C.7 Beam Dumps

C.7.1 Introduction

Three very different beam dumps are required for the ERL. These are the primary beam dump, tune-up dumps, and moderate power dumps for high energy beams. While these latter two dumps are relatively conventional, the primary beam dump has challenging performance requirements. We will discuss the details of these three dumps in separate sections below.

The primary beam dump must intercept the full beam current at the end of the energy recovery process, and safely dissipate the beam power as waste heat. The beam current is 100mA, and for the present purposes, we take the beam energy after recovery as 15MeV, leading to a beam power of 1.5MW. 15MeV electrons have a range of less than 8g/cm^2 in practical beam dump materials, and thus the beam power is deposited over a very small depth in these materials. The natural beam spot size is quite small, even after energy recovery. It is clearly necessary to expand the effective area of the beam to more than 1 m^2 where it intercepts the surface of the dump, to reduce the power density in the dump material to a level that can be safely handled. This expansion can be accomplished by several techniques, such as strongly defocusing the beam, rastering the beam over a larger area, or intercepting the dump surface at a shallow angle. All of these methods will be employed for the primary dump.

Several tune-up dumps will be installed at key locations, yet to be established, around the beam path. These small dumps will normally occupy a “fail-safe” position out of the beam path. The active part of the dump is within the accelerator vacuum system, and is moved in and out of the beam through a bellows isolated mechanism. The dumps are remotely inserted when it is necessary to, for example, set up beam following a shutdown, or check various accelerator parameters such as linear optics or cavity phasing. These dumps are capable of continuously dissipating only 10kW of beam power, corresponding to 2μA of average current at the full 5GeV beam energy. Thus, only very low duty factor beam or very small bunch charge at full duty factor can be used with these dumps. These beam conditions will be reliably and automatically established before a tune-up dump can be placed in the beam path. As the tune-up dumps are used a relatively small fraction of the time, and are low power, only very modest shielding will be required. They will be cooled by the water systems in the accelerator tunnel. The tune-up dumps are not technically demanding, and similar dumps have been used at other laboratories.

Finally, there is some likelihood that the ERL facility will be used to deliver high energy beams for special purposes. For example, one might deliver a CW train of high charge bunches at relatively low repetition rate for the production of exceptionally short duration (< 100fs) x-ray pulses, either by running highly temporally compressed electron bunches through an undulator, or by generating x-rays in a SASE or HGHG FEL. For these beams, the average beam current would be relatively low – of order 20 μA – and energy recovery would be economically unnecessary as well as technically difficult. Rather, the electron beam would be dumped at high energy. While the average beam power is relatively low in these cases – of order 100kW – the dump must be quite different, since high energy electrons penetrate a considerable thickness of matter and shower multiplication significantly increases the local power deposition. Such dumps have been developed at other laboratories, and the technical issues are well understood.

In the sections below, we will discuss the technical issues and design details for each of these three types of beam dumps, and where relevant provide comparisons to other similar beam dumps.

C.7.1.1 State of the Art

TJNAF has the following dump installations: a 45 kW, 67MeV injector tune-up dump, two 110kW all metal high energy tune-up dumps, and two 1MW, 5GeV primary dumps. These latter two dumps have been described in some detail [1].

C.7.2 The Primary Beam Dump

The primary beam dump must dissipate 1.5MW of beam power generated by a 100mA average current, 15MeV electron beam. The range of 15MeV electrons in matter is short – less than 8g/cm^2 in suitable dump materials. In addition, the natural beam spot size is quite small – much less than 1cm^2. Such an electron beam striking any material would very rapidly destroy it. It is necessary to greatly expand the beam size where it intercepts the dump surface to produce power densities low enough to be safely and reliably dissipated. Clearly the dump material must have a reasonably high thermal conductivity, to limit the maximum temperature at the uncooled entrance face of the dump. As there is no significant shower multiplication from 15MeV electrons, the entrance face of the dump, which is furthest from the cooling water, will have the highest temperature.

The only practical choice for the primary dump material is aluminum. Aluminum offers the very significant advantages of a high photoneutron threshold (13.3MeV) and relatively low residual radioactivity comprised primarily of relatively short lived isotopes. The relatively low residual radioactivity of aluminum is a significant consideration for the ultimate disposal of a decommissioned beam dump. Copper has a significantly lower photoneutron threshold, and much higher residual radioactivity of longer lived isotopes. Beryllium would be exceptionally expensive, and has a very low photoneutron threshold. Carbon, as pyrolytic graphite, is mechanically difficult, and has an extremely anisotropic thermal conductivity. The aluminum used will be an alloy, and the various alloying elements have lower photoneutron thresholds. These elements will be responsible for a fraction of the residual radioactivity of a 15MeV aluminum dump.

The dump must remain fully functional during several decades of operation at very high average power. With an aluminum dump, it is especially critical to control the water chemistry to avoid corrosion. Therefore, heat will be removed from the primary beam dump with a closed circuit de-ionized (DI) water circulation system which will be continuously powered. The only acceptable metals in this system are aluminum and stainless steel. The water chemistry will be carefully monitored at all times to assure proper pH, resistivity, and the absence of harmful ions.

It is very desirable to minimize the deposition of beam power directly in the cooling water, to minimize hydrogen production through radiolysis [2]. At the same time, it is desirable to locate the cooling water as close as practical to the beam face of the dump, to minimize thermal effects. These realities lead directly to the use of a dump shaped like an ogive (pointed arch) of revolution, similar, for example, to a high power klystron collector. Even with an optimum thickness dump wall, there will be enough radiolysis in the cooling water to require monitoring the hydrogen level in the closed cooling circuit. It is anticipated that the modest quantities of hydrogen generated can be vented to the atmosphere, with no need for hydrogen recombination systems. Were hydrogen recombination to prove necessary, reliable hydrogen recombination systems were developed for the high power beam dumps at SLAC, and were duplicated, with improved instrumentation, for the high power dumps at Jefferson Lab [1; 2]. The 15MeV beam energy is far too low to produce either tritium or ^{7}Be through spallation of oxygen, so there will be no direct long-lived radioactivity in the DI water circuit. Heat will be removed from the closed DI water circuit with a water-to-water heat exchanger. The pumps, deionization and filtration equipment, surge tank, hydrogen venting scheme, and water-to-water heat exchanger will be located remote from the dump itself, to allow servicing and to eliminate any potential for radiation damage. All plumbing and piping in the closed circuit system will be of either aluminum or stainless steel [3]. Copper must be scrupulously avoided in the closed water cooling loop.

The primary dump will be a powerful source of prompt low energy gamma radiation as well as a modest flux of low energy neutrons. The primary radiation shielding for the dump will result from locating it in a small diameter underground tunnel spur off the main accelerator building. Detailed calculations of the total radiation from the dump will be made with the code MCNP [4]. These calculations will be used to design the shielding at the entrance to the dump tunnel, and to determine if additional shielding is required around the dump to prevent ground water activation. A similar ogive-shaped aluminum beam dump, capable of dissipating 575kW maximum average beam power between 5 and 15.75MeV, has been constructed for the Phase1a ERL program. This dump is operated in an open room, and thus requires substantial local shielding. This shielding was also designed with the aid of MCNP. A detailed comparison of the measured effectiveness of this shielding with the MCNP calculations, for both neutrons and gammas, will be conducted during Phase1a beam operations.

If the dump were to be operated in normal air, significant quantities of nitric acid would be produced by radiolysis of nitrogen, leading to the production of nitric oxide, which oxidizes to form nitrogen dioxide, which, with water, forms nitric acid. As a consequence, the dump tunnel will be sealed and purged with a dry inert gas such as argon, to eliminate the possibility of nitric acid formation. This solution has proven very effective with the two high average power (1MW) beam dumps routinely operated at Jefferson Laboratory.

Although it is very desirable to isolate the dump from the accelerator vacuum system, this is simply not possible. For example, even in a beryllium window, the power deposition from the dE/dx losses of a 100mA average current beam is 30kW per mm of window thickness (the window thickness is irrelevant for cooling considerations). It is certainly not practical, and likely not possible, to remove such a large amount of heat from a thin window in vacuum. Thus, the beam dump will of necessity be within the accelerator vacuum system. A differential vacuum pumping system will be developed to isolate the high gas load from the dump when operating at high average beam power from the much lower pressure in the beam line from the accelerator. A similar differential pumping system has been constructed for the Phase1a program, and measurement of its effectiveness will be used to design the differential pump system for the primary dump. Finally, a reasonably fast acting (ca. 1s), RF shielded gate valve will be located well upstream of the beam dump, to provide protection to the accelerator in the event of a dump failure. This is very important as the superconducting linac is relatively close to the primary beam dump.

Examples of ogive-shaped beam dumps for high average power, low energy electron and proton beams are the dump for the Phase1a program and for the 100mA, 6.7MeV proton beam of the Low Energy Demonstration Accelerator (LEDA) of the Accelerator Production of Tritium (APT) program [5]. This latter dump was problem free during operation for extended periods at the full 670kW beam power [6]. In addition, ogive-shaped collectors operating in the MW power range have been used with high power klystrons for a very long time. Although this technology would seem to be well developed, and suitable for high power electron beam dumps up to beam energies where the electron range becomes too large, dissipation of such high powers must be approached with caution, as seemingly small errors can result in severe damage to the dump. For example, all three of the 1.9MW ogive-shaped collectors of the high power klystrons for the LEDA accelerator suffered severe damage during initial operation, and had to be rebuilt [7]. Furthermore, the higher energy of the dumped ERL beam compared to a klystron beam translates into dump physically much larger than a klystron collector, requiring different fabrication and assembly techniques. The primary dump will require careful tests during fabrication and assembly (e.g. rigid material certifications; x-ray, dye penetrant, and sonic inspection of welds; etc.) to assure the final dump will perform and survive as needed.

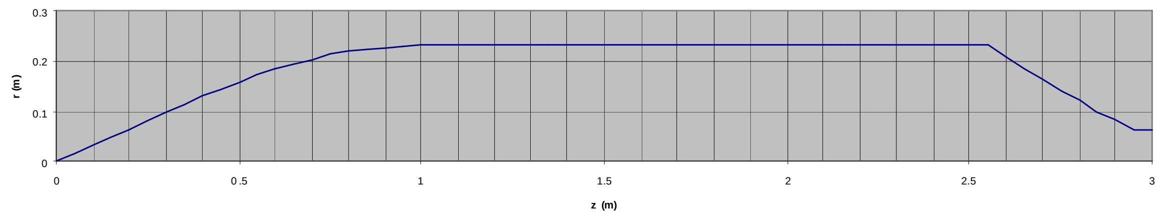

Figure C.7.2-1: The inner surface profile of the Phase1a beam dump

The profile of the inner surface of the dump built for the Phase1a project is shown in Figure A.1.2-1. The 3 meter long dump was assembled from three shorter segments by electron beam welding. A photograph of the completed dump is shown in Figure C.7.2-2. Water cooling channels are machined in the outer surface of the dump body, which is mounted inside an aluminum jacket. To reduce thermal stresses, the dump body is free to move longitudinally within the jacket. GEANT was used to calculate the power deposition in the dump body, and ANSYS calculations then determined the temperatures throughout the dump, the thermal stresses, etc. The results of some of these calculations are given in Figure C.7.2-3. Beam on-off cycles are sudden, and result in rapid temperature changes, which in turn may lead to eventual fatigue failure. The water flow was chosen to limit the maximum temperature differentials in the dump, leading to a very large number of temperature cycles before the onset of fatigue failure. For the design 60GpM water flow, the flow velocity is only 1.71m/sec. Erosion

Figure C.7.2-2: The completed Phase1a beam dump before installation of its shielding.

of water channels will therefore not be a problem.

The Phase1a dump has a peak power density, as calculated with GEANT4, of 30W/cm^2 with 600kW of incident beam power. This gives a maximum heat flux in the water cooling channels of ~ 60 W/cm^2. To reduce the peak power density in the full power primary dump, one must enlarge the dump surface area. If one were to retain the conservative 30W/cm^2 value, the dump would need to be enlarged by the square root of 3, or 1.73, in both radius and length,

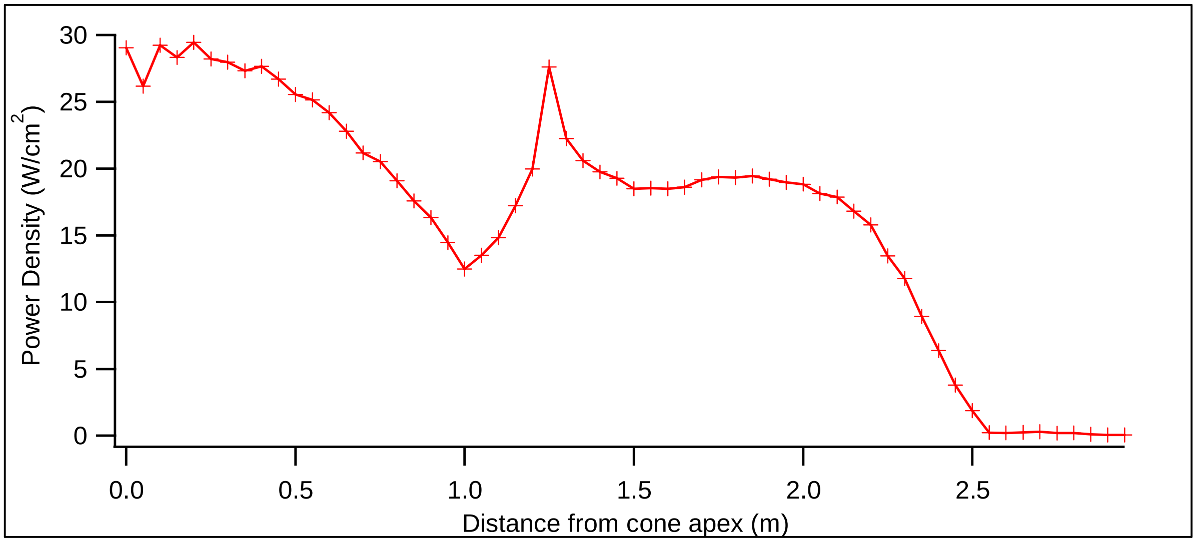

Figure C.7.2-3 Energy deposition for 600 kW beam power at optimized condition.

leading to a 5.2m long dump of 46cm radius. We anticipate that the final primary dump will be larger than the Phase1a dump, but likely not by the full factor of 1.73. The factor by which the Phase1a dump will be enlarged will be based on measurements made on that dump, and on further calculations. As with the Phase1a dump, GEANT will be used to model the energy deposition in the dump, and ANSYS will be used to study the equilibrium temperatures and the thermal stresses. The thermal stresses will be kept below a level that would pose a risk of fatigue failure over the dump operating life.

Obtaining the highest coherent flux of x-rays at 1 Angstrom wavelength is a major goal of the ERL facility. This places a premium on operating with the highest single bunch charge that will give a normalized emittance at the insertion devices of the ERL below 0.08mm-mrad. It is not anticipated that this small emittance will be reached initially at the full average current of the ERL. It may be desirable to increase the injection energy at reduced bunch charge to obtain the highest coherent x-ray flux at short wavelength. At dump energies up to 25MeV, there is no long-lived radioisotope production in the dump water. An energy this high would require the dump to have a thicker wall, to minimize radiolysis while fully absorbing the beam power. Tritium production begins above 25MeV, and at 31.86MeV, ^{7}Be production begins. Thus, to operate at an injection energy of 25MeV, the only change required would be to make the primary dump wall thickness greater. Above 25MeV injection energy, the dump cooling system would have to be altered to deal with tritium accumulation, and above 31.86MeV, it would be necessary to add ion exchange columns to capture the ^{7}Be. It is presently not planned to operate the injector at energies greater than 25MeV. If the primary dump were constructed with its inner wall thickness suitable for 25MeV operation, the peak temperature at the dump surface would increase when operating at lower injection energies. It may be practical to design an adequately cooled dump with the inner wall thickness matched to 15MeV operation, and the water jacket thickness adequate to allow 25MeV operation. In this latter case, hydrogen production by radiolysis would significantly increase, but not beyond levels that can readily be handled by practical hydrogen recombination systems. These and other possibilities will be explored before completing the design of the primary beam dump.

Two active devices are used to enlarge the beam area at the dump surface – quadrupoles that strongly overfocus the beam, and a raster magnet that moves the beam spot in a circular path at 60 revolutions per second. If either of these devices failed, the dump would locally overheat very rapidly, quite possibly to the point of damaging, or even melting the dump surface, particularly if there was a transition from nucleate to film boiling at the water-metal interface. Redundant hardwired interlocks will assure that each of the beam focusing and rastering magnets is properly powered. On any interlock failure, the beam will be rapidly terminated. Similar interlocks will be provided on the cooling water flow, pressure differential, and temperature.

It is important that the beam is not only properly enlarged, but that it is also correctly positioned in the dump. A quadrant detector at the entrance to the dump will assure the correct beam size and position at the dump entrance, while upstream BPMs will assure the correct entrance angle. Each element of the quadrant detector will cover close to 90 degrees of azimuthal angle, and will intercept a very small fraction of the beam. The elements must be water cooled, and the ceramics providing electrical isolation shielded from the possibility of charging from stray scattered electrons. Basically, each element is a low efficiency Faraday cup, and thus must be thick enough to assure beam electrons are stopped. Interlocks on the amplitude of the DC and 60 Hz left-right an up-down difference signals assure that the quadrupole overfocusing and raster amplitude are correctly set, and that the beam centroid is properly centered on the dump.

The design of the high power Phase 1a dump was independently reviewed by an outside expert [8]. This review concluded that the dump design was conservative at 500 kW, and likely acceptable at 600 kW. A number of areas that must be investigated during the design of the 1.5 MW primary dump were presented.

C.7.3 Tune-up Dumps

For a variety of beam setup activities, such as cavity phasing, establishing the linear beam optics, etc., it is desirable to use low average power beam, and to not have to transport this beam around the arcs and CESR ring all the way to the primary beam dump. Low power tune-up dumps will placed in key locations around the ERL, such as at the first high dispersion point after each linac, at the end of each turnaround arc, at the end of the CESR ring, etc. The tune-up dumps need dissipate only a low average power – on the order of up to 10kW – corresponding to 2µA average current at 5GeV. This current may be comprised of a 1.3GHz train of 0.8fC bunches, or of bursts of higher charge bunches at greatly reduced duty factor, as required for the particular task at hand.

The tune-up dumps are quite simple. For example, a copper cylinder 3.8cm in diameter and 15cm long, brazed into a stainless steel water jacket and cooled on its external surface, is quite adequate. The active section of the dump is completely within the accelerator vacuum system. The dump is mounted on a bellows mechanism and inserted into the beam line by a spring-loaded air cylinder. The "fail safe" position of the dump, provided by the spring loading, is out of the beam line. Redundant radiation hard interlock switches assure that when the dump is not in the "out" position, the average beam current cannot exceed 2µA. Special precautions will assure that HOMs will not be excited in the dump chamber when the dump is in its out position.

As the tune-up dumps never operate at high power, and are used only infrequently, they do not require extensive shielding. Local lead and iron shielding of modest thickness is all that is required. Cooling water is provided by the magnet cooling water.

A system of tune-up dumps very similar to those required for the ERL has been implemented at Jefferson Laboratory, for setting up beam in the CEBAF accelerator. We anticipate that the ERL tune-up dump system can be very largely copied from the Jefferson Lab system.

C.7.4 Moderate Power Dumps

For some specialized applications, such as the generation of very short duration pulses, or SASE or HGHG short wavelength FELs, it may be desirable to deliver high charge bunches in a relatively low repetition rate train, with a correspondingly low average current – on the order of 20μA. In this case, energy recovery is unnecessary, and would involve costly additional beam transport. Thus, beam dumps for these low currents of high energy beam are required. These dumps are very different than those above, as the electrons penetrate much further into material, shower multiplication produces energy deposition much higher than the dE/dx from individual beam electrons, and the gamma and neutron radiation produced is much harder and more intense.

Two 1MW average power beam dumps, each rated for 200μA at 5GeV or 100μA at 10GeV, were developed for Jefferson Lab [1]. The design of these dump systems had to address a large number of issues, such as ground water activation, production of H^3 and Be^7 in the cooling water, hydrogen recombination in the cooling water, nitric acid production in the dump tunnels, etc. Each of these dumps had its own locked and shielded above-ground pump building. The dumps themselves were placed in 15 foot thick concrete vaults at the end of 108ft long concrete tunnels, sealed and purged with dry argon. Personnel entry into the dump tunnels is of necessity a very rare and carefully controlled event. The details of these dump systems indicate the difficulty of disposing of a high average power, high energy electron beam. The use of beams requiring such elaborate dump systems is not anticipated at the ERL facility.

For average beam powers on the order of 100kW at high energy, it is practical to design dumps in which the entire beam energy is dissipated in metal. Two such dumps were developed at Jefferson Lab [1]. They are cooled by a closed circuit DI water system located immediately adjacent to the dump in the accelerator tunnel. The closed cooling circuit had a water-to-water heat exchanger to the regular accelerator tunnel DI water system. These dumps had three components, viz. (1) a copper entrance window to enlarge the beam diameter by multiple scattering, followed by a drift distance; (2) a surface cooled aluminum cylinder to absorb the majority of the beam power; and (3) a surface cooled copper cylinder to absorb the remaining beam power. The only reason for the copper section at the end was to shorten the length of the dump. It would be possible to make the dump with an all aluminum second section, if length were not an issue. This dump was rated at 200μA average current up to 600MeV, and 100kW for all energies above 600MeV. The 200μA current limitation below 600MeV was due to cooling the copper window.

The copper window was comprised of two 3mm thick edge-cooled copper discs, separated by pressurized helium gas. Loss of helium pressure served as an interlock indicating window failure. The beam was rastered in a circular pattern at 60 revolutions per second on the copper window. Two separate DI water circuits were required – one for the copper sections and one for the aluminum section, to prevent galvanic corrosion. In no case can copper and aluminum be used in the same DI water system. These dumps are relatively compact and have proved very reliable in service.

With engineering effort, it would be possible to extent the power rating of an all metal dump similar to that above beyond 100 kW, by extending the length of the system. Also the maximum current at lower energies could be increased beyond 200μA. An edge-cooled beryllium window could be the first element, followed by an edge cooled copper window. The raster diameter could be enlarged. By locating the aluminum section further from the windows, more beam power could be tolerated. Without detailed calculations, we estimate that a 250 kW average beam power, corresponding to 50 μA average current at 5 GeV, could by handled with a compact, all metal dump. Dump interlocks similar to those employed for the primary beam dump are adequate. With nearly all the beam power absorbed in metal, the issues of radioactivation and radiolysis in the cooling water are minimal. The relatively compact size of these dumps might allow them to be shielded locally in the accelerator building, though it would be much more preferable to place them in a small diameter underground tunnel isolated from the accelerator tunnel.

C.7.5 Summary

Solutions are presented for each of the three different types of beam dumps required for the ERL. With 1.5MW of low energy electrons, the primary dump is the most challenging. Two examples of dumps already constructed – the Phase1a dump for 600kW, 15MeV electrons, and the LEDA dump for 670kW, 6.7MeV protons, demonstrate that good technical solutions for this dump exist. The maximum energy of the primary dump will be selected based on the maximum injection energy envisioned for the ERL, and may be higher than 15MeV, although the power rating will not exceed 1.5MW. Extensive calculations, comparison with the performance of the Phase1a dump, and attention to design details and cooling system characteristics will assure that the dump will operate satisfactorily at full power for several decades. The use of aluminum minimizes the impact of the ultimate disposal of the dump.

Tune-up dumps, required for beam setup activities, are technically not demanding, and have been implemented elsewhere. We will simply copy what has already been done.

Full energy, low average current, all metal dumps will be developed as required for specialized beam uses, such as very short duration pulses, or various x-ray FEL schemes. An all metal dump meeting many of these requirements has been demonstrated at Jefferson Lab, and this technology can be extended to higher beam power and current if required.

C.7.6 References

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