Present Status and Future Trends on Radiation Tolerance in Large Scale Tracking Systems

- Radiation resistance in current LHC trackers
- Requirements for tracking @ L=$10^{35}cm^{-2}s^{-1}$
- A possible approach
- The challenge of new ideas

Workshop on 'Radiation-hard semiconductor devices for very high luminosity Colliders' CERN 28-30 November 2001

Tracking and Radiation Resistance @LHC

Radial region: 25cm<r<110cm :$10^{13}cm^{-2}<\Phi<10^{14}cm^{-2}$

Radiation resistant micro-strip silicon detectors

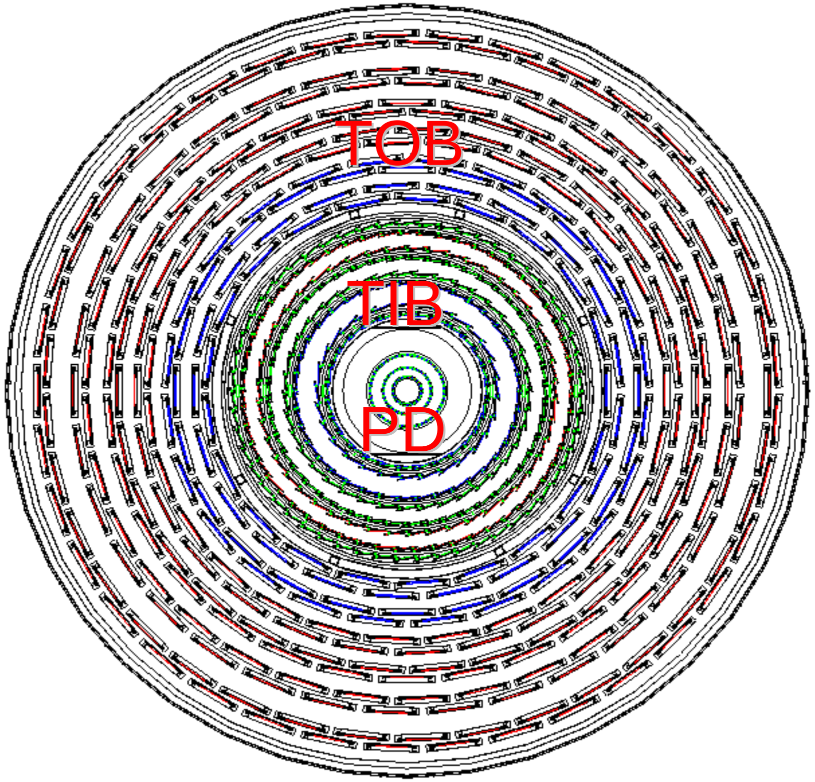
- High Voltage Operation ($V_b<500V$)
- Careful tuning of the detector characteristics
- Large scale production of ‘low cost’ high quality sensors

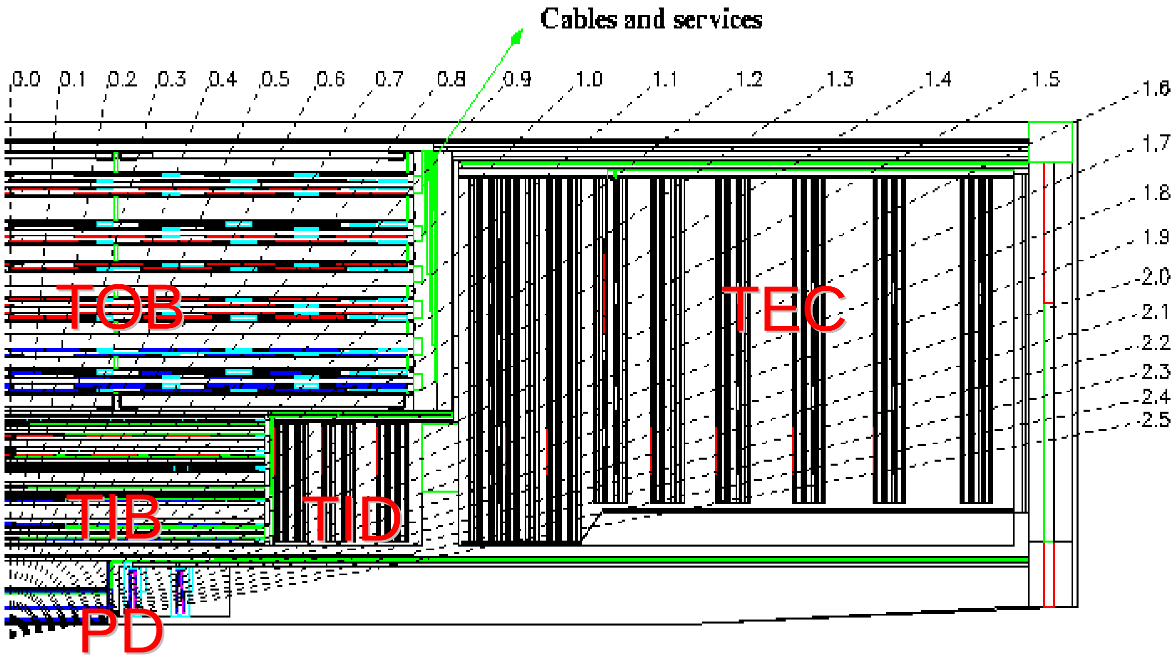
Radial region: 5cm<r<20cm :$10^{14}cm^{-2}<\Phi<10^{15}cm^{-2}$

Hybrid pixel technology

- Extreme segmentation
- Defect engineered sensors (rose-endeasd)
- Possible replacement of the innermost layers

The CMS Silicon Tracker

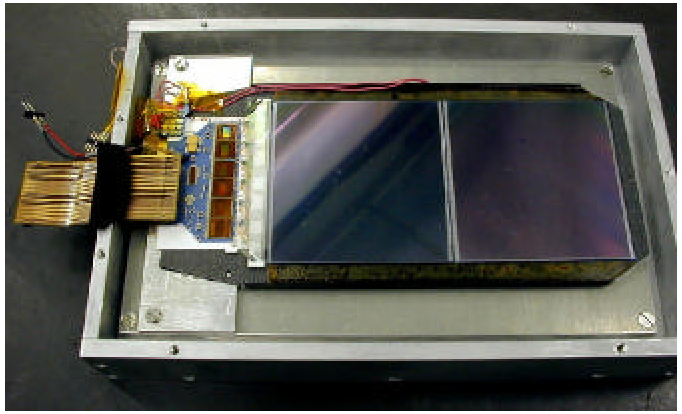


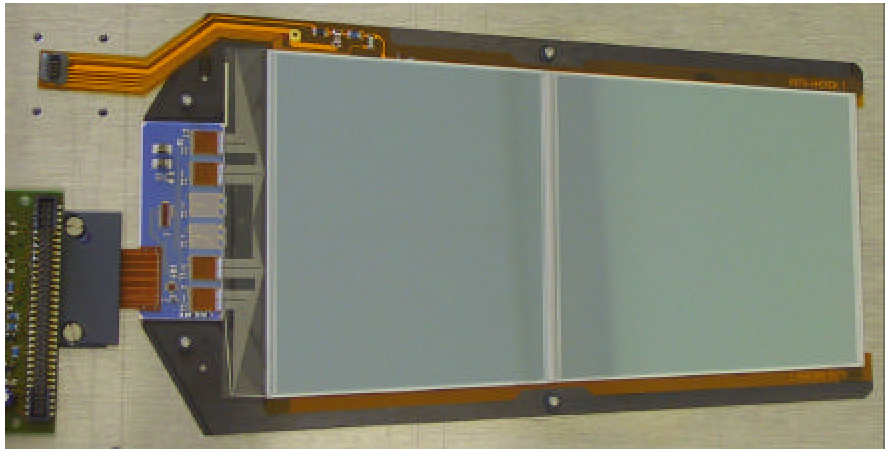


- 210m^2 of micro-strip silicon detectors 15.232 detector modules
- two highly reliable companies selected for the production of sensors: HPK (6136, 320µm) and STM (19292, 500µm); 6” wafers only.

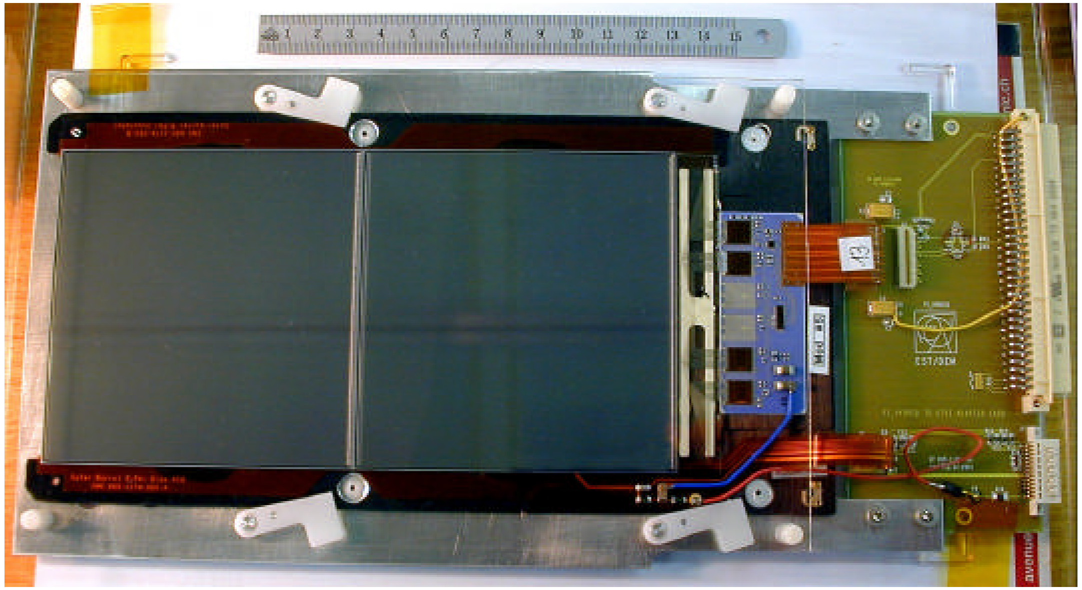
The CMS detector modules

- TIB module: 72cm^2;320μm thick HPK sensors





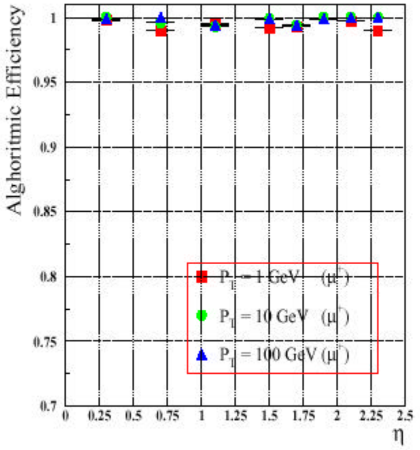
- TEC module: 180cm^2; 500μm thick STM sensors

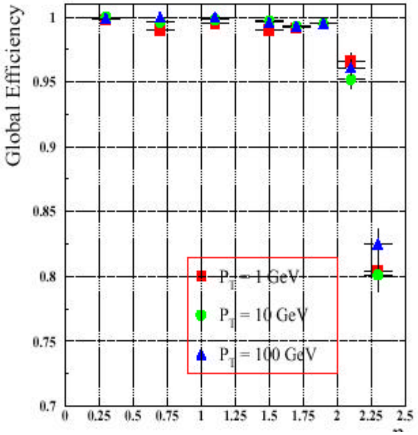


- TEC module: 180cm^2; 500μm thick STM sensors

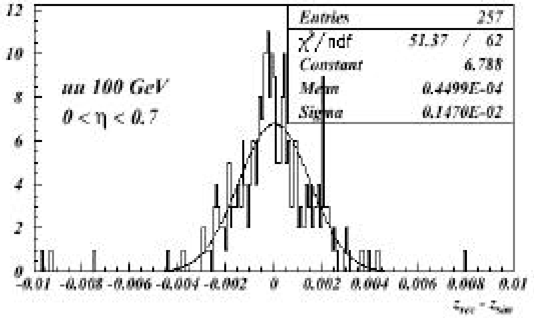
Tracking performance

- Track finding efficiency for isolated μ

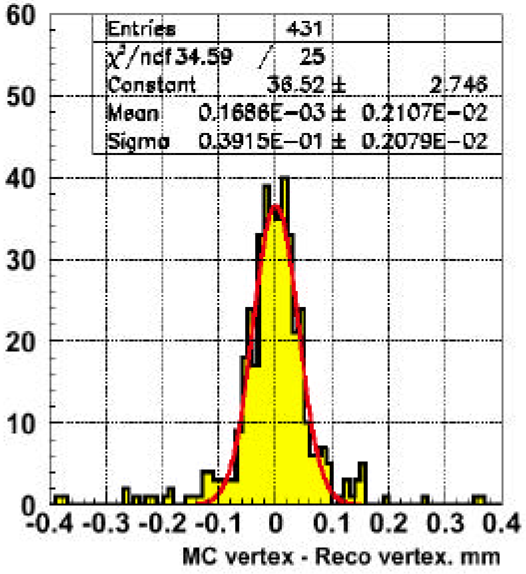




- Vertex reconstruction

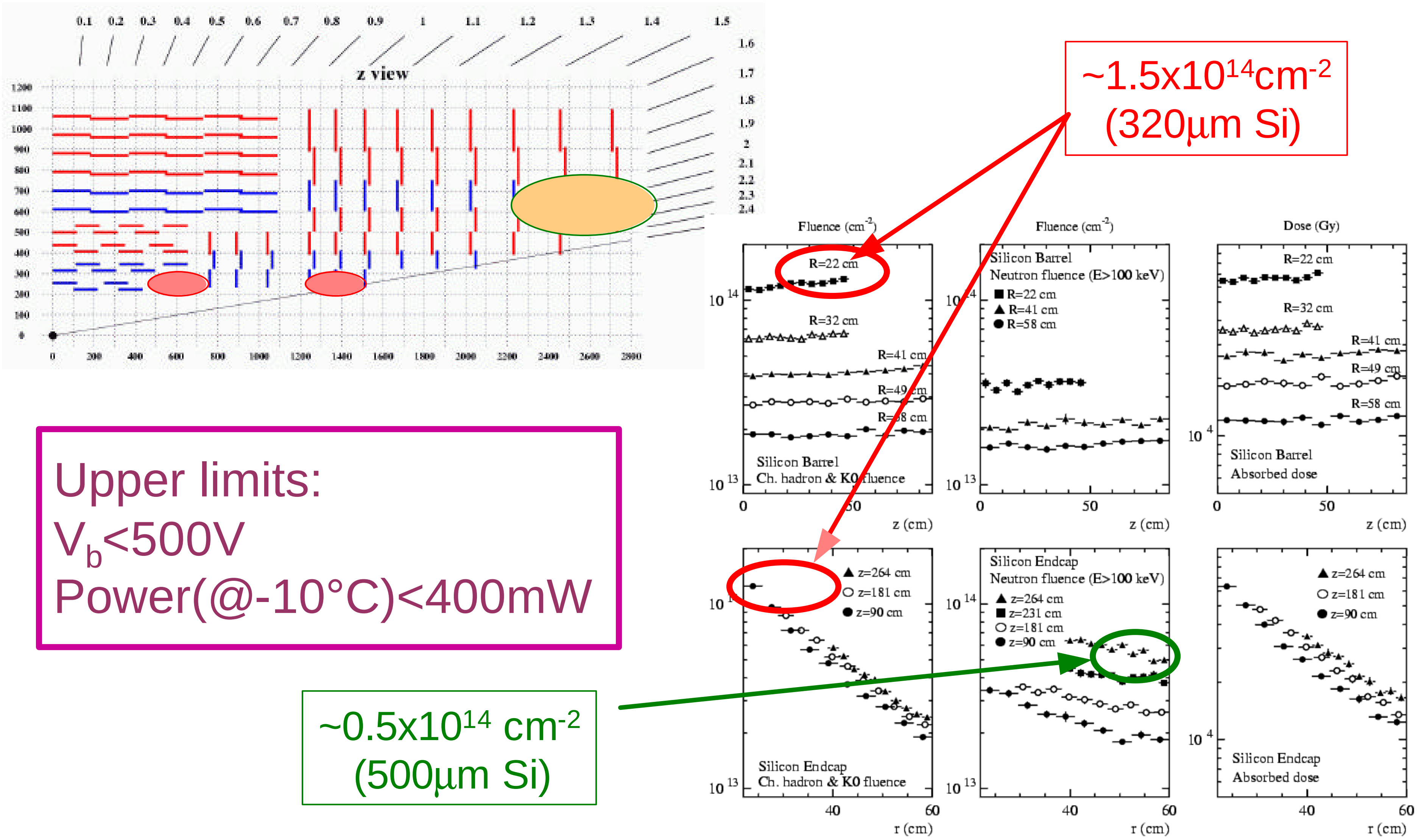


z-resolution of "signal" PV for uu-events (100 GeV, barrel) (PrincipalVertexReco)
$\sigma_z = 15\ \mu m$



z-resolution of "signal" PV for $H \rightarrow \tau\tau$
$m_H = 500$ GeV, $|\eta|<2$

Expected Fluences in the CMS Tracker

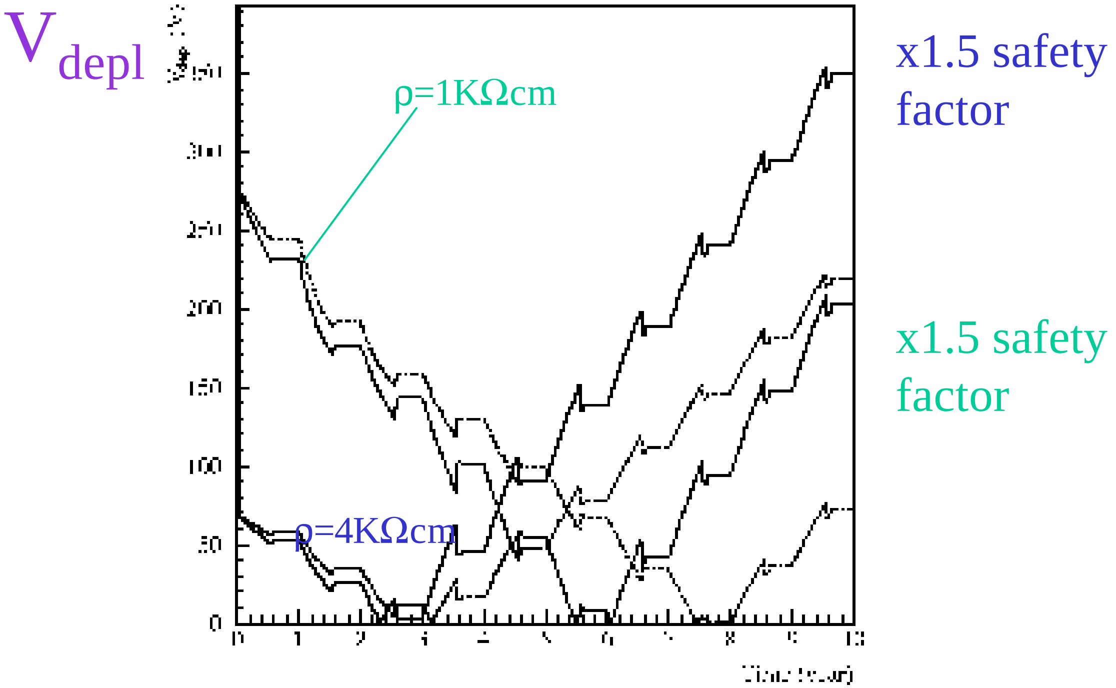


~1.5×10^{14} cm^{-2}
(320µm Si)

Upper limits:
V_b<500V
Power(@-10°C)<400mW

~0.5×10^{14} cm^{-2}
(500µm Si)

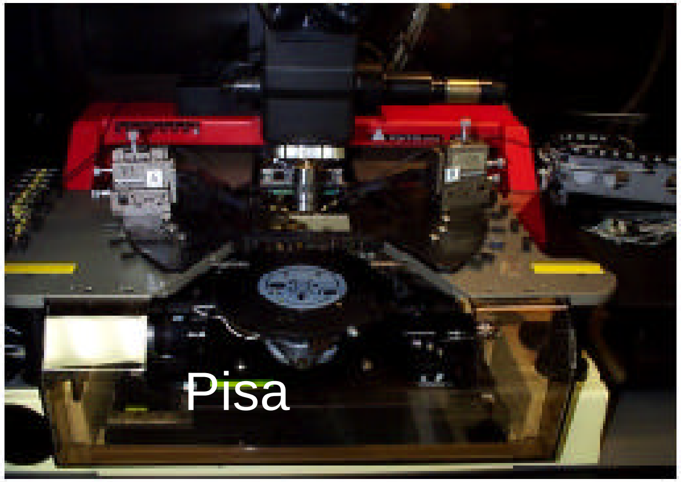
The approach for radiation tolerant silicon (CMS)



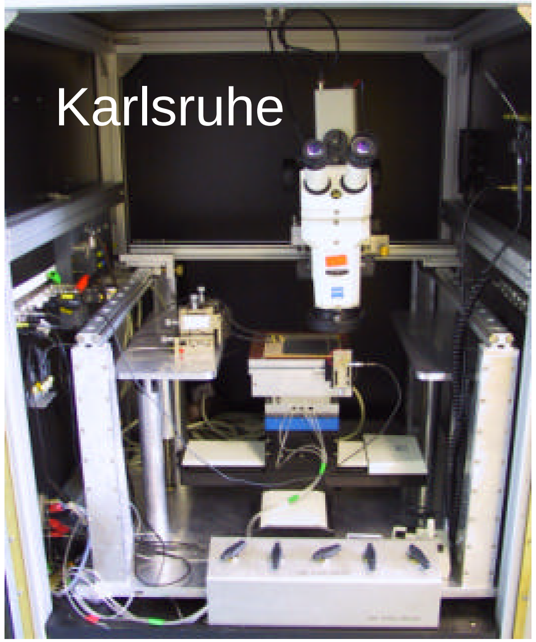
- Brute force: high voltage operation and cooling at –10°C
- Play with thickness and resistivity to equip the different radial regions and to cope with the corresponding levels of radiation damage but

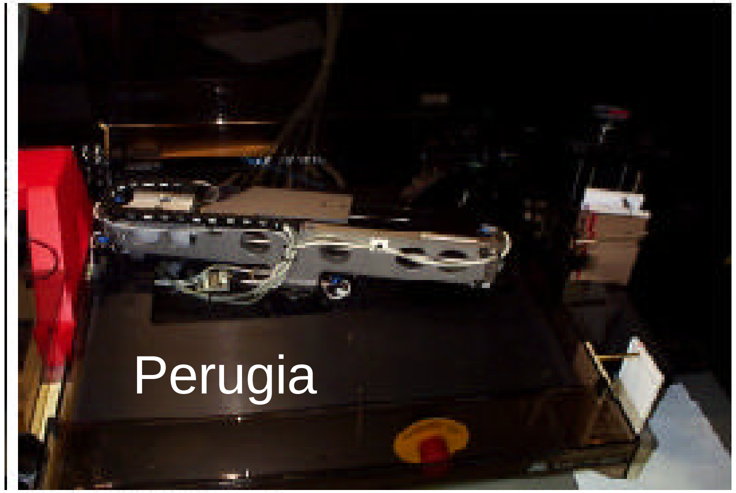
Is it really possible to produce 25.000 sensors with these characteristics?

Sensors Quality Control Centers (CMS)



- •Pisa, Perugia,
- •Karlsruhe, Vienna
- •all operational

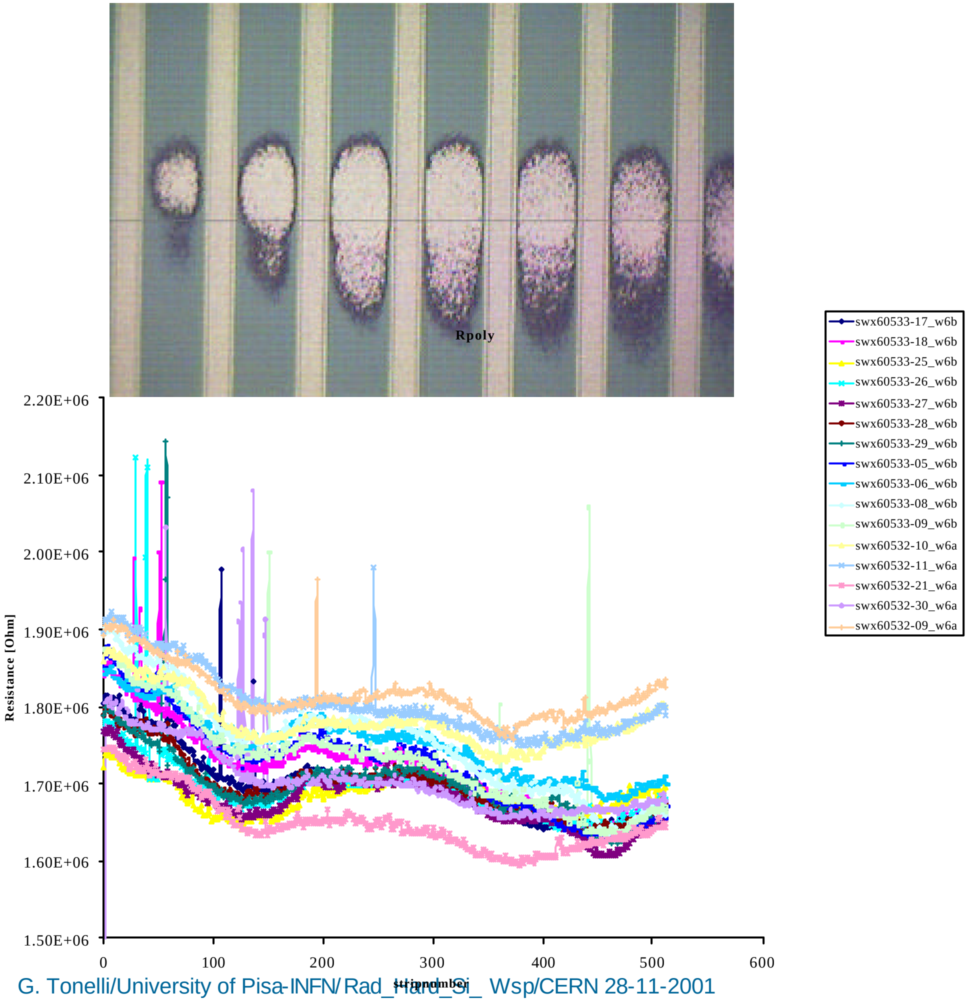


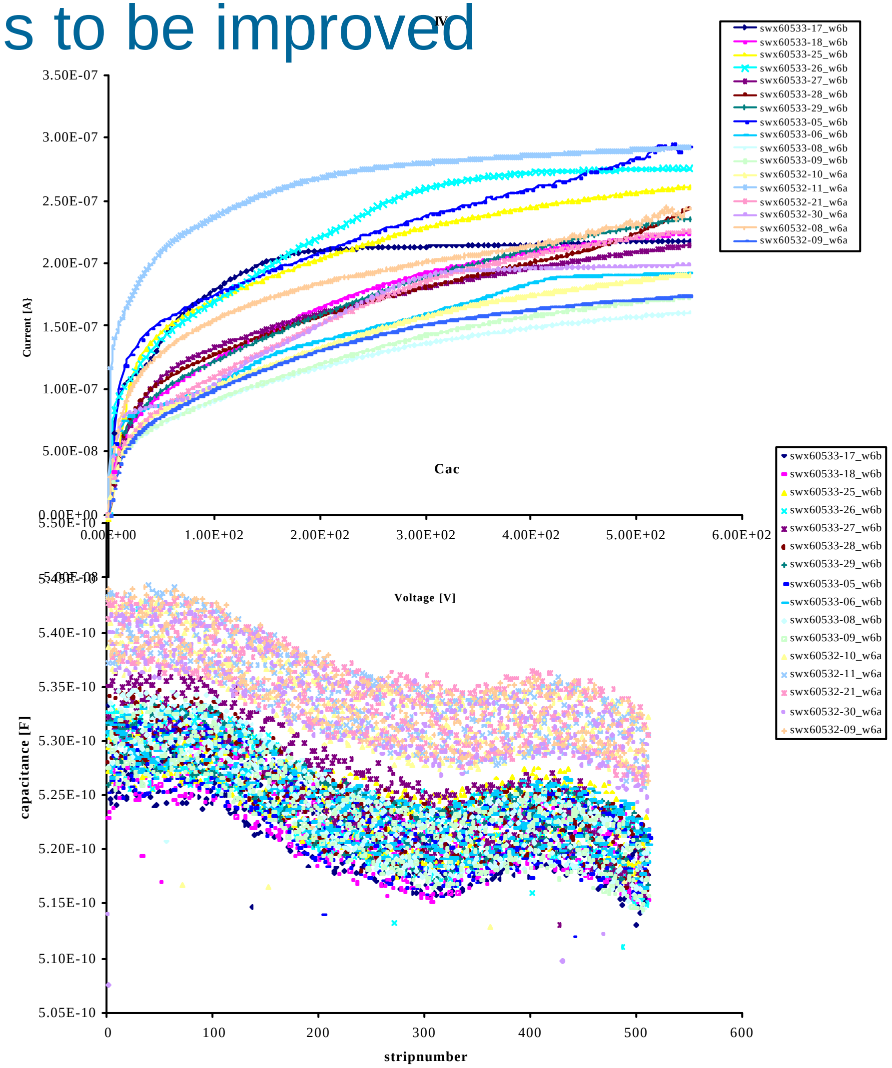


Sensor QC (CMS)

First 160 HPK sensors delivered and tested

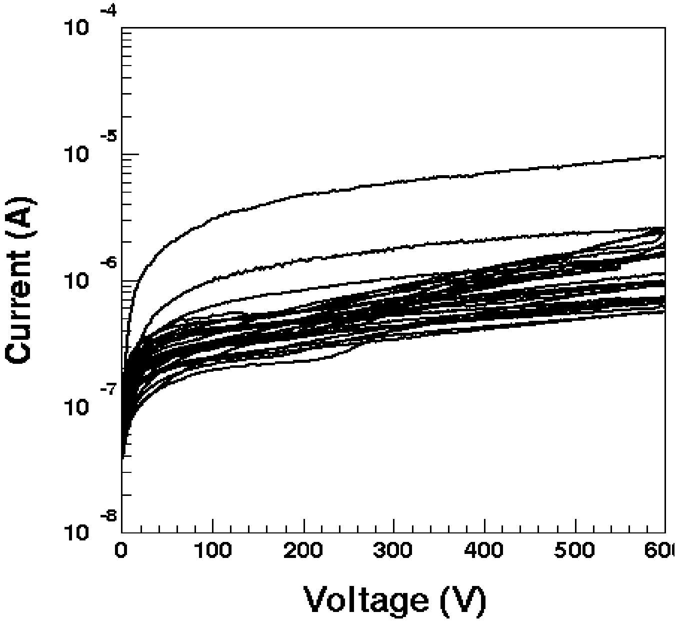
Very good quality; minor details to be improved

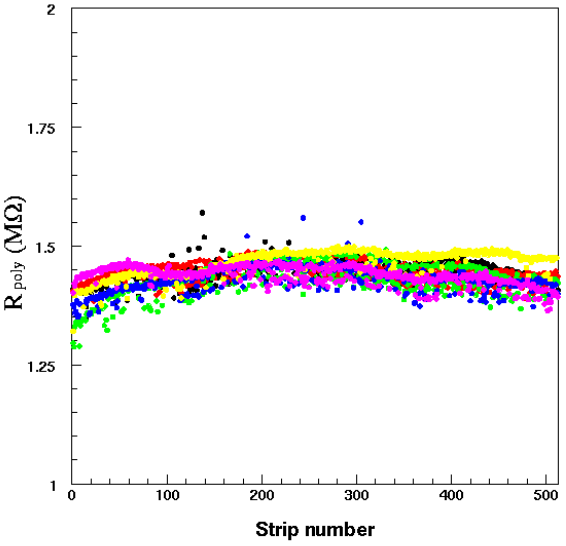


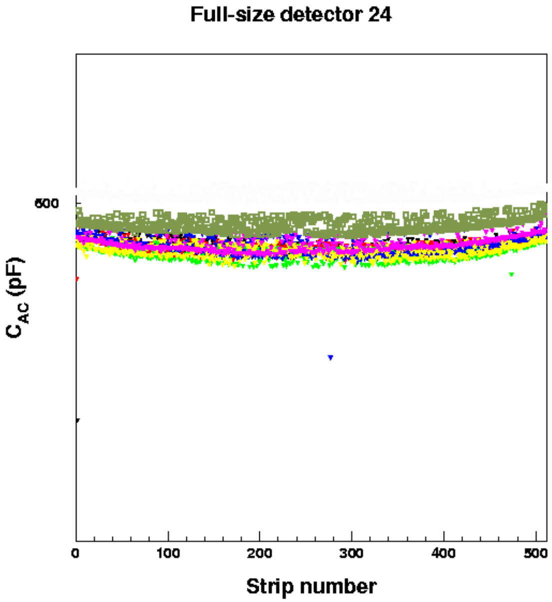


Sensors QC (CMS)

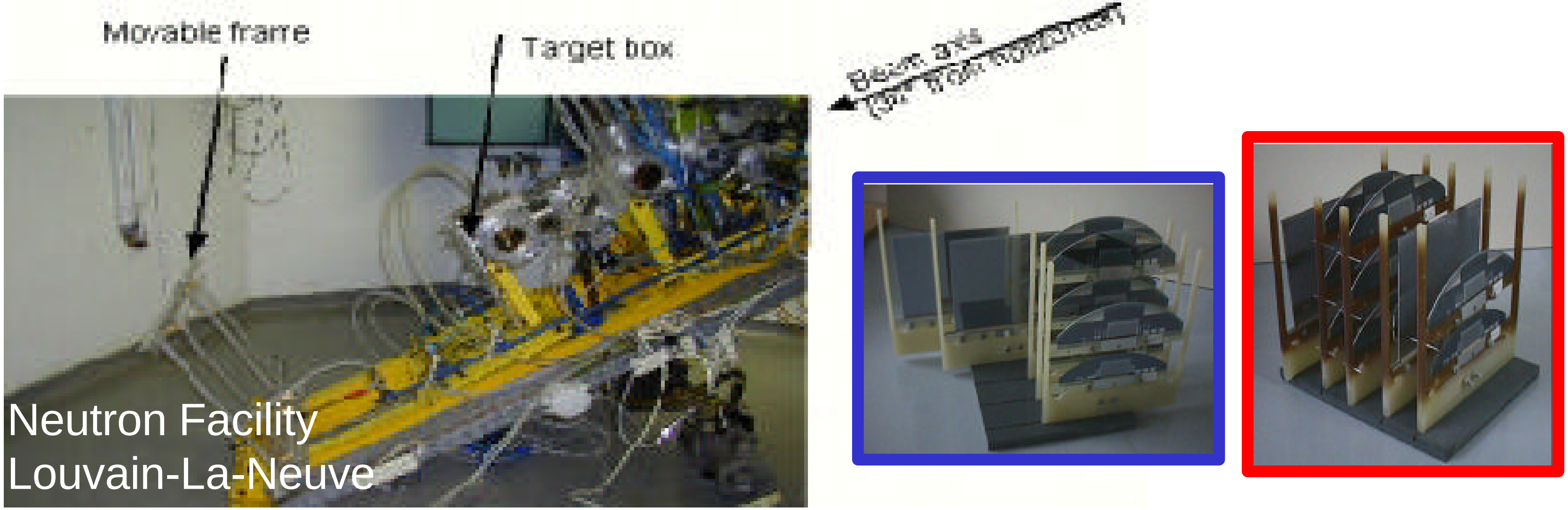
70/160 STM sensors delivered. 100 in delivery.
Good overall quality but some details still to be optimized.






Full-size detector 24

Irradiation Facilities (CMS)

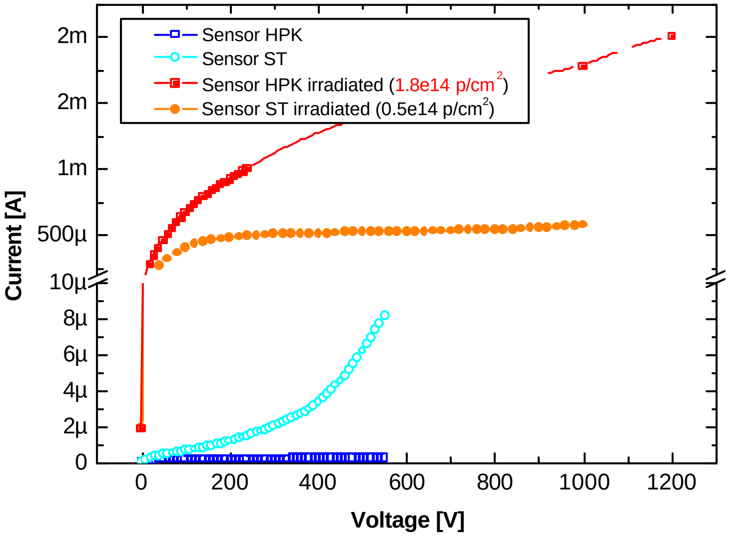


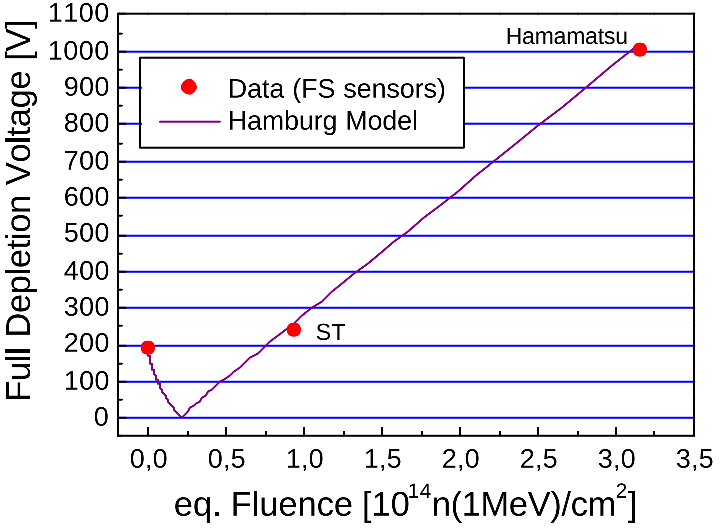
Neutron Facility
Louvain-La-Neuve

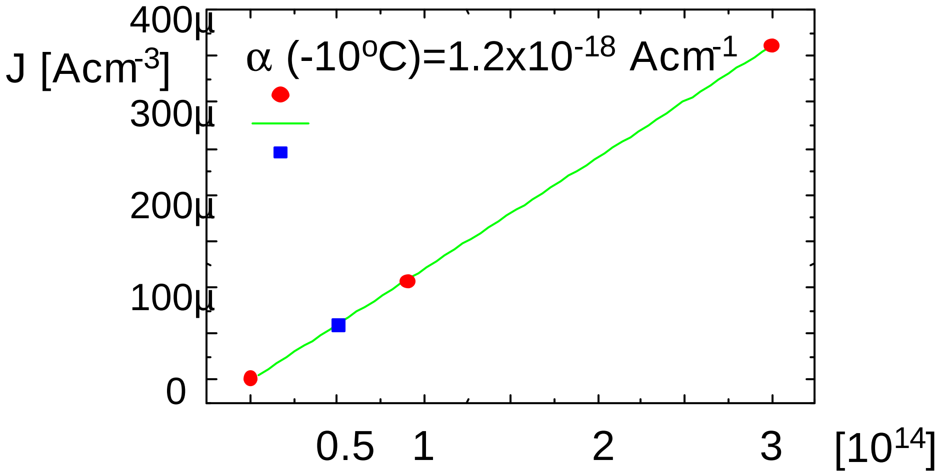
- 34 MeV p;1000 nA
- beam spot: 2cm^2
- T < -10°C; bias on
- area: 20x40cm^2
- duration: 100cm^2 in 15min
- fluence: 5x10^{13}pcm^{-2}

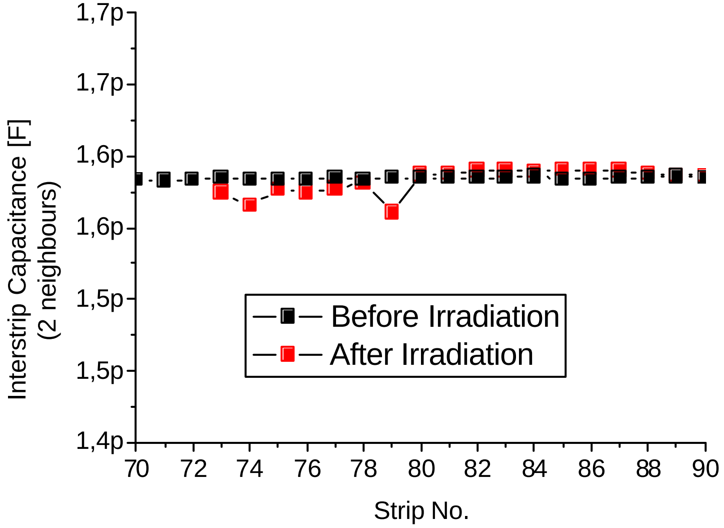
Compact Cyclotron
Forschungszentrum Karlsruhe

Post-irradiation results (CMS)





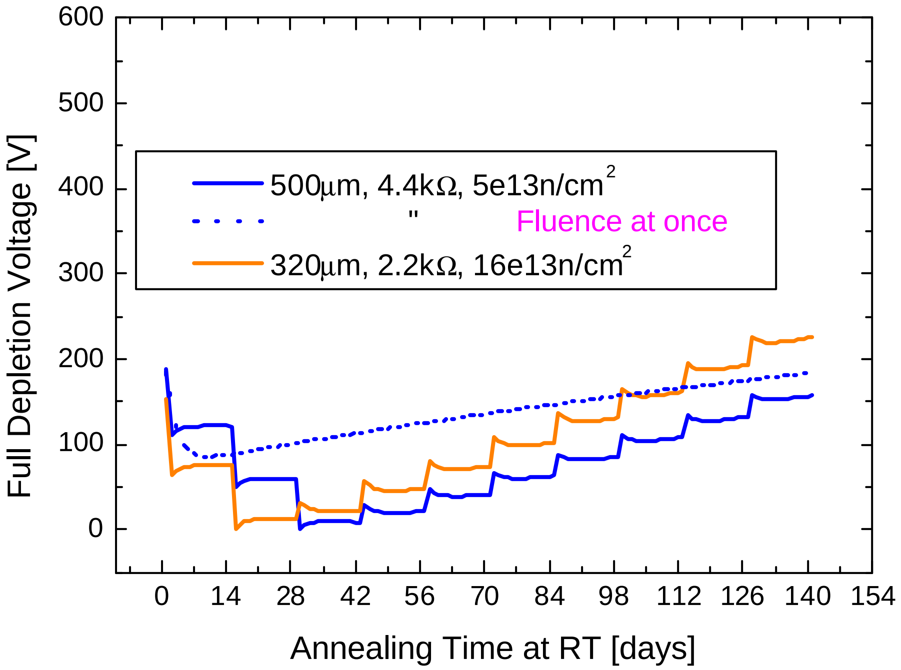




All results in good agreement with expectations and computations (Hamburg model)

Power dissipation and maintenance (CMS)

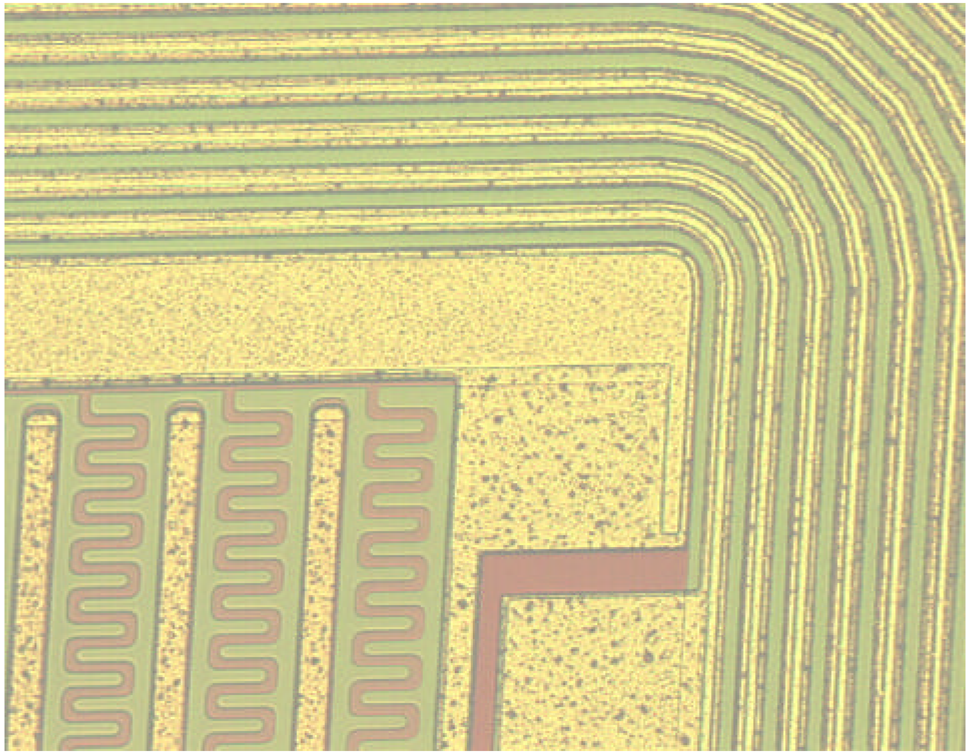
Annealing scenario:14 days at RT each year

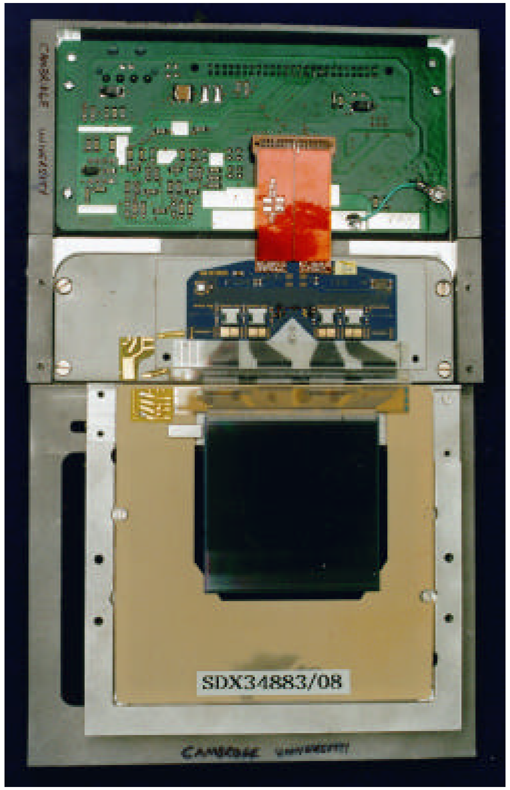


- 60µA/cm³ => I_{leak}@-10°C=540µA (W6) => P@**500V** =270mW/module
- 200µA/cm³=> I_{leak}@-10°C=460µA (IB2) => P@**500V** =230mW/module
- The cooling is designed to include everywhere safety factors between 1.5 and 2

Radiation resistant design (Atlas)

	Hamamatsu	CiS
Substrate Orientation	<111>	<111>
Oxygenation	None	W12 only
Bias Resistors	Polysilicon	Implant
Edge Design	Single Guard	14-multiguard
Strip Dielectric	Manufacturer Dependent	





Irradiation Tests (Atlas)

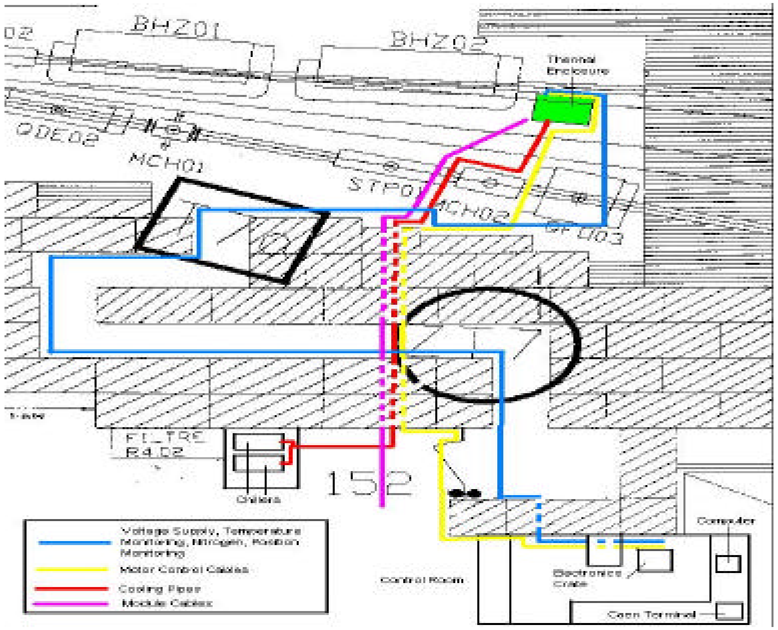
Samples of production sensors continue to be irradiated throughout production, to ensure that the post-irradiation performance is being maintained.

T7 irradiation facility at CERN PS: 24 GeV/c p up to 3×10^{14}p.cm^{-2}.

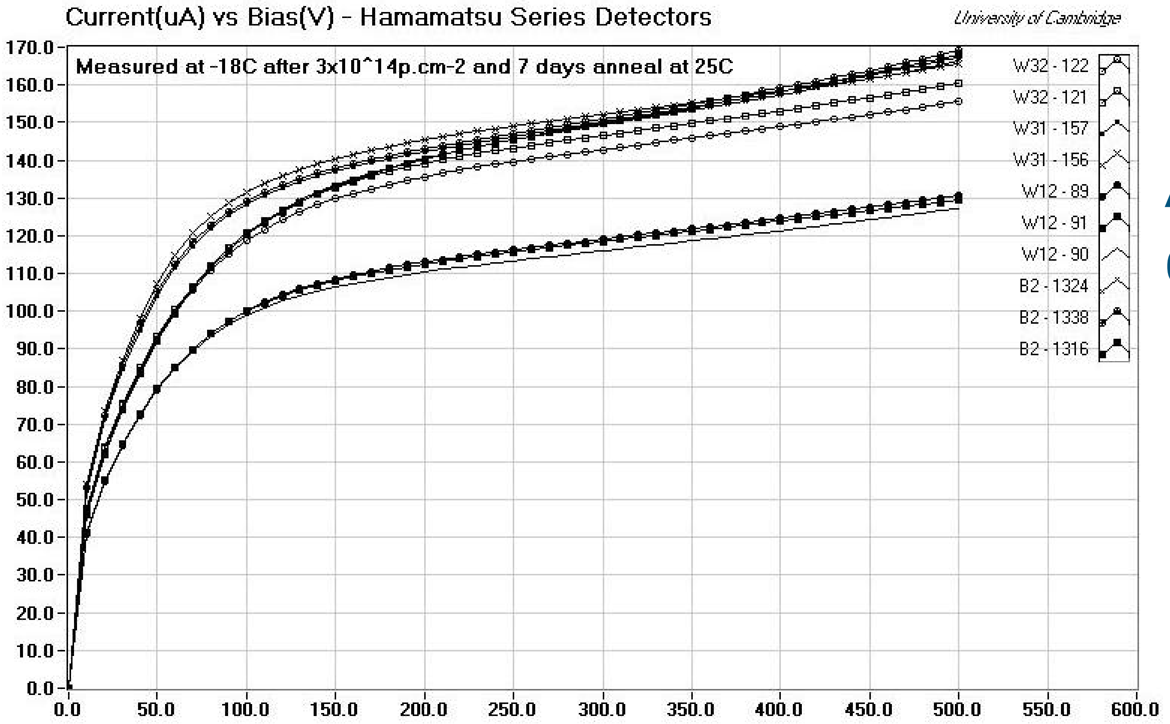
During irradiation, the detectors are chilled in nitrogen to -8°C, and biased at 100V with all strip metals grounded.

Typical irradiation time 6-10 days.

Post-irradiation treatment: annealing for 7 days at 25°C.



Post-irradiation leakage current (Atlas)



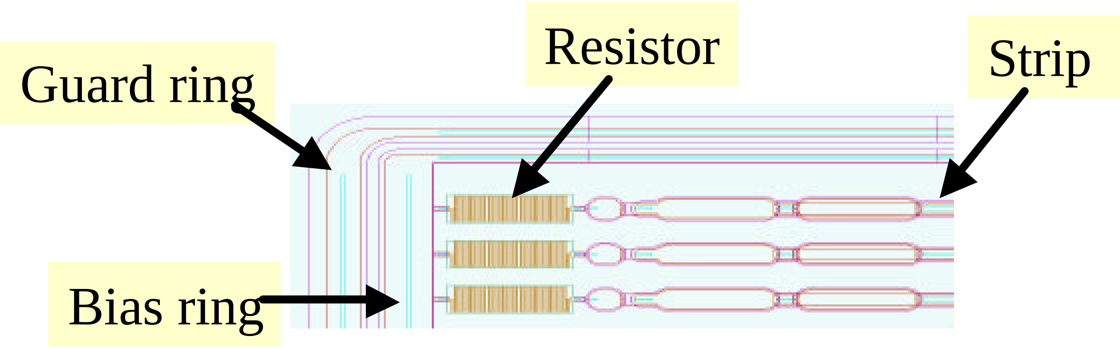
After $3\text{x}10^{14}$p.cm^{-2} and 7 days anneal at 25^{o}C

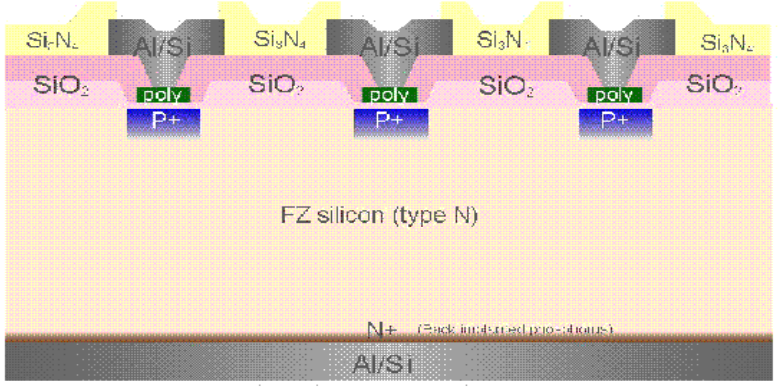
Excellent post-irradiation IV characteristics

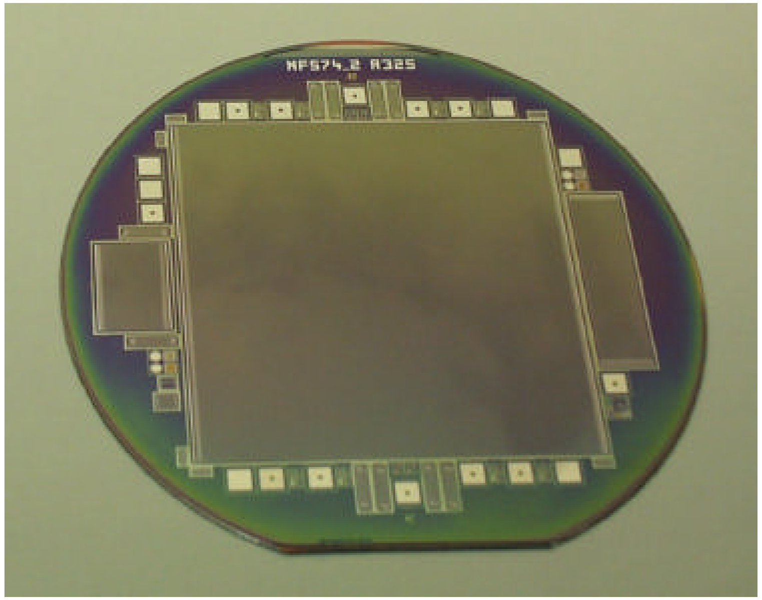
<160μA@500V at -18^{o}C, depending on geometry

Note: the 4 “groupings” are due to the 4 different sensor geometries

Standard Rad-hard Technology for Silicon





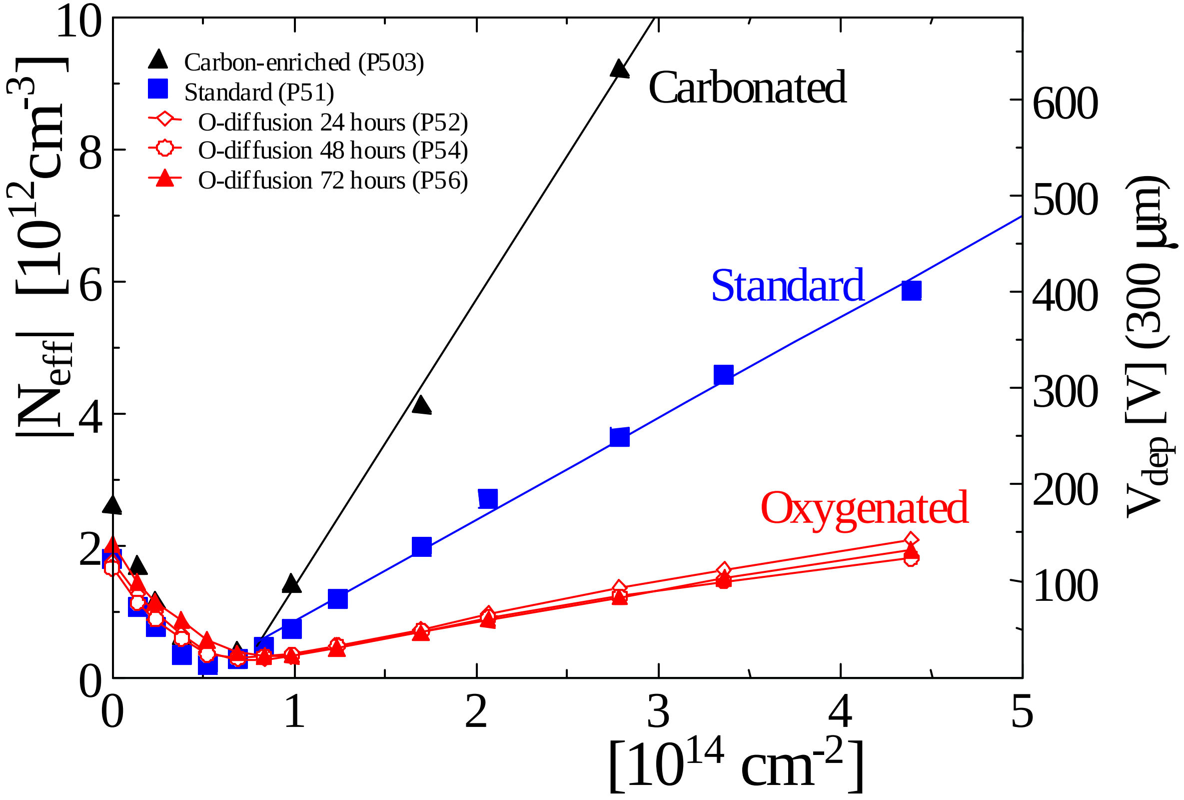


- <100> substrate
- Single-sided, p^+ on n
- AC coupled, poly biased
- N^+ channel at the edge
- Single guard structure
- Metal overhang on the strips
- Width/pitch 0.2-0.25

Further improvements by defect engineering of the substrate

Role of defects in radiation resistance (Rose)

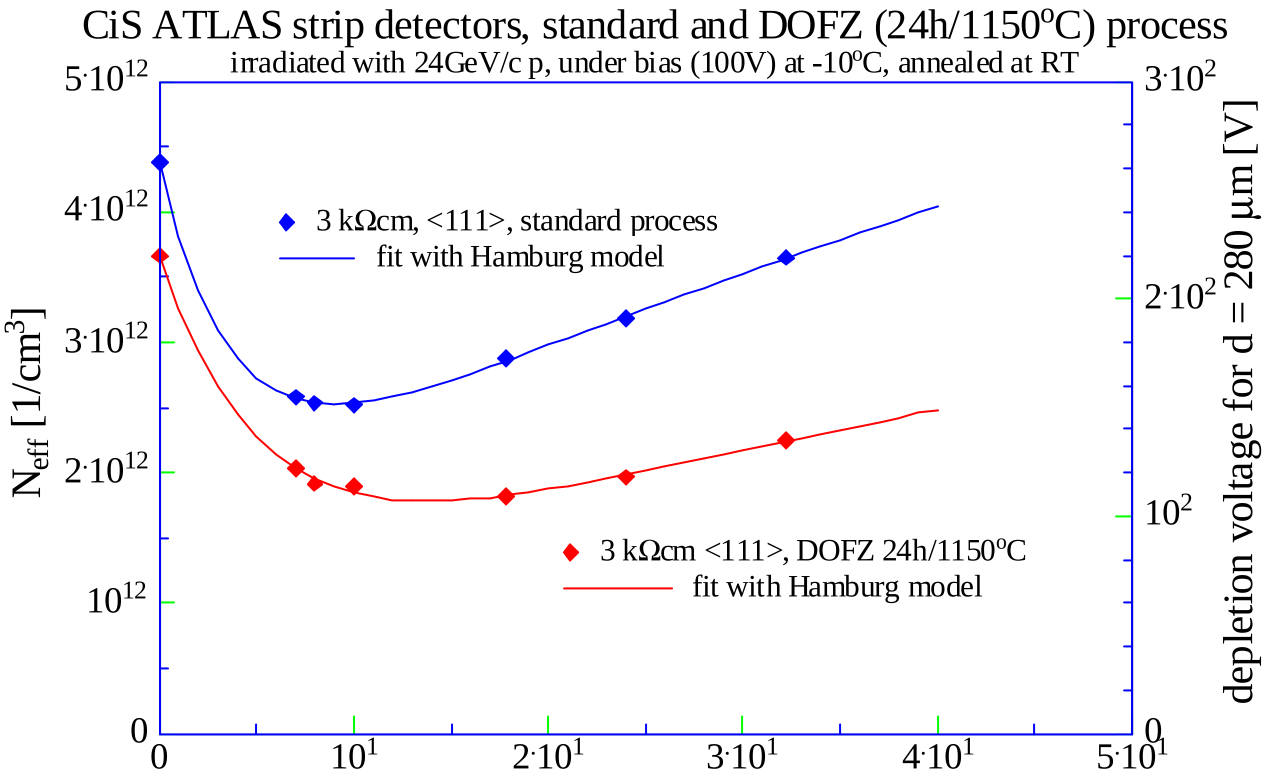
24 GeV/c proton irradiation



Compared to standard silicon:

- ♦ High Carbon ⇒ less radiation tolerant
- ♦ High Oxygen ⇒ more radiation tolerant

DOFZ Si-strip detectors (ATLAS)



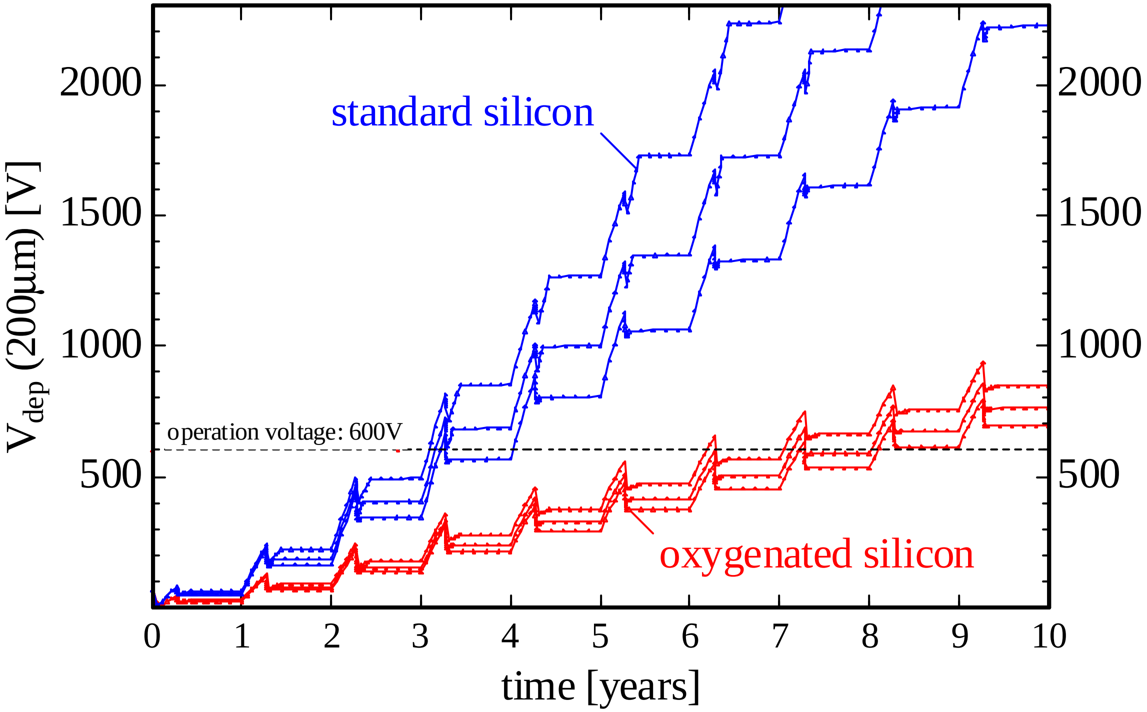
data from L. Andricek, MPI Munich

Oxygenation leads to large reduction of reverse annealing

Charge Collection Efficiency after 3×10^{14} p/cm^2 (24 GeV/c protons): oxygenated and standard 92%
(Sr90, SCT 128a, analogue, 20ns rise time)

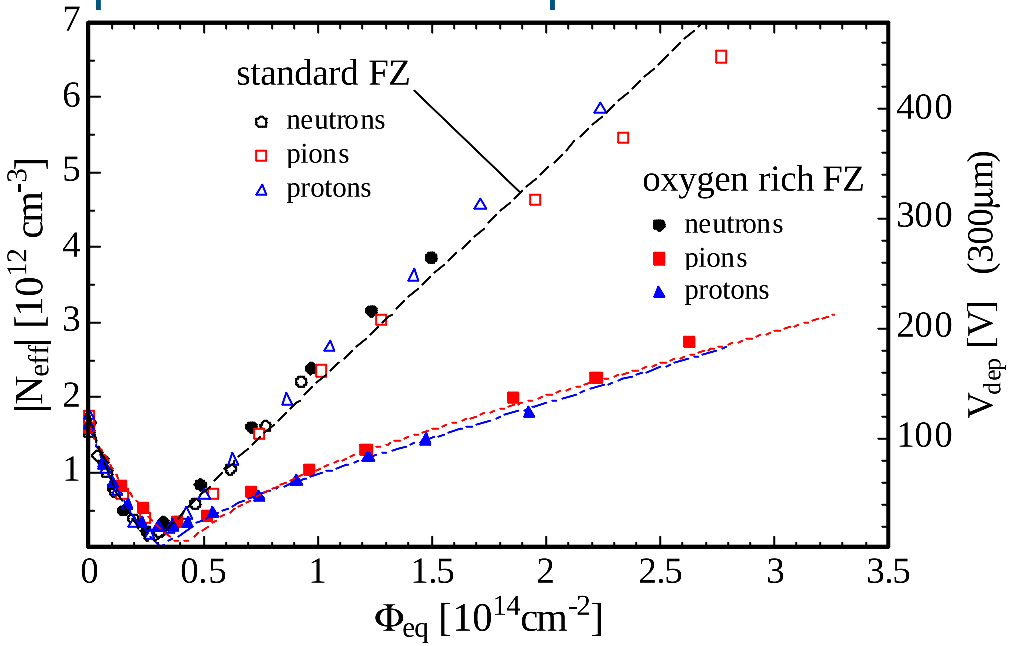
DOFZ Si used in the Atlas Pixel Detector

- B-layer @ r=4cm
- Radiation levels:
  - Φ_{eq}(year) = 3.5 × 10^{14} cm^{-2} ; full L : > 85% charged hadrons
  - 1 year = 100 days beam on ; temperature –7°C
- Three scenarios:
  - (1) 3 days 20°C and 14 days 17°C
  - (2) 30 days 20°C
  - (3) 60 days 20°C



DOFZ-Si: hadron-neutron puzzle (Rose)

23 GeV protons - 192 MeV pions - reactor neutrons



- ♦ Strong improvement for π and p
- ♦ Almost none for neutrons
- ♦ Role of Coulombian interactions in radiation induced defects? Dependence from the process and/or the starting material?
- ♦ A lot of progress, but still much to be understood

A new challenge: SLHC

Basic assumptions

- Luminosity $10^{35}cm^{-2}\ s^{-1}$
- Bunch spacing 12.5ns (10ns)

- Program of new physics with an integrated luminosity of $2500fb^{-1}$
- Start-up around 2012

- Need of maintaining B-tagging capability
- Momentum resolution
- Pattern recognition

- Fast (10ns) and low power (1-2mW/ch) electronics available

General approach

(L.Casagrande, M. Huhtinen, C.Joram, T. Niinikoski, S. Stapnes and G. Tonelli +many others)

Expected integrated fluences

•R=4cm	1.6x 10^{16}cm^{-2}
•R=20cm	8.0x 10^{14}cm^{-2}
•R=60cm	2.5x 10^{14}cm^{-2}
•R=115cm	1.0x 10^{14}cm^{-2}

- The Tracking systems of Atlas and Cms will not be able to cope with this luminosity (high bias voltage, increase in noise, thermal runaway, occupancy).

- A complete rebuilding of the Inner Detector Systems will be needed

- Current detector technologies with important new developments could work at a factor 3 larger radius; new ideas at smaller radius.

Tracking @ SLHC

- Radial region: 60cm<r<110cm ;

$1\text{x}10^{14}\text{cm}^{-2}<\Phi<2.5\text{x}10^{14}\text{cm}^{-2}$

Further developments in radiation resistant micro-strip silicon detectors.

- Radial region: 20cm<r<60cm;

$2.5\text{x}10^{14}\text{cm}^{-2}<\Phi<8\text{x}10^{14}\text{cm}^{-2}$

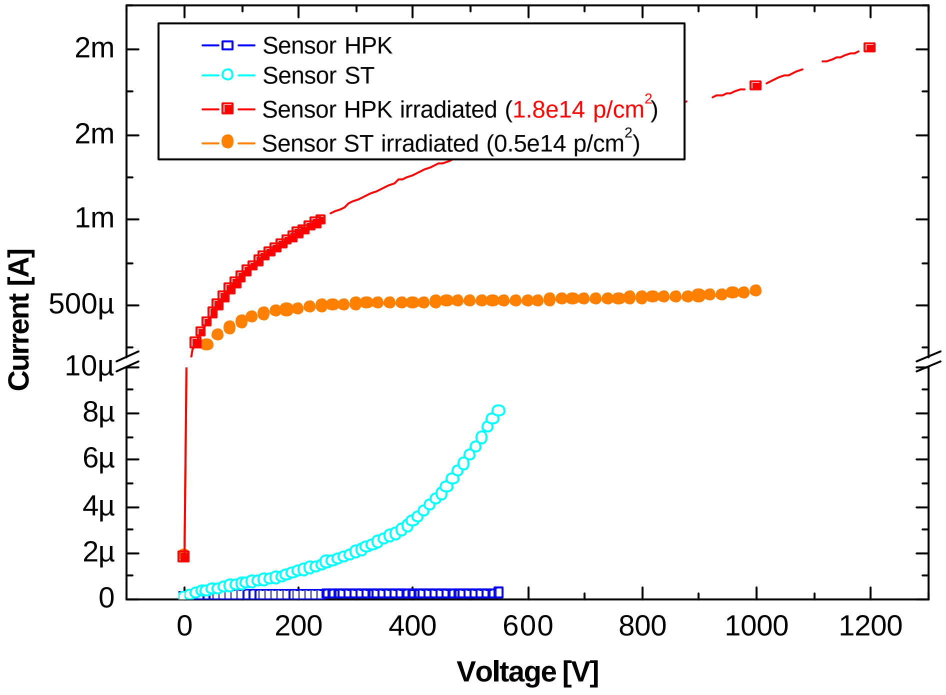
Extension of the actual pixel technology,defect engineering.

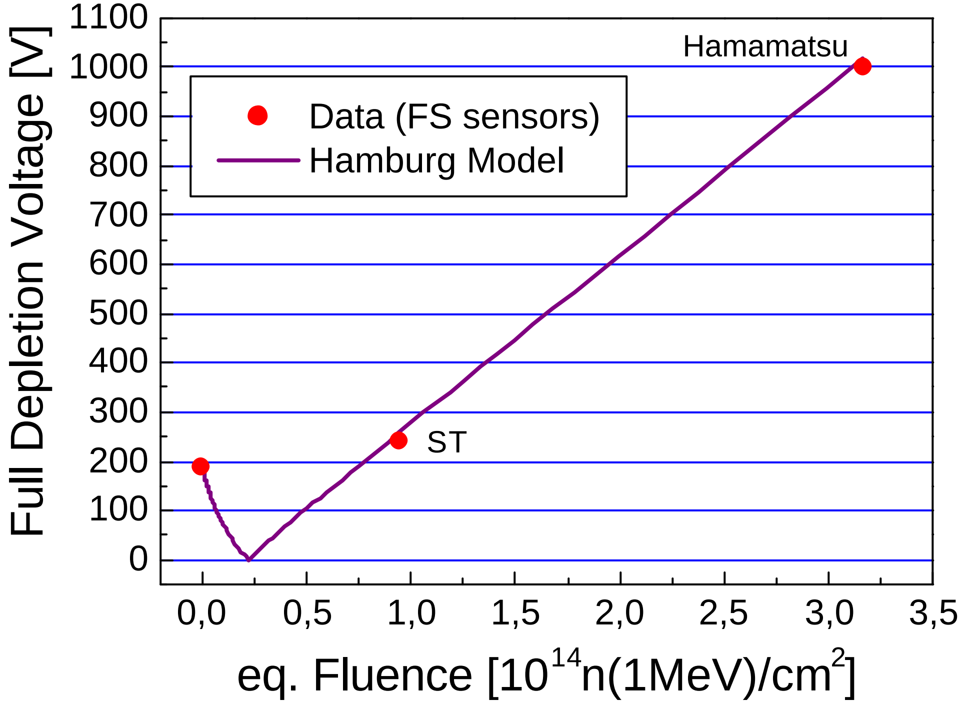
- Radial region: 5cm<r<20cm :

$10^{15}\text{cm}^{-2}<\Phi<10^{16}\text{cm}^{-2}$

New ideas, new materials.

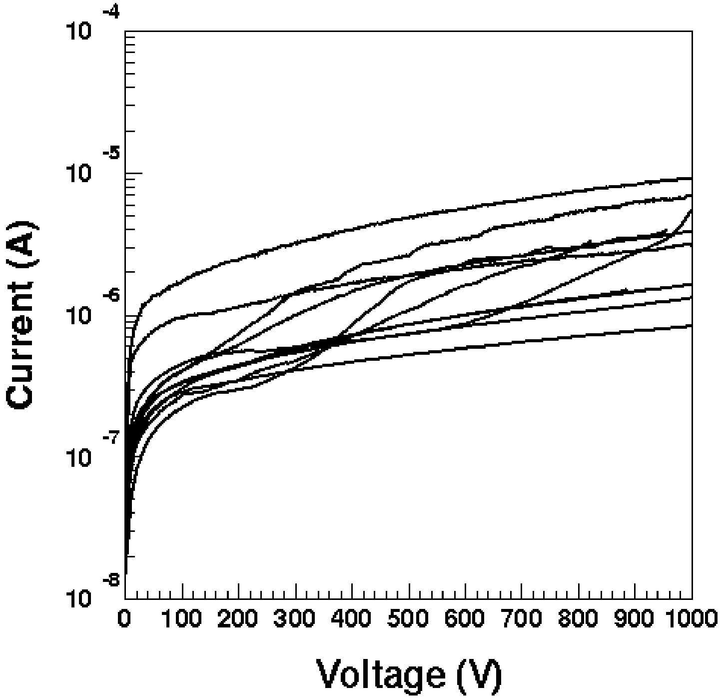
Radial region 60<r<110 cm

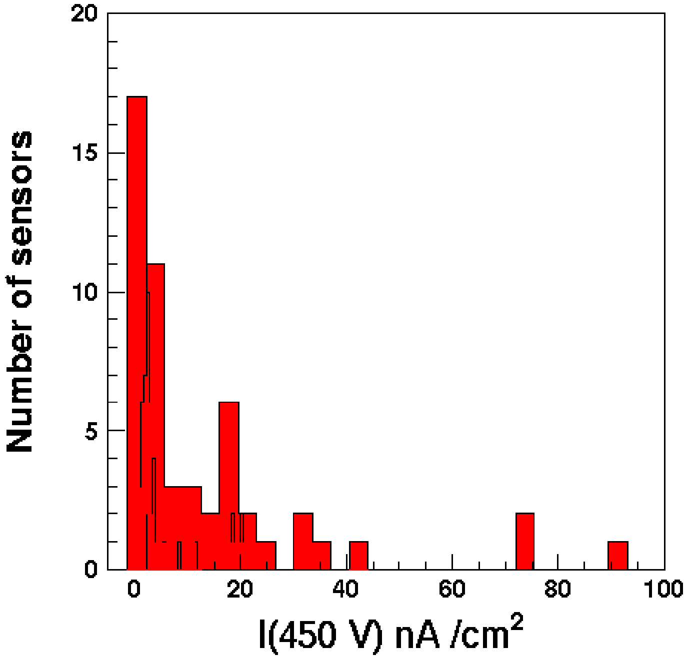




- Results for detectors of the CMS outer tracker (500µm thick) irradiated up to fluences corresponding to the ones expected in the outer region of the SLHC trackers (1-3x10^{14}p cm^{-2})
- Very high voltage operation (V_b>750V)

Very high voltage operation of Si detectors ?





- A careful tuning of the detector design and process characteristics is needed to explore the possibility of producing detectors that can be operated up to 1000V.
- The detector behavior in this regime, post-irradiation performance, system aspects etc. should be properly addressed.
- Since high volume production will be needed, we should address the issue of transferring the technology to the 8” processing lines (procurement of the raw material,standard thickness, access to the lines, compatibility of the process etc.)

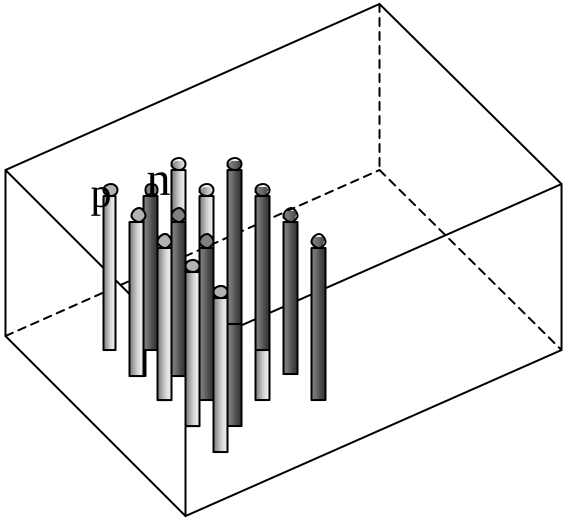
Radial regions 20<r<60cm and r>20cm

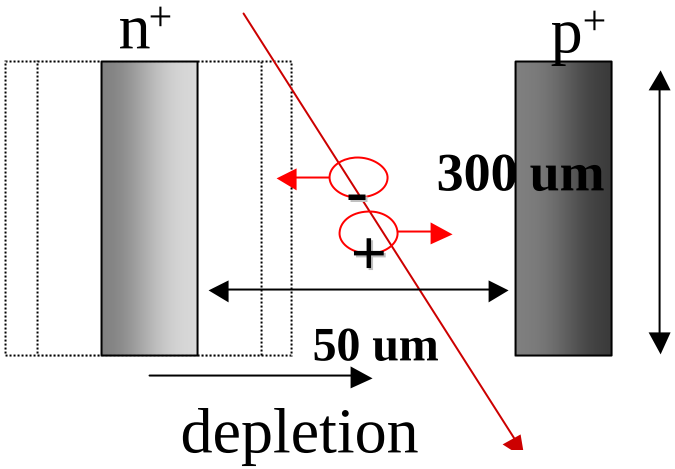
Pixel geometry (micro and macro-pixel)

•Extension of the existing hybrid pixel geometry to 3x larger radii
•Extensive use of defect engineered silicon (RD48)
•Use of CVD diamond as sensing element (10.000e^{-} and $5x10^{15}pcm^{-2}$ RD42)
• Monolithic pixels (several groups)
•Cryogenic approach (130^{o}K; Lazarus effect RD39).

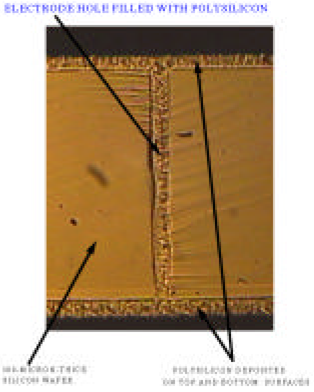
and new ideas……..

3D detectors (S. Parker et al.)



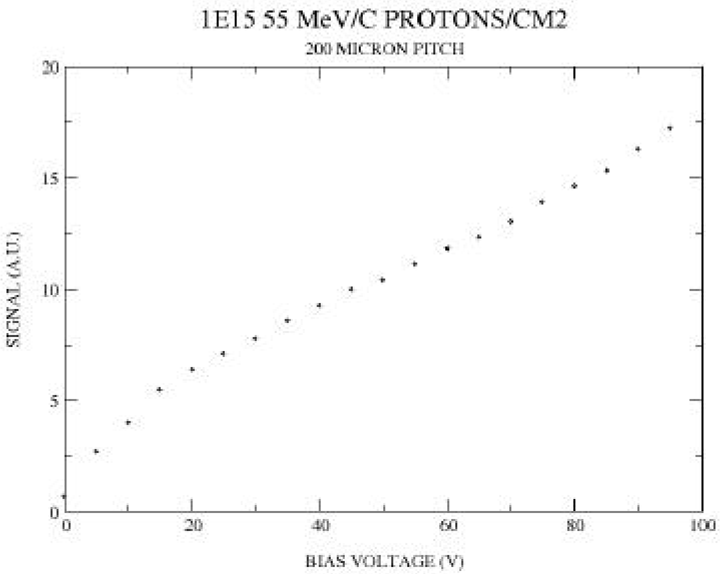


Deep reactive ion etching



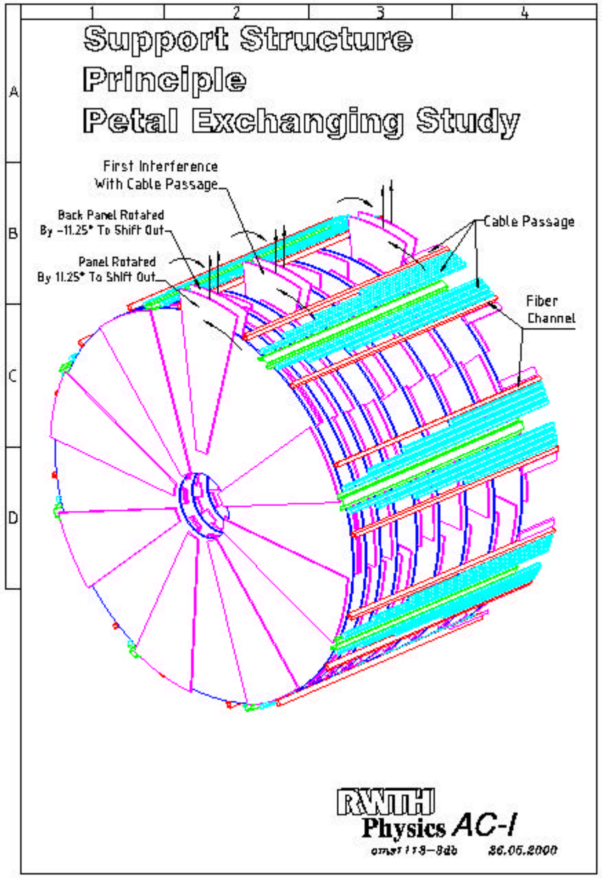
Si thickness	300- 500µm
Charge collection distance	50-100µm
Depletion voltage	5-10V

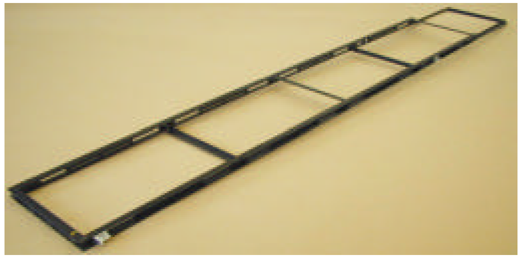
3D DETECTOR SIGNAL AFTER $2x10^{15}$ n/cm^2

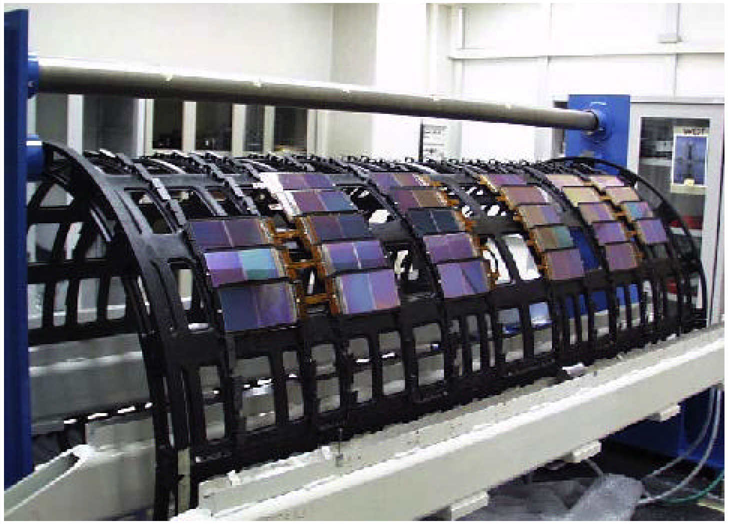


Mechanics and engineering

- Highly modular approach; carbon fibre composite supporting structure
- Serious cooling issues; operating temperature:-15^{o}C/-20^{o}C
- Low mass components, services, interconnections







Conclusions

•The current radiation tolerance for semiconductor detectors is marginal to cope with a x10 increase in luminosity of LHC

• The state-of-the-art technologies can be further developed to be used at large radii.

•New concepts or significant breakthroughs are needed for the innermost region.

•Although full priority will be given in the coming years to complete the current trackers, a low profile start-up of R&D activity on these issues would be necessary to prepare in time the adequate technical solutions.