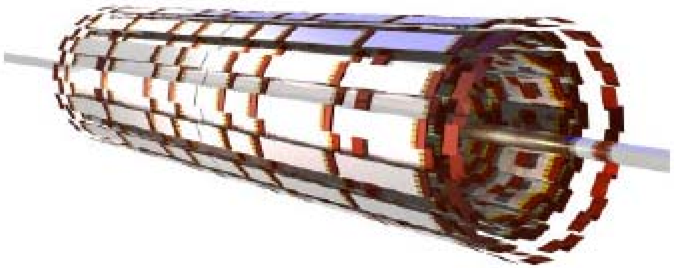
Radiation damage studies on DØ Silicon Sensors for Run IIb

- Lifetime studies on existing DØ Run IIa silicon detector
- Expectations for Run IIb
- Irradiation studies on Run IIb sensors
- Conclusions



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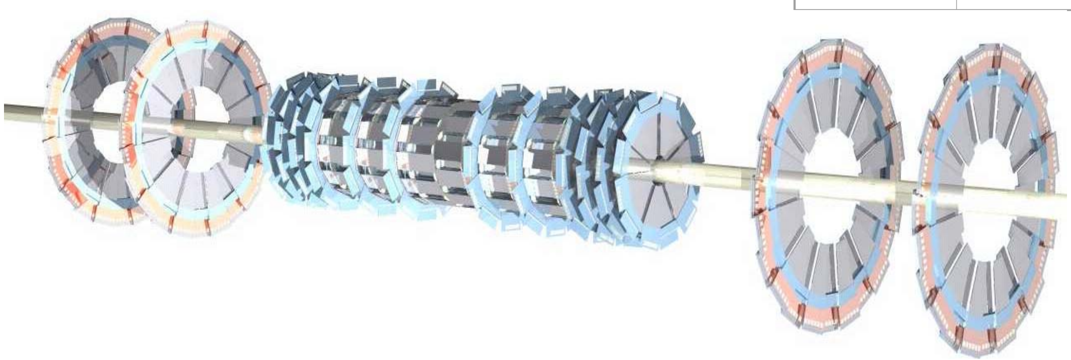
U Zurich

6th International Conference RD'03
Florence, Sept 30, 2003

The Run IIa Silicon Detector

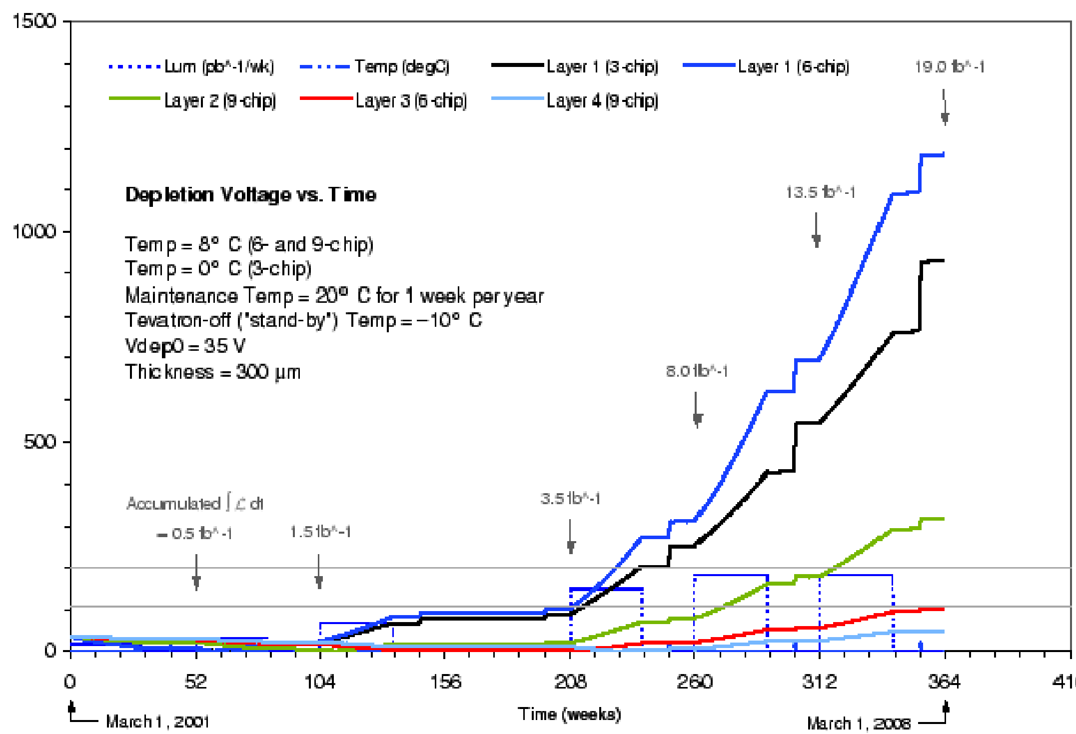
- existing Run IIa detector
  - commissioned during ’01
  - designed for a luminosity of 2fb^{-1}
    - ~250 pb^{-1} now delivered
  - variety of different geometries, technologies and types
  - mainly double sided silicon sensors, i.e. HV across coupling capacitors

Module	Type	Layer	Inner Radius (cm)	Outer Radius (cm)	Manufacturer
Central Disk	DS	-	2.57	9,96	Micron, Eurisys
Outer Disk	SS	-	9.5	26	Elma
Central Barrels	DSDM	1	2.715	3.645	Micron
	DS	2	4.55	5.554	
	DSDM	3	6.768	7.582	
	DS	4	9.101	10.51	
Outer Barrels	SS	1	2.715	3.645	Micron
	DS	2	4.55	5.554	
	SS	3	6.768	7.582	
	DS	4	9.101	10.51	



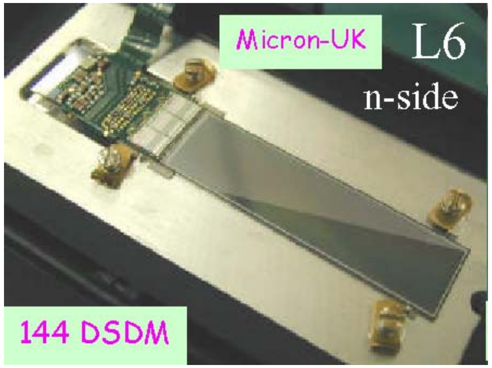
The Run IIa Silicon Detector - Lifetime expectations

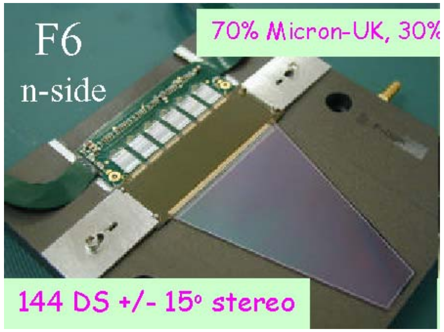
- depletion voltage prediction for Run IIa
  - expect 150-200V after 4 fb^{-1}
- unacceptable high values for bias voltage limit the lifetime for double sided sensors
  - coupling capacitors have breakdown at ~150V (specified)
  - aging or mechanical damage incurred during micro-bonding could lower breakdown threshold

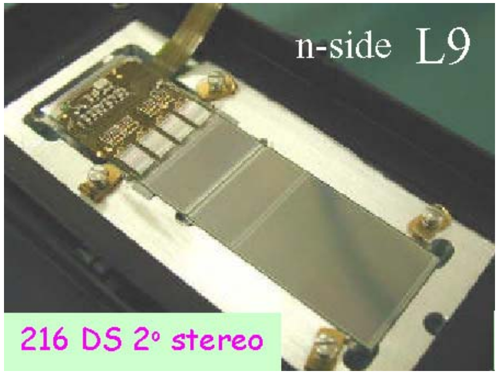


The Run IIa Silicon Detector - Radiation damage studies

- study radiation damage on Run IIa production spare ladders
- ladders identical to those in collision hall, i.e. mechanical support structures and R/O chips
- irradiation took place at 8 GeV proton Booster at Fermilab
  - irradiation in 5 steps up to 2 Mrad (~$7\cdot10^{13}$ 8 GeV p/cm^2)
  - equivalent to ~ 5 fb^{-1} for innermost layer in Run IIa detector
  - detectors kept during irradiation at 5°C and then annealed
  - characterization by laser and burn-in stand

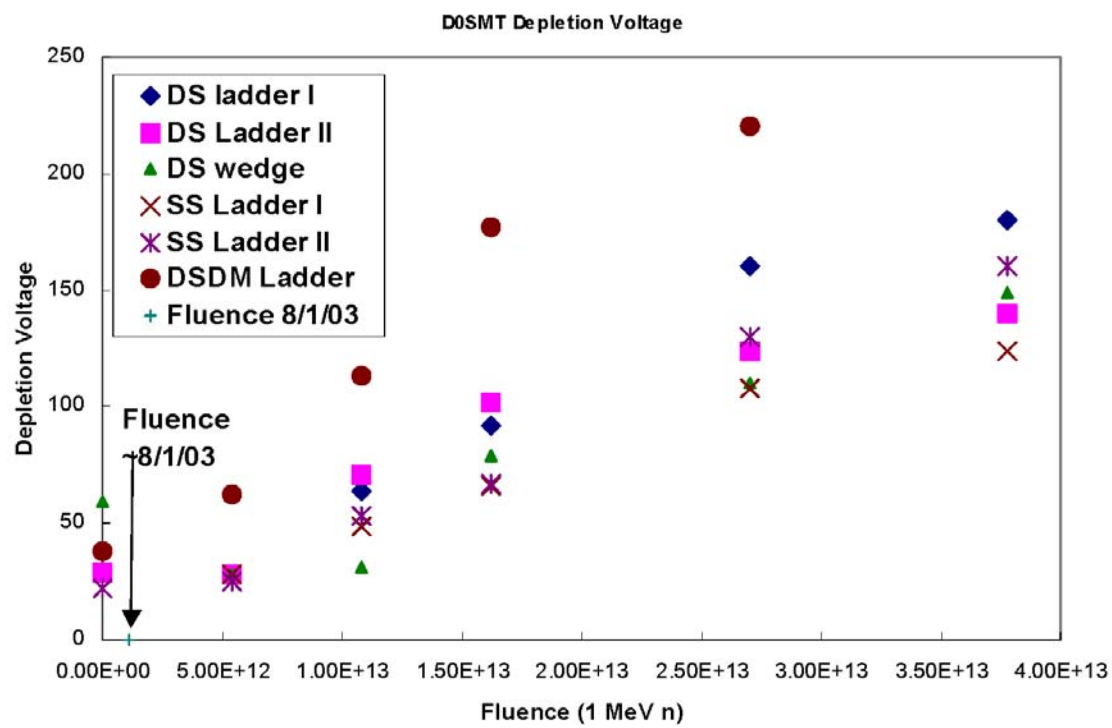






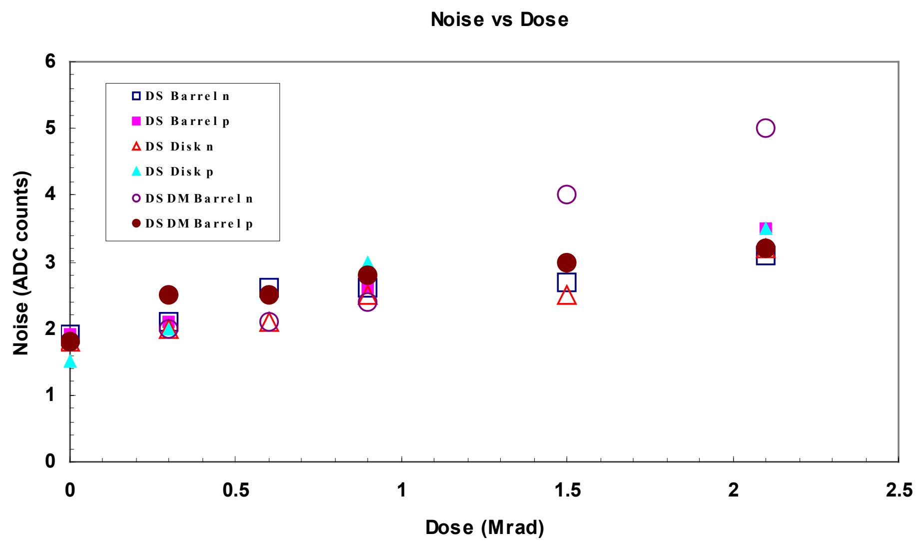
The Run IIa Silicon Detector - Radiation damage studies

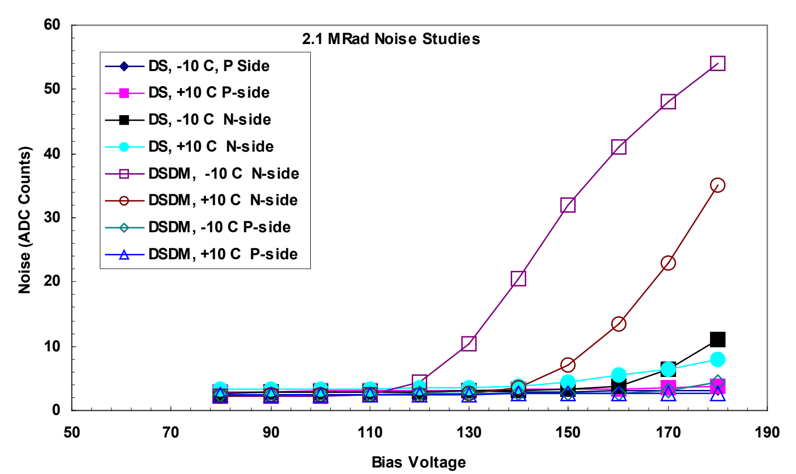
- measure depletion voltage as function of accumulated fluence for all DØ Run IIa silicon detector types
- most types perform as expected from RD48 studies
- double-sided double metal detectors (DSDM) show abnormal high depletion voltage
  - those detectors are in the inner central layer
  - made from 6"-wafers
  - sensors have ~1.5 μm PECVD layer between metal layers
- separate exposure on test diodes from DSDM wafers was behaved normal
- => PECVD layer has increased sensitivity to radiation



The Run IIa Silicon Detector - Radiation damage studies

- look at noise after irradiation
- after type inversion junction has migrated to n-side
- observe larger noise possibly due to micro-discharge effects:
  - increase in the magnitude of the electric fields at the p-n junction caused by fields associated with AC coupling structure
  - enhanced by excess charge in oxide or misalignment of aluminium layers
  - sensitive to AC coupling voltage
- lifetime of detector limited to onset of micro discharge
- expect noise will be unacceptable between 130V-170V bias voltage
- **inner layer will loose significantly in efficiency after 3.5 fb^{-1}**



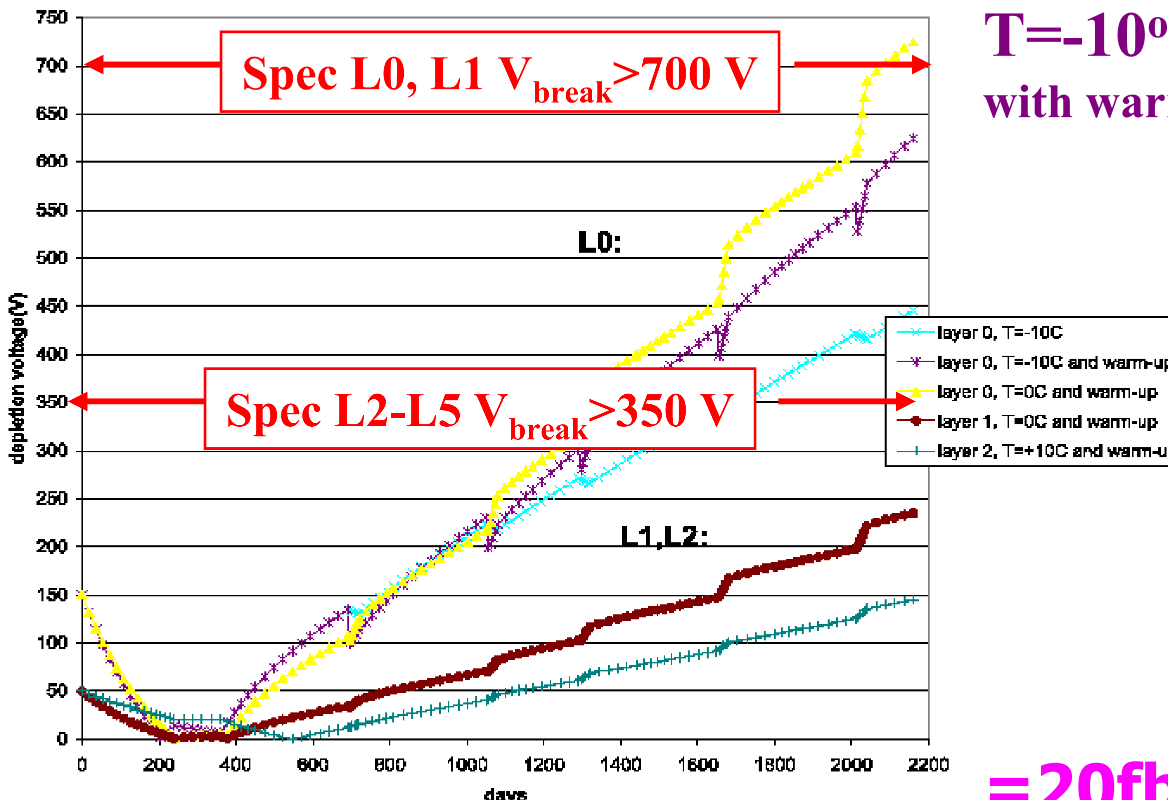


Lessons & consequences from this study for Run IIb

- useful lifetime of inner layers of existing Run IIa detector is limited by bias voltage applied across capacitors
- central inner layer detectors (DSDM) have increased sensitivity to radiation effects
- there is a capability of the detector to run up to 3.5 fb^{-1}
- it will certainly not survive extended Tevatron period with a total expected luminosity of 12-15 fb^{-1}
- a new Run IIb detector (see talk by Kazu Hanagaki) was designed as an improved, drop-in replacement of existing silicon for winter 2005
  - designed for at least 15 fb^{-1} – capability of up to 20 fb^{-1}
  - use of single-sided sensors only
  - minimize number of detector types
  - number of layers increased from 4 to 6
  - eliminate disk design
- The director at Fermilab, Mike Witherell, announced on Sept 3 2003, that "we will not include the silicon detectors (CDF & DØ) in the continuing upgrade projects"

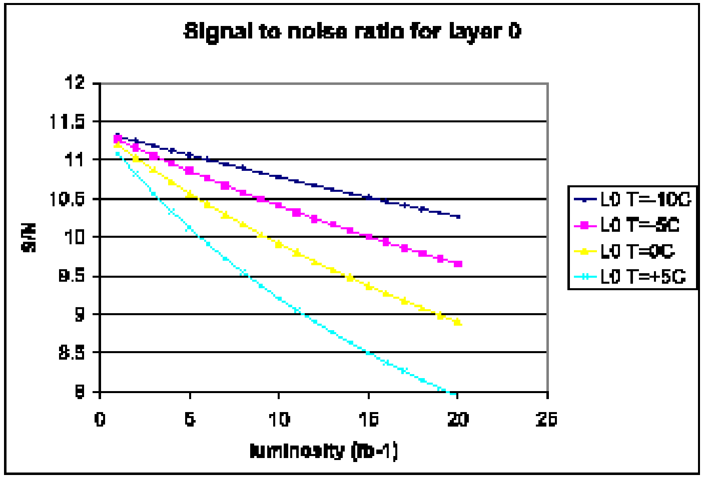
Run IIb - Radiation environment

Depletion Voltage Prediction:



T=-10°C

with warm up periods



Inner layer: S/N>10 after 20 fb^{-1}

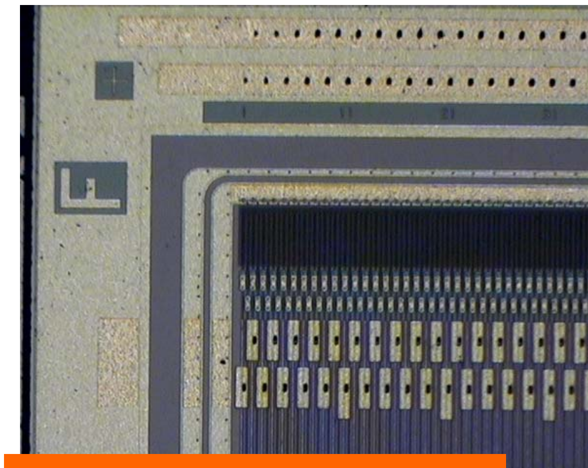
=20fb^{-1}

'Hamburg' model:
M. Moll DESY-Thesis-99-040

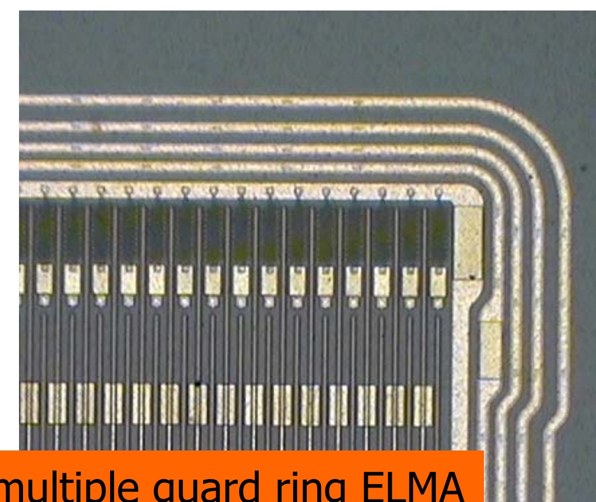
up to $2\cdot10^{14}$ 1 MeV eq. n/cm^2 in innermost layer (L0, r=1.7 cm from beam) after 15fb^{-1}

Sensor technology for Run IIb silicon detector

- Chosen sensor technology profited from R&D for LHC detectors :
  - single sided n+p
    - robust, simple and low number of dead channels <1%
  - crystal orientation <100>
  - pitch: 25 & 29 μm, every 2nd strip read out
    - improve single hit resolution
  - integrated AC coupling and polysilicon bias resistor
    - both features will work reliable after irradiation
  - guard ring structure design for necessary radiation resistance:
    - either multi-guard ring structure
    - or single guard ring design with peripheral n-well (Hamamatsu development)
  - overhanging metal on readout strips
    - significantly reduced risk of HV breakdown after heavy irradiation



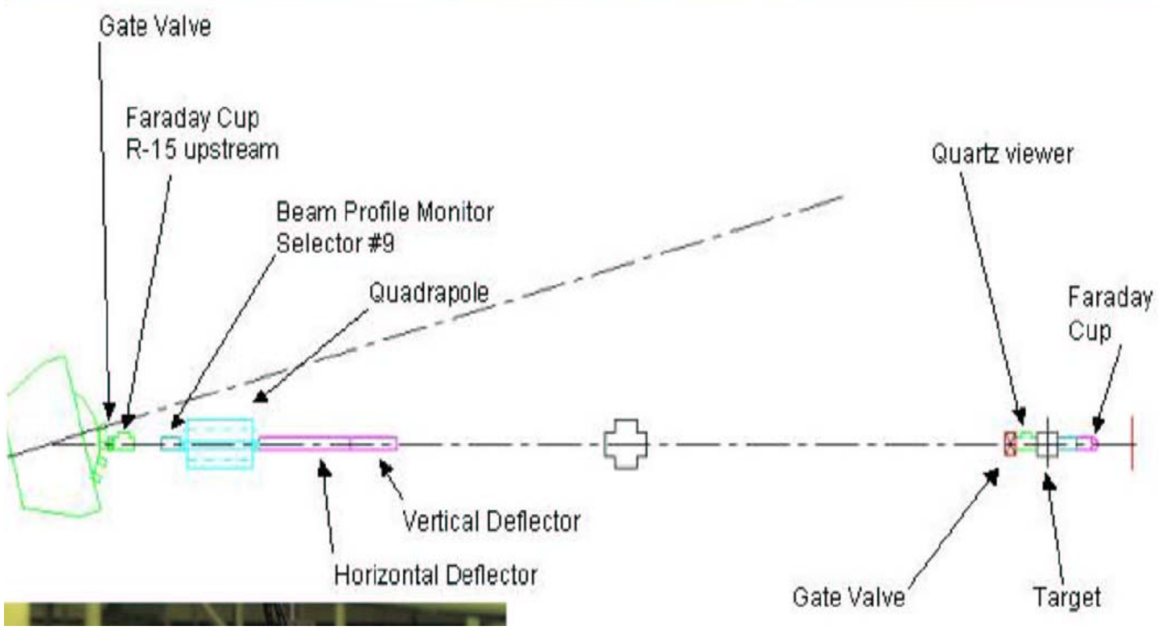
Single guard ring HPK

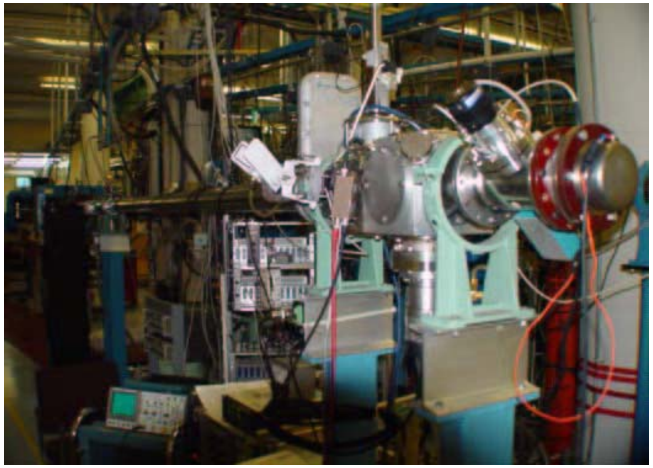


multiple guard ring ELMA

Irradiation on Run IIb silicon sensors

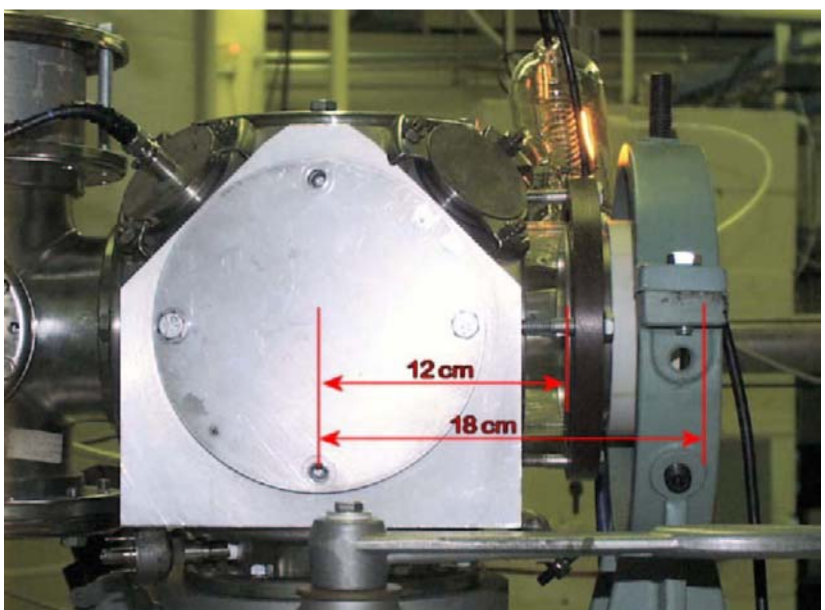
- use beam from 7MV Tandem Van de Graaff (mostly protons at 10 MeV) at James R. Mcdonald Lab at Kansas State University
- beam is rastered over sample using sawtooth pattern electric field
- current measured by Faraday cup/current integrator to 10pC least count
- runs are for fixed amount of charge with beam currents 10-100 nA

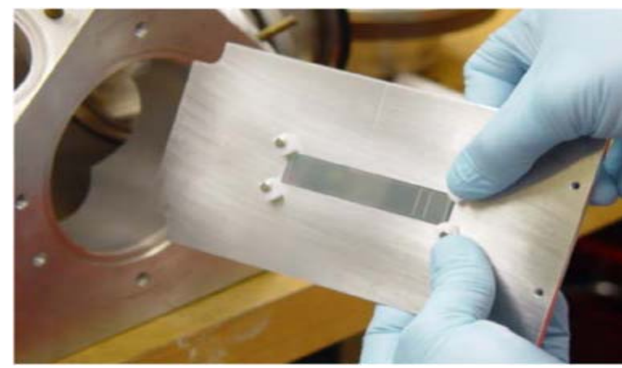


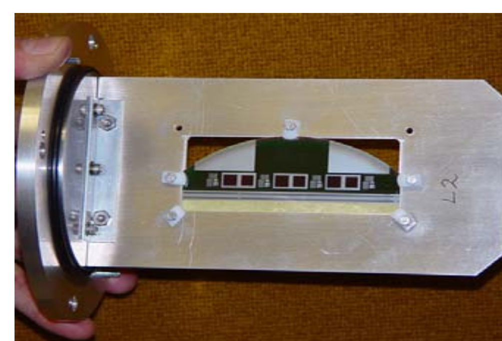


Irradiation on Run IIb silicon sensors

- sensors and test diodes are mounted (unbiased) in vacuum target chamber
- multiple fluence points are taken for sensors, single fluence points for test diodes
- sensors/test diodes annealed at 60°C for 80 minutes, then electrically tested
- long term storage of sensors at -20 °C





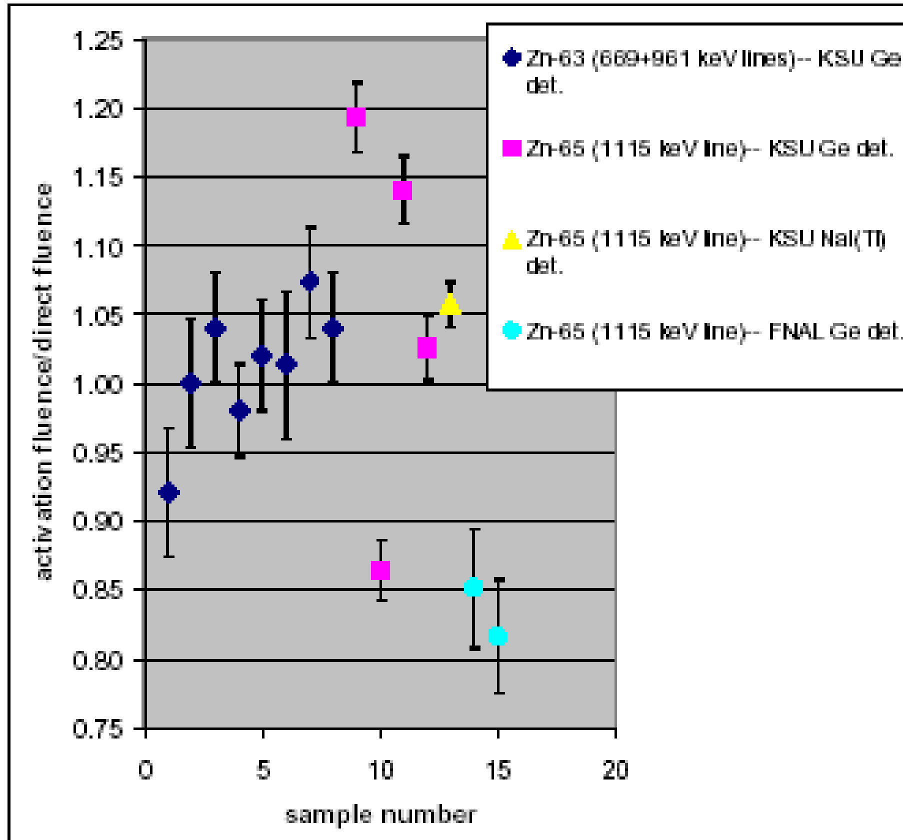


Irradiation on Run IIb silicon sensors

- detailed fluence (=integrated flux) cross checks
- Faraday cup is close behind target
  - only beam passing through samples in Al window is counted
  - acceptance corrections due to multiple Coulomb scattering are small (<10%)
    - built acceptance model by simple GEANT simulation
    - measure ratio of counts at same beam setting for two runs: sensor mounted on target and no sensor mounted
    - uncertainty ~10% -> largest error on fluence
  - Faraday cup cross checked against other cup (<1%)
  - independent fluence cross check by copper activation analysis

Irradiation on Run IIb silicon sensors

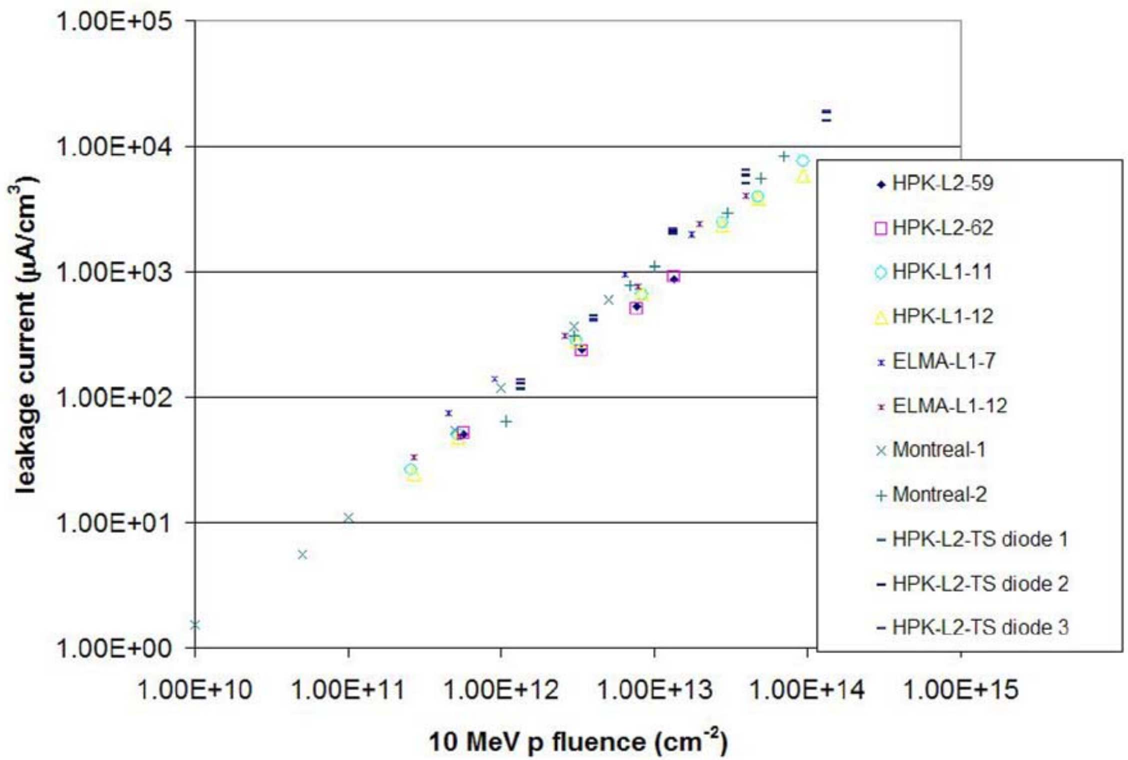
- 1.5 mil natural cooper foils irradiated in same beam with protons to produce Zn-63 (τ=38 min) and Zn-65 (τ=244 days), which β^+ or EC decay with accompanying γ's
- Zn-63 & Zn-65 rates measured at KSU Nuclear reactor Lab using Ge-counters -> agrees with direct fluence measurement to ~10%
- Zn-65 samples measured independently at FNAL -> 18%
- activation analysis are consistent with direct fluence measurements



Results on leakage currents

- best way to present our data is directly in terms of integrated proton fluence, rather than converting to 1 MeV eq. neutron fluence
- in doing this, we compare directly with measurements taken with a similar setup at Montreal (RD48/ROSE Collab., D. Bechevet et al., NIM A479:487-497, 2002)
- a fit to our 10 MeV proton data yields $\alpha_p = 11\cdot10^{-17}$ A·cm
  - approx. independent of sensor type & geometry
  - consistent with RD48 data ($\alpha_p = 10\cdot10^{-17}$ A·cm)

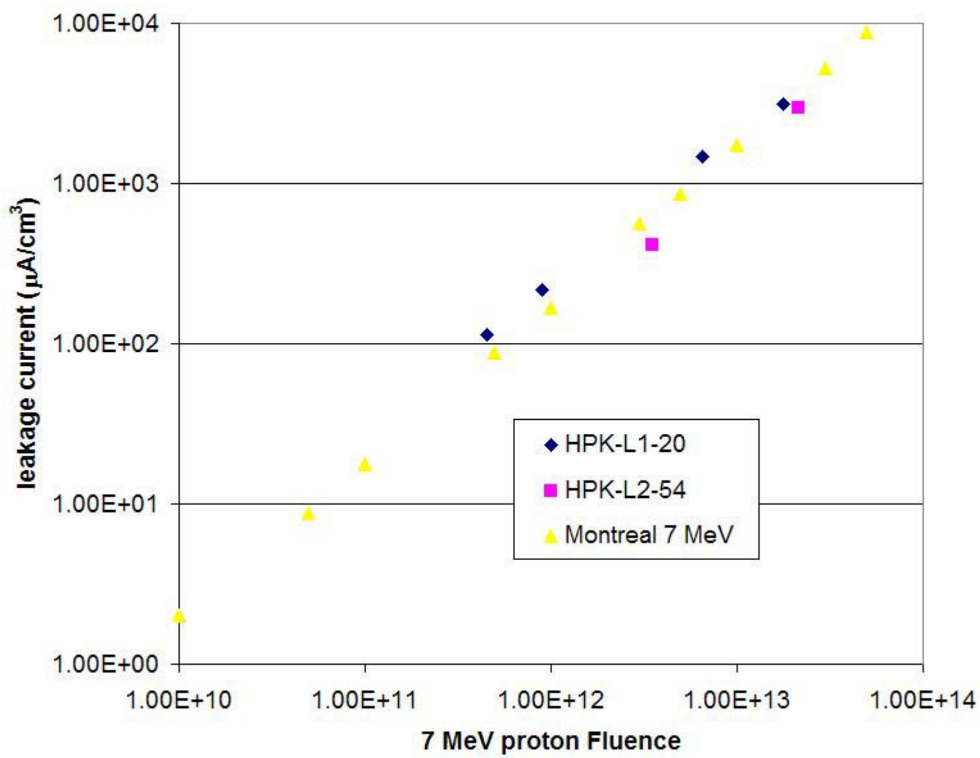
10 MeV p:



Results on leakage currents

- two sensors were exposed to an effective 7 MeV p beam
- α_p = 18·10^{-17} A·cm
- agrees with ROSE data set on 7 MeV (α_p = 17.2·10^{-17} A·cm)

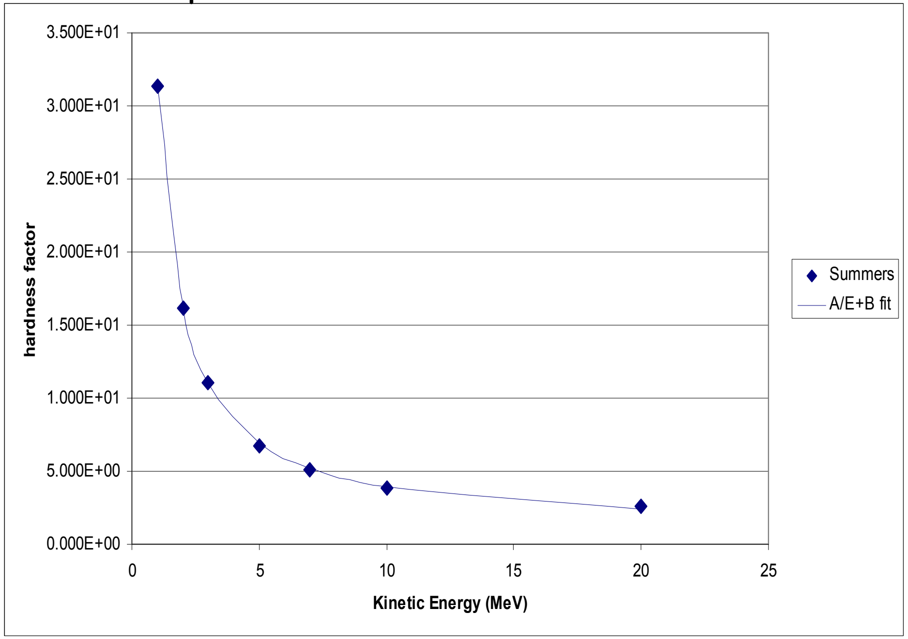
7 MeV p:



Hardness factor k of beam

- estimate equivalent 1 MeV n fluence: $\Phi_n = k \times \Phi_p$ from leakage current rise
- Theoretically:
  - values of k for protons tabulated in Summers et al. (on thin targets only !)
  - 10 MeV protons lose approximately 3.1 MeV in ~300 μm Si
  - calculate effective k: $k_{eff} = 1/\Delta E \times \int k(E) \cdot dE = 4.5$
- Experimentally:
  - $k_{exp} = \alpha_p$ (10 MeV p) / α_n (1 MeV eq. n)
  - $k_{exp} = 2.5$, i.e. ~40% less damage than NIEL scaling predicts
  - for 7 MeV: $k_{exp} = 4$, i.e. similar discrepancy to NIEL prediction (k=7.4)
- Bulk related damage in 7 MeV & 10 MeV p exposure ~40% lower than anticipated by NIEL

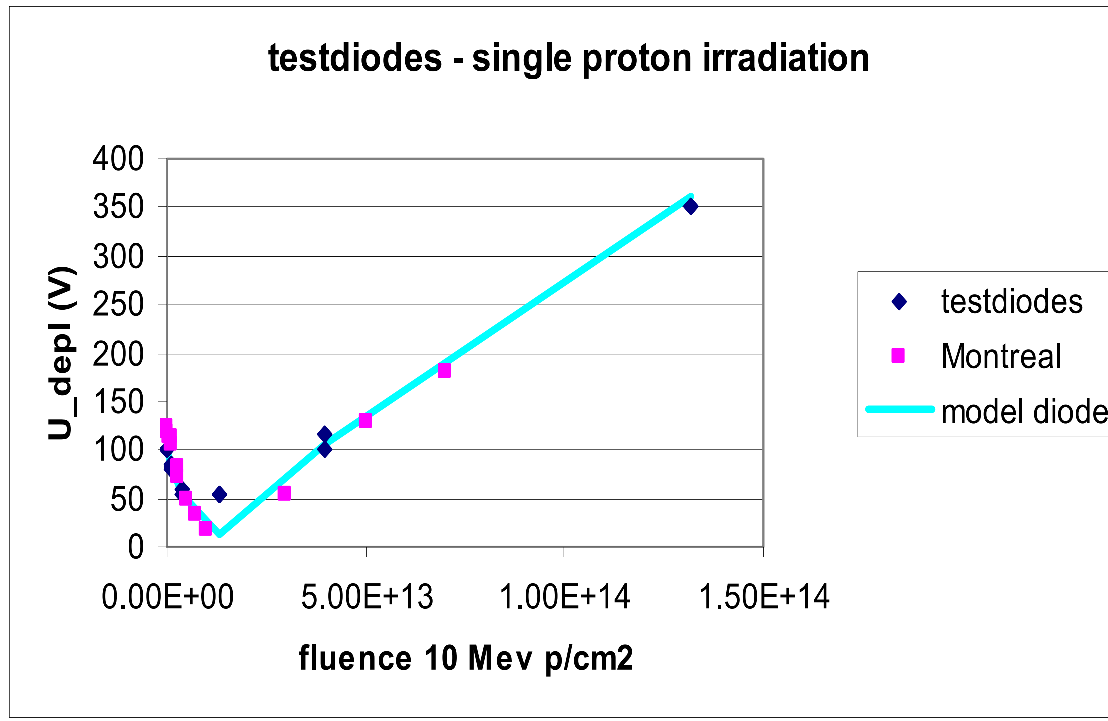
theoretical proton hardness factors based on NIEL:



G.P. Summers et al.: (IEEE NS40 (1993) 1372

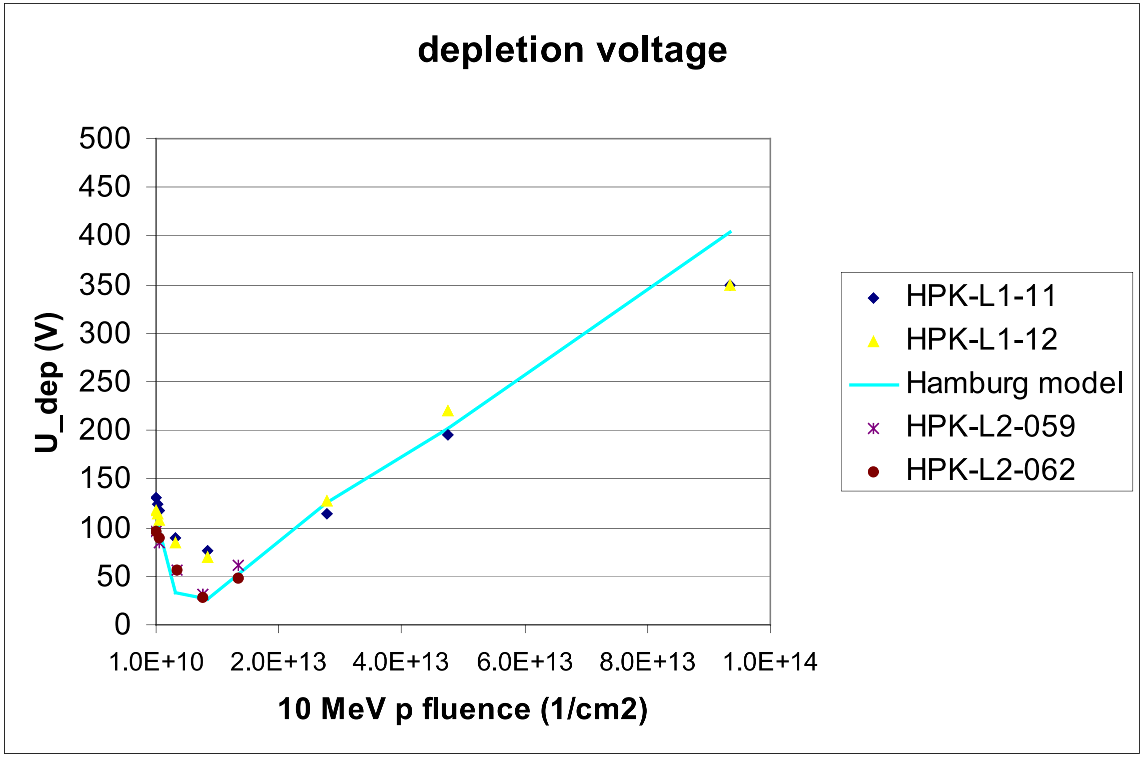
Depletion voltage I

- 5 test diodes from our production wafer lots have been exposed to 10 MeV p single irradiation
- adopt simple parameterization assuming complete donor removal in p-irradiation
- $N_{eff}=N_{eff,0} \cdot \exp(-c \cdot \Phi)-b \cdot \Phi$
  - Values for c, b as in ROSE publication:
    - $c=1.13 \cdot 10^{-13}\ cm^{-2}$
    - $b=3.4 \cdot 10^{-2}\ cm^{-1}$
  - good description up to $1.32 \cdot 10^{14}\ p/cm^2$



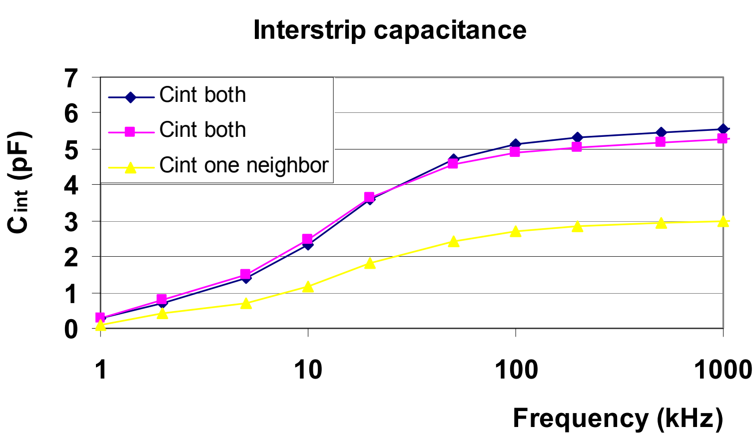
Depletion voltage II

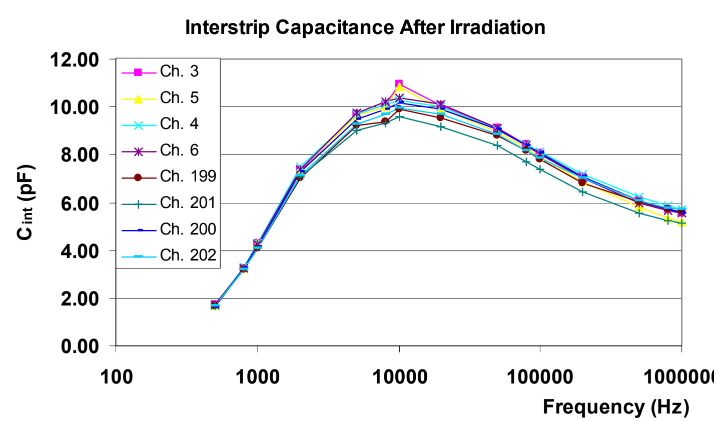
- successive irradiation of sensors compared to 'Hamburg' model taking anneling and reverse annealing towards larger fluences into account
- good agreement to model if measured hardness is taken into account



Other electrical tests:

- few Run IIb prototype sensors were tested after irradiation of up to $1 \cdot 10^{14}$ 10 MeV p/cm^2 for
  - breakdown voltage: no breakdown up to 800V bias
  - coupling capacitors: no change of capacitor value – no additional pinholes
  - implant, polysilicon and interstrip resistances: no indication of resistor value changes
  - interstrip capacitance: increase by 40% (!) at 1 MHZ
  - Total capacitance: 1.1 pF/cm -> 1.5 pF/cm





Conclusions

- Radiation Damage studies on Run IIa silicon ladders
  - indications that useful lifetime is limited to 3.5 fb^{-1} only
  - double-sided double-metal detectors show increased sensitivity to radiation, probably due to PECVD layer
  - onset of micro-discharge noise will limit the maximum bias voltage on ladders
- Radiation Damage studies on Run IIb silicon sensors
  - sensors & test diodes have been irradiated with 7 & 10 MeV protons
  - sensors behave well at doses exceeding the Run IIb expectations
  - observed damage for low energy protons is about 40% smaller than anticipated by NIEL scaling
  - good agreement to data measured by RD48
- While the Run IIb silicon tracker will not be built, we believe its design is sound and our R&D work may be helpful to others