der Bundeswehr
Universität München

Prospects of proton and ion microbeams for radiation hardness testing

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Content

- What do we not know from conventional radiation hardness testing?

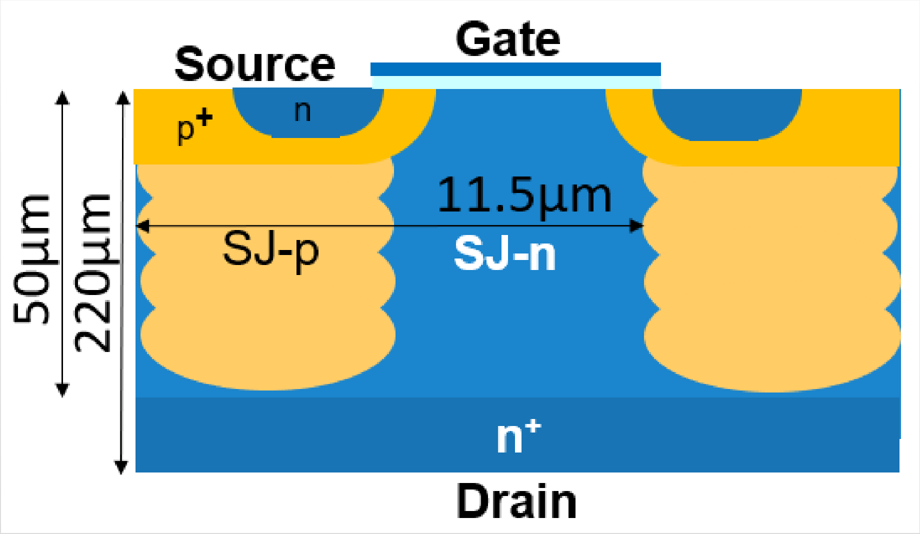
- How does an ion microbprobe work?

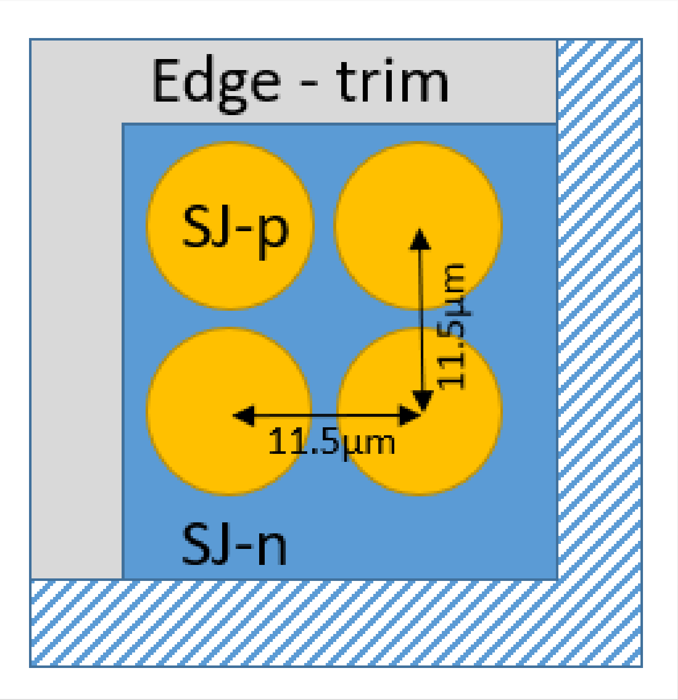
- Ion microprobes in radiation hardness testing:
  what can we learn?

- Micrometer focused, nanosecond proton bunches: a surrogate for heavy ion hardness testing ?

Vertical Silicon Superjunction MOSFET (Si-SJ-MOSFET)

- High voltage blocking capability;
- High current



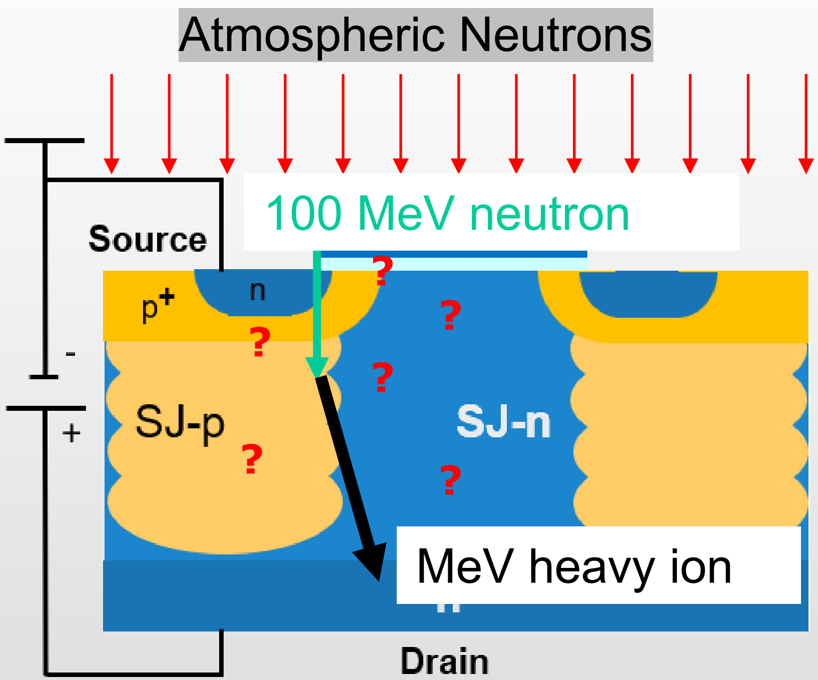


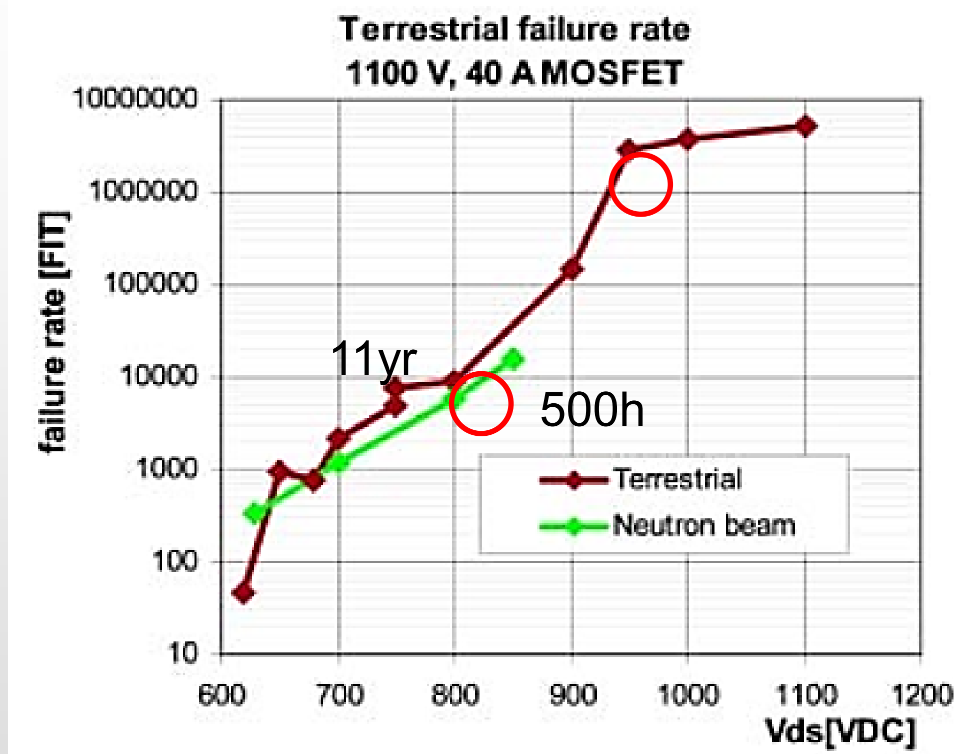
Cross sectional view (x-z-plane)

Top view (lateral x-y-plane)

M. Gerold et al., Microelectronics Reliability, 155 (2024) 115309
M. Gerold et al., IEEE, 2018, doi: 10.1109/IPFA.2018.8452587.

Failure Rate Testing:
State of the art radiation hardness testing





Lomonova et. al, Bodo's Power System Dec. 2011

- Voltage derating necessary
- sensitive areas and dynamics of the failure?
- Main reactions: heavy ion recoils from high energy neutrons
- Heavy ion microbeams to get knowledge on sensitive areas?

M. Gerold et al., Microelectronics Reliability, 155 (2024) 115309
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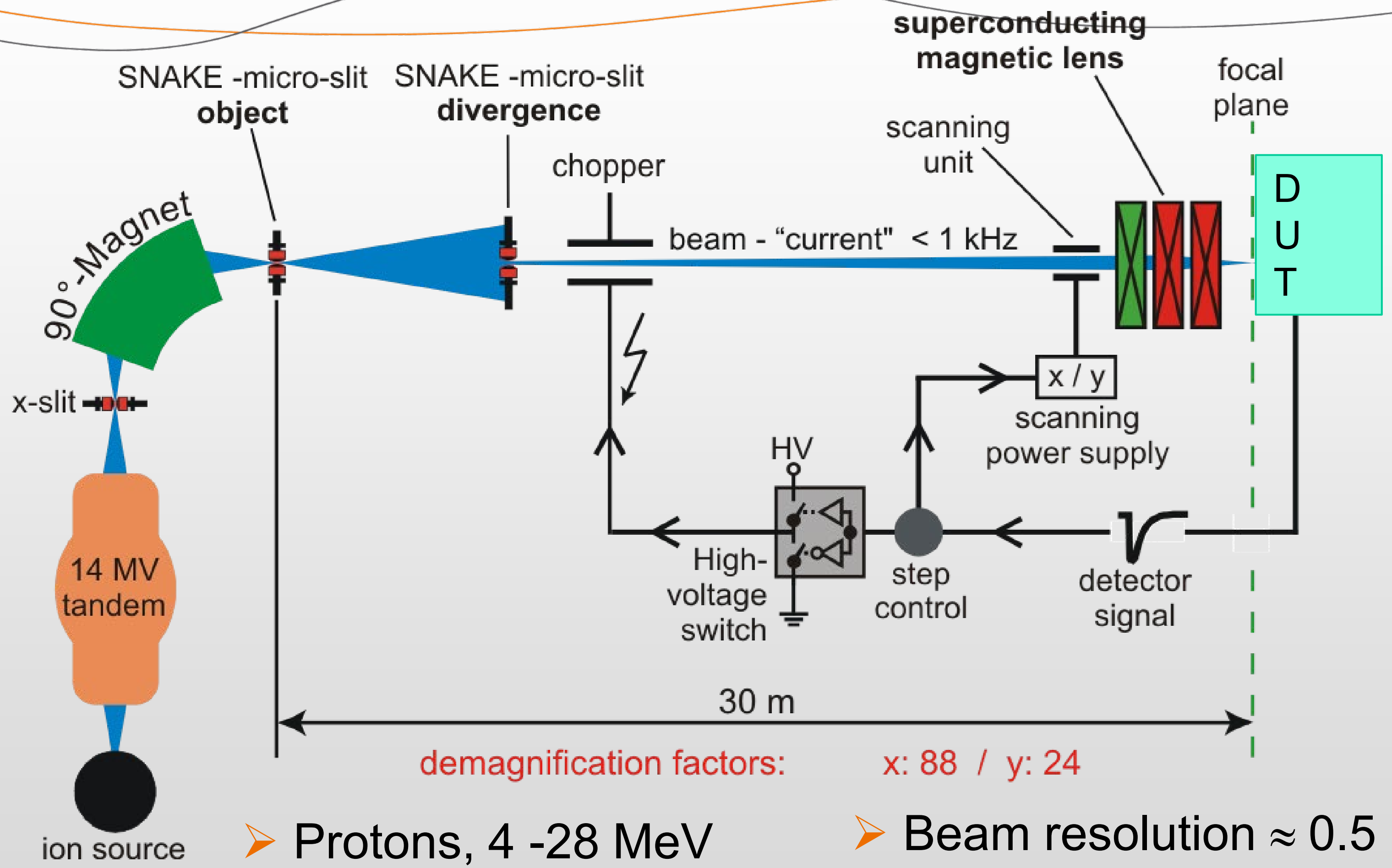
What is an ion microprobe
here: the former SNAKE facility

Superconducting Nanoscope for Applied nuclear (Kern-) physics Experiments

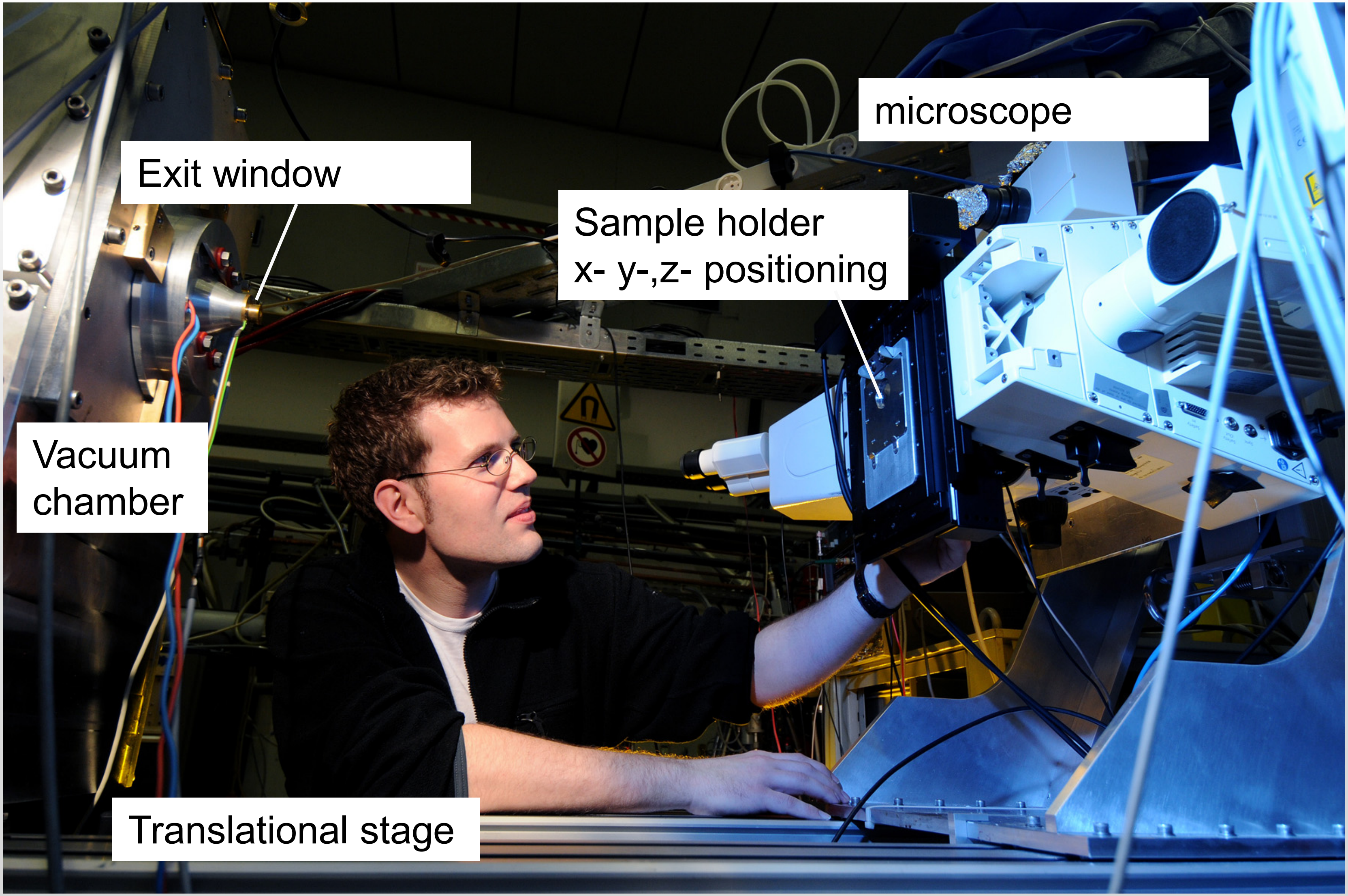


demagnification factors: x: 88 / y: 24

- Protons, 4 -28 MeV
- heavy ions – 200 MeV
- Beam resolution ≈ 0.5 µm (fwhm)
- Single ion irradiation facility

G. Datzmann et al; NIM B 181 (2001) 20, G. Dollinger et al; NIM. B 231 (2005) 195,
V. Hable et al, NIM B 267 12-13 (2009) 2090

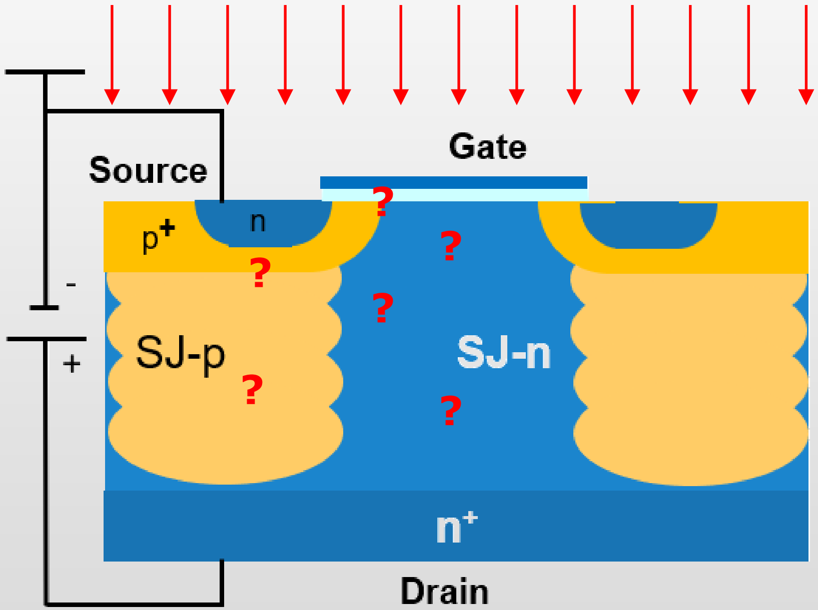
Sample environment in air, or alternatively in vacuum



Charge collection from heavy ion irradiation Si-Superjunction MOSFET

Focused, single 55 MeV ^{12}C-ions

(37.5 MeV Drift Region), LET 2.3 - 4.0 MeV cm^2/mg

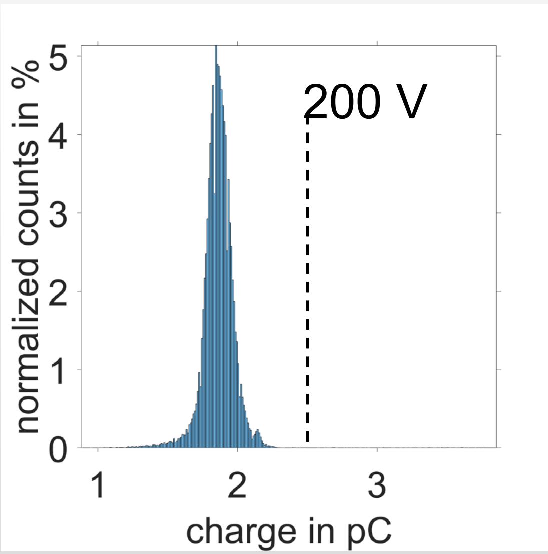


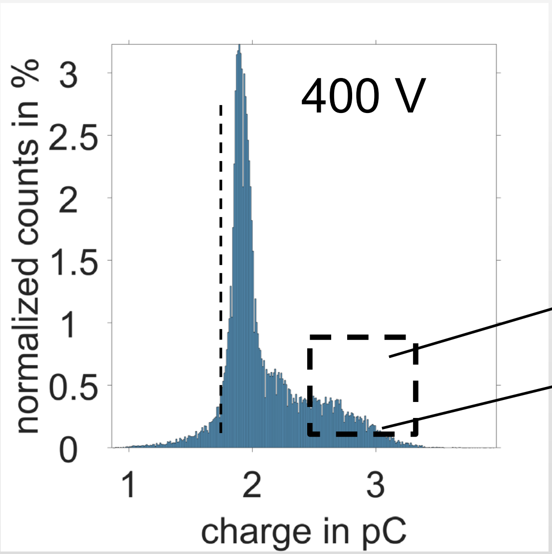
Ion mapping in dependence of voltage Si-SJ-MOSFET

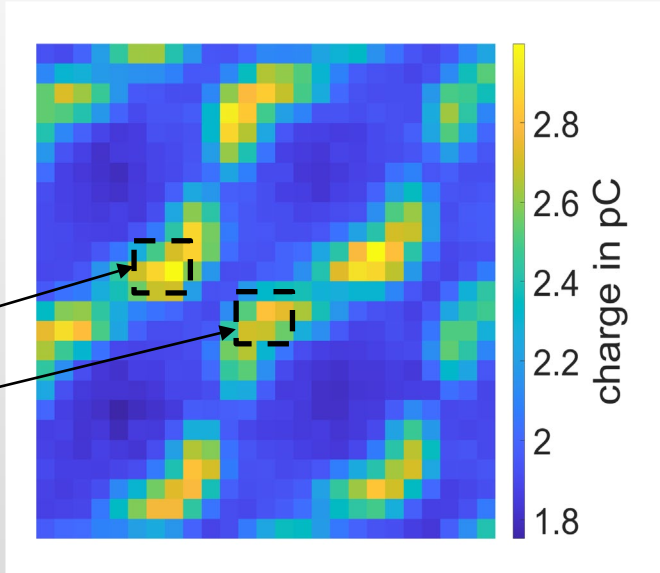
- 55 MeV Carbon
- Expected charge collection: 1.7 pC

Charge collection spectrum

25x25 µm charge collection map



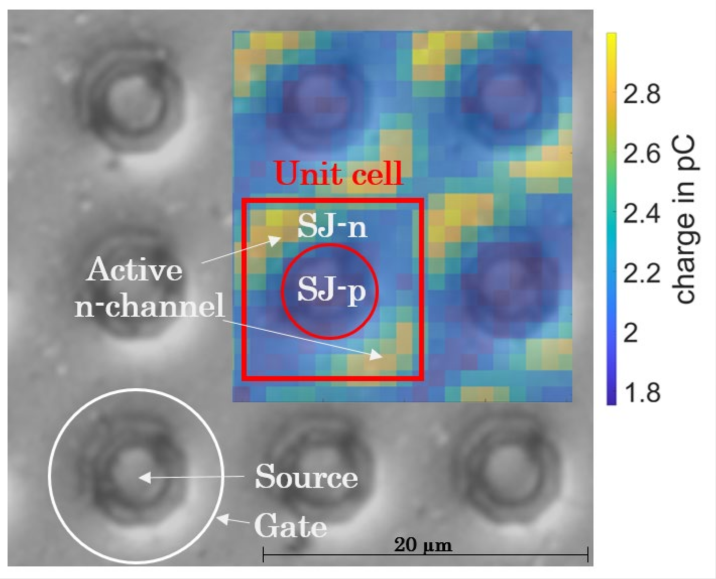


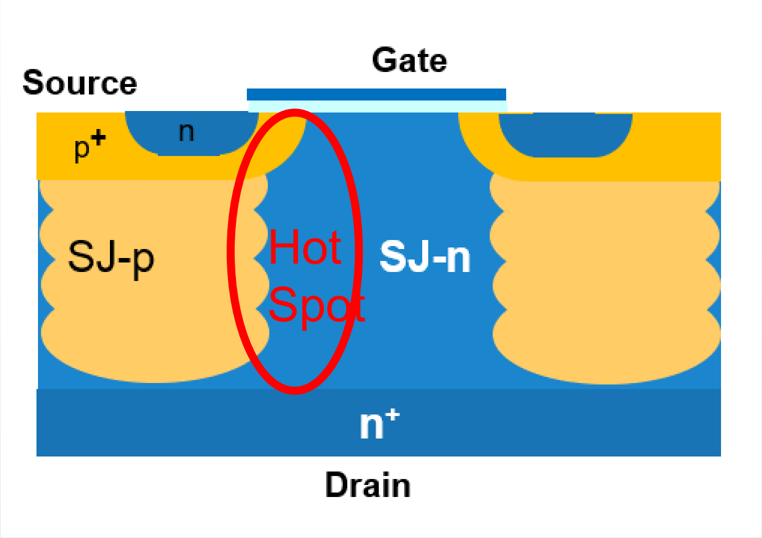


- Amplification at symmetric spots at 400 V

M. Gerold et al., Microelectronics Reliability, 155 (2024) 115309
M. Gerold et al., IEEE, 2018, doi: 10.1109/IPFA.2018.8452587.

Ion Mapping Results: Sensitive Locations





- Pattern evolves from 200V to 400V (SOA)

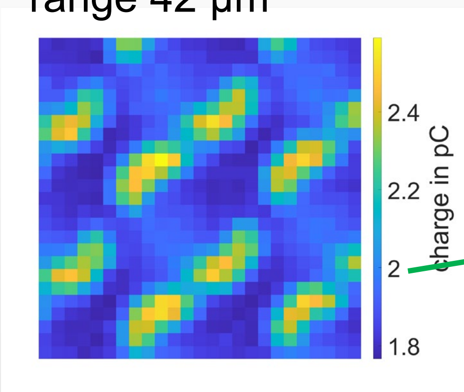
M. Gerold et al., Microelectronics Reliability, 155 (2024) 115309
M. Gerold et al., IEEE, 2018, doi: 10.1109/IPFA.2018.8452587.

Ion Mapping: Partial Penetration of Drift Region

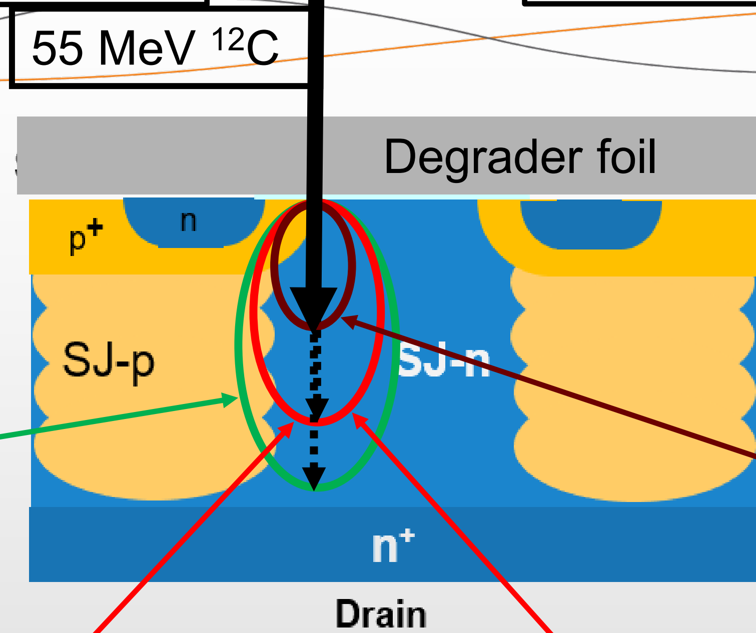
C, Max LET 5.2 MeV cm²/mg

S, Max LET 17.2 MeV cm²/mg

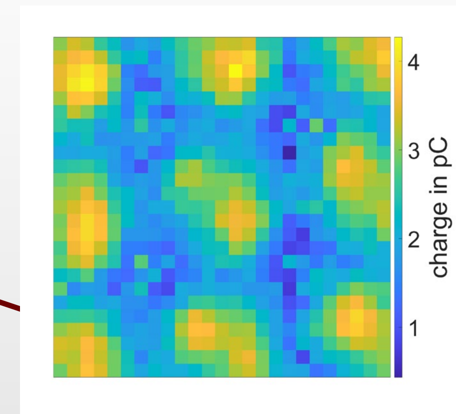
400 V, 55 MeV C, Ion range 42 µm



mean sensitivity x1.5

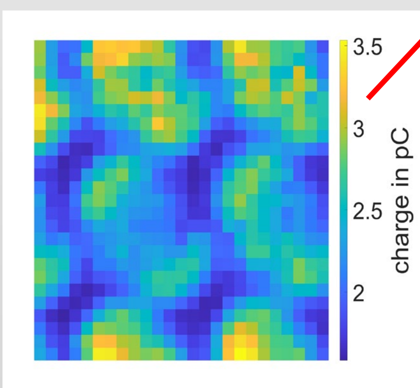


400 V, 14 MeV C, Ion range 13 µm



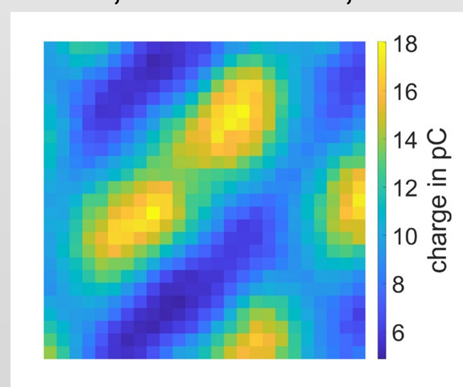
mean sensitivity x6.7

400 V, 27 MeV C, range 29 µm



mean sensitivity x2.2

370 V, 110 MeV S, Ion range 26 µm



mean sensitivity x4.5
Base sensitivity x1.5

M. Gerold et al., Microelectronics Reliability, 155 (2024) 115309
M. Gerold et al., IEEE, 2018, doi: 10.1109/IPFA.2018.8452587.

Single Event Transients (SET) in 65 nm CMOS IC GSI-Microbeam, 946 MeV Au (LET = 95 MeV cm²/mg)

M. Mitrovic, M. Hofbauer et al

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 8, AUGUST 2017

Spacing 0.12 µm
Pitch 0.5 µm

Spacing 0.25 µm
Pitch 0.63 µm

Spacing 2 µm
Pitch 2.38 µm

Spacing 4 µm
Pitch 4.38 µm

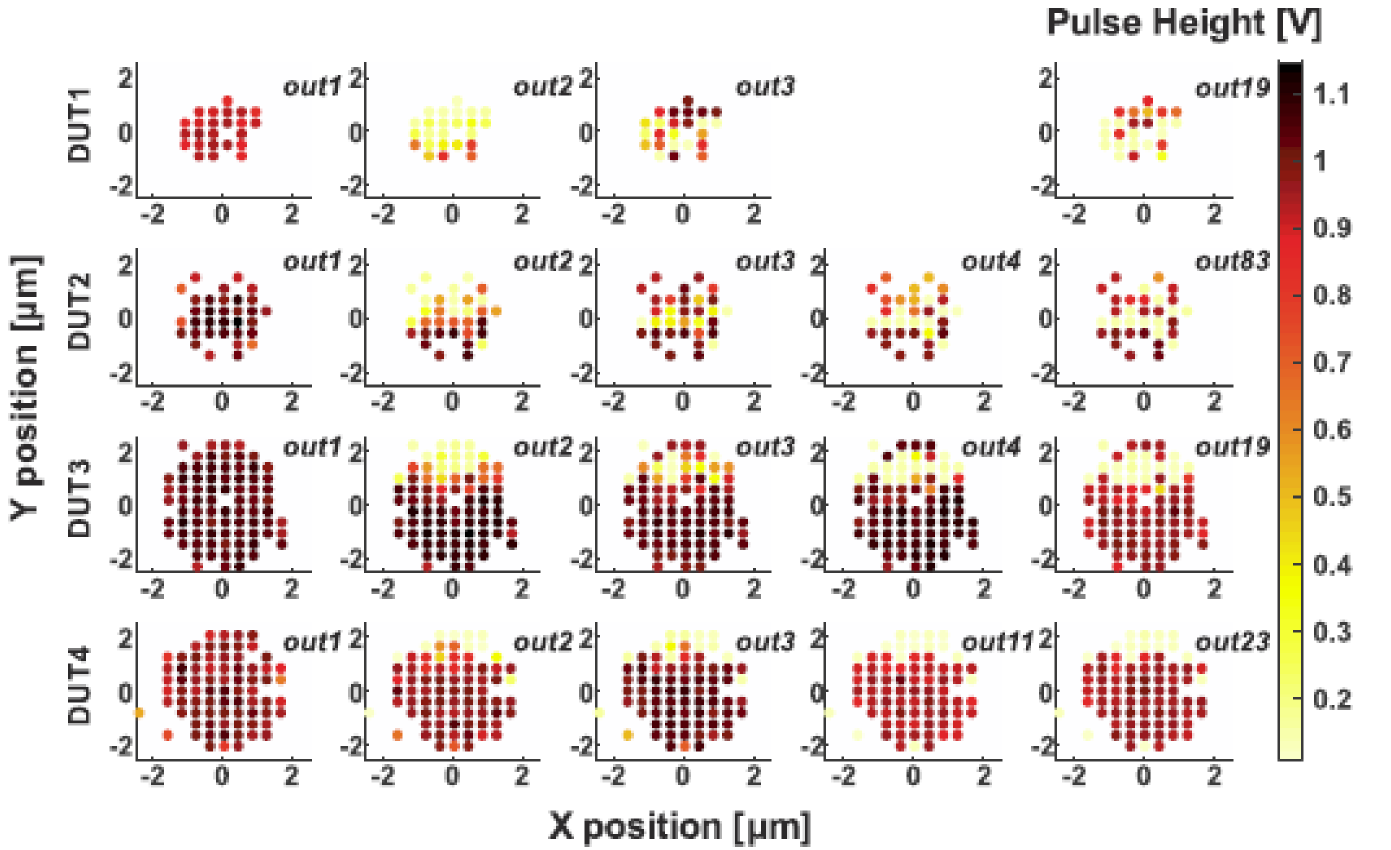
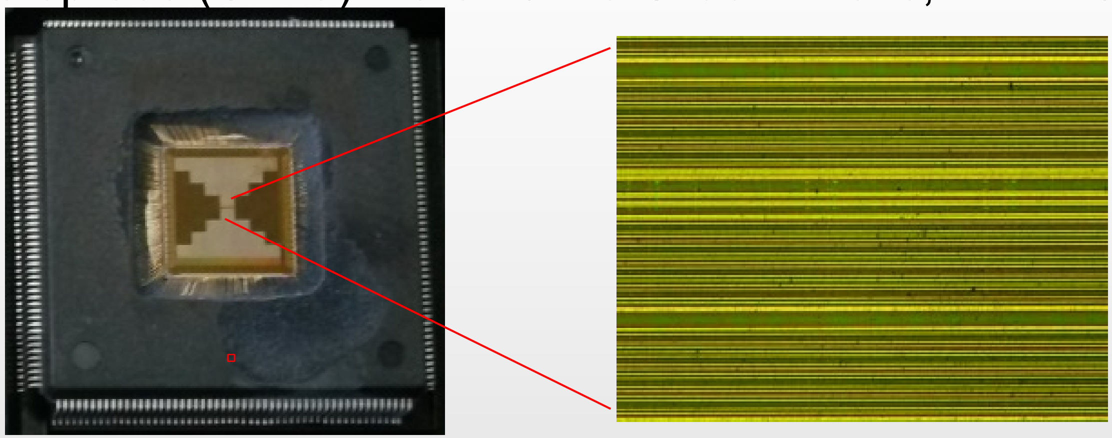
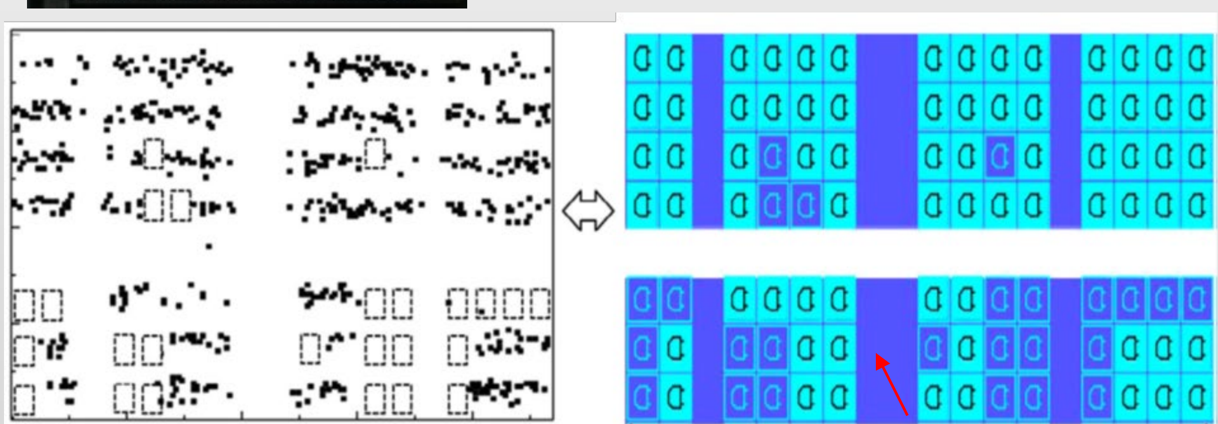


Fig. 8. Distribution of pulse heights for direct-hit SETs generated at the first inverter by ^{197}Au ions as a function of ion hit position, observed along the propagation through the chain.

Configure register of an FPGA, installed in Dark Matter Particle Explorer satellite-DAMPE

Lanzhou microprobe (China): here 25 MeV/nucl Kr-ions, LET=18.8 MeV cm²/mg





SEU image of configured DFFs in scanned area

The scanned area in logic configuration diagram

Individual bits without written data

IEEE TNS 69:890-899(2022)

In courtasy Guanghua Du, Lanzhou

NIMB 404:250-253 (2017)

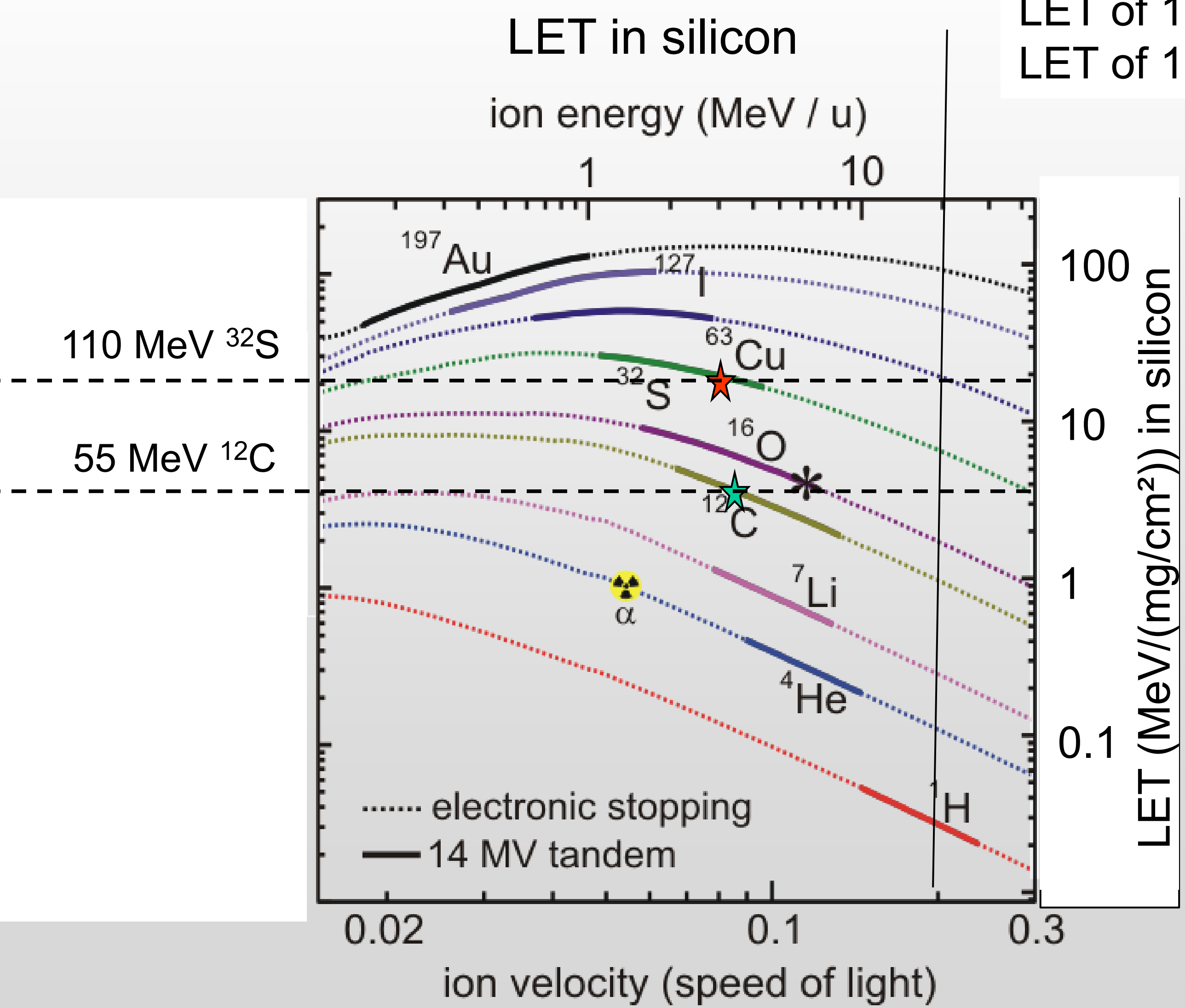
Some Heavy Ion Microprobes

- SNAKE, Munich/Germany, 14 MV tandem, no longer available
- GSI microprobe, Darmstadt/Germany, < 11 MeV/nucl, all heavy ions
- Helmholtz Zentrum Dresden Rossendorf (HZDR) 6 MV Tandem (under construction)
- Ruder Boscovic, Zagreb/Croatia,   6 MV Tandem
- Lanzhou, China, (cyclotron, e.g. 25 MeV/nucl Ar, Kr)
- ANSTO Sydney, 10 MV tandem
- JAERI, Takasaki, Japan
- Sandia national lab, (not in operation at the moment)

- Others?

Linear Energy Transfer (LET) of Various Ions

LET of 117 protons (20 MeV) equals
LET of 1 carbon ion (55 MeV)



Terestrial neutrons:
Recoil ions in
Si or SiC have A < 31

⇒ ^{32}S ions upper limit?

⇒ In space also heavier ions,

⇒ but most protons up to A < 58

Bunched Protons as a Heavy ion surrogate?

- Only a few facilities offer heavy ions of sufficient range

- A new ansatz:
  - Focus a bunch of 5 – 25 MeV protons (100 – 1000)
    - In time (~ ns)
    - In space (< 1 µm) (microprobe!) not easy!

  ⇒ Same LET as very heavy ions,

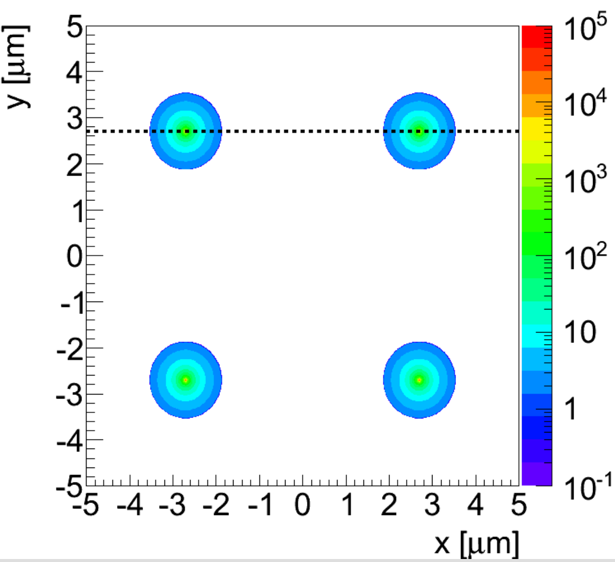
  ⇒ range from 200 µm to > 3 mm

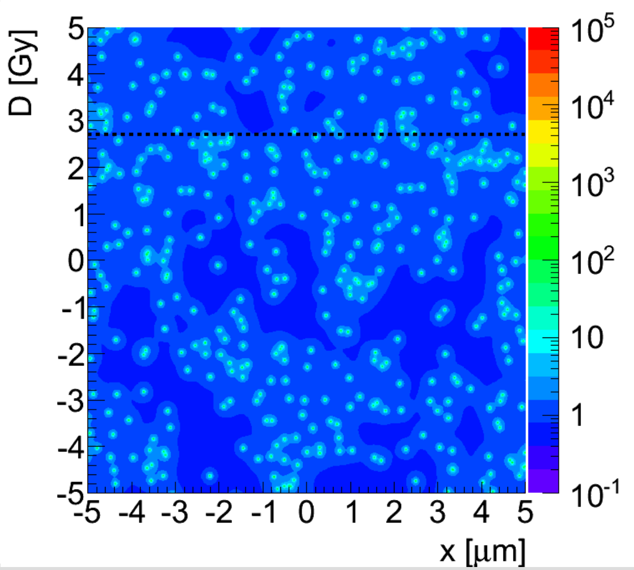
  ⇒ Available at medium sized tandem accelerators with bunching capabilities and ion microprobes?

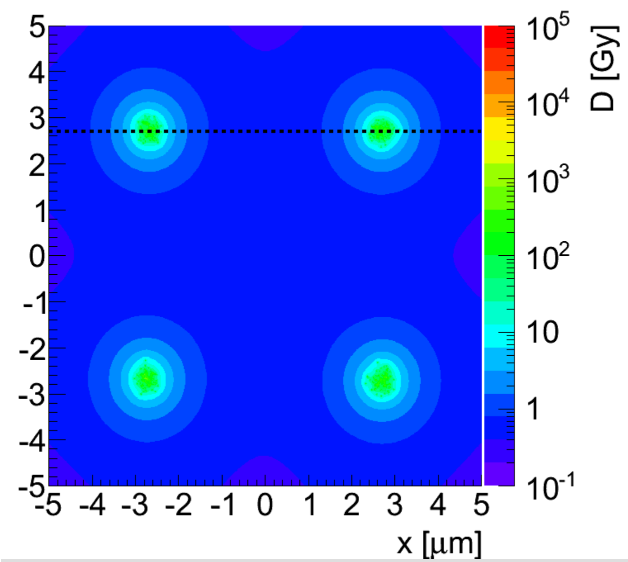
Bunched protons microdose distributions

LET (117 protons (20 MEV)) = LET (55 MeV carbon) = 304 keV/µm in water

1.7 Gy average dose







55 MeV carbon ions

20 MeV protons,
Randomly distributed

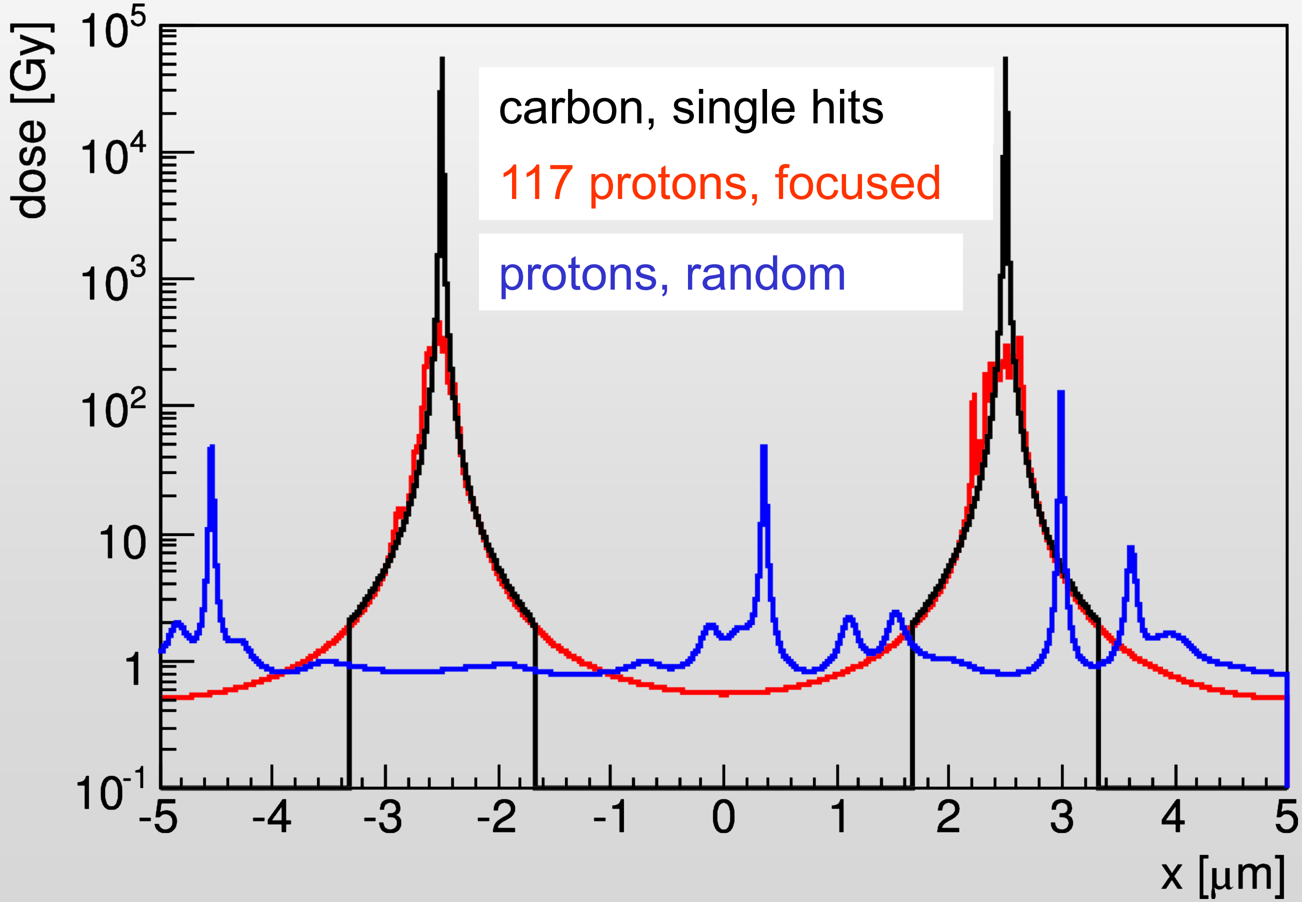
20 MeV protons,
117 protons per focus
300 nm diameter

Christoph Greubel, PhD theses, UniBwM 2013

Comparison of bunched protons to carbon ions

LET (117 protons (20 MEV)) = LET (55 MeV carbon) = 304 keV/µm in water

1.7 Gy average dose



matrix 5 * 5 µm²

matrix 5 * 5 µm²

300 nm focus

Conclusion

- Heavy ion microprobes:
  - Analyse areas in micro-electronics sensitive to heavy ions
  - Experienced people and longer experimental time needed
  - Only a few microbeams available world wide
  - Limited range of available heavy ion beams at many accaelerator centers
  - Proposal:

    bunched protons in space and time

    as a surrogate of high energy heavy ion (micro) beams

    Needs smaller accelerators but pulsed microbeams!?