Neutron poison burnout and effects on SNS moderator performance

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Neutron poison burnout and effects on SNS moderator performance

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Abstract. Detailed neutron absorber burnup calculations were performed for the poison plate and decoupler layers of the decoupled ambient water and liquid hydrogen moderators of SNS. Although local poison burnout was identified for the water moderator at 32 GWh and local decoupler burnout was becomes apparent at the hydrogen moderator at 37 GWh delivered proton beam energy, both moderators see major impacts to the moderator performance by increases of pulse widths and spectral changes only past the stated burnout energies.

1. Introduction

The Spallation Neutron Source (SNS) produces pulsed neutron beams for material research and fundamental physics applications based on a proton beam delivering sub-microsecond pulses into a mercury target at 60 Hz repetition rate and 1.4 MW design beam power. The fast neutrons originating in the spallation reactions in the target are moderated by four ambient water and liquid hydrogen moderators placed in close proximity of the target in the so-called inner reflector plug (IRP). To generate sharp neutron pulses for high resolution measurements, the water moderator and one of the three liquid hydrogen moderators are equipped with a gadolinium poison plate in the center and with a decoupler cadmium layers absorbing thermal neutrons arriving from the reflector.

High-neutron-flux exposure depletes the poison and decoupler materials in those isotopes with high neutron absorption cross section such that the pulse shaping ability is diminished over time. Indeed, the burnout of decoupler and poison is the lifetime limiting effect of the IRP containing the moderators. At the design, the thicknesses of the decoupler and poison layers were chosen to guarantee an IRP life of 30 GWh delivered proton beam on target as estimated by calculations of neutron absorption rates and the criterion that at end-of-life we wished to have a thermal neutron blocking fraction of at least 0.80. Burnout simulations of the poison plates by Lu confirmed the 30 GWh life time[1].

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Several reasons motivated us to revisit the IRP life time predictions. Lu performed his depletion analyses with the CINDER'90 code [2] fed with neutron fluxes provided by MCNPX [3] calculations for a layered gadolinium plate sliced vertically into 1-2 cm wide stripes.
As local variations of the neutron flux persist across the width of the moderator, neglecting this variation underpredicts the rate of burnup. On the other side, the use of CINDER'90 activation cross section in for the burnup calculation has found to overpredict the neutron absorption in the resonance region because of multi-group representation, and hence overpredict the burnout. Additionally, Lu did not include the burnout of the decoupler material in his analyses. Over the course of burnout, the neutron fluxes in the moderator increase by as much as 20% and hence also speedup the burnup over the IRP life. Also the decoupler may burn out locally before the poison does due to large variations of thermal neutron fluxes in the reflector peaking close to the target in the areas between neighboring moderators. Finally, we want to investigate the evolution of moderator performance, the growth rate of brightness and the changes to the pulse shapes due to poison and decoupler burnup to arrive at a more realistic criterion to establish the end-of-life of the IRP.
As of the time of the ICANS-XXII conference, SNS will approach 35 GWh delivered beam on target and we had plans to start the replacement of the present IRP by an identical replacement component.
Because of manufacturing problems with the replacement IRP, the changeout will have to deferred to the end of calendar year 2017 by the time SNS will have accumulated 41 GWh. The accumulated information was essential for making decisions about the feasibility of continuing operations to this time, and about the vulnerability of the various neutron instruments in the SNS science program.

2. Methods of calculation

The neutron absorption property in thermal neutron fields and hence the ability of functioning as neutron poison in and around the moderators is dominated by the isotope ^{113}Cd in the decoupler and by the isotopes ^{155}Gd and ^{157}Gd in the poison plates. All three isotopes are transmuted into stable isotopes. Also, the feed-in into these three isotopes is driven from stable isotopes with lower neutron numbers. For these reasons, involving a transmutation code solving complex systems of decay chains is not required to track the evolution of isotopic compositions of the poison and decoupler zones. The equations governing the nuclide concentrations ${}_Z^AN$ with time t are easily established from isotope production rates ${}_Z^AP$ as

$$ {}_Z^AN(t) = {}_Z^AN(0) + \left({}_Z^{A-1}P - {}_Z^{A+1}P \right) * t $$

where

$$ {}_Z^AP = {}_Z^{A-1}N \int {}_Z^{A-1}\sigma(E)\, \phi(E)\, dE $$

with the absorption cross section ${}_Z^A\sigma(E)$ for isotope of mass number A and charge number Z and neutron flux $\phi(E)$ varying with energy E. The isotope production rates are directly calculated by a transport calculation of neutron flux buildup due to the proton beam impact in the SNS target station for a given material composition of poison and decoupler materials.
The time evolution was calculated by a multi time-step Runge-Kutta predictor-corrector method with time steps of 1000-hours length. Numerical problems expressed in large fluctuations in the number densities of the leading isotopes are found when burnout of these isotopes is reached. These are easily dampened by forcing the number density of the leading isotopes to arrive in an equilibrium such the production rate from minor isotopes balances their destruction rate:

$$ \frac{d\,{}_Z^AN}{dt} = -{}_Z^{A+1}P + {}_Z^AP = 0 $$

$$ {}_Z^AN = {}_Z^{A-1}N \int {}_Z^{A-1}\sigma(E)\, \phi(E)\, dE \Big/ \int {}_Z^A\sigma(E)\, \phi(E)\, dE $$

All the analysis was cast into a PERL script, which obtains production rates by MCNPX calculations, performs the transmutation calculations for the time steps, establishes revised material compositions for the next round of calculations of production rates and repeats the loop to a requested value of delivered beam energy on target.

The calculations of isotope production rates were based on a detailed as-built model. All poison and decoupler layers with typical thicknesses of one millimeter were sublayered into 5 zones and split into segments of about 2x2 cm^2 in total 7x8x5=280 pieces. Likewise, the decoupler zones were split into pieces to allow to account for local variations of burnup. The decoupler layer is flame-sprayed on the vacuum vessel and water vessel of the hydrogen and water moderators, respectively, except for the view ports on the front and back faces of the moderators and extended for 50 cm up the supply piping. All decoupler is facing a thin water cooling channel followed by bulk beryllium reflector, except for the hydrogen moderator bottom and water moderator top that are set into a water-cooled aluminum structure towards the target, and a side edge of the hydrogen moderator, which faces a 40-cm thick water column integrated into the neighboring coupled hydrogen moderator. In order to consider uneven decoupler burnup effects of zones facing thicker water zones at the hydrogen moderator, the decoupler was subdivided not only around the perimeter but also along the poison plate plane in BL11-side and BL2-side zones.

At several time steps, detailed moderator performance analyses were conducted for a large number of proton histories to arrive at converged results for moderator brightness spectra, and pulse shape analyses.

3. Results of poison and decoupler burnup calculations

The poison plates and decoupler layers burn out the leading neutron-absorbing isotopes very unevenly as shown in Figures 1 and 2. The hydrogen moderator experiences burnout of the decoupler at the BL11 side at the bottom of the moderator pointing towards the coupled moderator at around 37 GWh delivered proton beam. At his time, the its poison plate has 7% of the neutron poison left in its fastest-burning location and would last for 3 GWh longer.

For the water moderator, the burnout is reached first in the top third of the poison plate at 32 GWh (see Figure 2). Its decoupler would hold up for 11 GWh longer before springing a neutron leak.

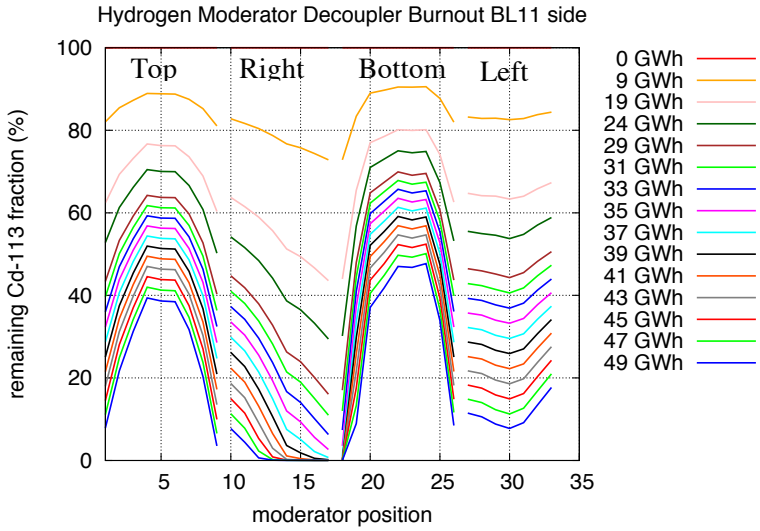

Figure. 1: Evolution of local loading of ^{113}Cd in the decoupler layer in percentage of initial loading of the decoupled poisoned hydrogen moderator at various stages of delivered beam energy on target with the moderator positions running around the circumference of the moderator.

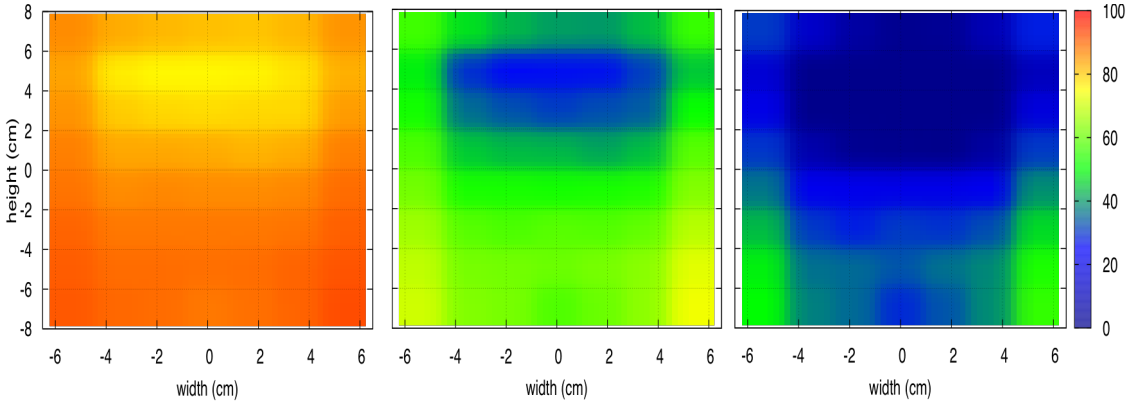

Figure 2: Local loading of ^{155}Gd+^{157}Gd in the poison plate of the water moderator in percent of initial loading: 9 GWh-left, 25 GWh-center, 40 GWh-right. The moderator is positioned at the bottom of the target.

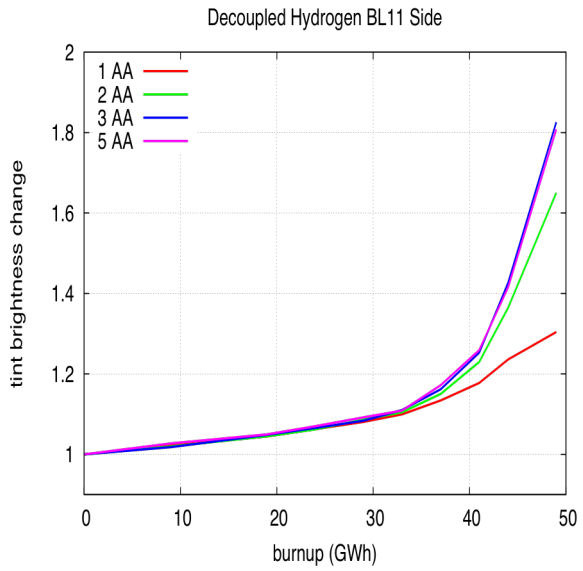

Figure 3: Change in time-integrated pulse brightness of the hydrogen moderator versus delivered proton beam energy as viewed from the BL11 side.

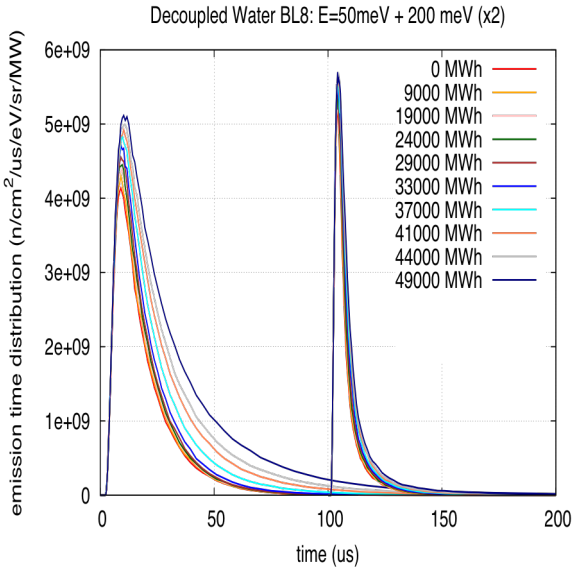

Figure 4: Neutron emission time distribution of water moderator at 50 and 200 meV evolving with delivered proton beam energy as viewed from the BL 8 side.

4. Impact of poison and decoupler burnup on moderator performance

With changes of the isotopic composition of the poison and decoupler due to burnup, the moderating processes, pulse-shaping effects, and the moderator performance change with time. The effect on moderator performance was analysed by performing longer transport calculations at various steps of the IRP life with decoupler and poison material compositions resembling the state of burnup of the requested time. A steady increase over integrated delivered beam energy is experienced up to about 15% increase, and much steeper increase thereafter for both the water and hydrogen moderators as shown in Fig. 3. The break-away points signal holes in poison or decoupler. The BL17 side of the water moderator with 25 mm water depth to the poison plate is much less sensitive than the BL8 side with 15 mm depth.

The emission time distributions of the pulses as shown in Figure 4 for the BL8 side of the water moderator for 50 and 200 meV (offset by 100 μs) neutron energies show that the increase in time-

integrated brightness after the break-away point pile in not so much in the pulse peak but rather in the tail of the distribution.
As the scheduled IRP replacement in March 2017 (at 37 GWh) has been postponed to beginning 2018 due to late delivery of the replacement IRP, the predicted moderator performance data and confirming performance measurements let us confidently extend the IRP life to 41 GWh.

Acknowledgement
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References
[1] Lu, W., Ferguson, P.D., Iverson, E.B., Gallmeier, F.X. and Popova, I., Journal of Nuclear Materials, Vol. 377(1), pp. 268-274 (2008).
[2] W. L. Wilson, T. R. England, K. A. Van Riper, Proceedings of the Fourth Workshop on Simulating Accelerator Radiation Environments (SARE4), Knoxville TN, Sept. 14-16, 1998.
[3] D. B. Pelowitz, MCNPX User's Manual, Version 2.6.0, Report LA-CP-07-1473, Los Alamos National Laboratory, Los Alamos, New Mexico, 2008.