REVIEW ARTICLE

Open Access

High-power proton accelerators for pulsed spallation neutron sources

Hideaki Hotchi

Abstract

With the spread of accelerator-driven pulsed spallation neutron sources and increasing need for higher neutron fluxes, the high-power performance of proton accelerators has greatly advanced from a few kilowatts to more than 1 MW in the last four decades. The most important concerns to realize such a high-power beam operation are controlling and minimizing beam loss, which are essential for sustainable beam operation that allows hands-on maintenance. This paper reviews key devices and beam handling techniques for beam loss control employed in the high-power proton accelerators that are currently in operation for pulsed spallation neutron sources, including their operational status and future upgrade plan.

Keywords: Proton accelerator, Pulsed spallation neutron source, Beam loss control

1 Introduction

Accelerator-driven spallation neutron sources are currently in operation worldwide, producing cutting-edge research results in a variety of fields, including materials and life sciences.

In the 1980s and 1990s, accelerator-driven spallation neutron sources became available with the advent of proton accelerators with beam powers ranging from a few kilowatts to 160 kW, such as ISIS at Rutherford Appleton Laboratory, LANSE at Los Alamos National Laboratory, IPNS at Argonne National Laboratory, and KENS at High Energy Accelerator Research Organization (KEK). Later, the need for even higher neutron fluxes increased for the next advanced studies. In the 2000s, the development and construction of MW-class high-power proton accelerators, such as SNS at Oak Ridge National Laboratory and J-PARC at Japan Atomic Energy Agency and KEK, were carried out, resulting in the creation of high-flux neutron sources based on these accelerators.

Most of the large-scale spallation neutron sources currently in operation are “pulsed” spallation neutron sources, which employ a pulsed proton beam of $< 1 \mu\text{s}$

to produce neutrons. The most important feature of the pulsed spallation neutron source is that the energy (= wavelength) of the neutrons can be determined with high resolution via the time-of-flight method. Besides, pulsed neutron beams significantly improve the signal-to-noise ratio by about two orders of magnitude due to the high peak intensity compared to the case of reactor-based neutrons [1]. Using such unique advantages of pulsed neutrons, various advanced researches, such as studies on the dynamical properties of materials and cell samples, have been actively conducted so far. This is the reason why the demand for pulsed spallation neutron sources has grown rapidly and spread to various science fields, resulting in the high demand for high-power proton accelerators.

Table 1 shows the main parameters of the high-power proton accelerators currently in operation for the major existing pulsed spallation neutron source facilities; ISIS, SNS, J-PARC, and CSNS at the Institute of High Energy Physics in China. As listed in the table, there are two possible approaches to a pulsed spallation neutron source; one is a combination of a lower energy negative hydrogen ion (H^-) linac and a rapid cycling synchrotron (RCS), while the other has a full-energy H^- linac and an accumulator ring (AR). ISIS, J-PARC, and CSNS employ the former (i.e., RCS scheme), while SNS the latter (i.e.,

Correspondence: hideaki.hotchi@j-parc.jp
Accelerator Laboratory, KEK, Oho, Tsukuba, Ibaraki 305-0801, Japan

Table 1 Main parameters of the high-power proton accelerators currently in operation for the major existing pulsed spallation neutron source facilities

	ISIS	SNS	J-PARC	CSNS
Accelerator configuration	H ⁻ linac and synchrotron	H ⁻ linac and accumulator ring	H ⁻ linac and synchrotron	H ⁻ linac and synchrotron
Repetition rate (Hz)	50	60	25	25
Linac energy (MeV)	70	1000	400	80
Linac peak current (mA)	25	33	50	15
Linac macro pulse length (ms)	0.2	1	0.5	0.42
Chopper beam-on duty factor	No chopping	0.68	0.56	0.5
Ring circumference (m)	163	248	348	228
Ring superperiodicity	10	4	3	4
Number of injected turns	130	1060	307	200
Number of protons per pulse	2.8×10^{13}	1.5×10^{14}	8.3×10^{13}	1.6×10^{13}
Output energy (GeV)	0.8	1	3	1.6
Output beam power (MW)	0.18	1.4	1	0.1
Laslett tune shift at injection: $\Delta\nu$	0.4	0.15	0.15	0.28
Transition gamma: γ_t	5.1	5.2	9.2	4.9

AR scheme). All the facilities, regardless of the RCS or AR schemes, implement charge exchange from H⁻ to proton with a foil during multiturn injection from a linac into a ring, because the charge exchange injection is the only method to achieve low-loss multiturn injection. A beam, which is accumulated from a linac into a ring over several hundreds to a thousand turns and compressed to <1 μ s, is fast extracted to the neutron production target. The neutron production rate is approximately proportional to the proton beam energy, if the proton energy is between 500 MeV and 3 GeV. Therefore, the number of neutrons is proportional to the proton beam power in this range of the proton energy.

In high-power proton accelerators, many factors that cause beam losses exist, such as space charge effects due to Coulomb interactions between beam particles, intra-beam stripping (IBST) of a H⁻ beam, beam instabilities due to interactions between beam particles and peripheral components surrounding the beam, and foil scattering during charge exchange injection. Besides, most beam losses typically increase in a nonlinear manner with the increase in the beam intensity. The high-power performance of the accelerators is often limited by such beam losses because the residual dose of the accelerator components must be limited to ensure sustainable beam operation allowing essential hands-on maintenance. Thus, in high-power proton accelerator facilities, controlling beam loss is always a critical challenge when attempting to maximize their performance.

This paper reviews the beam operations of the high-power proton accelerators listed in Table 1, specifically focusing on their approaches to beam loss issues. The

remainder of this paper is organized as follows. Section 2 provides a brief overview of the accelerator configuration and operational status of each facility including their future upgrade plan. Details of the key devices and beam handling techniques for beam loss control are described in Section 3. Then, Section 4 describes the characteristics of the AR and RCS schemes, including their advantage and disadvantage. In addition, Section 5 presents recent efforts to realize non-destructive H⁻ charge exchange injection, which is a key technology for the next-generation multi-MW high-power pulsed proton accelerators.

2 Operational status of high-power proton accelerators: ISIS, SNS, J-PARC, and CSNS

2.1 ISIS

The ISIS facility [2] (Fig. 1) has been in operation since 1984 and provides users with pulsed neutron and muon beams for a wide range of materials research.

The accelerator consists of an H⁻ ion source, a 665 keV RFQ, a 70-MeV drift tube linac (DTL), and an 800-MeV RCS. A 70-MeV H⁻ beam from the linac is injected into the RCS through a 0.25- μ m aluminum oxide foil, where 2.8×10^{13} protons are stored over 130 turns (0.2 ms). During injection, the beam is painted over a wide range of the transverse phase spaces to mitigate space charge. After injection, the beam is trapped, accelerated from 70 to 800 MeV and finally fast extracted. With a repetition rate of 50 Hz, ISIS currently provides an average beam power of around 180 kW with 90% availability, which is shared by two target stations.

The primary challenge in high-power operation of ISIS is minimizing and controlling beam loss, particularly in

Fig. 1 Schematic layout of ISIS

the RCS [3, 4]. The overall loss in the RCS is around 4% and concentrated in the low-energy region. Losses during the injection and accumulation process (-0.4 – 0.0 ms) are about 1%, which are mostly generated by unstripped waste H^0 and H^- particles during charge exchange injection and by emittance growths caused by space charge effects and foil scattering. Losses during RF trapping (0.0 – 2.5 ms) are around 3%, which arise from non-adiabatic capture process for the un-chopped beam from the linac. This part of the beam loss was originally around 10%, but it was greatly reduced to the present level via the installation and optimization of a second harmonic RF system. By superimposing the second

harmonic RF on the fundamental one, the RF bucket acceptance was increased, and thus the efficiency of RF trapping was greatly improved. Moreover, the bunching factor was improved by the second harmonic RF, which led to further space charge mitigation, resulting in a significant reduction in the beam loss. Another major beam dynamics issue is vertical head-tail instability, which occurs at around 2 ms. Although the beam loss is minimized by manipulating the vertical betatron tune and the longitudinal beam distribution, the beam instability is one of the primary factors limiting operational beam intensity. Most of the beam losses and radio-activations in the RCS are concentrated in 3 of the 10 superperiods,

including the injection, collimation, and extraction systems. The radio-activation levels in most of the RCS are maintained at 10–100 $\mu\text{Sv/h}$ at 1 m.

Future upgrades on higher-power performance include a damping system to counter the head-tail instability, and a beam chopper system, which makes a chopped intermediate bunch structure for the H^- linac beam to enable direct injection into the ring RF buckets and to minimize longitudinal beam losses during RF trapping [3].

Furthermore, various long-term upgrade plans are under study. Current ideas include upgrading the linac to 180 MeV, allowing a beam power of 0.5 MW from the existing ring [5], possibly followed by staged upgrades with rings RCS or fixed-field alternating gradient accelerator (FFA) in the existing tunnel [6, 7], which could feed multiple targets and be developed into a multi-MW regime. Detailed studies of optimal RCS and FFA ring designs for these ideas are in progress currently.

2.2 SNS

The SNS facility [8, 9] (Fig. 2) is the world's first pulsed spallation neutron source with a MW-class high-power proton accelerator. In contrast to ISIS, the accelerator is composed of a 1 GeV full energy H^- linac and an AR, which was commissioned in 2002, and the user program started in 2007.

The linear accelerator consists of an H^- ion source, a 2.5-MeV RFQ, an 87-MeV DTL, and a 186-MeV coupled cavity linac (CCL), followed by a superconducting linac (SCL) to 1 GeV. The SCL is the world's first superconducting H^- linac. The superconducting technology was chosen over the warm linac technology because of its lower construction and operation costs, higher availability compared to a warm linac, higher vacuum to mitigate beam-gas scattering, and larger aperture to reduce beam loss.

The SNS linac has a chopper system at the low-energy beam transport line (LEBT) between the ion source and the RFQ, which makes a chopped intermediate bunch structure for the H^- linac beam that is synchronized to the ring RF frequency. This provides sufficient time to allow the ring extraction kicker field to rise thereby minimizing beam loss at extraction, as well as preventing longitudinal beam loss during RF capture in the ring as occurs in ISIS. A 1 GeV H^- chopped beam from the linac is multiturn charge-exchange injected into the AR through a 300 $\mu\text{g}/\text{cm}^2$ carbon foil over 1060 turns (1 ms). During injection, the beam is uniformly painted over a wide range of the transverse phase spaces to mitigate space charge, and also to ease shockwaves on the neutron production target. A second harmonic RF system is also incorporated to make a longitudinal beam profile with a more favorable bunching factor for further space charge mitigation. With a repletion rate of 60 Hz, 1.5×10^{14} protons are accumulated and fast extracted, thereby producing an average beam power of 1.4 MW.

At the early stage of the beam power ramp-up phase, unexpected beam loss was observed in the SCL, which caused nearly uniform irradiation to the SCL components and increased the radiation level there. Experimental investigations revealed that this beam loss arises from H^0 particles created by IBST [10]. The reaction rate of IBST is proportional to the square of the particle charge density; thus, it can be mitigated by reducing the focusing strengths. With a 40% lower quadrupole setting, the beam loss has successfully been reduced to sufficiently low levels [11].

The major beam loss in the AR arises from foil scattering during charge exchange injection. The amount of the beam loss is as small as the order of 10^{-4} , and most of it is localized in the collimator region, but certain beam particles scattered at large angles are uncontrollably lost immediately downstream of the foil, causing significant, albeit acceptable, radio-activations in the

Fig. 2 Schematic layout of SNS

injection area. Another major beam loss source in the AR is space charge; however, it is sufficiently mitigated by transverse and longitudinal phase-space painting.

SNS reached its design beam power of 1.4 MW in 2015. However, it caused a premature target failure, so that the beam power was reduced to 1.1 MW to prioritize reliability for the neutron users. The beam power was then stepped up towards 1.4 MW along with target improvements. It reached the design value again in 2018. Since then, SNS has been providing a beam power of 1.4 MW normally with higher than 90% availability. The radio-activations are still maintained at acceptable levels of < 0.6 mSv/h in the linac, 10 mSv/h at the AR injection, 0.9 mSv/h at the AR collimator, 0.8 mSv/h at the AR extraction, and 0.05–0.4 mSv/h in the rest of the AR, all of which were measured at 30 cm [9].

Following the success of a 1.4 MW beam operation, SNS is now planning for a beam power upgrade to 2.8 MW to accommodate a second target station [12]. To achieve this, the beam energy will be increased from 1.0 GeV to 1.3 GeV, and the H^- average beam current will be increased from 25 to 38 mA (33 to 46 mA in the peak beam current). The new parameters provide approximately the same space charge strength as the present value in the AR, so that the space charge effect will not be a major concern. Detailed studies for potential issues, such as foil durability and beam instabilities, are underway in parallel with hardware developments.

2.3 J-PARC

The J-PARC facility [13] (Fig. 3) is a multipurpose proton accelerator complex, consisting of a 400-MeV H^- linac, a 3 GeV RCS, a 30 GeV main ring (MR), and three experimental facilities; a materials and life science experimental facility (MLF [14]), a hadron experimental facility (HD), and a neutrino experimental facility (NU). It was beam commissioned in 2006, and the user programs

for the MLF, HD, and NU started in 2008, 2009, and 2010, respectively [15–18].

The J-PARC linac consists of an H^- ion source, a 3-MeV RFQ, a 50 MeV DTL, a 191-MeV separated-type DTL (SDTL), and a 400-MeV annular coupled structure linac (ACS). A beam chopper system, which is installed at the medium energy beam transport line (MEBT) between the RFQ and the DTL, makes a chopped intermediate bunch structure for the H^- beam, which is synchronized to the ring RF frequency at the injection time. A 400-MeV H^- chopped beam from the linac is multiturn charge-exchange injected into the RCS through a $333 \mu\text{g}/\text{cm}^2$ carbon foil over 307 turns (0.5 ms). During injection, the beam is painted uniformly over a wide range of the transverse and longitudinal phase spaces to mitigate serious space charge in the low-energy region. Because of the beam chopper, no longitudinal beam loss occurs in the RF capture process. The RCS accelerates the injected protons up to 3 GeV with a repetition rate of 25 Hz. Most of the RCS beam pulses are delivered to the neutron and muon production targets for use in materials and life science experiments at the MLF, while only four pulses every few seconds are injected into the MR, and the 30 GeV beams accelerated at the MR are used for the HD and NU experiments [19]. The design beam powers to the MLF and the HD/NU are 1 MW and 0.75 MW, respectively.

The main beam loss in the linac arises from IBST [20], similar to the case of SNS. This caused nearly uniform irradiation to the ACS section and increased the radiation level there. However, the beam loss has now been mitigated to acceptable levels by applying a 25% weaker quadrupole setting, which is the same approach that SNS is implementing.

The most critical beam loss source in the RCS is space charge, which coupled with nonlinearities and imperfections of the lattice elements, caused a terrible beam loss of around 14% in the injection energy region. However, it has now successfully been reduced to the order of 10^{-3} by optimizing transverse and longitudinal phase-space painting together with betatron resonance correction using sextupoles [21, 22]. The major part of the residual beam loss is due to foil scattering during charge exchange injection. Certain beam particles scattered at large angles are uncontrollably lost in the injection area, but most of the other residual beam loss components are well localized at the collimators downstream of the injection section.

J-PARC is currently providing a beam power of 740 kW to the MLF with better than 90% availability. The radio-activations are still maintained at extremely low levels of $< 100 \mu\text{Sv}/\text{h}$ in the linac, $< 120 \mu\text{Sv}/\text{h}$ at the RCS injection, $< 130 \mu\text{Sv}/\text{h}$ at the RCS collimator, and $<$

Fig. 3 Schematic layout of J-PARC

8 $\mu\text{Sv/h}$ in the rest of the RCS, all of which were measured at 30 cm.

J-PARC is still in the course of gradually increasing the beam power to 1 MW while carefully investigating the durability and integrity of the neutron production target. However, the accelerator itself has already established a 1 MW beam operation to the MLF with sufficiently low fractional beam loss, as mentioned above.

The successful achievement of a low-loss 1-MW beam operation opened the door to further beam power ramp-up beyond 1 MW. The linac and RCS recently conducted 1.2–1.5-MW-equivalent high-intensity beam tests with promising results [22]. Although full acceleration of up to 3 GeV was not reached due to the limitation of the ring RF system, the beam loss in the low-energy region of the RCS, which was the cause for the most concern, was successfully reduced to the order of 10^{-3} even for such a high-intensity beam. Detailed studies for issues in aiming for a beam power of 1.5–2 MW, such as the upgrade of the ring RF system [23], beam instability [24], and foil durability, are in progress, looking ahead to future upgrades of J-PARC including the construction of a second target station in the MLF.

2.4 CSNS

The CSNS facility [25, 26] (Fig. 4) is the most recently constructed pulsed spallation neutron source, which was beam commissioned in 2017 and the user program started in 2018.

The accelerator consists of an H^- ion source, a 3-MeV RFQ, an 80-MeV DTL, and a 1.6-GeV RCS. An 80-MeV H^- chopped beam from the linac is multi-turn charge-exchange injected into the RCS through a $100 \mu\text{g}/\text{cm}^2$ carbon foil over 200 turns (0.42 ms). During injection, the beam is uniformly painted on both transverse and longitudinal planes to reduce space charge. The RCS accelerates the injected protons up to 1.6 GeV with a repetition rate of 25 Hz. The design beam power is 100 kW.

Since the start of the user program, the beam power has steadily increased and reached the design value of

100 kW in 2020 more than a year earlier than planned [27]. By careful transverse and longitudinal matching, the transmission of the DTL has been improved to higher than 99%. The beam loss in the RCS has also been reduced to 1.5% by optimizing betatron tunes, phase-space painting, closed orbits, and so on, and well localized at the collimator section except for large-angle foil scattering components, which uncontrollably cause losses in the injection section. CSNS is currently providing an average beam power of 100 kW with better than 94% availability. The radio-activation levels are still maintained at sufficiently low levels of $< 10 \mu\text{Sv/h}$ in the linac, $< 500 \mu\text{Sv/h}$ at the RCS injection, $< 150 \mu\text{Sv/h}$ at the RCS collimator, and $< 100 \mu\text{Sv/h}$ in the rest of the RCS, all of which were measured at 30 cm.

Following the achievement of a 100-kW beam operation, CSNS has started the upgrade work, which include replacing the DC sextupoles with AC ones, adding trim quadrupoles, and introducing a second harmonic RF system in the RCS. They will be used for dynamic chromaticity manipulation to suppress beam instabilities, tune and beta-function manipulations, and enhancing the bunching factor for further space charge mitigation, respectively. With these hardware upgrades, CSNS next aims for a beam power of 200 kW [27]. Further, a large-scale upgrade plan has been approved and is to begin in early 2022, where the beam power will be increased to 500 kW by upgrading the injector linac to 300 MeV adding a SCL section into the reserved 85-m-long space in the linac tunnel [25].

3 Key devices and beam handling techniques for beam loss control

This section presents several key devices and beam handling techniques that are indispensable for controlling beam losses in each facility and shows their benefits with specific examples.

3.1 Beam chopper

In order to avoid longitudinal beam loss during RF trapping in a ring as well as to secure sufficient time to allow ring extraction kicker fields to rise for low-loss extraction, a H^- linac beam must have a chopped intermediate bunch structure synchronized with a ring RF frequency. To realize this, a beam chopper system is widely used in linacs. In general, it consists of a kicker to deflect an unwanted part of the beam pulse off the axis and a scraper to absorb the deflected beam. Since it is advantageous to place the chopper at a lower energy, where it is easier to deflect the beam and to manage the beam power deposited on the scraper, the chopper system is generally installed at the LEBT and/or MEBT.

Figure 5 shows a beam chopper system employed in the J-PARC linac [28]. It is placed at the 3-MeV MEBT

Fig. 4 Schematic layout of CSNS

between the RFQ and the DTL and is composed of a two-gap RF cavity deflector with the same RF frequency as the RFQ, and two scrapers, one on each side. The RF cavity provides an electrical field of 2.6 MV/m with a rise/fall time of < 10 ns, deflecting an unwanted part of the beam pulse horizontally. The deflected beam is then captured by the downstream scrapers made of 5-mm-thick carbon fiber composition (CFC). The CFC has almost the same thermal conductivity as that of copper, which is brazed onto a water-cooled copper block and placed at a 45° angle to the beam. In order to reduce heat loads to the scrapers, the RF phase of the deflector is reversed by 180° for each intermediate pulse to distribute the deflected beam to the two scrapers alternatively.

Figure 6 shows the time structure of the J-PARC linac beam pulse formed by the chopper system; it consists of a series of intermediate pulses with a width of 456 ns and a period of 815 ns over 0.5 ms, where 44% of the beam is removed. The extinction rate in the 359-ns gap has been confirmed to be $< 2 \times 10^{-5}$, which sufficiently satisfies the requirements from the RCS.

SNS [8] and CSNS [29] also have a chopper system, but ISIS does not. Thus, in the ISIS RCS, significant longitudinal beam loss occurs during RF trapping. Since it is one of the major factors limiting the beam intensity, ISIS is also considering the introduction of a chopper system for future upgrades.

3.2 Intra-beam stripping and its solutions

Beam loss due to IBST, which is specific for H^- beams, was first identified in the SNS SCL [10].

Unexpected beam losses and beamline activations were found in the SNS SCL at the initial stage of beam power ramp-up. The measured beam losses were in stark contrast to the simulation results supporting the view that the high energy part of the SNS linac is nearly loss-free mainly owing to the large apertures and high vacuum of the SCL. Historically, the primary H^- linac beam loss mechanisms have been considered to be halo

Fig. 5 Chopper system in the J-PARC linac

Fig. 6 Temporal structure of the J-PARC linac beam; macro pulses created by the ion source (upper), and intermediate pulses formed by the chopper (lower)

formation by the space charge effects and gas stripping by the residual gas. However, the beam loss observed in the SCL cannot be explained by them.

The newly proposed mechanism for this beam loss is IBST, where inelastic scattering of the H^- ions within the beam bunch causes loosely bound electrons to be stripped off. The created neutral H^0 particles are unaffected by electromagnetic fields and subsequently are lost from the bunch. This beam loss is specific for H^- ions, so that a replacement of the H^- beam with a proton beam having similar beam parameters in the same linac should eliminate the beam loss if IBST is the primary cause of the beam loss. Such an experiment was performed at SNS [10], in which a H^- beam was replaced with a proton beam with similar size and dynamics, and it was confirmed that the loss of the proton beam is approximately one order of magnitude lower than that of the H^- beam, as shown in Fig. 7. Furthermore, it was observed that the beam loss has a strong beam intensity dependence for the H^- beam, while no significant dependence was observed for the proton beam, as shown in Fig. 8. These measurements

Fig. 7 Experimental results at the SNS linac; beam loss monitor signals (normalized by beam charge) for H^- (a) and protons (b) along the SCL [10]

concluded that the dominant beam loss in the SCL arises from IBST. The reaction rate of IBST is proportional to the square of the particle charge density, so that it can be mitigated by reducing the focusing strengths; the lower focusing strengths increase the transverse beam size and lower the beam particle density. With a 40% lower quadrupole setting, the beam loss in the SCL has successfully been reduced to sufficiently low levels [11].

In addition, in J-PARC, similar beam loss is observed in the high-beta (ACS) linac section. As in the case of SNS, the beam loss has well been reduced by almost half by increasing the transverse beam size with a 25% weaker quadrupole setting, as shown in Fig. 9 [20]. The use of an even weaker quadrupole setting may further reduce the IBST beam loss. However, this may cause side effects such as transverse-longitudinal coupling resonance. Thus, further mitigation of IBST will require overall parameter optimization including longitudinal focusing strengths, which is currently under investigation.

3.3 High- γ_t lattice

It is well known that beam loss is inevitable when the beam energy approaches the transition energy (γ_t) during acceleration; the restoring force for the phase oscillation vanishes and the phase stability is lost at the energy, resulting in significant longitudinal beam loss. As shown in Table 1, most modern high-power RCS avoid transition crossing by adopting a special lattice design, which provides a transition energy higher than the extraction energy, since a regular DOFO lattice requires too many cells to achieve a high transition energy.

The J-PARC RCS has a three-fold symmetric lattice, one superperiod of which is shown in Fig. 10. Each superperiod consists of two 3-DOFO arc modules and a 3-DOFO dispersion-free long straight insertion. As

Fig. 8 Experimental results at the SNS linac; beam loss monitor signals (normalized by beam charge) vs peak current for H^- (a) and protons (b) [10]

Fig. 9 a Simulation results for the J-PARC linac; beam envelopes along the ACS linac section. b Experimental results at the J-PARC linac; beam loss monitor signals along the ACS linac section. The red curves show the results with the original quadrupole setting, while the green ones represent the cases with the 25% weaker quadrupole strengths [20]

shown in the figure, each arc module has a missing-bend cell, which makes a horizontally high dispersion (~ 5 m), pushing up the transition energy to 7.7 GeV ($\gamma_t = 9.2$ in Lorentz factor), far beyond the extraction energy of 3 GeV [13, 16]. The effectiveness of this unique high- γ_t lattice has been demonstrated through the RCS beam commissioning and operation; no longitudinal beam loss occurs over the course of the acceleration.

Fig. 10 Lattice and optical functions (beta amplitude and dispersion functions) of the J-PARC RCS along one superperiod

3.4 Charge exchange injection

Charge exchange injection with stripper foils is widely used in high-power proton rings [30], because it is the only practical way to achieve low-loss multiturn injection. In multiturn injection without charge exchange, the injected beam and the circulating beam cannot overlap in the phase space. Such a conventional multiturn injection employs a septum with a programmed orbit bump, which brings the circulating beam close to the septum blade. The closed orbit is then slowly moved away from the septum, so that the early beam occupies the central region and the later beam occupies the outer part of the acceptance, resulting in a linear increase in the beam emittance with each turn. The disadvantage of this conventional scheme is to cause large beam losses of the order of 10% due to the circulating beam hitting the septum and to strongly limit the number of injected turns due to the limited acceptance. Conversely, charge exchange injection allows the injected beam (H^-) and the circulating beam (proton) to overlap in the same phase space area, which stacks many bunches over several hundreds to a thousand turns without a linear emittance growth, allowing the production of a high-density beam with less beam loss.

Figure 11 shows a schematic of the charge exchange injection system in the J-PARC RCS [31]. For the beam injection, two types of orbit-bump systems are prepared. One is the shift-bump system (four horizontal pulse dipole magnets; SB1–4) to produce a flattop field, making a horizontal orbit bump offset during injection. The other is the paint-bump system (four horizontal and two vertical pulse dipole magnets; PBH1–4 and PBV1–2) to make a time-dependent bump orbit for phase-space painting.

The J-PARC RCS employs three types of carbon stripper foils. The first one, which is installed at the middle of the horizontal orbit bump, is the main stripper foil

used for charge exchange for the 400-MeV H^- beam from the linac, that is, to strip the two electrons from each H^- . The thickness of the first foil is $333 \mu\text{g}/\text{cm}^2$, with the charge exchange efficiency from H^- to proton being 99.7% [31]. Although it is possible to further increase the charge exchange efficiency close to 100% by thickening the foil, the thicker foil increases the effects of foil scattering and foil heating. The former causes excessive losses, while the latter potentially shortens the lifetime of the foil. The thickness of the first foil is chosen carefully based on their tradeoff; the J-PARC RCS well balances a sufficient charge exchange efficiency of 99.7%, a low foil scattering loss of $< 1 \times 10^{-3}$, and a tolerable foil temperature of $< 1100 \text{ K}$.

The remaining 0.3% particles, which are not converted to protons, are mostly H^0 with only one electron stripped off; the amount of H^- , which remains intact with no electron stripped off, is as small as $< 2 \times 10^{-5}\%$. The injection beam power from the linac is 133.3 kW at 400 MeV (corresponding to 1 MW at 3 GeV), so that such waste H^0 and H^- components carry a power of 0.4 kW. They are converted to protons by two downstream $500\text{-}\mu\text{g}/\text{cm}^2$ thicker foils, the second and third foils, respectively, and directed to the injection beam dump with a capacity of 4 kW, as shown in Fig. 11.

Convoy electrons stripped from the H^- beam have the same Lorentz beta as that of the H^- beam, carrying a power of 145 W. Therefore, they also need to be handled carefully to prevent damaging the equipment surrounding the foil. To address this issue, a water-cooled electron catcher made of a graphite block is installed near the first foil, as shown in Fig. 12; the convoy electrons are bent by the fringe field of the injection bump magnet and absorbed by the catcher.

Most accelerator facilities that perform charge exchange injection, including ISIS [32], SNS [33], and CSNS [34], have similar injection systems. Stripper foils

Fig. 11 Schematic of the injection system in the J-PARC RCS

are the best technology available today for charge exchange injection into rings. However, provided that foils are used, beam loss is inevitable due to foil scattering, albeit slightly. In particular, beam particles scattered at large angles are uncontrollably lost in the injection area; thus, controlling radio-activations for the injection devices is a common issue in all the facilities.

3.5 Transverse phase-space painting

Charge exchange injection enables us to flexibly form different transverse particle distributions of the circulating beam from the multiturn injected beam, making use of a controlled phase space offset between the centroid of the injection beam and the ring closed orbit. This is called transverse phase-space painting. It is an essential technique to control the particle charge density, that is, to mitigate space charge, which is the most critical concern as a primary beam loss source, particularly in rings.

The J-PARC RCS uses four horizontal and two vertical pulse dipole magnets (PBH1–4 and PBV1–2 in Fig. 11) for transverse painting [35]. Figure 13 shows a schematic diagram of the transverse painting. In the horizontal painting process, PBHs, which are installed in the ring, produce a horizontal closed orbit variation at the first foil, by which the injected beam is distributed over a required range of the horizontal phase space. In the vertical painting process, PBVs, which are installed in the injection beamline nearly 180° upstream of the first foil in betatron phase advance, produce a vertical injection angle change at the first foil, by which the injected beam is similarly distributed for a required range of the vertical phase space. For this painting process, the phase-space offset of the injection beam relative to the ring closed orbit is varied as per a function of $(t/T)^{1/2}$ or $(1 - t/T)^{1/2}$ so that the beam distributions become uniform, where the parameters are the injection duration $T = 0.5$ ms and the time step t , which increases from $t = 0$

through the end of injection. Figure 14 shows the transverse particle distributions at the end of injection obtained without and with transverse painting, in which one can confirm that the transverse painting well decreases the charge density peak [21].

Transverse painting also has an important role in reducing foil hitting probability during injection. As shown in Fig. 13, the closed orbit bump variation used for horizontal painting serves to quickly move the circulating beam away from the foil; besides the larger amplitude beam than the vertical foil size formed by vertical painting acts to decrease the number of foil hits. In the J-PARC RCS, the average number of foil hits per particle during multiturn injection (307 turns) is well reduced to ~ 6 by introducing transverse painting.

Other facilities, such as ISIS [32], SNS [36] and CSNS [37], also operate transverse painting, but with slightly different techniques. In the SNS AR, four horizontal and four vertical pulse dipole magnets are symmetrically installed in the ring. They vary both horizontal and vertical closed orbit bumps at the foil during multiturn injection (1060 turns), thereby painting the beam over the required phase space areas, and also reducing the foil hits to ~ 8 . Meanwhile, in the ISIS RCS, horizontal painting is performed by making use of the moving dispersive closed orbit generated by an energy mismatch between the constant injection energy and the moving synchronous energy due to the changing main magnetic field in the RCS, while vertical painting is done by sweeping the vertical position of the injection beam using a pulse

Fig. 14 Simulation results for the J-PARC RCS; particle distributions on the two-dimensional transverse plane (x, y) at the end of injection, obtained without (upper) and with (lower) transverse painting, and their projections onto the x (solid curves) and y (dashed curves) axes [21]

dipole magnet. The vertical painting requires a larger foil; thus, it is disadvantageous in reducing foil hits. Therefore, the average number of foil hits per particle during multiturn injection (130 turns) is as large as 30. In addition, the horizontal painting using dispersion couples with the longitudinal motion; thus, the optimization is relatively limited. The J-PARC and SNS type painting schemes separate the transverse and longitudinal motions since they are implemented at the dispersion-free section. Thus, they are more flexible.

3.6 Longitudinal phase-space painting

Longitudinal manipulation during multiturn injection, called longitudinal phase-space painting, is also an essential technique for mitigating space charge.

The J-PARC RCS performs longitudinal painting by making use of a controlled momentum offset to the RF bucket in combination with the superposition of a second harmonic RF to obtain a uniform bunch distribution after multiturn injection [35, 38, 39]. Figure 15 shows a schematic diagram of the momentum offset injection, which produces a flat beam bunch through emittance dilution due to a large synchrotron motion excited by the

momentum offset. In this way, the superposition of a second harmonic RF plays an important role, which makes a flatter and wider RF bucket potential, helping to create a flatter bunch distribution. As an additional control in longitudinal painting, a phase sweep of the

Fig. 15 Schematic diagram of the longitudinal motion for the multiturn injection process without (left) and with (right) a momentum offset, where the boxes represent the injection bunch train from the linac

second harmonic RF is also employed. As shown in Fig. 16, this phase sweep enables further bunch distribution control through a dynamical change of the RF bucket potential shape including a position change of the stable fixed points during injection. Figure 17 shows the longitudinal particle distributions at the end of injection obtained without and with longitudinal painting, where one can see that the longitudinal painting well enhances the bunching factor [21].

ISIS [40] and SNS [41] also perform similar longitudinal manipulation using a second harmonic RF. Since the ISIS linac does not have a beam chopper system, the second harmonic RF plays a critical role not only in enhancing the bunching factor but also in reducing longitudinal beam loss that occurs when non-adiabatically capturing an un-chopped beam from the linac. A second harmonic RF system has not yet been implemented in CSNS, but it is under development and will be installed in the near future to further improve the capability of longitudinal painting for space charge mitigation.

3.7 Space charge mitigation by painting

Among various beam physics issues, space charge is the most critical concern as a primary bottleneck limiting the beam intensity, particularly for rings. Linear and nonlinear space charge fields not only produce tune shifts and tune spreads, but also are the main source of betatron resonances, which often result in huge beam loss. The Laslett tune shift is a useful indicator of the space charge strength; $\Delta\nu = -n_t r_p / (2\pi\beta^2\gamma^3\epsilon) / B_f$, where n_t is the total number of protons per pulse, r_p the classical radius of proton, β and γ the Lorentz factors, ϵ the transverse emittance, and B_f the bunching factor. It shows that the space charge effect is more severe at the higher charge density and the lower energy. Phase-space

painting serves to increase ϵ and B_f in the expression of $\Delta\nu$, thereby mitigating space charge.

Figure 18 shows the experimental results conducted in the J-PARC RCS to demonstrate the ability of phase-space painting for space charge mitigation [21]. This experiment was performed under a heavier space charge condition with a lower injection energy of 181 MeV; the space charge at injection was 1.6 times stronger than the design value. Before the introduction of phase-space painting, a terrible beam loss of 31% was observed at the injection energy, with space charge being most serious. However, it was drastically reduced to 1.6% by the combination of transverse and longitudinal phase-space painting. Figure 19 shows the space charge tune shifts calculated at the end of injection without and with painting. In this figure, one can find that the strong space charge in the absence of painting largely pushes the beam particles downward below various lower-order systematic resonances in the betatron tune space. Large emittance growth caused by the resonance crossing is the primary cause of the huge beam loss of 31%. The phase-space painting well decreases the charge density peak, as shown in Figs. 14 and 17. This charge density control reduces the effects of the resonances as well as the space-charge tune shifts, leading to the significant beam loss reduction. This experiment clearly demonstrated the powerful capability of phase-space painting for space charge mitigation.

3.8 Beam instability and its solutions

Beam particles propagating in an accelerator interact not only with the external fields (from the bending and focusing magnets, RF cavities, etc.) and themselves (leading to space charge effects) but also with the peripheral components surrounding the beam, which induce charges and currents in the surrounding structures, creating electromagnetic fields called wakefields. As the beam intensity increases, the effect of the wakefields on the beam increases, often causing significant beam instability. Thus, suppressing beam instability is also an important issue when aiming to achieve high-intensity performance.

In the ISIS RCS, vertical head-tail instability has been observed; a transverse wakefield generated by the head of the bunch exerts a force on the tail of the bunch, causing unstable bunch oscillations and beam loss at the initial stage of the acceleration cycle [3]. To counter this, a damper system, which consists of a split electrode beam position monitor (BPM) and a ferrite-loaded kicker, has been developed and tested [42]. The signal processing circuit detects transverse oscillations of the bunches using signals from the BPM and calculates feedback signals. These feedback signals are then sent to the kicker through the power amplifiers, compensating

Fig. 16 Temporal variation of the RF bucket potential well; the phase offset of the second harmonic RF (ϕ_2) is linearly swept from -100 to 0° during injection [21]

Fig. 17 Simulation results for the J-PARC RCS; particle distributions on the longitudinal phase space (ϕ , $\Delta p/p$) at the end of injection, obtained without (upper) and with (lower) longitudinal painting, and their projections onto the ϕ axis [21]

Fig. 18 Experimental results at the J-PARC RCS; circulating beam intensities from injection to extraction measured without and with phase-space painting

unstable beam oscillations. The most key challenge in ensuring the function of such a feedback system is to address the fast ramping of the acceleration frequency and the betatron tune, which has been overcome by employing a 3-tap digital finite impulse response filter and updating the filter coefficients through the acceleration cycle. Effective damping of the head-tail motion has been achieved at the full repetition rate of 50 Hz with this feedback system, as shown in Fig. 20 [42]. This is the first damper system, which has been successfully implemented on rapid cycling machines.

The J-PARC RCS also has a beam instability issue. In the RCS, the extraction pulse kickers are the dominant impedance source, causing horizontal beam instability in the latter half of the acceleration cycle [43, 44]. To suppress this, dynamic chromaticity manipulation is performed with sextupole magnets [45, 46]. In the low-energy region, the sextupole magnets are excited to correct a third-order betatron resonance, while, in the latter half of the acceleration cycle, they are excited in the opposite polarity to increase the chromaticity. By this latter manipulation, the chromaticity is increased by 15% over the natural value. The large negative chromaticity

enhances Landau damping through momentum spread, which favors the suppression of beam instability. Thereby, the beam instability has well been suppressed up to the maximum beam intensity corresponding to a beam power of 1 MW. In addition, the effort to reduce the kicker impedance itself is underway towards further beam power ramp-up beyond 1 MW; it is to insert diodes and resistors in each kicker power supply to reduce the beam-induced currents in the kicker magnets. In this way, the impedance can be reduced by less than half while maintaining the kicker performance [24]. A

prototype power supply has been developed and is currently being tested.

3.9 Collimation system

In order to ensure a sufficient hands-on maintenance environment in the accelerator tunnel, it is crucial not only to reduce beam losses but also to localize them. For this purpose, most high-power proton rings have a two-stage collimation system, which consists of a primary collimator and several secondary collimators, surrounded by radiation shield blocks. The primary collimator has minimum acceptance in the ring and is used to scatter protons with large deviations from the beam centroid. The scattered protons are then absorbed by the secondary collimators located downstream of the primary collimator, where the collection efficiency of the secondary collimators can be enhanced by scattering with the primary collimator.

In the J-PARC RCS, one primary collimator and five secondary collimators are installed right downstream of

the injection system in the first dispersion-free long straight insertion [47], considering the phase advance between the primary and each secondary collimators, as shown in Fig. 21. Each collimator has four plates, namely, upper, lower, right, and left, which are individually movable. The primary collimator plates are made of 1-mm-thick tungsten, where the material and the thickness are chosen from its high melting point and particle scattering angle. The secondary collimator plates are made of 200-mm-thick copper, which are decided from its sufficient stopping power for 400-MeV protons and high thermal conductivity to release heat loads. The capacity of this collimator system is 4 kW, which corresponds to a 3% beam loss at the injection energy.

The key to achieving a sufficient collimation efficiency is to ensure a large ratio of the ring acceptance to the primary collimator aperture, as shown in Fig. 22. The J-PARC RCS is designed to secure a large aperture ratio of 1.5, thereby achieving a good collimation efficiency of 98% [47]; the ring acceptance has 486π -mm mrad for a possible momentum spread of $\pm 1\%$, for which the primary collimator aperture is set to 324π -mm mrad with the secondary collimator apertures of 400π -mm mrad. The ability of the collimator system has experimentally been demonstrated in the actual high-power beam operations; no significant residual dose has been detected outside of the injection area where uncontrollable losses occur due to large-angle foil scattering.

Other facilities, such as ISIS [48], SNS [49], and CSNS [50], also use a similar two-stage collimator system to localize beam loss.

Fig. 21 Location of the collimation system in the J-PARC RCS

Fig. 22 Simulation results for the J-PARC RCS; collimation efficiency vs aperture ratio of the ring acceptance to the primary collimator aperture, estimated for two kinds of operational betatron tunes [47]

4 AR scheme vs RCS scheme

For pulsed spallation neutron sources, there exist two possible options; AR and RCS schemes. SNS and J-PARC have successfully demonstrated the effectiveness of the two schemes for MW-class high-power beam operations. This section compares the characteristics of the two schemes, including their advantages and disadvantages in achieving high-power performance, mainly considering SNS and J-PARC as examples.

The biggest advantage of the RCS scheme is that it can achieve the same output beam power as that of the AR scheme with the lower injection beam power from a linac into a ring. In high-intensity proton rings, the beam loss in the injection energy region is the most critical issue, which often poses a strong limit for high-power performance. Owing to the lower injection beam power, the RCS scheme has a larger tolerance for the beam loss rate at injection than that in the AR case. For example, the 4-kW beam collimator system of the J-PARC RCS allows 3% beam loss at injection, but the same system allows only 0.3% beam loss if applying the SNS parameters; the J-PARC RCS is 10 times more tolerant of the beam loss rate at injection.

In addition, the RCS scheme has less difficulty in charge exchange injection. In the RCS scheme, higher charge exchange efficiency can be achieved with a thinner foil than the AR case because of the lower injection energy. With a $333 \mu\text{g}/\text{cm}^2$ thin carbon foil, the J-PARC RCS gains a high charge exchange efficiency of 99.7% while minimizing the effect of foil scattering. The SNS AR also uses a similar $300 \mu\text{g}/\text{cm}^2$ carbon foil, but the charge exchange efficiency is as low as 97% because of the higher injection energy. Due to the poor charge exchange efficiency and the higher injection beam power, the unstripped waste H^0 and H^- components carry a

larger power of 42 kW (0.4 kW in the J-PARC RCS). Thus, the SNS AR prepares a more robust injection beam dump with a larger capacity of 150 kW, which is 37.5 times the capacity in the J-PARC RCS. In the AR scheme, convoy electrons stripped from H^- also carry a higher power; thus, more careful handling is required. In the SNS AR, the power of convoy electrons is as large as 1.6 kW (145 W in the J-PARC RCS), which damaged the foil bracket several times. To address this problem, they needed a specially designed water-cooled electron catcher with a large acceptance and a foil bracket made of a special material [30]. As to the charge exchange injection, it is certain that the RCS scheme, which has lower injection energy and beam power, is less difficult.

On the other hand, the advantage of the AR scheme is that it has less beam dynamics difficulty. The AR scheme has a higher injection energy into a ring, which mitigates space charge in a ring as per the scaling law of $\beta^{-2}\gamma^{-3}$. It leads to a smaller Laslett tune shift, making it easier to avoid resonance crossing. In addition, in the case of AR, there is no need to accelerate the beam; thus, the beam is extracted as soon as the injection is completed. In the SNS AR, the number of turns from injection to extraction is only 1060. Conversely, the J-PARC RCS needs to accelerate the beam from 400 MeV to 3 GeV, which takes about 15000 turns from injection to extraction. Due to the large number of turns, the beam is more susceptible to betatron resonances and instabilities. To avoid and/or compensate them, more complicated beam manipulations are often required. In terms of beam dynamics, AR is clearly simpler than RCS.

Another advantage of the AR scheme is that it has less technological difficulties for the major accelerator components. Therefore, the reliability of the AR scheme could be higher. Actually, SNS is currently running extremely well with high availability of better than 90%. In particular, the SCL has proven to be extremely reliable and is substantially more reliable than the normal conducting linac despite the large number of RF stations and the complexity of cryogenics. The AR is also running stably. The biggest difference in technological issues between the two schemes is due to the difficulties of the RCS technology. RCS needs large aperture AC magnets, rapid cycling power supplies, measures against eddy current effects, a high field gradient RF system, etc. That is, RCS is more difficult to build than AR. Further, RCS is more difficult to operate than AR. Therefore, the reliability of the RCS scheme may be lower. The J-PARC RCS has overcome such difficulties with various cutting-edge researches and developments [51, 52], which include IGBT-based resonant power supplies with high-order harmonic current control for a precise control of main magnets, stranded magnet coils impregnated by

polyimide resin and alumina ceramics vacuum chambers for reducing the eddy current effects, high field gradient magnetic alloy-loaded RF cavities for high-intensity beam acceleration, etc. Several heavy hardware troubles, such as the buckling of the RF core, occurred after the start of the user operation, but they were solved each time, and J-PARC has now achieved a reliable high-power beam operation to the MLF with better than 90% availability. However, it is fact that it took a little longer time to establish such a stable high-power beam operation compared to SNS.

Since both schemes have advantages and disadvantages, there is no simple conclusion as to which method is superior in achieving a stable high-power beam operation. Thus, all the above factors and the needs of users have to be considered carefully when deciding which approach to take for a pulsed spallation neutron source.

5 Key technology for multi-MW beam power: foil-free H^- charge exchange injection

1-MW class high-power beam operations have already been achieved at SNS and J-PARC. However, there are further needs for even higher multi-MW beam power towards the next-generation innovative researches. A critical issue in aiming for such a high-power beam is a stripper foil utilized for charge exchange injection. Continuous efforts on durable foil production have made remarkable progress on the foil lifetime. However, it is still unclear what happens to the foil when it is exposed to such a high-power beam. It could be difficult to maintain a reliable or tolerable lifetime due to overheating of the foil, which may pose a practical limitation for achievable beam power. In addition, the increase in residual radio-activation near the stripper foil due to foil scattering beam loss during injection is another serious issue, which could make difficult situations for facility maintenance.

In order to overcome such limitations and issues associated with a stripper foil, a material-free H^- charge exchange injection is indispensable. Thus, new charge exchange methods combining lasers and high magnetic fields to strip the two electrons from H^- have actively been studied at SNS and J-PARC. This section briefly introduces the recent efforts to realize non-destructive H^- charge exchange injection, which is a key technology for the next-generation multi-MW high-power pulsed proton accelerators.

5.1 Laser-assisted stripping

Development of a laser-assisted stripping method for a 1 GeV H^- beam is underway at SNS [53]. This concept has a three-step process for converting H^- to proton, as shown in Fig. 23. First, a loosely bound outer electron is

Lorentz stripped by a high field dipole magnet (~ 1.2 T), converting H^- to H^0 . Then, a laser is used to produce resonant excitation of the remaining electron to a higher quantum state (H^{0*}) with a lower binding energy. Finally, the excited electron is Lorentz stripped by a second dipole magnet, converting H^{0*} to proton.

As shown in Fig. 24, the experiment was successfully conducted at SNS, achieving $\sim 95\%$ stripping efficiency for a 10- μ s-long H^- pulse using a 1-MW peak power UV laser with several novel techniques that reduce the laser power requirement to allow high-efficiency stripping of microsecond duration beams with commercial laser technology. The techniques include temporal matching of the laser pulse to the H^- pulse structure, tailoring of the H^- beam trajectories to minimize Doppler broadening in the resonant excitation frequency of H^0 , optimization of the H^- beam size and divergence, etc. The achieved stripping efficiency is comparable to the foil-based approach of $\sim 97\%$.

The next step in this experiment is to extend the duration of the laser stripping to millisecond operating pulse lengths. This will require additional laser power savings. The cross section of the photon-particle interaction in the laser stripping process is quite small, and, thus, the loss of laser power is negligible. Therefore, the laser power can be recycled and enhanced if introducing an optical cavity. Currently, the development of cavity enhancement techniques for burst-mode laser pulses is underway to generate millisecond-long laser pulse lengths with a 1-MW peak power and to achieve high efficiency stripping to full millisecond operating pulse lengths.

5.2 Laser stripping

The injection energy of the J-PARC RCS is 400 MeV. For such a low energy, extremely high magnetic fields (>2 T) are required for Lorentz stripping [54]. In order to avoid the difficulty, J-PARC has proposed an alternative nondestructive H^- stripping method using only lasers [55, 56], as shown in Fig. 25. It is similar to the laser-assisted stripping method, but magnetic stripping of H^- to H^0 and H^{0*} to proton in the first and third steps are replaced with lasers. High-power Nd:YAG lasers can be used for those purposes. The main challenge of this method is to address the limited power of the laser,

similar to the case of SNS. Efforts for laser power savings, such as the optimization of the H^- and laser beam manipulations and the development of a laser cavity system that superimposes many laser pulses at the interaction point, are underway aiming to start the proof-of-principle experiment in 2022.

6 Summary

In the last four decades, the beam power of proton accelerators has advanced significantly from the few-kilowatt level to the 1-MW class with the spread of accelerator-driven pulsed spallation neutron sources and increasing demand for higher neutron flux. The biggest challenge in increasing the beam power is to control beam losses. The understanding of beam loss mechanisms and the development of beam handling techniques to control beam losses have contributed greatly to this progress. The proton accelerators in operation at the four major pulsed spallation neutron source facilities, ISIS, SNS, J-PARC, and CSNS, are currently providing beam powers of 0.18 MW, 1.4 MW, 0.74 MW (soon to be 1 MW), and 0.1 MW, respectively, with high availabilities of 90% or more, making significant contributions for creating cutting-edge research results in various scientific fields. Furthermore, various upgrade plans are underway at each facility to meet the need for even higher beam power for further advanced researches, which include the developments of key technologies towards the next-generation multi-MW high-power pulsed proton accelerators, such as foil-free H^- charge exchange injection methods. The work on high-

power pulsed proton accelerators has still been an active field in the accelerator world, and its further progress is highly expected.

Acknowledgements

The author acknowledges Prof. W. Namkung for giving the valuable opportunity to write this review article. The author is also grateful to Dr. D. J. Adams, Dr. A. Shishlo, Dr. S. Wang, Prof. Y. Liu, Dr. K. Hirano, Dr. K. Yamamoto, Dr. P. K. Saha, Dr. H. Harada, Dr. M. Yoshimoto, and Dr. S. Meigo for kindly providing a lot of useful information on the operational status of each facility and their efforts to beam loss issues, and Prof. T. Koseki for his helpful advice in writing this article.

About the Authors

Hideaki Hotchi is a professor at Accelerator Laboratory, KEK. He has been involved in the J-PARC project since 2003, leading the beam commissioning and beam dynamics study for the J-PARC accelerator. He was awarded the FAS Nishikawa Prize (2019) and the EPS/IPAC'20 Gersh Budker Prize (2020) for his significant contribution to the achievement of unprecedented low-loss 1 MW beam operation at the J-PARC RCS. His research field is accelerator and beam physics.

Author's contributions

The author wrote this review article by compiling information from the published papers from each facility. The author read and approved the final manuscript.

Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

Not applicable.

Received: 28 July 2021 Accepted: 16 September 2021

Published online: 04 October 2021

References

- R. Hall-Wilton et al., Status of the European Spallation Source ESS AB, the instrument selection process, and a fundamental physics beamline at the ESS. *Phys. Procedia* **51**, 8 (2014)
- J.W.G. Thomason, The ISIS Spallation Neutron and Muon Source—The first thirty-three years. *Nucl. Instr. Meth. Phys. Res. Sect. A* **917**, 61 (2019)
- D. J. Adams et al., Proc. HB2016, Malmo, Sweden, 2016, TUPM3Y01.
- C. M. Warsop et al., Proc. HB2014, East-Lansing, MI, USA, 2014, TUO3LR03.
- D. J. Adams et al., Proc. HB2014, East-Lansing, MI, USA, 2014, THO3LR02.
- C. R. Prior, Proc. HB2016, Malmo, Sweden, 2016, WEAM6X01.
- S. Machida, FFA Options for ISIS Upgrade and the Feasibility Study. *JPS Conf. Proc.* **33**, 011005 (2021)
- S. Henderson et al., The Spallation Neutron Source accelerator system design. *Nucl. Instr. Meth. Phys. Res. Sect. A* **763**, 610 (2014)
- S. M. Cousineau, Proc. HB2016, Malmo, Sweden, 2016, MOAM4P40.
- A. Shishlo et al., First Observation of Intrabeam Stripping of Negative Hydrogen in a Superconducting Linear Accelerator. *Phys. Rev. Lett.* **108**, 114801 (2012)
- M. Plum et al., Proc. IPAC2013, Shanghai, China, 2013, MOXBB101.
- M. Plum, Proc. IPAC2019, Melbourne, Australia, 2019, TUPTS086.
- High-intensity Proton Accelerator Project Team, J-PARC, JAERI Report, No. JAERI-Tech 2003–044 (2003)
- M. Arai, Japan Spallation Neutron Source (JSNS) of J-PARC. *AAPPS Bull.* **24**(2), 7–9 (2014)
- M. Ikegami, Beam commissioning and operation of the J-PARC linac. *Prog. Theor. Exp. Phys* **2012**, 02B001 (2012)
- H. Hotchi et al., Beam commissioning of the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex. *Phys. Rev. ST Accel. Beams* **12**, 040402 (2009)
- H. Hotchi et al., Beam commissioning and operation of the Japan Proton Accelerator Research Complex 3-GeV rapid cycling synchrotron. *Prog. Theor. Exp. Phys.* **2012**, 02B002 (2012)
- T. Koseki et al., Beam commissioning and operation of the J-PARC main ring synchrotron. *Prog. Theor. Exp. Phys.* **2012**, 02B003 (2012)
- T. Kobayashi, T2K experiment: T2K (Tokai-to-Kamioka) experiment detected indication of electron neutrino appearance in muon neutrino beam after 295-km travel from J-PARC to Super-Kamiokande. *AAPPS Bull.* **20**-21(2), 24–26 (2011)
- Y. Liu et al., Proc. IPAC2019, Melbourne, Australia, 2019, TUPTS027.
- H. Hotchi et al., Achievement of a low-loss 1-MW beam operation in the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex. *Phys. Rev. Accel. Beams* **20**, 060402 (2017)
- H. Hotchi et al., J-PARC 3-GeV RCS: 1-MW beam operation and beyond. *JINST.* **15**, P07022 (2020)
- M. Yamamoto et al., Conceptual Design of a Single-Ended MA Cavity for J-PARC RCS Upgrade. *J. Phys. Conf. Ser.* **1067**, 052014 (2018)
- Y. Shobuda et al., Reduction of the Kicker Impedance Maintaining the Performance of Present Kicker Magnet at RCS in J-PARC. *J. Phys. Conf. Ser.* **1067**, 062007 (2018)
- S. N. Fu et al., Proc. IPAC2019, Melbourne, Australia, 2019, MOZPLM1.
- F. Wang et al., Overview and Progress of the China Spallation Neutron Source. *AAPPS Bull.* **24**(2), 23–26 (2014)
- S. Xu et al., Beam commissioning and beam loss control for CSNS accelerators. *JINST.* **15**, P07023 (2020)
- K. Hirano et al., Proc. PASJ2015, Tsuruga, Japan, 2015, THP012.
- J. Peng et al., Proc. IPAC2017, Copenhagen, Denmark, 2017, TUOBA1.
- M. Plum et al., Proc. HB2016, Malmo, Sweden, 2016, TUPM6X01.
- P.K. Saha, Beam Commissioning Results of the J-PARC 3-GeV RCS Injection System with Upgraded 400 MeV Beam. *JPS Conf. Proc.* **8**, 012014 (2015)
- B. Jones et al., Proc. PAC07, Albuquerque, New Mexico, USA, 2007, TUPAN113.
- M. Plum, Proc. HB2008, Nashville, Tennessee, USA, 2008, WGC04.
- J. Y. Tang et al., Proc. EPAC2006, Edinburgh, Scotland, 2016, TUPLS118.
- H. Hotchi et al., Beam loss reduction by injection painting in the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex. *Phys. Rev. ST Accel. Beams* **15**, 040402 (2012)
- J. Beebe-Wang et al., Proc. PAC99, New York, USA (1999), p. 1743
- M.-Y. Huang et al., Study on the anti-correlated painting injection scheme for the Rapid Cycling Synchrotron of the China Spallation Neutron Source. *Nucl. Instr. Meth. Phys. Res. Sect. A* **1007**, 165408 (2021)
- F. Tamura et al., Longitudinal painting with large amplitude second harmonic rf voltages in the rapid cycling synchrotron of the Japan Proton Accelerator Research Complex. *Phys. Rev. ST Accel. Beams* **12**, 041001 (2009)
- M. Yamamoto et al., Simulation of longitudinal beam manipulation during multi-turn injection in J-PARC RCS. *Nucl. Instr. Meth. Phys. Res. Sect. A* **621**, 15 (2010)
- C. Prior, *ICANS XII, RAL Report*, vol 94025 (1994), p. A11
- J. Beebe-Wang et al., Proc. PAC99, New York, USA (1999), p. 2843
- A. Pertica et al., Proc. IBIC2019, Malmo, Sweden, 2019, MOPPO31.
- Y. Shobuda et al., Theoretical elucidation of space charge effects on the coupled-bunch instability at the 3 GeV rapid cycling synchrotron at the Japan Proton Accelerator Research Complex. *Prog. Theor. Exp. Phys.* **2017**, 013G01 (2017)
- P.K. Saha et al., Simulation, measurement, and mitigation of beam instability caused by the kicker impedance in the 3-GeV rapid cycling synchrotron at the Japan Proton Accelerator Research Complex. *Phys. Rev. Accel. Beams* **21**, 024203 (2018)
- H. Hotchi et al., Pulse-by-Pulse Switching of Operational Parameters in J-PARC 3-GeV RCS. *J. Phys. Conf. Ser.* **1067**, 052015 (2018)
- P. K. Saha et al., Proc. IPAC2019, Melbourne, Australia, 2019, MOPGW037.
- K. Yamamoto, Efficiency simulations for the beam collimation system of the Japan Proton Accelerator Research Complex rapid-cycling synchrotron. *Phys. Rev. ST Accel. Beams* **11**, 123501 (2008)
- H. V. Smith et al., Proc. IPAC2014, Dresden, Germany, 2014, MOPRI115.
- H. Ludewig et al., Proc. PAC2003, Portland, OR, USA (2003), p. 1428
- T. Wei et al., Beam collimation for CSNS/RCS. *Chin. Phys. C* **34**(4), 506 (2010)
- Y. Yamazaki et al., Proc. EPAC2008, Genoa, Italy, 2008, THPP084.

- 52. Y. Yamazaki, Proc. PAC09, Vancouver, BC, Canada, 2009, MO2BCI03.
- 53. S. Cousineau et al., First Demonstration of Laser-Assisted Charge Exchange for Microsecond Duration H^- Beams. *Phys. Rev. Lett.* **118**, 074801 (2017)
- 54. A.J. Jason et al., Neutralization of H^- Beams by Magnetic Stripping. *IEEE Trans. Nucl. Sci.* **28**(3), 2704 (1981)
- 55. P.K. Saha et al., Studies of Laser Power Reduction for the Laser Stripping of 400 MeV H^- Beam at J-PARC RCS. *JPS Conf. Proc.* **33**, 011025 (2021)
- 56. H. Harada et al., Development of Laser System for Laser Stripping Injection. *JPS Conf. Proc.* **33**, 011026 (2021)

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.