Radiation Safety Issues of High Energy Proton Accelerator for Regulation Body

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**Abstract.** Important high energy and high power, proton or radioactive beam accelerators have been constructed or planned in several countries. The multi-purpose high power proton accelerator, PEFP, is under construction in Korea. Korean regulation body needs the evaluation tool of the radiation safety of that type of accelerator facilities. The evaluation issues are categorized by six-safety terms: (1) inspection measure, (2) shielding analysis and activation estimation, (3) evaluation of accidental and abnormal operation (beam loss scheme), (4) operation policy (to reduce worker’s exposure), (5) decommissioning, and (6) high energy radiation measurement. The safety design and policy concepts, which have been determined or proposed by the design groups of several high power accelerator (JPARC, SNS, CSNS, PEFP, EURISOL), are analyzed and compared for each issue. Finally a standard idea and methods are developed and suggested for Korean regulation body. Those are discussed in the view of practical application.

**KEYWORDS:** high power accelerator; regulation body; radiation safety; evaluation issue; practical application.

1. Introduction

Recently remarkable high power and high energy proton accelerators have been constructed in several countries for neutron application and particle physics. The radioactive beam facility including high power proton or alpha beam has also been in design study. The beam powers of those accelerators are over 1MW, which is equivalent to one of old-type small research nuclear reactor. In the view of beam power, those are treated by serious regulation system. However the risk level to human society and environment is small relatively because of the inherent property of an accelerator. In Korea, a multi-purpose high power proton accelerator of 100 MeV, PEFP (Proton Engineering Frontier Project), is under construction \cite{1,2}. The proton beam energy is not so high comparing with other accelerators but 196 kW beam power can make lots of radiological problems. Finally the goal of PEFP is 1 GeV, a few MW proton beam. Korean regulation body, KINS (Korea Institute of Nuclear Safety), needs to evaluate the safety issues of such a high energy, high power particle accelerator because the construction of other high energy accelerator is considered too. In this paper, the evaluation issues were studied through the analysis of radiation safety design and policy concepts of dominant accelerator facilities (JPARC in Japan \cite{3,4,5}, SNS in USA \cite{6,7,8}, EURISOL in EU \cite{9,10,11,12}, CSNS in China \cite{13,14}, etc.) and categorized to six-safety terms. Each issue was necessary to design and operate a high power accelerator in practical view.

2. Design Specific and Status of Accelerator Facilities

The accelerator facilities which has been constructed recently such as JPARC and SNS or upcoming facilities are designed mainly to develop a pulsed neutron source using spallation reaction induced by proton interaction. And part of those or other high power accelerators aim at the Accelerator Driven System, the nuclear physics like studying neutrino and heavy isotope, cosmic radiation study, and

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even medical therapy. The composition specific of the high energy proton or heavy ion accelerator are classified to these two types. One type consists of a long linear accelerator and a main accumulation ring. The final beam energy is achieved at long linear accelerator which has high power beam easier. Another type consists of relatively short linear accelerator (lower energy beam) and high energy synchrotron. The beam power of synchrotron is limited. So the facilities, which hold a long linear accelerator, nearly have an upgrade plan to increase their proton or heavy ion beam power. It is one of important factors in the practical view of radiation safety design.

The design specific and status of remarkable facilities are listed in table 1. Every Facilities plans total operation time of 5000 ~ 5500 hours a year and neutron beam service over 90% operating time [3,6]. In the table, another important factor is long commissioning period. The machine operation is carefully done in the period to protect the machine itself and the radiation level is monitored coincidently. Until now some unexpected situation can occur because the high power beam operation is not well-known technology. It is very difficult to make clearly a quantitative relationship between beam operation and monitored radiation level because of infra structure to calibrate the diagnostic device and radiation detector. The nuclear data to estimate the radiation level is not sufficient too. Especially, it’s more requested at the target area and when a fertile nuclear material is used such as ADS. Several researches are ongoing for those subjects. There are also most important facilities in operation in the radiation safety view for benchmarking: TRIUMF cyclotron & ISAC (520 MeV, 50 kW) [15,16], PSI SINQ (590 MeV, 1 MW, Pb-Bi target (MEGAPIE)) [17], LANL LANSCE (0.8 GeV, 80 kW) [18], RAL ISIS (0.8 GeV, 160 kW) [19].

<table>
<thead>
<tr>
<th>Organization</th>
<th>SNS</th>
<th>JPARC</th>
<th>CSNS</th>
<th>EURISOL</th>
<th>PEFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>1 GeV</td>
<td>3 (50) GeV</td>
<td>0.23 GeV</td>
<td>1.33 GeV</td>
<td>0.1 GeV</td>
</tr>
<tr>
<td>Beam Power</td>
<td>1.4 MW</td>
<td>1 MW</td>
<td>120 kW</td>
<td>100kW, 5 MW</td>
<td>196 MW</td>
</tr>
<tr>
<td>Target Material</td>
<td>Hg</td>
<td>Hg</td>
<td>W</td>
<td>Hg+UCx, etc</td>
<td>Cu</td>
</tr>
<tr>
<td>Composition</td>
<td>1 GeV linac + accumulation ring</td>
<td>400 MeV linac + 3 GeV &amp; 50 GeV synchrotron</td>
<td>230 MeV linac</td>
<td>1 GeV linac</td>
<td>100 MeV linac</td>
</tr>
<tr>
<td>Commissioning starting</td>
<td>2006</td>
<td>2007</td>
<td>2011</td>
<td>Unplanned</td>
<td>2011</td>
</tr>
<tr>
<td>Status in safety view</td>
<td>low power op. 1 GeV, 183 kW</td>
<td>low power op. 185 MeV (linac)</td>
<td>In design</td>
<td>In design</td>
<td>First section op. 20 MeV Under construction</td>
</tr>
<tr>
<td>Upgrade or ongoing plan</td>
<td>1.3 GeV, 3 MW</td>
<td>2nd phase (600 MeV linac + ADS)</td>
<td>1.6 GeV, 0.5 MW synchrotron</td>
<td>1 GeV, 1 MW (synchrotron or linac)</td>
<td></td>
</tr>
<tr>
<td>Applications</td>
<td>Material science, bioscience, nuclear science using pulsed intensive neutron</td>
<td>Sciences using pulsed intensive neutron + neutrino and particle physics + ADS</td>
<td>Multi-purpose including cosmic radiation effect and medical therapy</td>
<td>Nuclear physics, nuclear astrophysics</td>
<td>Multipurpose including RI production and ADS</td>
</tr>
</tbody>
</table>

(a) Synchrotron means Rapid Cycling Synchrotron (RCS)
(b) ADS means Accelerator-Driven System

The RIB (Radioactive Ion Beam) facilities like EURISOL and ISAC generate heavy ion beam using metal target, etc. But the facility to accelerate proton or heavy ion is the same to other high power
accelerator and every issue in the radiation safety view is evaluated in the same. The figure 1 shows the schematic structure of PEFP facility in Korea.

**Figure 1:** Schematic drawing of PEFP accelerator and beam lines [1].

3. Design Issues for Radiation Safety Evaluation

As mentioned above, the accelerator has a unique property which is different with nuclear reactor of the same power. Even though the nuclear reactor is operated, there are nuclear wastes after operation and it was carefully treated. However the accelerator except of ADS generates few wastes and the residual activated material can be handled. Therefore, in the practical view of radiation safety, the evaluation issues of safe design of high power proton accelerator were categorized as followings. Above accelerator property was reflected in this classification. The remarkable issues are (1) inspection measure, (2) shielding analysis and activation estimation, (3) evaluation of accidental and abnormal operation (beam loss scheme), (4) operation policy (to reduce worker’s exposure), (5) decommissioning, and (6) high energy radiation measurement.

3.1 Inspection Measure

EURISOL project reviewed the radiation related regulation of EU because the beam power reaches almost 5 MW, which is the same level with old type research nuclear reactor. Finally the similar level inspection was recommended because EURISOL also used fertile nuclear material as a target material [9]. TRIUMF cyclotron was classified as Class 1B by Canadian regulation [16], which meant nuclear facility, not a radiation-generating device. However JPARC, which was near a public area, were assigned as non-nuclear facility and SNS accelerator was also non-nuclear facility, but SNS target was nuclear facility. SNS make a solution to keep the facility boundary at the far position of 1.3 km from public area [6].

In Korea, the beam power of PEFP was 196 kW at present [1]. Therefore authors recommend the PEFP would be classified as non-nuclear facility and the inspection measure should comply with Korean regulation related to radiation-generating device. However if the PEFP is upgraded to 1 GeV, 1 MW facility and especially, a ADS is included in the project, that recommendation will have to be reviewed again considering the operation experience of SNS and JPARC. The classification of present regulation would be reviewed and set up again through this kind of studies.

3.2 Shielding Analysis and Activation Estimation

Most of countries comply with ICRP 60 recommendation for their own control standard. However the design limits to identify the zone were applied differently according to their conservative measure. For the shielding analysis, Tesch’s semi-empirical formula [20] or Moyer model [21] were used and several Monte Carlo Codes were used for local area or complicated structure. The MCNPX [22], FLUKA [23], PHITS [24], MARS [25] and etc, were used, but the discrepancy between each code has been found as a little large at some benchmarking results until now and nuclear data and infra structure
for estimating radiation production and transport are insufficient in a world. So the factor of two is applied normally at the safety margin [3].

There are many ducts and labyrinths between accelerator tunnel and human access area because of many utilities and power connections. Proper design can reduce the cost and human exposure. The results of previous analytic studies agreed within a safety margin with one of the Monte Carlo calculation in simple maze structure [3]. However, the accuracy at higher energy above a few hundred MeV was not proven well. The source term of skyshine analysis at the proton accelerator is different with nuclear reactor. So the other empirical formulae like Stapleton’s equation were usually chosen for the skyshine calculation instead of the utility used at nuclear reactor condition [26]. The four-parameter approximating formula was also applied to develop the simple code, SHINE III [27].

As mentioned above, it is nearly possible to handle the residual activity because the accelerator usually generates short-half life radioactive isotopes [28]. There is the same problem of insufficient nuclear data in the estimation. For example, most of programs to calculate the isotope production had only the nuclear data of neutron less than 100 MeV. Theoretical estimation was mainly applied to neutron higher than 20 MeV [29]. Most design group including Japanese group carried out their own research program to evaluate the nuclear data.

In Korea, even though the beam energy range, 100 MeV, of PEFP is covered by one of other high energy accelerator, it is recommended that the benchmarking research is needed if considering the safety margin and insufficient factor. It’s why higher accelerator facility apply more conservative data at 100 MeV using higher energy data. The 230 MeV cyclotron of Korea National Cancer Center or 50 MeV cyclotron of KIRAMS will be useful candidate.

3.3 Evaluation of Accidental and Abnormal Operation (Beam Loss Mechanism)

One of other importance factors for shielding analysis and activation estimation is to estimate particle beam loss point and loss rate. Except of pre-defined beam dump, it is very difficult because of insufficient technology and sometimes its uncertainty can be bigger than the safety margin. The large beam loss in high power accelerator cause high residual activity to let human access and maintenance so hard. Therefore the accidental and abnormal operation should be evaluated carefully and the well-operation experience and technology are required. Especially the high power accelerator discussed in the study is normally new model to use high power beam. Operation technology is not set up well. Through long time commissioning, this technology have to be developed to estimate the beam loss.

At present the representative assumption of loss rate of high power accelerator was 1 W/m along the accelerator [3,8] and this value was applied to each accelerator depending on the assumption of loss distance. For example, 1 W beam is lost at the spot at every 1 m or 10 W beam is lost at the spot at every 10 m.

1 W/m is generally accepted number for accelerator maintenance with reducing worker’s exposure. So it is recommended to use 1 W/m first for a safety design. But the final loss rate at the detail positions has to be determined through deep discussion with accelerator operation group. The SLAC approach in the document, “Electron beam loss in the LCLS”, showed good model [30]. Therefore the inspection process of PEFP is recommended to be slow like step by step to develop the loss mechanism well.

3.4 Operation Policy

Practical the accelerator operation scheme will decide the amount of human exposure at normal condition and abnormal condition. The operation report of ISIS at RNL showed that the beam intensity has a deep relationship with amount of residual activity inside tunnel. The operator have been trained well continuously. Beam parameter is monitored continuously and automatically the operation is stopped by a interlock system when the value increase higher than pre-defined limits. It is recommended to reduce abnormal beam loss that well-trained operator and operation procedure are prepared and periodically it is reviewed and the manual of prompt response is prepared for the unexpected condition when the beam property and quality are changed. The permit process of beam operation has to be well developed too.
Beam loss monitor and beam current monitor are important devices to determine the operation quality. Several researches are ongoing to develop well-proven device and method. And the decision of defining the condition needs overall consideration of signals from more than one device. The target area is expected as high radiation area even after beam shut off. So the automatic replacement systems of targets are equipped at every facilities of spallation neutron source. However, the accidental condition occurs when the automatic system fail. Someone has to go into the target area. The access and maintenance procedure is required in advance to prevent unexpected exposure with the precise calculation of the radiation level.

3.5 Decommissioning

Naturally, the radioactive problem of accelerator facility was rare, but in the high power and high energy proton accelerator it’s not a small issue. The consideration of accelerator decommissioning is required. Moritz estimated the decommissioning cost of TRIUMF cyclotron and auxiliary building was $36 million in 2003 Canadian dollars [15]. Even though it was estimated very conservatively, the cost information lets us know the importance of decommissioning. The decommissioning was stepped at 2 years later, 25 years later, 45 years later. It is recommended that the residual activity at the expected decommissioning time is calculated and the commissioning plan should be prepared in inspection process.

3.6 High Energy Radiation Measurement

The higher proton beam energy is applied, the thicker shielding wall is required. In addition, the energy spectrum of neutron or gamma outside the shielding wall becomes broader and highest energy to be measured increases. Especially in the accelerator tunnel it is necessary to prove the exposure level at accidental condition. There is no proper detector in the commercial products at present. DARWIN of JAEA [31] can be one model to verify and calibrate the response of other detector. All kinds of detectors which are used in the high energy proton accelerator should be calibrated using the radiation source with higher energy if possible. Otherwise the safety margin can be added to measured radiation level measured by detectors calibrated normally. For example, the control value is assigned as twice of measured value like KEK practice. In Korea, both approaches are recommended.

4. Summary

The high power proton accelerator is not nuclear facility, but the abnormal safety design and operation can make lots of inconvenience in maintenance process and request huge costs. The specifics of high power and high energy accelerator were studied in the practical view of radiation safety. The main evaluation issues were classified by analysing and comparing the design concepts of remarkable accelerator facilities and the standard requirements were suggested for Korean regulation body. The PEFP is first high power proton accelerator facility in Korea and the inspection procedure and method should be evaluated carefully and set up. In the paper, important requirements were presented as six-safety terms and further study like benchmarking was recommended.

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REFERENCES