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HIGH POWER PROTON FACILITIES: OPERATIONAL EXPERIENCE, CHALLENGES, AND THE FUTURE*

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Abstract

High power proton accelerators are increasingly popular as drivers for secondary beams with a large variety of applications, such as neutron sources for materials science and neutrino factories for high energy physics. In the last few decades, average beam powers have increased substantially, giving rise to an array of challenges centered on providing high beam power and availability while maintaining low activation levels. This talk summarizes the current status of high power proton accelerators. It discusses recent operational experiences and lessons learned, and identifies the primary hardware and beam dynamics limitations. A brief review of planned next generation facilities and driving technologies is also presented.

INTRODUCTION

Modern day high power proton facilities are employed primarily in the production of secondary and sometimes tertiary particle beams for various applications. In the past quarter of a century, the number of high power proton facilities and the range of applications have increased dramatically [1]. This has been driven in part by the desire for a new generation of high power neutron sources with various pulse structures for materials and life science applications, and in part the emerging focus in HEP on "intensity frontier" applications such as neutrino beam production.

The average beam power is a combination of both the energy and average beam current, and these parameters are optimized to suit the desired application. In general, HEP applications require higher energies in the 10^2 GeV range for production of particles such as neutrinos, while materials science applications require mid-range energies on the order of a few GeV for neutron production. In the last quarter century, beam powers for these types of facilities have increased approximately an order of magnitude, as demonstrated by Figure 1, which shows beam powers for several facilities in the era 1988-1993 compared with operational beam powers today. A number of advances in accelerator technology and accelerator physics have enabled this evolution, including H- charge exchange injection, phase space painting, superconducting linear accelerators, massively parallelized simulations, and liquid targets.

Regardless of the end application, all high power proton facilities are designed and operated with the goal of providing stable beams with minimal beam loss and activation that allow for hands-on maintenance. In addition, user facilities such as neutron sources place a high degree of emphasis on machine reliability. While reliability is most often tied to hardware performance, activation levels are tied to beam dynamics challenges. Increases in beam power have to respect the reliability and activation goals, and therefore require troubleshooting of present limitations rather than "turning the knob up" on either beam current or energy.

This paper discusses the operational experience of today's highest power proton accelerator facilities, and the challenges that limit increases in beam power. Finally, it summarizes the high power horizon with a preview of future facilities and their driving technologies.

OPERATIONAL EXPERIENCE

Operational Metrics

Table 1 shows the operational metrics for eight high power proton accelerator facilities. Sustained operation at high power relies on preventative hardware maintenance and tight control over beam losses. Most facilities shown in the table operate for 4000-4500 hours per year, which allows for one to two extended maintenance outages.

For user based facilities, reliability, as defined by the ratio of the number of hours operated divided by the number anticipated, is the highest figure of merit, trumping even the average beam power. The reliability metrics in Table 1 are averages over the last 2-3 years. As seen, the spread is small with all facilities operating between 80-92%. In practice, it is very difficult to break the 90-92% threshold, possibly because much of the accelerator hardware is R&D in nature, or operating near technological limits.

Perhaps the parameter of highest interest to accelerator physicists, because it is closely tied to beam control, is activation. The gold standard for beam loss in an accelerator is considered to be 1 Watt/meter, on average. In practical terms, activation levels should not exceed roughly 100 mrem/hr in order to allow for routine hands on maintenance of the accelerator. Table 1 shows the typical and peak activation levels for six high power machines. Note that the activation levels include facility-specific nuances in terms of measurement time and distance, and a direct comparison between values is not meaningful. However, one can draw a few general conclusions from the survey data. First, the activation in linacs is 30 to 60 times lower than in rings. Second, typical activation levels fall below the threshold for hands on maintenance. Third, peak activation levels are roughly an order of magnitude higher than typical levels. The peak activations levels occur in localized regions, usually injection or extraction, where measures can be taken to provide extra shielding and work-practice controls. Even so, peak activation levels can limit the beam power.

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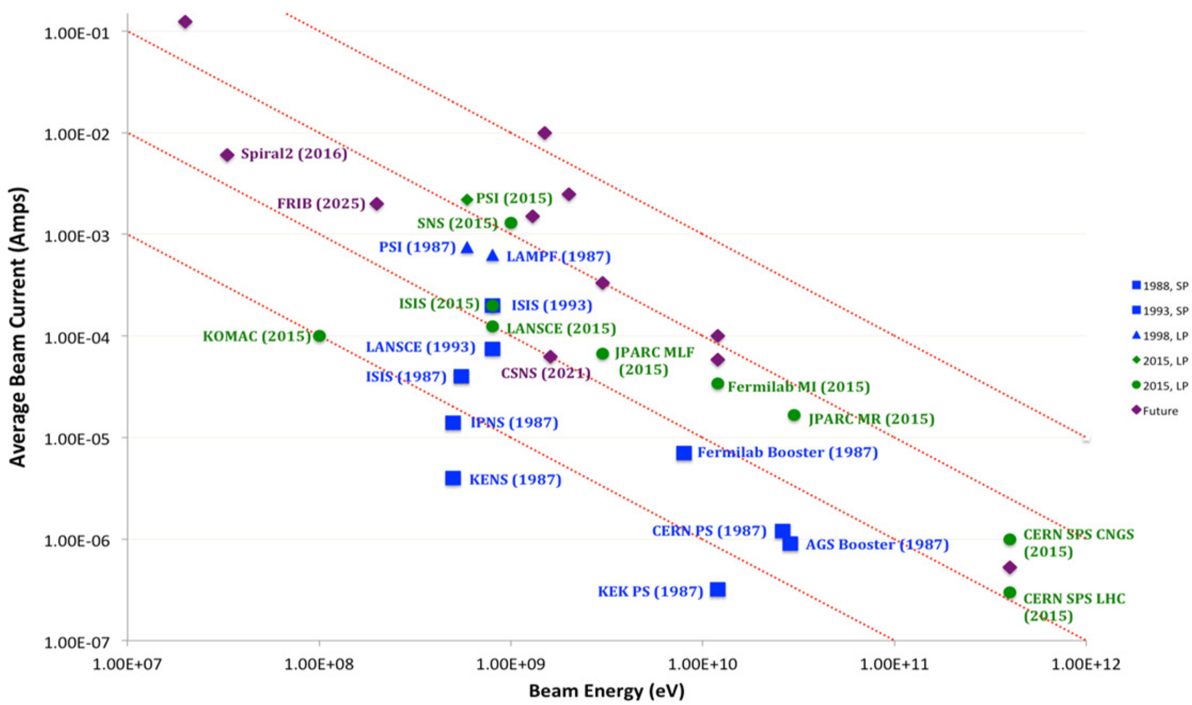

Figure 1: Operational beam powers for facilities ~25 years ago (blue), today (green), and the future (purple). SP indicates short pulse beams, and LP indicates long pulse beams including CW beams.

Table 1: Summary of Operational Metrics for High Power Proton Facilities

Facility (Operational Beam Power)	**Recent Reliabilty (%)**	**Typical Activation; Peak Activation (rem/h)**	**Measurement Condition (distance, time after shutdown)**
LANSCE (100 kW)	87	Linac: 0.01; 0.05 Ring:	30 cm, 12 hours
SNS (1.3 MW)	86	Linac: 0.03; 0.05 Ring: 0.1; 0.8	30 cm, 12 hours 30 cm, 12 hours
PSI (1.3 MW)	87	Cyclotron: 0.1; 3.0	10 cm, 4-6 hours
J-PARC RCS (400 kW)	90	Synchrotron: 0.002; 0.3	30 cm, 4 hours
ISIS (192 kW)	91	Linac: 0.002; 0.015 Synchrotron: 0.01; 1.2	Contact, 13 hours Contact, 26 days
CERN SPS CNGS (400 kW) CERN SPS LHC (110 kW)	80 90	Synchrotron: 0.1; 1.7 Same as above	100 cm, 30 hours Same as above
Fermilab MI (410 kW)	83	Not available	NA
KOMAC (10 kW)	87	Not available	NA

It is interesting to consider today's activation levels in the context of a few historical activation numbers. A 1974 survey of activation levels in the Fermilab booster reveals localized areas in the 1 – 10 rem/hr range, similar to the 2007 activation levels for the Brookhaven AGS Booster operating at ~80 kW [2]. During this era, the PSR at LANSCE was operating with peak levels on the order of 0.1 – 1 rem/h for 90 kW. These values demonstrate that while today's machines operate with beam powers approximately an order of magnitude higher, activation levels are the same or less. This accomplishment is born out of improvements in beam loss control at a rate proportional to or in excess of beam power increases.

Beam Power Ramp up at SNS and J-PARC: Expectations versus Realities

Despite comprehensive efforts to pre-empt technical and beam dynamics problems during design stages, increases in beam power often encounter unexpected setbacks. To demonstrate this point, this section discusses a few of the unexpected events during the recent power ramp ups of the J-PARC and the SNS accelerators.

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The initial SNS power ramp up to 1.4 MW was anticipated to occur over approximately 5 years [3], beginning in 2006 and reaching 1.4 MW in 2001. The actual ramp up took approximately 8 years, limited primarily by a sequence of target failures occurring between 2010 and 2014. The reaction to the failures was to run at lower beam power and preserve reliability at least until a sufficient number of spare targets were available. The problem is discussed in more detail in the next section.

The SNS SCL was the first large-scale superconducting H^- linac, and as such, it was not possible to predict all of the operational challenges during the design stages. The first problem encountered concerned the performance of the superconducting cavities. At the outset, 20 cavities were out of service due to various hardware issues, and most cavity in the high beta region (beta=0.81) were operating significantly below the design gradients. A decade long R&D effort, which has removed the HOM couples and addressed a plethora of other issues has resulted in cavities gradients much closer design. One lesson learned from this process is that the SCL is very flexible to accommodating different cavity gradient profiles, allowing for effectively tuning around absent cavities.

Likely the largest surprise in operating the SNS facility at high power was the higher than anticipated beam loss in the SCL, which exceed design predictions by one to two orders of magnitude. Empirical tuning of the quadrupoles reduced the loss significantly, and later it was understood that the beam loss was due to H^- intrabeam stripping [4]. As a result of the empirical tuning, the SNS SCL now operates in a mismatched state with quadrupole strengths 40% lower than the design values.

Both SNS and J-PARC have struggled with RFQ performance. The SNS RFQ has suffered 3 major detuning events, and in addition, the RFQ has also been declining in transmission for the last four years. Together, these issues have prompted the fabrication and commissioning of a new RFQ that will be installed in 2016 [5].

At J-PARC, discharge issues limited current transmission the first, 30 mA capable RFQ. In order to preserve reliability, beam powers were limited to < 200 kW in the years 2008 through 2012. The RFQ issues were resolved by a series of improvements in vacuum conditions as well as extensive RF conditioning.

The RFQ problems at J-PARC was the first of three significant events which impacted the facility's power ramp up schedule. The second was the earthquake in March of 2011. It resulted in extensive damage to many systems and flooding of the tunnel [6]. After an astoundingly quick recovery effort, J-PARC resumed operations in early 2012. The outage adversely affected the RFQ discharge problem, but the problem resolved after conditioning. Lastly, in 2013 an incident at the Hadron facility resulted in sustained beam operations for a few months. The facility resumed operations in 2014 and with a new, 50 mA capable RFQ, and has recently demonstrated 400 kW operation.

BEAM POWER LIMITING CHALLENGES

The fact that high power facilities are operating with high reliabilities and low activation levels begs the question of why not to increase the beam power further. A survey facilities reveals that today's beam powers are limited by an array of hardware and beam loss challenges. Here, these limitations are discussed, first in terms of hardware, and then in terms of beam loss.

Hardware Limitations on Beam Power

Table 2 shows the primary hardware limitations for high power facilities today. While it is not unexpected to find that higher power requires improvements in RF capabilities, the pervasiveness of target related beam power limitations is somewhat surprising. Targets are not generally considered as part of the accelerator system, nor do they have a home in the secondary particle beam framework. Yet they play a critical role in the overall facility capabilities, as there is not much point in increasing the beam power if there is no target that can accept the beam. Targets are designed for specific applications, and therefore each one is an experiment that requires testing in the high power beam environment it was designed. As such, early life target failures for young targets are somewhat expected, and they help to identify design weaknesses. In addition, targets are usually designed for specific beam conditions such as peak density and beam size, and violations these specifications even for short amounts of time can result in a failure.

There is much R&D work on-going in the area of target development for beam powers ≥1 MW. To give a few examples, high power, short pulse accelerators such as SNS and J-PARC that rely on liquid mercury targets are investigating gas injection into the mercury for mitigation of the pressure wave. At Fermilab, a neutrino production target for 1.2 MW beam powers for the PIPII upgrade is under development, based on modifications of the current 700 kW capable PIPI target. The new long pulse spallation source, ESS, will employ a rotating tungsten target, the first of its kind. And finally, the future China Initiative Accelerator driven systems (CIADS) is designing a windowless granular target that will circulate tungsten beads a through the target and a subsequent cooling loop.

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Table 2: Summary of Hardware Limitations on Beam Power

Facility	System	Problem
J-PARC	RF	DC power supply for RCS acceleration
	RF	Ringing of chopper RF
SNS	RF	RFQ detuning and transmission problems
	Target System	Target premature failure
PSI	Target System	Cooling of spallation target
	Target System	Heat load on collimators behind meson production target.
LANSCE	Target System	Power limitation (for isotope production)
	Target System	Window power limits
ISIS	Target System	Target 1 not rated for higher power
	Target System	Target 2 not rated for higher power
	Target System	Moderator cooling
	RF	Linac HPRF system
Fermilab	Target System	Thermal stress and fatigue
	RF	Booster and MI RF
CERN SPS	RF	Power limits to preserve tetrodes

Beam Loss Challenges

Even after hardware challenges have been overcome, it not a simple matter to "turn up the knob" on beam power. In the absence of pre-emptive measures to control beam loss at a finer level, activation levels will at best scale linearly with beam power. Though the comprehensive list of beam loss mechanisms that limit beam power is long and facility-specific, there are some common themes among today's high power facilities. These are discussed in this section.

H^- Charge Exchange Injection Losses For facilities which rely on H^- charge injection from a linear accelerator into a synchrotron, the injection area is usually highest activation region in the accelerator by an order of magnitude or more. Besides the issue of activation, the long term survivability of foils in a multi-megawatt beam power environment is unknown. At SNS, the injection foils have been demonstrated to survive routine beam operations of up to 1.3 MW. However, damage to foil brackets when operating above 1.2 MW has been routinely observed and is attributed to stripped electrons impacting the brackets after being reflected from the electron catcher below the foil. The problem is currently under investigation.

Foil technology is an active area of R&D that aims to develop foils that can survive in the multi-megawatt beam environment. An alternative technology under development is H^- laser assisted stripping. In this scheme a high gradient dipole magnet Lorentz strips the outermost electron, leaving H^0. The more tightly bound, inner electron is then resonantly excited by a laser to a higher quantum level with a smaller binding energy, and then stripped off by a second high gradient magnet while in the excited state. The concept has been demonstrated in proof of principle experiments but has not reached practical levels of implementation.

Extraction Losses After injection, the most common localized area of beam loss in a synchrotron is the extraction region. For the PSI cyclotron, the extraction region is the hottest area of the accelerator and limits the obtainable beam power. The beam loss in this region is a aggregate of source to septum history, and while some success has been seen in modelling the process, in practice the loss minimization is still a complex empirical process.

The CERN SPS is another synchrotron that faces beam power limitations due to extraction losses. In this case, the limiting loss is in the PS injector synchrotron, and occurs during the five turn octupole resonance extraction of the beam.

Instabilities Collective instabilities such as impedance driven instabilities or electron cloud instabilities are commonplace in the high intensity environment. While instabilities contain a seemingly inexhaustible supply of interesting physics puzzle appropriate to graduate work and other academic adventures, they also pose a great threat to obtainable beam powers. High power proton facilities go through large measures during the design phase to mitigate all anticipated instabilities. For instance, most of the SNS ring was coated in TiN to reduce secondary emission yield and prevent e-P instabilities; to date no significant e-P instability has been observed during nominal operation in the SNS ring.

In today's high power landscape, two high power proton facilities are limited by instabilities. First, at ISIS, the operational beam intensity is limited to 3e13 ppp due to resistive wall vertical head tail instability. A damper system is currently under development to mitigate the issues. Second, at the CERN SPS, both a longitudinal instability and transverse coupled mode instability are both present, with the longitudinal instability acting as a limitation on the beam power.

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In the Fermilab recycler ring, a transverse instability has been observed for certain bunch parameters, namely for short bunches. The source of the instability has not yet been definitively identified but e-P is a possibility [7]. While the instability does not threaten operations at 700 kW, it has the potential to be a problem for the future PIPII accelerator that will increase beam powers from the MI to 1.2 MW.

Other Important Loss Mechanisms Besides the three mechanisms listed above, high power facilities also suffer from an array of other beam loss mechanisms. For instance, both ISIS and the Fermilab Booster suffer losses during the adiabatic capture process. Additionally, at the Fermilab Booster there are significant losses due to longitudinal beam dynamics following the gamma transition jump, and losses created by a notching scheme to create a three pulse extraction gap. The beam loss reduction plan for the PIPI upgrade to 700 kW includes slower RF capture with harmonic RF, three additional RF cavities to aid with longitudinal dynamics, and laser notching system which will move the notching process into the MEBT.

Beam Loss Modeling

A common theme among all high power accelerators is that low loss tunes are achieved through complex empirical tuning that often requires both experience and intuition. While simulations have advanced significantly in the past few decades and can now qualitatively model many of the observed phenomenon [8], they have not yet reached the level where they can be used to quantitatively predict the evolution of beam halo and it's translation into fractional (10^{-3}) levels of beam loss. The general consensus among the high intensity computational community is that the limitation is not a failure of the codes, but a lack of knowledge of the initial beam distribution [9]. Initial distributions are usually simulated with RFQ codes or reconstruction from 1D or 2D measurements of the phase space assuming no correlations between the three degrees of freedom. Experiments at LEDA and SNS have demonstrated that this is not sufficient for modelling beam halo. Until improvement is seen in this area, the idea of a model-based approach for beam loss optimization is likely out of reach. In the meantime, the recent ability to model the gross beam dynamics processes in an accelerator once it has been empirically tuned represents a significant step forward in code capabilities and is quite useful for understanding beam dynamics in current and future accelerators.

FUTURE

In addition to the planned upgrades of most of today's facilities, a number of new high power proton facilities are under construction. Figure 1 shows the beam power landscape future upgrades and new facilities. Probably the most interesting feature of the plot is the population of the low energy, high beam current regime with ADS type machines for various applications, such as drivers for nuclear reactors (CIADS), and for the testing of materials for future fusion reactors (IFMIF).

The vast majority of future machines, including IFMIF, CIADS, CSNS, FRIB, ESS, MYRRHA, and Spiral2 will employ superconducting linacs as the driving technology for the accelerator. Based on the SNS ten-year experience operating a large scale proton SCL, the future for these machines is quite positive. The SNS SCL has ~98% reliability, suffering less than 1 trip per day, and low activation levels in the 10-30 mrem/hr range. The losses are due to mostly to H^- intrabeam stripping, which will not be present for the aforementioned facilities running proton beams. In addition, the SCL accommodates flexible gradient profiles, and due to recent control software improvements, all 81 cavities of the SNS SCL can be tuned up in less than a half an hour, allowing for very quick recovery from maintenance outages or cavity trips.

One interesting issue to note is that some of the future ADS facilities will require reliability in excess of today's best reliability thresholds. For instance MYRRHA requires 250 hrs between trips of > 3 seconds, which is an order of magnitude better than the SNS SCL trip rate. This will require a different design philosophy than what is adopted for instance with spallation sources which are not sensitive to trips at these timescales.

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