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Technical Problems on Accelerator Upgrade Path

Y. Yamazaki*

JAERI/KEK Joint Accelerator Team for the High-Intensity Proton Accelerator Project
High Energy Accelerator Research Organization, Tsukuba 305-0801, Japan
*E-mail: yoshishige.yamazaki@kek.jp

Abstract

Tecnical problems are summarized and discussed in order to further increase the intensity of the proton accelerators. Even for the planned project, we have many problems to solve for achieving the design intensities.

1. Introduction

High-intensity (typically higher than 0.1 mA), high-energy (higher than 1 GeV, but lower than 100 GeV) proton beams are required in various fields of science and industry, including pulsed spallation neutron experiments (materials science, life science), muon spin rotation/resonance/relaxation experiments, high-energy and medium-energy physics experiments, and nuclear-waste transmutation.

The 2-MW SNS project has been started, while the 1-MW JAERI/KEK Joint (JKJ) Project is about to be funded. Even higher-intensity like 5 MW is requested as the ESS project is proposing. Similarly, both the SNS and JKJ are keeping the upgradability to several MW. The parameters for these projects are summarized in Table 1. We have various possible accelerator schemes for these purposes. The necessary R&D items are summarized by listing the advantages and disadvantages of the parameter choices.

It should be emphasized that the beam current to be accelerated is actually limited by the amount of beam loss, which is critically dependent upon the amount of beam halo, both longitudinal and transverse. The optimum design is also dependent upon the future performances of the key components, such as high-intensity, low-emittance ion sources, high-pwer RF components. Thus, we should concentrate our efforts on the development of these components and innovative invention in order to realize these machines. Some examples of the efforts being made in this direction are also presented.

Table 1

Examples of the existing and planned high-intensity, high-energy proton accelerators for spallation neutron sources. The first two columns show the operational machines, while the others are planned. The MMF linac is partly operational.

	ISIS	LANSCE	MMF	SNS	JKJ	JKJ-up1	JKJ-up2	ESS	SNS-up
Energy (GeV)	0.8	0.8	0.6	1	3	4	1	1.33	1
Injection Energy (GeV)	0.07	0.8	0.6	1	0.4	0.6	1	1.33	1
Repetition Rate (Hz)	50	20	100	60	25	50	50	50	60
Average Current (mA)	0.2	0.2	0.5	2	0.33	1.25	5	3.8	5
Total Power (MW)	0.16	0.16	0.3	2	1	5	5	5	5

ISIS: Rutherford Appleton Laboratory, United Kingdom
LANSCE: Los Alamos Neutron Science CEnter, USA
MMF: Moscow Meson Factory, Institute for Nuclear Research, Russia
JKJ: JAERI/KEK Joint Project for High Intensity Proton Accelerator
JKJ-up: Upgrade plan to be optimized/ Phase II
ESS: European Spallation Source
SNS: Spallation Neutron Source, Oakridge, USA

2. Time Structure of a Beam

The optimum design of an accelerator is dependent upon its detailed specifications. In addition to the intensity and energy of the beam, the time structure and the emittance are very important factors. For example, the beam with a pulse length of a few 10 ns is required by muon spin rotation/resonance/relaxation experiments in order to study mainly materials science.

The beam with a pulse length of a few 100 ns is required by spallation neutron experiments with a high energy resolution, based upon the time-of-flight method. The CW or nearly CW beam is required by nuclear-waste transmutation/incineration and nuclear-physics experiments.

In contrast to electron guns a peak current of a few 10 A cannot be obtained directly from an ion source, the maximum peak beam current of which is on the order of 100 mA. In order to obtain the beam with a pulse length less than 1 μs, the typical schematic accelerator complex comprises an injector linac and a synchrotron/storage ring with a revolution time of a few 100 ns. The highest possible beam current will be filled up in the ring, and will then be fast-extracted. The ring is used as a compressor with a pulse length equivalent to its revolution time in this case. Additional bunch compression with a bunch rotation is possible down to a few 10 ns in a storage ring by applying a high voltage.

If what one needs is only a high average current, for example a few 100 mA, a unique solution would be a CW proton linac. However, if the necessary average current is much lower than the possible peak beam current in a linac, the CW proton linac scheme is extremely expensive. The best choice is again the accelerator complex comprising a linac and a ring, where the ring is used as a stretcher. The beam is slowly extracted from the ring in this case.

If the necessary energy exceeds around several GeV, one more ring should be built as in the case of JKJ Project.

3. Beam Loss

The beam current to be accelerated is really limited by the amount of beam loss. Beam loss in the high-energy region not only gives rise to a radiation-shielding problem, but also to the radioactivity of the machine itself. The radioactivity should be reduced to a certain level which would allow hands-on maintenance (at worst around 5 nA/m/GeV or 5 W/m hopefully, much less, for example 1 nA/m/GeV or 1 W/m).

At present it is believed that the behavior of the beam core can be well controlled during the injection, acceleration, and extraction processes. Also, we perhaps understand some mechanism concerning the growth of rms-emittance during the acceleration in linacs. However, beam loss at a level of 10^{-7} /m/GeV arises from the beam halo. The difficulty to reliably estimate the beam loss gives rise to controversy for determining the optimum design.

For this reason, considerable efforts have been devoted to a theoretical study of the beam-halo generation mechanism. For example, it was shown that the halo is formed from particles interacting with the core oscillation or breathing (Bob Jameson). "Parametric resonances can occur between single particle tunes and the frequency of the oscillating mismatched beam core." (Klaus Bongardt, LINAC98)

Many computer-simulation results have shown that a beam with a hard core eventually results in a soft beam during the course of acceleration in a proton linac. Since a halo comprising a fraction of

10^{-4} of the total beam current grows far beyond the Gaussian tail, these kinds of halos can not be recognized by watching only the rms-emittance growth.

It is quite common that non-linear phenomena are strongly influenced by the error field, such as a deviation from the ideal focusing or accelerating system in the present case. It has been theoretically known that emittance growth arises due to the following mechanisms: the charge-redistribution from the given one to a uniform one, the energy transfer among the longitudinal and transverse oscillations, rms-mismatching and structure resonances. The latter two mechanisms imply the effect of a deviation from the ideal focusing and/or accelerating systems within the framework of non-linear space charge dynamics, which is perhaps common in both halo-formation and rms-emittace growth.

Theories exist, but have never been empirically tested yet, since the existing machines have too large imperfections to be used for this purpose.

4. Rapid-Cycling Synchrotron (RCS) versus Storage Ring

The yield of the spallation neutrons is approximately proportional to the beam power, if the beam energy exceeds several hudred MeV. Then, there are two ways of obtaining MW proton beams with a μs pulse duration: combining a full-energy linac and a storage ring, or combining a low-energy linac and a rapid-cycling synchrotron (RCS). The former option is advantageous regarding 1) the space charge limit in a ring and 2) a relatively short stay of the beam in the ring. The RCS option requires 3) a larger number of powerful RF cavities in order to rapidly accelerate the beam, and 4) ceramic vacuum chambers with RF shields to eliminate any eddy current which would otherwise be induced by rapidly changing magnetic fields. The latter option is advantageous regarding 1) the lower beam current, if the energy of the ring is higher, and 2) the higher beam loss is allowed during the injection process. A beam loss of approximately an order of magnitude higher will be allowed in 200-MeV injection than in 1-GeV injection.

One may partly attribute the success of ISIS to its low injection energy (70 MeV) to RCS. Since the beam-loss mechanism in a ring is another, or more difficult problem, to understand, it is not yet a settled problem which is more advantageous between the two options.

Also, technological developments are influencing the conclusion of this problm. The following the examples of the developments which have been recently done for RCS.

1) One innovation overcoming one of disadvantages of RCS came from a new type of accelerating cavities loaded with magnet alloys(Yoshi Mori et al., KEK). This new cavity system will replace all the cavities in a proton synchrotron.

2) Another innovation may be the realizaition of a negative, or extremely small, momentum compaction factor, by which no transition needs be crossed during acceleration. The beam loss otherwise arising from the transition crossing will be drastically eliminated. This kind of lattice has been extensively and carefully tested in Super ACO, showing the validity of the theory.

3) Barrier-bucket acceleration

4) Flat-bottom elongation in the sinusoidally oscillating magnetic field of the RCS. The injection time will be lengthened by this.

5. Ion Source

If one has to inject the beam into the ring for an order of several hundred μs or turns, it should comprise negative hydrogen ions. In contrast to positive ions negative ones can be injected with the same condition as that of circulating positive ions (until the time is limited by other effects, such as the space-charge limit and/or beam instabilities and/or Coulomb scattering in a charge-exchange foil).

At present we are about to realize the ion source which meets all the requirements simultaneouly for MW machines: a peak current of several 10 mA, an emittance of 1 π mm•mrad (90 %, normalized), a pulse length of several 100 μs, and a repetition of several 10 Hz. It is very difficult to predict what will be the current limit of a single negative hydrogen ion source in the future. This is another reason for controversy regarding choosing parameters.

At first, the volume-production type of ion sources was considered to be advantageous regarding not only high brightness, but also the elimination of Cs vapors. There are some indications that the Cs vapors reduce the discharge limit, possibly being harmful to the high-field operation of the following RFQ. Since it has been indicated that the introduction of a very small amount of Cs vapor drastically (approximately by a factor three) improves the beam current, even in the volume-production type, it is important to empirically test the effect of this small amount of Cs on the discharge limit in the RFQ for a long term operation. It seems to be quite possible that a small amount of Cs vapor is practically harmless. Some development is noted concerning the driving of the ion sources. The RF drive is replacing the filament drive which has a finite lifetime.

For either option of compressor ring or RCS, the higher peak current is required, since the maximum injection time is limited even in the compressor ring. The higher order resonance becomes harmful due to the non-linear space charge force, as the storage time gets the longer.

The funneling technique may be necessary to effectively realize the high peak current, although this technique is not yet feasible even by any computer simulation.

6. Frequency Issue

The frequency is another important parameter which needs to be determined. Conventional proton linacs have been using around 200 MHz for the drift-tube linac (DTL). Most of the recently proposed designs have suggested the use of a higher frequency (300 MHz to 400 MHz) for the following reasons.

1) If one doubles the frequency, it is possible to halve the number of particles per bunch. In addition, the focusing period becomes more frequent both longitudinally and transversely. As a result the space-charge effect would be approximately halved.

2) The best advantage of the higher-frequency scheme is the use of klystrons, which are the most powerful and stable rf power sources, and having mature engineering techniques.

3) The discharge limit is increased approximately in proportion to a square root of the frequency. Thus, the higher is the frequency, the more stable is the operation.

4) The shunt impedance is also proportional to a square root of the frequency.

5) The sizes of components is inversely proportional to the frequency. Easy handling and more inexpensive.

It is difficult to increase the frequency of the low-energy front DTL further, if one wishes to contain quadrupole electromagnets in drift tubes in order to keep the flexibilty for the future upgrade of the peak beam current. Also, the optimum focusing parameters are not established yet, at least empirically (This is the reason why we choose 324-MHz DTL to accelerate the beam from 3 MeV.).

7. Radio-Frequency Quadrupole (RFQ) LINAC

An RFQ linac is an ideal device, in which both longitudinal and transverse focusings are incorporated together with the ideal adiabatic bunching. Therefore, it is preferable to use the RFQ up to the highest-possible energy. However, the field of a conventional four-vane RFQ is difficult to stabilize if the RFQ is elongated over four wavelengths in order to accelerate the beam up to typically 3 MeV. The π-mode Stabilizing Loop (PISL) (invented by A. Ueno, KEK) is easy to water-cool while keeping similar beam stabilizing characteristics to that of the vane coupling ring (VCR). The PISL will be used for both the SNS and JKJ. Together with a recent further development for elongating the RFQ, the 7-MeV RFQ has been realized for LEDA.

The transition energy from an RFQ to a DTL should be carefully chosen by taking into account the detailed design of the medium-energy transport (MEBT) for matching the beam both longitudinally and transversely. In addition we should find the optimum space for installing the chopper.

In the ESS design the 5-MeV RFQ was once separated into two parts, between which the chopper is located at 2 MeV. The beams of the two RFQ' s are funneled together into the DTL by choosing the frequency of the two RFQ' s as one half of that of the DTL. In this case one should find some means to minimize the emittance growth and halo formation during the funneling process.

8. Accelerating Structure

8. 1. Medium Energy: drift-tube linac (DTL)

In a conventional DTL the focusing magnets are contained inside the drift tubes, while in a separated DTL (SDTL) the focusing magnets are located outside the drift tubes. The following factors should be taken into account for choosing the SDTL and DTL.

1) The shunt impedance of the SDTL can be optimized even further, since the drift tubes become free from the constraint of containing the quadrupole magnets.
2) The drift tubes become significantly easier to fabricate by removing the magnets, resulting in a drastic reduction in the cost of the DTL.
3) The focusing quality of the SDTL is inferior to that of the conventional DTL (the focusing period of the SDTL is longer than that of the DTL). If one wishes to have a better quality in order to overcome various space-charge effects, one should choose a higher transition energy from DTL to SDTL (50 MeV for the JKJ).

There may be several versions of SDTL: a single SDTL to be used for JKJ, a Bridge-Coupled DTL (no example, so far), and a Coupled-Cavity DTL. Pros and cons of these versions should be discussed in more detail, but are omitted here.

8. 2. High β structure

The transverse electric kick existing in the side-coupled structure (SCC) gives rise to a slight amount of continuous transverse oscillation of the beam core, possibly resulting in halo formation. If this is really significant, the annular-ring coupled structure (ACS) is the one which has the balanced characteristics of both the shunt impedance and the field symmetry.

8. 3. At what energy should one make the frequency jump or any other abrupt transition ?

1) The frequency jump at lower energy is preferable from a power-saving point of view. In addition, the beam loss arising from the frequency jump at a lower energy can be managed more easily than that at a higher energy.
2) The ratio of the acceptance to the emittance is higher in the case of a high-energy frequency jump due to adiabatic damping, favoring the high-energy option from the beam-loss viewpoint.

It should also be noted that a low-energy, high-frequency structure is difficult to fabricate, particularly to equip it with water-cooling channels for a high-duty machine.

9. Super-Conducting Cavity (SCC) versus Normal Conducting Cavity (NCC)

It appears to be energy-saving to use a super-conducting cavity (SCC) structure. This is true only if the beam pulse is longer than a few ms, since the filling time of the typical super-conducting structure is of several 100 μs under practically "reasonable" beam loading. In a long beam-pulse machine the SCC approach implies the following additional advantages over the normal-conducting cavity (NCC) scheme (sometimes referred to as room-temperature cavity).

1) It is possible to use a low peak current in order to ease the space-charge problem by increasing the beam pulse length.
2) We can use large bore radii, which are unpractical in an NCC scheme due to the increase in power dissipation. This is advantageous regarding a reduction in the beam loss. (This is only true if the present theories concerning the halo formation correctly predict the behavior of the halo, which is characterized by a saturation in the halo-envelope development. Otherwise, the large bore radii may give rise to a delay in beam loss to the high-energy region, resulting in more radioactivity.)
3) We can use a higher field gradient, at lowest 5 MV/m and hopefully several 10 MV/m, than that of the NCC (typically around 1 MV/m for CW). The field gradient in the SCC is determined by the power capability through input couplers or by the refrigerator power consumption, while that in the NCC is usually determined by optimizing both the capital and operational costs.

Since the RF power becomes expensive both capitally and operationally as the pulse is elongated, the total shunt impedance must be increased by elongating the NCC's, that is, by decreasing the field gradient.

4) The stored energy in the SCC system is extremely higher, being immune against any variation of the beam loading, as in the case of beam chopping.

However, the SCC approach implies the following disadvantages. Lorentz detuning and microphonic detuning of the SCC in the pulse mode operation makes the amplitude-phase control much more difficult than the NCC scheme. In order to meet the tolerance of the amplitude-phase control, one cavity has to be fed by one klystron. As a result, the SCC scheme becomes more expensive than the NCC scheme for the pulse mode operation. It is noted that the tolerance of the amplitude-phase control in proton accelerators (typically 1 % and 1°, respectively, for each cavity) is much more severe than in electron accelerators.

The longer the beam pulse, the more advatageous the SCC scheme. However, if one wishes to inject the beam into a ring, there is a limit in the number of turns by which higher-order resonances can be excited. The number can be significantly reduced by the tune spread due to the space-charge effect, being the same order of magnitude as that of the typical filling time, as mentioned above. In addition, the beam instability and the Coulomb scattering by the charge-stripping foil effect limit the number of possible turns for injection.

A careful study is still necessary in order to settle the problem of whether the SCC scheme is really advantageous if the injection to a ring is required.

10. Injection Schemes to a Ring

We have two schmes for the longitudinal capture in a ring: an adiabatic capture and a chopper. The chopper system should be more advantageous than the former regarding beam loss during the capture process. However, we have no established chopping scheme for the several-MeV RFQ, although there are some proposed schemes. For example, a travelling wave chopper will be used for the SNS, while a low-Q deflecting cavity will be used for the JKJ linac. The latter is under investigation with the same frequency as those of the RFQ and DTL, in between which the chopper is located. It is most important to eliminate the beam during the beam-chopped period rather than the nominal values of the rise and falling time of the chopper. Both are suffering from similar problems: power sources with fast rising and falling times.

Also, a prechopper at the LEBT is necessary in order to ease the beam load on the scraper, which stops the deflected several-MeV beam. Without the prechopper the scraper cannot stand either the heavy thermal load or the sputtering due to the heavy beam load. Two methods are under development: the SNS-type (deflection by the electric focusing system of the LEBT) and the JKJ-type (energy modulation for the injection beam to the RFQ).

The painting is also necessary in the ring acceptance, both longitudinally and transversely, in order to suppress the space-charge effect. In addition the bunching factor should be decreased by some means, such as 2nd-harmonics cavities or barrier cavities which was first realized by the cavities loaded with magnetic alloys. The beam test was successful at AGS in BNL. So far, the barrier cavities could not incorporate the acceleration after the injection. The recently proposed scheme of the barrier-bucket acceleration (induction synchrotron) will make the acceleration possible.

A new charge exchange scheme may be necessary for increasing the beam current in a ring, such as a laser stripping method.

11. Conclusion

After LANSCE and ISIS were built, extensive studies were performed in order to improve the design of high-intensity, high-energy proton accelerators. The experience obtained by operating these accelerators has been playing an important role in the studies. However, since no such machine has been built afterwards, we have had only a few chances to test the new theories and shemes. This is the main reason why we have so many controversial issues.

It is really necessary to build and to operate new machines with improved designs and with newly invented devices such as PISL, SDTL, Chopper, ACS, SCC, magnetic alloy cavities, and so on in order to further upgrade the neutron sources to several MW. Also, many more innovations are necessary to reach several MW machines, such as Fixed Field Alternating Gradient (FFAG) accelerators.