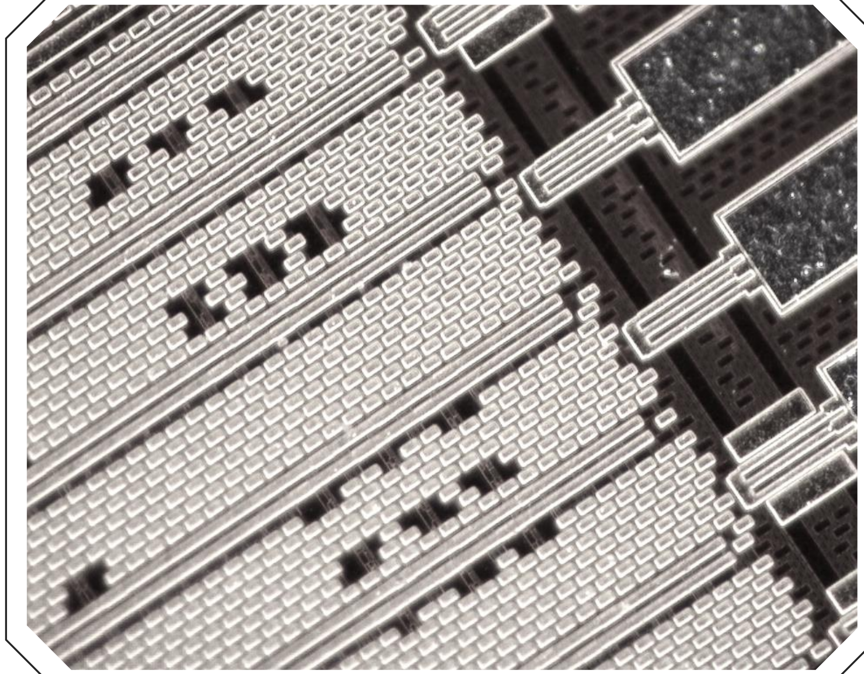


Irradiation Studies on single HBT Test Structures

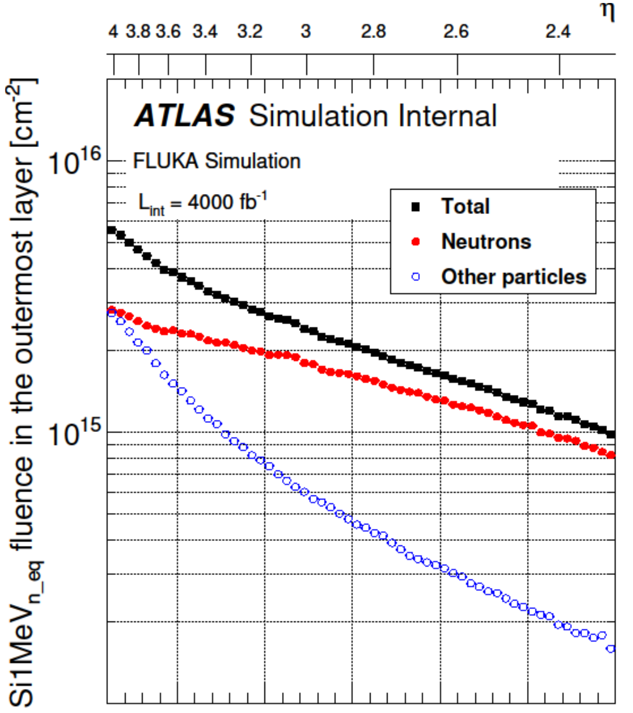
Benjamin Weinläder

06.03.2024

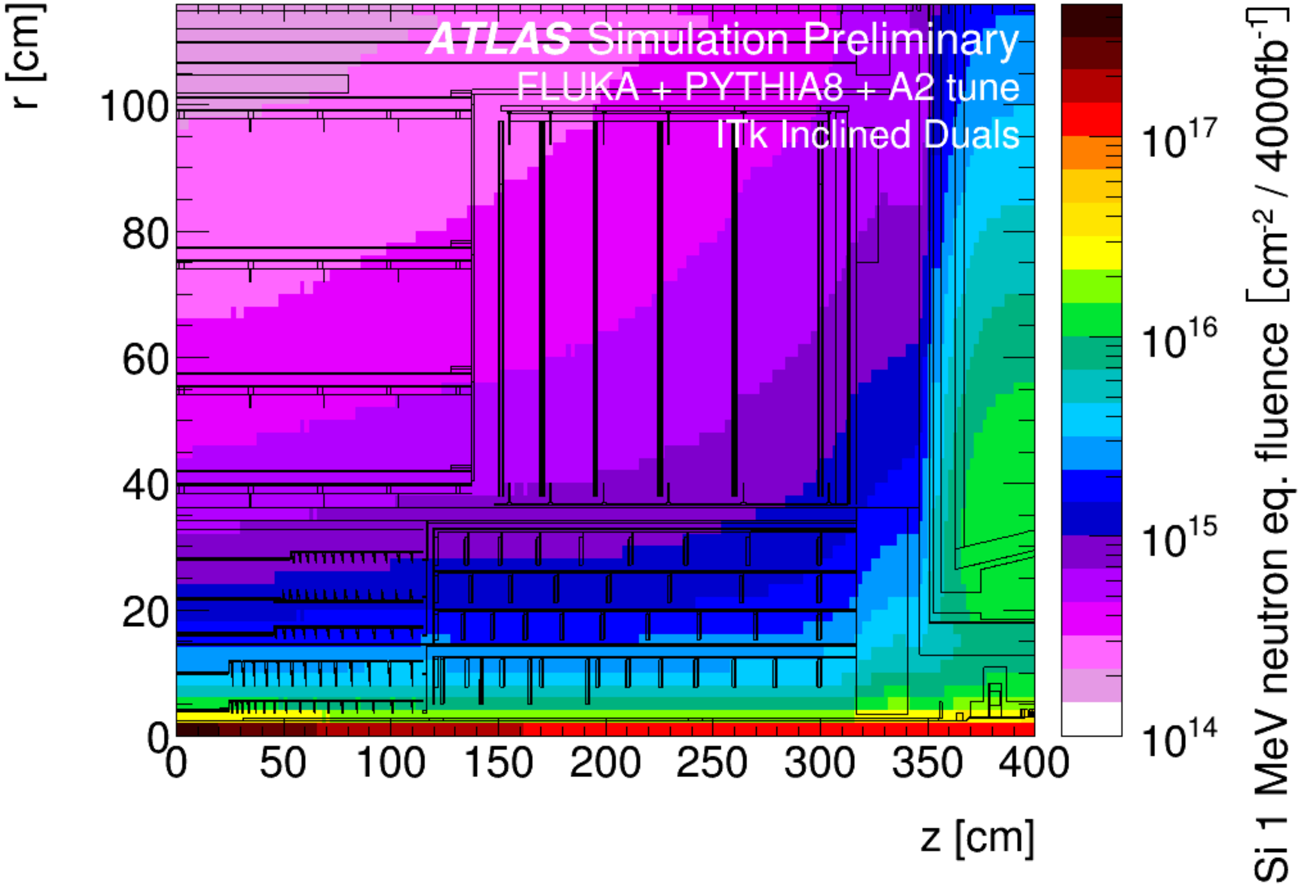
HighRR Seminar

Radiation Environment in HEP

- Example: Atlas Inner Tracker
  - Simulations for the HL-LHC upgrade after $4000\ fb^{-1}$



AtlasPublic



AtlasPublic

Radiation Damage

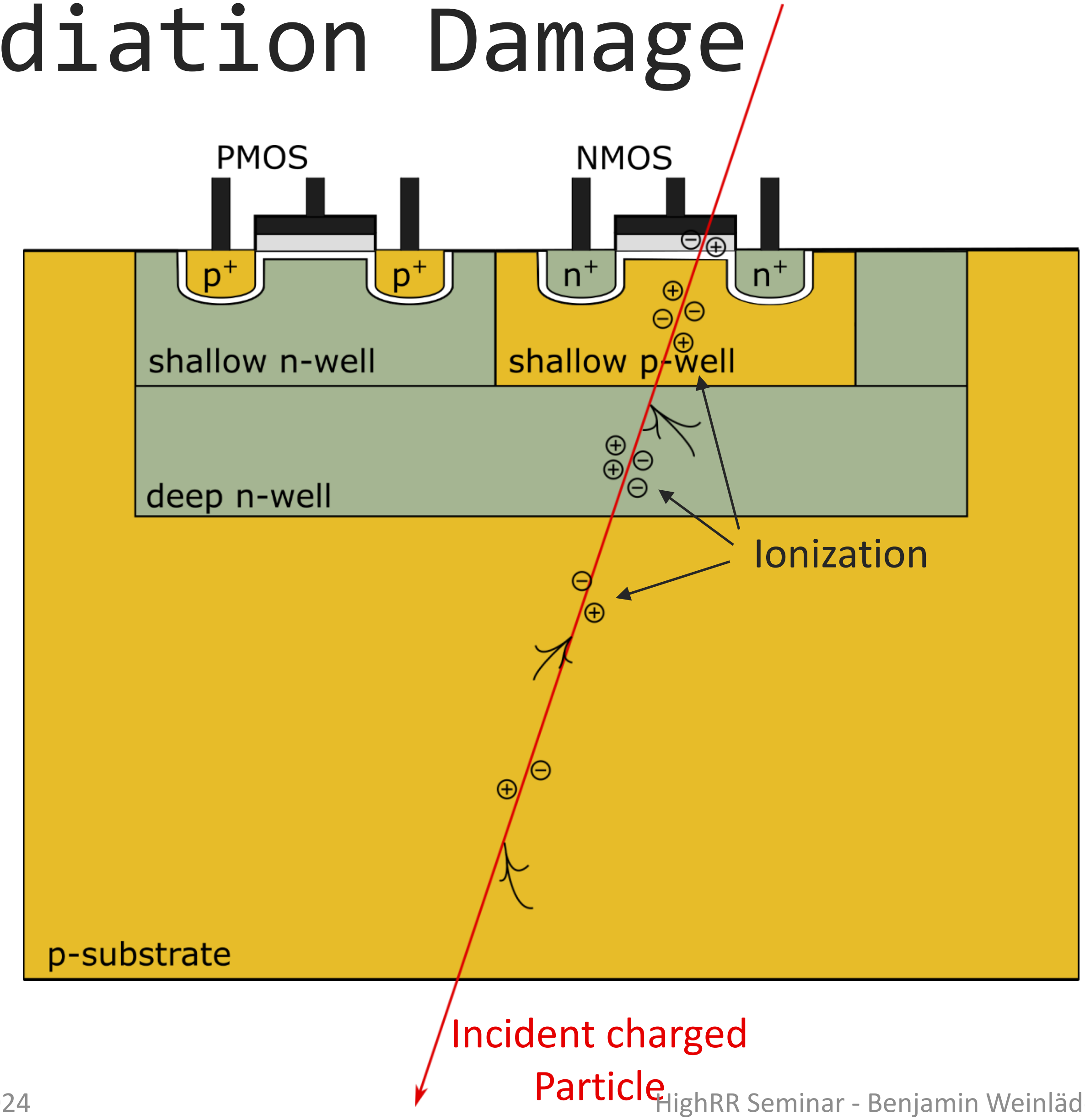
Dose Effects

- Slowly, over time
  - Accumulation of defects/ trapped charge
  - Shift of transistor properties
  - Increase of leakage current

Single Event Effect

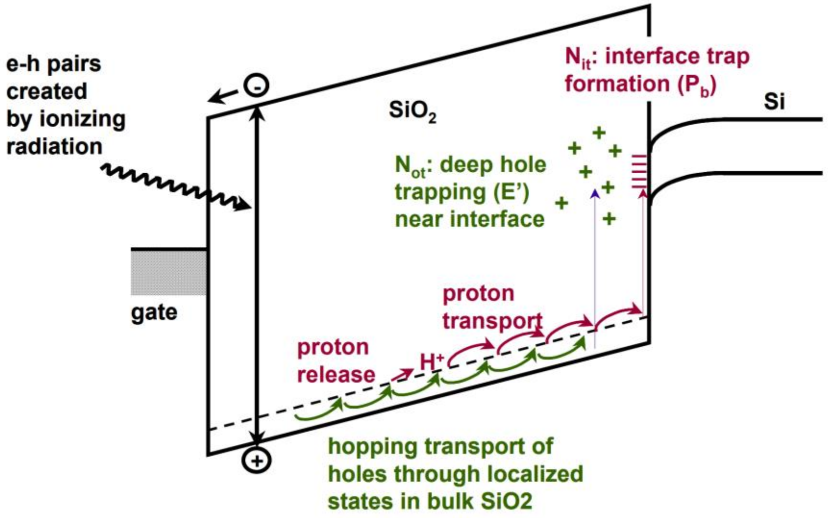
- Directly visible effect
  - Latch-up: Short, thus thermal destruction
  - Upset: Bit flips, errors in the digital part
  - Gate rupture: Destruction of the gate isolation

Radiation Damage



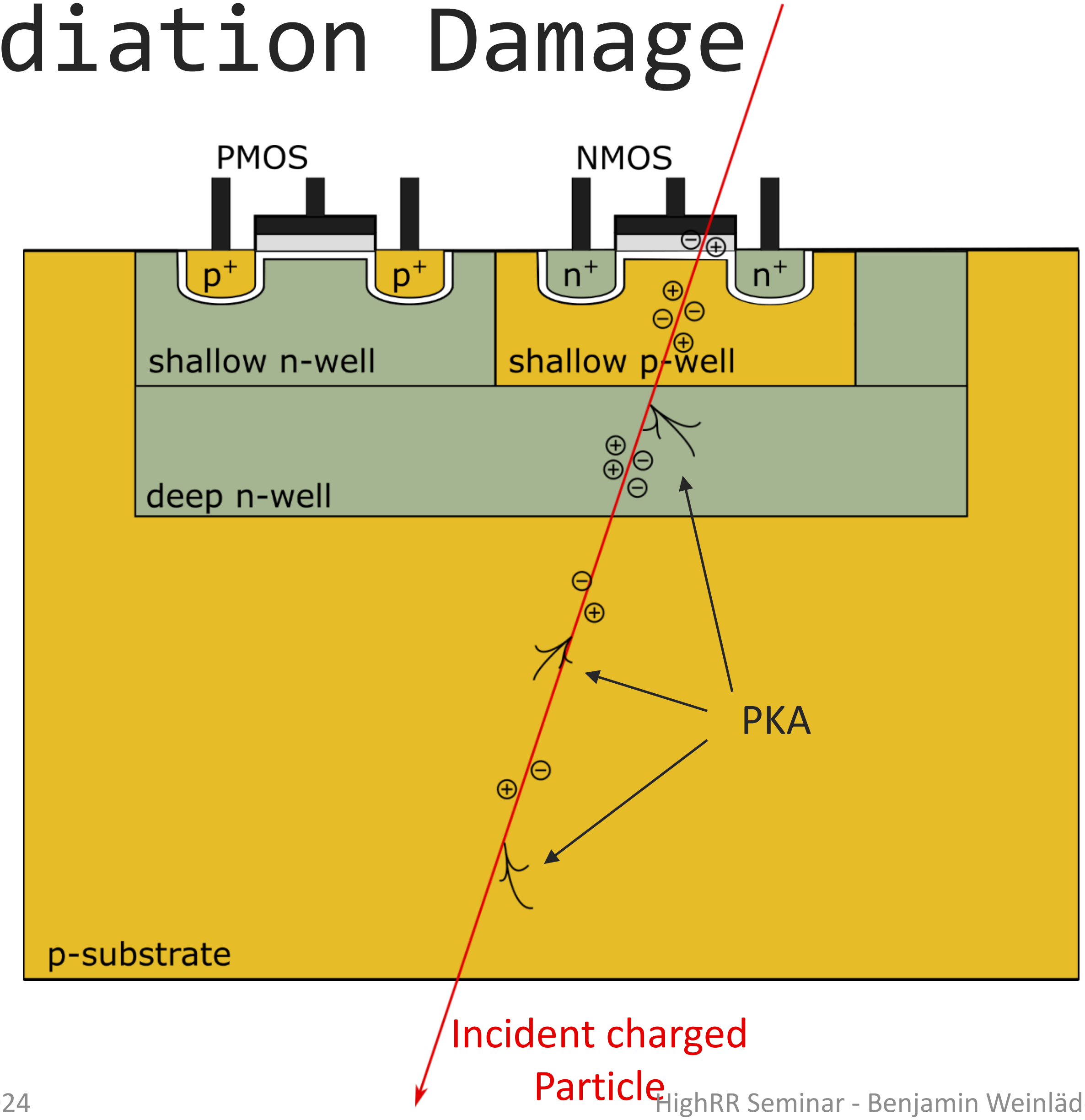
Ionization

- Silicon:
  - Charge recombines or is removed by exsiting elec. Fields
- Oxide:
  - Holes get trapped, accumulate at the surface
    - ! Change transistor threshold voltage !
    - ! Increase leakage current !



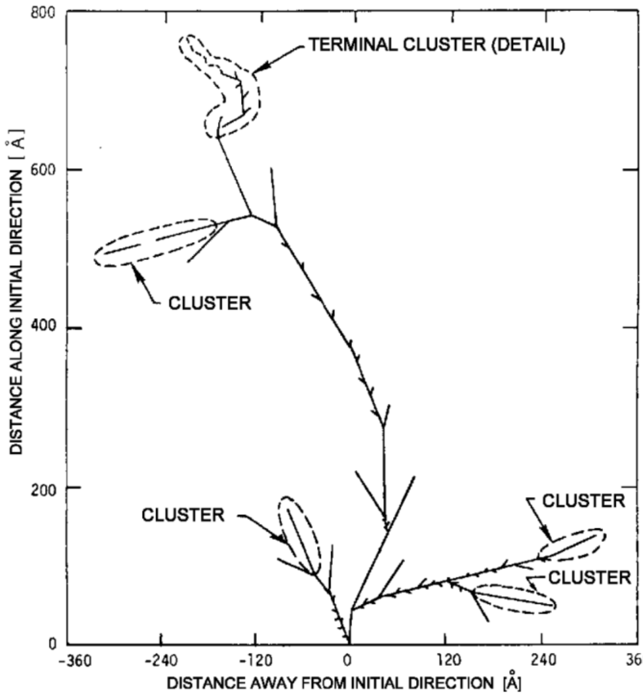
DOI: 10.1109/TNS.2008.2001040

Radiation Damage



Primary Knock on Atom (PKA)

- Displacement of a lattice atom
  - Impact energy $\gtrsim 25eV$ (depending on direction)
  - Recoils knock out additional atoms + energy transfer via ionization

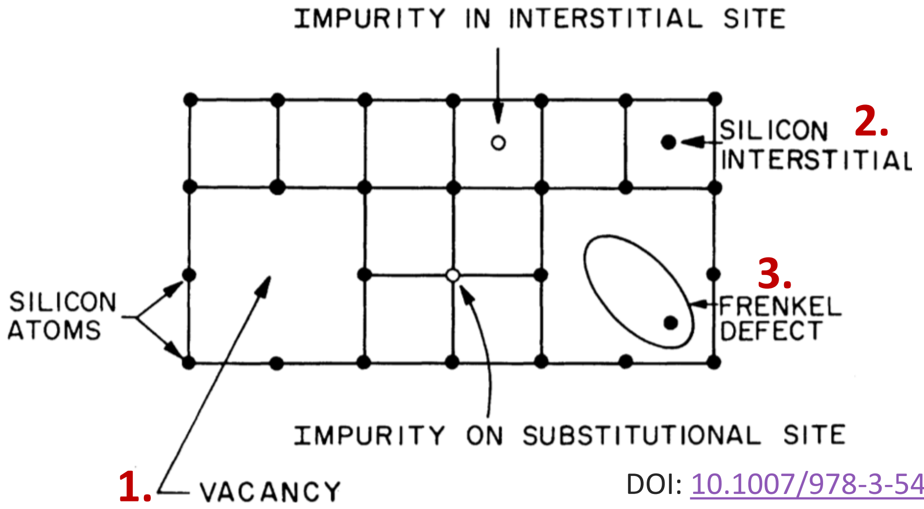


Van Lint et al., 1980

Primary Knock on Atom

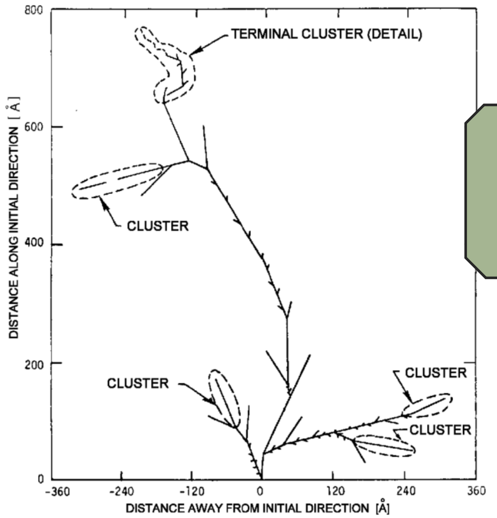
- Point defects
  1. Vacancies → empty lattice sites
  2. Interstitials → atoms outside the regular lattice
  3. Frenkel defects → combining both
- Clusters
  - Aggregation of point defects
  - Typically at the end of a recoil track
    - Scattering cross-section increases with decreasing energy

Different types of lattice defects



DOI: 10.1007/978-3-540-71679-2

Simulation of a PKA with $E_R = 50keV$



Van Lint et al., 1980

Electric Properties of Defects

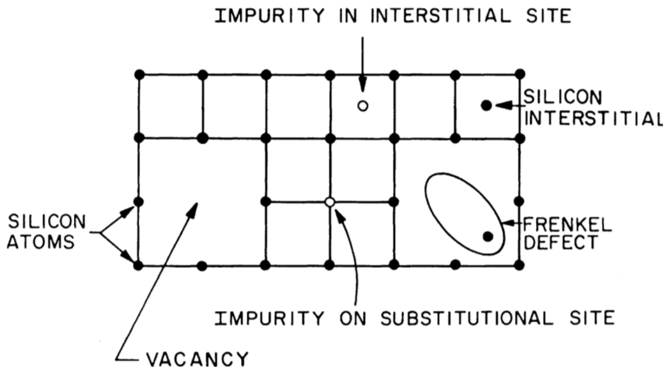
- **Recombination-generation center**
  - Capture or emit charge carriers
  - ! Increase of leakage current at junctions !
  - ! Shift in a transistor threshold voltage !
- **Trapping center**
  - Capture charge carriers and re-emits them with time delay
  - ! Generates timing-jitter on signals !
- **Change of charge density**
  - ! Change of the effective resistivity !

Also holds for defects caused by ionization

Increased hole density at the oxide surface → recombination-generation center

Annealing

- Position of most lattice defects are not fixed
    - At certain temperatures defects become mobile
    - Possibility to recombine with the respective counterpart increases
    - → Depends on temperature and time



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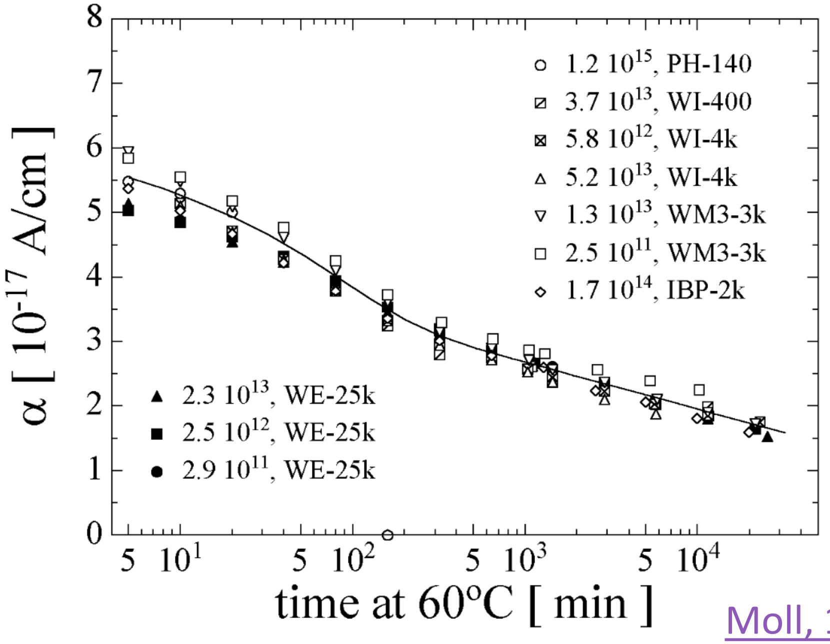
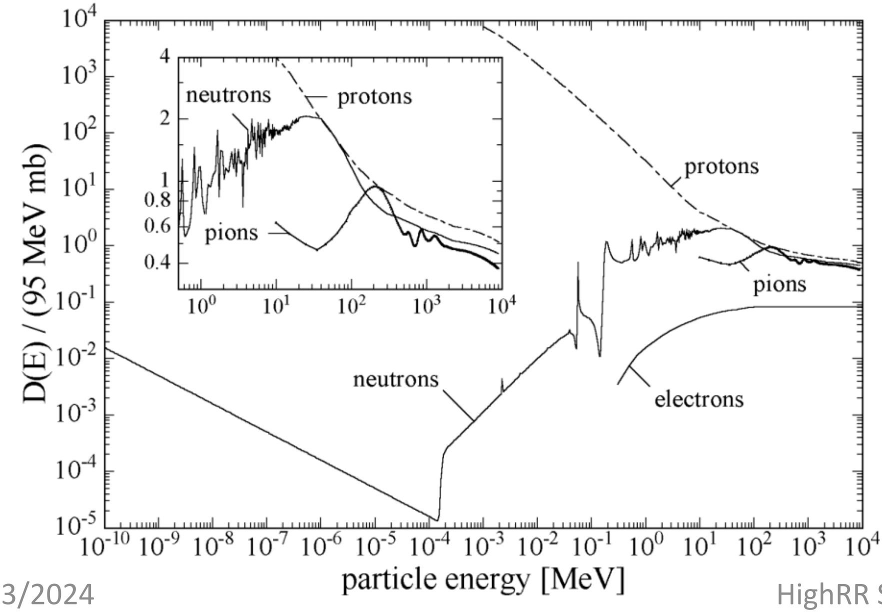
~ leakage current of diodes



Moll, 1999

Non Ionizing Energy Loss hypotheses

- Radiation damage depends on the incident particle type and energy
  - Differences are smoothed due to secondary interactions
- Radiation damage ↔ Non Ionizing Energy Loss (NIEL)
  - $NIEL \sim D(E)$ ← Displacement damage function
  - Normalized to $1MeV$ Neutrons: $D_n(1MeV) = 95MeVmb$



Moll, 1999

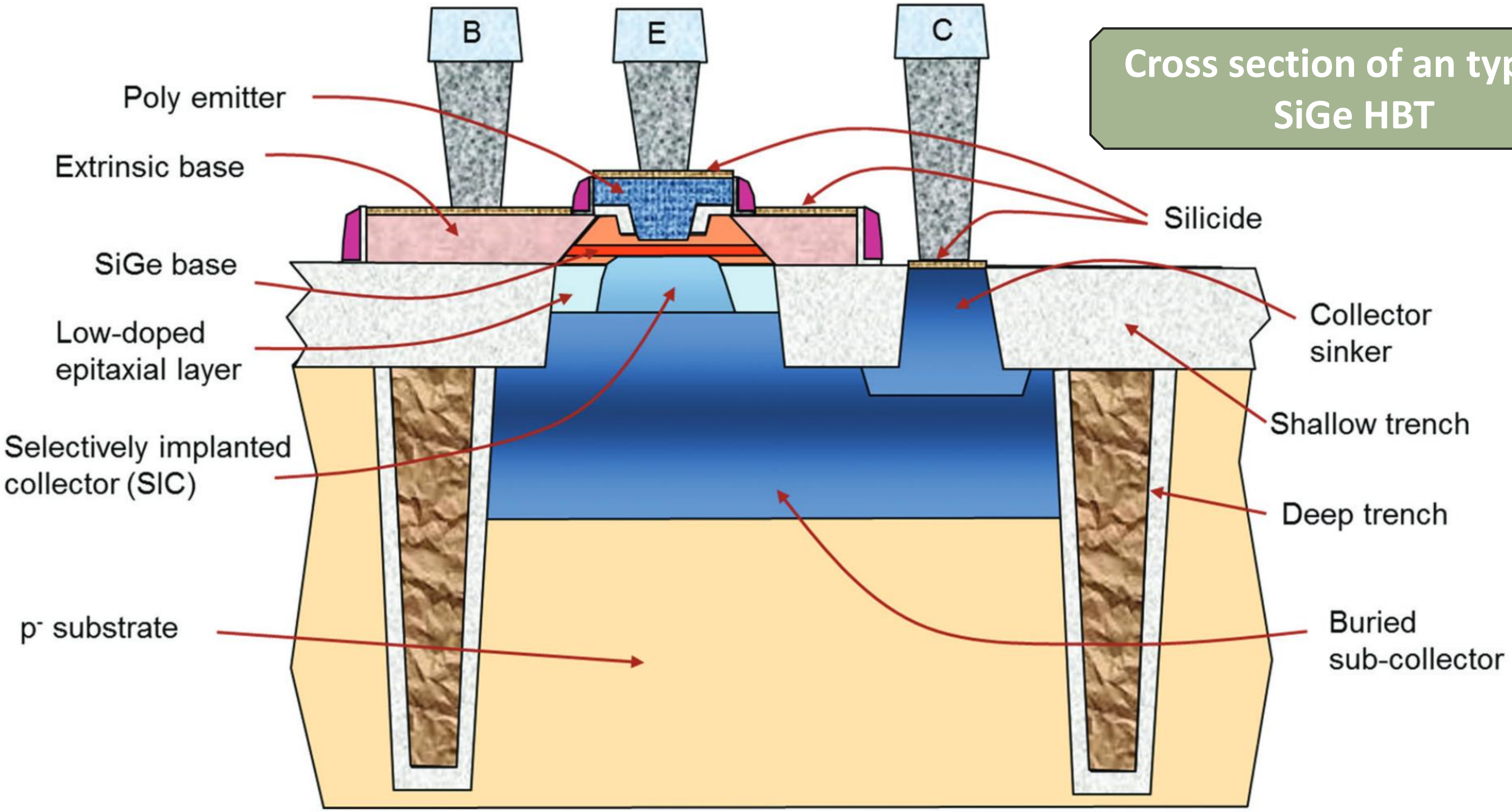
Hardness factor κ

- $\kappa = \frac{\int D(E)\phi(E)dE}{D_n(1MeV) \cdot \int \phi(E)dE}$
- Equivalent fluence:

$$\Phi_{eq} = \kappa \cdot \Phi = \kappa \cdot \int \phi(E)dE$$

Individual energy spectra $\phi(E)$

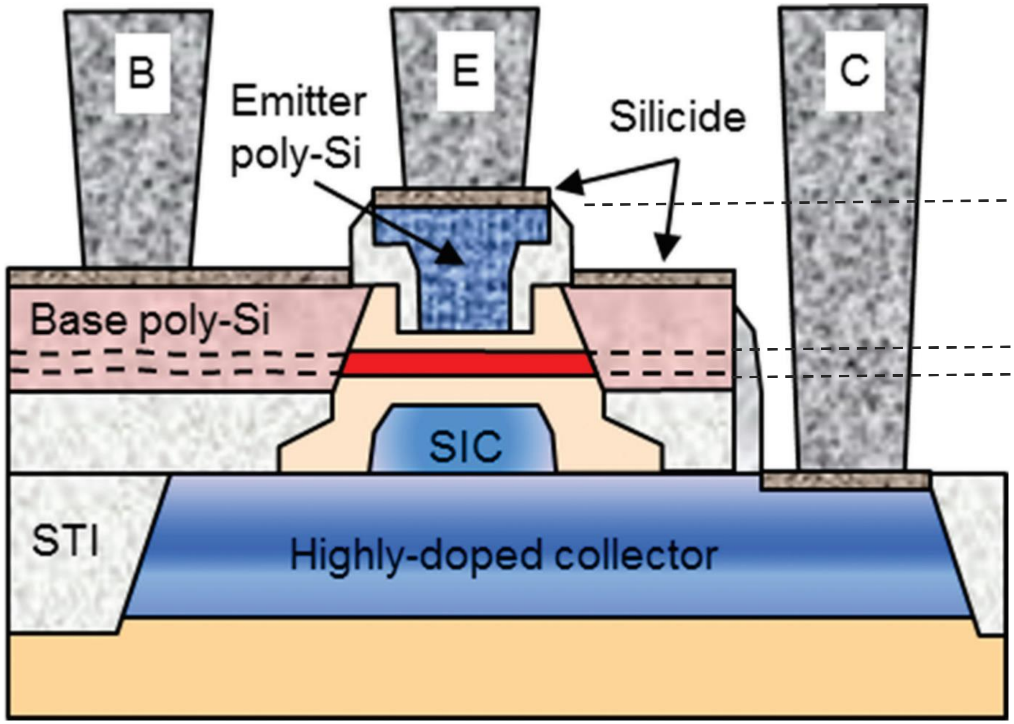
Heterojunction Bipolar Transistor



Cross section of an typical SiGe HBT

DOI: 10.1201/9781003339519-2

Heterojunction Bipolar Transistor



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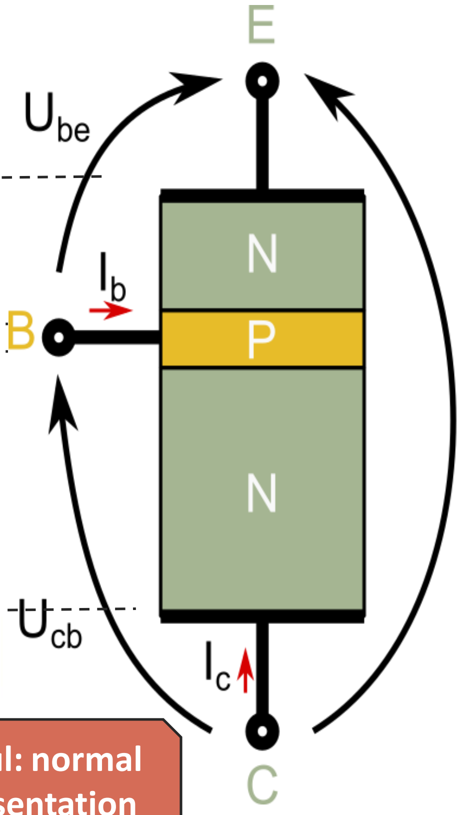
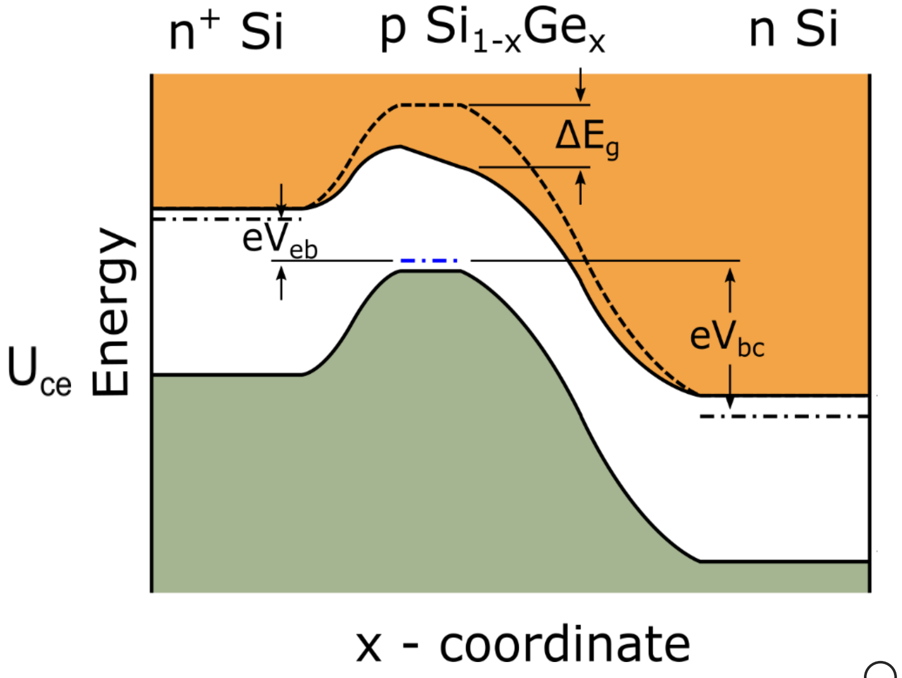
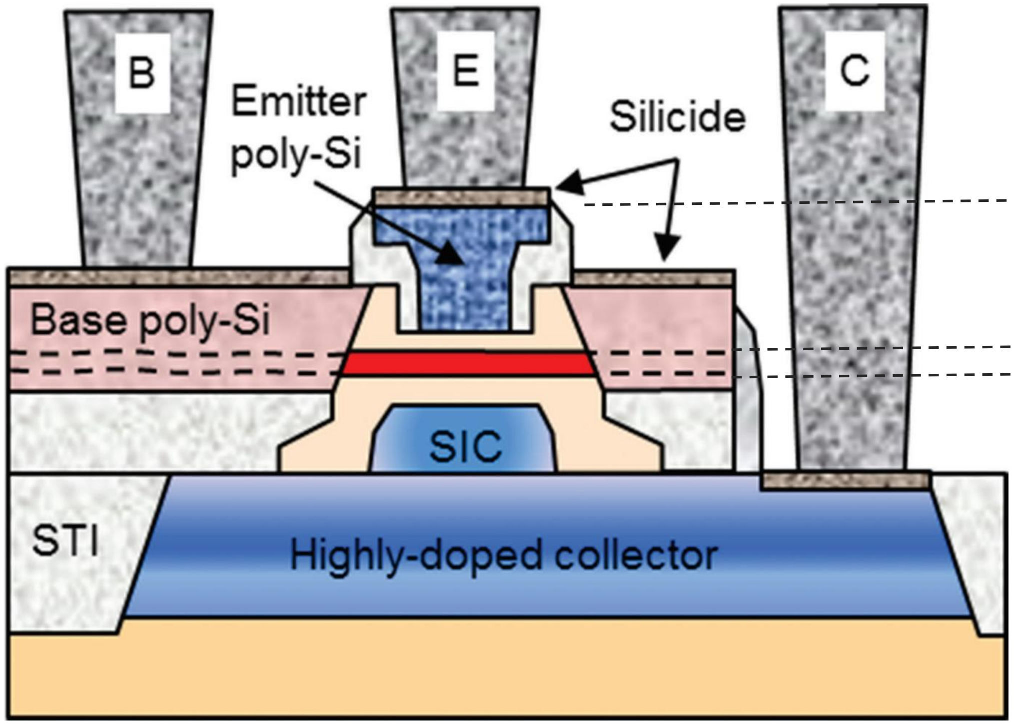




Careful: normal representation rotated by 180°

Heterojunction Bipolar Transistor



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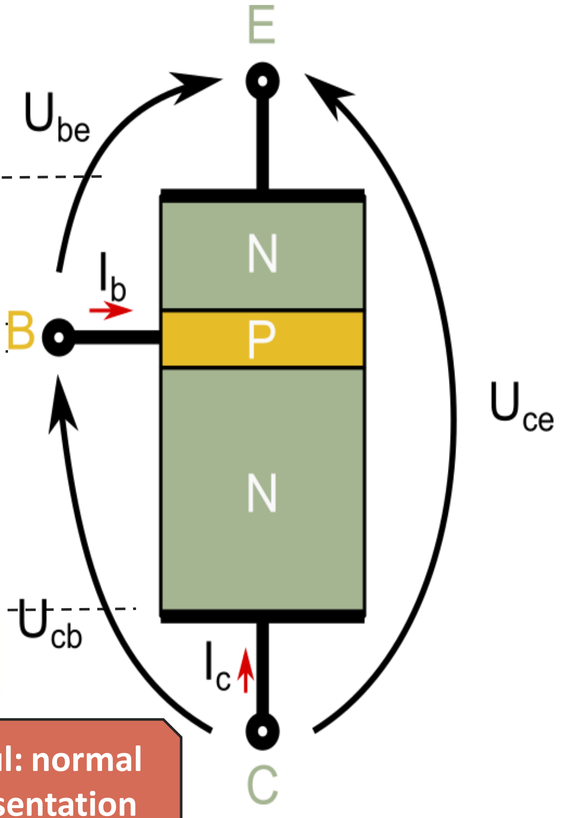

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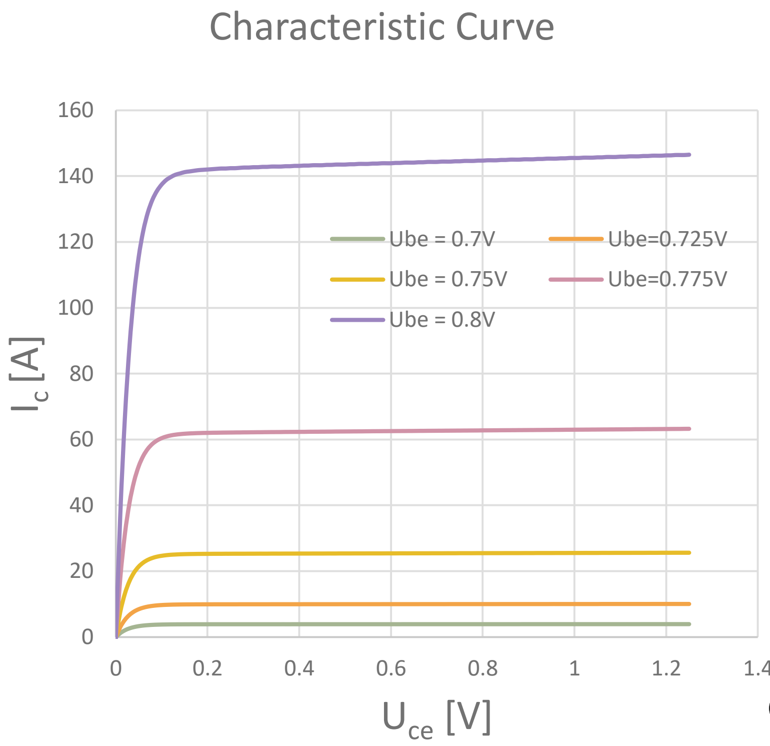
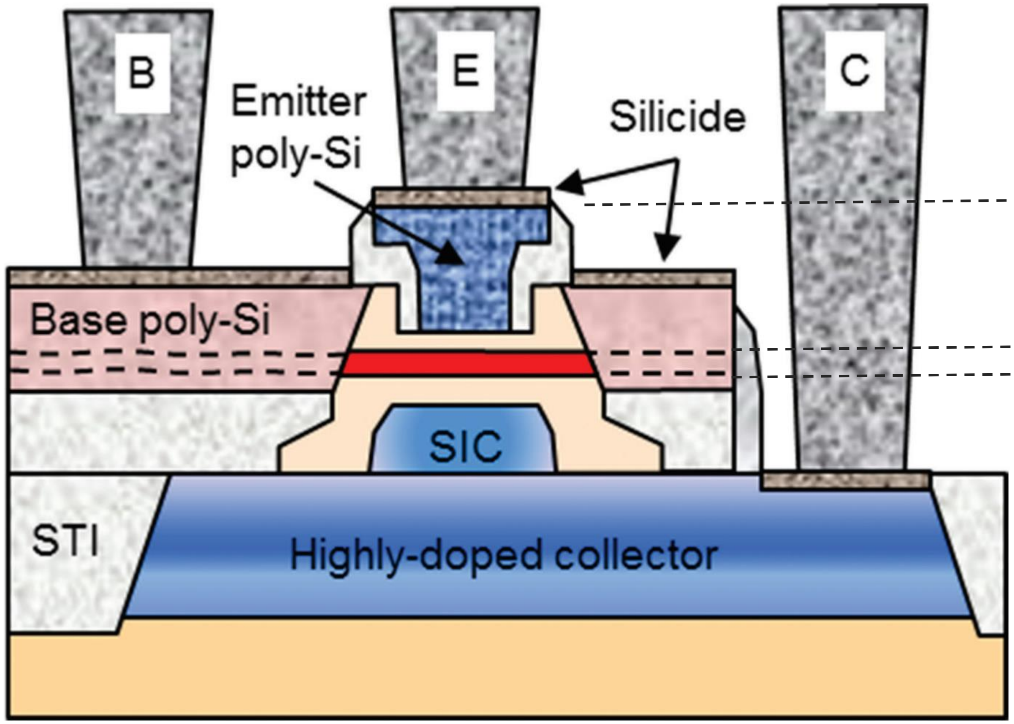


Heterojunction Bipolar Transistor



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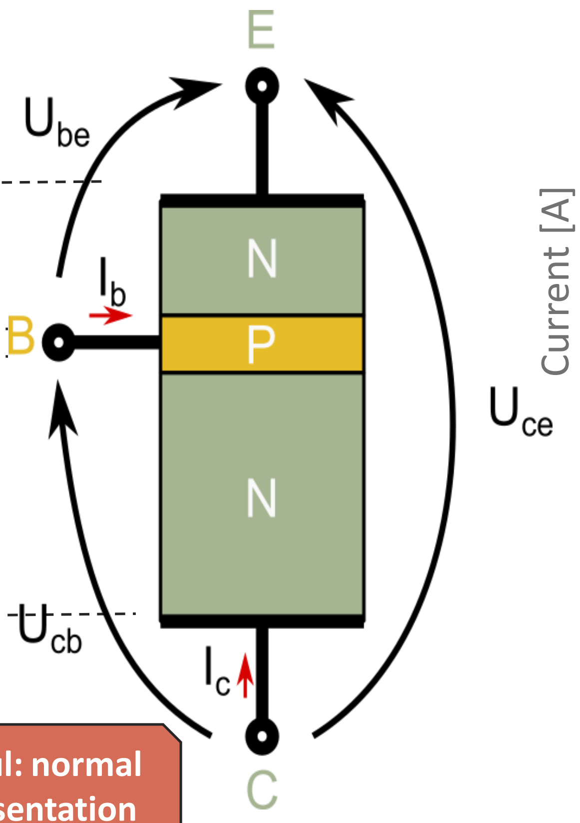

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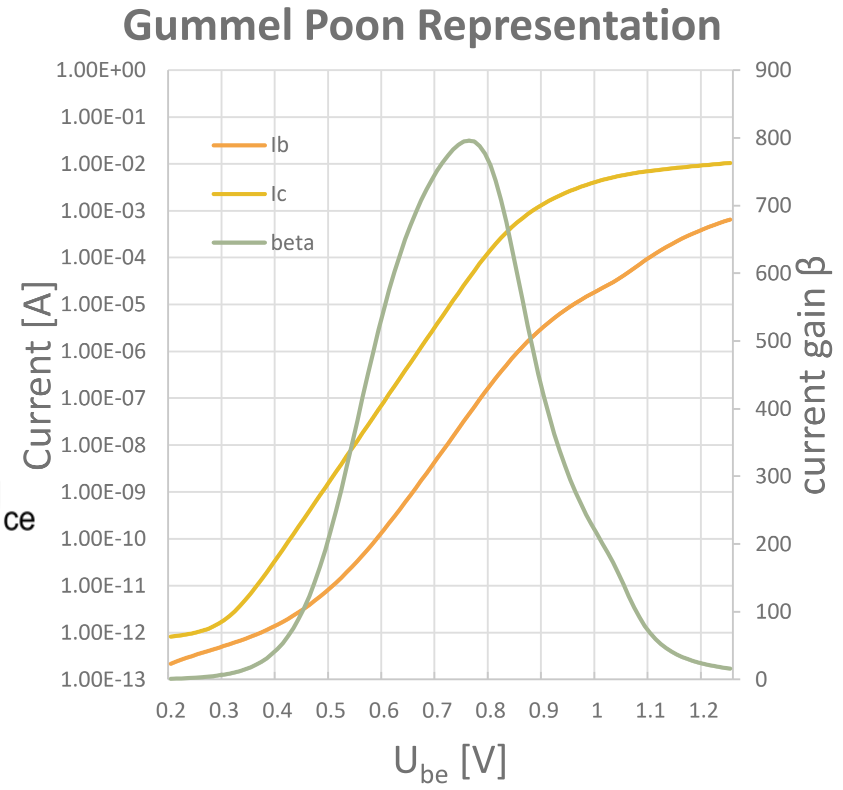
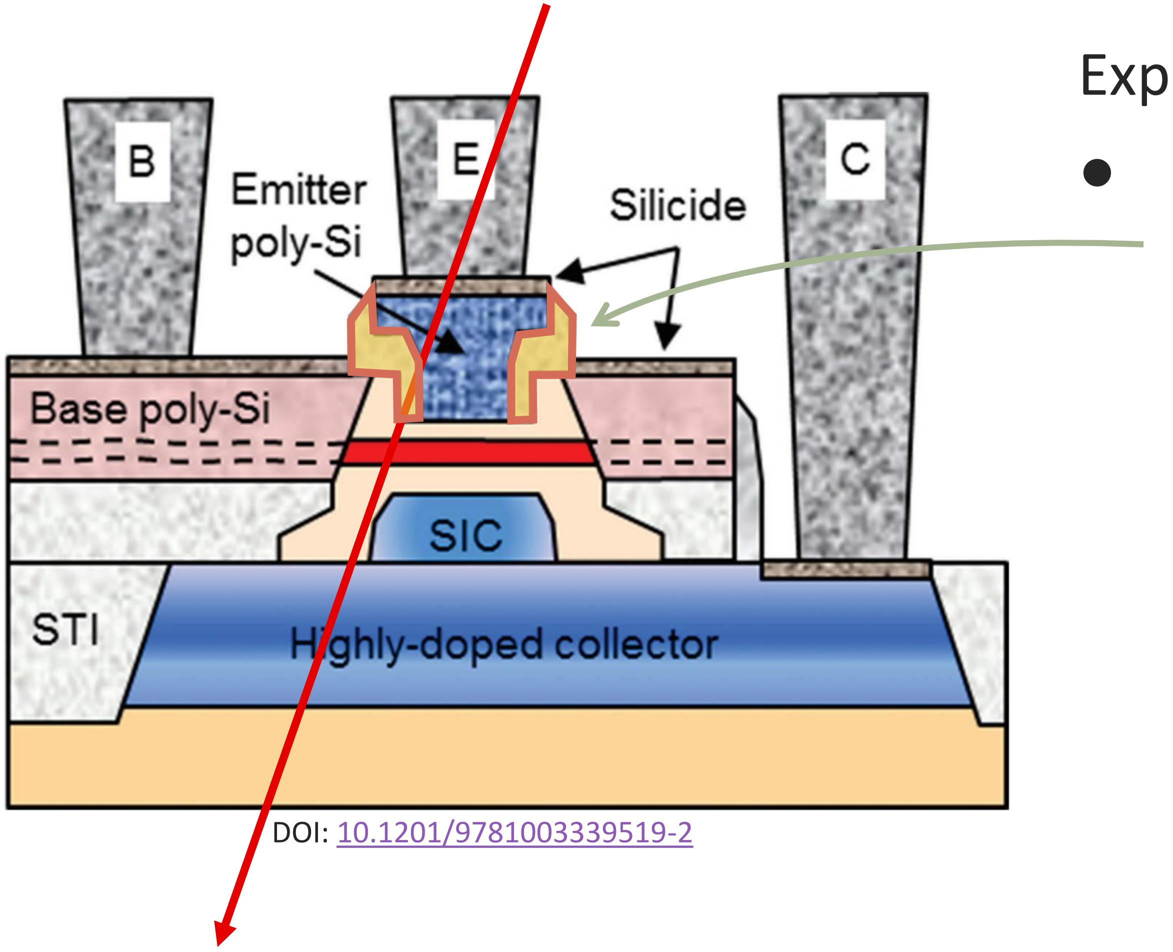


Current gain $\beta = \frac{I_c}{I_b}$

Heterojunction Bipolar Transistor



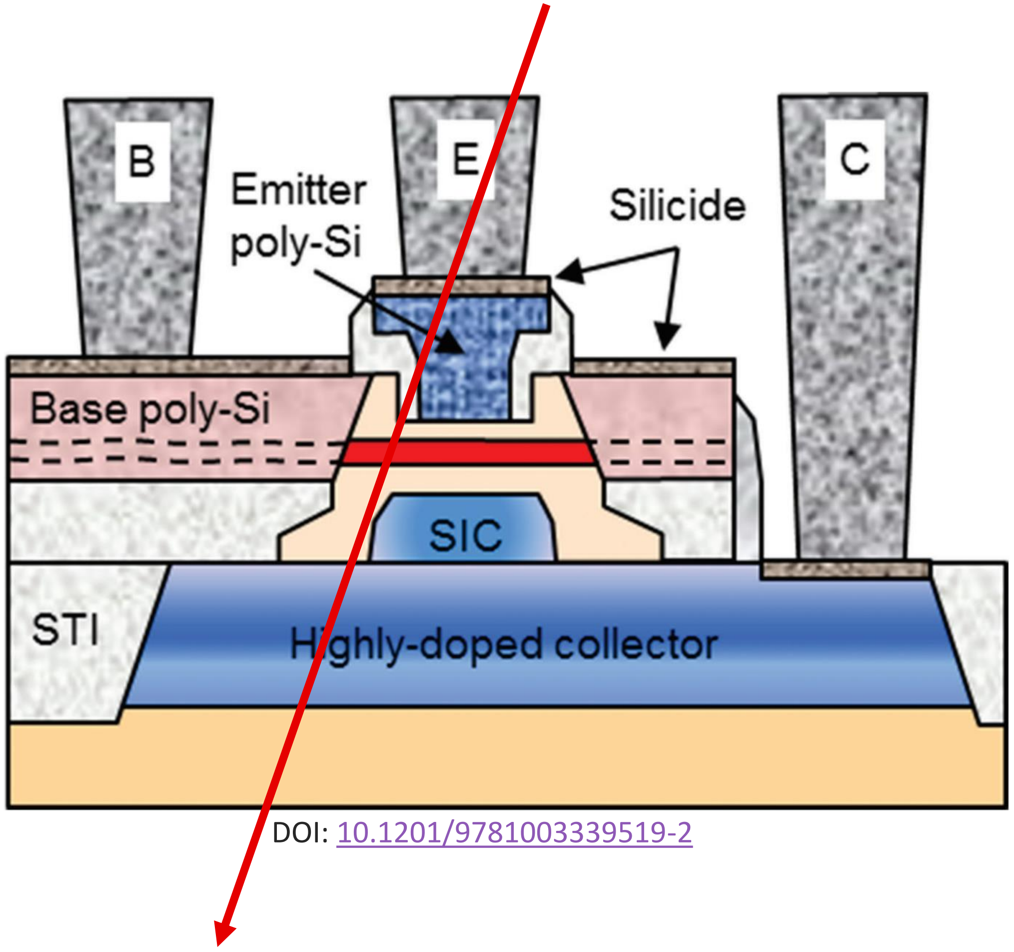
DOI: 10.1201/9781003339519-2

Incident Particle

Expected radiation damage

- Ionization:
  - ○ Trapped charge emitter-base spacer oxide
  - → Forming a **generation-recombination center**
  - → Additional recombination/ leakage current
  - → Increase in I_b
  - → Especially dominate for low V_{be} as

Heterojunction Bipolar Transistor



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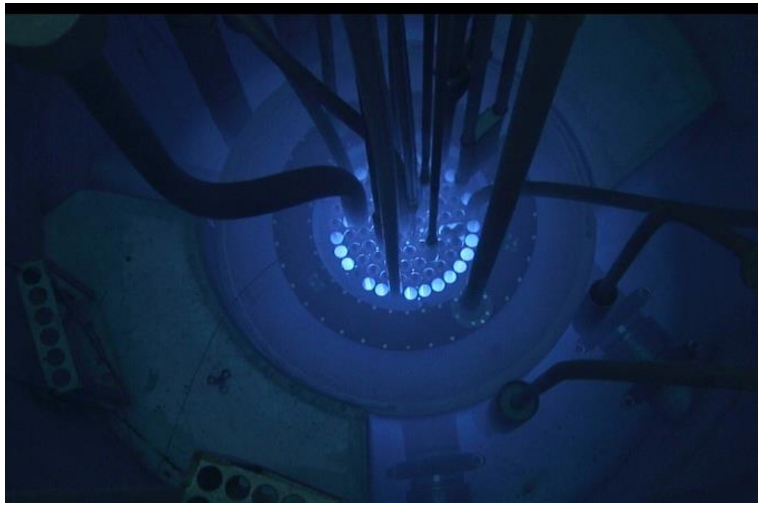
Incident Particle

Expected radiation damage

base is particularly prone as only very small currents flow

- Non-Ionizing:
  - ○ Defects in the base region
  - → **Also forming generation-recombination centers**
  - → Lifetime τ of minority charge is reduced
  - → $I_b \sim 1/\tau$ increase
  - ○ **Change of charge density**
  - → Resistivity change in n-type silicon (emitter and collector region)
  - → Resistance increases
  - → Overall decrease of I_c





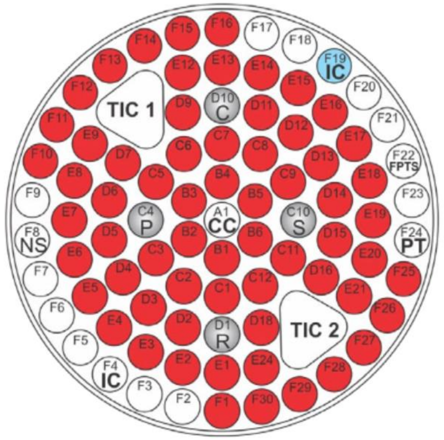
Institut Jožef Stefan

Neutron irradiation

Irradiation at the **Reactor Infrastructure Centre** in **Ljubljana**

- Research TRIGA reactor

Neutron irradiation



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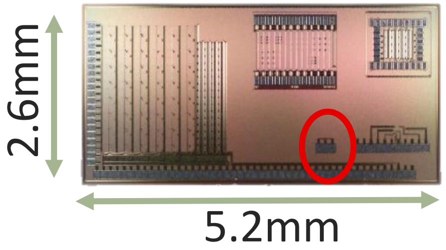
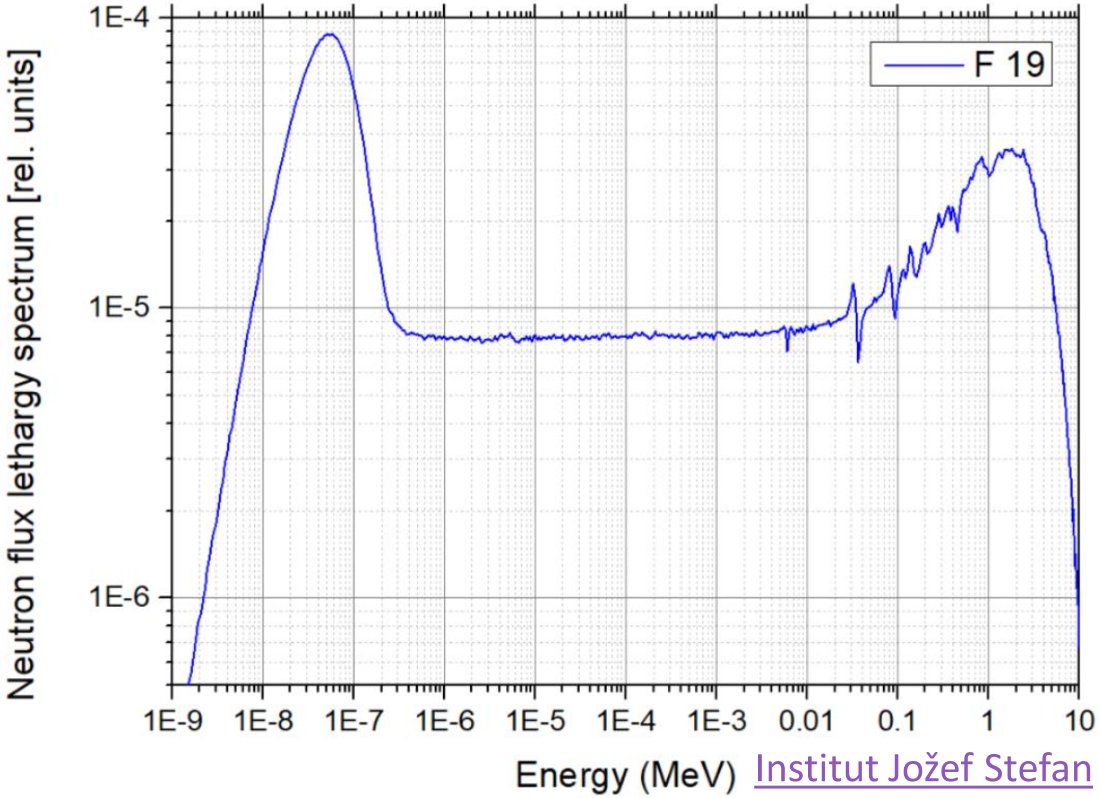
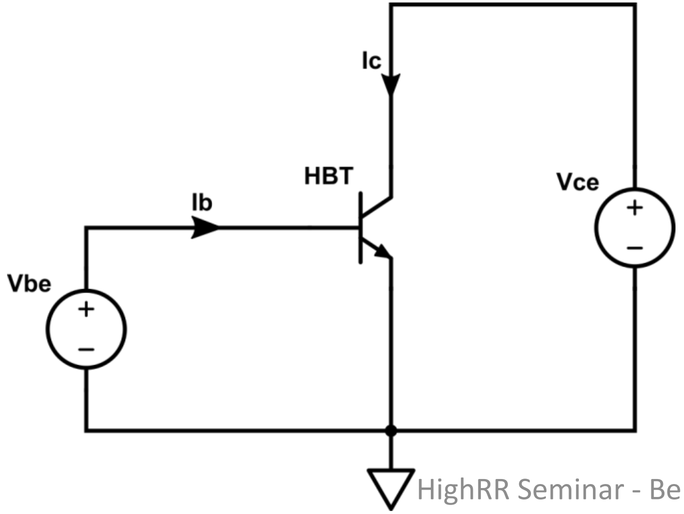


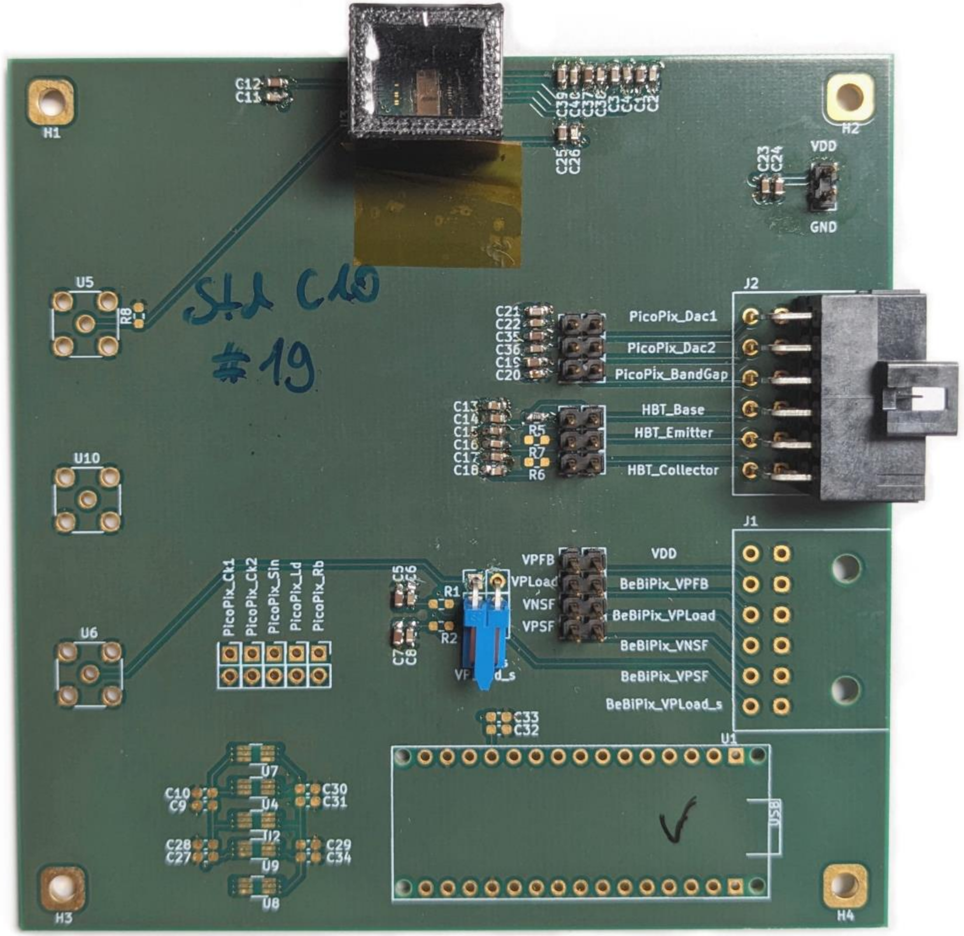


[Institut Jožef Stefan]

Setup

- Irradiated samples are glued and wire bonded on a test PCB
  - Stored in the freezer to minimize annealing
- HBT is powered via 2 Source Measure Units (SMUs)
  - Voltage is applied while currents are measured
- All measurements are done within a climate chamber at $T = -15°C$



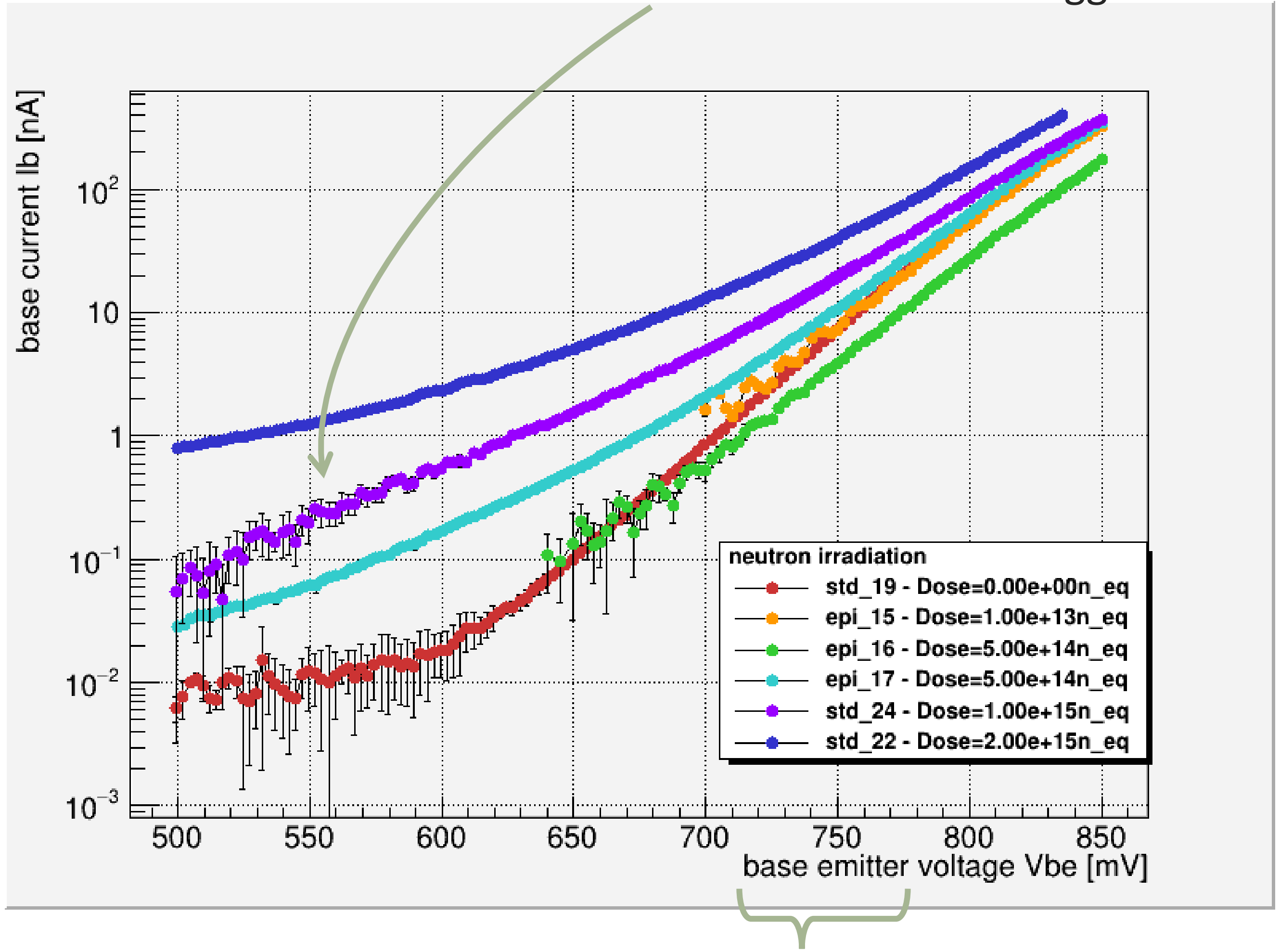


Results after irradiation

Base current I_b

- As expected: clear increase of the base current
    - ○ More dominate at low V_{be}
- Chip ‘epi_16’ clear outlier
    - ○ Could be sensor-to-sensor variation

Reference measurement before irradiation would help a lot



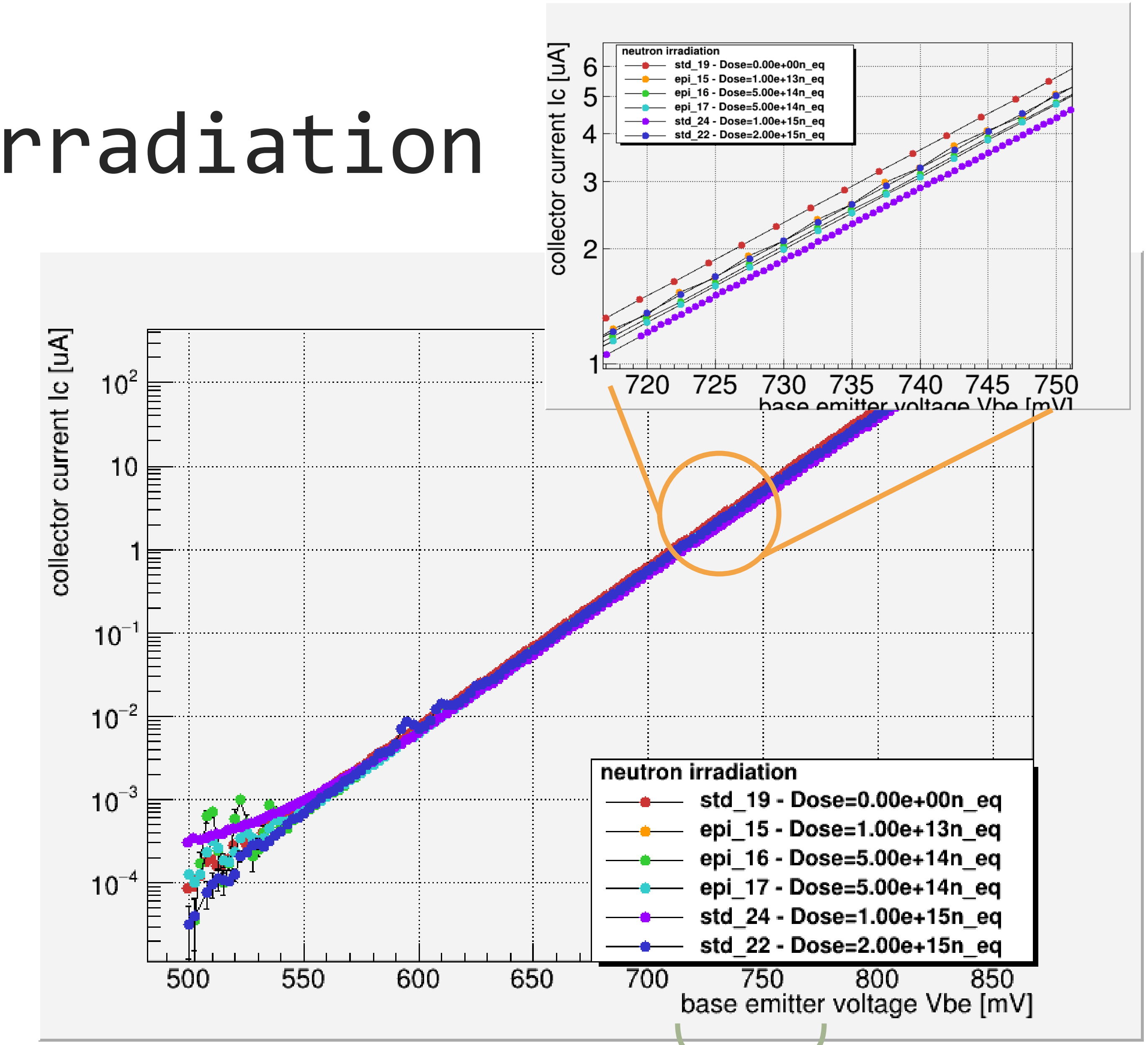
Decoupling capacities on PCB induce these wiggles

Typical operation range

Results after irradiation

Collector current I_c

- No significant dependency visible
    - Overall slight decrease after irradiation, but no direct relation
    - Most probably dominated by chip-to-chip variations



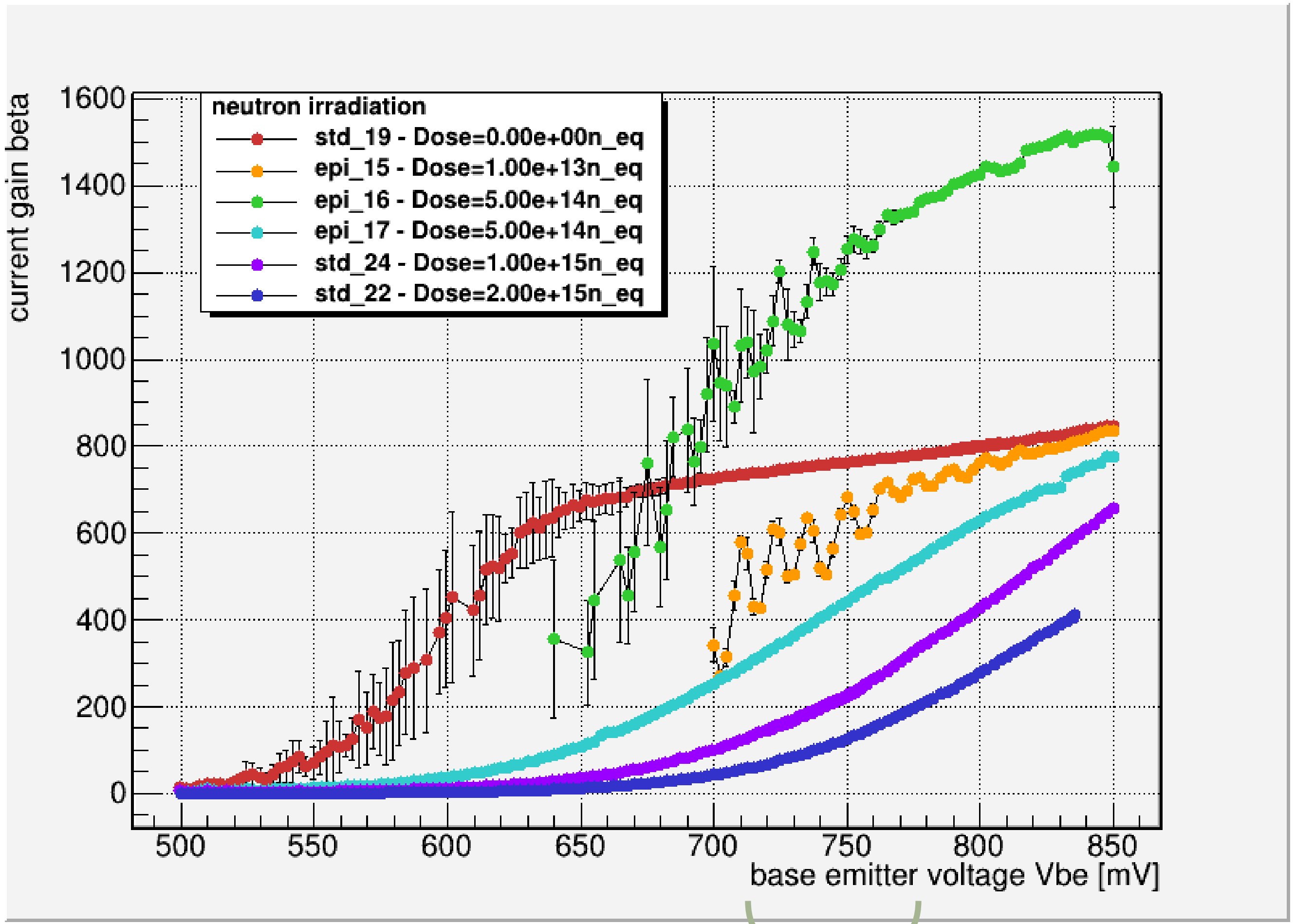
Typical operation range

Results after irradiation

Findings:

- HBT can be still operated after irradiated with a large dose ($2e15\ n_{eq}/cm^2$)
  - But the base current will increase significantly
  - Need to be considered already in the circuit design

Current gain $\beta = \frac{I_C}{I_b}$



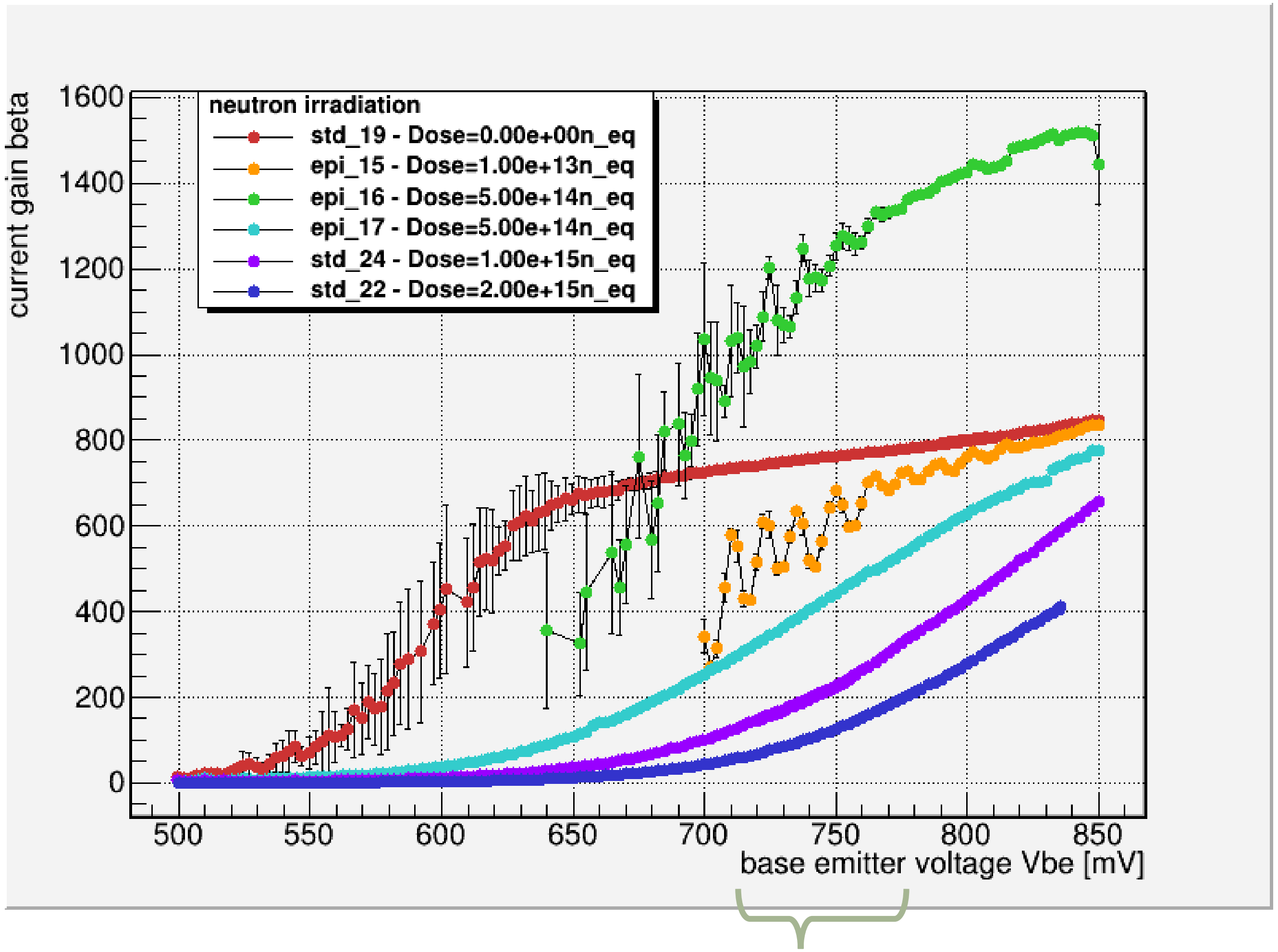
Typical operation range

Results after irradiation

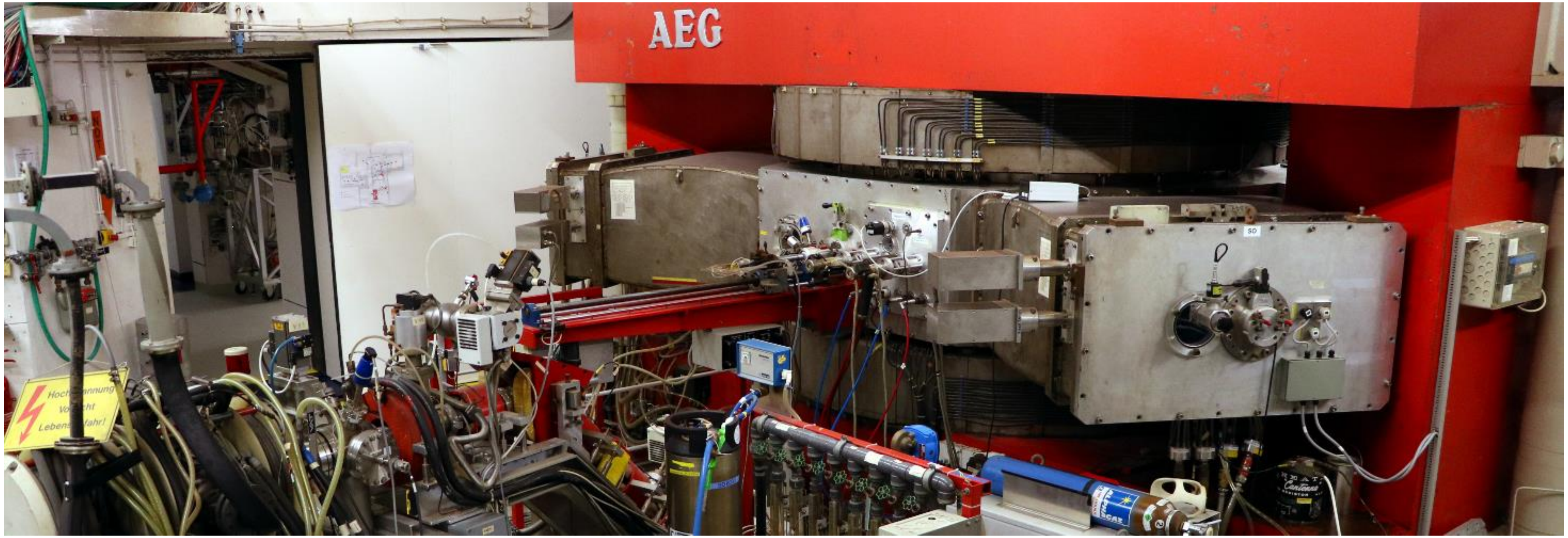
Problems:

- Reference measurements are missing to account for chip-to-chip variations
- Single Transistors are very vulnerable
  - ○ Several were destroyed while testing
  - → Limiting the statistics

Current gain $\beta = \frac{I_c}{I_b}$



Typical operation range



Proton irradiation

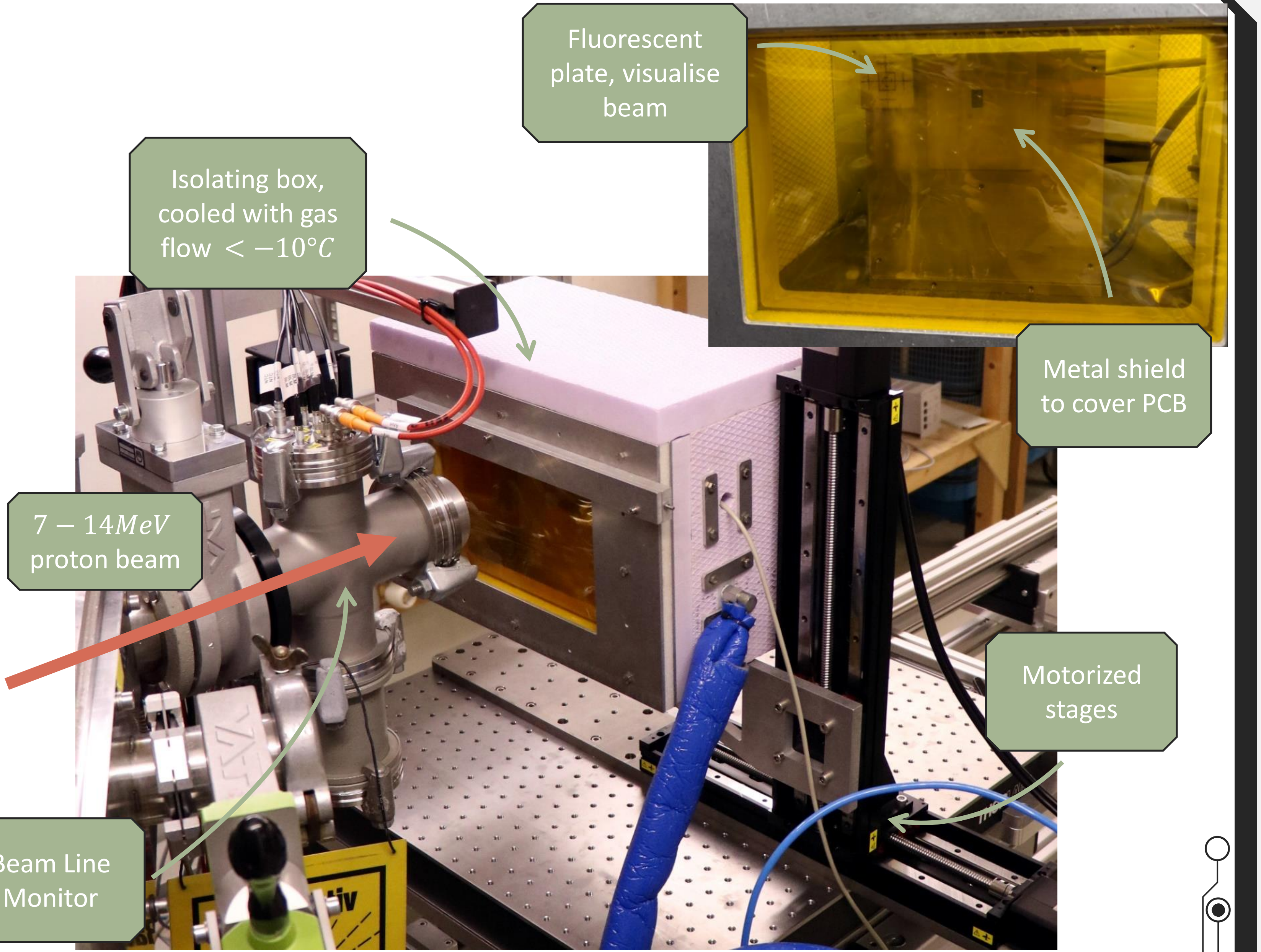
Irradiation at the **Helmholtz-Instituts für Strahlen- und Kernphysik** in Bonn

- Isochron-Zyklotron

Setup

- ~2h down time after irradiation
- 3-4h beam setup at each start-up

Measure same chip in between of irradiation steps

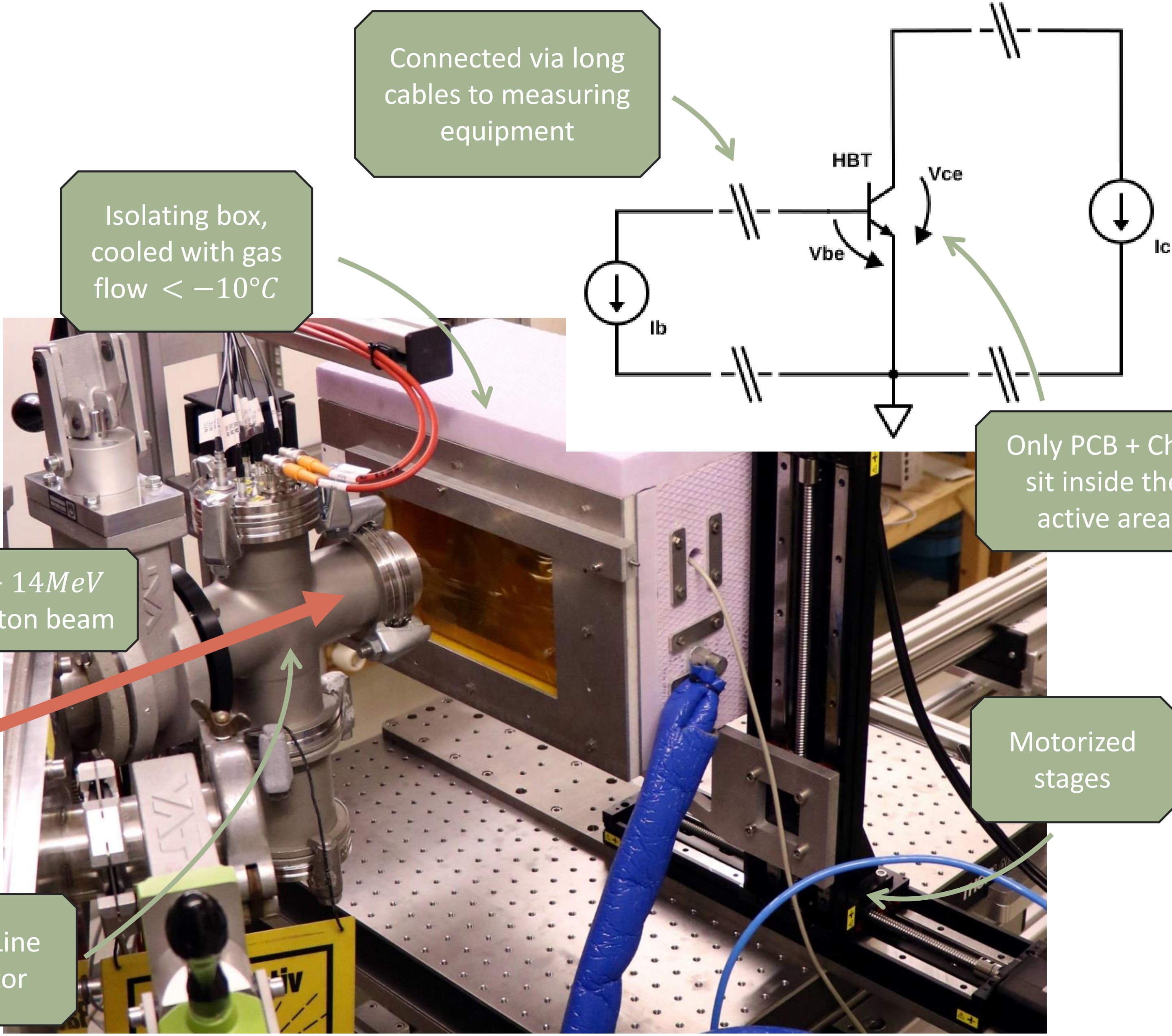


Setup

- 3 samples were measured
  - Up to $1.1e15\ n_{eq}/cm^2$
  - With ~5 steps in between

Problems:

- Due to the long cables no Gummel-Poon plots could be produced
- Temperature was not really stable



Connected via long cables to measuring equipment

Isolating box, cooled with gas flow $< -10°C$

Only PCB + Chip sit inside the active area

$7 - 14 MeV$ proton beam

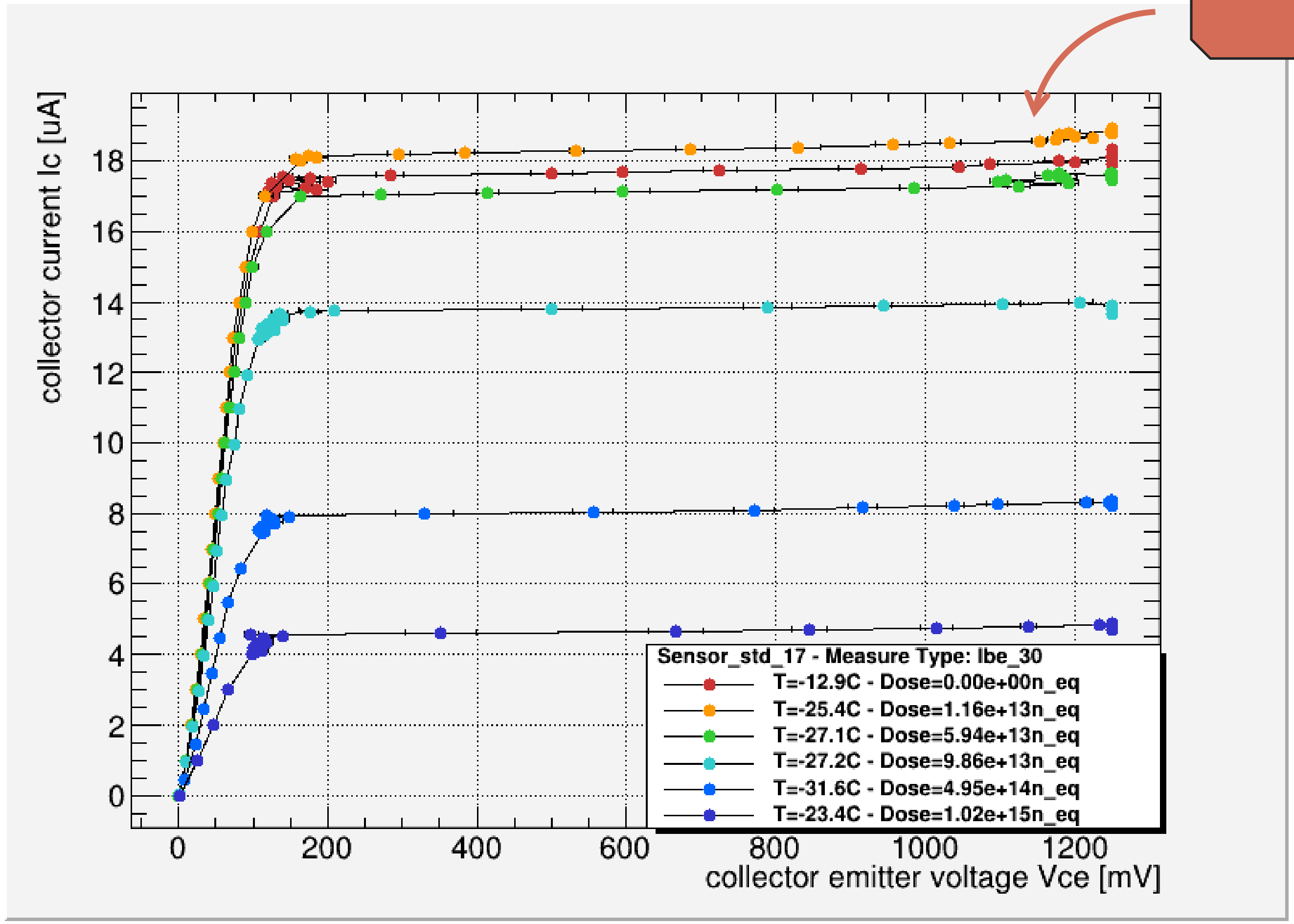
Motorized stages

Beam Line Monitor

Results after irradiation

- New measurement configuration:
  - Fixed value $I_b = 30nA$
  - Again β decreases with increasing dose
  - → I_c also decreases

Each curve is measured directly after an irradiation step



I_c increases after the first step?

Results after irradiation

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  - → I_c also decreases

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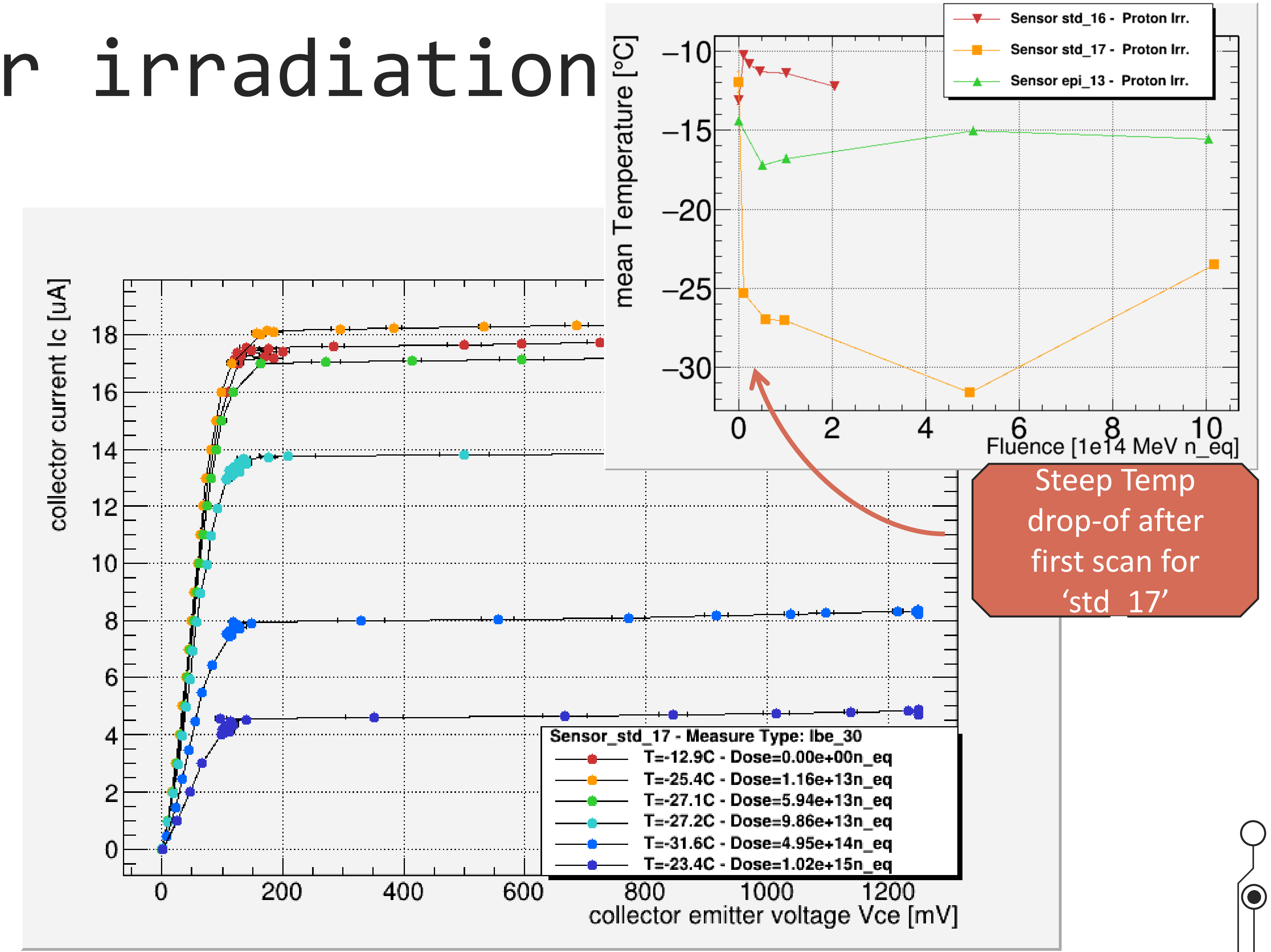
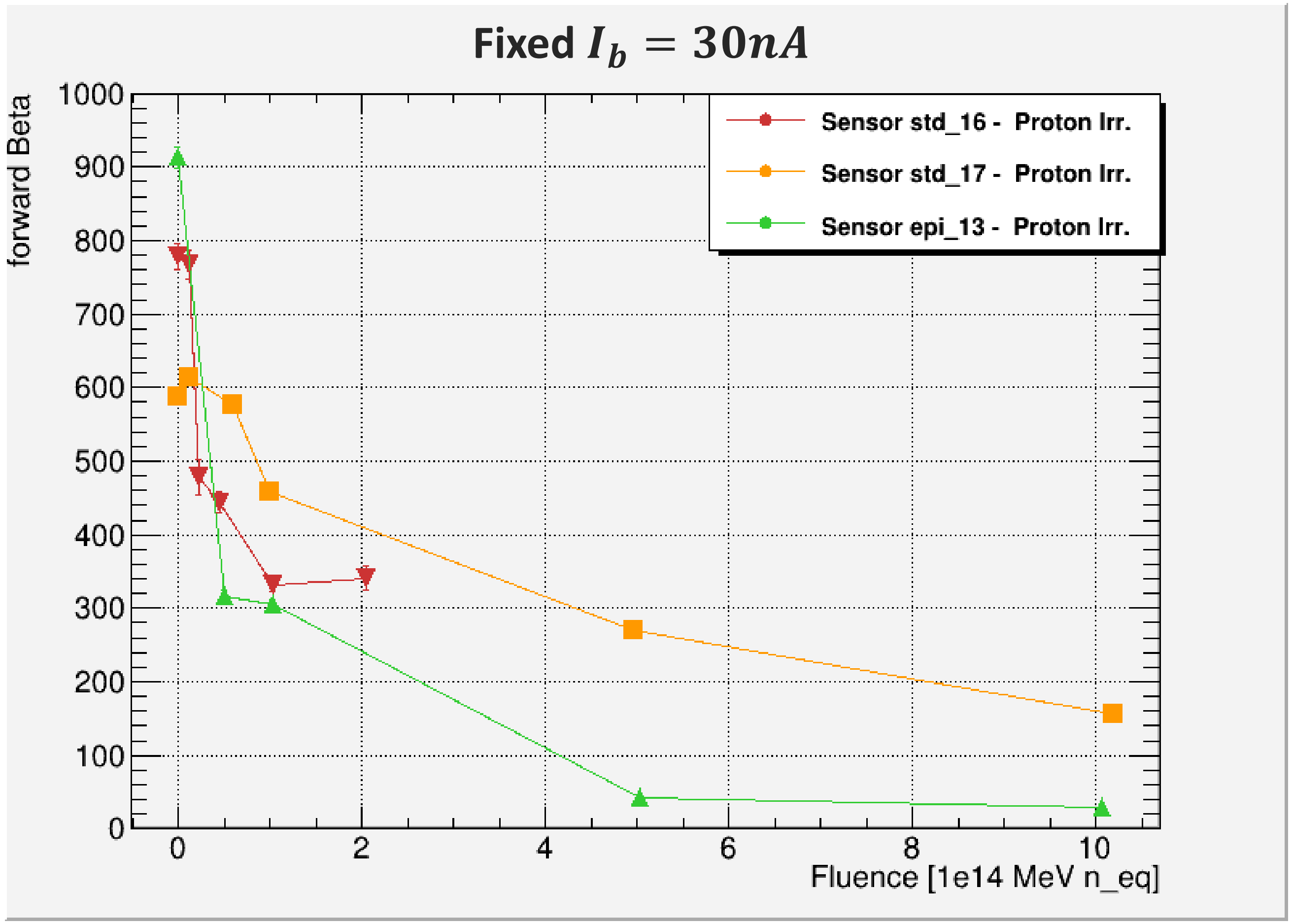


Steep Temp drop-of after first scan for 'std_17'

Results after irradiation

- For now: β is less temperate dependent
    - Most prominent dependencies from I_b and I_c cancel out
- Large chip-to-chip variation even before irradiation
- Steep performance decrease at low fluences

Keep in mind:
$I_b = 30nA$
is a low power working point



Results after irradiation

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    - Most prominent dependencies from I_b and I_c cancel out
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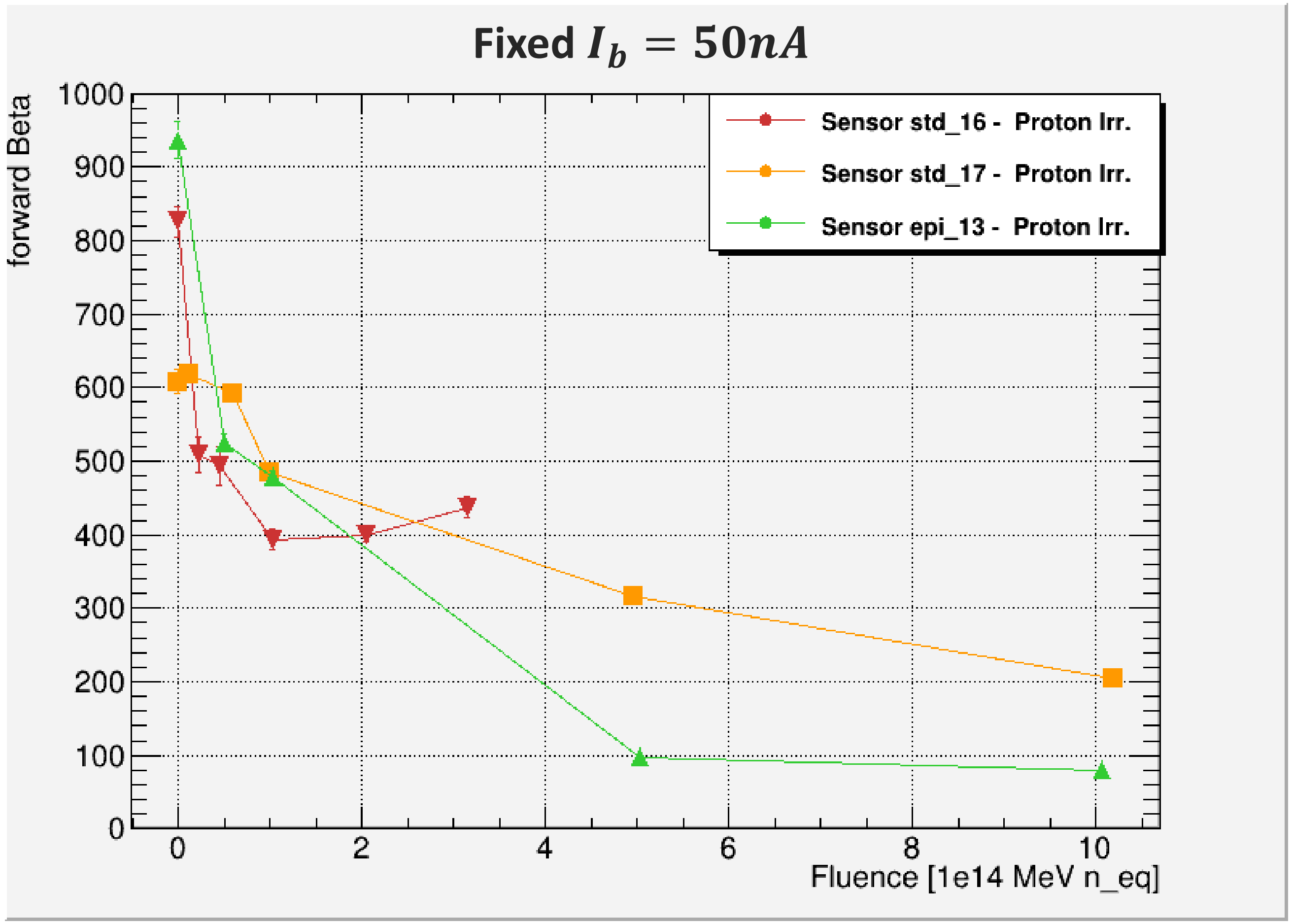
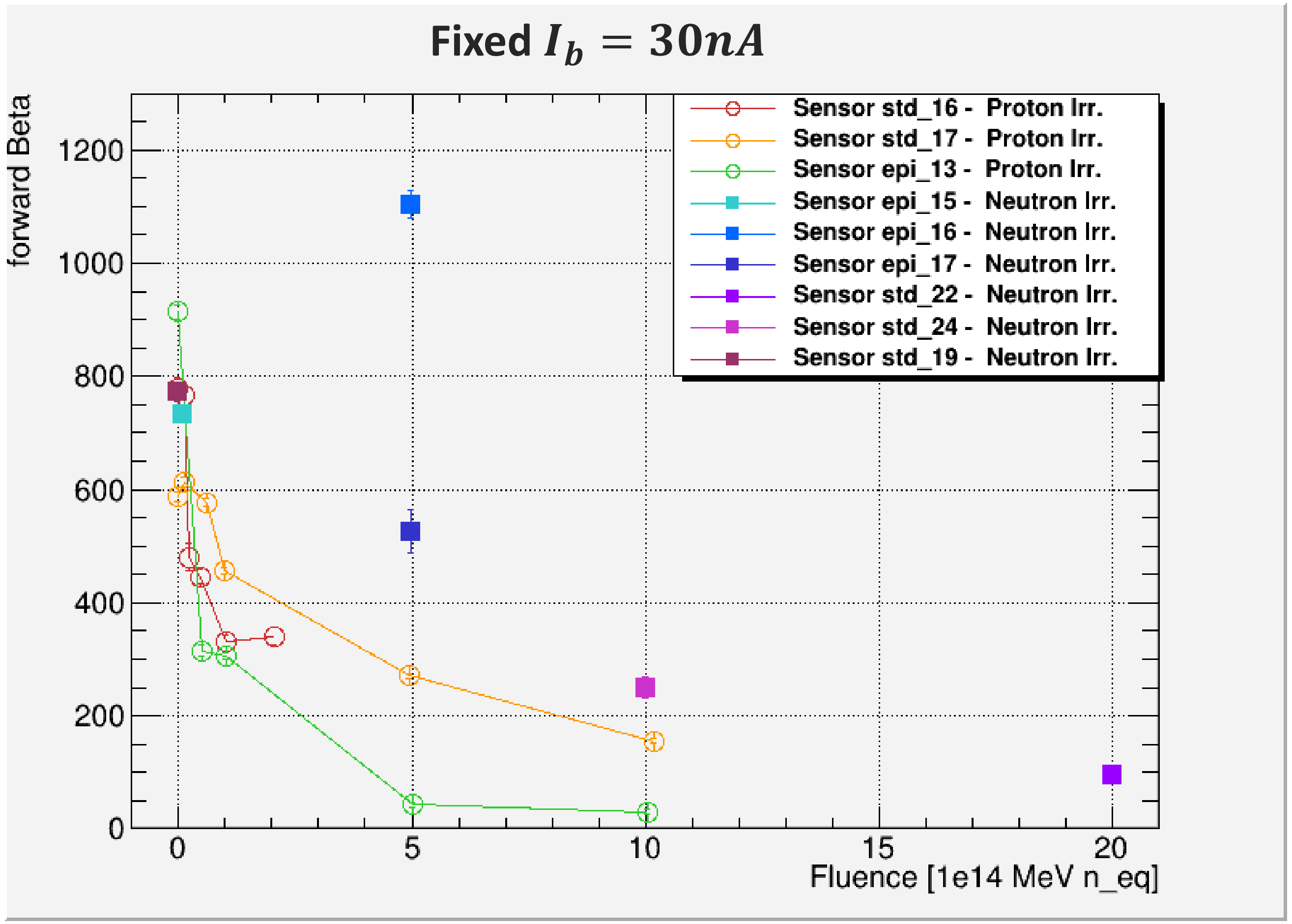
Performance increase already at $I_b = 50nA$

Fixed $I_b = 50nA$



Neutrons vs Protons

- Proton seem to have an larger effect already at lower fluences
  - ○ Additional Ionization damage
  - → Influence should be minimal, since the HBT was not powered during irradiation
- Chip-to-chip variations have an huge influence
- Even after a large dose all samples are still working



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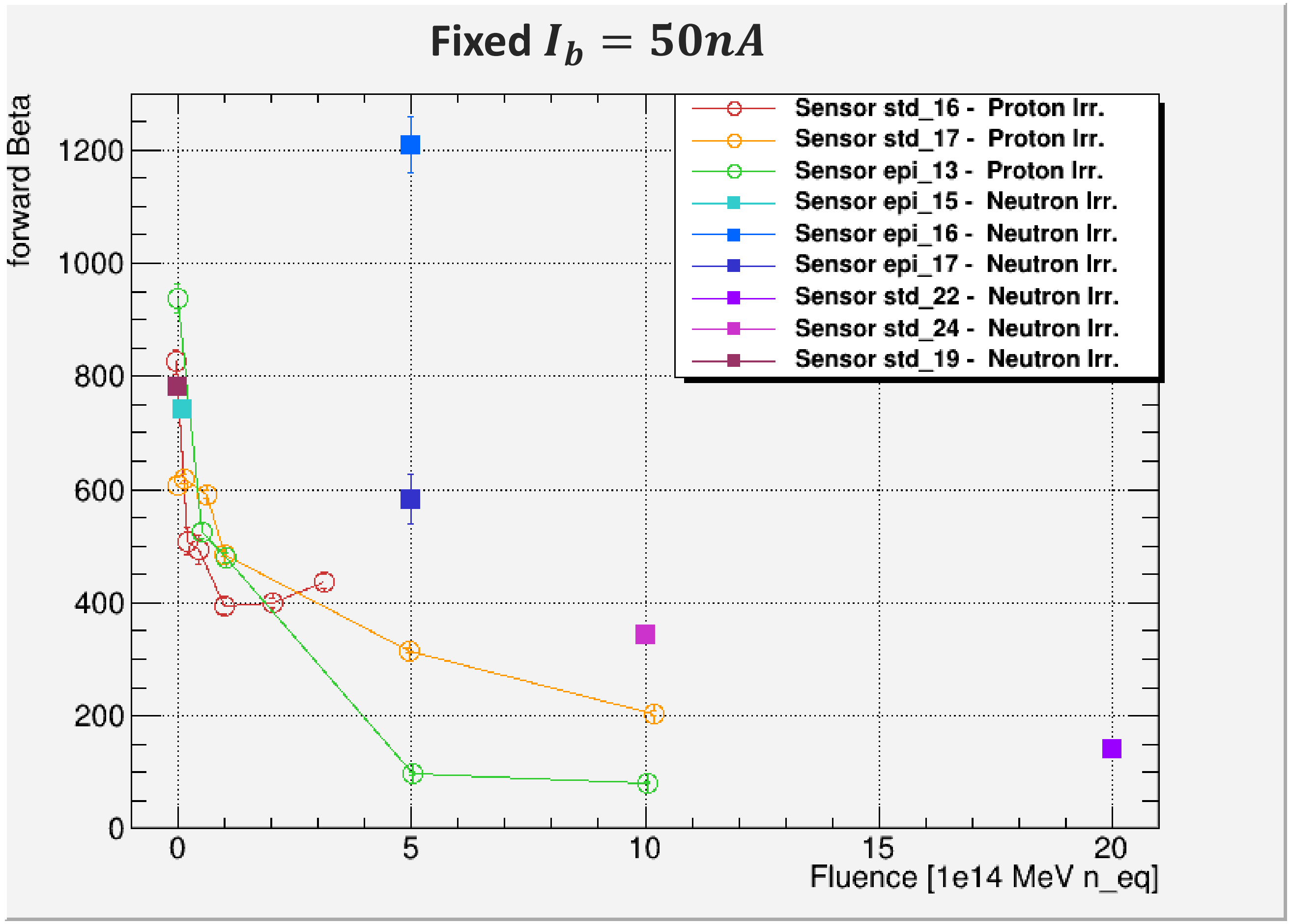

Lessons learned

Neutron irradiation

- Normally only possible to irradiate bare chips
  - → Reference measurement not easy
  - ! Need to deal with chip-to-chip variations !
- In principle, an in-situ measurement at the **TRIGA Mark II** research reactor in Mainz would be possible
  - Large effort needed, to bring a setup close to the reactor

Lessons learned

Proton irradiation

- Measuring in between irradiation steps offers a lot potential
  - Having a large distance between measuring equipment and a fragile test structure can induce some problems
  - A better/ more stable temperature control would help a lot
- The cyclotron needs a long time to power on, 3-4h until everything is setup
- For next time: also irradiate while the device is powered
  - Was not done to reduce the risk of total failure of the samples

In general:

❗Single transistor test structures are fragile❗

What else can be done?

- There was no further investigation of the proton irradiated samples
    - Still stored in Bonn
- Annealing studies
    - Repeating the measurement after different annealing times
- The Samples also hold some test sensors
    - First results for a bandgap and a digital-to-analog circuit are already produced

References

- John Cressler, Radiation Effects in SiGe Technology. 2013, DOI: 10.1109/TNS.2013.2248167
- Gerhard Lutz, Semiconductor Radiation Detectors. 2007, DOI: 10.1007/978-3-540-71679-2
- Michael Moll, Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties. 1999, Hamburg
- Xiang-Ti Meng et al., Effects of neutron irradiation on SiGe HBT and Si BJT devices. 2003, DOI: 10.1023/A:1022977828563
- Vinayakprasanna N. Hegde et al., Reliability studies on bipolar transistors under different particles radiation. 2023, DOI: /10.1016/j.sse.2023.108671