25-8-1-TL	> 2.30E+03		2.00E-11	
Power device	DC-DC converter	VICOR	V300B12C250AL and V375B5C200AL				See report
		CNB	CN17B'CERN DURCY'				< 1.00E-11

Only normalized test results were recorded in the database

Example of result : ASIC « ABCD »

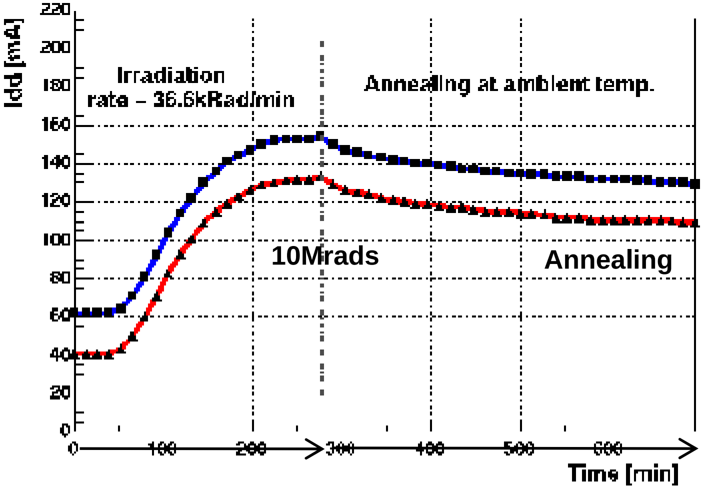
Technology: DMILL
Function: front-end ASIC for ATLAS silicon detector

Separate TID, NIEL and SEE tests.

TID test on every production lot using X-ray machine

NIEL tests in two different facilities
(0.8 MeV neutrons from Prospero at CEA-Valduc, and TRIGA reactor neutrons at Univ. of Ljubljana), to distinguish thermal neutrons effects from standard NIEL effects.

SEE tests performed on batch samples with the SPS 24GeV protons/pions beam at CERN



ABCD chip (pixel silicon detectors)
TID test results on power consumption

10 Mrads in 300 mn + annealing.

Blue: analog current.
Red: digital current.
After full annealing: ~ +10% on Idd

Example of result : small system « ELMB »

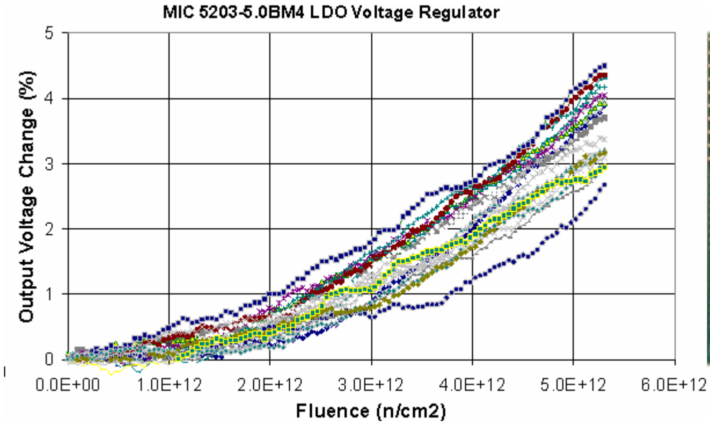
Technology: COTS
Function: local monitoring

TID and SEU tests on 12 units using 60 MeV proton beam (CYCLONE, Louvain-La-Neuve, Belgium)
Target : 1E11p/cm² & 140 Gy

	Number of bits tested	Number of SEEs	Cross-section cm^2/bit
SRAM	16384	1224	$6.2 * 10^{-14}$
EEPROM	16384	<1	$<5.1 * 10^{-17}$
FLASH	458728	<1	$<1.8 * 10^{-18}$
CAN registers	256	59	$1.9 * 10^{-13}$
ADC registers	264	5	$1.6 * 10^{-14}$
ATmega128 registers	80	1	$1.0 * 10^{-14}$

SEU test results on ELMB parts, with equivalent cross section for every component

NIEL tests on 12 units using 1MeV neutrons in Prospero (CEA Valduc, France)
Target : 5E12 n/cm²



Voltage change at the output of a "COTS" voltage regulator (bipolar technology => neutron sensitive)

Example of result : power supplies

Generally very sensitive to radiation.

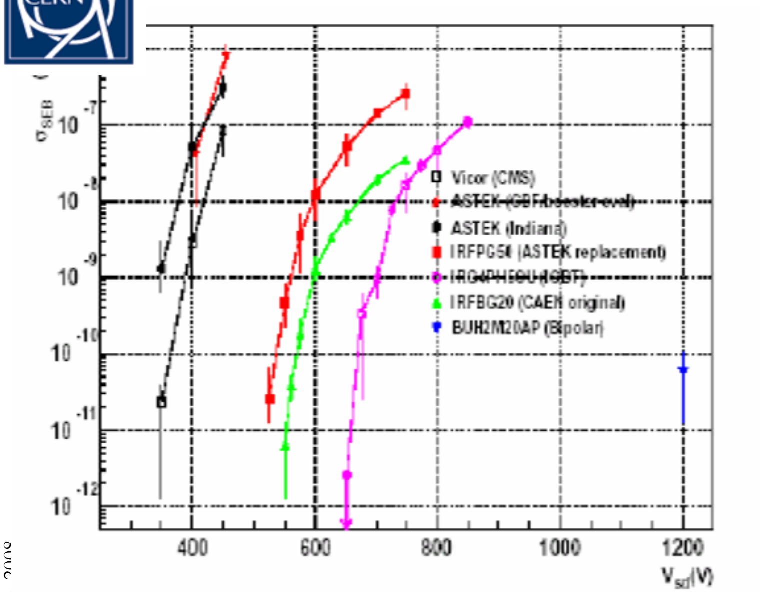
Especially developed for LHC by industrial companies.

Batches of power devices tested separately (neutrons, SEGR, SEB) and selected according to the results.

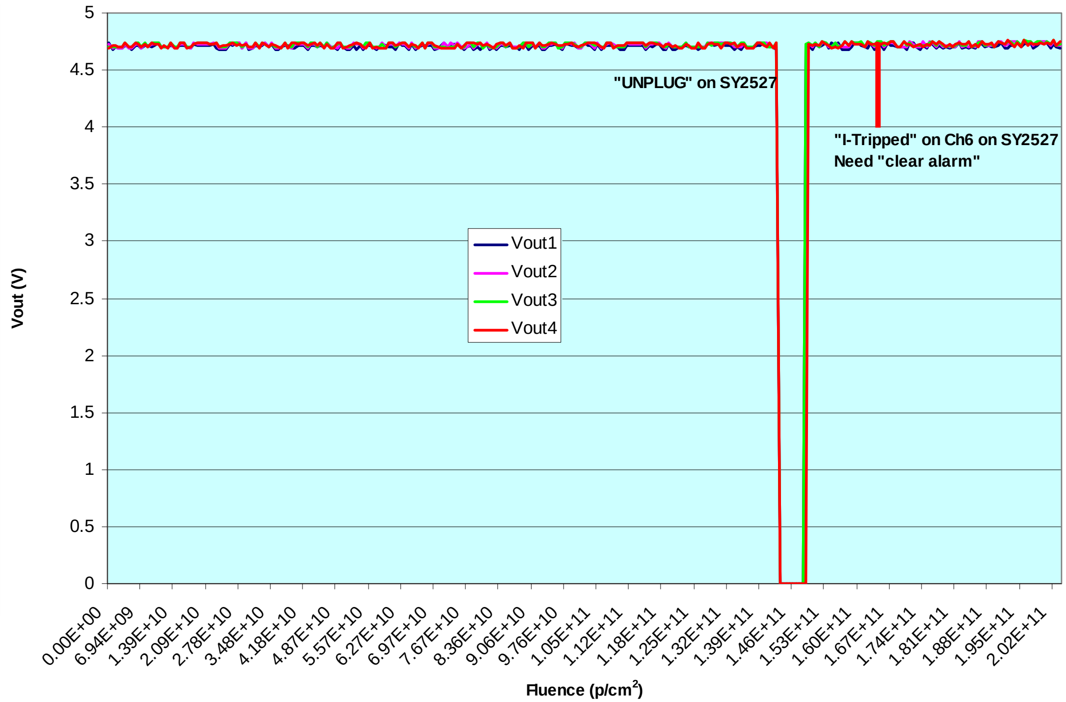
Global acceptance criteria for power supplies includes :
- TID tests up to 140 Gy,
- NIEL tests up to 2.10^{12} 1 MeV equivalent neutrons / cm^2
- SEE tests up to 1.10^{11} hadrons / cm^2 at energy > 20 MeV

First results were very disappointing. A lot of effort was required to achieve the required radiation tolerance.

Example of result : power supplies (cont.)



Power devices (MosFET) selected after irradiation tests (SEB)



To reduce SEB cross section, devices are generally used at Vds = 1/2 to 1/3 of nominal Vds

4 channels low voltage DC unit, irradiated with 250 MeV protons up to 2.10^{11} p / cm^2

The main difficulties of power supplies developments were the SEGR or SEB sensitivity of power devices and the SEU sensitivity of the control part of the power unit.

Summary (1/2)

Radiation can corrupt, damage or destroy electronics. A course explaying these effects was given to ATLAS and the other LHC collaboration to build a common basic knowledge in this field.

ATLAS simulated radiation levels reach up to 1 MGy, 4.10^{14} n/cm^2 (1MeV eq.) and 4.10^{14} p/cm^2.

Special electronics is needed to resist to these radiation levels:
- Rad-hard ASICs (DMILL rad-hard technology, or standard 0.25 µm CMOS + rad-tol layout)

For low radiation constrainst locations:
- Qualified COTS (Components Of The Shelf) used with radiation-tolerant architecture

This electronics was developed and qualified on the basis of the **ATLAS Policy on Radiation Tolerant Electronics,** which specifies :
- The procurement strategy for COTS and radiation-hard ASICs
- The applicable Radiation Tolerance Criteria
- The applicable Radiation Test Methods
- Etc.

Appliyng this policy was essential to ensure the robustness of the electronics against the foreseen radiation constrainst and thus the reliability and safety of the whole experiment.

Standard test results were recorded in a databased shared by the four ATLAS experiments.

Each system was reviewed against radiation tolerance. Formal acceptance was mandatory before installation in ATLAS.

Summary (2/2)

The Future

LHC beams at full energy and reduced luminosity are scheduled automn 2009.

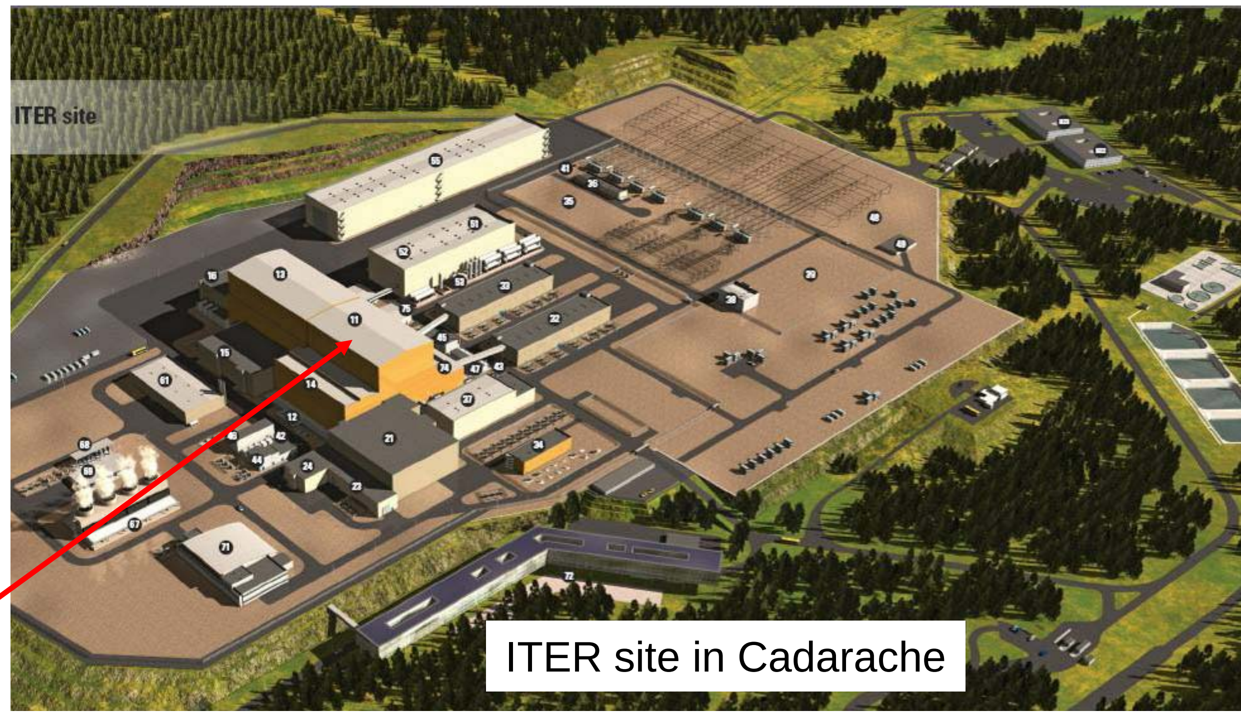
They will allow testing the robustness of the electronics against actual ATLAS radiation constrainst: SEU (immediately), then TID and NIEL (after cumulated irradiation).

The actual radiation levels will be measured using a large number of radiation sensors (electronic devices) installed in many locations of ATLAS. These measurements will allow correcting the simulated radiation levels and thus improving the predicted lifetimes and SEE rates of the electronics.

A close monitoring of the electronics will be performed during the 10 years of operation foreseen for ATLAS. Results will be compared to those obtained during qualification tests, and corrective actions will be decided if needed. Some of the electronics (inner detectors) will have to be replaced during that period.

The ITER Project

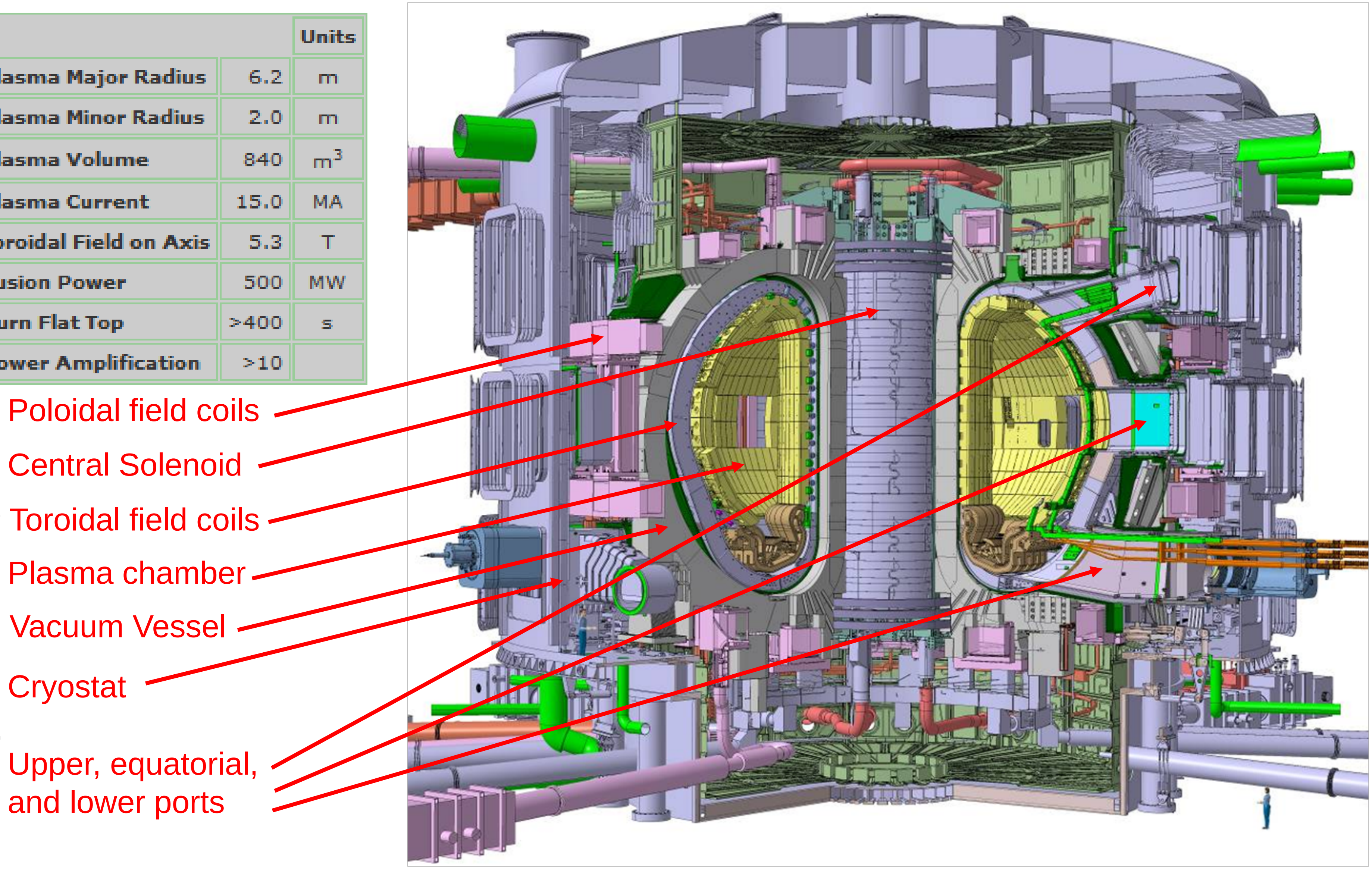
- ITER is a joint international R&D project that aims to demonstrate scientific and technical feasibility of fusion power.
- ITER Partners are China, India, E.U., Japan, Korea, Russian Federation, and U.S.A.



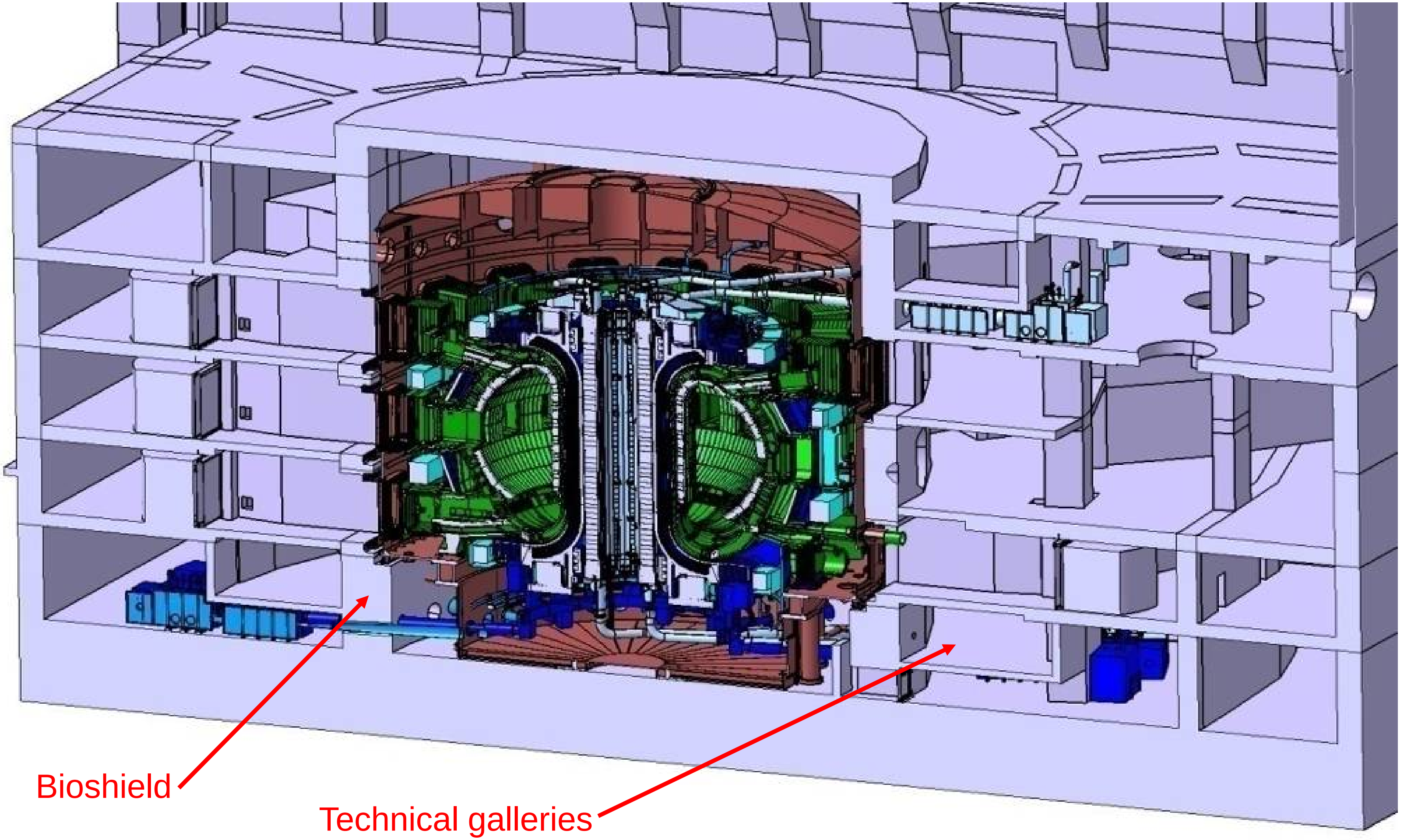
Tokamak Complex building

The ITER Tokamak

		Units
Plasma Major Radius	6.2	m
Plasma Minor Radius	2.0	m
Plasma Volume	840	m^3
Plasma Current	15.0	MA
Toroidal Field on Axis	5.3	T
Fusion Power	500	MW
Burn Flat Top	>400	s
Power Amplification	>10	



ITER Tokamak Building



Radiation Hardness Assurance

- Radiation constraints in ITER – preliminary figures
  - **During operation, outside the vacuum vessel**, the simulated dose rate is around **2.5 mGy/s**. Assuming that the lethal dose for standard electronics is ~**100 Gy**, this **corresponds to ~ 100 shots of 400 seconds each**.
  - **During maintenance, outside the vacuum vessel**, the simulated dose rate can be as high as 3 mGy/h. This corresponds to **100 Gy in 3.8 years**.
  - **During maintenance, inside the vacuum vessel**, the simulated level is **several hundred Gy/h**, well above the lethal dose of standard electronics.

- The ITER approach
  - ITER is currently developing a policy inspired from the ATLAS approach.
  - This policy will apply to any electronics exposed to radiation in ITER, including « visible » electronics (crates, etc.) and « hidden » electronics (in electromechanical systems such as motors, etc).
  - As for ATLAS, this policy should be coherent, based on recognized test methods, efficient and cost effective.
  - Once developed, the implementation of this policy will require a substantial learning period in the ITER community.

THAT YOU !