SNS PERFORMANCE AND THE NEXT GENERATION OF HIGH POWER ACCELERATORS*

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Abstract

The SNS accelerator at ORNL has been operating near the MW level for several years now. This presentation discusses the successes and challenges, new insight gained and lessons learned with regard to the operation of a modern high power accelerator. In particular, issues with the RFQ, the target and the superconducting RF linac are discussed. Also future high power proton accelerator plans and development needs are discussed.

RECENT SNS OPERATIONAL EXPERIENCE

The Spallation Neutron Source (SNS) accelerator reached the 1 MW operational power level in 2009. Over the past two years beam power has been run between 0.85 MW and 1 MW, as indicated in Fig. 1, with reduced power operation driven by considerations beyond accelerator components. For example the past year of operation, beam power was reduced to preserve target lifetime due to a target spare shortage. However, for the past few weeks, the operational power level has been increased up to 1.2 MW.

Extended running periods without power increase in 2010 – 2011 coincided with increased accelerator availability, as shown in Figure 2. After steady rises in operational hours and beam availability through 2011, the past 2 years show decreases in both these figures. These are due to target failures at the end of FY 2012, and the start of 2013 that severely reduced operational hours and negatively impacted the beam availability. The target issue is discussed in more detail below. Discounting the target failures, the accelerator availability for the years 2011-2013 was 92%, 94% and 89% (YTD) respectively.

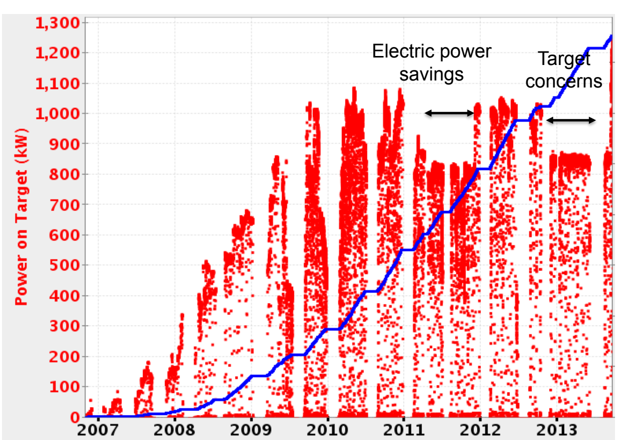

Figure 1: Power history of the SNS accelerator.

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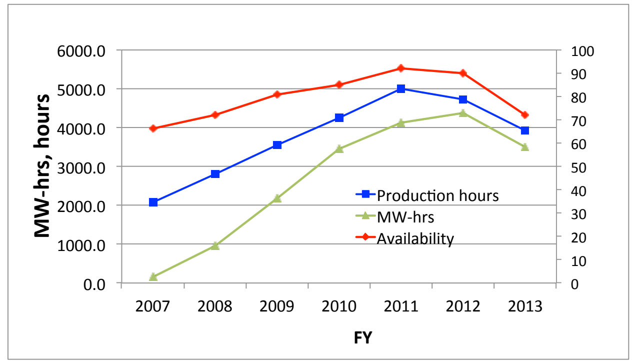

Figure 2: Operation hours and availability since initial operations in 2007.

RFQ Issues

The SNS RFQ experienced 2 detuning incidents in 2003 and 2009, which required retuning of the RFQ in order to operate. From the period mid-2011 through mid-2012 a reduction of beam current measured downstream of the RFQ was observed for all ion sources [1] (see Figure 3). This prompted a measurement of the field profile in the RFQ, and yet another perturbation was observed (see Figure 4). Interestingly, this field disturbance did not prevent operation of the RFQ, only a reduction in beam transmission. The first extended outage that allowed for retuning the field was summer of 2013. However, while there are suspected causes of the first two detuning incidents, this latest incident remains unexplained.

The field profile changes discussed above are likely specific issues related to the manufacturing of this RFQ. However, another perhaps more generic RFQ issue has been observed. This is the issue of discharge heating in the RFQ (in addition to the normal RF induced copper hearting [2]. The discharge related heating can be significant (~ 10% of total heat load) and is not constant, but rather dependent on the gas load history into the RFQ. Also it can change suddenly, complicating the cooling system and resonance control, which is designed for slower heat load changes. To accommodate this complication the low level RF control has been modified to provide fast modulation of the RFQ pulse length to help control the resonance error. However the additional pulse length margin used for this function is becoming limited as we reach the design pulse length of the machine (1 ms), and a new mitigation technique is being sought.

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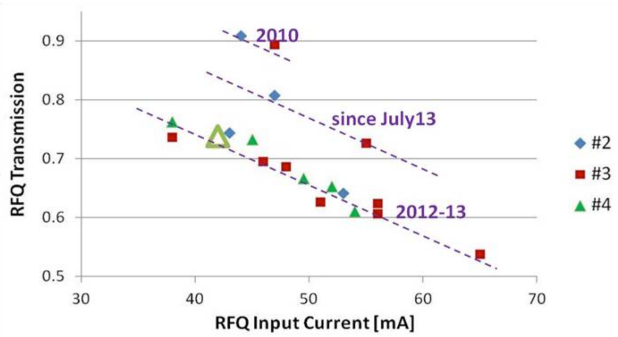

Figure 3: RFQ beam transmission as a function of input beam current indicating reduced transmission during the 2012-2013 detuned RFQ operation.

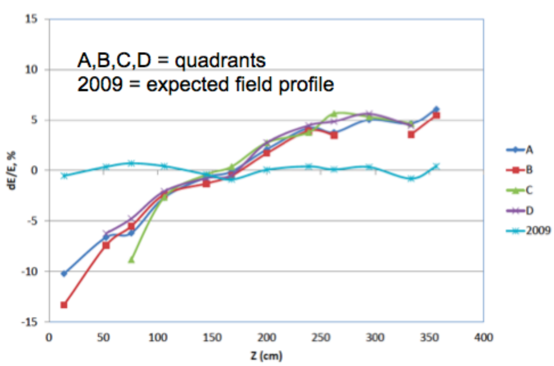

Figure 4: Field distribution along the SNS RFQ in 2012-2013 run.

Errant Beam

Machine protection has always been a major concern for high power operation at the SNS accelerator. Beam shut-off times were prescribed to protect the machine from prompt damage. Generally a 10-20 μs beam shut-off time has been accepted (damage can occur faster at lower beam energies where the stopping length is shorter). However, we have learned that the superconducting RF linac (SCL) cavities can be susceptible to performance degradation with beam loss periods lower than that required to actually approach melting temperatures [3]. In particular, beam trips caused by anomalies upstream of the SCL result in beam loss in the SCL, until the machine protection shuts off the beam. We refer to the beam lost in the SCL during these trips as “errant beam”. Even if each individual errant beam pulse does not harm the SCL, we have noticed degraded cavity performance after prolonged exposure to repeated errant beam pulses. A suspicion for the degradation cause is that the slight local heating (a few K) caused by errant beam pulses may initiate the migration of trapped gas in the cavity surface, to a more vulnerable region of the cavity. Figure 5 shows the history of the operational beam energy. Following an beam energy increase in 2009 resulting from cryomodule equipment fixes, during 2009-2011 operation, a slow energy degradation occurred, raising concern about errant beam.

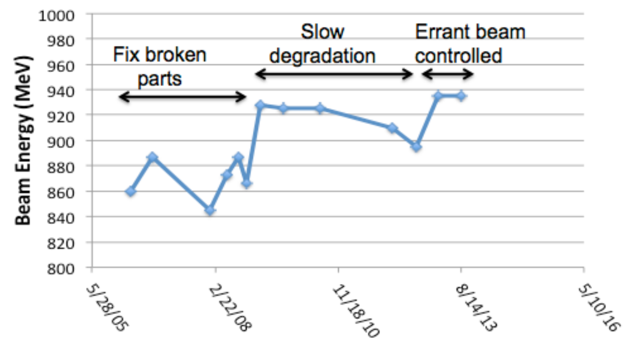

Figure 5: Operational linac output beam energy, indicating a period of performance degradation in 2009-early 2011.

An effort was initiated to identify and rectify causes of errant beam pulses. Two primary causes were identified: 1) pulses formed in the ion source with non-standard waveform shapes, and 2) pulses with premature upstream warm linac RF truncation. The first class constitutes < 10% of the trips and are caused by arcs in the source and electrostatic LEBT. Over 90% of the trips were caused by the RF faults, and the majority of effort was focused on these. We note that while the RF faults were damaging SCL performance, the actual down-time caused by the RF faults themselves was small (~ 30 trips per day each lasting < 1 minute).

One weakness identified, that contributed to increased RF fault rates, was insufficient attention to the vacuum quality which increased the frequency of arcs (hence RF trips). A more rigorous approach to vacuum maintenance improved this situation. Another reduction in fault frequency was reducing the number of trips allowed per second before requiring operator intervention from 2 to 1. Finally we also addressed a shortcoming the beam shutoff response time of the machine protection system. Namely, filters introduced to mitigate noise induced false machine trips also cased delays in the response time (up to > 300 μs in some cases). Even though electrical noise sources had been mitigated, the filters had not been removed. Eliminating these reduced the beam shut-off time to the design level of 10-20 μs and additional fast differential current systems are being deployed [4]. With these implementations the RF fault frequency was greatly reduced as shown in Figure 6. Also, the linac output beam energy has stabilized since instituting these changes, as indicated in Figure 5.

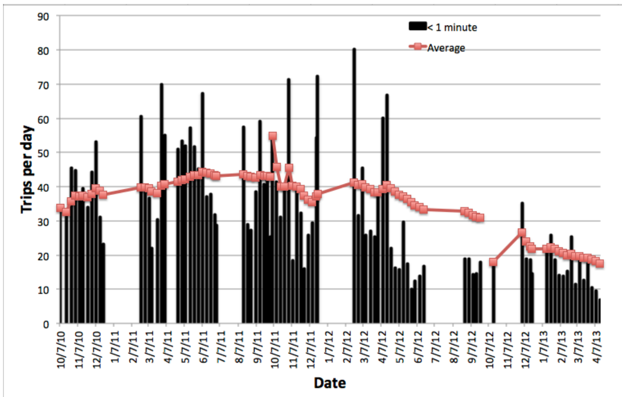

Figure 6: Short duration trip frequency (typical of warm linac RF faults) history at SNS.

Target Issues

High power accelerators require high power target systems. SNS uses a liquid mercury target system that has the advantage of combining the spallation material and coolant [5]. However the very short beam on target pulse (< 1 μs) introduces a complication of shock waves that cause cavitation damage. The target system includes a stainless steel vessel that contains the flowing mercury, and requires regularly scheduled replacement, using robotic, remotely controlled equipment. Until Sept. 2012, of the five target vessels used, there had been only one unplanned target replacement. However, in Sept. 2012 there were two target failures in rapid succession [6], which depleted the supply of spare targets, and resulted in the reduction of operating power (~850 kW) for almost one year, as seen in Figure 1. Investigation of the target failure mechanism resulted in identification of poor welds in a region of reduced stress that had not received adequate manufacturing oversight. Fabrication QA has subsequently been improved, but there is a time lag of ~ one year to manufacture these complicated, first of a kind structures, and replenish the target spare inventory.

In addition to the need to survive high power density, radiation damage effects, and intense pulsed stress levels the cavitation issue mentioned above introduces considerable uncertainty in target lifetime. Figure 7 shows a typical cavitation induced damage pattern, in sections of the upstream portion of the target vessel. There are 4 separate containment walls, and the inner-most bulk mercury facing wall is shown (this is the wall most subject to the cavitation damage). These cut-outs are part of an on-going target Post Irradiation Examination (PIE) effort. The cavitation pitting seen here is observed in a similar pattern as this on all targets. Especially pronounced is the narrow “cut-through” along the target mid-plane. The narrow line of cavitation damage is much more focused than the proton beam power distribution and is not well understood. Even if this layer is compromised, target operation is not limited. The following wall must also be compromised to produce a leak that halts operation, and to date this second wall does not show extensive damage. However PIE efforts are limited to date, we cannot see the entire second surface, and there is uncertainty in this area. New target designs include modified mercury flow patters to eliminate mercury stagnation near the region of observed pitting, and a removable outer shroud (outer vessel walls) to allow better PIE efforts. Targets with these changes are expected to be introduced into operation sometime in mid 2014.

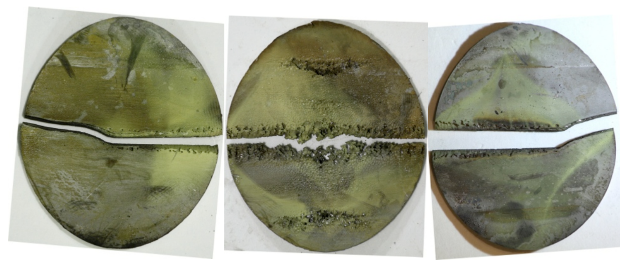

Figure 7: Three circular cross section cut-outs of the inner, front facing surface of target number 4 vessel – with a clear cavitation induced cut-through on the mid-plane.

A general lesson is that attention needs to be placed on the design and analysis of the target system, in addition to the accelerator. These systems are critical for operation of high power accelerators, and require development along side the accelerator components. Changes in this area require significant lead-time, and possibilities are limited due to the complete robotic maintenance approach that must be used.

NEXT GENERATION HIGH POWER PROTON ACCELERATORS

Recently the high power proton accelerator capabilities, planned upgrades and future facilities were surveyed [7], as part of the 2013 High Energy Physics Community Summer Study. Other facilities have high power proton accelerators in operations and in plans, and theses are summarized here. A more exhaustive facility list and explanation of R&D needs is explained in Ref. 7.

Existing Accelerators

There are many high power proton accelerators in operation today, in addition to SNS, as listed in Table 1. There are a number of different types of accelerators running at 100 kW or more today. Many of these involve rapid cycling synchrotrons (RCS) as part of the acceleration chain. Many of these operate, or have operated, as part of a higher energy collider chain. There are two accelerators that operate at the MW level: the PSI cyclotron chain and the SNS linac.

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Table 1:Parameters of Existing High Power Proton Accelerator Facilities

Facility	Max. Power (kW)	Energy (GeV)	Time Structure	Accelerator Type
TRIUMF	100	0.52	CW	cyclotron
LANSCE area A	80-120	0.8	120 Hz	linac
ISIS	200	0.8	40 Hz: TS1, 10 Hz: TS 2	linac + RCS
J-PARC MR (FX)	240	30	0.4 Hz x 5 us	3 GeV into RCS
J-PARC RCS	300	3	25 Hz x 1 us	181 MeV linac + RCS
FNAL MI	400	120	9.4 us every 2.2 s	Linac + RCS
CERN SPS	470	400	4.4 s cycle length	linac + 2 stage RCS
SNS	1,200	0.94	60 Hz	linac + accumulator
PSI	1,300	0.59	CW	2 stage cyclotron

Table 2: Parameters of Planned Upgrades for Existing Accelerator Facilities

Facility	Max. Power (kW)	Energy (GeV)	Time Structure	Accelerator Type
FNAL MI + ANU	700	120	9.4 us every 1.33 s	Linac + RCS
J-PARC MR (FX)	750	30	0.4 Hz x 5 us	3 GeV into RCS
CERN SPS	750	400	4.4 s cycle length	linac + 2 stage RCS
LANSCE area A	800	0.8	120 Hz x 625 us	linac
J-PARC RCS	1000	3	25 Hz x 1 us	181 MeV linac + RCS
SNS	2800	1.3	60 Hz	linac + accumulator

Table 3: Future High Power Proton Accelerators

Facility	Max. Power (kW)	Energy (GeV)	Time Structure	Accelerator Type
ESS	5	2.0	50 Hz x 2.5 ms	SRF linac + accumulator
CERN with SPL	4	5	50 Hz x 6 bunches	SRF linac + RCS
Project-X (stage 1+2)	3	3	CW linac /accumulator	CW SRF linac + accumulator
Project-X (stage 3)	2.3	60-120	10^{-5} duty factor	+ pulsed 8 GeV SRF linac + RCS
MYRHHA	2.4	0.6	CW	SRF linac
Daedalus	3	0.8	60 Hz	2 stage cyclotron

Planned Upgrades

Many of the existing accelerator facilities have plans for further power increases, and these are shown in Table 2. Here we consider upgrades being considered in the next 5-10 years with some active development effort. There are several MW class applications appearing, with the J-PARC upgrade, and several of the high-energy (> 10 GeV) RCS chains approaching the 1 MW level.

Future Facilities

Finally, future proton accelerators with at least 1 MW beam power and an on-going design or development effort are shown in Table 3. Interestingly, superconducting RF linacs play a prominent role in all cases, except Daedalus. Also, the beam energy in most cases is lower than those in Tables 1-2.

R&D Needs

Each specific high power project and application has unique development needs, but there are certain overarching common needs. A key consideration is management of beam loss to very low fractional levels when operating at or above 1 MW. The rule of thumb for hands-on maintenance (a necessary condition to make these accelerators affordable) is keeping beam loss below 1 W/m, which translates to < 1 part in 10^6 for 1 MW at full energy. Measuring beam profiles and emittance in the full 6-D phase space to this level is beyond present day capabilities. Improvements are needed in increased dynamic range for instrumentation and novel methods to measure the multi-dimensional phase space. Also, simulations cannot predict beam behaviour to this level. At present tuning for beam loss mitigation is largely an empirical exercise in high power facilities [8]. Significant advances in simulation are needed to directly use modelling tools for loss tuning (beyond machine design). As mentioned above, even low loss that does not introduce machine activation at SNS can cause equipment damage.

Another common area of concern for high power proton accelerators is designing a survivable target. Generally the targets are made as small as possible to provide an intense secondary beam, but this necessarily forces high hear loads, high radiation damage rates etc. As mentioned above for the pulsed SNS case there are cavitation issues. These high power targets require remote maintenance techniques for replacement and repair, and the possible activities are thus quite limited. In addition, construction and operation costs (e.g. spent target disposal) are considerable and need to be considered up front, along with the accelerator.

For the superconducting RF accelerators there are RF development needs. Generally the beam energy is quite low compared to linear collider applications, so the need to increase gradients to reduce the linac length is not as severe. However for the pulsed SRF applications, development of high power coupler and reduced cost high availability high peak power RF power sources are needed. For the CW applications, production of cavities with low Q is needed to minimize cryogenic loads.

For cases with ring injection, new charge exchange injection techniques need to e developed. Typically 10^{-4} of the beam is lost in an optimized foil stripping injection. As the beam powers increase, this localized beam loss may become intolerable. Also for cases with long injection times, the foil scattering in the circulating beam can cause intolerable emittance growth. Laser stripping [9] is an attractive alternative, but requires significant development.

Chopping beam gaps at low energy is needed for some multi-purpose accelerator applications to facilitate beam transfer to different targets / accelerator chains and to provide user desired timing characteristics. The chopping is planned for the micro-bunch time-scale at low energy for the Project-X case [10], and must be done at an extremely high efficiency to guarantee low loss at higher energy. These techniques remain to be proven.

Finally, for some applications high reliability is a major consideration. Traditional nuclear and high energy physics high power accelerator applications can tolerate short outages (hours – days), as they typically have single purposes with long collection periods (years). However the neutron scattering and accelerator driven systems (ADS) have more stringent reliability issues. Areas such as automatic recovery from failed RF stations and dual front-end systems are discussed, but remain to be demonstrated in operational conditions.

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