RADIATION MEASUREMENTS VS. PREDICTIONS FOR SNS LINAC COMMISSIONING *

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Abstract

To support Spallation Neutron Source (SNS) [1] accelerator commissioning stages, detailed predictions for radiation fields induced inside and outside of the accelerator tunnel were performed using the Monte Carlo code MCNPX. On the basis of neutronics analyses, proper shielding was developed and installed in key locations to reduce dose rates in occupied areas. Absorbed dose and dose equivalent rates were monitored by radiation measurement devices both inside and outside of the tunnel areas. The measured radiation fields were analyzed and compared to radiation transport simulations.

LINAC COMMISSIONING

Commissioning of the accelerator system is a critical step in the transition from the fabrication and installation phase to the operational phase. In accordance with the SNS Commissioning Program Plan [2] the LINAC sections were commissioned in stages adding consecutive accelerator structures and terminating H^- beam properly in the temporary beam stops or permanent beam collectors (Faraday cups).

The beam power deposited locally in the LINAC tunnel during the commissioning phases greatly exceeded typical operational line losses that are of the order of 1W/meter with the consequence of very high level radiation fields. Proper temporary shielding was installed in local areas near beam termination points (beam stops and beam collectors) and some critical locations, such as penetrations, in order to minimize dose rates in normally occupied areas.

General LINAC Layout

The SNS accelerator facility is powered by a high-intensity 2-mA, 1-GeV proton beam. This energy is achieved in the LINAC section, where the H^- beam is accelerated from 2.5 MeV up to 1 GeV. Then the beam is injected into an accumulator ring, as it is converted to a proton beam by having its electrons stripped away.

The proton beam is shaped into about 1 microsecond pulses in the accumulator ring through nominally one thousand turns and is extracted from the ring and transported by the ring-to-target-beam transport (RTBT) line to the mercury target.

Figure 1 shows the general LINAC layout. LINAC consists of: six drift tube LINAC tanks – DTL section; four coupled cavity LINAC modules, each with 12 segments, – CCL section, superconducting LINAC – SCL section, and a spare section for the future power upgreat.

LINAC Commissioning Steps

LINAC commissioning was done in four steps. Table 1 shows commissioning beam parameters and temporary beam stop materials.

Table 1: Commissioning steps parameters

<table>
<tr><td rowspan="2">Para-meters</td><td colspan="6">DTL tanks</td><td colspan="4">CCL modules</td><td>SCL</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>1</td><td>2</td><td>3</td><td>4</td><td></td></tr>
<tr><td rowspan="5">Beam stop mate-rial</td><td>Nickel</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">Copper</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="9">Copper</td><td></td><td></td></tr>
<tr><td colspan="10">Copper</td><td></td></tr>
<tr><td colspan="11">Copper</td></tr>
<tr><td>Beam energy MeV</td><td>7.5</td><td>22</td><td>40</td><td>57</td><td>73</td><td>87</td><td>107</td><td>132</td><td>157</td><td>157</td><td>10^3</td></tr>
<tr><td>Beam power, W</td><td>$1.6 \cdot 10^3$</td><td>160</td><td>160</td><td>160</td><td>160</td><td>160</td><td>250</td><td>250</td><td>250</td><td>250</td><td>250</td></tr>
</table>

In the first step DTL tank 1 was commissioned, with beam energy up to 7.5 MeV and beam termination at the end of DTL tank 1. On the second step DTL tanks 2 and 3 were added, with beam energy up to 39.5 MeV and beam termination at the end of DTL Tank 3. On the third step DTL tanks 4-6 and CCL modules 1-3 were added, resulting in beam energy up to 156 MeV and termination at the end of CCL module 4. DTL tanks 2 to 6 and the CCL modules 1-3 were commissioned into beam stops

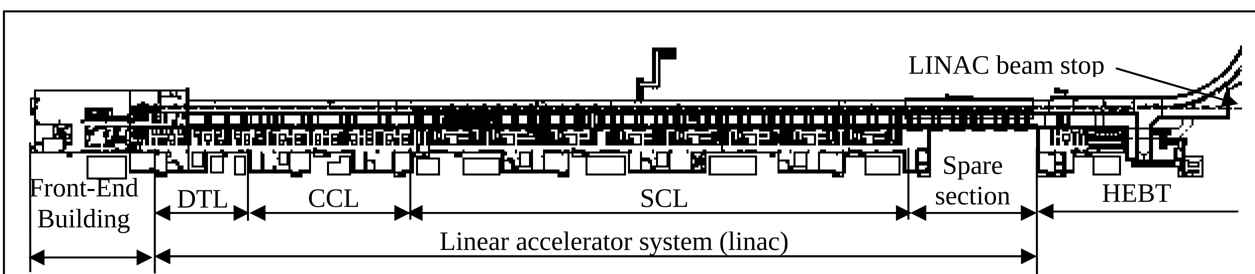

Figure 1: Layout of SNS LINAC facility.

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located at the downstream end of the tanks with beam energies as listed in Table 1. Beginning from the last CCL module (module 4), and continuing throughout the SCL cryogenic modules, beam was commissioned into two locations: the beam stop at the end of CCL module 4 and at the permanent LINAC beam dump.

METHODS AND TOOLS

In order to minimize dose rates in normally occupied areas, temporary shielding was developed and installed in local areas near beam termination points and near select penetrations connecting the accelerator tunnel to occupied areas. During the commissioning radiation levels in normally occupied areas were monitored in addition to those in the tunnel.

Calculation Tools

Shielding was designed based on neutronics studies using the Monte Carlo code MCNPX [3] applying realistic three dimensional geometry descriptions. Dose rates were calculated for each commissioning step to scope out the shielding needs in a first step of the analysis and in an final step to evaluate the shielding solution. Different beam energies and loss scenarios were considered to determine adequate shielding minimizing prompt dose rates, and also residual dose rates from activated beam line components. Neutronics analyses were performed for the normal commissioning parameters, for the worst possible beam accidents, and for the beam fault studies to predict the dose rates.

Source terms were described as a point beam incident on the beam stop with energy and intensity corresponding to each commissioning stage. For the beam accident and fault study, the axial beam loss distribution was described by a Gaussian function.

Radiation Monitoring Tools

Radiation monitoring was performed using the real time radiation measurement devices listed below and TLDs to measure absorbed dose and dose equivalent rates:

- Chipmunk: Fermilab-designed neutron and gamma sensitive PPS detector;
- Far West: Chipmunk equivalent unit;
- RO20: gamma sensitive;
- REM500 survey meter: neutron sensitive;
- RemBall, neutron sensitive;
- Albatross: neutron sensitive;
- Snoopy: neutron sensitive;
- MicroRem: gamma sensitive;
- Far West HPI 1030 survey meter for pulsed fields: gamma and neutron sensitive.

RESULTS

The measured radiation fields were analyzed and compared to the results from the transport simulations for each commissioning stage.

DTL Tank 1

DTL tank 1 was commissioned at full 16-kW beam power with 7.5-MeV energy into a beam stop. Results are presenting in Table 2. In some locations there is a large discrepancy between measurements and calculations, which is due to some complication during beam operation. For example an emittance slit was accidentally being moved into the beam at the downstream end of the DTL tank, and some beam scraped at a bellows located between the DTL tank and the temporary beam stop, creating secondary radiation sources upstream of the shielding not accounted for in the source modeling. TLD measured gamma dose rates compared well to the measured dose rates of real time instruments.

Table 2: Measurements vs. calculations, DTL tank 1 commissioning

Location/ Detector	Particle type	Dose rate (mrem/hr)		
		M	C	M/C
Above PE shield/TLD	neutron gamma	92 564	5 1100	18.4 0.51
Backscattering cone/TLD	neutron gamma	464 88	55 25	8.4 3.7
Detector cluster/RO-7	gamma	7	6	1.12
Detector cluster/chipmunk	neutron+ gamma	6.8	9.5	0.72
Detector cluster/ Far West	neutron+ gamma	6.8	9.5	0.72

For Tables 2 to 6, M means measurements, C means calculations, and M/C indicatea the ratio between measurements and calculations.

DTL Tank 1 to 3

During DTL tank 1 to 3 commissioning only TLDs were placed inside the accelerator tunnel to measure radiation fields. Table 3 shows the results. The maximum deviation between TLD measurements and calculations is about a factor of 1.8, which we regard as a satisfying agreement taking into account the complicated geometry model, and shielding thickness around source and the beam stop (about 0.8 m around the beam stop).

Table 3: Measurements vs. calculations, DTL tank 1 to 3 commissioning

Location/ Detector	Particle type	Dose rate (mrem/hr)		
		M	C	M/C
Back-streaming cone	Neutron	1.020	0.924	1.1
	Gamma	0.248	0.180	1.4
Top of beam stop shielding	Neutron	0.832	0.650	1.28
	Gamma	0.186	0.100	1.8
Tunnel wall at beam stop level	Neutron	0.182	0.100	1.8
	Gamma	0.054	0.075	0.72

DTL Tank 1 to 6 and CCL Modules 1 to 3

Specific to this commissioning stage was the fact that straight conduits (klystron wave guide ducts) penetrate the tunnel shielding near the DTL beam collectors going from the tunnel to the klystron gallery. As a result of radiation studies, shielding was installed inside the accelerator tunnel closing the penetrations. Additionally, access to the klystron gallery was controlled.

Table 4 summarizes commissioning results for DTL tanks 1 to 6 and CCL module 1 to 3 commissioning to the temporary beam stop located downstream of CCL module 4. The maximum deviation between TLD (Far West) measurements and calculations is about factor of 2.6.

Table 4: Measurements vs. calculations, DTL tank 1 to 6, CCL module 1 to 3 commissioning to the beam stop

Location/ Detector	Particle type	Dose rate (mrem/hr)		
		M	C	M/C
On the North side of the beam stop shielding monolith, against the block wall	Neutron	88,000	98,000	0.90
	Gamma	5000	6000	0.83
On the tunnel wall directly opposite the beam stop shield monolith	Neutron	32,000	16,000	2.0
	Gamma	1000	900	1.1
Along the tunnel north wall, 20' upstream of the beam stop	Neutron	7000	3500	2.0
	Gamma	180	130	1.4
Near the tunnel wall, next to the real time instruments	Neutron TLD	2300	900	2.2
	Neutron Far West	2000	900	2.6
	Gamma	61	31	2

Table 5 summarizes results for commissioning DTL tanks 1 to 5 onto a beam collector, located downstream of tank 5. Measured gamma dose rates are higher due to dark current effects originating from the microwaves powering the DTL tanks that were not considered in the calculations. There is higher inconsistency between calculations and the readings from TLDs located on the penetration side of the shielding inside the tunnel. Other numbers agree within a factor of 2.

Table 5: Measurements vs. calculations, DTL tank 1 to 5, commissioning to the beam collector

Location/ Detector	Particle type	Dose rate (mrem/hr)		
		M	C	M/C
On the collector side of penetration shielding	Neutron	320,000	257,000	1.3
	Gamma	11000	2420	4.6
On the penetration side of shielding	Neutron	215,000	42,000	5.1
	Gamma	5000	1082	4.6
On the North wall of the tunnel, directly opposite to the collector	Neutron	140,000	110,000	1.3
	Gamma	3200	1040	3.1
At the top of the penetration, in the center opening (RemBall)	Neutron TLD	5	11	0.5

DTL Tank 1 to 6, CCL Modules 1 to 4 and SCL

During the final commissioning stage, the beam was accelerated to the nominal energy of 1 GeV. The maximum commissioning accident – full beam loss in the SCL section close to klystron penetrations - was simulated as part of the fault studies among other measurements not elaborated here.

Table 6 shows measurements of a variety of radiation instruments compared with calculations during a simulated beam accident at 387MeV near penetrations 91, 94 and 95 in the klystron gallery. For these studies the penetrations were unshielded.

Table 6: Measurements vs. calculations during last LINAC commissioning stage, beam accident near penetrations

Detector type	Units, particles	Penetration 91		Penetration 94		Penetration 95	
		M	M/C	M	M/C	M	M/C
Albatross	(mrad/h)	1.00	0.42	4.00	0.20	15.00	0.75
Remball	(mrem/h)	2.70	0.18	19.00	0.16	15.00	0.13
Snoopy	(mrem/h)	0.40	0.03	0.70	0.01	1.70	0.01
Rem500	(mrem/h)	4.70	0.31	101.00	0.85	169.00	1.44
RO20	(mrem/h)	0.60	1.20	3.70	1.32	11.00	3.67
MicroRem	(μrem/h)	95.00	0.19	150.00	0.05	165.00	0.06
Calculations	(mrem/h) Neutrons	15.00		119.00		117.00	
	(mrad/h) Neutrons	2.40		20.00		20.00	
	(mrem/h) Gammas	0.50		2.80		3.00	

According to the Table 5 there is a large deviation between different instrument readings. Snoopy (neutrons) measurements are out of range compared to other instruments. The Albatross, Remball and Rem500 readings are generally lower than the calculations.

CONCLUSIONS

Detailed predictions for radiation fields, created inside and outside of the accelerator tunnel, were performed for each of the SNS accelerator commissioning stages, from the ion source throughout the entire LINAC. During commissioning, radiation was monitored using real time radiation measurement devices and TLDs. The measured radiation fields were analyzed and compared with transport simulations. TLD readings and calculations are in a good agreement, generally within a factor of two. A large inconsistency among instrument readings was observed, and an effort is underway to understand the differences.

REFERENCES

[1] *National Spallation Neutron Source Conceptual Design Report*, Oak Ridge National Laboratory, NSNS/CDR-2/VI, 1997

[2] *Spallation Neutron Source Commissioning Program Plan*, Oak Ridge National Laboratory, SNS 100000000P-PN0004-R00, July 2002.

[3] L.S. WATERS, ed., *MCNPX User's Manual – Version 2.1.5*, Los Alamos National Laboratory, NM, TPO-E83-G-UG-X-00001, Nov. 1999.