

DESIGN FOR A 1.3 MW, 13 MEV BEAM DUMP FOR AN ENERGY RECOVERY LINAC*

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Abstract

The electron beam exiting an Energy Recovery Linac (ERL) is dumped at an energy close to the injection energy. This energy is chosen to be as low as possible consistent with meeting the beam quality specifications. ERLs operate with high average beam current, requiring the dump to handle high beam power at low energy. Low energy electrons have a short range in practical dump materials, requiring the beam size at the dump face to be large enough to give acceptable energy deposition and heat flux in the dump. Cornell University is developing a 100 mA average current ERL as a synchrotron radiation source. The 13 MeV optimum injection energy requires a 1.3 MW beam dump. We present a mature design for this dump, using an array of water-cooled extruded copper tubes. This array is mounted in the accelerator vacuum normal to the beam. Fatigue failure resulting from the abrupt thermal cycles associated with beam trips is a potential failure mechanism. We expect to test a 500 kW, 5-15 MeV dump of this design within about 2 years.

INTRODUCTION

Beam dumps for ERLs must dissipate the high average power delivered by a CW high average current beam of low (injection) energy electrons, as the injector beam energy is not recovered. This energy is as low as possible consistent with achieving the beam quality. For the ERL being planned as a synchrotron radiation source at Cornell [1], a computational optimization of the injector shows the injection energy should be no lower than about 13 MeV [2]. With 100 mA average beam current, a 1.3 MW dump is required. The range of 13 MeV electrons in any practical dump material is short, leading to a thin dump along the beam direction. The transverse size of the beam at the dump face must be enlarged to the point where the energy deposition in the thin active volume of the dump, and the heat flux to the dump coolant, lead to tolerable temperatures and stresses in the dump body.

Dumping 1.3 MW per se is not challenging. Indeed, klystron collectors operating above this power level have been developed [3]. However, a klystron beam is much lower in energy and beam quality than that of an ERL injector, making it far easier to spread the beam over a large collector area. And, as noted in [3], klystron collectors at these power levels are subject to failure. Ideally, any beam dump system should be constructed of passive elements to the greatest extent possible, have long thermal time constants, be isolated from the main accelerator vacuum, be insensitive to small beam changes, and operate over a broad range of beam current and

energy. Some of these desiderata are difficult or impractical to achieve in a high power ERL beam dump.

BEAM DUMP DESIGN

Our approach to the ERL dump design was to develop a simple though non-optimal solution that would clearly perform adequately. ANSYS was used for all thermal and stress calculations. With a feasible solution in hand giving information on the parameters involved, variations on the design were examined to deal with problems.

Dump material and coolant selection

High thermal conductivity is important to provide good heat transfer to the coolant. Materials with a high melting temperature and yield stress are clearly desirable. The thermal conductivity, thermal expansion coefficient, and electron range in the dump material, along with the maximum allowed temperature and thermal stresses, determine the required transverse size of the beam striking the dump, and thus the dump size. From a practical standpoint, beryllium, carbon, aluminum, and copper are the only materials to consider. Beryllium was rejected on the basis of cost, while carbon (as pyrolytic graphite) was judged very difficult to develop for this application.

It is highly desirable to minimize or avoid neutron production. Aluminum, with a photoneutron production threshold slightly above 13 MeV, compared to 9.91 MeV for copper, is appealing. Even above threshold, for energies typical of ERL injectors, the bremsstrahlung weighted neutron production cross section from aluminum is considerably smaller than that of copper [4]. The relatively poorer thermal and mechanical properties of aluminum lead to an aluminum dump that is significantly larger than one of copper. We judged copper to be the best choice for an initial dump design. Nevertheless, with the optimum injection energy of our ERL above the neutron production threshold in copper, we have begun design calculations for an aluminum dump.

Water is the superior coolant for this application. We limited the water flow velocity to be no greater than 4.3 m/sec to avoid erosion of the copper [5,6]. Both analytic calculations and a CFD analysis gave a convective heat transfer coefficient of 20600 W/m²-K for circular channels using the most conservative fluid properties. For all ANSYS simulations we used 338K (a very conservative value) as the bulk outlet water temperature.

Dump thickness

The dump material should be no thicker than necessary to keep the incident electrons from losing significant

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energy in the cooling water. Energy loss in water forms hydrogen gas, and can also cause localized boiling, interfering with the heat transfer. Using a thickness greater than the minimum necessary causes the temperature of the dump to rise, while using the minimum thickness leads to a dump that should not be operated much above its design energy, even with the beam current reduced to maintain constant beam power.

The range of 13 MeV electrons in copper or aluminum is about 7.4 gm/cm^2 [7], corresponding to 8.25 mm of copper or 27 mm of aluminum. We selected a copper thickness of 8 mm for the closest approach of the coolant channels to the incident face of the dump. While the value of dE/dx decreases somewhat as the electrons lose energy in the dump material, our calculations assume a constant deposition of energy along the electron path. This approximation is unlikely to have a significant effect on the temperature or stress distributions in the dump.

Solid plate dump

Our initial design was a solid OFHC copper plate normal to the beam, with cooling channels beginning 8 mm behind the face of the dump. While it is desirable to isolate the vacuum at the dump from the accelerator vacuum system, this proved to be impractical. For example, a 100 mA beam delivers $\sim 7.5 \text{ kW}$ to a $250 \text{ }\mu\text{m}$ thick beryllium window. We judged it impractical to make a suitably large area window and remove the heat from it with edge cooling. Consequently, the dump face must be within the accelerator vacuum system.

We initially planned that the plate dump should also serve as the vacuum wall. Unfortunately, the vacuum load on the dump combined with the mechanical constraint of a rigid vacuum seal at the periphery of the dump led to unacceptable stresses in the dump body. Thus we are led to the dump being an unconstrained structure within the accelerator vacuum enclosure.

The final plate dump is square, 1.12 m on a side, and intercepts somewhat more than 95% of the incident power. 78 semicircular water-cooling channels of 10 mm diameter, spaced 4 mm apart, are located 8 mm from the heated face of the dump. We planned to manufacture this dump by brazing a copper plate with the semicircular channels machined into a second flat plate. With a radial Gaussian beam distribution having a 27.2 cm sigma, the maximum temperature at the center of the dump face is 158 C. The maximum Von-Mises stress is 39 MPa. Figure 1 shows a view of the temperature and stress distributions in the central region of the dump calculated with ANSYS. ANSYS calculations were done with a 2-D cross-section for the solid plate dump, and we would expect lower stresses in a full 3-D model.

Fatigue failure

In a high average current ERL, the beam must be interrupted very rapidly following detection of many kinds of faults, since beam loss can cause significant damage to the accelerator on a very short (microsecond) time scale. Abrupt termination of the energy input to the

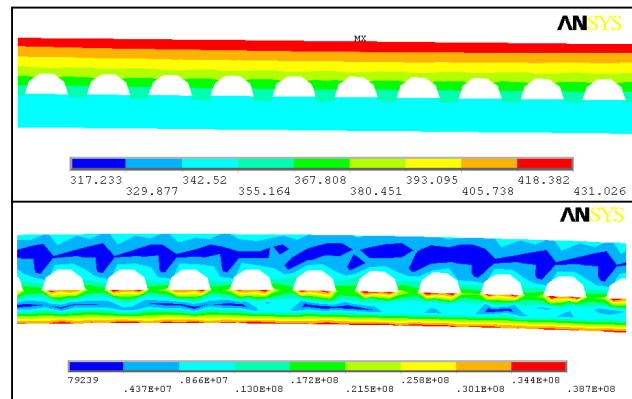


Figure 1. Temperature (K, top) and Von-Mises stress (MPa, bottom) distribution in the central region of the copper plate dump.

dump results in rapid temperature and stress changes in the dump body. Beam restoration will not be as abrupt as beam termination, but will still cause rapid changes. These beam off-on cycles will not be uncommon. In an ERL light source operated 5000 hours/year for 20 years, it would not be unreasonable to expect more than 10^5 abrupt beam off-on cycles, so fatigue failure clearly must be considered. The plate dump will conservatively survive well over 10^6 such abrupt off-on cycles. As the fatigue strength decreases rapidly with increasing temperature, it is important to note that the highest thermal stresses occur well away from the regions of highest temperature.

Extruded copper tube dump

The unconstrained plate dump can clearly dissipate the required beam power with conservative parameters. However, its construction requires brazing two large, complex pieces. The thermal performance may be compromised by significant voids in the braze joint. Connection to the water passages is also complicated. Copper is easily extruded into bars with water-cooling channels included, leading us to consider a design based on a planar array of individually cooled tubes. As the transverse heat flux in the plate dump is very small, the tube design gives very similar temperatures and stresses. This design eliminates the brazing and provides for easy water connections. Accordingly, we designed a dump using an array of 70 simple copper extrusions. Each tube is 16 mm wide with a 10 mm diameter channel for water flow. The calculated temperature and stress for the central extrusion of this design is shown in figure 2. In this case, we have used the symmetry of the problem to model only a quarter of the entire extrusion. The material properties chosen are for GlidCop AL-15 rather than OFHC copper.

The maximum temperature is now 172 C, while the maximum Von-Mises stress is 45 MPa. The maximum deflection of the extrusion is 6.2 mm, and the maximum heat flux into the cooling water is 275 W/cm^2 . These changes reflect the greater strength and somewhat reduced thermal conductivity of Glidcop.

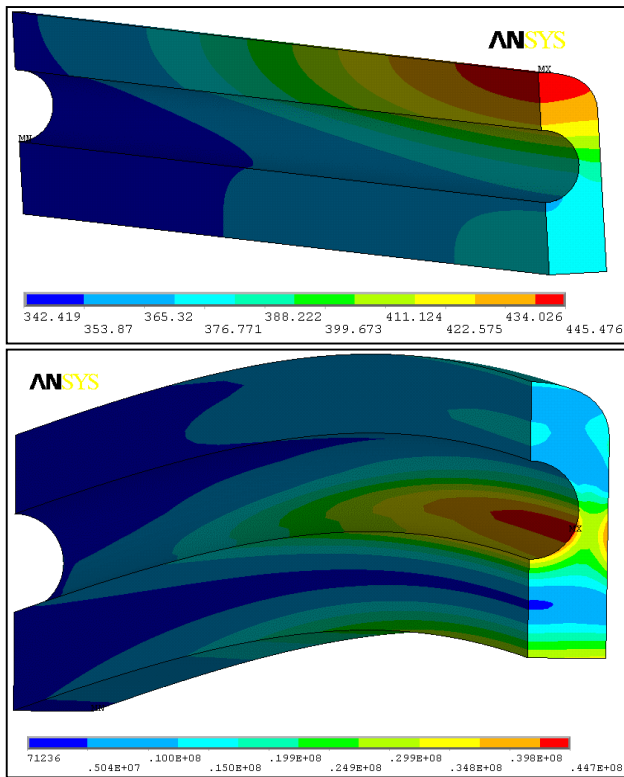


Figure 2. Temperature (K, top) and Von-Mises stress (MPa, bottom) distribution in the central extrusion of the Glidcop tube dump.

Aluminum extrusion dump

At beam energies of interest for an ERL injector, aluminum produces far fewer neutrons than copper. Though the less desirable thermal and mechanical properties of aluminum result in a physically larger dump compared to copper, the reduced neutron yield is a substantial advantage. We have begun to examine a design for an aluminum dump, based on the use of suitable extrusions. We kept the same 4.3 m/s water flow velocity as for the copper case. Using the material parameters of pure aluminum, a 2 m square dump appears quite feasible. Pure aluminum is of course not a practical material to consider for dump construction. Any aluminum dump would be manufactured from an alloy that would have poorer thermal and improved mechanical properties compared to pure aluminum. Figure 3 shows the calculated results for the central extrusion of this dump. The maximum temperature is 128 C, and the maximum stress is 19 MPa. We have not yet investigated the fatigue failure issue for aluminum, or the most suitable alloy to use for dump construction.

CONCLUSIONS

ERLs require beam dumps operating at high average power and low electron beam energy. This results in large area, thin dumps that must be free standing structures located within the primary accelerator vacuum system. Copper or aluminum extrusions incorporating a water-cooling channel offer a good way to construct such

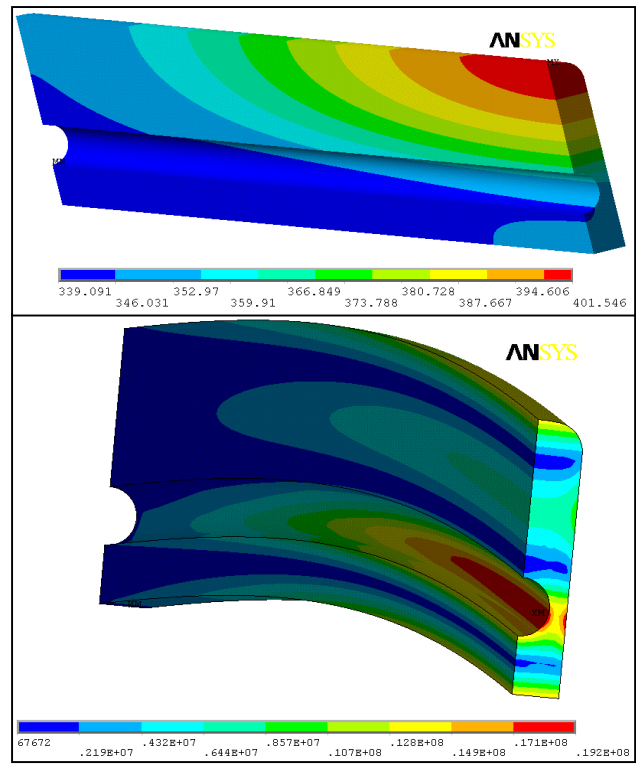


Figure 3. Temperature (K, top) and Von-Mises stress (MPa, bottom) distribution in the central extrusion of an aluminum tube dump.

dumps. Fatigue failure resulting from a large number of abrupt beam off-on cycles is an important issue. Designs that conservatively survive over 10^6 beam off-on cycles appear practical. The use of aluminum greatly reduces neutron production and induced radioactivity problems. The need to considerably enlarge the inherently small beam size of an ERL leads to a requirement for very good feedback stabilization of the beam position at the location of the beam size enlarging magnet(s). We anticipate full power testing of a 500 kW extruded tube dump within the next 2-3 years, as part of the Cornell program to develop a high brightness injector for an ERL synchrotron light source.

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