ESS Experiment Design for nnbar Observation

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THE UNIVERSITY OF TENNESSEE KNOXVILLE

The European Spallation Source

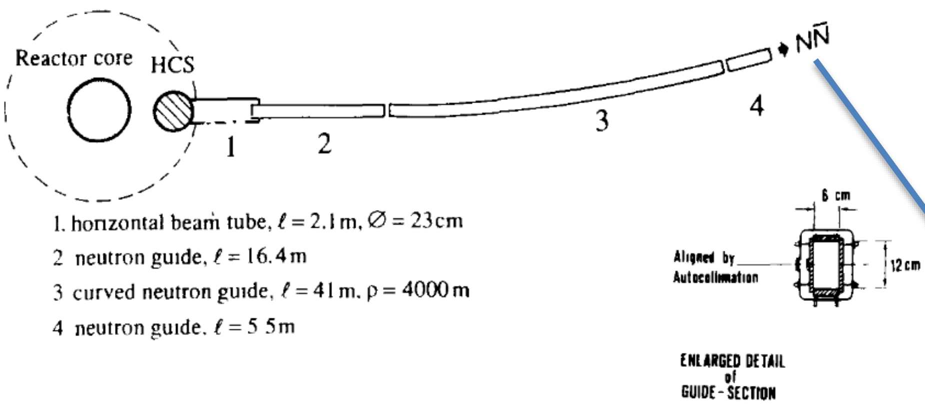
- A pulsed source of cold neutrons (~10meV,~2.8Å,~1400 m/s) designed particularly for neutron scattering instrumentation used in studies of advanced materials. (Condensed Matter, Engineering materials, Biological structures)
- Proposed startup in 2019.
- Will ultimately support over 40 instruments with two moderators coupled to the spallation target

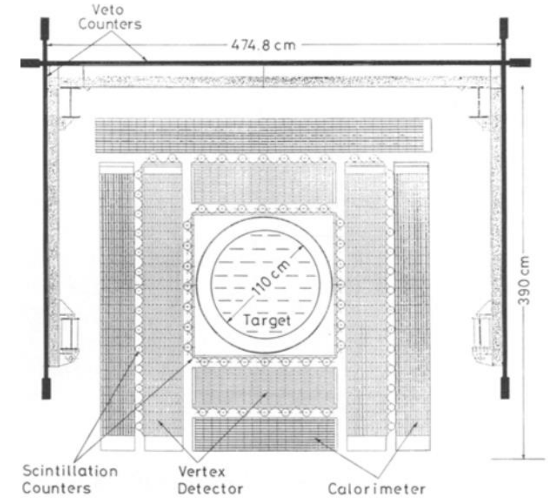
EUROPEAN SPALLATION SOURCE

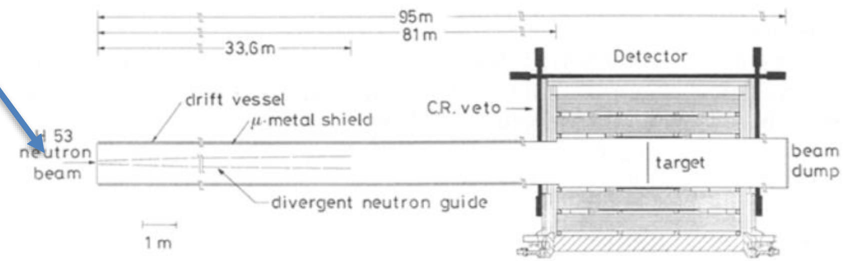
ILL nnbar Search (1991)

- The most recent experiment to try and observe nnbar set a lower limit on the oscillation time to be >0.86E8 seconds.

- In order to be relevant with regards to current BSM theories (PSB), an experiment sensitivity 1000x greater than the ILL search should be attempted.



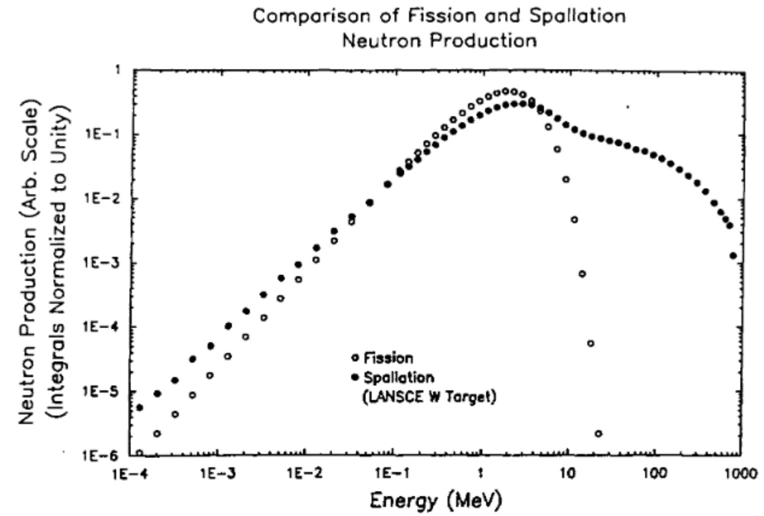


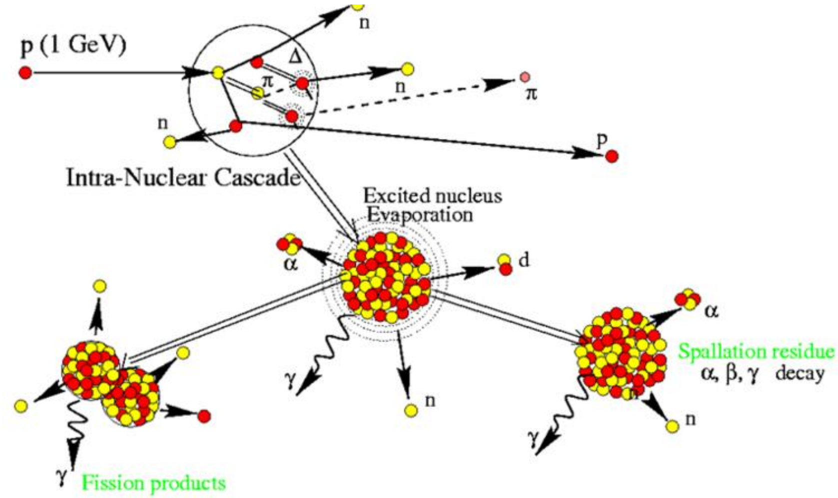


M. Baldo-Ceolin. Z. Phys. C 63, 409-416 (1994)

Neutron Production via Spallation

- A high Z material is bombarded with a high energy (>GeV) beam of protons.
- The high energy collision of the proton with the target nuclei causes excitation, with immediate hadron emission at very high energy, followed an internal reorganization of the excited nucleus
- The excited nucleus “evaporates” during the reorganization process, emitting multiple neutrons and other hadron products.
- Neutron Production up to 4x more efficient than fission

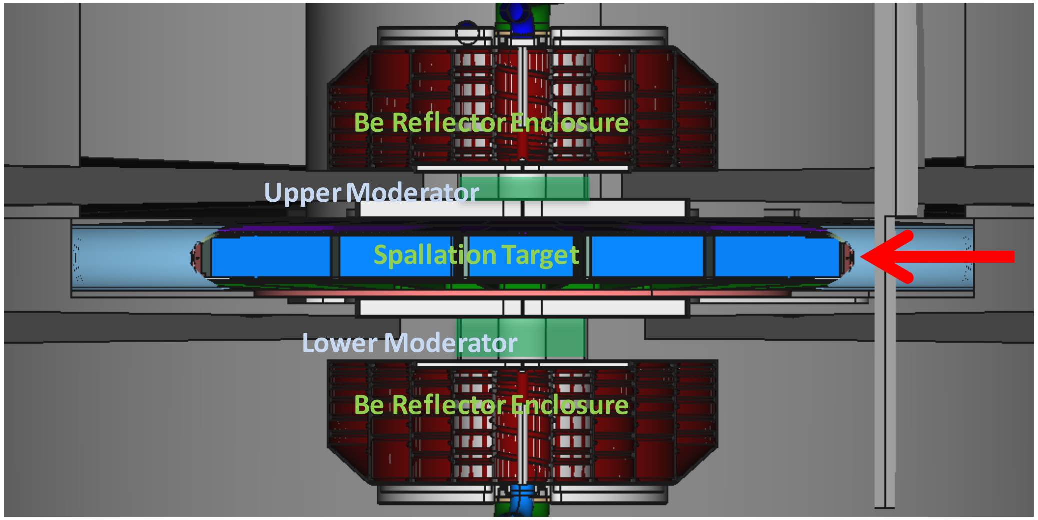


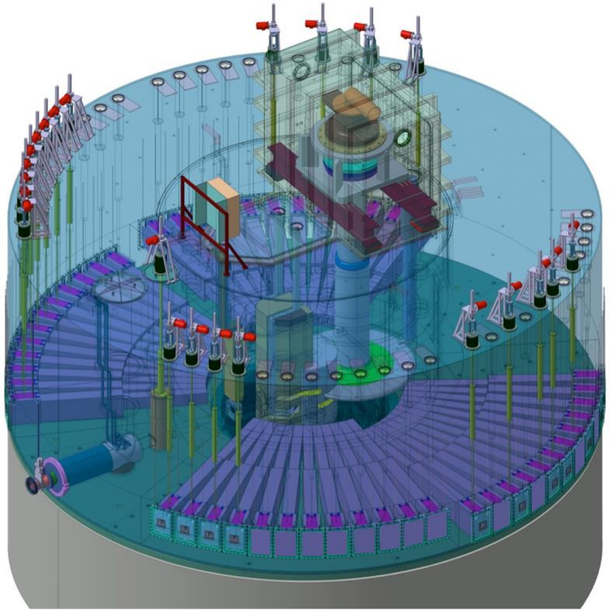


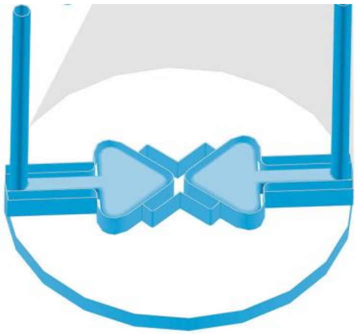
IAEA Nuclear Data Services, https://www-nds.iaea.org/spallations/

Neutron Production via Spallation

- Moderating media is placed in close proximity to the target, where the neutrons are slowed to sub-eV energies for extraction to instrumentation
- First optical components for instruments reside within 2 meters of the source
- Flux is propagated >30 meters using super-mirror reflecting guides and focused on to sample position.



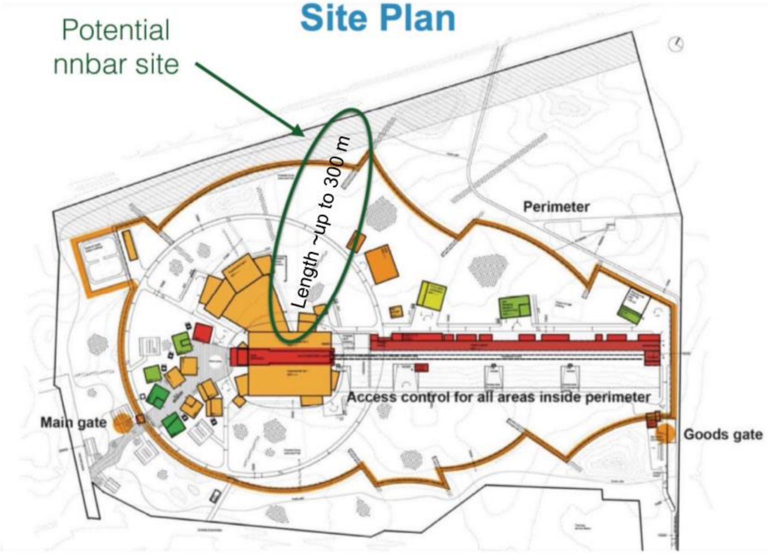


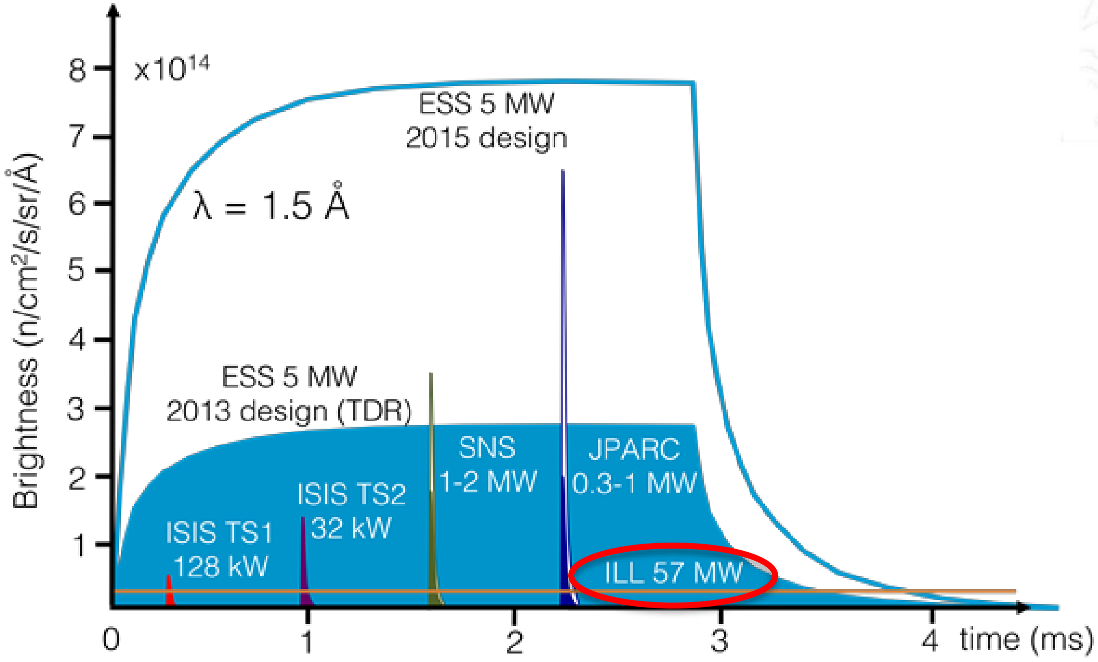


BF2 Moderator Design

ESS Experiment Features

- 5MW, 14Hz, ~3ms pulse width
- Competitive with other sources.
- Time Averaged brightness comparable to ILL





- Long flight paths are already planned for scattering instrumentation.
- Could accommodate over 200m long instrument

Experimental Figure of Merit

Figure of Merit: $\Phi\langle t^2\rangle$

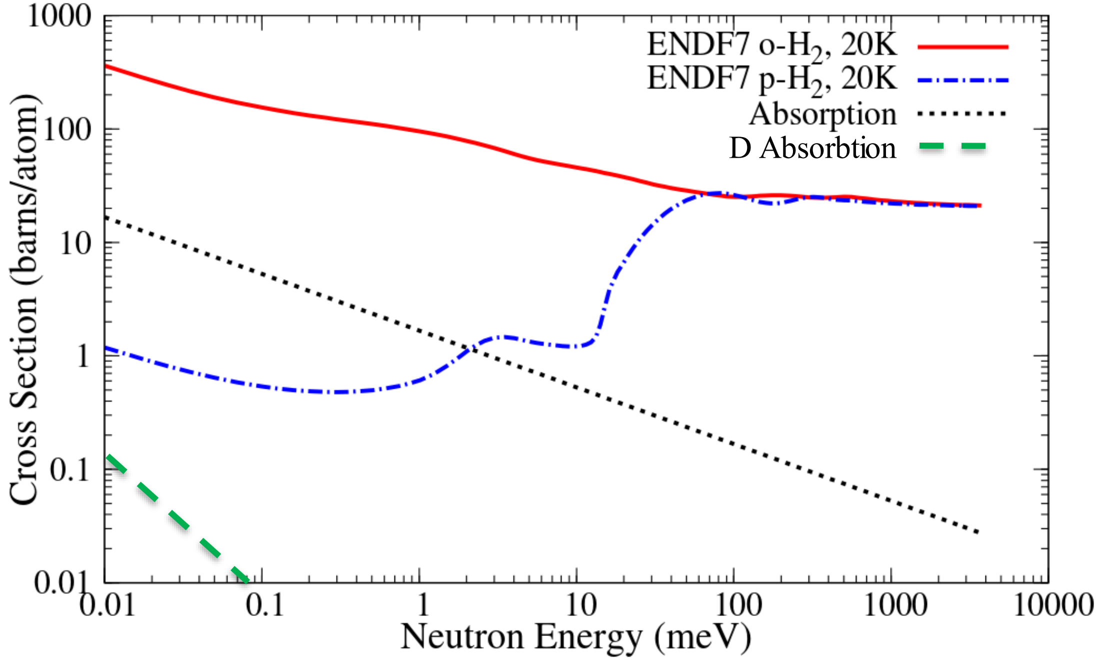
- $\Phi \rightarrow$Neutron intensity on detector (scales with source intensity)
- $\langle t^2\rangle \rightarrow$Square of Mean Flight Time (scales with wavelength)
- Sensitivity units are in "ILL/year"
  - Compared to last observation attempt at ILL in 1990.
- ILL/year is equivalent to 2.0e9 neutron-seconds using time-adjusted ESS operating cycle

Oscillation Time: $\tau = \sqrt{\Phi t^2 T/N}$

- *T* = Experiment Operating Time
- *N* = Number of Anti-Neutrons on Annihilation Target

Why use Cryogenic Hydrogen as a Neutron Moderator?

The domination of the para-hydrogen state at lower temperatures allows for a significant increase in the mean free-path length for neutrons with sub-thermal energies. The result is a moderating volume that efficiently slows high energy neutrons, but allows them to escape the volume once they have been sufficiently slowed. Deuterium is still more suited to larger moderating volumes given its significantly lower capture cross section.

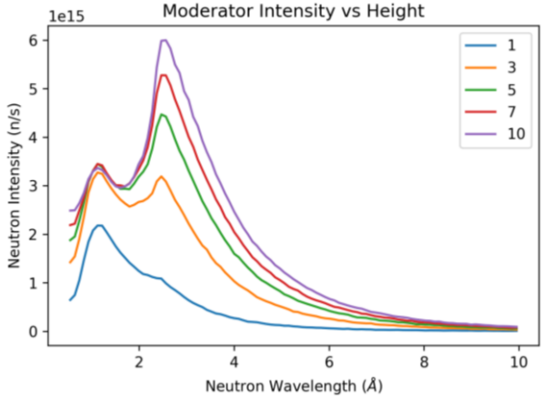


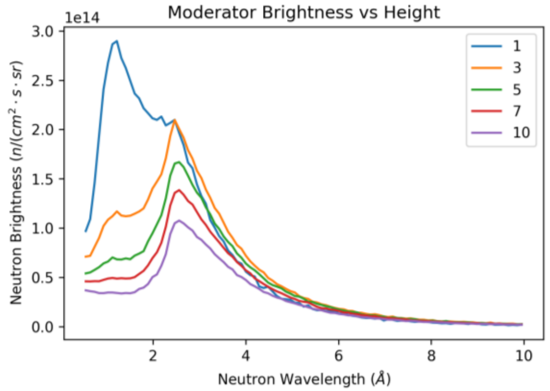
ESS Moderator Design Evolution

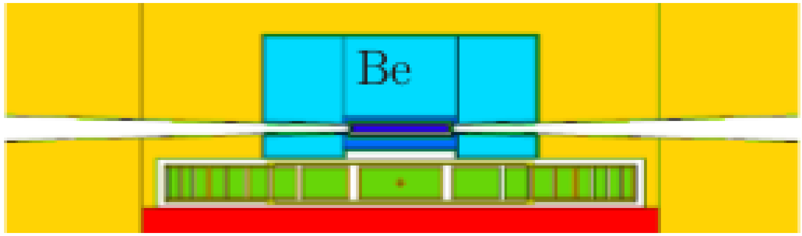
- Leveraging the relative transparency of para-hydrogen at low energies, designs that promote high brightness are feasible and ideal for strongly focusing optics a far distance away from the source.

- Unfortunately, brightness (neutrons/(cm^2-sr-s)) does not necessarily translate to intensity (neutrons/s)).

- The result was a push towards a disk-shaped moderating volume that significantly lowered the overall source intensity.

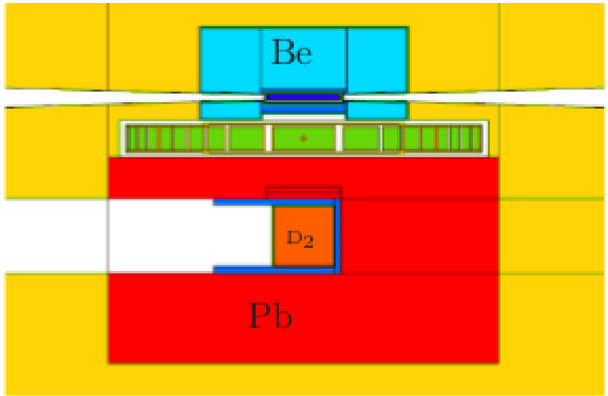


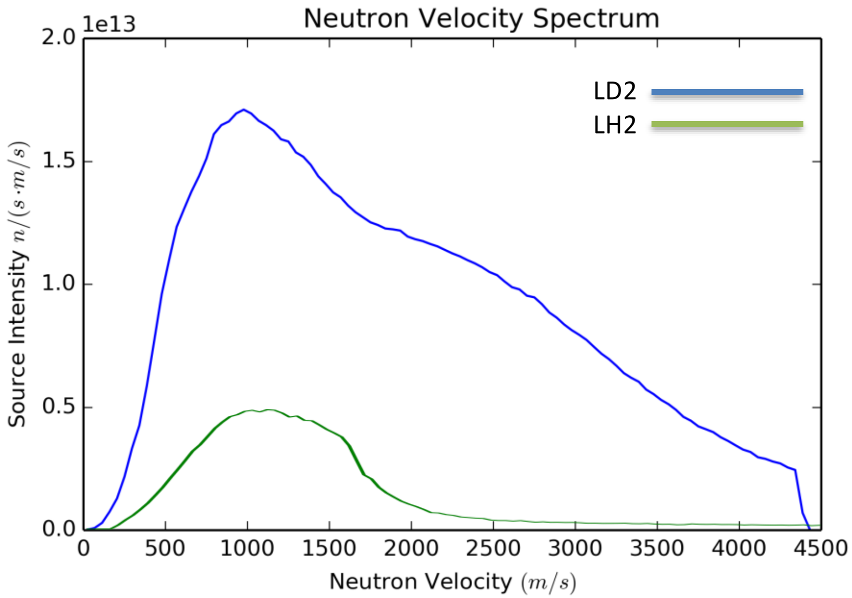


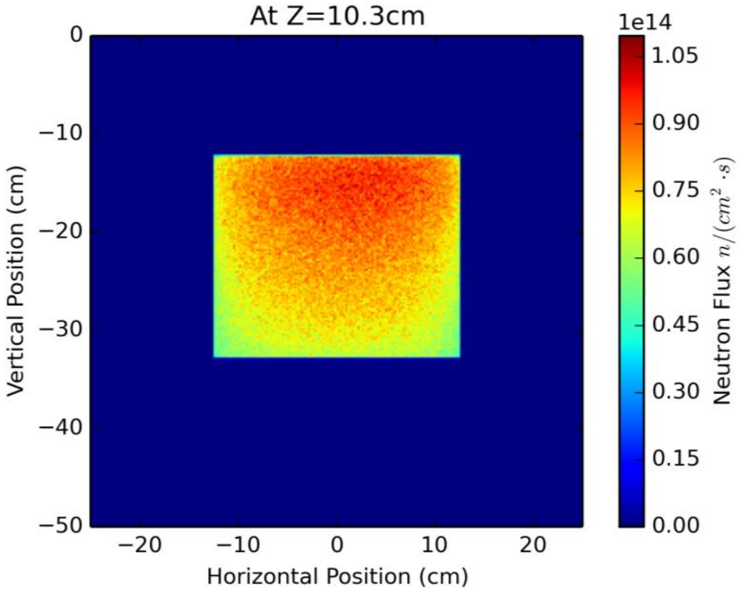


Hypothesized Liquid D_2 Moderator

- Offers a much higher overall intensity
- Colder spectrum
  - Longer free-flight time

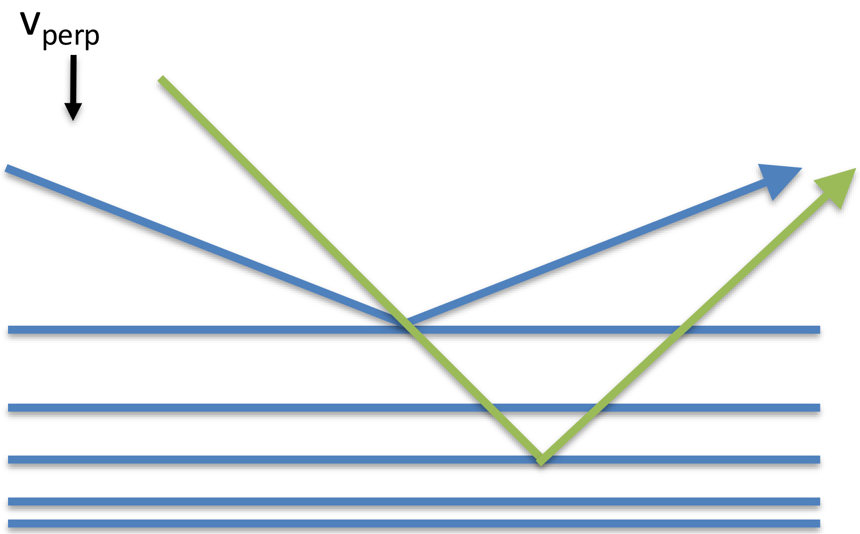


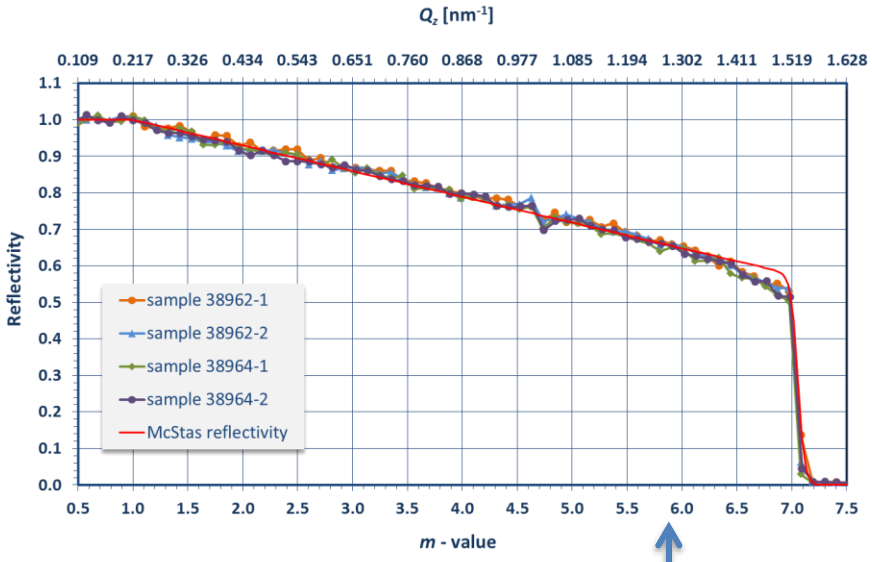




Neutron Super Mirrors

- Super-mirror Reflection
  - Multilayered, varied thickness surfaces allow for “smeared” super-lattice Bragg diffraction, enhancing the reflectivity far beyond the critical angle.





v_{perp}=40 m/s

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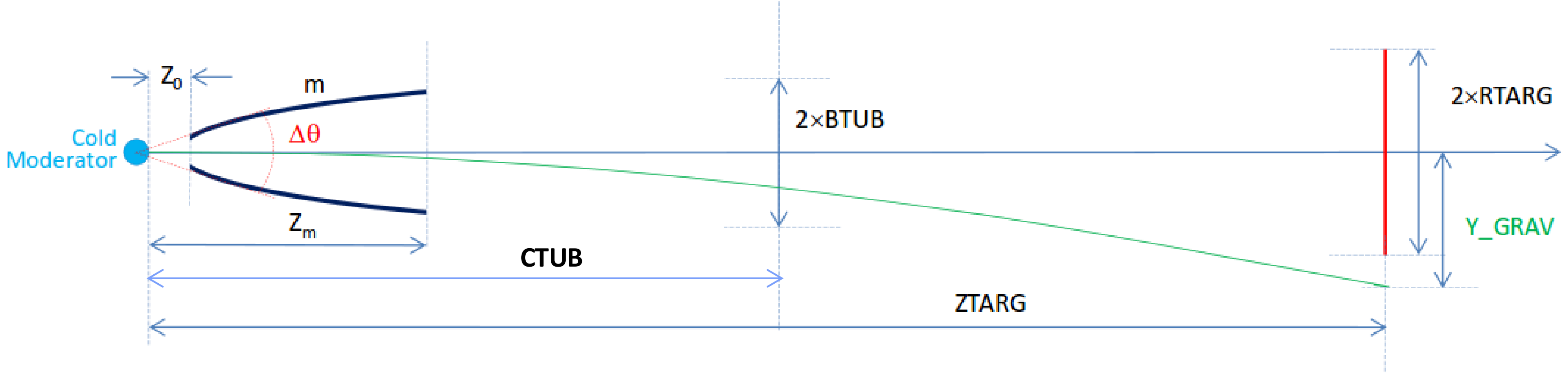
Baseline Experiment Geometry

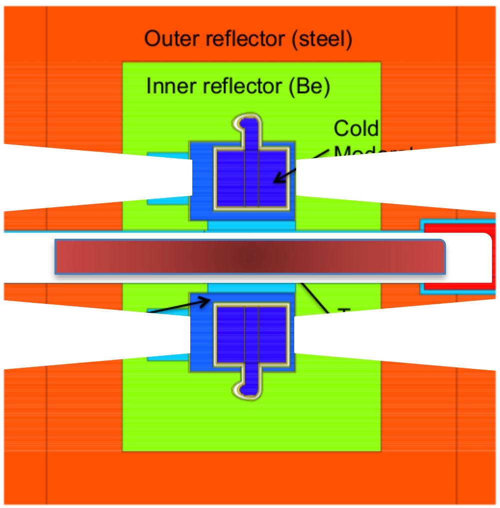
This optimization has shown performance gains ~100x beyond the ILL experiment at other cold neutron sources, and thus provides a good starting point to test with other cold source concepts.

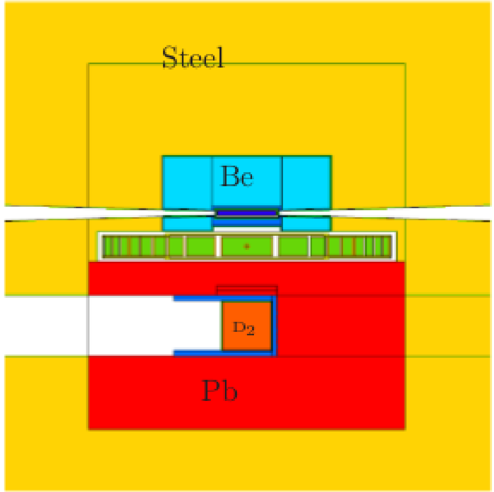
• Super Mirror Reflectivity	~m=6
• Minor Axis	~b=2 m
• Major Axis	~c=100 m
• Start/Stop reflector position	~10-50 m
• Acceptance Angle	~±5°
• Detector Efficiency	50%

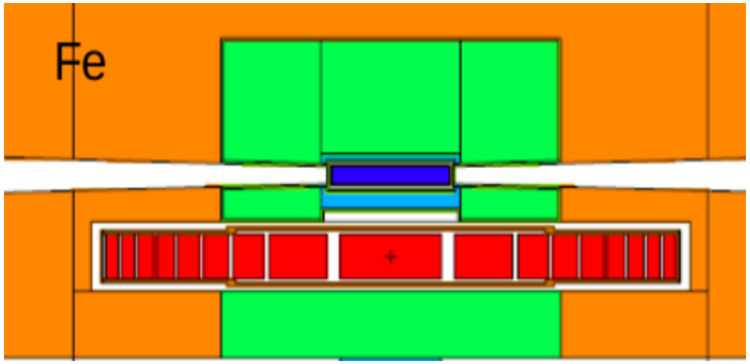


Previous Source Concepts

Preliminary investigations of the sensitivity with various proposed source designs proved useful in determining whether to pursue development of the experiment at ESS.







Moderator	TDR 2013 LH_2	LD_2	Pancake LH_2
FOM in ILL/yr	250	550	200

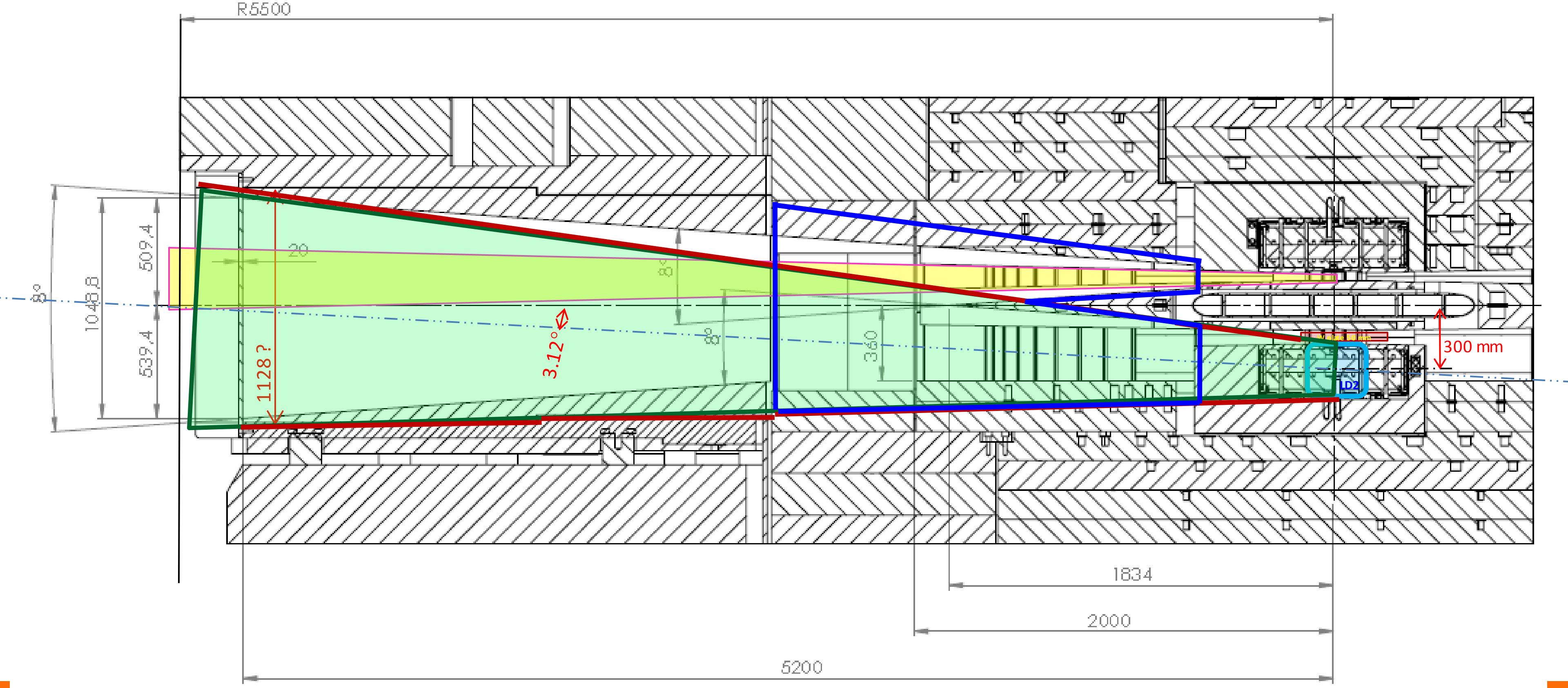
Unobstructed Experiment Configurations

- Initially, simulations used idealized, unobstructed (Large Beam Port Assumed) moderator geometries to estimate sensitivity.
- The results were good for initial comparison of moderator performance, but did not reflect the realities of the experiment interface near the source.
- Source intensities were taken at the moderator surface, rather than at the edge of the Be reflector/Fe Shielding volume (~60cm/200cm)

Moderator configuration	Spectrum temperature	Intensity n/s on annihilation target	Sensitivity Nt^2 in ILL units/yr
ESS TDR 2013	60K	8.8E12	250
Option of large LD_2 source	40K	1.2E13	550
Flat pancake with h = 3 cm	60K	7.0E12	200
ANNI with BF1 Source (Preliminary)	70K	~3e10	<0.8
ILL Cold Source LD_2	35K	1.5e11	1

NNbar Experiment Source Study

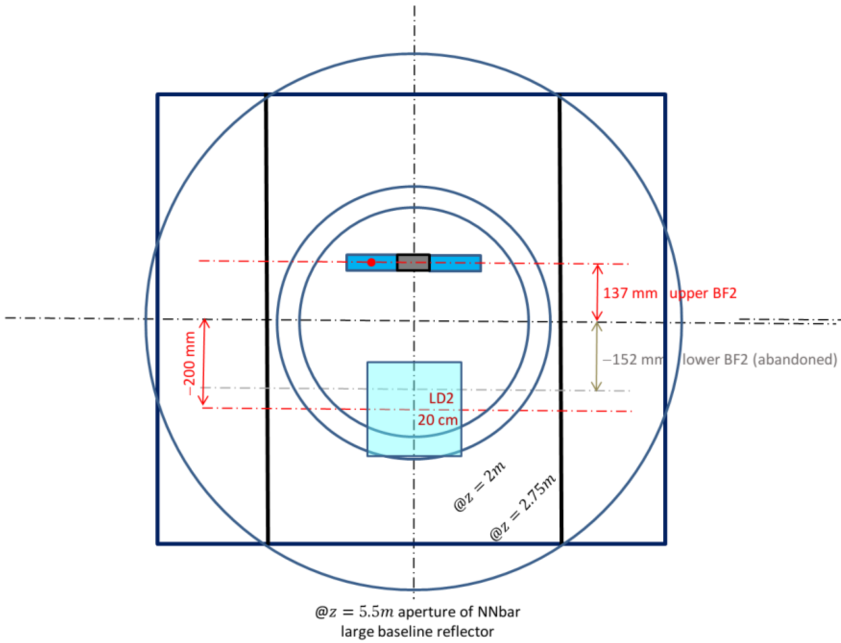
- As proposed will have a view of the bottom moderator
  - Proposed: 250mm tall LD_2 with 50mm Tungsten plate
- Uses recessed insert for a thinner vacuum window and additional optics closer to source



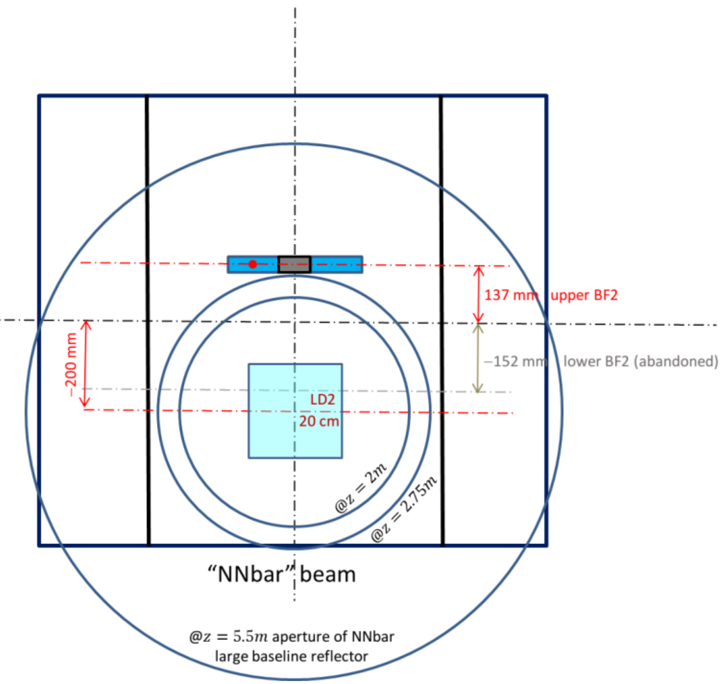
NNbar Experiment Source Study

- Novel optical materials and geometries can provide flexibility in design of ultimate source solution.
- Larger volume associated with LD_2 moderator limits interface design
- Possibility for reflector to be tilted to maintain suitable focus
  - Would require significant altitude adjustment of annihilation target
- Significant deviation from ideal ellipsoid could accommodate offset.

De-Focused/Unobstructed Source

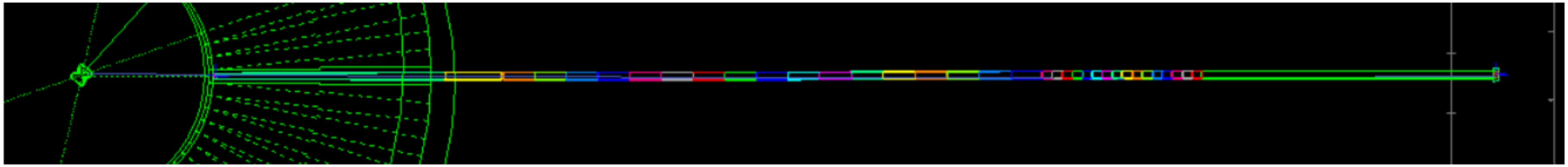


Focused/Obstructed Source

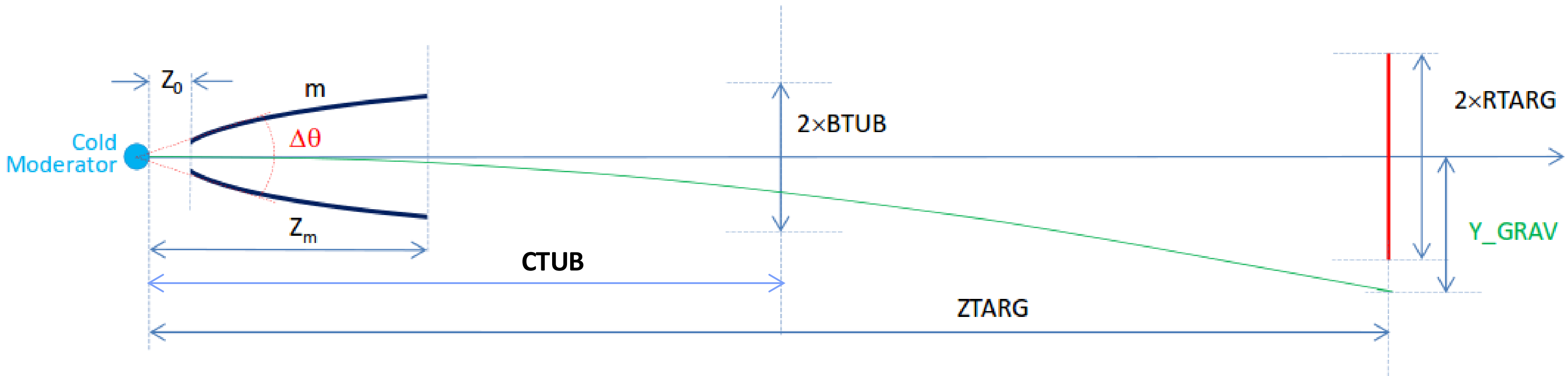


Proposed ANNI Instrument

- Another non-scattering neutron experiment has been competing for a spot at ESS.
- The ANNI Collaboration has an optimized design for cold neutron extraction that could be used for development and feasibility studies.
- Uses standard experiment port
  - Smaller acceptance angle
  - Intensity severely degraded
- In current state, provides <0.8 ILL/year sensitivity.
- Possible nn’ candidate.
  - Simulations in progress



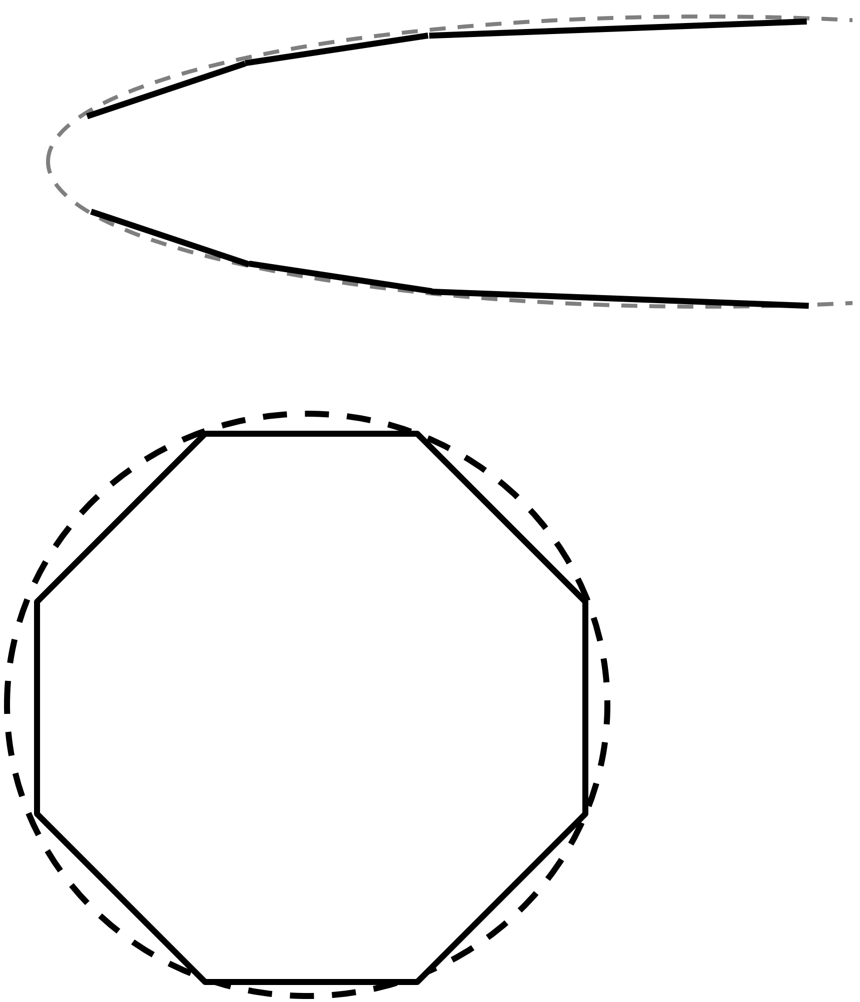
Neutron Reflectors for nnbar@ESS



- Super-mirror reflectors downstream
  - Lower incident angle lowers *m* requirements
- Gap between source and ellipsoid input
  - Bunker region
  - High Temperature/Radiation/Divergence → High Cost
  - Suitable location for a robust reflecting material
    - Diamond Nano-particles

Reflector Technical Challenges

- Initial simulations are performed using an ideal ellipsoid, but this ultimately will prove to be impractical.
- A method will be developed to most economically segment the reflector, while minimally impacting the overall sensitivity contribution.
- Typical super-mirror guide geometries are constructed of many surfaces approximately ~1 m in length, and ~10 cm width



Sensitivity Enhancement Inside Large Beam Port

- Expected increase in experiment sensitivity due to
  - Divergence redirection → More neutrons on specular reflector
  - In-elastic down-scattering → Longer Free Flight Time
    - If particles are actively cooled

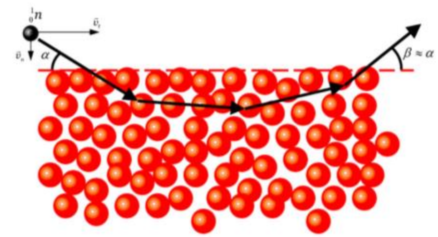
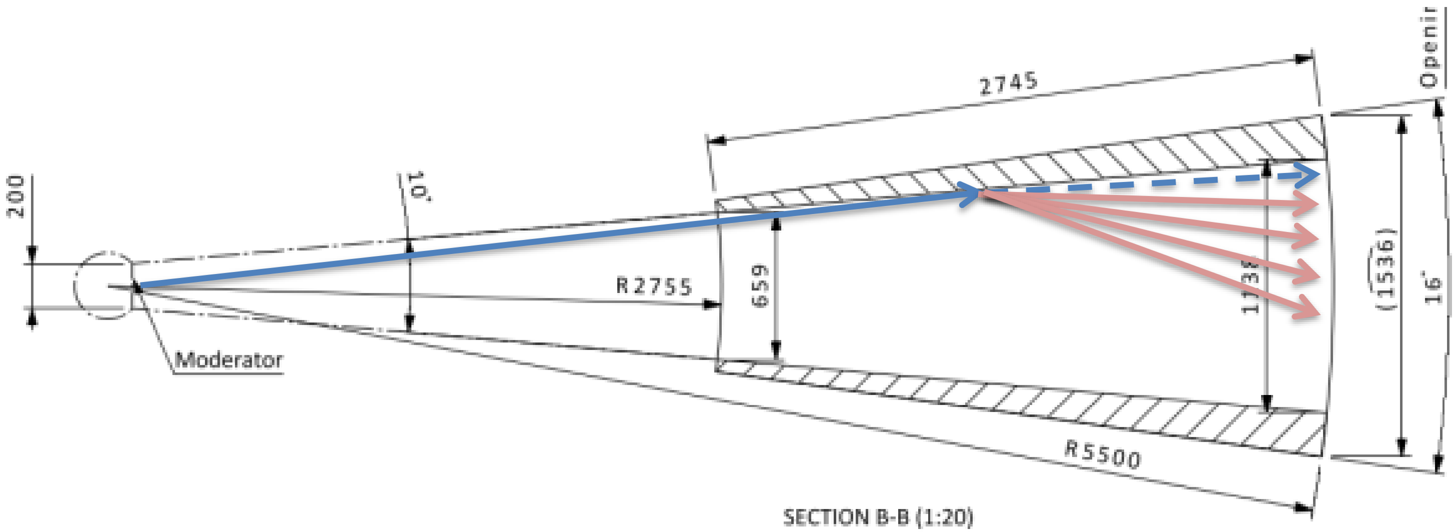


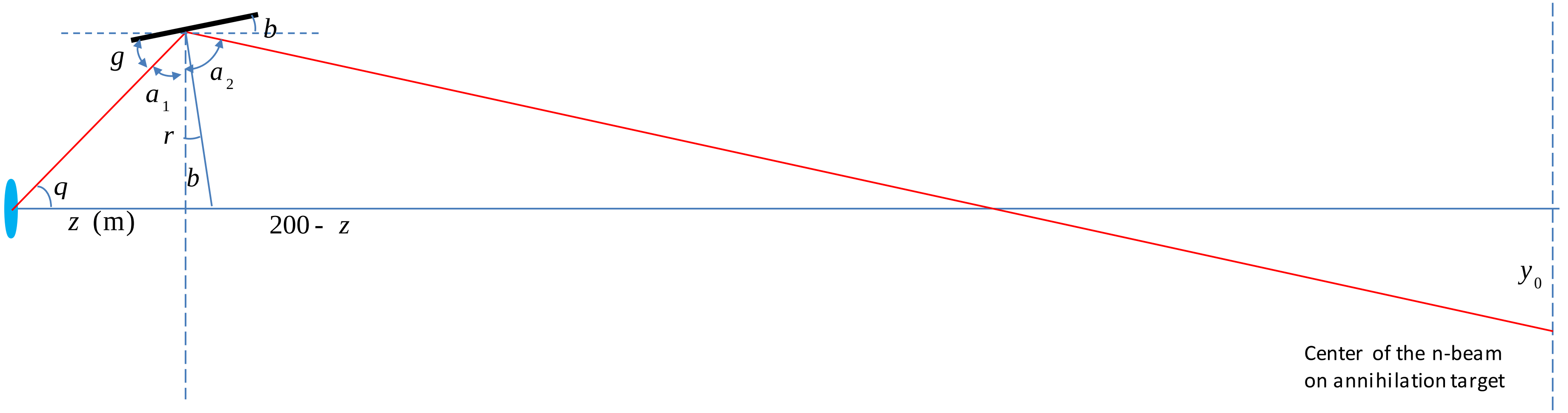
Fig. 1. Sketch of quasi-specular reflection of a cold neutron from powder of nanoparticles.

R. Cubitt et al. Nuclear Instruments and Methods in Physics Research A 622 (2010) 182–185



Sub-Thermal Neutron Phase Space Map/Event at R = 2755 mm to be used for further analysis.

Reflector Segment Optimization



- Refinement of the reflector segments' orientation and geometry could mitigate upstream interference challenges.
  - Overcome aforementioned Focusing/Obstruction Challenge
- Development of a segment optimization algorithm incorporating the current figure of merit and other cost/value functions.
- Can AI be used for such a task?
  - Very complex, ~100 parameters

Summary

- ESS is a good candidate source for an nnbar search
  - Significant Cold Neutron Intensity
  - Layout accommodates long flight path experiment
  - Time structure allows for simple background rejection
  - Current Neutron Scattering Instrument Technology facilitates sensitivity enhancements via proven mechanisms.
    - Super mirrors, Thermal Neutron Shielding Materials.
- New Moderator can be proposed for reflector change out in 2025.
  - LD_2 Volume would provide even more cold neutron intensity

Moderator configuration	Sensitivity Nt^2 in ILL units/yr
ESS TDR 2013	250
Option of large LD_2 source	550
Flat "pancake" with h = 3 cm	200
ANNI with BF1 Source	0.8