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M. I. Besana, E. Hohmann, M. Sapinski, J. Snuverink, D. Werthmüller :: Paul Scherrer Institute

INVESTIGATION OF LONG RADIAL PROBE ACTIVATION IN THE PSI MAIN RING CYCLOTRON

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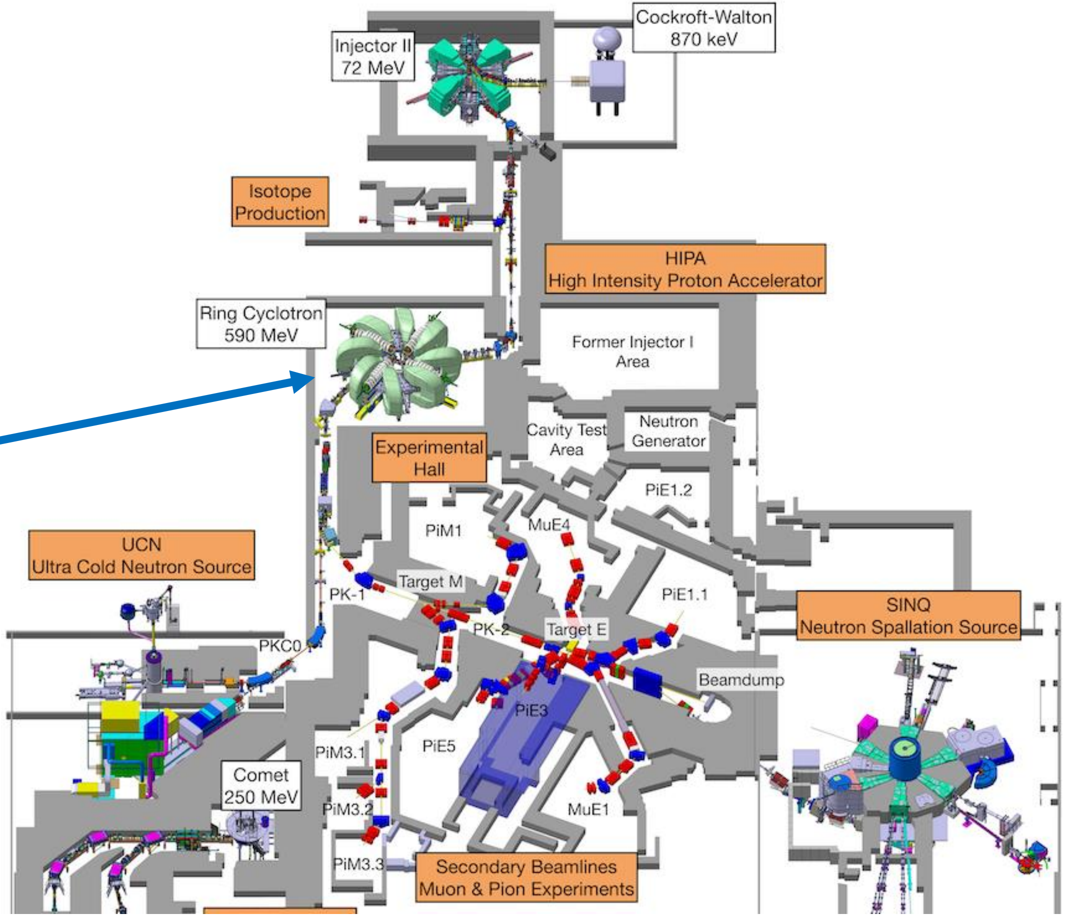
Outline

- Main Ring Cyclotron at the HIPA facility
- The Long Radial Probe (RRL) and the measured residual dose hot spot
- Monte Carlo simulations
- Spectra measurements
- Simulations/measurements comparison
  - most probable cause of dose hot spot
- Summary

The High Intensity Proton Accelerator (HIPA)

- Cyclotron facility at PSI → 590 MeV proton beam with current up to 2.4 mA

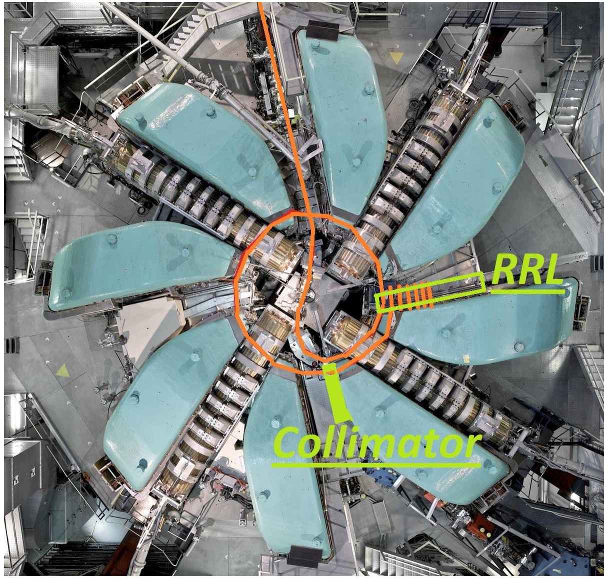
- Three acceleration steps:
  – Final acceleration in the large 8-sector Ring Cyclotron

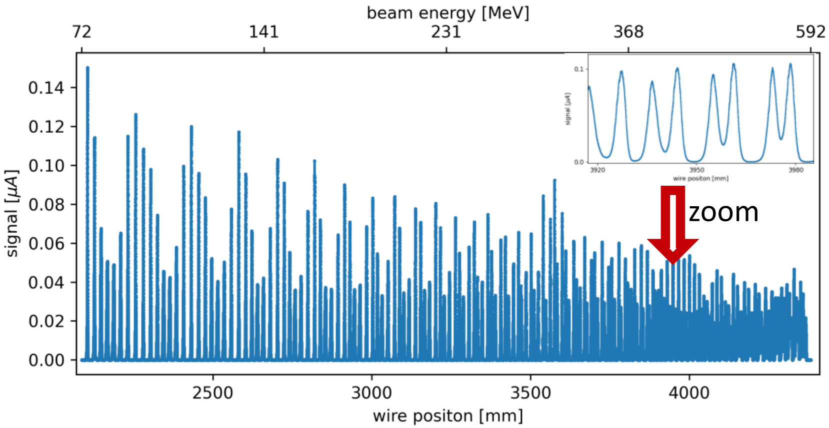


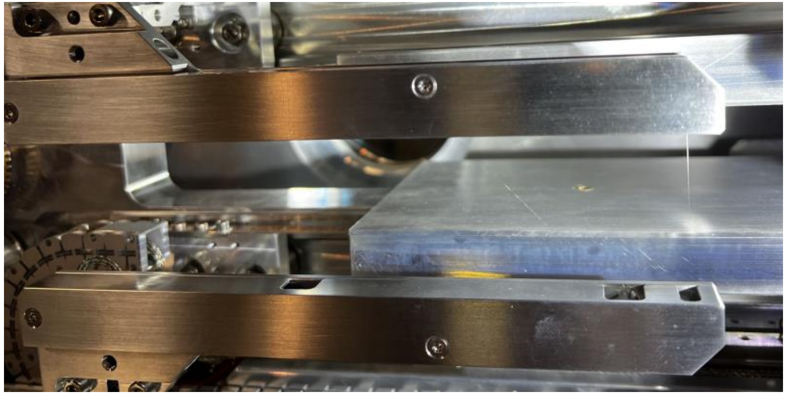
More information in the talk: *"IMPACT: A Substantial Upgrade to the HIPA Infrastructure at Paul Scherrer Institute"* from D. Kiselev (MOB02)

Long Radial Probe (RRL)

- Measures the beam profile of all (approx. 180) orbits
- Done by moving ϕ=30µm carbon fibers through the radius of the machine (2 to 4.5 m) and registering secondary electrons
- Wire is streched between two arms of a fork
- The arms move synchronously along supporting structures which limit the machine aperture

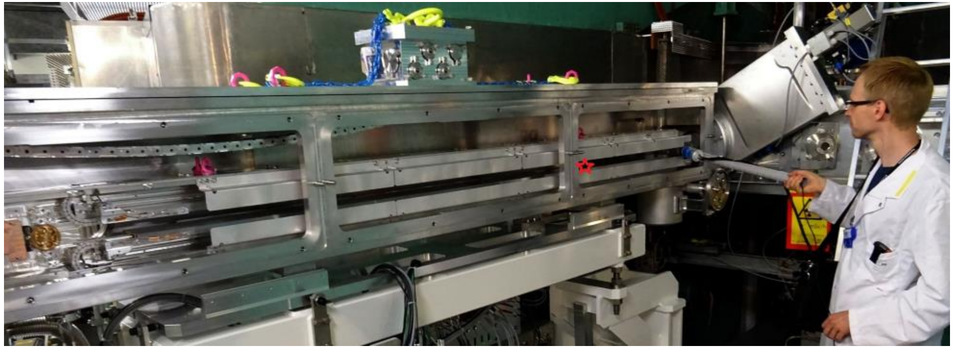






Long Radial Probe (RRL)

- After the first month of operation a hotspot was detected (>1mSv/h)
- Hotspot position corresponds to beam energy 150 MeV < E < 180 MeV
- Measurement with Al_2O_3:C dosimeters inserted into gap between supporting structures revealed that upper structure is 4x more activated than bottom



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Activation Simulations Strategy

Established procedure for activation calculations at PSI

=

coupling of the transport code **MCNP** and the nuclide inventory code **FISPACT**

MCNP simulations:

particles are transported from the source points to the regions of interest

FISPACT inventory calculations:

time-dependent growth and decay of all relevant radionuclides at any time instance

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Results:

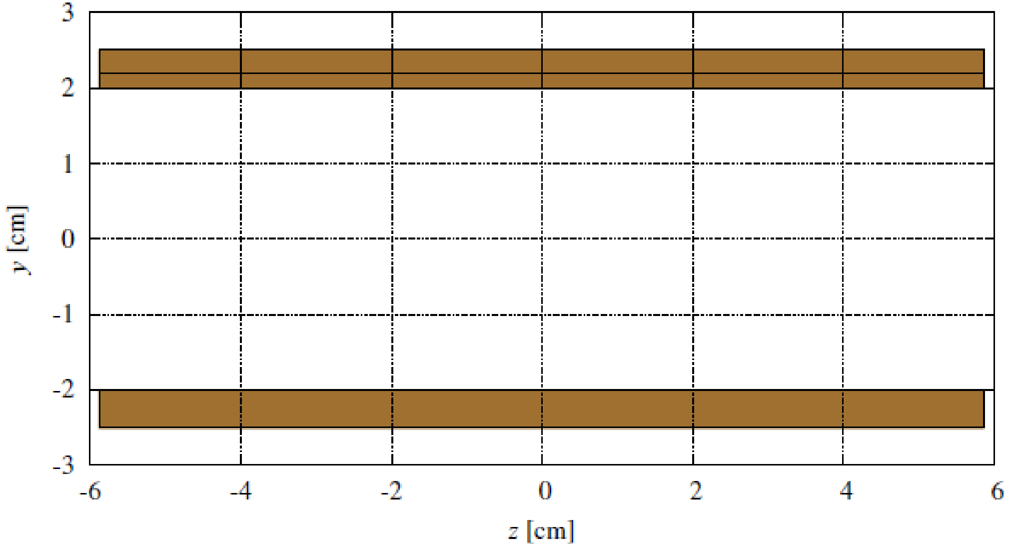
- nuclide inventory
- expected activity
- residual dose
- spectrum and flux rate of the emitted gamma rays

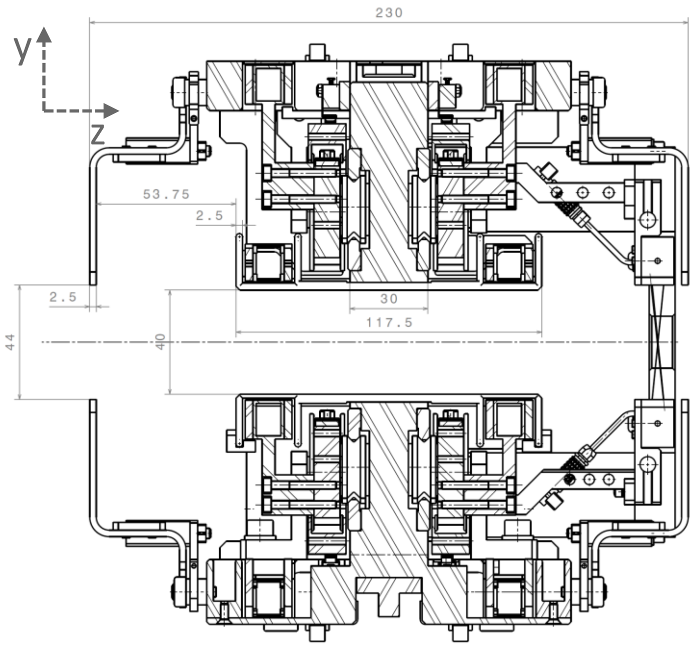
(expected activity and residual dose: for each nuclide)

at different locations and different time instances

RRL Model in MCNP

- The RRL device is modeled as 2 blocks Aluminum-Magnesium alloy
  - 92% Aluminum
  - 4.9% Magnesium
  - 1% Manganese
  - 0.4% Silicon & Iron
  - 0.25% Chromium & Zinc
  - 0.1% Titanium
  - 0.1% Copper
  - + trace elements





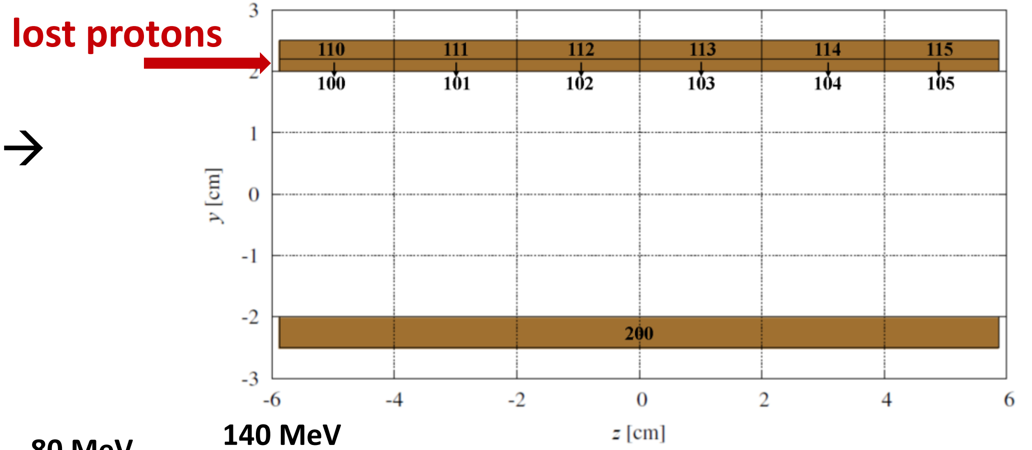
Dimensions in *[mm]*

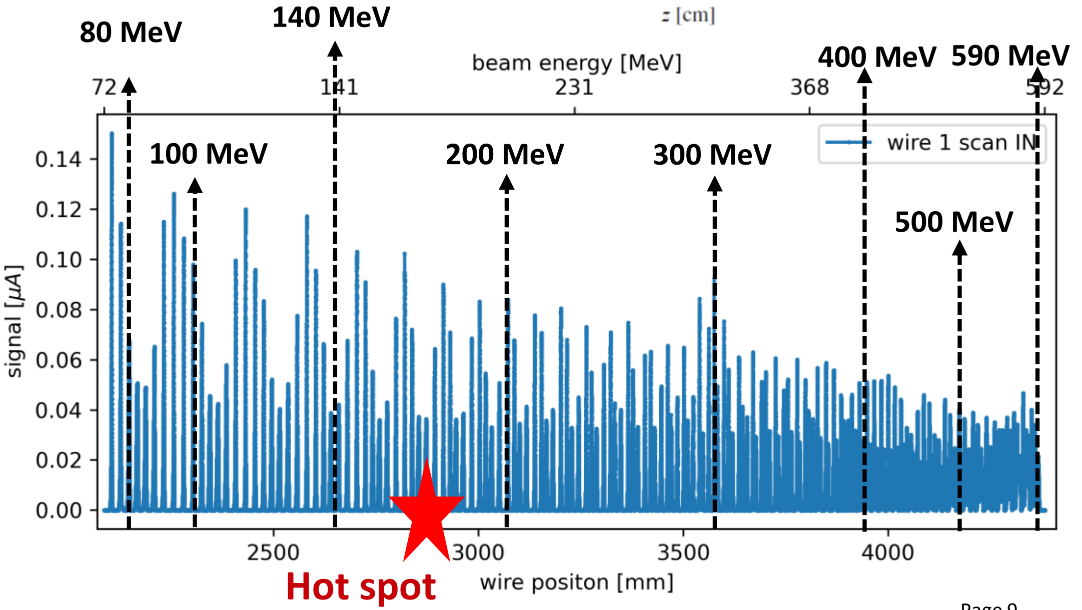
- Δy = 4 cm
- 11.75 cm in the beam direction (z)
- 0.5 cm in the vertical direction (y)
- 1 m in the radial direction (x)

Source Term

- Beam losses at the RRL not known → assumptions for the simulations:
  - lost protons moving along z-axis, impacting on the RRL upper part
  - 12 simulations with different beam energies:

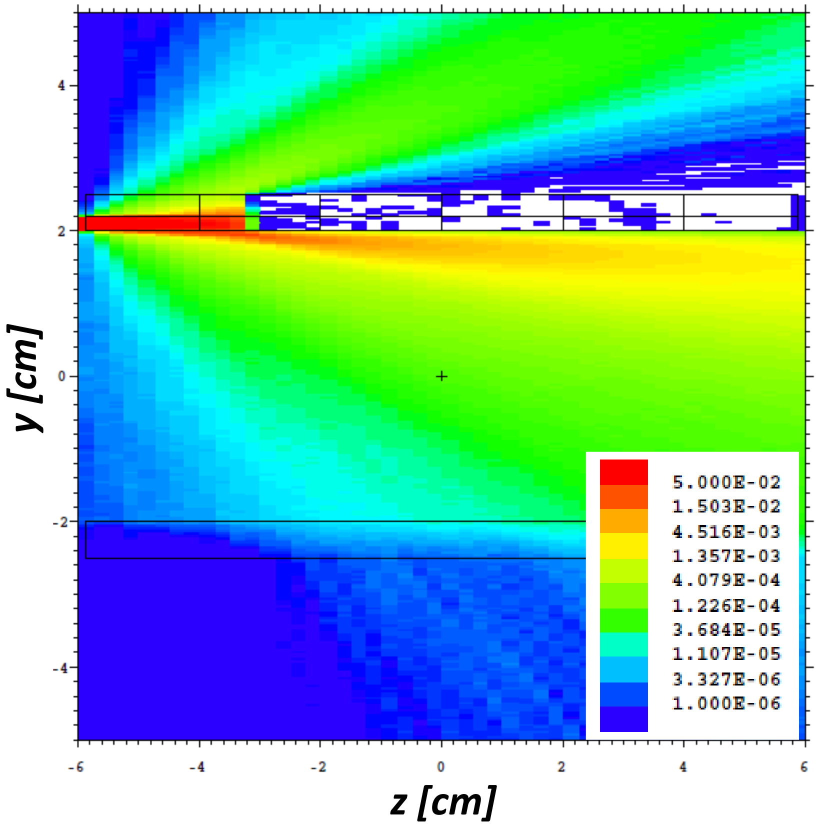
10 MeV	140 MeV
20 MeV	200 MeV
40 MeV	300 MeV
60 MeV	400 MeV
80 MeV	500 MeV
100 MeV	590 MeV



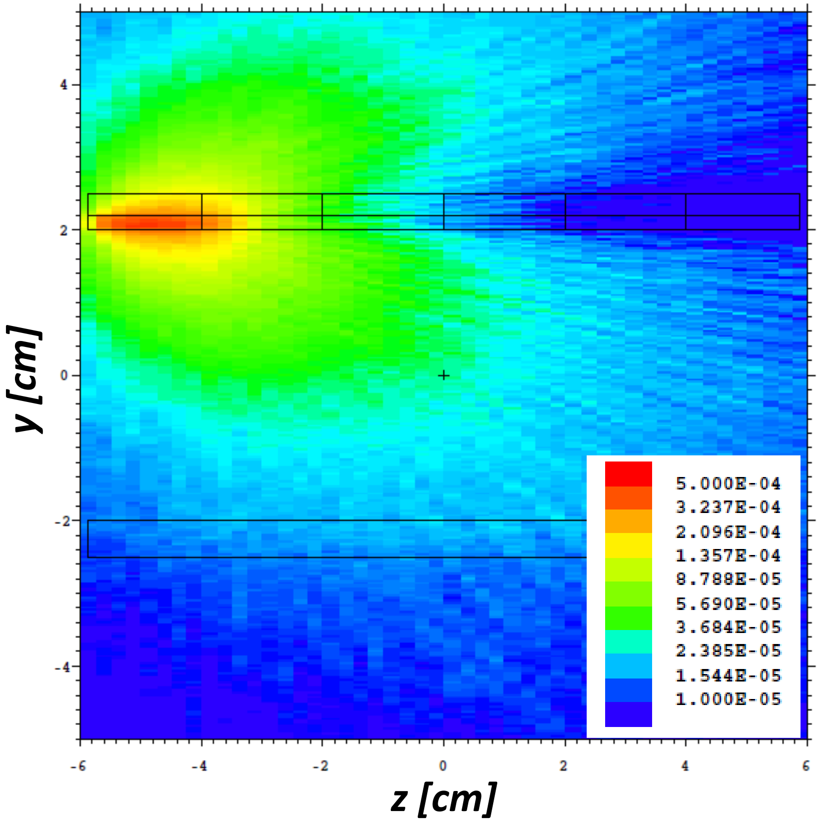


MCNP Results: 80 MeV Beam

Proton fluence [cm^{-2}/primary]

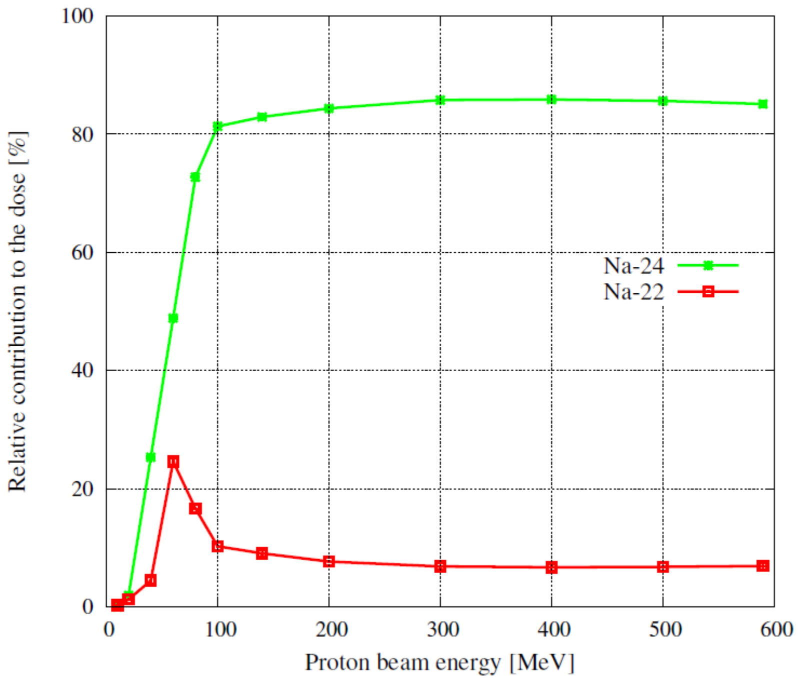


Neutron fluence [cm^{-2}/primary]



FISPACT Calculations

- Operation history:
  - 19 days irradiation
  - 36 hours of cooling → *hot spot identified*
  - 29 hours of cooling
  - 25 days irradiation
  - 12 hours cooling → *Gamma spectra measurement*



- Highest activation predicted where the beam impacts [cell 100]
  - E_{beam} < 60 MeV: large contribution to the residual dose from V-48, Co-56 and Mn-52
  - $E_{beam} \geq$ 60 MeV: >75% of the dose from Na-22 and Na-24
  - $E_{beam} \geq$ 80 MeV: >80% from Na-22 and Na-24 → dominated by Na-24

Gamma Spectroscopy (G-Spec)

Goals

→ Determine nuclide contributions in activated area

→ Estimate proton beam energy

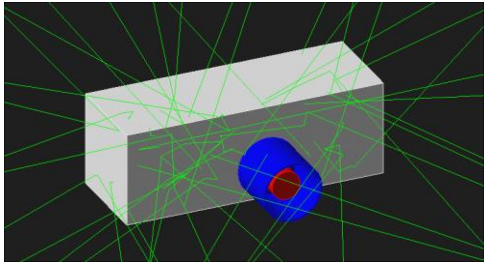
Measurement

- ELSE Nuclear B-RAD: $LaBr_3$ handheld spectrometer
- Energy resolution: 3.3% (FWHM) at 662 keV

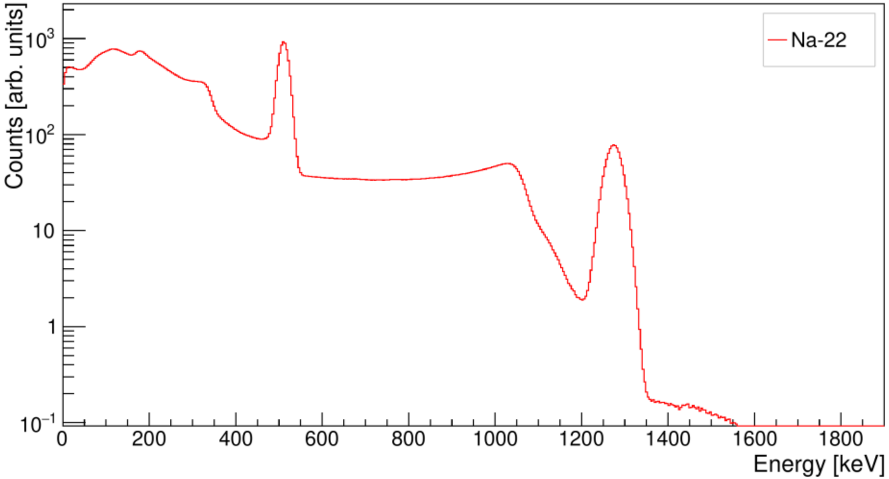
G-Spec: Simulation of Detector Spectra

Detector simulation

- Simplistic Geant4 model
- Radioactive decays of key nuclides
- Deposited energy folded with detector resolution
- Obtain spectral distributions of key nuclides $s_i'(E)$

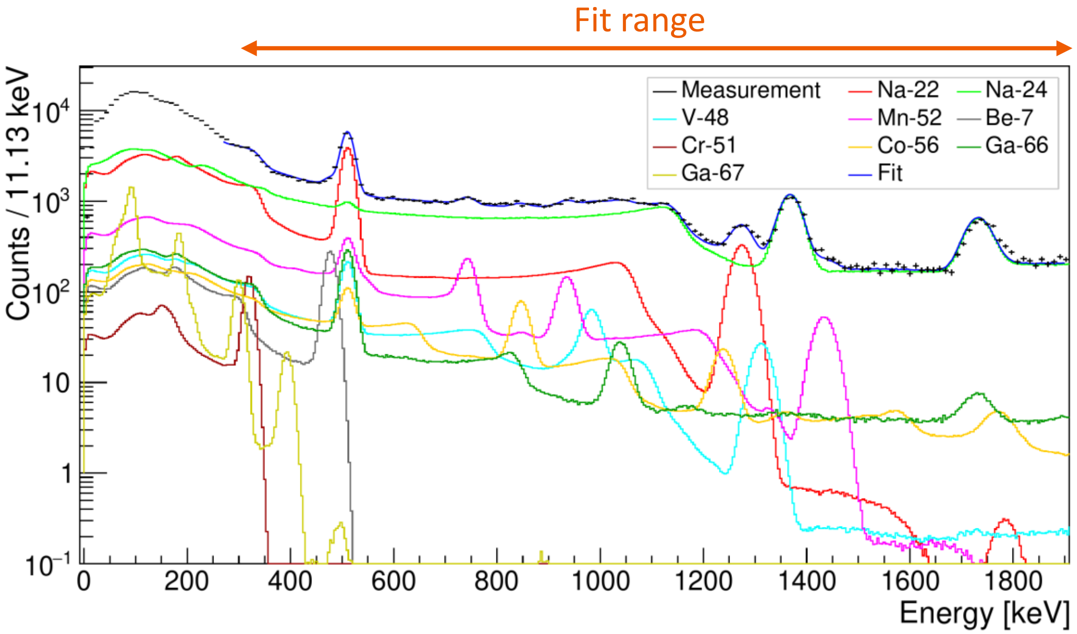


Example: Na-22



→ Fit sum $S(E)$ of simulated spectra to measured spectrum

G-Spec: Fitting the Spectrum



→ Key nuclides identified from MCNP/FISPACT calculation

→ Fit ansatz: $$S(E) = \sum_{Nuclide\ i} c_i \cdot s_i'(E)$$

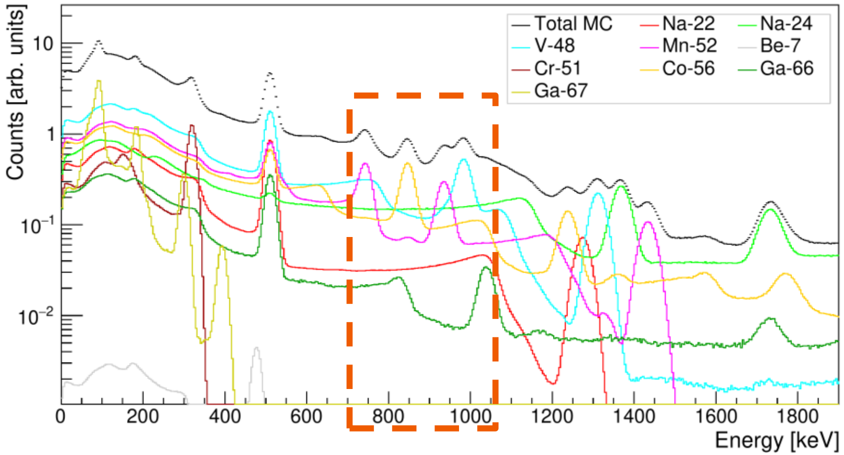
Key nuclide results

Nuclide	$T_{1/2}$	c_i [%]
Na-22	2.6 y	24.6
Na-24	15.0 h	60.0
V-48	16.0 d	2.6
Mn-52	5.6 d	6.9
Be-7	53.2 d	0.9
Cr-51	27.7 d	0.3
Co-56	77.2 d	2.3
Ga-66	9.5 h	2.2
Ga-67	3.3 d	0.3

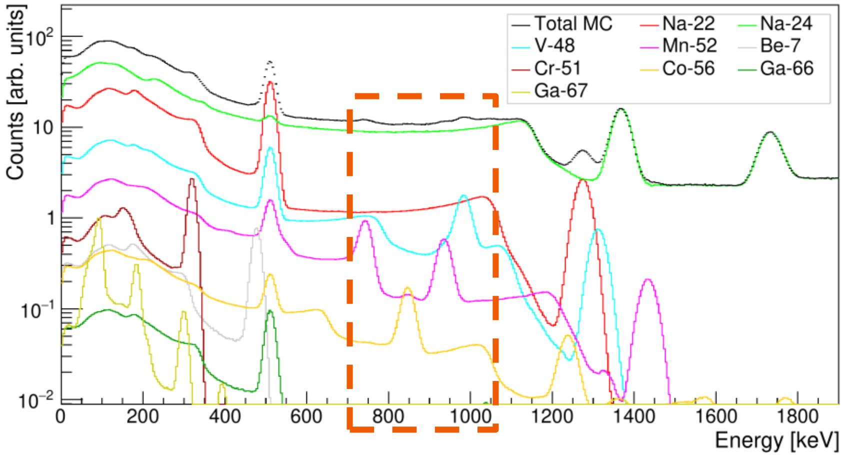
G-Spec: Simulated Nuclide Contributions

- Characteristic gamma energy distributions for different proton energies
- Example: Region [700, 1000] keV for 40 and 140 MeV proton beam energies

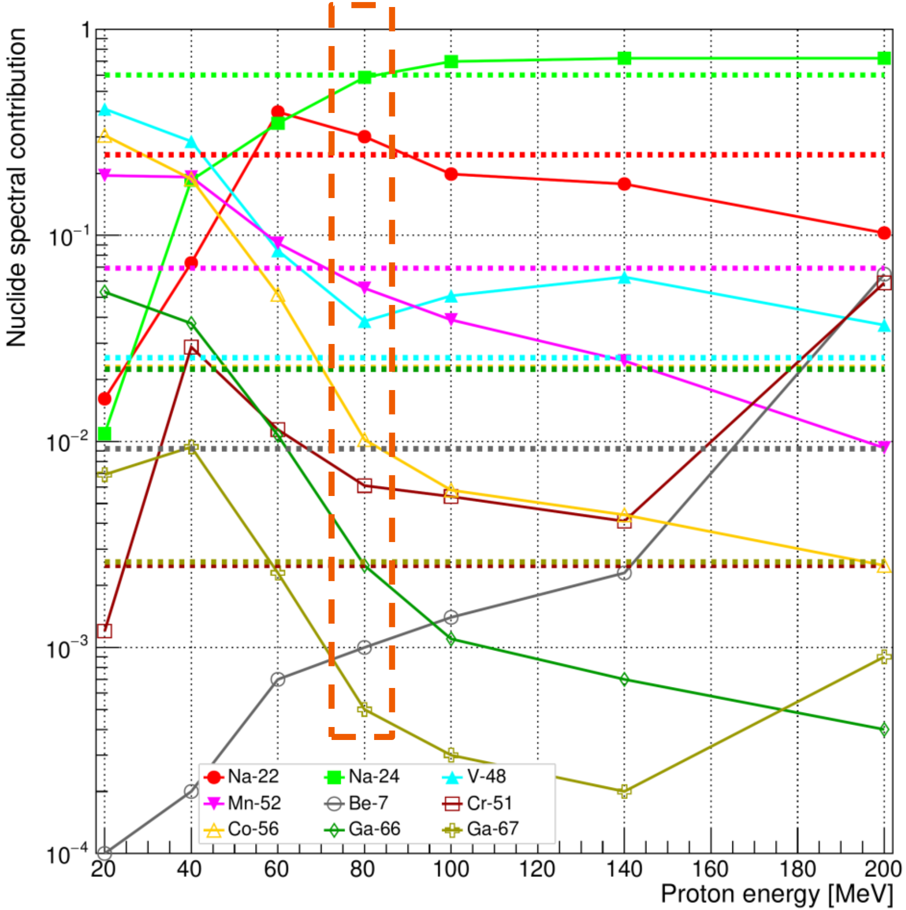
40 MeV



140 MeV



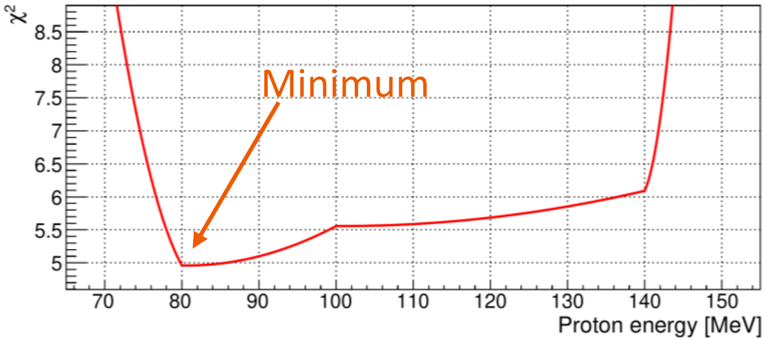
G-Spec: Estimation of Proton Energy



- Compare c_i from calculation (curves) at different proton energies with c_i from measurement fit (horizontal lines)
- Calculate

$$\chi^2 = \sum_{Nuclide\ i} \left(\frac{c_i(Calc) - c_i(Fit)}{c_i(Fit)} \right)^2$$

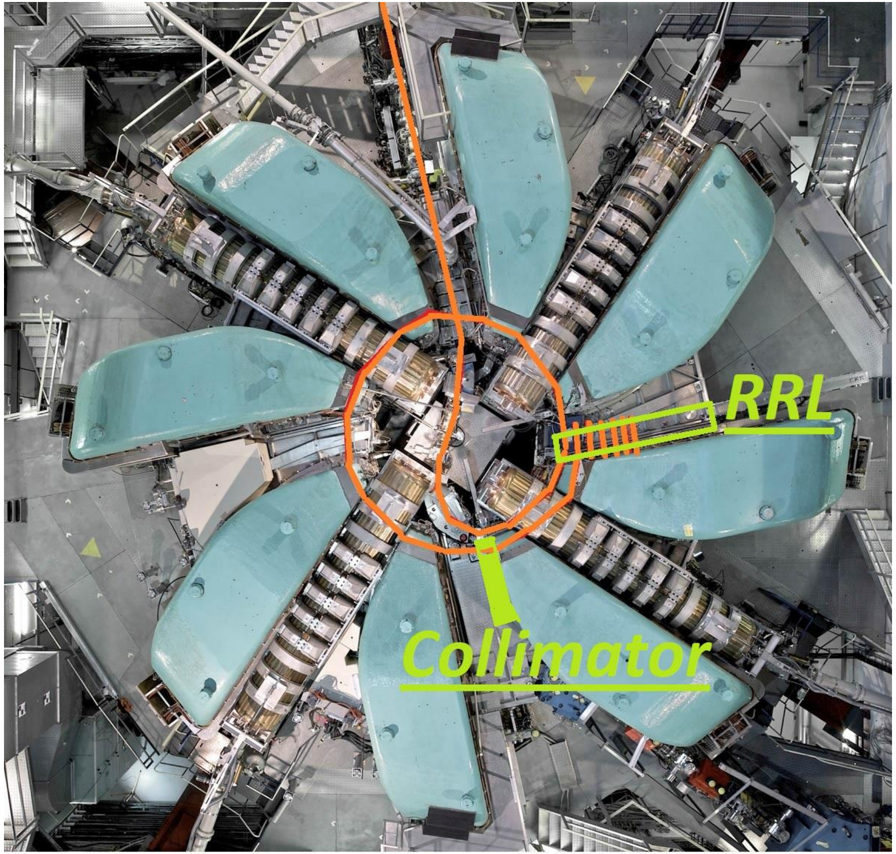
→ Estimated proton energy: 80 MeV



Cause of the Hot Spot

- Simulations – measurements comparison → energy of lost protons **= 80 MeV**
- Proton energy at the position of the hot spot 150 MeV < E < 180 MeV

Most probable cause of dose hot spot = protons scattered on the upstream collimator



Summary

Activation hot spot in the RRL investigated with measurements and Monte Carlo simulations

- Estimated proton energy is **80 MeV**
  - **activation from protons scattering at the collimator**

- Most of the activation comes from relatively **fast decaying radioisotopes** (Na-24, $T_{1/2}$ = 15 hours)
  - **the residual dose drops quickly during shutdowns**

Summary

Activation hot spot in the RRL investigated with measurements and Monte Carlo simulations

- Estimated proton energy is **80 MeV**
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Thanks for your attention

My thanks go to

- L. Bossin
- R. Dölling
- M. Hauenstein
- S. Lindner
- D. Reggiani
- M. Rohrer
- E. Yukihara
- PSI operator team

Activation Simulations Strategy

Coupling of MCNP6.2 Monte Carlo simulations with nuclide inventory code FISPACT

Inputs for MCNP:
- model of the geometry
  - small cells to study the activation at different positions
- material composition
- source term
- physics models and data libraries

MCNP simulation 1:
particles (protons, neutrons, photons, pions, …) are transported from the loss points to the regions of interest

MCNP output:
- neutron fluxes (E< 20 MeV)
- residual nuclei production rates calculated for or each cell

Activation script

Inputs for FISPACT:
- spectra and production rates from MCNP
- operation history

FISPACT calculations:

for each cell and at each time step different quantities are calculated:
- nuclide inventory
- relative contribution of the different nuclides to activity and residual dose
- spectrum and flux rate of the emitted gamma rays

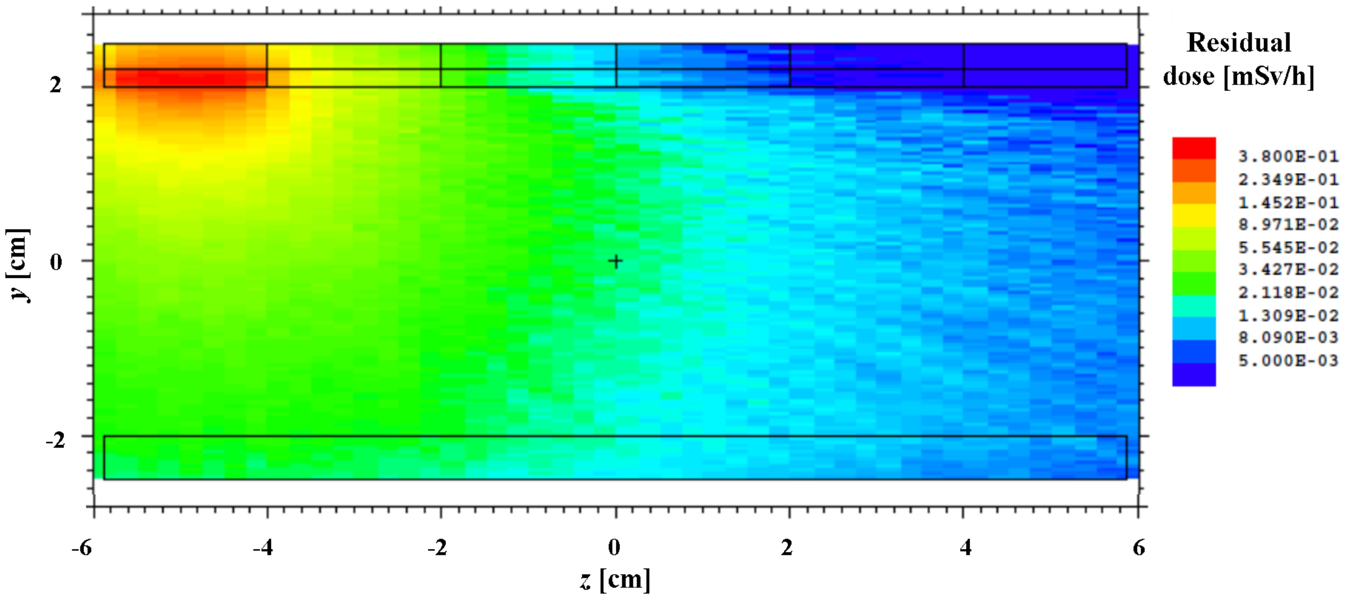
Gamma script

MCNP simulation 2:
the emitted photons are used as source term for a second MCNP simulation

Residual dose map

Residual Dose Map

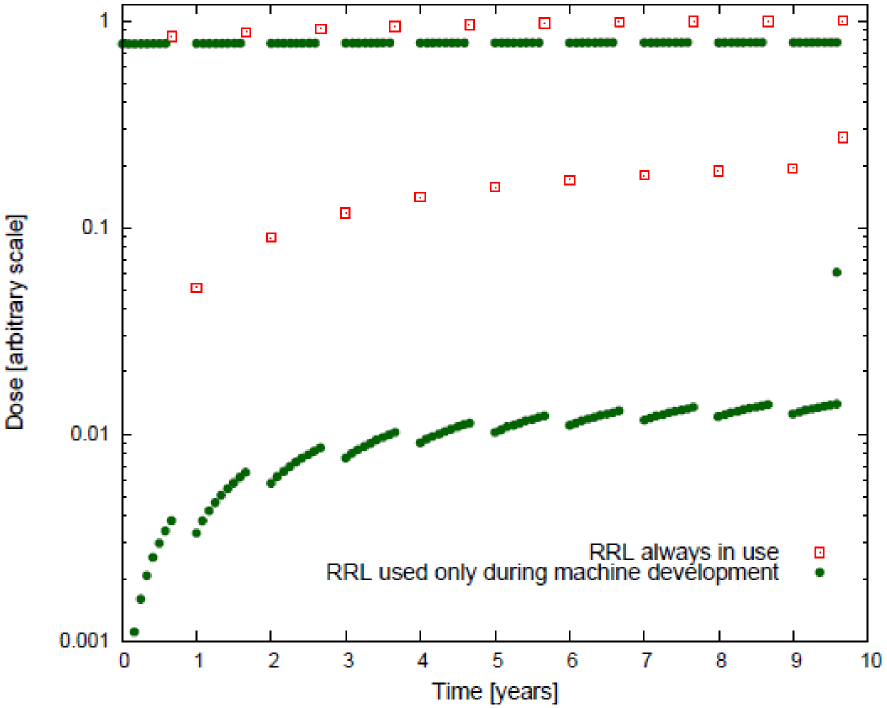
- Residual dose map at the time of the first measurement for beam energy of 80 MeV:



  - the dose value depends on assumptions on
    - beam distribution
    - lost current = 1 nA

Long Term Activation

- Most of activation from short living Na-24
  – the residual dose drops quickly
- Time evolution of residual dose rate in 10 years of operation:
  – when RRL device always intercepting the beam
  – when RRL device irradiated only 2 days per month



- Ratio ($Dose_{In}$/ $Dose_{Out}$) after 10 hours of cooling time is ~4.5
  – motorization of the probe in the next winter shutdown