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Beam Dump Design for the Rare Isotope Accelerator Fragmentation Line

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Abstract

Beam dumps for the heavy ion beams of the fragmentation line of the Rare Isotope Accelerator have been designed. The most severe operational case involves a continuous U beam impacting the beam dump with a power of 295 kW and a nominal spot diameter size of 5 cm. The dump mechanically consists of two rotating barrels with a water cooled outer wall of 2 mm thick aluminum. The barrels are 70 cm in diameter and axially long enough to intercept a variety of other beams. The aluminum wall absorbs approximately 15% of the U beam power with the rest absorbed in the water downstream of the wall. The water acts as an absorber of the beam and as a coolant for the 2 mm aluminum wall. The barrel rotates at less than 400 RPM, maximum aluminum temperatures are less than 100 °C and maximum thermal fatigue stresses are low at 3.5×10^7 Pa (5 ksi). Rotation of the dump results in relatively low radiation damage levels with an operating lifetime of years for most beams.

1. Introduction

The Rare Isotope Accelerator (RIA) has an ISOL beam line with proton and helium beams and a Fragmentation beam line with heavy ion beams of U, Sn, Kr, and Ca. For the fragmentation line, the heavy ion beam first impinges on a target where a fraction (20%) of the beam is absorbed and the rest of the beam passes through the first dipole magnet and is absorbed in a beam dump just downstream of the dipole magnet. The desired ions generated in the target are sent down the centerline of the accelerator and the beam, other ions and other fragments are absorbed in the beam dumps. The beam dump design consists of a rotating barrel shape with the beam partially absorbed in 2 mm of aluminum material and the rest of the beam absorbed in several cm of depth of flowing water behind the aluminum.

Analyses of the energy deposition of the beam in the dump material were made. The thermal and structural response of the dump due to the energy deposition was also analyzed. Rotation of the dump is necessary to reduce the volumetric energy deposition in the Al dump material and in the water coolant/absorber and to result in lower acceptable temperatures, thermal stresses and radiation damage.

2. Mechanical Design

The beam dumps for the fragmentation line are located downstream of the first dipole magnet and in front of the multipole magnet. The dump consists of two rotating barrel shapes that are placed to each side of the beam centerline. The dumps rotate about a horizontal axis. Figure 1 shows the two barrel dumps and related hardware. The dumps are located in a vacuum space surrounding the dipole magnet.

The dumps consist of two assemblies with each assembly consisting of a barrel shape with a shaft that penetrates a vacuum wall structure, a rotating vacuum pass-through at the vacuum wall, a water union coupling, an electric motor and drive belt, and an expansion joint with a motor to allow horizontal motion of each dump.

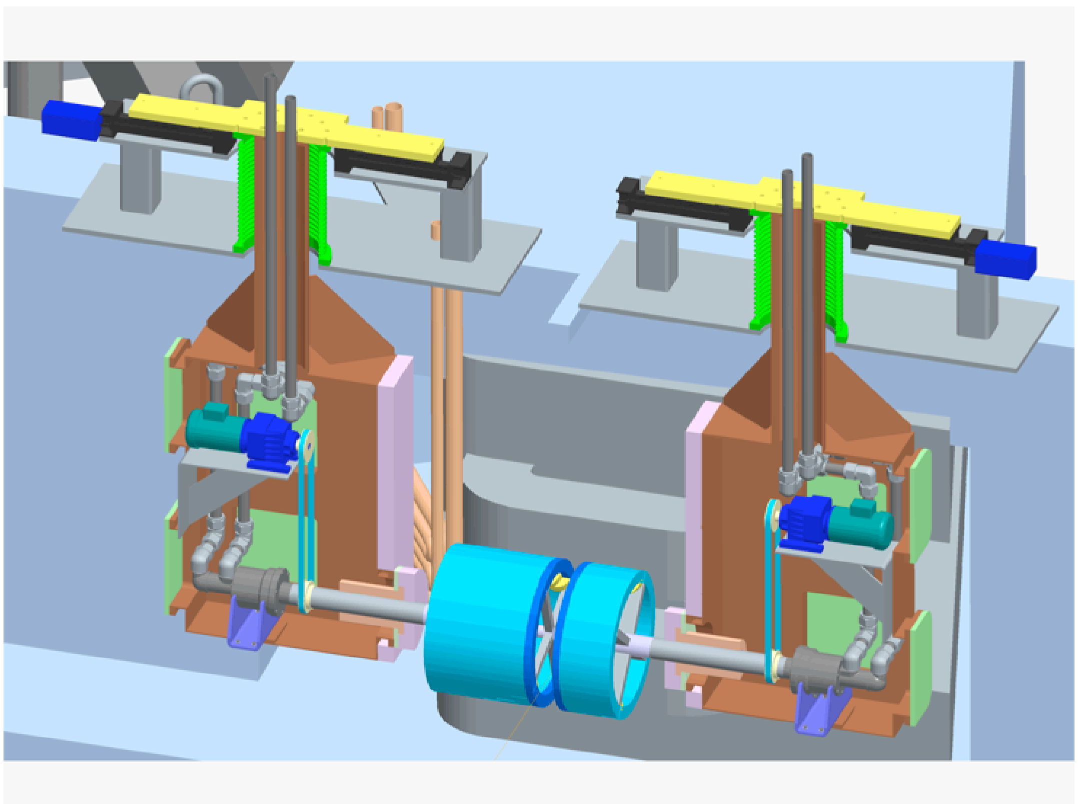


Figure 1. Barrel shaped beam dumps located downstream of the first dipole magnet.

Operation of the dumps involves rotating the barrels in order to spread out the beam power over the perimeter of the barrel. Water is used to cool the metal of the dumps and absorb the beam power that penetrates the barrel wall. The water cooling enters and exits the barrels along the rotating hollow shafts that are connected to the building water pipes with the water union. An electric motor is used to drive the rotation of the shaft and barrel.

The dump assembly support structure is part of the vacuum enclosure of the dipole magnet. The barrel shaft penetrates this support structure and a rotating vacuum pass-through is used seal the shaft penetration from the vacuum side to the air side containing the union and motor. The beam dump support structure is supported by an expansion joint assembly at the top of the dipole magnet vacuum enclosure for the purpose of allowing 10 cm of horizontal motion of the barrels. This motion is necessary for beam operating conditions where the main beam is only a few centimeters from the accelerator centerline. A support table and track is connected to the expansion joint to allow lateral motion by use of an electric motor.

3. Detail of dump barrels

Figure 2 shows the barrel geometry. The barrels have an outside diameter of 70 cm and are 50 cm or 28 cm long. The barrel material is an aluminum alloy and the outer wall thickness is 2 mm. Water flows in the 6 cm deep channels to convectively cool the barrel wall and to act as an absorber of the fraction of the beam that is not absorbed by the

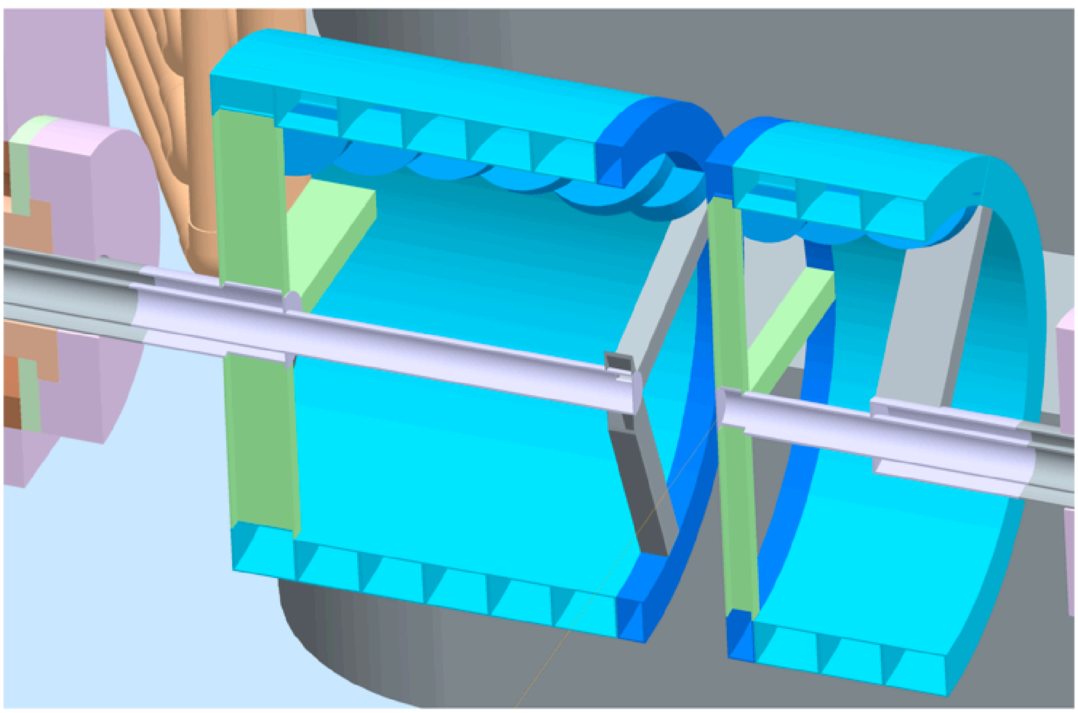


Figure 2. Barrel and shaft cross section

aluminum wall. The shaft consists of a 3 inch diameter inner pipe and a 4 inch diameter outer pipe. The water flow path is from the building supplied water pipe, through the rotating water union, to the inner pipe of the shaft, to a set of hollow spokes, to the water channels around the perimeter of the barrel, to a set of hollow spokes connecting to the outer return flow pipe of the shaft. Water flow velocities in the barrel channels are expected to vary between 9 m/s to 3 m/s. The water volume flow rate is 4 gps. Water pressure drop in the barrels is 8 psi.

The barrels are rotated at a nominal 400 RPM, in the same direction as the water flow direction in the channels along the barrel perimeter. For dump operation with the small spot size (1 cm) Uranium beam at full power, it is necessary to rotate the right barrel at 600 RPM in order to keep temperatures and stresses at acceptable levels.

Figure 3 shows a schematic of the beam dump assembly.

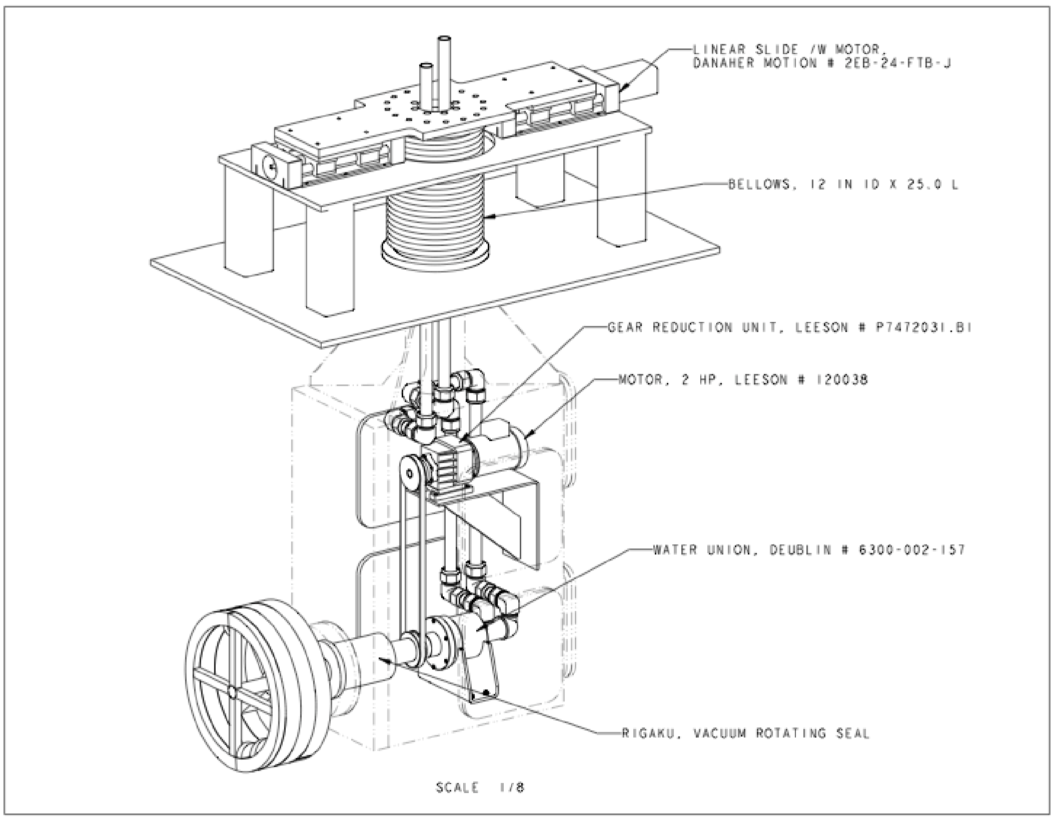


Figure 3. Schematic of a barrel shaped beam dump.

4. Rotating vacuum pass-through

The mechanical operation of the vacuum pass-through from the point of sealing capability and operational lifetime in the radiation and magnetic field environment

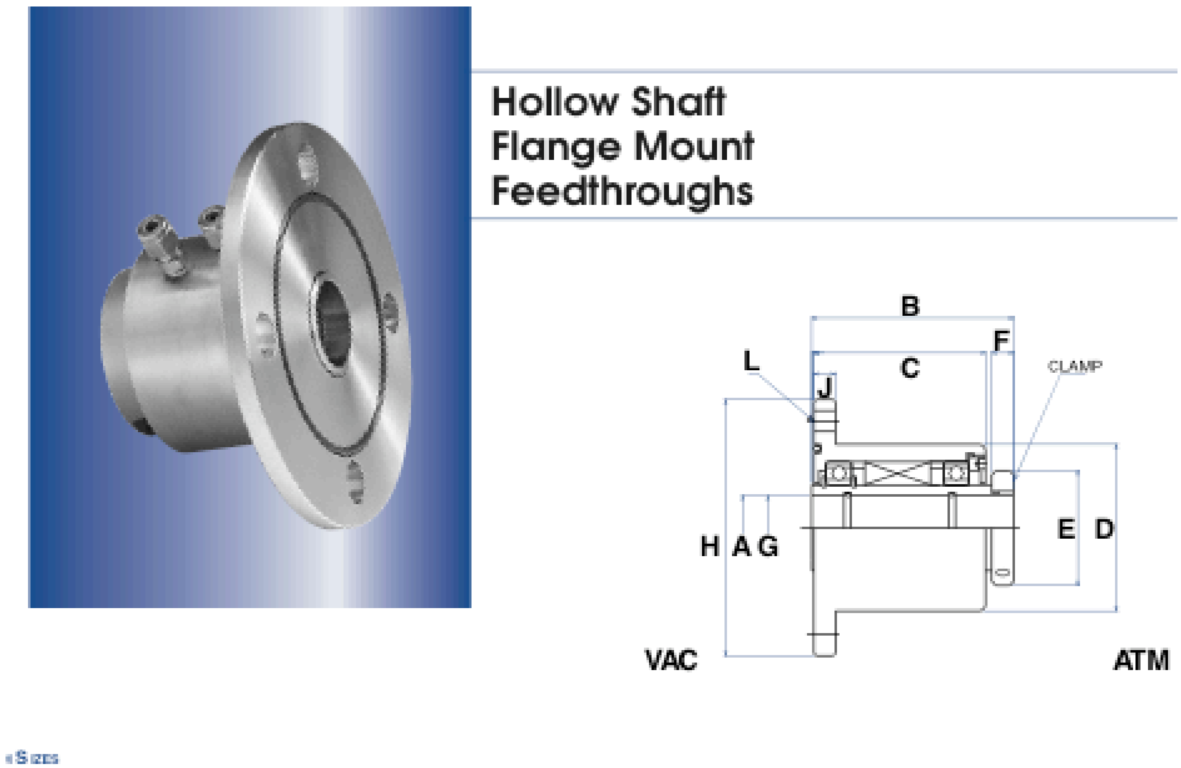


Figure 4. Rotating vacuum pass-through for barrel shaft vacuum wall penetration.

is of considerable concern. Commercial products by Ferrotec and Rigaku, figure 4, appear to meet our requirements. For anticipated shaft loads and 400 RPM, the manufacturers anticipate operating lifetimes of years. The pass-throughs can operate in magnetic fields up to one Tesla. Operation in the RIA anticipated radiation environment will have an affect on the ferro-fluids and permanent magnets in the pass-throughs. Based on radiation field calculations presented in section 5 of this report, acceptable lifetimes can be had for the ferro-fluid and the magnet. Further study of radiation damage effects on magnets is necessary, however, the problem may be engineered away by placing additional shielding around the pass-through.

5. Beam dump heavy Ion beam parameters

Anticipated operation of the RIA fragmentation line includes the beams listed in table 1 (1). The beam of major concern is the Uranium beam with almost 300 kW of power and a 5 cm spot size. Other beams include a Xe, Kr, Sn, and Ca beam.

Fragment	Beam	Charge State	Beam Power in Target (kW)	Dump Power (kW)	Beam Range in Cu (cm)	Beam Range in Al (cm)	Beam Range in Graphite (cm)
122Zr	136Xe	54	153	247	0.36	1	1.1
130Cd	136Xe	54	139	261	0.45	1.3	1.36
78Ni	86Kr	36	150	250			
22C	48Ca	20	166	234	0.57	1.62	1.7
200W	238U		102				
		92		11.92			
		91		86.42			
		90		178.8			
		89		17.88			
		88		0.894			
100Sn	112Sn	50	186				

Table 1. RIA beams and fragments

The beam dumps physical axial dimensions are designed to intercept the above beams, with some of the beams hitting the left beam dump and some the right beam dump of figure 2. The relative location of the beams of Table 1 are shown in figure 5. The barrel dumps are designed to intercept all the beams of figure 5 except the Ca beam. For this beam, a separate stationary dump has been designed and is described in section 15 of this report.

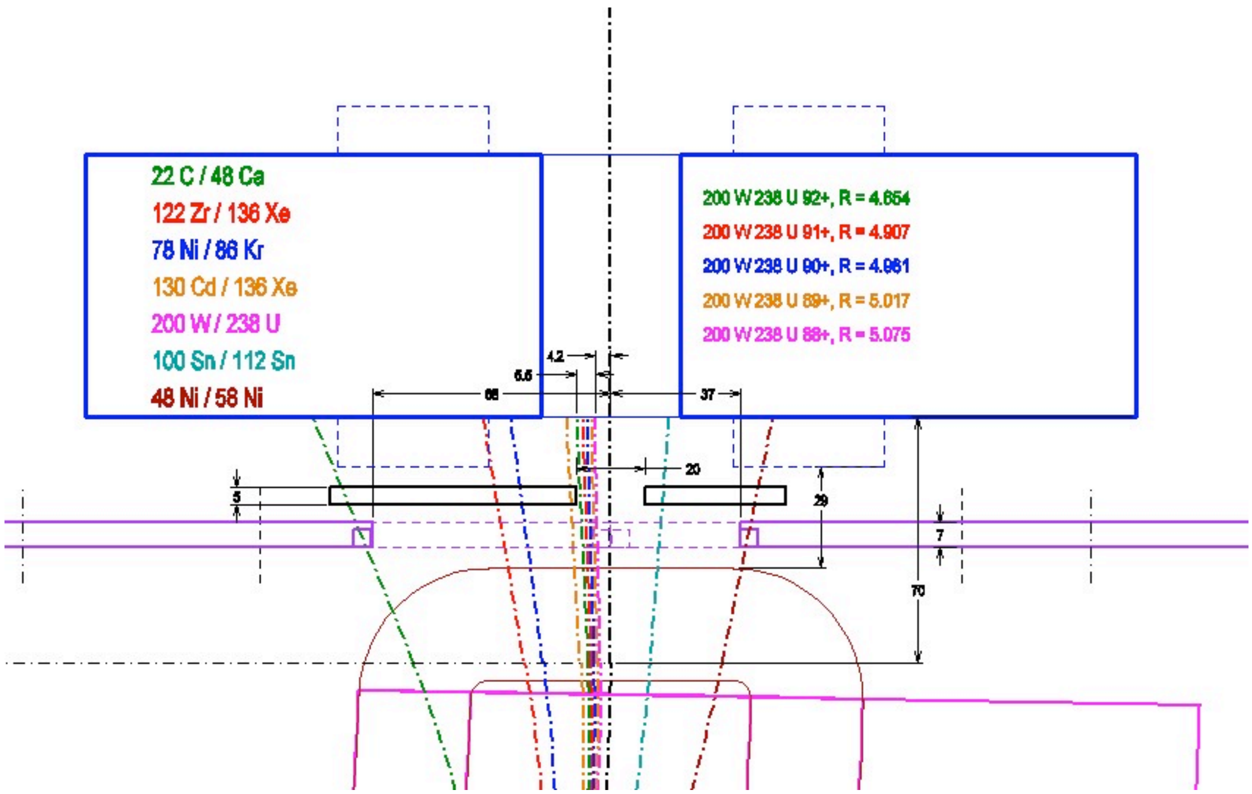


Figure 5. Beam location relative to the accelerator centerline.

6. Beam energy absorption in Al and water

The operation of the beam dumps involves the use of Al and water to absorb the beams. The Al outer wall of the barrel essentially acts as a window for the beam and the water behind the Al acts to absorb the remainder of the beam. In the calculations for temperatures and thermal stress in the barrel for the various beams, the data in table 2 applies. The table shows the fraction of each beam's energy absorbed in 2 mm of Al and the water depth required to absorb all of a beam's power.

Beam	Fraction absorbed in 2mm of Al (%)	Water depth required to absorb the beam
U 320 Mev/u	15	2 cm
Ca 272 Mev/u	5	5.2
Xe 326 Mev/u	10	2.8 cm
Kr 325 Mev/u	7	3.9 cm
Sn 267 Mev/u	14	2 cm

Table 2. RIA heavy ion beam absorption in Al and water.

7. U and Ca beam spot sizes

A typical U beam impacting the beam dump has a power of 295 kW and has a profile in the horizontal direction as shown in figure 6. The beam ions have an energy of 320 Mev per nucleon.

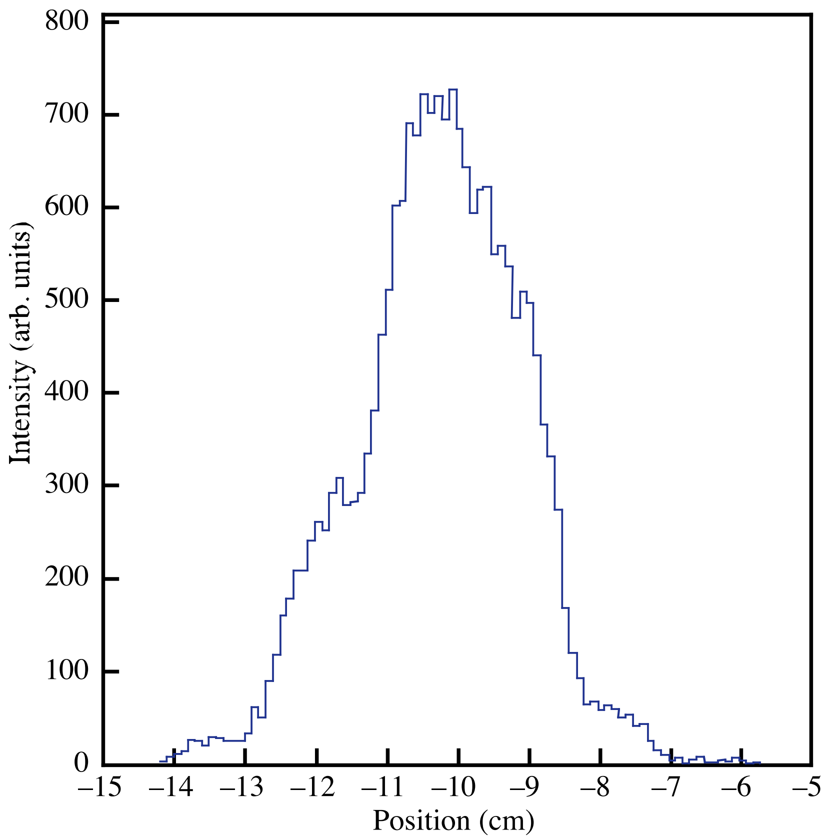


Figure 6: U beam horizontal profile [1].

The Ca beam of Table 1 has a spot size discernable from figure 7 below (2). The spot size is approximately 5 cm horizontal by 40 cm vertical with a power of 234 kW spread over the beam size shown in the figure. Absorbing this beam can be accomplished by a stationary water cooled beam dump described in section 15.

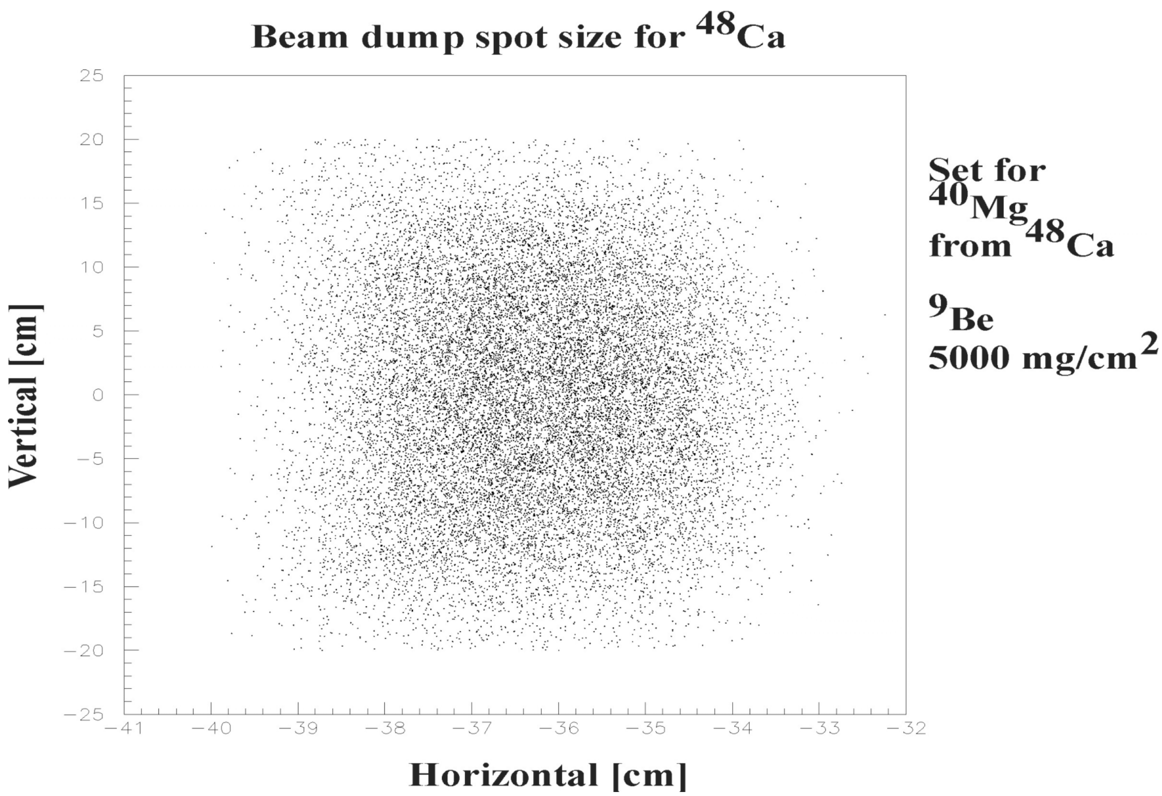
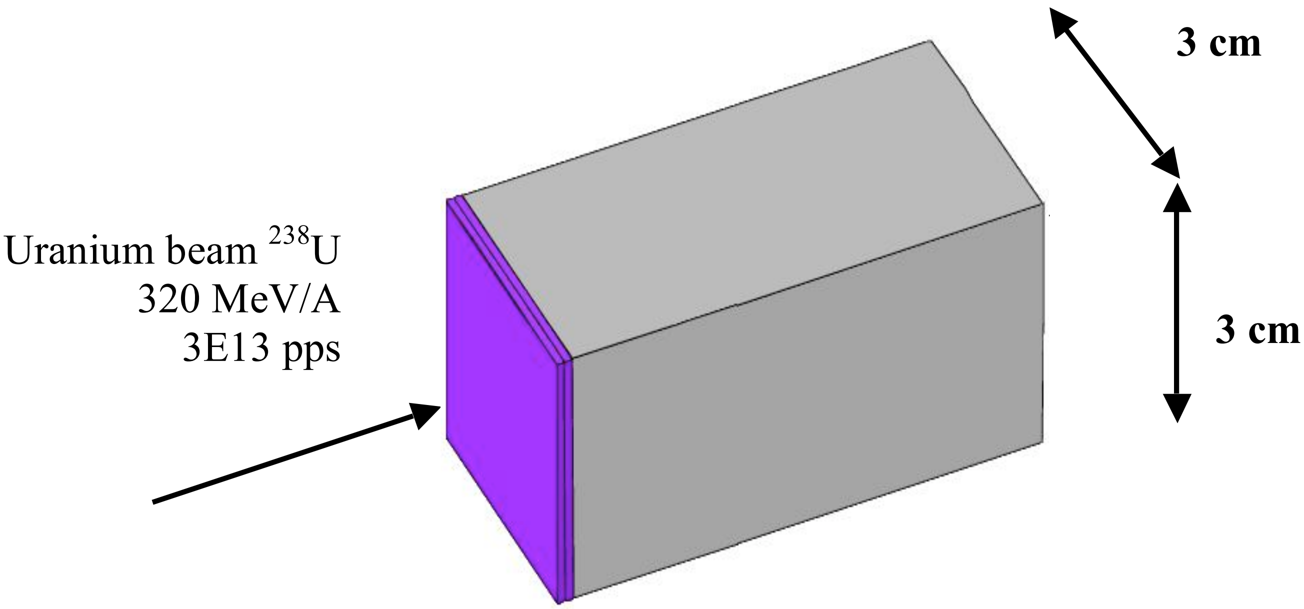


Figure 7. Ca beam spot size is 5 cm x40 cm.

8. Radiation damage from U beams

The impact of the U beam on the Al wall of the barrel results in radiation damage in the material. This damage results in a degradation of the structural properties of the material including loss of ductility and brittleness. To estimate the damage in the Al material, a simulation of damage quantified by displacements of atoms per atom , DPA, was made (3) and the results shown in figure 8. The PHITS code was used to simulate a U beam passing through a window of Al or Be with a thickness of 1 or 2 mm. The beam is assumed uniformly spread out over a 3 cm x 3 cm area. The results show that for a 2 mm Al window that 9.9×10^{-3} DPA/day are generated by the U beam over a 3cm x 3 cm area. For the case of a rotating barrel surface, this damage is spread out over a surface area of nominally 5 cm x 220 cm (perimeter of barrel) and results in a value of 2.3×10^{-4} DPA/day. For an estimated allowable value of 5 DPA, this results in a lifetime of years.

If the U beam were completely stopped by Al material, the peak value of damage at a depth of 7 mm would be 3 DPA/day if the beam was deposited over a 3 cm x 3 cm area. For our case the surface area is 5 cm x 220 cm and the damage is $7x10^{-2}$ DPA/day which gives a lifetime of 8 weeks for an allowable dose of 5 DPAs. For the barrel designs, there are spacer ribs separating the water channels that may see higher DPA values but the beams are expected to primarily impact only in regions of the 2 mm thick Al wall.



Be window	DPA / day
0 - 1 mm	1.3E-03
1 - 2 mm	1.4E-03

Al window	DPA / day
0 - 1 mm	8.2E-03
1 - 2 mm	9.9E-03

Figure 8. PHITS DPA calculations for Be and Al windows

The U beam impacting the barrel Al surface and water coolant results in a prompt dose of radiation on the materials of the vacuum pass-through. For this equipment the NdFeB magnet material and FerroFluid liquid material may be susceptible to radiation damage and Table 3 gives an estimate that allowable limits are not exceeded after 4 months of operation (4). Some additional shielding was placed around the pass-through to result in acceptable lifetimes.

Material	Density (g/cc)	Effective dose (MGy/yr)	Limit (MGy)
NdFeB	**6**	**0.05**	**0.1**
SmCo	**8.82**	**0.30**	**100**
Kapton	**1.42**	**0.19**	**10**
FerroFluid	**1.42**	**0.69**	**>1?**

Table 3. Radiation transport results, prompt dose and DPA values.

9. Barrel temperature response due to a U beam

A U beam with a 5 cm wide spot size deposits energy into the 2 mm thick Al wall of the barrel as it rotates past the beam impact point. Approximately 15 % of the 295 kW power of the beam is deposited in the 2 mm of the Al wall and 85 % is deposited in the water cooling this surface. The thermal response of the wall is that of a temperature jump as Al material rotates past the beam. The temperature jump is then relaxed by conduction in the Al and by convective heat transfer to the adjacent cooling water. The temperature jump is dependent on the velocity of the perimeter of the barrel. For a perimeter velocity of 14.7 m/s (400 RPM) the temperature jump is as shown in figure 9. This figure shows the results of a thermal calculation (using Topaz-3d [5]) and shows a temperature jump of 19 °C as the beam of figure 5 impacts the dump material. Every time the Al material rotates past the beam a similar 19 °C jump occurs and then this temperature relaxes back down to a steady state condition due to the convective heat transfer to the water coolant.

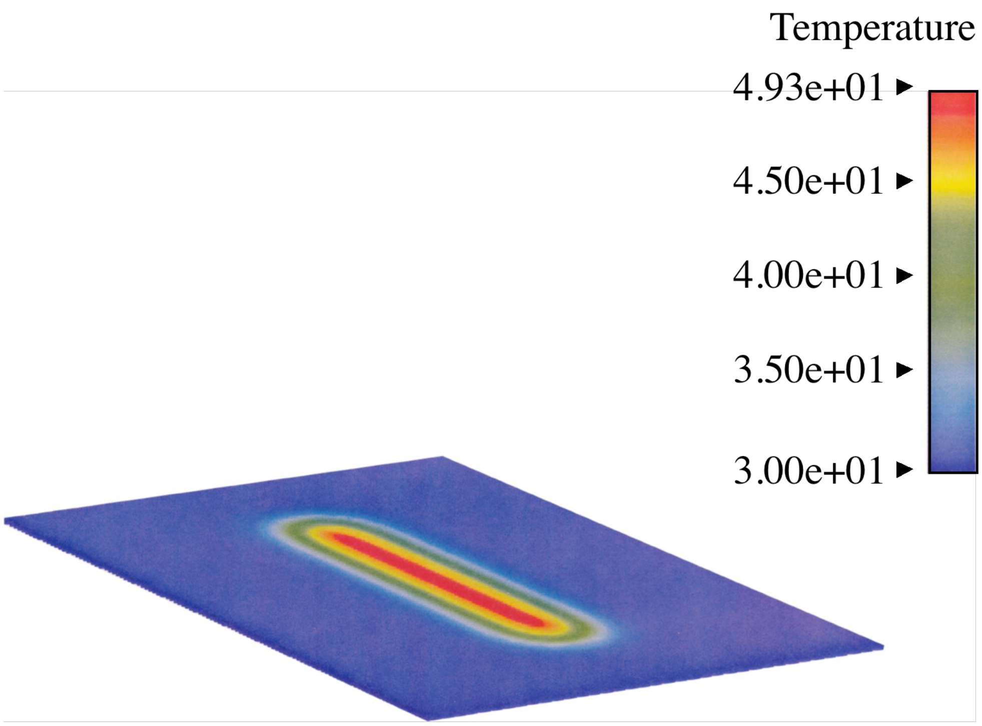


Figure 9. Temperature, °C, jump as the U beam penetrates and moves along the aluminum material of the dump barrel.

10. Cooling water heat transfer response – U beam

Water is used to cool the beam dump aluminum material and is used to absorb the portion of the beam that passes through the aluminum outer surface of the barrel. The water velocity along the barrel surface is 9 to 3 m/s and results in a convective heat transfer coefficient of 9 kW/m^2-°C (for 3 m/s) based on Nusselt correlations. With this heat transfer coefficient, the aluminum metal temperature in the heated ring region around the barrel will be an average of 45 °C above the channel water temperature. This temperature rise is calculated from a convection cooling heat balance calculation:

$$Q \times f = h \times A \times dT$$

$$dT = 45\ °C$$

Q = beam power of 295 kW
f = fraction of beam power absorbed in the 2 mm Al wall, 15 %
h = convective heat transfer coefficient for 3 m/s water velocity, 9 kW/m^2-°C
A = barrel surface area impacted by the U beam, 220 cm x 5 cm
dT = barrel average surface temperature above coolant temperature

As the water flows by the beam penetration region on the barrel surface, approximately 85% of remaining beam power is absorbed in the 2 cm depth of the water. A heat balance calculation for the volume flow rate of water and the energy deposition rate of the beam results in an estimate of the water temperature jump:

$$Q \times f = Vel \times A \times Rho \times Cp \times dT$$

$$dT = 4\ °C$$

Q = beam power of 295 kW
f = fraction of beam power absorbed in the 2 cm depth of water, 85 %
Vel = water velocity past the beam, 10 m/s surface velocity + 3 m/s water velocity
A = cross sectional area of water flow absorbing the U beam, 5 cm x 2 cm
dT = water temperature jump
Rho = water density, 1000 kg/m^3
Cp = heat capacity of water, 4200 J/kg-°C

This dT= 4 °C represents the water temperature jump if the beam deposited its energy uniformly in the water but there is a peak value that is approximately 5 times greater near the end of the deposition range and thus the localized peak temperature jump may be as high as 20 C. This peak temperature may be, however, mitigated somewhat by the turbulence of the water.

Thus if 15 °C water is used as a coolant, then the maximum temperature that the Al reaches is approximately 70 °C.

11. Thermal stress structural response of aluminum surface – U beam

The beam impacts the rotating aluminum material of the dump and causes a rapid temperature jump or rise over the spot dimension of the beam along the direction of rotation of the dump. This increase in the aluminum temperature results in thermal stresses in the Al due to the material trying to expand. The resultant stress from this energy deposition was modeled using a structural analysis code (Dyna3d [6]). Figure 10 shows the results of the calculations with a peak stress of 3 ksi (2.14×10^7 Pa). The allowable fatigue stress for aluminum alloys may be as high as 20 ksi (1.4×10^8 Pa) and thus the calculated stress is well below allowable limits. The relatively low stresses therefore suggest that the barrel RPM could be lowered to values closer to 200 RPM.

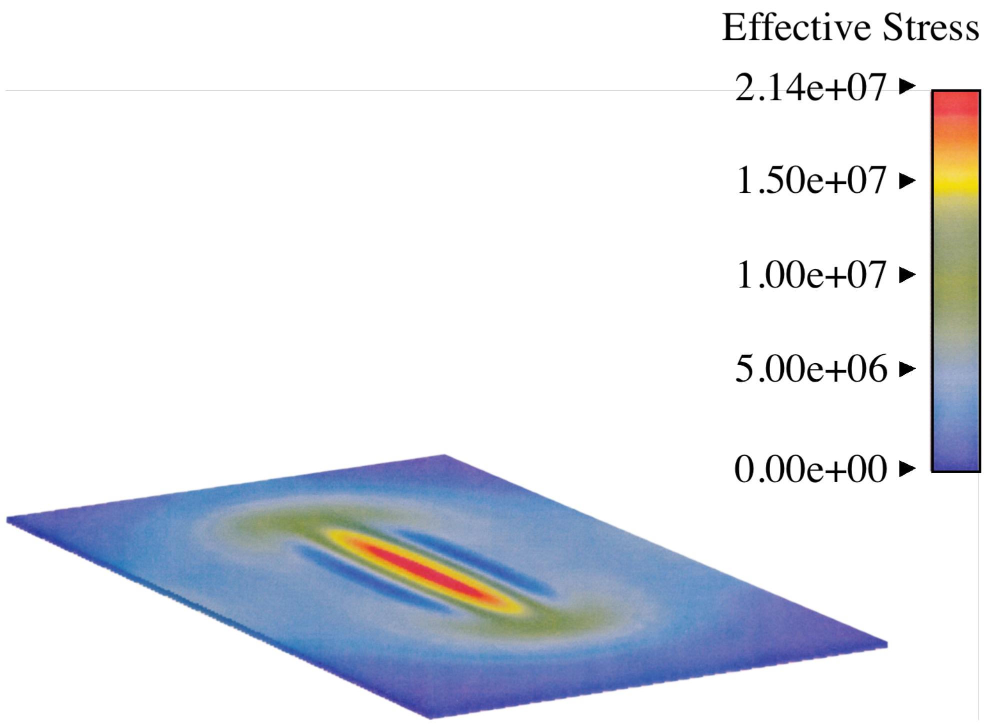


Figure 10.Thermal stress, Pa, in the aluminum window of the barrel dump due to a U beam (5 cm spot size) penetration.

12. Dump performance for 1 cm spot size U^{+92} beam

The most severe beam profile is for an essentially fully ionized U beam with a narrow spot size as shown in figure 11. The U^{+90} charge state here is the part of the beam of most concern because its width is less than 1 cm and its power is high at 184 kW. This beam impacts the dumps very near the accelerator ion/particle centerline and very near the edge of the dump.

To accommodate this U^{+90} beam, the barrel is rotated at a more rapid rate, 600 RPM, and this results in a maximum expected Al wall temperature jump of 40 °C and a thermal stress of 6 ksi. For this beam the water channel velocity is 9 m/s, and the peak water temperature jump is 30 °C. Radiation damage in the 2 mm Al barrel wall is still expected to be low and result in Al wall lifetimes of years for an allowable 5 DPA level.

13. Dump performance for other heavy ion beams, Ca, Sn, Kr, Xn, and Ni.

Other driver beams besides the U beam, such as Ca, Sn, Kr, Xn, and Ni beams, are expected to have ranges of spot sizes and powers similar to the U beams. For these beams, the barrel dump is expected to operate under less severe thermal, structural, and radiation damage conditions.

The energy deposition range of these other beams in Al and water is greater than that of the U beams and thus some beams may pass through one side of the beam dump and impact the far side of the beam dump. To avoid any beams impacting the centerline shaft, the shaft centerline is raised 10 cm above the accelerator beam line.

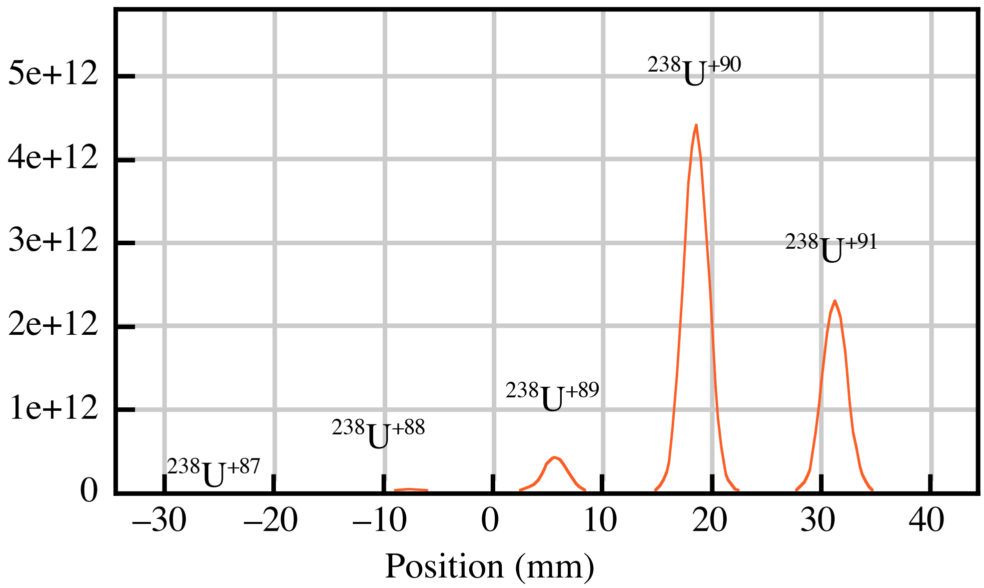


Figure 11. Narrow width U^{+90} charge state beam, 184 kW [2].

14. Magnetic force field effects on dump rotation

The rotation of the barrels in a strong magnetic field will result in forces retarding motion. A simplified estimate to quantify the horsepower (Watts) required to power the turning of the dumps was made.

For an estimated magnetic B field of 0.25 Tesla and perimeter velocity of the barrel of 10 m/s and Al material, the power, P, required is given by:

$$P = Vel^2 \times B^2 \times Vol / Res$$

$$P = 8 \text{ Hp}$$

Where P = horsepower required to rotate the barrel
Vel = barrel surface rotational velocity, 10 m/s
B = magnetic field, 0.25 Tesla
Vol = volume of Al material rotating past the B field, 25 cm x 2 mm x 10 cm
Res = resistivity of Al, estimate at 5×10^{-8} Ohm-m

Further refinements to the design to reduce magnetic fields, operating conditions and electric currents in the Al metal of the dump may result in considerably lower powers.

15. Stationary beam dumps (Ca beams)

For some cases of beam rigidity, the beams curve sufficiently that they exit the dipole magnet cavity toward one side and do not impact on the barrel beam dumps. For these beams, the spot sizes are large and thus they can be absorbed by a non rotating beam dump. A typical beam of this type is the Ca beam of Table 1, and figures 5 and 7. For this Ca beam, a stationary beam dump can be used to absorb this beam.

Figure 12 shows one possible design that consists of an arrangement of two banks of tubes. The tubes are arranged so they intercept all beams exiting along one side of the dipole magnet. For some beams, the beam penetrates through one tube and is absorbed in the tube of the second banks of tubes. The beams are expected to impact the dump surface at angles of 30° or less and also a significant fraction of the beam impacts inside the dipole magnet cavity. The dump physical design involves 5 to 8 cm diameter pipes with 1/2 mm thick Al walls with water flow to cool the wall and absorb the penetrating beam. Water velocities in the 5 cm diameter tubes is 5 m/s with a volume flow rate of 5 gps.

The beam dump tube wall maximum temperatures are nominally 50 °C above the water bulk temperature and thermal stresses are less than 5 ksi for any of the beams that may impact the stationary dump.

Radiation damage of the dump is expected to allow a minimum continuous operating time of 3 months but with expected RIA operating scenarios a lifetime of greater than a year is expected.

16. Beam dump maintenance/repair

Maintenance of the dumps is currently envisioned by removing a section of the floor above the dipole magnet vacuum cavity and using a crane to vertically lift the dumps up to the above crane access hall. From there the dumps will be moved to a remote repair room. Before lifting the dumps out, remote actuators will be required to disconnect water lines, electric lines, and break vacuum seal joints.

Due to the large size of the dump assemblies, mechanical separation of the barrels and the pass-through and water union from the rest of the assembly is desirable and should be engineered to be accomplished before moving to the remote repair room.

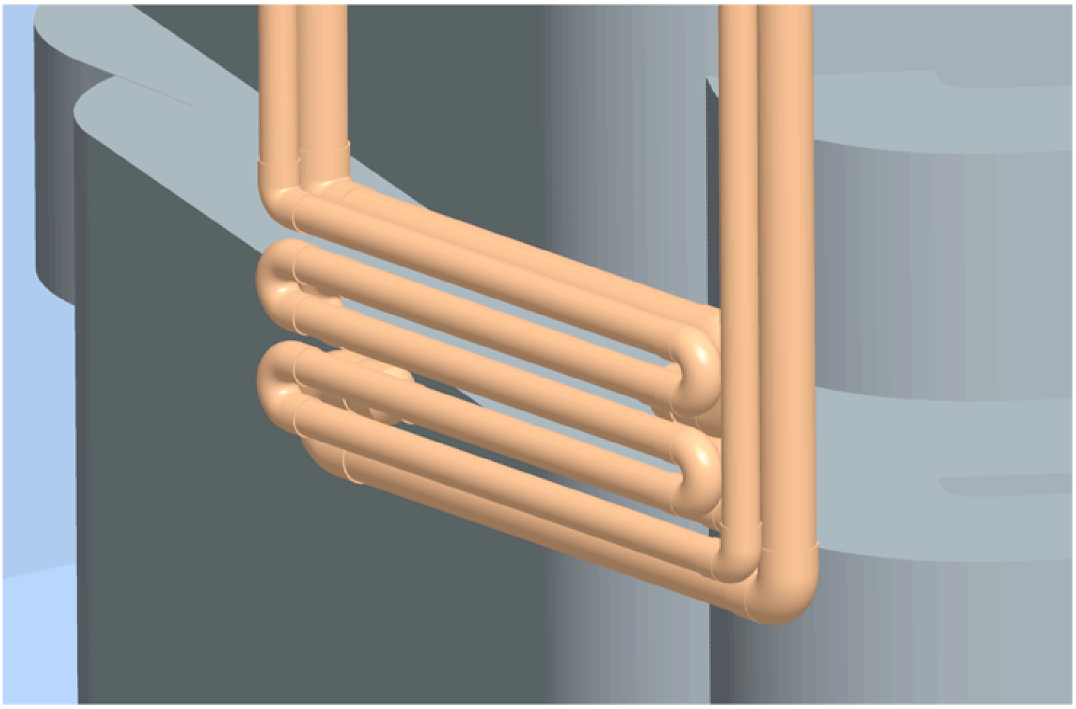


Figure 12. Stationary beam dumps to one side of the dipole magnet.

17. Summary

The RIA fragmentation line beam dumps are designed to absorb heavy ion beams up to 300 kW. Due to the high rate of energy deposition in materials of the dump, the beam is allowed to deposit a fraction of its energy in a thin window layer of aluminum alloy before depositing the bulk of its energy in a layer of water. To further reduce the volumetric energy deposition rate in the dump, the dump is designed as a rotating barrel which results in spreading the energy deposition around the perimeter of the barrel. Material and water temperatures are below 100 °C and thermal stresses are below 5 ksi.

Mechanical design of the dump includes an electric motor to rotate the barrel, a rotating vacuum/air shaft seal, and a bellows arrangement that allows remote horizontal movement.

The dumps are designed to allow continuous operation of the dump for at least 10 weeks for the range of expected RIA beam types.

18. References

[1] B. Sherrill, private communication, Michigan State University, Video Conference, 20 May 2004.

[2] B. Sherrill, private communication, Michigan State University, 28 February 2005.

[3] J. Boles, private communication.

[4] S. Reyes, private communication.

[5] A. B. Shapiro,"Topaz3d-A Three-dimensional finite element heat transfer code," LLNL, UCID-20484, 1985.

[6] J. A. Hallquist,"Dyna3d User's Manual," LLNL, UCID-19592, May 1989.