DISCUSSION ON RCS VERSUS AR ON THE BASIS OF J-PARC BEAM COMMISSIONING FOR PUSLSED SPALLATION NEUTORN SOURCE

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Abstract

Over a decade it has been one of the most controversial issues which of RCS or AR should be chosen for the pulsed spallation neutron source. In order to simplify the discussion, we compare the 3-GeV RCS with the 1-GeV AR. The former is J-PARC scheme, while the latter is SNS scheme. To summarize the discussion, RCS technology is much more difficult than AR technology, although RCS has many advantages over AR regarding its low beam current for the same beam power. Now, the J-PARC 3-GeV RCS was actually commissioned. On the basis of its experience, the discussion will be resumed.

INTRODUCTION

It is widely known that neutron beams with a pulse length of around 1 μs and a repetition rate of around 25 Hz are very useful tool for studying materials and life sciences. For the pulsed neutron sources we have two possible accelerator schemes: AR and RCS, where AR and RCS stand for Accumulator Ring with a full energy linac and Rapid-Cycling Synchrotron with a low energy linac, respectively. Typical examples for AR include SNS [1] and LANSCE, while those for RCS do J-PARC [2-15] and ISIS. The beam parameters are summarized in Table 1. It has been one of controversial issues which scheme is more suitable or advantageous. In addition to ISIS and LANSCE, SNS and J-PARC have begun to generate the neutron beams. In this occasion it is worthwhile to resume the issue, since many points at issue are technical rather than theoretical. Also, one can discuss on the basis of empirical data rather than theoretical calculation results.

SUMMARY OF POINTS AT ISSUE

In order to generate the high-intensity neutron beams the spallation mechanism is most efficient by bombarding the proton beams on the heavy metal 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. There is another requirement for the proton beams. The time-of-flight method is widely used to measure the neutron energy, that is, the energy spectra. For this purpose the pulse length of around 1 μs is required together with a low repetition rate to cover the low energy neutron spectra. Typical parameters are listed in Table 1. Since no ion source can produce the required number of protons per 1 μs, the protons are accumulated in a ring with a circumference of around 300 m for an order of 1 ms and are fast extracted to the neutron production target. Here, the issue is whether to accelerate the protons in the ring or not. The naïve answer is that one should accelerate, "if possible."

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

	J-PARC RCS	SNS AR
Beam stored energy per pulse, kJ	40	24 (40)
Number of protons per pulse, 10^{13}	8.3	15 (25) a)
Beam pulse length, μs	< 1	< 1
Beam energy, GeV	3	1
Beam power, MW	1	1.4 (1)
Beam current, mA	0.333	1.4 (1)
Repetition, Hz	25	60 (25)
Injection energy, GeV	0.4	1
$\beta^2\gamma^3$	1.475	6.750
Beam emittance at painting, π mm mrad	216	91 b) (142)
Lasslette tune shift	- 0.16	- 0.15 (- 0.16)
Linac peak current, mA	50	38 (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

By acceleration we can increase the beam power, or we can generate the same beam power with the low beam current. In other words, the RCS scheme has a great advantage over the AR scheme, regarding lower beam current for the same or more beam power. For example, the beam current of the 1-MW, 3-GeV RCS is 333 μA, which is one third as high as that of the 1-MW, 1-GeV AR (1 mA). Here, note that the 3-GeV AR is impossible practically speaking for the neutron source with a pulse

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length of 1 μs. The highest injection energy is around 1.3 GeV for this size of the ring as follows. The negative hydrogen beams should be injected to a ring, since the multi-turn injection is necessary to continue the injection during a period of around 1 ms. Then, the outer-most valence electron of the negative hydrogen ion would be stripped by Lorentz stripping, if the H^- ions go through the strong magnetic field. In order to avoid the Lorentz stripping, we are forced to use the weak magnetic field, requiring the long straight section for injecting the high-energy negative hydrogen beams. Since the circumference of the ring is limited by the pulse length of the extracted beam, the highest injection beam energy is practically limited to around 1.3 GeV.

The low beam current implies that the scheme is immune against the beam instability and the space charge effect. Practically speaking, however, the injection energy to an RCS, that is, the energy of a linac is reduced by taking advantage of this immunity in order to save the construction cost. The injection energy is to be determined by the following trade-off between the space charge effect and the construction cost. The lowering in the injection energy, that is, the linac cost, increases the space charge effect, which should be compensated by enlarging the RCS aperture, that is, increasing the RCS cost.

The trade-off can be exemplified as follows. The strength of the space charge force is scaled by $\beta^2\gamma^3$ as revealed, for example, in Lasslette tune shift, where β and γ are Lorentz factors. We are not insisting that the space charge force can be fully described in terms of Lasslette tune shift, but will use the scaling law of $\beta^2\gamma^3$ for discussing the space charge force. In other words, we can assume that the beam behaves in the same way, if the beam distribution and the following parameter are the same:

$$\frac{N}{\varepsilon\beta^2\gamma^3},$$

where N and ε are the number of particles and the beam emittance, respectively. This parameter is quite similar for both the J-PARC and SNS as seen from the Lasslette tune shift in Table 1. Then, the beam emittance, that is, the magnet aperture can be small for the high energy injection as exemplified in the table 1.

It is here noted that the low energy injection to the RCS implies another advantage regarding the power of the beam loss at many places in the ring. Here, we assume that the beam loss is concentrated at the beam injection period. The beam loss power is immediately related to the shielding of the radiation, the amount of the radio-activation of the accelerator, and the cooling of both the beam collimators and the H^0 beam dump. If we use the parameters listed in Table 1 as an example, the RCS allows the beam loss rate, which is 7.5 times as high as the AR case. For example, the 4-kW beam collimator system of the J-PARC RCS can accept a beam loss of 3 per cent during the injection, while the same system can stand a beam loss of 0.4 per cent in the AR case.

It is well known that the radio-activation of the ring components should be suppressed to the level, which allows their hands-on maintenance. Then, the uncontrollable beam loss should be reduced to the level of 1 W/m in order to keep the radiation level lower than 1 mSv/h at 30-cm from the activated components several hours after the beam shut down. Regarding this issue, the RCS has also an advantage over the AR.

Summarizing these discussions, 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 to 3 GeV for example. In the following sections, we will report how we have overcome these technical issues.

TECHINICAL ISSUES

High Field RF System

The high accelerating field is required for rapid acceleration. The J-PARC 3-GeV RCS (25 Hz, 0.18 to 3 GeV) accelerates the beam twice as fast as the ISIS RCS (50 Hz, 70 to 800 MeV), which have been the world rapidest so far. In addition, the missing bend lattice (see the next section) requires longer arc sections than those of the conventional FODO lattice. Since the circumference of the RCS for the pulsed neutron source is limited as mentioned repeatedly, the missing bend lattice results in shorter straight sections. For this reason, the acceleration field of the J-PARC RCS RF system amounts to 25 kV/m which is 2.5 times as high as those for the conventional ring. This high accelerating field loads the magnetic core with the denser magnetic flux, which the conventional ferrite cannot stand. Partly for this reason, we have chosen the RF cavities loaded with the Magnetic Alloy (MA). We have to undergo many kinds of hardships during the course of manufacturing the high-field MA-loaded cavities. In particular, the transverse electric field on the MA cores near the acceleration gap damaged the core materials.

It was found that the rare shorts between the MA tapes, which form the cores by winding, were damaged by powering, giving rise to catastrophic results. Finally succeeding in solving these problems, we made full use of the MA-loaded cavity system.

Large Aperture Magnets

In order to keep the sufficient acceptance for the low energy beam injection all the magnets must have the large physical apertures. As a result, most of the quadrupole magnets are quite short with the large apertures, and are located very close to each other. This is partly because the ring circumference was limited, partly because the frequent focusing is necessary for mitigating the space charge defocusing effect. In other words, the fringing field effects are substantial for these magnets, and the interference between the fields of the two neighboring magnets is not negligible. In addition, the saturation effects should be taken into account at the core ends. These effects altogether might give rise to large higher multi-pole components in their fields, resulting in the small dynamic aperture. At first, we kept it in mind to install the octa-pole magnets later in order to compensate the octa-pole components, if necessary. Fortunately, the dynamic aperture was still sufficiently large, when the magnetic fields measured for the actual magnet layouts were taken into account in the beam simulation.

Magnetic Field Tracking

The J-PARC RCS is in operation with seven families of quadrupole magnets and one family of bending magnets. The quadrupole magnets are driven by seven parallelly resonant circuit networks, while the bending magnets are driven by single series-resonant cicuit networks. All the circuits are driven by IGBT-based power supplies. The precise control is necessary for tracking all the eight families of the magnets, in particular, in the present case that each family of the magnets has its own saturation effect. For this purpose, the IGBT devices are ideal by its fast switching characteristics. On the other hand, the fast switching implies that care should be taken of even very high-frequency components of the electromagnetic power. The components of the eight resonant circuits are driven by the power supplies with the very high frequency components. From the beginning it was foreseen that the electromagnetic compatibility issue would be hard to solve. For this reason, we scheduled nearly one year for powering and controlling tests in-situ. In fact, the circuit systems altogether form distributed three-dimensional circuit systems coupled with each other. Even some chassis or some grounds revealed several hundred volts at some frequency components. After nearly one year painstaking effort almost all the electromagnetic issues have been solved, except for the shift-bump system. Together with these magnet-excitation tests the in-situ efforts were exerted to improve the signal-to-noise ratios of almost all the beam diagnostics systems, by means of filtering the noises.

Ceramics Vacuum Chambers and Other Eddy Current Effect Mitigation

For mitigating the eddy-current effect, all the vacuum chambers exposed to the fast varying magnetic fields have been manufactured of the alumina ceramics. In order to keep the large aperture with the reasonable cost for the bending magnets, we decided to choose the cross section of the race-track shape for the BM vacuum chambers. In addition, the special shapes of vacuum chambers have been produced for the injection section. Since the development and/or the mass production of the ceramics vacuum chambers, in particular, with the special shapes, took much longer time than expected, some chambers were delivered to the J-PARC site just in time.

Injection and Extraction

The injection and extraction devices for the large aperture of the beams were another challenge to develop and manufacture. In particular, the injection bump magnets, comprising the shift bump and the painting bump, have still some issues arising from the fast switching of the IGBT and others, since the decay of these magnetic fields should be faster than 100 μs for reducing the number of hitting of the circulating beams on the charge-exchange foil. The capacitors installed to the ceramics vacuum chamber, through which the mirror current passes, were damaged by this fast falling field.

BEAM COMMISSIONING OF TRANSITION-FREE LATTICE

If the beam loss happened during the acceleration, most of the RCS advantage over the AR would have been lost. It is well known that the beam loss is inevitable at the transition energy, through which the beam passes during the course of the acceleration, if the conventional FODO lattice is chosen. Thus, the transition energy of the J-PARC RCS is raised to 9 GeV far beyond the final energy of 3 GeV by adopting the missing bend lattice. The beam loss data is presented in Ref. [2], where you can observe practically no beam loss during the acceleration. It should be emphasized that the beam commissioning of the RCS is extremely easy [2] in contrast to the expectation.

CONCLUSTION

Almost all the technical issues for the RCS as one option for MW-class pulsed spallation neutron source have been solved to some extent. Since the beam power of 1 MW has not been achieved in either AR or RCS, the controversy has not yet come to conclusion. However, the successful start of the beam commissioning of the J-PARC RCS made the RCS option very promising as well as the AR option. The electric power necessary for the operation of the J-PARC (excluding MR) is similar to that of the SNS, while the total construction cost of the J-PARC is also similar to that of the SNS, although the J-PARC cost includes the MR and its experimental facilities, excluding the man power for the linac and the RCS (75 x 7 man-years).

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