Application of Supermirror surfaces in MCNP6: MIRACLES shielding estimation

Consorcio ESS-BILBAO

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Pre-existing code

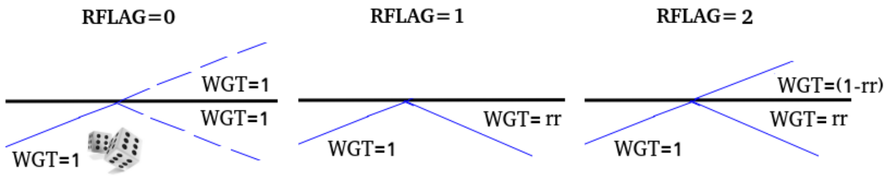
Before performing this work, an MCNPX patch for including supermirror physics existed and was tested. While the code worked as intended, there were several limitations intrinsic to it

- Lack of balance load in MPI: While we try to reduce long histories as much as possible, it is to some extent unavoidable, and this can significantly delay calculations when using weight windows with low minimal values.
- TMESH type mesh tally: When using a large mesh (and, in a long guide, a large mesh is a need), TMESH slows the calculations several orders of magnitude.

These limitations are overcome in MCNP6. Ryan Bergmann (PSI) ported the patch, and a test & improvement work was started.

RFLAG for neutron reflection mode

While the port to MCNP6 is a good step forward by itself. Ryan Bergmann implemented a flag to make neutron split into reflected and transmitted part, as opposed to rolling the dice to see if it transmits or reflects. This effectively makes neutron transport through the guides deterministic.



The case for using deterministic neutron reflection

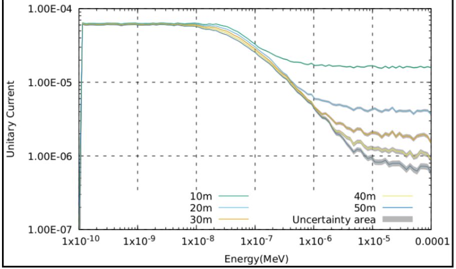
RFLAG=0 (analog) Particles don't split after a reflection/transmission event.
RFLAG=1 (deterministic, discarding reflected part) is more focused to pure guide transport for instrument performance, so we have not done a lot of testing there.
RFLAG=2 (deterministic) allows us a much better sampling of the neutron transmitted specially in the later parts of the guides, which in turn helps us to better assess the gamma production. This is very significant in shielding problems. When particles becomes negligible reflecting angle, they split weight many times by a large number, to the point of floating point underflow, to weight zero and eventual crash. Solution: No longer split rather than roulette once we are below a threshold.

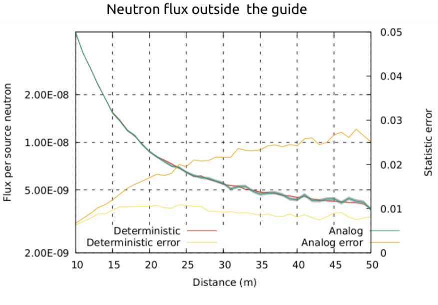
Deterministic reflection vs stochastic (analogue) reflection

In order to show the improvement of the results thanks to this method, a simple simulation was set up and has been run both analogue and deterministic reflections. In left figure we compared the fluxes along the guide and the spectra at each point. The effect of using deterministic reflection over analogue is a reduction of uncertainties. Inside the guide the reduction is negligible as we can see on the left chart but outside the guide the error in the deterministic calculation stays much flatter and at the end of the guide it is almost 4 times lower as it is shown on the right.

Neutron flux and spectra inside the guide

Distance (m)	10	20	30	40	50
Analog	3.884E-3	3.281E-3	3.115E-3	3.014E-3	2.931E-3
Deterministic	3.885E-3	3.280E-3	3.116E-3	3.014E-3	2.932E-3





DXTRAN compatibility

MCNP is very explicit in warning that using DXTRAN spheres with their own reflective surfaces. because it cannot calculate the scattering of a particle via reflection to the sphere, but it will still kill the particles that end up in the sphere after a reflection. The very same reasoning applies to supermirrors.
However, an alternative is allowing reflected particles to go to the sphere. For this purpose, an additional variable in pbl is added and it is set to 0 at source and at any collision, and set to 1 after a reflection.

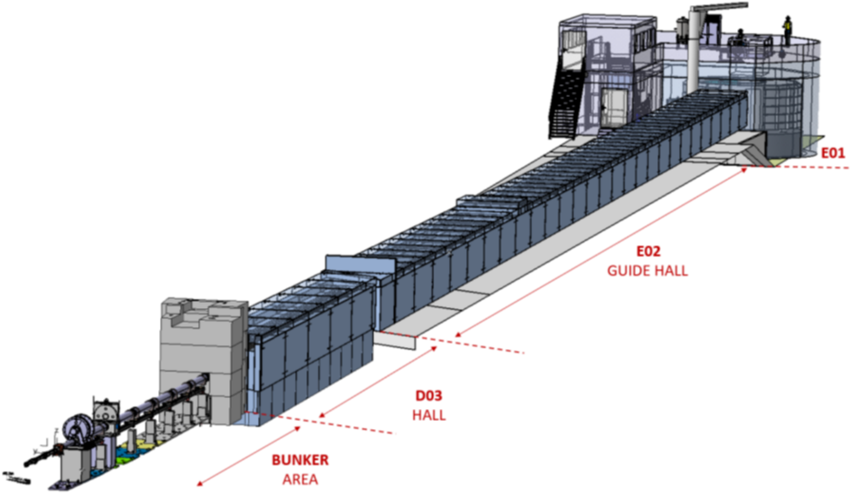
DXTRAN behaviour

- From source: variable=0 Contribute as usual, killed as usual if going straight to the DXT.
- Reflected: variable=1 Not killed if arriving at the DXT, no contribution made.
- After collision: variable=0 Contribute as usual, killed as usual.

Notice that this means that, for the neutrons travelling through reflections, the DXT spheres do not exist. But, if splitting particles at the mirrors, *they do not need to exist, because the transport is already deterministic*

Application to MIRACLES

We have used supermirror patched version of MCNP6 to calculate the neutron transport through the MIRACLES instrument.



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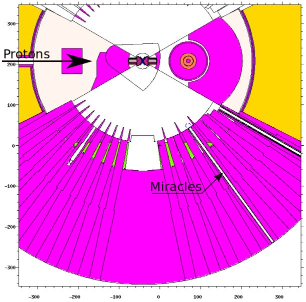
Variance reduction

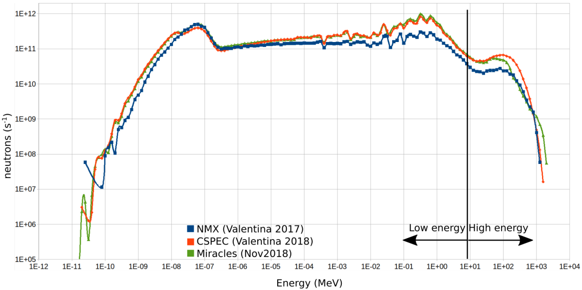
In addition to the above, several other Variance Reduction techniques were employed:

- MAGIC-Weight Window: As usual in our shielding calculations.
- Exponential attenuation of the WW cap: A modification to the WW that limits the maximum of the Weight Window to a value that decreases exponentially through the guide. Used to keep the gradients in check along the guide.
- Exponential transformation in bunker wall: Used to not to waste too much time in the calculation of particles in said area, as we are more interested in the transmission through it (which is minimal anyway!)
- High-Energy source separation: Neutrons over 10 MeV, which constitute around 2-3% of the source but can have a very drastic effect at least up to the point where we lose LoS are run in a separate calculation with a different WW. This allows MUCH better sampling of high energy neutrons.
- Time roulette: Neutrons are rouletted at 10 and 100 ms. We detected many long histories with a lot of thermal collisions in that range that are not really contributing that much.
- Photon generation control Reduces the amount of photon generated in some cells to reduce the number of photons per source particle.

Neutron source term

We have developed a source term for Miracles. Following instructions of Valentina Santoro we have defined the Miracles NBOA in a target station model (TSV31-TS5).





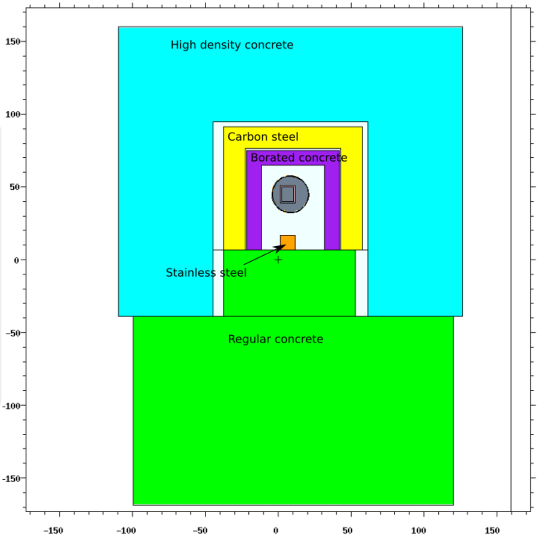
The behaviour of neutrons is completely different depending of its energy and many variance reductions techniques depends of it. Because of that, we have split the source term in high and low energy and the variance reduction techniques are different among them.

The neutron current through the Miracles NBOA (≈4.8 cm heigh x ≈ 6.0 cm width) is around $2.77x10^{13}$ neutrons; High energy $6.49x10^{11}$ (2.3%) and low energy $2.71x10^{13}$ neutrons (97.7%).

Shielding configuration

Most of the outer shielding is high density concrete, the basement is regular concrete and inside the HD concrete some parts have additional layers of shielding like carbon steel and borated concrete.

The size of the walls changes along the guide to limit the dose up to less than 3 $\mu Sv/hour$.

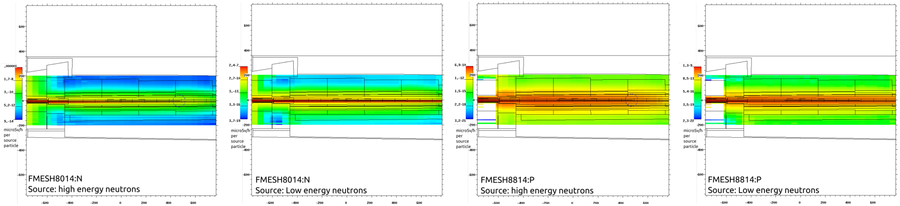


Meshtal manipulation

The FMESH tally recorded in the meshtal file can be easily visualize in 2D by MCNP but the data error is not directly observable and the imaging quality is not as astonishing as anybody would like.

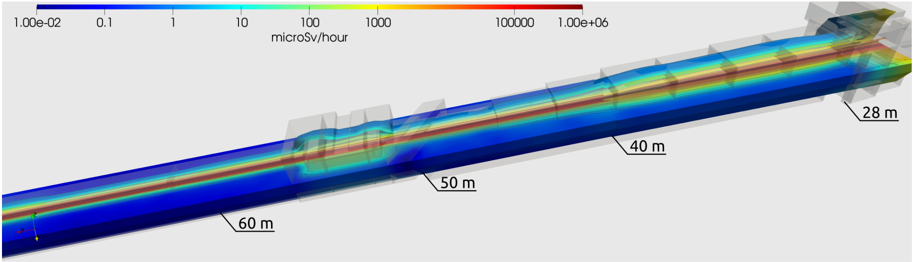
In ESS-Bilbao we have developed an important set of python tools to manipulate and visualize FMESH tally results.

This set of tools generates some python objects with all the useful information of the meshtal file which can be manipulate, visualize and even added to other meshtally objects to generate more complex analysis.



Prompt dose rate

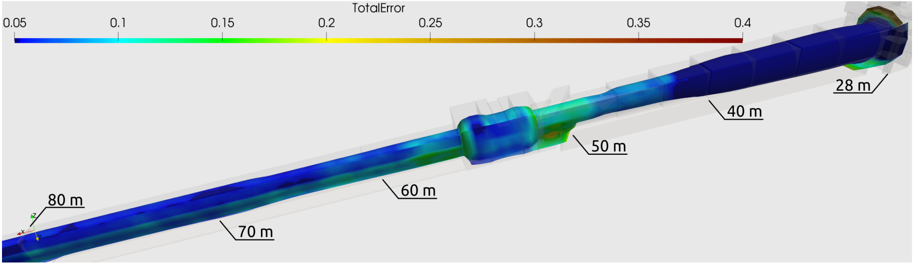
For example, in this case we have been able to add the weighted fmesh results of a neutron and gamma prompt dose rate of 2 separate calculations (low & high energy calculations) to visualize the total dose rate all along the MIRACLES instrument in 3D as a vtk file.



We show a detailed view of the Miracles shielding, 28 to 70 m. Translucent material represents an approximation to the shielding size of Miracles.

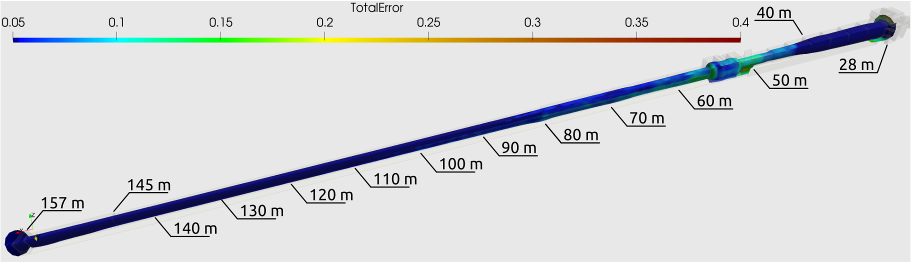
Prompt dose up to 3 $\mu Sv/h$

We show a detailed view of the Miracles shielding, 28 to 80 m. The contour surrounds the prompt dose over 3 $\mu Sv/h$ and the colour of the contour indicates the estimated error of the value. Translucent material represents an approximation to the shielding size of Miracles and it keeps inside the full contour.



Prompt dose up to 3 $\mu Sv/h$

We show a general view of the Miracles shielding. The contour surrounds the prompt dose over 3 $\mu Sv/h$ and the colour of the contour indicates the estimated error of the value. Translucent material represents an approximation to the shielding size of Miracles and it keeps inside the full contour.



Conclusions

- Supermirrors have been ported to MCNP6 allowing us to take advantage of the features of the code over older versions.
- RFLAG variable allows us to use deterministic reflections through the guide.
- DXTRAN can be employed now, with only a minimal overestimation (which we may still be able to fix).
- Combination of these advancements with variance reduction has made solving a long guide over 150m like MIRACLES.

Thank you so much

Highlights of Miracles shielding configuration

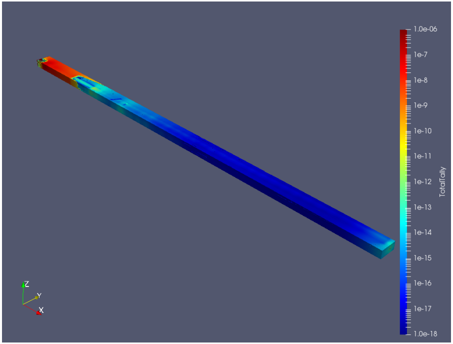
From	to (m)	Composition from outside to inside
Bunker	34	75cm HD concrete, 15 Carbon Steel, 10 cm Borated concrete
34	37	65cm HD concrete, 15 Carbon Steel, 10 cm Borated concrete
37	40	60cm HD concrete, 10 cm Carbon Steel, 10cm Borated concrete
40	43	30cm HD concrete, 5 cm Carbon Steel, 10cm Borated concrete
43	46	20cm HD concrete, 5 cm Carbon Steel, 10cm Borated concrete
46	49	45 HD concrete
49	51.5	10 cm regular concrete, 30 HD concrete
51.5	55.5	30 HD concrete, 5cm Borated concrete
55.5	62	40 HD concrete, 5cm Borated concrete
62	65	40 HD concrete, 5cm Borated concrete
65	71	40 HD concrete, 5cm Borated concrete
71	76	35 HD concrete, 5cm Borated concrete
76	82	35 HD concrete, 5cm Borated concrete
82	95	30 cm HD concrete
95	145	30 cm HD concrete
145	152	40 cm HD concrete
152	end	40 cm HD concrete

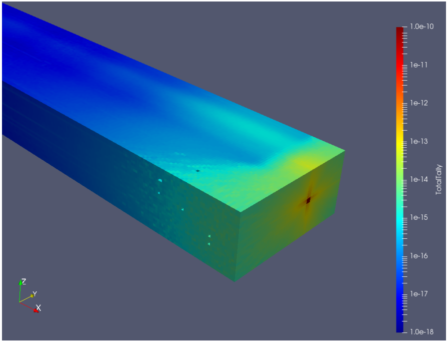
Summary of Miracles total dose outside the shielding (Jan19 v3)

From	to (m)	X m	Outside $\mu Sv/h$	Inside $\mu Sv/h$	Up $\mu Sv/h$
27	34	28.5	0.434	0.361	0.463
34	37	35	0.972	2.963	1.038
37	40	38	0.896	1.022	1.088
40	43	41.25	1.216	1.209	1.481
43	46	44	1.980	1.720	1.953
46	49	47	0.817	0.697	2.210
49	51.5	51.25	2.963	1.648	1.985
51.5	55.5	54.55	2.152	1.410	0.662
55.5	62	55.75	1.619	1.243	1.400
62	65	63	0.671	0.723	0.647
65	71	70.01	0.992	0.630	0.963
71	76	72	2.715	1.803	1.716
76	82	80	0.883	0.749	1.363
82	95	90	1.447	1.554	2.381
95	145	120	1.006	1.248	1.562
145	152	150	0.305	0.372	0.446
152	147	155	0.512	0.566	0.677

Results

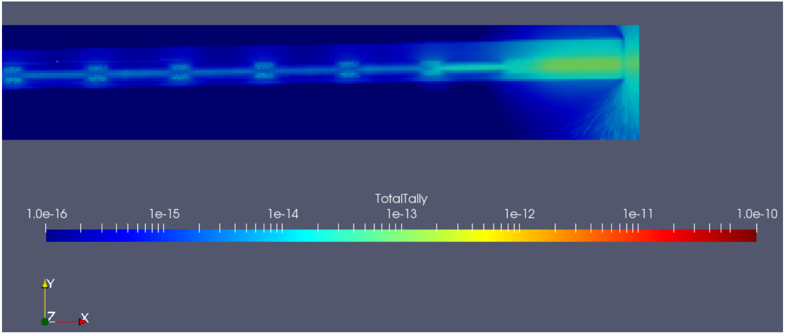
The results show notable achievements with regards to solutions. The final focusing is reflected in the flux increment in the end.

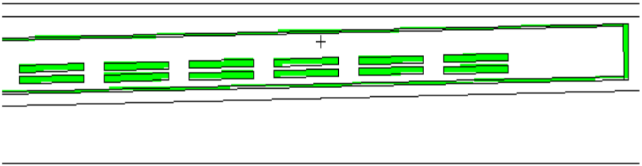




Results

The 'shadow' of supports, walls and shielding is clearly visible.





PZ=-61

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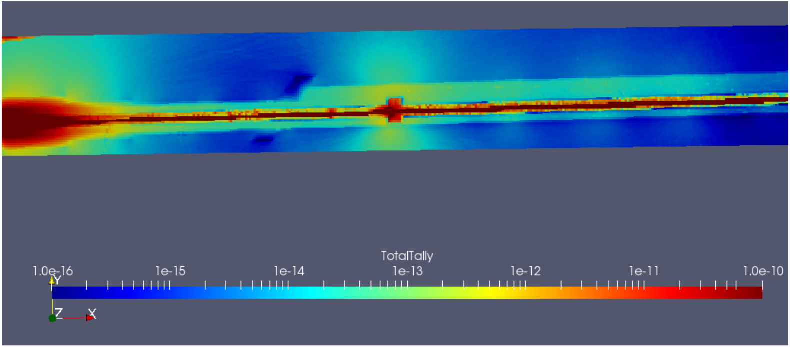

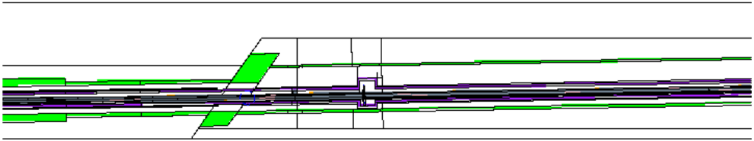

Results

More calculation time is needed to be thrown behind the low energy solution.