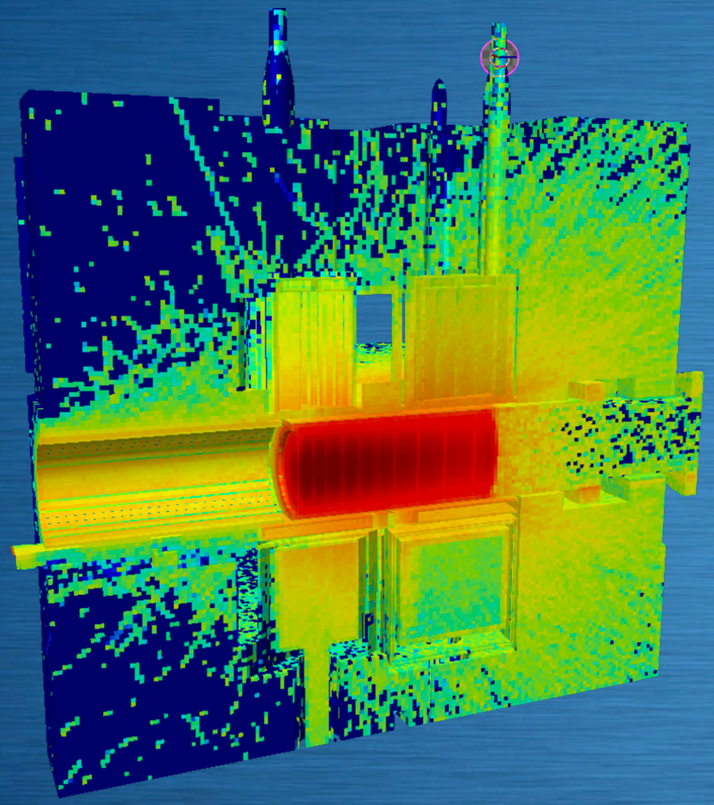
Science & Technology Facilities Council
ISIS Neutron and Muon Source



SIMULATING NEUTRON TRACKS IN THE NEW TS1-TRAM AT ISIS WITH FLUKA CODE: SOME INSIGHTS TOWARDS AN OPTIMISED AND MORE EFFICIENT TARGET-MODERATOR-REFLECTOR ASSEMBLY FOR HIGH POWER SPALLATION SOURCES

L. Quintieri, S. Lilley

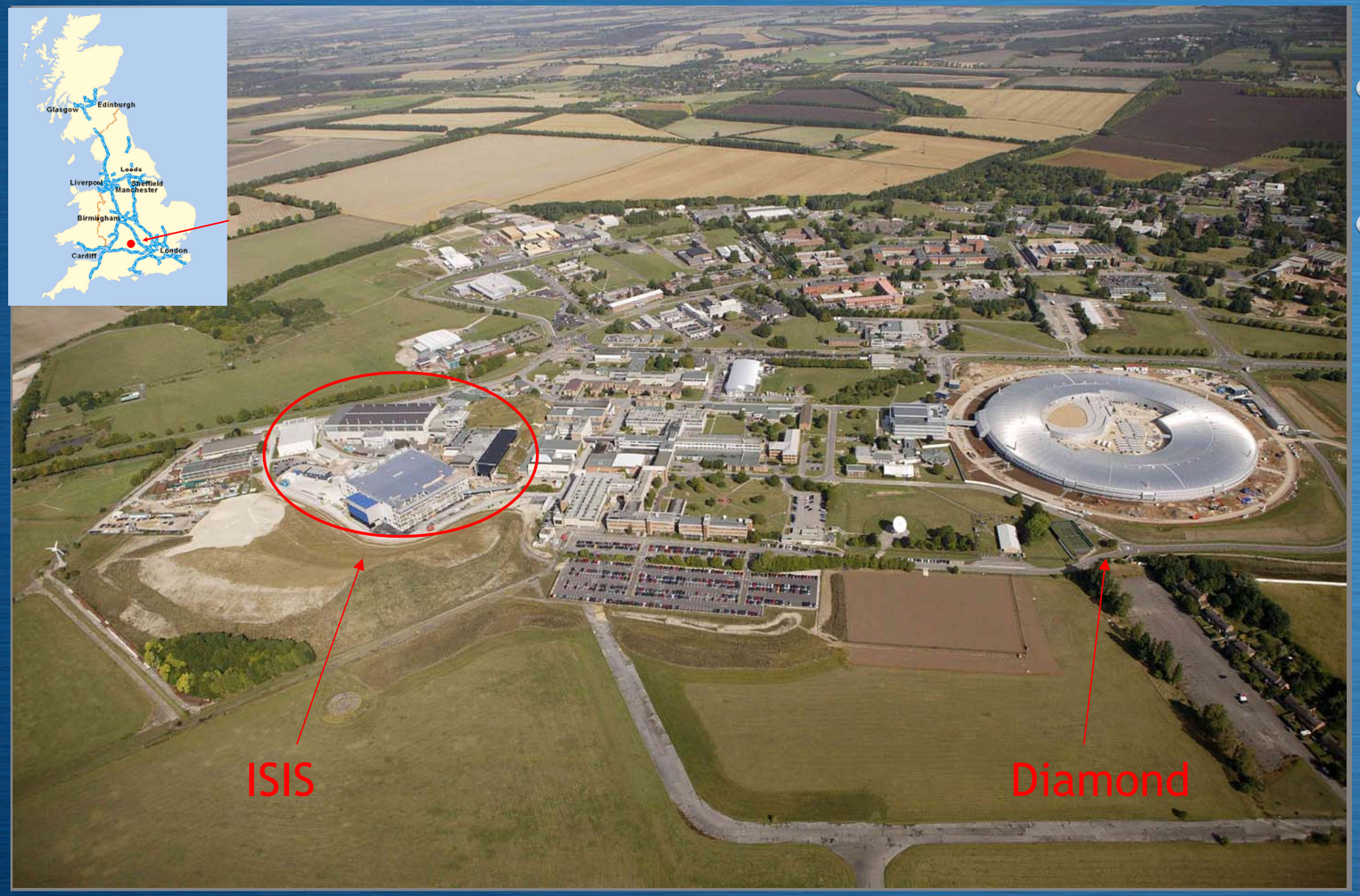
ENS PSI, Villingen, 2- 5 Sep 2019

OUTLINE

- **The FLUKA model of the upgraded ISIS-TS1 TRAM**
  - A general overview
- **“Standard” simulation results (feedback on accuracy of the model):**
  - Fluence spectra of escaping particles (not only neutrons)
  - Energy deposition comparison with MCNP (indirect model validation)
- **“Advanced” simulations for neutron tracking (for a more efficient TRAM design):**
  - Target plate contribution to the neutron TRAM leakage (i.e neutron plate efficiency to improve the target design)
  - “Flagging” neutrons across clue regions (i.e moderators) to assess their effective contribution to the instrument beam (some specific estimation on Polaris and Maps)
- **“Conclusion & ongoing activity”**

ISIS: PULSED NEUTRON & MUON SPALLATION SOURCE

UKRI: STFC Science & Technology Facilities Council



Rutherford Appleton Laboratory in Harwell Campus-Oxford

- ISIS is one of the world's leading spallation neutron and muon facilities
- ISIS accelerators drive neutron and muon factory
- ~750 experiments/year
  ~1500 visitors/year (~4500 visits)

Sweden
5-year agreement with the Swedish Research Council from January 2015.

India
A 5-year agreement with India to provide contributions to the Zoom instrument.

Italy
Renewal of a 6-year agreement with Italy, contributing to several ISIS instruments.

ISIS has more than 20 international partnerships and agreements with 11 different countries.

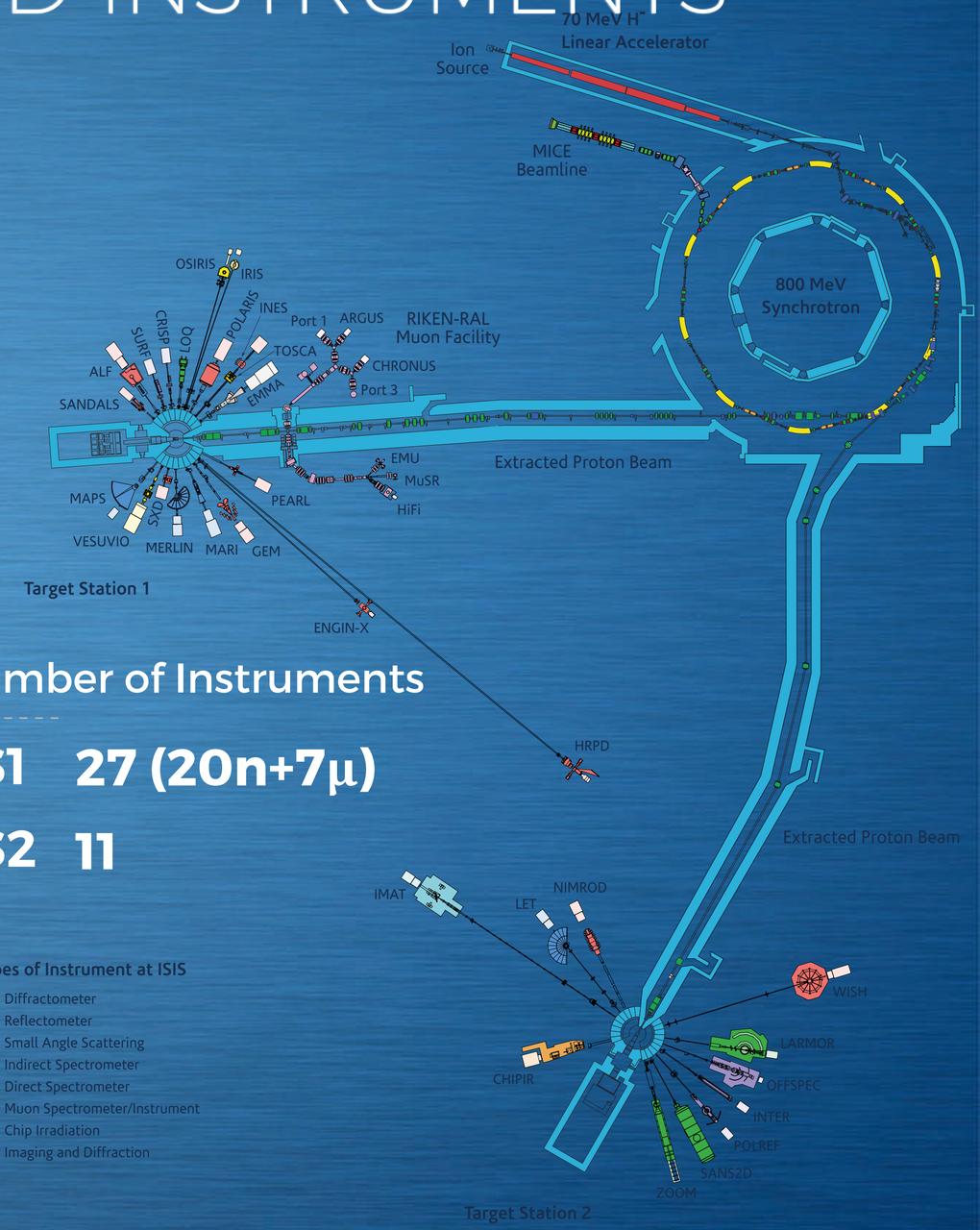
Science & Technology Facilities Council
ISIS Neutron and Muon Source

ISIS: ACCELERATOR COMPLEX AND INSTRUMENTS

Targets 2 × W (Ta coated)

Protons 800 MeV

- The ISIS accelerator produces a beam pulse at 50Hz with every fifth pulse delivered to TS-2, the rest to TS-1.
- Currently ISIS has two spallation targets, TS1 operating at proton beam powers of up to 200 kW, and TS2 operating to 45 kW.



Number of Instruments

TS1 27 (20n+7μ)

TS2 11

Types of Instrument at ISIS

- Diffractometer
- Reflectometer
- Small Angle Scattering
- Indirect Spectrometer
- Direct Spectrometer
- Muon Spectrometer/Instrument
- Chip Irradiation
- Imaging and Diffraction

FLUKA MODEL OF THE UPDATED TS1-TRAM

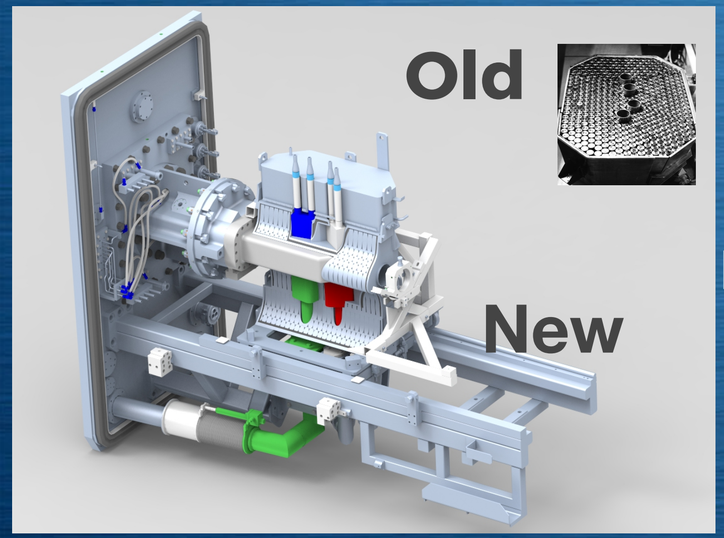
GEOMETRY, PHYSICS, SOURCE

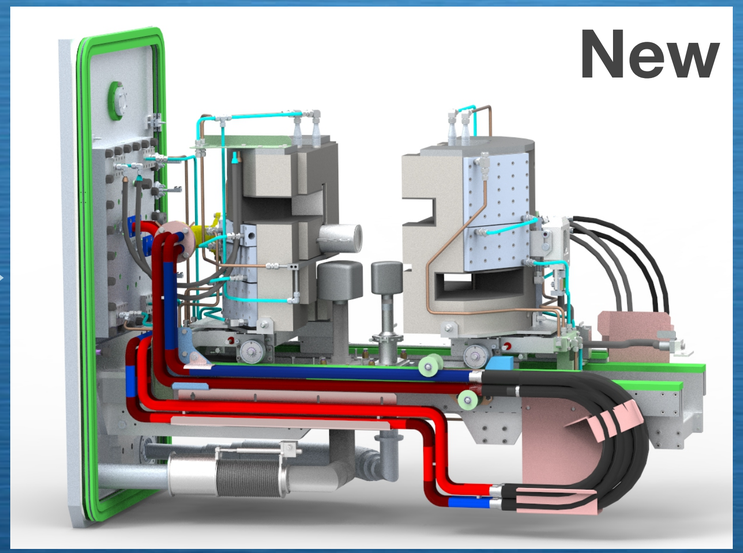
TRAM MODULE: UPDATES

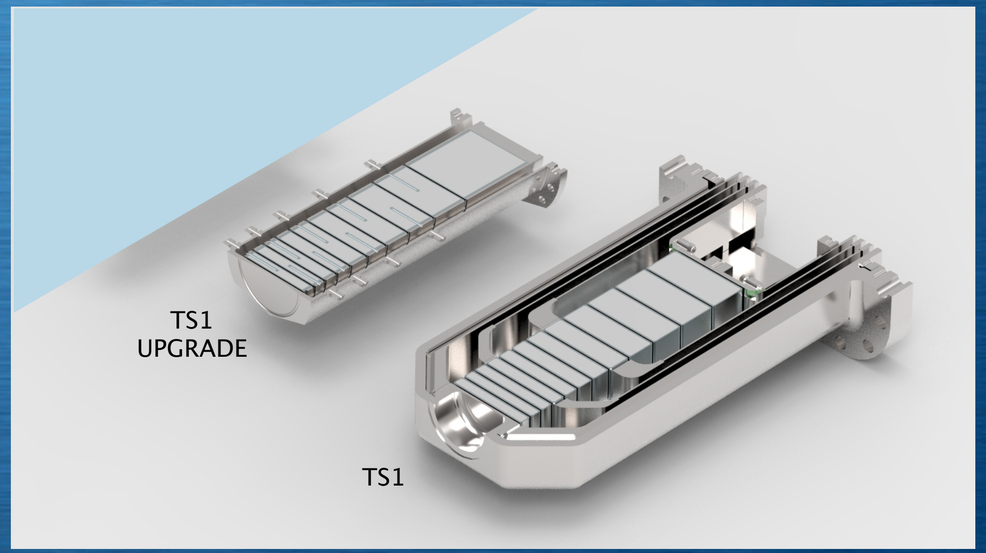
- Smaller Reflector: the SS vessel filled with Be rods changed with a Be multi brick structure, edge cooled
- Boral layer around the reflector
- Flight-line liners: steel removed, only Boral
- Cooling pads added

- Methane moderator: 3rd aluminum layer removed. Second Gd foil inserted
- Hydrogen moderator: height reduced
- Inserted water pre-moderators
- Target shape changed from rectangular to cylindrical
- 10 plates in place of 12

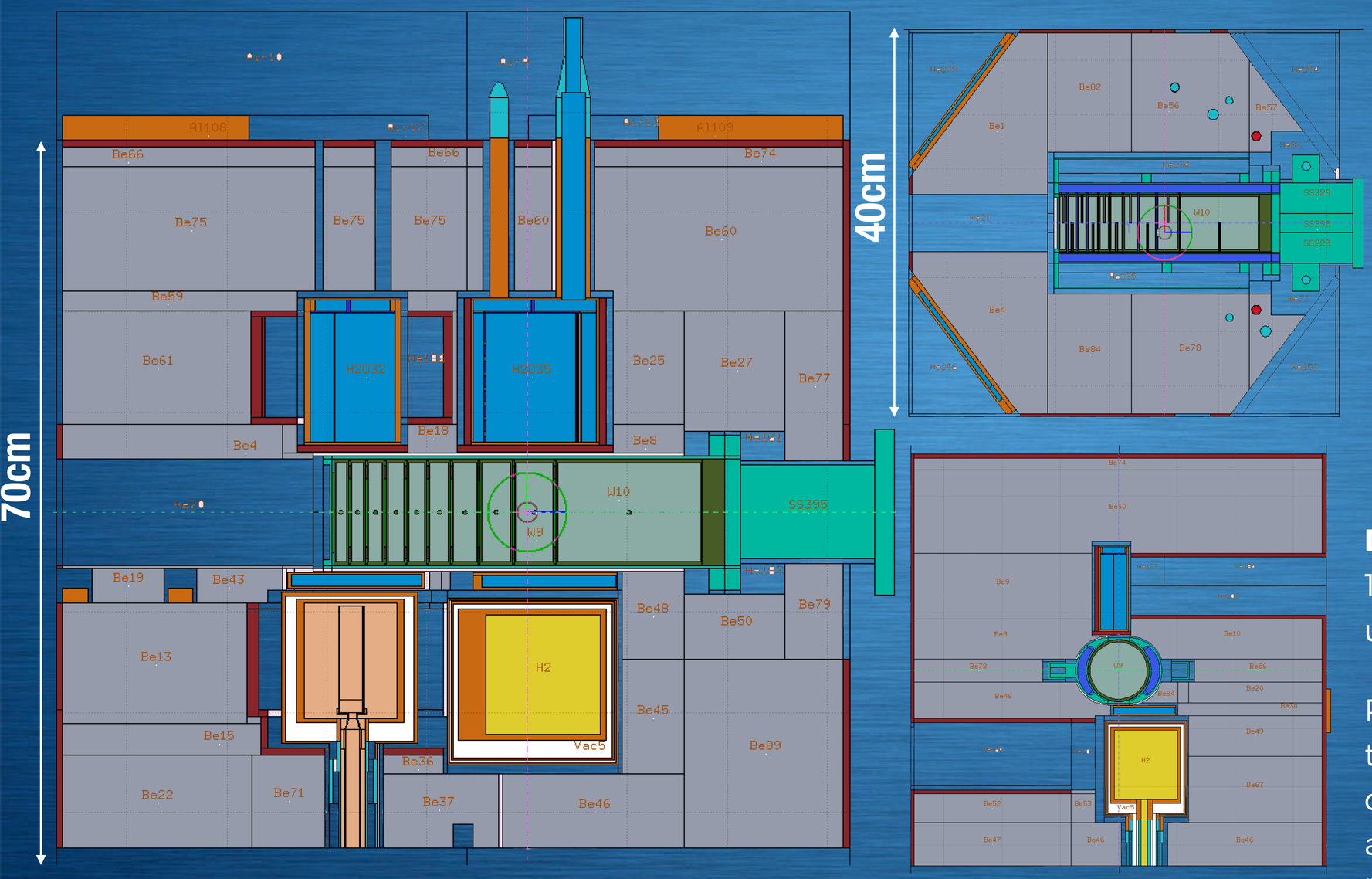
	Mass [kg]		
Material	**Current Ts1**	**TS1 Upgrade**	**Reduction**
SS	73.8	8.1	89%
Ta	32.7	6.9	79%
W	47.3	46.0	2.8%
Total	153.8	61.0	60.3%







UPGRADED TS1 TRAM: THE FLUKA MODEL



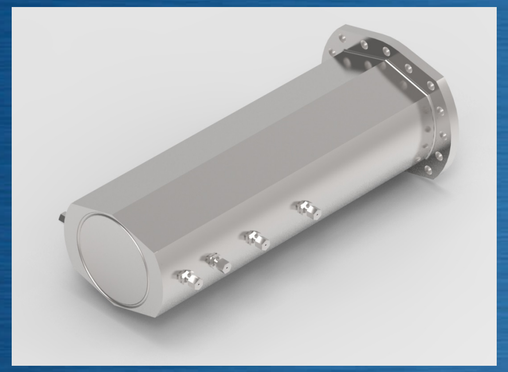
Detailed geometry

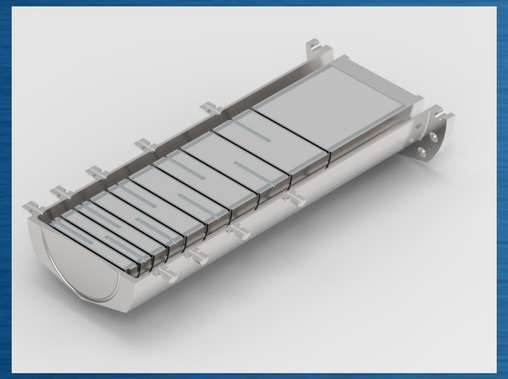
1683 regions and 31 materials cards used for the model

Post-process oriented model in order to get direct neutron track-length density estimation in each assemblies and subassemblies that could be “monitored" or “measured”.

GEOMETRIC ACCURACY OF THE MODEL

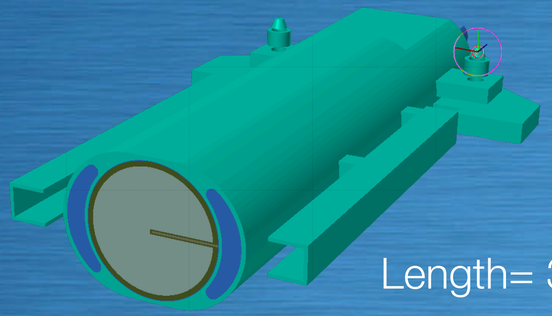
CAD



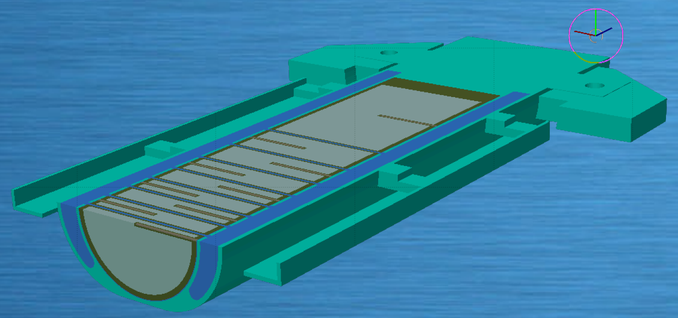


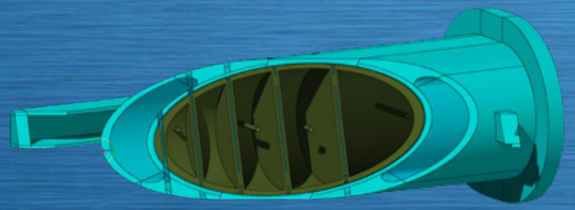
The target core is made of 10 tungsten plates, each of 4.9 cm radius, cladded with tantalum (cladding thickness is 0.2 cm).

FLUKA



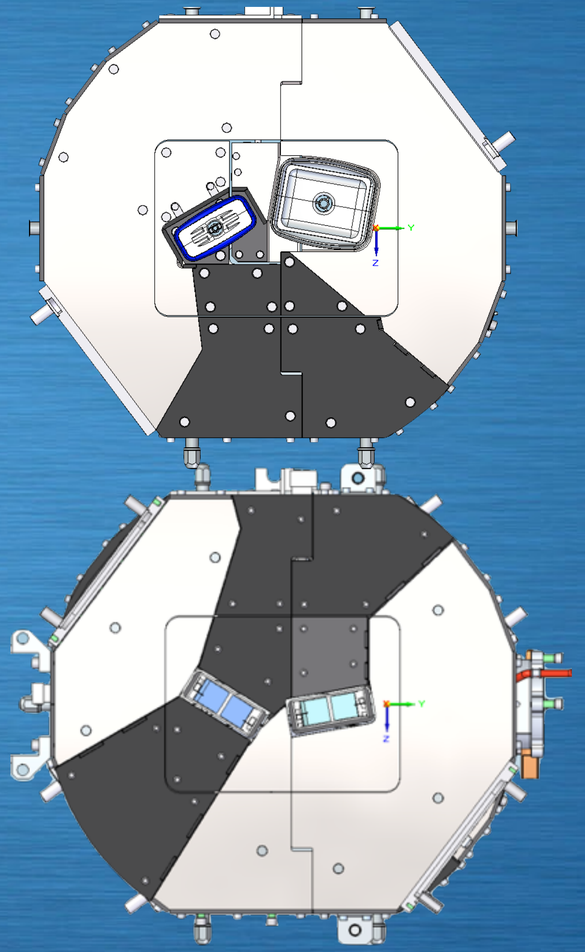
Length= 38cm





Ta cladded thermocouples are introduced in the Fluka model as well

CAD



FLUKA

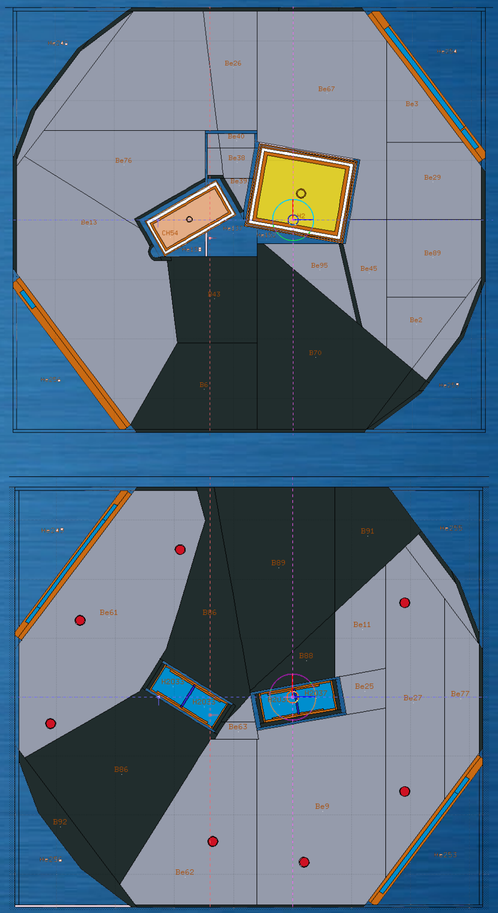
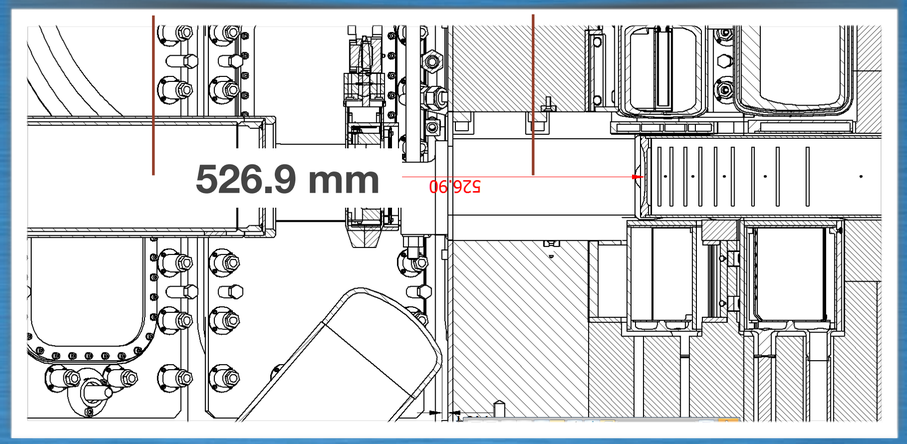


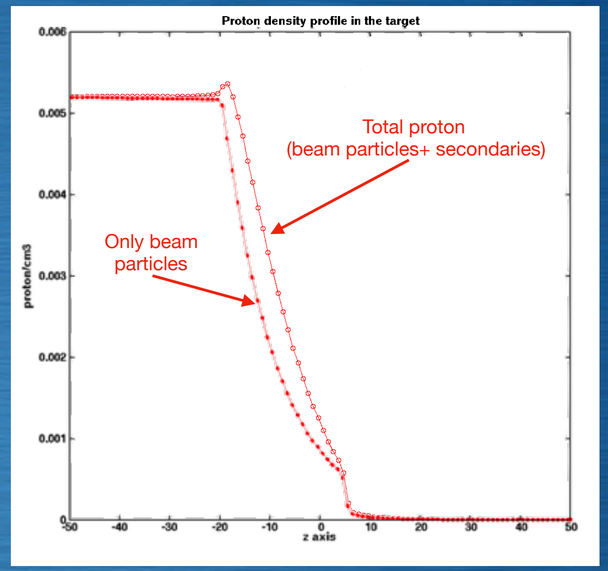
FIGURE OF MERIT: Very accurate model of the whole TRAM: between CAD and FLUKA model, the maximum difference in the volumes for each components is always less than 3%

IMPLEMENTED SOURCE: PROTON BEAM

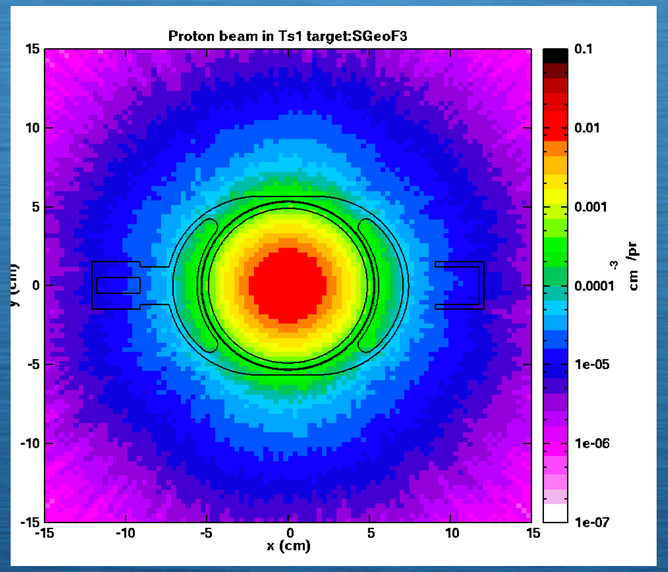
Primary Beam Characteristics	
Particle	Protons
Energy profile	Gaussian
Mean Energy	800 MeV
Energy spread	±0.4%
FWHM	7.4 MeV
Spatial profile	Gaussian
FWHM	4.2 cm
Divergence in V	100 π mm-mrad
Divergence in H	90 π mm-mrad
Angular divergence	0.88 mrad

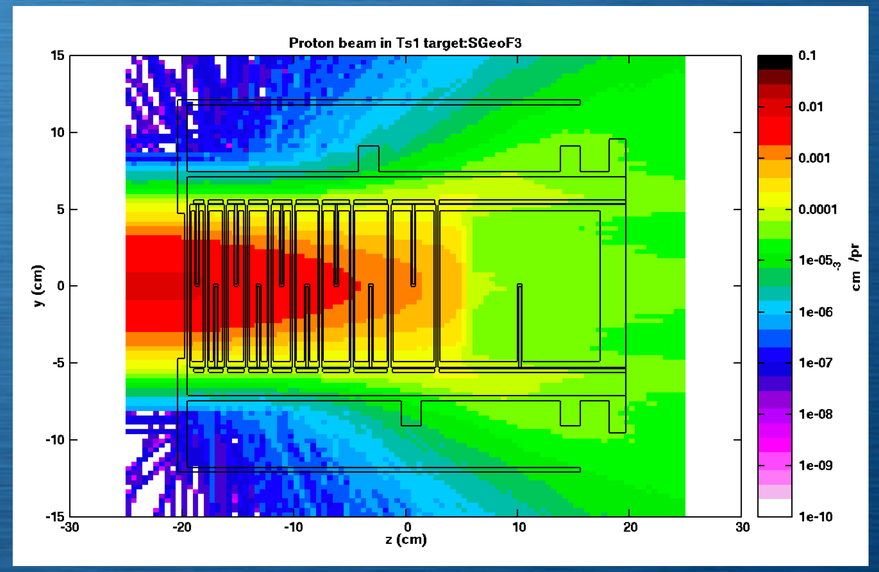


Proton density (1D projection)



Proton density (2D projections)





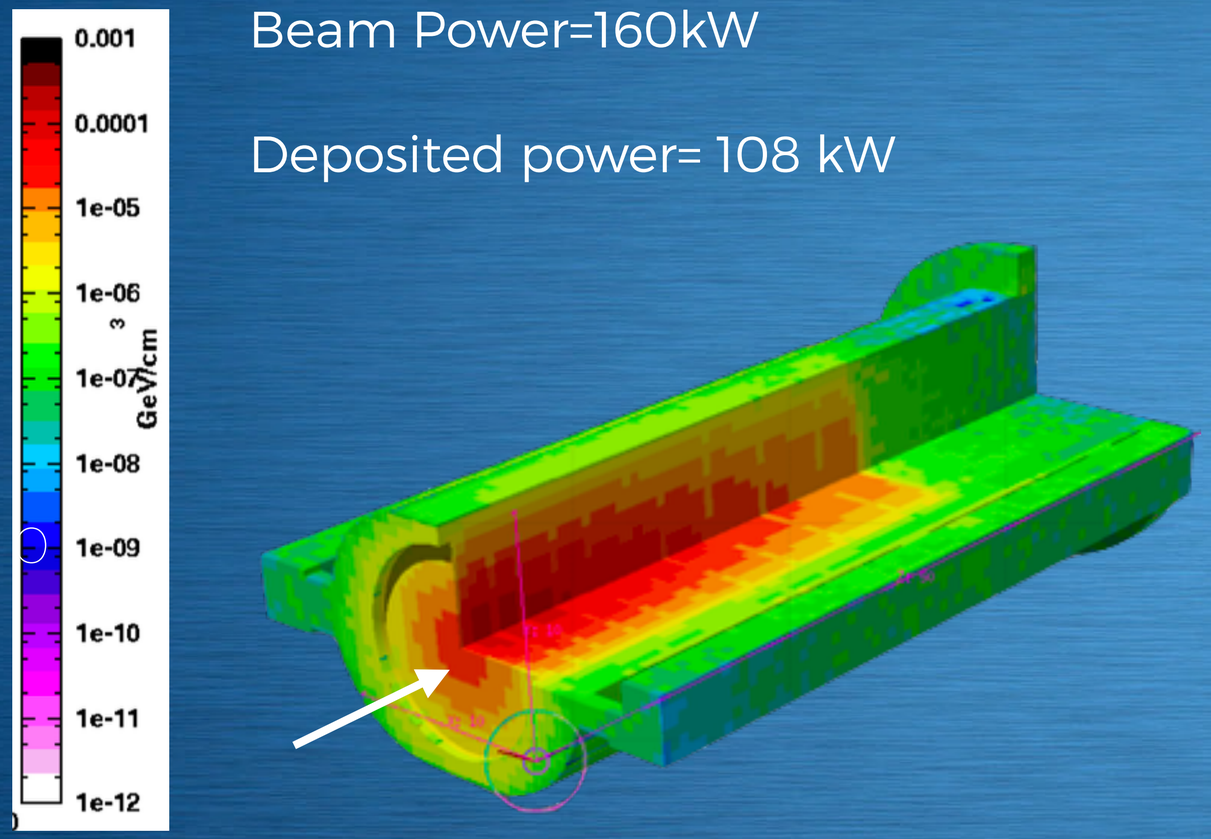
ENERGY DEPOSITION PROFILE:

COMPARISON WITH THE MCNP REFERENCE MODEL

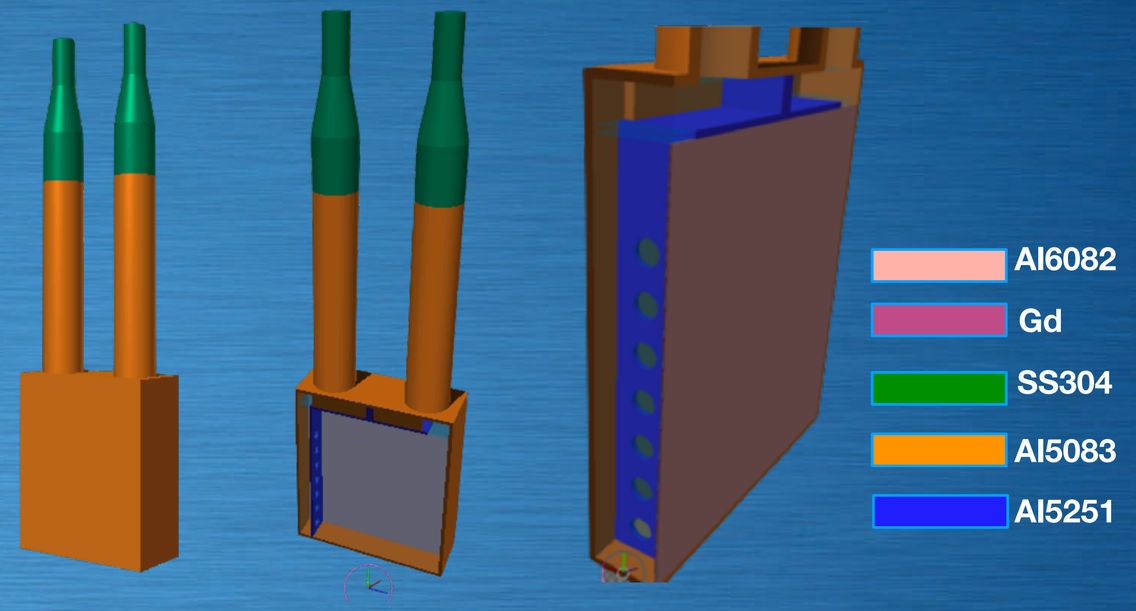
UPGRADED TARGET: ENERGY DEPOSITION

Beam Power=160kW

Deposited power= 108 kW



MATERIAL	FLUKA (MeV/pr)	MCNP** (Mev/pr)	Δ/MCNP
Total	541.5 ±0.4%	474.6	14%



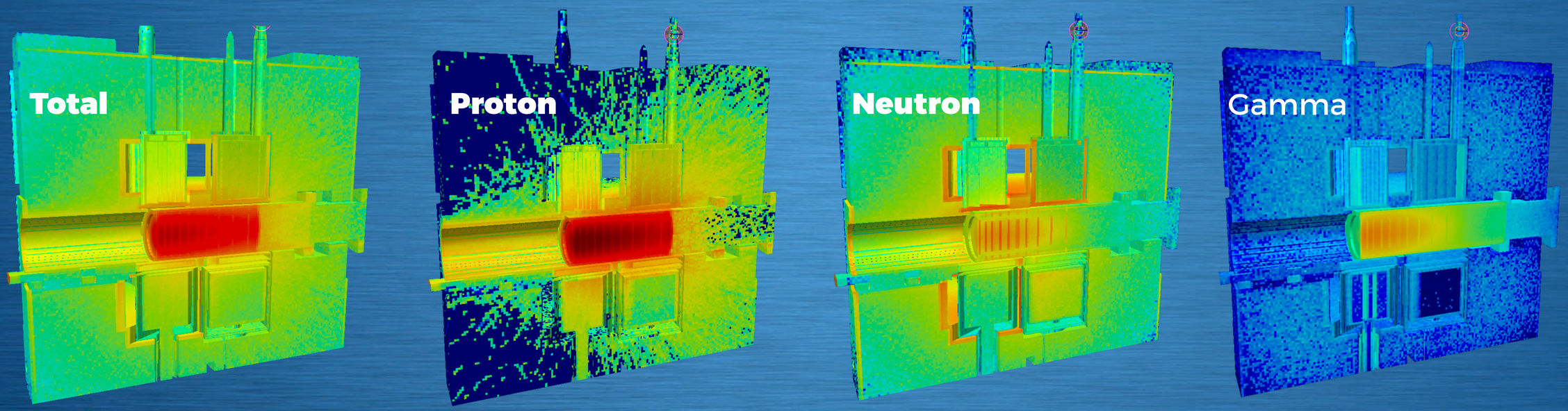
Hydrogen moderator operates at 20K

WATER MODERATOR (symmetric Gd)	FLUKA (MeV/pr)	MCNP (MeV/pr)	Δ/MCNP
Total	3.27	3.36	3%
Water	0.881 ±0.05	0.84	4.6%
Boral (decoupler)	2.042 ±4.68E-2	1.84	11%
Poison (Gd+Al)	0.017 ±5.6E-3	0.04	57%

ENERGY DEPOSITION: PARTICLE CONTRIBUTION

Rate of secondary escaping particles from TRAM (primary beam: 800 MeV proton - 200μA

Source strength	Neutron	Proton	Pion +/-	Muon +/-	Photon	Electron	Positron
(s^{-1})	7E+15	4E+13	1.8E+12	2.5E+11	1E+16	7E+13	6.5E+12

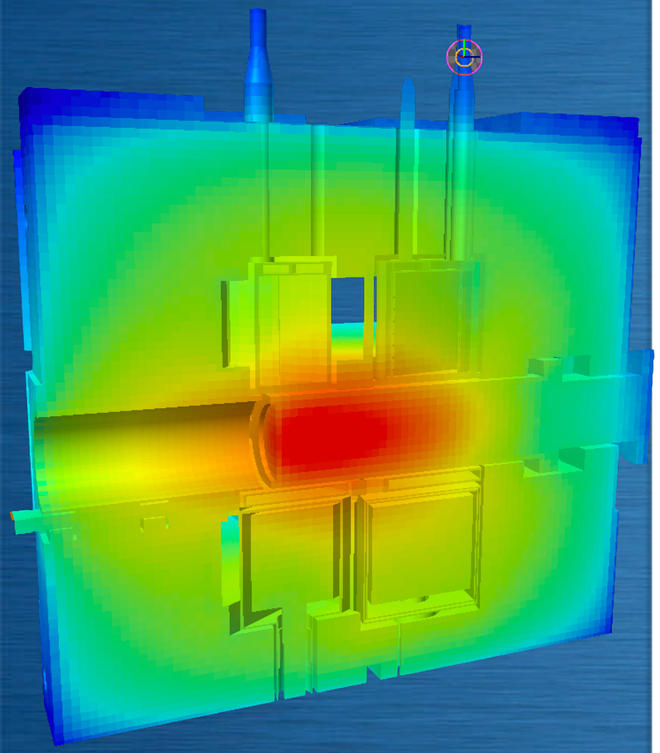


REFLECTOR	FLUKA (MeV/pr)	MCNP (Mev/pr)	Δ/ MCNP
Total	82.86 ± 7%	80.77	3%
Be	54.24	58.97	8%

E_{dep} (MeV/pr)	TRAM	TARGET
Total	541.5 ± 2.3%	427
Neutron	37	4.2
Proton	401	380
Gamma	1.6	1.5

NEUTRON YIELD

NEUTRON BALANCE IN THE WHOLE TRAM



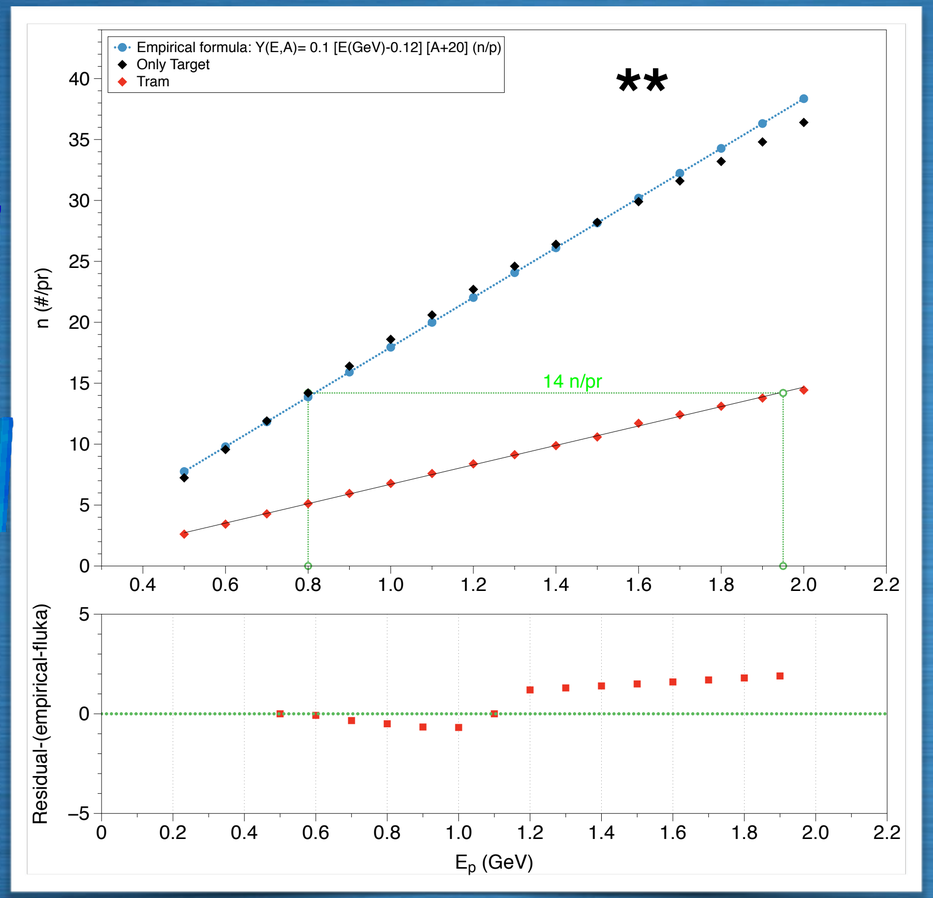


Table 4: Neutron balance* per primary proton

800 MeV proton		Bare Target [n/p]	TRAM [n/p]
Target	W	11.88±0.4%	11.14±0.5%
	Ta	2.07±0.9%	0.81±2.9%
	SS	0.19±1.5%	-0.28 ±1.7%
	Ni (thermocouples)	0.003±13.7%	0.003±18.9%
	MixWater**	0.029±3.1%	0.023±4.8%
Reflector	Be	-	1.43±0.6%
Poisons and liners	Boral	-	-7.07±0.2%
	Gd	-	-0.26±0.9%
Cold Moderators	Liquid CH4	-	-0.02±3.3%
	Liquid H2	-	-0.002±7.9%
Water moderators	Water	-	-0.09±1.5%
Structural and auxiliary materials	Al alloys	-	-0.10±1.6%
	Ti alloys	-	-0.17±1.1%
	SS	-	-0.10±1.5%
Total net balance		~14.2 ±0.4%	~5.3±0.5%

**The Neutron balance is the net contribution "<+production -absorption>" of neutrons in each region.*

***MixWater is made of 80%D_2O+20%H_2O*

Bare target:

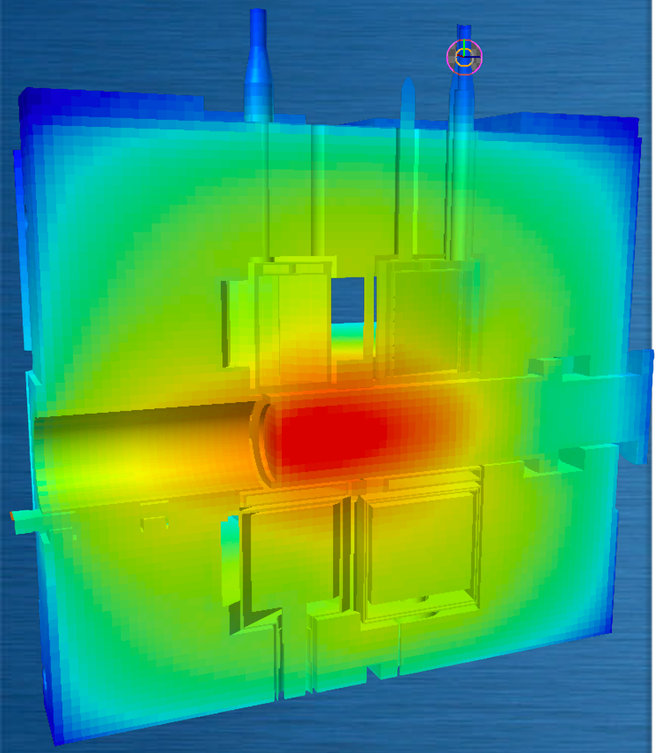
- An average of **14.1 neutrons** per impinging 800 MeV proton **escaping from the target**.
- **83.5%** of the escaping neutrons are produced in **Tungsten**

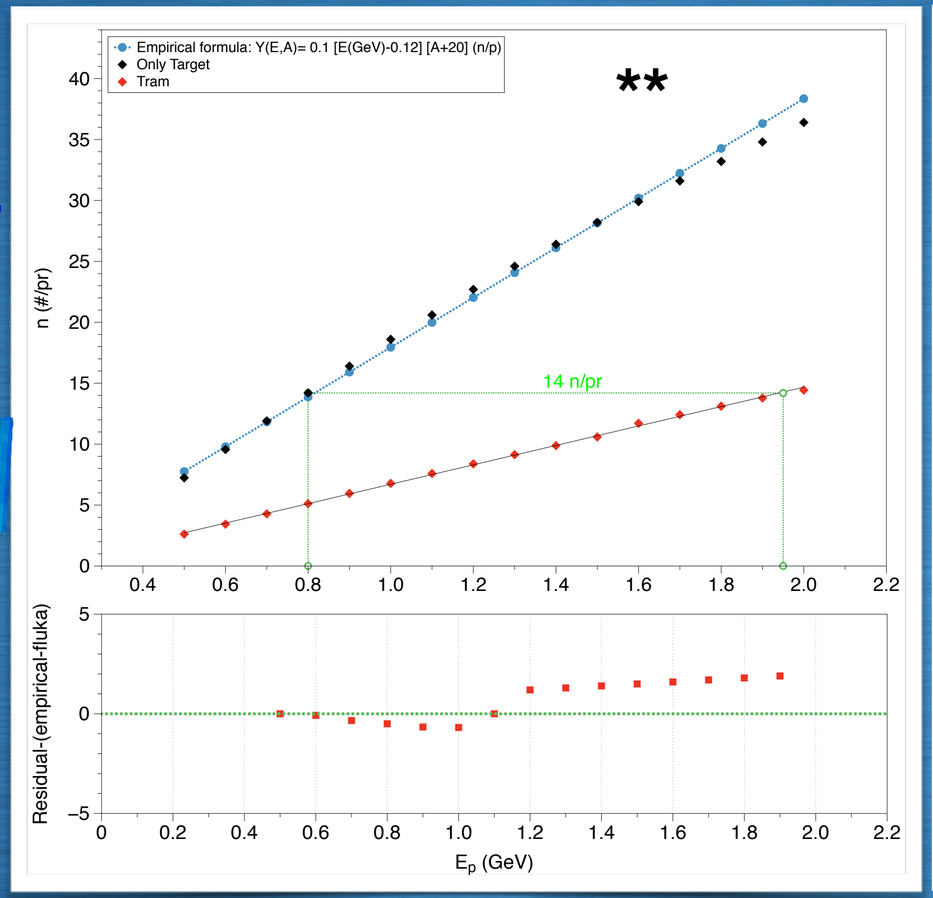
TRAM:

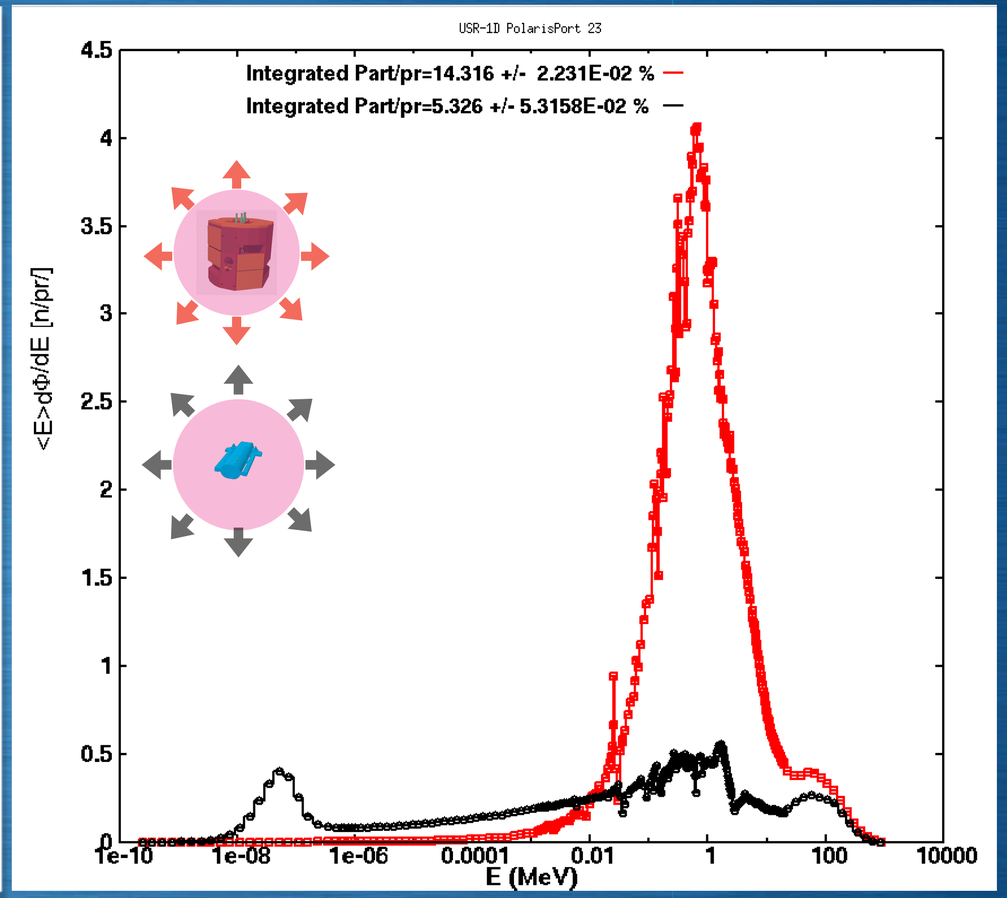
- An average of **5.3 neutrons** per impinging 800 MeV proton **escaping from the TRAM**.
- **68%** of the escaping neutrons are produced in **Tungsten**

**** NIM 145 (1977) 91-13 JM Carpenter**
Watanabe N. Rep. Prog. Phys. 66 (2003) 339–381

NEUTRON BALANCE IN THE WHOLE TRAM







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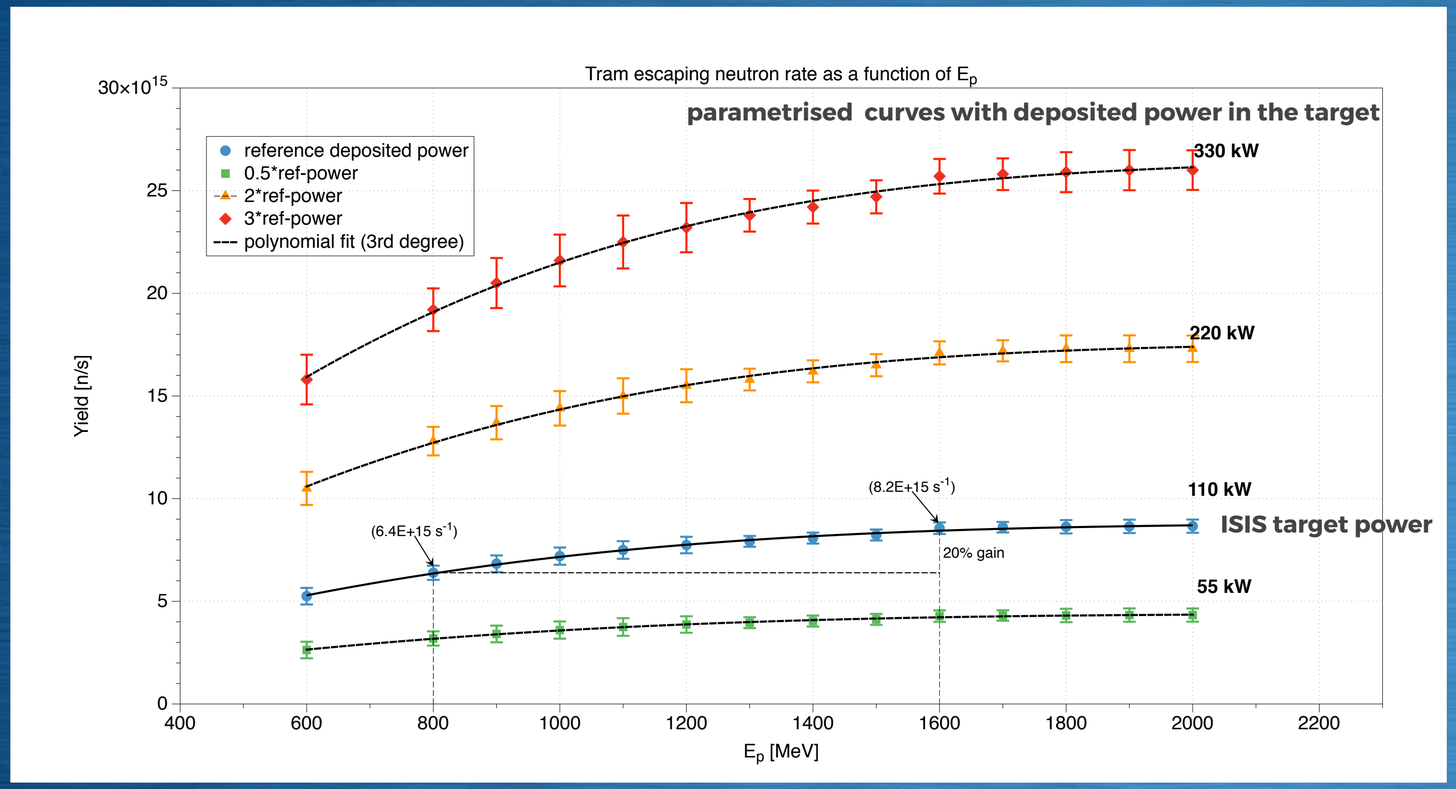
MAXIMISE THE ESCAPING NEUTRON RATE: SEEKING THE BEST STRATEGY

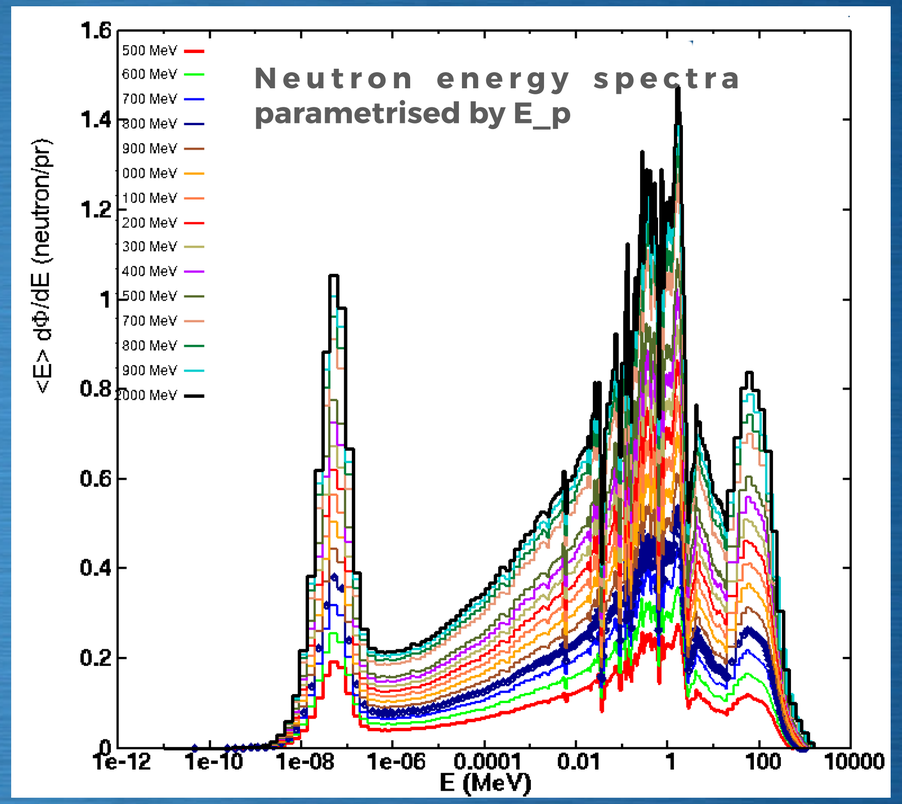
- More than 2/3 of the target produced neutrons is lost, taking into account that also the auxiliary materials (i.e. Beryllium, etc) are contributing.
- 2 possible options to increase the neutrons flux have been investigated so far:
  - **Option1:** Increasing the primary proton energy. This implies the increasing of the neutron rate over all the energy spectrum (i.e. not optimised for useful neutrons only) and more severe energy deposition issues.
  - **Option2:** Improve the design of the reflector and moderators: both in the geometry configuration and in the material selections. This strategy could be better focused on the "useful" neutrons rather than on the total neutron rate.

Option 1

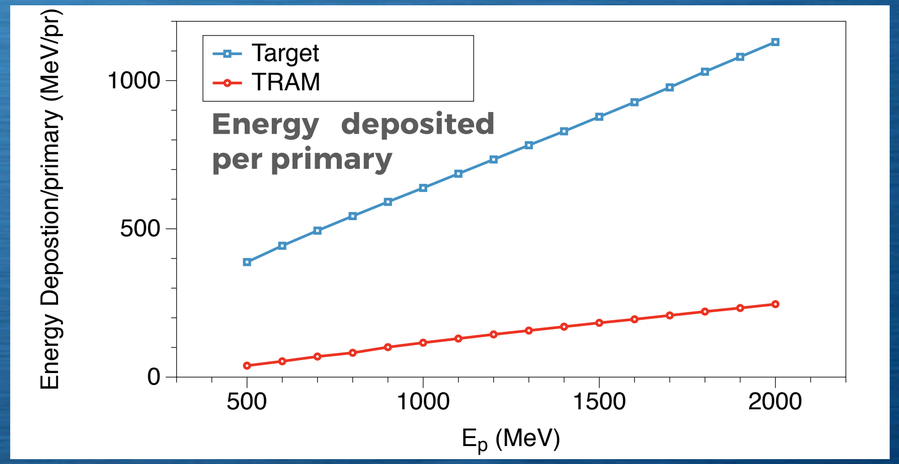
INCREASING THE PRIMARY PROTON ENERGY

INCREASING THE NEUTRON YIELD BY INCREASING THE PROTON ENERGY





- Doubling the proton energy, but keeping unchanged the total power deposited in the target, would lead to an increase of the integrated neutron rate of about 20%.
- Keeping the proton energy unmodified (i.e 800MeV) but doubling the power deposition in the target would increase of about 60% the neutron yield (from 5 to about 13 n/pr).
- but more severe engineering constraints have to be considered for the design (i.e. more severe heat transfer, neutrons shielding constraints)



Option 2

A SYNERGIC DESIGN OF TRAM AND NEUTRON BEAM LINES

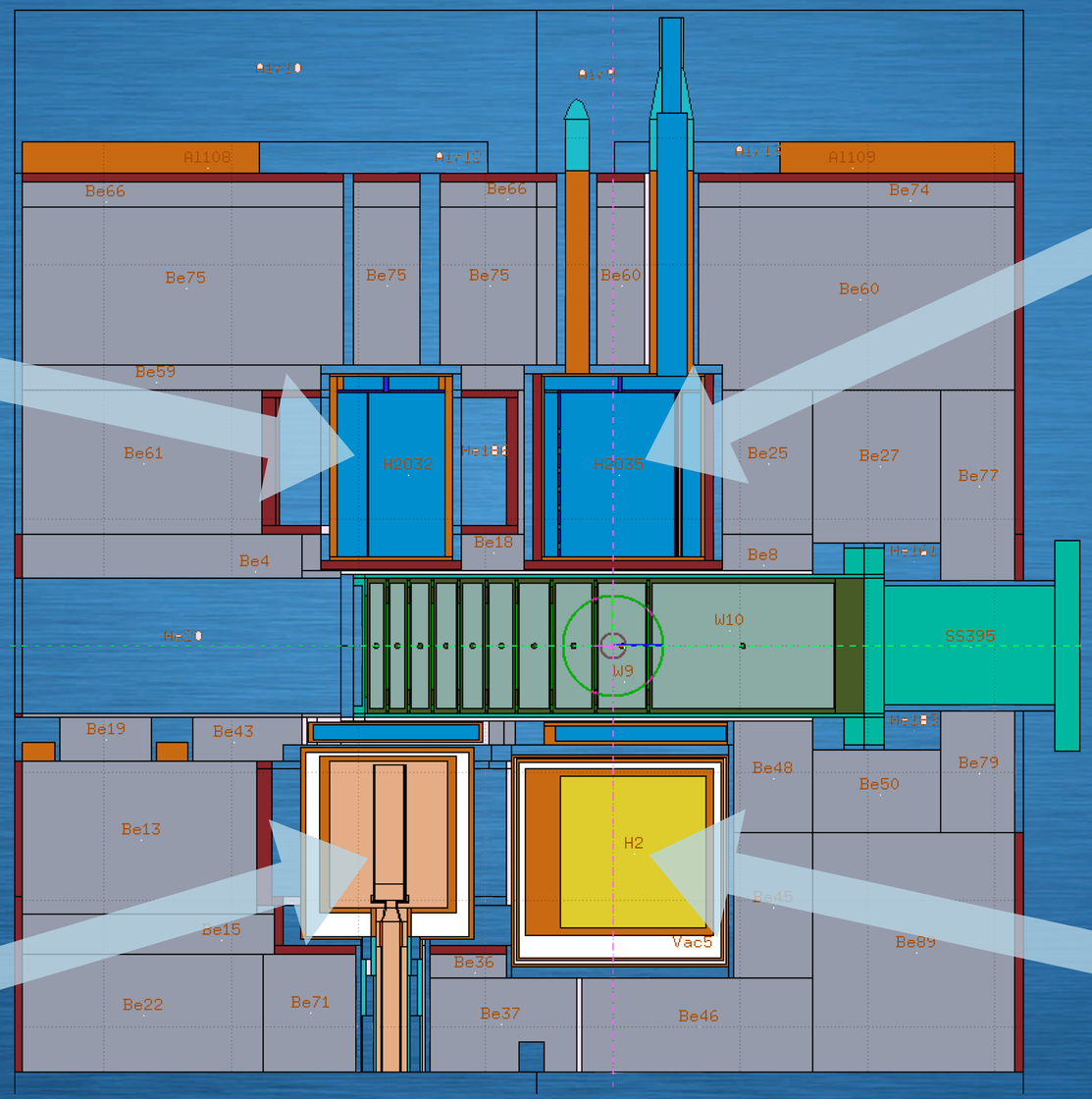
FLAGGING NEUTRONS THROUGH MODERATORS

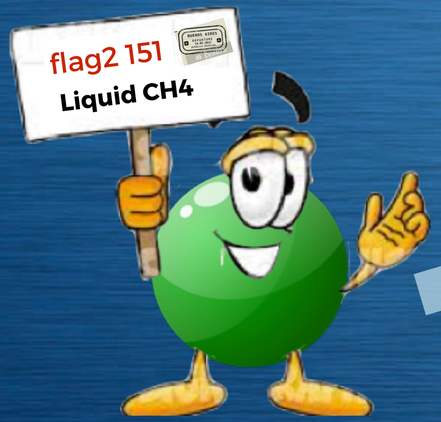
Asym. pois. water moderator

flag1= 131

Sym. pois.water moderator

flag1= 130



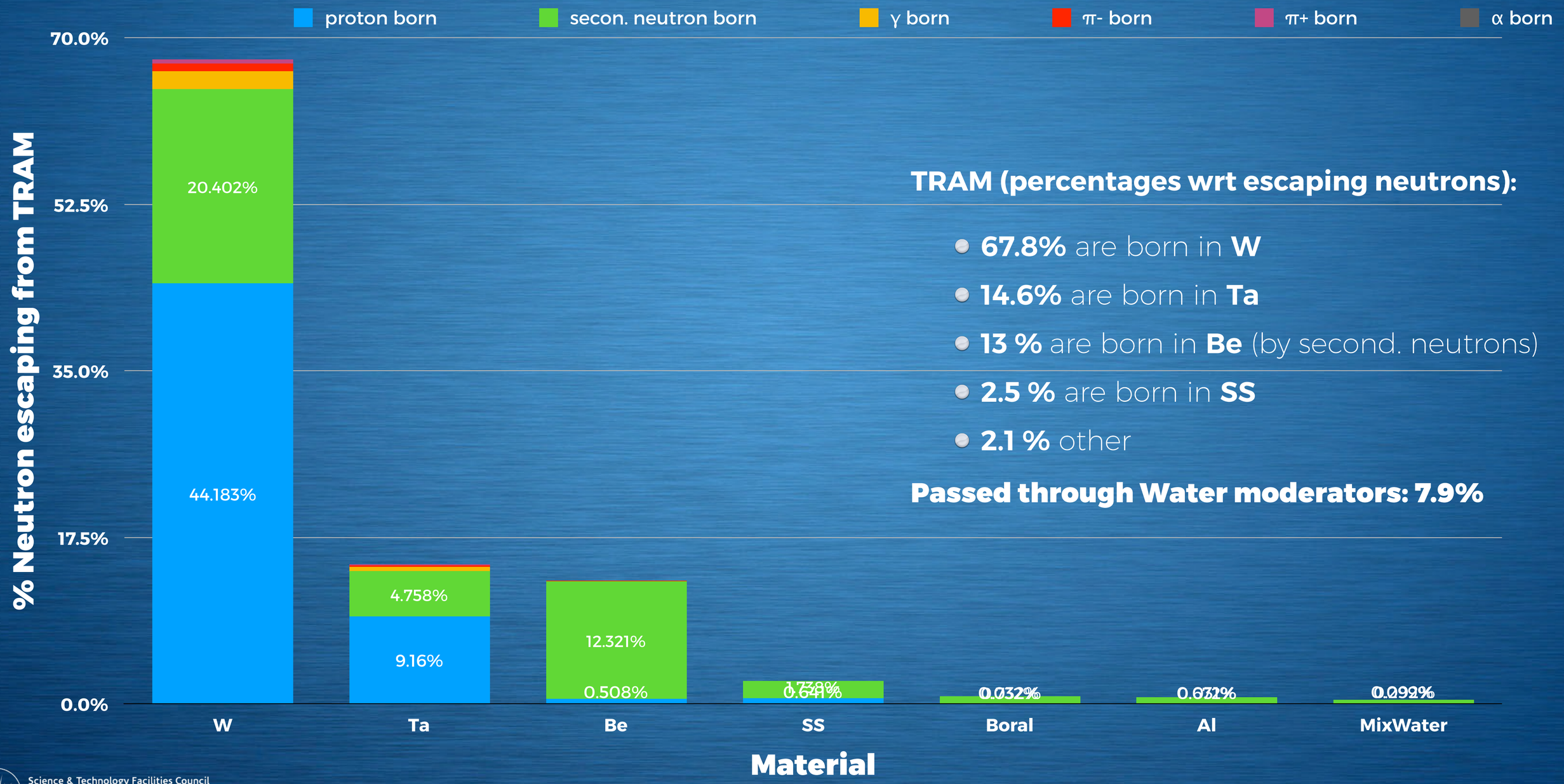


ESCAPING "FLAGGED" NEUTRONS

TRACKING THE TRAM ESCAPING NEUTRONS:

ANCESTORS, ORIGIN REGIONS AND “VISITED" MODERATORS

NEUTRONS ESCAPING THE TRAM: ORIGIN'S MATERIAL AND PARENT PARTICLES

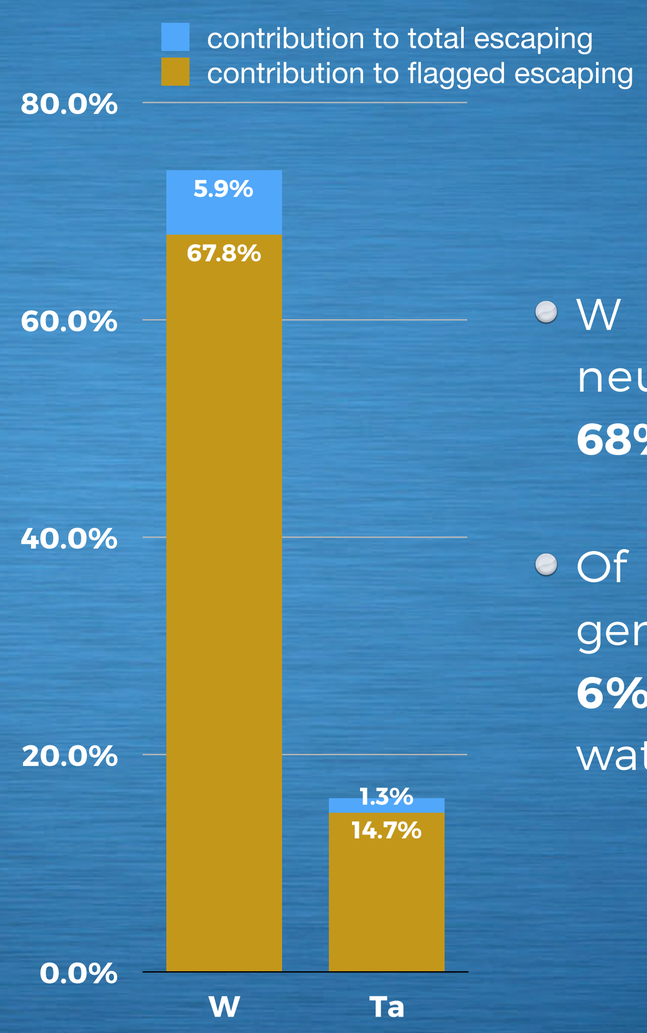


TRAM (percentages wrt escaping neutrons):

- **67.8%** are born in **W**
- **14.6%** are born in **Ta**
- **13 %** are born in **Be** (by second. neutrons)
- **2.5 %** are born in **SS**
- **2.1 %** other

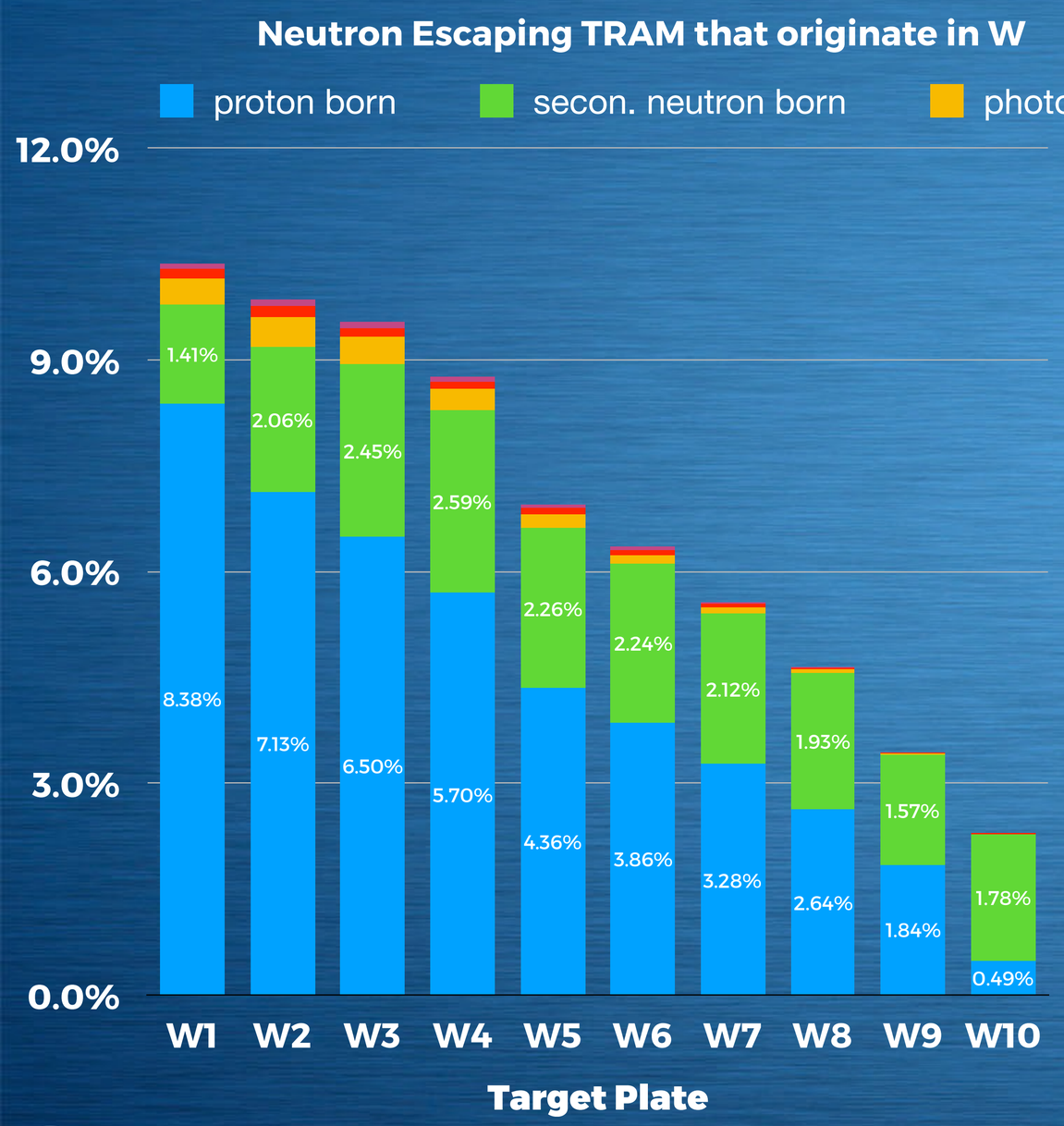
Passed through Water moderators: 7.9%

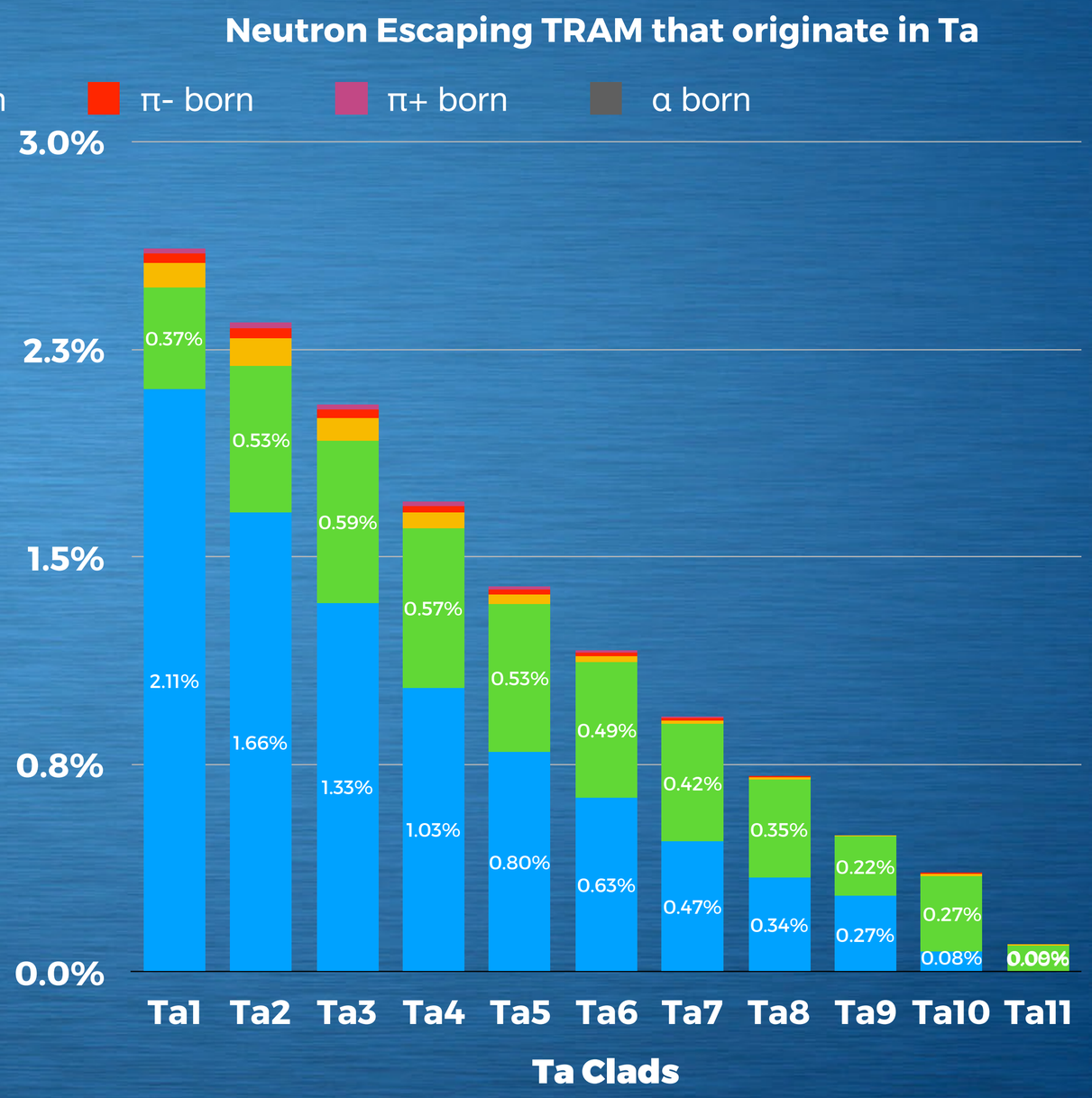
TUNGSTEN PLATE CONTRIBUTION TO WATER MODERATOR "FLAGGED" NEUTRONS



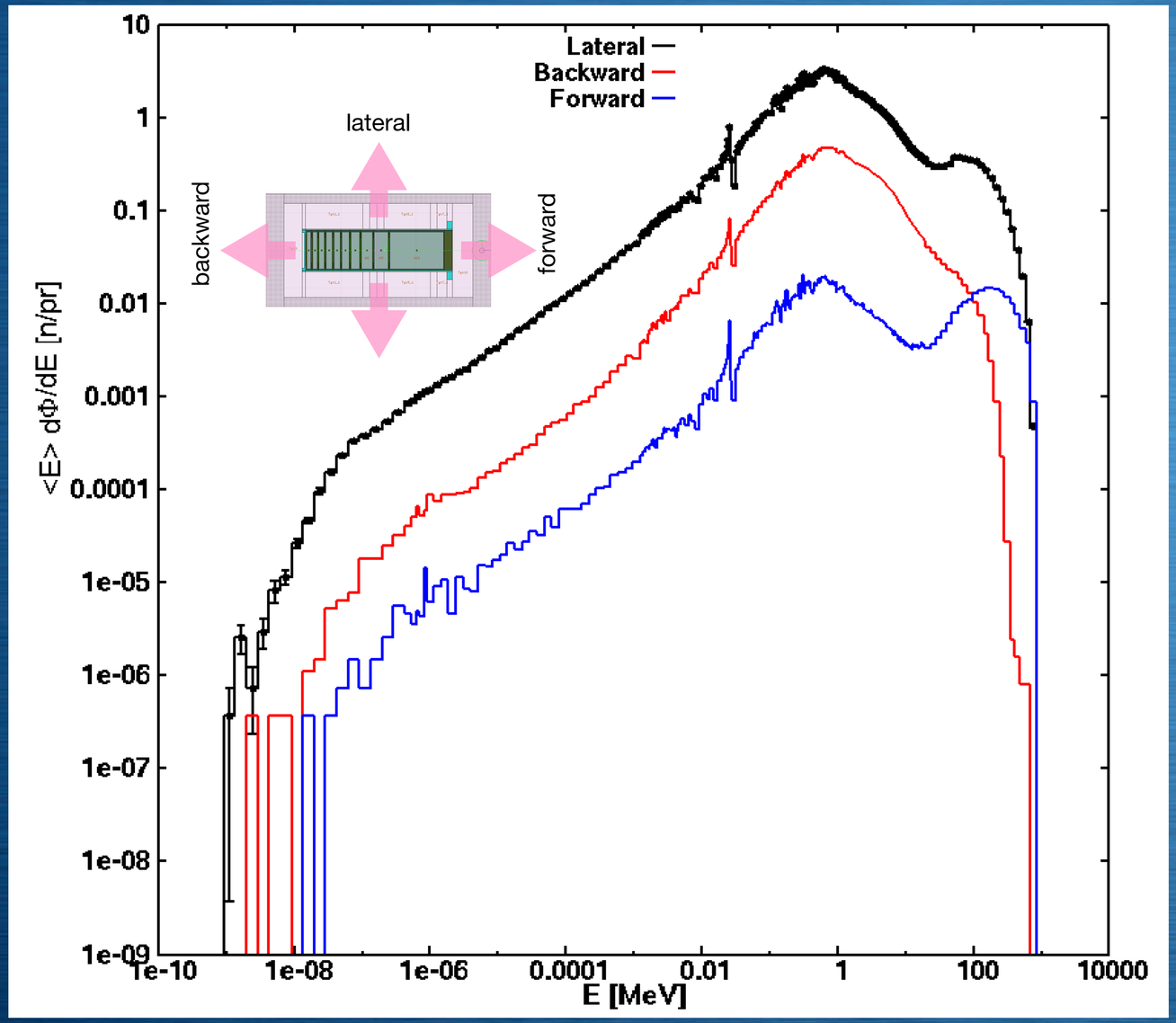
- W plate contribution to the neutrons escaping the TRAM: **68%** of total escaping
- Of the TRAM escaping W-plate-generated neutrons only about **6%** have passed through the water moderators

ESCAPING NEUTRONS GENERATED IN THE TARGET





NEUTRON ESCAPING BARE TARGET: ANGULAR DISTRIBUTION



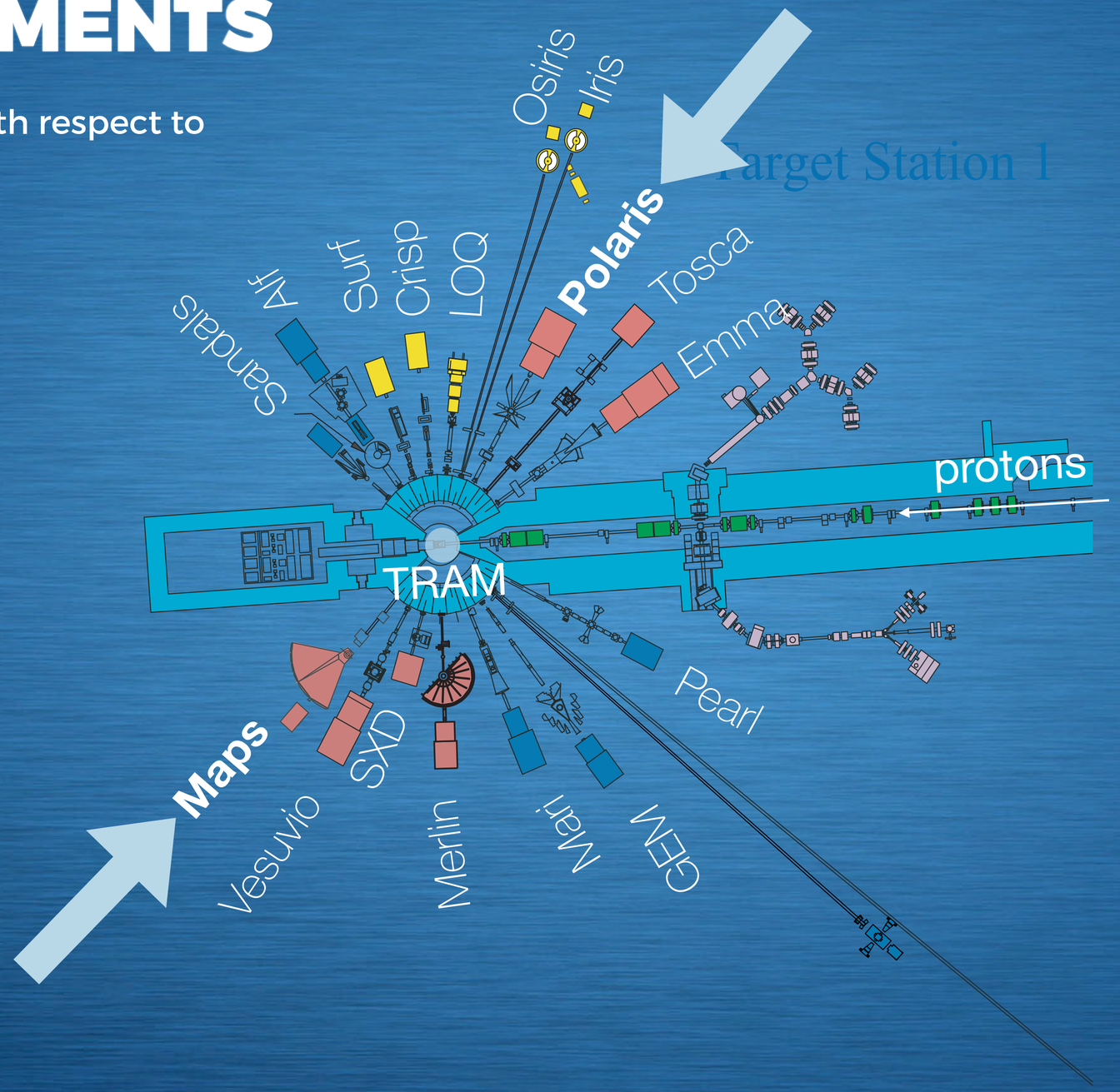
- **Very few** high energy neutrons (E> 100 MeV) **escaping backward**, because mainly emitted forward.
- The **side cylindrical surface** contributes to the overall neutron leakage by almost **83%** of the total.
- The **side leakage** is made mainly of neutrons coming from the evaporation stage (Maxwellian distribution around 0.7 MeV) of the heavy fragments in the spallation process, while only few of them (about 7% of the side leakage) have energy higher than 20 MeV and are produced by direct spallation process.
- The **backward current** is about **11.5%** of the total leakage and **does not exhibit the peak** around 100 MeV, while the **neutron leakage forward** is less than **6%** of the total.
- These results are obtained simulating only the target without reflector and moderators

SOME PRELIMINARY ESTIMATIONS FOR BEAM LINES

POLARIS AND MAPS

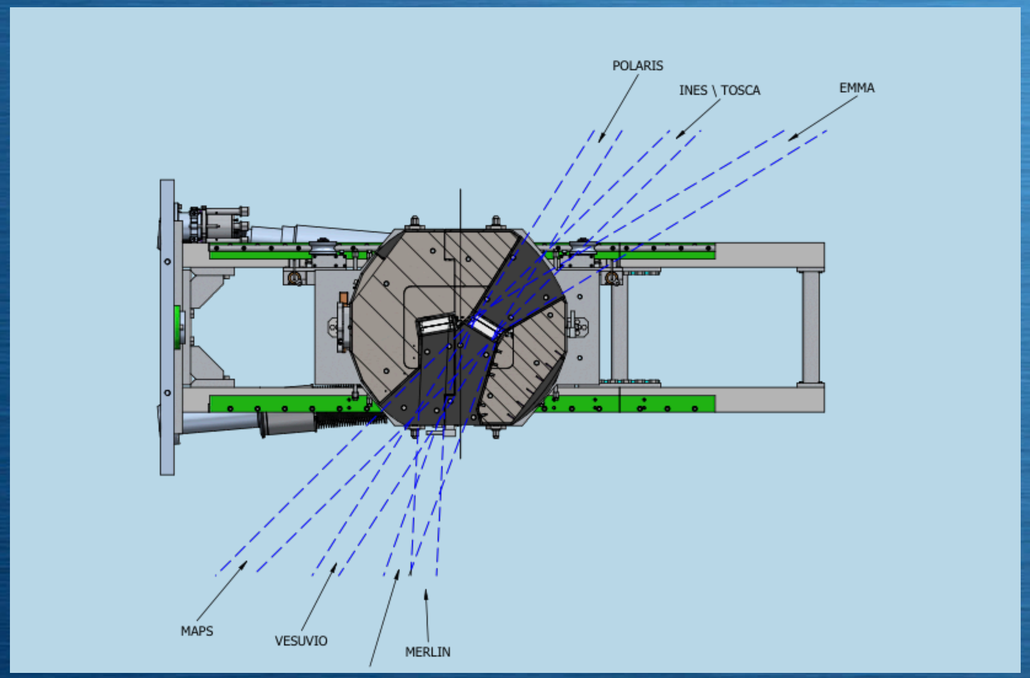
TS1 INSTRUMENTS

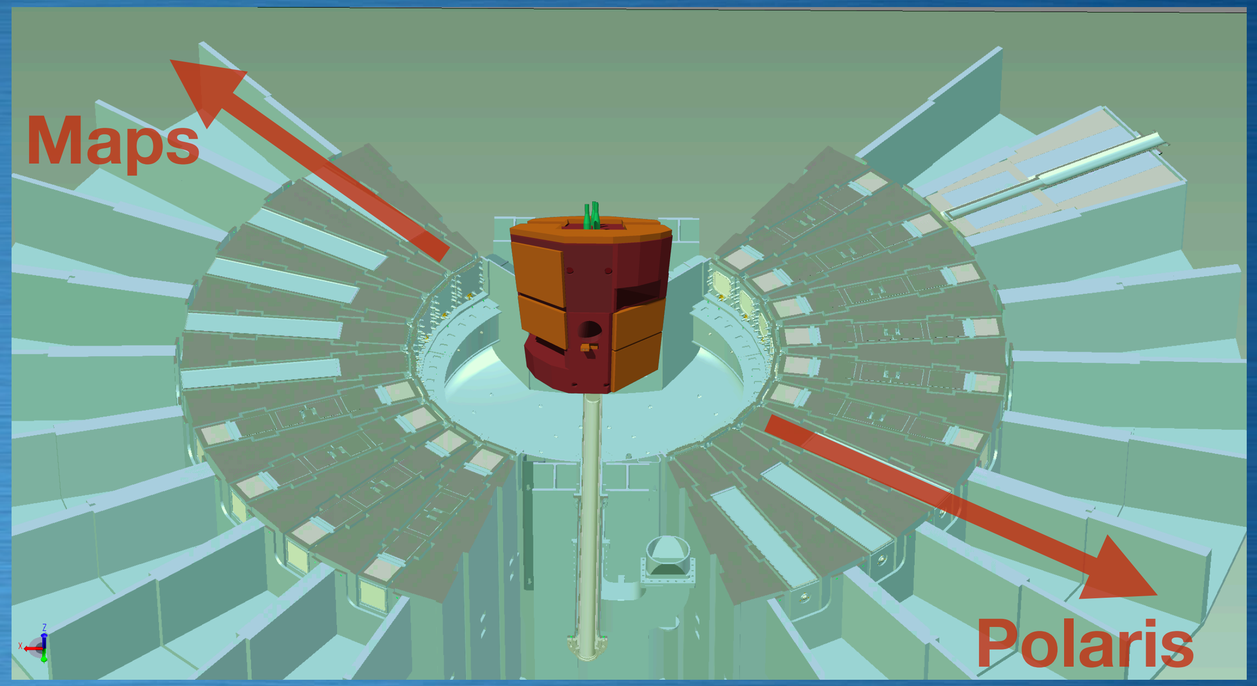
Polaris and Maps layout with respect to the central TRAM



POLARIS AND MAPS

POLARIS instrument at ISIS is a high intensity, medium resolution **powder diffractometer**. It is optimised for the rapid characterisation of structures, the study of small amount of materials (as little as ~1mm^3), the collection of data sets in rapid time (with data collection times down to ~5 minutes) and the study of materials under non-ambient conditions.

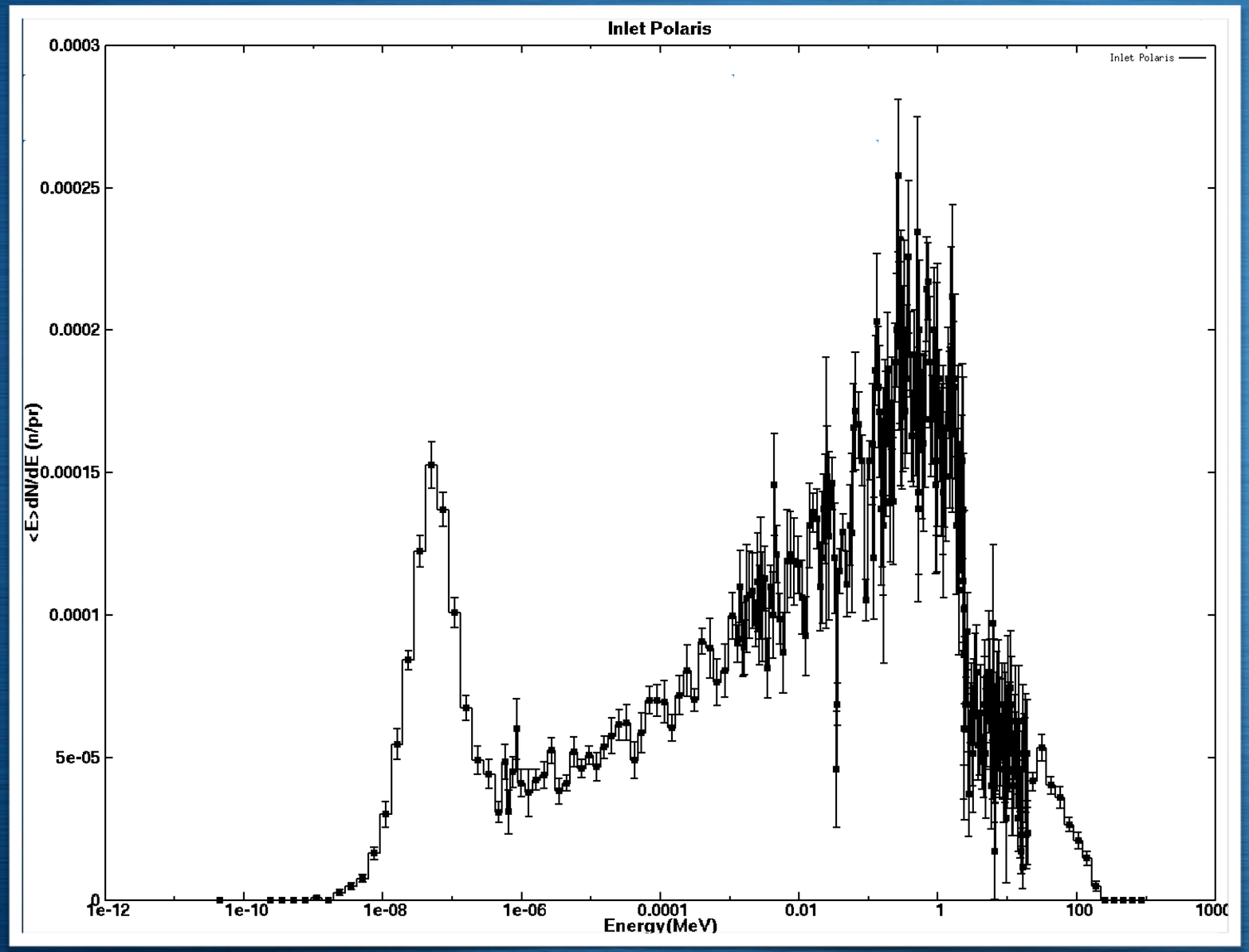




MAPS has been in operation since 2000. It was the first **chopper spectrometer** to employ a large array of position sensitive detectors and the first to be designed solely for the purpose of measuring excitations in single crystals. A significant proportion of the beam time is devoted to single crystal excitation experiments involving the use of thermal neutrons, measuring excitations with energies as low as a few meV.

NEUTRONS INTO POLARIS

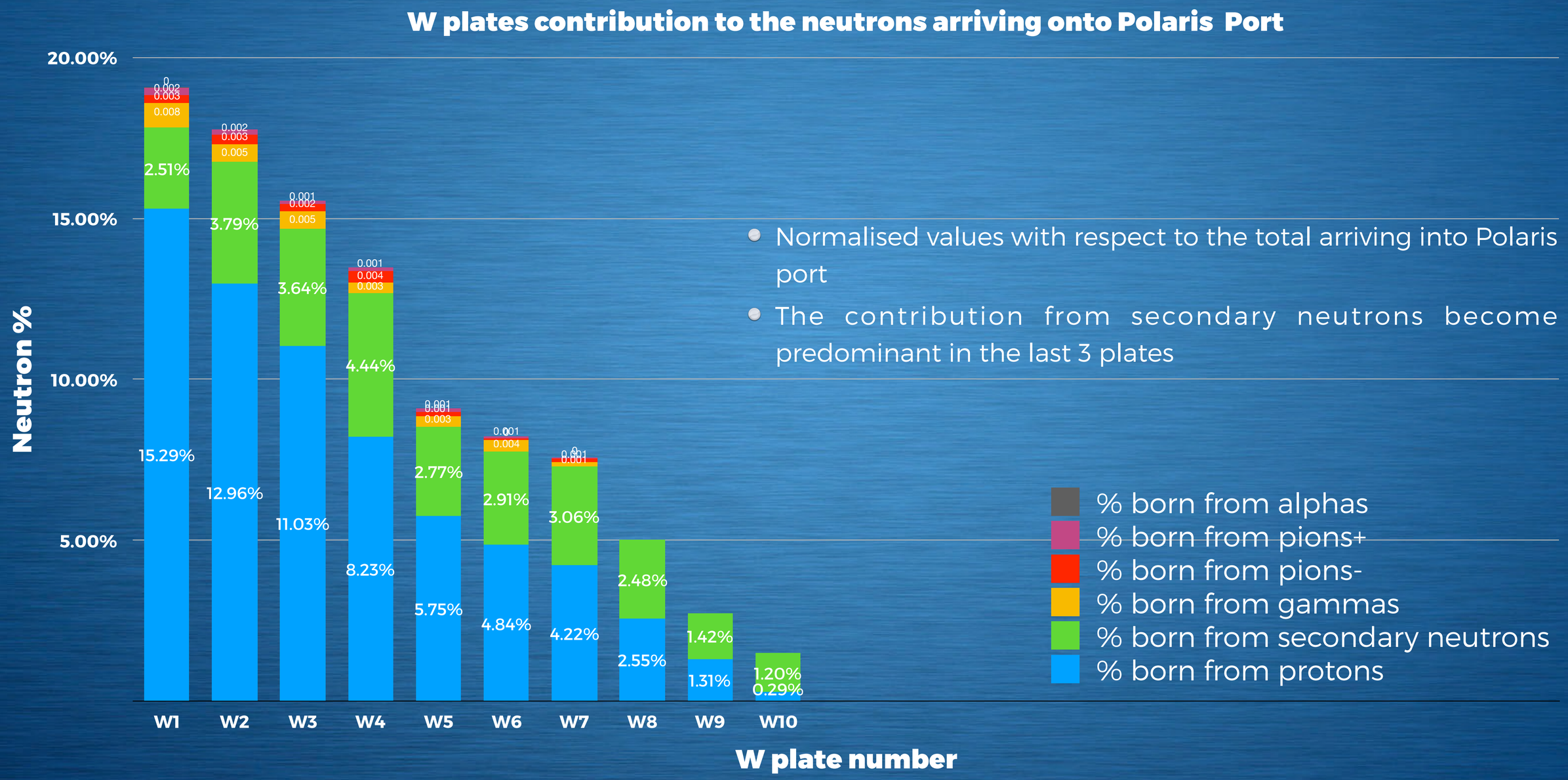
ENERGY SPECTRUM OF NEUTRONS IN POLARIS INLET



- **INLET**: (Part/pr) **2.06E-3 +-1.267%**
- **0.04%** is the fraction of total TRAM escaping neutrons arriving on Polaris:
- Among those neutrons: **36.6%** are below **1 keV**; **63.4%** above **1keV**;
- **16.25%** of all the impinging neutrons on Polaris have been flagged **131 (ASYM. POIS. WATER MODERATOR)**

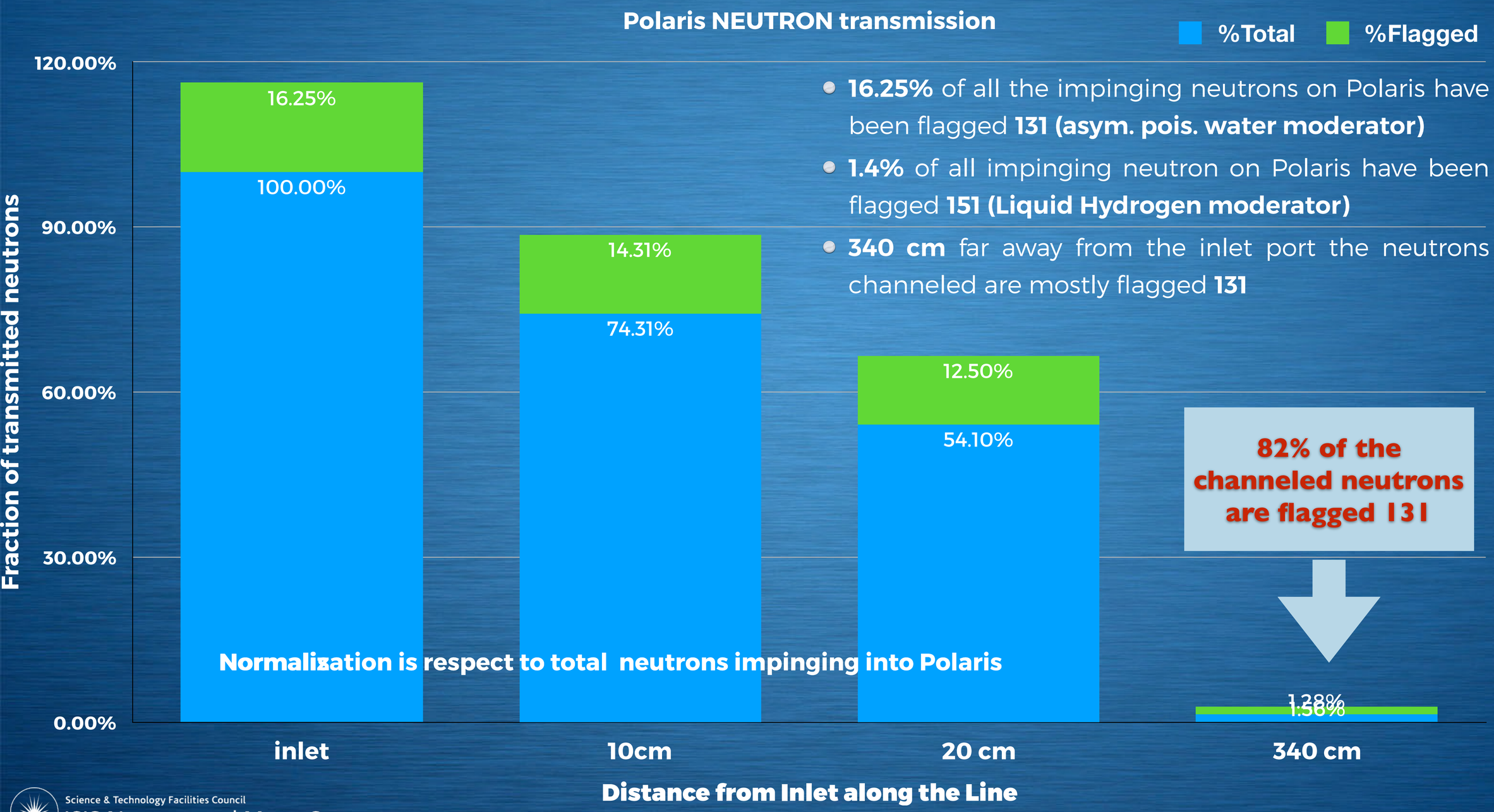
These results have been obtained by using blackhole material around the beam line. This provides the best optimistic scenario of useful "uncontaminated" neutrons coming from TRAM and channeling into the Polaris beam line.

POLARIS INLET: DETAILED TARGET PLATE CONTRIBUTION



- Normalised values with respect to the total arriving into Polaris port
- The contribution from secondary neutrons become predominant in the last 3 plates

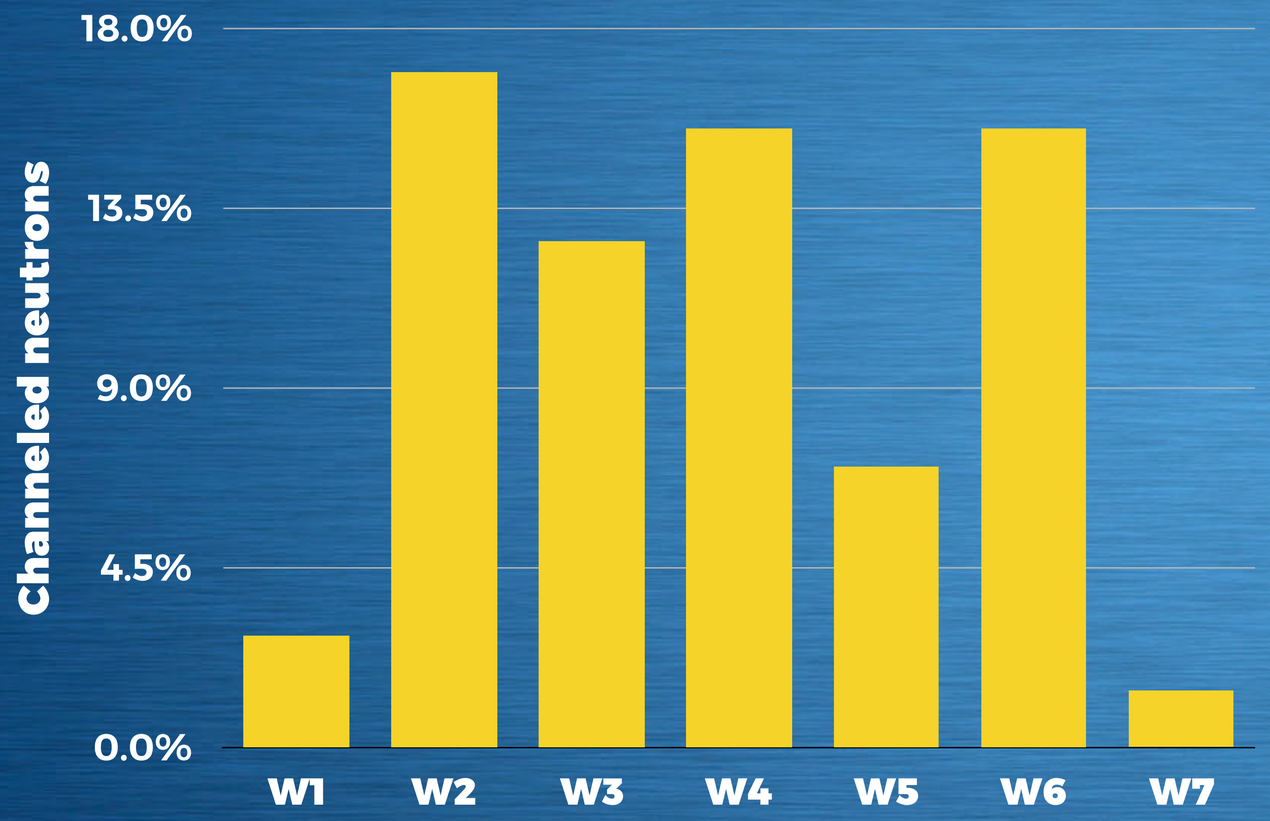
POLARIS NEUTRON TRANSMISSION



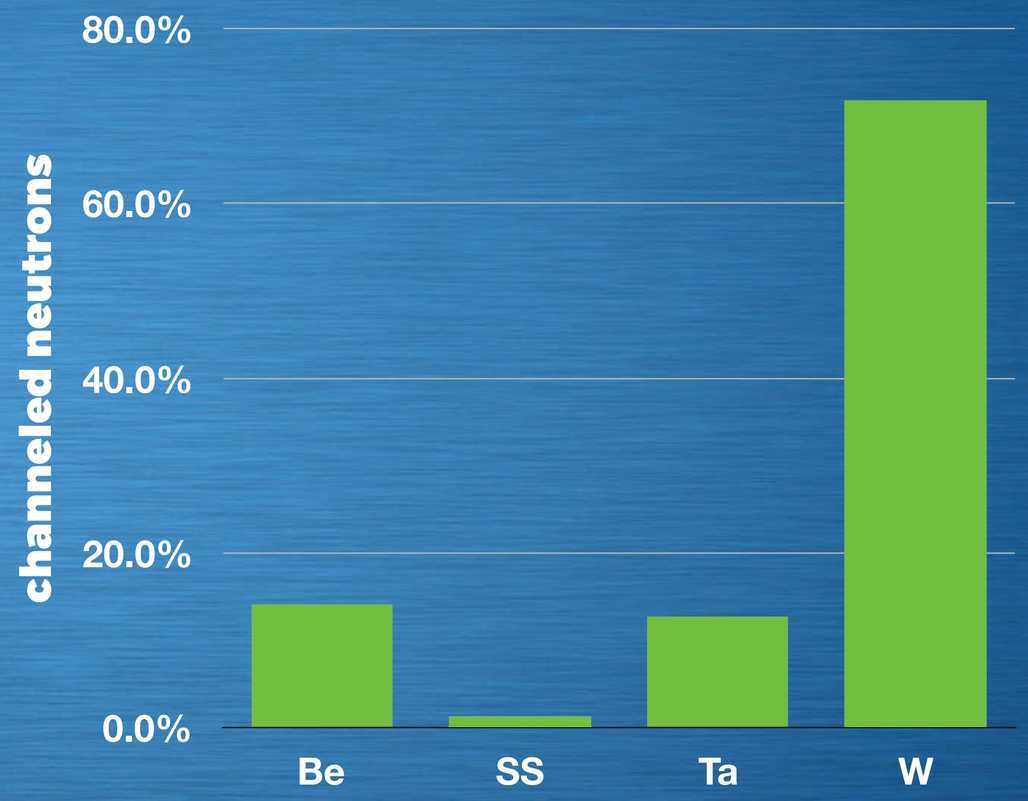
- **16.25%** of all the impinging neutrons on Polaris have been flagged **131 (asym. pois. water moderator)**
- **1.4%** of all impinging neutron on Polaris have been flagged **151 (Liquid Hydrogen moderator)**
- **340 cm** far away from the inlet port the neutrons channeled are mostly flagged **131**

POLARIS CHANNELED: W PLATE AND TRAM MATERIAL CONTRIBUTION

Distribution of channeled neutrons according their origin (normalisation wrt total channeled)



Neutron channeled in Polaris at 340 cm from the inlet have been generated mainly by direct spallation in the central target plates (any contribution form plates n.8 to 10)



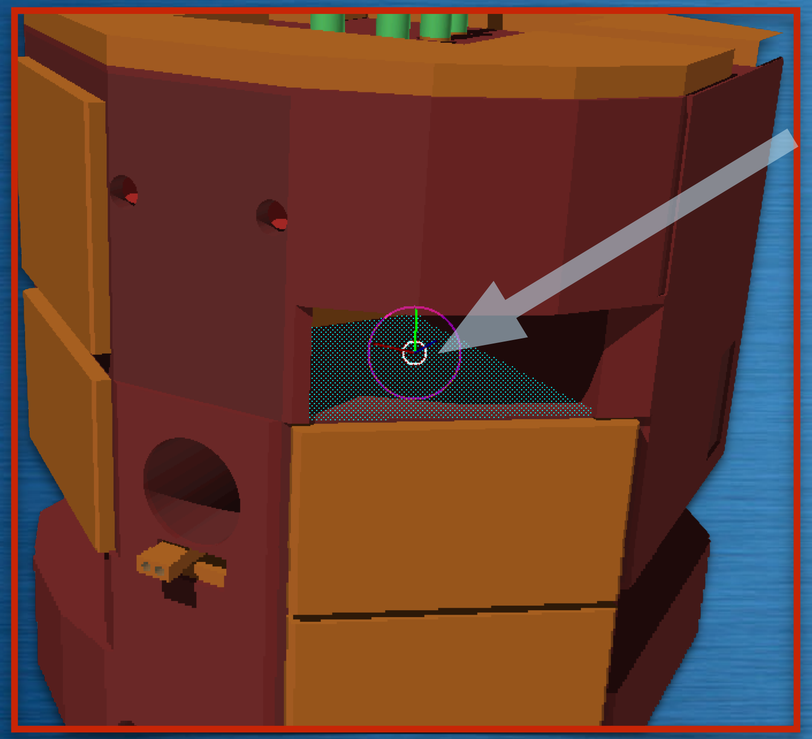
72% of the channeled neutrons in Polaris have been produced in W, A not negligible contribution comes from Be born neutrons

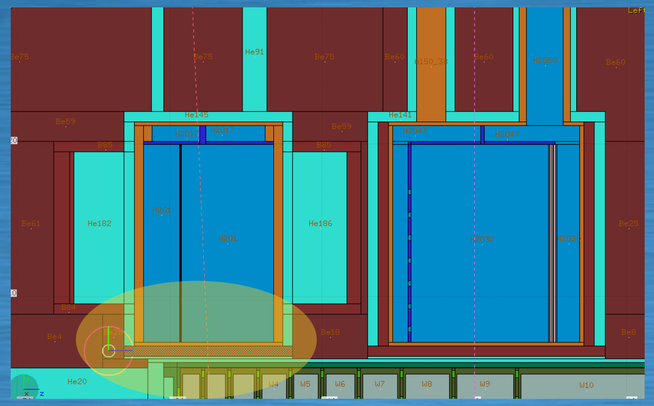
But actually all the 131 flagged neutrons that are channeled in POLARIS have passed by the Beryllium region after “visiting” the asymmetric poisoned water moderator regions and before leaving the TRAM

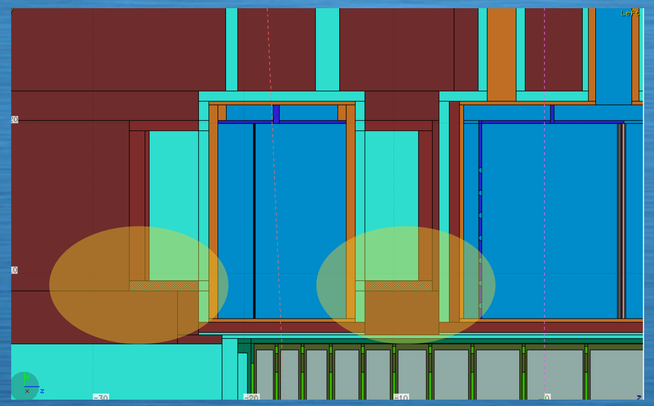
Ideal for instruments supposed to be served by water moderators

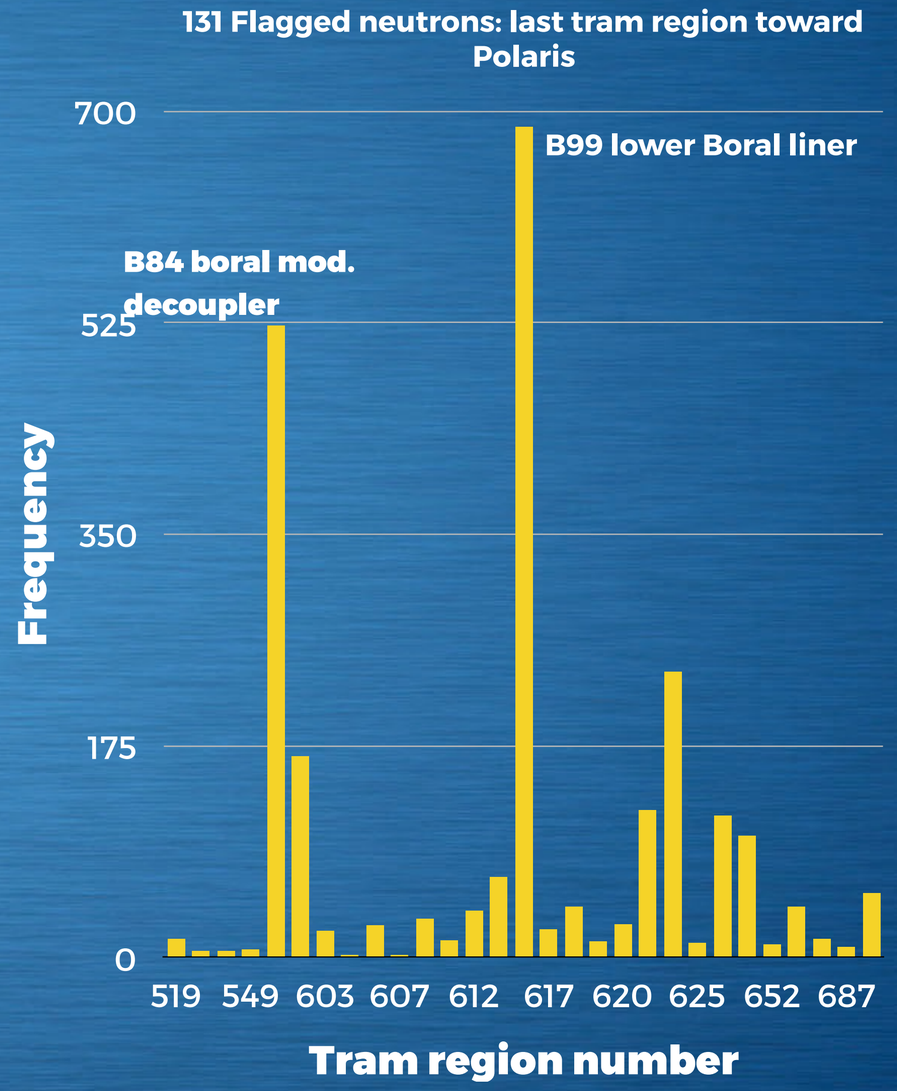
“VISA”of channeled neutrons in POLARIS as estimated by FLUKA

LAST TRAM REGIONS "VISITED" BY NEUTRONS CHANNELED IN POLARIS







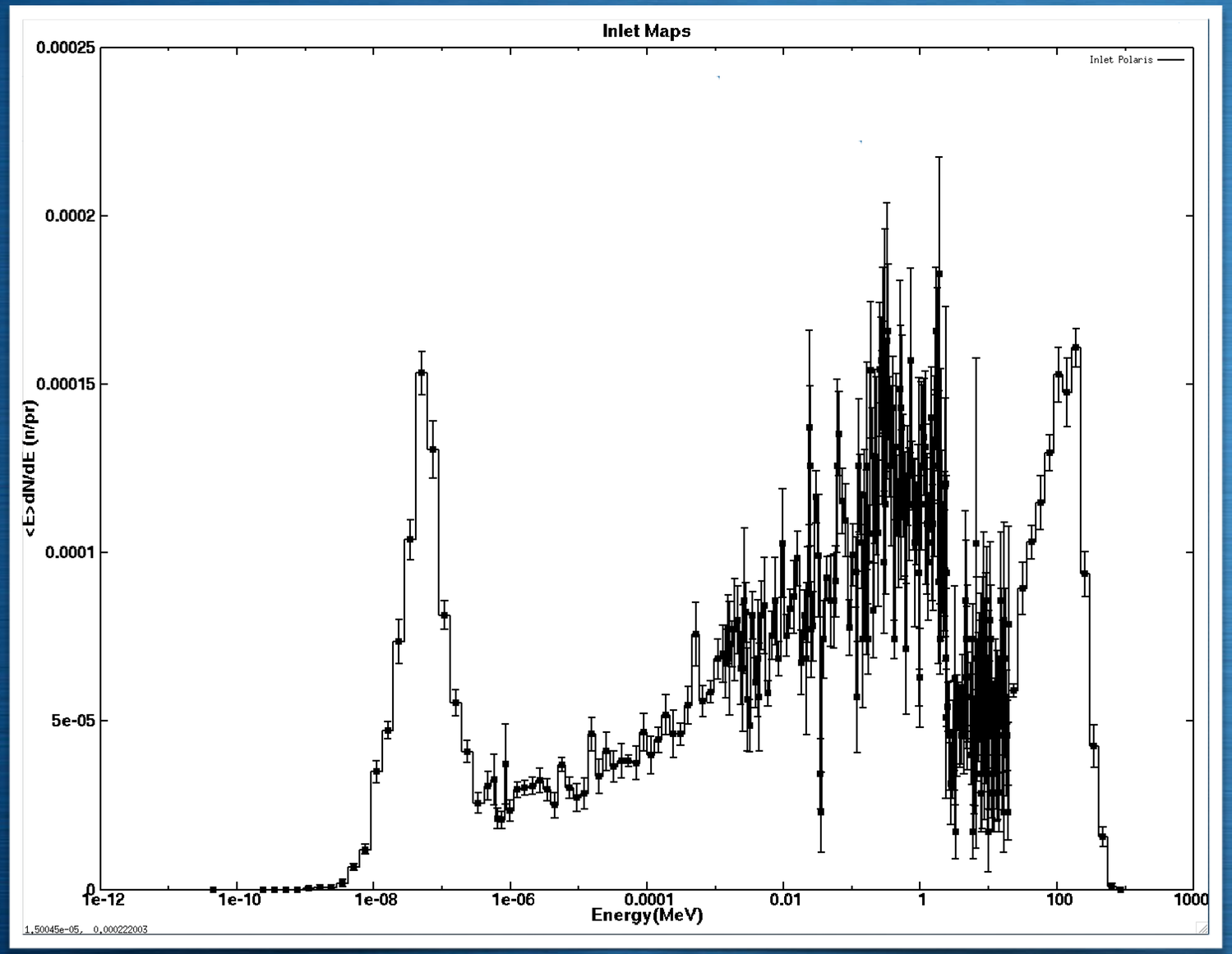


(case of 7E+6 primary protons)

Most of the 131 flagged neutrons (asym. poi.water moderator) come from region n. 601 (boral moderator decoupler) and n.616 (Boral liner): that is, after having been in the asymmetric water moderator, neutrons pass across those regions before leaving the TRAM in their flight toward POLARIS inlet port.

NEUTRONS INTO MAPS

ENERGY SPECTRUM OF NEUTRONS IN MAPS INLET



- **INLET**: (Part/pr) **1.789E-3 +-0.6%**
- **0.035%** is the fraction of total TRAM escaping neutrons that arrives on Maps
- **INLET**: **17.13%** of all the impinging neutrons on Polaris have been flagged **131 (asym. pois. water moderator)**
- **77.87%** of transmitted neutrons (at 340 cm) are flagged.... BUT... **only 131 (asym. pois. water moderator)**
- Note: only very few "**130" (sym. pois. water moderators)** neutrons are transmitted into Maps

These results have been obtained by using blackhole material all around the beam line hole. This provides the best optimistic scenario of useful "uncontaminated" neutrons coming from TRAM and channeling into the Maps beam line.

CONCLUSION AND FUTURE PLAN

- Exploiting high performance computing resources and advanced Monte Carlo code skills, it is possible to track the escaping neutrons by transporting relevant information of their history (ancestors origin region, last TRAM region crossed before leaving, moderator "visited"...)
- Some preliminary estimations have been provided for the total TRAM leakage and for couple of instrument beam lines (Polaris and Maps)
- A more systematic and complete analysis is ongoing for all the instruments of ISIS-TS1 and a suitable complete postprocessing tool is under development (based on Matlab)
- The main goal is to provide useful hints to be studied and analysed for a more efficient TRAM design and/or for providing a valuable support for instrument scientist to assess quantitatively the effects of possible upgrading actions in the TRAM

Thank you for your attention!

https://www.isis.stfc.ac.uk/

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