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Nuclear Physics for Semiconductors & Solar Cells

- Nuclear Physics in a Nutshell
- Origin of Particles
- Interaction with Matter
- Irradiations
- Conclusion

Nuclear Physics meets Electronic Technology

- **from the website:**
  “The school is intended for PhD students, young post-docs, and researchers in the fields of nuclear physics, solid-state physics, and electrical engineering”

→ **different background, different knowledge**

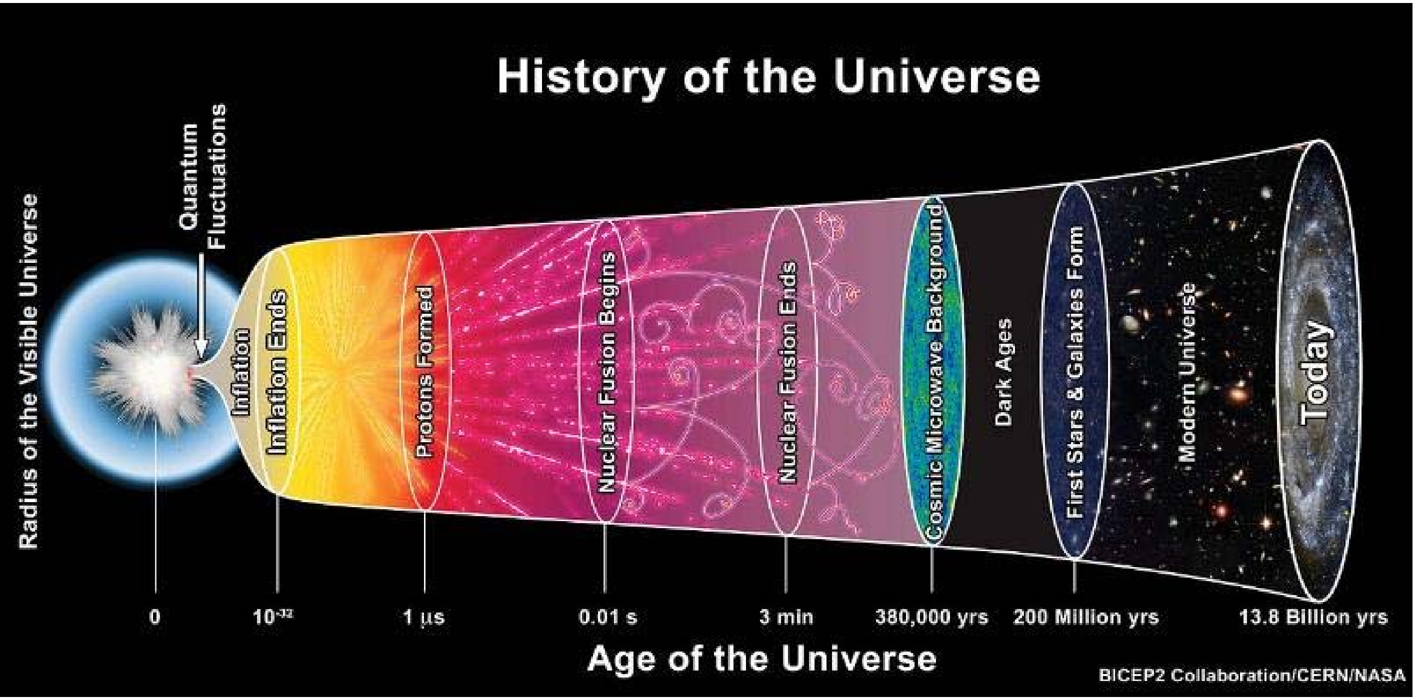
please accept my apologies if I am carrying owls to Athens

www.bundesbank.de/en/tasks/cash-management/euro-coins/regular-coins/greece-623692

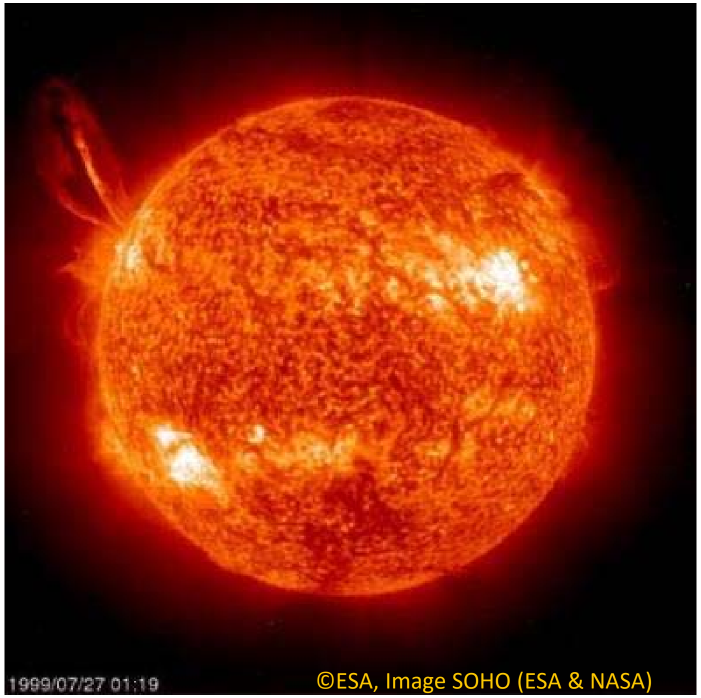
Nuclear Physics: Origin of the Elements

- **Big Bang: formation of Hydrogen and Helium in the first minutes**
- **humans consist of Carbon, Oxygen, …**

  all these elements are produced by nuclear reactions in stars



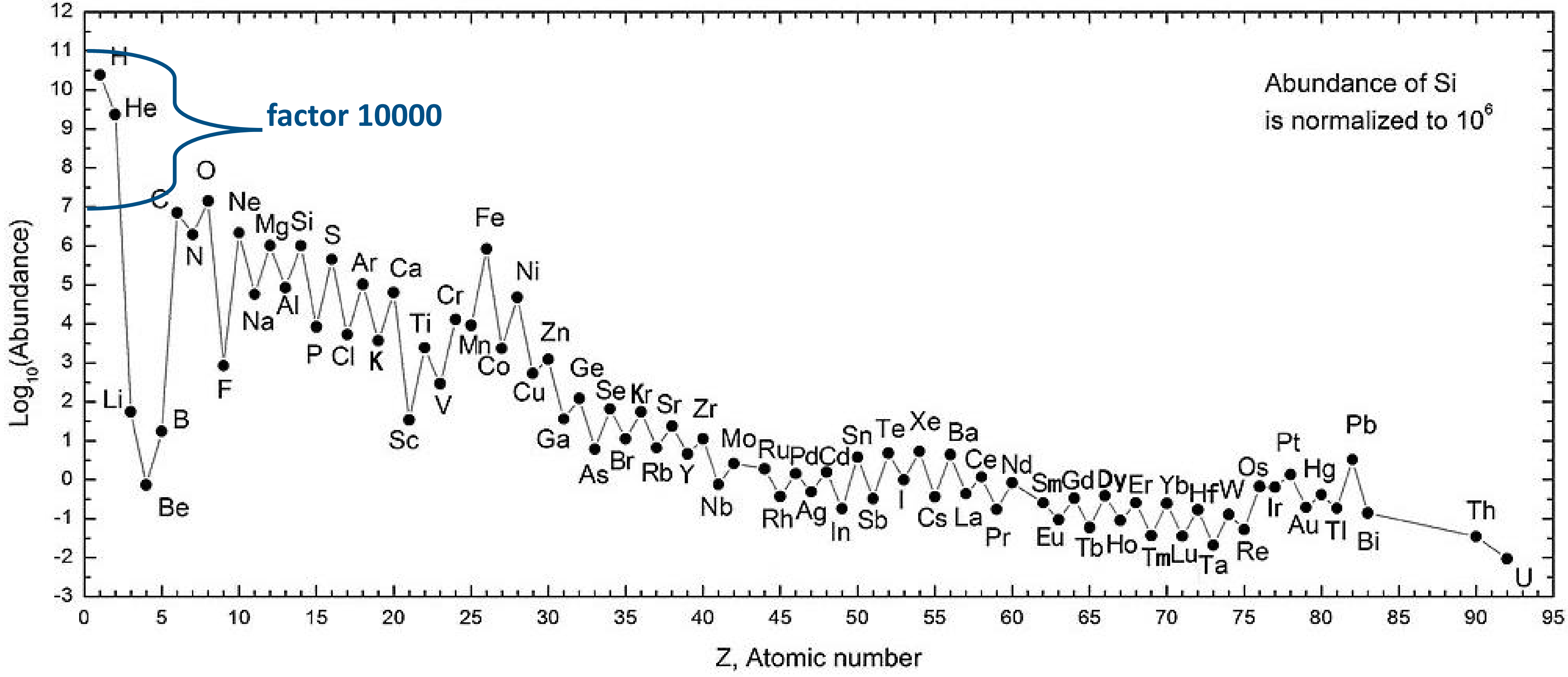
BICEP2 Collaboration/CERN/NASA



©ESA, Image SOHO (ESA & NASA)

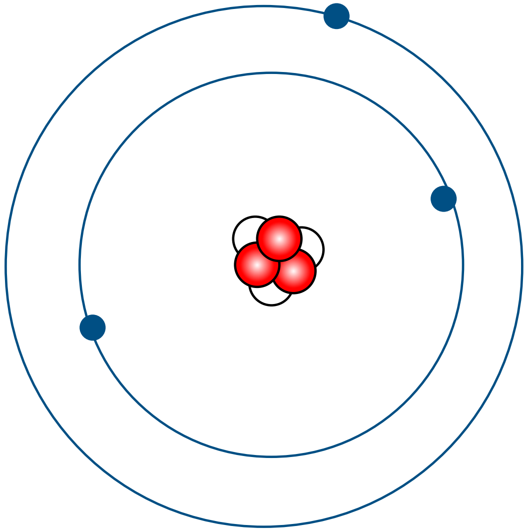
Relative Abundance of Elements in the Solar System

- **Hydrogen and Helium by far most abundant**



https://en.wikipedia.org/wiki/File:SolarSystemAbundances.jpg

Atomic structure and Notation of Particles

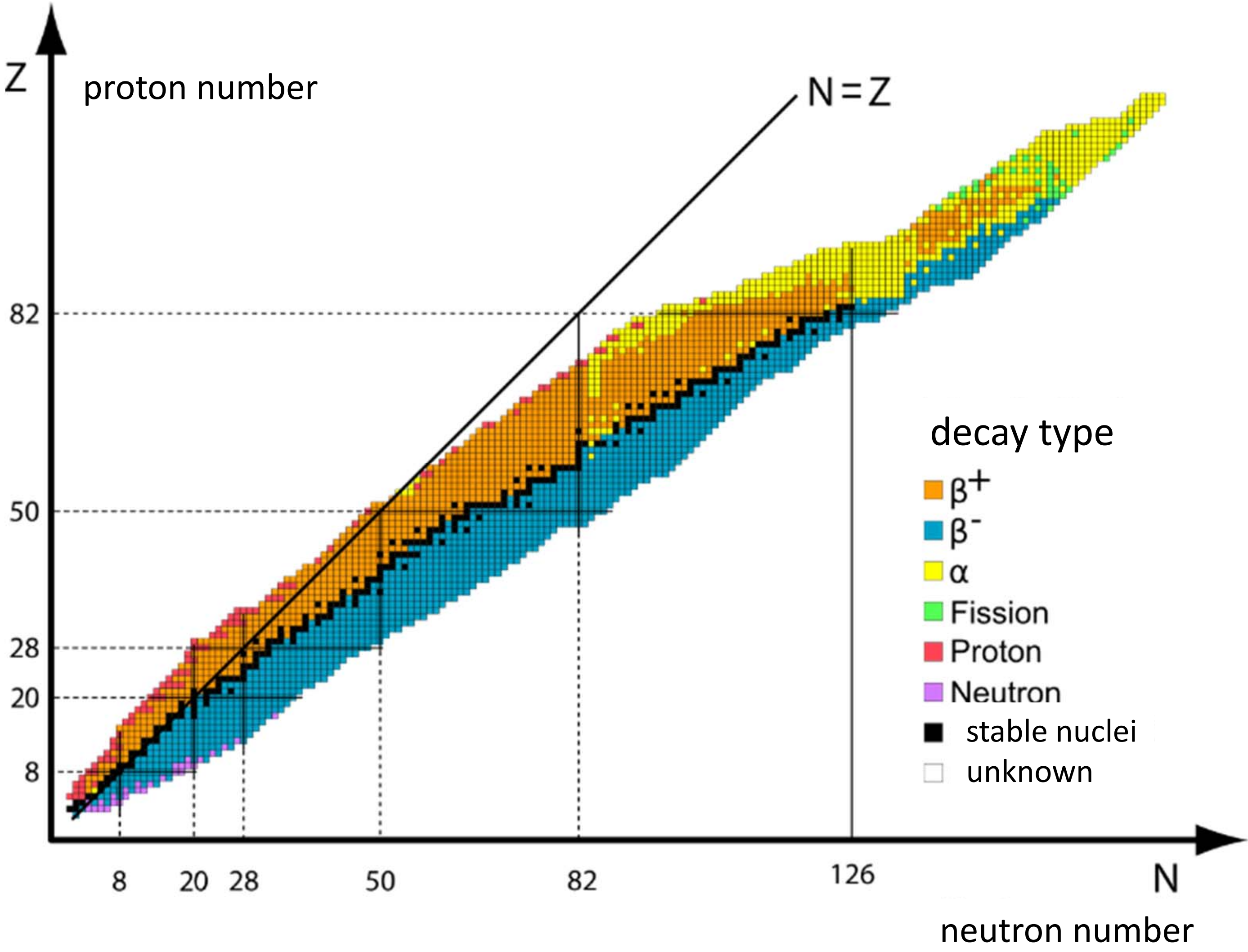


- **atom**
  - **electron shell with Z electrons**
  - **atomic nucleus with A nucleons: Z protons and N neutrons**
  - **Z + N = A**
- **notation:** ${}^{Z+N}_{Z}element = {}^{A}_{Z}element$

- **physicists count: 1 proton, 2 protons, 3 protons, …**
- **chemists count: Hydrogen, Helium, Lithium, …. = H, He, Li, ….**
- **usual notation:** ${}^{A}element$ **, e.g.:** ${}^{1}H$, ${}^{4}He$, ${}^{12}C$

Chart of Isotopes

- **sort atomic nuclei as a function of proton and neutron number**
- **Isotopes:**
  - **same Z**
  - **same chemical properties**
- **Isotone**
  - **same N**
- **Isobare**
  - **same A (Z+N)**
- **neutron number increases more than proton number**



Karlsruhe Chart of Isotopes

- **sort atomic nuclei as a function Z and N**
- **valley of stable isotopes: black boxes**
- **colours indicate decay type:**
- **pink:** $^{13}_{8}O \rightarrow {}^{13}_{7}N + \beta^{+} + \nu$
- **light blue:** $^{12}_{4}Be \rightarrow {}^{12}_{5}B + \beta^{-} + \overline{\nu}$
- **yellow :** $^{8}_{4}B \rightarrow {}^{4}_{2}He + \alpha$
- **orange:** $^{16}_{9}F \rightarrow {}^{15}_{8}O + p$
- **half lives, rule of thumb:**
  the further away from the valley, the shorter the half live

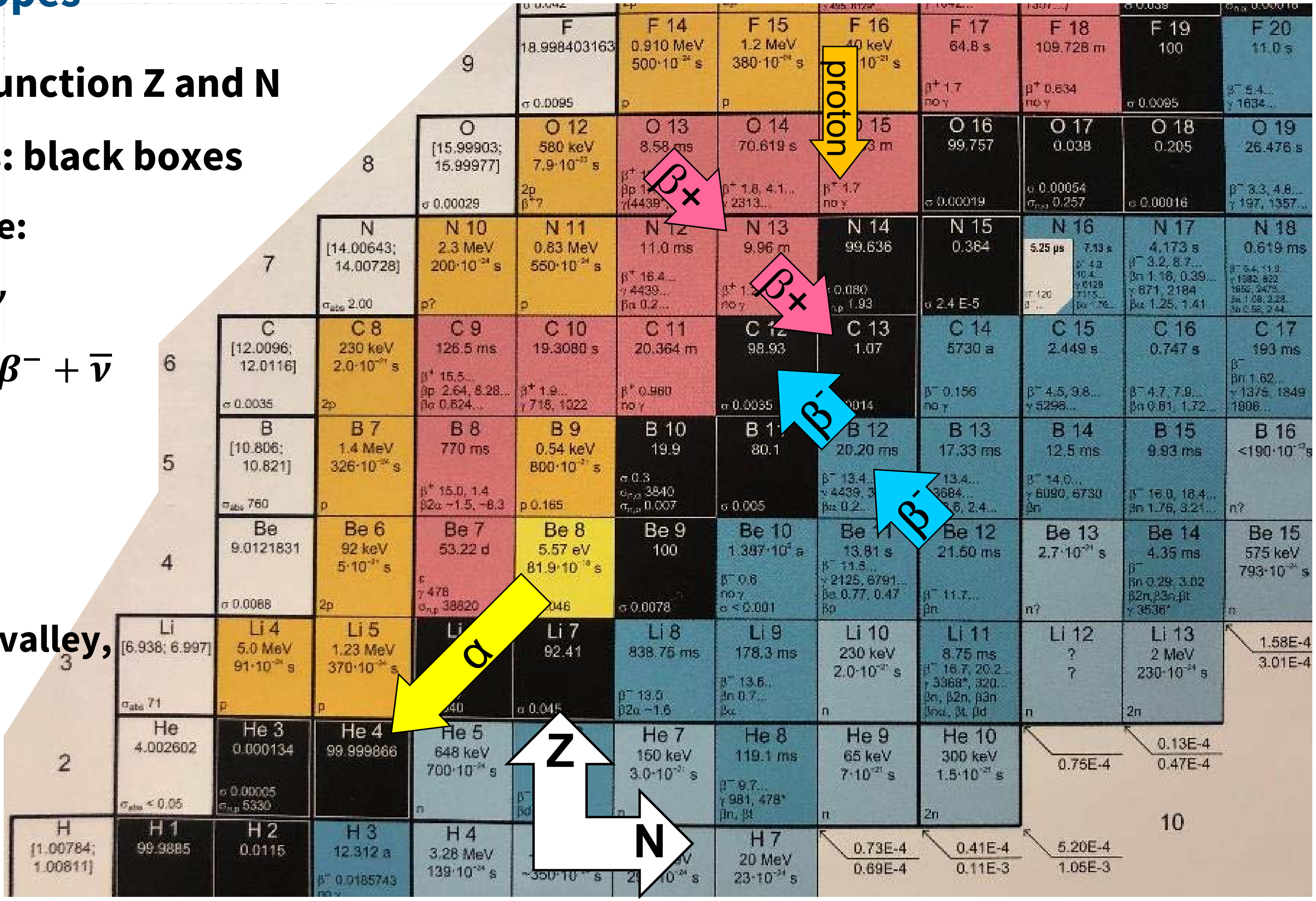
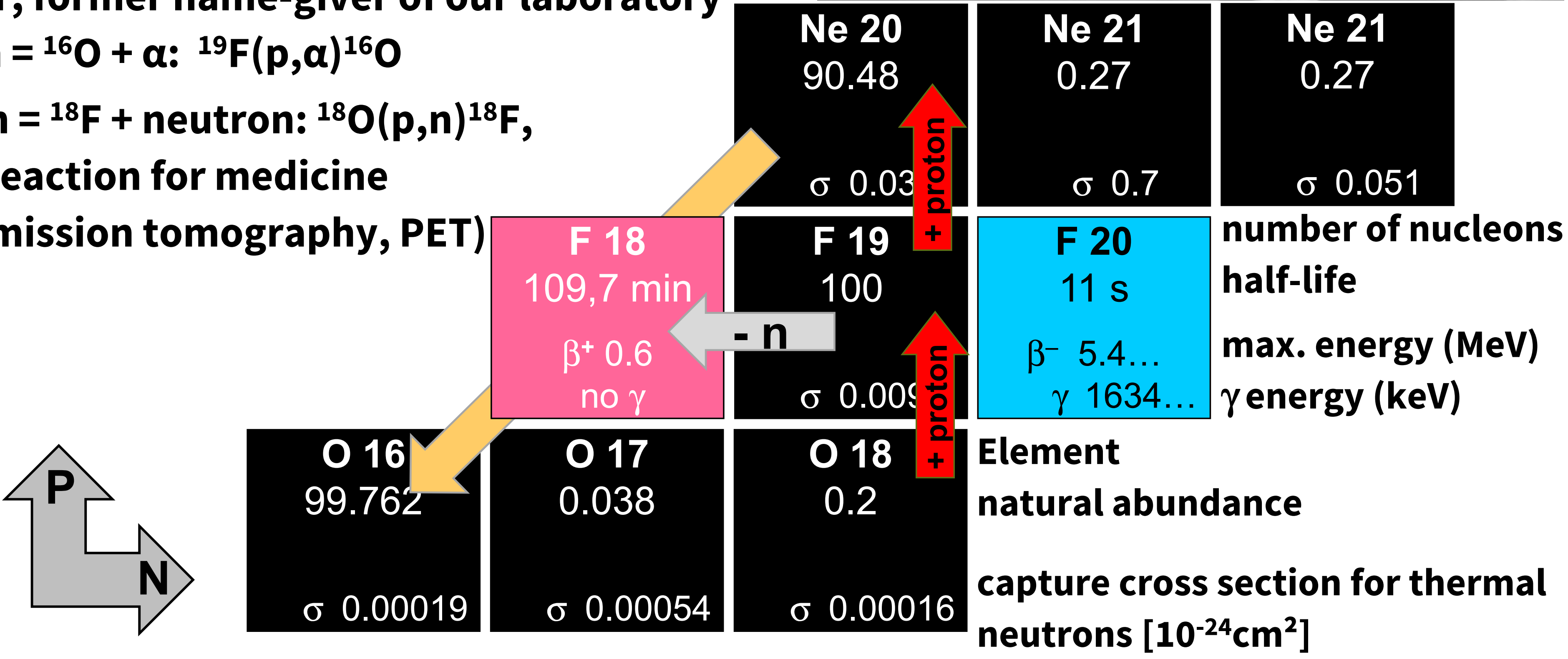


Chart of Nuclides: Details & Nuclear Reactions

- **Information about natural abundance and probability of neutron capture**
- **information about energies of emitted particles**
- **Lise Meitner, former name-giver of our laboratory** **^{19}F + proton = ^{16}O + α: ^{19}F(p,α)^{16}O**
- **^{18}O + proton = ^{18}F + neutron: ^{18}O(p,n)^{18}F, important reaction for medicine (positron emission tomography, PET)**

https://hzbblog.de/lise-meitner



Ne 20
90.48
σ 0.03

Ne 21
0.27
σ 0.7

Ne 21
0.27
σ 0.051

F 18
109,7 min
β⁺ 0.6
no γ

F 19
100
σ 0.009

F 20
11 s
β⁻ 5.4…
γ 1634…

O 16
99.762
σ 0.00019

O 17
0.038
σ 0.00054

O 18
0.2
σ 0.00016

+ proton

+ proton

- n

P

N

number of nucleons
half-life
max. energy (MeV)
γ energy (keV)

Element
natural abundance

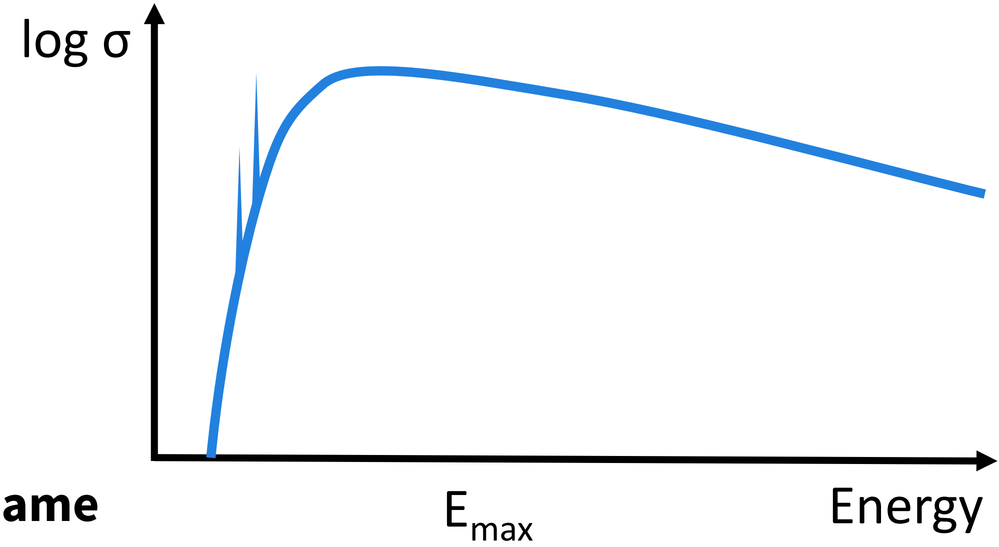
capture cross section for thermal neutrons [10^{-24}cm^2]

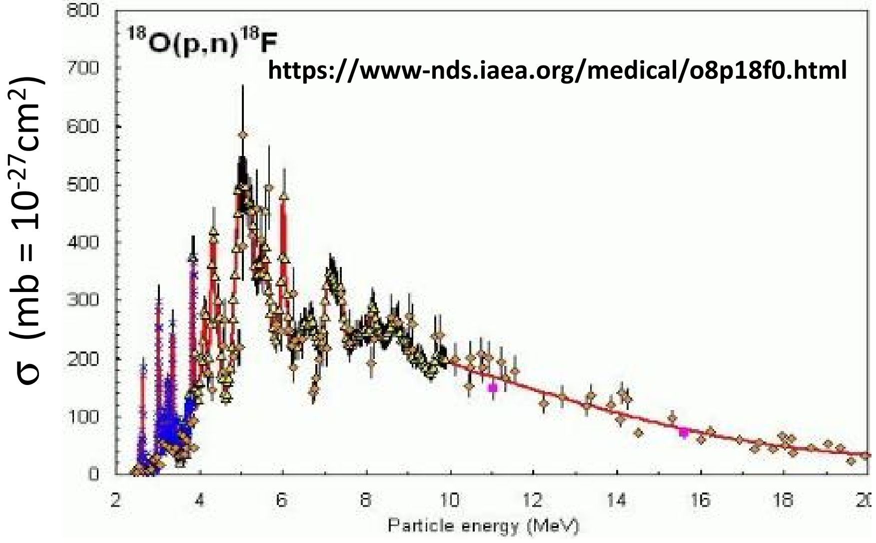
Nuclear Reactions and Cross Sections

- **cross section σ = probability for nuclear reaction**
- **endotherm (left) and exotherm reactions possible**
- **σ increases with projectile energy**
- **resonances due to energy levels in the nuclei**
- **above E_{max}: competing nuclear reactions with the same incident particle**
- **example $^{18}O(p,n)^{18}F$, 20 MeV protons:**
  $6 \cdot 10^{12}$ protons/s lead to ~ $14 \cdot 10^{9}$ nuclear reactions
- **particle energy below Coulom barrier: few reactions**

$$E_c = 1,44 \frac{Z_1 Z_2}{1.2\,(A_1^{1/3}+A_2^{1/3})} \quad \text{(in MeV)}$$

for $^{18}O(p,n)^{18}F$: $E_C = 2.7$ MeV

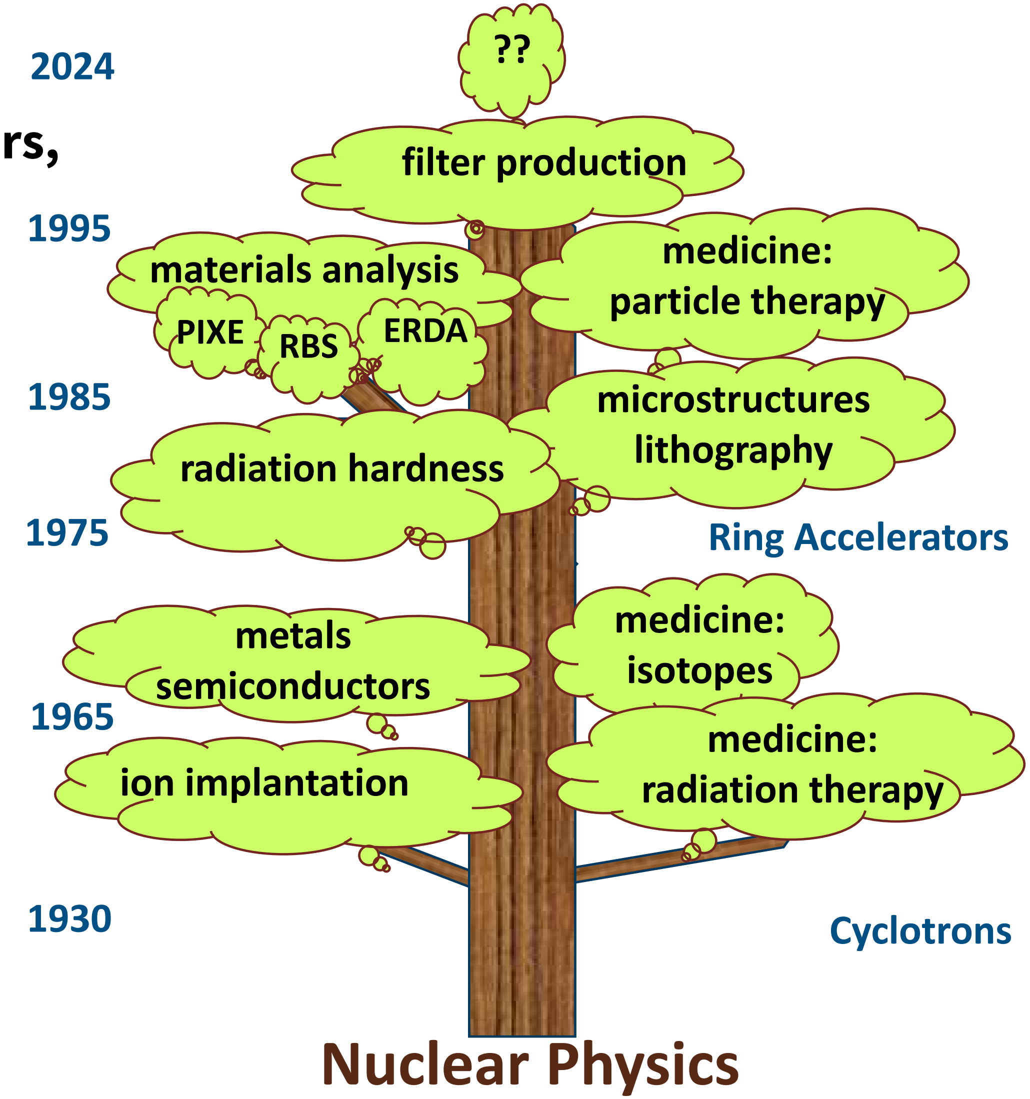




https://www-nds.iaea.org/medical/o8p18f0.html

Accelerator Tree

- **nuclear physics drove development of accelerators, applications emerged**
- **today: more than 10000 accelerators world wide, Industry, museum, hospitals**
  - **Most of them: electrons and light ions up to a few MV**
  - **Heavy ions up to several 100kV**



2024

??

filter production

1995

materials analysis

PIXE

RBS

ERDA

medicine: particle therapy

1985

microstructures lithography

radiation hardness

1975

Ring Accelerators

metals semiconductors

medicine: isotopes

1965

ion implantation

medicine: radiation therapy

1930

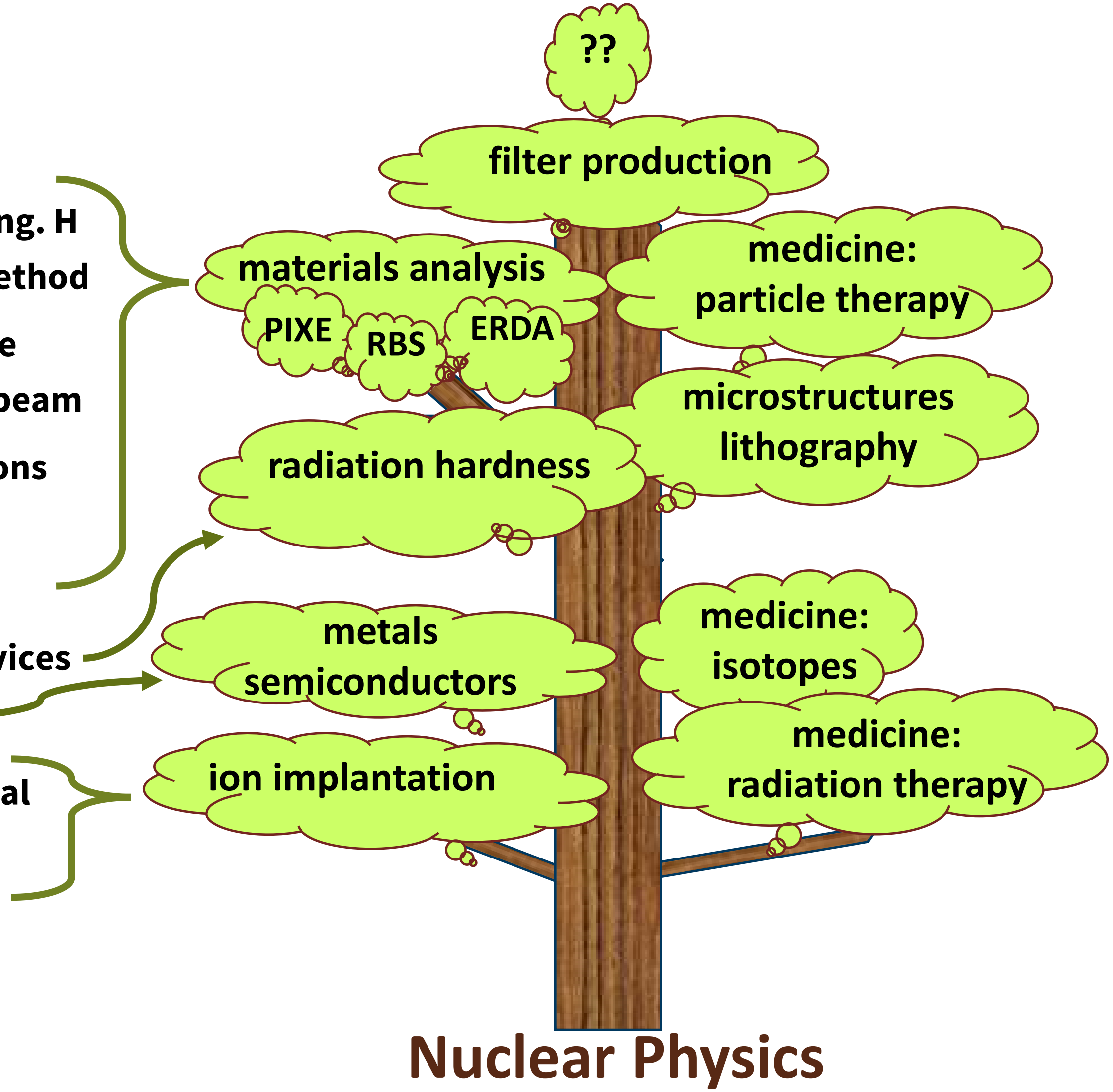
Cyclotrons

Nuclear Physics

* after K. Betghe, Nucl. Phys. News, 9/1 (1999) 20

Accelerators: Applications

- in this school
  - Rutherford backscattering analysis and the method of channeling. H and D induced Nuclear Reaction Analysis as a complimentary method
  - Hands-On: Identification of the composition and thickness of the surface layers of a Schottky diode using a 4He charged particle beam
  - Principles of PIXE and PIGE, advanced techniques and applications
  - Measurements of Hydrogen concentrations with an 15N-beam - principle and applications
  - Overview of the radiation induced degradation of electronic devices
  - Introduction to semiconductors. Doping and hyperdoping
  - Electrical activation of implanted dopants: Statistical mechanical aspects of defect recovery and Hall effect characterization
  - ....

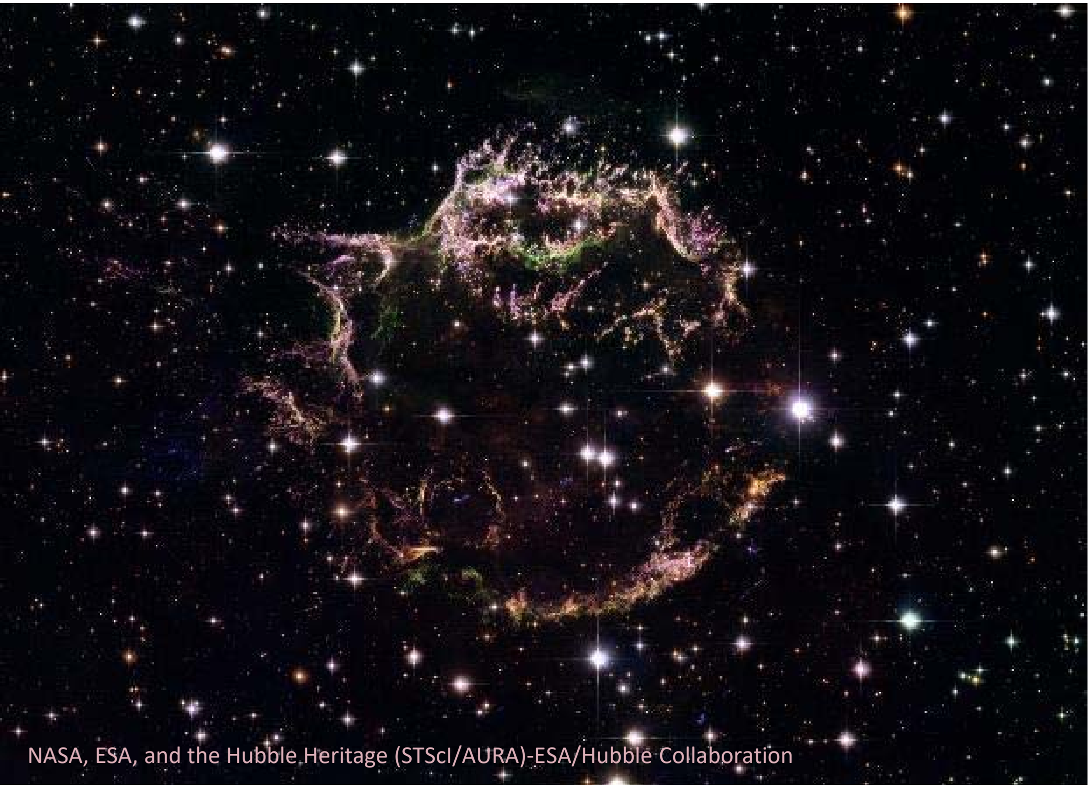


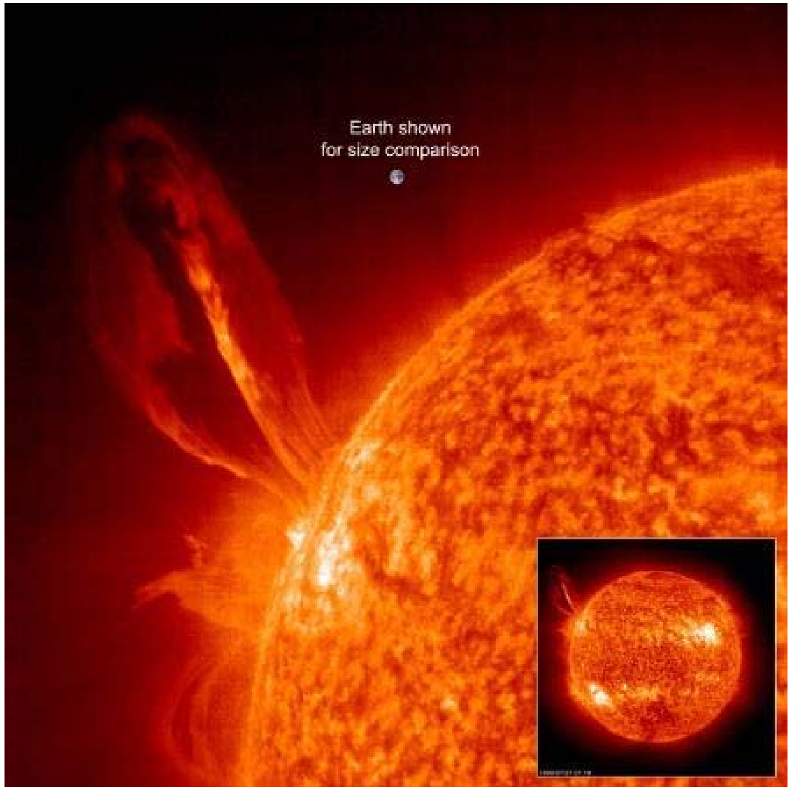
* after K. Betghe, Nucl. Phys. News, 9/1 (1999) 20

Origin of Energetic Ions in Space

- **supernova explosion of stars eject elements into space**

  (Hubble’s view of supernova explosion Cassiopeia A)
- **solar wind, flares, and coronal mass ejection bring solar material into space**


NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration



Sources of High-Energy Ions:

- solar wind and flares, mainly electrons, protons

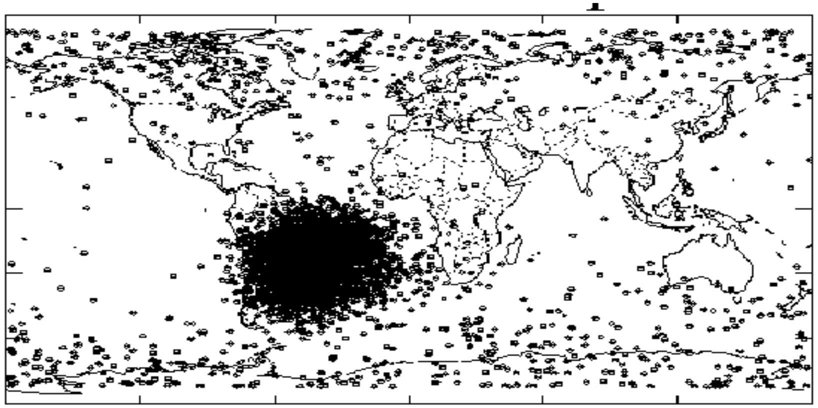
  10 keV/amu $< E_{kin} <$ 300 MeV/amu

- galactic cosmic rays

  p, α, C, N, O, Z> 20

  10 keV/amu $< E_{kin} <$ 300 MeV/amu

- trapped ions in radiation belts of the earth
- all accompanied by x- and γ-rays
- interact with material

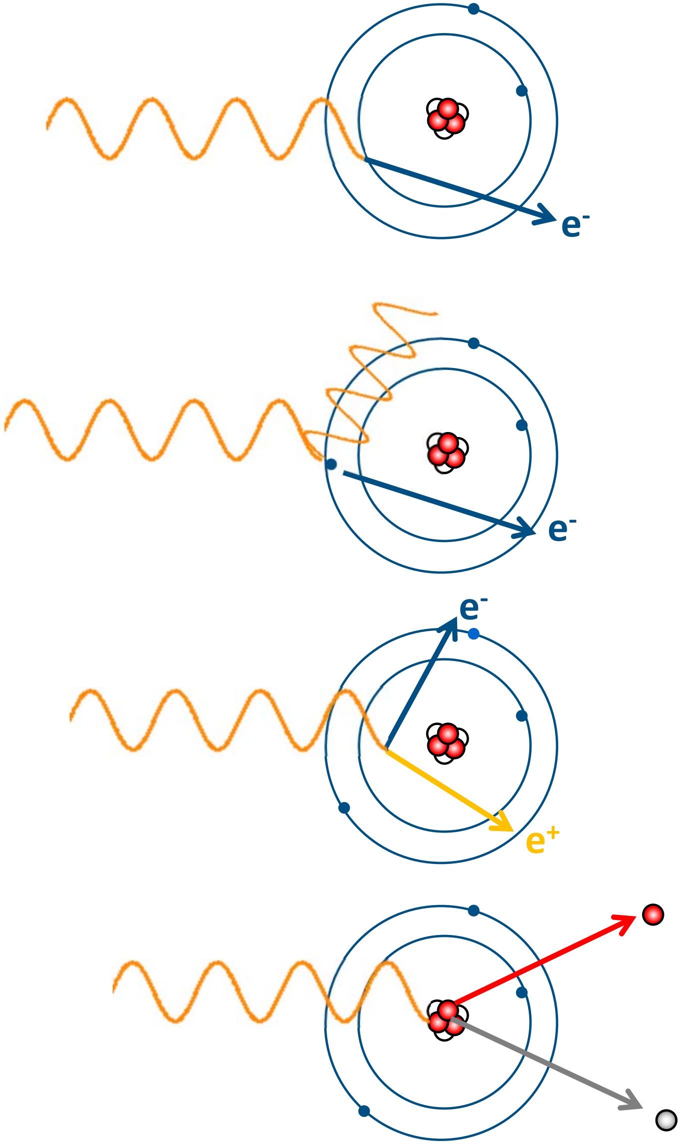


distribution of errors of UoSAT3 in polar orbit

Polar lights observed in south Germany, 10.5.2024
© Alisa Aleker

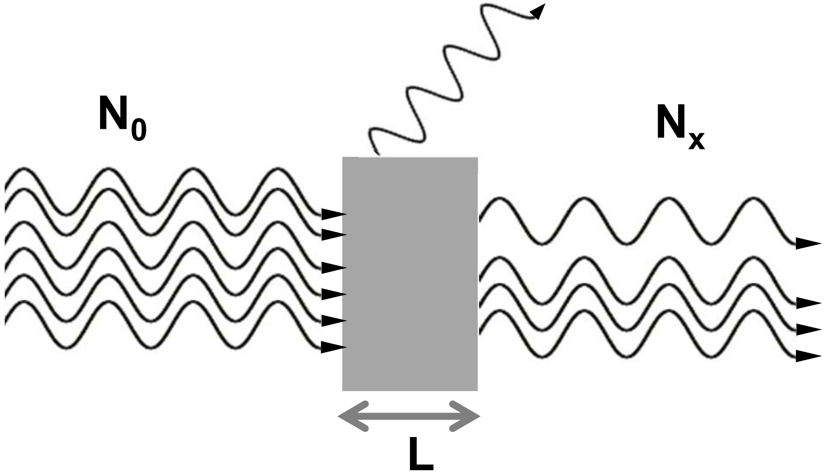
Interaction of Photons with Matter

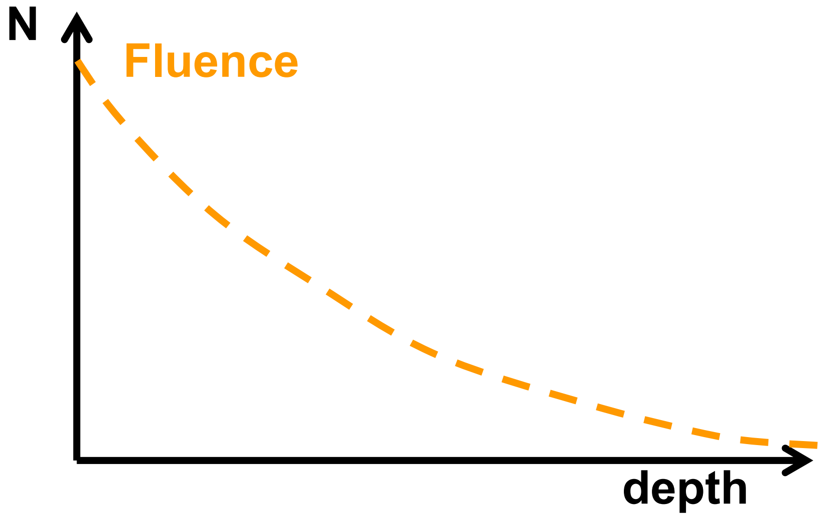
- **photoelectric effect: 5 eV < E_{photon} < 100 keV**
  - **excitation of atom ($E_{transfer}$ < $E_{binding}$)**
  - **ionisation ($E_{transfer}$ > $E_{binding}$)**
- **Compton effect: 50 keV < E_{photon} < 1 MeV**
  - **photon scatters on electron, change of direction and energy**
- **pair production: 1.0222 MeV < E_{photon} < 6 MeV**
  - **energy is used to create an electron-positron pair**
- **photodisintegration: 2.18 MeV < E_{photon} < 16 MeV**
  - **emission of nucleons**



Interaction of Photons with Matter

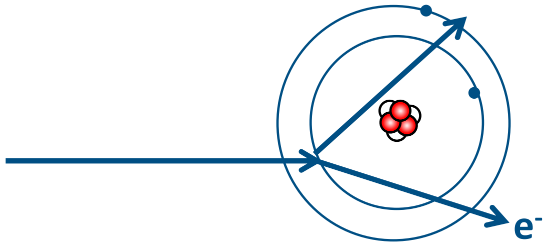
- **photons are scattered or absorbed = loss to the beam**
- **Photon number decreases exponentially:** $N_x = N_0 e^{-\mu L}$
  - **µ: constant, depends on material and photon energy**
- **exponential decrease: infinite range**
  - **practice: define a threshold**

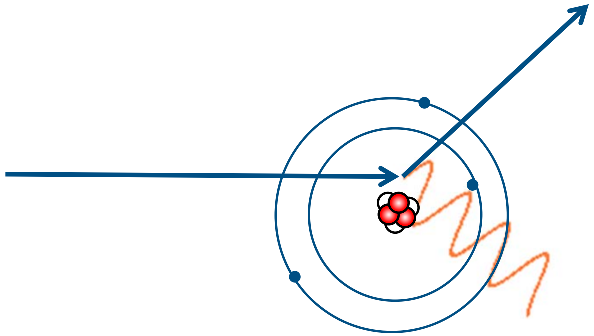




Interaction of Electrons with Matter

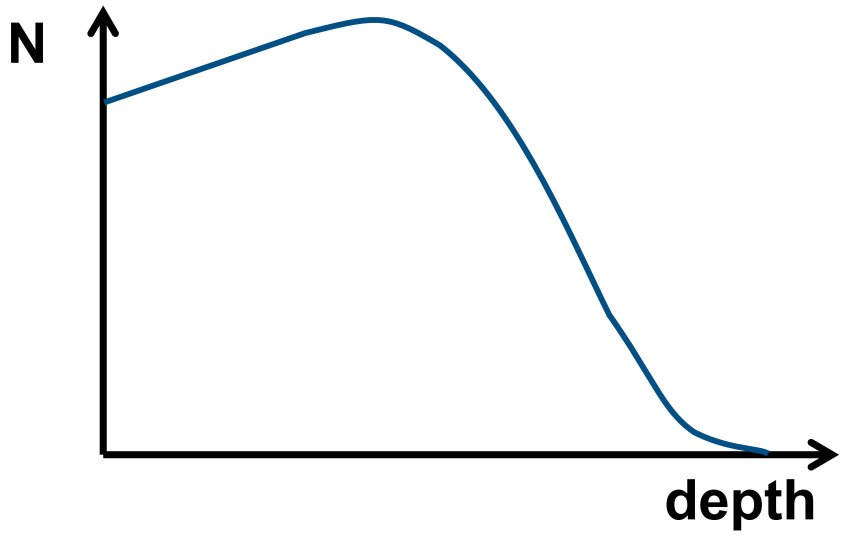
- **electron “meets” electron**
  - **excitation of atom ($E_{transfer} < E_{binding}$)**
  - **ionisation ($E_{transfer} > E_{binding}$)**
  - **large changes of direction → Bremsstrahlung**
- **scattering on atomic nucleus**
  - **change of direction in Coulombfield → Bremsstrahlung**
- **inelastic scattering on atomic nucleus**
  - **excitation of atomic nucleus**

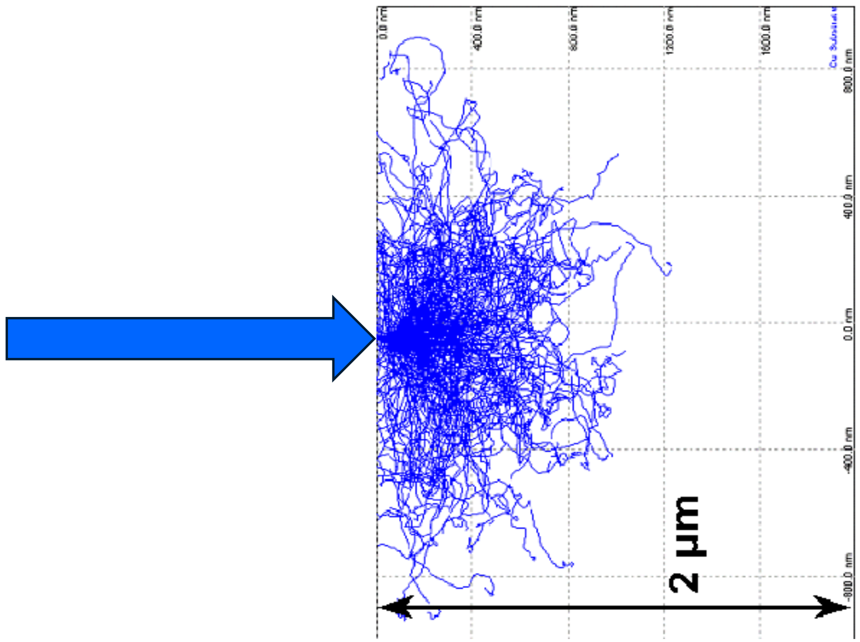




Interaction of Electrons with Matter

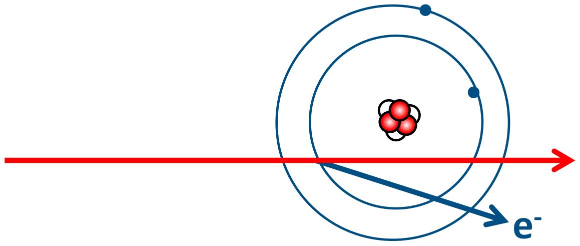
- **large scattering angles**
- **increase of electrons by scattering**
- **finite (!) range**



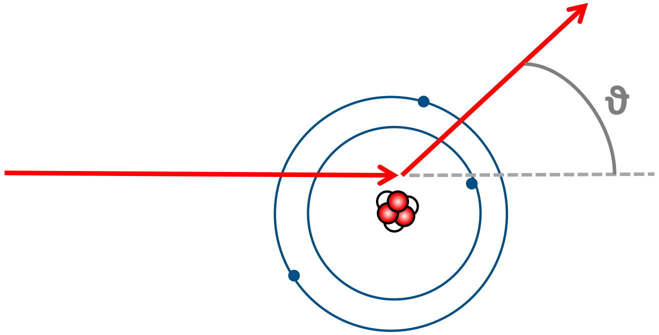


1 MeV electron beam on copper

Interaction of Ions with Matter

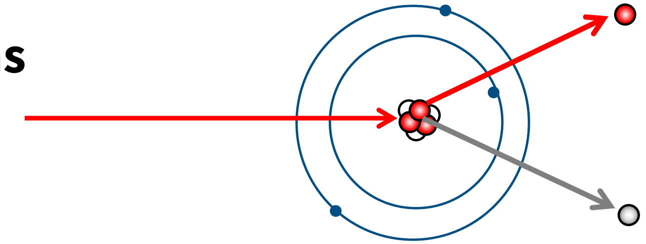


- **with electrons**
  - **excitation of atom ($E_{transfer} < E_{binding}$)**
  - **ionisation ($E_{transfer} > E_{binding}$)**
  - **small energy transfer, as $M_{ion} >> M_{electron}$**



- **elastic scattering on atomic nucleus**
  - **change of energy and direction**

$$\frac{d\sigma}{d\Omega} \sim \frac{1}{\sin^4\left(\frac{\vartheta}{2}\right)}$$

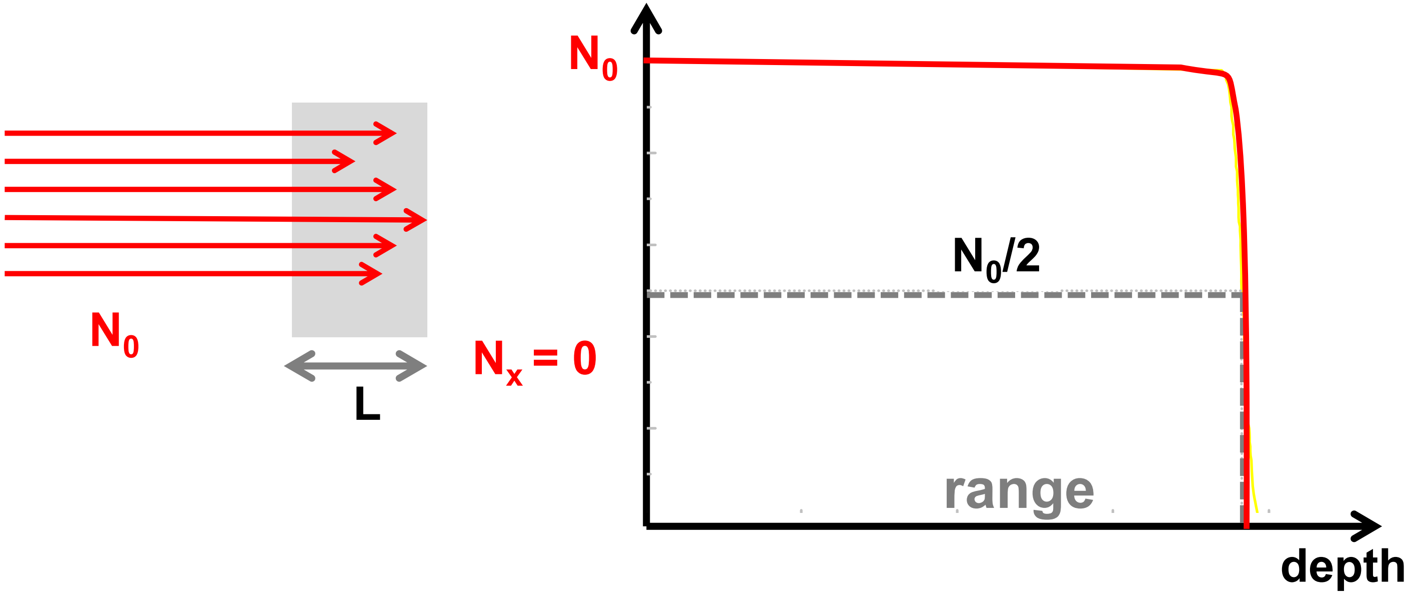


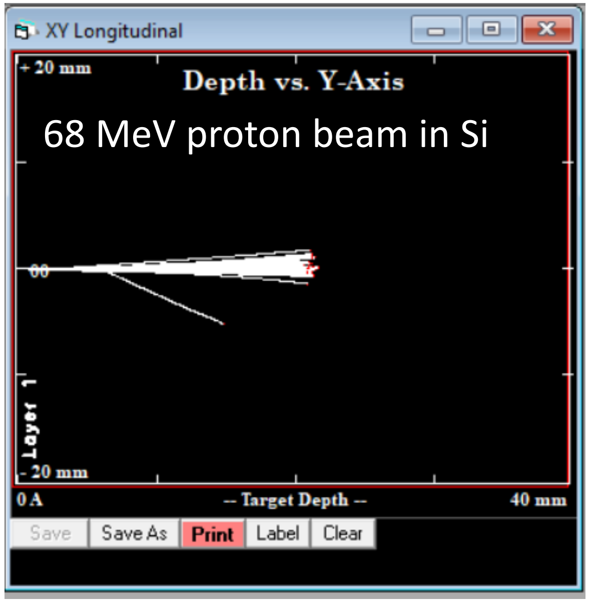
- **inelastic scattering on atomic nucleus: energy nuclear reactions**
  - **e.g. (p,p'), (p,α), (p,2n),....**
  - **large changes in energy and direction**

Interaction of Ions with Matter

- **ions have many interactions in the material**
- **small energy loss per interaction, exception: nuclear reactions**
- **finite (!) range, defined as depth where ion number has halved**
- **simulation code: SRIM (Stopping and ranges of ions in matter)**

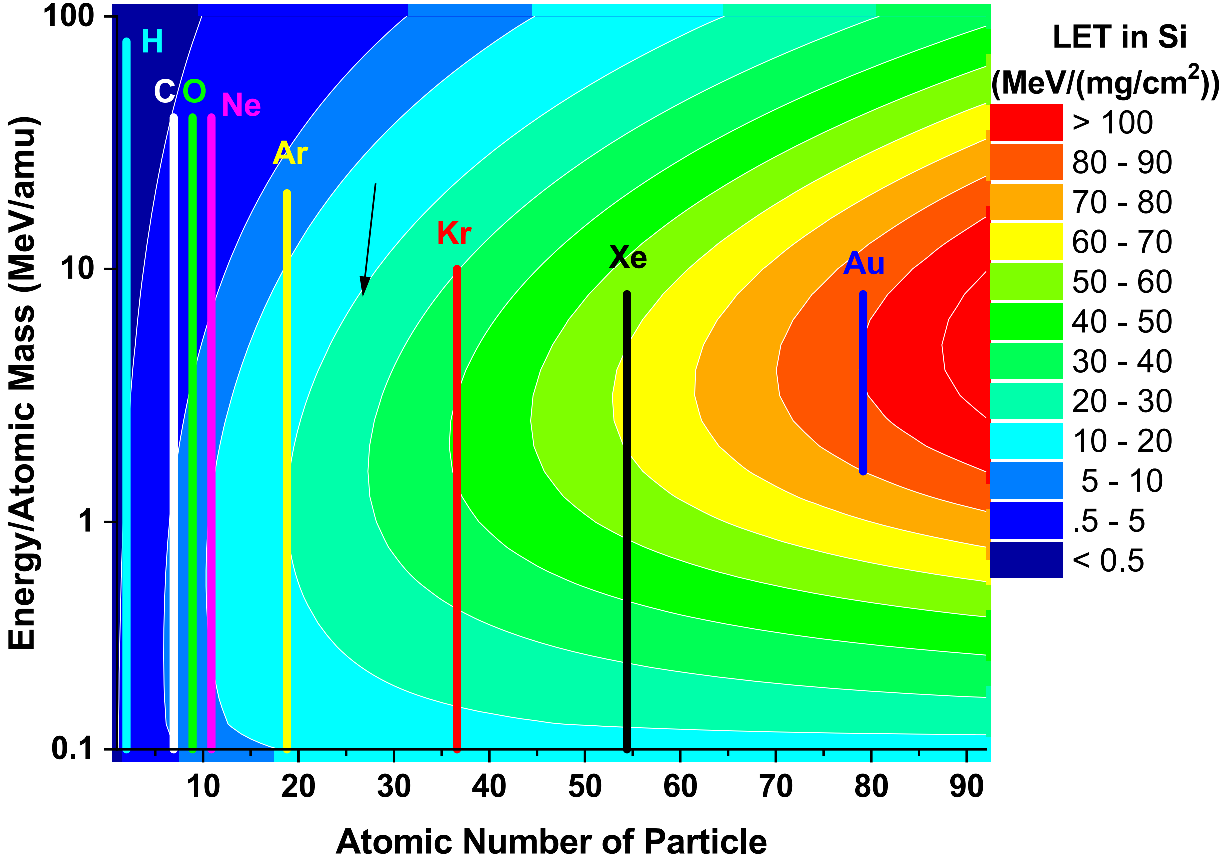
this afternoon: Hands-On – Simulation of Ion implantation with SRIM software.





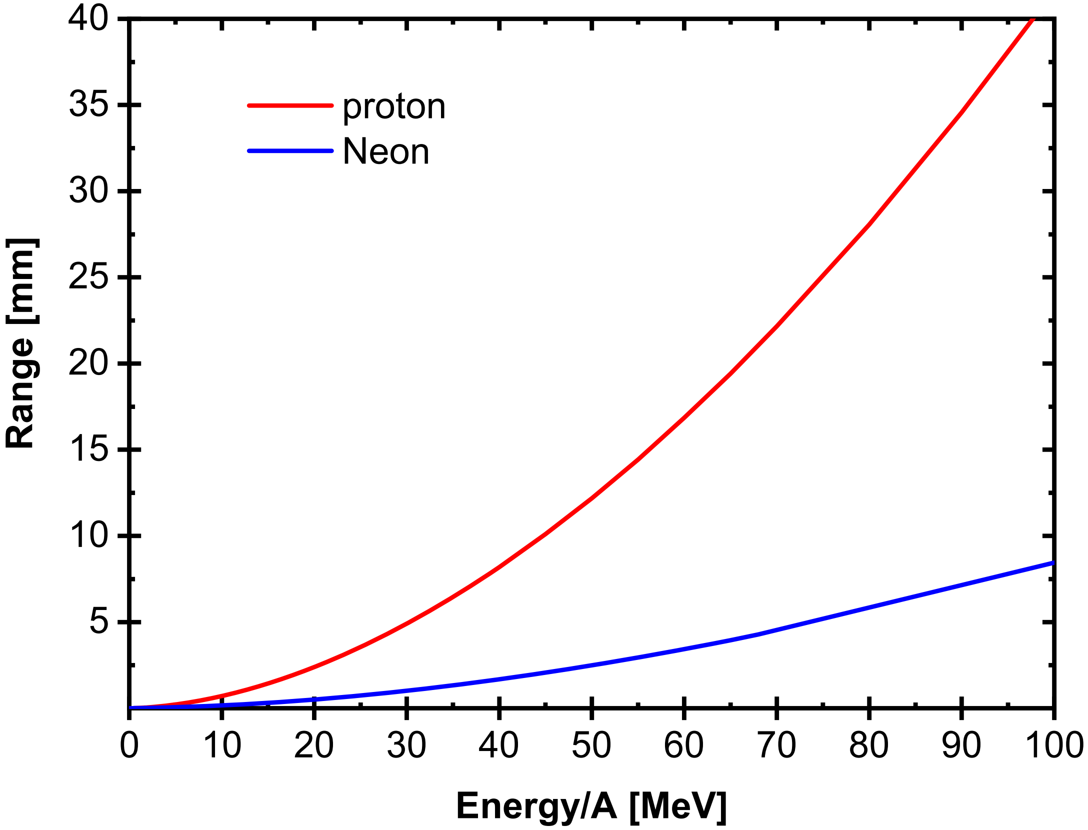
Energy Loss of Ions in Material

- **loss of energy = stopping power**
  linear energy transfer (LET) = dE/dx
- **depends on**
  - **particle energy**
  - **irradiated material**
- **examples:**
  - **protons, 3 MeV in water: 12 keV/µm**
  - **protons, 68 MeV in water: 1 keV/µm**
  - **protons, 68 MeV in Si: 1.6 keV/µm**
  - **Neon, 68 MeV in water: 920 keV/µm**
  - **Neon, 1360 MeV in water: 97 keV/µm**
  - **Neon, 1360 MeV in Si: 160 keV/µm**



Energy Loss in Material: Range

- energy loss leads to finite range
- depends on
  - particle energy
  - irradiated material
- non-linear
- example: range of protons and Ne in Si
  x-axis: Energy/nucleon number ~ velocity

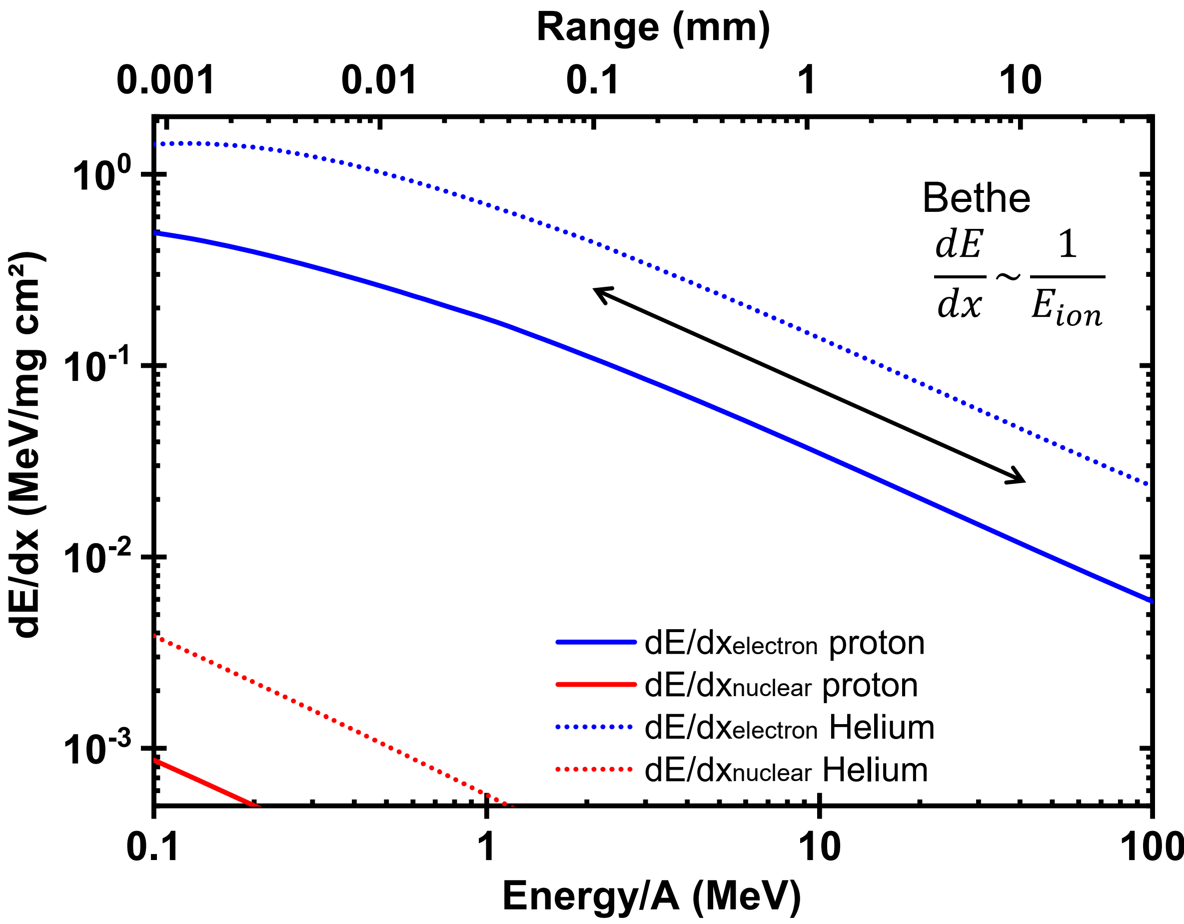


Energy Loss in Material, here: protons and Helium in Silicon

- **energy loss due to interaction with atomic nucleus neglectable**
- **Bethe-Bloch formula describes energy loss due to interactions with electrons:**

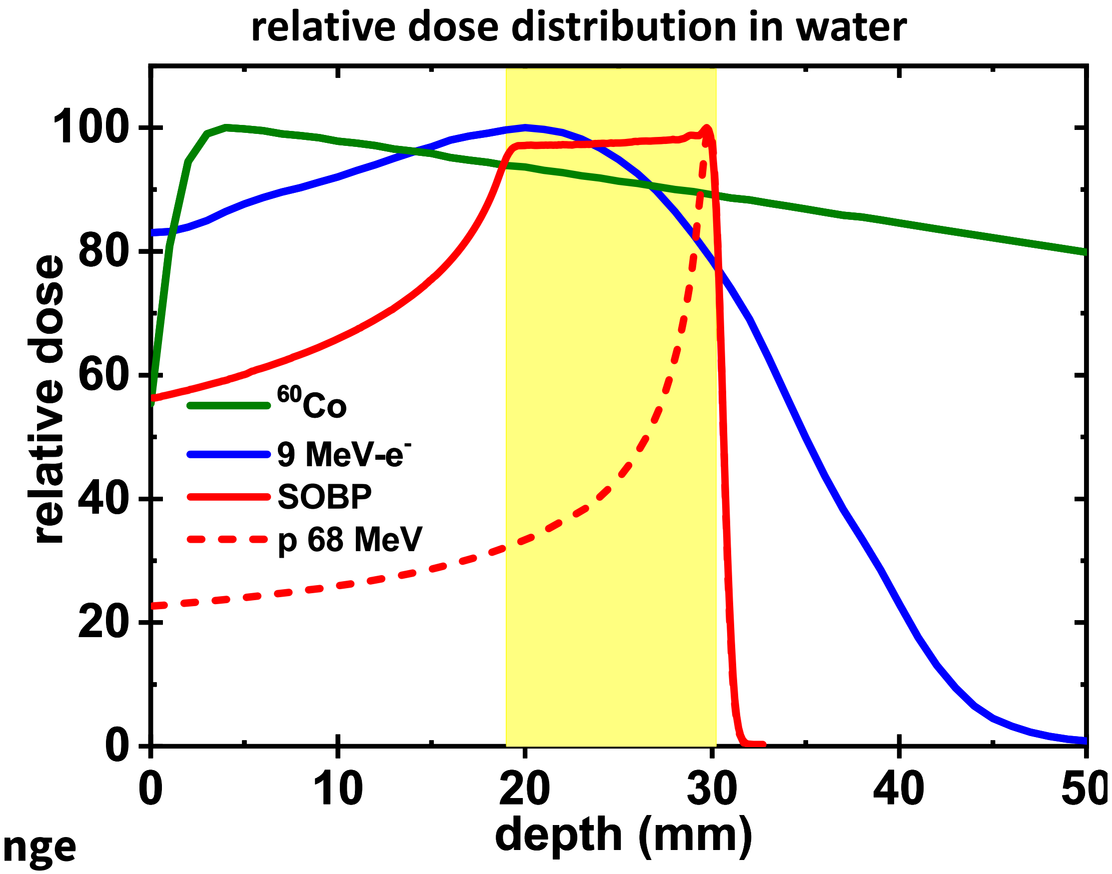
$$-\frac{dE}{dx} = \frac{4\pi}{m_e} n Z^2 \left(\frac{e^2}{4\pi\epsilon_0 v}\right)^2 \left(ln\left(\frac{2m_e v^2}{I(1-\frac{v^2}{c^2})}\right) - \frac{v^2}{c^2}\right)$$

- **n: electron density of material**
- **Z: atomic number of projectile**
- **in practice:**
  energy loss proportional to E_{ion}^{-1}



Energy Deposition of Ionizing Radiation

- **dose defined as deposited energy per mass**
- **unit: Gray (Gy) = Joule/kg**
- **photons:**
  - **build-up due to secondary electrons**
  - **exponential decrease**
- **electrons:**
  - **build-up due to secondary electrons**
  - **finite range**
- **ions, here protons:**
  - **maximum of energy deposition before end of range**
  - **Bragg-Peak**



Effects of Ionizing Radiation for Earth

- radiation exposure to humans:
  - formation of free radicals in cells
  - double strand ruptures in DNA
  - problem in space- and air flights (between Apollo 16 and 17 the radiation exposure by charged particles was so high, that 10 h after beginning of the flare lethal doses would have been achieved)
  - desired effect in radiation therapy

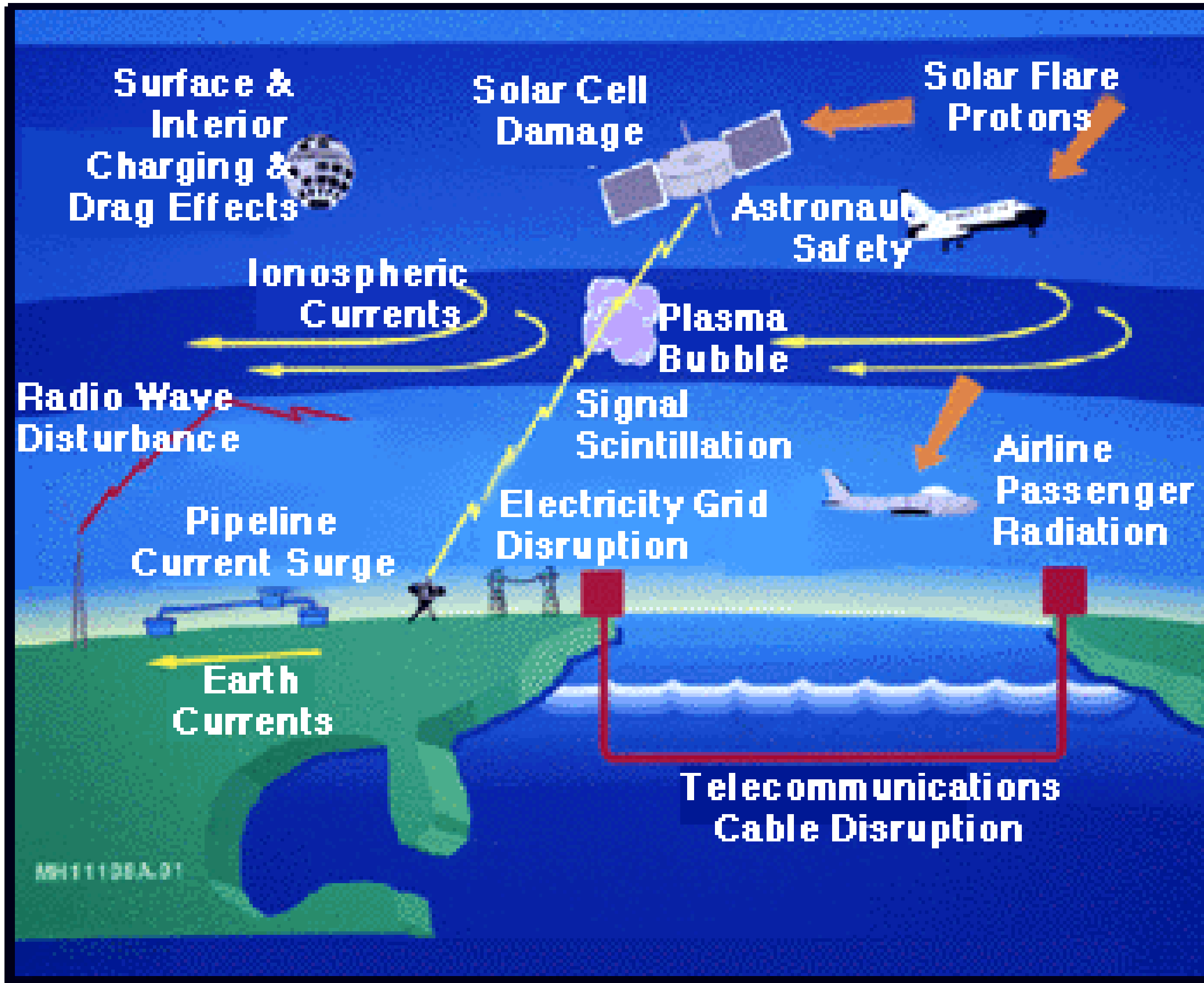
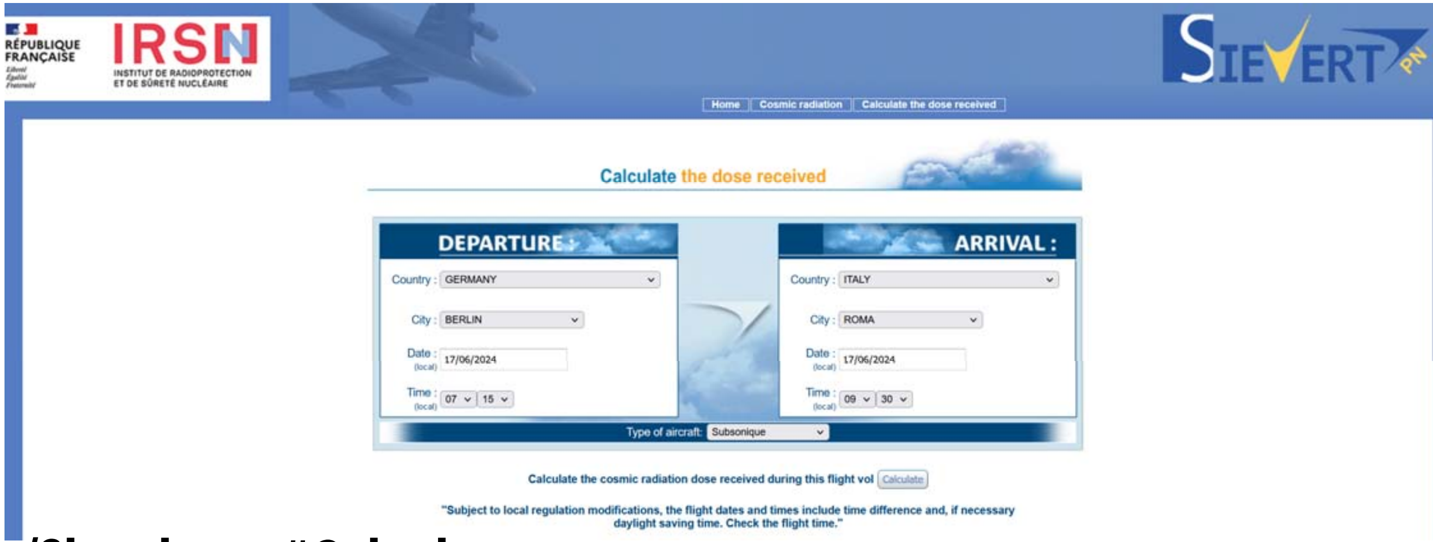


Image Credit: L. J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.

Dose in Air Traffic

- **effective dose: unit Sievert (Sv) takes into account irradiation type and sensitivity of organs**
- **website for dose by flights: https://www.sievert-system.org/?locale=en#Calcul**
- **prediction for my flight on Monday, Berlin - Rome: 4.4 µSv**



Calculate the dose received

DEPARTURE :

Country : GERMANY
City : BERLIN
Date (local) : 17/06/2024
Time (local) : 07 15

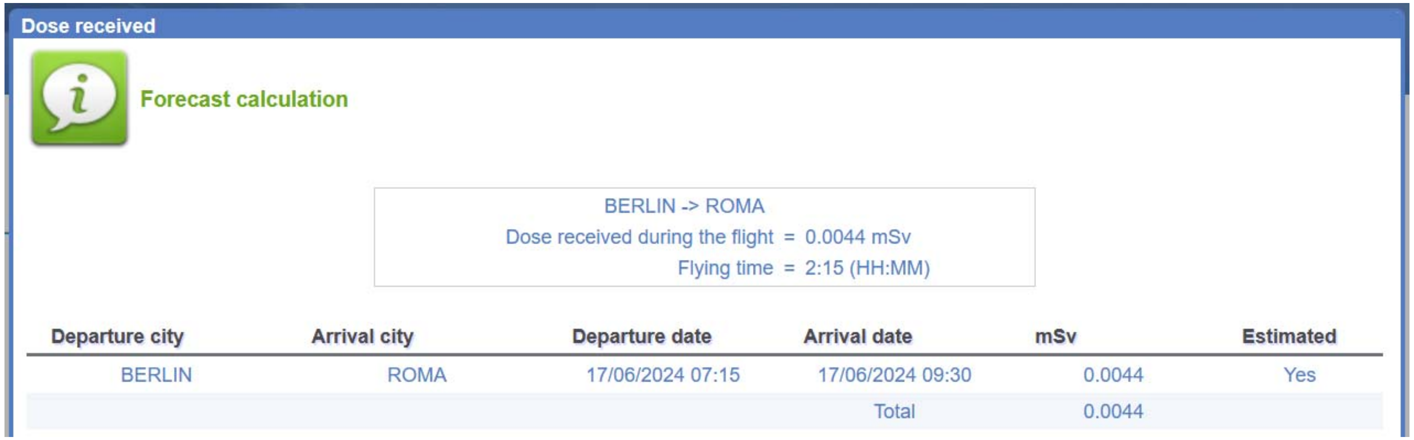
ARRIVAL :

Country : ITALY
City : ROMA
Date (local) : 17/06/2024
Time (local) : 09 30

Type of aircraft: Subsonique

Calculate the cosmic radiation dose received during this flight vol

"Subject to local regulation modifications, the flight dates and times include time difference and, if necessary daylight saving time. Check the flight time."



Dose received

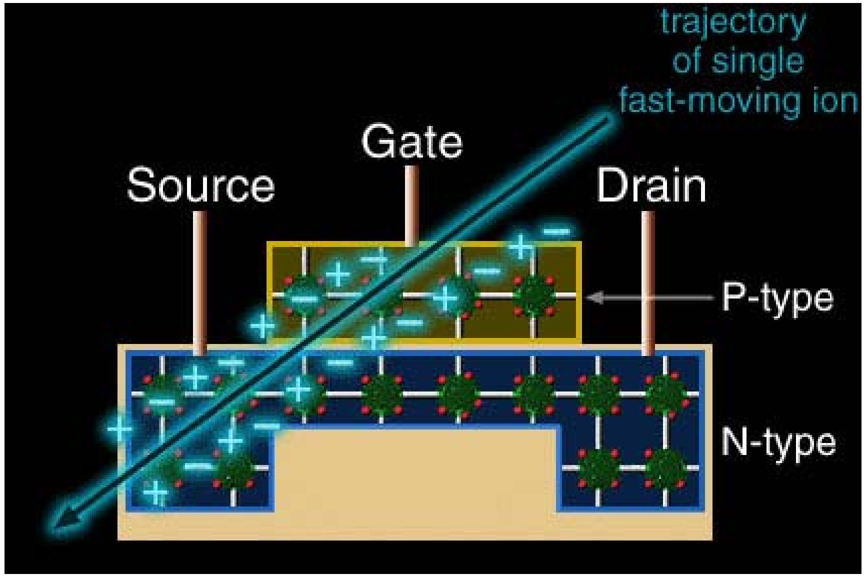
Forecast calculation

BERLIN -> ROMA
Dose received during the flight = 0.0044 mSv
Flying time = 2:15 (HH:MM)

Departure city	Arrival city	Departure date	Arrival date	mSv	Estimated
BERLIN	ROMA	17/06/2024 07:15	17/06/2024 09:30	0.0044	Yes
			Total	0.0044	

Radiation Hardness: Single Event Effects

- SEE = each measurable effect on circuits or devices (digital, analogue, optical) produced by an impinging ion
- results in errors in the electronics:
- logical errors:
  - Single Event Upset in memory or on discs, can be removed by rewriting
- hard errors:
  - Single Event Latchup – system in undefined status, hardware reset necessary
  - Single Event Burnout – high charges destroy device, already observed on ICE – diodes at sea-level
- this afternoon: “Overview of the radiation induced degradation of electronic devices.”



Credit: http://www.windows.ucar.edu/spaceweather

Radiation Hardness: Change of Material Properties

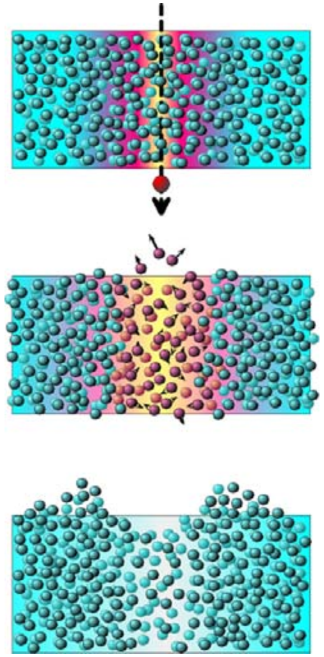
- radiation induced chemical reactions → polymerization
  - liquids become viscous
  - plastic becomes brittle or sticky

    Teflon: 100 Gy photons, polyethylene from 10 kGy on

  sometimes desired: electron irradiation of shrinking foil and tubes
- colour changes in glass and plastic
  - normal glass starts changing from 100 Gy on

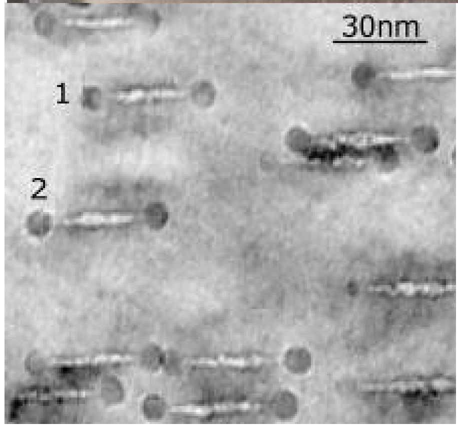
    example: plexiglass after several months of proton irradiation
  - lenses, optocouplers and optical fibres loose functionality
- heavy ions:
  - highly ionizing density
  - permanent tracks

    example: 350 MeV Au-Irradiation of NiO; single, hollow tracks in TEM picture



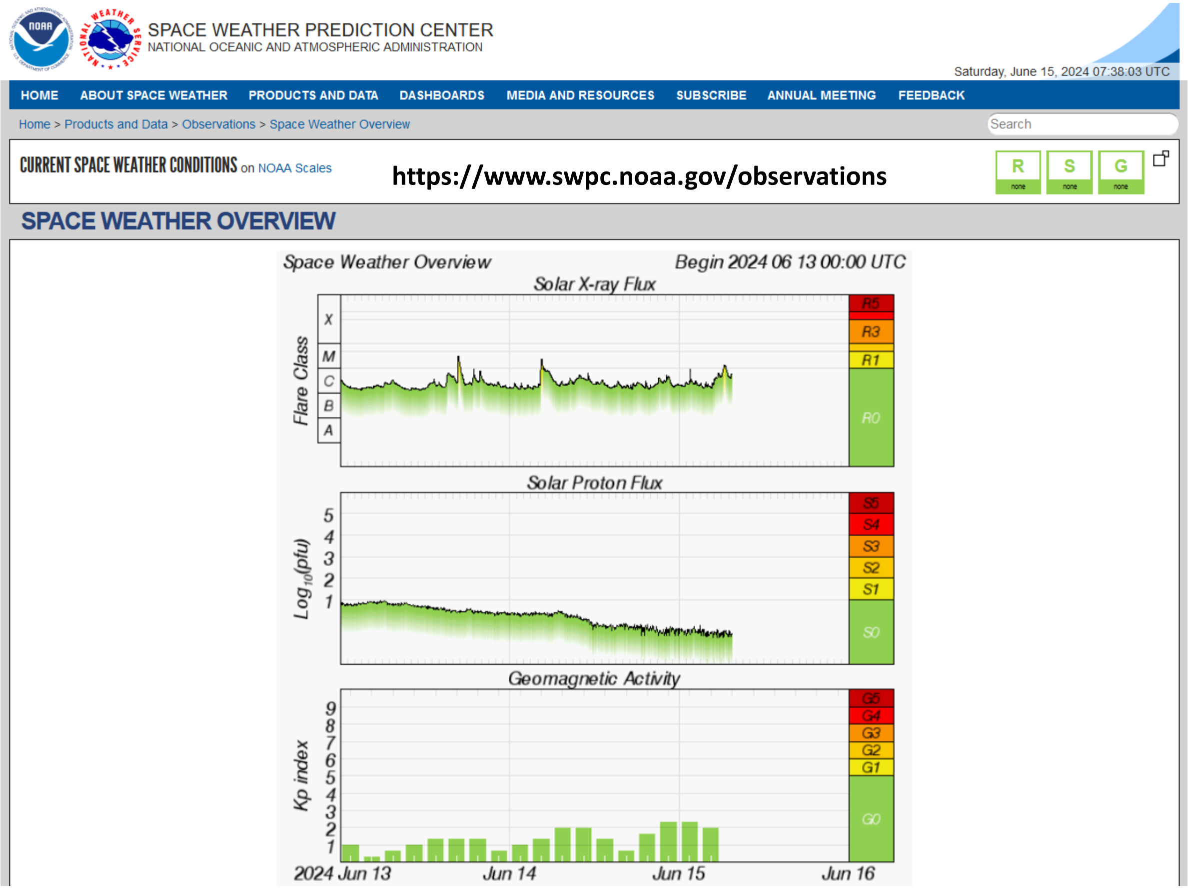
© Gregor Schiwietz

Photo: Reidar Hahn, Fermilab
Accelerators for America's Future



Satellites: Spectra and Intensity of Radiation

- **depend on orbit: polar, equatorial, flight height,…**
- **stellar activities: solar eruptions, supernova explosions**



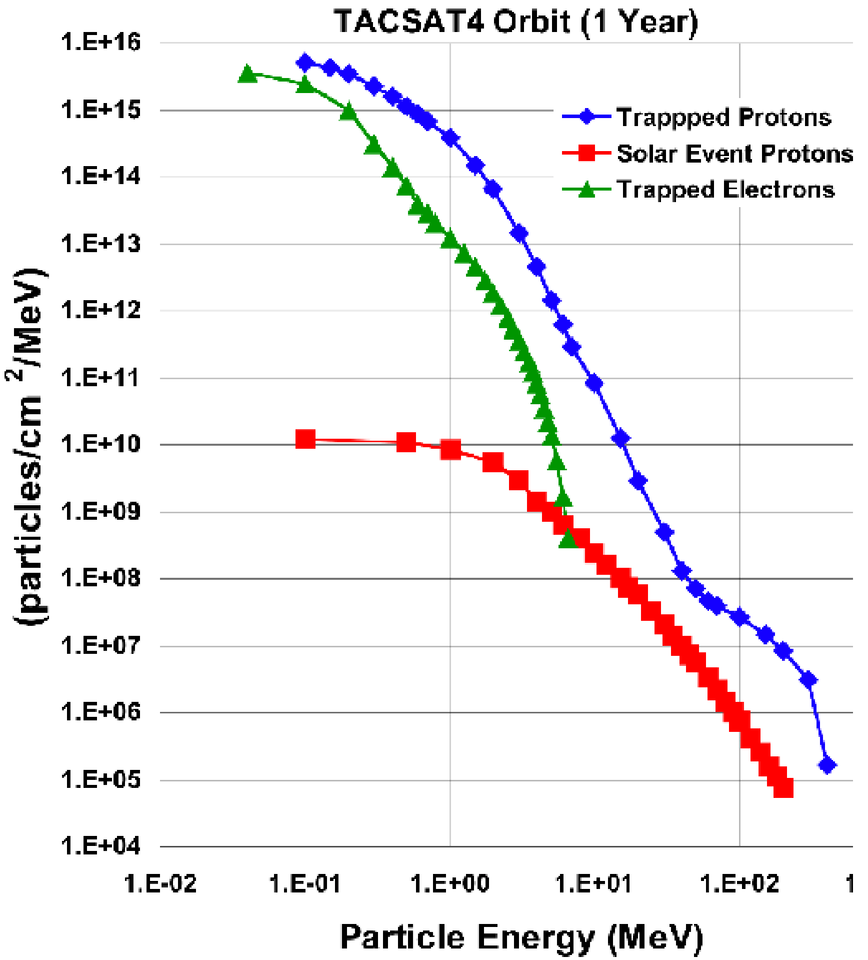
SPACE WEATHER PREDICTION CENTER
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Saturday, June 15, 2024 07:38:03 UTC

CURRENT SPACE WEATHER CONDITIONS on NOAA Scales

https://www.swpc.noaa.gov/observations

SPACE WEATHER OVERVIEW



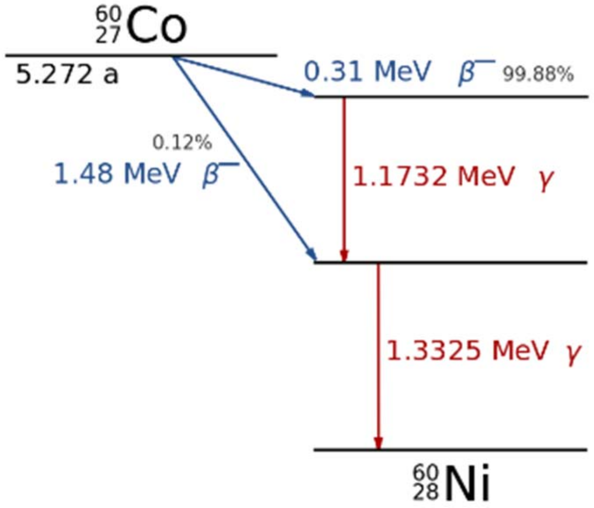
apogee: 12000 km, perigee of 700 km,
TACSAT-4 SOLAR CELL EXPERIMENT: ADVANCED SOLAR CELL TECHNOLOGIES IN A HIGH RADIATION ENVIRONMENT, P. Jenkins et al, doi: 10.1109/PVSC.2009.5411774

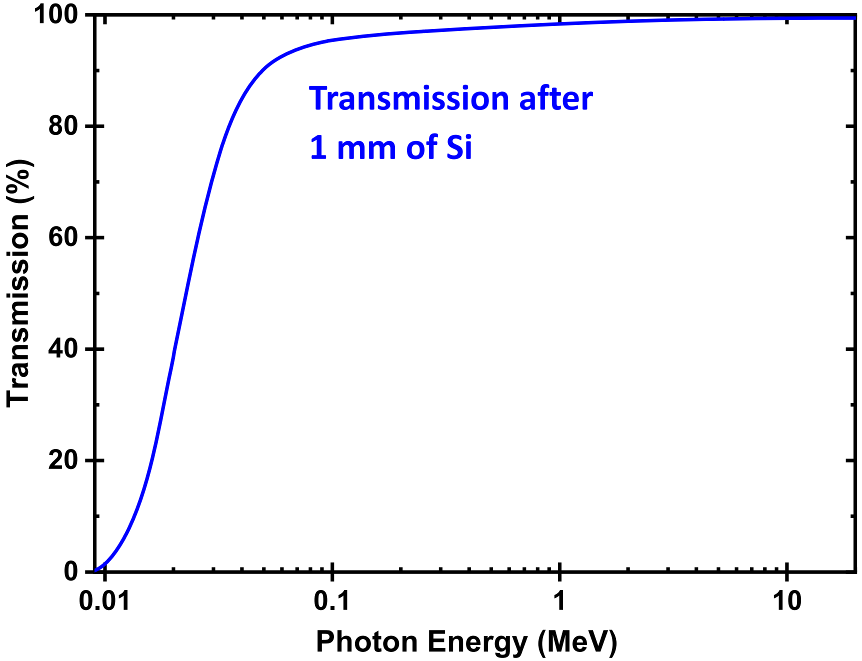
Total Ionizing Dose Tests (TID) Test Requirements

- European Space Components Coordination:
  ESCC No. 22900 by ESA
- radiation source: Cobalt 60 or electron accelerator beam
- accuracy & non uniformity: 10%
- radiation level: depends on mission,
  varies between 30 Gy (Si) up to 10000 Gy
- dose rate: 36 Gy/h – 360 Gy/h („standard“)
  or 0.36 Gy/h – 3.6 Gy/h („low“ rate)
- ambient temperature: +20°C ± 10°C
- exposure time: < 96 h
- test steps & exposure: 3 steps:
- $1/3 \cdot \text{Dose}_{\text{specified}} \mid 1 \cdot \text{Dose}_{\text{specified}} \mid 3 \cdot \text{Dose}_{\text{specified}}$

γ-rays: Cobalt Source

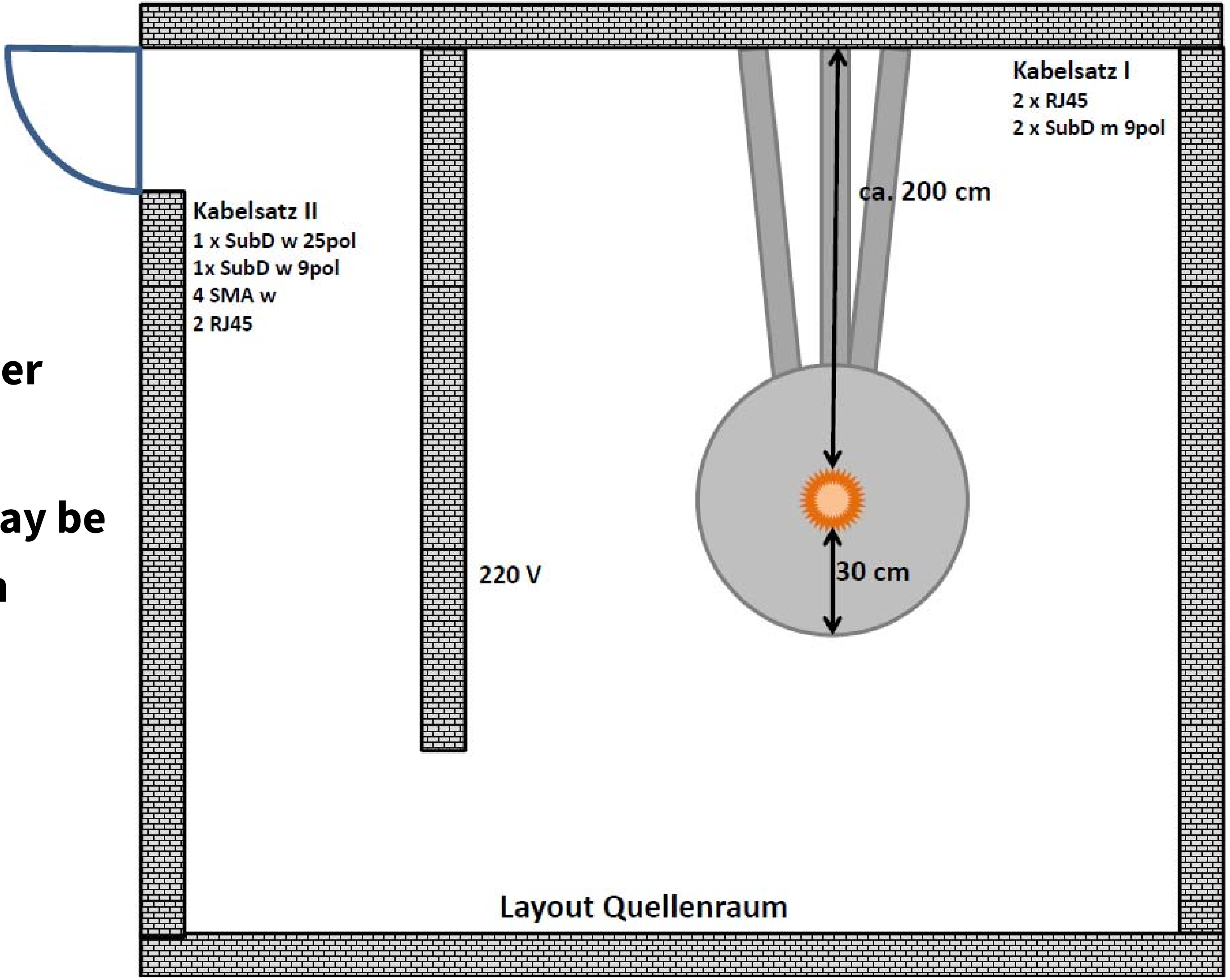
- ^{60}Co created by neutron capture of ^{59}Co,
  ß$^-$ decay to ^{60}Ni
  excited nucleus → deexcitation by γ-rays emission
- pure γ-rays
  (ß$^-$-rays shielded by stainless steel tube)
- γ-energy: 1.17 MeV und 1.33 MeV
  → samples can leave the laboratory directly
  after the irradiation





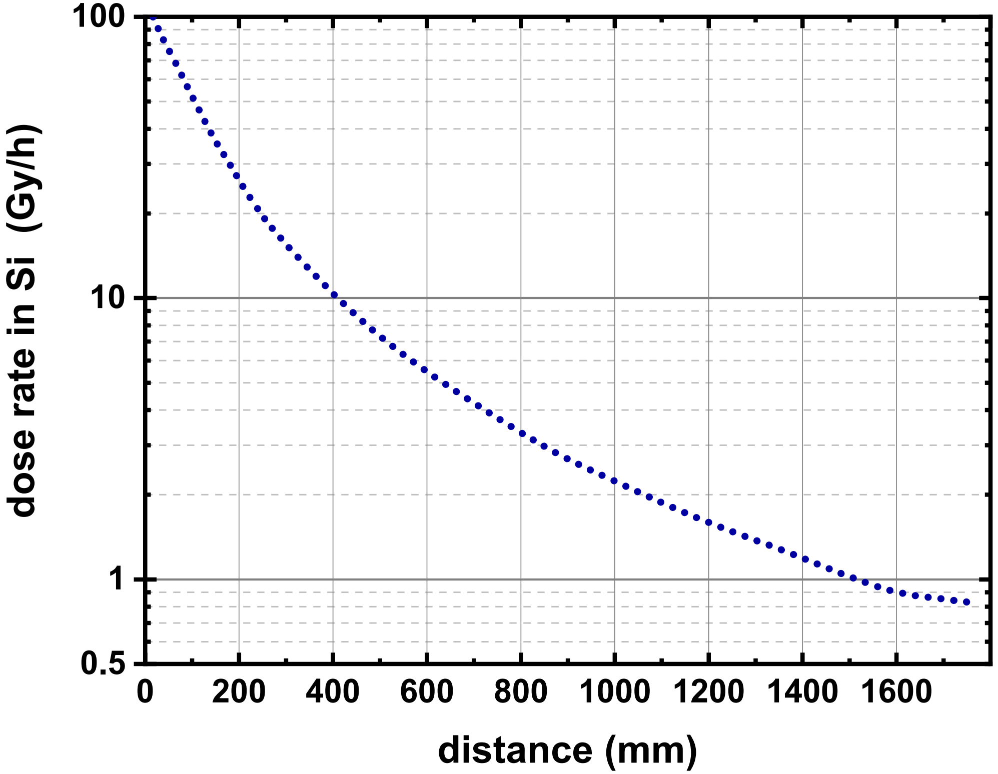
Cobalt Source: Irradiation Room

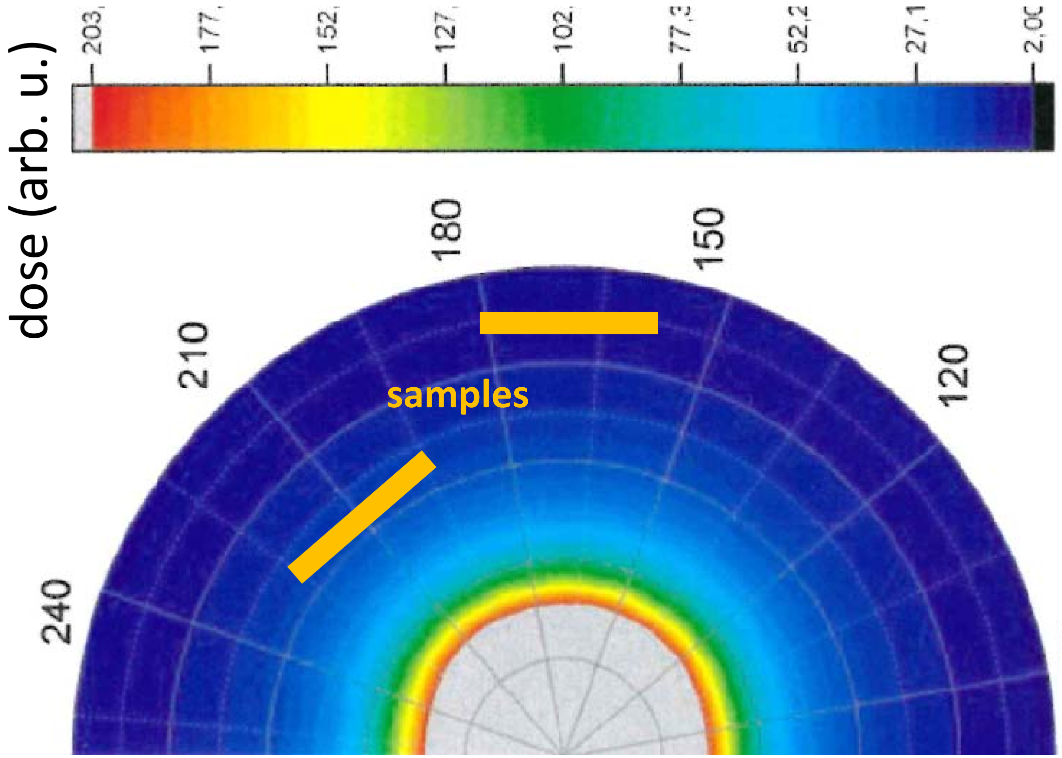
- ^{60}Co rods, ~ 20 cm high
  → large samples possible
- large room: ca. 3 m · 4 m
- various cables and connectors for operating/read out of devices under test
- sensitive measurement devices may be installed outside of the irradiation room



Cobalt Source: Dose Rate

- **determination of dose with calibrated dose monitor**
- **dose rate 2024: between 0.4 Gy/h und 100 Gy/h in Si (0.04 krad/h to 10 krad/h), T½ = 5.2 years**
- **decrease of dose rate with increasing distance to source**

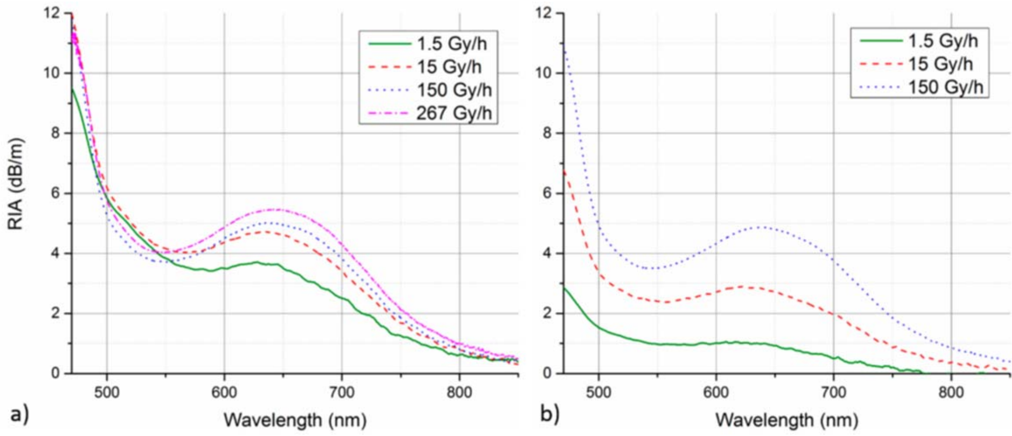




Cobalt Source: Examples

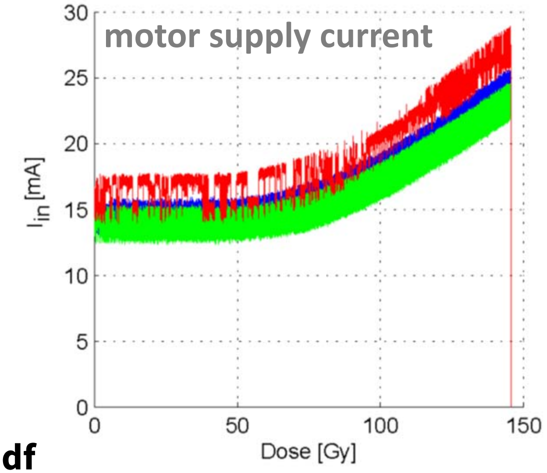
- **Spectral shape of GigaPOF-50SR (l) and Fontex (r) radiation induced attenuation, measured for irradiation to 100 Gy at different dose rates**

  P. Stajanca and K. Krebber,
  Sensors 2017, 17, 1959; doi:10.3390/s17091959



- **MASCOT (Mobile Asteroid Surface Scout) mission: TID of 4.2 kRad expected → test criterion for commercial of the shelf devices: 10 krad**

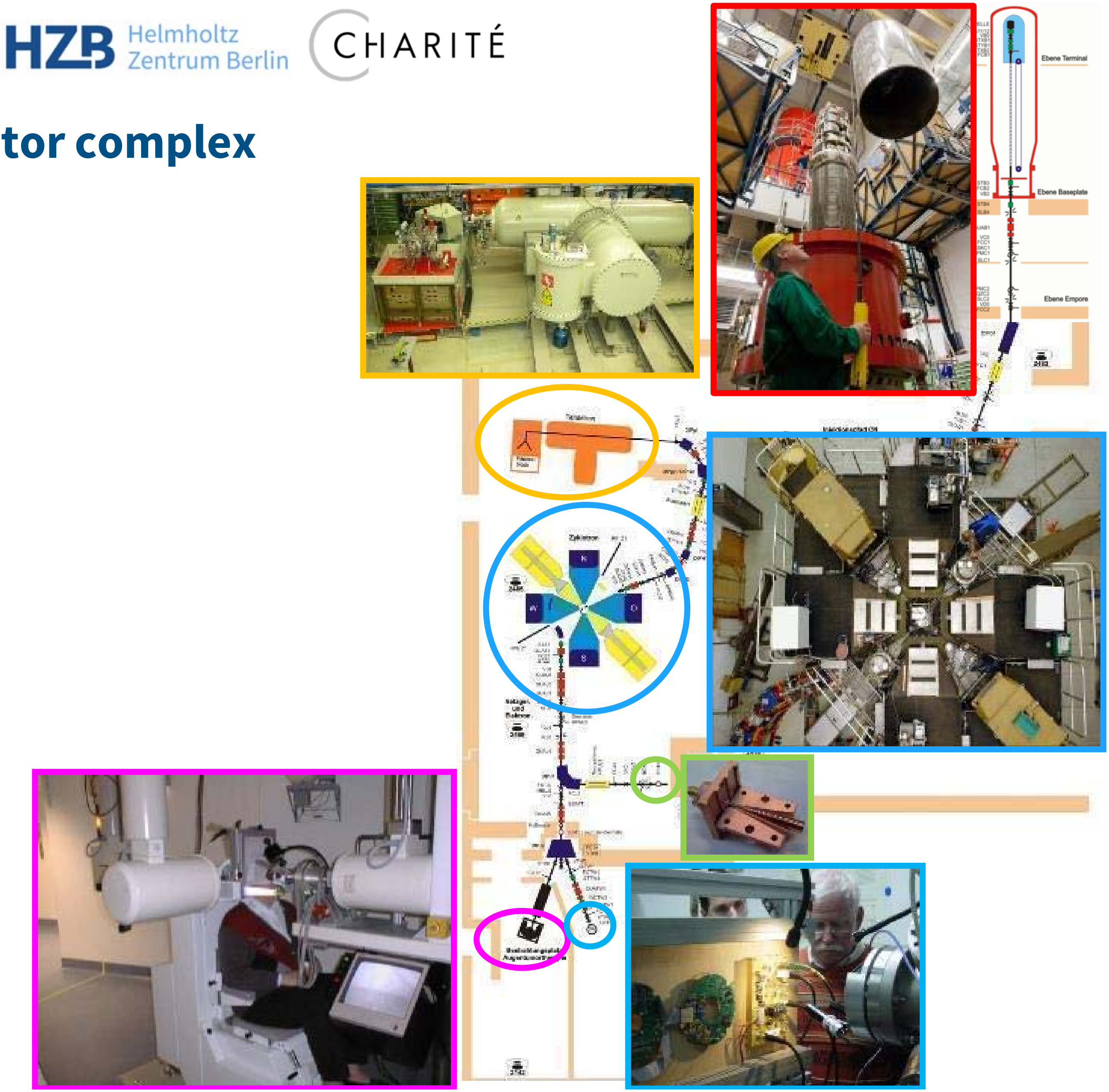
  J. Reill, et al, Development of a Mobility Drive Unit for Low Gravity Planetary Body Exploration,
  http://robotics.estec.esa.int/ASTRA/Astra2013/Papers/reill_2824197.pdf



HZB Helmholtz Zentrum Berlin CHARITÉ

Proton Tests: Layout of the accelerator complex

- k = 130 isochronous sector cyclotron
  10 – 20 MHz
- two injectors:
  - 2 MV Tandetron™
  - 6 MV Van-de-Graaff, backup, time structures
- three target stations:
  - treatment room
  - experimental station (I_{max}(DC) = 10 nA)
  - beam line end for tests in cyclotron vault

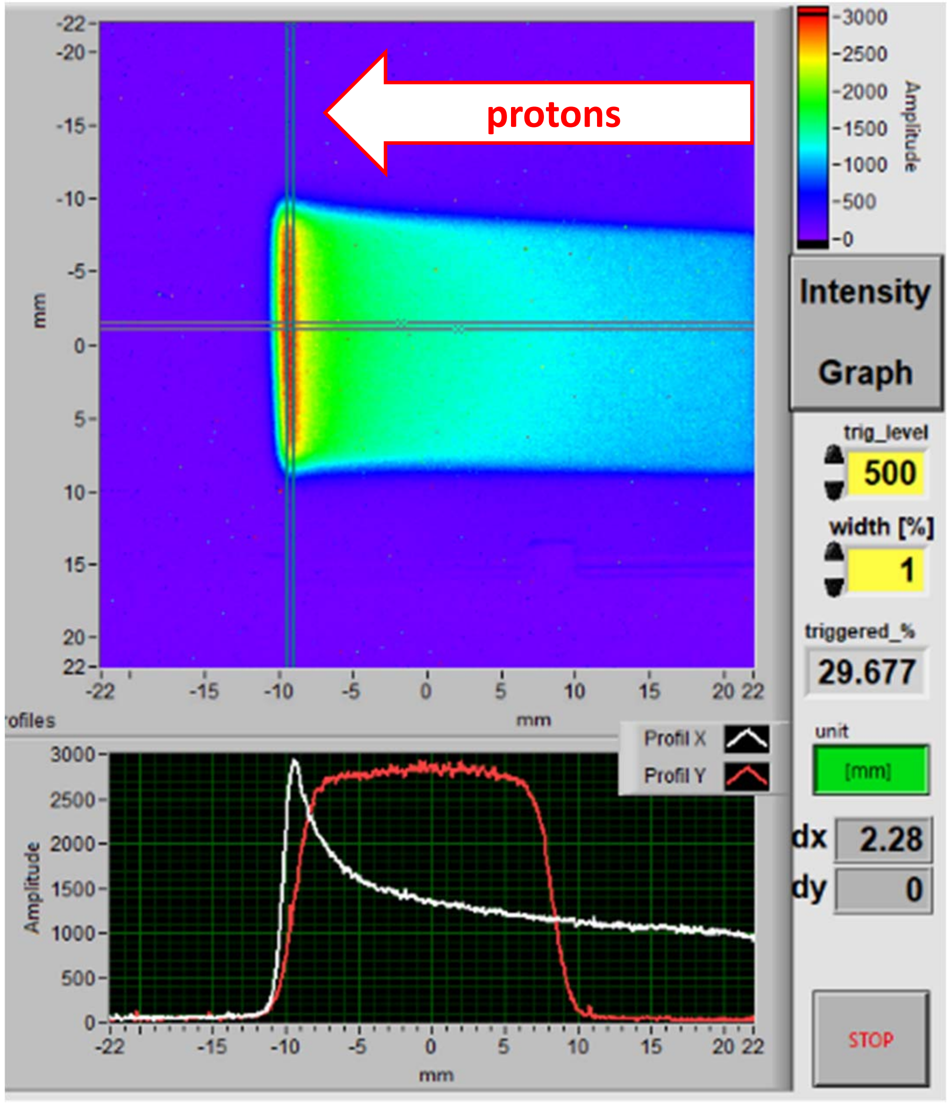


Protons: Energy

- **from accelerator: monoenergetic protons**
  - energy range: 15 MeV ≤ E_{Proton} ≤ 72 MeV
  - change of energy at accelerator: ca. 6 h

- **standard energy: 68 MeV (therapy beam)**
  - energy spread < 0.2 MeV

- **lower energies by absorber plates**
  - typical: 30 MeV und 50 MeV
  - energy spread: ~ 1 MeV
  - change of energy: 2 min.
  - energy determined by 3D camera



trig_level 500

width [%] 1

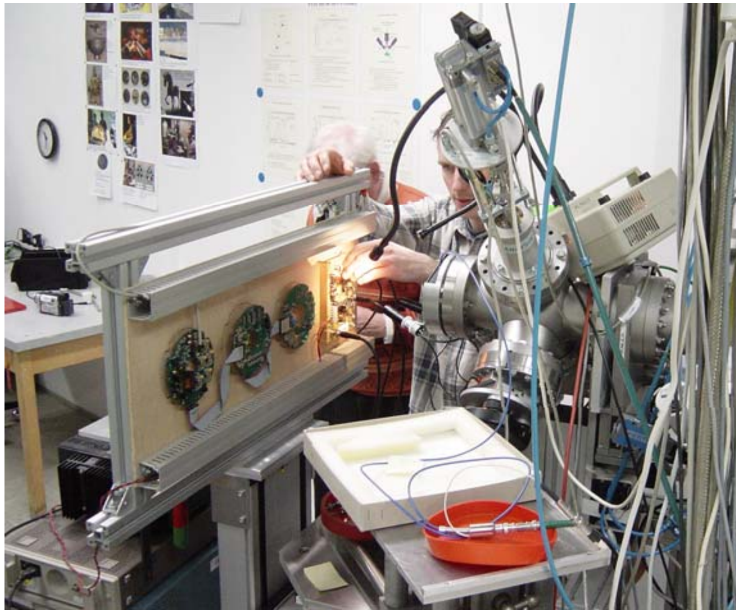
triggered_% 29.677

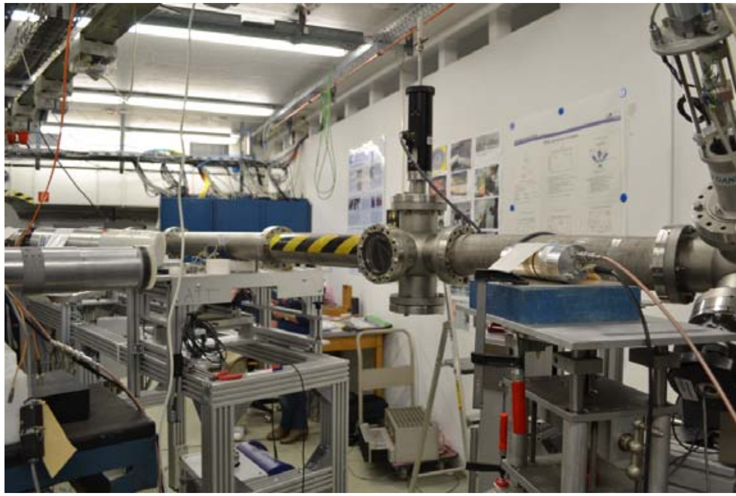
unit [mm]

dx 2.28

dy 0

Protons: Experimental Station - General



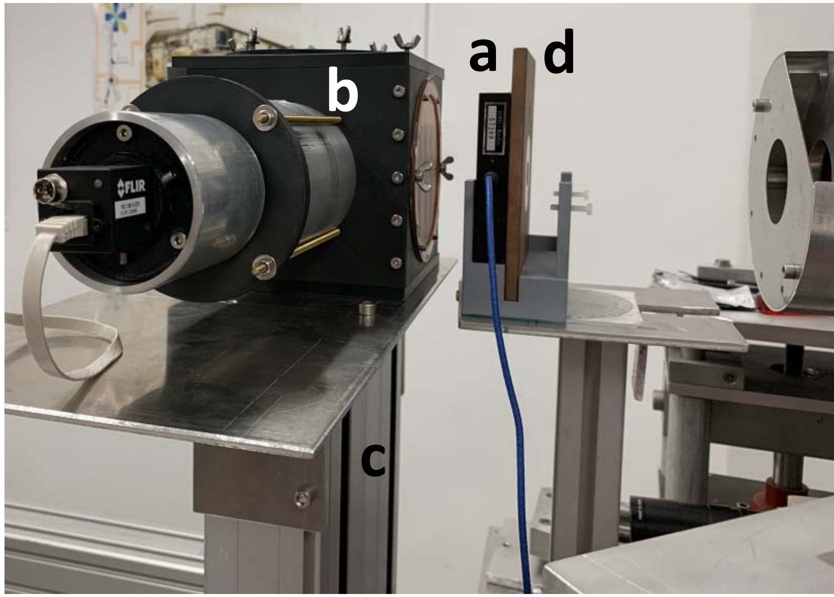


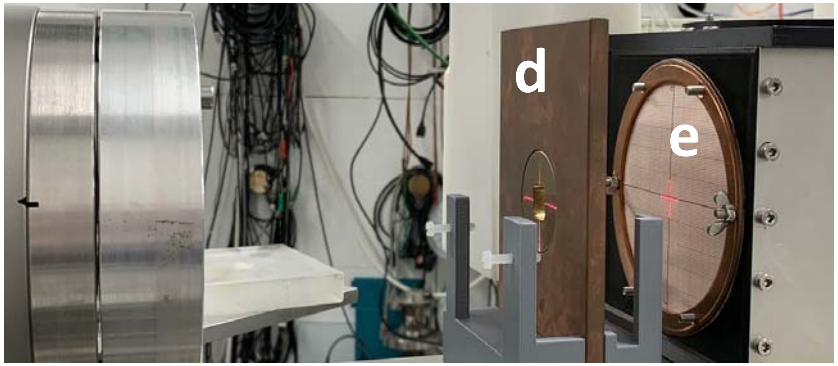
- irradiations in air:
  - beam leaves vacuum of beamline via 80 µm Kapton
  - remote controlled (no access to room when beam is “on”)
  - determination of field by apertures or slits
  - samples may be operated during the irradiation
  - samples on xy-table with 0.1 mm precision of positioning
  - stroke: 50 cm in x and y
  - max. weight of samples for the table: 50 kg
  - samples and/or instruments monitored by camera

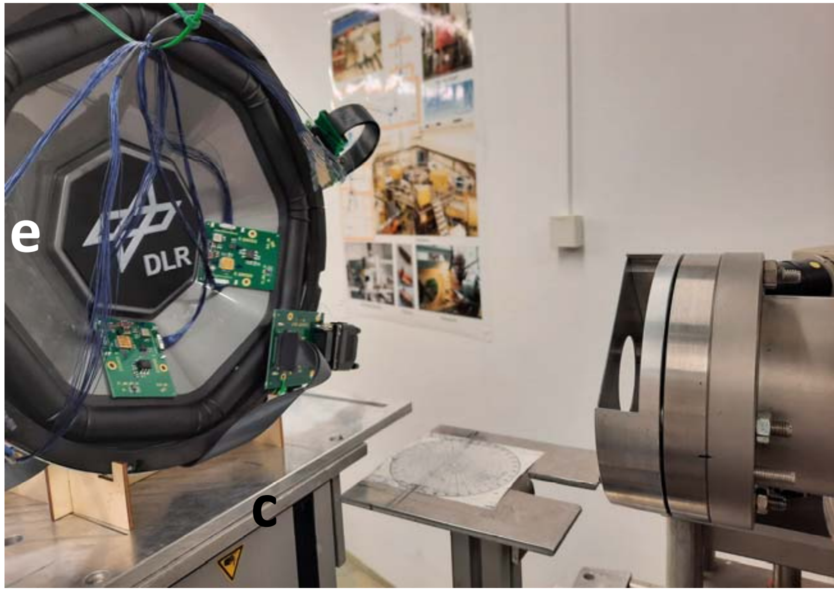
- if needed: irradiations in vacuum possible

Protons: Experimental Station - Details

- **irradiations in air:**
  - a) **on-line measurement of protons by ionization chamber and automatic switch-off of the beam**
  - b) **verification of field size by 2D camera**
  - c) **samples on xy-table with 0.1 mm precision of positioning**
  - d) **aperture for field definition**
  - e) **position of samples verified by laser cross-hair**
  - f) **samples may be operated during the irradiation (movement sensor of the DLR)**

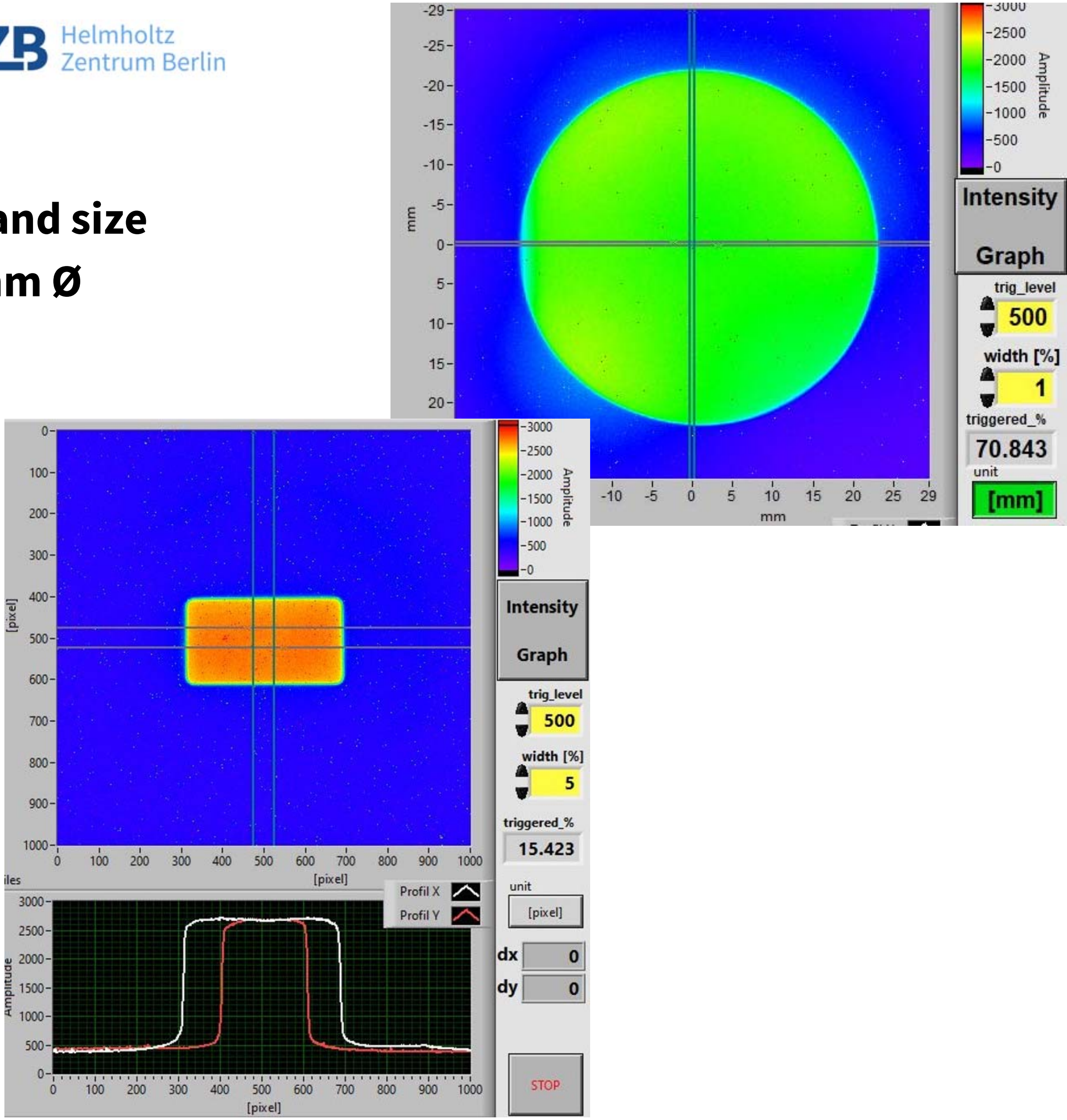






Protons: Irradiation Field

- 2D camera for determination of profile and size
- broad beam (scattering system I) ~ 45 mm Ø
  - very homogeneous: ± 3%
  - max. $1 \cdot 10^8$ p/(cm²s)
- broad beam (scattering system II)
  - homogeneous: ± 10% for 20 mm Ø
  - max. $5 \cdot 10^9$ p/(cm²s)
- rotational symmetry, rectangular or quadratic fields achieved by apertures

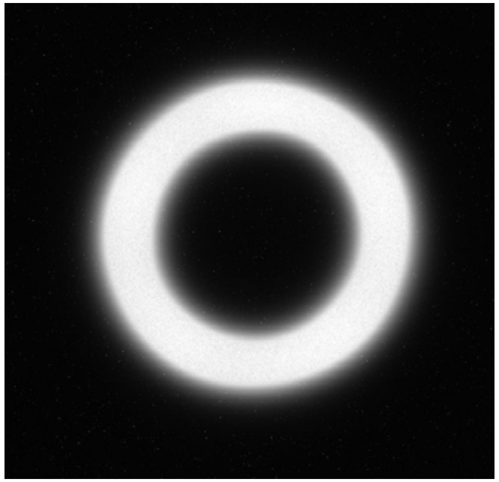


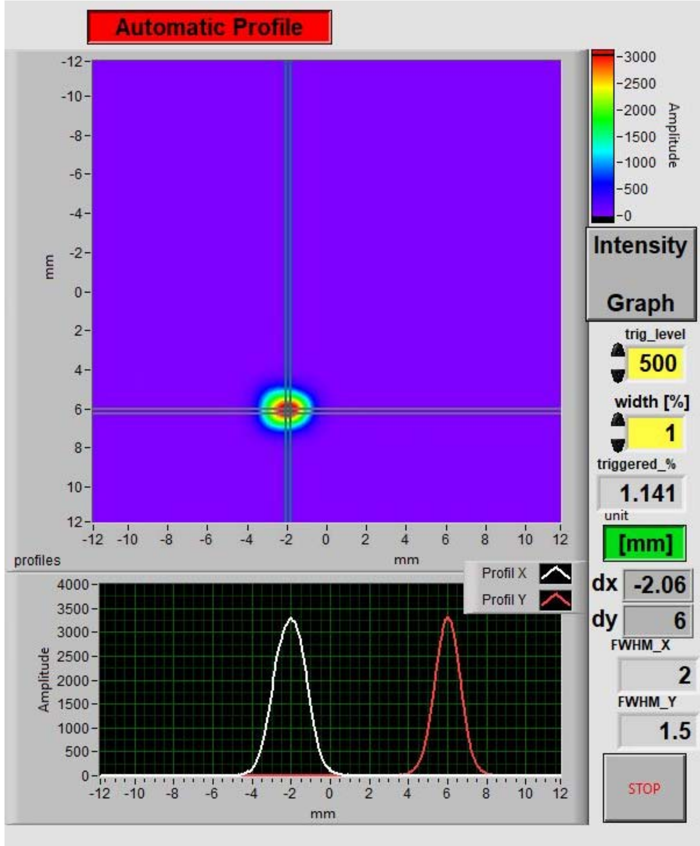
trig_level 500
width [%] 1
triggered_% 70.843
unit [mm]

trig_level 500
width [%] 5
triggered_% 15.423
unit [pixel]
dx 0
dy 0

Protons: Irradiation Field

- **for high intensities: focused beam,**
- **down to diameter ~ 1 mm Ø**
  - **max. $5 \cdot 10^{10}$ p/s**
- **scanned beam**
  - **up to 30 mm · 30 mm**
  - **various shapes possible**





trig_level 500

width [%] 1

triggered_% 1.141

unit [mm]

dx -2.06

dy 6

FWHM_X 2

FWHM_Y 1.5

Protons: Activation – Radiation Protection

- rule of thumb: above 5 MeV nuclear reactions no more negligible
- increasing the energy: more reaction channels open (p,n), (p,α), (p,2n), (p,3n)….

→ after irradiation check of samples for activation

- national laws apply! Germany:
  - radiation safety department does “freimessen”
  - dosimetry and γ-spectroscopy (identification of isotopes)
  - each isotope has its own upper limit
- proton reach isotopes, generally short half-lives
- samples can be released after a few days

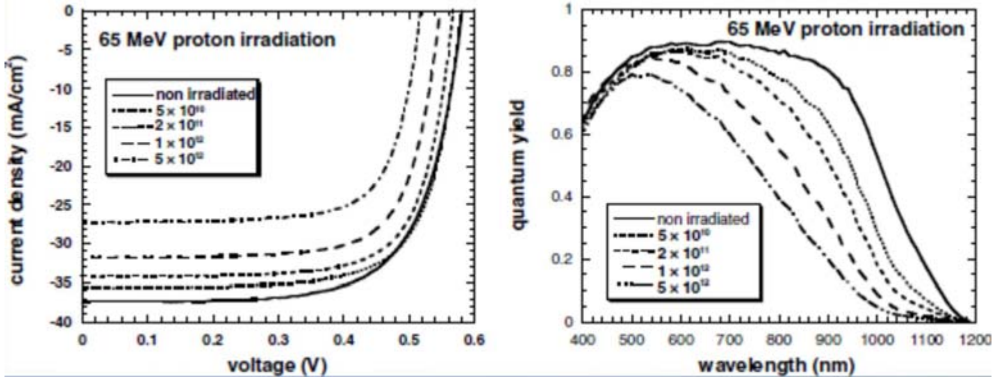
Protons: Examples of Irradiations of Solar Cells

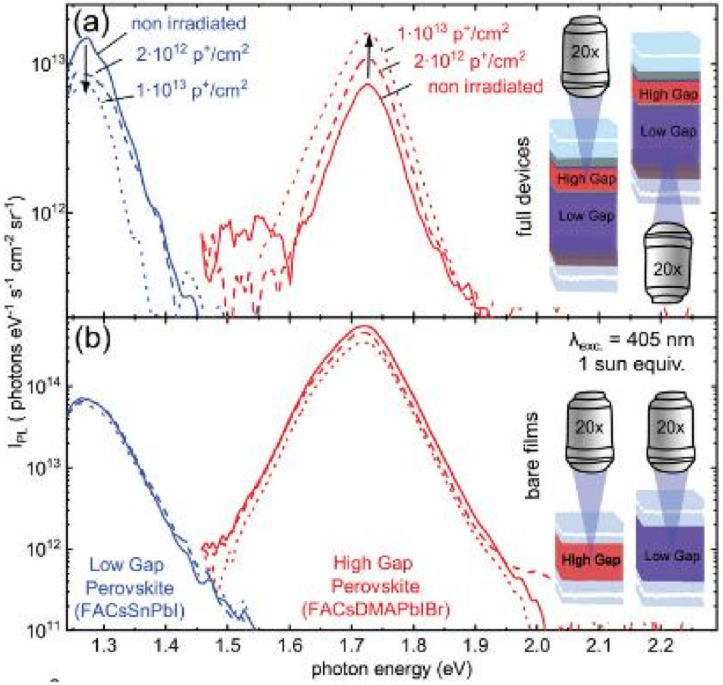
- **proton induced damage in c-Si solar cells, changing the IV-characteristics under AM1.5 illumination and the quantum yield spectra**

  H.-C. Neitzert et al, EL efficiency degradation of c-Si solar cells after irradiation with protons, phys. Stat. sol. (b) No. 9 (2008) 1877-1883

- **absolute PL spectra of the high-gap and low-gap absorbers within the perovskite 2J solar cells (a) and bare absorbers (b) after proton irradiation**

  F. Lang et al, Proton-Radiation Tolerant All-Perovskite F. Multijunction Solar Cells, Adv. Energy Mater. 2021, 11, 2102246 doi/10.1002/aenm.202102246



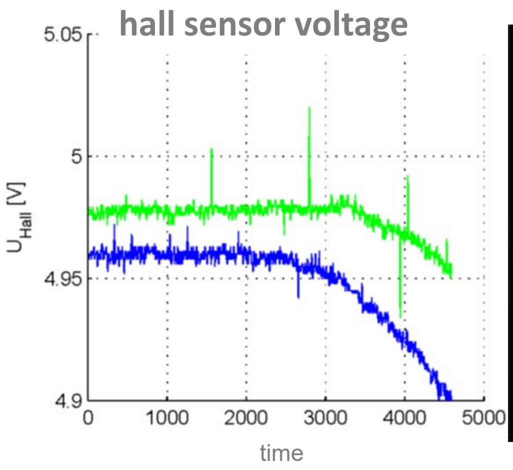


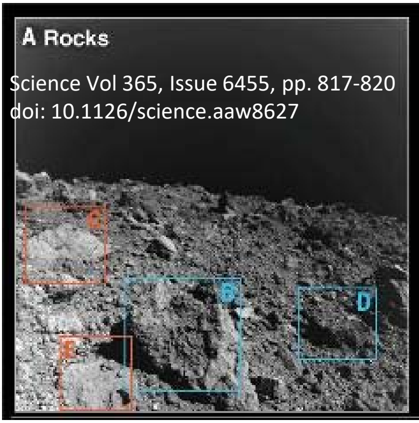
Protons: Examples of Irradiations of Electronics

- **MASCOT (Mobile Asteroid Surface Scout) mission: commercial of the shelf devices: $1.7 \cdot 10^{10}$ p/cm^2,**

  October 2018: lander did relocate on asteroid surface, enabled views on asteroid Ryugu!

  J. Reill, et al, Development of a Mobility Drive Unit for Low Gravity Planetary Body Exploration,
  http://robotics.estec.esa.int/ASTRA/Astra2013/Papers/reill_2824197.pdf

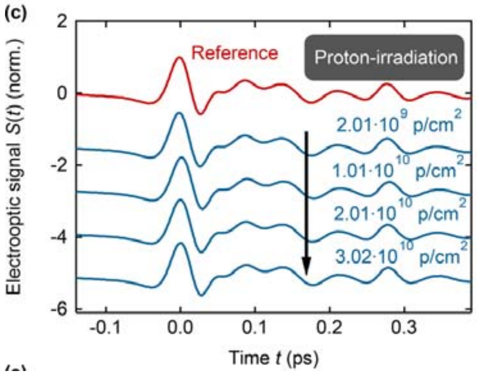


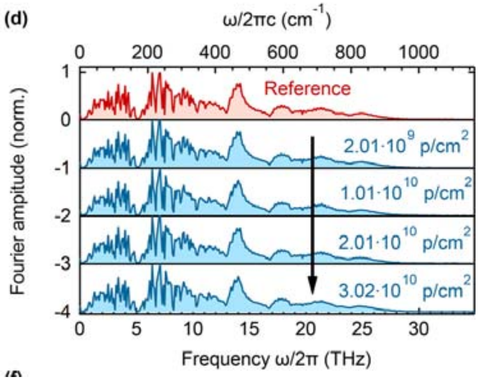


Science Vol 365, Issue 6455, pp. 817-820
doi: 10.1126/science.aaw8627

- **time-domain waveform (c) and frequency-domain spectrum (d) for different irradiation levels of high energy 68 MeV protons**

  O. Gueckstock, Radiation hardness of ultrabroadband spintronic terahertz emitters: En-route to a space-qualified terahertz time-domain gas spectrometer,
  Appl. Phys. Lett. 124, 000000 (2024); doi: 10.1063/5.0196951





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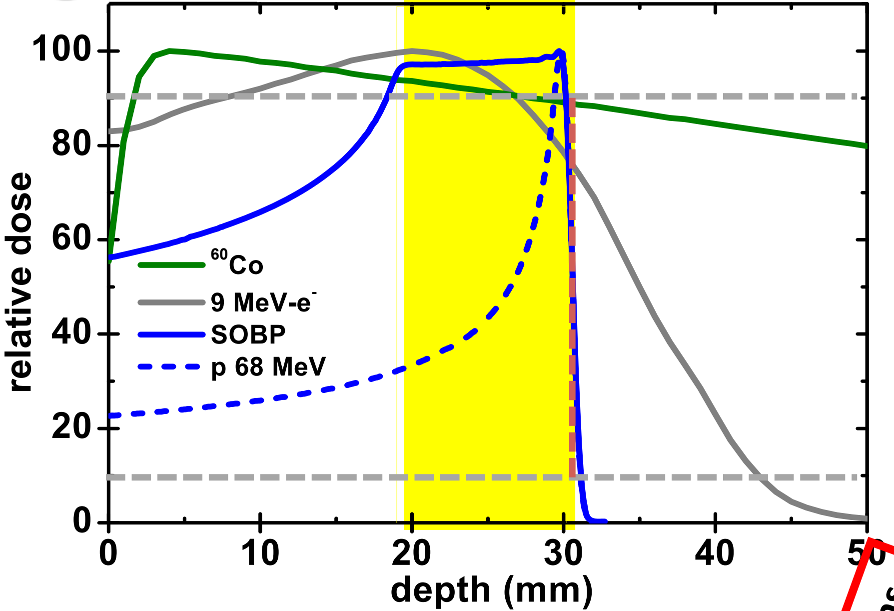
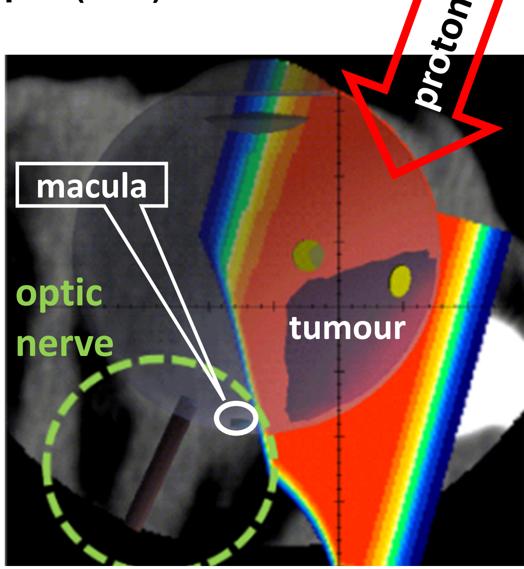
Proton Therapy of Ocular Melanoma

- over 25 years treatment of ocular melanoma together with Charité – Universitätsmedizin Berlin
- more than 4600 patients treated (12/23)
- local tumour control: 96%
- eye retention rate: 95%

- protons permit confinement of dose to tumour
- HZB: proton energy of 68 MeV
- well adapted energy:
  sharp distal fall-off, less than 1 mm 90% - 10% of dose
- enough beam current, treatment time < 1 minute/fraction
- ideal for small structures like eyes (~ 23 mm diameter)





Conclusion

- nuclear physics: important on all scales – from atoms to galaxies
- accelerators:
  - originally driven by needs of nuclear physics
  - today solve problems in solid state physics, medicine, space flights,….
- radiation hardness tests: years between tests and mission → long breath needed

Thank you for your attention!

patient statistics based on the apertures used