Irradiations in Karlsruhe

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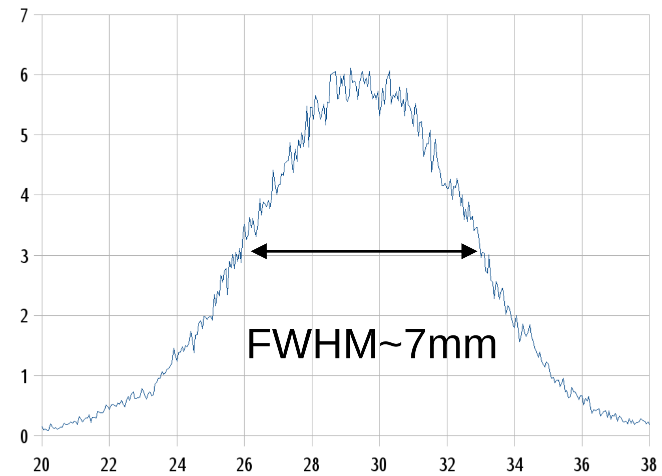
The Karlsruhe Proton Cyclotron KAZ

- Run by private company ZAG
- We are customers and have to pay per beam time
- Proton energy at extraction: 25.3MeV
- Typical proton current: 1.5µA
- Temperature in box: ~ -40 C
- Beam spot ~ 7mm (varying)
- Flux ~ 2.5e13 p/(s·cm²)



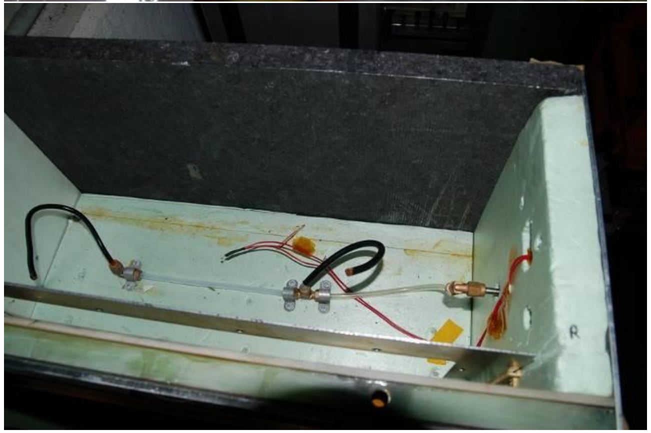
Sample box on XY-stage with beam line

Man placing LN_2 box

Control room

Sample Box

- Insulated box, cooled by cold nitrogen gas
- Goose-necks lead gas to individual samples
- Graphite plate to stop protons at the back
- Window with two Kapton foils for insulation
- Samples glued on Kapton tape fixed to Al-frames, which can be fixed in the box
- Mounted on movable XY-stage since beam spot does not cover samples size
- New box in preparation to hold 3 layers of samples
- Box positions during scans can be logged
- On-line measurement of beam current is planned



Restrictions

- Gluing of samples with Kapton tape limits the maximum fluence in one session to 5e15neq/cm², since silicone glue gets brittle.
  - You might have remnants on the samples, which should be removable with acetone, isopropanol or a sticky tape
  - Please report any problems with this!
  - Yesterday I heard that Freiburg had problems removing it…

- We cannot book irradiation time weeks before.
  - On Mondays the plan of the week is made and if there is a free slot we can get it
  - Usually, we can get one session (~5h) per week
- Nitrogen for cooling lasts for about 6 hours irradiation
- Materials possibly only silicon with aluminum…

Choice of Materials

- In general, metals are bad!
- For 25MeV protons Al is fine since activation of Na-22 starts at higher energies
- In general, at test activation is a good idea
- During activation tests we had a surprise:
  Polyamide screws are bad as well! With $F=2e15 n_{eq}/cm^2$:
  - Be-7 ($t_{1/2}$=270d): 2.2kBq, 24.4kBq/g
  - Limits: 1e4kBq, 1kBq/g
  - Have to wait 5 x $t_{1/2}$ = 270days !

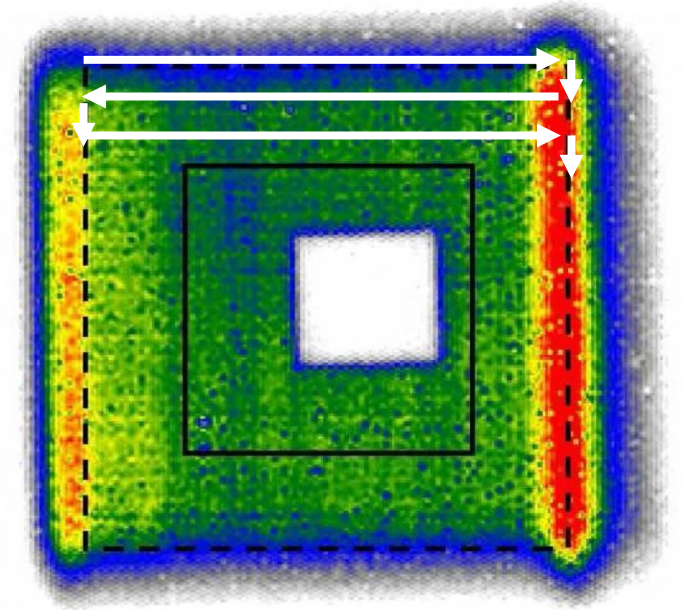
- The specific activity can be reduced if there is other material, which is not activated on the same sample
- And the limits only hold if we want the samples to be freely handled
- Sending active stuff at minimal effort is possible according UN2910, which allows <5 µSv/h at the surface of a container (some paperwork, shipping costs ~100.-, an institute qualified to receive radioactive samples)
- We definitely prefer the radioactive FREE shipment !!!

Scanning Procedure

- Samples are scanned in 1mm spaced rows
- Edge regions are inhomogeneous and a margin of ~1cm is used
- Proton fluence is calculated by:

$$F_{est} = n_{scan} \cdot \frac{I_p}{q_{el} \cdot v_x \cdot \Delta y}$$

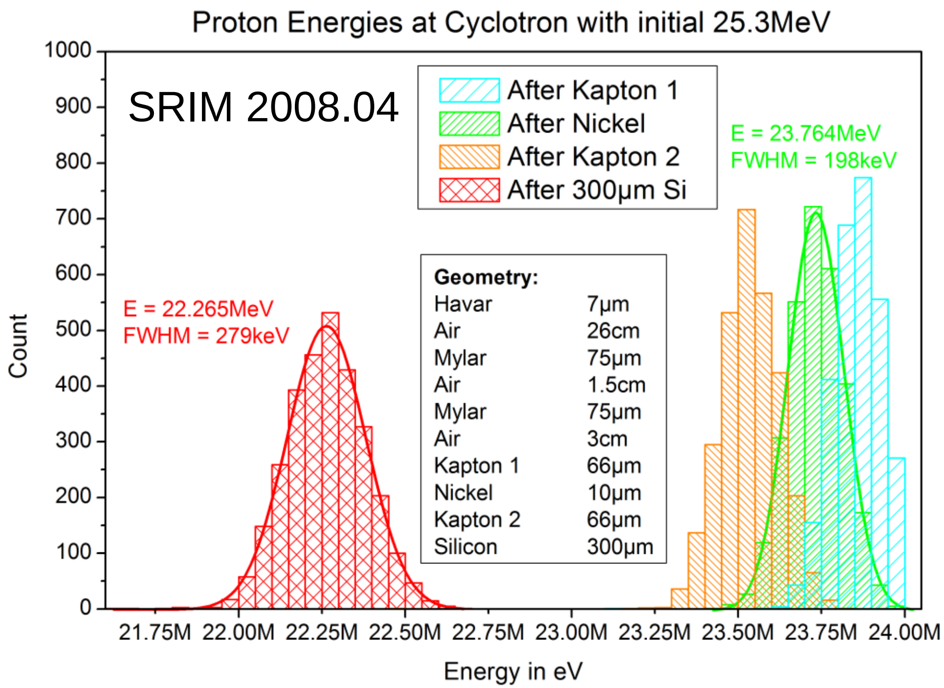
- The proton current I_P is always measured at the last beam stop
- At the nominal values of I_P=1.5µA and v_x=115mm/s we generate 1.5e13n_{eq}/cm² per scan



Autoradiographic image of a large Ni-foil scanned in the described procedure. The white area is a cut out for further dosimetry.

Energy at Target

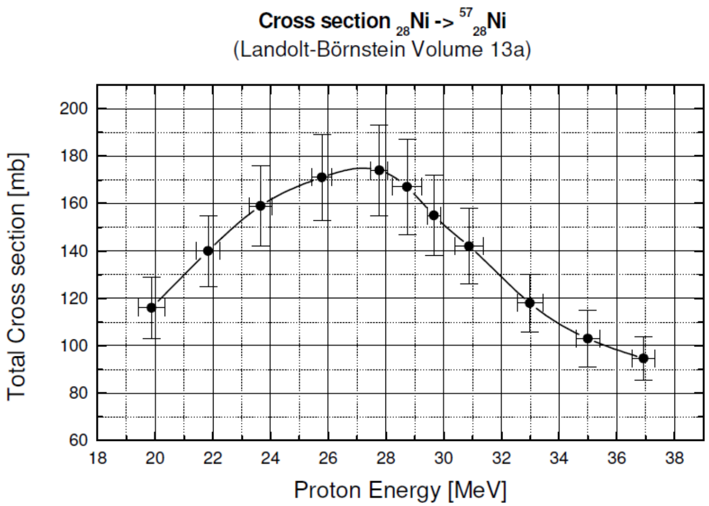
- 25.3MeV is the energy in the beam line
- Protons have to pass several materials until they hit the samples
- SRIM gives us a proton energy entering the samples of about 23.8MeV and on average in the sample: **22.9MeV**
- Samples covered by Nickel foils see lower energy ~22.8MeV



Dosimetry

- For dosimetry we use Nickel foils and the specific activity of the Ni-57 isotope ($F_{Ni} = k_{Ni} \cdot a$)
- Two independent calibration measurements gave similar results:
  - Single spot on 4 stacked foils (0.5A, 20sec): k_{Ni}=(0.80 0.05)e12 p/cm² mg/Bq
  - Scanned area on 4 stacked foils (1.5A, 433sec): k_{Ni}=(0.81 0.02)e12 p/cm² mg/Bq
- Most critical is the knowledge of the beam current, for which we have to trust the measurement at the beam stop…
- Ni-foils are cut, weighted and placed in front(!) of the samples, since Ni-57 cross-section is very sensitive to energy
- Activation is measured with a Ge-spectrometer at ZAG
- Errors are composed of:

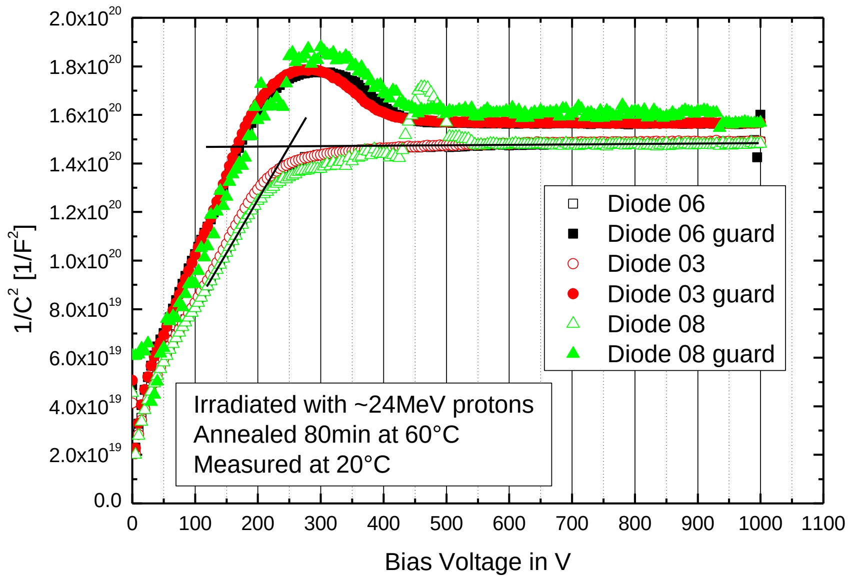
$$\frac{\Delta F}{F} = \left|\frac{\Delta k_{Ni}}{k_{Ni}}\right| + \left|\frac{\Delta A}{A}\right| + \left|-\frac{\Delta m}{2m}\right| = 2.5\% + 10\% + 1.25\% = 13.75\%$$

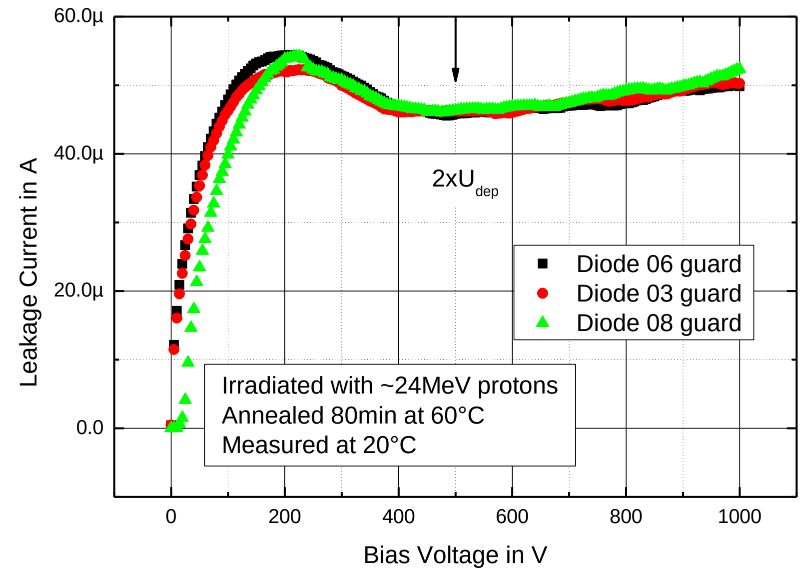


Calibration with Diodes

- 3 ELMA diodes from HH
  - Diode 03:
    U_{dep} = 44V, I_{dep} = 0.2nA, I(2*U_{dep})= 5nA, V=0.25cm^2 x 374µm = 9.36e-3cm^3
  - Diode 06:
    U_{dep} = 46V, I_{dep} = 2nA, I(2*U_{dep})= 5nA, V=0.25cm^2 x 375µm = 9.37e-3cm^3
  - Diode 08:
    U_{dep} = 45V, I_{dep} = 0.2nA, I(2*U_{dep})= 0.4nA, V=0.25cm^2 x 374µm = 9.36e-3cm^3
- Irradiation with I_{beam} =1.04µA, v_x=115 mm/s, n_{scans}=5
  - **F_{est} = (0.56   0.06)e14 p/cm^2**
- Ni-foils:
  - **F_{Ni} = (0.60   0.07)e14 p/cm^2**

Calibration with Diodes

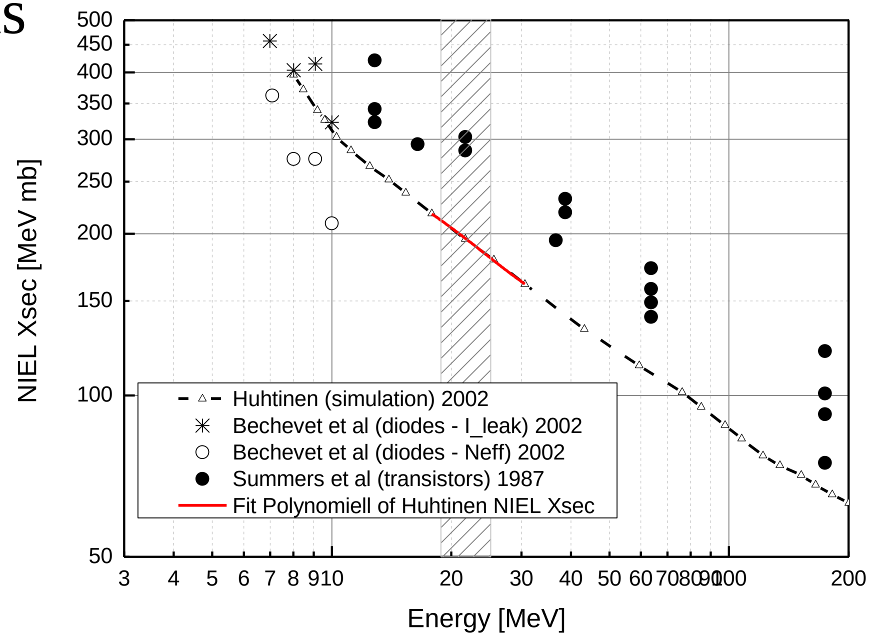




- Specific leakage currents after irradiation:
  - Diode 03: I(2xU_{dep}) = 46.2µA, ΔI/V = 4.925e-3 A/cm³
  - Diode 06: I(2xU_{dep}) = 45.8µA, ΔI/V = 4.888e-3 A/cm³
  - Diode 08: I(2xU_{dep}) = 46.3µA, ΔI/V = 4.947e-3 A/cm³
- Including a 1 C error for temperature measurement we get ΔI/V = (4.9 0.5)e-3 A/cm³
- And finally with α = 3.99 0.3e-17 A/cm² at 20 C after annealing for 80min at 60 C: $\mathbf{F_{diode}}$ = (4.9 0.5)e-3 A/cm³ / α = **(1.23 0.22)e14 n_{eq}/cm²**

Hardness Factor κ

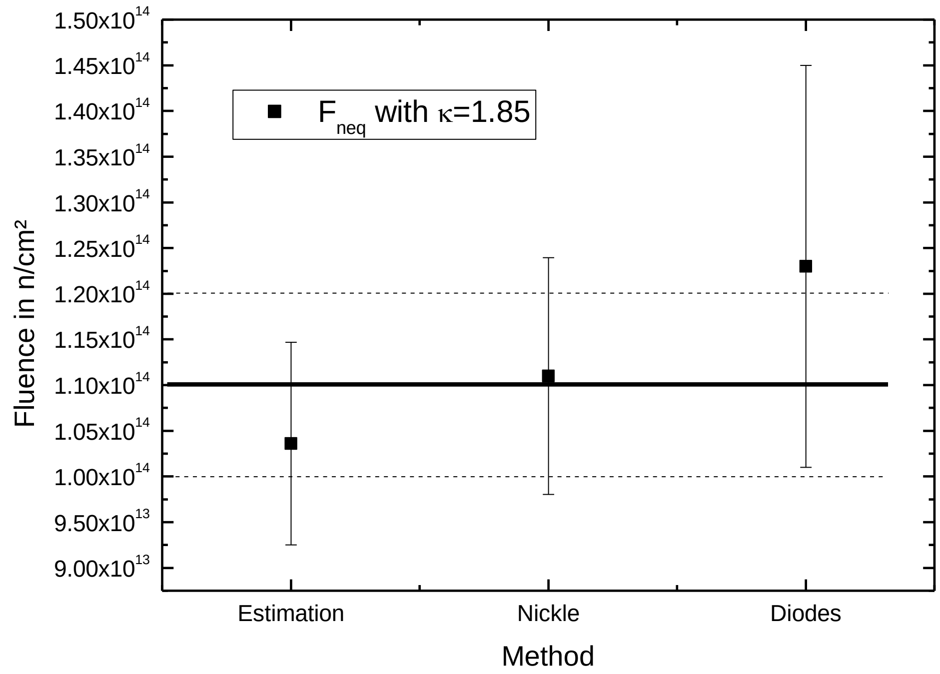
- The hardness factor could be derived by
  $\kappa = F_{diode}/F_{Ni}$ = **2.05 0.61**
- Previous assumption was **1.85** for **26MeV** protons
- Hardness factor was derived from simulated NIEL data by Huhtinen[1]
- Assuming about 22.9 MeV protons on average in the sample, we get **κ = 2.00 ??**
- Alternative measurements of NIEL show quite a spread…



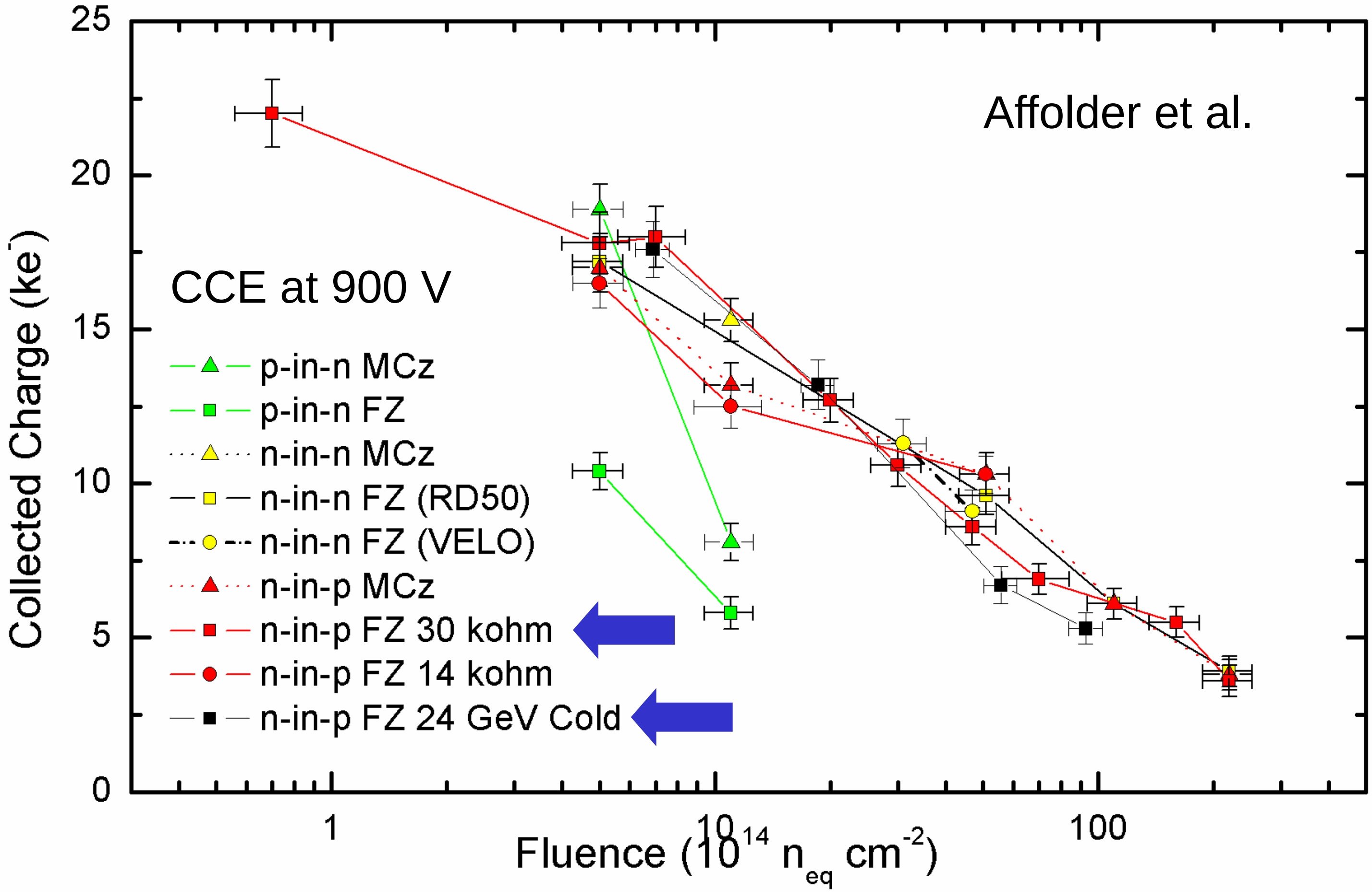
[1] M. Huhtinen, "Simulation of non-ionising energy loss and defect formation in silicon", NIM A 491 (2002) 194-215

Considering the Errors

- With the used value of 1.85 one still gets an agreement of the equivalent fluence from the different methods considering the errors !
- Considering the nice agreement of measured hardness factor and derived hardness factor from NIEL simulation one could claim the hardness factor for our protons to be **more like 2.0** (+10% to prev. value).
- In general, the stated fluence is **not better than 20% !**



Comparison by Toni Affolder



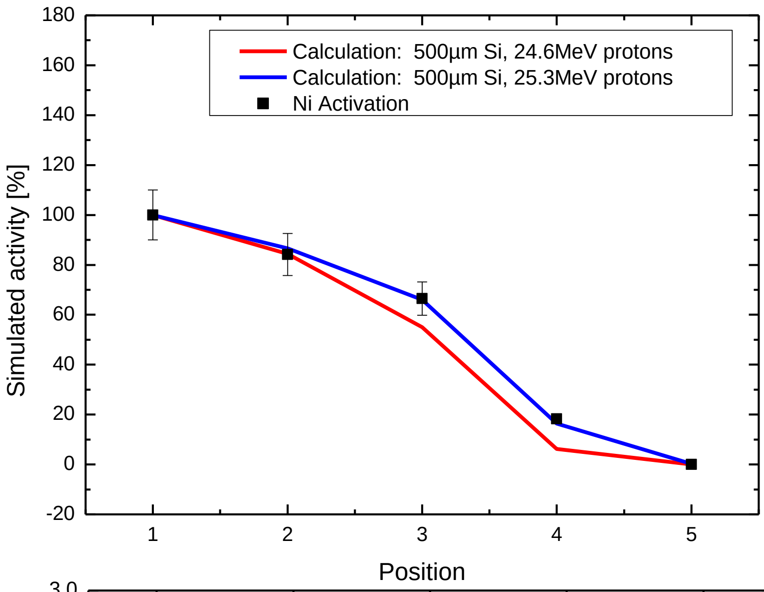
All samples irradiated in Karlsruhe except black squares, which are chilled irradiations at CERN PS on n-in-p FZ 30 kΩ pieces.

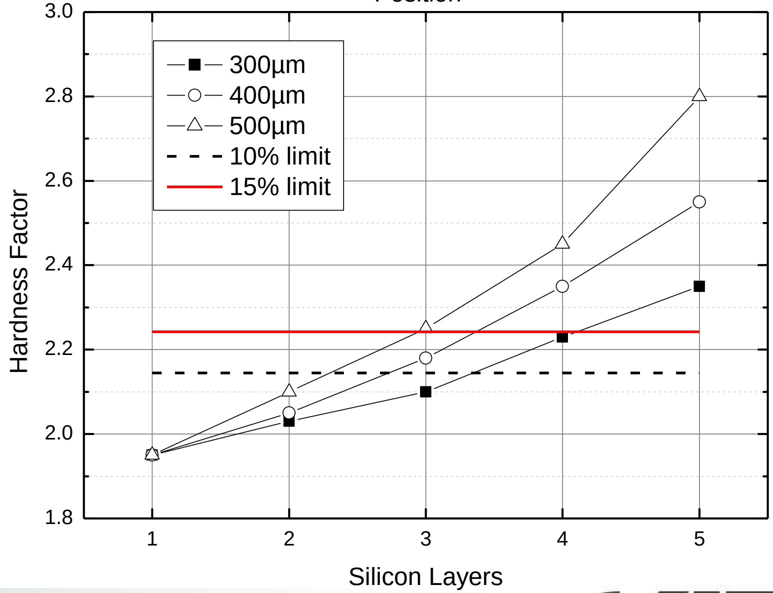
Good agreement!

NIEL is assumed not to be violated for protons with different energies and FZ material…

Stacks of Si-samples

- Activation of Ni-foils between Si-layers taken to verify simulation of energy loss
- Simulation applied to stacks of Si-samples of different thickness
- κ(E) taken from Huhtinen
- Result shows that **three** layers of 300µm Si will get different fluences within 10%, which is acceptable. More layers is not recommended
- An analysis of diode leakage currents is ongoing…





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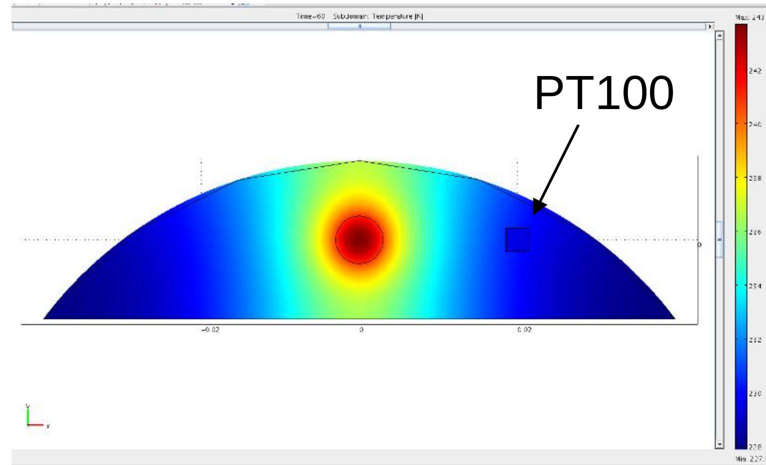
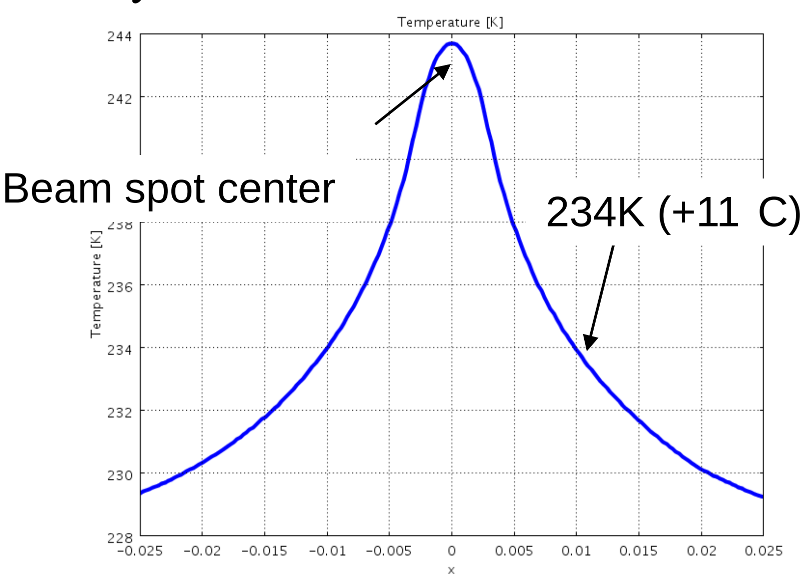
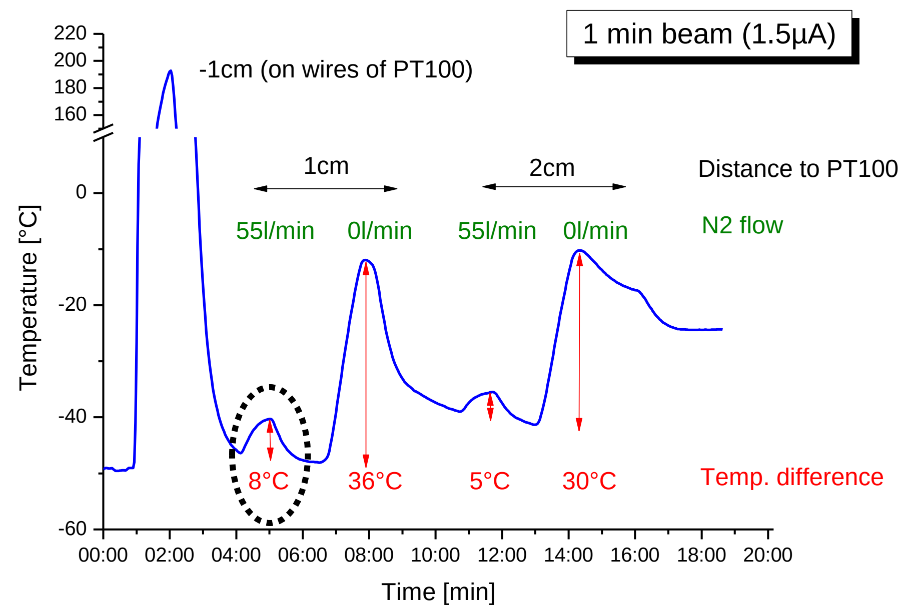
Temperature during Irradiation

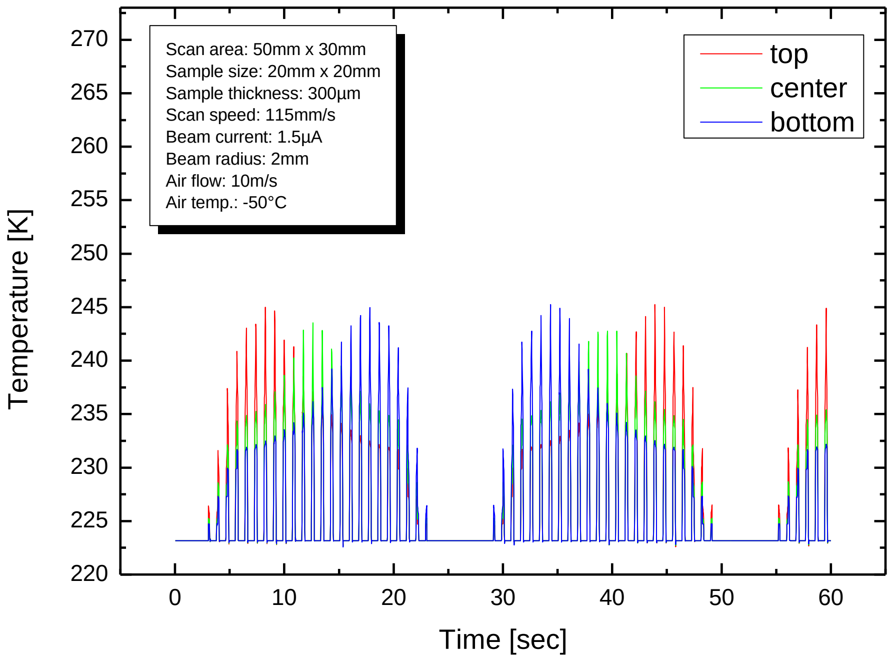
- T at beam spot cannot be directly measured, since protons influence PT100 signal
- PT100 glued on halfmoon and beam pointed to a position at a distance of 1-2 cm
- N_2 flow usually kept > 50 l/min
- Now a FEM simulation is performed to reproduce the measured behavior (dashed circle)
- ΔT of ~10 C @ 1cm could be reproduced with simulated air flow of 10m/s!
- This flow parameter was taken for the next analysis…



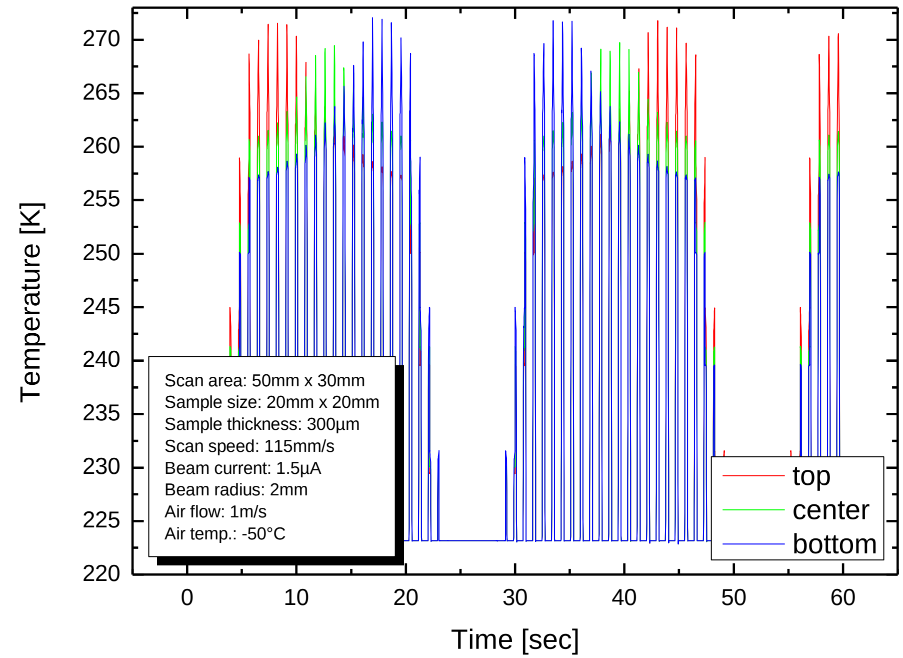




Sample Temperature during Scan

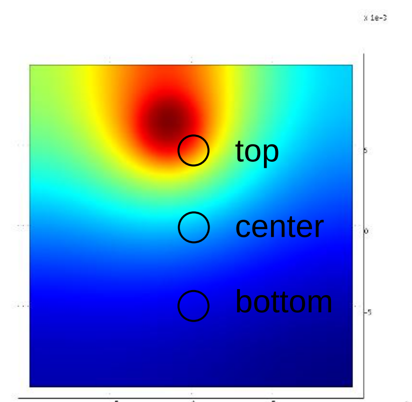


Air flow: 10m/s



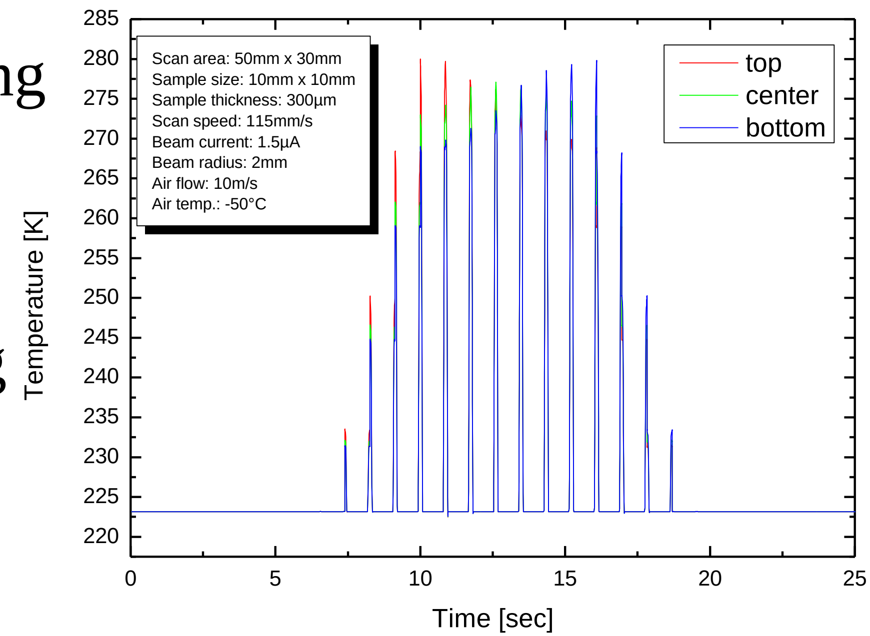
Air flow: 1m/s

- 20mm x 20mm piece of 300µm Si was scanned on area of 50mm x 30mm with the nominal beam parameters
- Local temperatures stay below 0 C even for small air flow
- Larger structures no problem, since surface big enough to get rid of the heat
- What happens with small diodes ?



Temperature on Small Diode

- Small mass cannot absorb the energy and small surface cannot get rid of it fast enough, so that we reach temperatures up to 10 C during irradiation
- The time spent at high temperature is the time when the beam hits the sample
- With the flux of about $2.5e13 p/(s \cdot cm^2)$, one would spend about 20 seconds at 10 C for $1e15 n_{eq}/cm^2$
- That would still be a small annealing effect if any
- But since the air flow conditions are not well controlled, there is a change for annealing effects during irradiation for small samples



Publications with Samples from KAZ

With participation of our group:

A. Dierlamm, "Studies on the Radiation Hardness of Silicon Sensors", IEKP, Univ. Karlsruhe, 2003, IEKP-KA/2003-23

A. Furgeri, "Qualitätskontrolle und Bestrahlungsstudien an CMS Siliziumstreifensensoren", IEKP, Univ. Karlsruhe, 2005, IEKP-KA/2005-1

A. T. Aghdiri, "*Entwicklung für Bestrahlungen am Karlsruher Kompaktzyklotron und erste Tests des Weltraumdetektors AMS-02 mit kosmischer Strahlung*", IEKP, Univ. Karlsruhe, 2008, IEKP-KA/2008-02

Th.Liamsuwan, "Untersuchung zur Strahlenhärte von Magnetic Czochralski-Siliziumstreifensensoren", IEKP, Univ. Karlsruhe, 2008, IEKP-KA/2008-07

Ch. Rühle, "Entwicklung eines schnellen Auslesesystems für Diamantstrahlmonitore am CMS-Experiment", IEKP, Univ. Karlsruhe, 2009, IEKP-KA/2009-11

M. Neuland, "Untersuchungen der Kenngrößen von hochbestrahlten Magnetic-Czochralski-Siliziumstreifensensoren im Rahmen des SLHC-Projekts",IEKP, Univ. Karlsruhe, 2009, IEKP-KA/2009-12

M. Schneider, "Lorentzwinkelmessungen in hochbestrahlten Siliziumstreifendetektoren", IEKP, Univ. Karlsruhe, 2009, IEKP-KA/2009-14

M. Frey, "Entwicklung von hoch strahlenharten Siliziumstreifensensoren für den Einsatz am Super Large Hadron Collider", IEKP, Univ. Karlsruhe, 2009, IEKP-KA/2009-18

R. Eber, "Untersuchungen an MCz-Dioden nach gemischter Bestrahlung mit Neutronen und Protonen mittels der Transient Current Technique", IEKP, Univ. Karlsruhe, 2009, IEKP-KA/2009-30

P. Luukka u. a., "TCT and test beam results of irradiated magnetic Czochralski silicon (MCz-Si) detectors," *NIM A* 604, Nr. 1 (Juni 1, 2009): 254-257.

J. Härkönen u. a., "Test beam results of a heavily irradiated Current Injected Detector (CID)," *NIM A* 612, Nr. 3 (Januar 11, 2010): 488-492.

P. Luukka u. a., "Test beam results of heavily irradiated magnetic Czochralski silicon (MCz-Si) strip detectors," *NIM A* 612, Nr. 3 (Januar 11, 2010): 497-500.

Customers:

Anthony Affolder, Phil Allport, und Gianluigi Casse, "Studies of charge collection efficiencies of planar silicon detectors after doses up to and the effect of varying diode configurations and substrate types," NIM A 604, Nr. 1 (Juni 1, 2009): 250-253.

Ulrich Parzefall u. a., "3D silicon strip detectors," NIM A 604, Nr. 1 (Juni 1, 2009): 234-237.

Ulrich Parzefall u. a., "Silicon microstrip detectors in 3D technology for the sLHC," NIM A 607, Nr. 1 (August 1, 2009): 17-20.

Anthony Affolder, Phil Allport, und Gianluigi Casse, "Charge collection efficiencies of planar silicon detectors after reactor neutron and proton doses up to," NIM A 612, Nr. 3 (Januar 11, 2010): 470-473.

J. Bernardini u. a., "CCE measurements on heavily irradiated micro-strip sensors," NIM A 612, Nr. 3 (Januar 11, 2010): 478-481.

Gianluigi Casse, "Radiation hardness of p-type silicon detectors," NIM A 612, Nr. 3 (Januar 11, 2010): 464-469.

Anthony Affolder, Phil Allport, und Gianluigi Casse, "Collected charge of planar silicon detectors after pion and proton irradiations up to 2.2 1016 neq cm-2," NIM A In Press, Corrected Proof (o. J.), http://www.sciencedirect.com/science/article/B6TJM-4YH99K0-T/2/8d35cb8eb54742ac41f4eef8464355a5.

M. Beimforde, "The ATLAS Planar Pixel Sensor R&D project," NIM A In Press, Uncorrected Proof (o. J.), http://www.sciencedirect.com/science/article/B6TJM-4YYGGSV-7/2/69a1b88494d7445642f1e59a59590708.

Gianluigi Casse u. a., "Enhanced efficiency of segmented silicon detectors of different thicknesses after proton irradiations up to 1 1016 neq cm2," NIM A In Press, Corrected Proof (o. J.), http://www.sciencedirect.com/science/article/B6TJM-4YH4PT3-4/2/4edddd4c05a47b4ef7541b070d90ac8b.

K. Hara u. a., "Testing of bulk radiation damage of n-in-p silicon sensors for very high radiation environments," NIM A In Press, Uncorrected Proof (o. J.), http://www.sciencedirect.com/science/article/B6TJM-4YYGGSV-9/2/183cc0c21e3f26a578b4921f3f451c68.

Ulrich Parzefall u. a., "Efficiency measurements for 3D silicon strip detectors," NIM A In Press, Corrected Proof (o. J.), http://www.sciencedirect.com/science/article/B6TJM-4YH99K0-K/2/9f9de75bba40b3a229e8c1d9e2c2fcf9.

If you don't find your paper here, please let me know !

Summary and Outlook

- The KAZ is frequently used for high fluence irradiations (~100h in 2009, 28h in 2010)
- The hardness factor for our protons of 1.85 is well in the measurement accuracy of calibration measurements, but a value of 2.0 fits better
- Fluence statements are not better than 20% at the moment
- 300µm Si samples could be stacked in three layers to safe time and money
- Annealing effects during irradiation are minimal

- Next huge projects are:
  - CMS HPK campaign (~1000 pieces!) from September on
  - CMS environmental sensors (commercial pieces of unknown composition…) starting next week

Backup

The Fluence Estimation

In a homogeneous area *A* each point sees the integral of the proton current density function, i.e. the complete beam spot, and therefore the total proton current I_p. With this one can estimate the fluence by:

$$F = \frac{I_p \cdot t}{q_{el} \cdot A}.$$

The time during which the beam hits this area can be calculated like:

$$t = n \cdot \frac{W}{v_x} = \frac{H}{\Delta y} \cdot \frac{W}{v_x} = \frac{A}{\Delta y \cdot v_x}$$

with the number of lines n, the width of the area *W*, the horizontal scan speed v_x, the height of the area *H* and the line separation Δy. Combining these two equations results in a formula for the fluence we get for one scan. Multiplying with the number of scans n_{scan} we get the equation we were looking for:

$$F_{est} = n_{scan} \cdot \frac{I_p}{q_{el} \cdot v_x \cdot \Delta y}$$

Alternative Hardness Factors

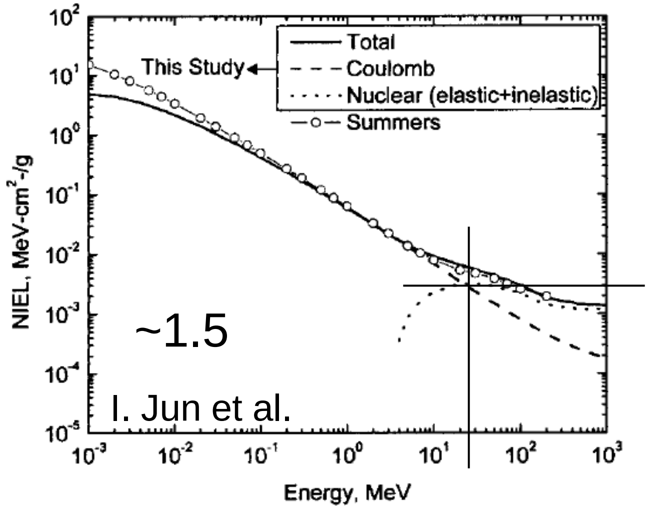
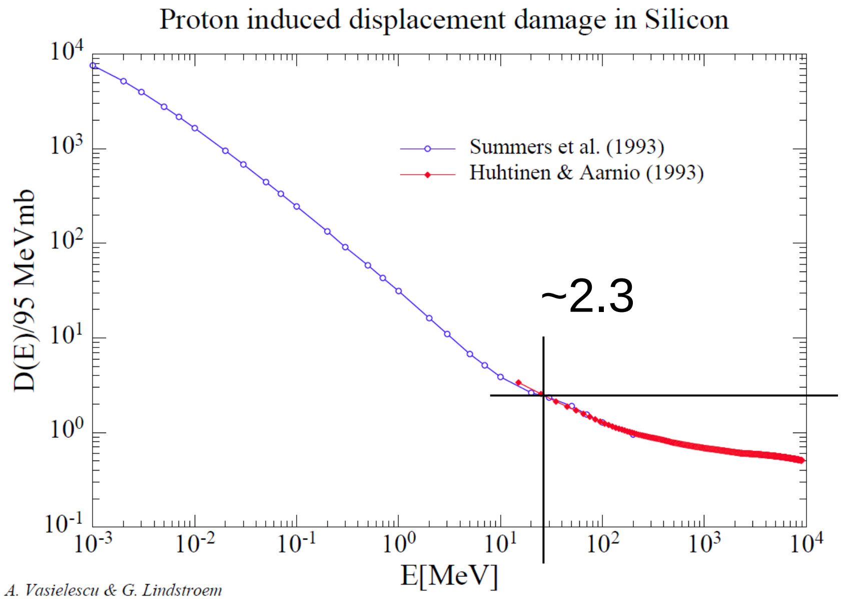


Fig. 3. Proton NIEL for Si obtained in this study, compared to the Summers et al. results [6]. For the Coulomb contribution, the ZBL screened Coulomb potential was used for E<50 MeV, and relativistic energy transfer cross section was used for E≥50 MeV.



Displacement damage is about half the total NIEL !

There is a variety of values on the market…

SLHC Fluences