Active Radiation Monitoring Sensors for the High-Energy Physics Experiments of the CERN LHC

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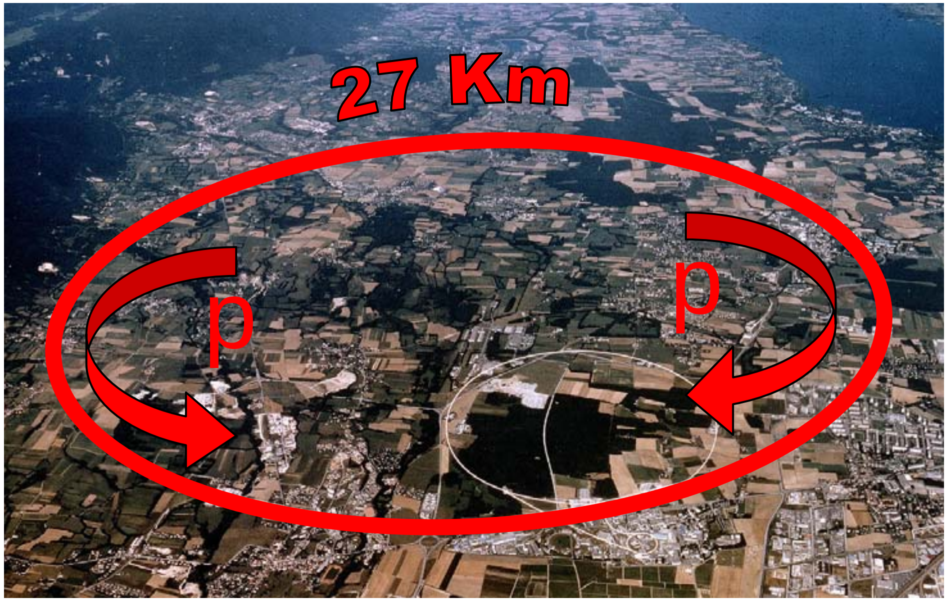
On behalf of RADMON Working Group

Outline

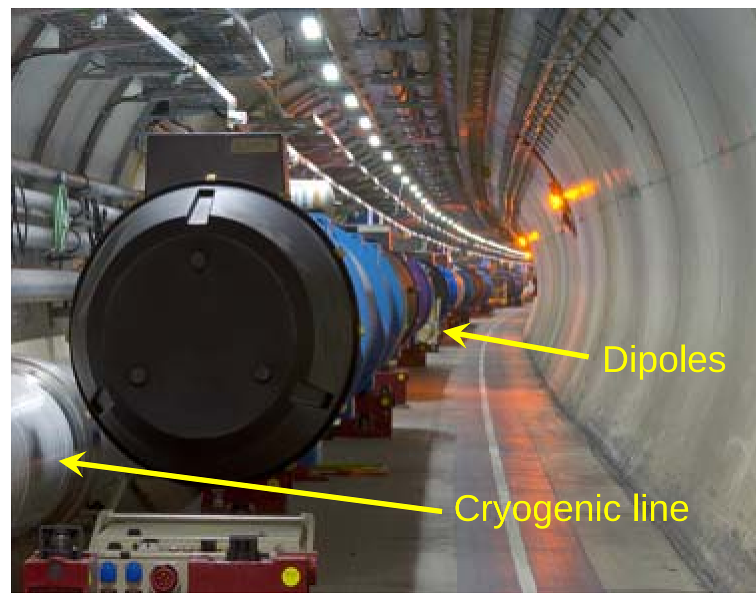
- CERN, LHC, Accelerator & Experiments Radiation Field;
- Radiation Monitoring issues at the LHC;
- Active Dosimeters: RadFET and *p-i-n* diode;
- Validation test in “LHC-like” environment;
- Integration issues at the LHC Experiments;
- Conclusions;

Development of OSL-based dosimeters → D. Benoit talk

Large Hadron Collider

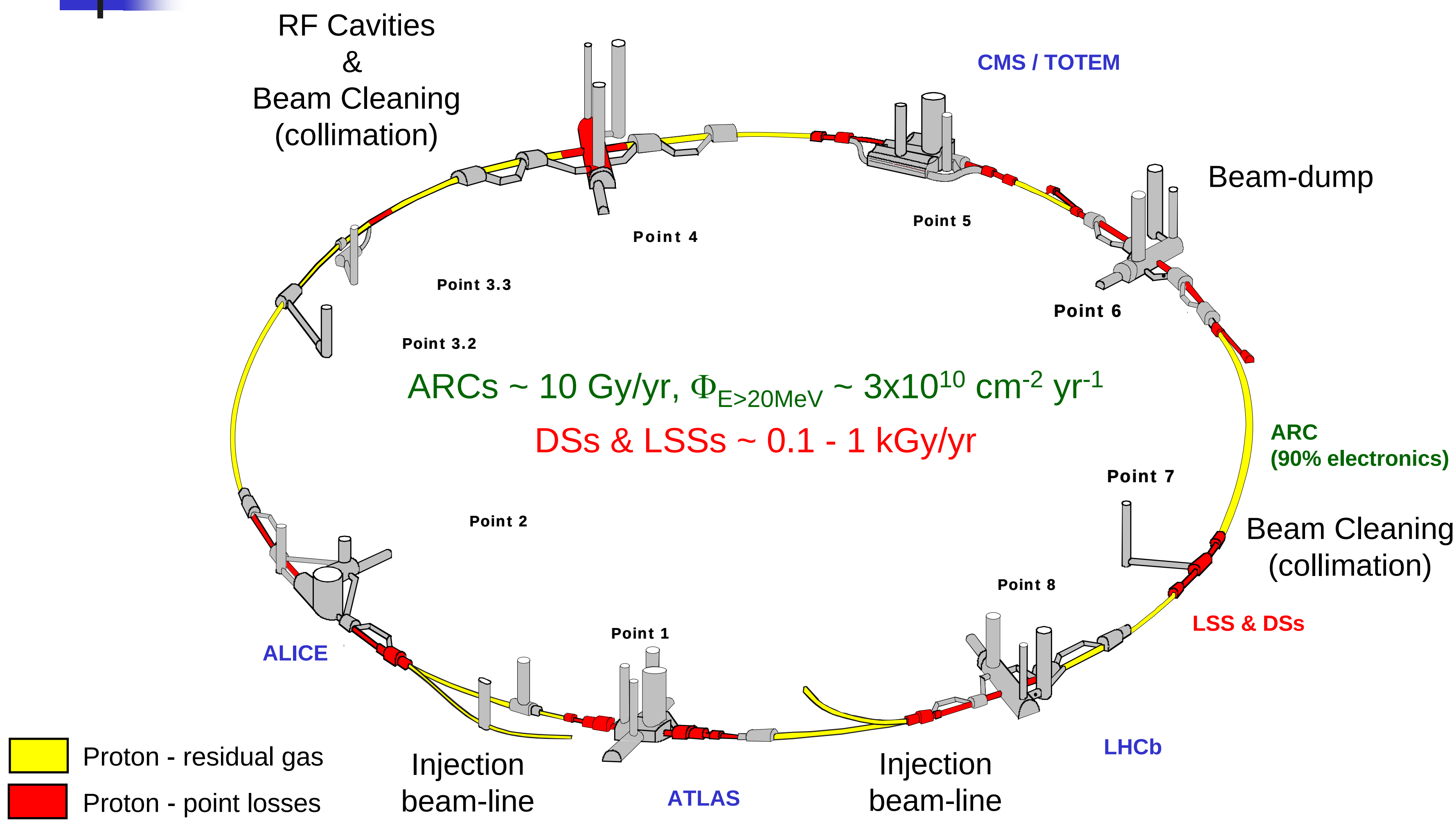


- proton-proton collider;
- superconducting magnets;
- Starting up for physics in **May 2008**;
- Commissioning the LHC to full energy in one go.



Number of dipole magnets	1232
Dipole field at 7 TeV	8.3 T
Luminosity	10^{34} $cm^{-2}\cdot s^{-1}$
Protons/bunch	1.1×10^{11}
bunches/beam	2808
Nominal bunch spacing	25 ns
Typical beam size in arcs	200-300 μm

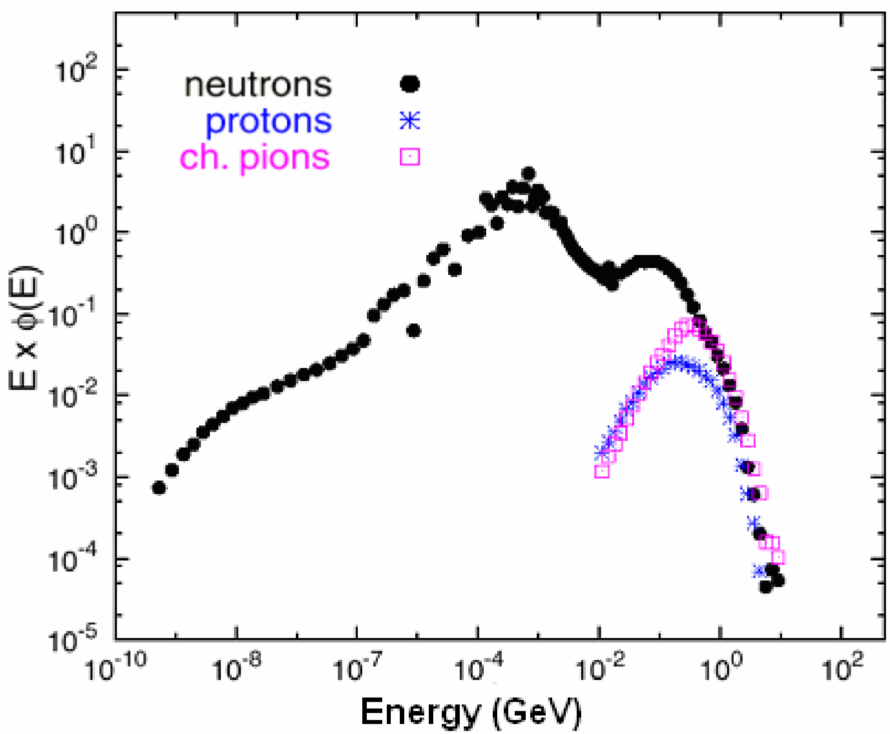
LHC Radiation Field



ARCs ~ 10 Gy/yr, $\Phi_{E>20MeV}$ ~ $3x10^{10}$ cm^{-2} yr^{-1}

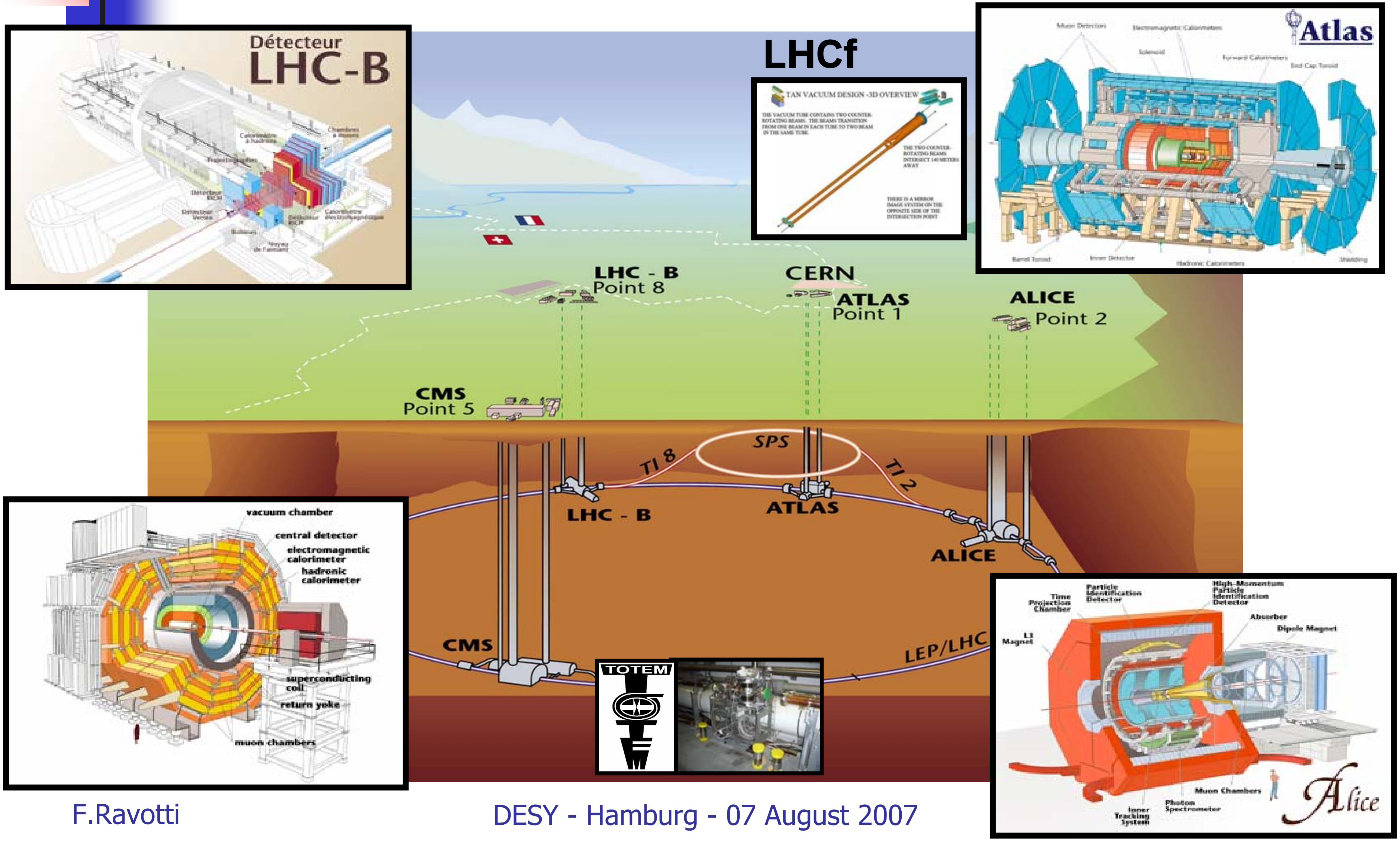
DSs & LSSs ~ 0.1 - 1 kGy/yr

LHC Radiation Field

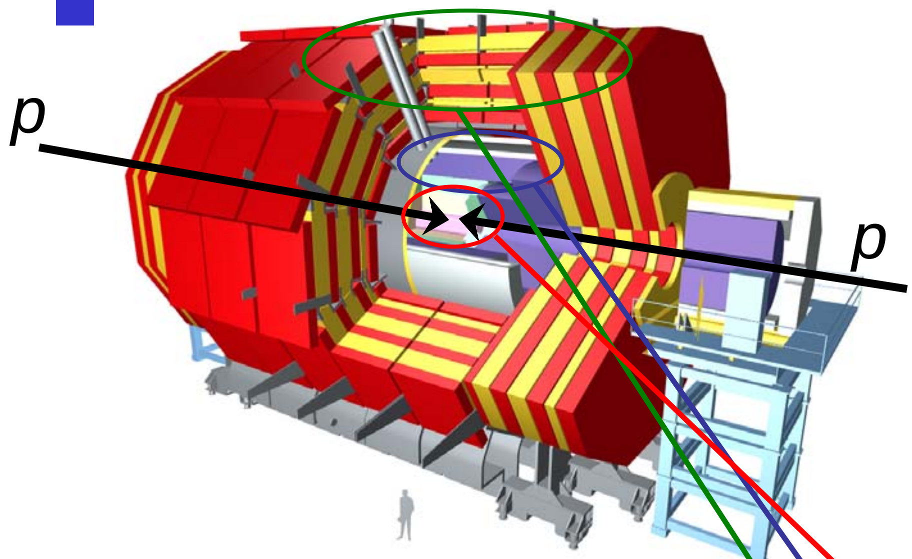


Particle spectrum expected just outside the magnet cryostats [C. Fynbo, 2001]

LHC Experiments



Experiments Radiation Field



- **Example: CMS radiation field**
- **MC simulation predictions:**
  - gammas, protons, neutrons, pions, …
  - different energies and intensities;
  - $f(r,\theta,z)$ with respect to IP;

	Dose rate [Gy/s]	Dose [Gy/year]	Ch. Hadrons [cm²/year]	Neutrons [cm²/year]
Pixel	$2x10^{-2}$	$1X10^{5}$	$2x10^{14}$	$2x10^{13}$
HCAL	$2x10^{-6}$	10	10^{12}	10^{13}
Muon	$2x10^{-9}$	0.01	10^{8}	10^{10}

neutrons, photons << Ch. particles

neutrons ~ photons ~ Ch. particles

neutrons, photons >> Ch. particles

eV < n < 1OO MeV
MeV < γ < GeV
100 MeV < p , π < 10 GeV

- Dose and fluence in sub-detectors differ up to **7 orders of magnitude**.

Radiation Monitoring Purposes

LHC Experiments are designed for 10 years of physics operation

Equipment failures due to radiation damage are not expected, **but**

- Some components might be not well qualified in radiation hardness;
- Some long-term effects in complex radiation field are not predictable;

  ⇨ **Radiation level survey needed for damage and failure analysis**

- Radiation field simulations accuracy within factor 2-3;

  ⇨ **Verification and improvement of simulations**

- Layers of shielding materials are installed to reduce internal/external irradiation;

  ⇨ **Improvement of shielding**

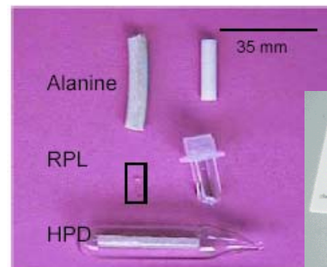
Radiation Monitoring at LHC

The complexity of the LHC radiation field make its monitoring **challenging**;

Ideally measure full spectrum (particle type, energy and intensity at all location);

In reality the effects of this radiation field on specific materials are measured;

To cover the **broad ranges/spectra** expected **several sensors are needed**:

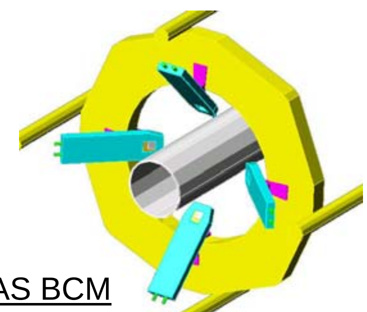


→ Passive Sensors (TLDs, Alanine, RPL, ...);

→ **Active Sensors;**

→ Fast Beam Condition Monitors (CVD diamond);

→ Specific Monitoring Devices (scintillators, metal foils, ...);

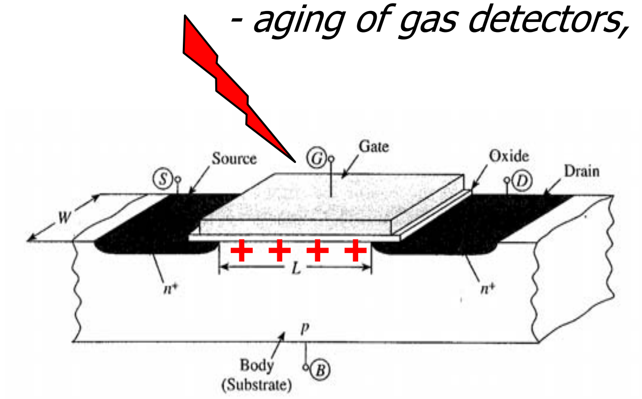


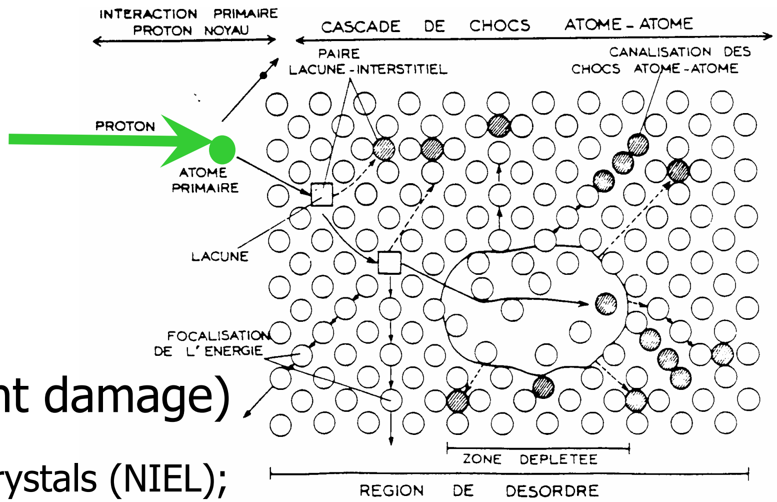
ATLAS BCM
[A. Gorišek, JSI]

Radiation Monitoring Quantities

What can / should be measured ?

- **TID – Total Ionizing Dose** (energy deposited by ionization)
  - represents the Ionizing Energy Loss (IEL) measured in **Gy** = 1 J/Kg;
  - *causing e.g.- accumulation of charge in SiO_2 ⇨ damage to microelectronic components*
    - aging of gas detectors, scintillators, optical fibers, …



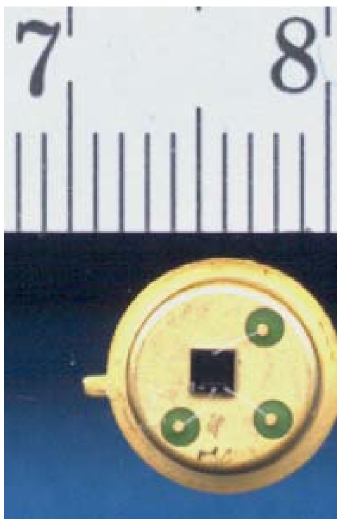


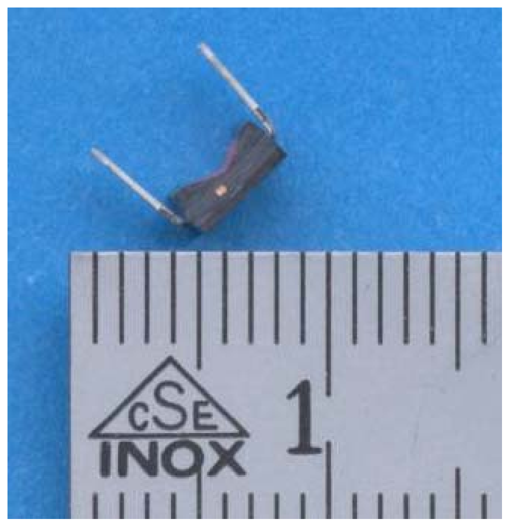
- **Φ_{eq} – 1-MeV Equivalent Fluence** (displacement damage)
  - represents the energy imparted in displacing collisions in crystals (NIEL);
  - *causing e.g. defects in semiconductor crystals ⇨ silicon detector damage, optical devices, CCDs, ..*
  - damage normalized to the one induced in Si from 1-MeV neutrons measured in **cm^{-2}**;

Radiation Monitoring Sensors

ACTIVE DOSIMETERS ("on-line")

- Radiation-sensing Field Effect Transistors (RadFETs) **– TID –**;
- Forward biased *p-i-n* silicon diodes **– Φ_{eq} –**;





- Optically Stimulated Luminescent Materials (OSL) **– dose-rate, TID –**;

→ See following talk by D. Benoit

RadFET Sensors (TID)

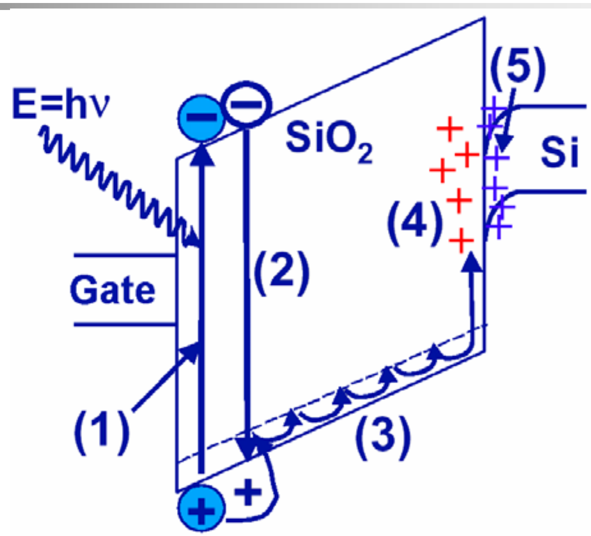
(1) e^-/h^+ pair generation;

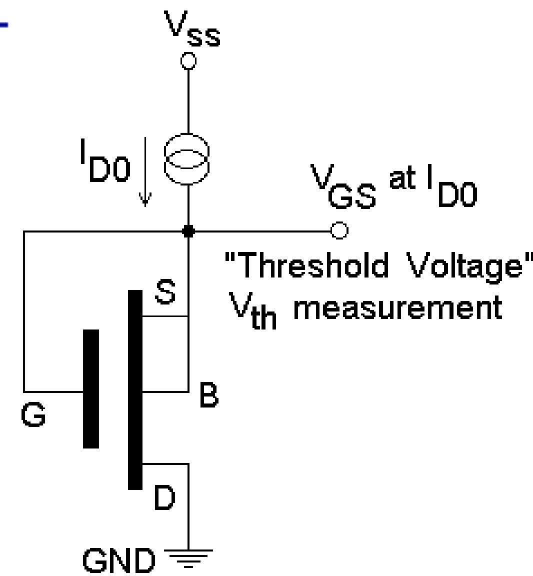
(2) e^-/h^+ pair recombination;

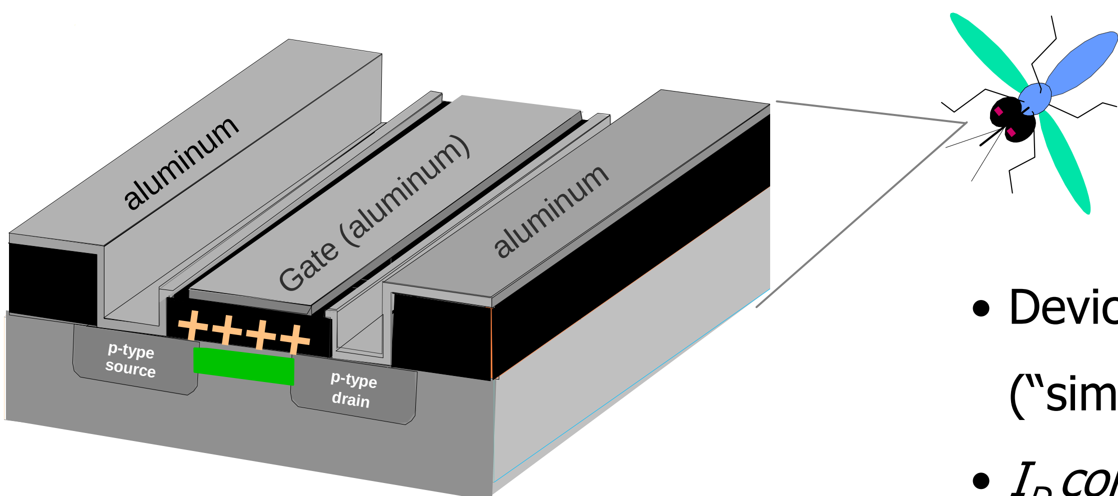
(3) e^-/h^+ transport;

(4) hole trapping;

(5) Interface states buildup.







- Devices grounded during exposure ("simple" readout as required for LHC)
- I_D *const.* → $V_{th} \propto$ TID.

RadFET selection & characterization

9 RadFET devices from 4 producers (REM, NMRC, LAAS, T&N)

Evaluation of packaging effects → Radiation response to γ, *n*, *p*, $\pi^{\pm}$,..

↓

ΔV_{th} stability evaluation with experimental Isochronal Annealing method

"Accelerated" Procedures

↓

SELECTION

- - - - - - - - - - - - - - - -

CHARACTERIZATION

Recommended Devices

↓

Measurem. of key param. (T_c,..)

- Temperature coefficients;
- Readout currents;
- Signal drift-up;
- …

↓

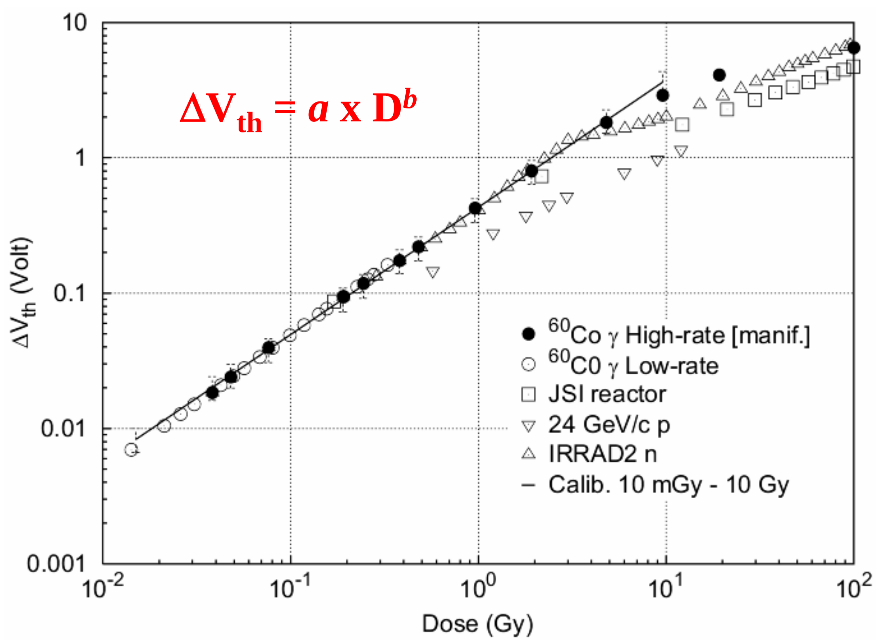
Evaluation of displacement damage effects → Studies on the long-term Isothermal annealing behaviours

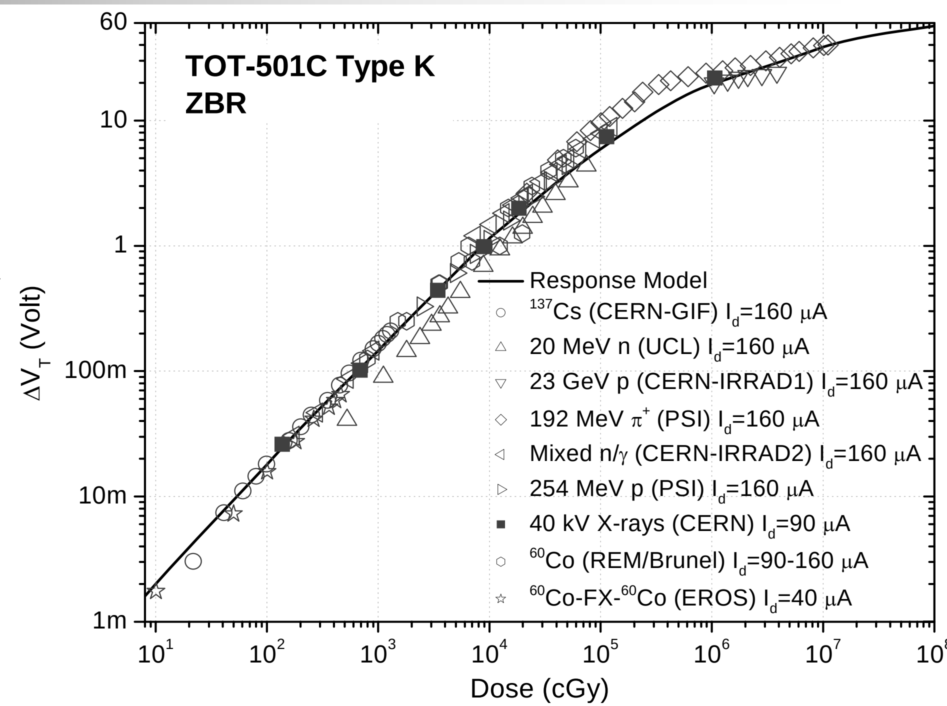
↓

Response in Low Dose-Rate (LDR) mixed hadron radiation environment

RadFETs for the LHC

- Thin-Oxide RadFET dies (0.25 μm):
  - Producer: REM Oxford Ltd, UK;
  - ~ 20 mV/Gy ÷ 0.1 Gy to ~ 10 kGy;
  - Suited inner-detector regions.



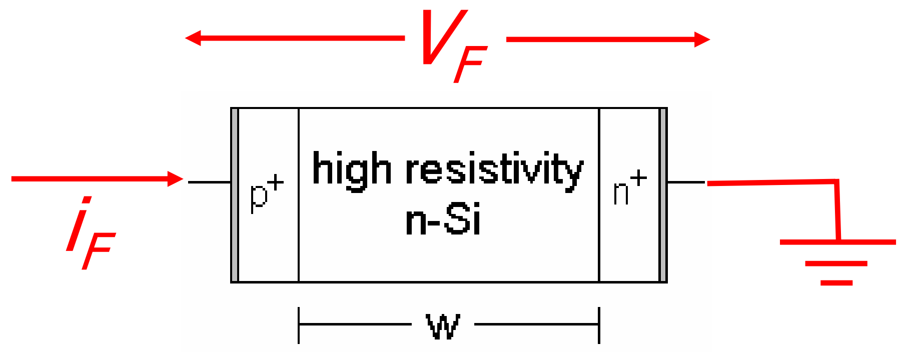


- Thick-Oxide RadFET dies (1.6 μm):
  - Producer: CNRS-LAAS, France;
  - ~ 500 mV/Gy ÷ ~ 1 mGy to 10 Gy;
  - Suited for outer-detector regions;

p-i-n diodes (Φ_{eq})

Displacement damage in high ρ Si-base

→ Macroscopic effect linear with Φ_{eq}



FORWARD BIAS

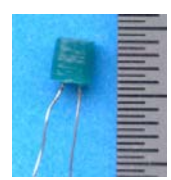
Fixed i_F → $V_F \propto \Phi_{eq}$

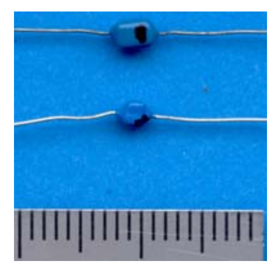
Dosimetric effect at **intermediate / high injection levels;**

Devices **grounded** during exposure; Readout by **current pulses**

$V_F = f$ (material parameters [τ,ρ,L], geometry [W], readout current [J], pulse length)

CUSTOM MADE, High-Sensitivity (CMRP, LBSD)





Characterization of *p-i-n* diode devices

High-Sensitivity *p-i-n* diodes are devices developed mainly for medical and military applications. Extensive characterization done for LHC

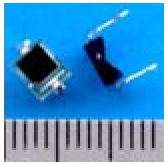
(sensitivities, dynamic range, annealing, temperature effects …);

The High-Sensitivity (10^7-10^8 mV/cm^2) imply a low dynamic range ($\Phi_{eq} \leq 10^{12}$ cm^{-2})

→ **These devices alone cannot satisfy all LHC requirements;**

These devices need to be complemented by diodes with higher range (10^{12} cm^{-2} < Φ_{eq} < 10^{14}-10^{15} cm^{-2});

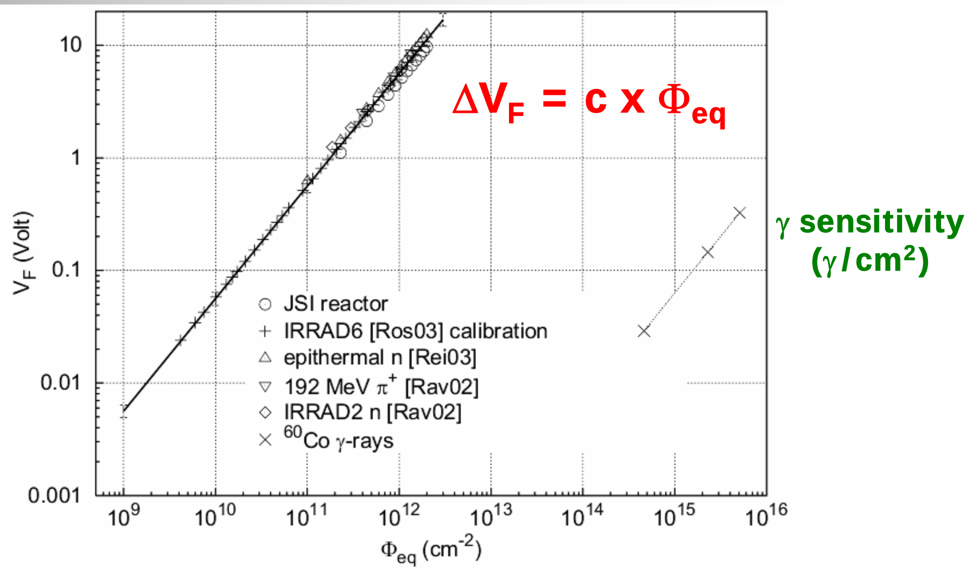
→ **Study of the Commercial *p-i-n* diodes BPW34F**



p-i-n diodes for the LHC

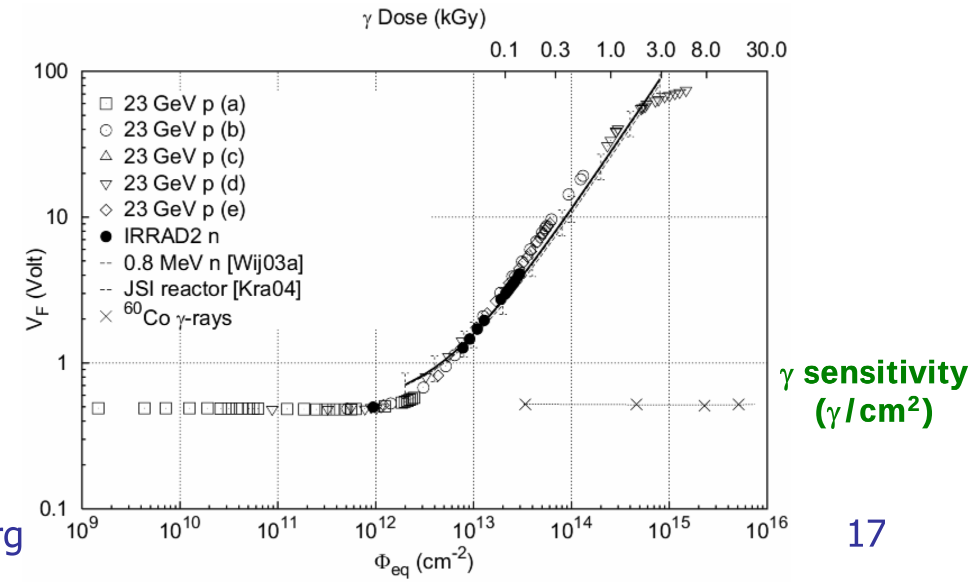
- High-Sensitivity *p-i-n* diodes:
  - Producer: CMRP, Australia;
  - S = 5.9 mV/10^9 cm^{-2} ± 13 %;

    $\Phi_{eq,max}$ = 2×10^{12} cm^{-2};
  - Suited for outer-detector regions;



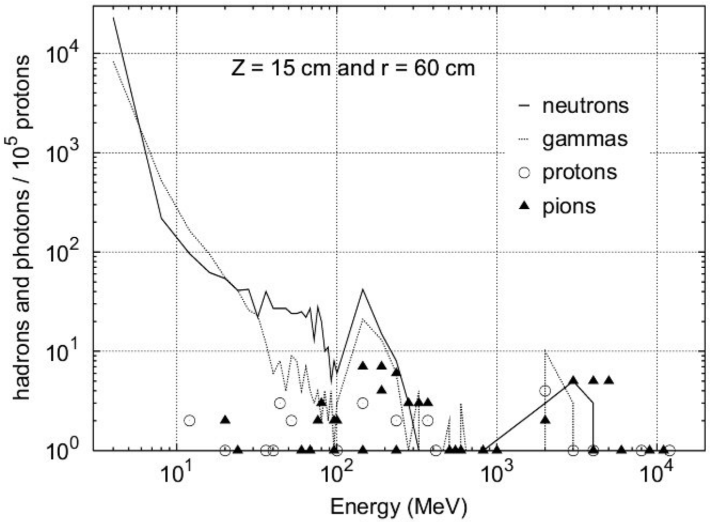
- Commercial *p-i-n* diodes:
  - BPW34 from OSRAM
  - S = 0.1 mV/10^9 cm^{-2} ± 20 %;

    $\Phi_{eq,max}$ = 4×10^{14} cm^{-2};
  - Suited for inner-detector regions;



Validation Test

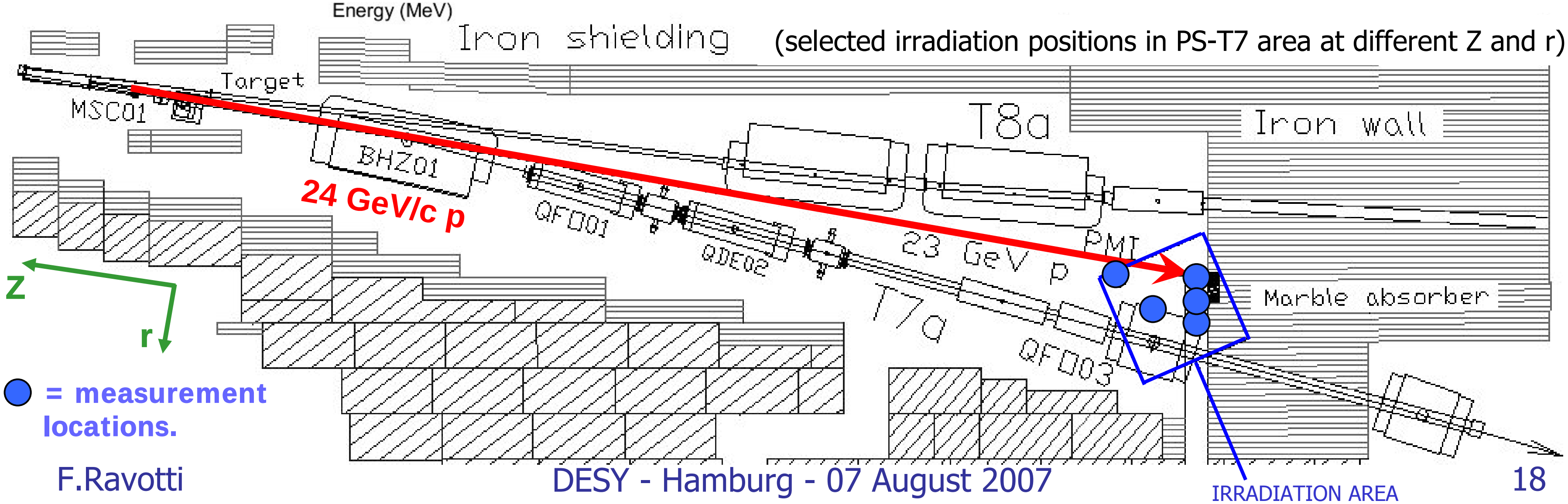
[UdeM-GPP-EXP-98-03, 1998]



From the "accelerated" characterization to the "real" LHC conditions!

- MIXED RADIATION FIELD;
- DIFFERENT INTENSITIES f(r,Z)
  → Low Dose Rate (LDR);
- SEVERAL MONTHS IRRADIATION.

(selected irradiation positions in PS-T7 area at different Z and r)

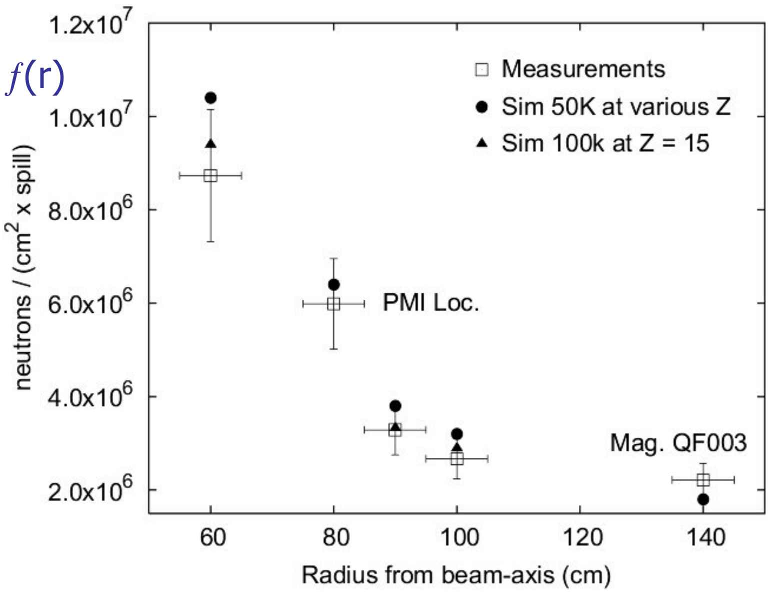


Validation Test

Sim-A f(r,Z) and **Sim-B** f(r)

- Different Composition;
- Different area layout.

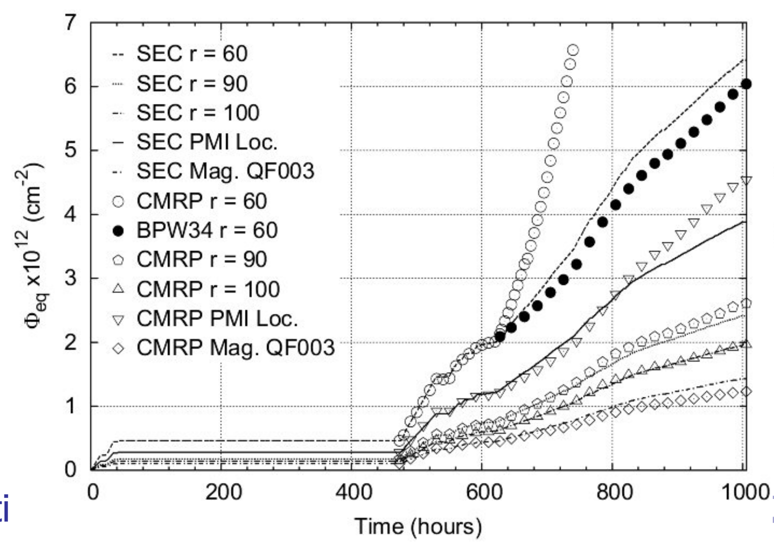
$\varepsilon_{\text{fluence}} = \pm$ **16.2 %**

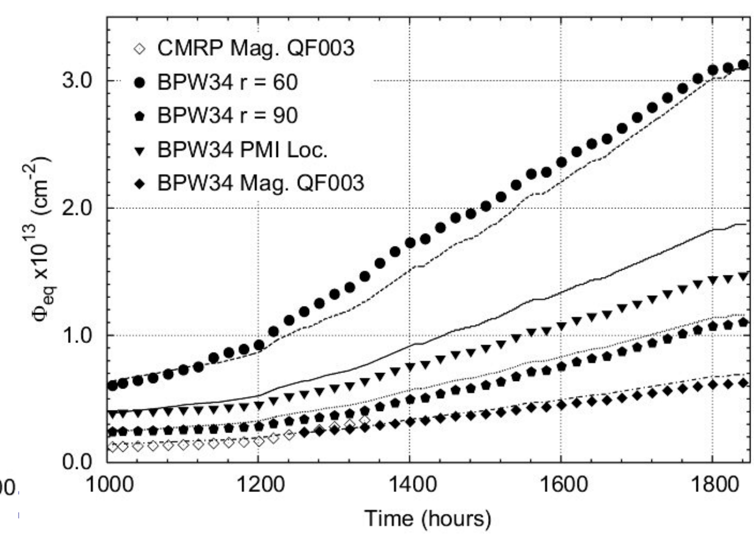


Comparison Φ_{eq} measurements against MC simulations

Variations in the Φ_{eq} successfully monitored on-line!

High Sensitivity *p-i-n* diode (CMRP)





Comm. *p-i-n* diode (BPW)

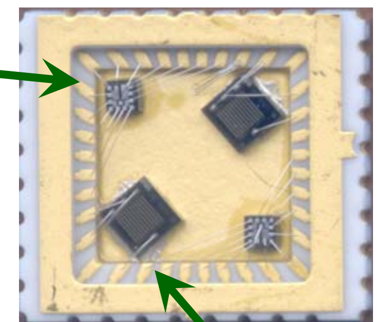
RadFET Packaging

~~Development by External Company~~

Commercial Packaging (i.e. TO-5, DIL) cannot satisfy all Experiment Requirements (dimensions/materials)

Development / study in-house at CERN

~ 10 mm^2 36-pin Ceramic carrier



REM

LAAS

Simulated model

[Geant4 Team, INFN Genova]

– high integration level;

– modular, customizable;

– standard connectivity;

– satisfactory radiation transport proprieties.

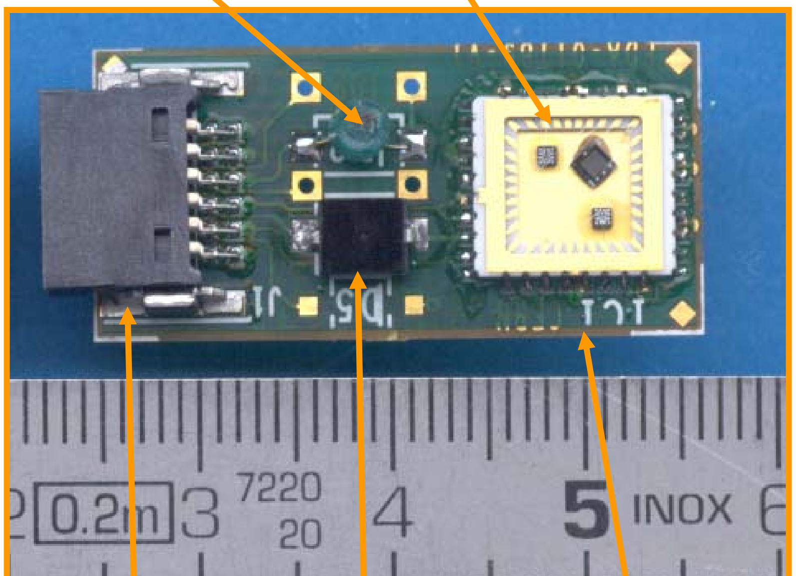
– validate packaging and calculations;

– optimize packaging lid.

Integrated sensor carrier

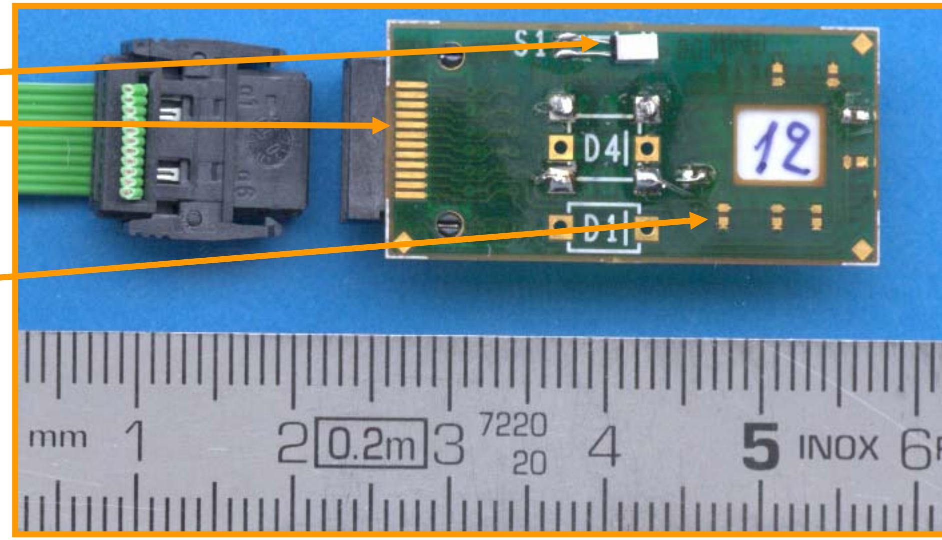
INTEGRATED SENSOR CARRIER
(4 sensors, same readout method)

Temperature probe
Soldering pads
CMRP diode
RadFET package
Selection pads

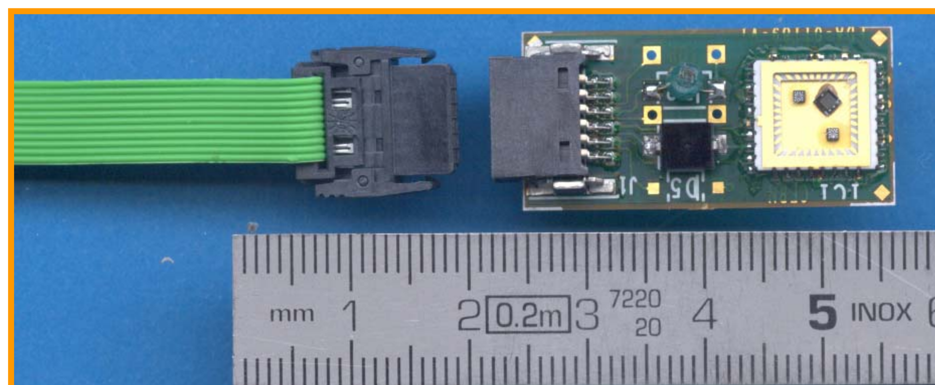


BPW34 diode
250 µm PCB
Connector plug 12 ways (11 channels + common GND)

- Back-Side

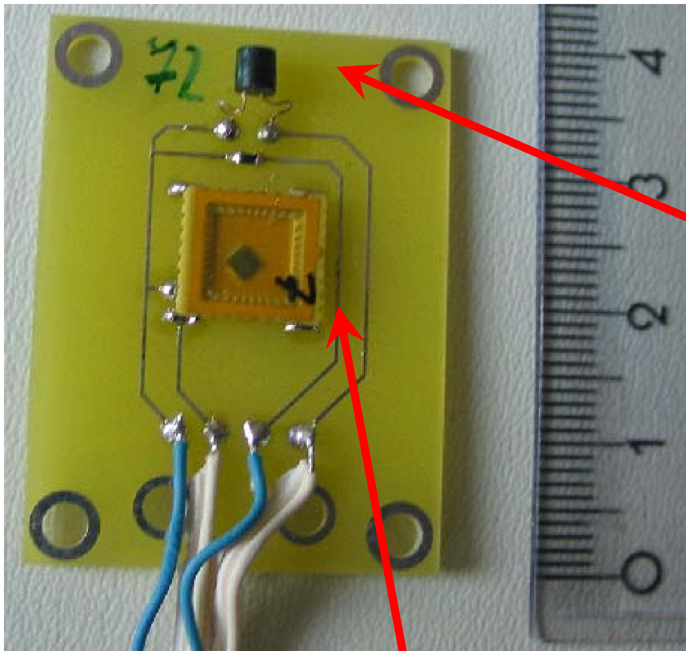


- Front-Side



Integration in the ATLAS Experiment

ATLAS Outer detector regions

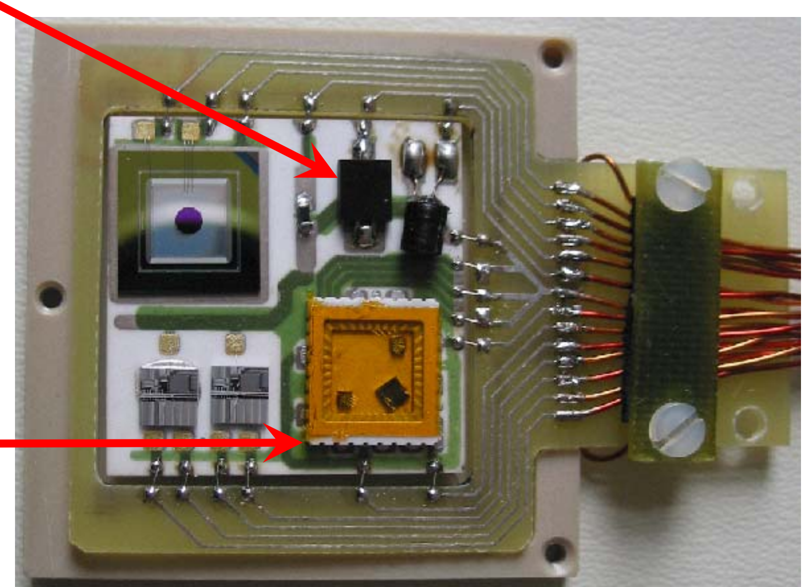


ATLAS RADMON

(IEL, NIEL, **thermal neutrons**)
> 200 sensors at LHC startup;

p-i-n diodes

ATLAS Inner Detector

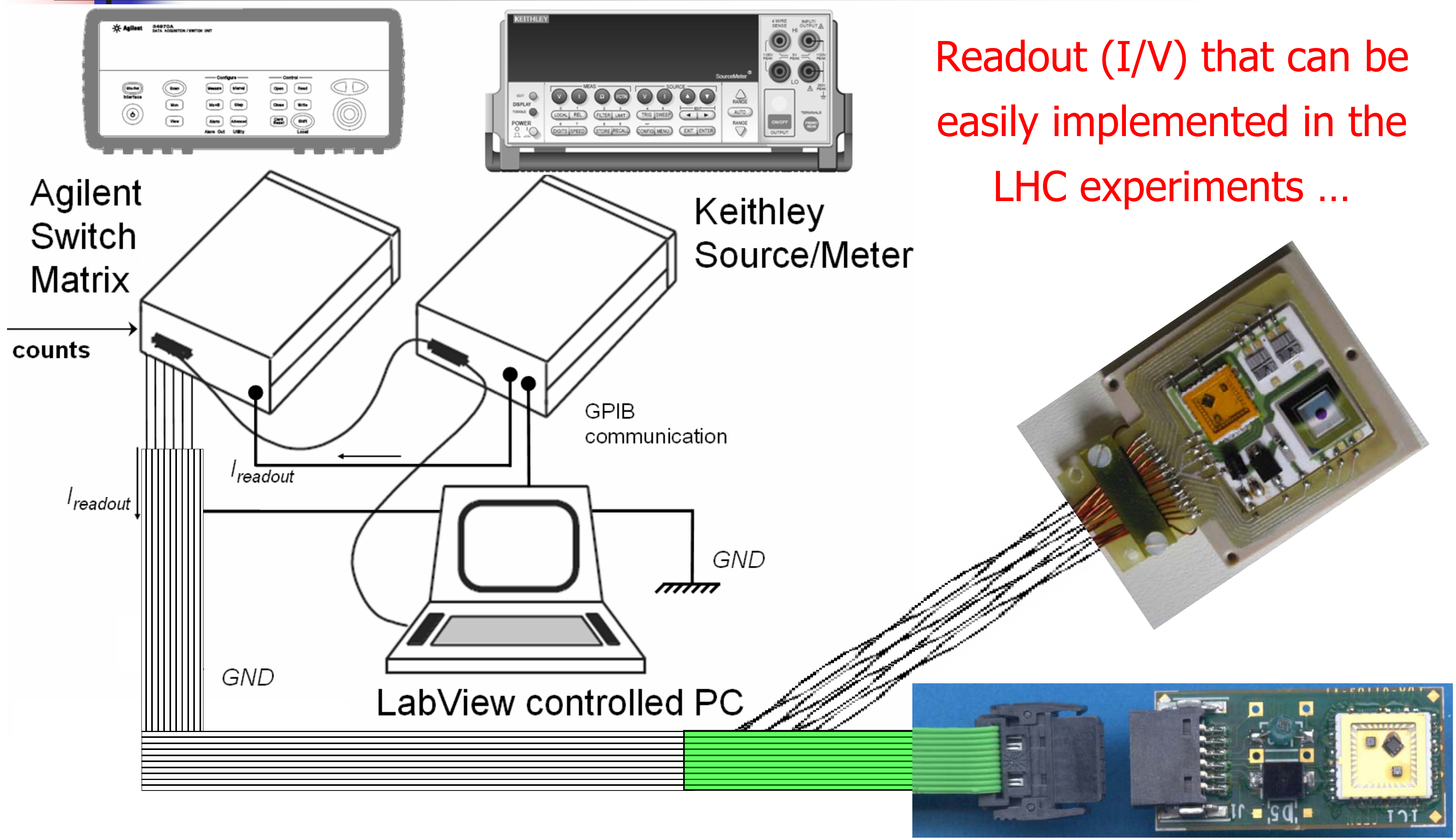


RadFET Packaging

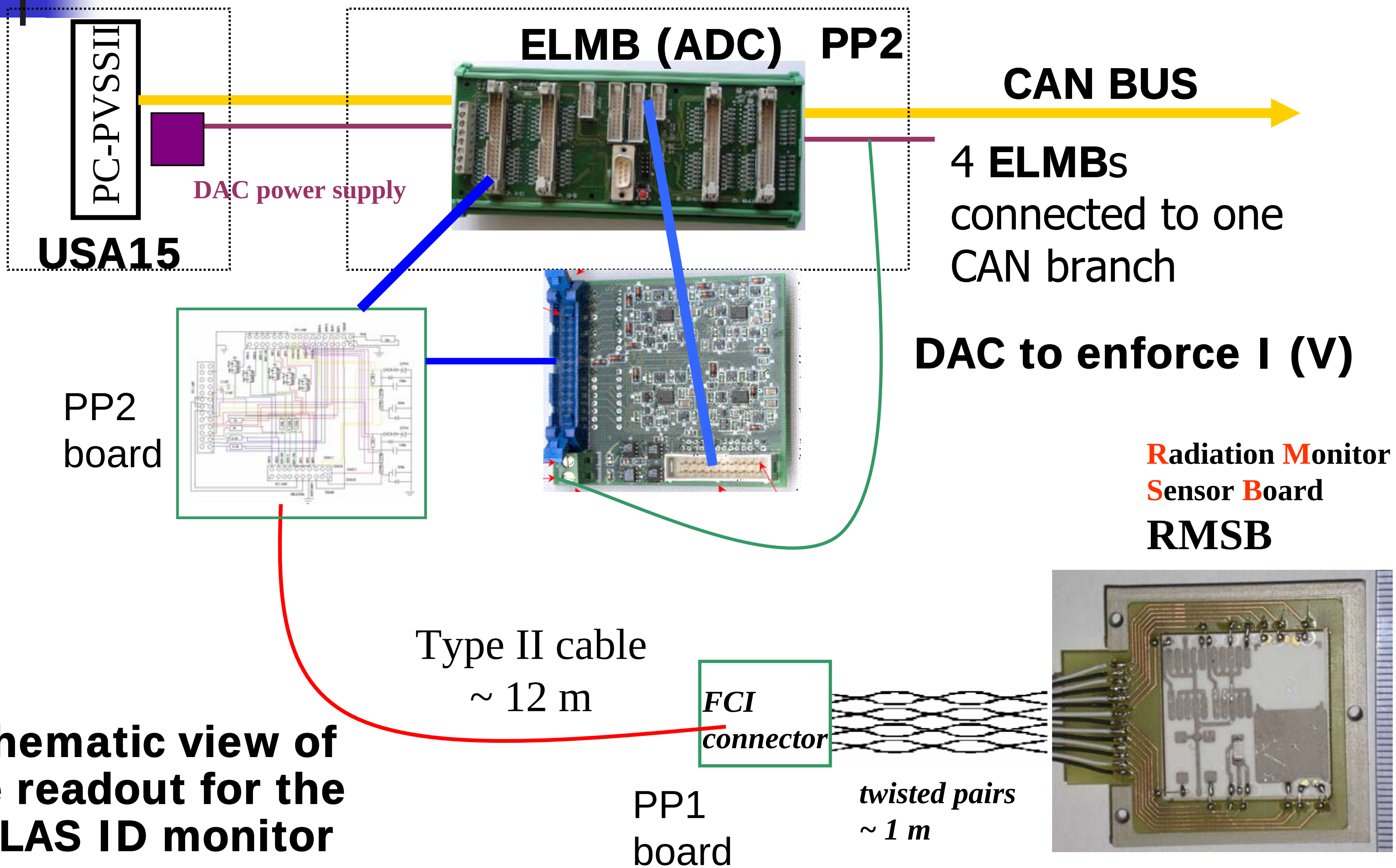
[I. Mandic, JSI]

Sensors Readout scheme

Readout (I/V) that can be easily implemented in the LHC experiments …



Sensors Readout at the LHC experiments



Schematic view of the readout for the ATLAS ID monitor

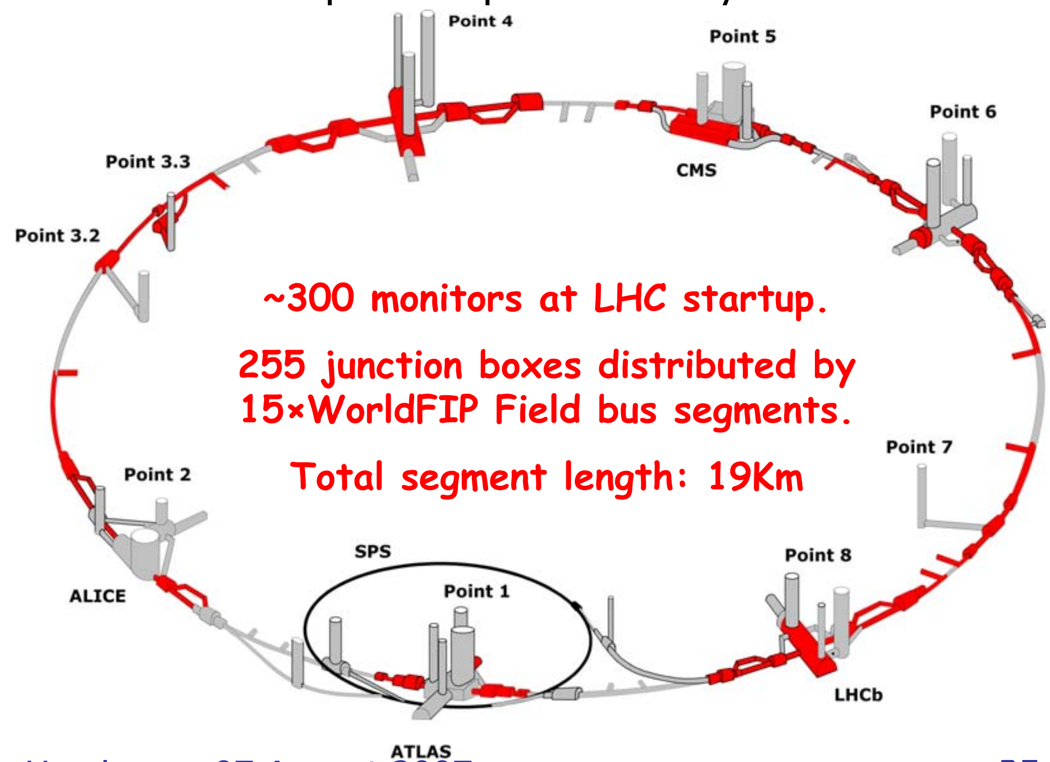
RADMON in LHC tunnel

[C. Pignard, T. Wijnands, CERN]

11 x 9 x 5 cm^3

RADMON Box

(IEL, NIEL, **SEU**)
LHC tunnel, alcoves, caverns
integrated readout, robust.
The dosimeter design uses COTS components
and can operate up to a 200 Gy total dose.



~300 monitors at LHC startup.

255 junction boxes distributed by
15×WorldFIP Field bus segments.

Total segment length: 19Km

Radiation Monitoring at LHC experiments: Overview

	ATLAS	ALICE	CMS	LHCb	TOTEM
RADMON active sensors on integrated carriers	**Yes**	**Yes**	**No**	**Yes**	**Yes**
RADMON box (LHC) in experimental areas	**No**	**No**	**Yes**	**Yes**	**No**
Passive Dosimeters	Yes	Yes	Yes	Yes	Yes
BCM fast (bunch by bunch)	Yes	Yes	Yes	Yes	No
Thermal neutron sensors	Yes	No	No	No	No
Relative luminosity monitoring	Yes	?	Yes	?	No
Thin aluminum foil dosimeters	No	?	No	Yes	No
Scintillator panels for halo	Yes	?	Yes	?	No

Conclusions

- RADMON at the LHC Experiments is a **challenge** for semiconductor sensors to be used for **Radiation Monitoring**;

- **Selection** and **characterization** of **ACTIVE sensors** brought **to recommend** a set of **two RadFET devices** (LAAS 1600 & REM TOT501C) and **two *p-i-n* diodes** (CMRP & BPW34F) that fulfill the LHC experiments need;

- The devices **operation has been validated** in condition similar to the ones expected at the LHC (LDR test at CERN-IRRAD6);

- **Packaging** studies and **devices integration** have been carried out in function of the experiments need;

- Use of **different sensors** and measure of **different quantities** in **several locations** is the adopted Radiation Monitoring strategy at the LHC Experiments.