TECHNOLOGICAL CHALLENGES FOR HIGH-INTENSITY PROTON RINGS*

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Abstract

High-intensity, pulsed proton accelerators have been and will be requested by a wide variety of scientific fields and industrial and medical applications, for example, pulsed spallation neutron sources and neutrino sources. We will focus our discussion on the proton rings with a pulse length of a few micro second and a beam power of MW, but will make a brief comparison with CW machines. The pulsed accelerators may be used for boosting injectors to higher-energy accelerators, like a neutrino factories. At first, we will discuss on the space-charge force which limit the stored charges in a ring together with the negative-ion injection scheme. The pulsed spallation neutron sources are classified into two schemes. One is the combination of a full-energy linac and an accumulation ring (AR) exemplified by SNS and LANSCE. The other is that of a low-energy linac and a Rapid-Cycle Synchrotron (RCS) exemplified by J-PARC RCS and ISIS. In general, pros and cons of accelerator schemes are dependent upon the technological development results. Pros and cons of AR versus RCS will be discussed on the basis of recent technological developments and beam experiment data together with the future perspectives for MW-class machines.

INTRODUCTION

In order to understand why high-intensity proton accelerators are requested by so many fields of science and industrial acceleration, the multi-purpose J-PARC project [1, 2] can be used as one example. Here, J-PARC stands for Japan Proton Accelerator Research Complex, which is Joint Project of High-Energy Accelerator Research Organization (KEK) and Japan Atomic Energy Agency (JAEA). The J-PARC comprises a 400-MeV linac (at present, 180 MeV and the upgrade to 400 MeV is ongoing), a 3-GeV Rapid-Cycling Synchrotron (RCS) and a 50-GeV (at present, 30 GeV) Main Ring (MR) Synchrotron. The 1-MW, 3-GeV beams are used for materials and life science, while the several 10 GeV beams from the MR are used for nuclear and particle physics experiment. In future, the linac will be further upgraded to 600 MeV for the basic Research and Development of the Accelerator-Driven nuclear waste transmutation System (ADS).

The reason why the high-intensities are required is that the number of the secondary particles per second to be utilized is proportional to the proton beam power, if the beam energy exceeds the threshold to produce those specific secondary particles. The high beam power is thus requested, while the radioactivity is also proportional to the beam loss power. This is the reason why the beam power front of the "pulsed" protons had been located approximately at 100~200 kW (CW proton beam power was already 1 MW as shown in the next section), before the Spallation Neutron Source (SNS) [3, 4] and J-PARC were in operation. In order to increase the beam power from 100~200 kW to 1 MW, the SNS and J-PARC had to reduce the beam loss rate by one order of magnitude.

It should be noted that the number of the secondary particles "per pulse" is crucial for some important experiments rather than the averaged one. As such, high intensity (or high power), which is a product of beam energy and beam current, is not sufficient for specifying accelerator performance. Time structure and emittances (brightness if the current divided) are other important factors [5]. For the pulsed beams with a pulse length of 1 μs, which is widely required for the neutron science experiments, the beams are accumulated in a ring and then fast extracted. Here, the beams are accelerated by the RCS rings for J-PARC and ISIS (this is not an acronym) [6], while they are extracted immediately after stored in Accumulator Ring (AR) for SNS and Los Alamos Neutron Science Center (LANSCE) [7]. The discussion of pros and cons of these two schemes (RCS and AR) is one of the main parts of this paper. Designed parameters are listed in Table 1 together with the achieved ones. It is also emphasized that availability, stability, reproducibility and cost belong to another category of the important machine "performance", in particular, the former three being vital for maximizing the scientific outputs.

We start the discussion from the CW proton ring accelerators for achieving the high intensity proton beams, and then proceed to pulsed accelerators. Here, space charge force plays an important role in giving rise to the beam loss, limiting the beam power. On the basis of these results, the pros and cons of the RCS scheme and AR scheme will be discussed. Since the highly rapid, high energy RCS requires high field gradient RF system, the discussion is then focused on that in the following section, and summarized by showing the future prospect.

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Table 1: Parameters of J-PARC RCS, SNS AR, ISIS RCS and LANSCE AR

	J-PARC RCS	SNS AR	ISIS RCS	LANSCE AR
Beam pulse length, μs	< 1	< 1	< 1	0.29
Ring Circumference, m	348	248	163	90
Repetition, Hz	25	60	50	20
Beam stored energy per pulse, kJ	40 (11[b)]/12[c)]/17[d)])	24 (17[b)]/19[f)])	4	4.5
Number of protons per pulse, 10^{13}	8.3 (2.3[b)]/2.6[c)]/3.5[d)])	15 (11[b)]/15.5[f)])	2.8	3.4
Beam energy, GeV	3	1 (0.925[b)]/1[f)])	0.8	0.8
Beam power, MW	1 (0.28[b)]/0.31[c)]/0.42[d, e)])	1.4 (1[b)]/1.08[f)])	0.2	0.09
Beam current, mA	0.333 (0.093[b)]/0.103[c)]/0.142[d)])	1.4 (1.1[b)]/1.1[f)])	0.225	0.11
Injection energy, GeV	0.4 (0.18[a)])	1 (0.925[b)]/1[f)])	0.07	0.8
$\beta^2\gamma^3$	1.475 (0.505[a)])	6.750 (6.08[b)]/6.75[f)])	0.166	4.497
Beam emittance at painting π mm mrad	216	91	300	7[g)] / 12[h)]
Lasslette tune shift (Measure of space charge)	- 0.16	- 0.15	- 0.4	- 0.22[g)] / -0.18[h)]
Linac peak current, mA	50 (15[b)]/15[c)]/20[d)])	38 (38[b)]/42[f)])	25	10
Linac beam pulse length, ms	0.5	1 (0.8[b)]/1.0[f)])	0.2	0.63
Beam-on rate after chopping, %	56	68	100 (no chopping)	81

a) The values in the parentheses are those obtained. b) User operation. c) 1 hour operation. d) 1 pulse operation. e) If operated at 25 Hz. f) Record. g) horizontal. h) vertical.

CW RING ACCELERATOR

For the time being, just leave aside the time structure and emittances, and then, in order to obtain the high intensity beams,

1. Inject and store protons as many as possible in a ring
2. Accelerate them to an energy as high as possible and extract.
3. Repeat these as frequent as possible (CW or DC is most preferable)

Here, the uncontrolled beam loss should be reduced to typically 1 W/m for keeping the feasibility of hands on maintenance. A typical example of the CW ring accelerator is a cyclotron, and the world highest beam power of 1.3 MW has been realized by 590-MeV PSI Ring Cyclotron with an extraction efficiency of 99.98 percent [8, 9], where PSI stands for Paul Scherrer Institute. The cyclotron will be upgraded to a beam power of 1.8 MW. The beam power is, however, limited by the radioactivity arising from the beam loss at the beam extraction. The separation of the beam to be extracted from the circulating is the main issue for the further power upgrade.

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Fixed Field Alternating Gradient (FFAG) Synchrotron [10] are similar to cyclotrons only in a sense that their magnets are DC powered, but making use of strong-focusing in contrast to the weak focusing of cyclotrons. Complicated FFAG magnets need 3-D design and the rapid acceleration needs high field gradient acceleration. Thus, FFAG was rediscovered only after these have been developed.

Since the FFAG is inherently difficult to inject and to extract [11], further efforts are necessary to overcome this issue. Otherwise, FFAG application would be quite limited like a use of internal beams for RI production.

PULSED RING ACCELERATOR AND SPACE CHARGE EFFECT

A linac is easy, since beams go straight and only deviations from this should be corrected. A ring is easy, since particles can stably circulate along a periodic lattice. Difficult is to inject beams into a ring and to extract particles from it. Then, for ring designs, effort should be devoted to the injection and extraction. Difficult is not only acrobatic beam optics design, but also high power pulsing devices with fast rising and falling and uniform flat top. In addition, they should be in operation highly reliably and stably.

The peak current of a pulsed ring is by an inverse of its duty factor higher than that of a CW ring with the same average beam current and size. For this reason, the space charge effect, in many cases, limits its stored charges. Lasslette tune shift can be a measure of the space charge effect or can be used for scaling:

$$\Delta\nu_y = -\frac{N r_p}{\pi \varepsilon_y \left(1+\sqrt{\frac{\varepsilon_x}{\varepsilon_y}}\right)\beta^2\gamma^3}\frac{F}{B_f}$$

Here, N is the number of charges, ε_y and ε_x are vertical and horizontal emittances, respectively, and r_p is a constant of classical radius. This formula is just derived for the coasting beam case with the uniform transverse charge distribution. The deviation from this case is included in the form factor F and bunching factor B_f, both of which are unity for the coasting, uniform beam. Energy dependence of $\beta^2\gamma^3$ is universal, being model-independent. This scaling reflects that, as the particles are accelerated, the magnetic force further cancels the repulsive Coulomb force, while their masses increase, reducing the defocusing effect.

When we compare the space charge effects in Table 1, some comments are necessary for the parameters regarding J-PARC RCS, which has not yet achieved its design beam power. The reason is that the present injection energy of 180 MeV is lower than the design value of 400 MeV (the linac energy upgrade is scheduled during summer shut down in 2013). If we use the scaling law of $\beta^2\gamma^3$, the power of 0.31 MW for 1 hour is equivalent to 1 MW at 400 MeV injection (the operation of 1 hour at this power has been limited by the target performance, but the target is now ready for starting the user operation at 0.31 MW in fall, 2012). Scientifically speaking from the space charge force, the J-PARC RCS has accomplished its design beam power, since the measured beam loss, that is, the residual radioactivity [12-14], is still linear around a beam power of 0.3 MW, predicting the modest beam loss, which will allow the hands-on maintenance, at the 1-MW operation by the 400-MeV injection. In other words, it is meaningful to use Table 1 for the space charge discussion. Technically speaking, the J-PARC, of course, has not yet achieved its design performance. In particular, it is required that both the shift and paint bump systems, being pulsed at high powers, shall be reliably in operation, although the reduction in the beam energy swing eased the multi-family rapid cycling magnet systems and high-field gradient RF systems.

It is interesting to note that both the Lasslette tune shifts of SNS and J-PARC are around 0.15, being significantly smaller than that of ISIS. It is reasonable to attribute this to the big difference in the injection beam power. In order to increase the beam power, both the SNS and J-PARC had to reduce their tune shifts by further enlarging their acceptances and their bunching factors and by decreasing their form factors. Very large tune shift of ISIS probably arises from the low injection energy of 70 MeV. It is only beyond the proton energy of 500 MeV that the residual radioactivity is approximately proportional to the beam loss power. In particular, below 70 MeV, it becomes very smaller than the linear curve. It is highly probable that the high beam power of ISIS derived the full benefit from its low injection energy.

RCS VERSUS AR

The RCS scheme has an advantage over the AR scheme [5, 15], regarding the lower beam current for the same or more beam power, if the RCS accelerates higher than the AR energy (the highest injection energy is practically limited to around 1.3 GeV for the reason of Lorentz stripping in the short injection section affordable for μs pulsed beam ring). The low energy injection to the RCS implies another advantage regarding the power of the beam loss as typically seen from the ISIS case discussed in the previous section. Compare the 3-GeV J-PARC RCS with 1-GeV SNS AR in Table 2. The beam loss rate in the 400-MeV injection to the former is by a factor of 3 GeV/400 MeV more than the latter for the same radioactivity.

Then, the point at issue is entirely regarding the engineering technique, that is, whether it is possible or how difficult it is or how costly it is to accelerate the beam current of 0.333 mA from 400 MeV to 3 GeV, if one takes an example from the J-PARC RCS. In general, it is however not a right decision to make use of technically difficult option. J-PARC, however, had no other choice than the RCS scheme, since it should play another role of a boosting injector to the higher-energy MR.

The J-PARC RCS needed the following technical challenges.

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1. Wide aperture magnets for storing a number of protons against the space charge force
2. Stranded coils for the magnets against the eddy current effect
3. Ceramics vacuum chambers against the eddy current effect with copper plated strips confining the electromagnetic wave from radiating
4. Magnetic Alloy (MA)-loaded cavities to ensure the rapid acceleration by its high field gradient (25 kV/m in contrast to around 10 kV/m of conventional ferrite-loaded cavities)

In order to keep the large aperture with the reasonable cost for the bending magnets (BMs), we chose the cross section of the race-track shape for the BM vacuum chambers. The chamber, in addition, curves along the beam orbit.

For the conventional FODO lattice, the beam passes the transition during the course of acceleration. Here, the transition gamma γ_T is defined by

$$\alpha \equiv \frac{1}{\gamma_T^2},$$

where α is a momentum compaction factor. If α is small, γ_T is high. If α is negative, γ_T becomes imaginary, that is, no transition energy. At the transition, the beam becomes unstable giving rise to the beam loss, since the restoring force disappears. If the beam were thus lost during the acceleration, the most important advantage of the RCS scheme regarding the beam loss at the low energy would have gone. Therefore, the high and imaginary γ_T lattices are chosen for the J-PARC RCS and MR, respectively, in order to avoid any transition passing during the acceleration. As a result no beam loss was observed during the acceleration in either the J-PARC RCS or MR.

In order to reduce the momentum compaction factor, the momentum dependence of the orbit was changed from the conventional FODO lattice by pulling out some bending magnets from the arc section. Then, we need longer arc section, shortening the straight section for the RF acceleration for the RCS, a circumference of which is limited by its pulse length shorter than 1 μs. This is another reason why we need further higher field gradient for the RF system.

Another effort to minimize the beam loss in the RCS was exerted in the linac. The linac beam which cannot be accepted by the ring RF is eliminated at the linac MEBT. The RF chopper was devised by T. Kato [16], and developed together with Shininan Fu [17]. No beam was observed during the chopped period (world-best performance) in contrast to the "Meandor"-type chopper being used everywhere.

Almost all the technical issues for the RCS as one option for MW-class pulsed spallation neutron source have been thus solved to some extent. However, the controversy has not yet come to conclusion, since the beam power of 1 MW has not yet been achieved in any RCS. The successful start of the beam commissioning and the stable user operation of the J-PARC RCS made the RCS option very promising as well as the AR option. We believe that RCS will accomplish the beam power of 1 MW as well as AR. Then, we can combine both the technologies, SNS SC GeV linac and J-PARC RCS, together in order to realize the several and/or ten MW beam power, like Super B factory which will make use of both the KEKB ARES and PEPII comb filter together.

Table 2: Parameters of J-PARC RCS and SNS-like AR

	J-PARC RCS	SNS-like AR
Beam stored energy per pulse, kJ	40	40
Number of protons per pulse, 10^{13}	8.3	25 a)
Beam pulse length, μs	< 1	< 1
Beam energy, GeV	3	1
Beam power, MW	1	1
Beam current, mA	0.333	1
Repetition, Hz	25	25
Injection energy, GeV	0.4	1
$\beta^2\gamma^3$	1.475	6.750
Beam emittance at painting, π mm mrad	216	142 b)
Lasslette tune shift	- 0.16	- 0.16
Linac peak current, μA	50	75
Linac beam pulse length, μs	500	1000
Beam-on rate after chopping , %	56	68 (56)

a) The values in the parentheses are scaled from the SNS ones by assuming the same repetition rate and the beam power as those of J-PARC for the comparison between the RCS and AR schemes.

b) This value is estimated from the tune shift, by using the same bunching factor and form factor as those for J-PARC

HIGH FIELD GRADIENT RING RF FOR RAPID ACCELERATION

The MA-loaded cavity RF system [18] was one of the major items to develop for the high-power J-PARC RCS, since the required electric field gradient exceeding 20 kV/m is impossible to achieve by means of conventional ferrite-loaded cavities. The μQf value response of the MA is flat beyond the magnetic flux density to generate the field gradient of 100 kV/m, while the ferrite response rapidly goes down beyond 10 kV/m. In addition its extremely low quality factor makes it possible to eliminate the complicated tuning inherent to the ferrite-loaded cavities. On the other hand, it requires a sophisticated low-power RF feed-back system to ensure the system stability by compensating its extremely high R/Q value.

J-PARC RF team invented a cut-core method to adjust the quality factors of MA-loaded cavities. The Q value for MR Cavities is thus optimized, while the RCS cores have approximately the optimum Q value without cutting. The cut surface was damaged during the operation of the MA core, but this issue was solved by the polishing improvement by means of the diamond polishing. This is one example of the improvement efforts. After a lot of these efforts, the RF systems are in operation for user run.

Further effort has been devoted to the increase in the field gradient by annealing the MA cores under the magnetic field. The result is promising to generate the field exceeding 35 kV/m [19]. This will contribute to the increase in the repetition rate of the J-PARC MR, which KEK is planning for the beam power upgrade.

SUMMARY AND FUTURE

The 1-MW achievement of SNS and 0.4-MW of J-PARC are the results of the huge efforts of the high-intensity proton accelerator community world-wide during last one decade and a half. After LAMPF(LANSCE), SIN(PSI), TRIUMF, MMF and ISIS started their operations, no high-intensity proton accelerator project had not been funded for so long time, until the SNS and J-PARC did.

The J-PARC accelerator technology is definitely based upon these efforts as well as developments starting in 1986 for Japan Hadron Project in KEK, Omega Project in JAERI (now JAEA) and others. It took 22 years. During the course of the development and construction, the technology in general has been in progress, while young scientists have grown up. This is the reason for the on-schedule, successful beam commissioning of the SNS and J-PARC accelerator. However, we still need the further effort to overcome some technological issues and for path forward and beyond. The developments and the operational experiences in SNS, J-PARC and others will contribute a lot to the world-wide technological advance in the accelerator field, for several-MW neutron sources, neutrino factories, and beyond. Therefore, we have to continue the Research and Development for the coming 20-years.

Finally, it is noted that a heavy ion linac is joining the beam power front by making a full use of superconducting RF technology. Facility for Rare Isotope Beams, FRIB [20], has a driver linac to accelerate all the stable ion species up to uranium to a beam power of 400 kW with a typical beam energy of 200 MeV/u, using SC linac from 500 keV/u to be detailed in [21].

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