Studies of Muon-Induced Radioactivity at NuMI

David Boehnlein
Fermi National Accelerator Laboratory
(on behalf of the JASMIN Collaboration)

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The JASMIN Collaboration

- D. J. Boehnlein, A. F. Leveling, N. V. Mokhov*, K. Vaziri
  - Fermi National Accelerator Laboratory
- Y. Iwamoto, Y. Kasugai, N. Matsuda, H. Nakashima*, Y. Sakamoto*
  - Japan Atomic Energy Agency
- M. Hagiwara, Hiroshi Iwase, N. Kinoshita, H. Matsumura, T. Sanami, A. Toyoda
  - High Energy Accelerator Research Organization (KEK)
- H. Yashima
  - Kyoto University Research Reactor Institute
- H. Arakawa, N. Shigyo
  - Kyushu University
- H. S. Lee
  - Pohang Accelerator Laboratory
- K. Oishi
  - Shimizu Corporation
- T. Nakamura
  - Tohoku University
- Noriaki Nakao
  - Aurora, Illinois

* Co-Spokesperson

The JASMIN Experiment

- **JASMIN – Japanese & American Study of Muon Interactions and Neutron Detection (Fermilab T972)**
- **A study of shielding and radiation physics effects at high-energy accelerators**
- **Studies to date have focused on the anti-proton production target (AP0) and NuMI.**
- **We present here status of work in progress to study activation at the NuMI muon alcoves.**

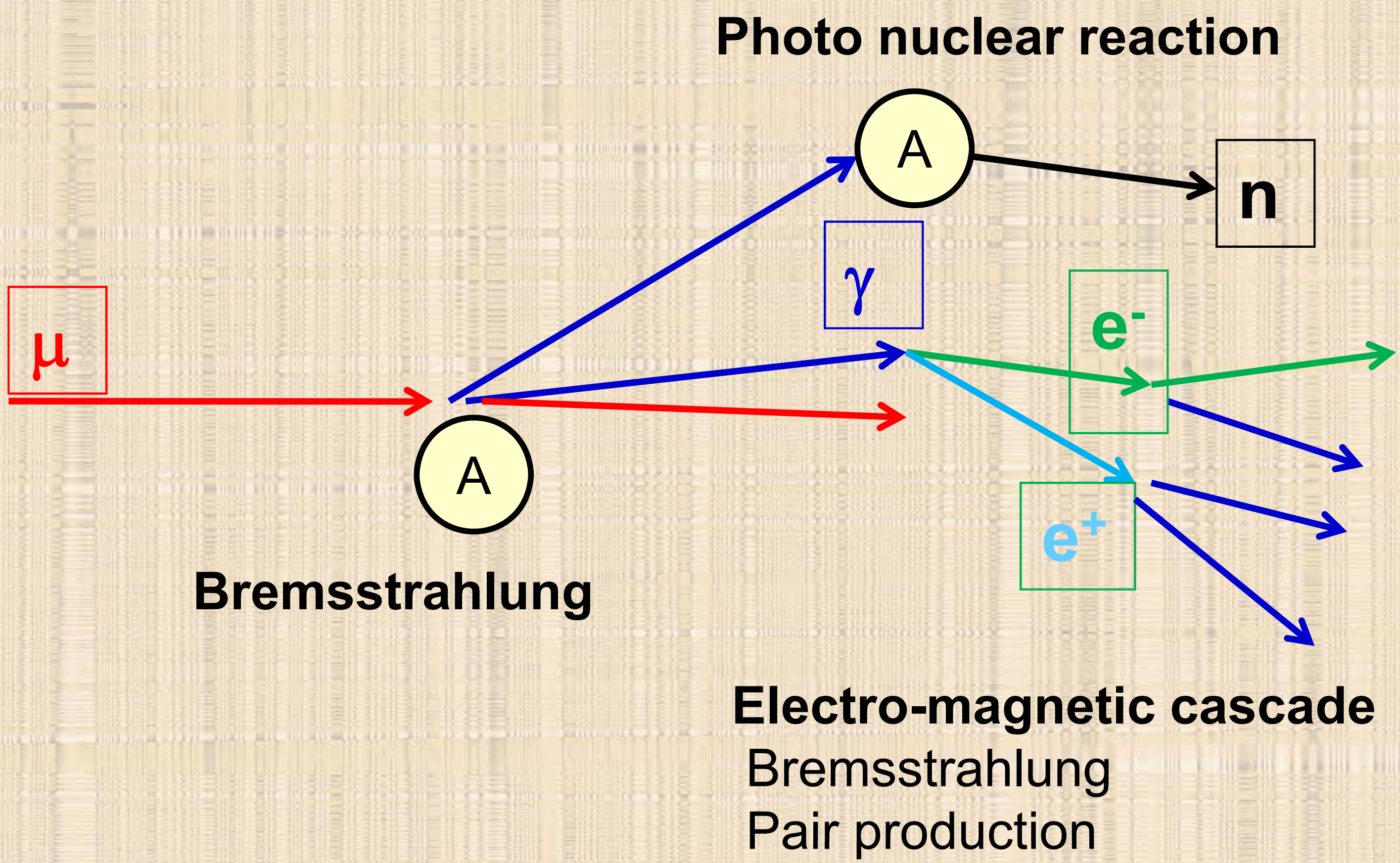
Experimental Goals of JASMIN

- **Benchmarking of Monte Carlo codes**
- **Radiation safety**
- **Study of muon interactions**
  - **Material activation**
  - **Shielding**
  - **Muon detection & measurement**
- **Improved characterization of NuMI muon monitors.**

Motivation

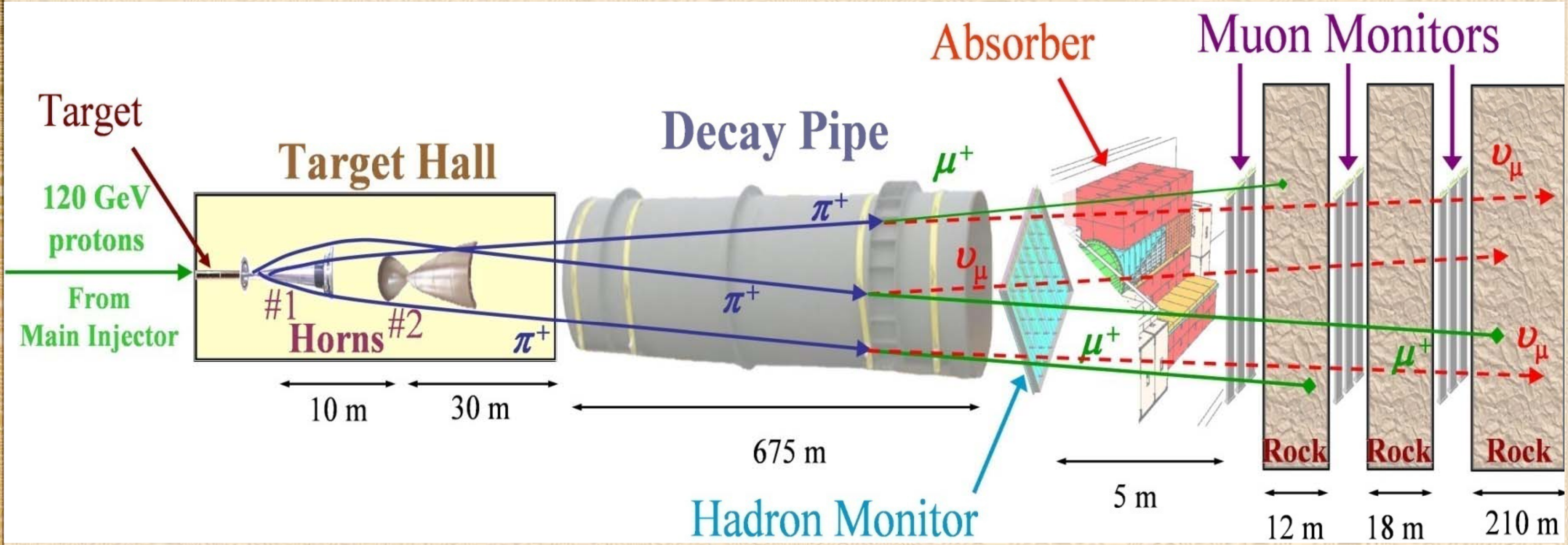
- **Why is a neutrino experimenter talking to a group of accelerator physicists about radiation physics?**
- **This workshop is considering machines that could produce unprecedented muon intensities.**
- **If such machines are to be built, one must consider the radiological issues, including the potential for radioactivation due to muons.**
- **Monte Carlo codes used for simulations should accurately account for it.**

Source of electron, photon and neutron



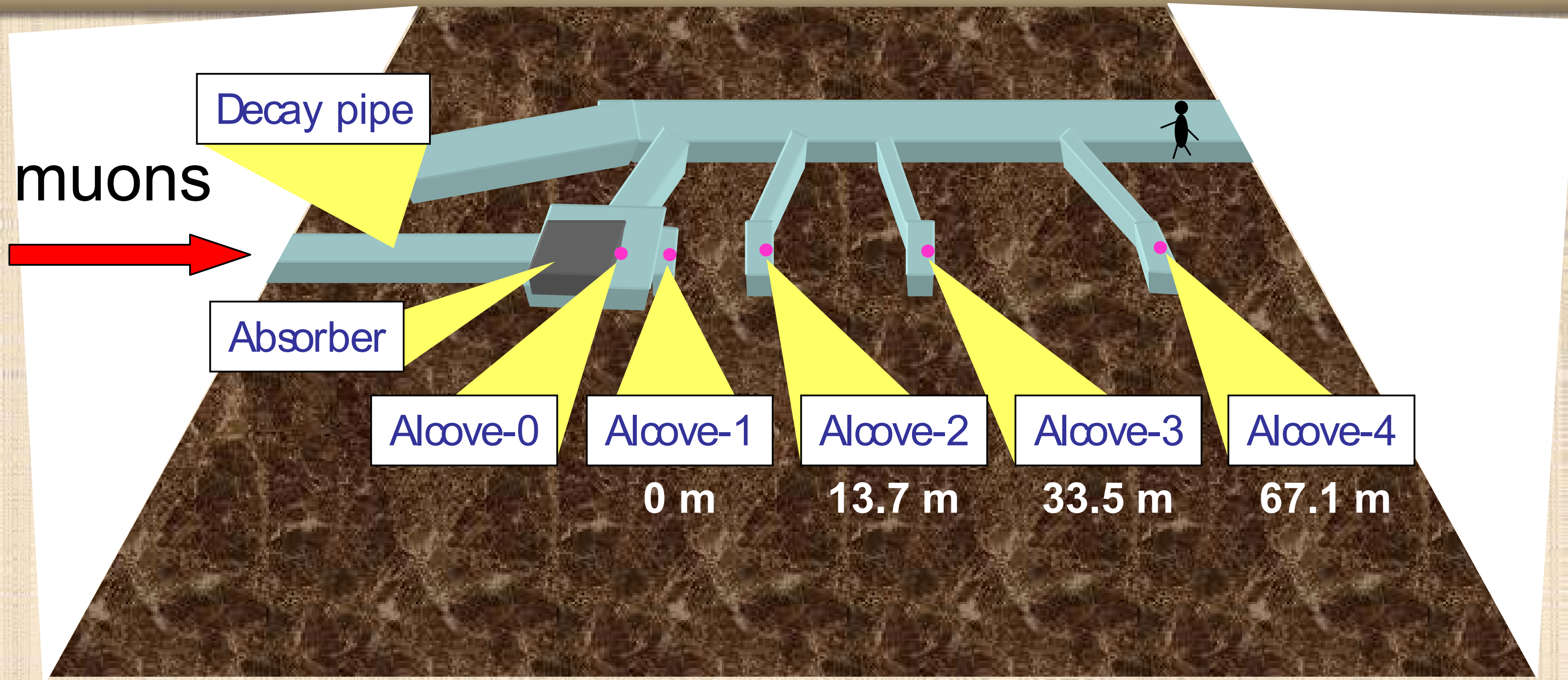
Radiations around intense muon beam (T.Sanami)

Neutrinos at the Main Injector



- **The NuMI beamline focuses a ν_μ beam toward Soudan, Minnesota.**
- **Since the neutrinos come from 2-body pion decay, the world's most intense neutrino beam is also the world's most intense muon beam.**
- **Arrays of ionization chambers in downstream alcoves monitor muons co-produced with the neutrinos.**

NuMI Muon Monitoring Alcoves



- Schematic layout of the muon alcoves at NuMI
- Note that Alcove 1 is in the Absorber Hall.
- See L. Loiacono's talk at this workshop for a discussion of the muon monitors.

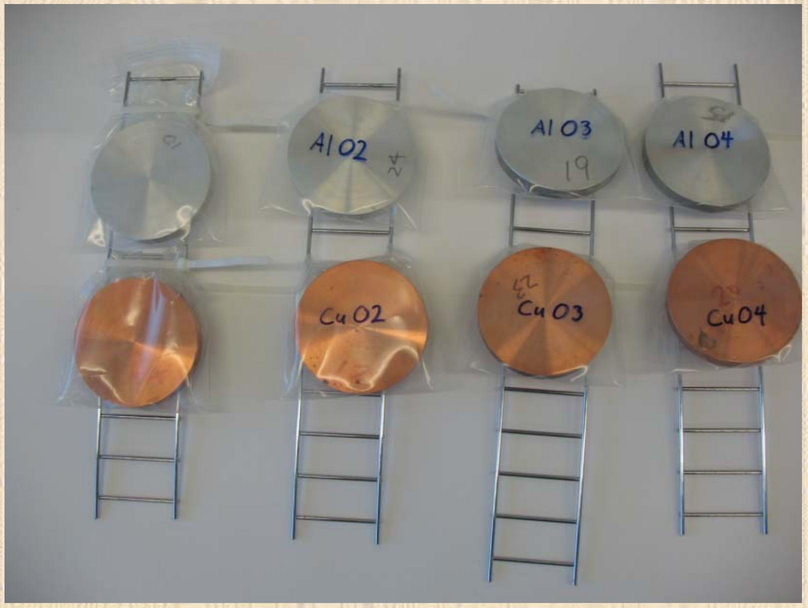
Estimated Muon Fields

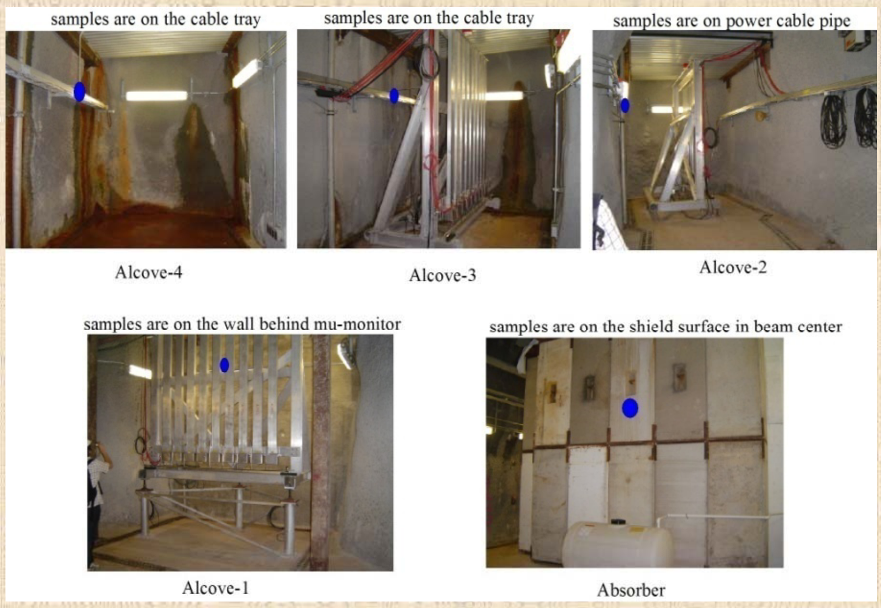
Alcove	Charged Particle Fluence	Beam Size
1	$6.5 \times 10^5 cm^{-2} 10^{-12} ppp$	190 cm
2	$0.9 \times 10^5 cm^{-2} 10^{-12} ppp$	250 cm
3	$0.35 \times 10^5 cm^{-2} 10^{-12} ppp$	190 cm

- **Predicted data from Kopp et al. [NIM A 568 (2006)503]**
- **Assumes Low-Energy Beam.**
- **Beam size is FWHM.**
- **Neutrons < 1% in downstream alcoves.**

Procedure I

- **Copper and Aluminum disks were placed in alcoves 1 -4.**
- **Disks are 8 cm diameter x 1 cm thick.**
- **Beam exposure was 22.8 hours.**
- **NuMI beam put 6.26 x 10^{17} p.o.t.**
- **Additional samples were placed to measure neutron activation.**





Procedure II

- **JASMIN operates parasitically with NuMI.**
- **Samples are placed and retrieved during natural beam-down periods.**
- **Isotopic signatures are measured on High-Purity Ge counters at High-Intensity Lab.**
- **Operations so far have occured in November 2007 and November 2008.**

Radionuclides observed in Samples

- **This table summarizes the radionclides observed in the exposed copper samples.**
- **^{54}Mn, ^{57}Co, ^{60}Co have substantial half-lives (beyond a reasonable cool-down period for accelerator maintenance).**

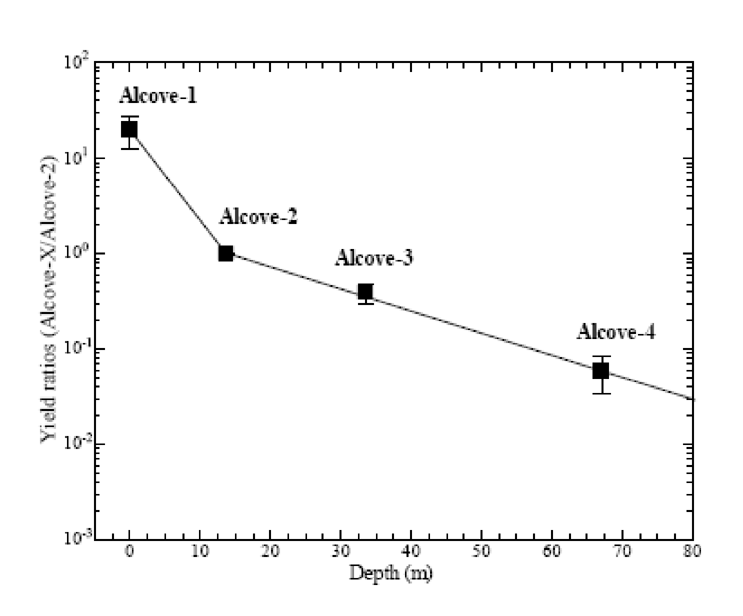
Table 1 Relevant nuclear data

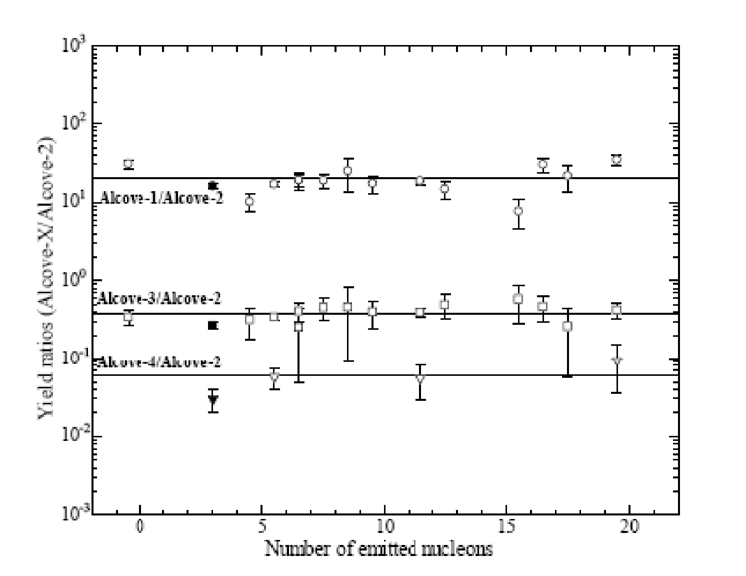
Nuclide	Half-life	Type	Eγ (keV)	Intensity(%)
Na-24	14.959 h	C-	2754.03	99.944
K-42	12.36 h	I	1524.70	18.08
K-43	22.3 h	C-	617.49	79.2
Sc-43	3.891 h	C+	372.76	22.5
Sc-44m	2.44 d	I	271.10	86.7
Sc-46	83.79 d	I	889.28	99.984
Sc-47	3.345 d	C+	159.40	67.9
Sc-48	43.67 h	I	1037.50	97.6
V-48	15.9735 d	C+	944.13	7.76
Cr-51	27.702 d	C+	320.08	9.86
Mn-52	5.591 d	C+	744.20	90.6
Mn-54	312.12 d	I	834.85	99.976
Fe-59	44.503 d	C-	1099.25	56.5
Co-55	17.53 h	C+	931.10	75
Co-56	77.27 d	C+	846.77	99.935
Co-57	271.79 d	C+	122.06	85.60
Co-58	70.82 d	I	810.78	99.448
Co-60	5.2714 y	I	1332.50	99.9820
Ni-57	35.6 h	C+	1377.63	81.7
Cu-64	12.700 h	I	1345.77	0.473

I: Independent yields, C–: Cumulative yields for β^- decay, and C+: Cumulative yields for β^+ decay and/or electron capture

Preliminary Results

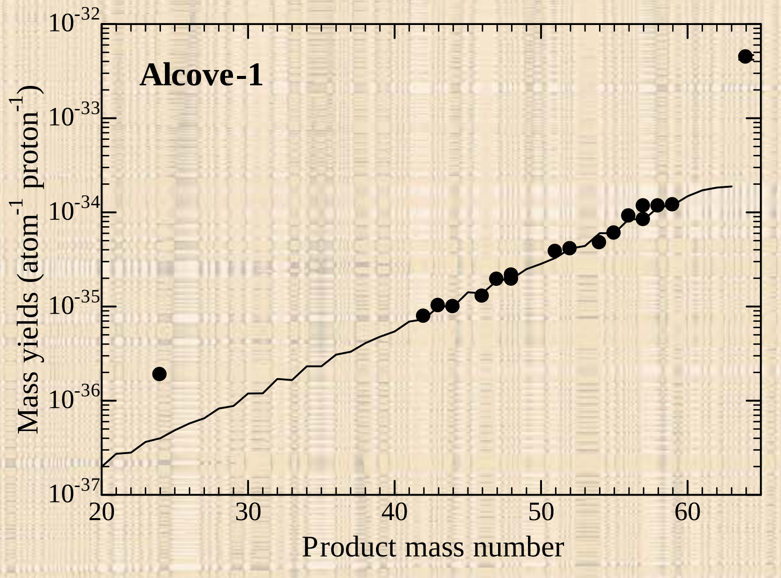
- Attenuation of muons, as shown by yield ratios normalized to Alcove 2.
- Yield ratios vs. distance (top)
- Yield ratios vs. nucleons emitted from target nucleus (bottom)
- Note Aluminum results are included (^{24}Na).
- Figures courtesy of H.

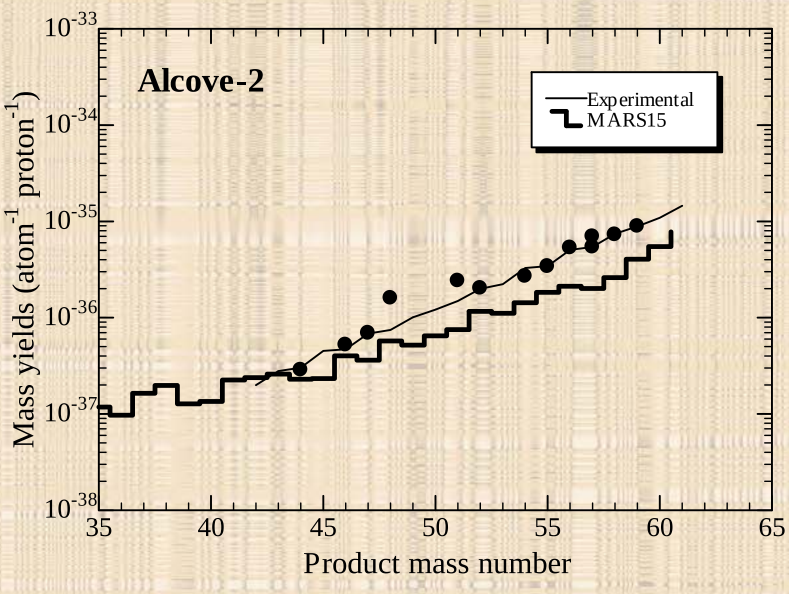




Preliminary Results II

- Activation Products on copper samples by mass number.
- Alcove 1 shows evidence of neutron activation.
- The narrow line is a fit to an empirical formula for photospallation (Rudstam et al. Phys Rev 126, 5 (1962) 1852).
- The lower plot histogram is a



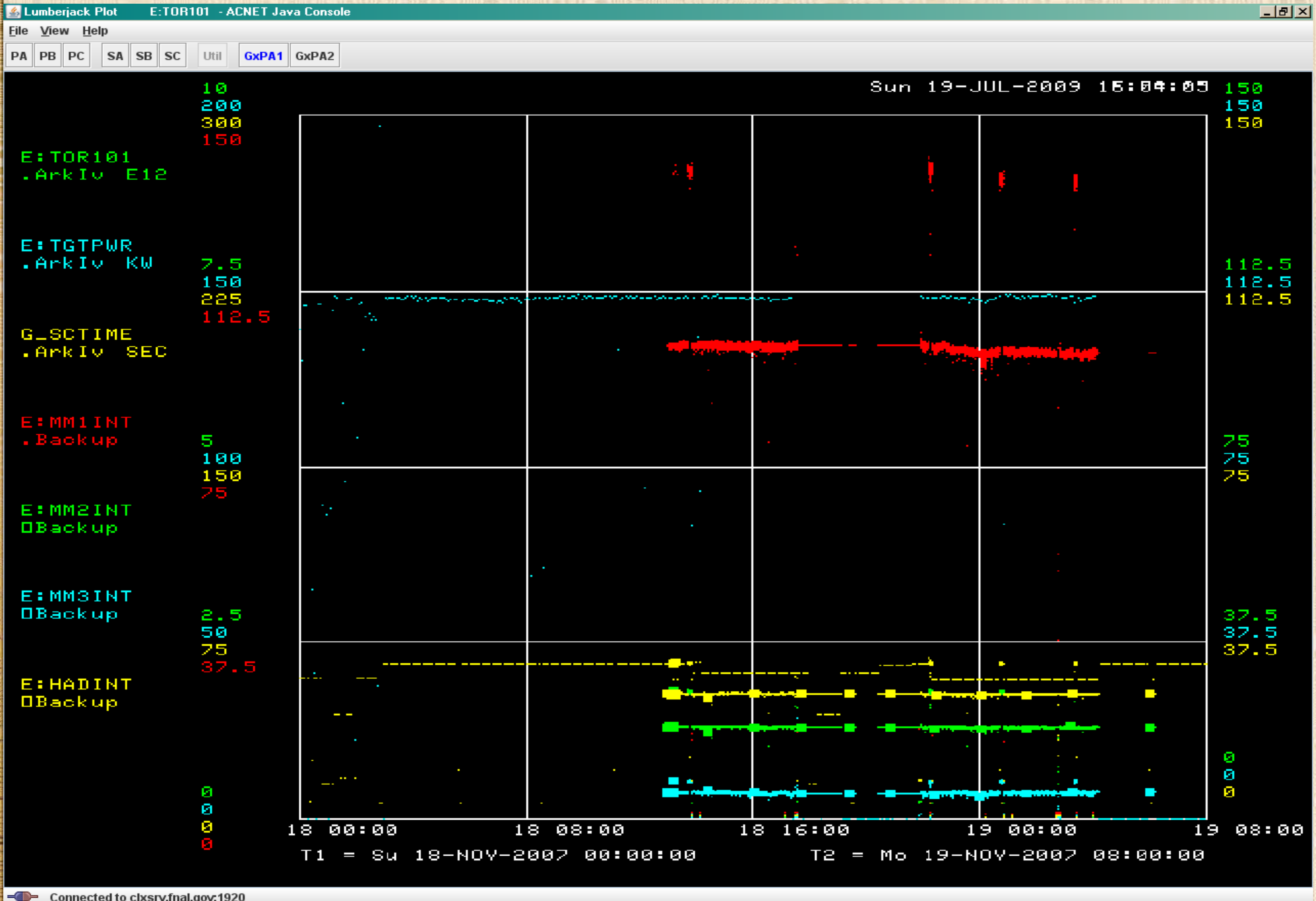


Summary

- **JASMIN has measured radionuclides produced in Aluminum and copper in the muon alcoves**
- **It's not clear how much of the activity is produced by muons and how much by muon-produced neutrons (for radiation safety, does it matter?)**
- **MARS15 simulations give good predictions of dose rates and activation.**
- **Studies will continue in Fall 2009.**

Backup Slides . . .

ACNET Readout for Exposure



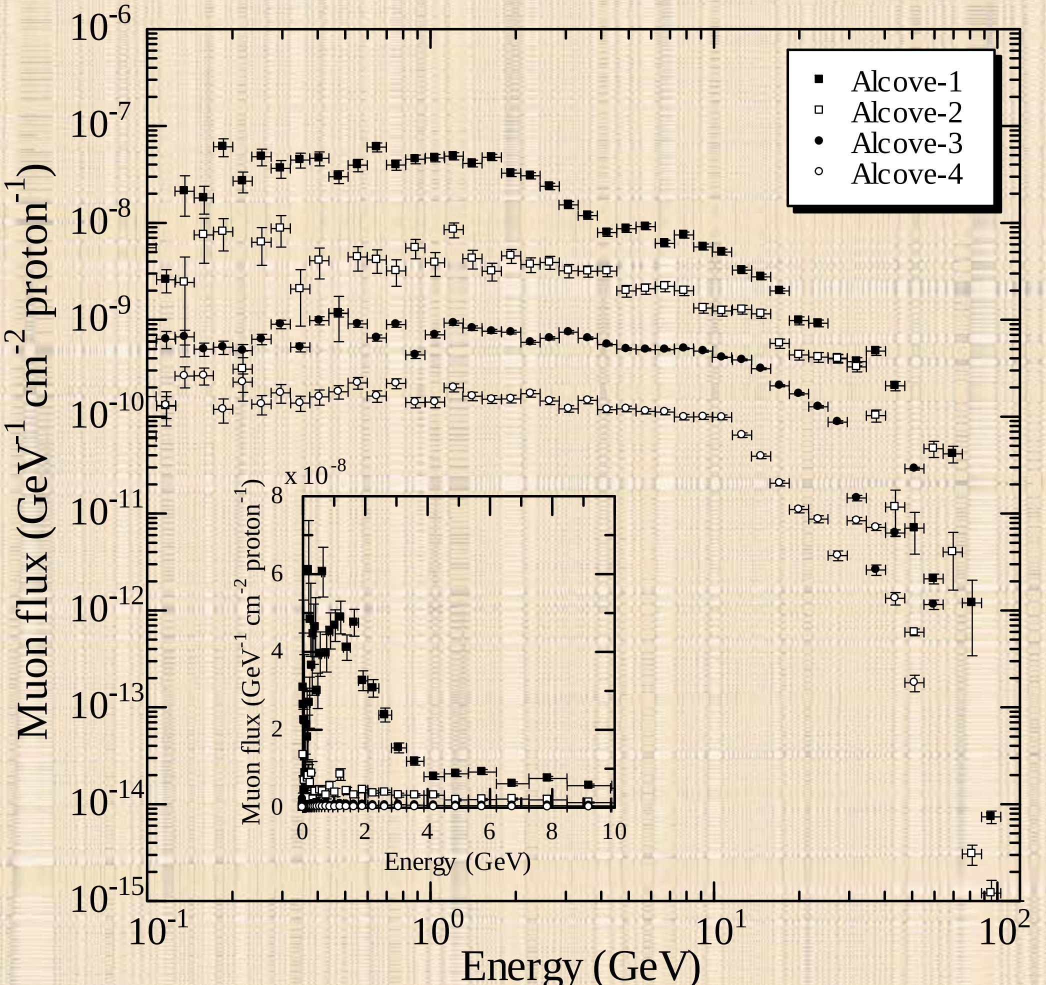
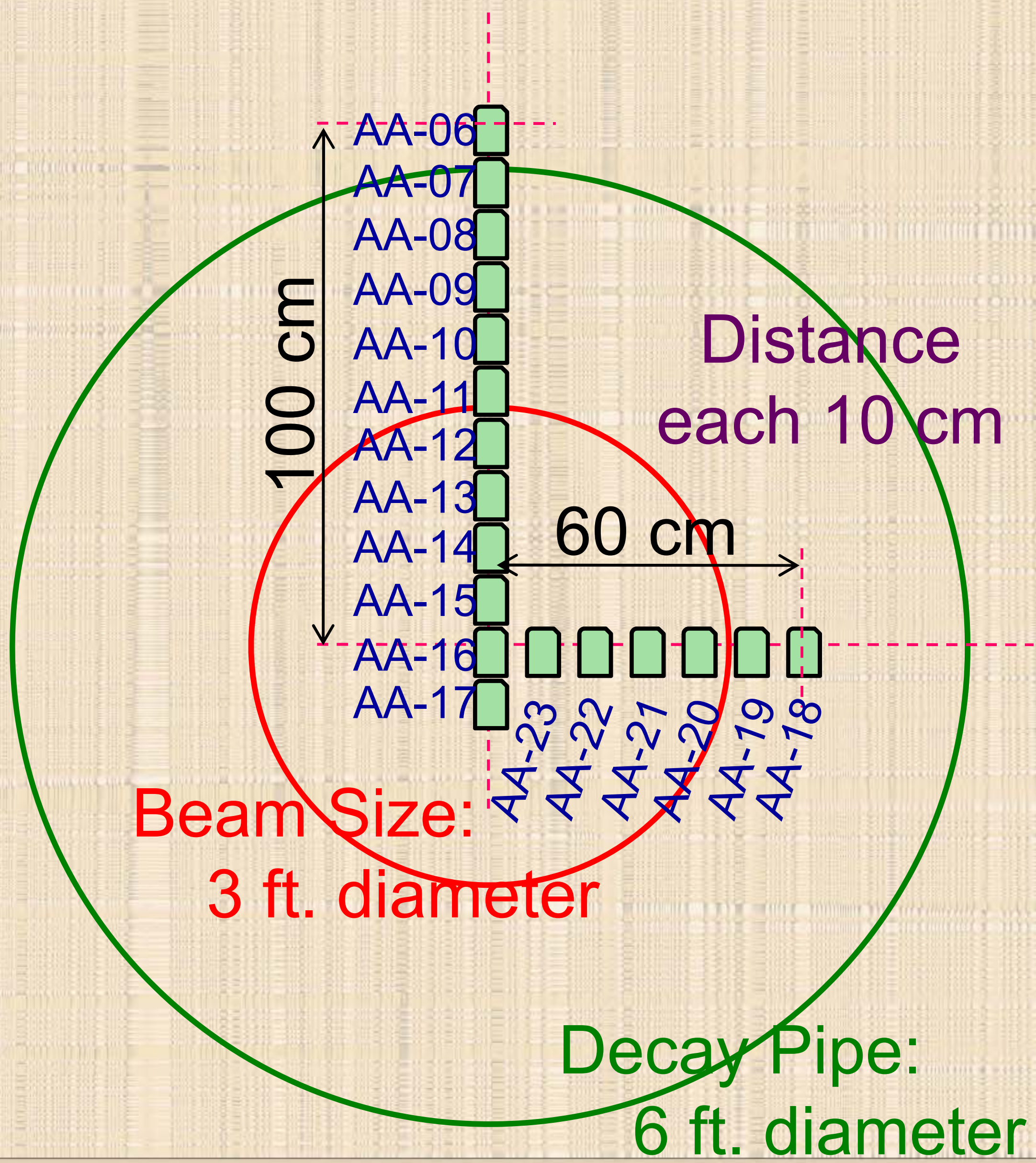


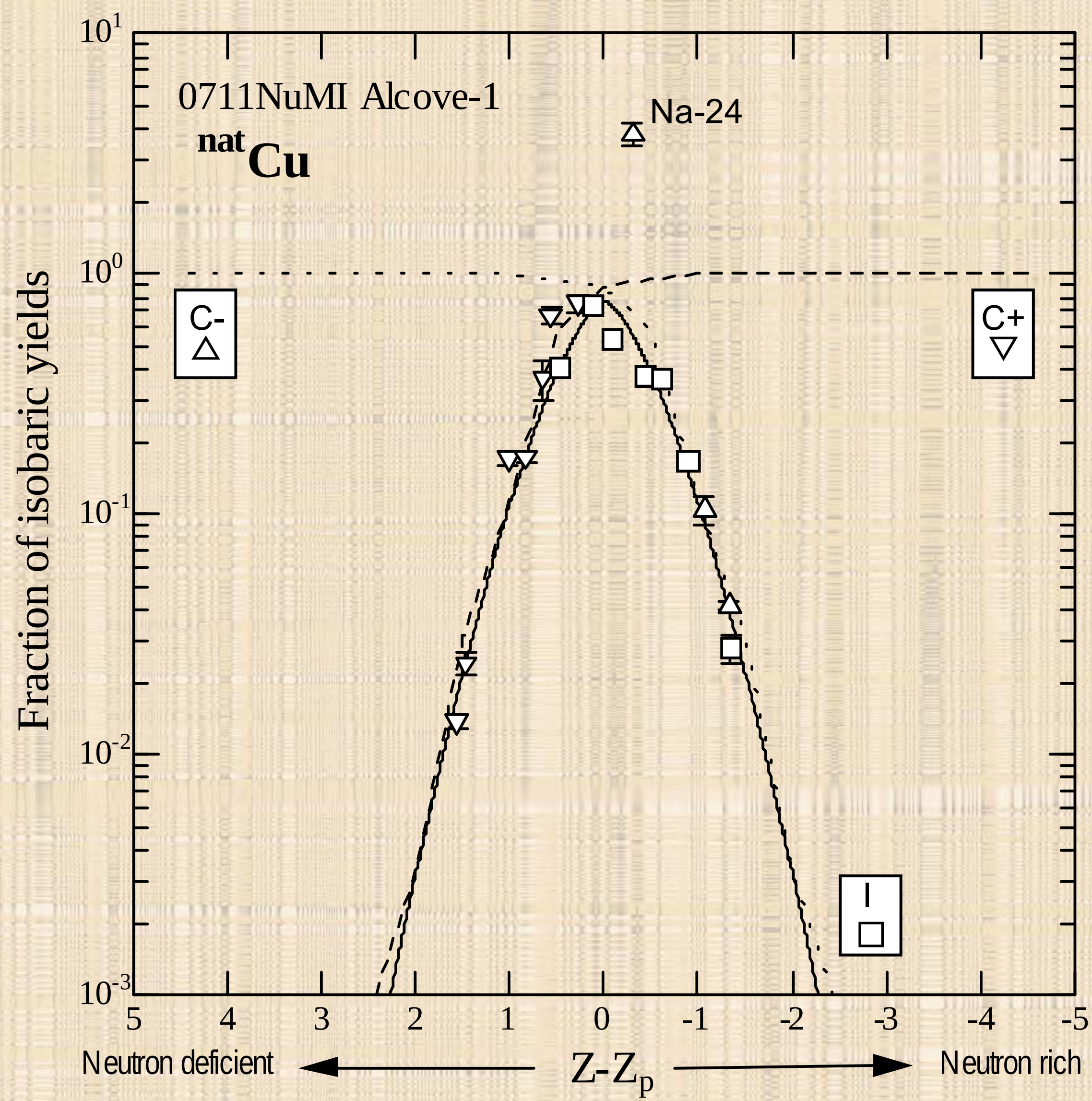
FIG. Calculated muon spectra in units of number of muons per GeV, per cm^2, and per primary proton in Alcove-1, Alcove-2, Alcove-3, and Alcove-4.

Samples for Neutron Studies

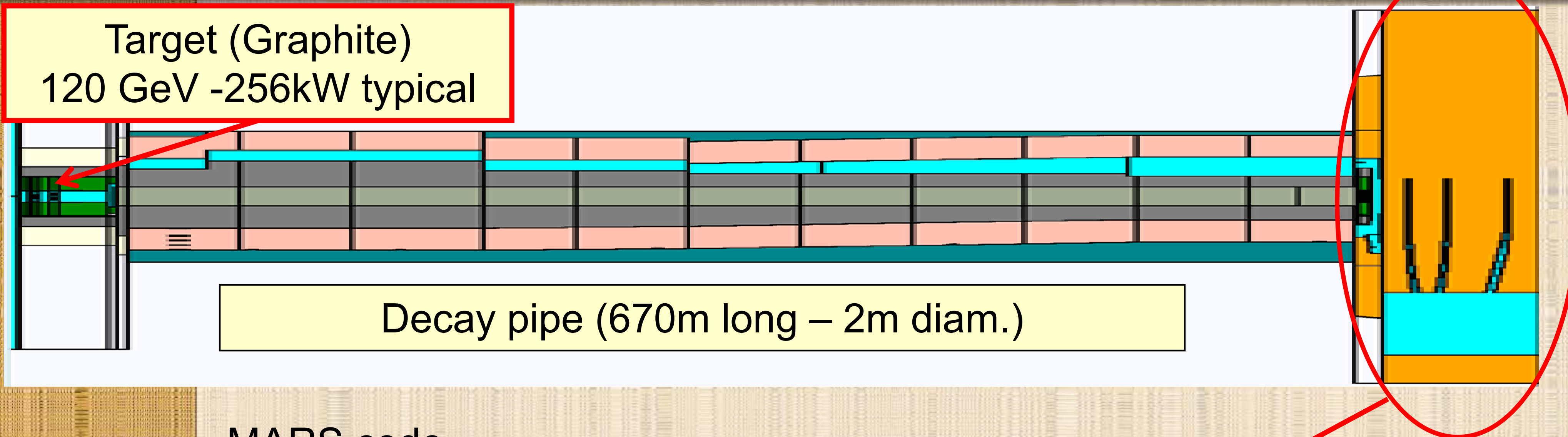


Activation Yields vs Charge

- **Alcove 1**
- **Plot of nuclides vs change in nuclear charge.**
- **Fitted to Rudstam's empirical formula.**

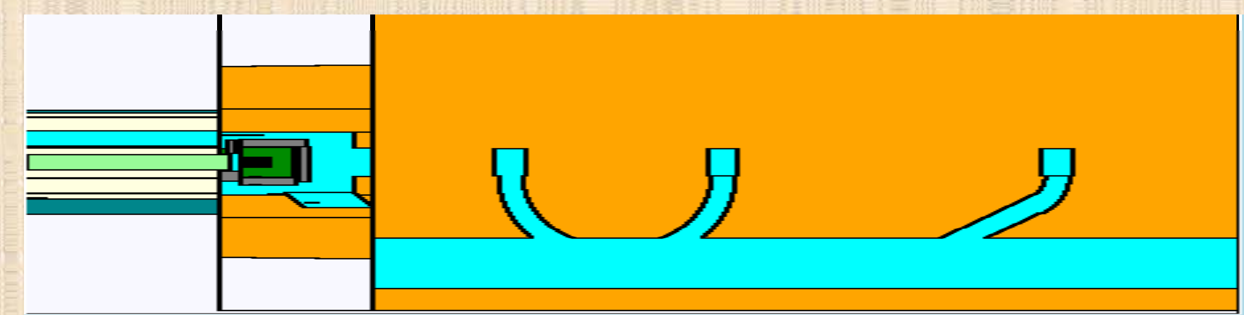


Theoretical calculation



MARS code
Simulate interaction and transport of 120 GeV proton and secondary particles

Fermilab rock
Ca : O : C : Mg : H = 0.09 : 0.56 : 0.17 : 0.08 : 0.10
ρ=2.85 g/cm^3



Absorber hall and muon alcoves

Radiations around intense muon beam (T.Sanami)