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Pre-conceptual Design Activities of the NIST Neutron Source

Preliminary Layout of Cold and Thermal Neutron Instruments

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Abstract

This technical note is part of a series of notes describing preliminary analyses and planning for the pre-conceptual design of a reactor to replace, in due course, the National Bureau of Standards Reactor (NBSR) at the NIST Center for Neutron Research. The replacement reactor, dubbed as the NIST Neutron Source (NNS), - destined to provide enhanced neutron research opportunities for the US into the future - is currently planned to be a 20 MW pool-type compact core cooled and moderated by H_2O and fueled with high-assay low-enriched U-10Mo. The core consists of nine fuel assemblies in a 3 × 3 square lattice encased in a chimney and surrounded by a D_2O-filled reflector tank that contains two LD_2 cold sources on opposite sides of the core.

This report outlines preliminary studies undertaken to assess possible cold and thermal neutron beam and instrument layouts for the pre-conceptual NNS design. It makes use of a current wish list of cold and thermal instruments (outlined in Appendix A) and estimated instrument footprints, accommodating those requiring end-positions and allowing for accessibility. A model with sixteen cold neutron guide tubes with curved-straight geometry (having no direct line-of-sight to the source from their exits) conducts the cold neutron beams in opposing directions from two cold neutron sources into two neutron guide halls. The thermal neutron beams, possibly using thermal neutron guides to locate more instruments further from the reactor face, emerge approximately tangentially to the cold neutron beams. In both cases, the beams are tangential to the fuel, limiting acceptance of unscattered fast neutrons and gamma rays. The modeled cold neutron guides are manufacturable with current technology and chosen to provide high cold neutron flux with low short-wavelength contamination with a characteristic wavelength of 0.3 nm (3 Å) for all 16 curved guide sections. Further improvements, optimizations, and the possibility to accommodate an increased number of instruments will be explored later as the NNS design evolves.

Keywords

Cold Neutrons; Cold Neutron Sources; Neutron Guides; Neutron Instrumentation; Neutron Research; Research Reactors; Thermal Neutrons, Low Enrichment Uranium (LEU).

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Acknowledgments

The design is actively being updated, and the current iteration of the design is not meant to be the finalized form of the design. The finalized design may be significantly different than the current iteration. The authors would like to acknowledge the team of individuals working on the design, which includes current members from NCNR, active contributors outside of NCNR, and the past contributors. The names are listed in alphabetical order.

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1. Introduction

To help guide the design of the NIST Neutron Source (NNS), this note discusses a desirable suite of thermal and cold neutron instruments that could be accommodated by the reactor design. A useful start has been provided by preliminary discussions with scientists on cold and thermal neutron instrument needs (see Appendix A), which are ongoing. Many of these instruments require end-positions and some are physically large, requiring careful planning to separate instruments while providing room for shielding and unimpeded instrument access. In the proposed suite, there are 17 cold neutron instruments plus several monochromatic side positions (likely most suited to the outermost guides), of which 15 to 16 require end positions. Some of these instruments require substantial lateral floor space and some (e.g. SANS) instruments occupy significant longitudinal space.

The NBSR facility (Figure 1 shows ca. 2017) currently has a total of 22 cold neutron instruments, 12 cold neutron guides, and 6 thermal instruments. Since 2017 aCORN has been superseded by the neutron lifetime experiment and the NDP instrument (not shown) has been relocated from the end position of NG5 to a newly-installed dedicated bender guide (NGA′) splitting off from the lower part of NGA upstream of the neutron spin-echo (NSE) instrument. Figure 1 shows how these instruments have been accommodated on three main groups of cold neutron guides. The three groups issue from three beam tubes with an angular span of 33° viewing a large liquid hydrogen (LH_2) cold neutron source (CNS). An additional cold neutron instrument, MACS, is located on a dedicated compact LH_2 CNS in BT-9.

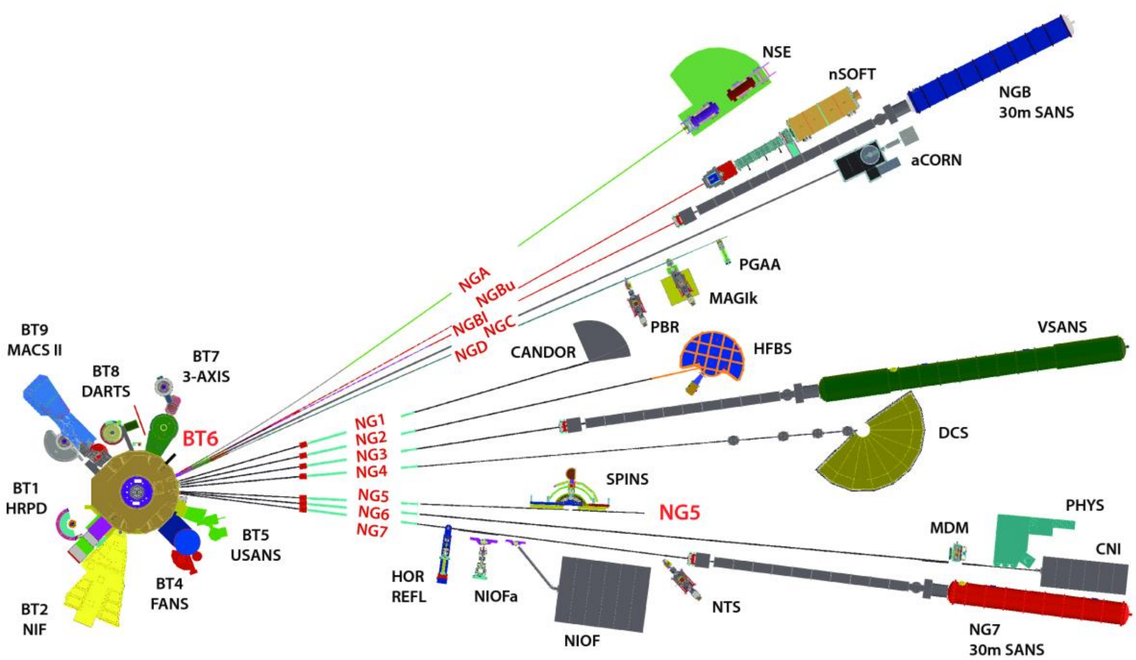

Figure 1. NBSR facility ca. 2017. Currently, all instruments on neutron guides (to the right) are cold neutron instruments. The only cold neutron instrument in the reactor hall currently is MACS on its dedicated "Peewee" LH_2 cold source.

The central cavity housing the large CNS is centered on a large thimble containing the cold neutron source cryostat and shield plug. The side tubes, CTW and CTE, have a more restrictive diameter ∅ 18.42 cm (7.25”) – see Figure 2.

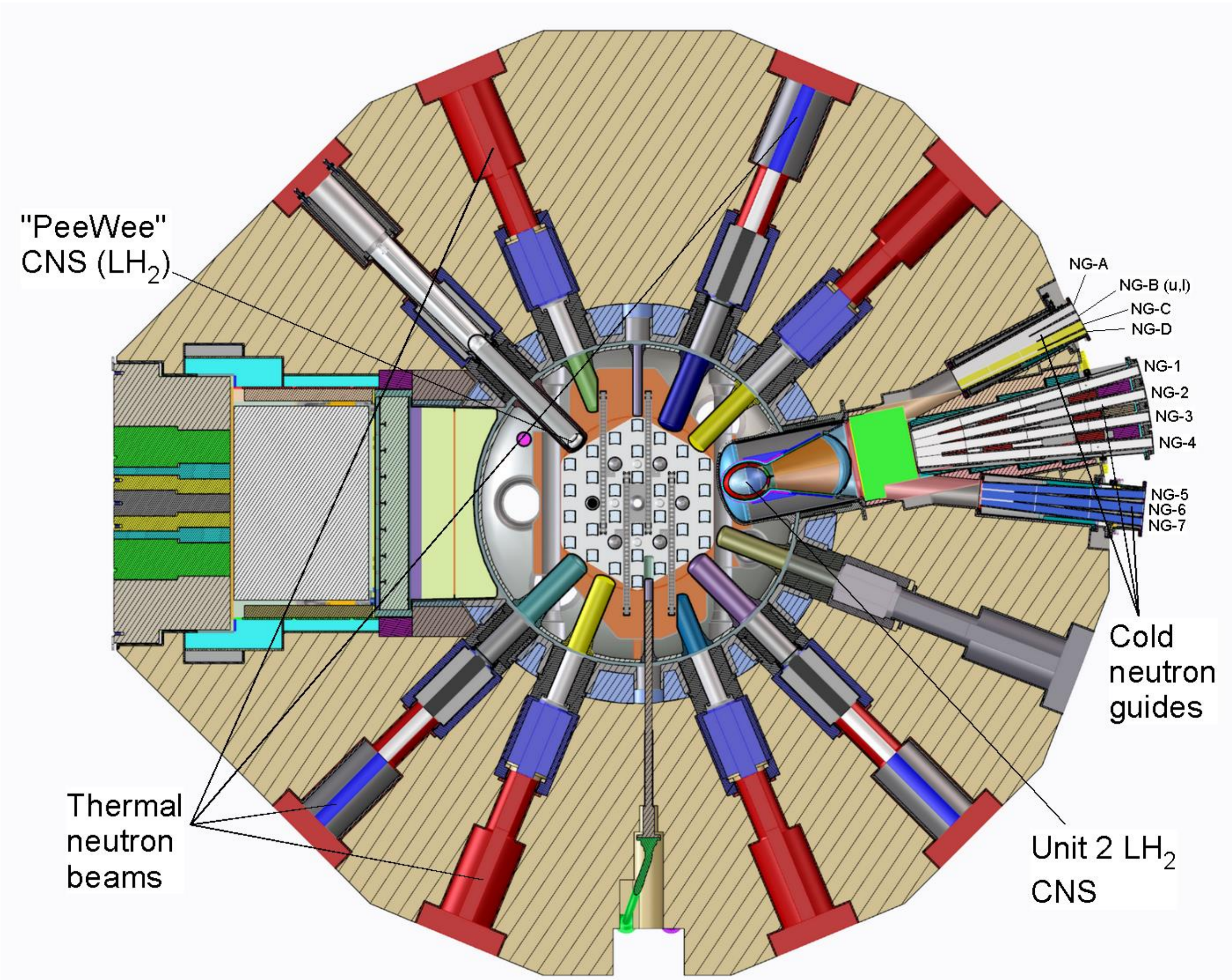

Figure 2. View of the NBSR showing the Unit 2 LH_2 CNS in the large cryogenic port and the compact “peewee” LH_2 CNS serving the MACS instrument.

From the beginnings of the Cold Neutron Research Facility in the early nineties 7 cold neutron guides (NG-1 to 7 - Figure 2) were online. However, when CTW became available by moving the MACS instrument to its dedicated CNS, a major cold neutron expansion project (2007 – 2012) provided another 5 cold neutron guides (NG-A, Bl, Bu, C, and D) [1]. The fifth guide was feasible because two reduced height beams required by the SANS instruments are provided by a split NG-B guide (NG-Bu and NG-Bl), one passing above the other and curving in opposite directions. The only minor consequence is the slightly different sample heights of the two instruments.

The NNS (**Figure** 3) is envisaged with two cold neutron sources. The neutron guides should be directed at the peak cold neutron flux centers of these sources in such a way that they don’t directly view the fuel element within their angular acceptance range. The thermal beams may be extracted approximately perpendicular to the cold neutron beams tangentially to the sides of the fuel that are unencumbered by the cold neutron sources. They are positioned to tap the unperturbed thermal flux peak which lies outside of the fuel region.

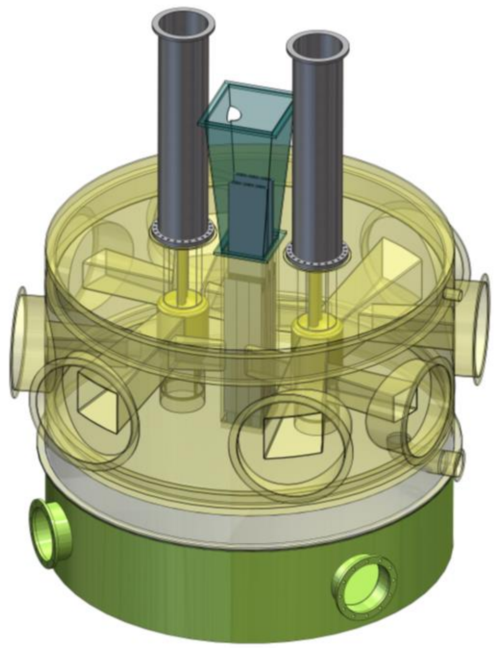

Figure 3. NNS core showing two cold neutron sources and the fuel assembly at the center.

The cold neutron guides may view each cold neutron source from opposing sides, as illustrated schematically in Figure 4.

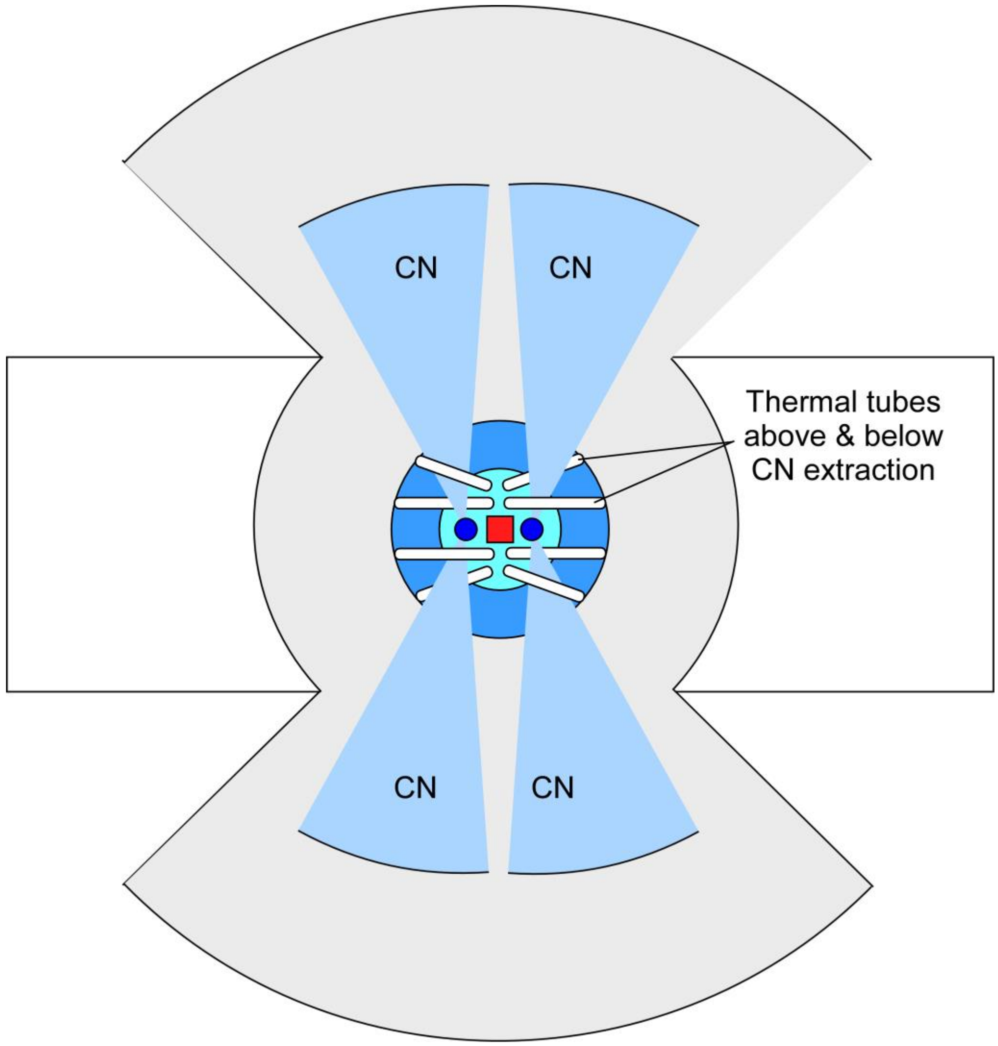

Figure 4. A rough schematic layout with possibly 16+ cold neutron guides and up to 8 thermal beams.

2. Curved neutron guides

The use of curved neutron guides (usually curved in the horizontal plane) is not only a means of physically separating beams but also of substantially reducing fast neutron and gamma contamination, especially if direct lines of sight through the guide are eliminated. Theoretically, even with no line of sight, zero transmission of reflected fast neutrons is achieved only in the limit that the neutron wavelength tends to zero. Nonetheless, continuously curved or curved-straight guide geometries are common. Sometimes, however, eliminating short-wavelength neutrons leads to excessive losses of some of the required neutron wavelengths due to the form of the transmission function. For example, the theoretical transmission of an ideal "long" (no line of sight) curved guide is 2/3 at the so-called "characteristic wavelength", λ_c [2]. λ_c, in turn, depends on the critical angle of the reflective coating on the outer radius (concave surface) of the guide and the "characteristic angle", ψ_c, which depends on the guide width and radius of curvature, but is independent of the reflective coatings (Figure 5). λ_c is given by Eq. (1)
.

$$\lambda_c = \frac{\psi_c}{\gamma_{Ni} m_{out}} = \frac{1}{\gamma_{Ni} m_{out}} \sqrt{\frac{2W}{\rho}} \qquad (1)$$

where W is the width, ρ is the radius of curvature, and the product $\gamma_{Ni} m_{out}$ is the effective critical angle per unit wavelength of the reflective coating on the outer radius, where m_{out} is the so-called "*m*" value of the outer radius coating. Note that for illustrative purposes Figure 5 is highly exaggerated with $\rho >> W$ in practice for most guide systems. For example, W is typically several cm, whilst ρ may be ~ km, consequently, small-angle approximations almost always apply. We see from Figure 5 that λ_c is reduced by increasing the m value of the outer radius coating, m_{out}. An additional drawback of (non-line-of-sight) curved guides is that the spatial distribution of neutrons at the guide exit is increasingly skewed towards the outer radius for shorter wavelengths and, as the wavelength passes below λ_c, the intensity becomes zero at the inner radius. By employing a curved-straight guide geometry with increased m_{out}, it is possible to mitigate these undesirable behaviors and create (ideally) conditions for spatial uniformity of the beam above a given wavelength [3]. This principle, dubbed "Phase Space Tailoring" (PST), was employed for some of the NCNR Expansion Project guides [1]. The PST principle is summarized in Appendix B.

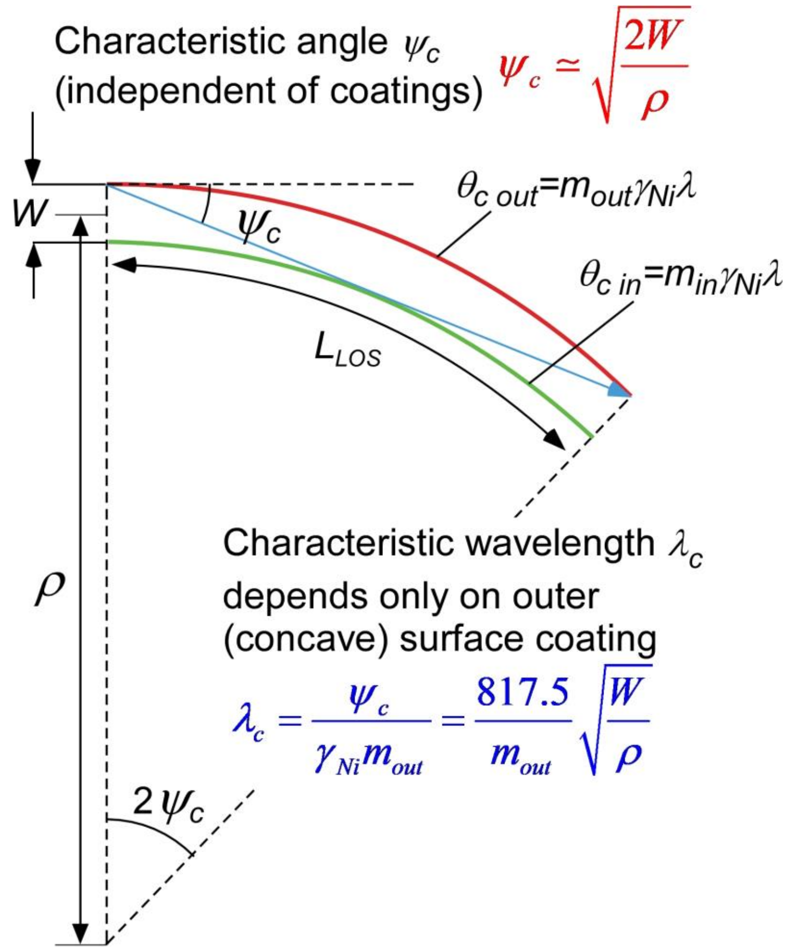

Figure 5. Some quantities related to long (no line-of-sight) curved guides.

The lateral displacement of a pure curved guide exit is illustrated in Figure 6. In the small-angle approximation, the lateral displacement with respect to the guide axis at its entrance is given by Eq. (2).

$$D_{LOS} \approx 4W \tag{2}$$

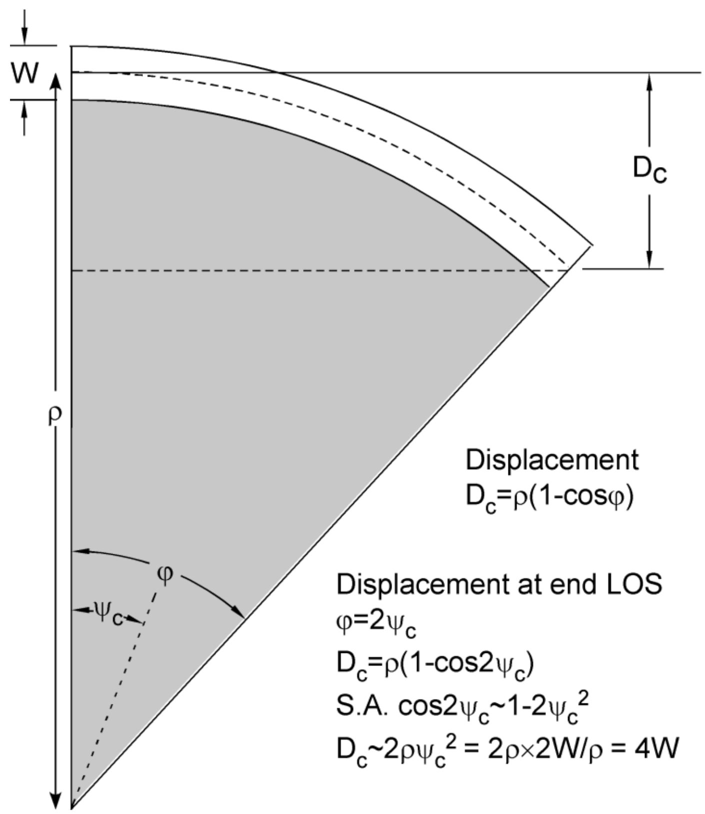

Figure 6. Lateral displacement of a curved neutron guide.

At the end of the line of sight $\varphi = 2\psi_c$ (Figure 5, Figure 6) and the arc length of the curve, L_c, at that point = $L_{LOS} = \rho\varphi$, therefore,

$$L_{LOS} = \rho\varphi \quad = 2\rho\psi_c \quad \approx \sqrt{8W\rho} \tag{3}$$

The arc length of the curved guide (L_c) is usually known. Given that $\varphi[\text{rad}] = \frac{L_c}{\rho}$, the displacement of a curved-straight guide (D_c) can then be found per Eq. (4).

$$D_c(L_c, \rho) = \rho(1 - \cos\varphi) \quad = \rho\left(1 - \cos\frac{L_c}{\rho}\right) \tag{4}$$

The displacement of a curved-straight guide (a curved guide followed by a straight guide section that is tangential to the curve at its exit) is illustrated in Figure 7.

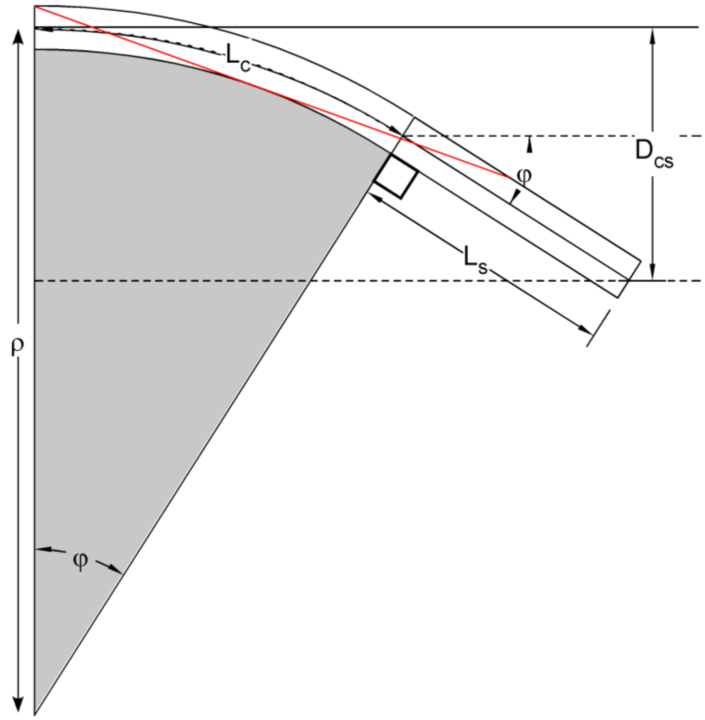

Figure 7. Lateral displacement of a curved guide followed by a straight guide.

The lateral displacement for a curved section (arc length L_c) followed by a straight section L_s is given by D_{cs} per Eq. (5). In terms of total guide length L, L_c and ρ, we have D_{cs} per Eq. (6).

$$D_{cs}(\rho, L_c, L_s) = \rho(1-\cos\varphi) + L_s \sin\varphi \quad = \rho\left(1-\cos\frac{L_c}{\rho}\right) + L_s \sin\frac{L_c}{\rho} \tag{5}$$

$$D_{cs}(\rho, L_c, L) = \rho\left(1-\cos\frac{L_c}{\rho}\right) + (L-L_c)\sin\frac{L_c}{\rho} \tag{6}$$

At the NCNR, retrofitting guides NG-1 through 7 with curved guides is hampered by the narrow penetration through the 7 m thick reinforced concrete wall that exists between the reactor hall C100 and the guide hall G100 for these guides. This structure means that little or no curvature of the guide is practically possible before the guide is most of the way through the penetration or into G100. This is the case for the future NG-6 guide, for example. However, for the NNS, no such restrictions exist yet, thus the designers are free to curve the guides quite close to the source helping with instrument separation.

3. Some geometry definitions and positions of guide exits

The basic geometry of a curved-straight guide with respect to an origin, O_s, which is defined as the center of the cold source and a central (*y*) axis of symmetry (which may be the bisector of a group of angularly separated guides viewing the cold source) is illustrated in Figure 8. φ_0 is the initial orientation, with respect to *y*, of the axis of a short straight in-pile guide element, length L_{IP}. This axis is assumed to pass through O_s. The distance from the source to the center of the in-pile guide entrance is d_{sg}. The initial axis is co-linear with the tangent to the curved guide axis at its entrance, $d_0 = d_{sg} + L_{IP}$ is the distance from the cold source center to the center of the curved guide entrance, L_c is the (arc) length of the purely curved part of the guide, and L_s is the length of the final straight part of the guide tangent with axis of the curved guide exit (point Q). The center of the guide exit is point R.

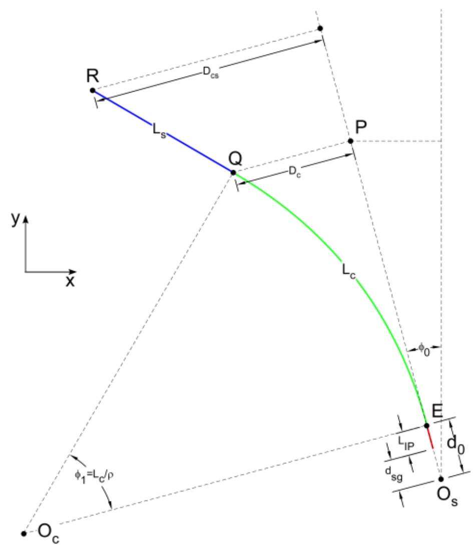

Figure 8. Geometry showing the guide geometry with respect to the cold source center O_s and a reference axis *y*. The guide consists of an initial straight portion (red), followed by a curved section (green), and a final straight section (blue). The red and blue lines are tangent to the curve at its entrance (E) and exit (Q), respectively. The guide exit is point R.

The chosen sign convention is shown in Figure 9 for the angles and in Figure 8 for the sense of the curvature of the guides with respect to the *xy* coordinate system.

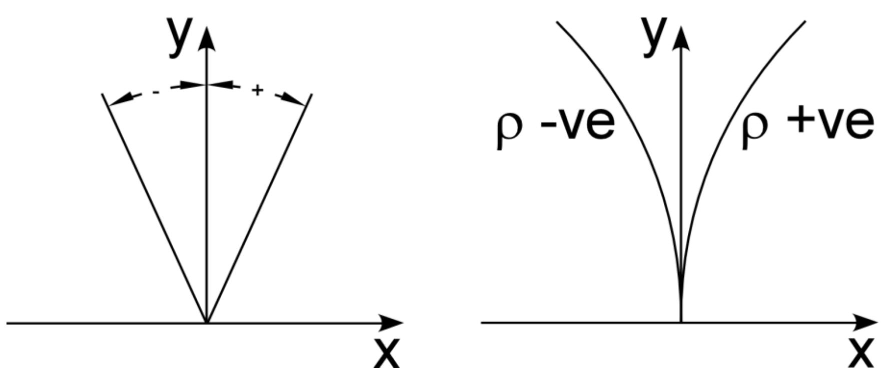

Figure 9. Sign convention for angles and curvatures.

We see that in this system, the center of the purely curved section is O_c, which has the following coordinates shown in Eq. (7). This enables Eq. (8) to represent the circular curved part of the guide.

$$O_c = [x_c, y_c] = [d_0 \sin\varphi_0 + \rho\cos\varphi_0,\, d_0\cos\varphi_0 - \rho\sin\varphi_0] \quad (7)$$

$$(x - x_c)^2 + (y - y_c)^2 = \rho^2 \quad (8)$$

The entrance to the curved section (point E), which may be downstream of an initial straight in-pile section is found per Eq. (9). The exits of guides starting "north" will always end up in the upper two quadrants for any realistic case, therefore from Figure 8 with the sign convention in Figure 9, the point P is given by Eq.(10), where $\varphi_1 = \frac{L_c}{\rho}$ is the arc angle of the curved section. Therefore, point Q is given by Eq. (11).

$$E = [x_E, y_E] = d_0[\sin\varphi_0, \cos\varphi_0] \quad (9)$$

$$\begin{aligned} P &= [x_P, y_P] = [x_E, y_E] + \rho\sin\varphi_1[\sin\varphi_0, \cos\varphi_0] \\ &= (d_0 + \rho\sin\varphi_1)[\sin\varphi_0, \cos\varphi_0] \end{aligned} \quad (10)$$

$$\begin{aligned} Q &= [x_Q, y_Q] == [x_P, y_P] + \rho(1 - \cos\varphi_1)[\cos\varphi_0, -\sin\varphi_0] \\ &= \begin{bmatrix} d_0\sin\varphi_0 + \rho[\cos\varphi_0 - \cos(\varphi_0 + \varphi_1)], \\ d_0\cos\varphi_0 + \rho[\sin(\varphi_0 + \varphi_1) - \sin\varphi_0] \end{bmatrix} \end{aligned} \quad (11)$$

The angle of the tangent at point Q is $\varphi_0 + \varphi_1$, therefore the point R (the coordinates of the guide exit center with respect to the cold source center O_s) is given by Eq. (12), and the line QR is defined by Eq. (13).

$$\begin{aligned} R &= [x_R, y_R] = [x_Q, y_Q] + L_s[\sin(\varphi_0 + \varphi_1), \cos(\varphi_0 + \varphi_1)] \\ &= \begin{bmatrix} d_0\sin\varphi_0 + \rho[\cos\varphi_0 - \cos(\varphi_0 + \varphi_1)] + L_s\sin(\varphi_0 + \varphi_1), \\ d_0\cos\varphi_0 + \rho[\sin(\varphi_0 + \varphi_1) - \sin\varphi_0] + L_s\cos(\varphi_0 + \varphi_1) \end{bmatrix} \end{aligned} \quad (12)$$

$$y = y_R + (x - x_R)\cot(\varphi_0 + \varphi_1) \quad (13).$$

3.1. Assumed curved-straight guide configurations for initial instrument layouts of the NNS

Even with a common curved-straight guide geometry, there is a multitude of possible guide configurations with different combinations of ρ, L_c and L_s. Two (or more) guides may also issue from a single in-pile "port" with different heights and curvatures. An example of the latter is provided by the NCNR guides NG-Bl and NG-Bu for the 10 m SANS and 30 m SANS instruments, respectively on the CTW beam tube. NG-Bu (upper) takes the upper 5 cm and NG-Bl (lower) takes the lower 5 cm portion of the beam from a common in-pile entrance and the guides curve in opposite senses. Therefore, a total of 5 separate guides emanate from 4 in-pile ports initially. This may be possible for some or all of the guide groups viewing the NNS cold sources, however, for simplicity, we will assume a configuration of 4 guides (and 4 in-pile ports) in each group.

For the NNS we could have up to four separate groups of cold neutron guides in opposing directions, as indicated schematically in Figure 4, providing a minimum of 16 end-positions, which could satisfy the wish list given in Appendix A. To further allow for monochromatic instrument side positions, facilitate instrument accessibility, and accommodate "wide" instruments, typically with some duplication of + and - scattering angles as well as "slim" SANS-type instruments on the end positions, we choose to start by making the two central guides of each group longer than the two outer guides and to adequately separate the outer guides from the inner guides. We attempt to adequately separate the end stations of each group of 4 guides by choosing simple constraining criteria:

1. We define an "exclusion radius", R_i, at the end of each guide such that the defined circles do not intersect. This implies that Eq. (14) is true.

$$\sqrt{\left(\left(x_{R,i}-x_{R,i+1}\right)^2+\left(y_{R,i}-y_{R,i+1}\right)^2\right)} \geq \left(R_i+R_{i+1}\right), \qquad i=1,2,3 \tag{14}$$

For the longer central guides, this exclusion could be more longitudinal than lateral and the axes of the adjacent guides could still be quite close. Therefore, for the two outer guides, we impose an *additional* exclusion requirement:

2. For the two outer guides, we define the perpendicular to their axes at their exits and lines *a* and *b* defining the initial and final axes of the adjacent inner guides (Figure 10). We then insist that the minimum distance of the perpendiculars to lines *a* and *b* exceed a defined minimum separation D_i. A couple of limiting examples for which the minimum intersection distance equals D_i are illustrated in Figure 10. The actual minimum separation of the guides may be slightly less than D_i if the intersection occurs with the curved section of the inner guide first (see the example on the right of Figure 10), however, the difference is typically sufficiently small to avoid complications of solving for intersections with the curve as well.

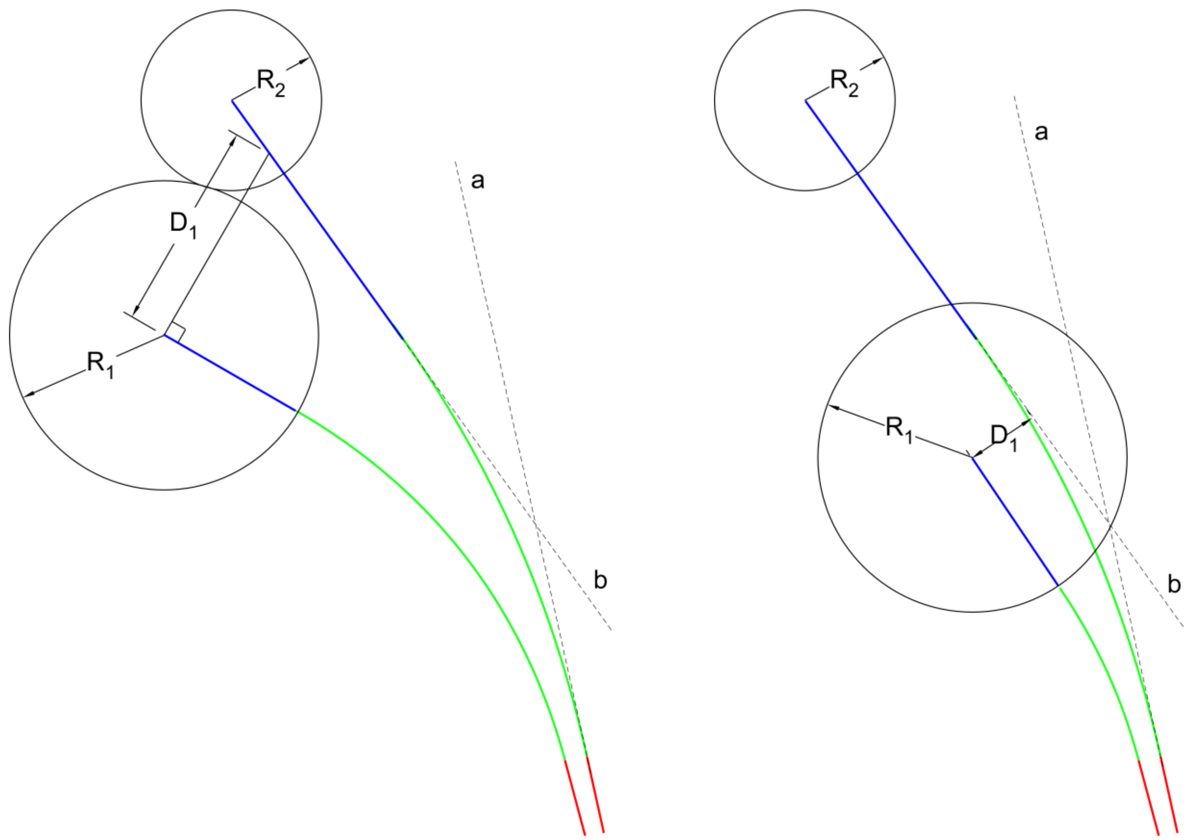

Figure 10. Examples of the exclusion radii (R_1 and R_2) at the ends of two guides and a required minimum perpendicular guide separation distance, D_1. In both figures, the guide exit exclusion radii do not intersect and a minimum perpendicular from the exit of the shorter guide, specified by D_1, is satisfied.

From Eq. (12), the unit vector $\overrightarrow{\hat{\mathbf{Q}}\mathbf{R}} = \left[\sin(\varphi_0+\varphi_1), \cos(\varphi_0+\varphi_1)\right]$. Therefore, the perpendicular to the guide axis at its exit (point R) must be along $\mathbf{R}_\perp = \left[\pm\cos(\varphi_0+\varphi_1), \mp\sin(\varphi_0+\varphi_1)\right]$, consequently, the perpendicular at the exit for the outer guide is defined by the line in Eq. (15).

$$y_\perp = y_{R,outer} + \left(x_{R,outer} - x\right)\tan\left(\varphi_{0,outer} + \varphi_{1,outer}\right) \tag{15}$$

Per Eq. (15), x_R and y_R are given by Eq. (12). Line *a* for all guides intersects the source origin, O_s, (see Figure 8) which defines [0,0] in this coordinate system, therefore, line *a* for the inner guide is defined by Eq. (16). The intersections of Eq. (15) for the outer guide with Eq. (16) occurs per Eq. (17). It then follows that the distance of the perpendicular to line *a* is given per Eq. (18).

$$y = x\cot\varphi_{0,inner} \quad \text{Line } a \tag{16}$$

$$x_a = \frac{y_{R,outer} + x_{R,outer}\tan\left(\varphi_{0,outer} + \varphi_{1,outer}\right)}{\left[\cot\varphi_{0,inner} + \tan\left(\varphi_{0,outer} + \varphi_{1,outer}\right)\right]}$$

and (17).

$$y_a = x_a \cot\varphi_{0,inner}$$

$$D_a = \sqrt{\left(\left(x_R - x_a\right)^2 + \left(y_R - y_a\right)^2\right)} \quad (18)$$

Line *b* is given by Eq. (13) with x_R, y_R, φ_0, and φ_1 appropriate for the inner guide. The intersection of Eq. (15) for the outer guide with Eq. (13) for the inner guide occurs in Eq. (19). Therefore, the distance of the perpendicular to line *b* is found per Eq. (20).

$$x_b = \frac{y_{R,outer} + x_{R,outer}\tan\left(\varphi_{0,outer} + \varphi_{1,outer}\right) - y_{R,inner} + x_{R,inner}\cot\left(\varphi_{0,inner} + \varphi_{1,inner}\right)}{\left[\tan\left(\varphi_{0,outer} + \varphi_{1,outer}\right) + \cot\left(\varphi_{0,inner} + \varphi_{1,inner}\right)\right]}$$

and (19)

$$y_b = y_{R,outer} + \left(x_{R,outer} - x_b\right)\tan\left(\varphi_{0,outer} + \varphi_{1,outer}\right)$$

$$D_b = \sqrt{\left(\left(x_R - x_b\right)^2 + \left(y_R - y_b\right)^2\right)} \quad (20).$$

Finally, the second constraint above requires that Eq. (21) is valid. Considering Eq. (15), it then follows that the coordinates of the limit of the restriction be defined by D_i as follows in Eq. (22), where sgn(*a,b*) are found per Eq. (23) to set the appropriate sign for the square root in Eq. (22).

$$\min\left(D_a, D_b\right) \geq D_i \quad (21)$$

$$x_D = x_{R,outer} + \mathrm{sgn}\left(a,b\right) D_i \frac{1}{\sqrt{\left[1 + \tan^2\left(\varphi_{0,outer} + \varphi_{1,outer}\right)\right]}}$$

$$y_D = y_{R,outer} + \left(x_{R,outer} - x_D\right)\tan\left(\varphi_{0,outer} + \varphi_{1,outer}\right) \quad (22)$$

$$\mathrm{sgn}\left(a,b\right) = \begin{cases} sign\left(x_a - x_{R,outer}\right); & \min\left(D_a, D_b\right) = D_a \\ sign\left(x_b - x_{R,outer}\right); & \min\left(D_a, D_b\right) = D_b \end{cases} \quad (23)$$

4. Initial angular separation of guides and view of the source

The initial angular separation, $\Delta\varphi_0$, of the individual guides helps separate the beams and instruments, further facilitated by the curvature of the guides which also filters the beams. We also wish to make efficient use of the solid angle subtended by the source, minimizing guide under-illumination (see Sec. 5). The latter requires that the guide entrances are sufficiently close to the source. Radiation heating of the guide usually limits their practical closest approach but if full illumination conditions are satisfied for the desired neutron wavelength range there is no need for a closer approach. The initial guide axes should converge on the source center, so the separation of the guide entrances is then $d_{sg}\Delta\varphi_0$. The most compact arrangement of divided guide entrances (i.e., the reflective coatings of both sides of the guide extend to d_{sg} from the source) occurs when $d_{sg}\Delta\varphi_0 \approx W$ as shown on the right-hand side of Figure 11. For d_{sg} = 150 cm and W=6 cm this occurs when $\Delta\varphi_0 \approx 2.3°$.

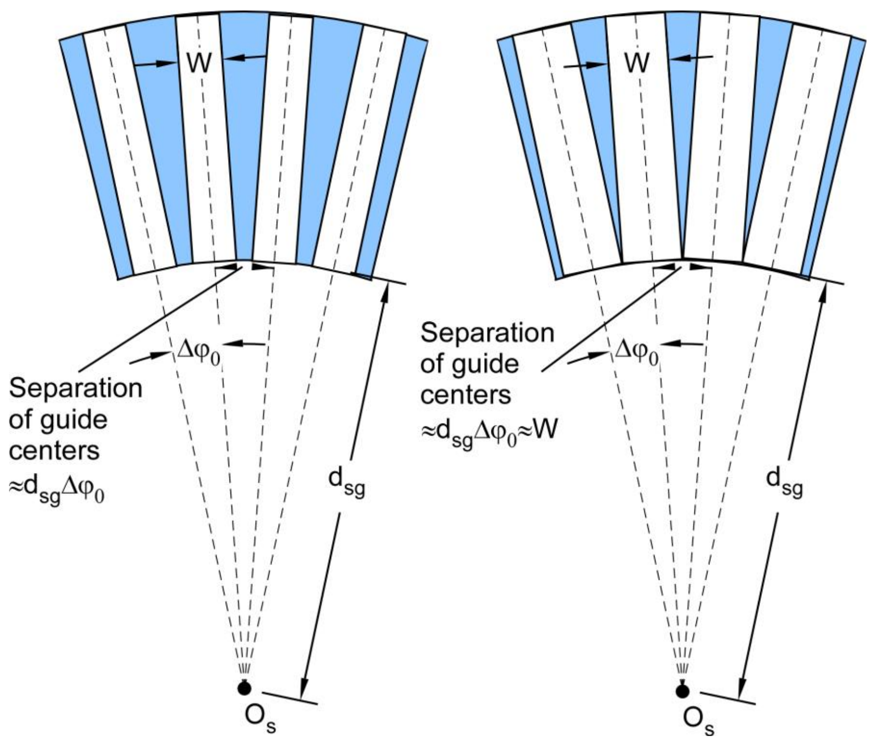

Figure 11. Arrangement of in-pile guide axes initially converging on the source center, O_s. The separation of the guide centers at the entrance is about $d_{sg}\Delta\varphi_0$. The case for $d_{sg}\Delta\varphi_0 \approx W$ is shown in the right figure.

5. Cold source dimensions and the onset of guide under-illumination

A further consideration of the limits of width and height of the guide entrances is their *illumination* by the source. The effect of under-illumination is illustrated schematically in Figure 12 for a long straight guide.

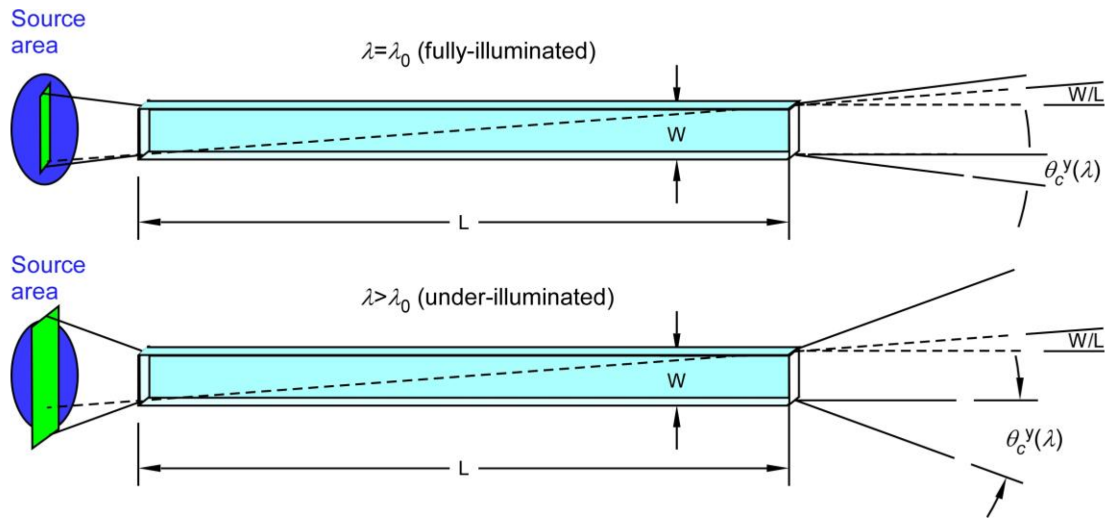

Figure 12. A schematic illustrating the effect of under-illumination for a long straight guide. The blue oval represents the cold source area and the green patch represents the acceptance of the neutron guide for a given wavelength. Usually, the size of the green patch increases proportionally to the wavelength in each dimension, therefore this patch should remain within the source area up to the longest desired (useful) wavelengths, if possible.

Under-illumination occurs when the acceptance solid angle of the guide begins to fall beyond the region of the source area (in this case the cold source moderator region). Under-illumination tends to increase with increasing wavelength, increasing separation between the source and the guide entrance, and with increasing guide entrance size or decreasing source size. Because neutron guide cross-sections are rectangular (and the guide acceptance area projected onto the source is also rectangular), the source cross-section should be rectangular also, if possible, as is the case for the vertically-oriented cylinder proposed for the NNS. Usually, a minimum approach of the guide entrances with respect to the source is imposed by radiation damage and heat load to the in-pile sections of the neutron guide, however, if the conditions for full illumination of the guide entrances are satisfied for all useful wavelengths, there is nothing to be gained from a closer approach to the source. For the NBSR guides, a compromise between radiation damage and heating and illumination must be tolerated and the guide entrances are typically about 1.3 to 1.6 m from the cold source center. For the larger potential cross-sectional area of the NNS source, improved illumination (to longer wavelengths) may likely be achieved, despite the potential for increased radiation flux and heating Figure 12, illustrates the case of a long straight guide for wavelengths where the critical angle, $\theta_c(\lambda)$ is greater than the line-of-sight angle W/L. In such a case, under-illumination for rectangular cross-section sources may be estimated in a similar way to neutron losses at guide cuts, with the width and height of the downstream guide replaced by the width and height of the cold source. If the source is assumed uniformly bright over its area, the formalism is given in

Appendix B of Ref. [4], which also allows for horizontal/and or vertical offsets (for example, if the guide central axis is not aligned on the cold source center, as is the case for NG-Bl and NG-Bu at the NCNR).

An example of under-illumination, calculated for all *m*=2 and all *m*=3 long straight guides of entrance dimension 6 cm(w) × 15 cm(h) and 6 cm(w) × 20 cm(h) at 1.5 m from a cold source similar to OPAL's (of assumed effective cross-section 29.7 cm(w) × 30.5 cm(h)), is given in Figure 13 and Figure 14. The blue curves are the horizontal plane illumination, the red curves are the vertical plane illumination, and the black curves are the product (overall illumination), where 1 implies full illumination. The horizontal illuminations in Figure 13 and Figure 14 are identical because only the guide height was changed. This example shows that for a 6 cm-wide entrance guide, horizontal under-illumination onsets for wavelengths above about 23 Å for *m*=2 and about 15 Å for *m*=3. For the 15 cm-high guide vertical under-illumination occurs above about 15 Å for *m*=2 and about 10 Å for *m*=3, and for the 20 cm-high guide, vertical under-illumination occurs above about 10 Å for *m*=2 and about 7 Å for *m*=3. Because the vertical under-illumination onsets at shorter wavelengths than the horizontal for both the 6 cm(w) × 15 cm(h) and the 6 cm(w) × 20 cm(h) guides, the vertical under-illumination thresholds define the onset of *any* under-illumination for each guide example.

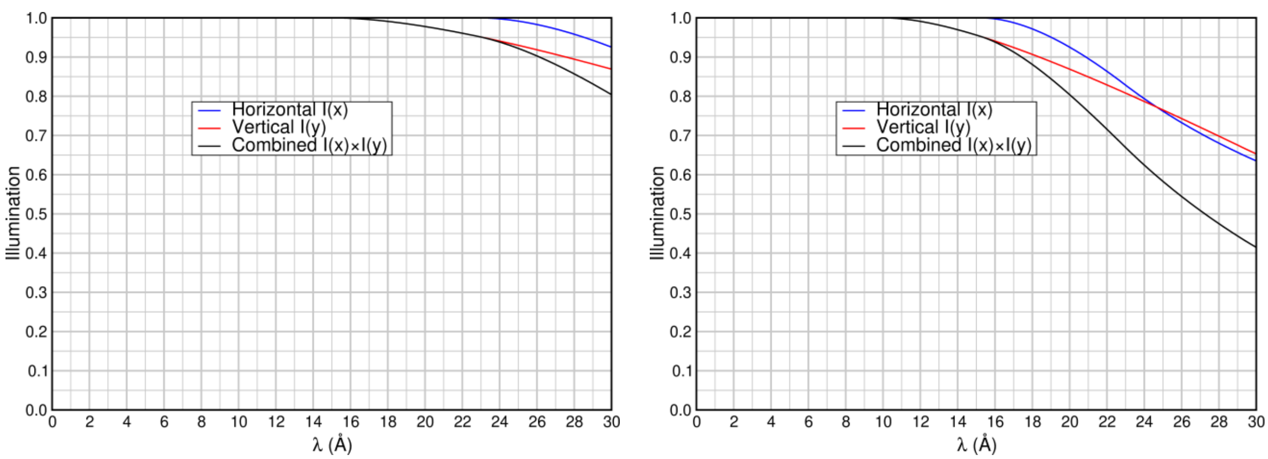

Figure 13. Estimated illumination of a 6 cm(w) × 15 cm(h) long straight guide, entrance at 1.5 m from a 29.7 cm(w) × 30.5 cm(h) source, with all *m*=2 (left) and all *m*=3 (right) as a function of wavelength. The blue curve is the horizontal illumination, the red curve is the vertical illumination, and the black curve is the product (overall illumination).

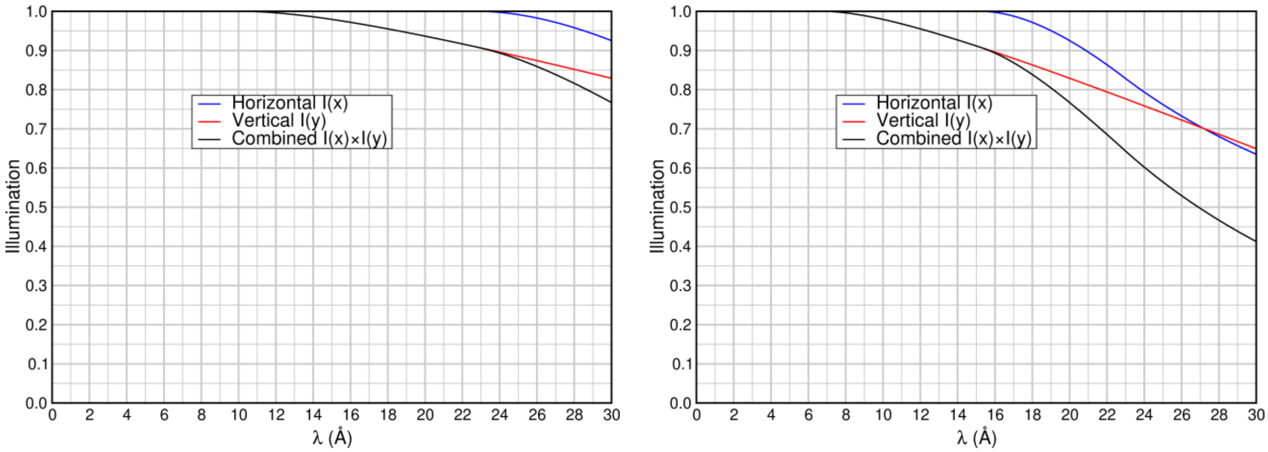

Figure 14. Estimated illumination of a 6 cm(w) × 20 cm(h) long straight guide, entrance at 1.5 m from a 29.7 cm(w) × 30.5 cm(h) source, with all *m*=2 (left) and all *m*=3 (right) as a function of wavelength. The blue curve is the horizontal illumination, the red curve is the vertical illumination, and the black curve is the product (overall illumination). The horizontal illumination is identical to the 6 cm(w) × 15 cm(h) case in Figure 13 because only the height of the guide has been changed.

6. Characteristic wavelength of the guides and likely supermirror coating requirements

Based on the geometry of the curved section of the guide, assuming that the curve has no direct line of sight, the characteristic wavelength, λ_c, provides a measure of the short-wavelength "cut-off" in the transmission of the guide. λ_c, in turn, depends on the curved section geometry (width, W, and radius of curvature, ρ) and on the supermirror coating (designated by m_{out}, which is the ratio of the supermirror high Q reflectivity cutoff with respect to that of the critical Q of natural Ni). λ_c is given by Eq. (1):

It is pointless designing a guide with a radius of curvature requiring an impractically large value of m_{out}. Nowadays m of up to about 8 or more is possible [5] but these can be prohibitively expensive with a required number of deposited supermirror layers typically varying as ~m^4 and the supermirror layer thickness increasing as ~m^3. The latter can significantly affect shielding requirements because of the gamma radiation caused by neutron absorption in the supermirror. m=2 or m=3 is much more routine (and affordable) for modern guides. Furthermore, if the exit divergence is not controlled, as in a PST guide (see Appendix B), rarely can instruments fully exploit a large horizontal beam divergence typically associated with a high m guide. This often imposes an upper limit on m, especially the side coatings. However, in some cases, the vertical divergence is less restrictive and sometimes desirable, and vertical focusing of the beam can frequently be considered. For an idealized "perfect" curved guide, λ_c is the wavelength below which the transmission falls below 2/3 of an equivalently-coated straight guide. Frequently, we do not want λ_c too low otherwise excessive epithermal and fast neutrons may be transmitted. On the other hand, if λ_c is too high, the shorter wavelength intensity used by the instruments may be excessively compromised. For reference, the "idealized" values of λ_c for the curved sections of the CTW guides are approximated in Table 1. We see from Table 1 that a value of $\lambda_c \approx 3$Å is usually a reasonable compromise between transmitting useful shorter wavelengths and fast neutron filtering of the beam.

Table 1. Inferred values of λ_c for the NCNR CTW "letter" guides based on idealized approximations of the guide parameters. Note that for a stronger curvature, a larger value of m_{out} is required to achieve a given λ_c (see Eq. (1)).

Guide	Width of constant width part of curve, W_c (cm)	Radius of curvature, ρ (m)	Coating on outer radius (concave surface) of constant width part of curve, m_{out}	λ_c (Å)
NG-A	5	150.8	3.6	4.14
NG-Bl	5	780.6	1.65	3.97
NG-Bu	5	1432.4	1.5	3.22
NG-C	11	933.2	3.6	2.47
NG-D	6	906.6	2.0	3.33

7. A simplified illustrative example of guide/instrument separations

A simplified example from the discussion above is chosen, placing some realistic constraints on the neutron guides.

7.1. Example parameters and constraints

1. Assume all guides curved-straight geometry with a 1 m long section of straight in-pile guide (L_{IP} = 1 m), with total guide length, $L = L_{IP} + L_c + L_s$ (see Figure 8).
2. The distance of the in-pile guide entrance from the cold source center is d_{sg}=1.5 m, so that d_0 = 2.5 m.
3. The entrance width of all guides is fixed at W = 6 cm and their angular separation, $\Delta\varphi_0$, at 2.3°, so that $d_{sg}\Delta\varphi_0 \approx W$ and their entrances are close-packed at d_{sg}=1.5 cm (as illustrated in Figure 11).
4. The length of the *curved* section, L_c, is chosen to be 20% longer than the line-of-sight distance so that L_c=1.2$L_{LOS} \approx$ 1.2×√(8$W\rho$) (see Eq. (3)). This guarantees that the curved section exit is comfortably beyond the direct line of sight to the source with the straight section providing additional margin (and improved beam uniformity – see [3] and Appendix B).
5. Assume 4 in-pile ports per guide group. (For the NNS we envisage 4 such groups (one roughly 'north' and one roughly 'south' on each cold source) so that there would be a total of 16 guides for the NNS).
6. The maximum length of any guide, L_{max}, is 60 m.
7. There is an exclusion radius at the exit of each guide, R_{excl}, required to guarantee instrument access or avoid mechanical interference. This can be estimated for each instrument type, but to simplify this example we use a fixed value of R_{excl} = 5 m (see Sec. 3.1, Eq. (14), and Figure 10).
8. The additional spatial constraint on the perpendicular distances from the two *outer* guide exits with respect to the principal axes *a* and *b* (Eqs. (16) and (13)) of the two *inner* guides (see Eq. (21) and Figure 10) must be greater than or equal to 2 m on both sides (i.e. $D_i \geq$ 2 m, i=1 or 4).
9. Arbitrarily choose the radius of curvature, ρ, of the curved sections of the two external guides of each group to be *half* the radius of the two inner ones.
10. The two guides on each side of each group centerline must curve in *opposite* directions.
11. m_{out}-ρ combinations of the 6 cm-wide guides must produce a characteristic wavelength, λ_c, of 3 Å for each guide.

7.2. Results for the simplified example

A group configuration that satisfies the constraints set out in Sec. 7.1 with radii of curvature of the curved sections of the outer guides, ρ_{outer} = 750 m (inner guides ρ_{inner} = 1500 m) is illustrated in Figure 15 and some of the final guide parameters are summarized in Table 2. Note that the values of m_{out} (2.4 outer guides, 1.7 inner guides) are perfectly reasonable for obtaining a λ_c of 3Å.

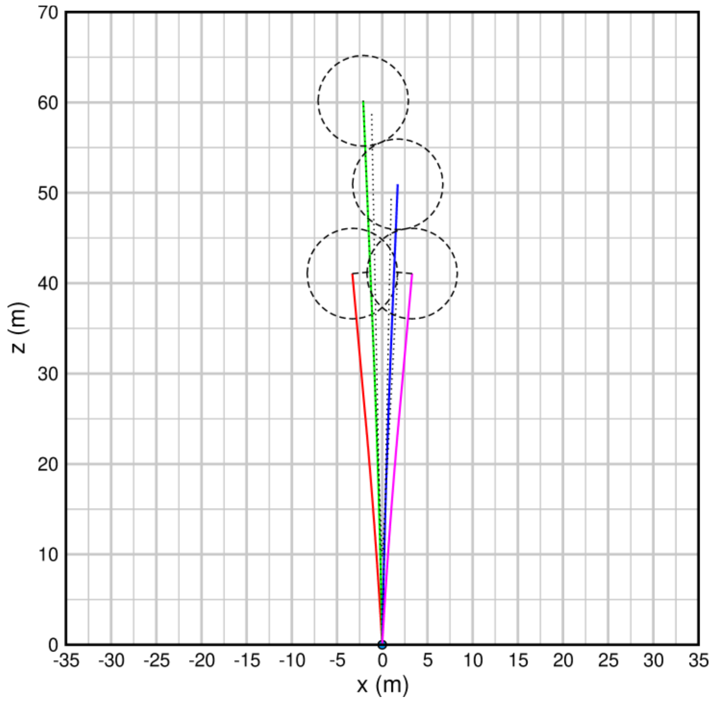

Figure 15. Scale layout of 4 curved-straight guides with a ratio of ρ inner to outer of factor 2, satisfying the radial and perpendicular physical exclusion and maximum guide length constraints. Some of the resulting guide parameters are summarized in Table 2.

Table 2. Summary of some of the guide parameters satisfying the constraints of the example with ρ_{outer} = 750 m.

GUIDE #	1	2	3	4
φ_0 (rads)	-0.0602	-0.0201	0.0201	0.0602
Distance source center-in-pile guide entrance, d_{sg} (m)	1.50	1.50	1.50	1.50
Distance straight part of in-pile before curve, L_{IP} (m)	1.00	1.00	1.00	1.00
Distance source center-*curved* guide entrance, d_0 (m)	2.50	2.50	2.50	2.50
W (cm)	6.00	6.00	6.00	6.00
Radius of curvature, ρ (m)	-750.0	-1500.0	1500.0	750.0
Line of sight distance for curved section, L_{LOS} (m)	18.97	26.83	26.83	18.97
Length of curved section, L_c (m)	22.77	32.20	32.20	22.77
φ_1 =arc angle of curved section =L_c/ρ (rads)	-0.0304	-0.0215	0.0215	0.0304
Length of straight section, L_s (m)	15.93	25.52	16.27	15.93
Total length of guide, $L=L_c+L_s$ (m)	39.70	58.72	49.47	39.70
Displacement of end of guide with respect to initial axis, D_{cs} (m)	0.829	0.893	0.695	0.829
x_R (m)	-3.307	-2.102	1.718	3.307
y_R (m)	41.07	60.18	50.94	41.07
Crow-flight separation guide exits i-(i+1) (m)	19.15	10.00	10.00	
D_a (m)	2.49			2.49
D_b (m)	2.00			2.00
MIN(D_a,D_b)	2.00	N/A	N/A	2.00
$\|\psi_c\|$ (rad)	0.0126	0.0089	0.0089	0.0126
m_{out} for λ_c=3Å	2.44	1.72	1.72	2.44

8. Feasible guide configurations for the NNS based on the proposed *cold* neutron instrument suite given in Appendix A

In Appendix A, we envision 15 to 17 cold neutron instruments that require end-guide positions. For the NNS we envision a minimum of 16 end positions (4 groups of at least 4 guides "north and south" on two large LD_2 cold sources). We can likely create additional end positions with benders on guides whose end-position instruments do not require the full beam height (e.g. regular SANS instruments) and monochromatic positions may be created on the sides of the longer guides and also on outer guides where the full beam height may not be required. These instruments may be roughly classified as in Table 3.

Table 3. A rough summary of cold neutron instrument types listed in Appendix A. "Symmetrical" implies approximately equal space is required on each side of the beam: 2π implies a significant $\pm 2\theta$ scattering angle, π implies a mostly one-sided detection with possibly a small range of negative scattering angle overlap, "narrow" implies something like a SANS instrument.

Instrument type	Total Number	End position	Instrument geometry type	Estimated minimum exclusion radius at guide exit (m)	Estimated minimum exclusion perpendicular to exit (shorter outer guides, if applicable) (m)	Likely preferred position
SANS	3	YES	Symmetrical (narrow)	3 m	2 m	Inner PST guide or outer PST guide next to a narrower instrument?
Reflectometer (CANDOR type)	2	YES	Asymmetrical (π)	4.5 m	2.5 m	Outer more curved guide
Cold neutron imaging (CNI)	2	YES	Symmetrical (moderate)	3.5 m	2 m	Probably a less-curved PST guide?
Cold 3-axis	2	YES	Asymmetrical (π)	4 m	1.5 m	Likely a less curved guide with available space on one side
Backscattering	2	YES/NO?	Symmetrical (2π)	4 m	2 m	Stronger curved outer guide
NSE (Mezei-type)	1	YES	Asymmetrical (π)	5 m	1.5 m	Probably more curved outer guide
NSE (WASP type)	1	YES	Symmetrical (2π)	4.5 m	4.5 m	Probably more curved 4-12Å (but must have lateral space on both sides)
High current physics experimental position	1	YES	Symmetrical (variable to large)	5 m	5 m	Long inner guide end position
PGAA	1	YES	Symmetrical (narrow)	2.5 m	2.5 m	
NDP	1	YES	Symmetrical (narrow)	2.5 m	2.5 m	Possibly next to NSE (no B fields)
Materials Diffractometer (> 3Å)?	1?	YES	Symmetrical	3 m	3 m	Possibly on bender under a regular SANS instrument beam??
Interferometer		NO	Asymmetrical (π)		6 m	Outer guide
Monochromatic PL positions	2-3	NO			6 m	

Miscellaneous monochromatic/ test positions	2-3	NO			6 m	
uSANS	1	NO	Asymmetrical	3 m	3 m	
TOTAL	23-24	16-17				

The exclusion radii at the guide exits and perpendicular constraints of Table 3 may be used to roughly configure 4 guide group layouts. Additionally, it is assumed that the approximate instrument footprints given in Table 4 apply for defining instrument access.

Table 4. Assumed instrument footprints for instrument layouts.

Instrument type	Length (m)	Width range (m)	Max height (m)
SANS	16	-1.1 ≤ *x* ≤ 1.1	1.1
vSANS	28	-1.5 ≤ *x* ≤ 1.5	1.5
Refl (CANDOR)	5	±(-4.5 ≤ *x* ≤ 2.0)	1.5
CNI	11	±(-3.0 ≤ *x* ≤2.0)	1.5
CN3x	9.5	±(-1.5 ≤ *x* ≤ 4.0)	1.25
BS	5	-2.5 ≤ *x* ≤ 2.5	2.0
NSE-Mezei	10	±(-5.2 ≤ *x* ≤ 1.8)	1.5
NSE-WASP	4.5	-2.25 ≤ *x* ≤ 2.25	1.5
Physics	11	±(-5.5 ≤ *x* ≤ 2.5)	2.0
PGAA	4	±(-1.0 ≤ *x* ≤ 3.0)	1.25
NDP	4	-2.0 ≤ *x* ≤ 2.0	1.25

Four feasible curved-straight guide group layouts that could accommodate the instrument suite proposed in Appendix A are shown in Figure 16 to

Figure **19**. The corresponding guide properties are summarized in Table 5 to Table 8, respectively. Note that the beam height could be up to 20 cm for OPAL-like LD_2 cold sources, therefore, there may be ample opportunities for monochromatic side positions and possibly additional bender-type end positions (similar to NGA ʹ), especially on the exterior guides, where the whole height of the beam cannot be used by the end-station instruments (for example, the traditional SANS instruments). These are indicated schematically in the figures, not for any specific instrument. The layouts below are by no means final or optimized with respect to guide configuration. The exercise here is to demonstrate that all these instruments can be potentially accommodated and supplied with a broad cold neutron spectrum with realistic ranges of maximum supermirror *m* required to achieve λ_c = 3.0Å. The SANS instruments would likely be PST guides with m_{out} characteristic of the outer radial coating (concave surface) of the curved sections of these guides, as is the case for the 10 m and 30 m SANS currently on the NBSR guides NG-Bl and NG-Bu.

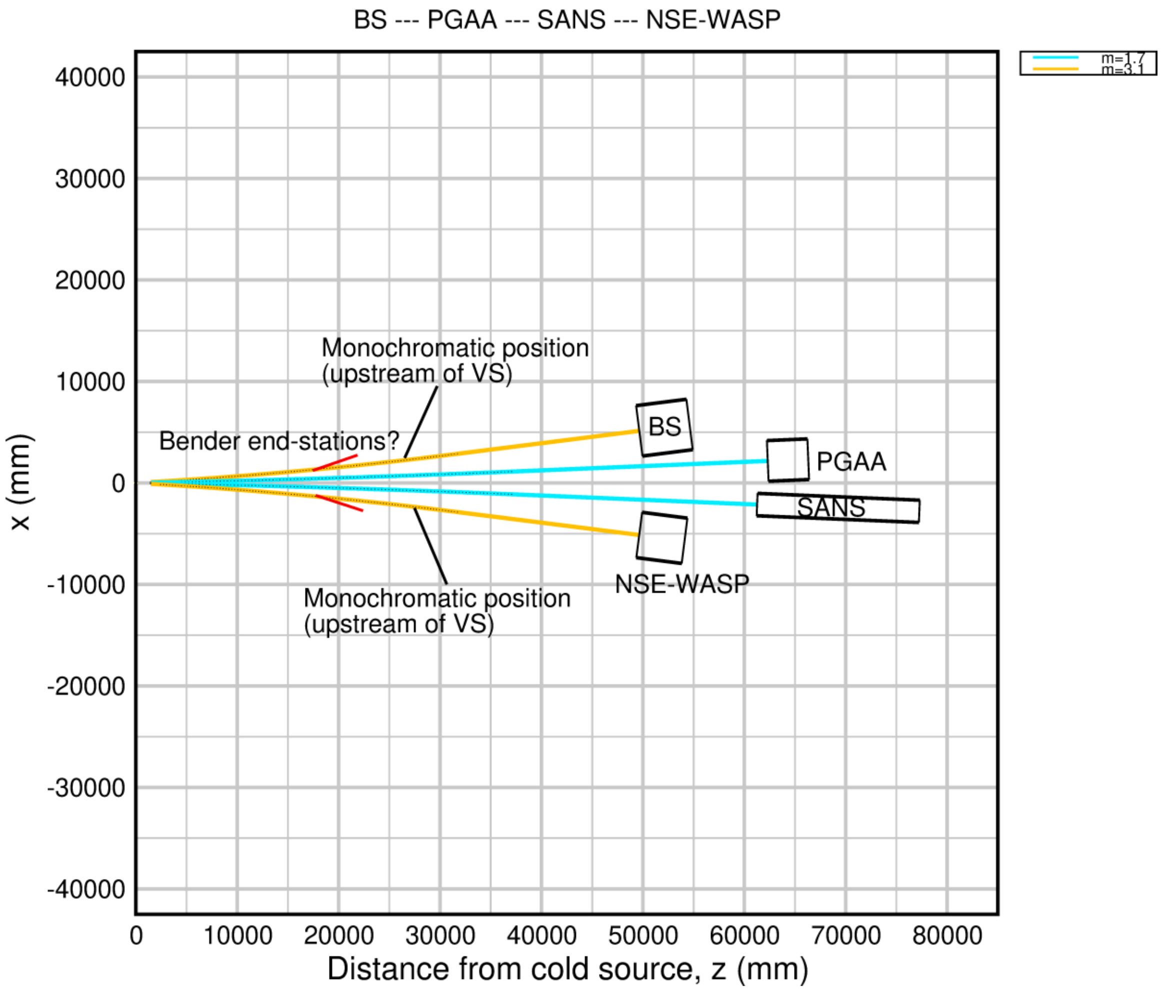

Figure 16. A possible NNS cold neutron guide/ instrument group 1 layout.

Table 5. Summary of the NNS cold neutron guide/ instrument group 1 layout parameters illustrated in Figure 16.

Guide	W (cm)	H (cm)	d_{sg} (m)	L_{IP} (m)	ρ (m)	L_c (m)	L_s (m)	L_{tot} (m)	m_{out} (λ_c=3Å)	Instrument
1	6	20	1.50	1.00	-450	29.39	18.00	48.39	3.1	BS
2	6	20	1.50	1.00	-1600	34.64	25.00	60.64	1.7	PGAA
3	6	20	1.50	1.00	1600	34.64	24.00	59.64	1.7	SANS
4	6	20	1.50	1.00	450	29.39	18.00	48.39	3.1	NSE-WASP

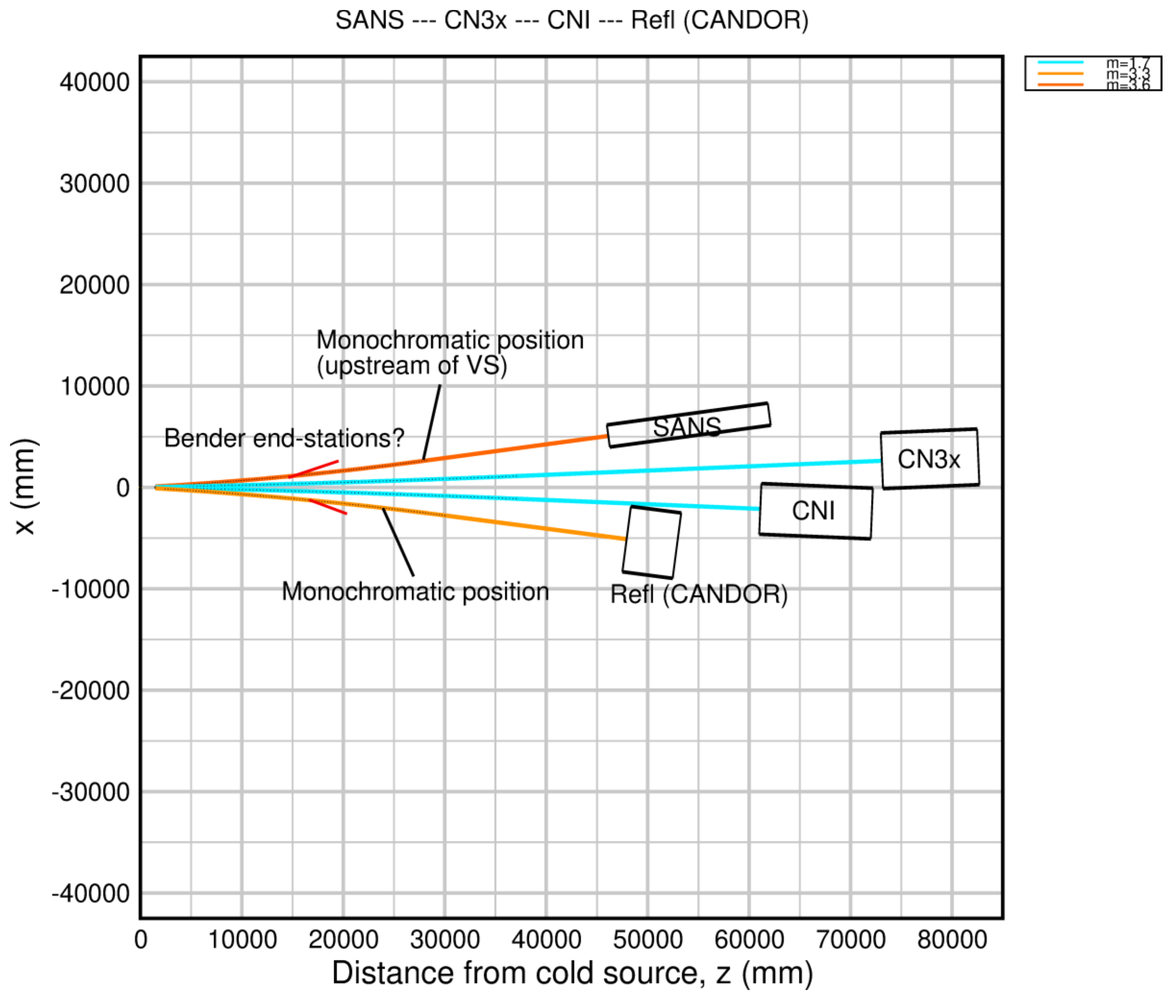

Figure 17. A possible NNS cold neutron guide/ instrument group 2 layout.

Table 6. Summary of the NNS cold neutron guide/ instrument group 2 layout parameters illustrated in Figure 17**.**

Guide	W (cm)	H (cm)	d_{sg} (m)	L_{IP} (m)	ρ (m)	L_c (m)	L_s (m)	L_{tot} (m)	m_{out} (λ_c=3Å)	Instrument
1	6	20	1.50	1.00	-350	25.92	18.00	44.92	3.6	SANS
2	6	20	1.50	1.00	-1600	34.64	36.00	71.64	1.7	CN3x
3	6	20	1.50	1.00	1600	34.64	24.00	59.64	1.7	CNI
4	6	20	1.50	1.00	400	27.71	18.00	46.71	3.3	Refl (CANDOR)

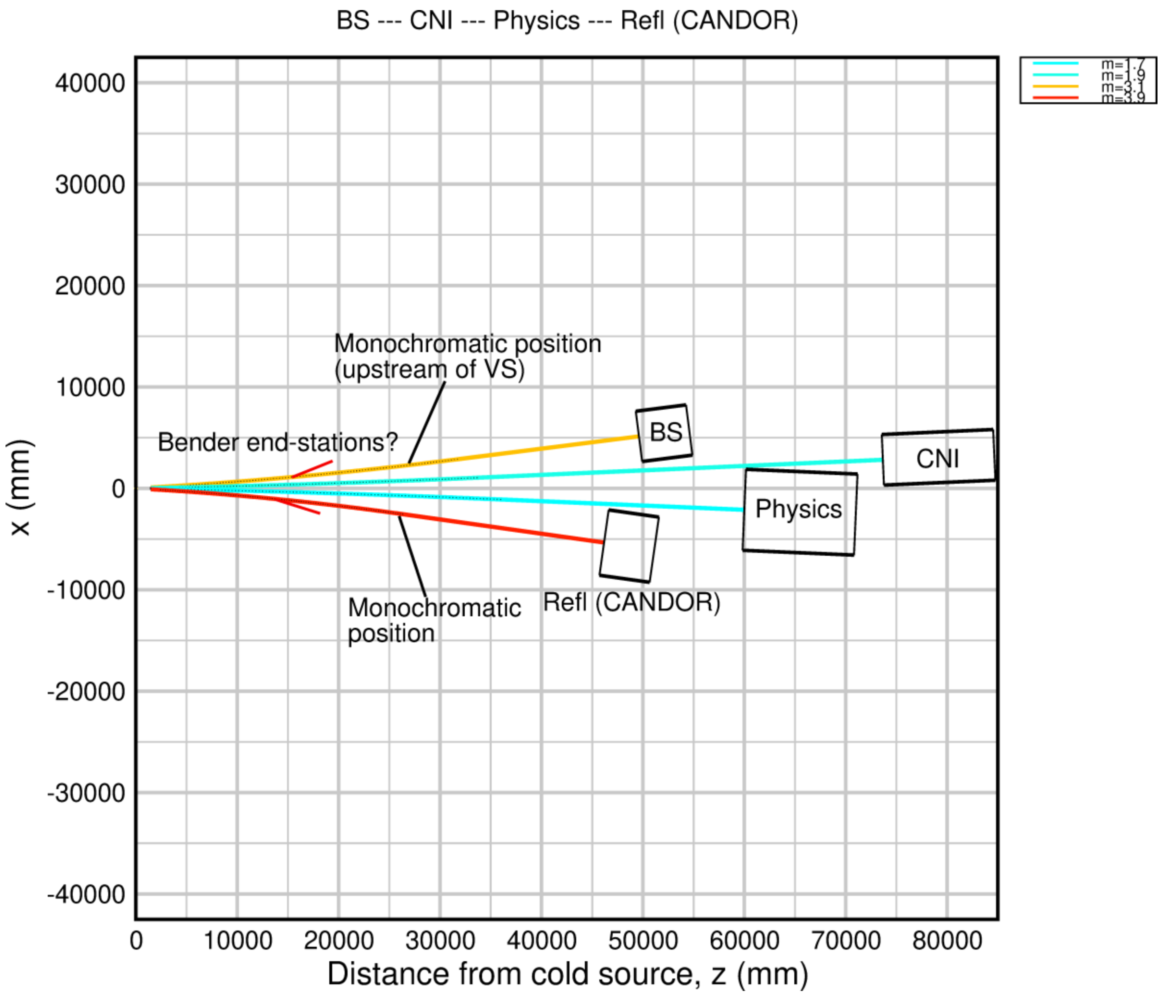

Figure 18. A possible NNS cold neutron guide/ instrument group 3 layout.

Table 7. Summary of the NNS cold neutron guide/ instrument group 3 layout parameters illustrated in Figure 18.

Guide	W(cm)	H(cm)	dsg (m)	L_{IP} (m)	ρ (m)	L_c (m)	L_s (m)	L_{tot} (m)	m_{out} (λ_c=3Å)	Instrument
1	6	20	1.50	1.00	-450	29.39	18.00	48.39	3.1	BS
2	6	20	1.50	1.00	-1300	31.22	40.00	72.22	1.9	CNI
3	6	20	1.50	1.00	1500	33.54	24.00	58.54	1.7	Physics
4	6	20	1.50	1.00	300	24.00	20.00	45.00	3.9	Refl (CANDOR)

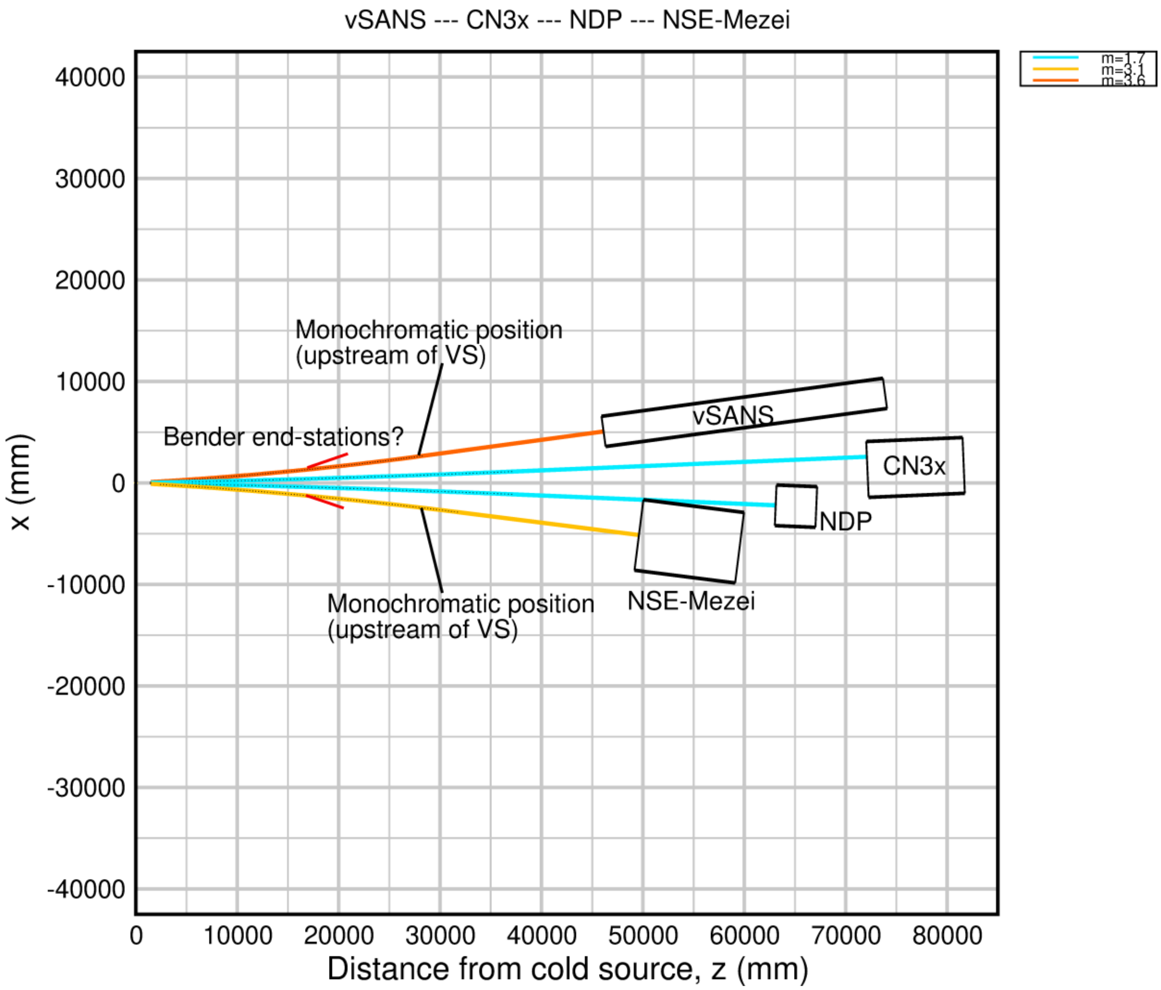

Figure 19. A possible NNS cold neutron guide/ instrument group 4 layout.

Table 8. Summary of the NNS cold neutron guide/ instrument group 4 layout parameters illustrated in Figure 19.

Guide	*W*(cm)	*H*(cm)	*dsg* (m)	L_{IP} (m)	ρ (m)	L_c (m)	L_s (m)	L_{tot} (m)	m_{out} (λ_c=3Å)	Instrument
1	6	20	1.50	1.00	-350	25.92	18.00	44.92	3.6	vSANS
2	6	20	1.50	1.00	-1600	34.64	35.00	70.64	1.7	CN3x
3	6	20	1.50	1.00	1600	34.64	26.00	61.64	1.7	NDP
4	6	20	1.50	1.00	450	29.39	18.00	48.39	3.1	NSE-Mezei

8.1. Combined layout of the 4 guide groups on 2 cold sources

The two adjacent groups of guides and instruments from the two cold sources on each side must clear each other spatially with acceptable passageways in between. It is assumed that the cold sources reside about 0.45 m on either side of the core center. In this case, in order to separate adjacent guide groups, we require an angular offset of the central axis of each in-pile group (i.e., the *y*-axis in Figure 8), such that each group is angled towards the core slightly. Figure 20 shows how group 1 adjacent to group 2 and group 3 adjacent to group 4 respectively would look if each has a fixed angular rotation of 10° in opposite senses. Such a rotation provides a minimum clearance between the extremes of the instrument footprints near the center of more than 2 m (~7 ft), but one can see that that could be readily increased, for example by extending the inner two guides of group 1 in Figure 20, or the inner guides of groups 3 and 4.

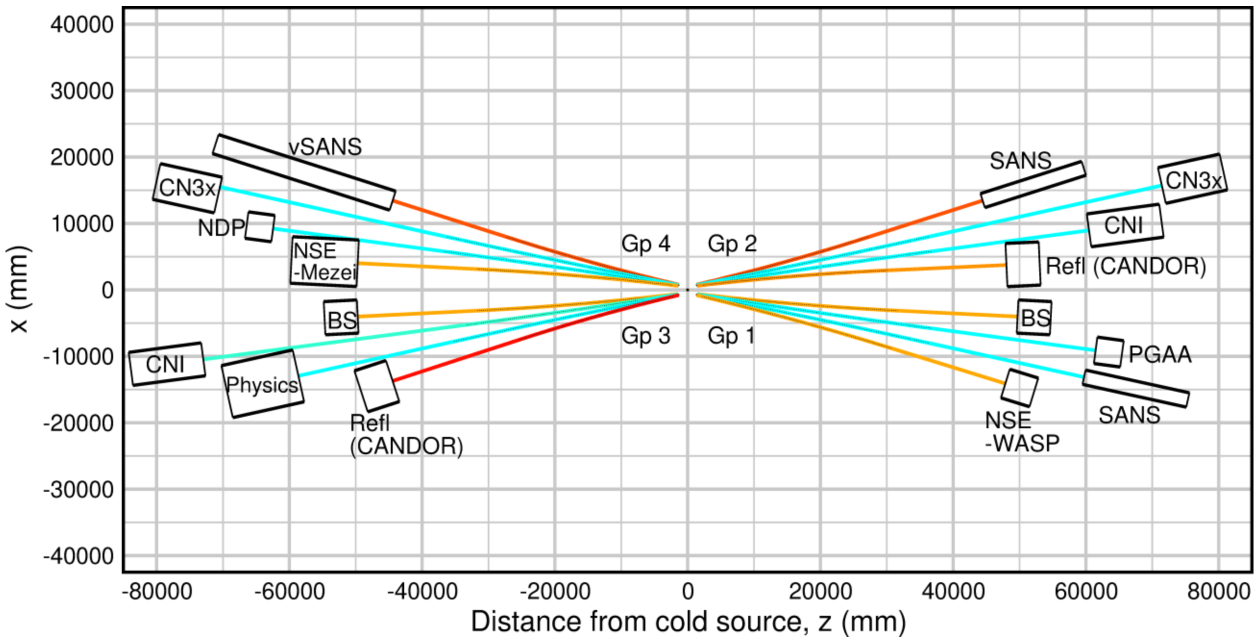

Figure 20. Groups 1 (Figure 16, Table 5), 2 (Figure 17, Table 6), 3 (Figure 18, Table 7), and 4 (Figure 19, Table 8) on adjacent cold sources (assumed separated by 0.9 m) rotated in opposing directions each by 10° to form a central clearance of the instrument footprints.

9. Thermal Instruments

The NNS aims to accommodate at least 8 thermal beam instruments. This may require several instruments (possibly a Neutron Microscope, High-res powder diffractometer, Fast powder diffractometer, uSANS, neutron physics, PGAA (with imaging capability and a chopper system for nPGAA)) being located on neutron guides which may be straight or curved.

The neutron guides not only allow a greater distance of the instruments from the source, facilitating their placement, but they also push the instruments into areas of lower ambient background radiation as well as potentially reducing beam-dependent background by not transmitting neutrons outside of the usable divergence range of the instrument. The transmitted spectrum is also naturally shifted towards longer wavelengths because the critical angle is proportional to the neutron wavelength. This natural filtering effect of the guide increases as the line of sight angle through the guide becomes small compared with the critical angle.

Because it is desirable to reflect shorter wavelength neutrons effectively (maybe down to about 1.2 Å), the *m* values of the supermirror coatings tend to be quite large. Furthermore, these guides are likely to be relatively large in width for some instruments and, if they are curved, we know from Eq. (1) that λ_c (for a non-line-of-sight guide) is given by $\lambda_c = \sqrt{2W/\rho}\Big/\gamma_{Ni} m_{out}$. Therefore, these guides may have to be quite long and/or strongly curved if a direct line of sight ($L_{LOS} \approx \sqrt{8W\rho}$ (Eq. (3))) is to be avoided. If they are strongly curved (ρ is small), the curvature must be compensated with a sufficiently large m_{out} value in order to transmit the required shorter wavelength neutrons that may be needed by thermal instruments. Therefore, in many cases the thermal guides are likely to be straight with a large proportion of fast neutrons, often requiring bismuth gamma filters and fast neutron filters such as MgO, sapphire, or quartz.

Studies are presently underway to assess practical thermal beam tube placement in the core, however, a configuration similar to that shown in Figure 4 may be required with beams at split levels in order to facilitate extraction of the cold neutron beams from both sides of each cold source at a central level. Figure 21 is a revised version of Figure 4 with more realistic proportions in which the diameter of the thermal beam hall would be about 30 m. The layout shows 8 roughly to-scale instrument cartoons which would be fed by thermal neutron guides penetrating the mid-pool region around the core. Further study of such arrangements is necessary. Such studies will assess the benefits of introducing thermal neutron guides through the shield to optimize the extraction of the thermal beams for the instruments as well as engineering constraints, such as providing sufficient cooling, etc.

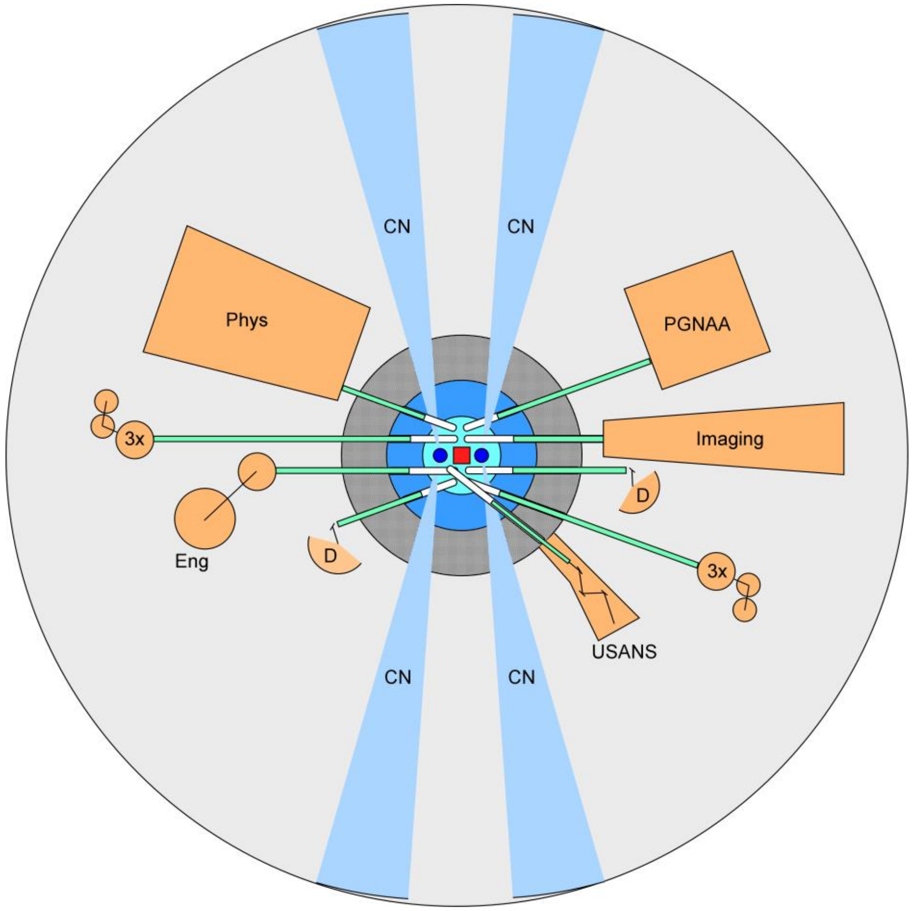

Figure 21. A slightly more realistic scale version of the thermal beam hall part of Figure 4 showing schematics of thermal instruments of the types referenced in Appendix A. In this schematic, the outer radius of the experimental area would be about 15 m. All instruments are shown potentially fed by thermal neutron guides penetrating close to the core. The thermal beam tubes are tangential in order to minimize the very fast neutron component of the beam.

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Appendix A. Cold and Thermal Neutron Instruments for New Guide Hall

A.1. Cold Neutron Instruments for guide hall (* is for end positions)

A.1.1. Diffraction

- *vSANS (perhaps using a mirror)
- *SANS (2 of these) (with enhanced optics like on vSANS including slit geometry which may benefit from a somewhat taller guide)
- *Reflectometer (2 of these) (CANDOR)
- *Materials diffractometer (perhaps)
- uSANS (perhaps)

A.1.2. Imaging

- *Neutron microscope (2 of these)

A.1.3. Inelastic scattering

- *3 – axis (constant E) (MACS)
- *3 – axis (constant Q) (SPINS)
- *Backscattering (IN16 -type with BATS)
- ?Backscattering (GaAs) (might be able to use a side position)
- *NSE (Mezei type)
- *NSE (WASP type)

A.1.4. Neutron Physics

- Interferometer
- Constant wavelength side positions
- *High neutron current position

A.1.5. Analytical Chemistry

- *PGAA (with imaging capability and a chopper system for nPGAA (nearly))
- *Depth Profiling

A.2. Thermal Neutron Instruments

A.2.1. Imaging

- Neutron Microscope (white beam needs lots of space)

A.2.2. Diffraction

- White beam engineering diffractometer (with CANDOR-type detector) (needs lots of space)
- High-res powder diffractometer (needs large area)
- Fast powder diffractometer
- uSANS (perhaps)

A.2.3. Inelastic scattering

- 3-axis (2 of these with different optimizations on the backend)

A.2.4. Neutron Physics

- They always want more stuff

A.2.5. Analytical Chemistry

- PGAA (with imaging capability and a chopper system for nPGAA)

Appendix B. PST guide notes

PST works *ideally* for $\lambda \geq \lambda'$, where

$$\lambda' = \frac{m_{out}}{\sqrt{\left(m_{out}^2 - m_{in}^2\right)}} \lambda_c$$

where m_{in} is the *m*-coating on the inner radius (convex surface) of a "long" (no line-of-sight), purely circularly-curved guide, and m_{out} is that on the outer radius (concave surface). λ_c is the characteristic wavelength of the long curved guide of radius of curvature, ρ, and width, *W*, given by

$$\lambda_c = \frac{\psi_c}{\gamma_{Ni} m_{out}} = \frac{1}{\gamma_{Ni} m_{out}} \sqrt{\frac{2W}{\rho}} \text{ and } \psi_c = \sqrt{\frac{2W}{\rho}}$$

where γ_{Ni} is the critical angle per unit wavelength of natural Ni = 1.73×10^{-3} rads $Å^{-1}$. Ideal PST operation requires the following set of conditions:

1. The length of the curved section, L_c, must be greater than the line of sight distance, L_{LOS}, where $L_{LOS} \approx \sqrt{8W\rho} = 4W/\psi_c$
2. The length of the straight section, L_s, is considered "long" at least for $\lambda > \lambda'$, requiring $L_s \geq W/\theta_{c\,str}\left(\lambda'\right)$
3. For a straight section with coatings matching m_{in} (which is common practice), this requires $L_s \geq W/\gamma_{Ni} m_{in} \lambda'$

A.1. Example of new NG-6

W=6 cm, ρ=1400 m, m_{in}=2.0, m_{out}=2.7, L_c=26 m, L_s=10.5 m.

We have the following

- λ_c=1.98Å (ψ_c = 9.26 mrad)
- λ'=2.95Å
- L_c(min) = L_{LOS} = 25.92m
- L_s(min) = 5.88m

Therefore the new NG-6 satisfies the ideal PST requirements for $\lambda > 2.95$Å.