(Neutron Guide) shielding basics

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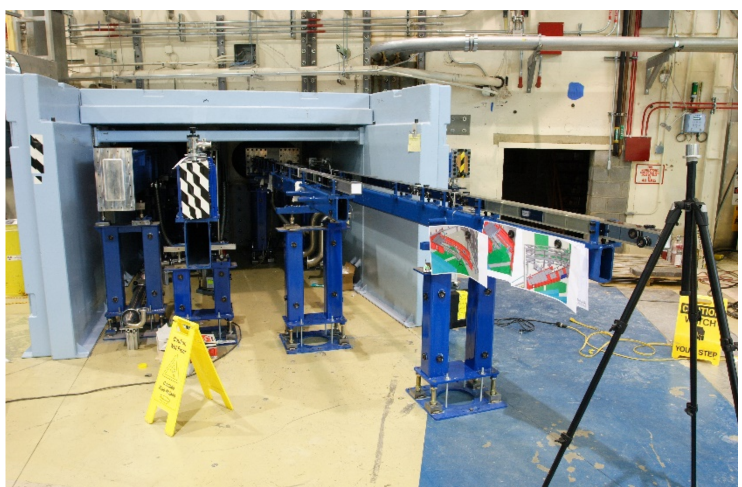

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Guide shielding basics
Outline

- What do we shield and why?
- Personnel dose rates and regulatory limits
- Principal types of ionizing radiation encountered in neutron guide shielding
- How to shield different types of radiation
- Commonly-encountered shielding types
- Miscellaneous

Guide shielding basics
Why shielding?

- Ionizing radiations produced
  1) Directly from the source
  2) From neutron interactions in materials in the beam
  3) Naturally from the environment
- Radiation shielding usually required for some or most of the beam from the source to the instrument
  - Reduce exposure to personnel (cell damage)
  - Reduce instrumental background (false counts from radiations other than the neutrons scattered from the sample)

Guide shielding basics
Radiation dose limits/ averages

- NRC (Nuclear Regulatory Commission, US)
  - Occupational Dose Limit (radiation worker) = 5 rem/yr (5000 mrem/yr, 50 mSv/yr)
  - General public dose limit at facility = 100 mrem/ yr =1mSv/yr
  - **Average dose to US public = 360 mrem/yr** =3.6mSv/yr
  - **Average dose to NIST researcher ~ 50 mrem/yr** =0.5mSv/yr (100x less than ODL)
  - **Want to avoid "*radiation areas*" in guide hall (radiation area ≥ 5 mrem/h =50μSv/h) – <u>preferably much less</u>**

- Regulatory limits (and especially average doses) vary somewhat from country to country and geographical location

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Radioactive sources and environmental radiaton

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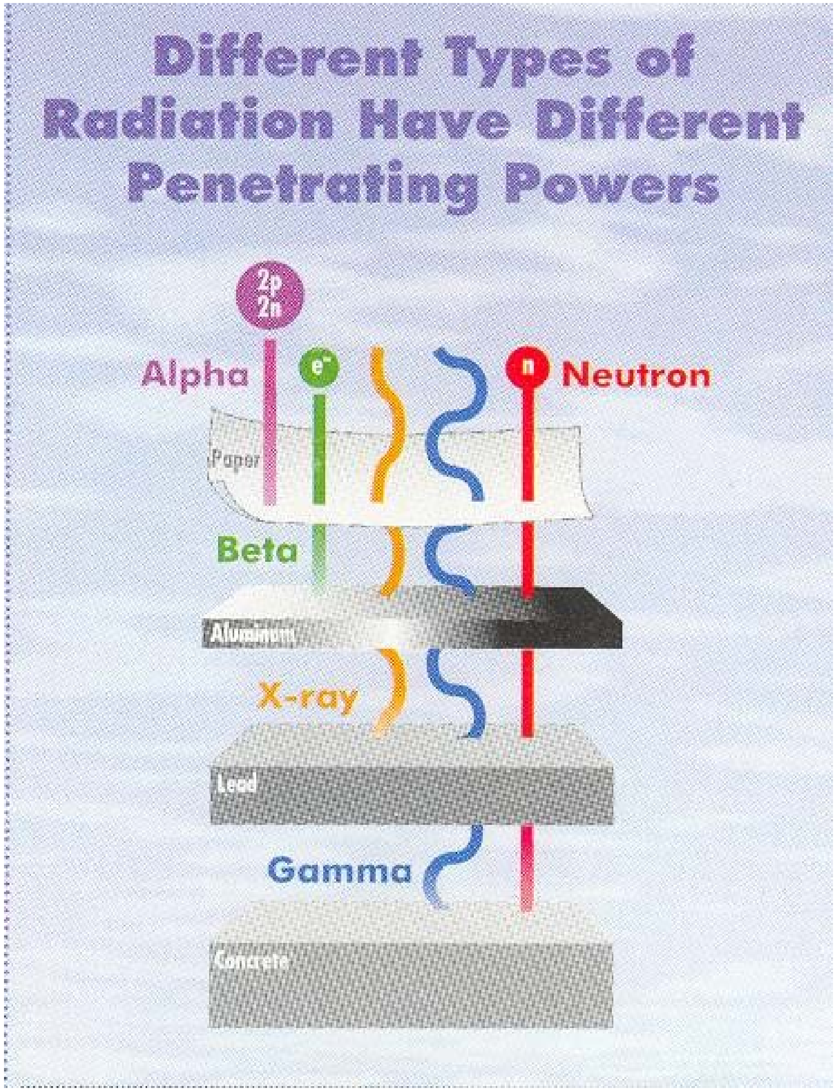
Principal radiations encountered in neutron guides

- **Slow (thermal/cold) neutrons**: The ones we want to transmit to instruments – very high *in-beam* dose rate, very low outside of borated substrate guides *except* at scattering sources (windows, filters, monochromators etc.)
- **Fast neutrons**: Directly from source mainly, but also from (n,xn'), (γ,n) reactions etc.)
- **Gamma rays**
  - Directly from source
  - **"Prompt" gammas** from neutron absorption in materials
  - Emitted from **radioactive sources** produced by neutron absorption in materials in beam (e.g. aluminum windows: ^{28}Al produced by n absorption in ^{27}Al β-decays to ^{28}Si with emission of 1.78MeV gamma)
- **x-rays** – Usually easily stopped by guide shielding
- **Charged particles:** β (electrons), α (^{4}He nuclei)

Guide shielding basics

Principal radiations encountered in neutron guides

- **Charged particles** β (electrons), α (^{4}He nuclei) – not usually a concern behind shielding if radioactive source is (a) not fluid or (b) confined because:
  - Charged particles short ranged even in air
  - Most β stopped by mm of Al, α stopped by sheet of paper (or skin)
  - Very low risks associated with ^{41}Ar inhalation ($T_{1/2}$=1.8h, β, γ emitter) produced from neutron absorption in ^{40}Ar in air



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Guide shielding basics
^{41}Ar example (not a shielding problem per se)

- ^{41}Ar is β-radioactive with ($T_{1/2}$=1.8h) from neutron absorption in ^{40}Ar in air
- <u>**Example**</u>: Study for ***Neutron Lifetime experiment*** **(guide NGC)** for worst-case leak in **8.35m long beam chamber** (**1 Atm air**, beam ON many×$T_{1/2}$ i.e., **^{41}Ar concentration at saturation level**)
  - <u>**Results**</u>:
  - Estimated 41μCi ^{41}Ar (in 49 liters) at saturation (8.4×10^{-4} μCi/ml)
  - NRC 10CFR20 Derived Air Concentration (DAC) value for inhalation is 3×10^{-6} μCi/ml
  - **HOWEVER**
    - DAC=Concentration of a given radionuclide in air which, if breathed by the reference man **for a working year of 2000 hours** under conditions of light work (with an inhalation rate of 1.2 cubic meters of air per hour)
    - DAC value is based on annual integrated gamma dose rate limits
    - DAC assumes **semi-infinite cloud submersion**

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^{41}Ar example

- Release 49 liters to semi-infinite cloud dilution and exposure time wrt DAC render ^{41}Ar exposure **insignificant** from regulatory point of view (similar for leaking guides)

- No guide hall beam experimental proposals at NCNR usually require ^{41}Ar safety reviews for air-leak scenarios

- **Try to avoid long, confined, air-filled beam paths in guide as much as possible** (but **more for transmission performance and (borated glass) guide longevity** than for ^{41}Ar safety reasons)

Guide shielding basics

Means of protection from neutron guide radiation

1. Limit time of exposure
2. Increase distance from source
3. SHIELDING

Guide shielding basics
Gamma rays

- Usually **main source** of radiation from guides **outside of the shielding** (usually what we are measuring with yellow Victoreen survey meters in experimental areas)
- Originate from neutron capture in:
  - Reflecting mirror/ supermirror elements (e.g. Ni, Ti) – note supermirror thickness increases ~ m^3 - **high *m* guides can lead to significant shielding challenges**
  - Guide substrate elements
    - Non-borated (soda lime) glass (e.g. Na, Si capture)
    - Borated glass (**mainly 478 keV from $^{10}B(n,\alpha)^7Li$ reaction**)
    - Aluminum, Nickel, Copper, steel
  - Vacuum windows (Al, Mg, Be, sapphire etc.)
  - Crystal filter materials
- From radioisotopes produced from neutron absorption (e.g. ^{28}Al, ^{65}Zn (in borated glass) etc.)
- Often enhanced shield thicknesses required around V-polarizers with silicon wafers, filters (e.g. sapphire), velocity selectors or choppers with Gd_2O_3, etc., which produce energetic capture gamma rays

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Capture gamma yields (n,γ) reaction

- Prompt gammas per neutron capture by γ energy group

		Energy group (MeV)										
	σ_γ (b)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11
H	3.32E−1	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Li	3.63E−2	0.1242	0.0491	0.8933	0.0000	0.0000	0.0000	0.0107	0.0402	0.0000	0.0000	0.0000
Be	9.20E−3	0.2552	0.0000	0.2415	0.4629	0.0000	0.0201	0.6290	0.0000	0.0000	0.0000	0.0000
B	1.03E−1	0.0000	0.0000	0.0000	0.0000	1.1014	0.0000	0.3950	0.4785	0.0000	0.0000	0.0000
C	3.37E−3	0.0000	0.2975	0.0000	0.3240	0.6827	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N	7.47E−2	0.1302	0.0000	0.5168	0.4683	0.2284	0.1969	0.2465	0.0000	0.0000	0.0000	0.0000
O[a]	2.70E−4	1.0000	0.8200	0.8200	0.1800	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Na	4.00E−1	0.9267	0.2047	0.7265	0.6536	0.0323	0.0633	0.2244	0.0000	0.0000	0.0000	0.0000
Mg	6.30E−2	0.5963	0.6875	0.6404	0.9583	0.0662	0.1077	0.1157	0.0372	0.0474	0.0075	0.0000
Al	2.30E−1	0.2751	0.0877	0.3125	0.2602	0.3709	0.0812	0.1029	0.3874	0.0000	0.0000	0.0000
Si	1.60E−1	0.1172	0.1328	0.3193	0.8266	0.6378	0.0450	0.1361	0.0704	0.0203	0.0000	0.0000
P	1.80E−1	0.4066	0.5411	0.5213	0.5448	0.2690	0.1289	0.1809	0.0789	0.0000	0.0000	0.0000
S	5.20E−1	0.7555	0.0000	0.7718	0.3642	0.1794	0.6348	0.0000	0.0391	0.0266	0.0000	0.0000
Cl	3.32E+1	0.3130	0.7353	0.3015	0.2099	0.1379	0.1346	0.3773	0.2037	0.0299	0.0000	0.0000
K	2.10E+0	0.5435	0.4671	0.5927	0.3855	0.2617	0.3736	0.0352	0.0610	0.0000	0.0000	0.0000
Ca	4.30E−1	0.2401	0.9349	0.5187	0.1711	0.2303	0.1254	0.4384	0.0216	0.0000	0.0000	0.0000
Ti	6.10E+0	0.3097	0.8089	0.0695	0.1249	0.1114	0.0239	0.8495	0.0030	0.0019	0.0000	0.0000
V[a]	5.04E+0	0.3837	0.2486	0.1335	0.0591	0.0877	0.3158	0.3947	0.1972	0.0000	0.0000	0.0000
Cr	3.10E+0	0.4051	0.1607	0.2067	0.0922	0.0421	0.1103	0.1189	0.2461	0.3766	0.1097	0.0000
Mn	1.33E+1	0.1750	0.1242	0.2421	0.1542	0.1705	0.3134	0.1076	0.3799	0.0000	0.0000	0.0000
Fe	2.55E+0	0.2783	0.2476	0.0954	0.1132	0.1122	0.1093	0.1012	0.5886	0.0082	0.0415	0.0011
Co	3.72E+1	0.9374	0.2054	0.1594	0.1784	0.1566	0.3362	0.3467	0.1139	0.0000	0.0000	0.0000
Ni	4.43E+0	0.2616	0.0659	0.0605	0.0365	0.0370	0.0745	0.1704	0.1404	0.5899	0.0000	0.0000

Note this is (n,γ) cross-section for boron which is v. small wrt (n,α) cross-section so very small fraction of these wrt 478keV gamma from (n,α)

Guide shielding basics

Neutron capture in **boron**

- **Most** gammas from neutron absorption in boron are from the **$^{10}B(n,\alpha)^{7}Li$ reaction (E_γ=0.478 MeV, Q=2.79 MeV)**

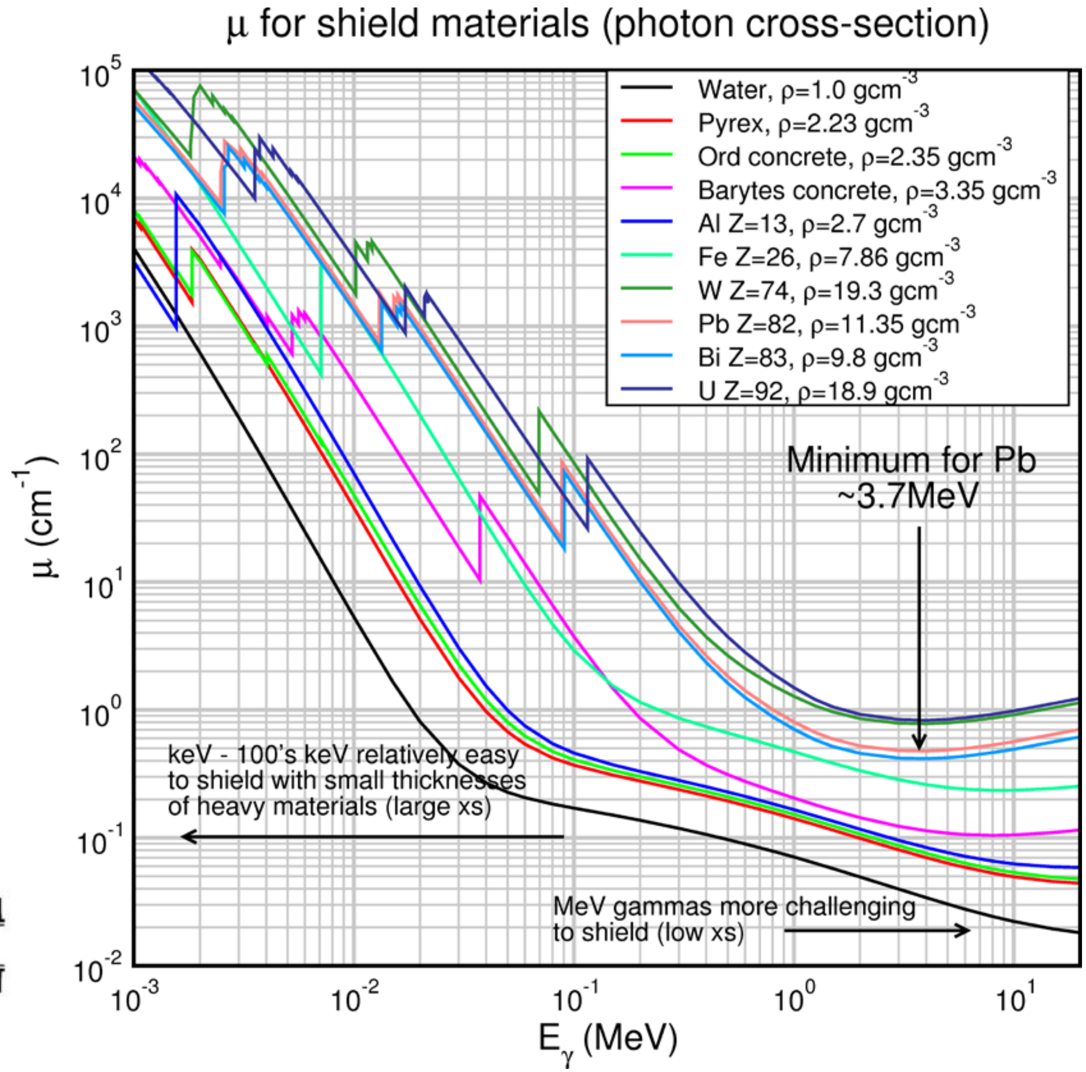
- 0.478 MeV gammas (yield=0.93/capture on average): <u>Relatively easy to shield</u>

- Local heating from stopping of α and ^{7}Li nucleus (depositing energy Q) in surrounding material = 4.47×10^{-8} rads/absorption (4.47×10^{-13} J/g/absorption)

- A few (~10^{-6} per thermal neutron absorption) **fast neutrons** (up to ~16MeV) emitted (from charged particle interactions in the material)

Guide shielding basics
Gamma ray shielding

- Photon (gamma-ray) absorption coefficient (cross-section)



$$T\left(E_\gamma\right) \sim \exp\left(-\mu\left(E_\gamma\right)t\right)$$

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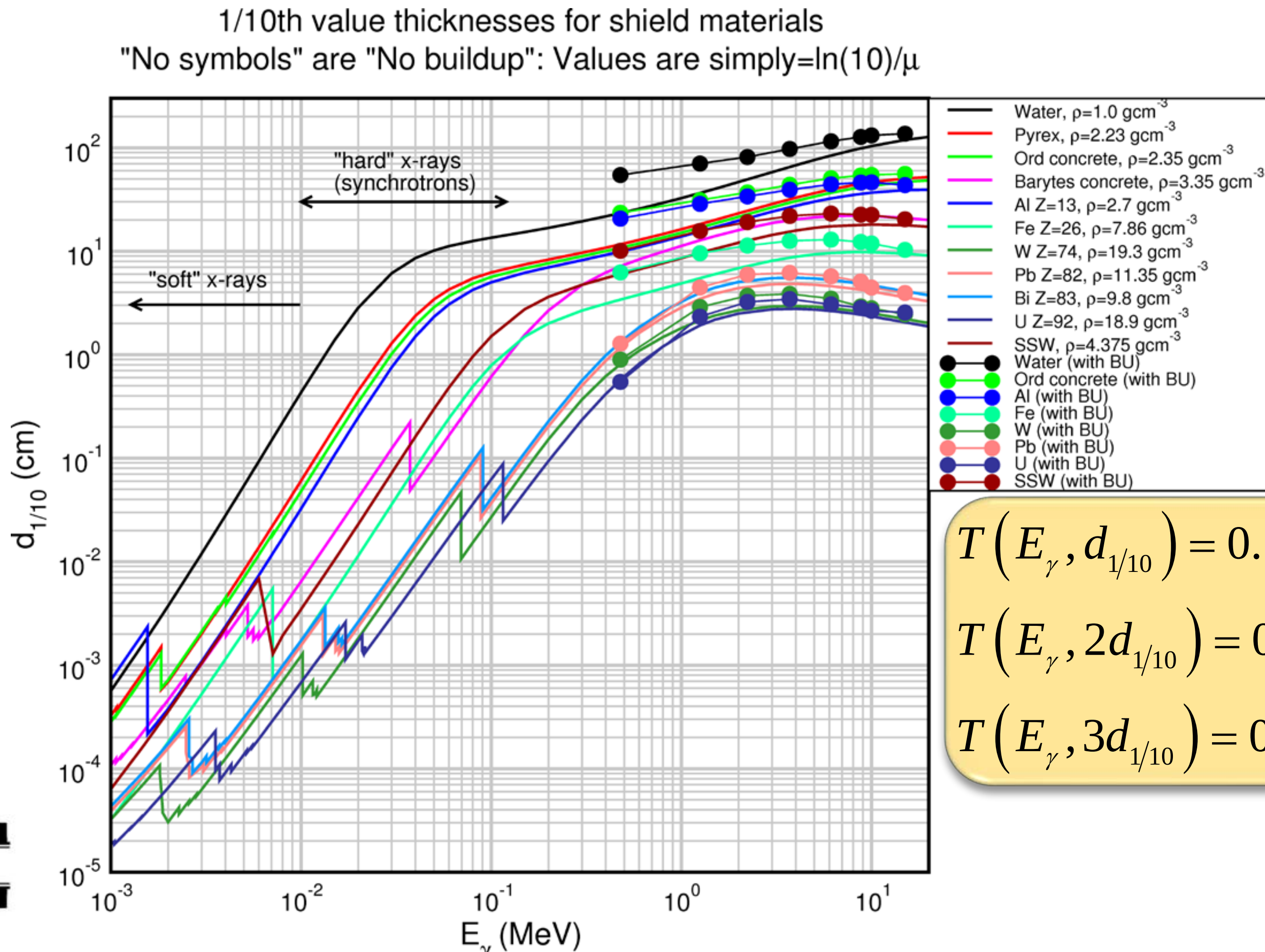
Guide shielding basics
Gamma ray shielding

- 1/10th value thicknesses



$$T\left(E_\gamma, d_{1/10}\right) = 0.1$$

$$T\left(E_\gamma, 2d_{1/10}\right) = 0.01$$

$$T\left(E_\gamma, 3d_{1/10}\right) = 0.001\ etc.$$

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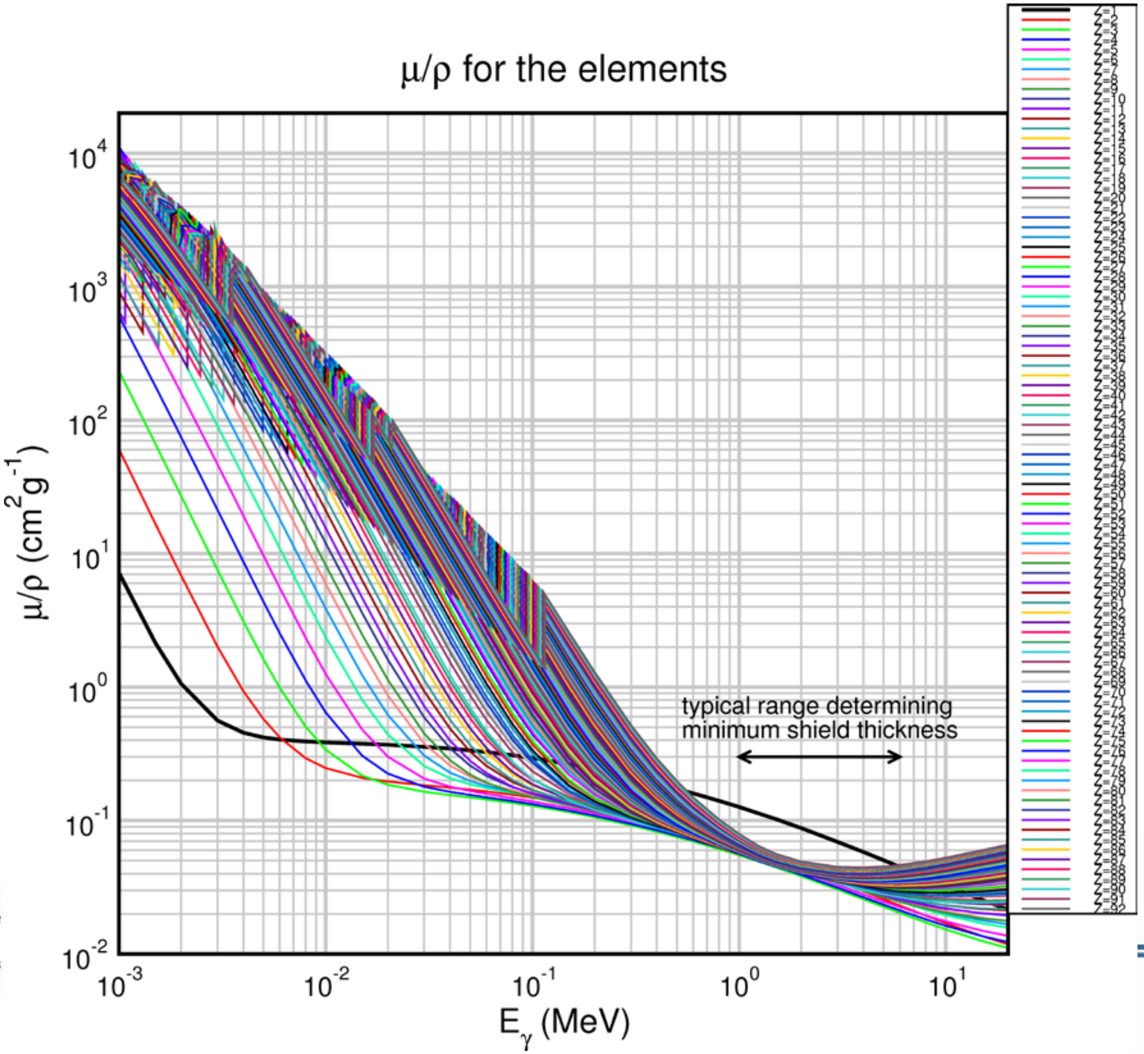
Guide shielding basics
Gamma ray shielding

- Useful “**rule of thumb**” for gamma-ray shielding



With the exception of hydrogen, **photon cross-section divided by material mass density is approximately constant** in the energy range of interest for determining the minimum shield thickness

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Guide shielding basics
Gamma ray shielding

- Useful “rule of thumb” for gamma ray shielding

$$T \approx \exp(-\mu x) \quad = \exp\left(-\frac{\mu}{\rho}\rho x\right) \quad \approx \exp(-K\rho x)$$

Therefore **if $\frac{\mu}{\rho}$ approximately independent of shield material, shields with $\rho_1 x_1 = \rho_2 x_2$ have approximately equal transmission**

Whatever the shield material, you need approximately a **constant mass** of shield

For example: If a Pb gamma shield with ρ=11.35gcm^{-3} is to be replaced by a concrete shield with ρ=2.35gcm^{-3}, the latter should be approximately 5× thicker

Guide shielding basics
Thermal (slow) neutron shielding

- Task: Stop thermal neutrons that will not reach sample
- Easy to shield with <u>relatively thin</u> (~mm thick) materials containing elements with high thermal neutron absorption cross-sections (e.g.):
  - B (767b)/ ^{10}B (3837b)
  - Li (71b)/ ^{6}Li(940b)
  - Cd (2520b)
  - Gd (48890b) etc.
- Thermal neutron shielding should usually be ***first line of shielding*** in a mixed thermal neutron, gamma, fast neutron field (avoids unnecessary activation/ gamma production in following shield materials)

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Guide shielding basics
Thermal (slow) neutron shielding

- **Borated materials (Borkron, borofloat glass, borated Al, Boral, Boroflex etc.)**
  - Gammas relatively easy to shield
  - Permits use of borated materials inside guide shields (e.g. beam shutters, beam masks)
  - Borkron, borofloat substrate guides: **Unreflected thermal neutrons 100% absorbed in glass**
  - Avoid borated glass in high lifetime neutron fluences (>~10^{17}n/cm^2 on surface – embrittlement due to He defects/tracks in structure from $^{10}B(n,\alpha)^7Li$ reaction)
  - For evacuated guides with gaps, mask **exposed ends** with borated Al (EDM) – reduce risk of implosion
  - Use borated absorbers to **limit neutron scattering** (from windows, crystal filters etc.) **into shields or support structures** (reduces secondary gamma production (e.g. 2.2MeV H capture gamma in hydrogenous shields) and materials activation)
  - Borated shield materials include:
    - B_4C (hot-pressed or cast in epoxy)
    - boroflex
    - borated Al (now hard to find!)
    - Boral (B4C and aluminum composite)
    - borated polyethylene (various B concentrations)
    - borated wax (borax) – not used any more in steel weldments at NCNR (acidity, boron-rich separation)
    - boron nitride etc.

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Guide shielding basics
Thermal (slow) neutron shielding

- **^{6}Li-containing materials – LiF scintered tile, lithiated polymer "Lithoflex ", lithiated polyethylene, also lithiated glass etc.**
  - ^{6}Li has **very low gamma production**, BUT
  - ^{6}Li-enriched materials are strategic, expensive, difficult to obtain in large quantities
  - **Tritium contamination** when exposed to neutrons (via ^{6}Li(n,α)^{3}**H** reaction)
  - Emits **high energy (up to ~16MeV)** (hard-to-shield) neutron spectrum (~10^{-4} per thermal neutron absorbed)
  - Can **rarely justify their use inside guide shielding** over borated materials
- **Cadmium (Cd)** - not good for > eV neutrons ("Cd cutoff" (cross-section drops dramatically) above 0.3eV), produces high-energy gammas (difficult to shield)
- **Gadolinium (Gd)** very large thermal absorption cross-section (**can be thin**) but produces high-energy gammas (difficult to shield). Gd_2O_3 often found in chopper disks, velocity selectors, etc.
- **Non-borated substrate guides**:
  - May require surrounding with borated absorber especially close to source- limit activation in surrounding structures, secondary gamma production etc.

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Guide shielding basics
Fast neutrons

- Direct from source (usually a few % of total flux)
- Biological dose rate of fast ns in beam can be **comparable to thermal neutron beam**
- **Much harder to shield than thermal/cold neutrons**
  - Slow them down first! (moderate)
  - **> 1 MeV**: Reduce energy by ***inelastic scattering*** (W, Fe, Pb good) (spallation source neutrons – usually heavy use of steel shields around target)
  - **< 1MeV**: Slow down by elastic scattering: Hydrogen is best - **use high number density hydrogenous materials – polyethylene (7.9e+22 cm^{-3} H) , paraffin wax (8.3e+22 cm^{-3} H) , H_2O (6.7e+22 cm^{-3} H)** , also Masonite (~4.8e+22 cm^{-3} H), concrete (< 1e+22 cm^{-3} H, depending on hydration), etc. (bulky - tend to need 10's of cm of higher H materials for MeV neutrons)
  - When slowed down (thermalized) neutrons are **readily absorbed in thermal neutron absorbers**

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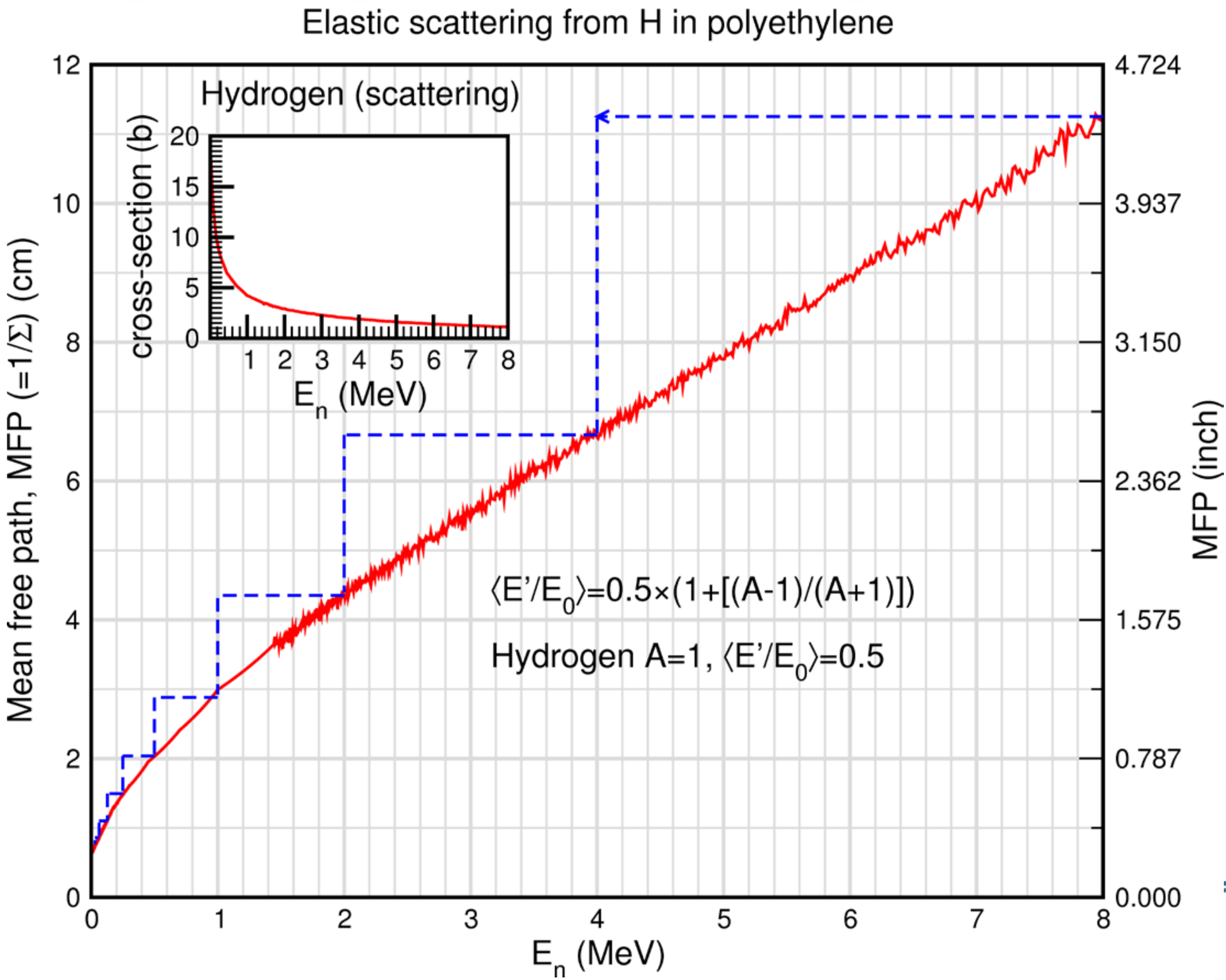
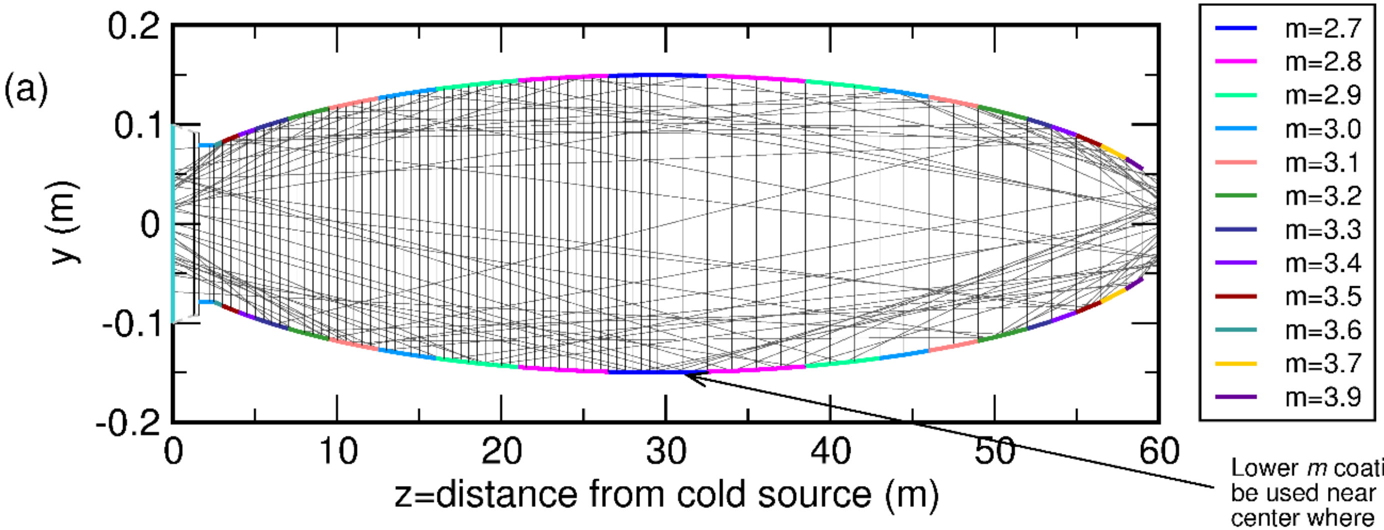
Guide shielding basics

Fast neutrons

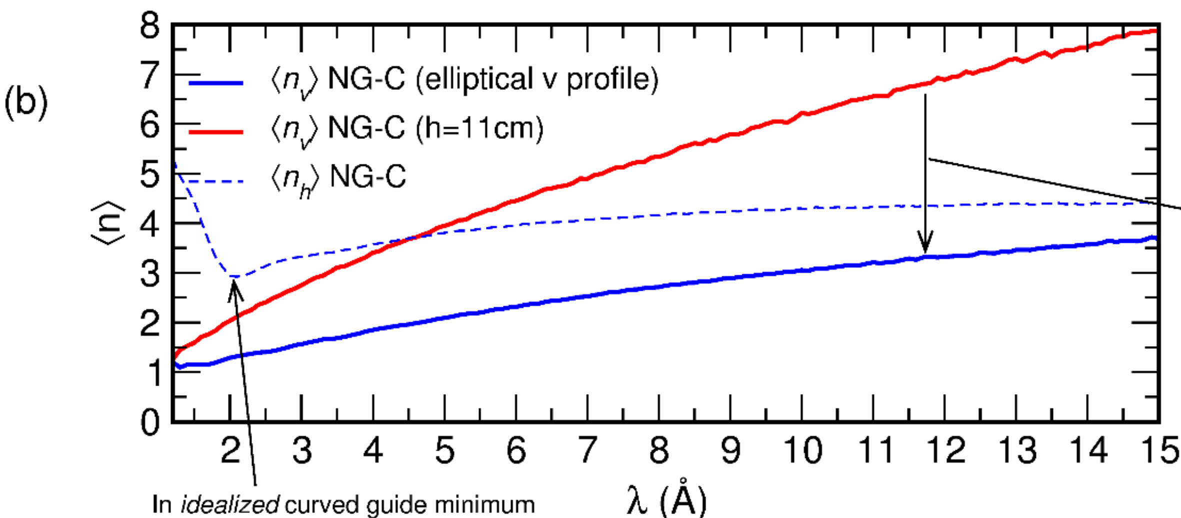


Guide shielding basics

Shielding of profiled and curved guides



Lower *m* coating can be used near center where beam divergence lowest



Mean number of top/bottom reflections approximately halved wrt straight sided guide with *h*=exit height=11cm

In *idealized* curved guide minimum number of side reflections would occur at $\lambda=\lambda_c \approx (2W/\rho)^{1/2}/\gamma_{Ni} m_{out}$

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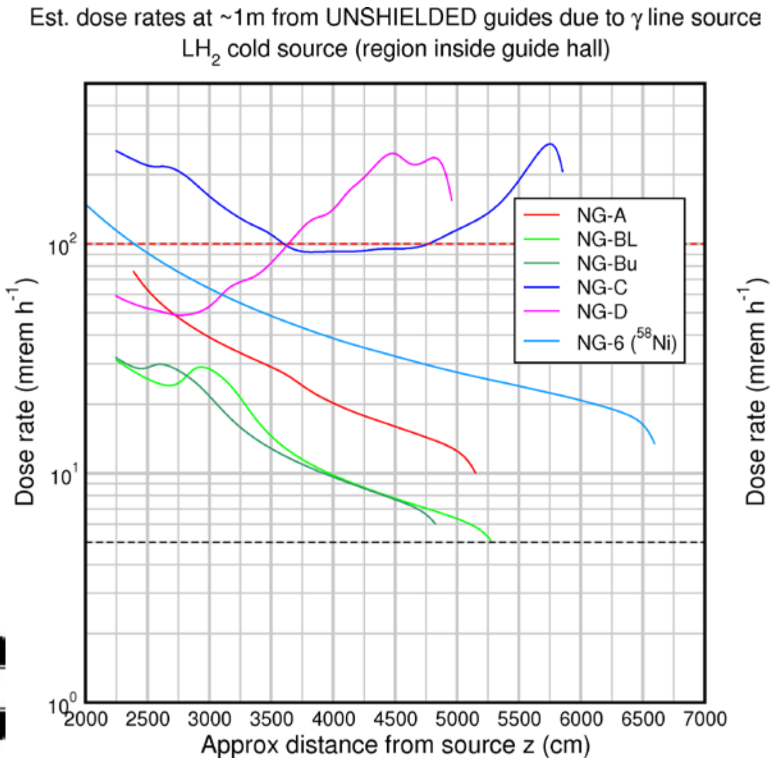
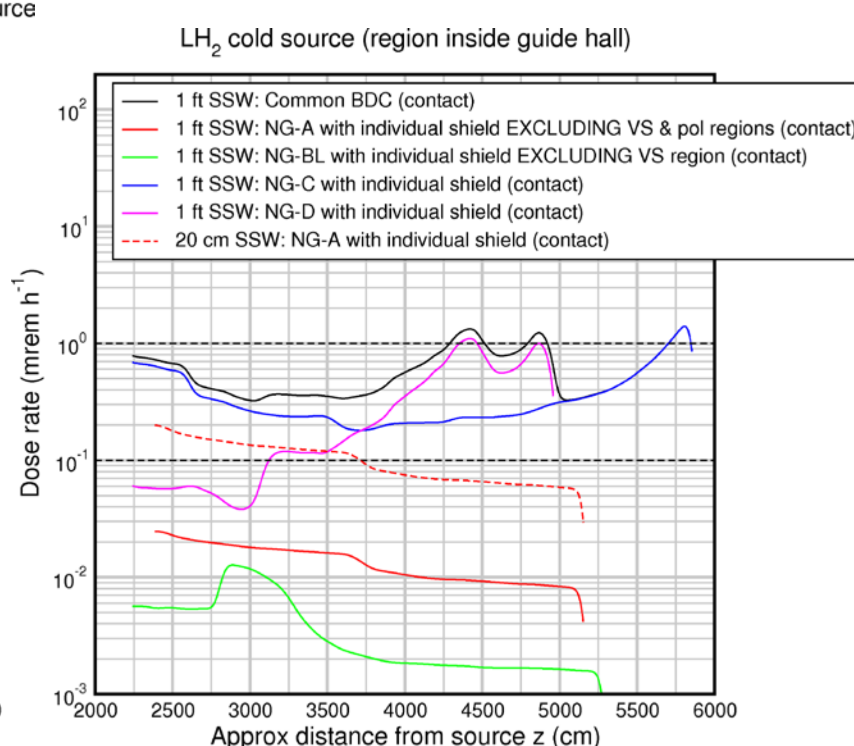
Guide shielding basics
Shielding of profiled and curved guides

- Losses in guides (lead to gamma production– supermirrors, substrates) – see "simulations" presentation
  - Can increase towards ends of focusing sections or in curves of guides (sometimes require more shielding at ends than in middle)
  - Also around crystal filters, polarizers etc.





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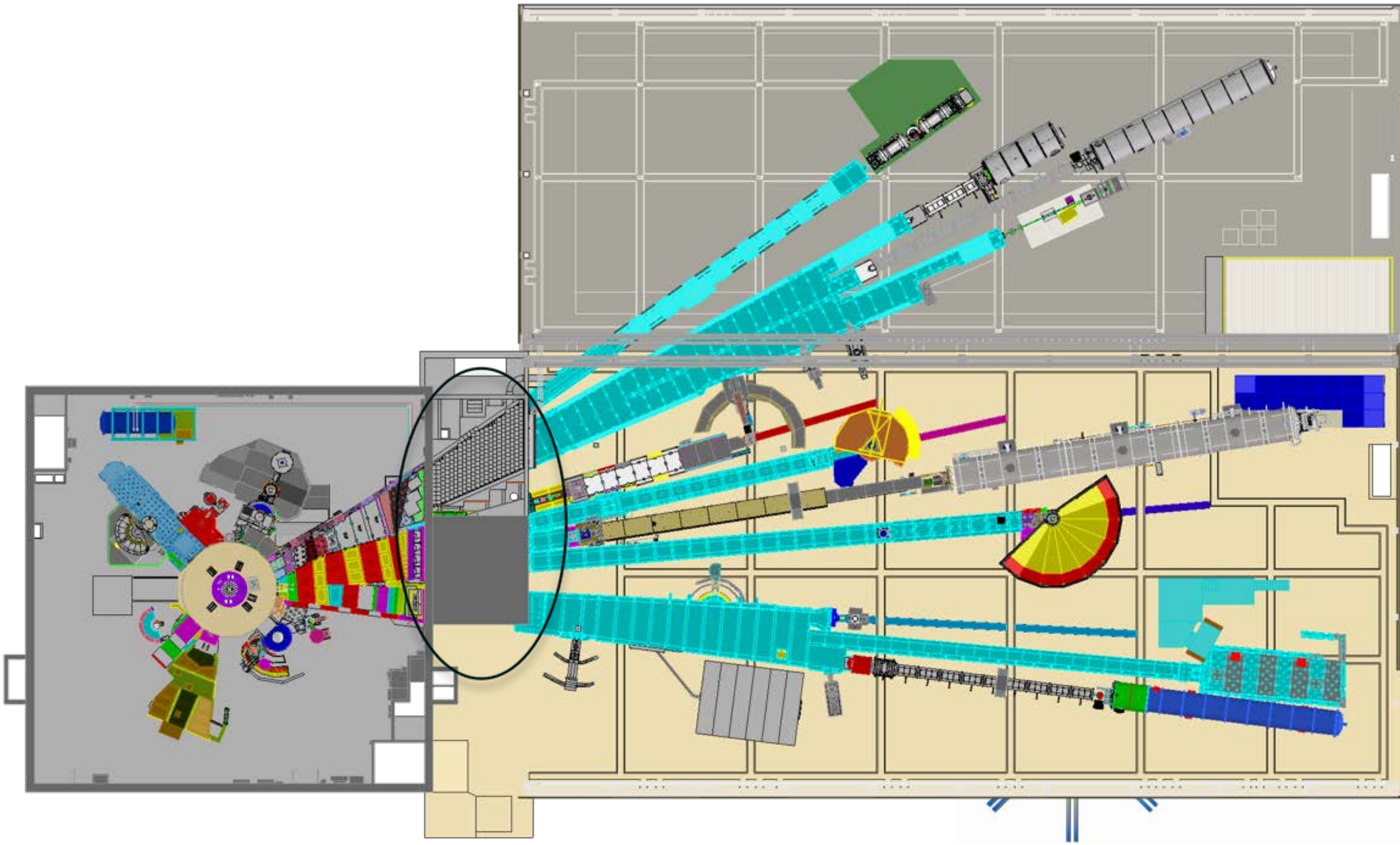
Guide shielding basics
Some commonly-encountered types of shielding

- **Regular concrete** shielding (relatively inexpensive, ρ~2.35 gcm^{-3} bulky, requires painting to avoid dust, chips)
  - 7.5m thick wall between reactor hall and guide hall is reinforced concrete (contains penetrations for guides NG1 to 7)
  - Until now guide penetrations had oil-filled casings to reduce radiation streaming around exterior of guides
  - NCNR uses regular poured concrete in room between reactor hall and guide hall for guides NGA-D
  - Also some concrete shields near magnetically sensitive areas of Neutron Spin Echo instrument



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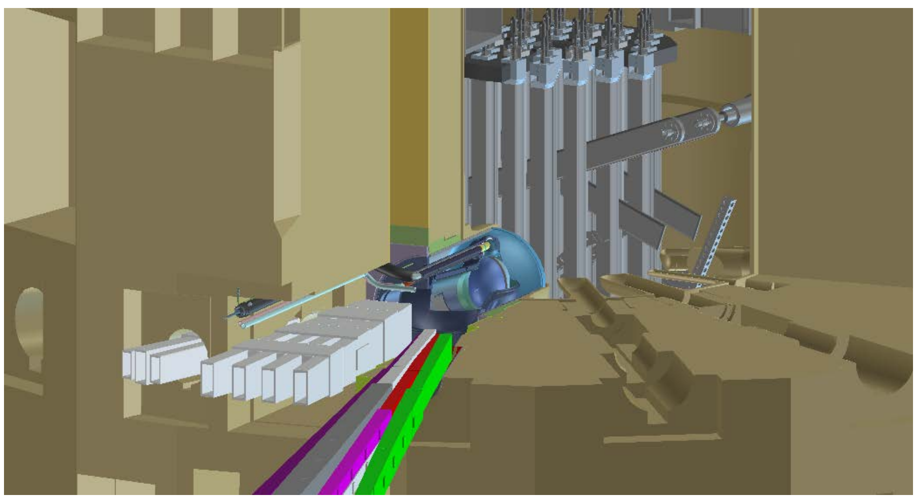
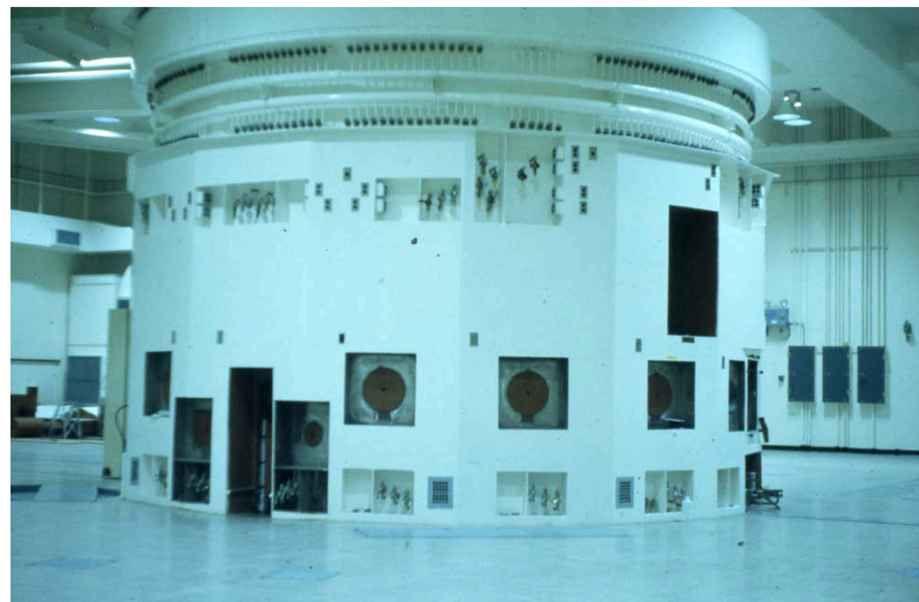
Guide shielding basics

Some commonly-encountered types of shielding

- **<u>HCON</u>** – Concrete mixed with e.g.
  - Magnetite
  - $BaSO_4$ (barytes)
  - Magnetite and steel punchings, etc.
- e.g. NIST reactor biological shield (ρ~3.6 gcm^{-3} ~ 2.2m thick)





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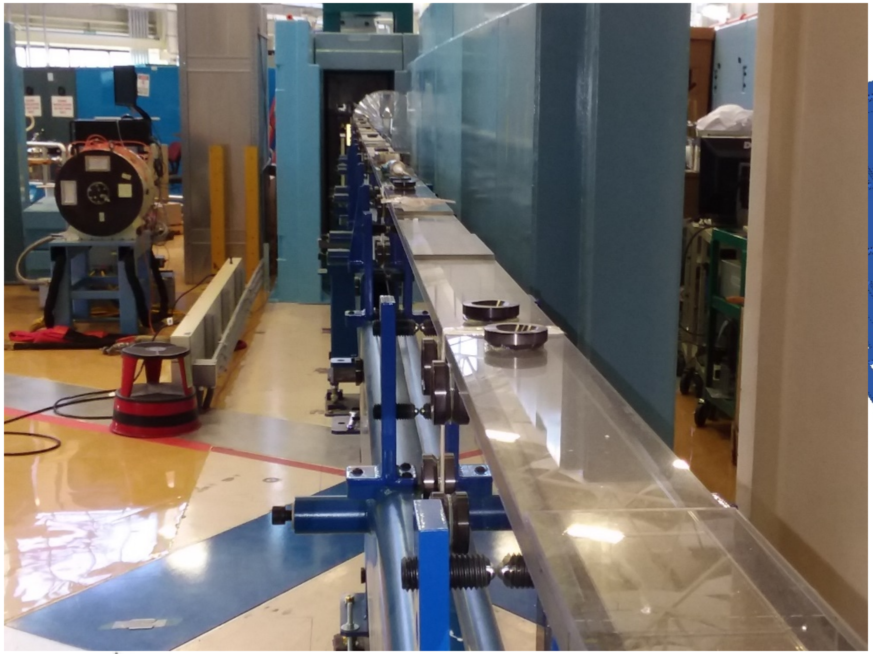
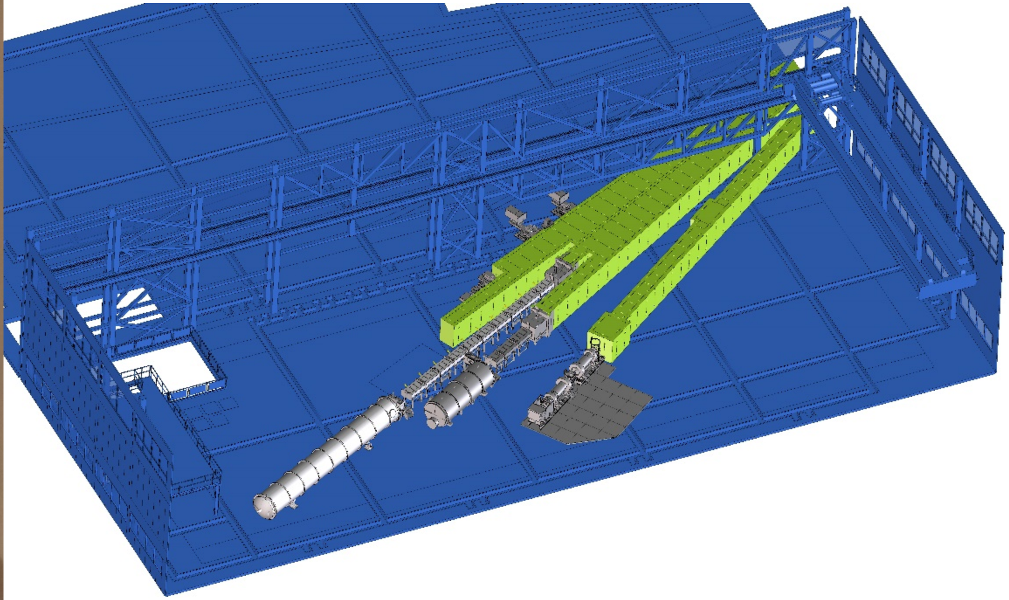
Guide shielding basics
Some commonly-encountered types of shielding

- **<u>Steel shot/paraffin wax (SSW)</u>** - NCNR uses steel weldments (typically 1ft thick) filled with SSW. Very effective for combined fast neutron/ gamma fields (sometimes weldments filled only with wax or even empty ~ physical barrier/protection)
- Most sky blue shielding you see in NCNR guide hall





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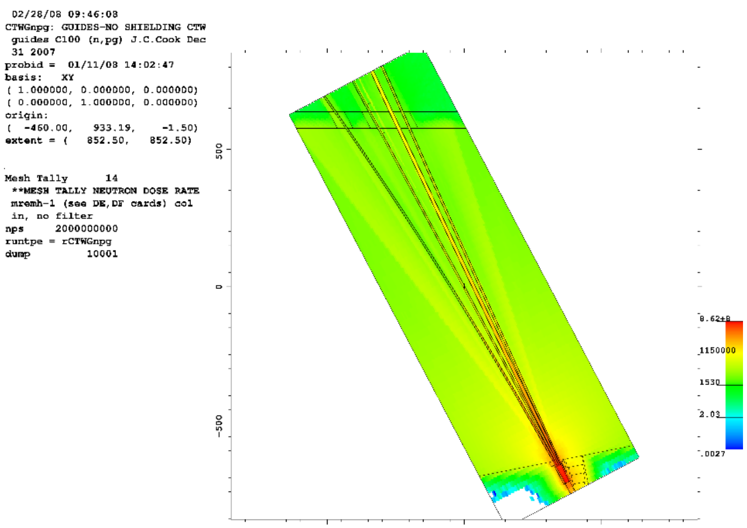
Approximate cost steel shot/wax (SSW) shielding

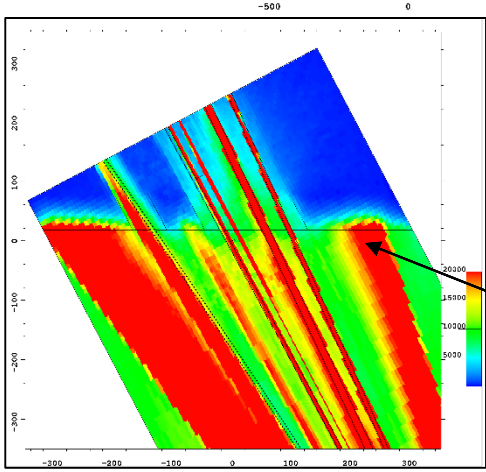
- Approx \$4.25/lb filled
- Cost/ft standard 1ft thick SSW shield ≈\$19829 = **\$65/mm** (quite alot!)
- **1 standard 4' long section (2 sides + 1 roof) ≈\$80K** (~19000 lbs, 8.5 tonnes)
(1 standard side ≈ \$32K, 1 standard roof ≈\$16K)

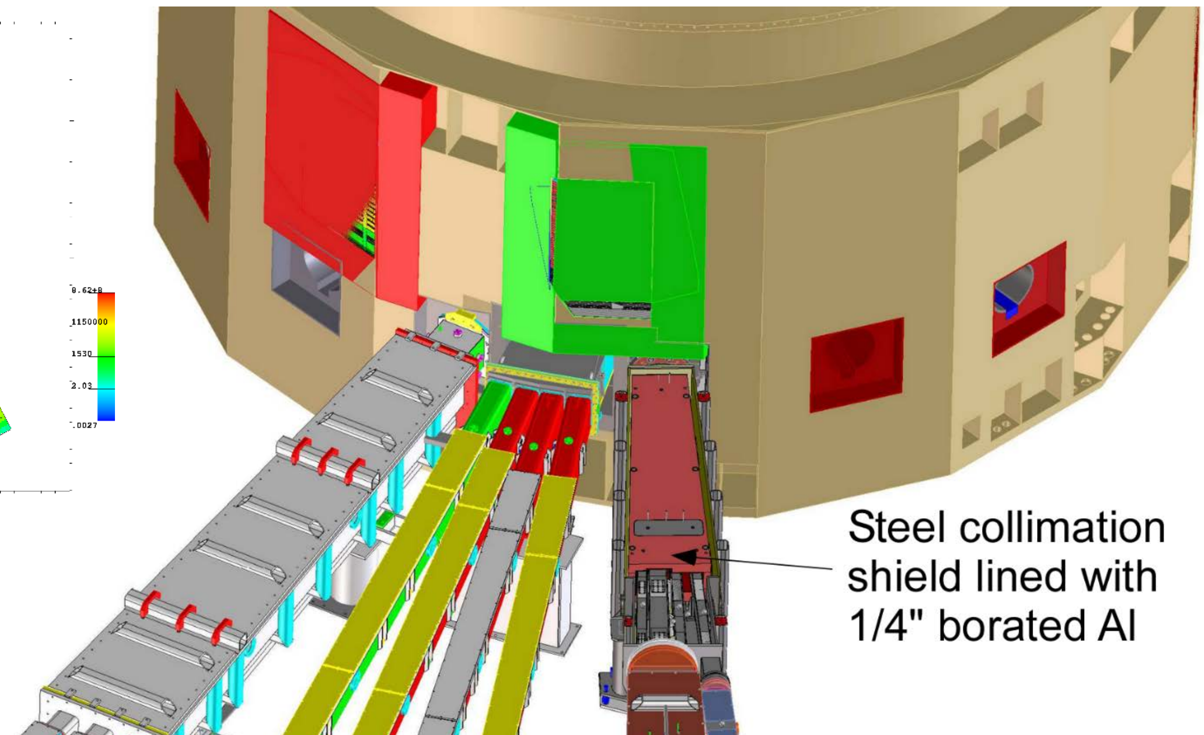
Guide shielding basics

Some commonly-encountered types of shielding

- **<u>Steel shielding</u>**
- Usually when only gamma shielding is a concern e.g. end of NGC (also good for inelastic scattering of fast neutrons)
- Steel collimation "tub" shield (NGA-D) to limit radiation streaming into guide hall







Steel collimation shield lined with 1/4" borated Al

~20rem (0.2Sv) neutrons & gammas at C100 north wall if unshielded!

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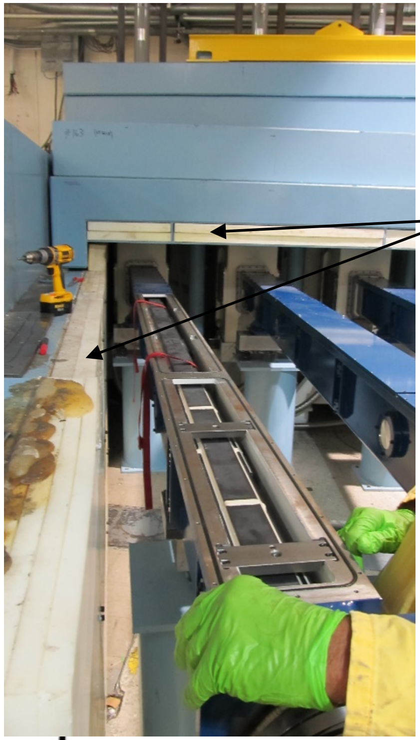
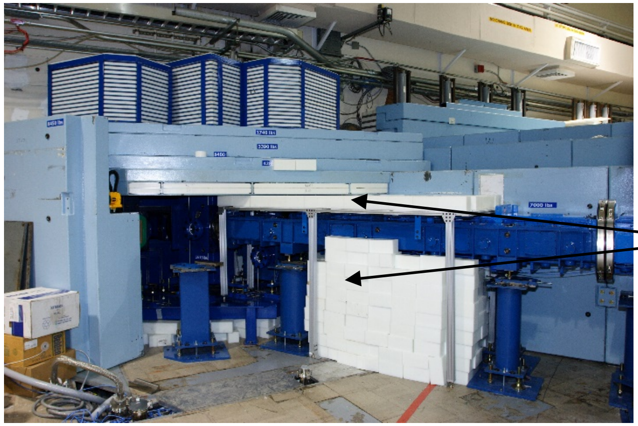
Some commonly-encountered types of shielding

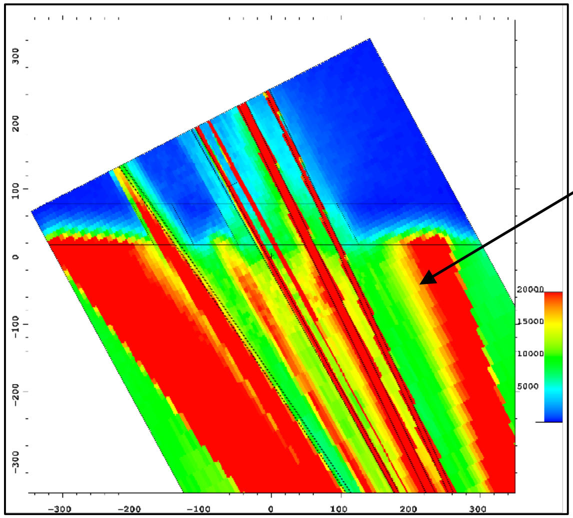
- **Polyethylene**: May use poly sheets on inside of shield near fast neutron scattering sources (e.g. crystal filters) but not near very strong gamma sources. At NCNR have had poly bricks very close to the reactor face crumble to dust (breaking of polymer chains). Most resistant plastics show change of elastic properties at < 10^{10} rads (10^8 Gy = 10^5 J/g), least resistant (e.g. Teflon) may fail at 10^6 rads (10^4 Gy)



Polyethylene sheets on inside of guide shields in reactor hall C100



Polyethylene stack near C100 north wall



~20rem (0.2Sv) neutrons at C100 north wall if unshielded

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Guide shielding basics

Some commonly-encountered types of shielding

- **Lead (Pb)** - (ρ~11.3 gcm^{-3})
  - Good gamma shield, used near gamma hotspots created by neutron capture in beamline elements etc.
  - Avoid direct exposure to neutrons (e.g. in beam shutters) - radioactive and chemically toxic – mixed waste – may justify use of W instead
  - Pb poor attenuator of thermal neutrons
- **Tungsten (W) -** (ρ~19.3 gcm^{-3})
  - Very effective gamma shield
  - Combined with hydrogenous material (e.g. polyethylene) is effective high energy (> 1 MeV) neutron moderator because of W inelastic scattering cross-section
  - Disadvantage:
    - Expense and difficult to machine (less expensive and less dense variants are available– Tungsten Hevimet (ρ ~17 – 18 gcm^{-3}), and compressed W shavings (ρ >~ that of Pb))
    - Becomes β radioactive when exposed to neutrons

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- Miscellaneous issues
  - Mechanical stability (C.G.) etc. very important in shield design. Credible seismic events are now considered in shield designs in most neutron scattering facilities
  - Avoid very strong source of gammas on SSW (gamma heating in steel and poor heat exchange can transition wax through M.P. (~60C) with ~10% volume increase!)

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- Questions?