Modeling tritium production and release in high-energy proton accelerators

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Outline

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- Tritium production
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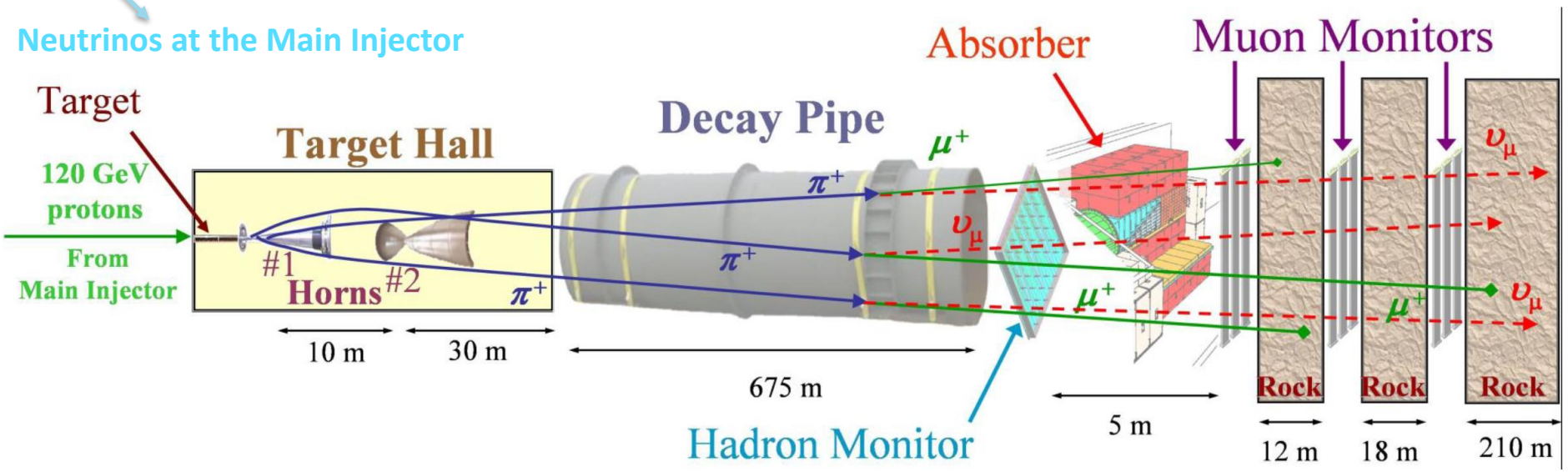
  - Radiation transport calculations: FLUKA, MARS, PHITS
  - Tritium production in target and shielding components
- Tritium release
  - Study of tritium release from various materials
  - Release rate evaluation based on diffusion times for different materials
- Summary

Introduction

- Tritium is a well-known byproduct of particle accelerator operations. To keep levels of tritium below regulatory limits, tritium production is actively monitored and managed at Fermilab.
- We study tritium production in the targets, beamline components, and shielding elements of the Fermilab facilities such as NuMI, BNB, and MI-65.
  - In this work, we present the NuMI target analysis.
  - We construct a simple model and use 3 Monte-Carlo radiation codes – FLUKA, MARS, and PHITS – to estimate the amount of tritium produced.
  - This analysis also serves as an intercomparison between these codes related to tritium production.
- To assess the actual amounts of tritium that would be released from various materials, we employ analytical diffusion model.
- The results of this analysis are compared to the experimental data whenever possible.
  - This approach also helps to optimize proposed target materials with respect to the tritium production and release.

NuMI Neutrino Beam Line Concept

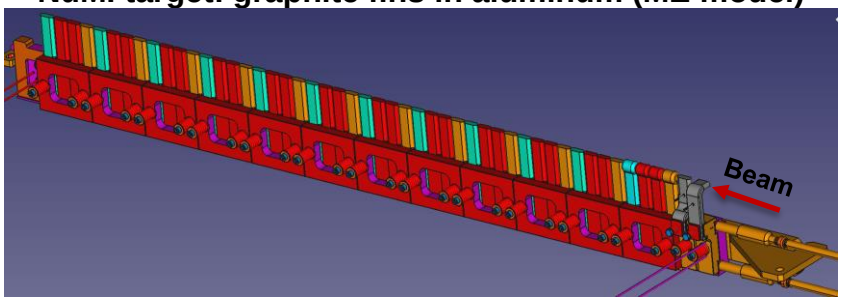


- Beam of 120 GeV protons comes down carrier tunnel
- Protons strike graphite target in target pile, producing pions (and other particles)
- Charged pions focused by toroidal magnets (horns) in target pile
- Long decay path required for pions to decay to neutrinos (Decay Pipe)
- Absorber (aluminum, steel, & concrete) at end absorbs leftover hadrons & EM
- Muons range out in rock; neutrinos continue
- Tritium producing particle shower power is deposited ~1/3 in each of (i) target hall, (ii) decay pipe, and (iii) absorber

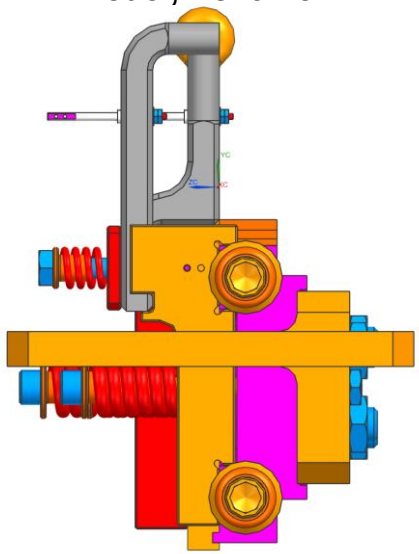
Input: Simple Model of the NuMI Target

- Simple model for 3H production estimate
- Input: 120 GeV/c protons, 1.1 MW (ideally), effective intensity 5.25e13 pps
- Radiation transport calculations using 3 major Monte-Carlo rad codes
  - FLUKA, MARS, PHITS
  - Similar geometry, materials, physics models, E thresholds, …
- Output – in graphite, steel, concrete, water
  - Tritium production rates
  - Activation after 1 year beam-on scenario
  - Instant (no cooling) and 1 year beam-off (cooling) time

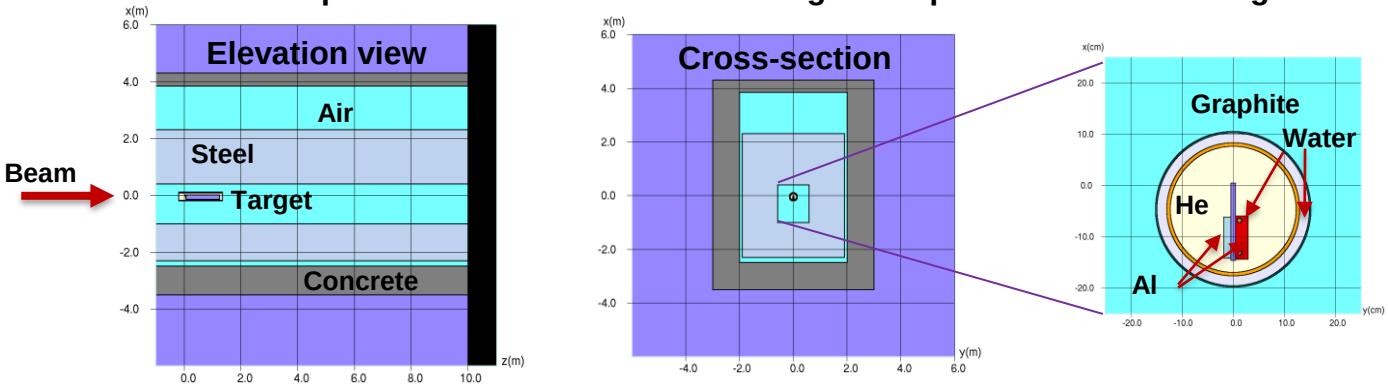
NuMI target: graphite fins in aluminum (ME model)



ME model, front view



Simple MARS model of the NuMI target components and shielding



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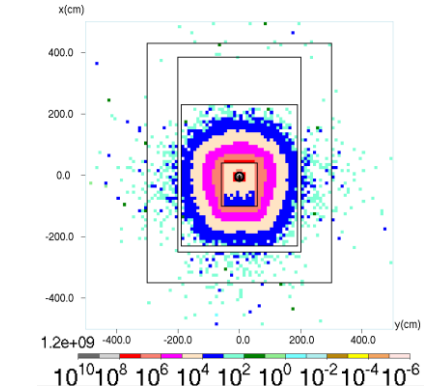
Calculated Tritium Production Rates & Activation

- Tritium production rates and activities
  - Activities after 1 year irradiation
  - No cooling and 1 year cooling
    - 1 year = 365.25 days → FLUKA default
- Ratios between the 3 code results are shown in purple



3H production rate (3H/cm2/s)

Tritium production rates

Region	Tritium production rate, 3H/s			Ratio	
	MARS	FLUKA	PHITS	M/F	M/P
Graphite Target	4.4E+13	2.9E+13	5.6E+13	1.5	0.8
Steel shielding	1.6E+14	2.7E+14	3.6E+14	0.6	0.4
Concrete	5.1E+10	4.6E+10	7.2E+10	1.1	0.7
Water	3.4E+12	6.8E+12	9.2E+12	0.5	0.4

Component activation, 1 year irradiation, no cooling

Region	Activity, Ci (1y beam on)			Ratio	
	MARS	FLUKA	PHITS	M/F	M/P
Graphite Target	64.0	41.6	79.0	1.5	0.8
Steel shielding	231	383	520	0.6	0.4
Concrete	0.08	0.06	0.2	1.2	0.3
Water	5.0	9.5	18.4	0.5	0.3

What could cause the differences? Tritium production cross-sections?

Differences between the FLUKA and MARS outcomes are smaller than these between PHITS and MARS.

Component activation, 1 year irradiation, 1 year cooling

Region	Activity, Ci (1y beam on, 1y beam off)			Ratio	
	MARS	FLUKA	PHITS	M/F	M/P
Graphite Target	61.9	39.4	74.7	1.6	0.8
Steel shielding	219	383	491	0.6	0.4
Concrete	0.07	0.06	0.2	1.1	0.3
Water	4.7	9.5	17.4	0.5	0.3

Tritium Production Rate Estimates from Cross Sections

- Production rate = HE hadron flux * cross section * target atom density
  - Let's compare production rates in water and steel
    - Tritium production cross section is 10 times higher for iron than for oxygen
    - Target atom density is about twice higher for iron than oxygen
- Assuming same neutron flux, production rates will be ~20 times higher in steel compared to water
- Cross-sections are calculated using various methods; an example is shown
- We calculate HE hadron flux using 3 MC rad codes, then estimate tritium production rates using same cross-section value for all 3 codes.

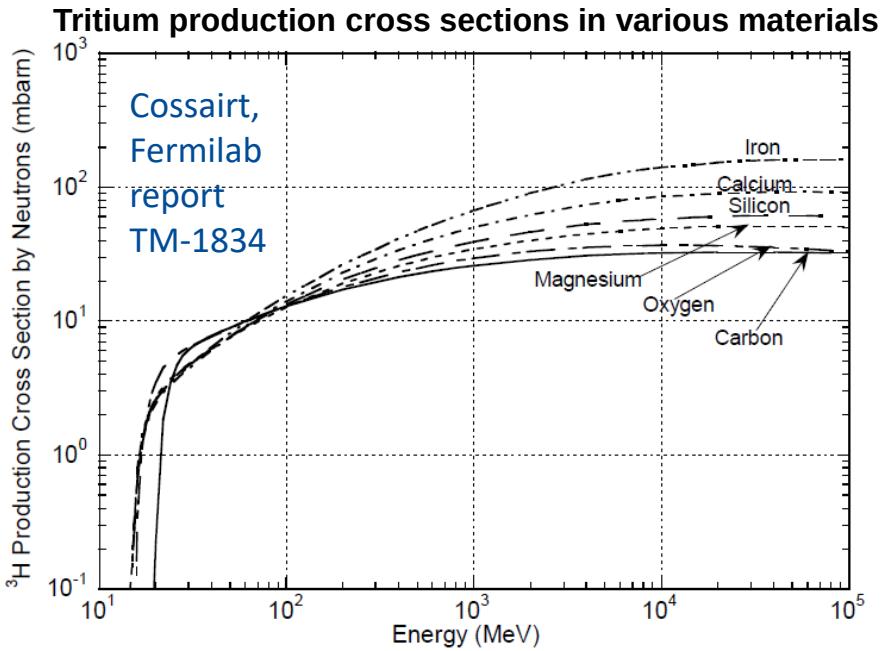
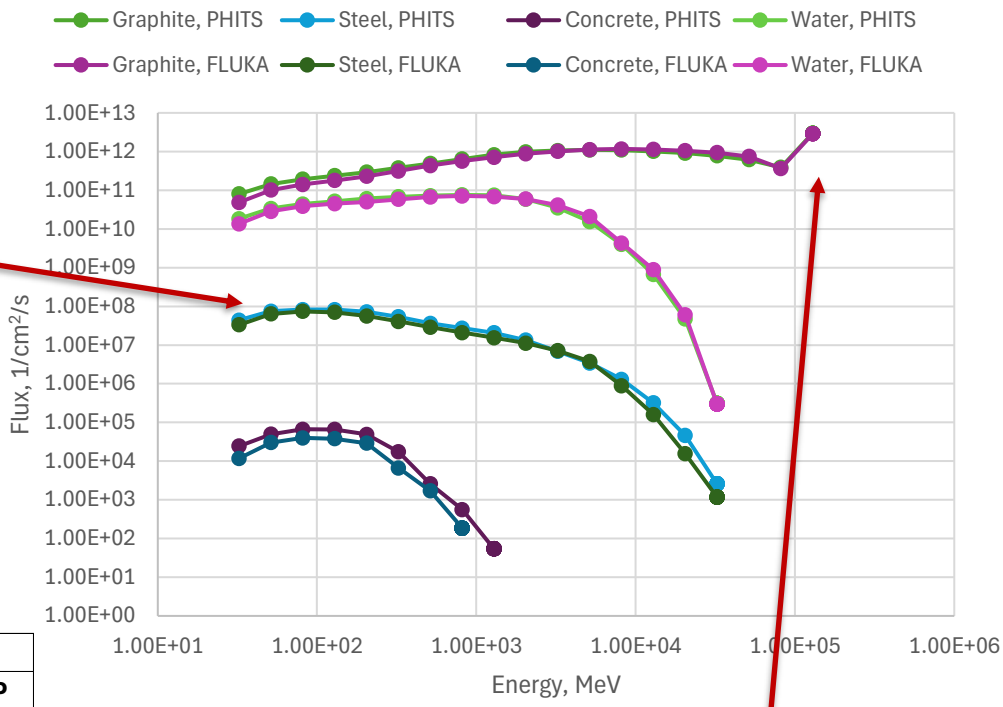


Fig. 8.4 Cross sections for the production of ^{3}H due to neutron bombardment of materials commonly found in soil and rock as a function of neutron energy. The calculations have been performed following the method of Konobeyev and Korovin (Ko93). Results for aluminum are quite similar to those found for silicon and the results for sodium are quite similar to those found for magnesium.

HE Hadron Fluxes & Spectra

- Comparing HE hadron fluxes and their energy spectra
  - HE (E>30 MeV) traditional MARS output
  - Same E threshold set in FLUKA & PHITS



HE hadron flux in steel shield peaks around 100 MeV because the energies of the main contributors are already very much reduced by the time they reach the steel part.

HE hadron flux in graphite peaks at 120 GeV because the proton beam goes directly into graphite fins.

High Energy Hadron Flux in Components

Region	HE (E>30 MeV) Hadron Flux, 1/cm2/s			Ratio	
	MARS	FLUKA	PHITS	M/F	M/P
Graphite Target	1.43E+13	1.41E+13	1.43E+13	1.0	1.0
Steel shielding	4.28E+08	4.27E+08	5.19E+08	1.0	0.8
Concrete	2.40E+05	1.57E+05	2.76E+05	1.5	0.9
Water	1.67E+11	5.70E+11	6.16E+11	0.3	0.3

Total HE hadron fluxes are almost identical in graphite across the 3 codes. Therefore, it's the tritium production cross section difference that makes the tritium production rates different between these codes.

Estimating Tritium Production Rates

- Production rate estimates
  - Using calculated tritium production cross sections from K&K
  - Same cross sections for all 3 codes

Graphite target:
HE hadron flux spectrum peaks at 120 GeV →
Carbon HE cross-section ~30 mbarn @ 1e5 MeV

Production Rate, 3H/s	FLUKA	MARS	PHITS
Calculated with MC code	2.86E+13	4.42E+13	5.62E+13
Estimated from X-sections	3.09E+13	3.05E+13	3.03E+13
Ratio calculated/estimated	0.9	1.4	1.9

Iron shield:
HE hadron flux spectrum peaks at 100 MeV →
Carbon HE cross-section ~20 mbarn @ 100 MeV

Production Rate, 3H/s	FLUKA	MARS	PHITS
Calculated with MC code	2.74E+14	1.56E+14	3.58E+14
Estimated from X-sections	1.20E+14	1.29E+14	1.45E+14
Ratio calculated/estimated	2.3	1.2	2.5

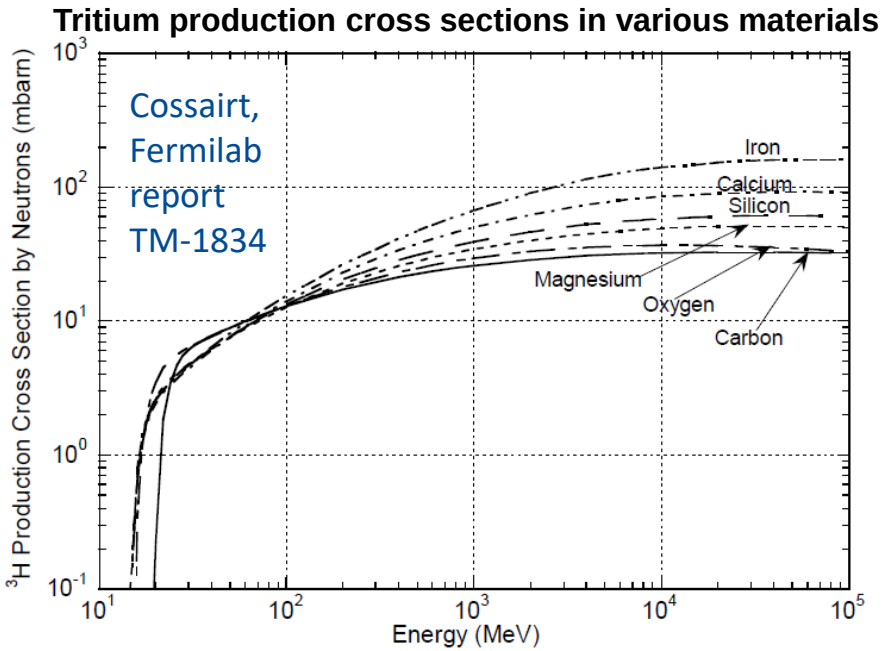
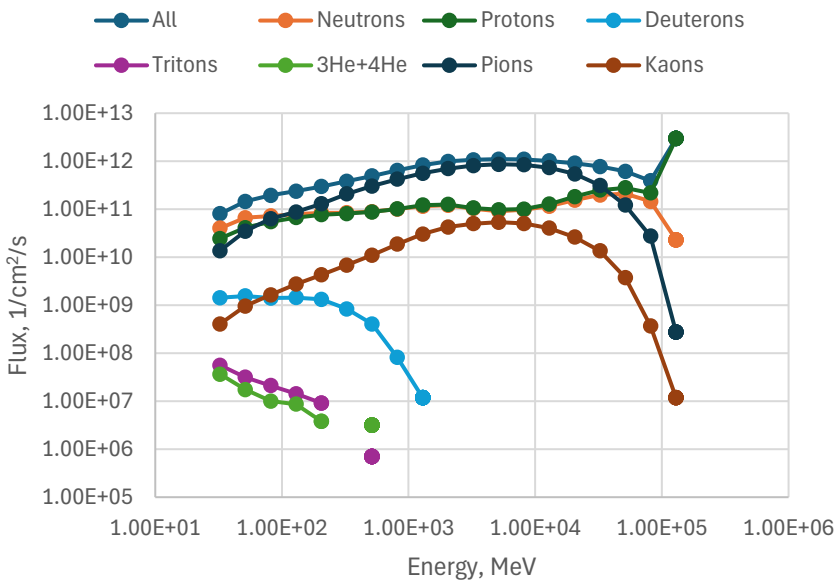


Fig. 8.4 Cross sections for the production of ^{3}H due to neutron bombardment of materials commonly found in soil and rock as a function of neutron energy. The calculations have been performed following the method of Konobeyev and Korovin (Ko93). Results for aluminum are quite similar to those found for silicon and the results for sodium are quite similar to those found for magnesium.

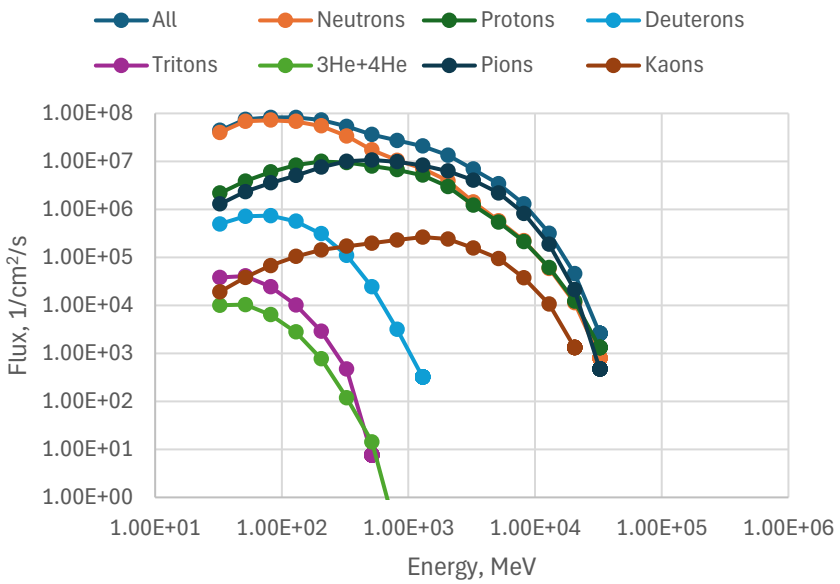
Would be better to fold in the cross sections… need to obtain the actual numbers – digitize the graph? ☺

HE Hadron Fluxes: Various Particle Contributions

- Graphite target
  - Pions dominate at lower energies
  - Neutrons & protons at higher energies
  - Proton peak at 120 GeV

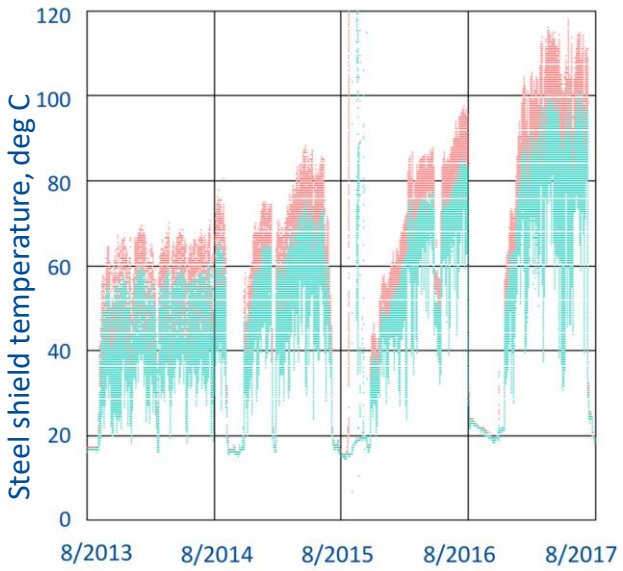


- Steel shield
  - Major contributors peak around 100 MeV
  - Neutrons at lower E, pions at higher E



NuMI Tritium Production & Release

- At higher beam power, fraction of produced tritium release increased rapidly
- Best explanation: steel shielding temperature increase

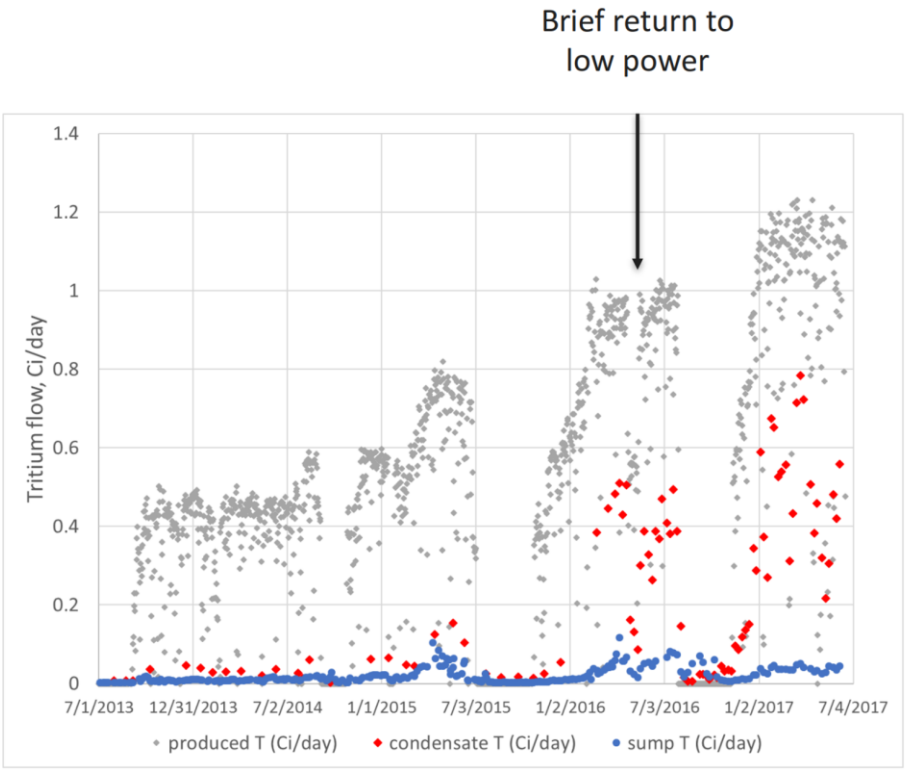


Comparison of

Tritium produced, based on Monte Carlo times protons delivered (not including absorber)

Tritium collected in condensate and evaporated

Tritium to MINOS sump (to lab water + ponds)



Release amount would always be capped by the production rate

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Tritium Release

- If all produced tritium would have been instantaneously released into the air, this would represent a worst-case scenario
- In reality, tritium is released from different materials on different diffusion lengths and scales
  - Diffusion coefficients widely vary; they are strongly temperature-dependent
    - Example: for graphite, diffusion coefficients are D=8.0e-35 cm2/s @ 50C and D=1.2e-11 cm2/s @ 1000C.

To estimate tritium diffusion from materials, one can use activation equation augmented with diffusion and air ventilation terms:

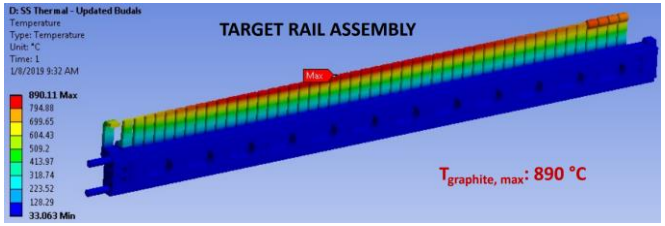
$$a(t) = a_{sat}\{1-\exp(-[\lambda_{3H}+\lambda_{diff1}]t_{irr})\}\{\exp(-[\lambda_{3H}+\lambda_{diff2}]t_c)\}$$

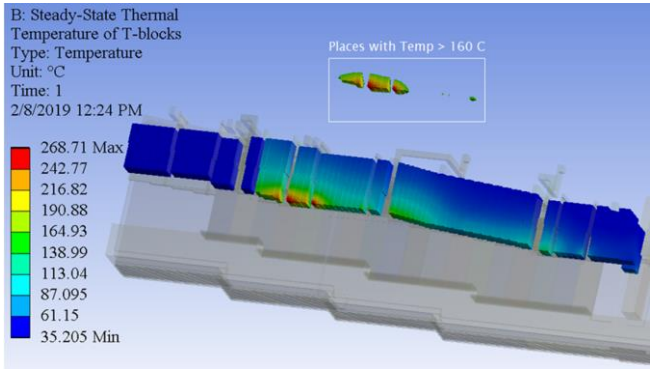
where a_{sat} is saturation activity; λ_{3H} is tritium decay constant, or inverse of tritium half-life; λ_{diff1} and λ_{diff2} are diffusion decay constants for materials at temperatures T1 (during irradiation) and T2 (after cool-down); t_{irr} is irradiation time, t_c is cooling time. Diffusion times are calculated from diffusion lengths L and diffusion coefficients D as $t = L^2/2D$; L is half of the attenuation length in a given material, estimated from MC calculations.

To account for ventilation, $a'_{sat} = a_{sat} * \lambda/(\lambda + r)$, where λ is a composite decay constant taking into account both natural tritium decay and diffusion, and r is the number of air changes per unit time.

Diffusion Coefficients, Times, Lengths

- Diffusion coefficients for relevant materials / temperatures are found in literature
- Thermal analysis results used to assess operating temperatures





- Diffusion effective lengths are conservatively estimated from MC calculations as
  - Half of attenuation length for a thick component
  - Half of a component thickness if a component is thin compared to attenuation length
- Diffusion time estimated as $T_{diff} = L^2/(2*D)$, where L is diffusion length
- Diffusion decay constant is $\lambda_{diff} = 1/T_{diff;}$ this constant is used, along with the tritium natural decay constant λ_{3H}, in the modified activation equation.

Tritium Release Estimates

- Release estimates are based on the production rates from MARS
  - An example of the diffusion calculation setup:

	H3 production from RT calcs	Temperature T1 (during beam-on)		Diffusion D1 (at T1)	Temperature T2 (during beam-off)	Diffusion D2 (at T2)	Diffusion length	Irradiation time	Cooling time	Diffusion half-time at T1	Diffusion half-time at T2	Diffusion constant lambda1	Diffusion constant lambda2	Number of 3H after irradiation wo diffusion	Number of 3H after irradiation w diffusion	Fraction diffused	Number of 3H after irradiation & cooling wo diffusion	Number of 3H after irradiation & cooling w diffusion	Fraction diffused
Material / Component	**P_3H, 1/s**	**Beam on**			**Beam off**		**L, cm**	**T_irr, h**	**T_cool, h**	**T_diff1, h**	**T_diff2, h**	**λ_diff1, 1/s**	**λ_diff2, 1/s**	**Ki**	**Ki_diff**	**Ri_diff**	**Kic**	**Kic_diff**	**Ric_diff**
		T1, C		**D1, cm2/s**	**T2 , C**	**D2, cm2/s**													
Graphite Target	4.4E+13	1000		2.1E-11	50	8.0E-35	0.45	8766	8766	1.4E+06	3.5E+29	1.4E-10	5.5E-34	1.4E+21	1.4E+21	2.2E-03	1.3E+21	1.3E+21	2.2E-03
Iron Shielding	1.6E+14	300		2.3E-05	50	3.2E-06	10	8766	8766	6.0E+02	4.3E+03	3.2E-07	4.4E-08	4.8E+21	4.9E+20	9.0E-01	4.5E+21	1.1E+20	9.7E-01
Concrete Walls	5.1E+10	50		2.1E-07	50	2.1E-07	12	8766	8766	9.5E+04	9.5E+04	2.0E-09	2.0E-09	1.6E+18	1.5E+18	3.1E-02	1.5E+18	1.3E+18	9.1E-02
	Input																		

After 1 year irradiation, 90% of the tritium produced in iron shielding is diffused

After 1 year irradiation and 1 year cooling, 97% of the produced tritium is diffused from iron

At a lower beam power, iron shield temperature is lower

→ Diffusion coefficients are lower

→ Less tritium is diffused from materials

E.g., in the same setup at a room temperature, only 46% of the produced tritium would be released from iron shielding.

For NuMI and eventually other Fermilab facilities, we plan to perform detailed tritium production calculations based on the beam input parameters; then estimate tritium release and compare to the outcome of the tritium release measurements at the lab (Tritium Task Force activities).

Caveat: Data on diffusion coefficients are abundant yet not always consistent.

Summary

We study tritium production and release in Fermilab's NuMI target components. We calculate tritium production using three major Monte-Carlo radiation codes: FLUKA, MARS, and PHITS. This analysis also serves as an intercomparison between these codes with respect to the tritium production. The resulting production rates are consistent between the three codes. We look for possible explanations to account for minor differences.

We use modified activation equation to estimate tritium diffusion from various materials. The results of our analysis offer a detailed explanation for the unexpected jumps in tritium production with the NuMI beam power increase observed over the past years. This analysis will also allow us to make predictions for the future tritium releases at various Fermilab facilities. Finally, this approach helps to optimize proposed target and beamline materials with respect to their tritium production and diffusion properties.

Acknowledgements

I would like to express my gratitude

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