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

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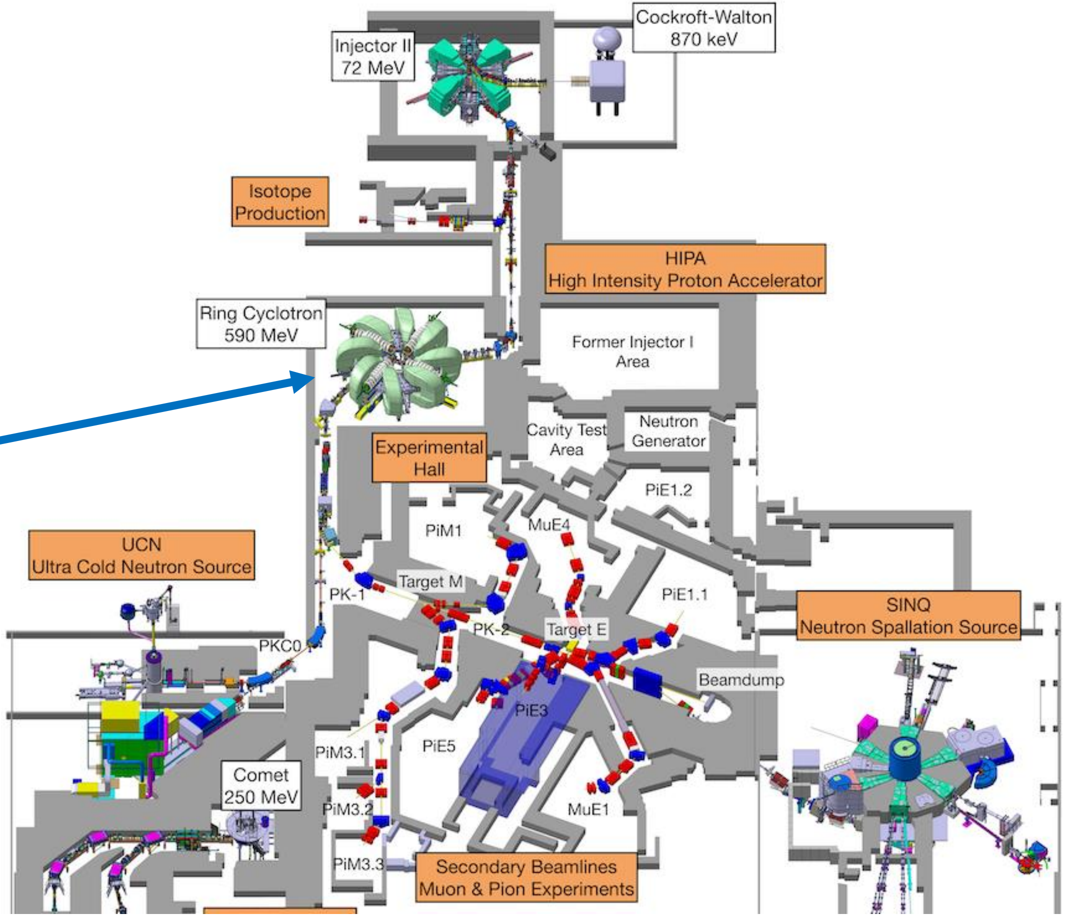
# Outline

- 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)

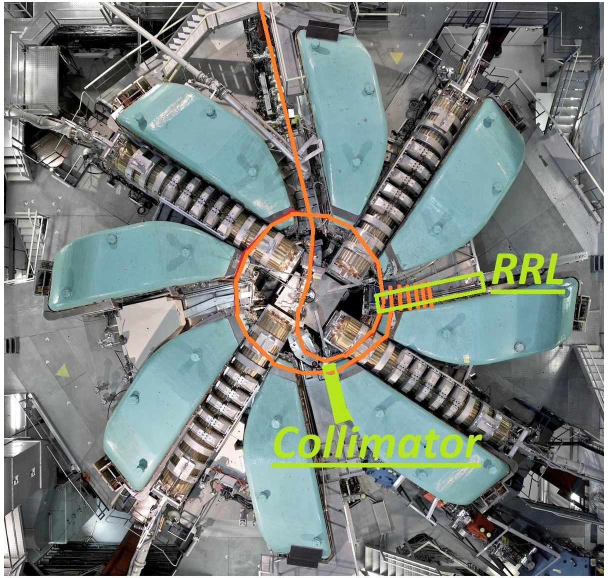
- Cyclotron facility at PSI → 590 MeV proton beam with current up to 2.4 mA

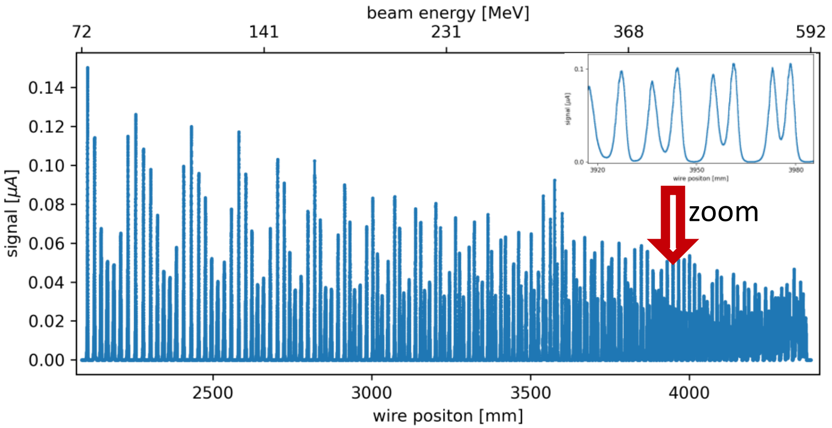
- Three acceleration steps:
  - Final acceleration in the large 8-sector Ring Cyclotron

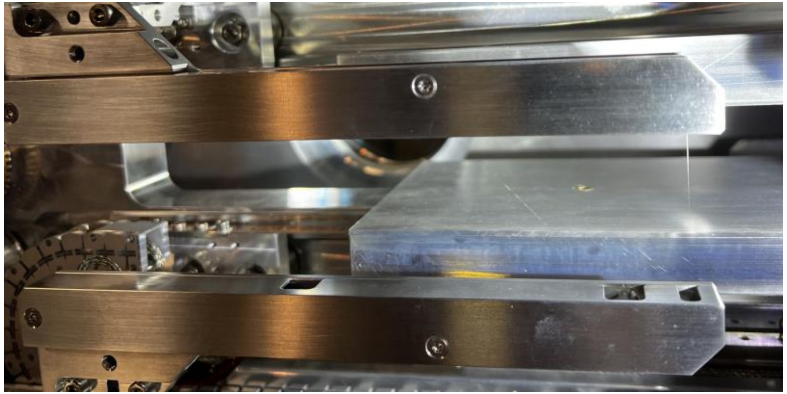


# Long Radial Probe (RRL)

- 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

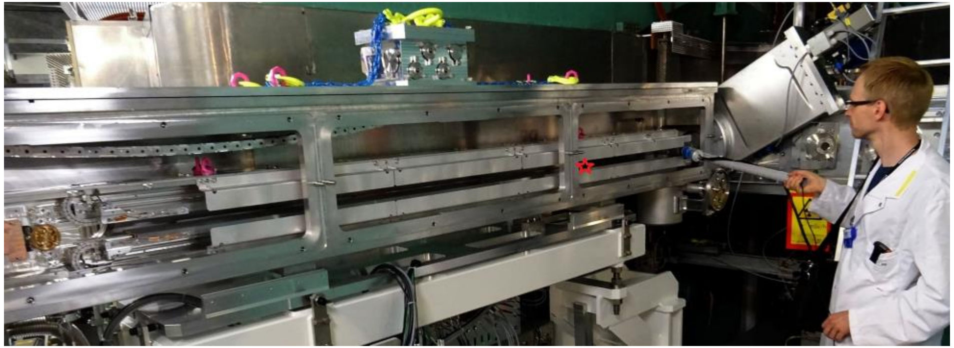


# Long Radial Probe (RRL)

- After the first month of Operation a hotspot was detected (>1mSv/h)
- Hotspot position correspond to beam energy 150 MeV < E < 180 MeV
- Measurement with Al2O3:C dosimeters inserted into gap between supporting structures revealed that upper structure is 4x more activated than bottom



# 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:**

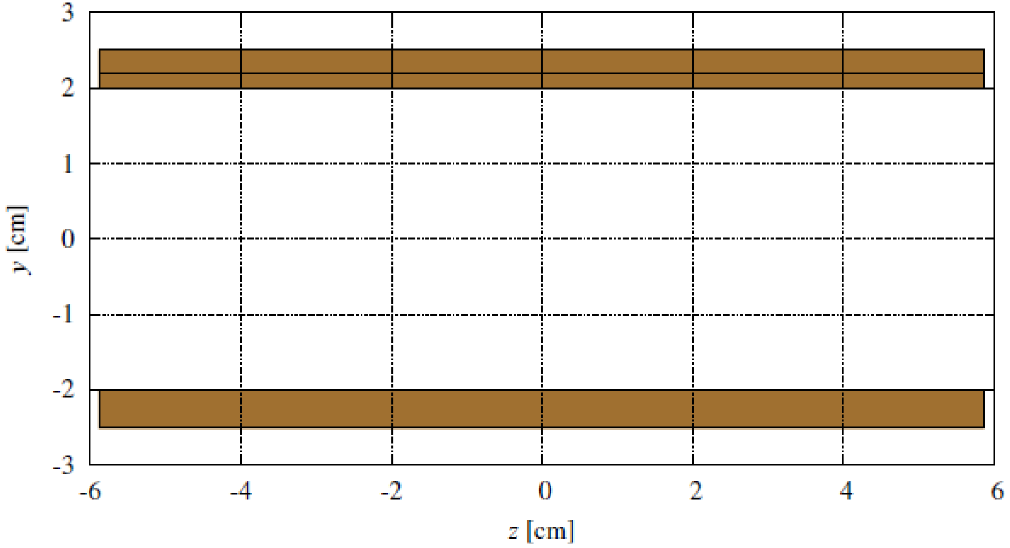
- nuclide inventory
- expected activity
- residual dose
- spectrum and flux rate of the emitted gamma rays

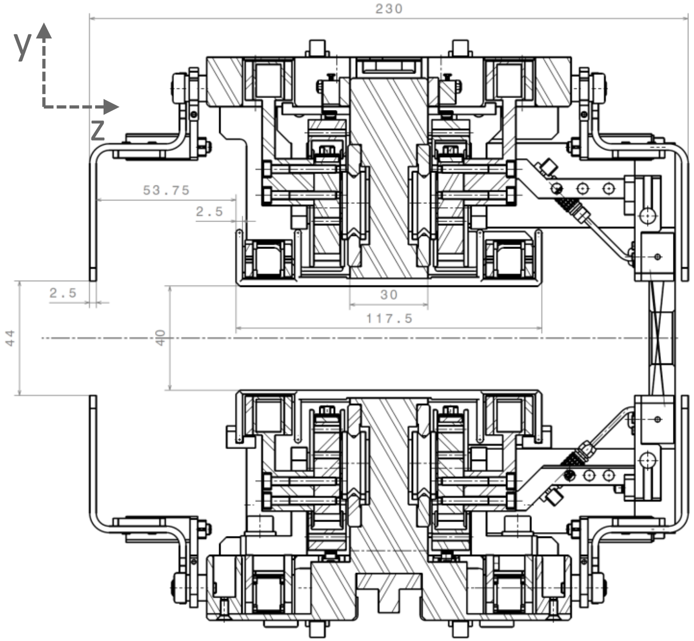
(expected activity and residual dose: for each nuclide)

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




- 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)

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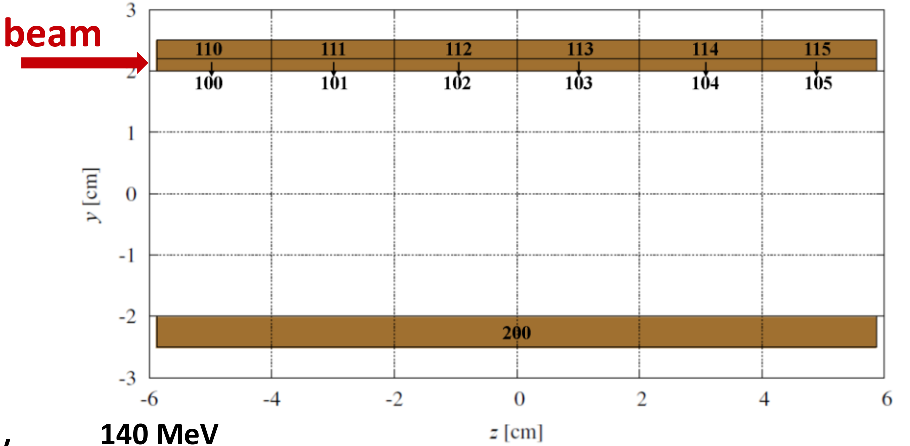
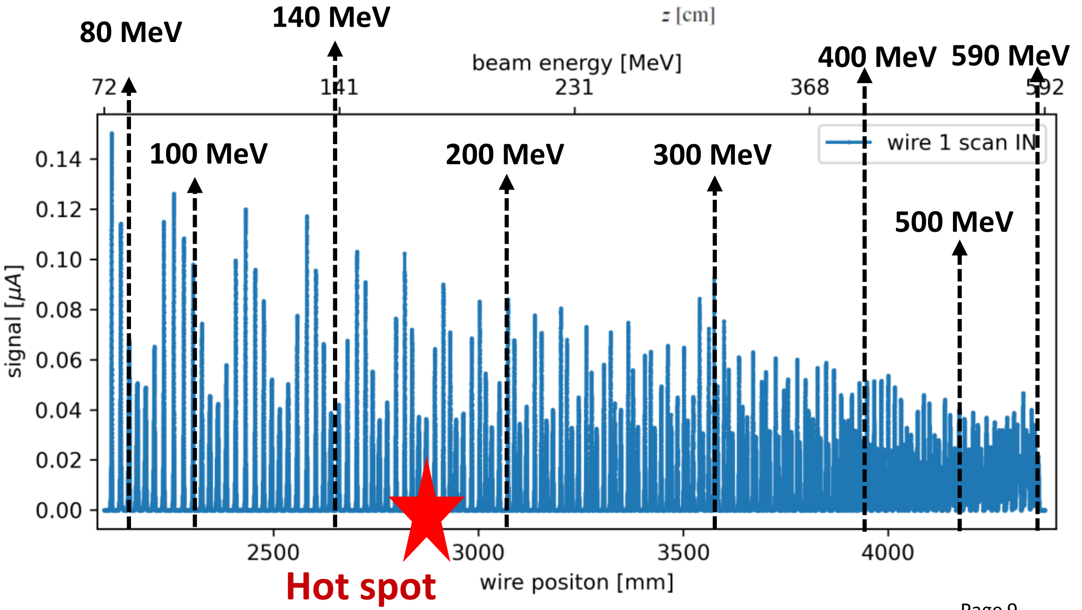
# Source Term

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

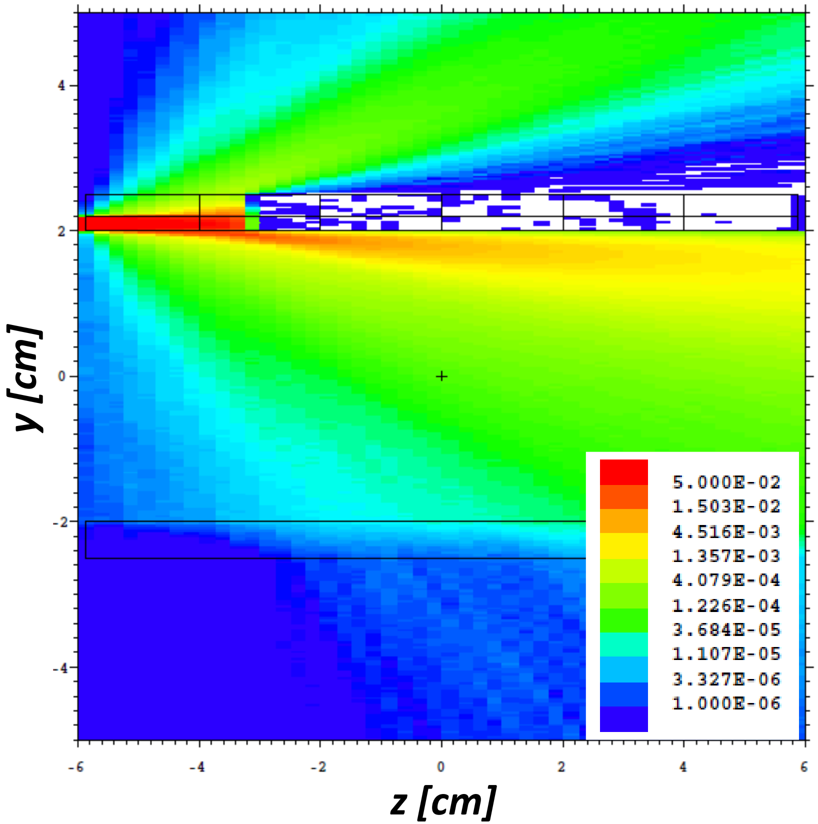
| | |
|---|---|
| 10 MeV | 140 MeV |
| 20 MeV | 200 MeV |
| 40 MeV | 300 MeV |
| 60 MeV | 400 MeV |
| 80 MeV | 500 MeV |
| 100 MeV | 590 MeV |



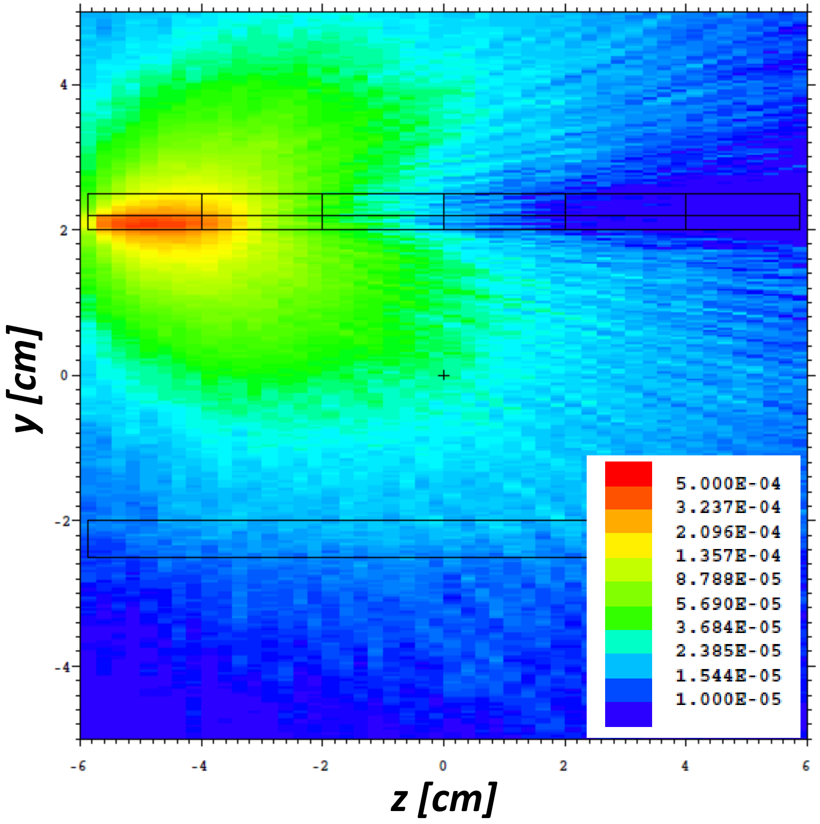



# MCNP Results: 80 MeV Beam

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

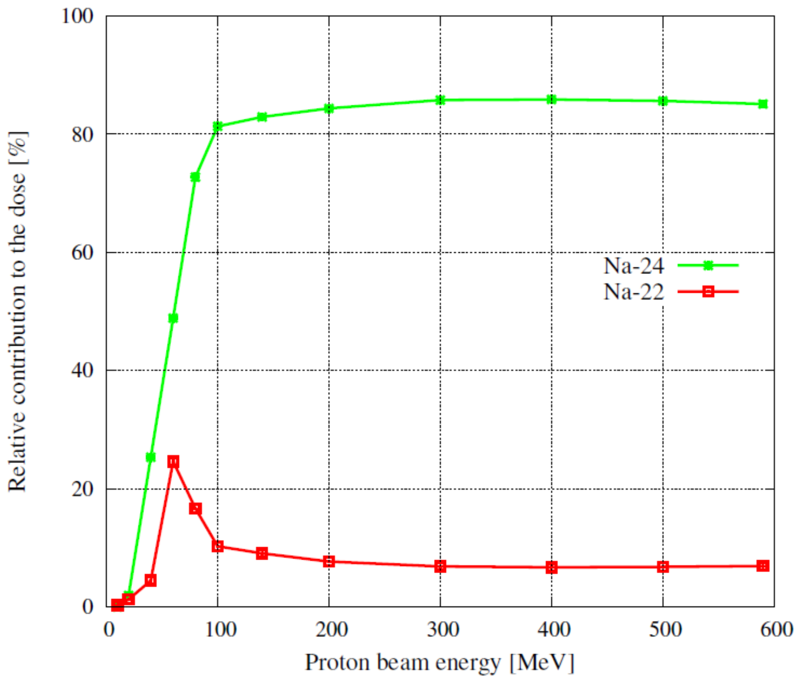



Neutron fluence [cm$^{-2}$/primary]



# FISPACT Calculations

- Irradiation history:
  - 19 days irradiation
  - 36 hours of cooling → *hot spot identified*
  - 29 hours of cooling
  - 25 days irradiation
  - 12 hours cooling → *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

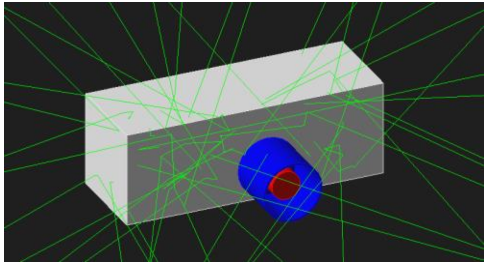
**Measurement**

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

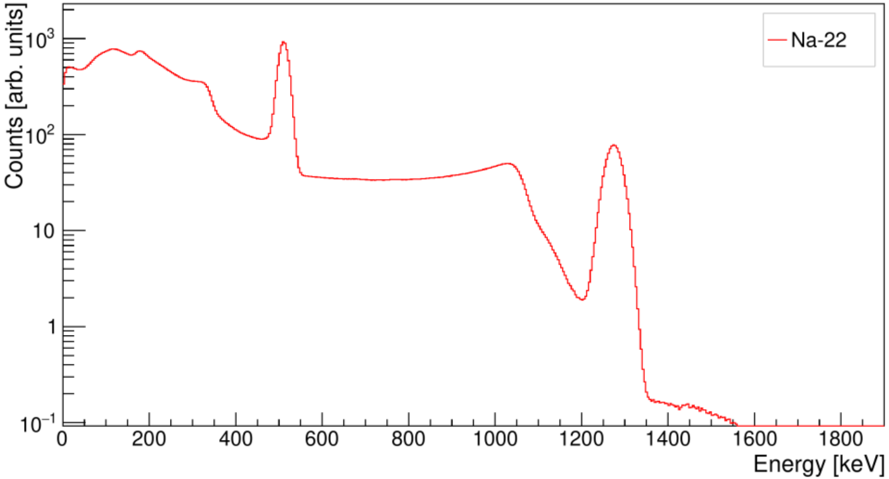
# G-Spec: Simulation of detector spectra

**Detector simulation**

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

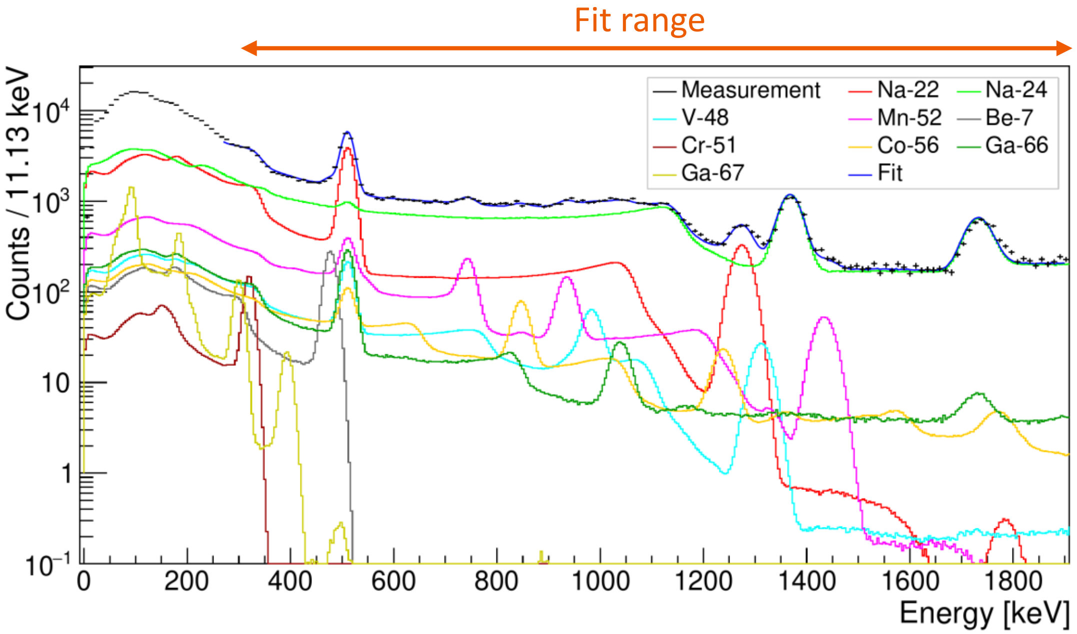


Example: Na-22




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

# G-Spec: Fitting the spectrum




→ Key nuclides identified from MCNP/FISPACT calculation

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

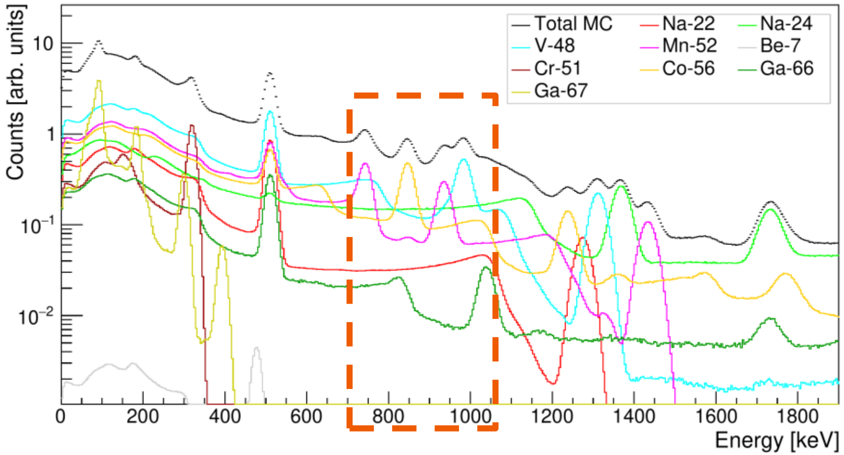
## Key nuclide results

| 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 |

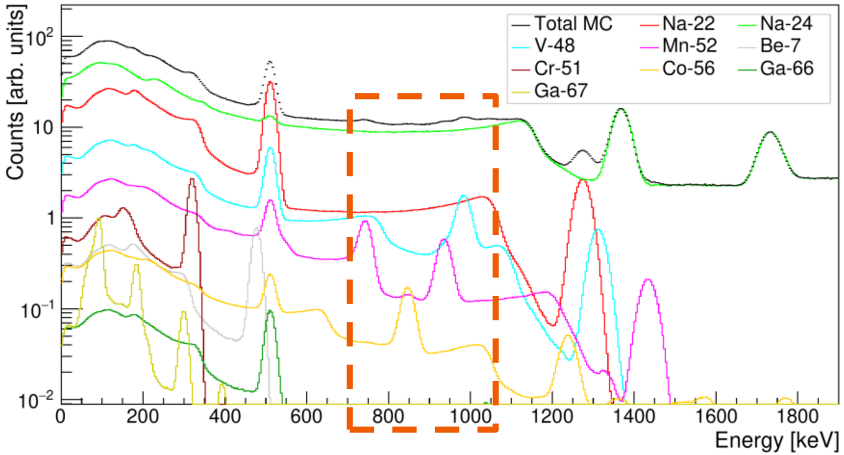
# G-Spec: Simulated nuclide contributions

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

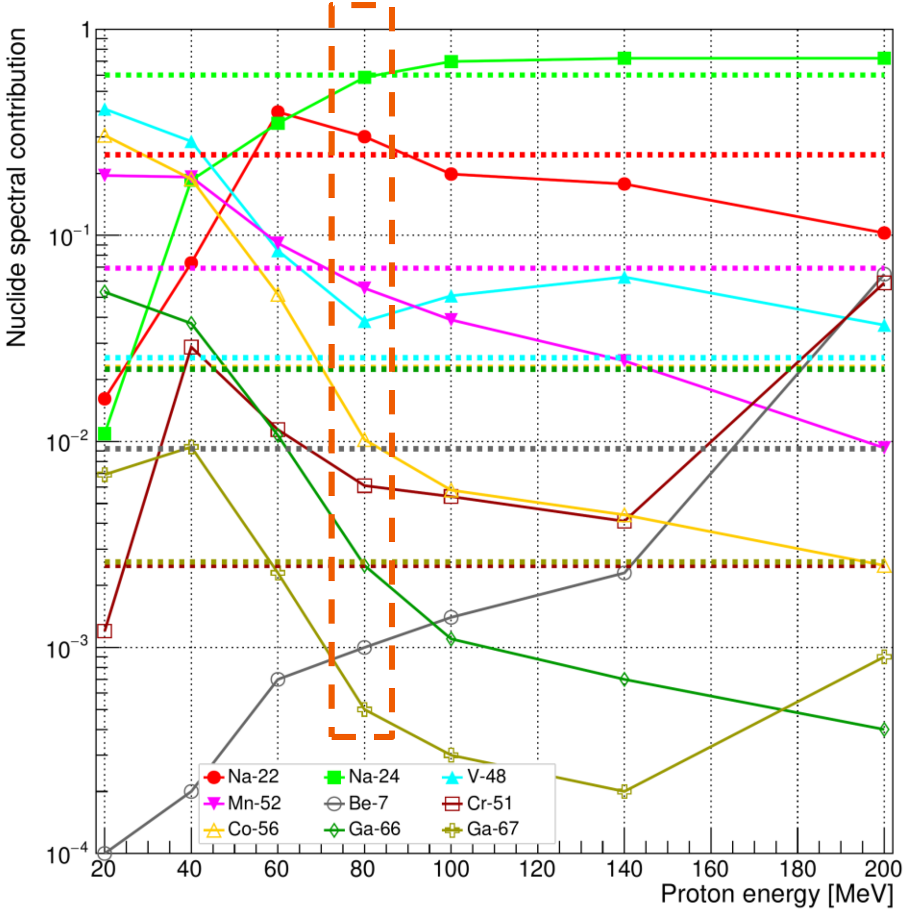
40 MeV




140 MeV



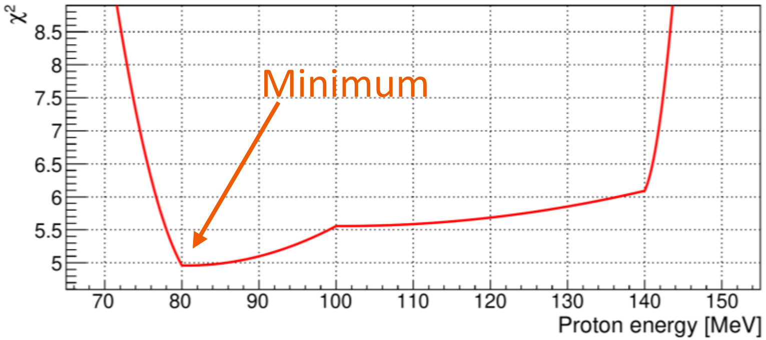
# G-Spec: Estimation of proton energy




- 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

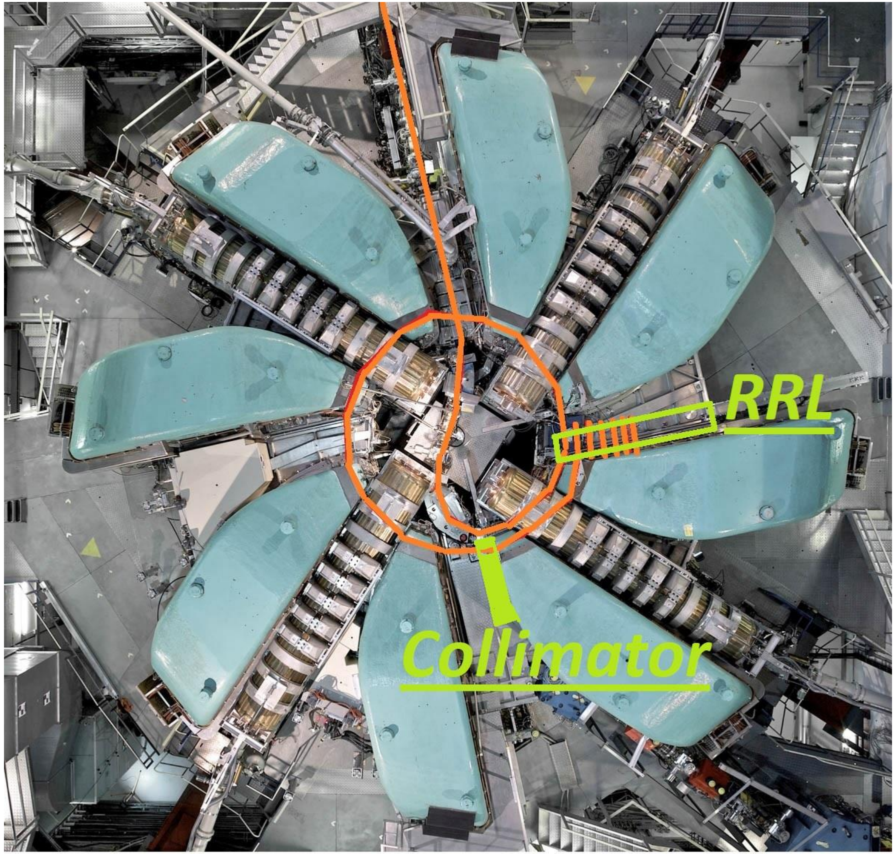


# Cause of the Hot Spot

- 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**

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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

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# 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
- Irradiation 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*

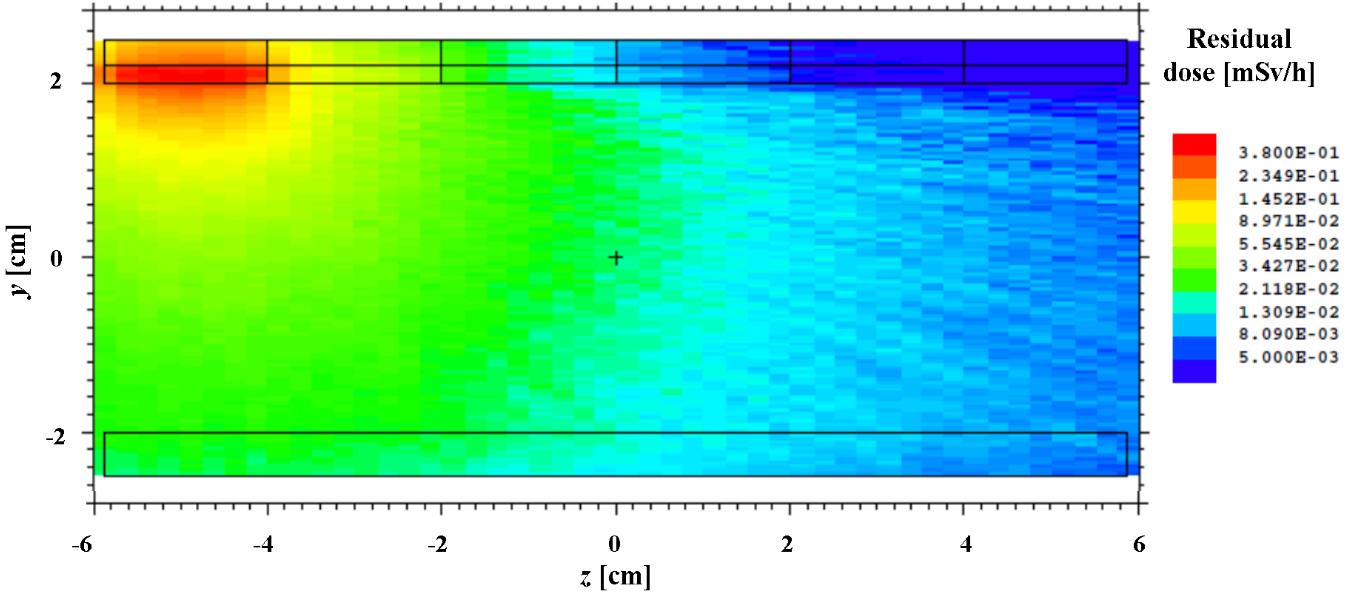
**MCNP simulation 2:**

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

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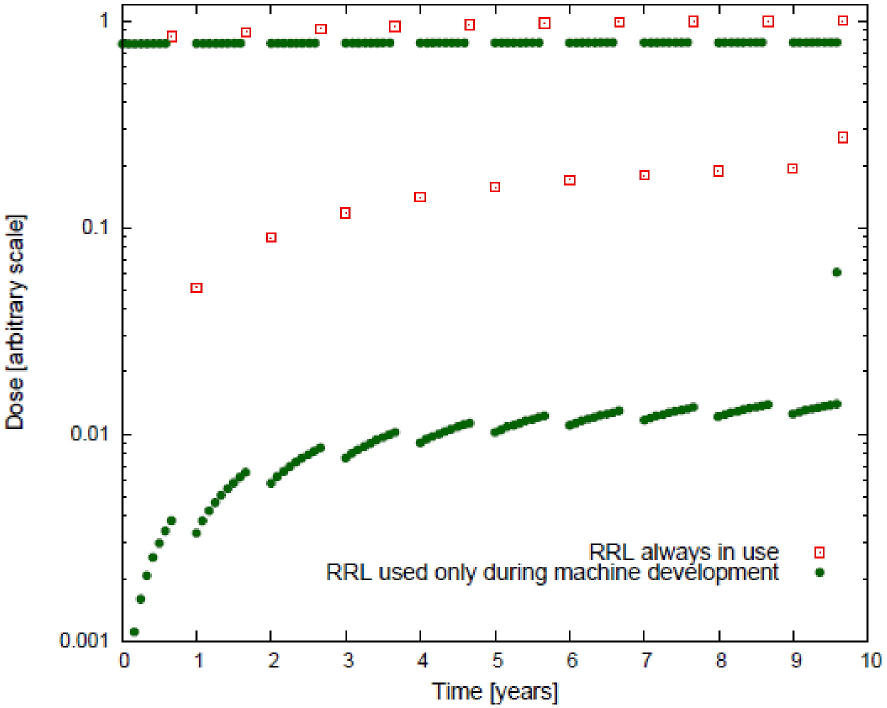
# Long Term Activation

- 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 hors of cooling time is ~4.5
  – motorization of the probe in the next winter shutdown