On an alternative neutron source

Genevieve Harrisson, Ph.D. (CNL, Applied Physics Branch)

Zin Tun, Ph.D. (Canadian Neutron Beam Centre)

Ron Rogge, Ph.D. (CNL, Material Sciences Branch)

Bryan van der Ende, Ph.D. (CNL, Applied Physics Branch)

Gang Li, Ph.D. (CNL, Applied Physics Branch)

2018 Canadian Association of Physicists Congress

Tuesday, 12 June 2018

Outline

1. Introduction
    a. What is the problem?
    b. How may it be solved?
    c. What is novel?
2. Feasibility study based on Monte Carlo simulations
    a. Implementation of high speed moving media in GEANT4
    b. Modeling of the rotating neutron moderator in GEANT4
    c. Neutronic properties of the rotating neutron moderator
3. Development of neutron scattering instrument
    a. Principle of the instrument
    b. Modeling of the deflector
    c. Coupling McStas with GEANT4 using MCPL
4. Conclusion

1. Introduction

a. What is the problem?

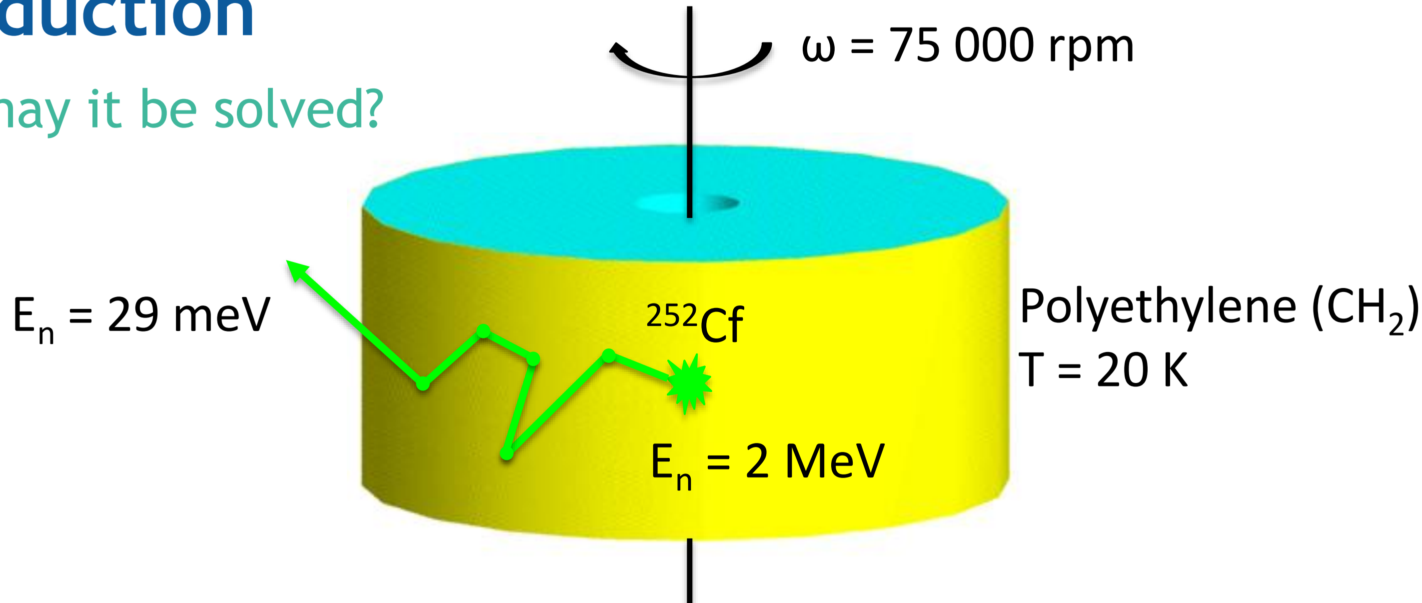
- Higher neutron fluxes would be advantageous for neutron scattering experiments.

- Neutrons are produced at high energy (MeV (10^6 eV)).
- Most applications use thermal neutrons (meV (10^{-3} eV)).
- Neutrons must be slowed down in a moderator (hydrogen-rich material).

- The energy of the neutrons follows the Maxwell-Boltzmann distribution.
- At room temperature, the distribution is broad. At cold temperature, the distribution is much narrower. The flux is low in both cases (low *n* and low m).
- Flux unit: [*n* m/m^3/s].

1. Introduction

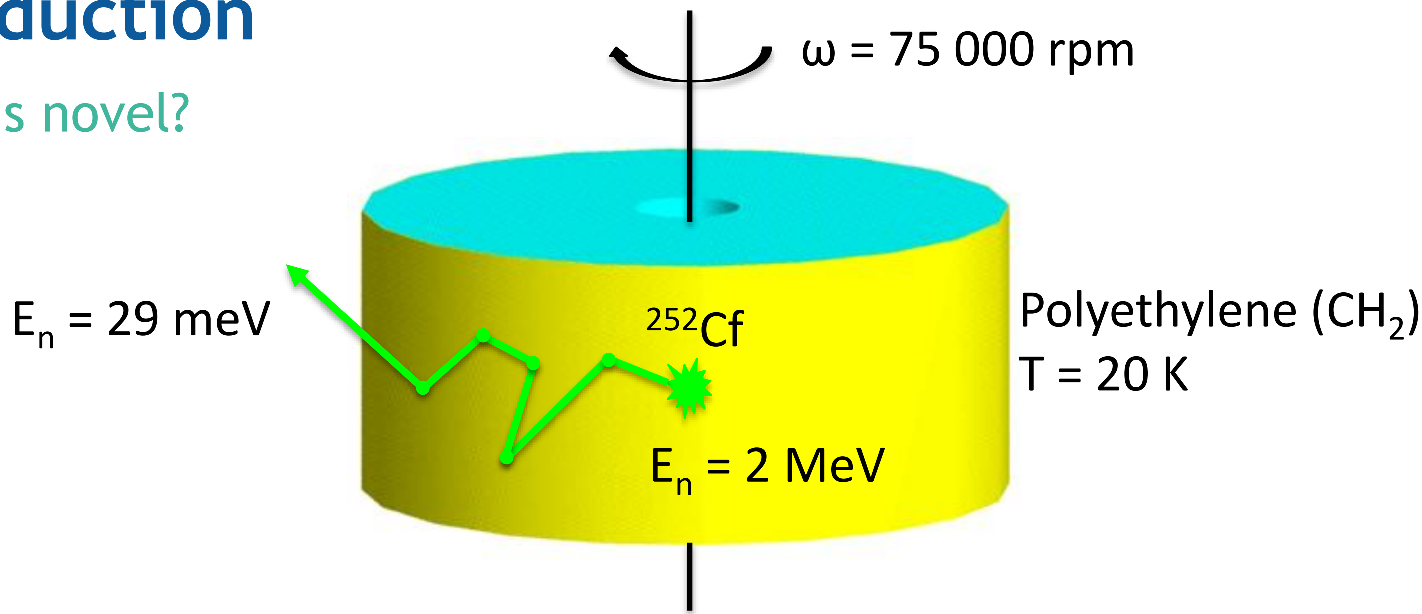
b. How may it be solved?



- A narrow energy distribution at energies corresponding to room temperature (≈ 29 meV).
- A cold moderator (20 K) should produce a sharp spectrum at low energy (≈ 2 meV).
- A rotation speed is expected to apply a directional force on the neutrons which should accelerate them (the spectrum should move towards higher energies and maintain its shape).

1. Introduction

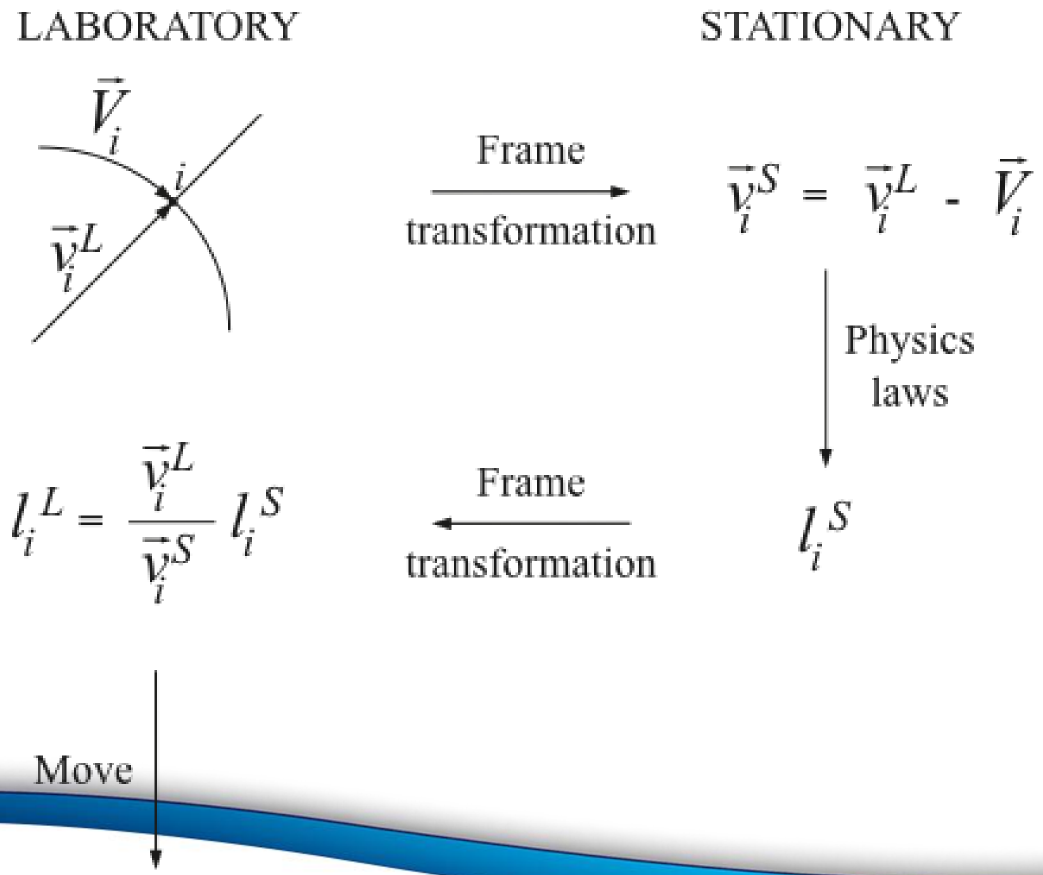
c. What is novel?



- Three technologies involved:
  - Neutron generation and moderation
  - Fast rotation speeds
  - Cryogenics to cool the moderator down to a few Kelvin
- Combine them to create a device never built anywhere in the world.

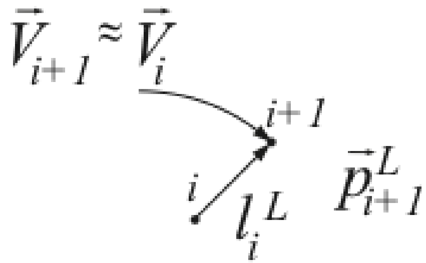
2. Feasibility study based on Monte Carlo simulations

a. Implementation of high speed moving media in GEANT4



2. Feasibility study based on Monte Carlo simulations

a. Implementation of high speed moving media in GEANT4



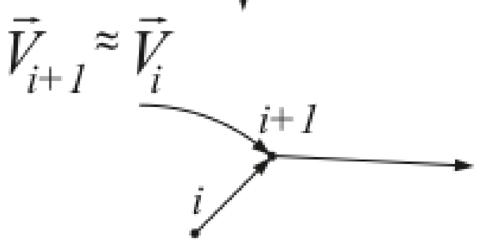
Frame transformation →

$$\vec{p}^{\,S}_{i+1} = \vec{p}^{\,L}_{i+1} - m\vec{V}_i$$

↓ Physics laws

$$\vec{p}'^{\,S}_{i+1}$$

← Frame transformation



$$\vec{p}'^{\,L}_{i+1} = \vec{p}'^{\,S}_{i+1} + m\vec{V}_i$$

$$E'^{\,L}_{i+1} = \frac{\left|\vec{p}'^{\,L}_{i+1}\right|^2}{2m}$$

2. Feasibility study based on Monte Carlo simulations

a. Implementation of high speed moving media in GEANT4

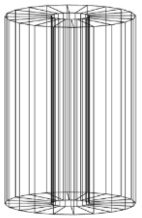
Source files modified in GEANT4

Files	Emplacement
G4HadronicProcess.cc	geant4.9.6.p04/source/processes/hadronic/management/src
G4HadronElasticProcess.cc	geant4.9.6.p04/source/processes/hadronic/processes/src
G4HadProjectile.cc	geant4.9.6.p04/source/processes/hadronic/util/src

- The angular velocity of the medium is fixed by the user from the *omega* variable defined in the three modified files. *omega* must be assigned to the same value in the three files.
- The stationary state is now obtained with $\omega = 0$ rpm.
- The angular velocity is applied clockwise.

2. Feasibility study based on Monte Carlo simulations

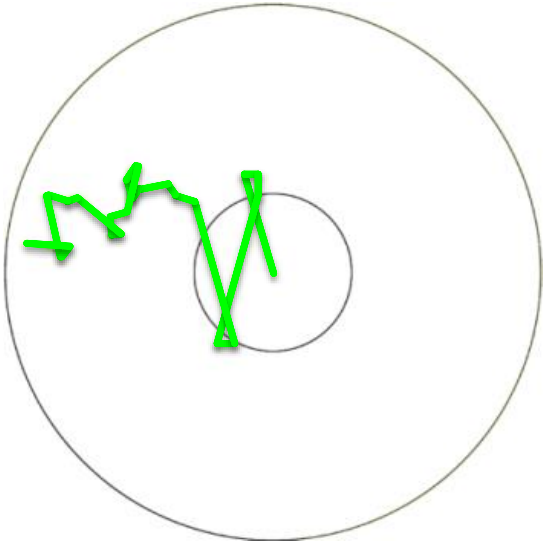
b. Modeling of the rotating neutron moderator in Geant4



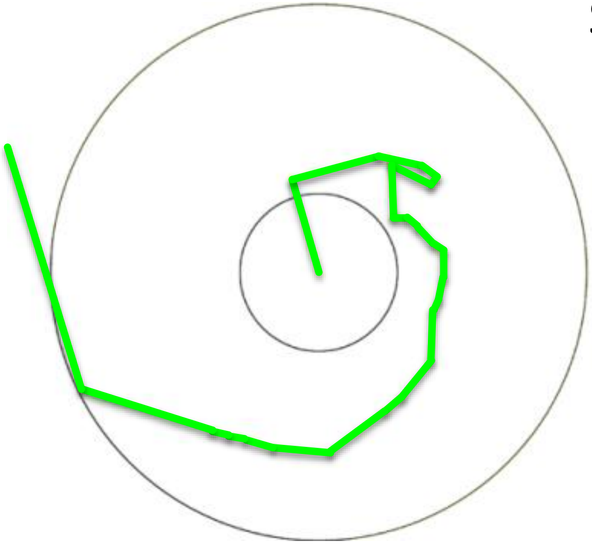
Smallest wheel

Impact of the rotating moderator on neutron trajectories

Top view with 1 primary neutron



Static, 0 rpm



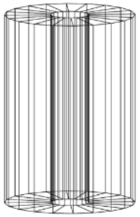
Rotating, 285 000 rpm

2. Feasibility study based on Monte Carlo simulations

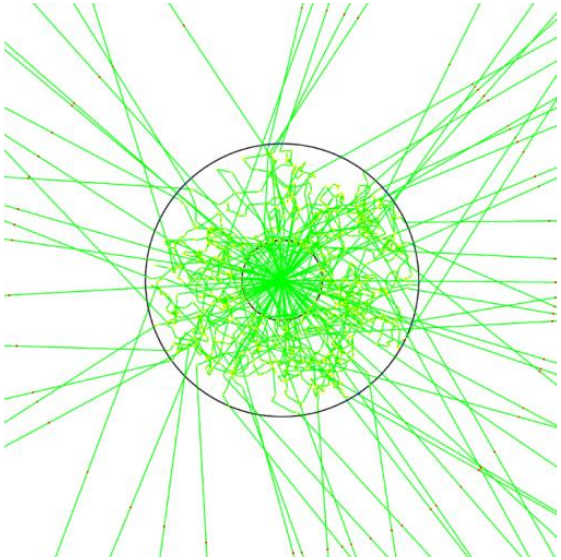
b. Modeling of the rotating neutron moderator in Geant4

Impact of the rotating moderator on neutron trajectories

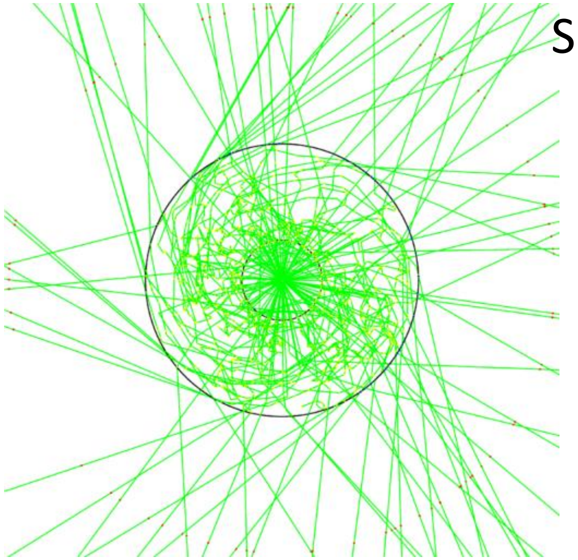
Top view with 100 primary neutrons



Smallest wheel



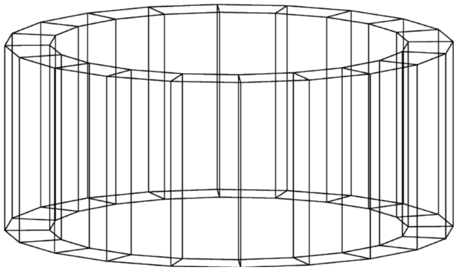
Static, 0 rpm



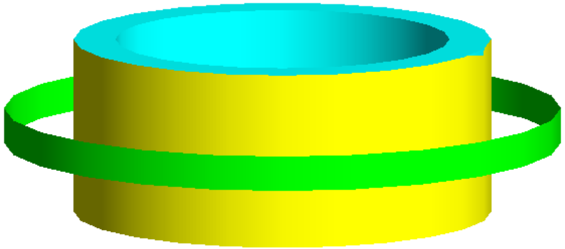
Rotating, 285 000 rpm

2. Feasibility study based on Monte Carlo simulations

b. Modeling of the rotating neutron moderator in Geant4



Big wheel



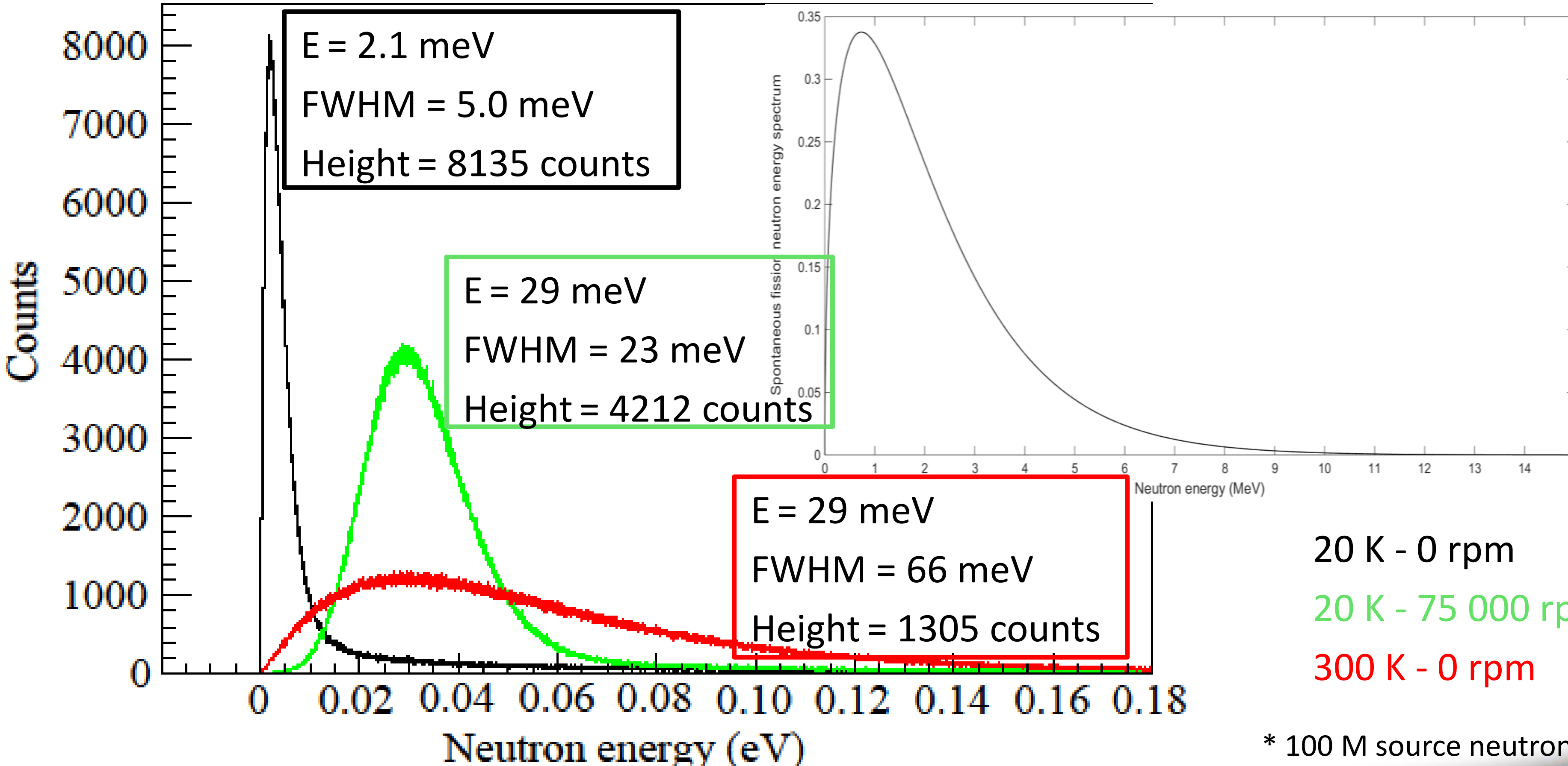
Detectors (yellow and green) with the moderator (cyan)

Dimensions

	Height (cm)	Thickness (cm)	Inner radius (cm)	Outer radius (cm)	Material
Small wheel	25	6	2.5	8.5	Polyethylene (CH_2)
Big wheel	25	6	24	30	Polyethylene (CH_2)
First detector	25	0.0001	30.0100	30.0101	G4_Galactic
Second detector	5	0.0001	40.0000	40.0001	G4_Galactic

2. Feasibility study based on Monte Carlo simulations

c. Neutronic properties of the rotating neutron moderator



20 K - 0 rpm

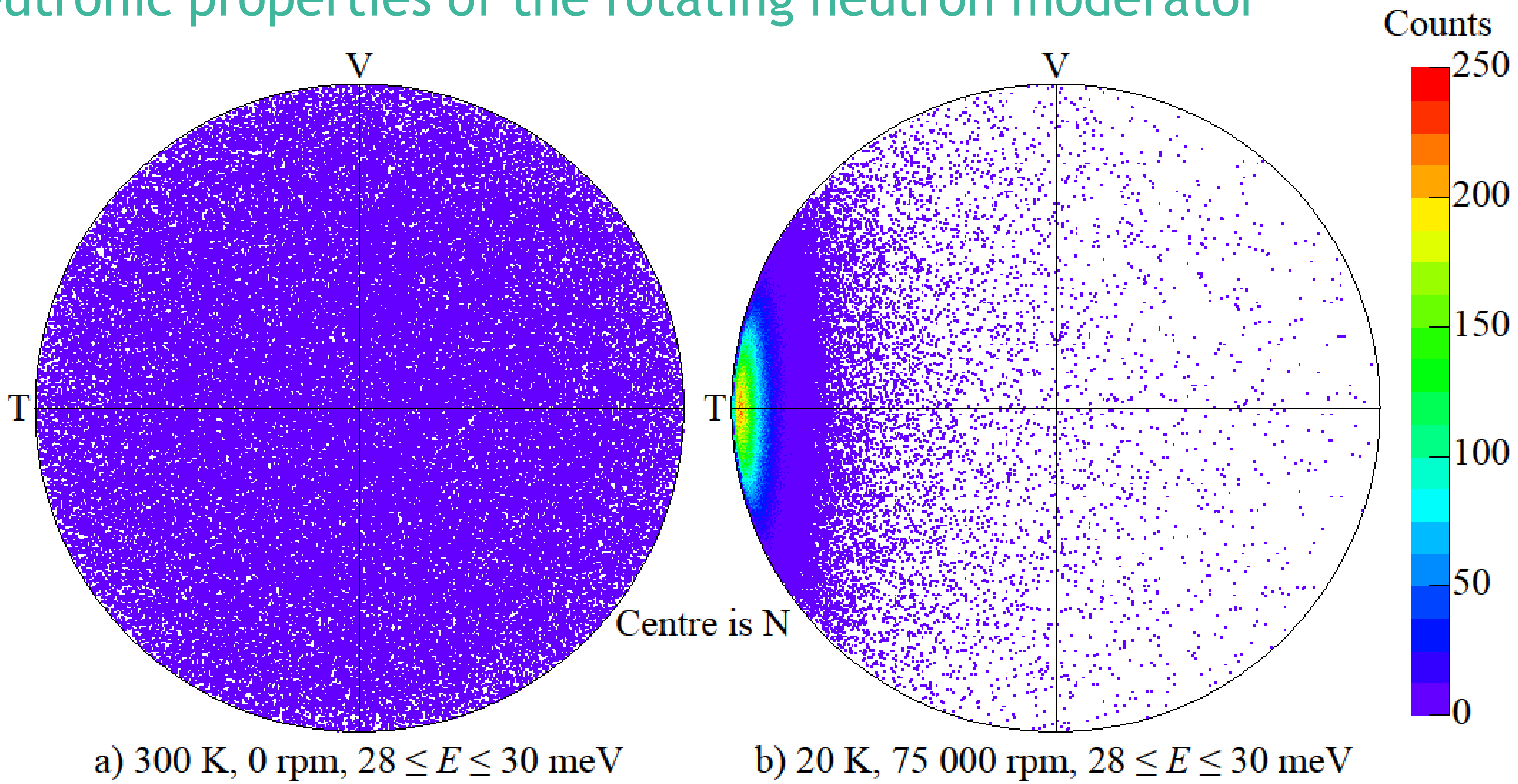
20 K - 75 000 rpm

300 K - 0 rpm

* 100 M source neutrons

2. Feasibility study based on Monte Carlo simulations

c. Neutronic properties of the rotating neutron moderator



Spatial distribution of exit directions in the NTV system (*E* around peak)

2. Feasibility study based on Monte Carlo simulations

c. Neutronic properties of the rotating neutron moderator

- *n* with 28 ≤ E ≤ 30 meV (± 1 meV around the peak);
- *n* emitted from the moderator with θ ≤ 1°;
  - for the stationary moderator, θ is the angle with the normal of the curved surface of the moderator;
  - for the rotating moderator, θ is the angle with the most probable exit direction:

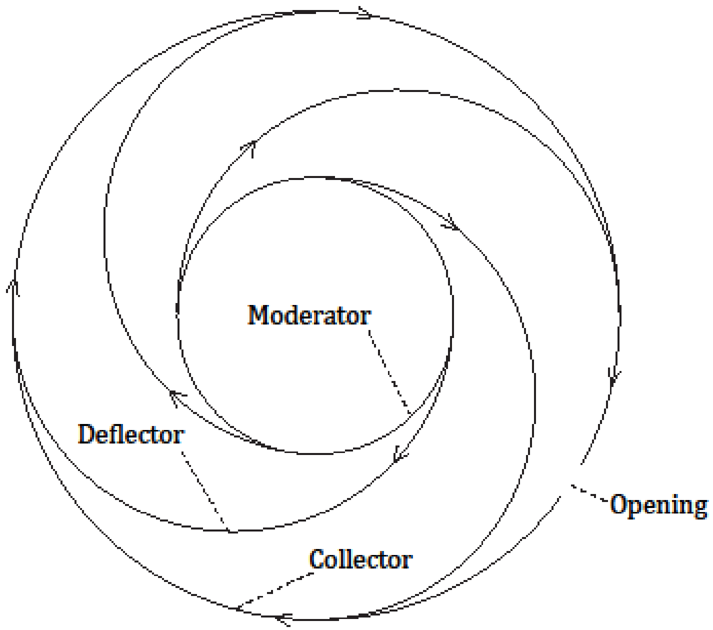
$$\overrightarrow{\mathrm{Mped}}_{28\leq E\leq 30\ \mathrm{meV}} = 0.25\hat{N} + 0.97\hat{T} + 0\hat{V}$$

- *n* falling in a 5 cm tall circular band located radially 10 cm away from the moderator.

- The enhancement factor is 64.3

3. Development of neutron scattering instrument

a. Principle of the instrument



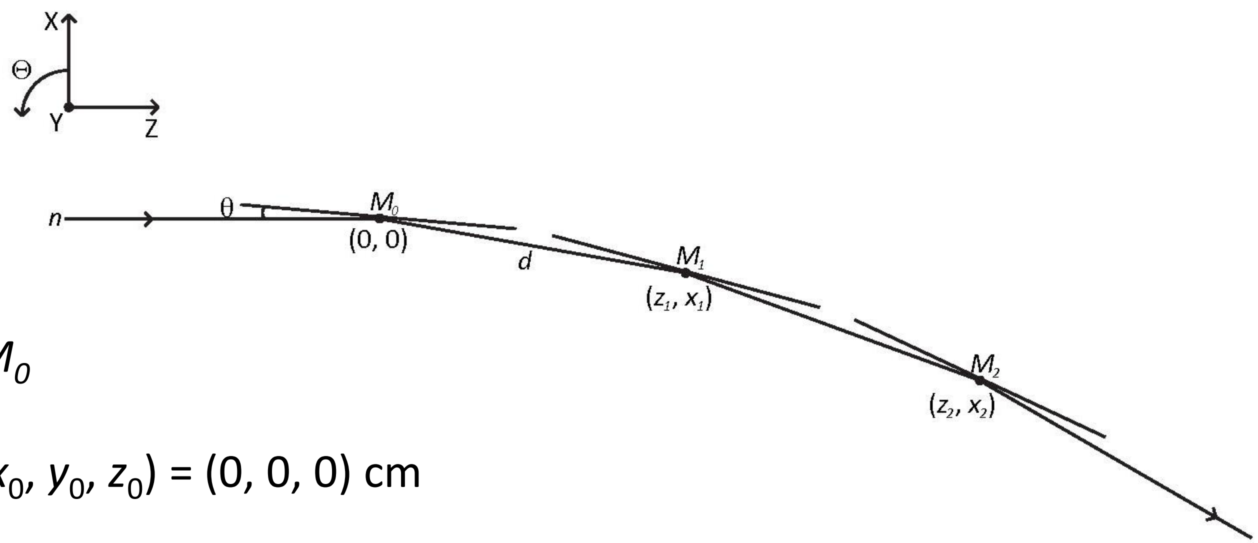
Schematic of the proposed instrument (dimensions not to scale)

3. Development of neutron scattering instrument

b. Modeling of the deflector

M_i

$1 \le i \le (180/2\theta_{max} - 1)$



M_0

$(x_0, y_0, z_0) = (0, 0, 0)$ cm

$\Theta_0 = 90 - \theta$

$$x_i = -d \sum_{n=1}^{i} \sin(2n\theta)$$

$$y_i = 0$$

$$z_i = d \sum_{n=1}^{i} \cos(2n\theta)$$

$$\Theta_i = 90 - (2i + 1)\theta$$

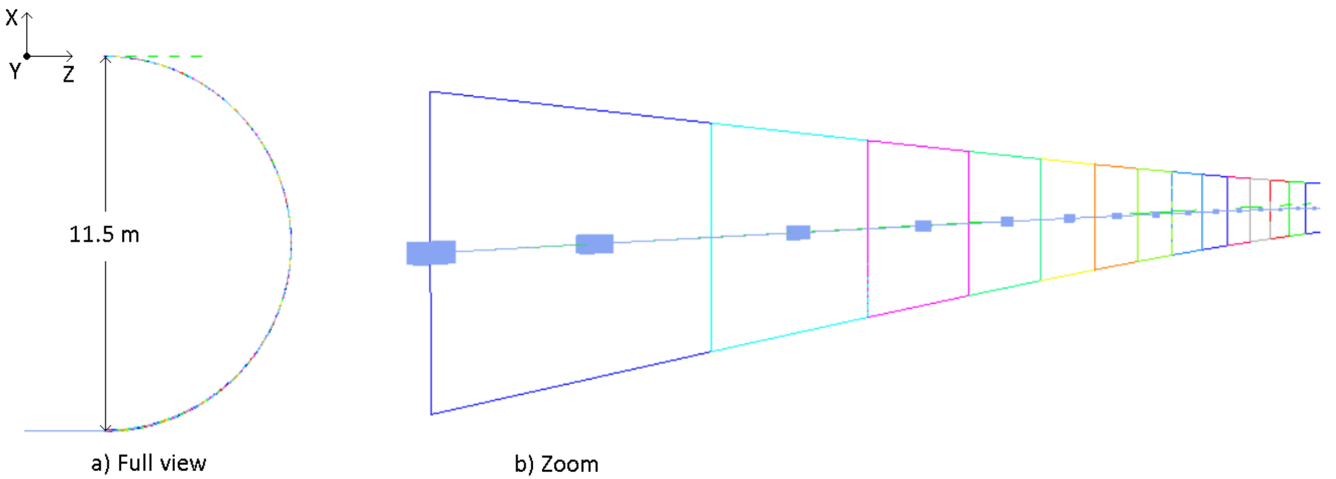
Schematic of the deflector

3. Development of neutron scattering instrument

b. Modeling of the deflector

For testing purposes:

- deflector exposed to 29 meV neutrons
- mirrors of 10 cm x 10 cm
- $\theta = \theta_{max}(29\ \text{meV}) = 0.5°$
- *d* = 10 cm



Deflector as modeled in McStas

The deflector makes use of 180 mirrors (each reflection deflects the neutron trajectory by $2\theta = 1°$)

3. Development of neutron scattering instrument

c. Coupling McStas with GEANT4 using MCPL

To write a MCPL file, a GEANT4 simulation requires four more files:

```
G4MCPLWriter.cc
mcpl.c
G4MCPLWriter.hh
mcpl.h
```

Slight alterations in `DetectorConstruction.cc`:

```
# include "G4MCPLWriter.hh"
G4MCPLWriter * mcplwriter = new G4MCPLWriter("myoutput.mcpl");
SensitiveDetectorManager -> AddNewDetector(mcplwriter);
Volume -> SetSensitiveDetector(mcplwriter);
```

3. Development of neutron scattering instrument

c. Coupling McStas with GEANT4 using MCPL

Neutrons properties are stored in the output file (`myoutput.mcpl`), for example:

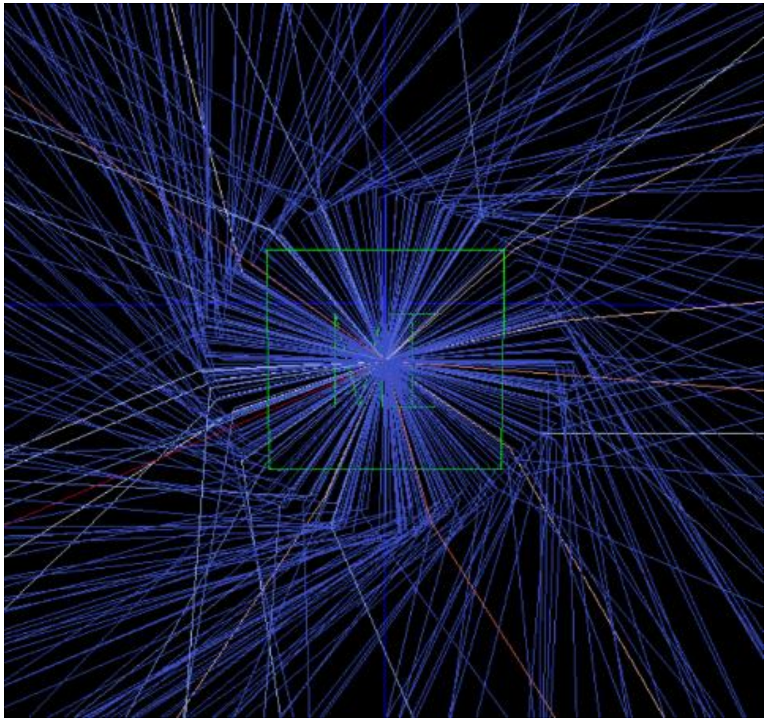
Index	pdgcode	ekin [MeV]	x [cm]	y [cm]	z [cm]	ux	uy	uz
0	2112	0.968	48.887	10.493	11.228	0.954	0.205	0.219
1	2112	0.026	20.285	45.701	-3.285	0.665	0.702	-0.255
2	2112	8.978e-09	38.675	31.690	6.157	0.967	0.140	-0.213
3	2112	2.250e-05	23.339	-44.219	4.162	-0.400	-0.913	-0.084

In McStas, the source is defined by specifying the MCPL file as the input:

```
COMPONENT NSource = MCPL_input(filename = "myoutput.mcpl")
```

3. Development of neutron scattering instrument

c. Coupling McStas with GEANT4 using MCPL



Source implementation in McStas from a GEANT4 simulation of the rotating neutron moderator

4. Conclusion

- Main conclusions
  - From the neutronic point of view, the rotating neutron moderator is a feasible concept.
  - GEANT4 simulations have shown that neutrons emitted isotropically from a point source can be focused in energy and space by a rotating polyethylene tube.
  - Compared to a static moderator, it has been shown that it is possible to collect with a rotating moderator about 60 times more neutrons with energy around 29 meV.
  - But, neutrons travel fast (~2200 m/s at room temperature), therefore tip speed of the wheel has to be as high; challenge for present technologies to support those speeds.
  - McStas simulations have shown that neutron supermirrors can be used to guide thermal neutrons emitted in preferential directions in space.

4. Conclusion

- Future work
  - The principle of the concept could be shown at lower speeds.
  - Experimental data could be used to verify the accuracy of the simulations.
  - Further evaluation would need to consider questions such as: considering the large dimensions of the instrument, should gravity also be taken into account in the design? How much improvement is achieved over the original rotating moderator setup? How many deflectors do we need for this to be effective?

- Reference

  - Li, G., Ciungu, B., Tun, Z., Harrisson, G., Rogge, R.B., van der Ende, B.M. and Zwiers, I. (2017) Neutron transport simulation in high speed moving media using GEANT4. *Nuclear Instruments and Methods in Physics Research Section A.*

Thank you!