2.8 Beam Stops

2.8.1 Introduction

Three very different beam stops are required for the ERL. These are the primary beam stop, tune-up stops, and moderate power stops for high-energy beams. While these latter two stops are relatively conventional, the primary beam stop has challenging performance requirements. In the sections below, the technical issues and design details for each of these three types of beam stops are described, and where relevant, comparisons to other similar beam stops are included.

The primary beam stop must intercept the full beam current at the end of the energy recovery process, and safely dissipate the beam power as waste heat. The design beam current is 100 mA, and for the present purposes, the maximum beam energy at the beam stop is 15 MeV, leading to a beam power of 1.5 MW. The range of 15 MeV electrons is less than $8\,\mathrm{g/cm^2}$ in practical beam stop materials, and thus the beam power is deposited over a very small depth. The natural beam spot size is quite small, even after energy recovery. The effective area of the beam then needs to be expanded to more than $1\,\mathrm{m^2}$ where it intercepts the surface of the stop, to reduce the power density in the stop 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 stop surface at a shallow angle. All of these methods will be employed for the primary stop.

Several tune-up stops will be installed at yet to be established key locations around the beam path. These small stops will normally occupy a 'fail-safe' position out of the beam path. The active part of the stop is within the accelerator vacuum system, and is moved in and out of the beam through a bellows isolated mechanism. The stops are remotely inserted when it is necessary to set up a beam following a shutdown, or check various accelerator parameters such as linear optics or cavity phasing. These stops are capable of continuously dissipating only 10 kW of beam power, corresponding to $2\,\mu$A of average current at the full 5 GeV beam energy. Thus, only a very low duty-factor beam or a very small bunch charge at full-duty factor can be used. These beam conditions will be reliably and automatically established before a tune-up stop can be placed in the beam path. As the tune-up stops 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 stops are not technically demanding, and similar stops have been used at other laboratories.

Finally, the ERL facility will be used to deliver high-energy beams for accelerator-physics studies. For example, one might deliver a CW train of high-charge bunches at a relatively low-repetition rate for investigation of various FEL ideas. For these beams, the average beam current would be relatively low – of order $10\,\mu$A – and energy recovery would be unnecessary. Rather, the electron beam would be stopped at high energy. While the average beam power is relatively low in these cases – of order 50 kW – the stop must be quite different, since high-energy electrons penetrate a considerable thickness of matter and shower multiplication significantly increases the local power deposition. Such stops have been developed at other laboratories, and the technical issues are well understood.

2.8.2 State of the Art

CEBAF at Jefferson National Laboratory has the following installations: a 45 kW, 67 MeV injector tune-up stop; two 110 kW all-metal high-energy tune-up stops; and two 1 MW, 5 GeV primary stops [1].

2.8.3 The Primary Beam Stop

The primary beam stop must dissipate up to 1.5 MW of beam power generated by a 100 mA average current, 10- to 15 MeV electron beam. The range of 15 MeV electrons in matter is short – less than 8 g/cm^2 in suitable stop materials. In addition, the natural beam spot size is quite small – much less than 1 cm^2. Such an electron beam striking any material would very rapidly destroy it. Thus it is necessary to greatly expand the beam size where it intercepts the stop surface to produce power densities low enough to be safely and reliably dissipated. Clearly the stop material must have a reasonably high-thermal conductivity, to limit the maximum temperature at the uncooled entrance face of the stop. As there is no significant shower multiplication from 15 MeV electrons, the surface of the stop, which is furthest from the cooling water, will have the highest temperature.

The only practical choice for the primary stop material is aluminum. Aluminum offers the very significant advantages of a high-photoneutron threshold (13.3 MeV) and relatively low-residual radioactivity comprised primarily of short-lived isotopes. The relatively low-residual radioactivity of aluminum is a significant consideration for the ultimate disposal of a decommissioned beam stop. The aluminum used will be an alloy, and the various alloying elements have lower photo-neutron thresholds. These elements will be responsible for a fraction of the residual radioactivity of a 15 MeV aluminum stop. Copper has a significantly lower photo-neutron 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 stop must remain fully functional during several decades of operation at very high average power. With an aluminum stop, it is especially critical to control the water chemistry to avoid corrosion. Therefore, heat will be removed from the primary beam stop 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 interior surface of the stop to minimize thermal effects. These realities lead directly to the use of a stop shaped like an ogive (pointed arch) of revolution, similar to a high-power klystron collector. Even with an optimum thickness stop 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 stops at SLAC, and were duplicated, with improved

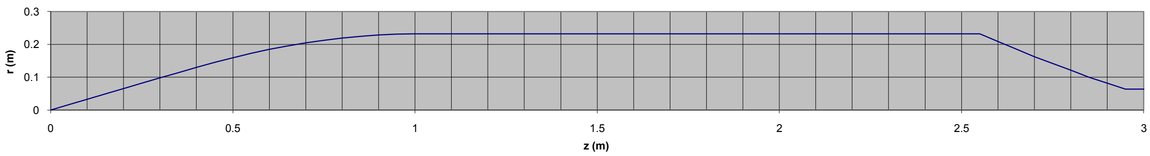

Figure 2.8.1: The inner surface profile of the Phase 1a beam stop

instrumentation, for the high-power stops at Jefferson Lab [1, 2]. The 15 MeV 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 stop 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].

The primary stop 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 stop will result from locating it in a small-diameter underground tunnel spur deep underground. Detailed calculations of the total radiation from the stop are being made with the code MCNP [4]. These calculations are being used to design the shielding of the stop tunnel, and to determine if additional shielding is required around the stop to prevent groundwater activation [5]. A similar ogive-shaped aluminum beam stop, capable of dissipating 575 kW maximum average beam power between 5 and 15.75 MeV, has been constructed for the Phase 1a ERL program. This stop 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 Phase 1a prototype-injector beam operations.

If the stop 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 stop 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 (1 MW) beam stops routinely operated at Jefferson Laboratory.

Although it is very desirable to isolate the stop 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 100 mA average current beam is 30 kW 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 stop will of necessity be within the accelerator vacuum system. A differential vacuum pumping system will be used to isolate the high-gas load from the stop 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 Phase 1a program, and measurement of its effectiveness is being used to design the differential pump system for the

Figure 2.8.2: The completed Phase 1a beam stop before installation of its shielding.

primary stop. Finally, a reasonably fast-acting, RF shielded gate valve will be located well upstream of the beam stop, to provide protection to the accelerator in the event of a stop failure. This is very important as the superconducting Linac is relatively close to the primary beam stop.

Examples of ogive-shaped beam stops for high average power, low-energy beams are the stop for the Phase 1a program and for the 100 mA, 6.7 MeV proton beam of the Low Energy Demonstration Accelerator (LEDA) [6, 7]. 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 stops 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 stop. For example, all three of the 1.9 MW ogive-shaped collectors of the high power klystrons for the LEDA accelerator suffered severe damage during initial operation and had to be rebuilt [8]. Furthermore, the higher energy of the ERL beam compared to a klystron beam translates into a physically larger system than for a klystron collector. The primary beam stop 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 stop will perform and survive as needed.

The profile of the inner surface of the stop built for the Phase 1a project is shown in Fig. 2.8.1. The 3-meter-long stop was assembled from three shorter segments by electron beam welding. A photograph of the completed stop is shown in Fig. 2.8.2. Water cooling channels are machined in the outer surface of the stop body, which is mounted inside an aluminum jacket. To reduce thermal stresses, the stop body is free to move longitudinally within the jacket. GEANT was used to calculate the power deposition in the stop body, and ANSYS calculations then determined the temperatures throughout the stop, the thermal stresses, etc. The results of some of these calculations are given in Fig. 2.8.3. Beam on-off cycles are sudden, and result in rapid temperature changes, which in turn may lead to eventual

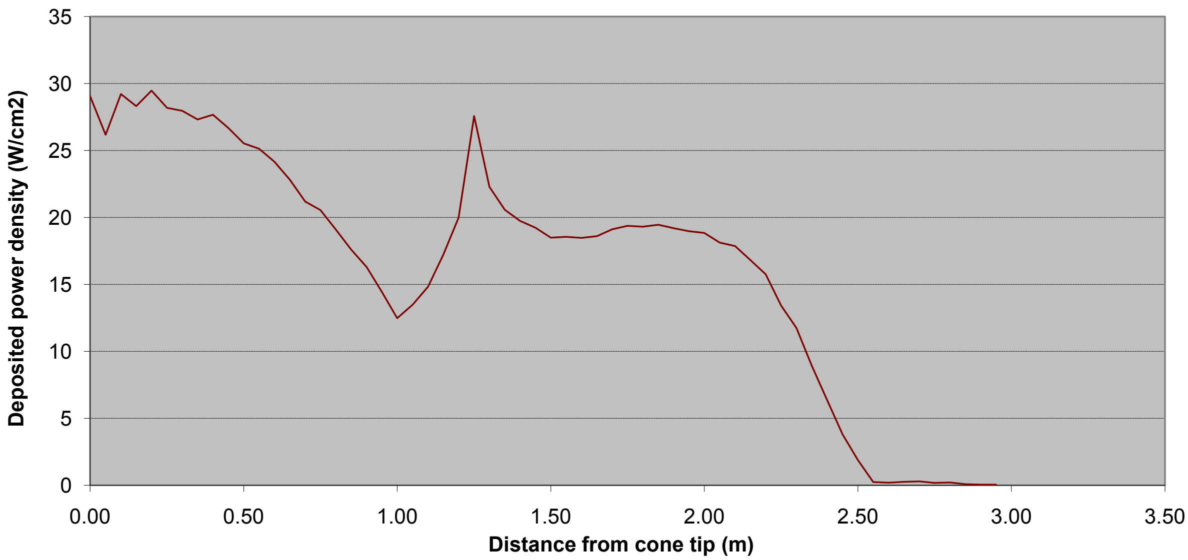

Figure 2.8.3: Energy deposition for 600 kW beam power at optimized condition

fatigue failure. The water flow was chosen to limit the maximum temperature differentials in the stop, leading to a very large number of temperature cycles before the onset of fatigue failure. For the design of a 60 gpm water flow, the flow velocity is only 1.71 m/sec. Erosion of water channels will therefore not be a problem.

The Phase 1a stop has a peak power density, as calculated with GEANT4, of 30 W/cm^2 with 600 kW 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 stop, one must enlarge the stop surface area. If one were to retain the conservative 30 W/cm^2 value, the stop would need to be enlarged by the square root of 3, or 1.73, in both radius and length, leading to a 5.2-m-long stop of 46 cm radius. We anticipate that the final primary stop will be larger than the Phase 1a stop, but likely not by the full factor of 1.73. The size of available electron beam welding machines will also limit the maximum dimensions to be less than this. The factor by which the Phase 1a stop will be enlarged will be based on measurements made on that stop, and on further calculations. As with the Phase 1a stop, GEANT is being used to model the energy deposition in the stop, and ANSYS is being 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 stop anticipated operating life.

Two active devices are used to enlarge the beam area at the stop surface – a quadrupole that strongly over-focus the beam, and three deflector magnets arranged as a sextupole powered by three-phase, 60 Hz AC that move the beam spot in a circular path at 60 Hz. If either of these devices failed, the stop would rapidly overheat, quite possibly to the point of damaging, or even melting the stop surface, particularly if there were a transition from nucleate to film boiling at the water-metal interface. Redundant hardwired interlocks will assure that each of the beam focusing and rasterring magnets is properly powered. On any interlock failure, the beam will be aborted. Similar interlocks will be provided on the cooling water flow, pressure differential, and temperature. Field strengths, cooling requirements, and sweep amplitudes of the said system for this design are based on experiences with the successful Phase 1a dump.

It is important that the beam is not only properly enlarged, but that it is also correctly positioned in the stop. A quadrant detector at the entrance to the stop will assure the correct beam size and position at the stop 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, protected from RF heating, 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 and up-down difference signals assure that the quadrupole over-focusing and raster amplitude are correctly set, and that the beam centroid is properly centered on the stop.

The design of the high-power Phase 1a stop was independently reviewed by an outside expert [9]. This review concluded that the stop 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 stop were presented.

2.8.4 Tune-up Stops

For a variety of beam setup activities, such as cavity phasing or establishing the linear beam optics, it is desirable to use low-average power beam, and to not have to transport this beam around the entire machine. These tune-up stops need to dissipate only a low average power – on the order of up to 10 kW – corresponding to 2 μA average current at 5 GeV. This current may be comprised of a 1.3 GHz train of 0.8 fC bunches, or of bursts of higher charge bunches at a greatly reduced duty factor, as required for the particular task at hand.

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

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

2.8.5 Moderate Power Stops

For various accelerator physics studies, 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

$10\,\mu$A. In this case, energy recovery is unnecessary and would involve costly additional beam transport. Thus, beam stops for these low currents of high-energy beam are required. These stops are very different than those above, as the electrons penetrate much farther into the 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.

For average beam powers on the order of 50 kW at high energy, it is practical to design stops in which the entire beam energy is dissipated in metal. With nearly all the beam power absorbed in metal, the issues of radio-activation and radiolysis in the cooling water are minimal. Such stops were developed at Jefferson Lab with power-handling capability of 100 kW or more [1] which can be adopted for these accelerator physics studies.

2.8.6 Summary

Solutions are presented for each of the three different types of beam stops required for the ERL. With 1.5 MW of low-energy electrons, the primary stop is the most challenging. Three examples of stops already constructed – the Phase 1a stop for 600 kW, 15 MeV electrons, the LEDA 1.9 MW klystron collectors, and the LEDA stops for 670 kW, 6.7 MeV protons – demonstrate that good technical solutions exist. Extensive calculations, comparison with the performance of the Phase 1a stop, and attention to design details and cooling system characteristics will assure that the device will operate satisfactorily at full power for several decades.

Tune-up stops, 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 stops will be developed as required for specialized beam uses. An all-metal stop 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.

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