Beam power nonlinearity: twice the power, but not twice the neutrons?

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Abstract. Over the course of SNS operations, the neutronics team has observed indicators of a non-linear relationship between proton beam power and neutron brightness on multiple beamlines. As we prepare to replace the inner reflector plug, we have conducted our largest and most complete tests of this non-linearity in dedicated experiments. We will discuss our findings and subsequent experiments, their impact and our investigation of possible explanations for this behaviour.

1. Introduction

It would be reasonable to assume that increasing the beam power of a spallation neutron source by increasing the proton current by a certain percentage would result in a neutron production increase by the same percentage. It was therefore troubling to find indicators based on several individual measurements that the target/moderator system at SNS exhibits nonlinearity between beam power and resulting neutron yield.[1] Recent dedicated facility wide measurements confirm this for certain moderators.

1.1. Metrics

In order to measure the impact of changes to the moderator system, beam monitor data as well as instrument detectors were used. It is useful to define a metric “neutron yield”, which is “detector counts per proton charge delivered to the target”. In an ideal case, the neutron yield would be constant, meaning that e.g. doubling the beam power results in as many neutrons being delivered to the user instruments.

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Y_{\text{id}} = \frac{\text{instrument detector counts}}{\text{proton charge}} \sim \frac{\text{count rate}}{\text{beam power}}
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Y_{\text{bm}} = \frac{\text{beam monitor counts}}{\text{proton charge}} \sim \frac{\text{count rate}}{\text{beam power}}
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The two neutron yields each are sensitive to different parameters and serve different purposes: The instrument detector counts in $Y_{id}$ differ drastically from experiment to experiment and depend on extrinsic effects like the sample in place, the exact sample location and a wide variety of instrument settings such as slit settings and chopper configuration. At the same time, the instrument detectors offer high precision, little intrinsic effects like dead time, and (data being collected in event mode) the ability to reconstruct a finely binned time line.

Beam monitors, on the other hand, are usually built into the flight path far enough upstream to be unaffected by most instrument changes. However, they often suffer from dead time effects, which can introduce a systematic error at increasing beam powers, and usually collect data only as histograms, which means the finest time resolution available is the duration of the experiment.

Therefore, $Y_{id}$ is best used for limited time dedicated experiments where the instrument is left at a certain configuration and the source characteristics (proton beam power, moderator temperature …) are modified, whereas $Y_{bm}$ is best used to monitor moderator health in the background during ongoing operations on a timescale that stretches months or even years. Attention has to be paid in this case to either comparing only data collected at identical power levels, or to develop a reliable calibration method to adjust for possible dead time issues.

Neither $Y_{id}$ nor $Y_{bm}$ can account for beam line components such as neutron guides, and both are convoluted with a wide range of parameters like detector efficiency, bandwidth selection and instrument background. They can therefore not be expected to deliver absolute neutron production numbers. However, it is reasonable to assume that –within the boundaries just discussed- changes in these metrics reflect changes in the target/moderator performance itself.

2. Experimental setup
In order to measure the impact of proton beam characteristics on neutron yield, we decided to perform a series of dedicated experiments using the neutron scattering instrument suite at SNS as detectors. For that, we chose one or two instruments per moderator surface, and asked the instrument scientists to illuminate the instrument detectors. In most cases, this was achieved by putting a piece of Vanadium into the sample position. Data was then taken continuously in event mode or, if this was not feasible, in five minute increments for the duration of the experiment.

2.1. Experiment 1: beam power dependence
These were tests to investigate any direct beam power dependence on moderator performance. To this aim, the beam power was first ramped up continuously to 450 kW, and following that increased in 30 kW steps (~20 minutes each) up to the final power (1 MW). The accelerator protocol used for this sequence is identical to the one used for foil conditioning routines.

2.1.1. Decoupled poisoned Hydrogen moderator.
The neutron yield of the decoupled poisoned liquid Hydrogen moderator shows strong power dependence. As the beam power was increased, the total number of neutrons detected in the TOPAZ instrument (BL12) decreased (Graph 1a). The same holds true for the opposite side of the moderator (not pictured). The decline seems to proceed in a linear fashion. Upon further analysis, it can be seen that the changes are wavelength dependent (Graph 1b). While the neutron yield in the wavelength range from 1.0 to 1.2 Å declines by approximately 10% when the proton beam power is increased from 100 kW to 1 MW, neutron yields at ~2 Å and ~3 Å fall by closer to 15%. The ramifications of this change in the neutron spectrum are significant: calibration measurements at one beam power are not necessarily valid at other power levels any more.
2.1.2. Ambient water (thick side). An example of a moderator not influenced by proton beam power can be seen in Figure 2. The ARCS instrument on the thick side of the water moderator does not see substantial changes in neutron yield over the course of a 1 MW ramp up. Apparent changes can be seen at low beam powers. Possible explanations for this might be a lack of background subtraction (artificially increasing the detector counts encountered per proton charge), or errors due to the fact that any effective beam power during a rapid ramp up such as here is necessarily averaged.

2.2. Experiment 2: investigation of repetition rate
To establish whether the moderator changes described above are a result of time averaged power or of the power per individual proton pulse, an experiment changing accelerator repetition rate was conducted. Several beam power levels were reached by adjusting beam current and repetition rate inversely. This led to the accelerator settings of e.g. 500kW@60Hz and 500kW@30Hz, where the latter has proton pulses twice as intense, but only half as often as the former.
As can be seen in Fig 3, the repetition rate has no influence on neutron yield at low beam powers. At 500kW, a small difference in neutron yields can be seen: 500kW@30Hz produces slightly more neutrons than 500kW@60Hz. This would mean that a more evenly distributed proton beam delivery has a larger detrimental effect than individual, highly intense pulses. However, the substantial differences in proton pulses between these two settings required comparably large changes in proton beam footprint to prevent damage to the target, which might have caused changes in the neutronics characteristics of the overall target/moderator system. More experiments focused on keeping the proton beam footprint consistent will be necessary. However, the extent of the changes suggest that the primary source of the nonlinearity effects is the average beam power, with possibly a secondary effect of pulse intensity.

3. Possible explanations
Several factors might influence moderator performance of a hydrogen system in a radiation field:
- Changes in ortho/para ratio
- Changes to temperature, especially through formation of ‘heat pockets’ by inconsistent flow patterns
- Changes in density, e.g. by the shockwave of the pulse rippling through the moderator at precisely the time that moderation occurs

Ortho/para ratio and temperature are both mostly dependent on average beam power, whereas density effects would likely be on the time scale of individual pulses. Calculations by Iverson suggest that the effects we see would be consistent with a hydrogen concentration of at least 30% ortho-H₂. Further insight will be gained upon installation of future generations of IRPs, which will offer improved flow patterns in the decoupled/poisoned hydrogen moderator and the incorporation of an ortho/para converter system.

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References
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