# Single Event Effects in the pixel readout chip for BTeV

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FNAL (USA)

**10th** International Workshop on **Vertex Detectors**
**Brunnen, Switzerland, 23-28 September 2001**

# Outline of the talk

- Introduction
- Radiation tolerant FPIX chip
- Single Event Effect in CMOS devices
- 200MeV proton irradiation tests
- Results:
  - » Total dose
  - » Latch-up
  - » Gate rupture
  - » Single Event Upset
- Single Event Upset in BTeV pixel vertex detector
- Conclusions
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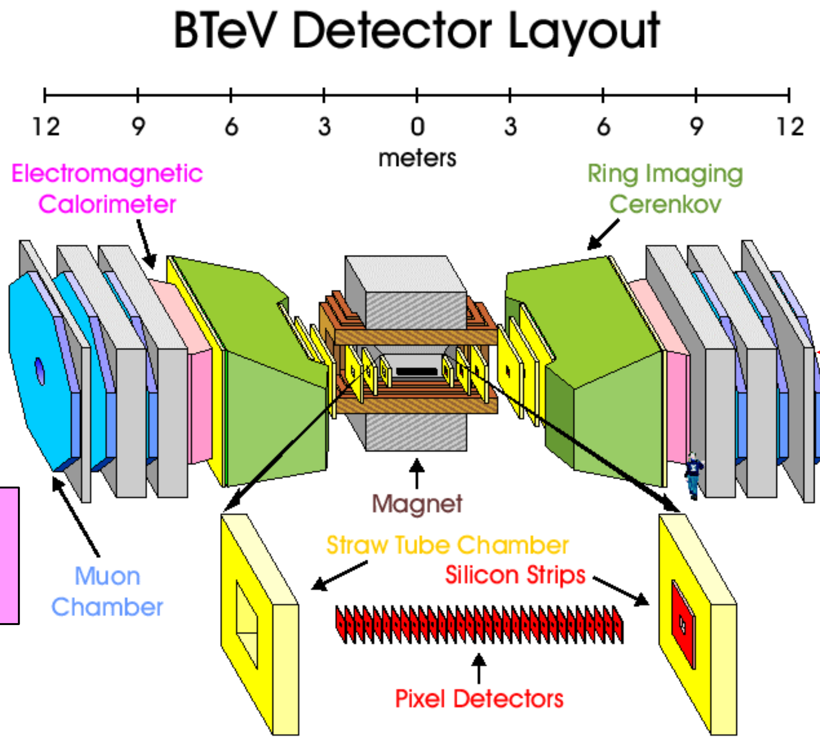
# Introduction:

## The BTeV pixel vertex detector

1TeV p




1TeV antip

Luminosity= $2.10^{32}$ $cm^{-2}s^{-1}$

• BTeV is a double arms spectrometer optimized to do b physic at the Tevatron hadron collider.

• It covers the "forward region" of the interaction point at a luminosity of $L=2.10^{32}cm^{-2}s^{-1}$.

• It employs silicon pixel vertex detector to provide hits for L1 detached vertex trigger.

(M. Artuso's talk)

• The "hottest" pixel readout chips are located 6 mm from the beam (fluence about $10^{14}cm^{-2}y^{-1}$).

➢ Radiation-hard pixel readout chip is a MUST.

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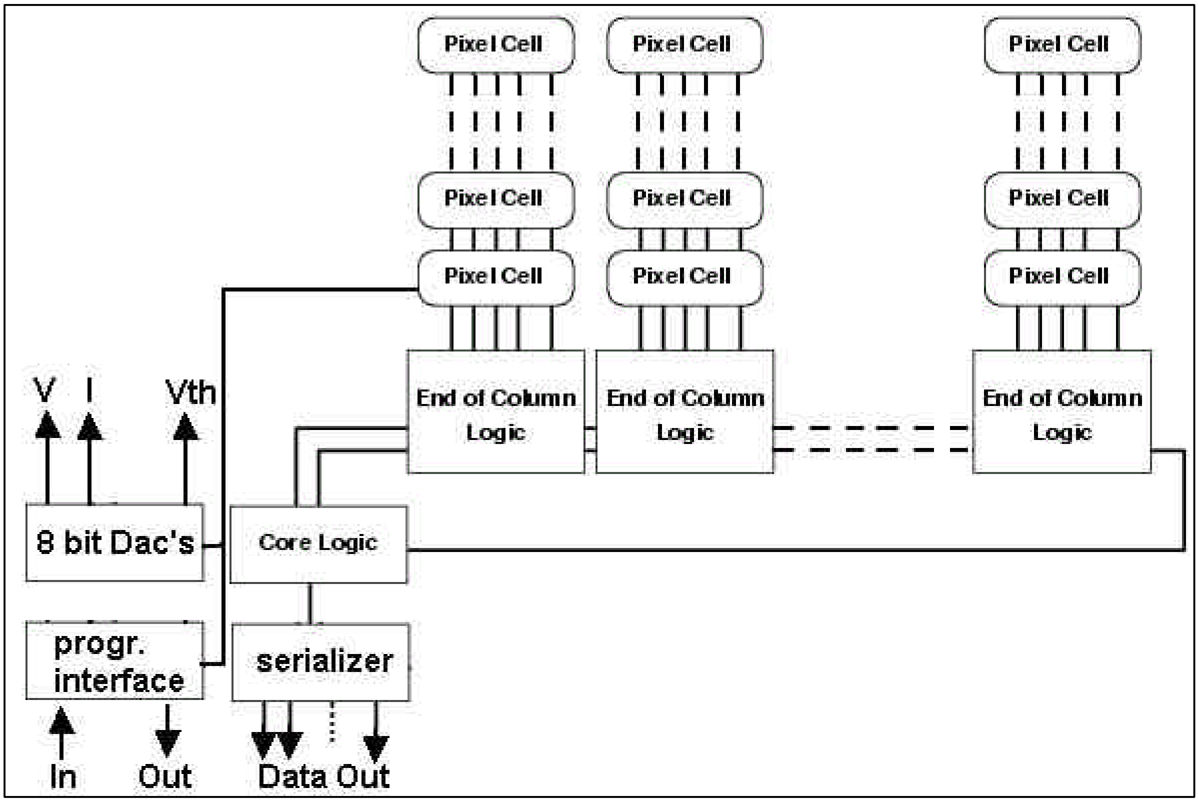
# Radiation tolerant FPIX chip:
## Block diagram




- FE optimized for 132 ns BCO.
- DC leakage current compensation.
- 3 Bit FADC/cell.
- Kill and charge-injection shift-registers.
- Four timestamp registers in the End of Column.
- High speed data driven column architecture.
- Very high speed data output serializer.
- Programmable bias and threshold by DAC's.

# Radiation tolerant FPIX chip:

## FPIX history

- 1997: FPIX0, 12x64 array, HP 0.8 um CMOS
  - Two stage front-end, analog output digitized off chip, data driven non-triggered Readout.
  - Successfully used in beam tests.

- 1998: FPIX1, 18x160 array, HP 0.5 um CMOS
  - Two stage front-end, 2 bit FADC/cell.
  - Fast triggered/non triggered R/O.
  - Successfully used in beam tests.

- 1999: PreFPIX2_T, 2x160 array, TSMC 0.25 um CMOS
  - New leakage compensation strategy implemented in radiation tolerant techniques.
  - 3 bit FADC/cell
  - $\gamma$ irradiation to a total dose of 33 Mrad.

- 2000: PreFPIX2_I, 18x32 array, CERN 0.25 um CMOS
  - Complete fast non-triggered RO.
  - p irradiation test in this talk.

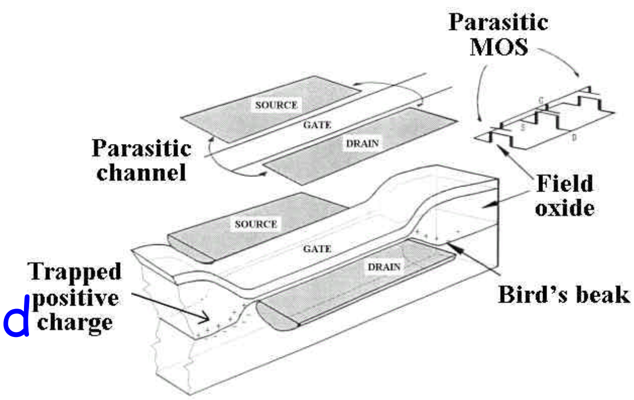
  PreFPIX2_Tb 18x32 array, TSMC 0.25 um CMOS
  - Programmable 14 x 8 bit DAC's.
  - p irradiation test in this talk.

# Radiation tolerant FPIX chip:

## Motivation of the 0.25 um CMOS approach

In CMOS ionizing radiation charge-up $SiO_2$ :

- $V_{th}$ shift.
- Leakage currents within and between devices.



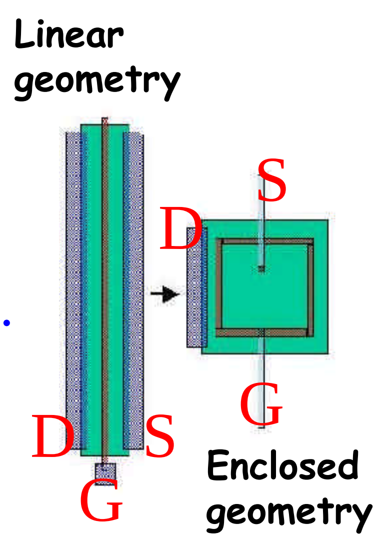

G.Gaillard, J.-L.Leray, O.Musseau et al., "Techniques de durcissement des composant, circuits et systemes electroniques", Notes of the Short Course of the 3rd European Conference on Radiation and its Effects On Components and Systems, Arcachon (France), Sept. 1995.

Radiation tolerance of thin gate oxide:

- Rad-induced holes removed by $e^-$ tunneling ($t_{ox}$ <6nm).

Radiation tolerant rules (RD49 collaboration):

- Edgeless NMOS (No parasitic MOS).
- NMOS with guard ring (No leakage path between MOS).




Features of the technology:

- High density, good speed, low noise low power, high yield and low cost.

➢ Excellent for pixel readout chip

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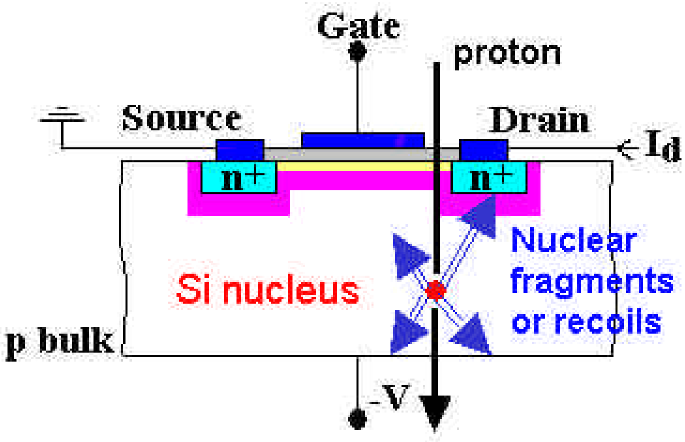
# Single Event Effect in CMOS device:

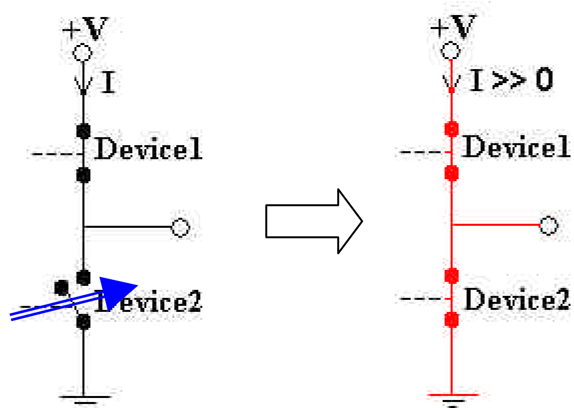
## Radiation induced operational failures




Hadrons can produce short range and high charge secondary particles releasing high Linear Energy Transfer.

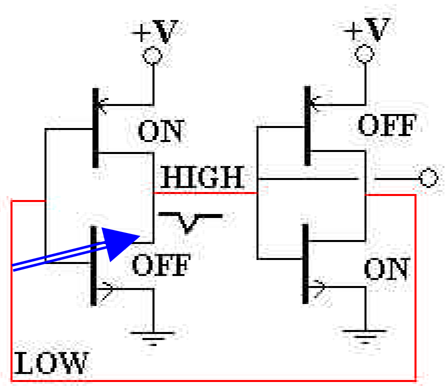
A) Gate Rupture (SEGR):
Total or partial damage of the dielectric gate material due to an avalanche breakdown.

B) Latch-up (SEL):
Turn on of a (parasitic) device resulting in high current self-sustained state.




Short Circuit!

C) Upset (SEU):
Change of state of a sensitive circuit node.




Bit flip:
$1 \rightarrow 0$

# Single Event Effect in CMOS device:

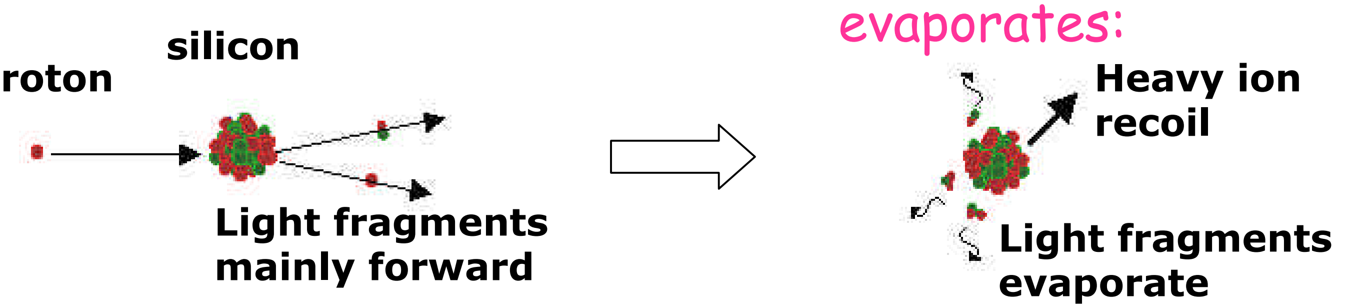
## Basic phenomena

Production of ions by the interaction of protons with silicon nucleus can be described by a two stage process (CLUST-EVAP Code).

**"Internuclear Cascade – Evaporation Model for LET Spectra of 200 MeV Protons Used for Parts Testing." P.M. O'Neill, G.D. Badhwar, and W.X. Culpepper.** IEEE Trans. Nucl. Sci. 45, 2467 (1998).

I) Intranuclear cascade:

II) Excited nucleus evaporates:



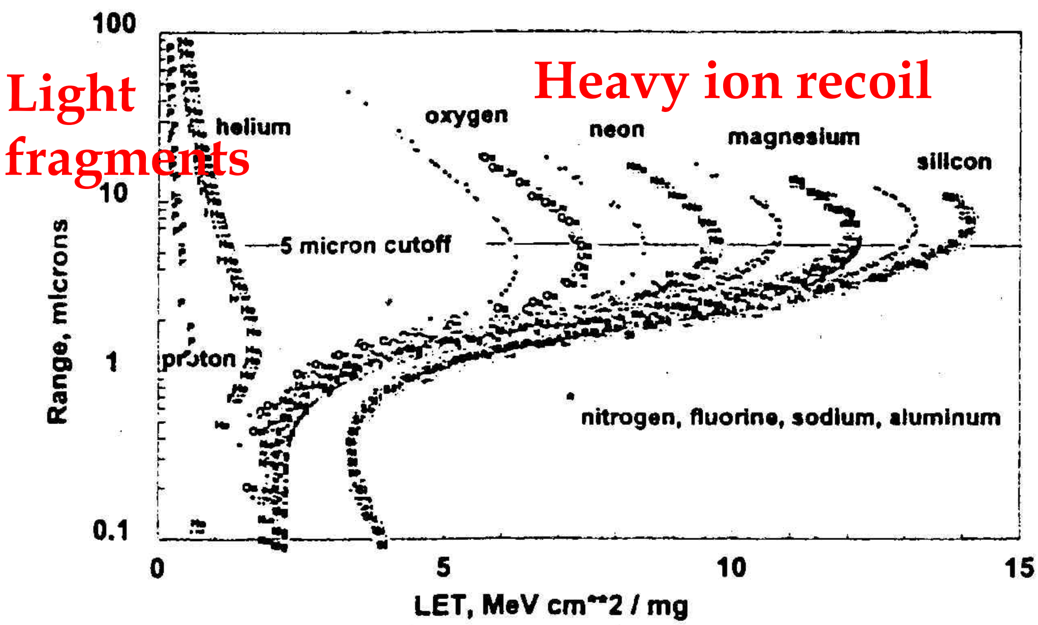
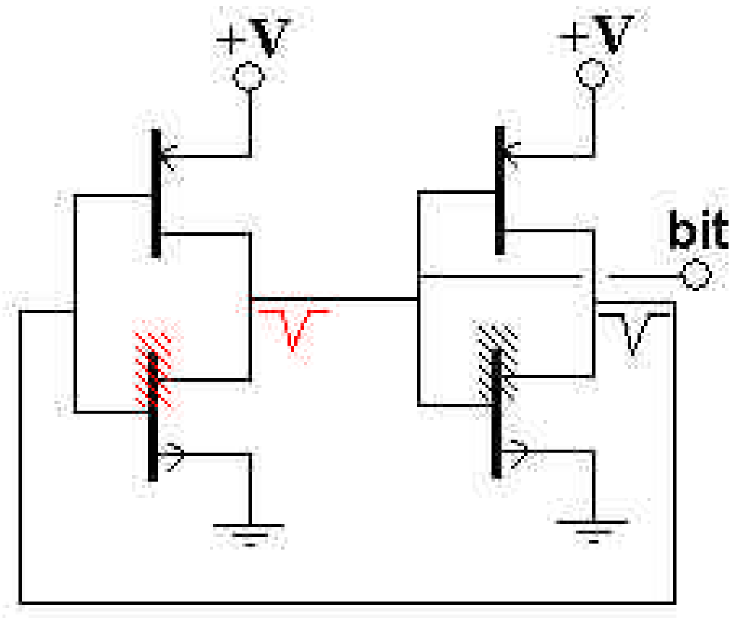




Figure 3.Range versus LET of each particle upon arrival at the observation point

$$\frac{dE}{dx} \propto \frac{Z^2}{b^2}$$

# Single Event Effect in CMOS device:
## SEU sensitive volumes and energy thresholds

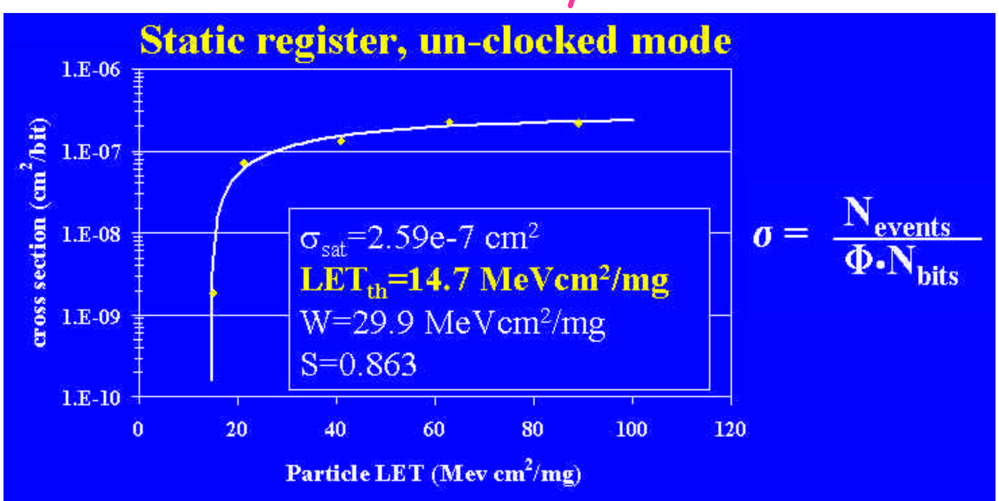



Sensitive volumes:
- Technology dependent.
- Circuit dependent.
- Layout dependent.

Sensitive volume 0 → 1

Sensitive volume 1 → 0

Energy threshold measured by ion irradiations in DSM




F. Faccio et al., "Single Event Effects in Static and Dynamic Registers in a 0.25 μm CMOS Technology", *IEEE Transactions on Nuclear Science*, vol. 46, no. 6, Dec. 1999 , pp. 1434-1439.

$E_{threshold}$ -> $Q_{critical}$

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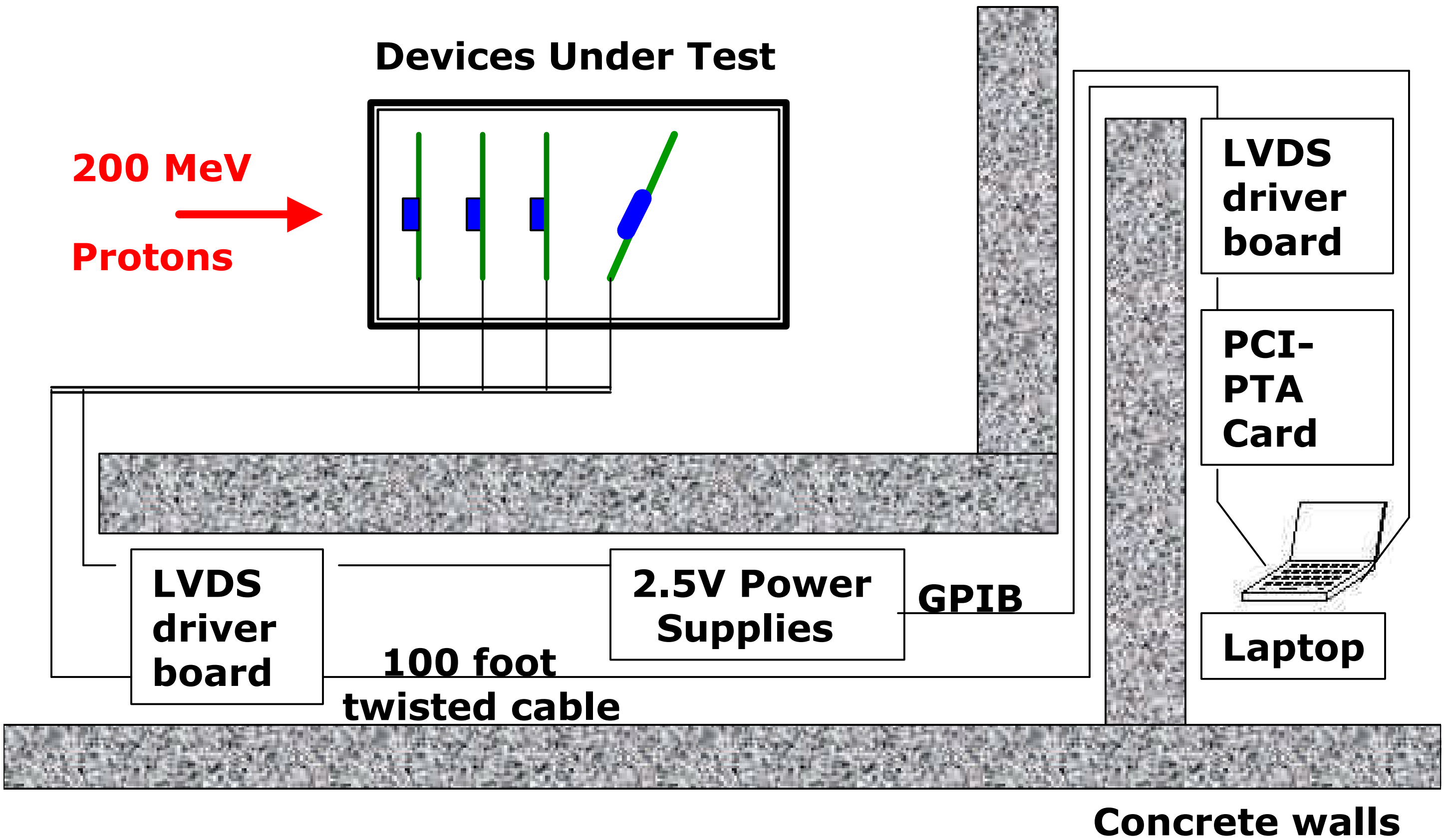
# 200MeV proton irradiation tests :

## Experimental setup at the
## Indiana University Cyclotron Facility (IUCF)




- Irradiation done in air at room temperature.
- No low energy particle or neutron filter.
- Nominal flux $2 \cdot 10^{10}$ protons/(cm$^2$s).
- 1.5cm beam spot diameter measured with a sensitive film (flux 90% center value).
- Laser spot alignment and remote video monitoring.
- Dosimetry : Faraday cup + Sec. Emiss. Elect. Monitor

# 200MeV proton irradiation tests :
## Chip prototypes irradiated

Dec. 2000:
- 4 preFPIXI irradiated to a total dose of 26 Mrad.

Apr. 2001:
- 1 preFPIXTb irradiated to a total dose of 14 Mrad.

Aug. 2001:
- 4 preFPIXTb irradiated to a total dose of 29 Mrad.
- One of the boards was used in Apr. 2001 test collected a total dose of 43 Mrad.
- One of the boards was placed at 45 degrees.

$$1\text{Mrad(Si)} = 0.58 \cdot 10^{13}\text{cm}^{-2}\text{s}^{-1}$$

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# Experimental results :
## Results: Total dose and SEL

Analog and digital currents were constantly monitor during irradiation separately for each board:

- $I_{analog}$ decreased slightly during irradiation.
- $I_{digital}$ increased slightly during irradiation.
- No evidence of Single Event Latch-up.
- No evidence of significant radiation induced $I_{leakage}$.

preFPIX2I:

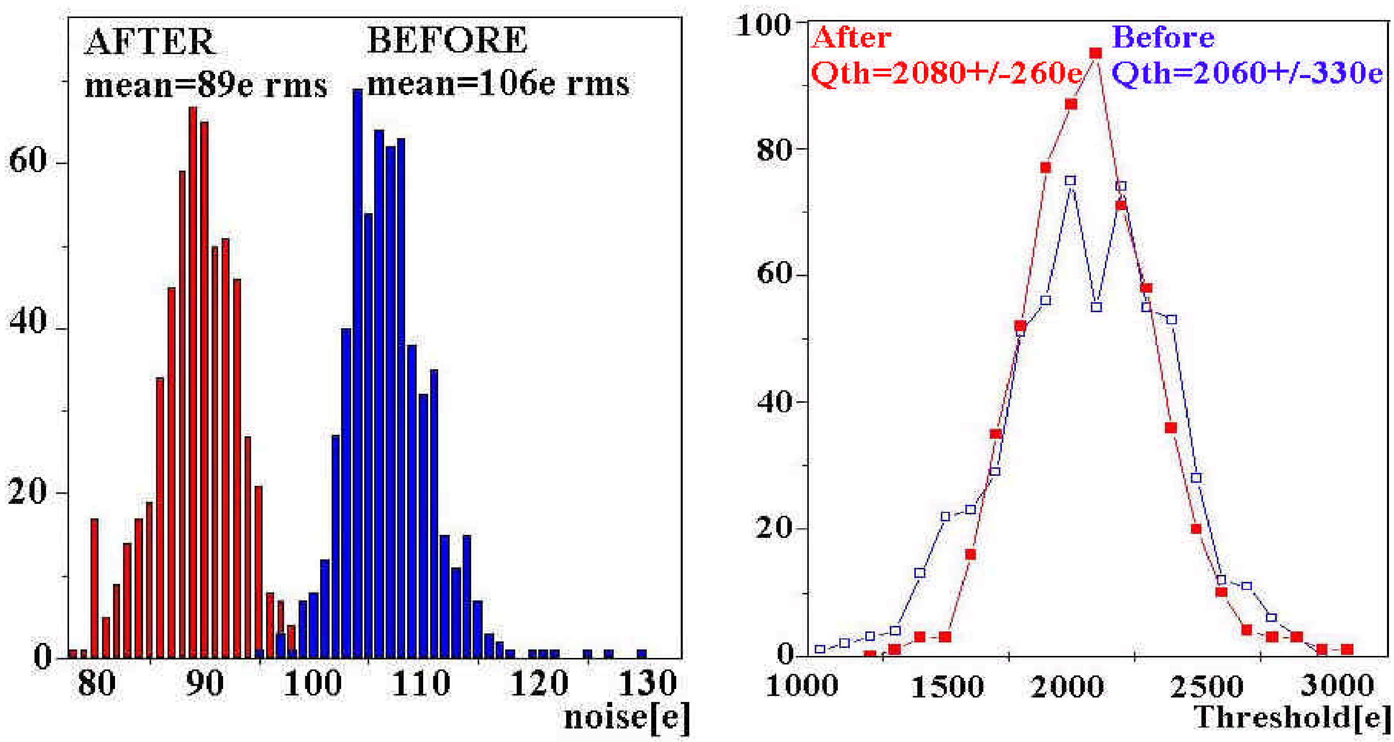
- Inferred threshold shift of – 6mV for the NMOS.
- Inferred threshold shift of –105 mV for the PMOS.
- 10 % decrease in the Front End rise time.
- No change in the Front End falling time.

# Experimental results :

## Results: Total dose and SEGR (1)

- Noise and discriminator threshold of each individual cell was measured before and after irradiation.
- For the four preFPIX2I chips (Dec. 00) all the 32rows x 18cols x 4chips = 2304 cells work after 26 Mrad proton irradiation:
  - The noise is decreased by about 10%.
  - The threshold dispersions is decreased by about 20%.

**Noise and thresholds distribution before and after 26 Mrad proton irradiation for one preFPIX2I chip.**



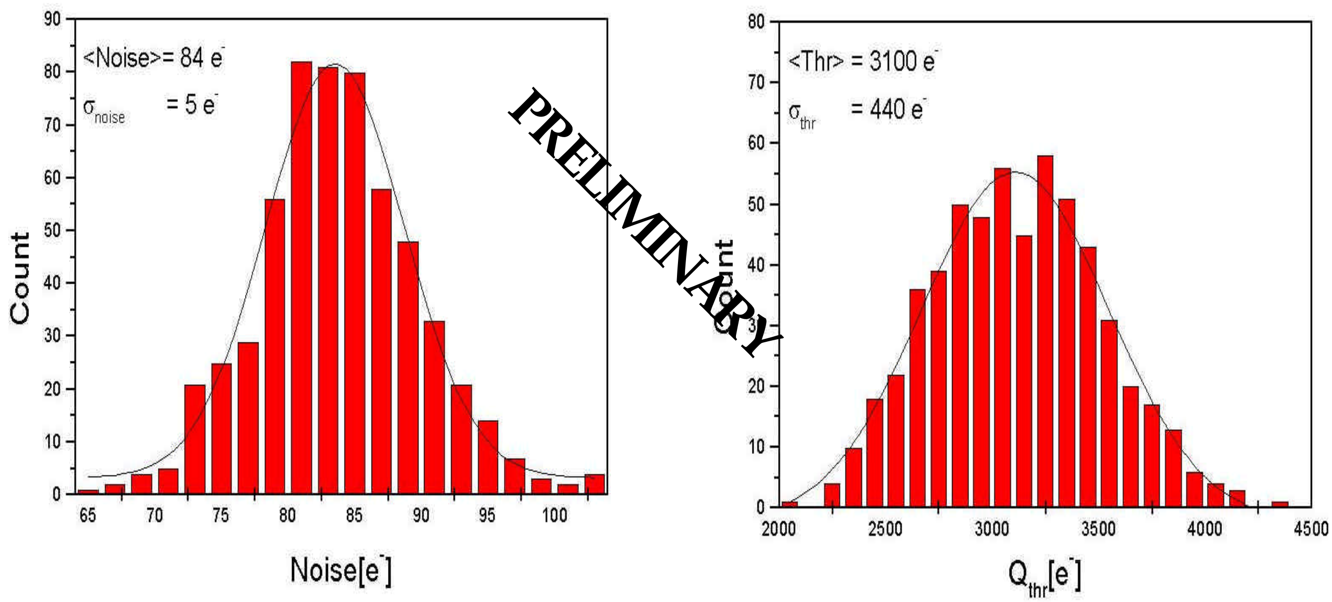
# Experimental results :

## Results: Total dose and SEGR (2)

For preFPIX2Tb chip irradiated in Apr. 01 all the 32rows x 18cols = 576 cells work after 14 Mrad proton irradiation:

- The noise is decreased by about 15%.
- The threshold dispersion is decreased by about 10%.

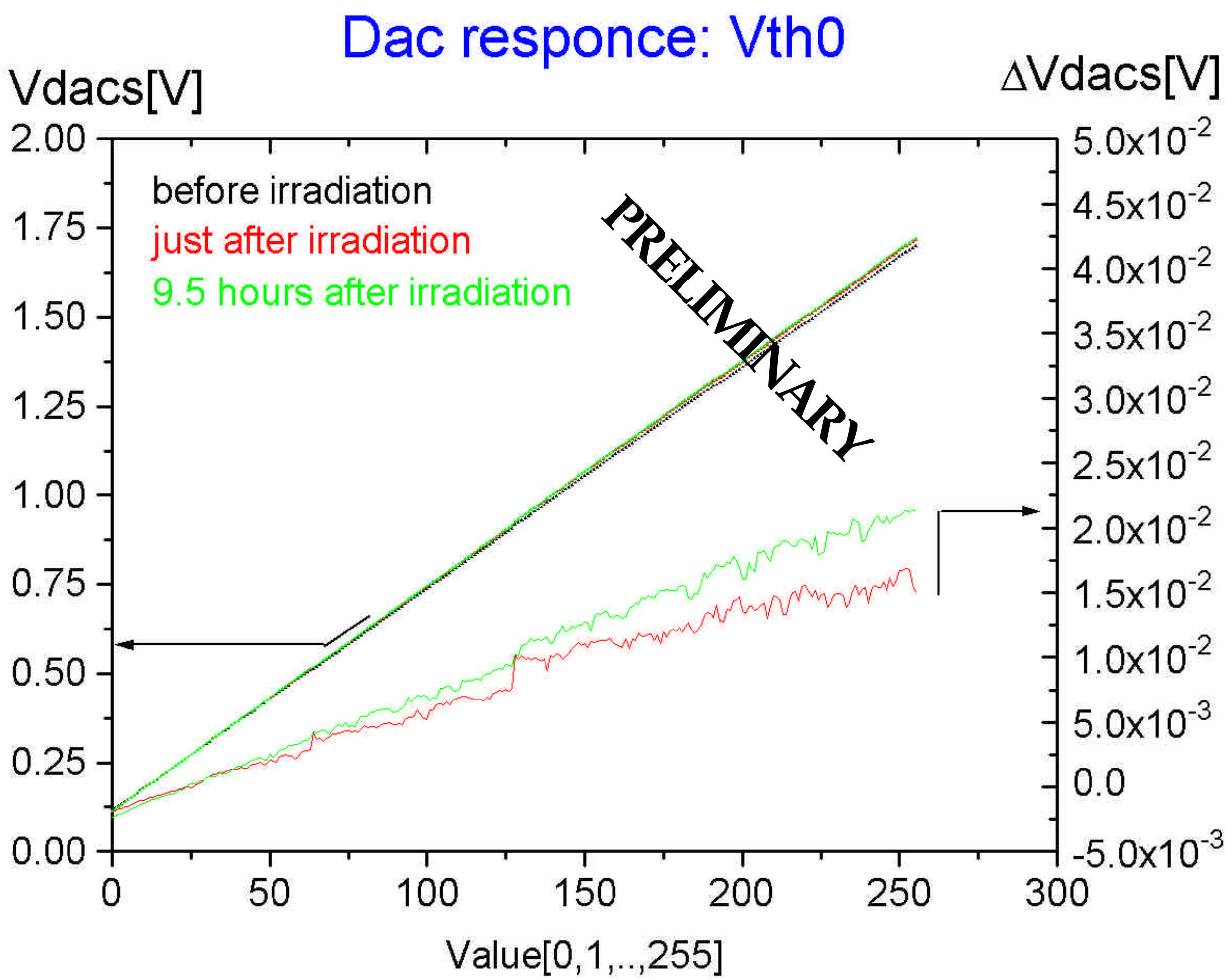
**Noise and thresholds distribution after 14 Mrad proton irradiation for a preFPIX2Tb chip.**




Results for the four preFPIX2Tb irradiated in Aug. 01 (one board exposed to 43 Mrad and three to 29 Mrad) available in October.

# Experimental results :
## Results: DAC analog response

**Vth0 DAC voltage output before and after 14 Mrad proton irradiation for a preFPIX2Tb chip.**




The DAC voltage output shift not more than 20 mV on the full range after 14 Mrad proton irradiation.

# Experimental results :

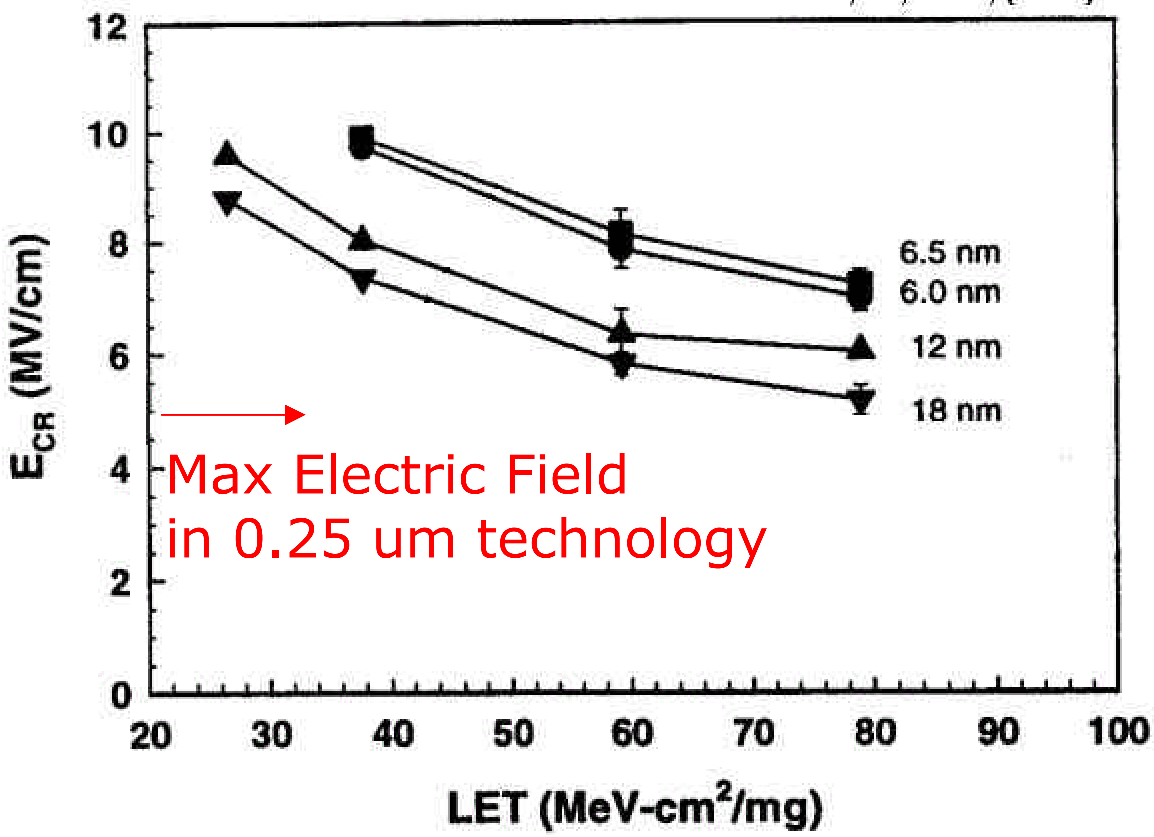
## Results: SEGR and scaling

Irradiation tests suggests that SEGR failure is likely not to be a concern (more statistic available in October):

- All cell working.
- Absence of noisy cell.
- Absence of large difference in individual thresholds.
- Small change in the DAC response.

Smaller feature size technology are expected to be more SEGR immune.

F.W. Sexton, D.M. Fleetwood et al., "Single Event Gate Rupture in Thin Gate Oxides" IEEE Trans. on Nucl. Sci., 44, 2345, (1997).



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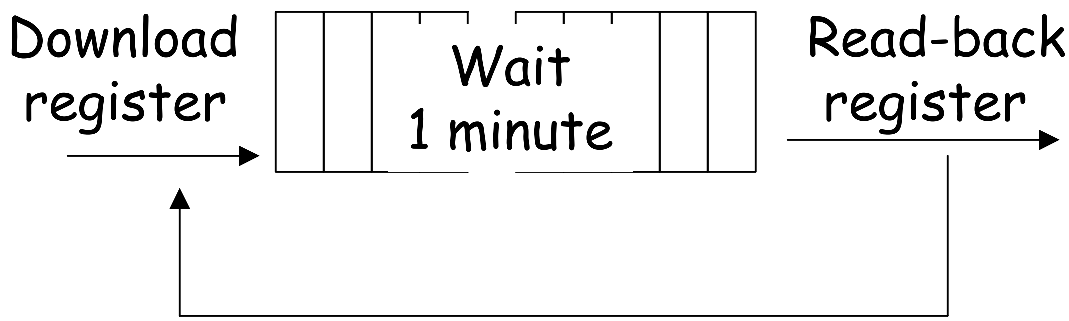
# Experimental results :
## SEU testing procedure

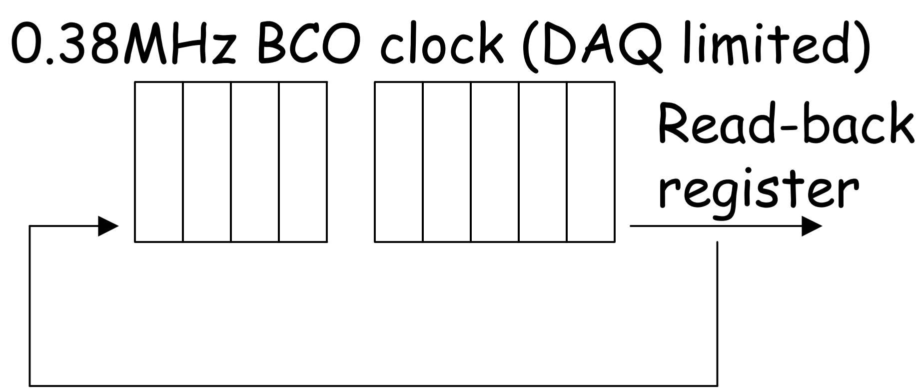
## Test 1: un-clocked registers




## Test 2: clocked shift-register

a) Download pattern.

b) Continuous
read-back.




c) Stop when an error is detected.

# Experimental results :

## Results: SEU error table

N.B. In Apr.01 the DAC registers were downloaded with 82 0's and 30 1's.

| Time | Board | Fluence [$cm^{-2}$] | Bit errors in S-R [2x576 bits] | Bit errors in DAC [8x14 bits] |
|---|---|---|---|---|
| Apr.01 | 1 | 2.33E14 | 53=18↑+35↓ | 10=8↑+2↓ |
| Aug.01 | 2 | 3.65E14 | 74=22↑+52↓ | 19=9↑+10↓ |
| Aug.01 | 3 | 3.65E14 | 86=27↑+59↓ | 19=8↑+11↓ |
| Aug.01 | 1 | 3.65E14 | 80=23↑+57↓ | 20=8↑+12↓ |
| Aug.01 | 4 ($45^0$) | 3.65E14 | 77=14↑+63↓ | 31=19↑+12↓ |

No statistical significant beam angle dependence.

-=transition from 0 to 1
¯=transition from 1 to 0

Kill and Charge-injection shift-registers:

- DFF with Nor-not cross-coupled gates
  (expected asymmetry in 0->1 and 1->0 upset rate).
- Random pattern with equal number of 0's and 1's.

DAC registers:

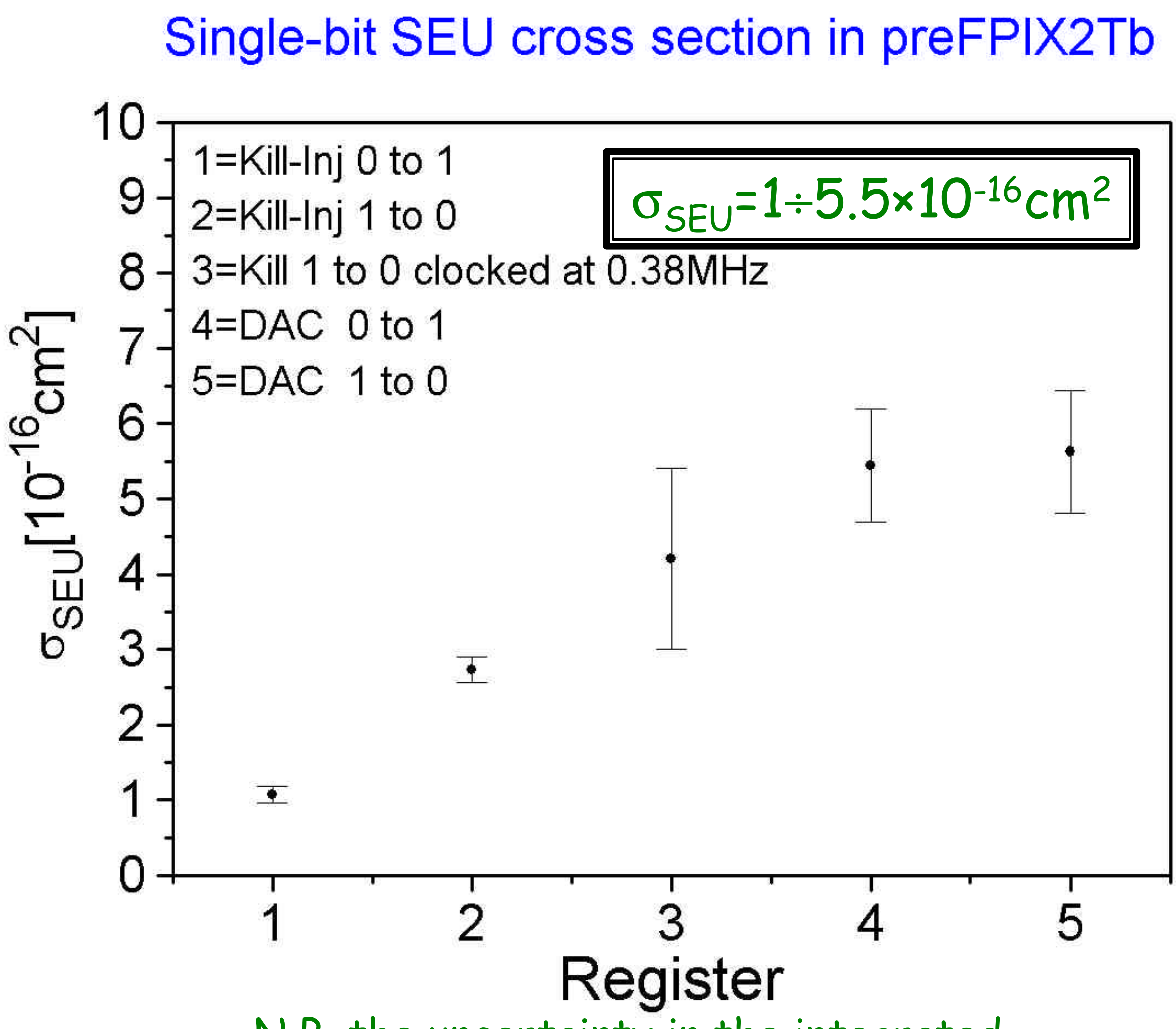
- DFF with Nor-Nor cross-coupled gates
  (expected symmetry in 0->1 and 1->0 upset rate).
- Constant pattern with equal number of 0's and 1's.

# Experimental results :

## Results: SEU cross sections

$$N_{error} = F \cdot N_{bits}\, s_{one\ bit}$$

- $N_{error}$ = total bit errors
- F = I*time = integrated fluence
- $N_{bits}$ = number of bits exposed
- $\sigma_{bit}$ = one bit SEU cross section

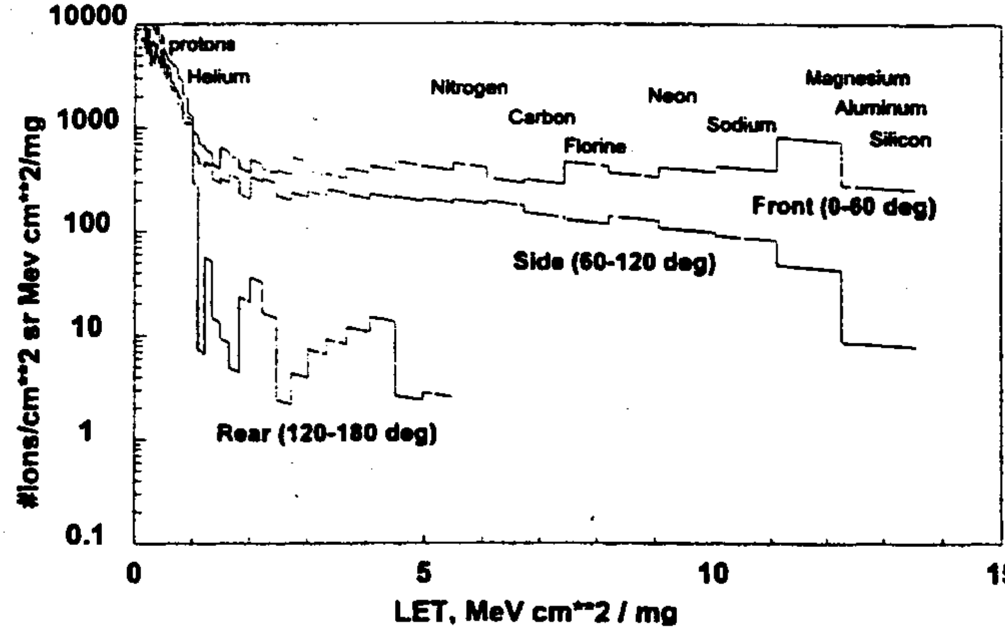



N.B. the uncertainty in the integrated fluence is less than 10%

# Experimental results :

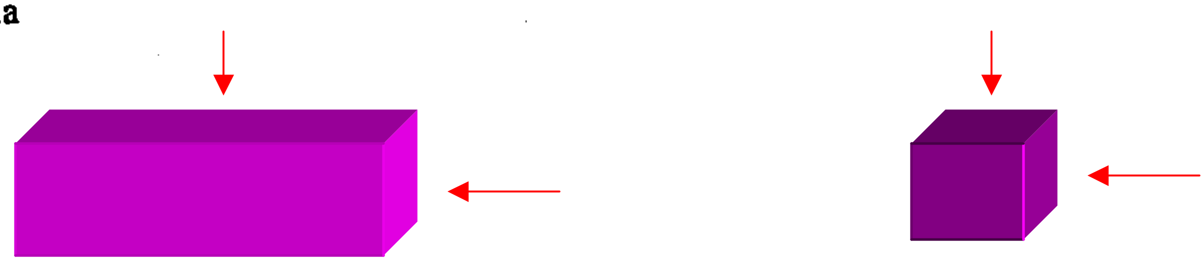
## Results: SEU beam angular dependence

• Beam angle dependence is expected for 200 MeV p, in device with thin sensitive volumes and $E_{th}$>1 MeVcm$^2$/mg.




**P.M. O'Neill, et al,** **Trans. Nucl. Sci. 45, 2467 (1998).**

Figure 4. Double Differential LET fluence ($d^2\Phi/dLd\Omega$) produced by $10^{10}$ protons / cm$^2$ (200 MeV incident protons) at an observation point located ~100 µ below the surface of a semi-infinite silicon media



In deep submicron technology the sensitive volumes look more cubic shaped than slab shaped.

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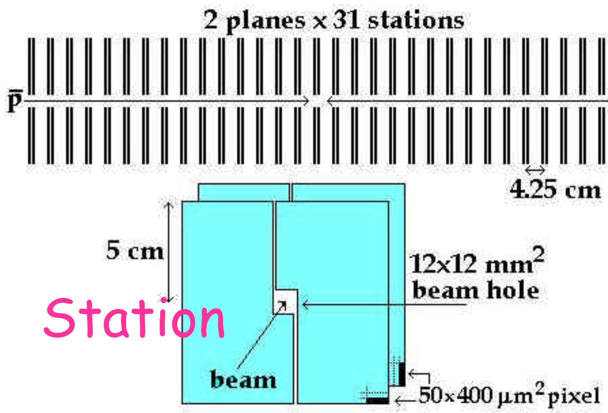
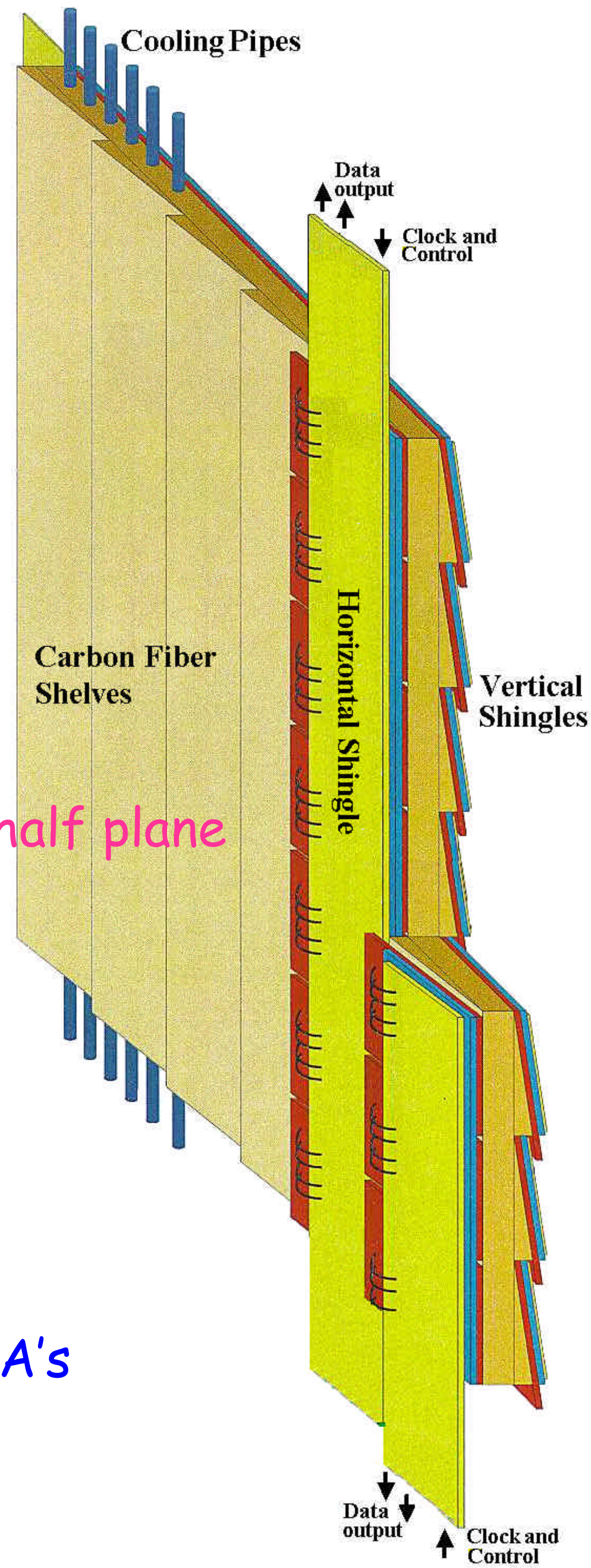
# SEU in BTeV vertex detector :

## Vertex detector

Planar pixel vertex detector




Station

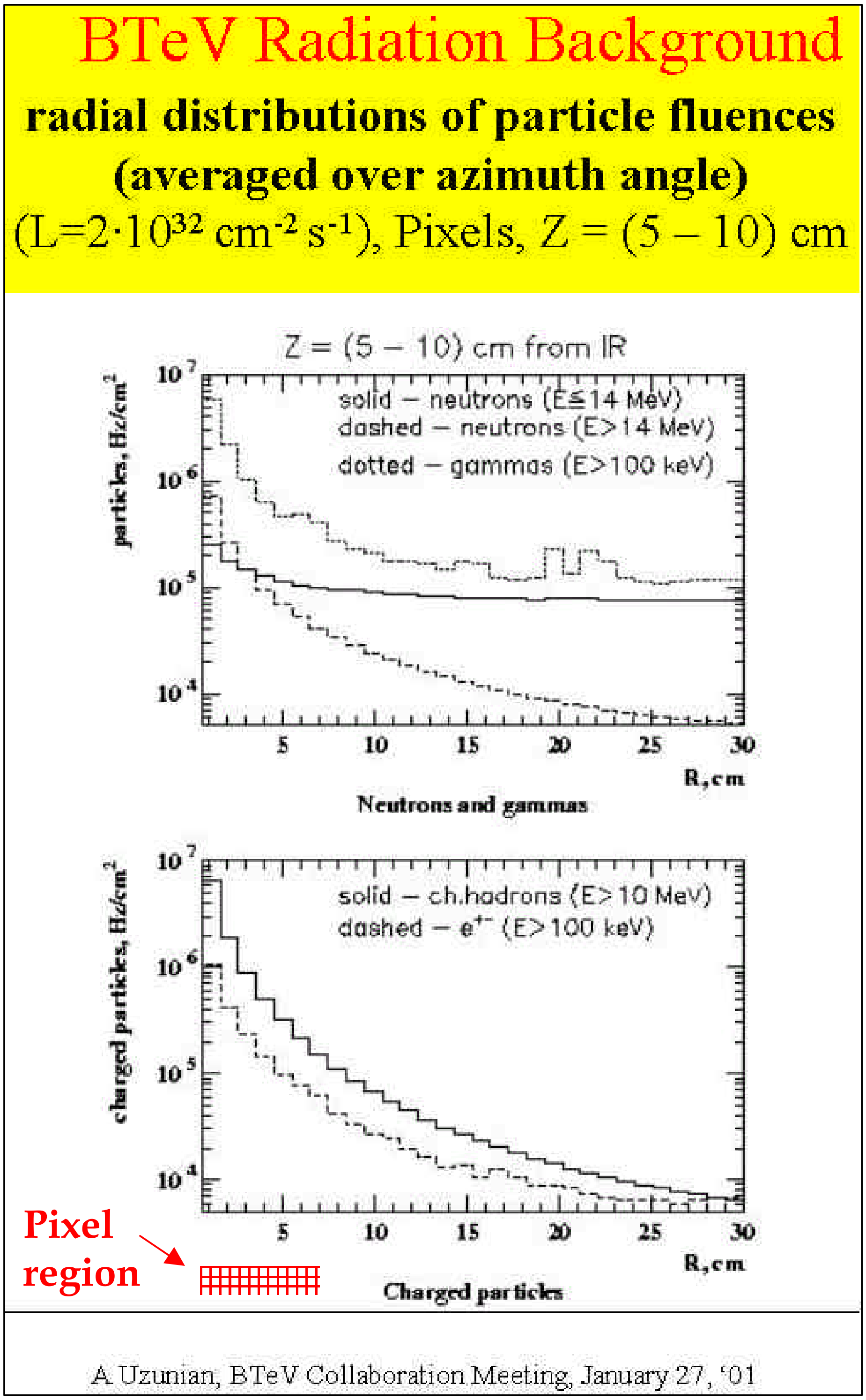



L-shape half plane

- The detector is crossed by particles coming from any direction (IR=30 cm along z).
- FPIX readout chips is the only active device on the module.
- Copper point-to-point links will connect the FPIX chips to FPGA's located behind the magnet.

# SEU in BTeV vertex detector :

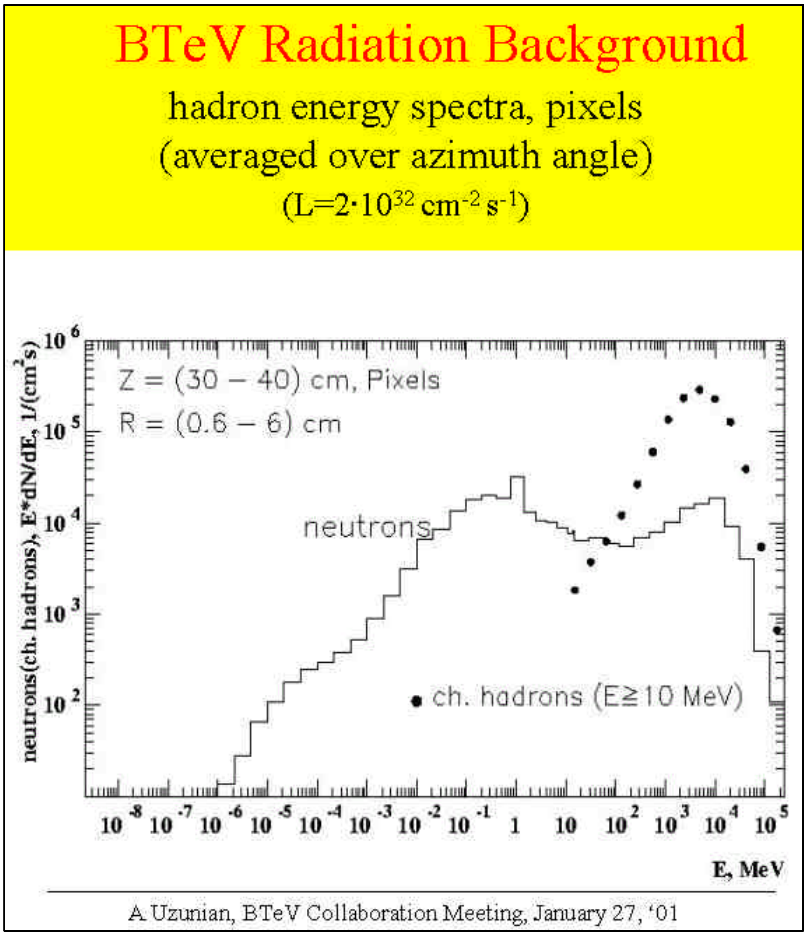
## Particle fluxes




- Simulation done with MARS code.
- The flux for charged species and gamma's decreases as $1/r^2$.
- The neutron flux reach a plateau.

# SEU in BTeV vertex detector :

## Particle spectrum




- The SEU cross section for proton saturates with E > 200 MeV and is less with E < 200 MeV.
- The SEU cross section for pions is not bigger than for protons.
- The SEU cross section for neutrons with E > 1 eV is less than for protons.
- Epithermal neutron (E<1eV) has large SEU cross section but very low flux: $n + {}^{10}B \rightarrow \alpha + {}^{7}Li$ .

# SEU in BTeV vertex detector :

## Estimated error rate

$$s_{SEU,SR}^{0\to 1} = (1.0 \pm 0.1) \cdot 10^{-16} cm^{-2}$$

$$s_{SEU,DAC} = (5.5 \pm 0.6) \cdot 10^{-16} cm^{-2}$$

$$s_{SEU,Ser} = 2 s_{SEU,DAC}$$

| | **Ch.Had. E>10MeV** | **Neu. E>14MeV** | **<Neu.> E<14MeV** | **e , g E>0.1MeV** |
|---|---|---|---|---|
| **Flux per pl. [Hz]** | **1.4E8** | **0.15E8** | **0.20E8** | **3E7, 1.4E8** |
| **SRkill[seu/h]** | **10** | **1 x Hn** | **1.4 x Ln** | **0** |
| **DAC [seu/h]** | **2** | **0.2 x Hn** | **0.3 x Ln** | **0** |
| **24 bits Data Output Serializer [seu/h]** | **1 x $f_{clock}$** | **0.09 x $f_{clock}$ x Hn** | **0.1 x $f_{clock}$ x Ln** | **0** |

- Energy dependence neglected.
- Unknown factors for neutrons( Hn, Ln < 1).
- Angular dependence neglected.
- Unknown frequency clock factor (1< $f_{clock}$< 100[?]).

SEU in reg's can be handled by a periodic read-back:
1. During data taking.
2. During major beam gaps.

# Conclusions

200 MeV Proton irradiation results:

- Small change of the bias currents and no evidence of Latch-Up up to 43Mrad total dose.

- No evidence of Gate Rupture in the 5 chips tested so far up to 26Mrad total dose.
- No degradation of the DAC analogue response up to 14 Mrad total dose.

<u>More statistic available in early Oct. 01.</u>

- We measured SEU's in 0.25um preFPIX2Tb in two different Registers:
  - » $\sigma_{SEU}=1\div5.5\times10^{-16}cm^2$
- No significant variation in the SEU cross section rate between different chips of the same batch.
- No incident beam angle dependency has been found in the upset rate.

# Next

- Characterization of the Sintef BTeV pixel sensors irradiated (Aug. 01).
- Irradiation of sensors bump-bonded to readout chip (Sept. 01).
- Submission of full-size FPIX readout chip for BTeV (before the end of the year).
- Test beam with irradiated sensors bump-bonded to readout chip (next year).