

PAUL SCHERRER INSTITUT



WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

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

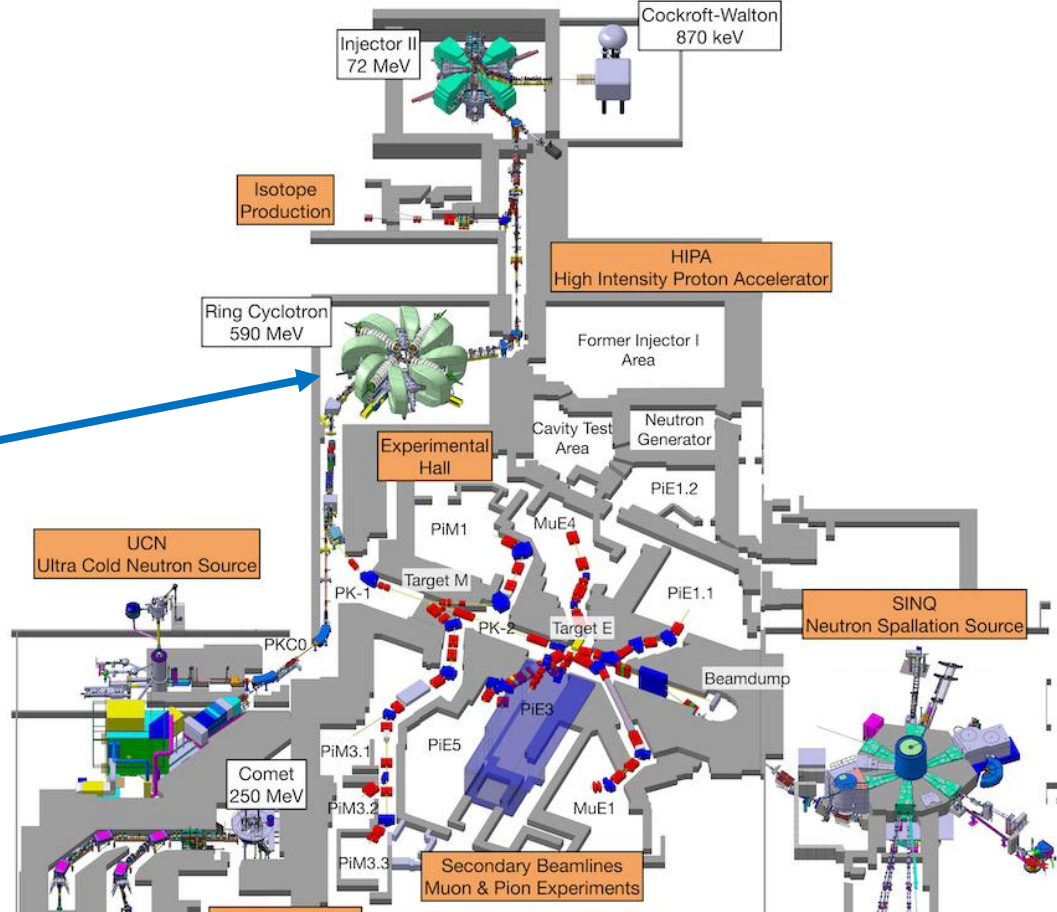
23<sup>rd</sup> International Conference on Cyclotrons and their Applications, 07/12/2022, Beijing, China

- 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)

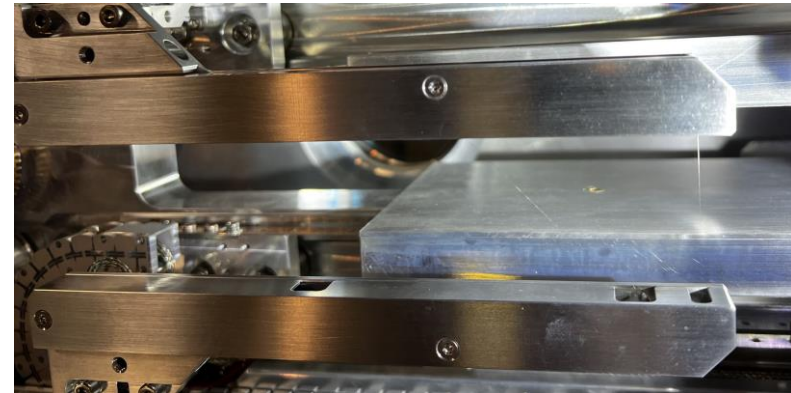
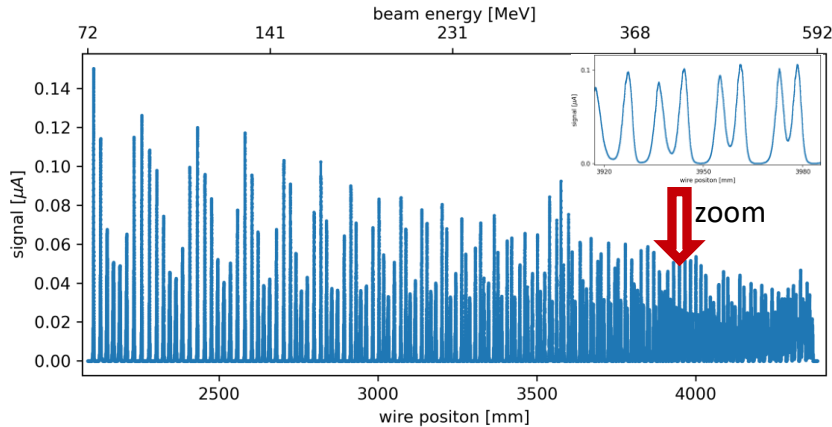
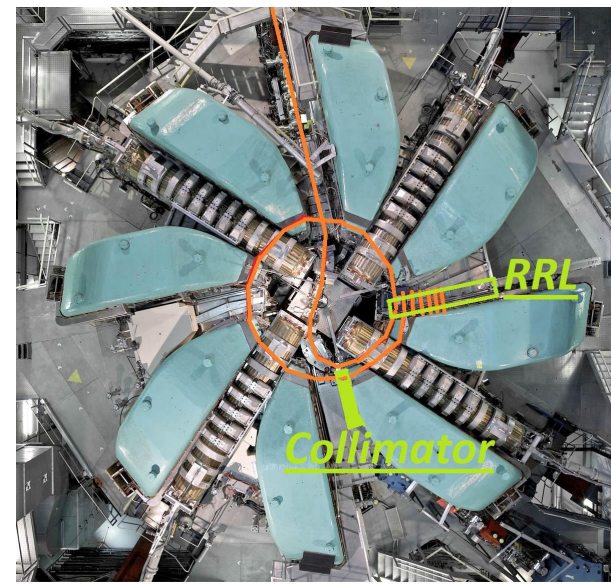
- Cyclotron facility at PSI → 590 MeV proton beam with current up to 2.4 mA
- Three acceleration steps:
  - Final acceleration in the large 8-sector Ring Cyclotron



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  $\phi=30\mu\text{m}$  carbon fibers through the radius of the machine (2 to 4.5 m) and registering secondary electrons
- Wire is stretched 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 ( $>1\text{mSv/h}$ )
- Hotspot position corresponds to beam energy  $150\text{ MeV} < E < 180\text{ MeV}$
- Measurement with  $\text{Al}_2\text{O}_3:\text{C}$  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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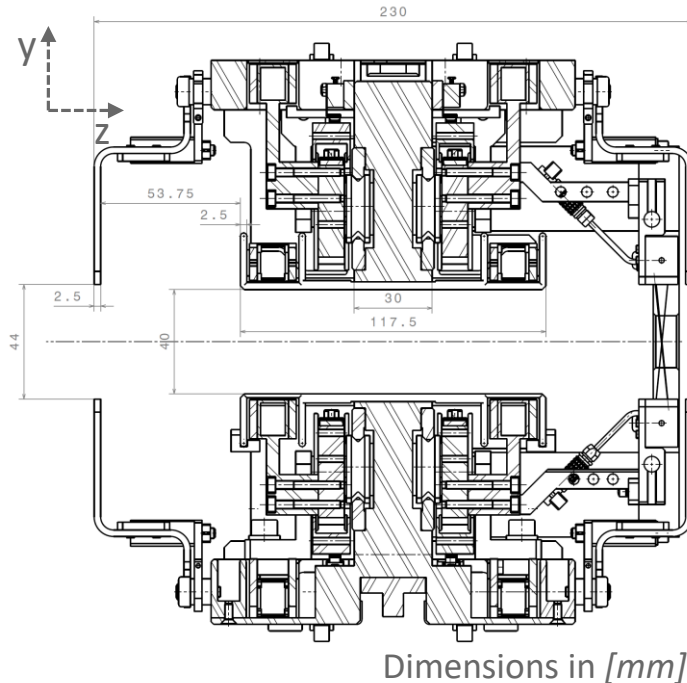
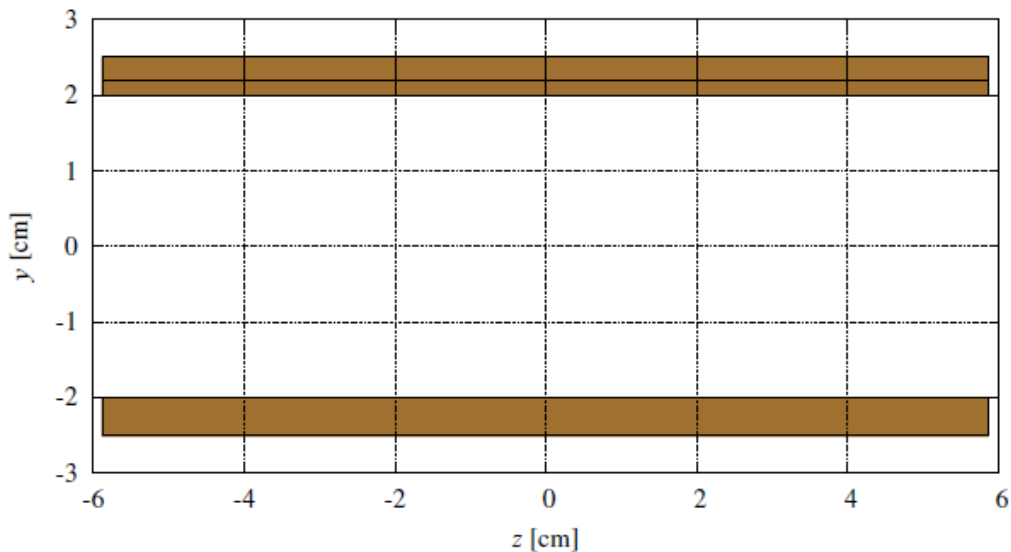
time-dependent growth and decay of all relevant radionuclides at any time instance

## Results:

- nuclide inventory
  - expected activity
  - residual dose
  - spectrum and flux rate of the emitted gamma rays at different locations and different time instances
- } for each nuclide

# 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

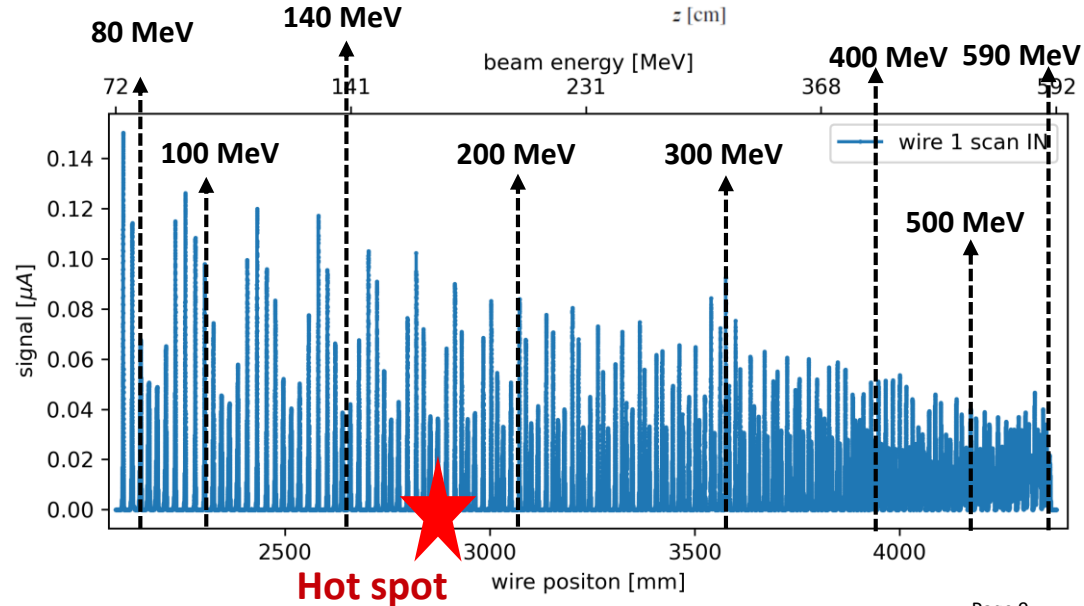
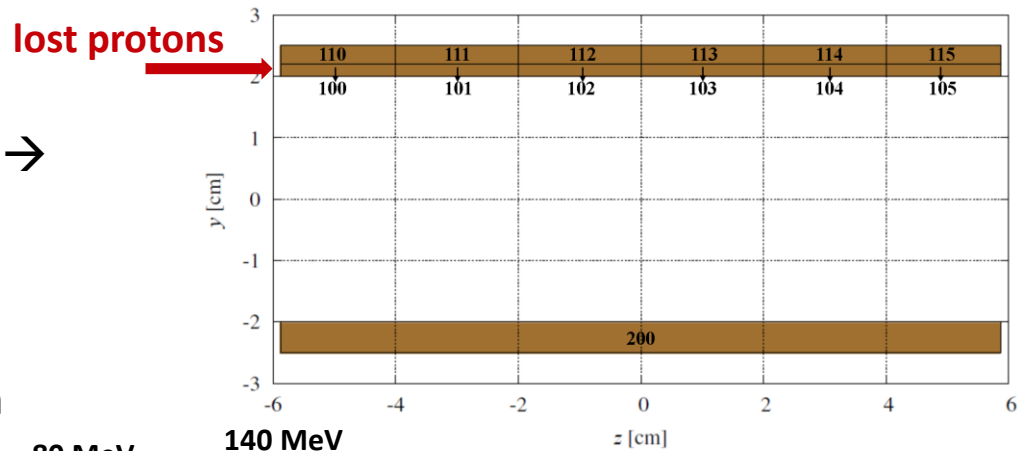


- $\Delta y = 4$  cm
- 11.75 cm in the beam direction (z)
- 0.5 cm in the vertical direction (y)
- 1 m in the radial direction (x)

# Source Term

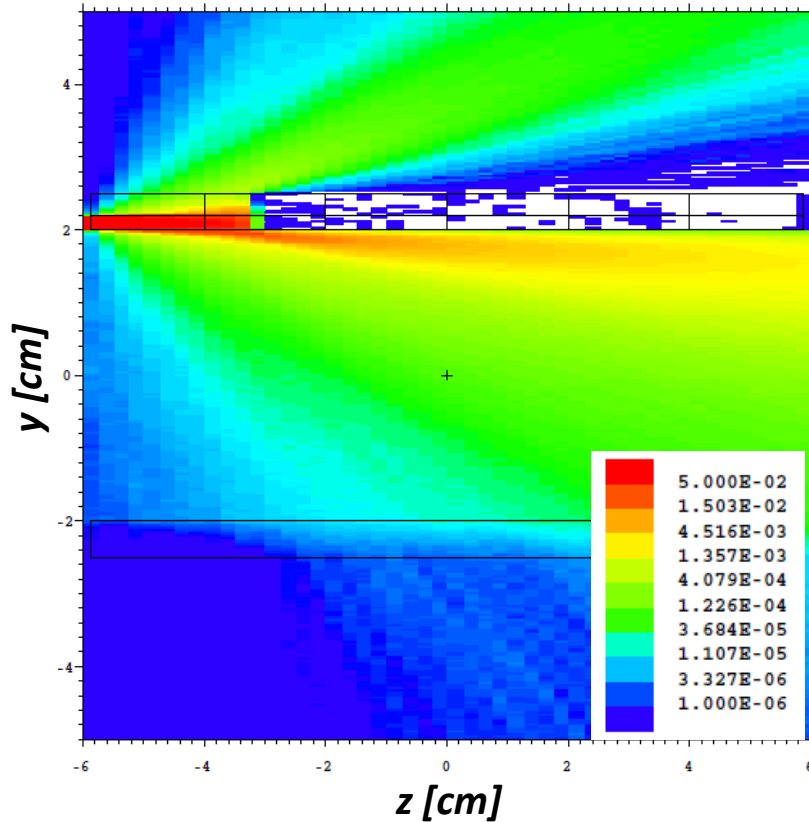
- Beam losses at the RRL not known → assumptions for the simulations:
  - lost protons moving along z-axis, impacting on the RRL upper part
  - 12 simulations with different beam energies:

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

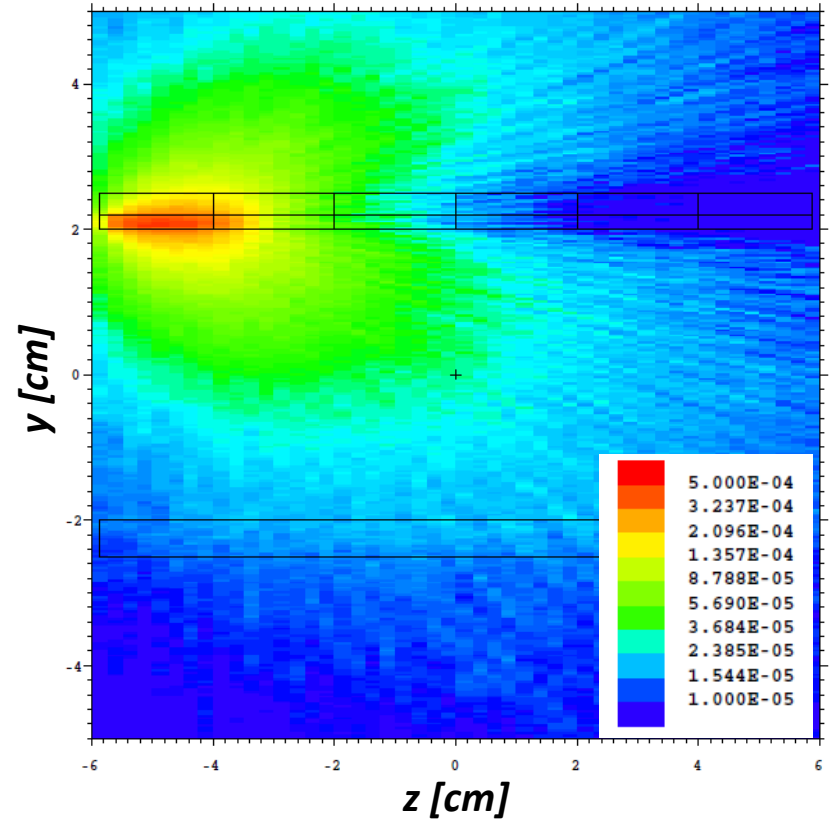


# MCNP Results: 80 MeV Beam

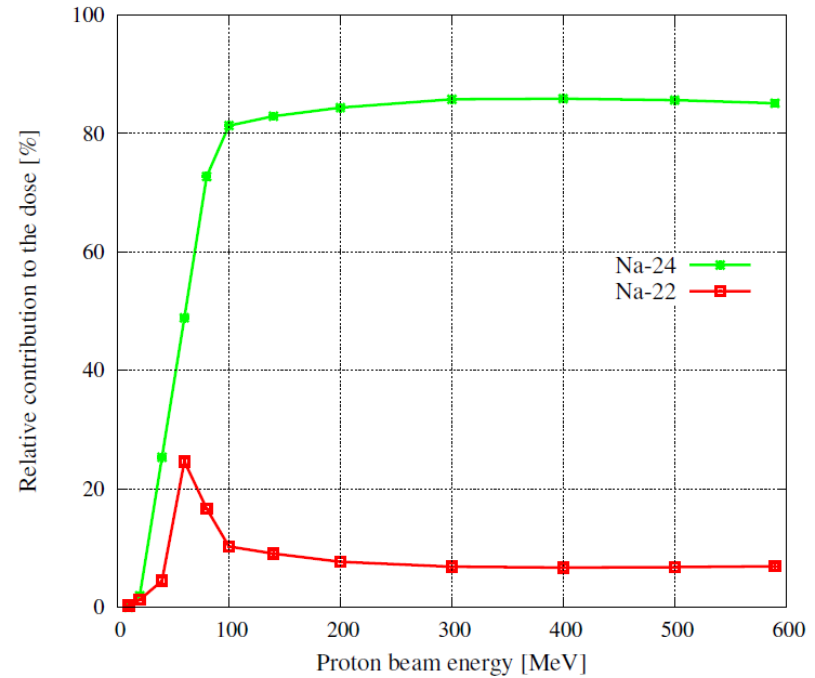
Proton fluence [ $\text{cm}^{-2}/\text{primary}$ ]



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



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

## Goals

- Determine nuclide contributions in activated area
- Estimate proton beam energy

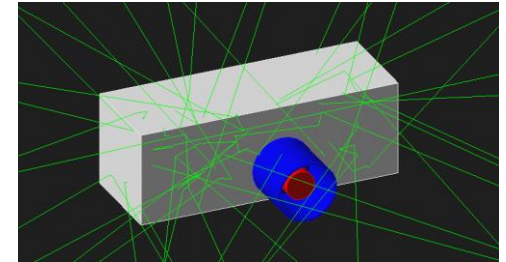
## Measurement

- ELSE Nuclear B-RAD: LaBr<sub>3</sub> handheld spectrometer
- Energy resolution: 3.3% (FWHM) at 662 keV

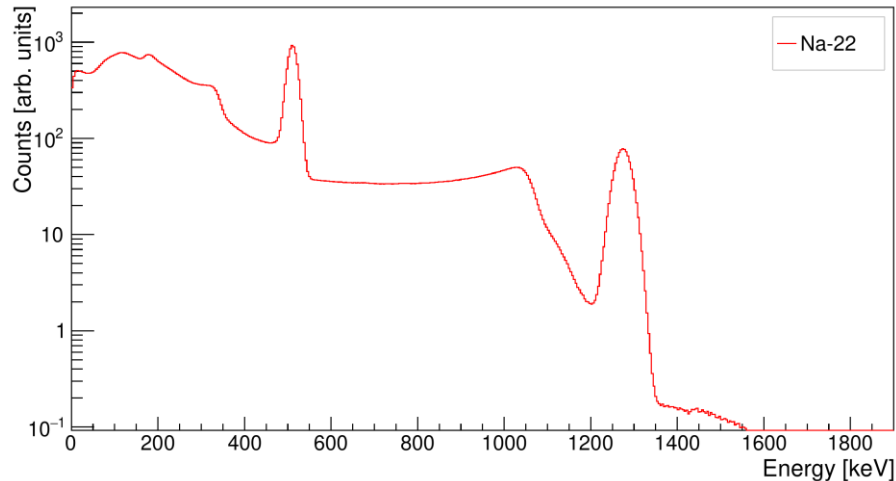


## Detector simulation

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

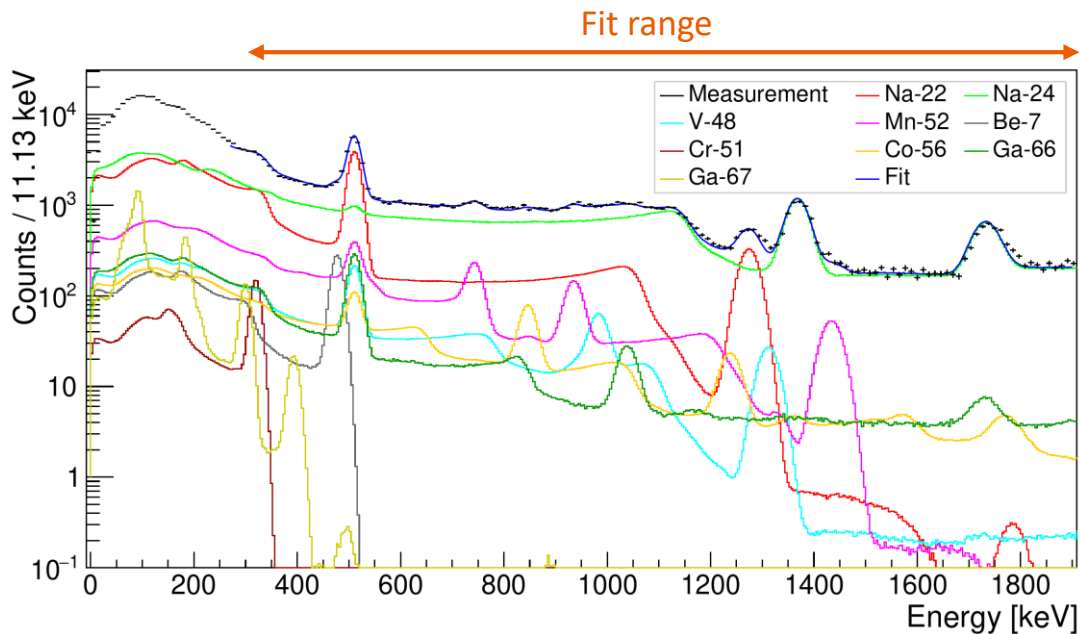


Example: Na-22



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

# G-Spec: Fitting the Spectrum



→ Key nuclides identified from MCNP/FISPACT calculation

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

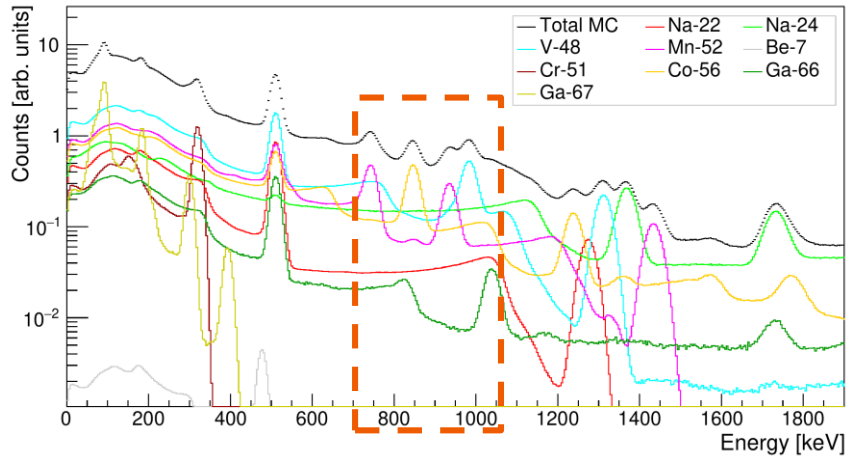
## Key nuclide results

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

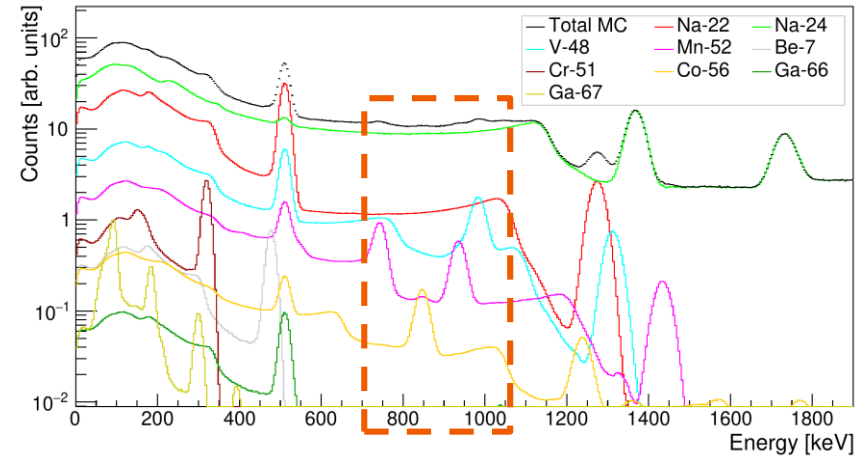
# G-Spec: Simulated Nuclide Contributions

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

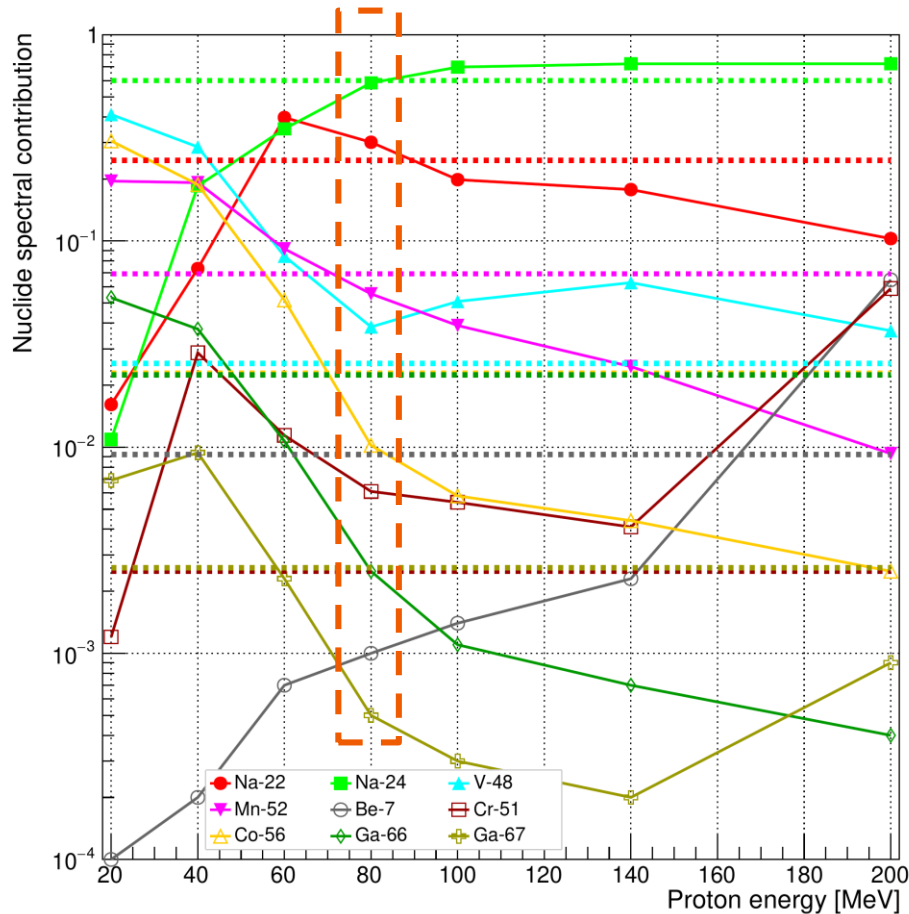
40 MeV



140 MeV



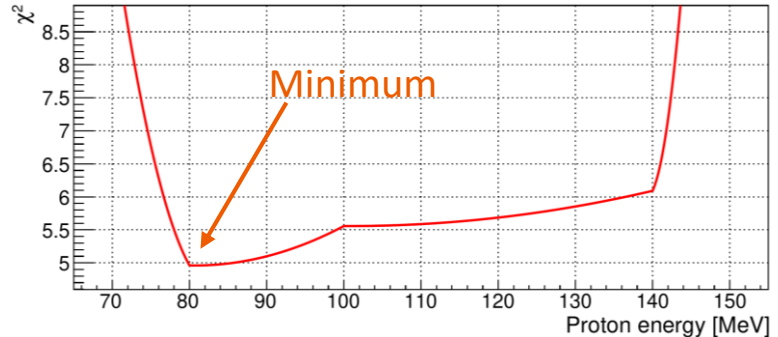
# G-Spec: Estimation of Proton Energy



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

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

→ Estimated proton energy: **80 MeV**

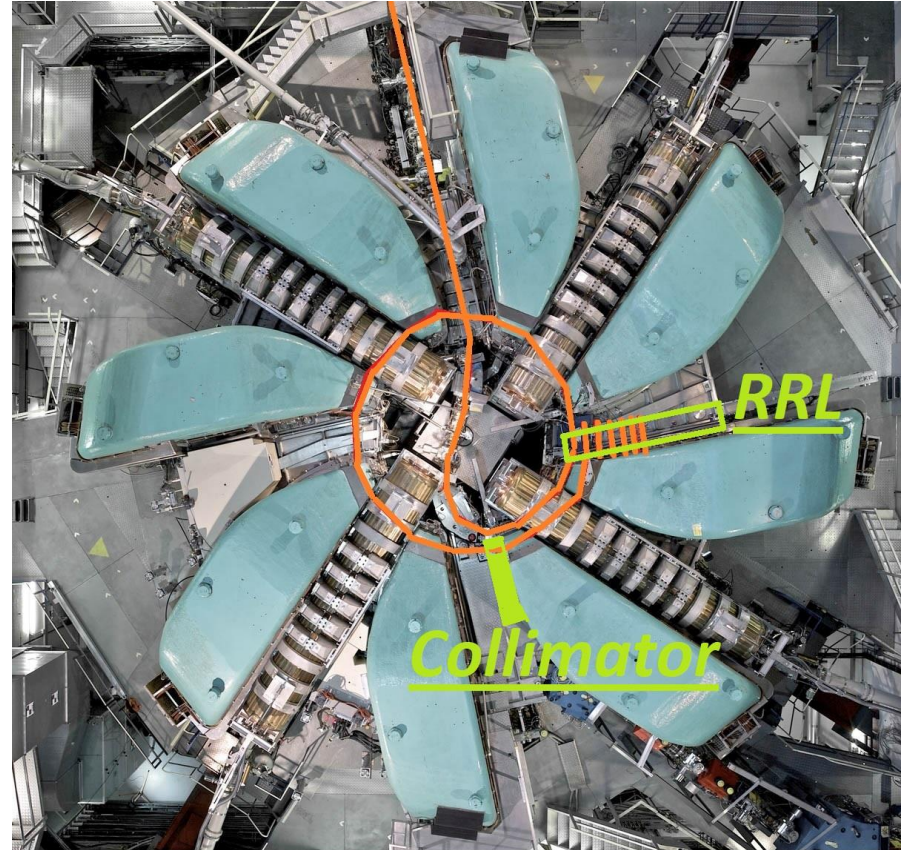


# Cause of the Hot Spot

- Simulations – measurements comparison → energy of lost protons = 80 MeV
- Proton energy at the position of the hot spot  $150 \text{ MeV} < E < 180 \text{ MeV}$



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



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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**Thanks for your attention**



## My thanks go to

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

