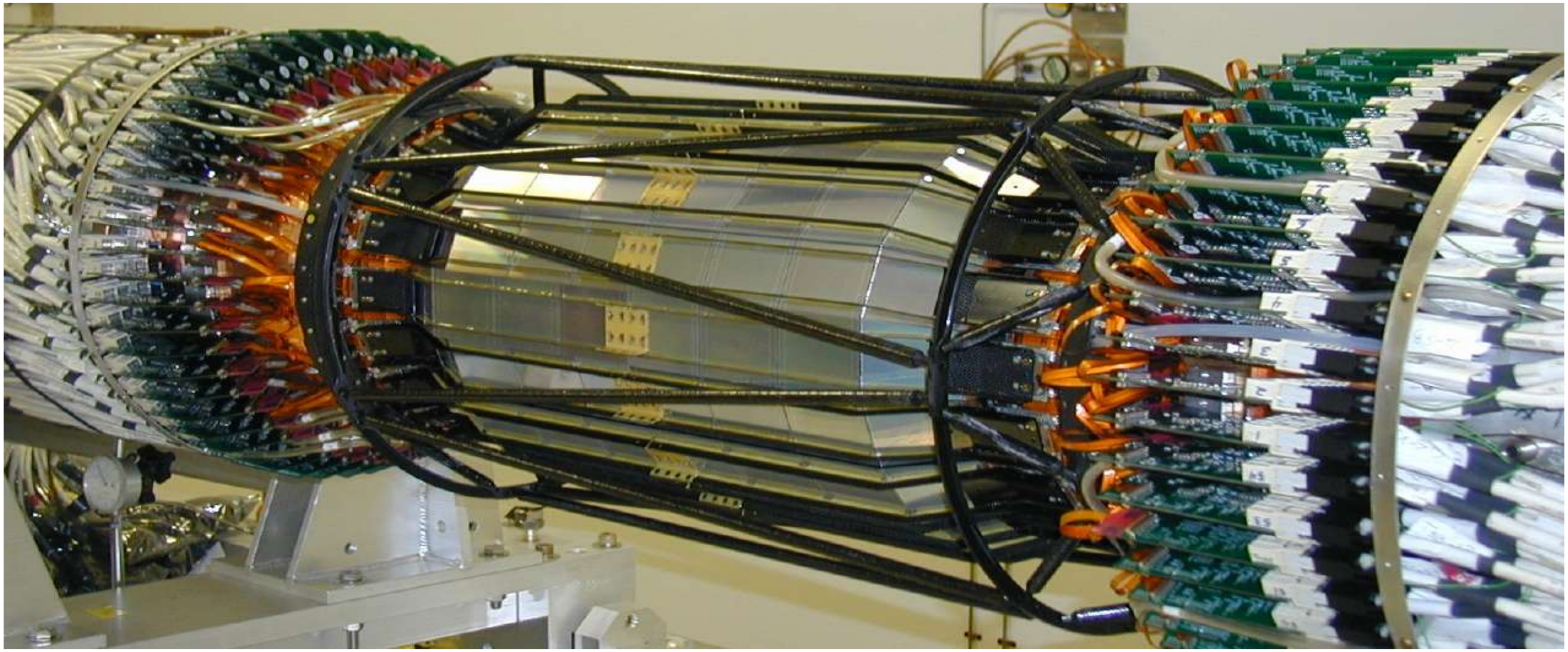
# BaBar SVT: Radiation Damage and Other Operational Issues

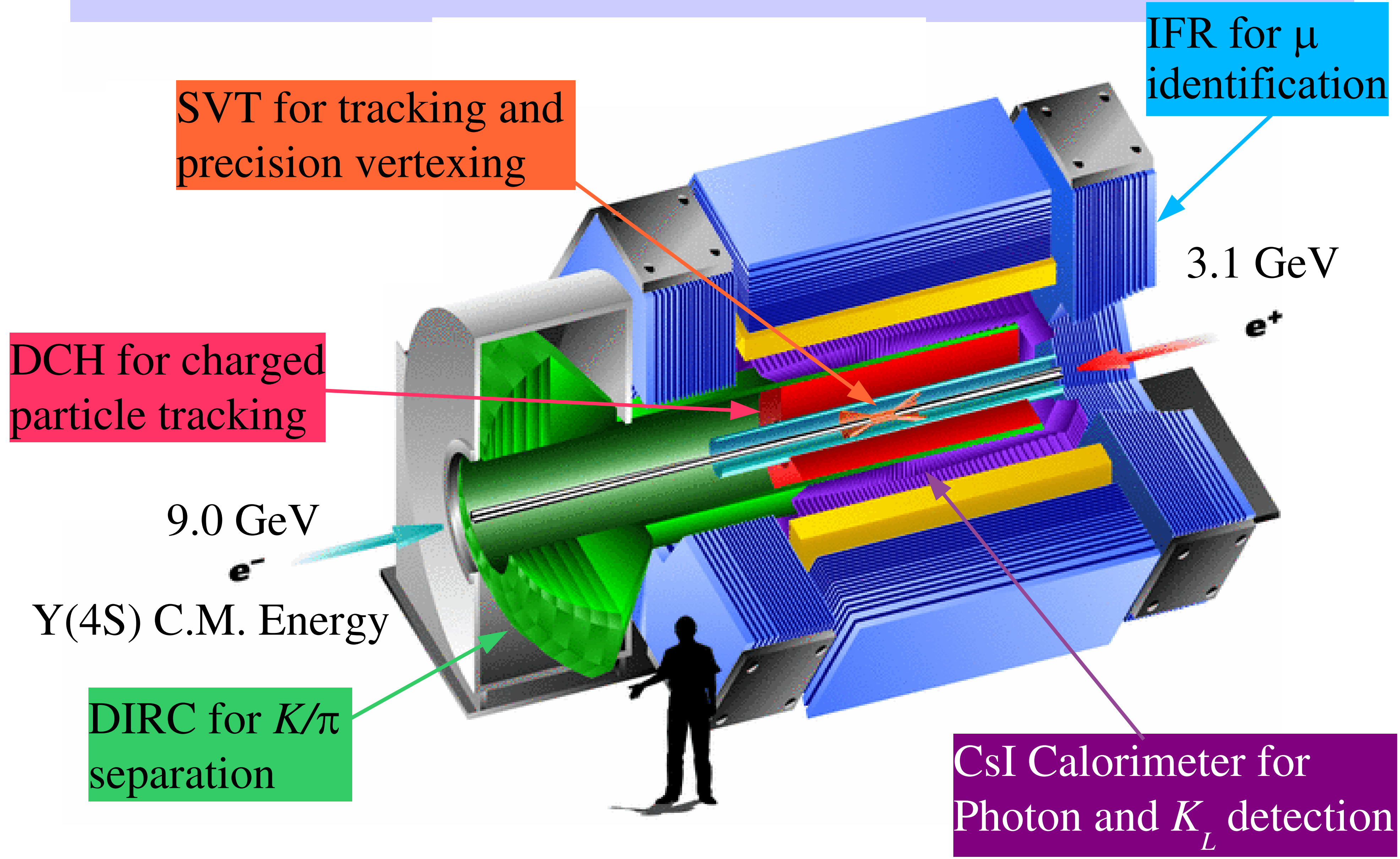
Gabriele Simi
SLAC



# Outline

- Intro to BaBar and SVT
- Radiation Environment
- Damage to Si Detectors
- Damage to Front End Electronics
- Performance Degradation
- Other mysteries

# BaBar Detector



# SVT Requirements and Constraints

**PEP-II Constraints**

- Permanent dipole (B1) magnets at +/- 20 cm from IP.
  - Polar angle restriction: $17.2^0 < \vartheta < 150^0$.
  - Must be clam-shelled into place after installation of B1 magnets
- Radiation exposure at innermost layer (nominal background level assumed at time of construction):
  - Average: 33 kRad/year.
  - In beam plane: 240 kRad/year.
- SVT was originally designed to function in up to 10 X nominal background.

**Performance Requirements**

- $\Delta z$ resolution < 130 μm.
- Single vertex resolution < 80μm.
- Stand-alone tracking for Pt<100MeV/c.



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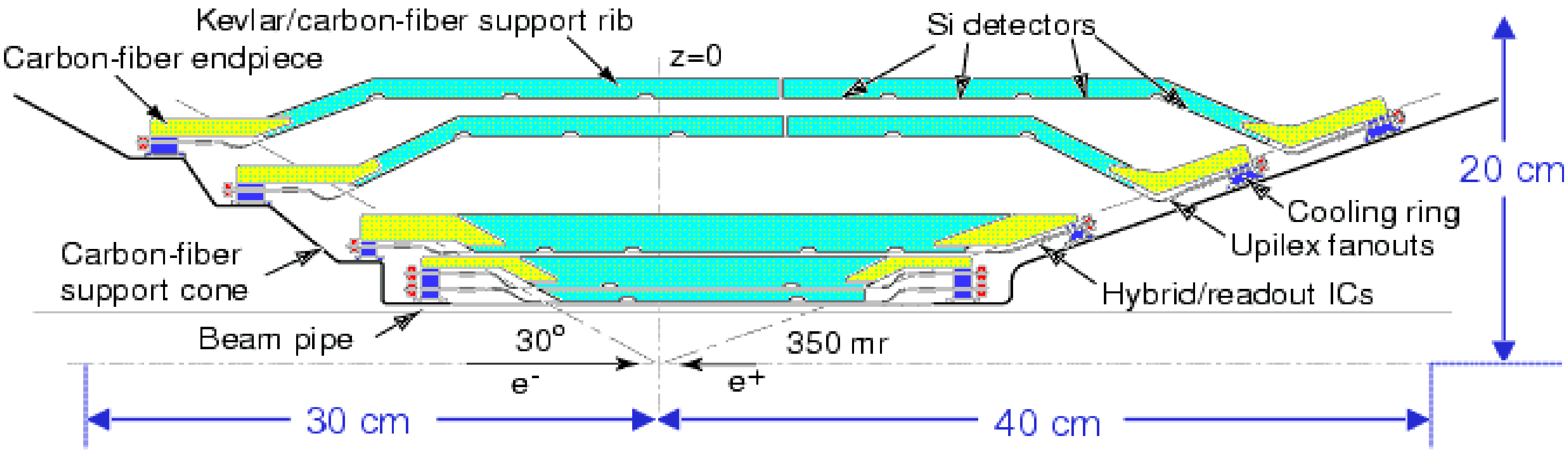
# Design

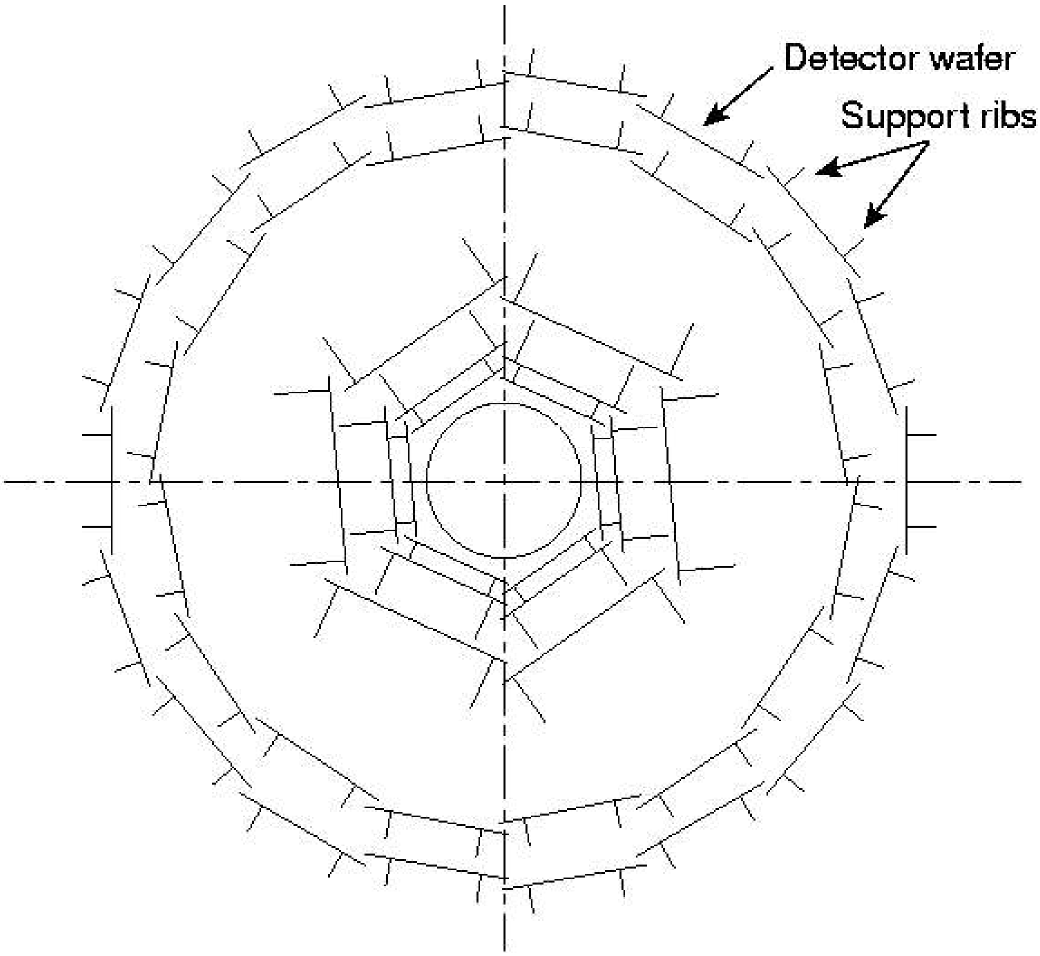



- Double sided n-bulk silcon sensors, 6-30 kΩ cm
- Custom front-end chips (honeywell 0.8 μm)
- Arch shaped outer layer modules to reduce $L_{rad}$
- Stand alone tracking for 70 MeV< pt < 120 MeV
- Angular acceptance limited by bending magnets

# Geometry

- Inner 3 layers for angle and impact parameter resolution
- Outer 2 layers for pattern recognition and low $p_t$ tracking

| Layer | Radius |
|---|---|
| 1 | 3.3 cm |
| 2 | 4.0 cm |
| 3 | 5.9 cm |
| 4 | 9.1 to 12.7 cm |
| 5 | 11.4 to 14.6 cm |

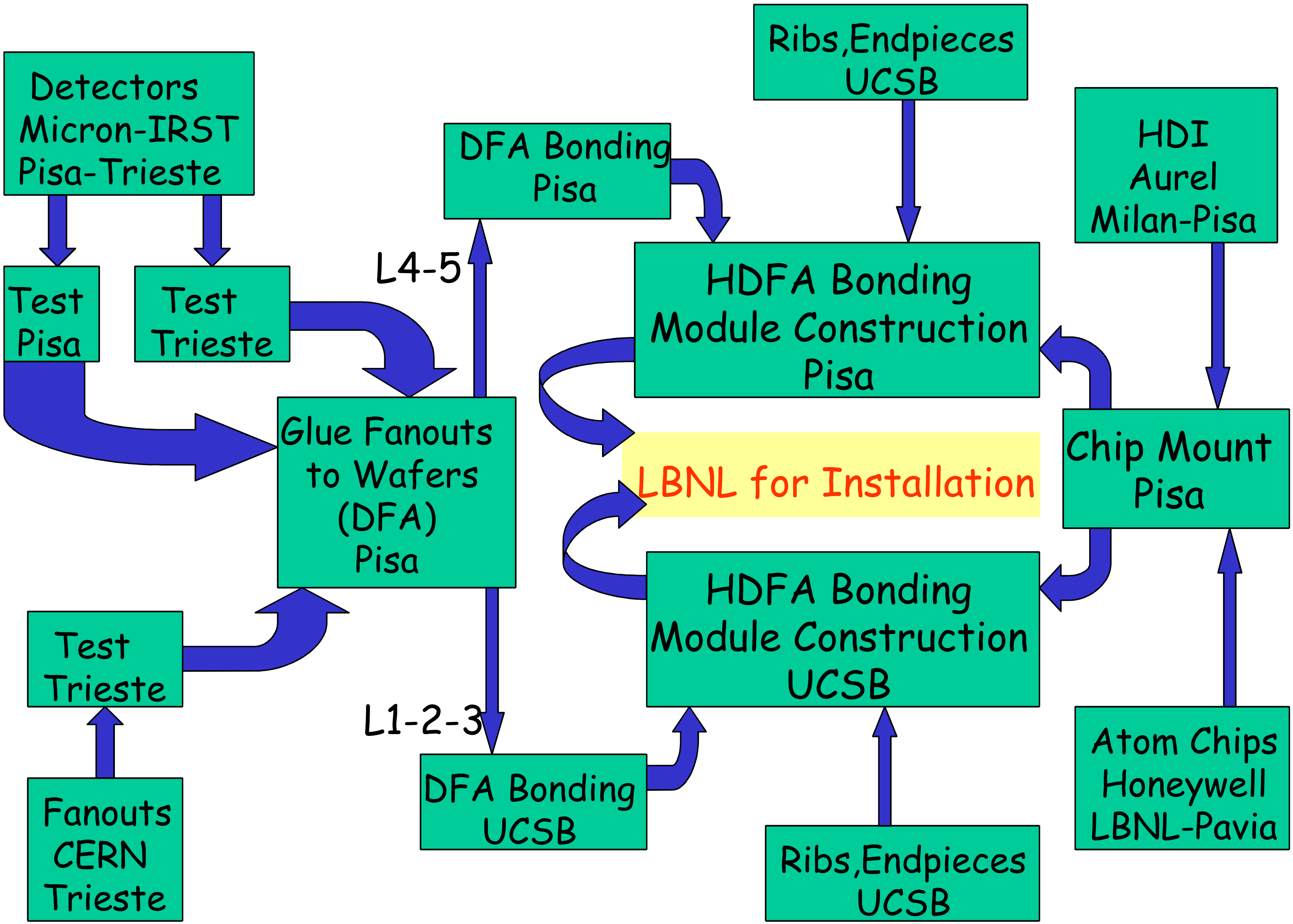



(Arched wedge wafers not shown)

# SVT in Numbers

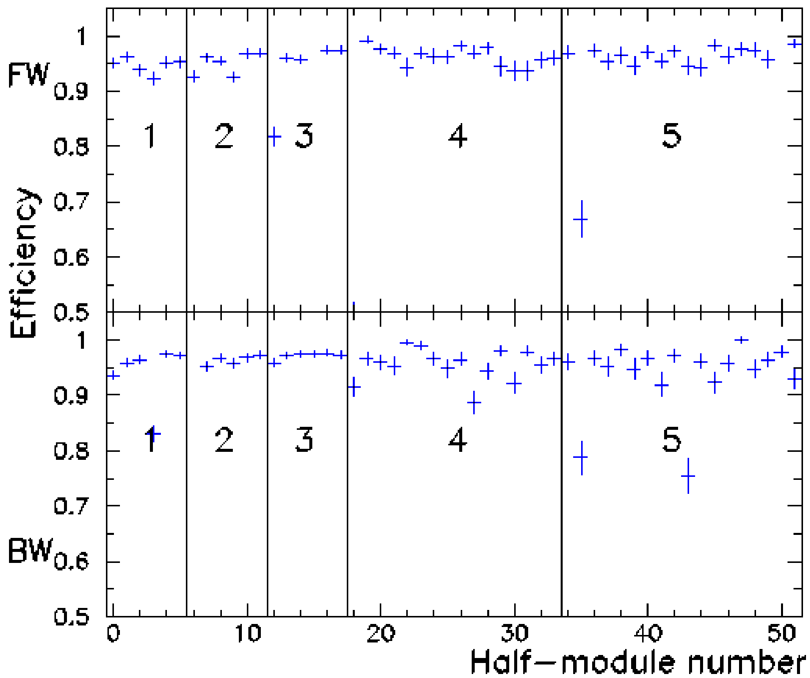
- 5 layers, double sided
  - Barrel design, L4 and L5 not cylindrical
  - 340 wafers, 6 different types
  - ~1$m^2$ of silicon area
- 104 Double-sided HDI
  - Outside tracking volume
  - Mounted on Carbon Fiber cones (on B1 magnets)
- 1200 Atom chips
- 140K readout channels
- 0.3 million micro bonds

# A Simple Construction Process..

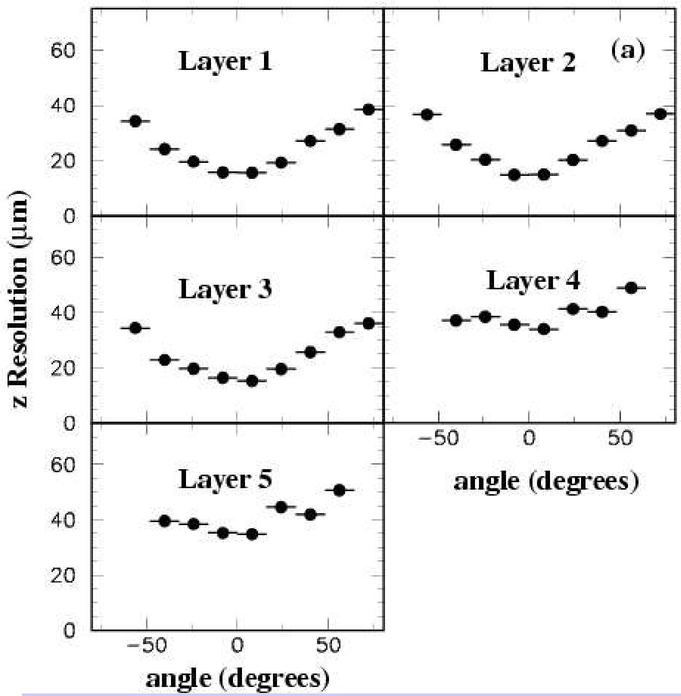


# Performance

Hit efficiency




Hit resolution on z side

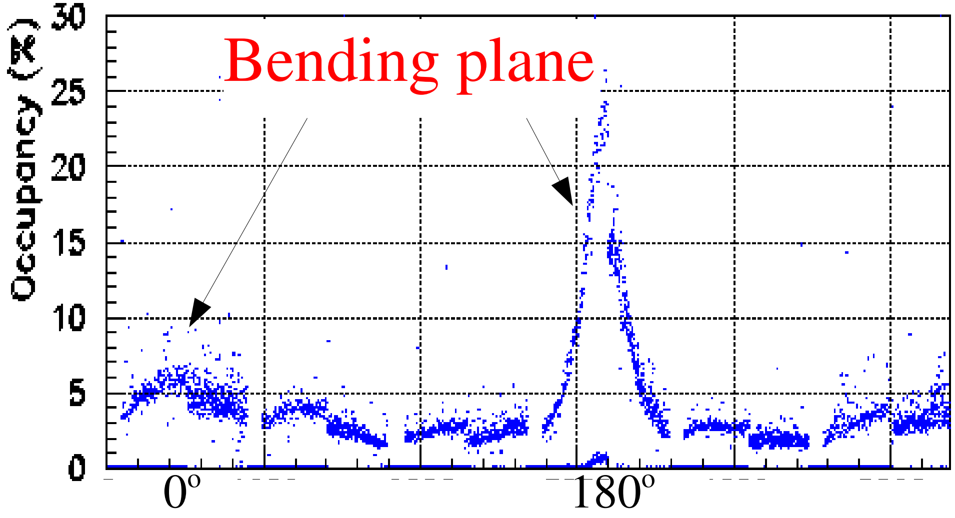


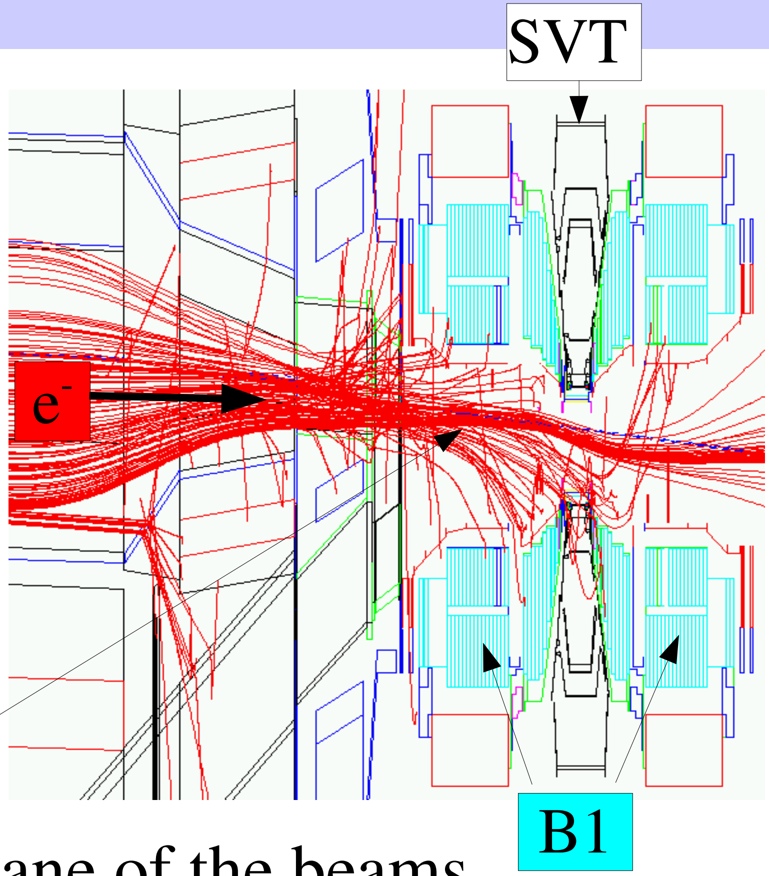

- Hit Efficiency tipically 97%
- Soft efficiency >70% for pt>50 MeV/c

- Hit Resolution for pt>1GeV/c, ⊥ wafers
  - Layer 1-3: 10-15 μm
  - Layer 4-5: 30-40 μm

# Radiation Environment

φ occupancy L1 Backward

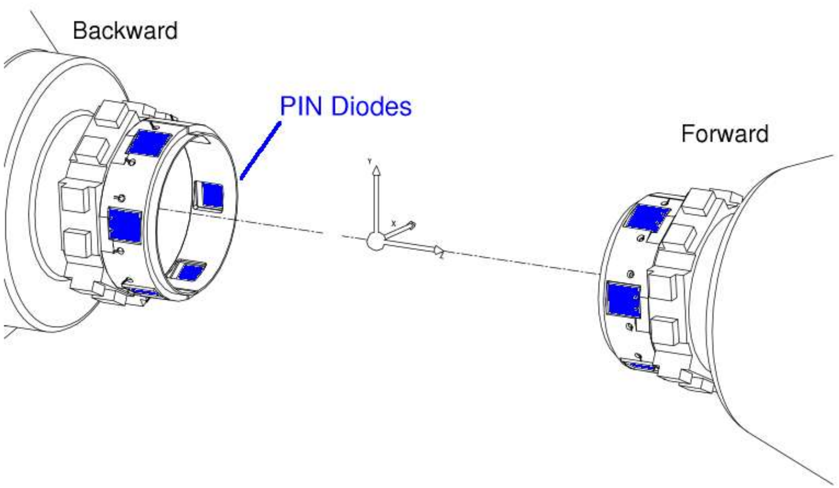


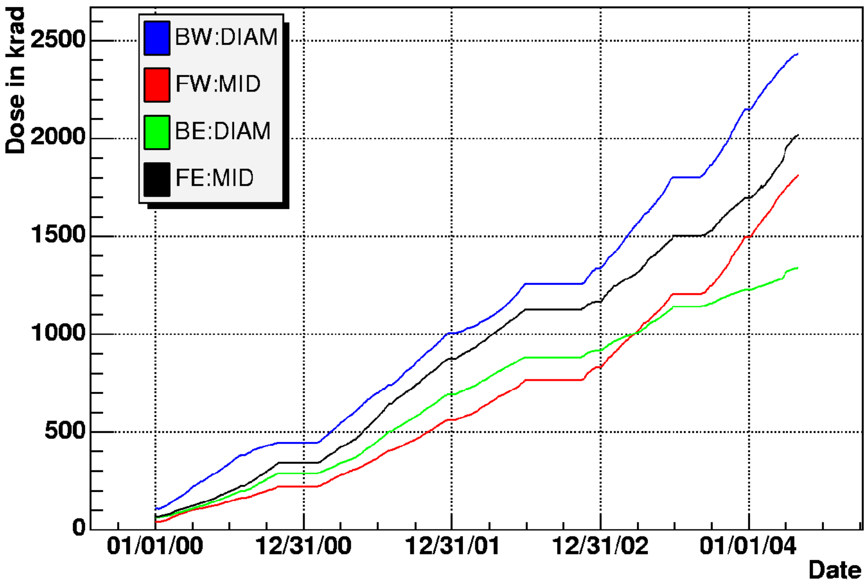




- Non uniform irradiation
- Concentrated in the bending plane of the beams
- Particles overbent by the B1permanent magnets near the IP
- Originates from beam-gas scattering along the ring

# Radiation Monitoring

- 12 reverse-biased PIN diodes
  - 6 forward, 6 backward
  - Active area: 1cm x 1cm x 300 μm
- MID plane dose budget:
  - 4 MRad by july 2005
- TOP/BOM budget
  - 4 MRad by 2009



# Radiation Effects

- Damage to the silicon detectors
- Damage to the front end electronics
- Occupancy and performance degradataion
- Unexpected effects

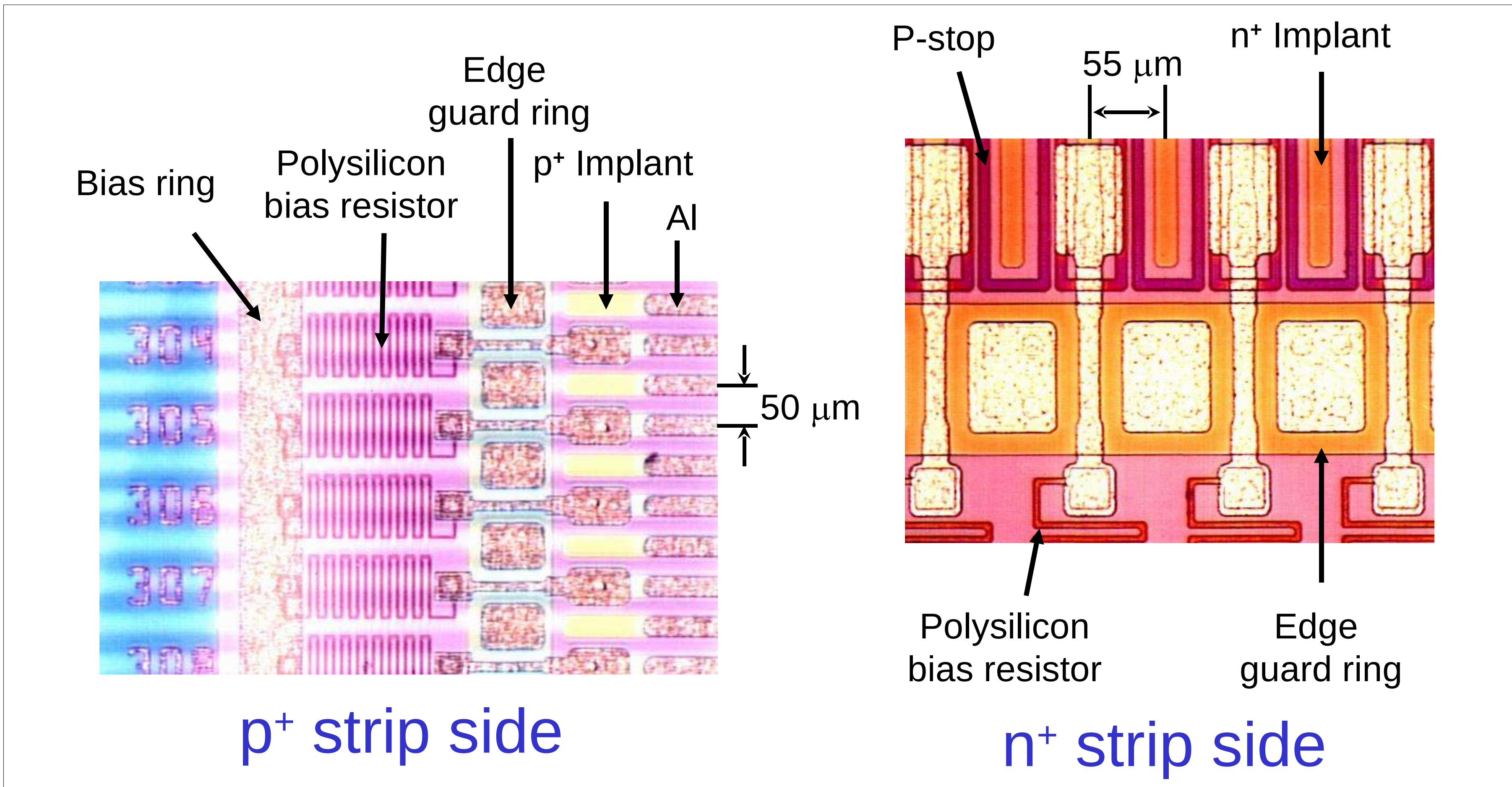
# Damage to the Silicon Detectors

- Details of the silicon wafers
- Depletion voltage shift
- Lekage current increase
- Disuniform irradiation
- P-stop shorts creation
- Leakage current in real SVT
- Radiation distribution
- Charge Collection Efficiency

# Silicon Wafers

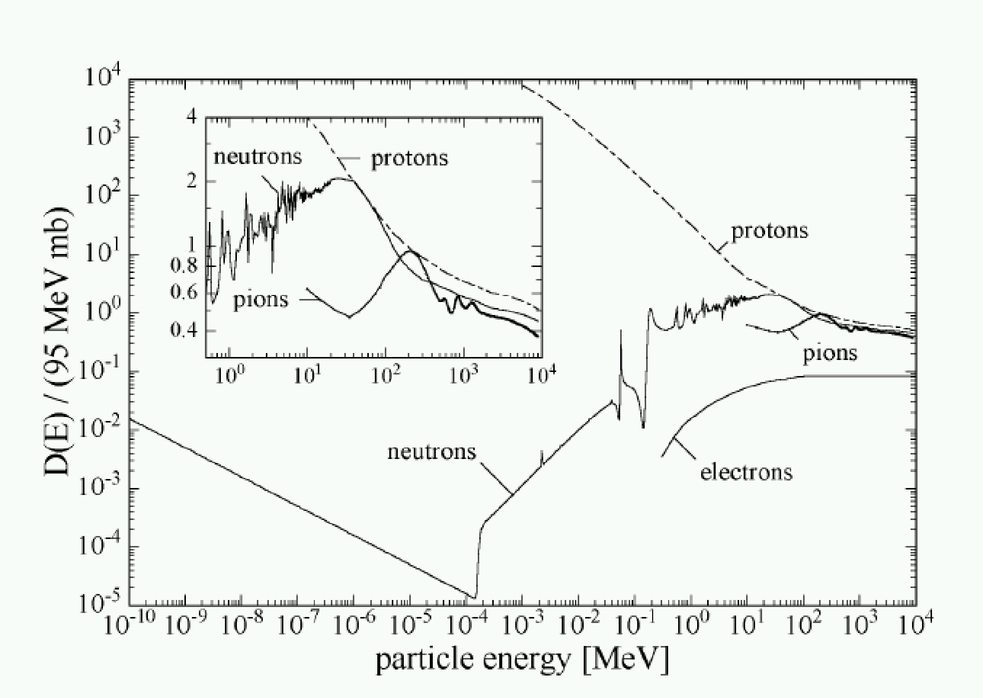
Manufactured at Micron
300 μm thick
n-bulk, 4-8 kΩ cm

AC coupling to strip implants.
Polysilicon Bias resistors on wafer, 5 MΩ



# Damage Mechanism

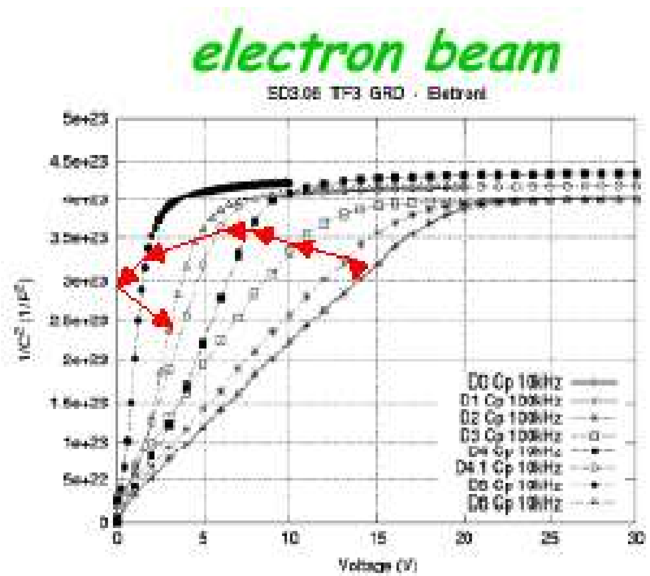
- Displacement of a *primary knock on atom* ($E_{th}$=25eV), creation of interstitial and vacancy
- Details of the damage can be very complicated but in the Non Ionizing Energy Loss hypothesis the damage is linearly proportional to the energy imparted in displacing colli

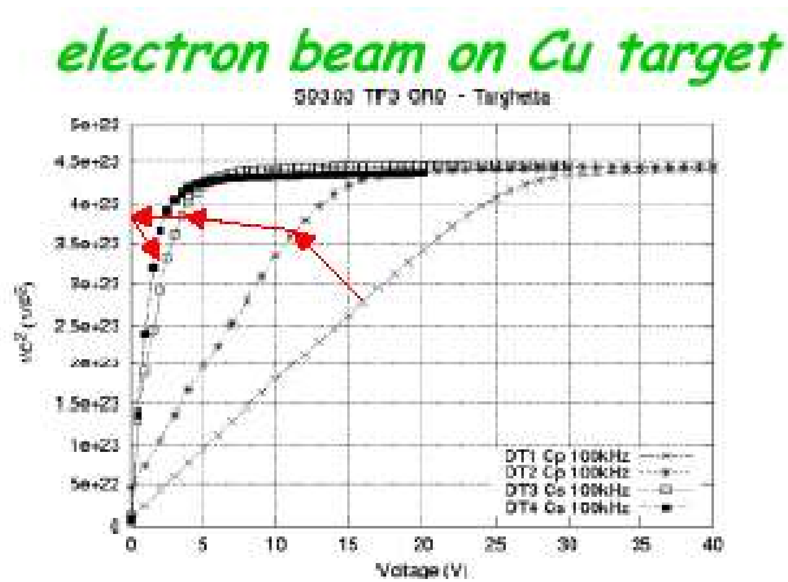



- The damage function D(E) relates different types of particles and energies
- $\frac{dE}{dx} = \phi D(E)$
- 1GeV e- are ~1/10 less effective than the reference 1 MeV neutrons

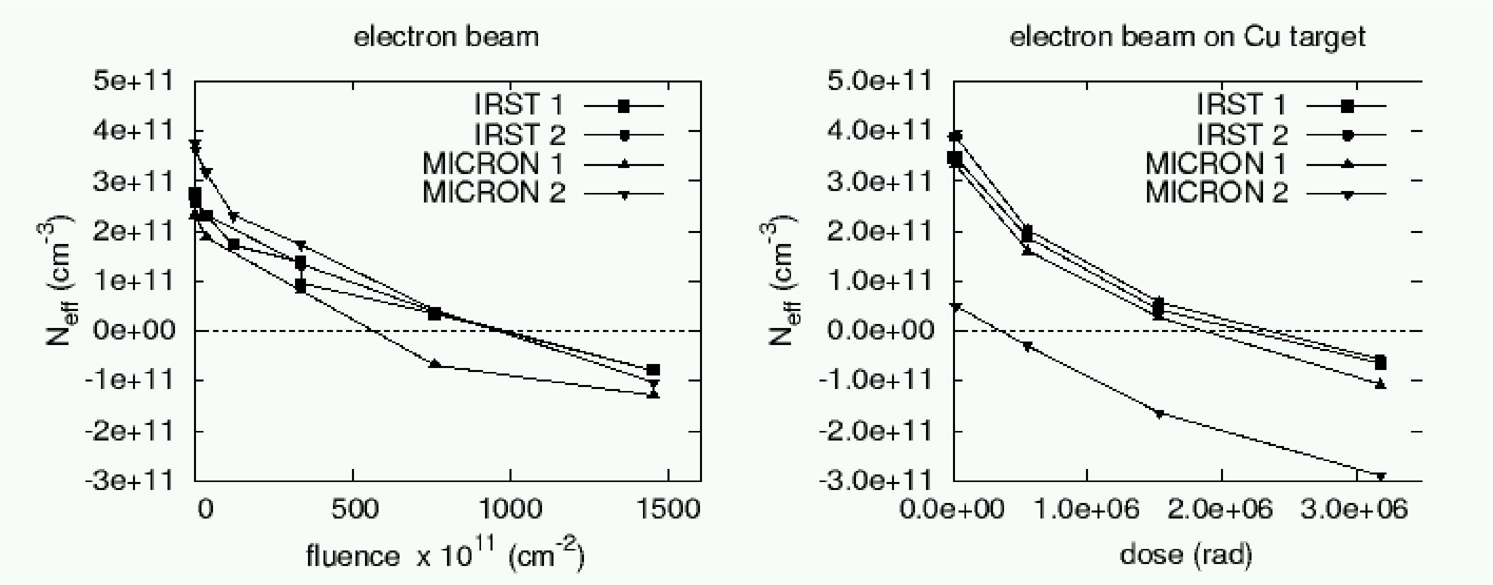
# Depletion Voltage

- Si detectors with strips and test structures irradiated with 900MeV $e^-$
- Depletion voltage shift extracted from diode structures



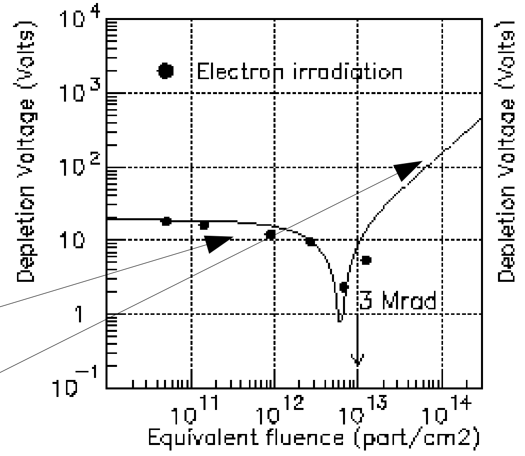
# Effective Doping Concentration



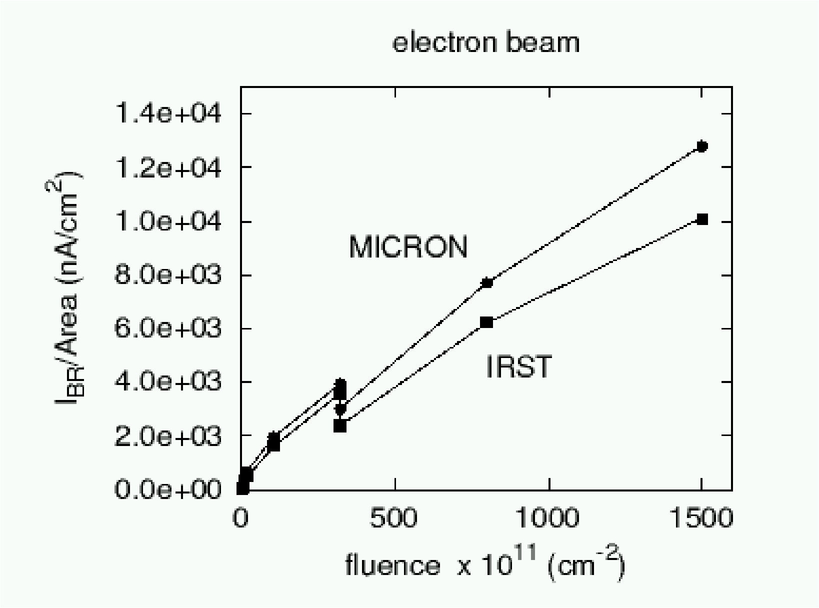

- $N_{eff} = V_{depl} \, 2\varepsilon_s / ed^2$
- Inversion of type occurs around 2.5Mrad

# Depletion Voltage and Reverse Leakage Current

- Accordance with NIEL scaling
  - Exponential donor removal
  - Linear acceptor creation

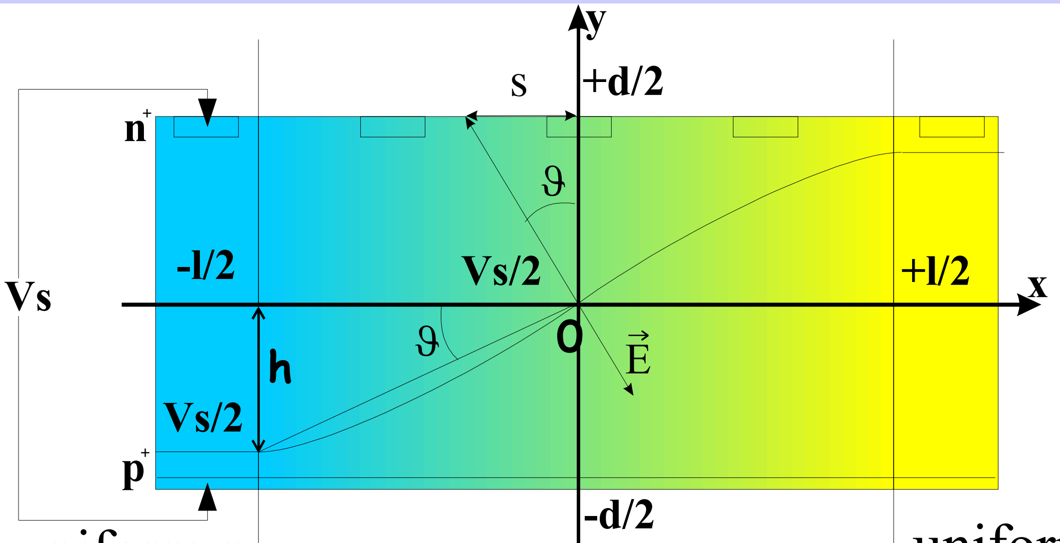



- Leakage current increase dominated by bulk generation $2\mu A/cm^2/Mrad@23^oC$




- Strip isolation OK

# Non-uniform Irradiation: Spatial Resolution




uniform n doping $N_d$

transition region (over-depleted)

uniform p doping $N_a$

- average shift ***s*** of the ionization charge in the transition region (diffusion neglected):

- Assumptions:
- $N_d = N_a$
- bias voltage just enough to deplete uniformly doped region
- l = 1cm    d = 300 um

$$s = \frac{\delta}{2} = \frac{d}{2} tg\,\theta \qquad tg\,\theta = \frac{h}{l/2} = d\left(\frac{\sqrt{2}-1}{2}\right)\frac{2}{l} = 0.12 \qquad s = \frac{\delta}{2} = 9\,\mu m$$

smaller than the resolution



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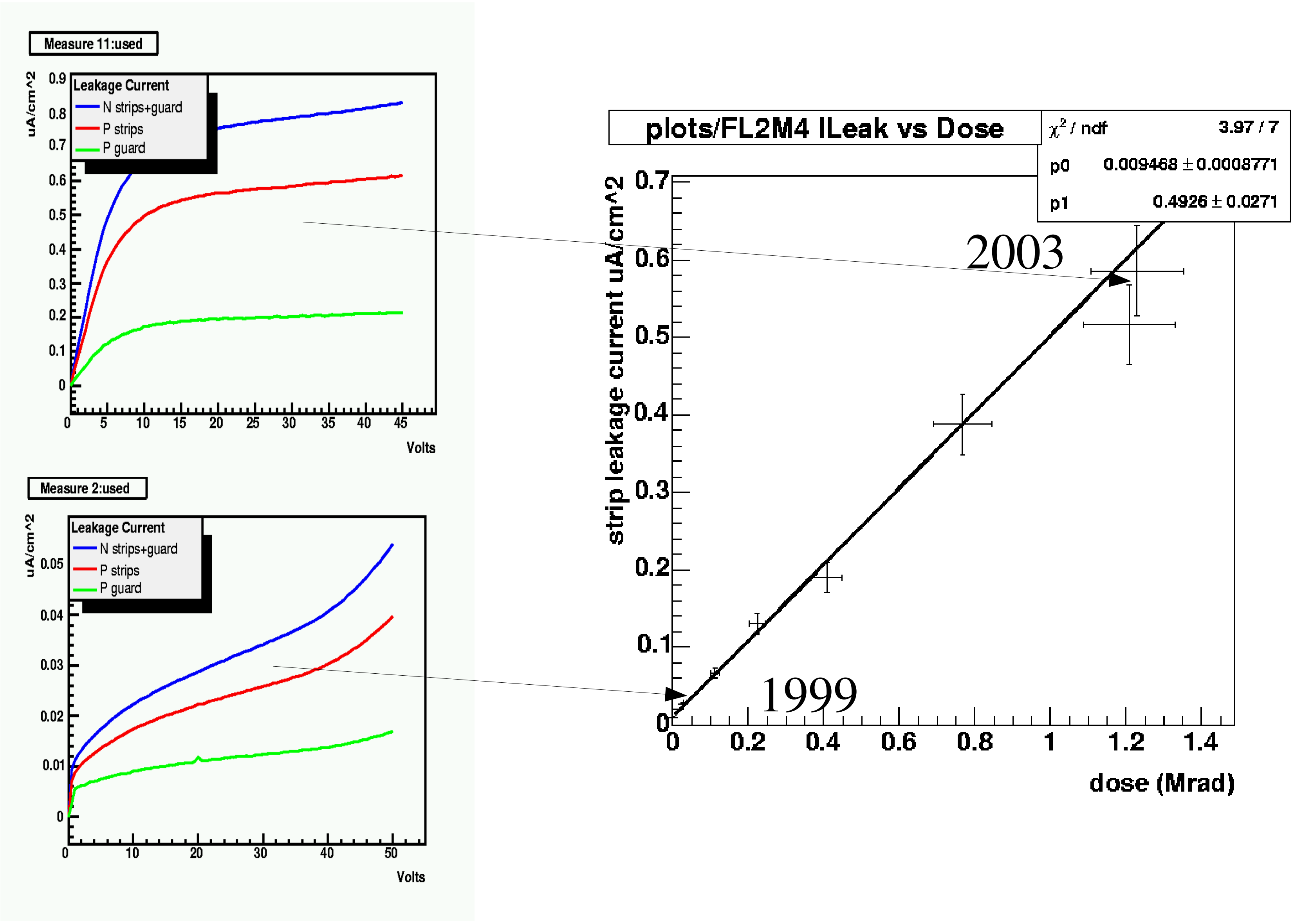
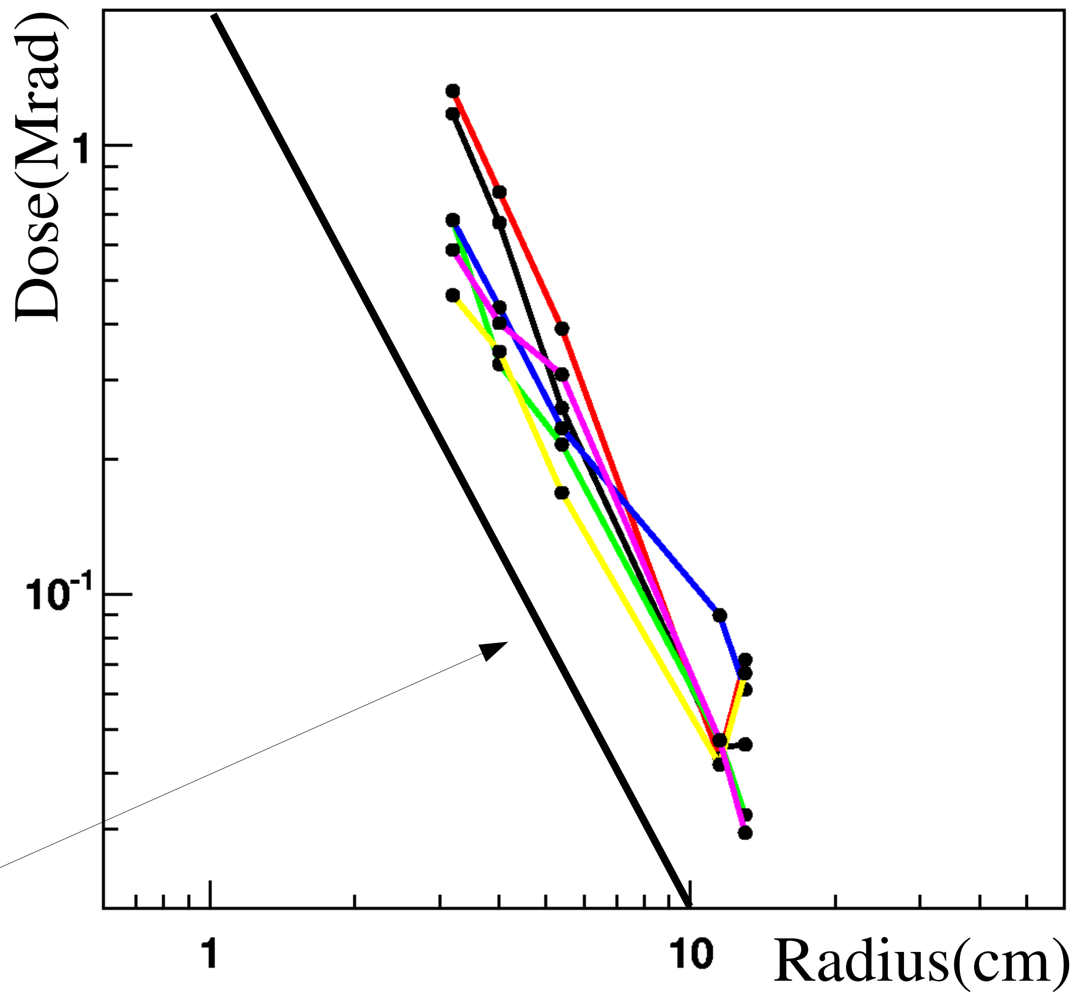
# I-V Characteristic in Real SVT



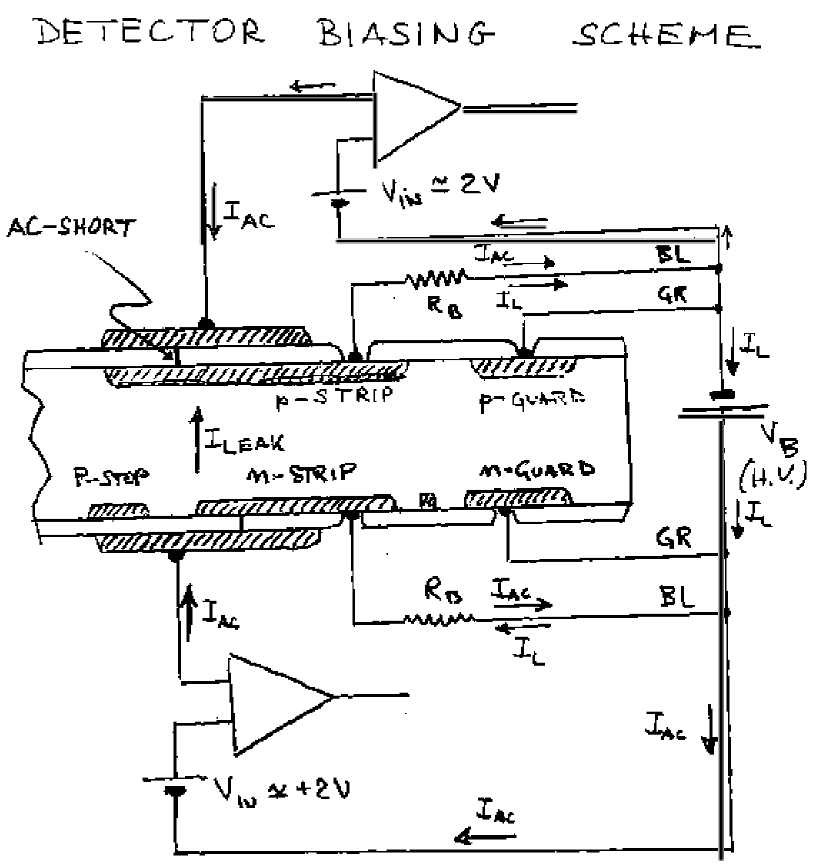
# Radial Distribution

- The average leakage current increase measured on real SVT $1\mu A/cm^2/Mrad$@ $23^{o}C$
- Compute the dose assuming the above coefficient
- $1/r^2$ dependence



# Instantaneus Damage to Detectors




Intense burst of radiation

=>discharge of detector capacitor

=>Vbias (40V) momentarily drops across the coupling capacitors

-deposited charge needed

$$Q_R = \left(C_D + \frac{C_N C_P}{C_N + C_P}\right) V_{Bias} \simeq 2.6\, nC/strip$$

on a time scale < t = $R_{Bias}$*$C_{det}$~1ms

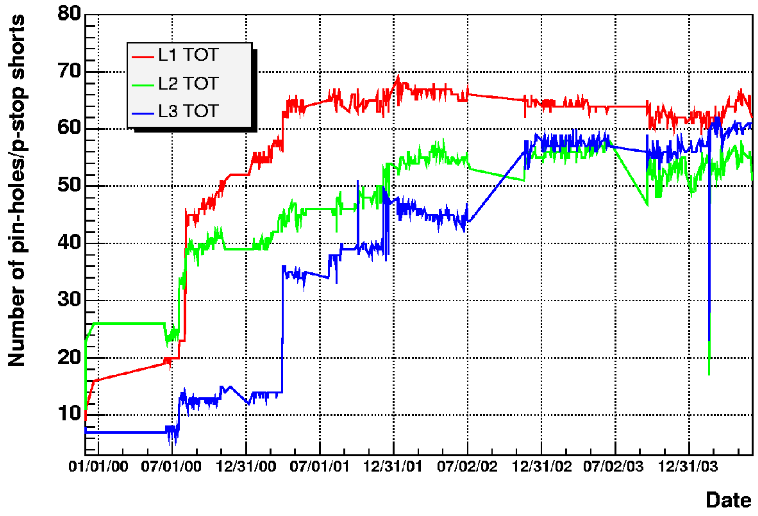
=> critical radiation: 1 Rad/1 ms

# Damage Rate

- All the sensors have been tested for AC breakdown up to 20V during construction
- A later study on detectors with a pitch similar to the SVT inner layers has shown an expected rate of failures of about 1-2%

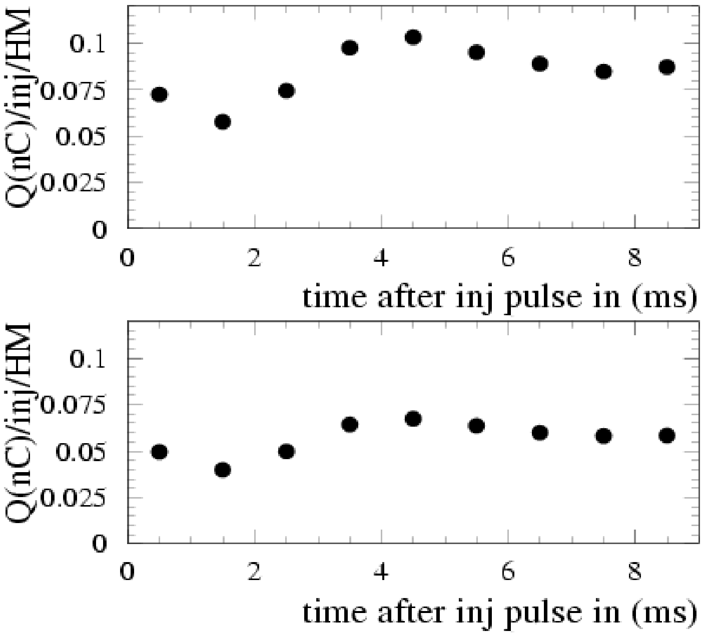
- The effect has been observed in the real system:

– 65 pin-holes /20k channels in L1,2



# Trickle Injection

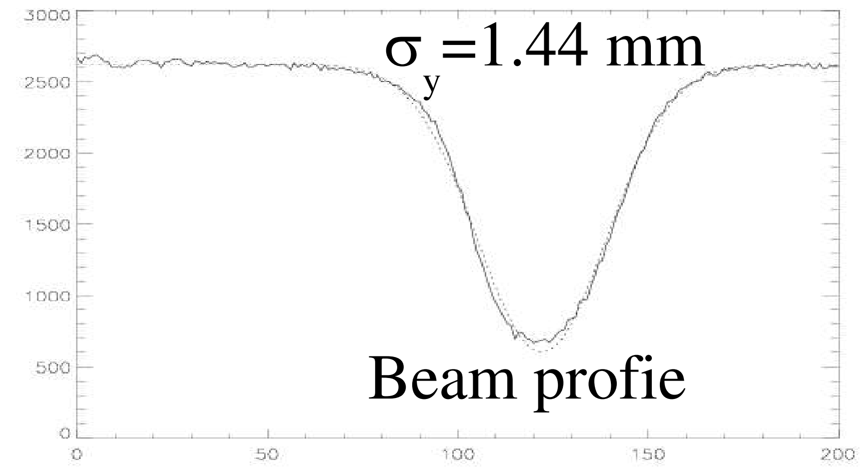
- Trickle injection => intense bursts of radiation associated to injected bunch => instantaneous damage ?
- We measured deposited charge in the detector after the injected pulse using the silicon sensors themselves: limit is 2600nC/HM/1ms

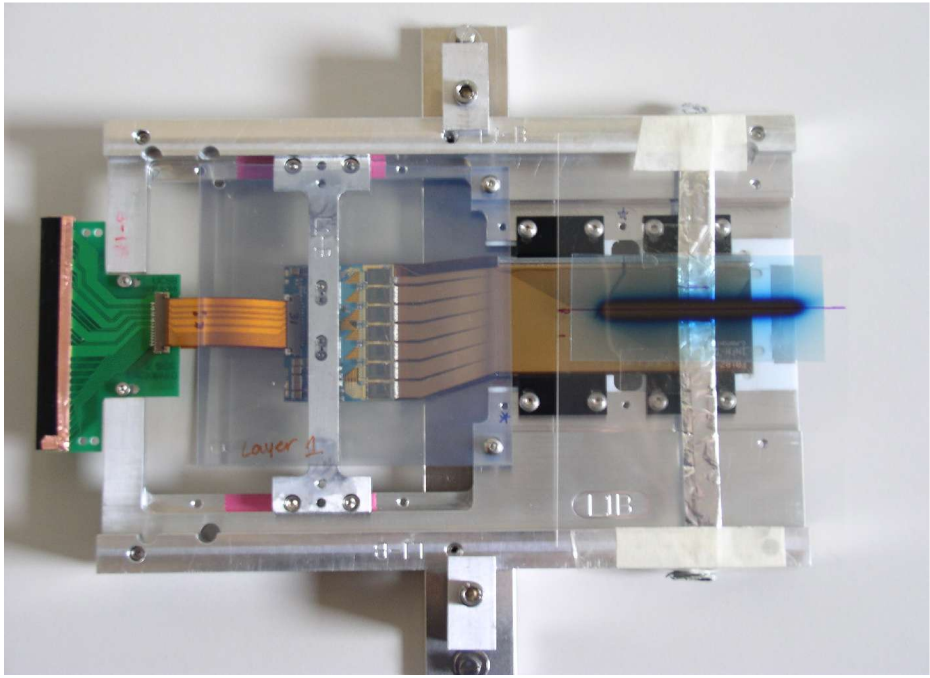



- =>3 orders of magnitude safety

# Rad Damage to the Si: CCE

- Creation of traps in the bulk→ inefficiency in collecting charge
- Irradiation of detector with 0.9 GeV e- at Elettra (Trieste)
- Fron-end chips not irradiated, needed for readout
- Spot size $_{y}$=1.44 mm to simulate non uniform radiation environment
- Peak dose: 10 MRad. in 6 steps



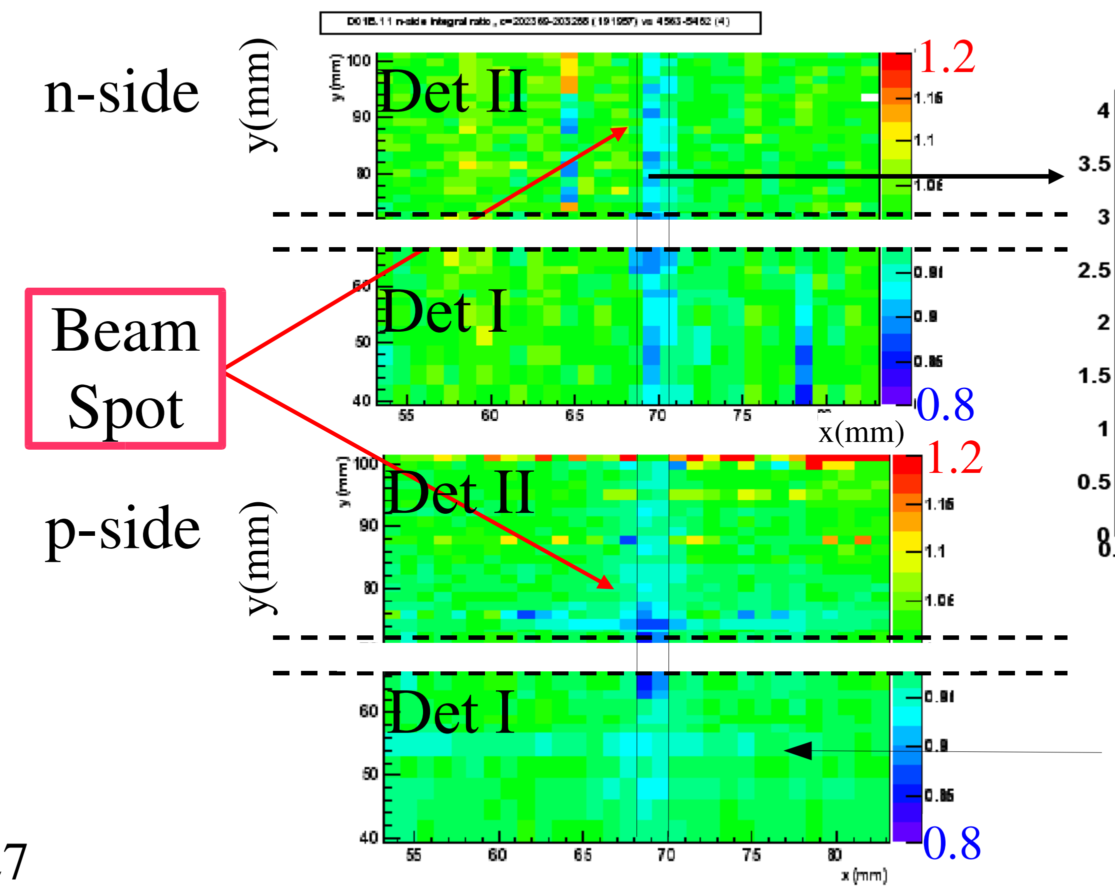



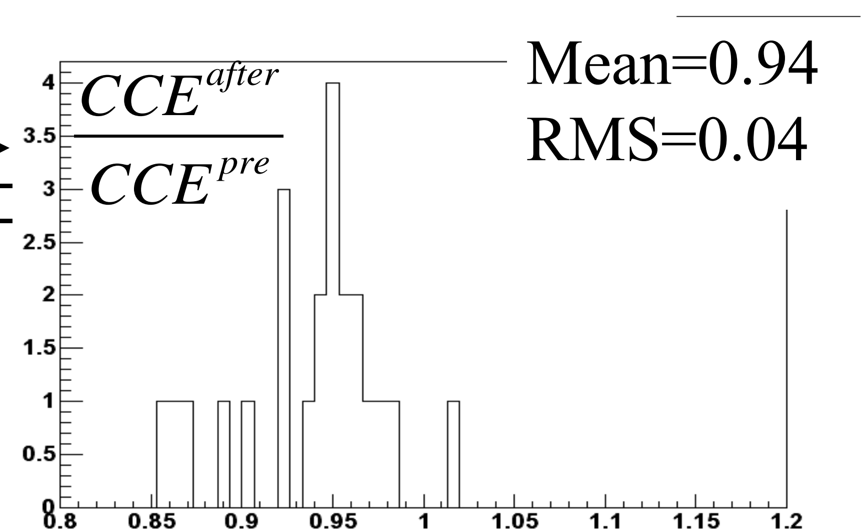
# CCE: method

- Illuminate silicon sensor with penetrating LED $\lambda$=1060 nm, $\sigma$= 0.5 mm
- Determine "50% turn-on point" of threshold (T(i)) as a function of light intensity (Vled) for each channel i
- Fit for the slope of T(i) vs Vled, correct for measured gain, sum all channels:
  $\sum \frac{slope(i)}{gain(i)} = B * CCE$ , B depends only on the LED shape and disappears in the ratio $\frac{\sum slope^{after}}{\sum slope^{pre}} = \frac{CCE^{after}}{CCE^{pre}}$

# CCE: results

- Illuminate silicon sensor with penetrating LED λ=1060 nm, $\sigma = 0.5$ mm
- At 5.5 Mrad (after type inversion) the ratio is 94%±4% -> we start to see inefficiency




Measure the CCE ratio on a 30x30 grid

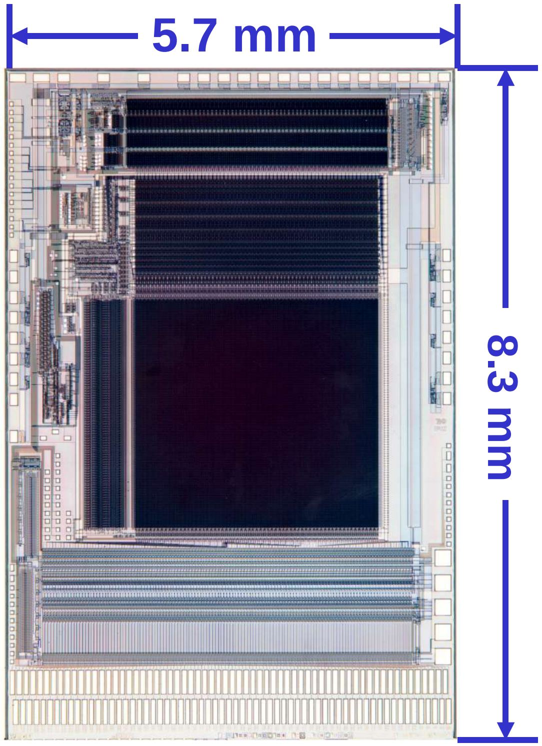
# Damage to the Electronics

- AToM characteristics
- Noise increase and gain decrease
  - In $^{60}$Co irradiation
  - In the real SVT
- Threshold Shift
  - Real SVT
  - Chip Irradiation

# The AtoM chip

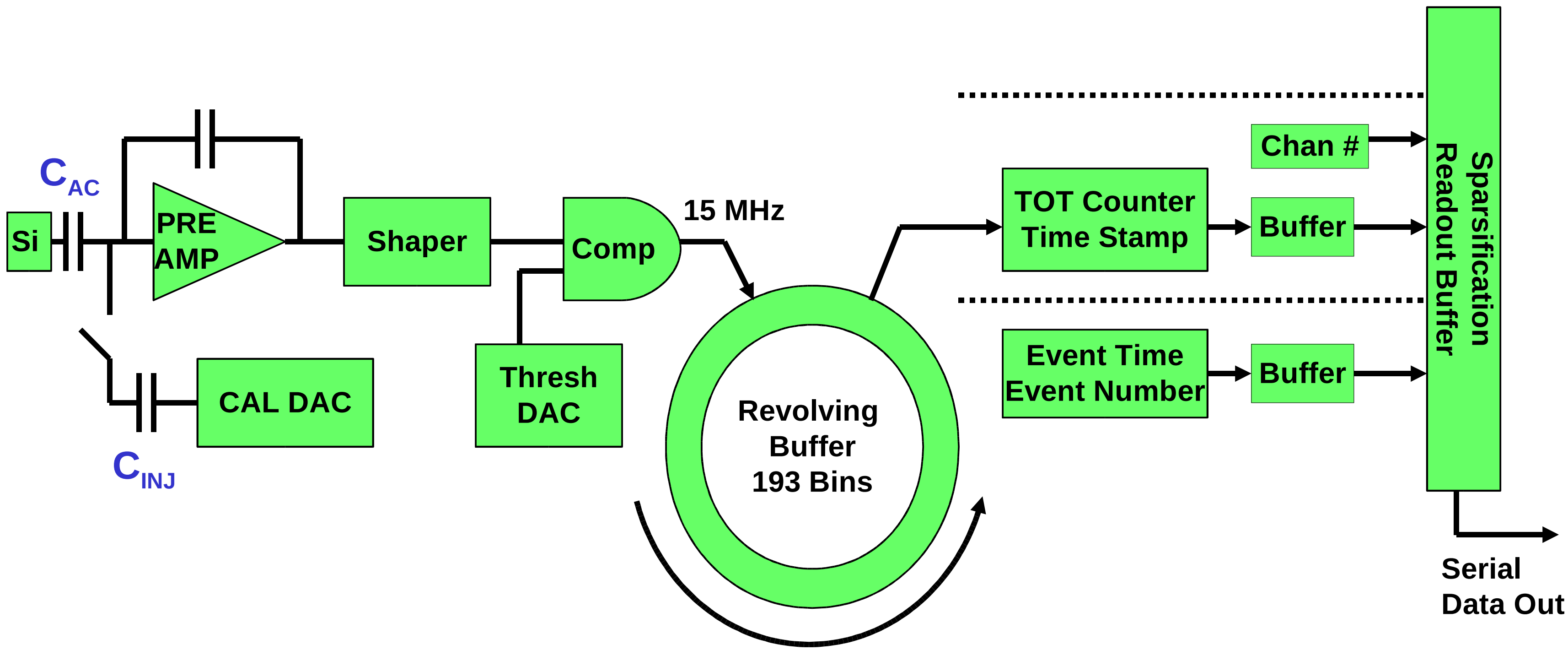
- AToM = A Time Over threshold Machine`
- Custom Si readout IC designed for BaBar by:LBNL,INFN-Pavia, UCSC

FEATURES
•128 Channels per chip
•Rad-Hard CMOS (Honeywell 0.8μm)
•Simultaneous
  – Acquisition
  – Digitization
  – Readout
•Sparsified readout
•Time Over Threshold (TOT) readout
•Internal charge injection

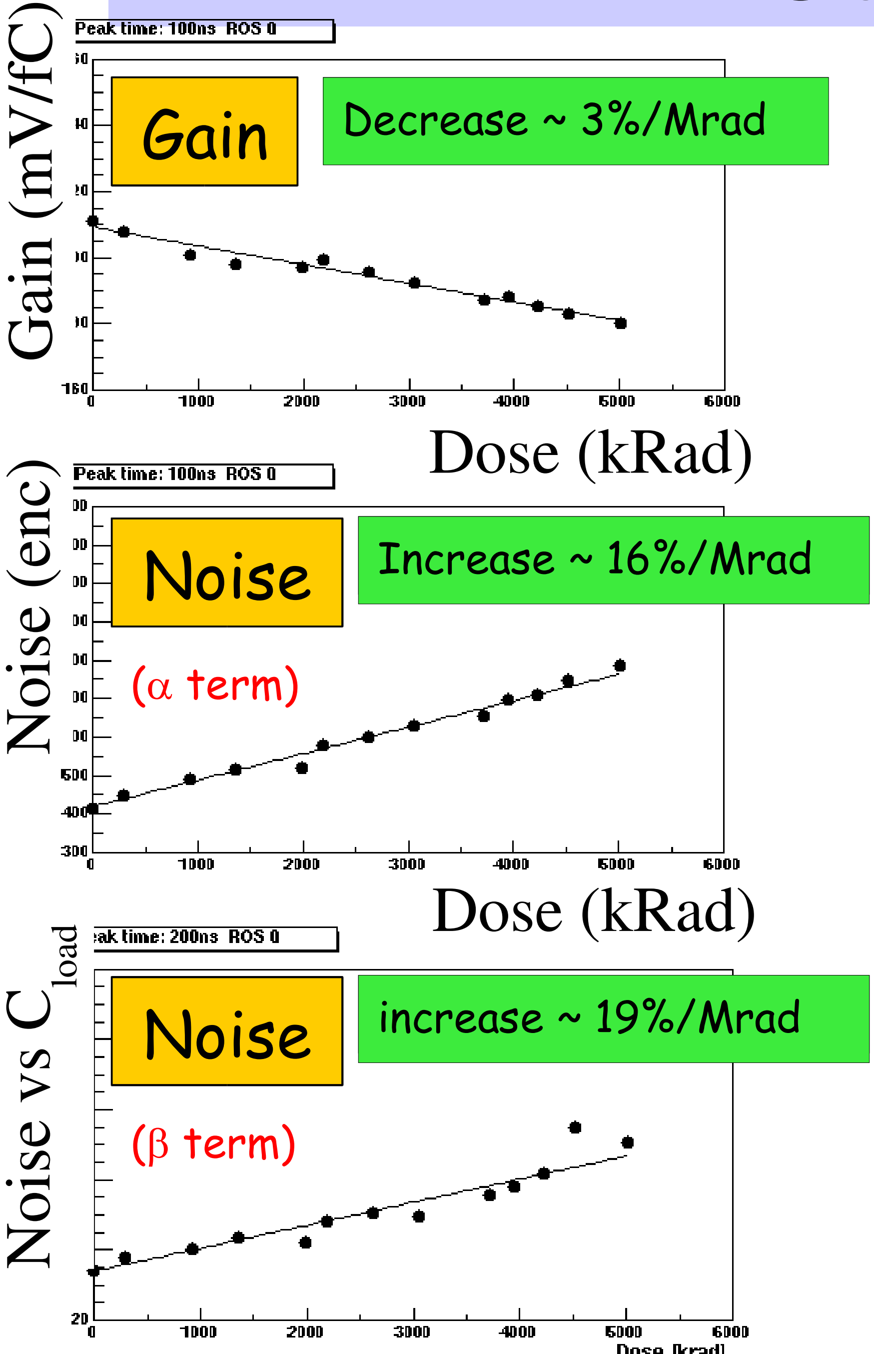


# The AtoM chip

- Block diagram



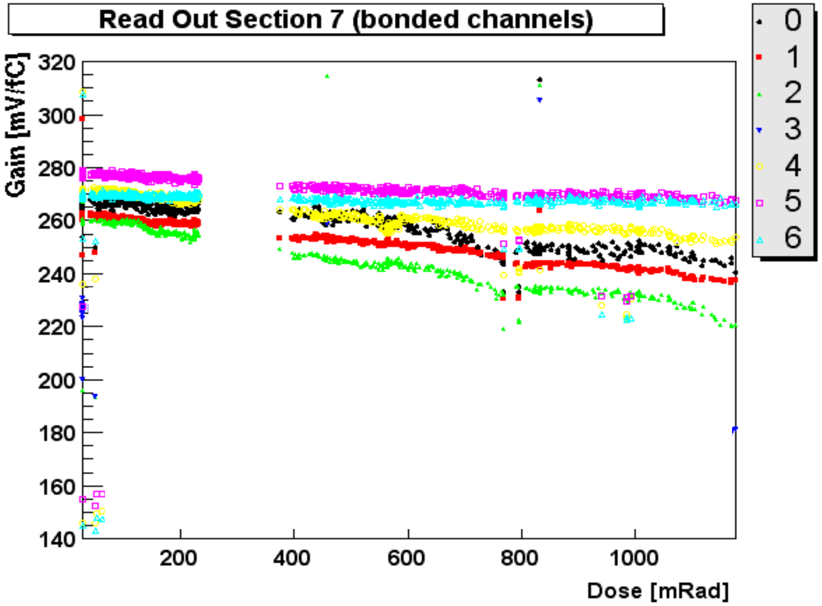
# $^{60}$Co Irradiation

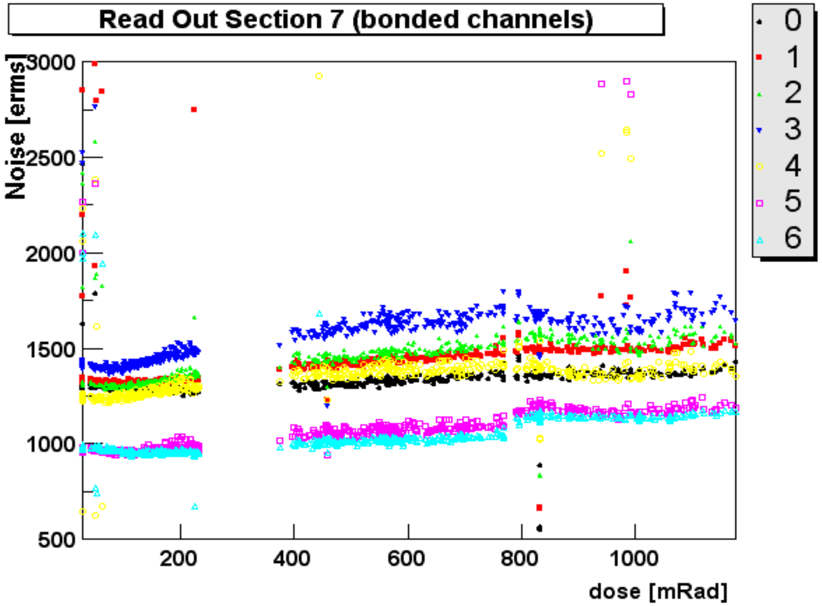



- Controlled irradiation of Atom chips up to 5MRad in 2001 at SLAC and LBL
- Chips were powered and running during the irradiation
- No digital failures observed
- $Noise = \alpha + \beta * C_{load}$

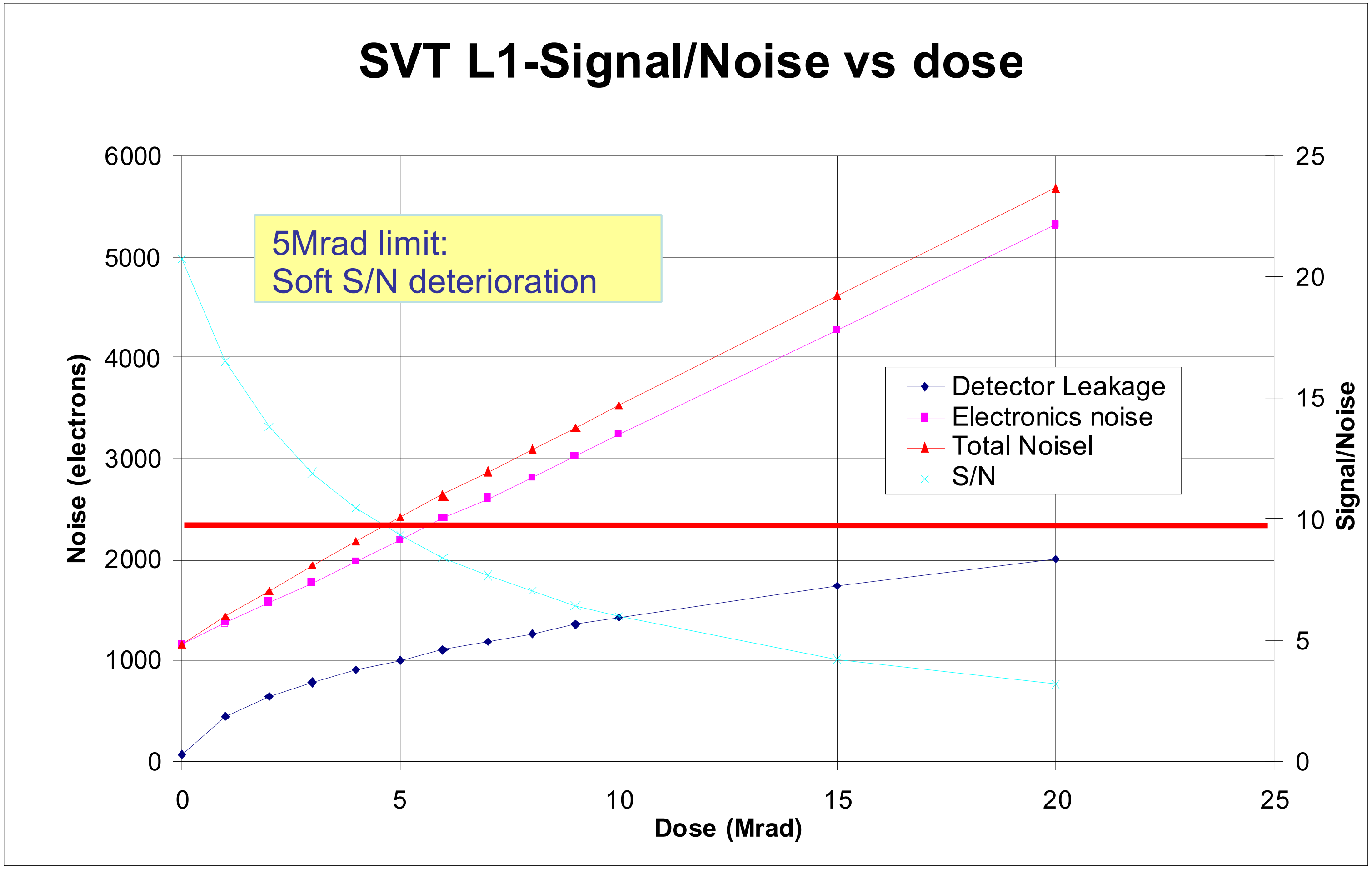
# AToM degradation Observed in SVT

- Radiation estimated from the nearest pin diode
- 1-2 MRad depending on the module
- Analog parameters degradation on installed chips is consistend with $^{60}$Co measurements
- New unespected effects seen on threshold offset

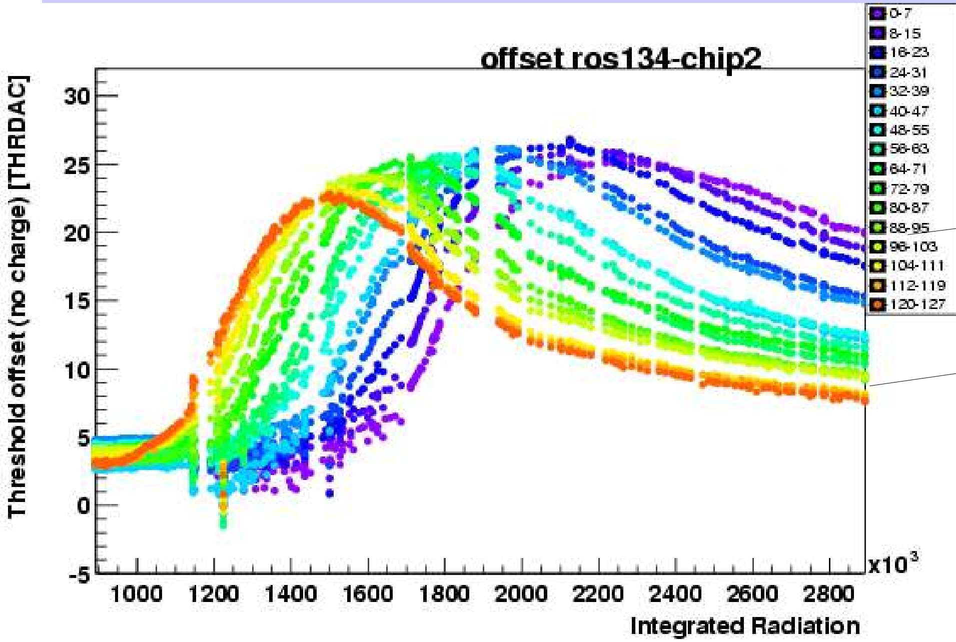


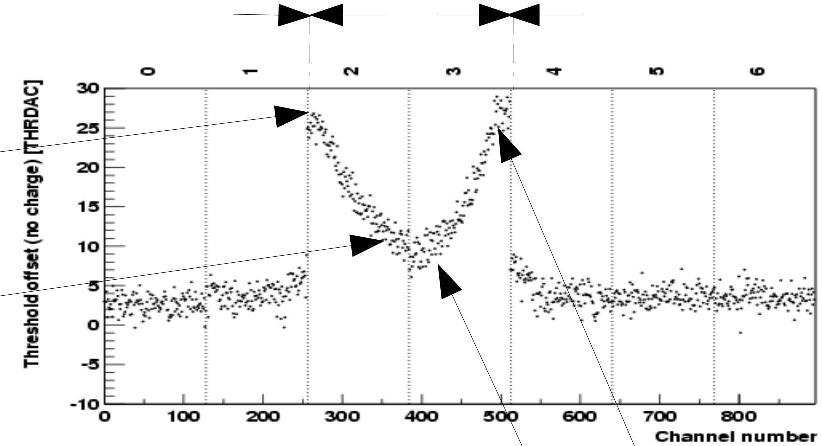
# Noise prediction as a function of dose

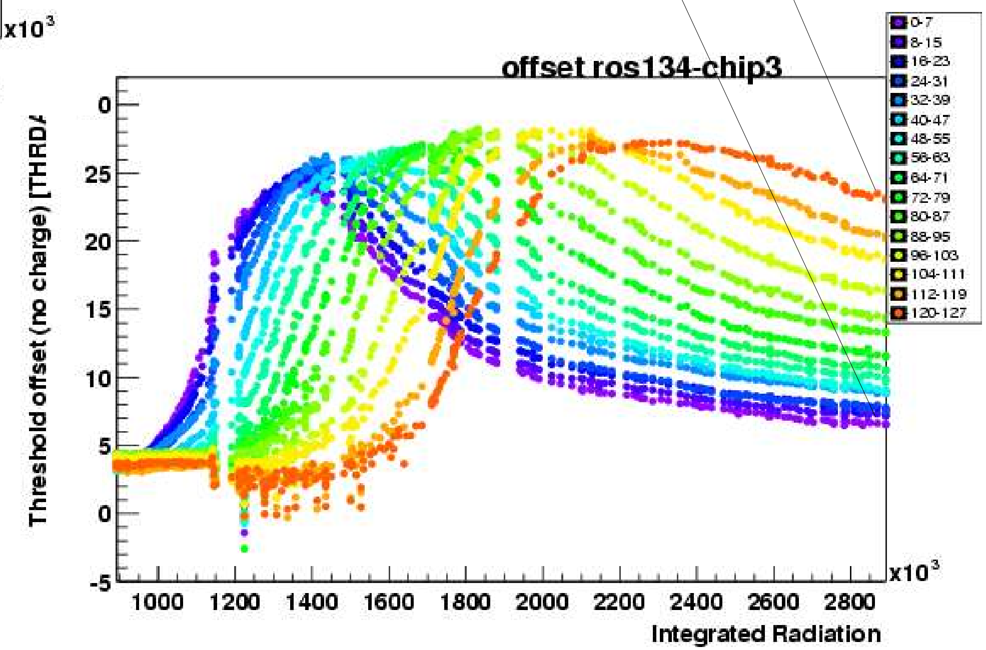


# Things we know we don't know




Space betweeen chips not shown

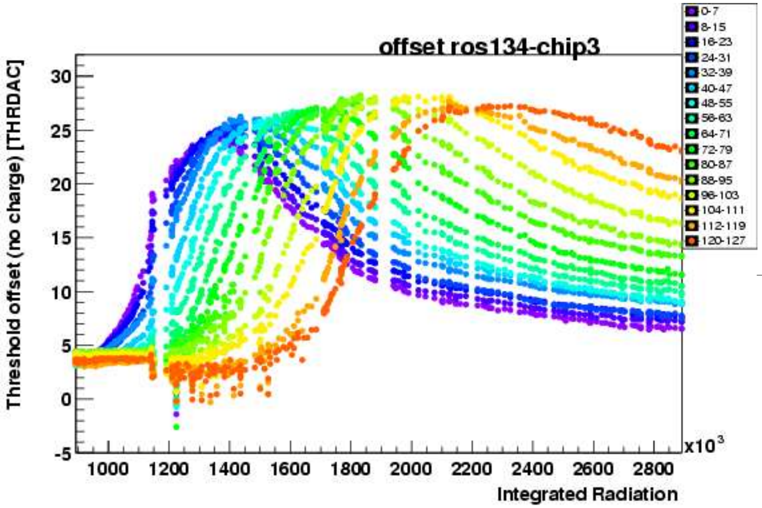


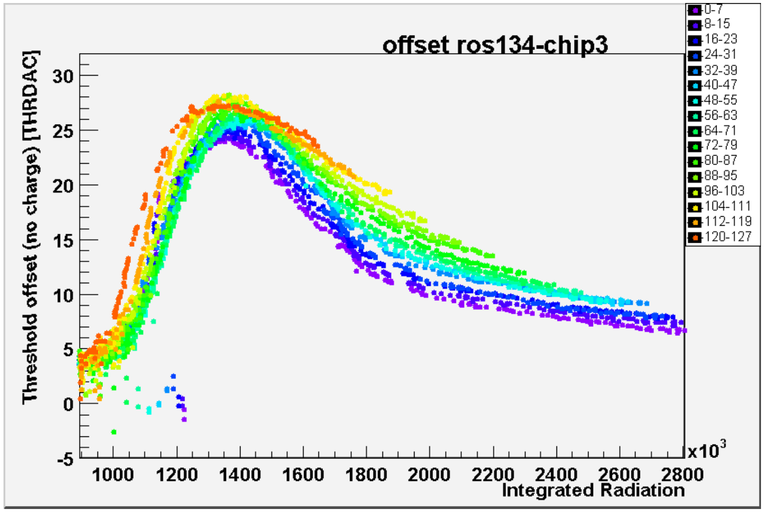




- Not consisten with $^{60}$Co irradiation
- Affects chips in the bending plane
- Onset at 1Mrad
- Goes back at 2 Mrad
- Gain is OK

# Is it a function of the radiation?

- The horizontal axis represents the peak dose but the radiation is not uniform across the chip channels
- Rescaling the dose using the radiation profile...



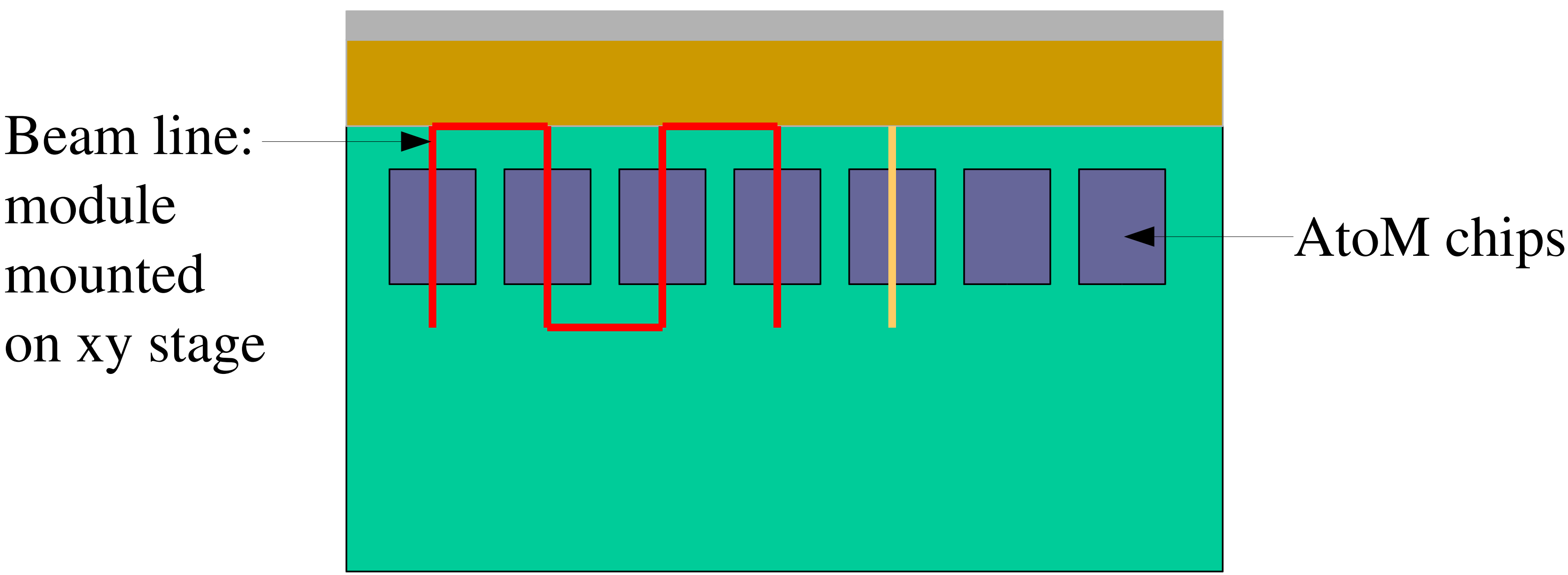



# Threshold Shift in controlled irradiation

- To understand/reproduce the pedestal shift effect, FEE chips (one L1 HDI, one L2 spare HM) have been irradiated at Elettra synchrotron (1GeV $e^-$) in Trieste
  - Dose rate between 1 and 10 krad/s at fluence peak
  - Doses up to 9 Mrad
- A pedestal shift of comparable magnitude as in the real SVT has been observed, but...
  - Gain doesn't drop as much as in SVT
  - Pedestal is not going back (beside annealing)
  - Dose scale is different
- Irradiation with a neutron source is also planned

# AToM Irradiation Setup

- Rate of 10 Krad/s, integrated dose exceeding 6 Mrads on chip 0-1-2-3
- To study the effect of instantaneous rate, chip 4 has been irradiated at a lower rate



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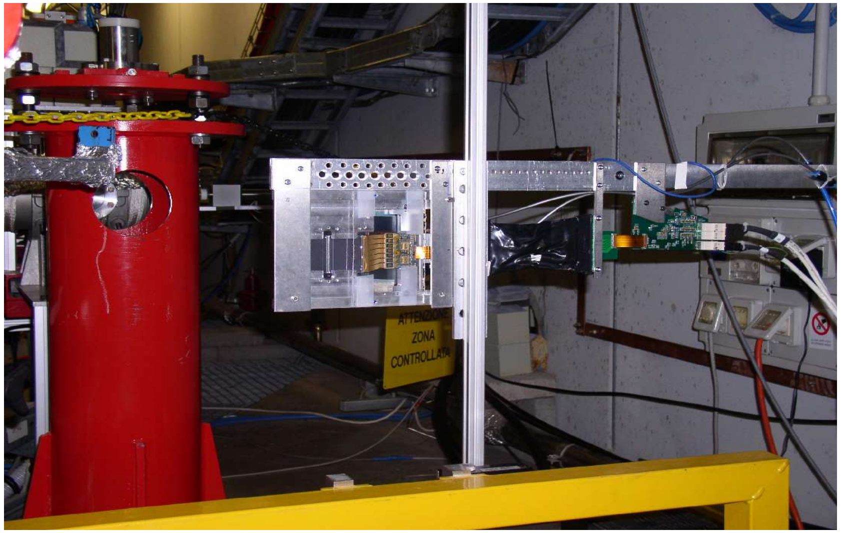
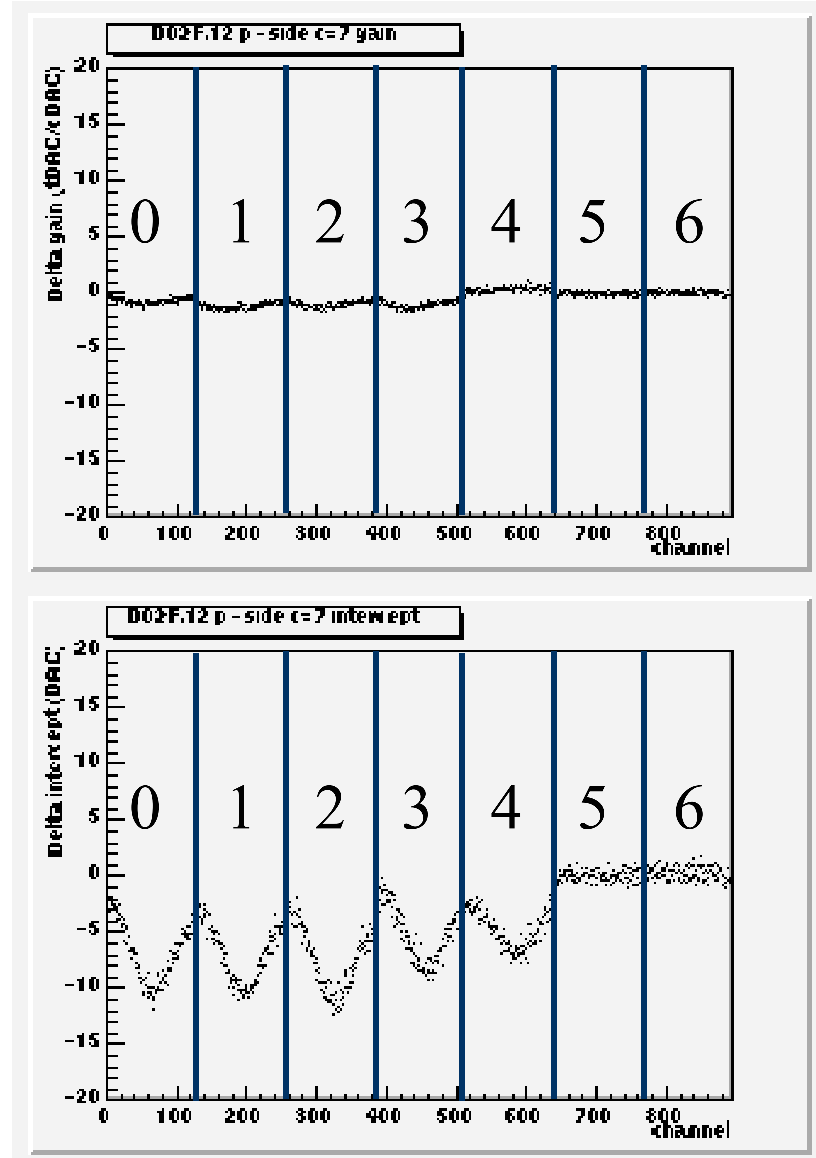
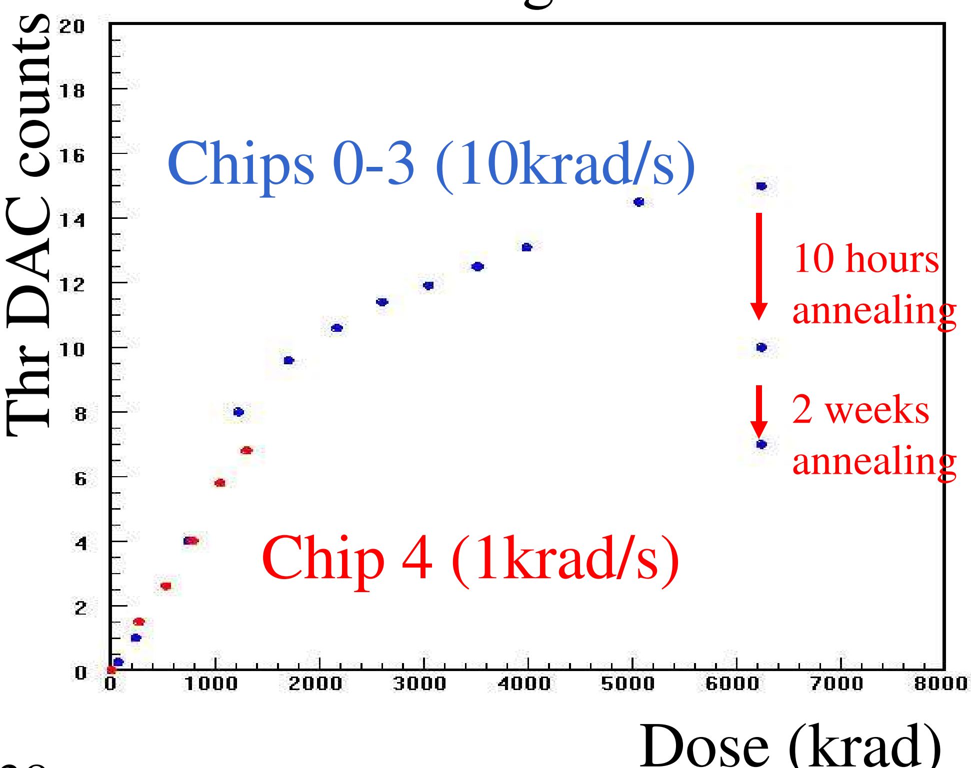
## Module setup



## Gain and Threshold change vs channel after 6 Mrad



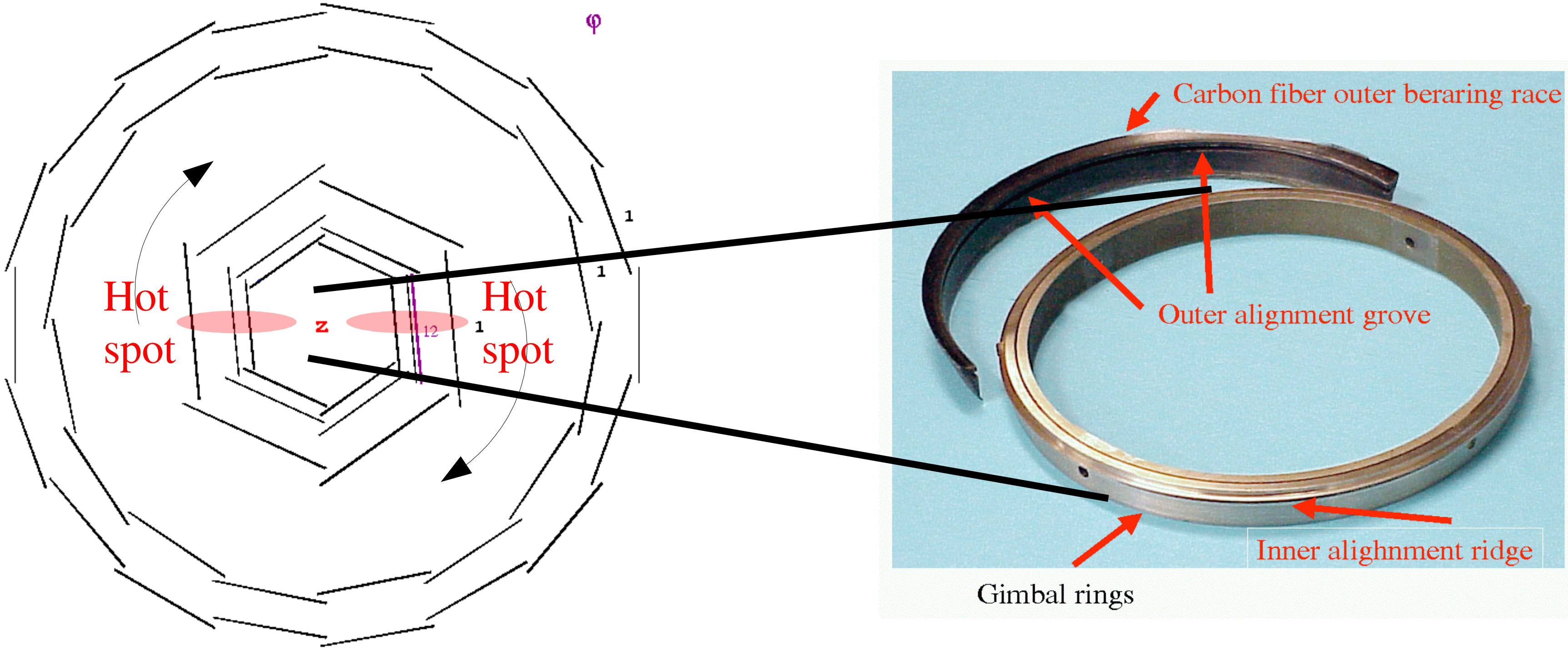

## Threshold change vs dose

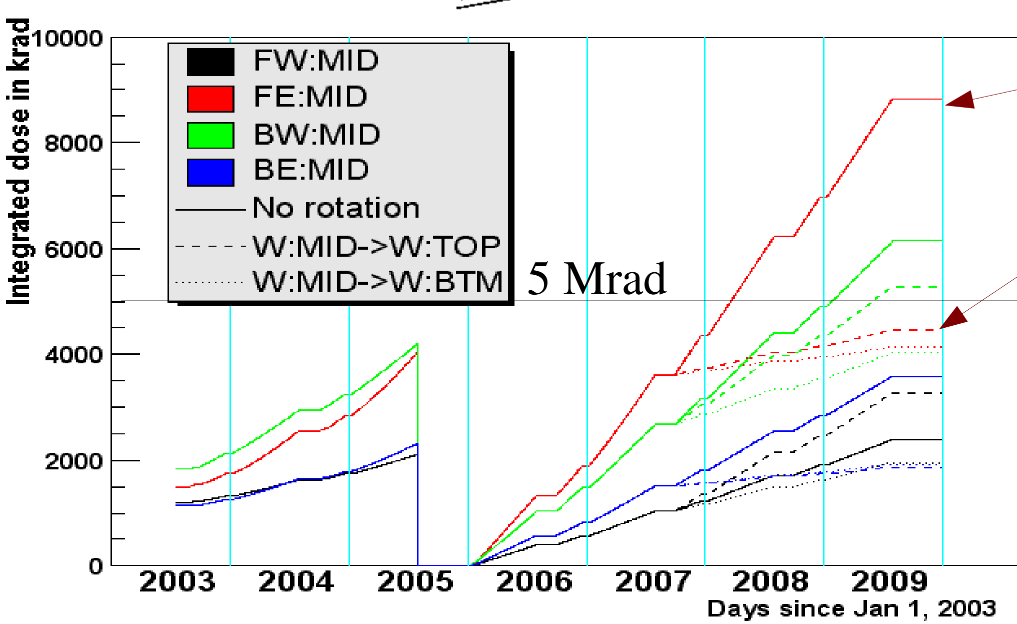


# First indications from analysis

- We can reproduce the threshold shift using 1 GeV electrons, but :
  - beside annealing there is no indication of pedestal going back to non irradiated levels
  - the dose scale is different
  - Gain doesn't show a significant change
- Any ideas on the generating mechanism?

# Rotate or not rotate?

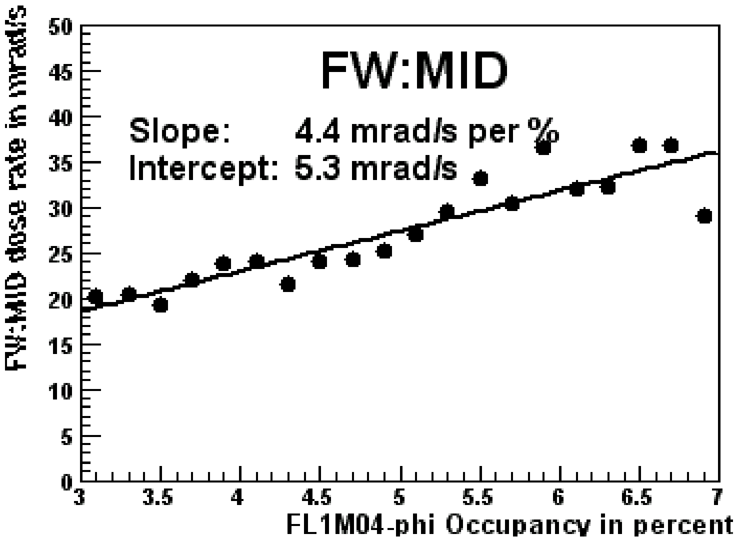



- No Rotation
- Rotation Scenario
- Dose<5Mrad but spreads the threshod shift around

# Reversible degradation

- The machine background radiation not only degrades the performance of the SVT detector in expected (and unexpeted) ways because of the integrated dose, but also the instantaneus rate has a significant impact
- The performace degrades with occupancy which in the inner layer is proportional to the background rate

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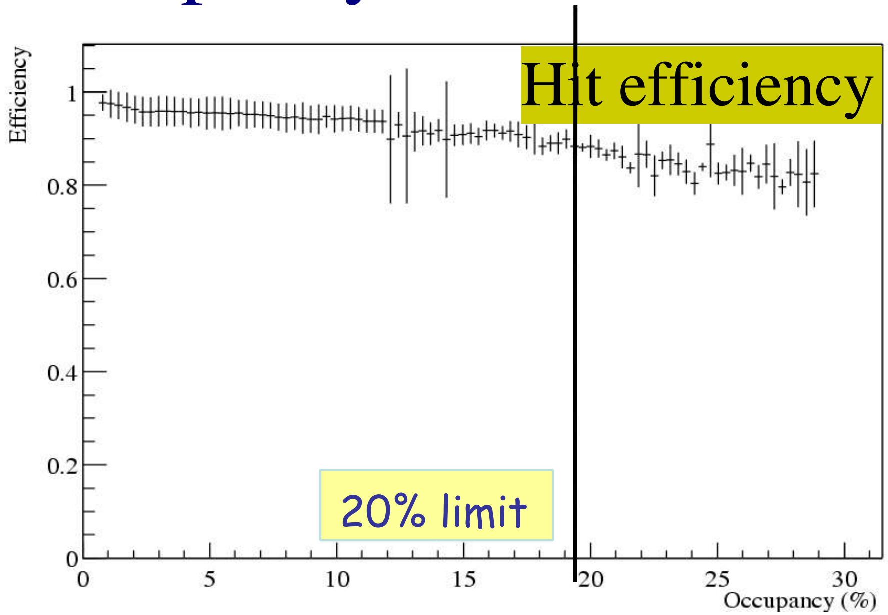
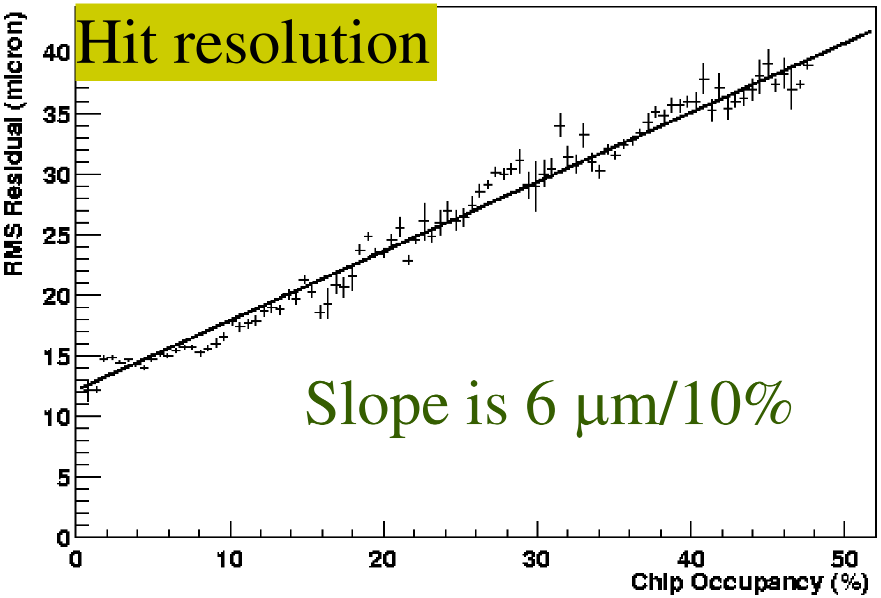
# Performance with high instantaneus background rate

- Look in data at hit efficiency and resolution as a function of occupancy in the FEE



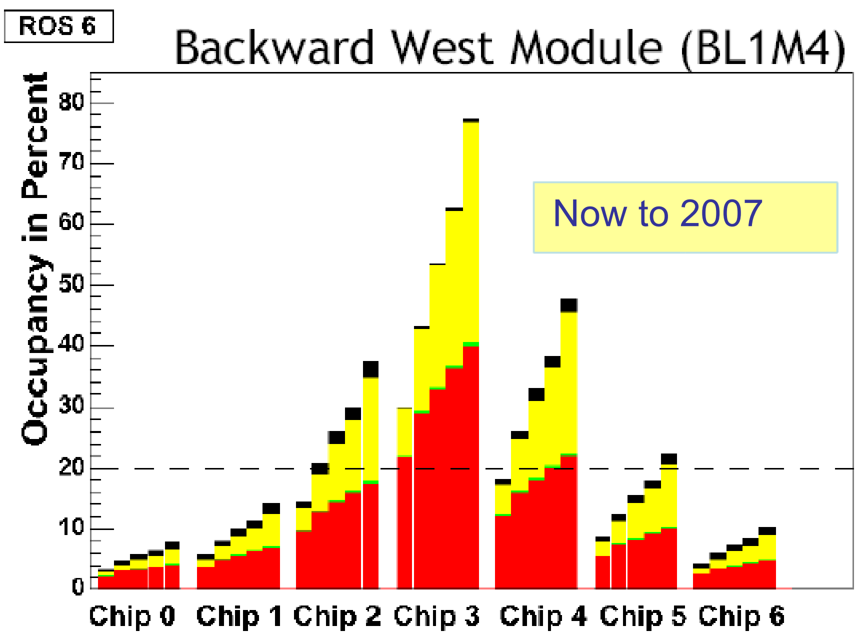

- The effect is expected to be significant in 1/10 of layer 1

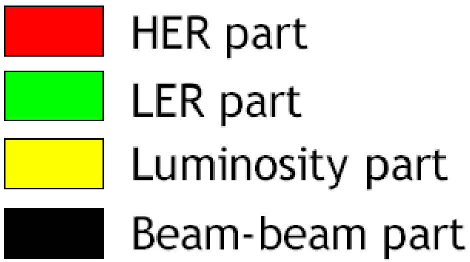
# Occupancy projections

- Use parametrization fitted on background studies data to extrapolate to future running conditions

$bkgd = a + b \cdot I_{HER} + c \cdot I_{LER} + d \cdot Luminosity$

| | HER | LER | Luminosity |
|---|---|---|---|
| NOW | 1.2 A | 1.9 A | $7.2 \times 10^{33}\ cm^{-2}s^{-1}$ |
| 2004 | 1.6 A | 2.7 A | $12.1 \times 10^{33}\ cm^{-2}s^{-1}$ |
| 2005 | 1.8 A | 3.6 A | $18.2 \times 10^{33}\ cm^{-2}s^{-1}$ |
| 2006 | 2.0 A | 3.6 A | $23.0 \times 10^{33}\ cm^{-2}s^{-1}$ |
| 2007 | 2.2 A | 4.5 A | $33.0 \times 10^{33}\ cm^{-2}s^{-1}$ |



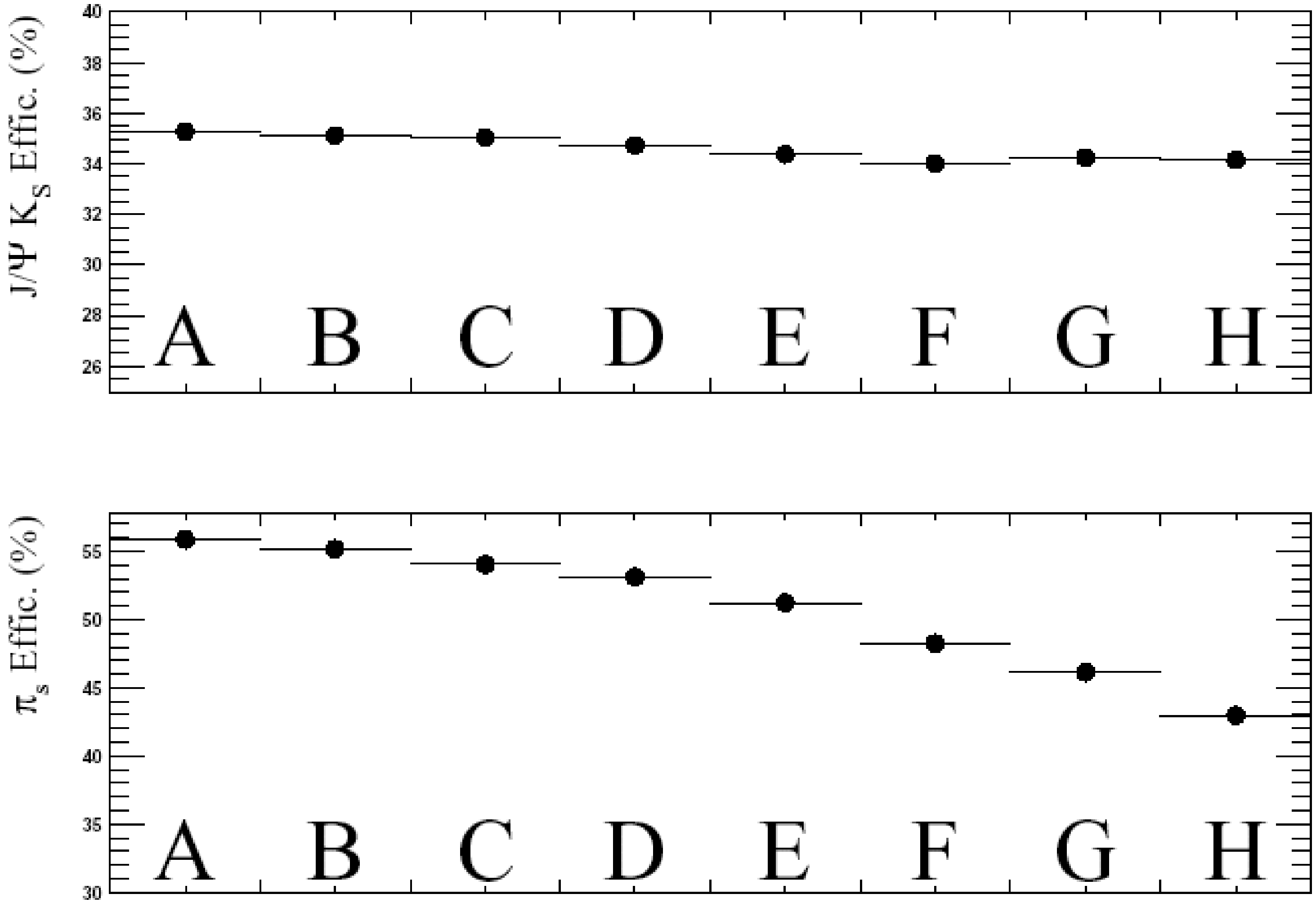




Inside a given chip each bin is one year

# Summary

- SVT originally designed for 240krad/yr has now integrated 2.4Mrad in the worst case
- Extensive studies have been made to understand the effects of radiation damage
- Si: Leakage current increased x 10
- Electronics degradation: S/N=10 @ 5Mrad
- Unexpected effects reproducible, not understood
- Soft degradation after 5 Mrad

# What if we Loose the Mid-plane?




A = perfect

E = midplane chips off in L1& 2 (32 ICs)

F = E with 2 additional dead chips

H = midplane modules off in L1&2



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