The Bern Cyclotron Proton Irradiation Facility

Joint Annual Meeting of SPS and ÖPG

Armin Fehr

Laboratory for High Energy Physics
University of Bern

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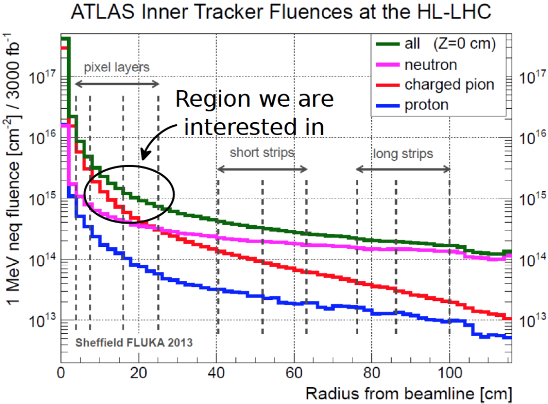
Radiation environment in high luminosity ATLAS

- Develop sensors for high luminosity upgraded Large Hadron Collider experiments → Test sensors for radiation hardness
- Need to perform irradiation tests, precise knowledge of beam characteristics

→ Bern medical cyclotron for proton irradiation



Region we are interested in

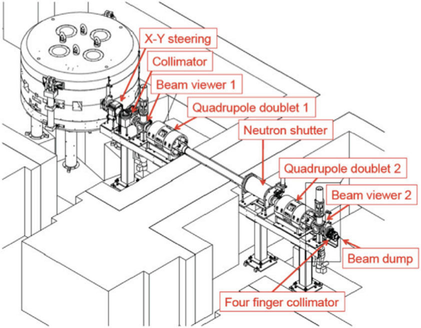
Multi-purpose Bern Cyclotron facility

- Partnership between Bern University Hospital, University of Bern and private investors
- Radioisotope production during the night for PET scanning, research during the day
- Applications for accelerator physics, novel particle detectors, radiation biophysics etc.

Start of operation end of 2012

Facility layout

Regular access to beam area without limiting routine use of cyclotron

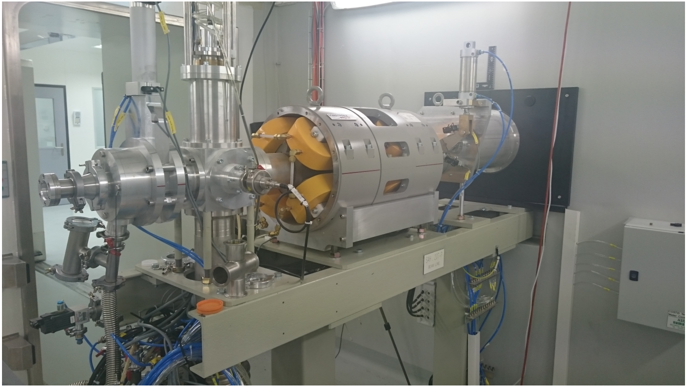


- Beam transfer line from cyclotron to separate bunker for research
- Protection from neutrons by neutron shutter → can enter experimental bunker anytime
- Physics laboratory and workshop for preparation of experiments
- Possibility to remotely connect to computers and experiments in bunker

→ Unique facility layout gives many possible applications

Accelerator and beam characteristics

Energy	(18 ± 0.36) MeV
Current	(1.5 ± 0.5) pA - 150 μA, 8 orders of magnitude!
Transmission efficiency	≥ 95 %
Collimator size	Variable up to 2×2 cm^2
Beam flat within	2×2 cm^2

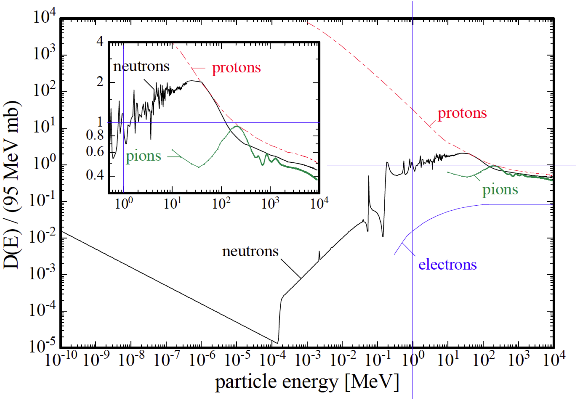


Non-ionizing energy loss (NIEL)

NIEL scaling uses hardness factor κ. Radiation damage is normalized to the damage done by 1 MeV neutrons.

$$\kappa = \frac{1}{D(1\text{MeV neutrons})} \cdot \frac{\int D(E)\Phi(E)dE}{\int \Phi(E)dE} \rightarrow \kappa(18\text{ MeV } p^{+}) = 3.4885$$

D is the damage function, Φ is the spectral fluence



From fluence to dose

- Future Inner Tracker (ITk): fluence $= 1.5 \cdot 10^{15}$ 1 MeV $\mathrm{n_{eq}/cm^2}$ for outermost pixel layer
- How many 18 MeV protons do the same amount of non-ionizing damage?

$$\frac{n_\mathrm{p}}{\mathrm{cm}^2} = \frac{\text{fluence}}{\kappa}$$

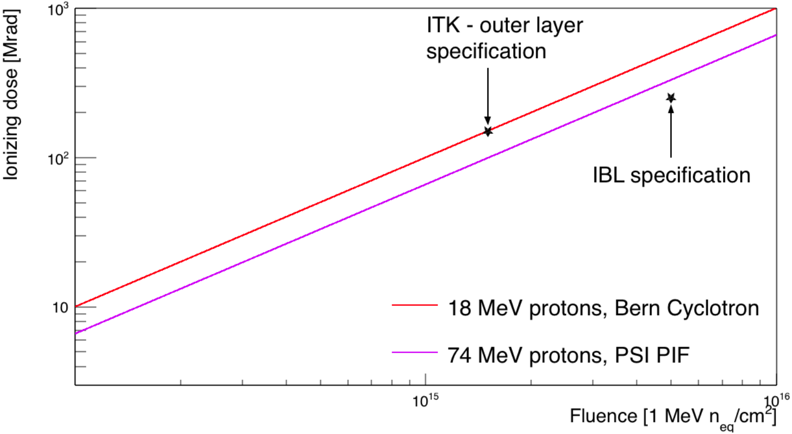
- How about total ionizing dose (TID)?

$$\mathrm{TID[Mrad]} = \frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \cdot \frac{n_\mathrm{p}}{\mathrm{cm}^2} = \frac{1.6 \cdot \frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \cdot \text{fluence}[1\ \mathrm{MeV\ n_{eq}/cm^2}]}{\kappa \cdot 10^{14}}$$

- TID depends on density, energy loss of the particle and κ

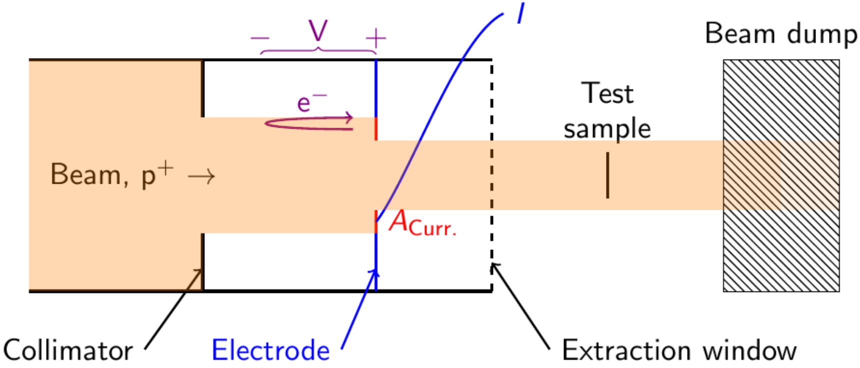
Comparison with other proton irradiation facilities

- Damage done by Bern Cyclotron is very similar to radiation environment in ITk outer layer (ratio ionizing to non-ionizing damage)
- Other differences to consider: Current, availability, flux uncertainty. etc.

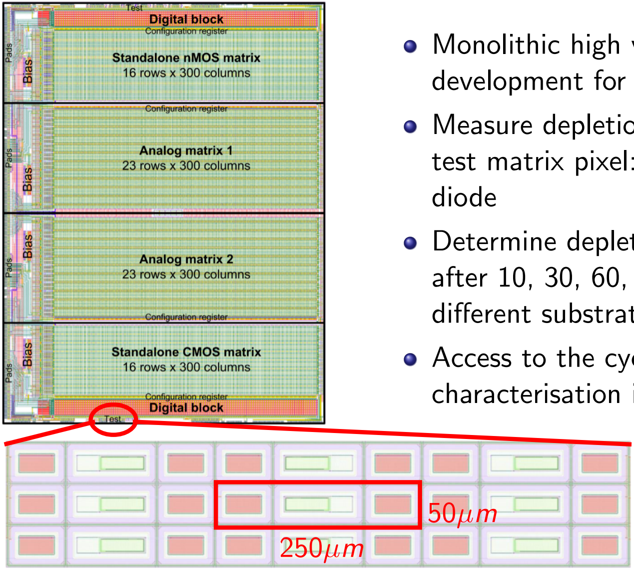


On-line dose monitoring

- Measure current on $A_{\text{Curr.}}$, produced by protons
- Voltage applied to prevent secondary electrons leaving the current measuring plate, would falsify current measurement
- Measure current I → Flux $F = \frac{I}{e}\frac{1}{A_{\text{Curr.}}}$ (if beam flat!)
- On-line beam monitoring system available → control beam flatness



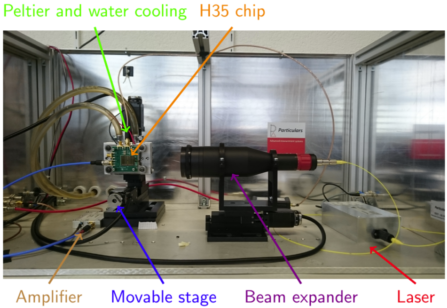
Example irradiation campaign: H35 demonstrator chip

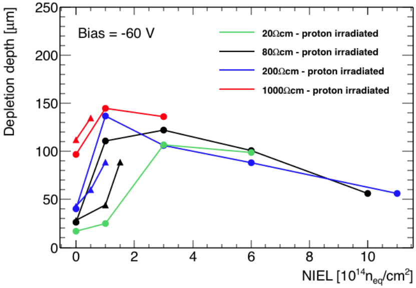


- Monolithic high voltage CMOS development for ITk
- Measure depletion depth using central test matrix pixel: No electronics, only diode
- Determine depletion depth before and after 10, 30, 60, 100, 150 Mrad, four different substrate resistivities
- Access to the cyclotron every week, characterisation in between

Example irradiation campaign: Characterisation with TCT

- Using Transient Current Technique to measure depletion depth (see talk of Claudia Merlassino)
- All steps for radiation hardness research in house!





Conclusions and outlook

- Regular irradiation with wide range of currents down to pA
- Operating test chip during irradiation
- Precise dose monitoring and well known beam characteristics
- Pixel development group at University of Bern is open for collaboration (don't hesitate to contact us)

Improvements:

- Mount samples on movable stage
  - Irradiate larger areas or multiple samples after each other without opening bunker
- Cooling of samples during irradiation (see Thomas Weston's talk)
  - Radiation damage on silicon depends on temperature
    → replicate ATLAS conditions

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Questions?

Literature about Bern Cyclotron

- Saverio Braccini.
  Particle accelerators and detectors for medical diagnostics and therapy.
  arXiv preprint arXiv:1601.06820, 2016.

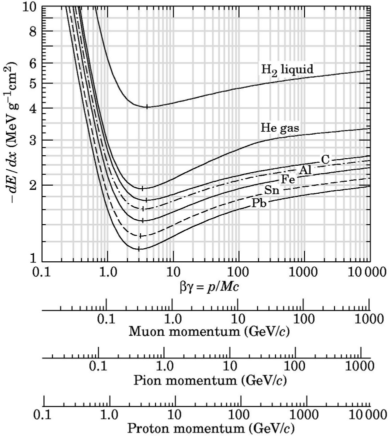
- Martin Auger, Saverio Braccini, Antonio Ereditato, Konrad Pawel Nesteruk, and Paola Scampoli.
  Low current performance of the bern medical cyclotron down to the pa range.
  Measurement Science and Technology, 26(9):094006, 2015.

- Saverio Braccini, A Ereditato, Paola Scampoli, and Konrade von Bremen.
  The new bern cyclotron laboratory for radioisotope production and research.
  In *Proceedings of the Second International Particle Accelerator Conference–IPAC2011 (3618). San Sebastian, Spain*, 2011.

Particle interaction with matter: Charged particles

- Charged particles loose energy mainly by ionization, described by Bethe-Bloch formula in the range $0.1 < \beta\gamma < 1000$

$$-\langle\frac{\mathrm{d}E}{\mathrm{d}x}\rangle = \frac{4\pi r_e^2 m_e c^2 N_A Z z^2 \rho}{A\beta^2}\left(\frac{1}{2} ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right) - \frac{C}{Z}\right)$$

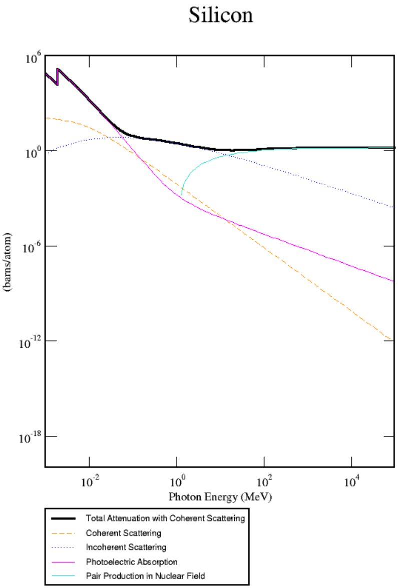


- Energy loss depending on material (Z,A,ρ), energy of particle ($\beta\gamma$), velocity of particle (β) and charge of particle z
- Radiative losses for $\beta\gamma \geq 10^4 \rightarrow$ big $\mathrm{d}E/\mathrm{d}x$
- Minimum of 1-2 $\frac{\text{MeV}}{\rho\text{cm}}$ at $\beta\gamma \approx 3 \rightarrow$ Minimum ionizing particle (MIP)

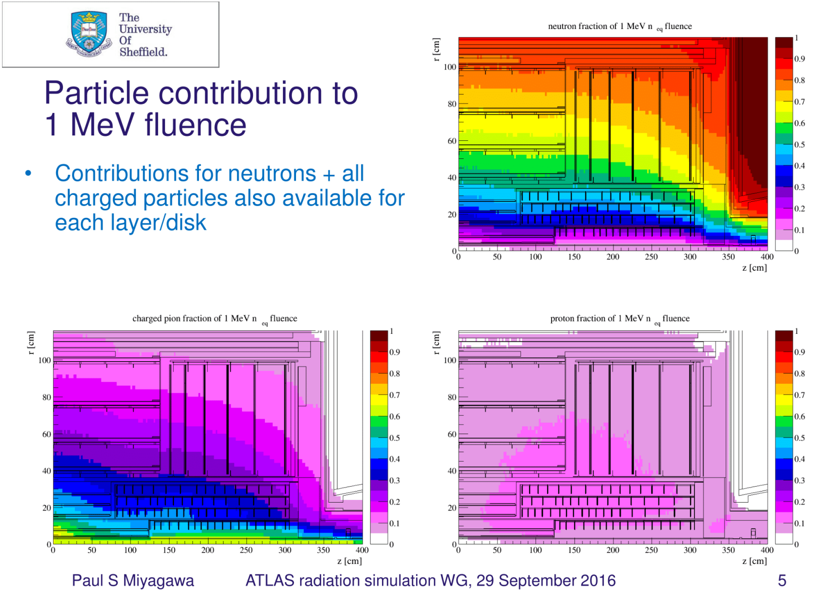
Particle interaction with matter: Photons

- Photoelectric effect: Dominant at $E \leq 0.1$ MeV, $\propto Z$
- Rayleigh scattering (coherent scattering): Small σ, $\propto Z$
- Compton effect (incoherent scattering): Dominant for 0.1 MeV $\leq E \leq 100$ MeV, $\propto Z$
- Pair production: Dominant for $E \geq 100$ MeV, threshold at $2m_e = 1.022$ MeV

σ small for high energetic photons → only rarely detected in silicon pixel detectors, would need lot of matter (e.g Pb, high ρ and Z)



HL-LHC particle radiation environment



The University Of Sheffield.

Particle contribution to 1 MeV fluence

- Contributions for neutrons + all charged particles also available for each layer/disk

Paul S Miyagawa ATLAS radiation simulation WG, 29 September 2016 5

Depletion depth

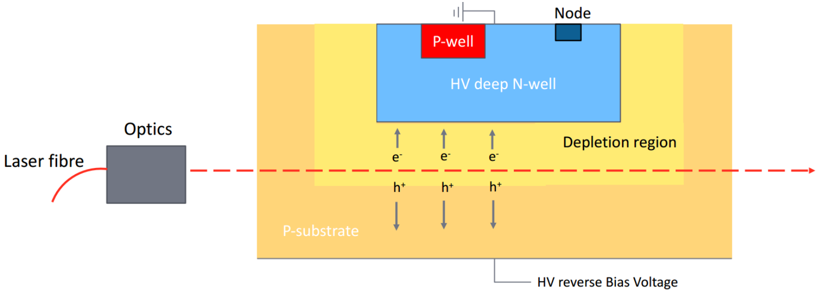
- Ionizing particles generate e^--h^+ pairs along track in depletion region
- e^- and h^+ drift towards electrodes due to E-field: $\vec{v_{\mathrm{h,e}}} = \mu_{\mathrm{h,e}}(|\vec{E}|)\vec{E}$, with $\mu_{\mathrm{h,e}}$ being the mobility of the hole or electron
- Typically, $\vec{v}_{\mathrm{e}} \sim 10 - 100\ \mu\mathrm{m/ns}$
- Depletion depth d depends on bias voltage V, acceptor and donor concentration (N_{A} and N_{D}) and the relative permittivity of silicon ϵ_{Si}
  $$d = \sqrt{\frac{2\epsilon_{\mathrm{Si}}\epsilon_0(N_{\mathrm{A}} + N_{\mathrm{D}})}{eN_{\mathrm{A}}N_{\mathrm{D}}}(V_{\mathrm{bi}} + V)} \overset{N_{\mathrm{D}} >> N_{\mathrm{A}}}{\approx} \sqrt{\frac{2\epsilon_{\mathrm{Si}}\epsilon_0}{eN_{\mathrm{A}}}(V_{\mathrm{bi}} + V)}$$
- This can also be expressed in terms of resistivity $\rho = \frac{1}{e\mu N_{\mathrm{A}}}$
  $$d = \sqrt{2\epsilon_{\mathrm{Si}}\epsilon_0\mu\rho(V_{\mathrm{bi}} + V)}$$
- This description only holds in the planar geometry case (length of electrode comparable to thickness of sensor, field lines have to be orthogonal to sensor edge)

Signal seen by silicon pixel detector

How many e^--h^+ pairs are produced by a MIP in silicon?

- Take $-\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} = 1.661$ MeV cm^2/g (PSTAR)
- For $\rho_{\mathrm{Si}} = 2.336$ g/cm^3, we get $\frac{dE}{dx} = -3.880$ MeV/cm
- Assume a depletion depth of 100 μm and the MIP not stopping in the silicon
- Average energy needed to produce an e^--h^+ pair is 3.6 eV
- We get $N_e = \frac{3.880 \text{ MeV/cm} \cdot 100\ \mu\text{m}}{3.6 \text{ eV}} \approx 10778$ e$^-$ being produced by the crossing of one MIP
- This charge signal has to collected, amplified and digitized

Functioning principle of edge TCT

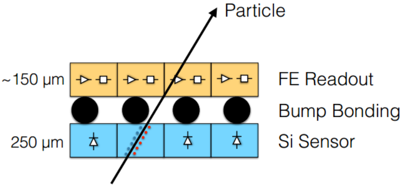


Courtesy of figure: Thomas Weston

- IR Laser produces electron-hole pairs in the sensor
- Signal is MIP like
- TCT measures the induced charge
- Characterize depletion region of detector

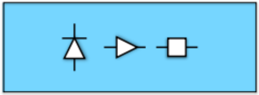
Hybrid vs. monolithic sensor

Hybrid Pixel (current technology)



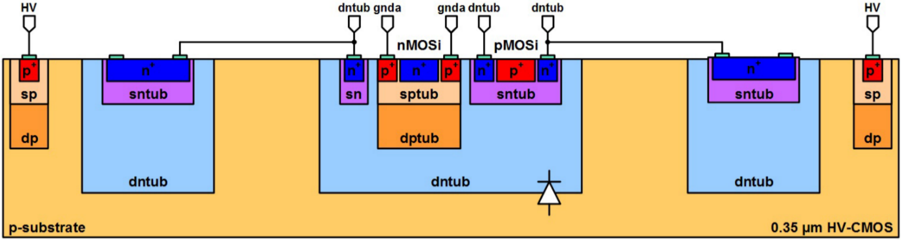
- Silicon Sensor + Front end (FE) read out
- Small Signal read by FE
- High production cost

Monolithic Pixel (development)



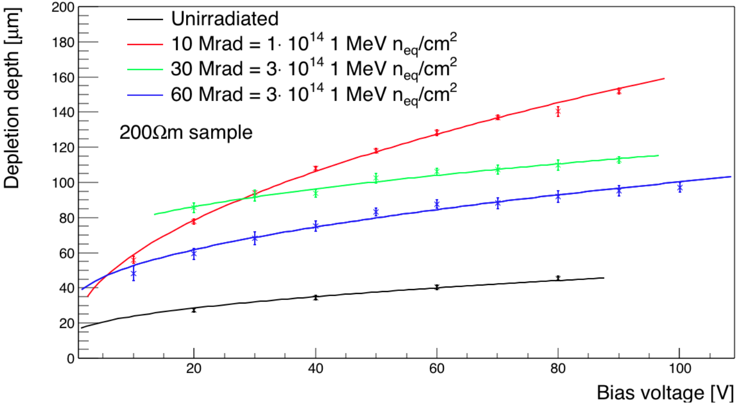
- Charge collection, amplification of signal and digitalisation all in one
- Small pitch

Sub-pixel structure of H35



http://iopscience.iop.org/article/10.1088/1748-0221/11/01/C01012

Evolution of depletion depth with bias voltage after irradiation



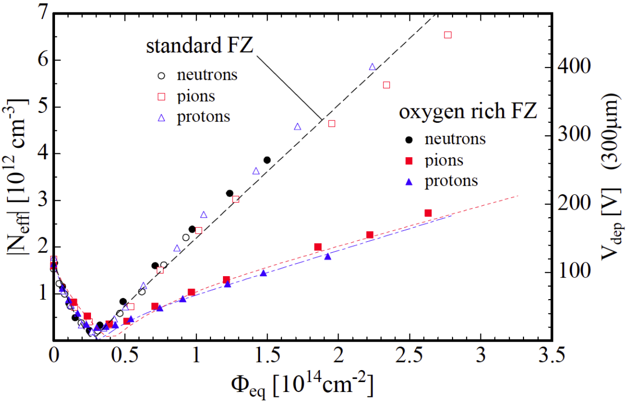
- Depletion depth increases for small dose, goes down again for high dose due to acceptor removal

Radiation damage: Impact of defects

- Create additional energy levels
  - Middle of band gap: Recombination-generation centers → increase of reverse-bias current (leakage current)
  - Close to bands: Trapping centers for e^- and h^+ → signal charge is trapped and delayed, reduction of signal, trapping $\propto \Phi$
- Both recombination and trapping change the effective doping, as free charge carrieers are removed → Higher depletion voltage
- Exponential dependence of leakage current on temperature → radiation damage also depending on temperature

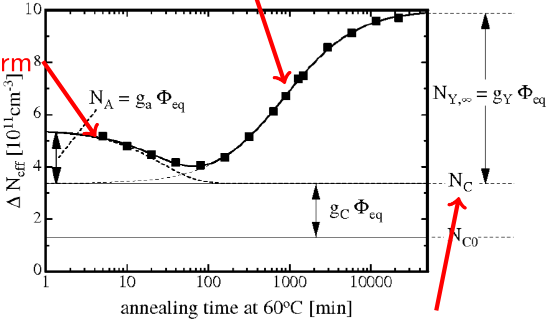
Depletion depth evolution

- Decrease in effective doping concentration leads to decrease in depletion voltage (= increase of depletion depth) and vice versa
- Not monotonic increasing
- Also seen in our irradiation campaign of H35



Radiation damage: Annealing

- Two types of annealing: Short-term or beneficial and reverse annealing
- The stable damage is at N_C



Reverse annealing

Short-term

Stable damage

Fig. 2.25. Typical annealing behavior of the irradiation induced changes of the effective doping concentration ΔN_{eff} at a temperature of 60° C after irradiation with a fluence of $1.4 \cdot 10^{13}$ cm^{-2} [105]