Radiation transport and protection calculation for the in-flight fragment separator facility of Rare Isotope Science Project in the Republic of Korea

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Abstract

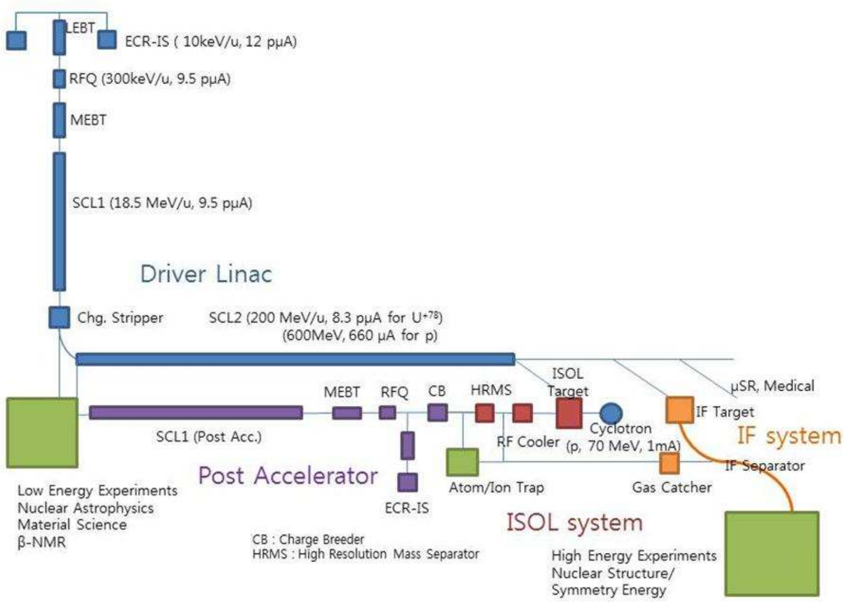
A rare-isotope accelerator facility is planned to be constructed in the Republic of Korea, named as Rare Isotope Science Project (RISP). The facility contains three accelerators: a heavy-ion superconducting linear accelerator as the driver for the in-flight fragment separator (IF) system, a proton cyclotron for the isotope separation on-line (ISOL) system and a superconducting linac for secondary beam acceleration. The driver accelerator will provide uranium beam for the IF system up to 200 MeV/u at a maximum beam power of 400 kW, and the cyclotron a 70-MeV proton beam at 70 kW. The IF system consists of pre- and main separators. An isotope beam of interest is separated in the pre-separator, and then purified for identification in the main separator. A main function of pre-separator is to remove the primary and unwanted fragments by stopping them at a beam dump. Due to the high beam power, it is important to evaluate radiation transport and shielding especially in the pre-separator area. Heat deposition and radiation dose rate in the components of pre-separator have been estimated using PHITS.

Introduction

The Institute for Basic Science was established in 2011, and is the host institution of a next generation rare isotope beam facility in the Republic of Korea. The Rare Isotope Science Project (RISP) was created to carry out the technical design and the construction of the accelerator complex in December 2011. The goal of this accelerator complex is to produce a variety of stable and rare isotope beams to be used for research in both basic and applied sciences.

The rare isotope beams can be produced either by target spallation in the isotope separation on-line(isol) system or projectile fragmentation and fission in the in-flight fragmentation (IF) system. Two different methods produce rare isotope beams of different characteristics, and thereby can provide wider varieties of isotope beams than in other facilities operating only one of the two methods. More diverse users from the basic and applied sciences can be accommodated. Especially high-intensity and high-purity RI beams near the drip line can give us tremendous opportunities to explore the entire universe from microscopic to macroscopic world.

Figure 1: Schematic diagram of the accelerator complex of RISP



The schematic diagram of the facility is shown in Figure 1. The accelerator complex consists of a heavy ion linear accelerator as the main driver for the IF system, a proton cyclotron as the driver for the ISOL system and a post-accelerator for the ISOL system. The ISOL and the IF systems are to be operated independently. In addition, the RI beams produced in ISOL can be injected into the driver linac for accelerating the RI beams to higher energies, so that the IF system can produce even more exotic rare isotope beams. The advantage of this two-step process needs to be further evaluated. In a future upgrade, the proton beam, which is accelerated up to around 600 MeV by the main linac, can be used for the ISOL system. Table 1 shows the beam specifications of the driver linac. The various kinds of RI beams of proton- and neutron-rich nuclei, which are requested for research, are summarised in Table 2. This list was prepared by the user community of the RISP after the analysis of current research trends and future perspectives of the RI science.

The production and selection of RI beams of interest can induce large amounts of radiation flux and heat in the IF components. The separation of the RI beam of interest from the primary beam non-reacted is an important design issue for the high-power RI beam facility. A major goal in the IF separator design is the delivery of sufficiently pure RI beam to the experimental set-ups. This paper presents some preliminary results of the magnitude of the radiation fields and the estimation of the lifetime of superconducting magnet coils in the high-radiation region of the IF system using PHITS [1].

Table 1: Driver linac beam specification

Ion species	Ion source output		SC linac output			
	Charge	Current(pμA)	Charge	Current(pμA)	Energy(MeV/u)	Power(kW)
proton	1	660	1	660	610	400
^{40}Ar	8	42	18	34	300	400
^{86}Kr	14	22	34-36	18	265	400
^{136}Xe	18	19	47-51	13	235	400
^{238}U	33-34	12	77-81	8	200	400

Table 2: Selected RI beam requirements for RISP research opportunities

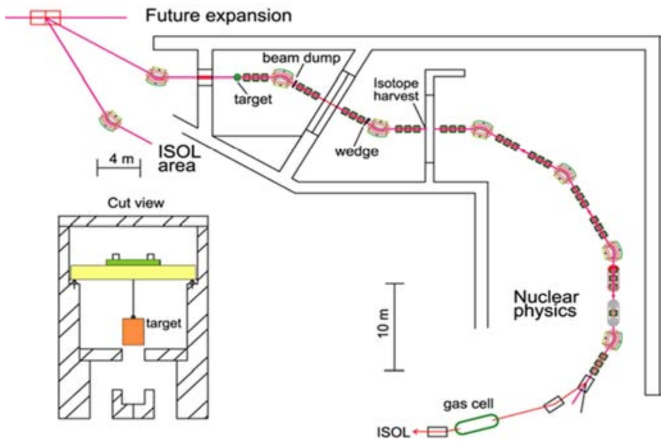
RI Beam species	Energy range	Desired intensities [particles/sec]	Research fields
^{80}Ni, ^{76}Fe,^{132}Sn,^{144}Xe	>100 A MeV	> 10^{9}	nuclear structure
^{80}Ni,^{76}Fe,^{132}Sn,^{144}Xe	5-20 A MeV	>10^{8}	nuclear structure
^{15}O, ^{14}O	<10 A MeV < 30keV	>10^{10-11} >10^{8}	nuclear astrophysics material science
^{26m}Al	5-20 A MeV	> 10^{7-8}	nuclear astrophysics
^{45}V	0.613-2.25 A MeV	>10^{7} – 10^{9}	nuclear astrophysics
^{39}Si, ^{36}Mg	5-10 A MeV	>10^{7-9}	nuclear Structure
^{68}Ni, ^{106}Sn, ^{132}Sn, ^{149,142}Xe	10-250 A MeV	>10^{9}	symmetry energy
^{6,8}He, ^{12}Be, $^{24-30}$O	50-100 A MeV	>10^{9}	nuclear study with polarised target
^{17}N,^{17}B,^{12}B,$^{14-15}$B,$^{31-32}$Al,^{34}K	50-100 A MeV	>10^{9}	nuclear study with polarised RI beam
^{8}Li, ^{11}Be, ^{17}Ne	< 30 keV	>10^{8}	material science
$^{133-140}$Sn	<60 keV	>1	atomic physics
^{8}B,^{8}Li,^{9}C,^{11}C,^{15}O	≥ 400 A MeV	>10^{7} ~ 10^{9}	medical and bio science

In-flight fragment separator system

Figure 2 shows a schematic view of the IF facility layout. The IF system consists of pre-and main-separators. The pre-separator includes the target system for the production of rare isotope beams by mechanisms such as projectile fragmentation and in-flight fission. The isotope beam of interest passes through the pre-separator, and the remaining beam, which is mostly the primary beam, needs to be dumped in the localised areas. This front-end of pre-separator including a target and beam dump should be well-shielded from the other regions. Most of the parts will be made in detachable modular form so that any malfunctioning can be repaired by taking out the affected module to the designated repair areas. This remote handling will require careful mechanical design on the joining parts as they are related to vacuum sealing and alignment. Modern robot system for remote handling often heavily uses semiconductor devices, which are weak to radiation damage. Major parts of the handling system should use metallic components to avoid fast radiation damage. An efficient approach to the system development would be to adopt established technology at the high-current beam facility in operation such as the MEGAPI collaboration at the PSI and the SNS in the US.

The superconducting magnets in the pre-separator region are exposed to large amount radiation heating and high-level doses. In particular, the first quadrupole magnet set downstream of the target receives the highest level of radiation dose, and still needs to have a large aperture for the large acceptance of isotope beams. High-Tc superconducting magnets have been developed for the FRIB project by the BNL group [2], and we plan to develop a similar magnet also in collaboration with the BNL group.

Figure 2: Layout of the IF separator and the following beam line



Target and beam dump

The target for in-flight fragmentation needs to endure about 30% of the primary beam power in an average case. The resultant power density inside the target is very high, and thus cooling is critical. The high-power target for in-flight fragmentation has been numerically studied using PHITS, which is a heavy-ion radiation transport code to evaluate the generation of heat and radiation. The highest power density is around 65 MW/cm^3 for a U beam of 200 MeV/u at 400 kW, which is calculated by PHITS, and can be reduced to tens of kW/cm^3 by using a rotating target. The maximum allowable temperature for graphite target is around 1 900^{0}C, but the temperature inside the target goes higher for a single-layer target with a thickness of over 1 mm for the U beam. A multi-slice target with a thickness in the order of 0.1 mm can reduce the temperature by enhancing radiation cooling, but then a structural problem has been observed at high rotating speed [3].

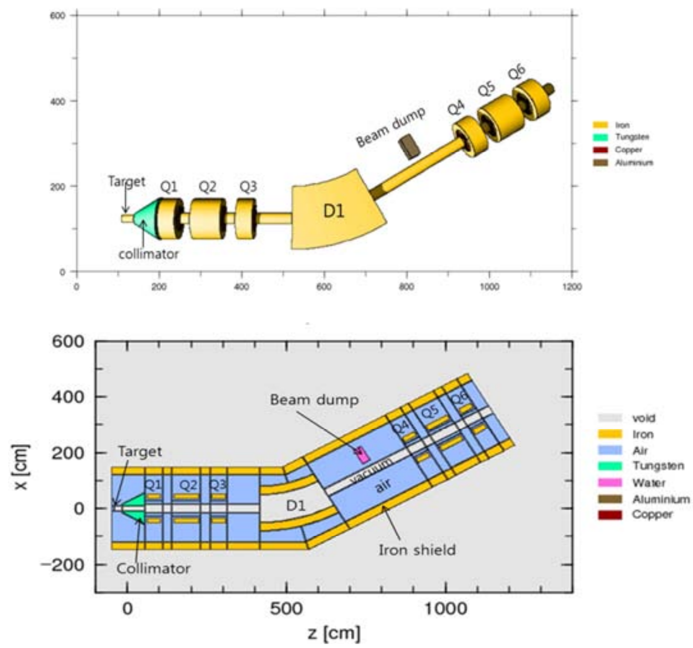
The beam dump is a movable device to select the momentum dispersion of the isotope beam and to completely remove the primary beam. In normal operation, it absorbs about two thirds of the full power of 400 kW, and the short range of the heavy ion beam inside the material results in extremely high power density. The envisioned concept of the beam dump is based on stopping the beam in a water-filled rotating drum, which is similar to the one that has been developed for the FRIB. There are two critical issues in the beam dump. One is material damage to the water container that can severely limit its lifetime, and component failure due to the high-radiation fields. The other is water activation which produces radiologically significant nuclides in the water, for instance ,^{3}H, ^{7}Be, and ^{14}C.

Radiation transport and heating calculation

Set-up geometry of pre-separator for PHITS calculation

Figure 3 shows a 3D model and material compositions of the pre-separator used in PHITS. We use large-aperture superconducting quadrupole triplet magnets and a dipole magnet in the front-end of the pre-separator. High-Tc superconducting coils will be used for those magnets instead of superconducting coils operating at 4 K, considering the efficiency of radiation heat removal. Magnetic fields of those magnets are also included in PHITS calculations, for which the magnetic fields were obtained using beam optics codes such as TRANSPORT. A typical primary beam is U beam of 200 MeV/u at 400kW, which bombards the graphite production target. The optimal target thickness of ~2 mm was determined using LISE++ to have maximum yields of ^{132}Sn isotope beam, which is one of the most important radioactive nuclei.

Figure 3: A 3D pre-separator geometry used in PHITS calculation and material compositions used



Higher: 3D pre-separator geometry used. Lower: material compositions used.

Calculation of radiation heating and evaluation of lifetime of superconducting coil

Figure 4 shows the distribution of radiation heating in the front-end of the pre-separator area by PHITS calculation in units of MeV/cm3. The projectile fragments produced by a thin target and non-reacted uranium beams are separated by the downstream magnet system. The unwanted beams hit the collimator and the beam dump, which produces intense radiation and deposits the heat on the magnetic elements. By using a cooling system and shielding blocks, heat deposition especially in the superconducting coils should be reduced. To estimate the lifetime of superconducting coils, the heat deposition only to the coil was considered. Figure 5 shows a sectional view of heat distribution in the coil region of the first quadrupole magnet. The average power deposition in the quadrupole magnets is shown as dose rates along the magnet length in MGy/yr in Figure 6. Table 3 shows the maximum energy deposition for the Q1~Q6 magnets. To estimate the approximate lifetime of high-Tc conductor coils, the radiation lifetime of Nb_3Sn (500MGy) and the density of copper (8.96 g/cm^3) were used instead because data on the high-Tc superconducting magnet materials are not yet available. Assuming yearly beam operation of 5 600 hours, lifetimes of the coils are estimated as listed in Table 3.

Figure 4: Heating in the pre-separator area when a 400kW, 200MeV/u ^{238}U beam bombards graphite target

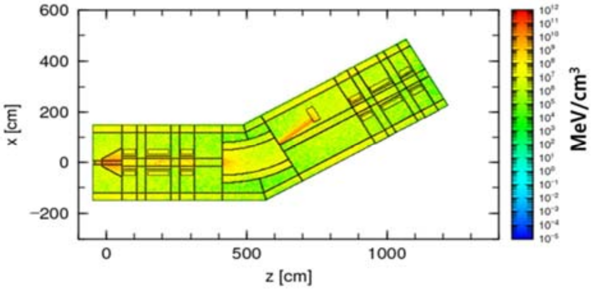


Figure 5: Heat distribution around the coil region of the first quadrupole magnet downstream of the target when ^{238}U beam is used

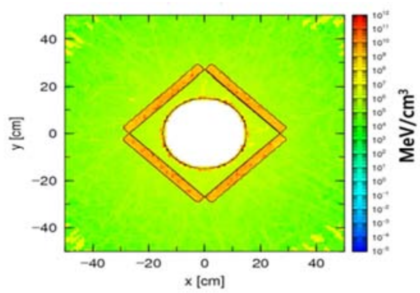


Figure 6: Dose deposition in the quadrupole magnets of the frond-end of pre-separator as a function of the length along the beam

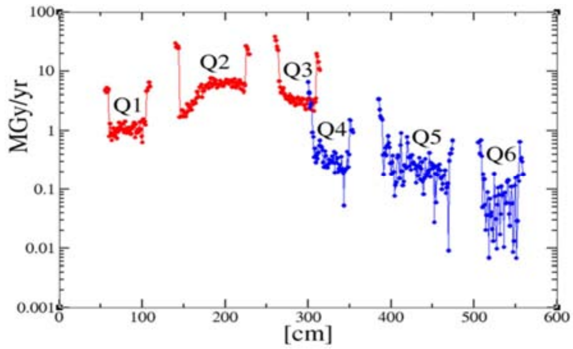


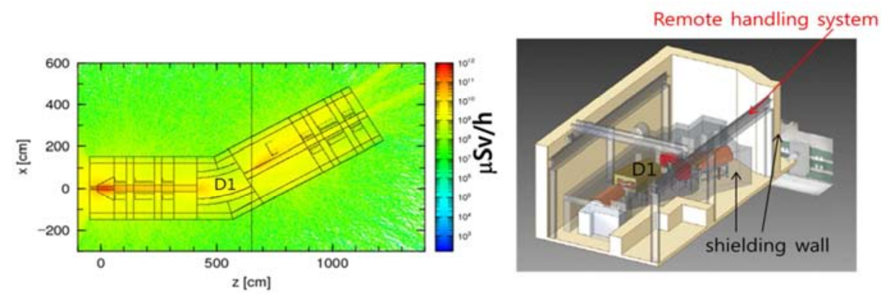
Table 3: Dose rates and lifetime estimation of the six coils when ^{238}U beam is used

	Dose Rates (MGy/yr)	Lifetime (year)
Q1	6.533	77
Q2	29.752	17
Q3	38.348	13
Q4	6.554	76
Q5	3.434	146
Q6	0.640	781

Prompt dose rates

The particle fluxes and the radiation dose rates mainly by neutrons and photons in the pre-separator area were calculated. Figure 7 shows the distribution of prompt dose rates, which can be used to estimate optimum shielding thickness necessary to reduce the radiation dose rates outside the shielding below regulatory limits. The strong radiation fluxes are shown around the target and the beam dump. They can be more effectively reduced by piling up the concrete blocks close to the target and the beam dump. A shielding structure with a remote handling system will also be constructed as shown in Figure 7. Detailed calculations are in progress.

Figure 7: Prompt dose rates for the ^{238}U beam (left); a 3D conceptual view of shielding structure with remote handling system (right)



Conclusion

A heavy-ion accelerator facility is planned to be constructed in the Republic of Korea. The next-generation RI beam facility using high-beam power requires elaborated evaluation on the radiation transport and shielding in the area of RI beam production and separation. Some preliminary results were obtained at the front-end of the pre-separator region, where the radiation level is the highest. Heat deposition and radiation dose rate on the components of the pre-separator were calculated using PHITS. The lifetime of the coils in superconducting magnets was then estimated based on assumed beam operation scenario of the facility. More detailed calculation is in progress, and the validation on the Monte Carlo computation is planned by beam experiments in the existing heavy-ion beam facility.

Acknowledgements

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References

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