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OPERATING EXPERIENCE WITH HIGH POWER BEAM ABSORBERS IN THE SLAC BEAM SWITCHYARD*

W. A. Reupke and D. R. Walz

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Summary

In four years of operation at progressively increasing levels of average power new observations on the performance of slits, collimators, and beam dumps of various designs have been accumulated. The inherent longevity of high power beam absorbers based on low-Z or graded-Z design philosophy has been successfully demonstrated. Early operating experience at low power levels in the SLAC beam switchyard has been described previously.[1] The performance of multiple protective interlock circuitry is described and system response patterns are given. Two types of beam line failures are discussed: The air burst resulting from the melting of soft-metal vacuum seals and stainless steel transport pipes at modest power densities; and the water burst resulting from the failure of heat transfer surfaces at high power densities. Problems of beam line restoration in a radiation environment are briefly discussed. Downtime to date attending beam-induced failure of the vacuum envelope has been of the order of 350 hours, averages less than 10 hours per event, and accounts for some 15% of the unscheduled downtime from all sources combined.

A Multiple Beam Interlock System

A SLAC electron beam approaching 1 MW/cm^2 average power density can raise uncooled aluminum to its melting point in 45 beam pulses and uncooled copper to its melting point in 15 pulses. Since the pulse recurrence interval is 2.7 ms, an automatic interlock system is clearly required.

The generalized interlock scheme for a high power beam absorber at SLAC is shown in Fig. 1. Most of the beam absorbers are for practical reasons equipped with fewer interlocks than are shown. As yet no device incorporates all of them. Only if all interlocks in the diagrammed loop are satisfied is it possible to send a permissive pulse to the injector. Since the beam pulse width is 1.6 μs and it takes 50 μs for a signal to propagate from the switchyard along the two-mile path to the injector, it is clear that by the time a beam pulse results in a fault signal it is too late to interrupt that pulse. In practice a 1 ms injector interrupt network suffices to inhibit the second beam pulse. The fault sensing device itself will open its 50 μs reed-type relay anywhere from one to a thousand pulses after the beam absorber has begun to fail depending on which of the interlocks is involved. Beam absorber failure can proceed along one of two routes, where either excessive beam power or a cooling system fault initiates a fast sequence of events in the beam-sensing interlock system or the cooling water interlock system.

The pattern of response in the event of excessive beam power is as follows: The beam sensors — current toroids, secondary emission monitors, and ion chambers — signal the condition anywhere from one to a hundred pulses after beam impingement. The rise times of the 24 mH toroids and the associated RG22U cable and amplifiers do not exceed 0.1 μs. The system output can be fed to an errant beam detector logic module, which interrupts all beams within a pulse or two if a beam programmed for one channel is erroneously switched into another channel. Operating on a slower time scale are the ion chambers and secondary emission monitors. Each ion chamber circuit is calibrated by setting the integrator threshold to trip the interlock when a beam of known power is steered into the absorber surface, with allowances being made for shadowing effects arising from certain steering situations. As the beam is translated along the surface the response will vary as in Fig. 2. In most cases it would be incorrect to set the trip level at point "A" since a beam of double the rated power could under certain circumstances be directed to a less sensitive point "B" and cause the beam absorber to fail. The signal generated by the ion chamber at a power level which just trips the interlock normally reaches the integrator threshold in 100 ms. Thus a beam of ten times the rated power would be interrupted after only four pulses instead of forty pulses. A convenient feature of the ion chamber is that its output is proportional to the beam power and not the beam current. The secondary emission monitor integrates the low energy secondary electron current emitted from thin foils placed in the beam in close proximity to the beam absorber surfaces. Such a monitor provides a more accurate measure of beam impingement (in terms of current) on a particular surface element than does the ion chamber. The integration time is comparable to that of the ion chamber. An average current monitor with an integration time on the order of 300 ms drives a beam-interlocked meter relay. As yet, there is no provision for a peak current beam interlock operating on a pulse-to-pulse basis. An average power monitor derives its output from the average current system and appropriate bending magnet settings to present a digital display; but it is not yet interlocked with the beam. Together these devices — the current toroid, the ion chamber, and the SEM — provide fast interlock protection for beam absorber surfaces subjected to excessive beam power.

Malfunctions in the cooling system may result in power levels that appear safe to the beam-sensing interlocks but which portend imminent disaster at heat transfer surfaces. Several internal interlocks are involved in the radioactive water system. High- and low-level liquid sensors in the surge tank warn of leaks or obstructions in the system. To prevent the seepage of radioactive water from the main pump, a positive pressure gradient is maintained by a seal pump system containing low-level, low-flow, and differential pressure interlocks. An additional interlock is associated with the differential pressure maintained to prevent flow of radioactive water into the cooling tower side of the heat exchanger. The opening of any of these coolant subsystem interlocks actuates a summary interlock and shuts off the main pump, which in turn is beam interlocked. A separate low-flow interlock is provided on the return side of the energy absorber and shuts off the beam directly.

Thermal sensors provide a useful measure of the effects of excessive beam power or a fault in the cooling water system which may go undetected. Gradual temperature rises are accurately tracked until a threshold comparator trips the beam in a time of the order of 10 ms. Generally, the threshold is set well below the 156°C melting point of the indium metal vacuum seals used throughout the beam switchyard. Immersion-type sensors at the water inlet and outlet ports monitor the power carried off by the water and will trip the beam at a predetermined temperature differential. Because of the finite amount of material interposed between the shower maximum and the sensors, wall failure may occur before the temperature sensor can interrupt the beam if the power is sufficiently high. Thus, a temperature sensor mounted 1 cm away from a given area where the beam impinges on an aluminum surface will lag the temperature at the given area by about 1 s. Within this time interval a 200 kW SLAC electron beam can raise uncooled aluminum to the melting point.

The replaceable thermal plug or blowout fuse[2] shown diagrammatically in Fig. 1 consists of a diaphragm of low-melting (58°C) eutectic alloy separating the beam absorber vacuum from the atmosphere at a specific point near the beam absorber surface. The T^4 dependence of the heat input into the diaphragm assures rapid melting of the plug. After

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melting has occurred, the sequence of events in the interlock system is similar to that caused by burnout from direct beam impingement. This will now be described.

If the temperature sensors do not act in time to prevent burnout, large volumes of water vapor or air enter the beam line with explosive force. In ten to a hundred milliseconds the shock front propagates to the nearest vacuum switch. A gaseous discharge within the switch causes the high voltage supply to trip off on a circuit-breaker action. Simultaneously, the holding currents are removed from each solenoid in a pair of spring-driven "fast" valves resting on beam interlocked limit switches. Each valve is located at a considerable distance from the beam absorber so that the shock front will not yet have reached the valve within its characteristic 20 to 30 ms closing time. In order to maintain vacuum in the unaffected sections over long time periods, a pair of high vacuum isolation valves are driven shut by pneumatic cylinders in approximately two seconds. Again, limit switches act to provide a beam interrupt as the valve begins to close. The two second closing time of the isolation valves is actually quite rapid on the time-scale of beam line filling; ambient air undergoing frictionless flow through a 1 cm^2 hole will raise the pressure in a typical 5000-ℓ system to 50% of atmospheric pressure in about 130 s.

If the beam absorber failure is the result of excessive power in a water-cooled system, the cooling system interlocks will eventually come into operation from the indirect effects of loss of water. A low-flow switch may come into play within milliseconds due to the pressure transient. After a much longer time period the surge tank low-level sensor will shut down the main circulation pump and open a beam interlock relay. Thus, at a pressure differential of 4.5 atmospheres, a 1 cm^2 opening in the water-to-vacuum interface will provide a frictionless flow of 3 ℓ/s. A typical high power radioactive water system has a capacity of 6000 ℓ, and the surge tank sensor is normally set to respond after the loss of some 700 ℓ of water, or in approximately 4 minutes. The escape of water will continue until the remotely controlled solenoid valves are energized by the control room operator. Since not all of the systems are equipped with such solenoid valves, considerable volumes of radioactive water may be released into the beam line. To provide an earlier indication of water loss, a float switch may be employed at the bottom of the beam absorber tank.

In four years of operation the complex beam interlock system has performed quite satisfactorily. Significant problems have occurred only in systems with a minimum of interlock protection, as in the case of certain protection collimators or beam stoppers protected by a single ion chamber. In one instance the concurrent failure of a pulsed deflection magnet and a single ion chamber protecting an uncooled copper beam stopper allowed a high power branch beam to impinge directly onto the stopper with the result shown in Fig. 3. Note that melting has occurred precisely at shower maximum for SLAC beam energies. Installation of thermal plugs has since improved the interlock protection for uncooled stoppers, and a reevaluation of these stoppers is now under way.

Design and Operating Limits

The same factors which lead to the design criteria for a beam absorber determine the limits of safe operation. A full explanation of the SLAC beam absorber design philosophy has been given elsewhere.[3] From an operational standpoint some highlights of this philosophy are significant. The incident electron beam assumed in the design analysis is characterized by the energy, the dimensions and orientation of the beam envelope impinging on the absorber surface, and the average power.

To a first approximation the power limit is independent of energy. The beam energy determines the location of the shower maximum and the shower multiplicity at that point. Thus at 10 GeV the shower maximum in aluminum occurs at 4.5 radiation lengths (40 cm) and at 20 GeV at 5.2 radiation lengths (47 cm). The 7 cm difference can account for a large variation in the time response of a thermal sensor element placed at a fixed location, explaining in part our experience that temperature sensors cannot always be relied upon to warn of incipient burnout. Multiple or linear strip sensors can reduce this effect.

At the shower maximum the multiplicity for a 10 GeV incident electron beam is 34 and the average energy of the secondary electrons has decreased by a factor of $e^{4.5}$ or 90; this corresponds to 0.11 GeV. Similarly, a 20 GeV incident beam has a shower multiplicity of 64 and the average energy of the secondary electrons has decreased by a factor of $e^{5.2}$ or 180; this also corresponds to 0.11 GeV. Thus, for incident beams of 10 and 20 GeV with equal average power, the 20 GeV beam contains only half the number of particles and therefore, the total number of secondaries at the shower maximum is approximately the same at the same energy of 0.11GeV. Hence, power absorption per unit length is quite comparable at 10 and 20 GeV. For substantial incident energy differences the power deposition per unit volume decreases moderately with decreasing energy due to the inverse proportionality of energy and mean square angle of scattering (0.5 cm (rms) instead of 0.4 cm for an incident beam having an effective radius of 0.3 cm for 10 and 20 GeV respectively).

The dimensions and orientation of the incident electron beam depend on the phase space of the accelerated beam and the optical transformations occurring in the beam transport system. To first approximation the local volume heating rates and wall temperature differentials depend inversely upon the projected area of the beam at the absorber surface. As a result, some knowledge of the beam dimensions at various points in the transport system under actual operating conditions is essential. Methods for empirically determining the beam profile at SLAC include the use of phosphor screens, Cerenkov cells,[4] glass plate exposures, emulsion exposures, and collimators located upstream from a current measuring toroid. Saturation effects at the phosphor screen and in the camera vidicon limit the first two devices to qualitative determinations of quadrupole focusing effects. At selected points it is possible to obtain a rather precise but time-consuming measurement of the beam profile by means of variable aperture collimator jaws inserted into the beam. Empirical measurements may be combined with the SLAC TRANSPORT algorithm[5] to make reasonable estimates of the beam profile at beam absorber sites which are not accessible for instrumental observation. Experience has shown that when the proper beam profile is determined, beams may be operated extremely close to design limits without failure of the energy absorber.

Performance to Date

Since initial beam turn-on in May 1966 sufficient experience has been gained to permit some generalizations concerning beam absorber performance. Beam induced vacuum failures tend to occur primarily in uncooled stainless steel transport pipes and associated flanges which were never intended to absorb significant power. Replaceable indium seals (m.p. 156°C) at the vacuum flanges normally fail before more serious damage can occur, usually as a result of diffuse shower production by beams striking various apertures at grazing angle incidence. The medium-Z and low thermal conductivity of stainless steel account for a few instances of direct puncture of the transport pipe by well-focused kilowatt-level beams which have been misteered in regions with marginal interlock protection. Altogether some thirty vacuum pipe and flange incidents have occurred. In the early stages of beam operations at SLAC the power handling capability of the principal high resolution transport system was limited to 100-200 kW because of such incidents. Modification of troublesome apertures and progressive improvement in operating techniques together with a considerable increase in the accelerator beam breakup threshold has made possible the routine delivery of high power beams through this transport system. In October of 1970 an electron beam of 630 kW average power was successfully transmitted through the entire high resolution system in the course of a search for neutrino-like particles.[6]

Far fewer instances of vacuum loss at slits, collimators, stoppers, and beam dumps have been encountered. Four high power beam absorbers of low-Z construction described previously[3] have not yet been subjected to their full 2.2 MW design load but have thus far performed flawlessly at levels approaching 750 kW. Compact sphere beam dumps[7] of economical, low-Z construction have successfully absorbed beams in excess of 500 kW. Because of space limitations and optical considerations it is sometimes necessary to employ medium- or high-Z beam absorbers. Devices fabricated from such materials are prone to steep thermal gradients when exposed to high power beams and instances of failure have been observed. A water-cooled copper slit which normally intercepts only a fraction (20 to 40 kW) of the incident beam was periodically subjected to full incident beam power (80-100 kW) owing to the intermittent cycling of accelerator klystrons and failed after some two years of operation, as did a replacement slit of similar construction. A similar slit in the high resolution channel suffered damage after four years of operation, owing in part to the above phenomenon and in part to the additional fact that the slit may not always have been fully withdrawn during very high power operations. In both cases examination showed the failure to be due to thermal stress fatigue. Voids created by thermal stress fatigue account for partial closure of a 1mm circular aperture in a water-cooled copper collimator operating at 15-20 kW. In one case extreme space limitations led to the construction of a tungsten-jawed variable aperture collimator for removal of beam halo which posed unique problems. Because a water-cooled tungsten positron source had previously resulted in a major water contamination problem the decision was made to cool the tungsten via a copper interface. The tungsten was furnace-brazed to the water-cooled copper core of the jaw. The tungsten was a free-machining type with 92% W and the balance nickel and copper. This is not an alloy but a powder-metallurgical product where the individual constituents retain their physical characteristics, specifically the melting point. Power in excess of the design value was deposited in the tungsten jaws during operation with a well-focused beam. The resulting destruction of one jaw caused a large volume of water to flow into the beam transport vacuum system. The water was highly contaminated with radioactive metal particles. A close examination of the jaw showed a path which the beam had gouged across the beam-defining face, from the shower maximum to the down beam end. The heat affected zone close to the gouge appeared to be porous and brittle, with many small cracks. The material in the gouge showed signs of melting and the area was littered with small spherules of copper and nickel. Thus the melting point of copper, not tungsten, determined the effective power limit. (See Figs. 4 and 5.)

Several compact beam dumps and numerous instrument protection collimators constructed of water-cooled copper have performed flawlessly at power levels from 20 kW to 100 kW. In one instance a 3 r.l. water-cooled tantalum target has been successfully operated in a 600 kW beam.

Beam Line Restoration in a Radiation Environment

Timely restoration of the vacuum envelope to operational status following beam-induced rupture is a problem compounded by the simultaneous presence of residual radioactivity in beam line components and cooling water. The principal isotopes formed directly in the switchyard atmosphere — O^{15} (2 min), N^{13} (10 min), C^{11} (20 min), and small amounts of Ar^{41} (110 min) are allowed to decay for several minutes before the switchyard is vented of nitric acid vapor and ozone. Upon entry of personnel additional short-lived isotopes have already decayed and a preliminary survey reveals the extent of the radiation problem. Levels of 10 Rad/hr at contact have occurred, reducing stay time to a few minutes. Only rarely are levels in excess of 100 Rad/hr encountered from residual radioactivity. Operations in the unaffected beam lines may be continued while the affected area is allowed to decay to acceptable levels. In particular, Na^{24} (15 hr) and Cu^{64} (12.9 hr) may be allowed to decay for several hours with advantage.[8] Thus far at SLAC careful planning of crew schedules has avoided the necessity of semi-remote handling techniques in all but a few cases.

Contamination of the coolant arises principally from tritium and Be^7 evolved in the water by photospallation of O^{16}. The Be^7 has a significant half-life but is effectively removed by resin filters. Small amounts of beam-activated impurities arise from corrosion and erosion mechanisms. Levels measured to date in the beam switchyard coolant systems are generally below maximum permissable concentrations for occupational exposure. After rupture of the vacuum envelope a larger concentration of radionuclides may accompany the water, and protective garments are worn to guard against possible contamination. Radioactive components which must be removed from the area are subject to monitor and control by the SLAC Health Physics department.[9]

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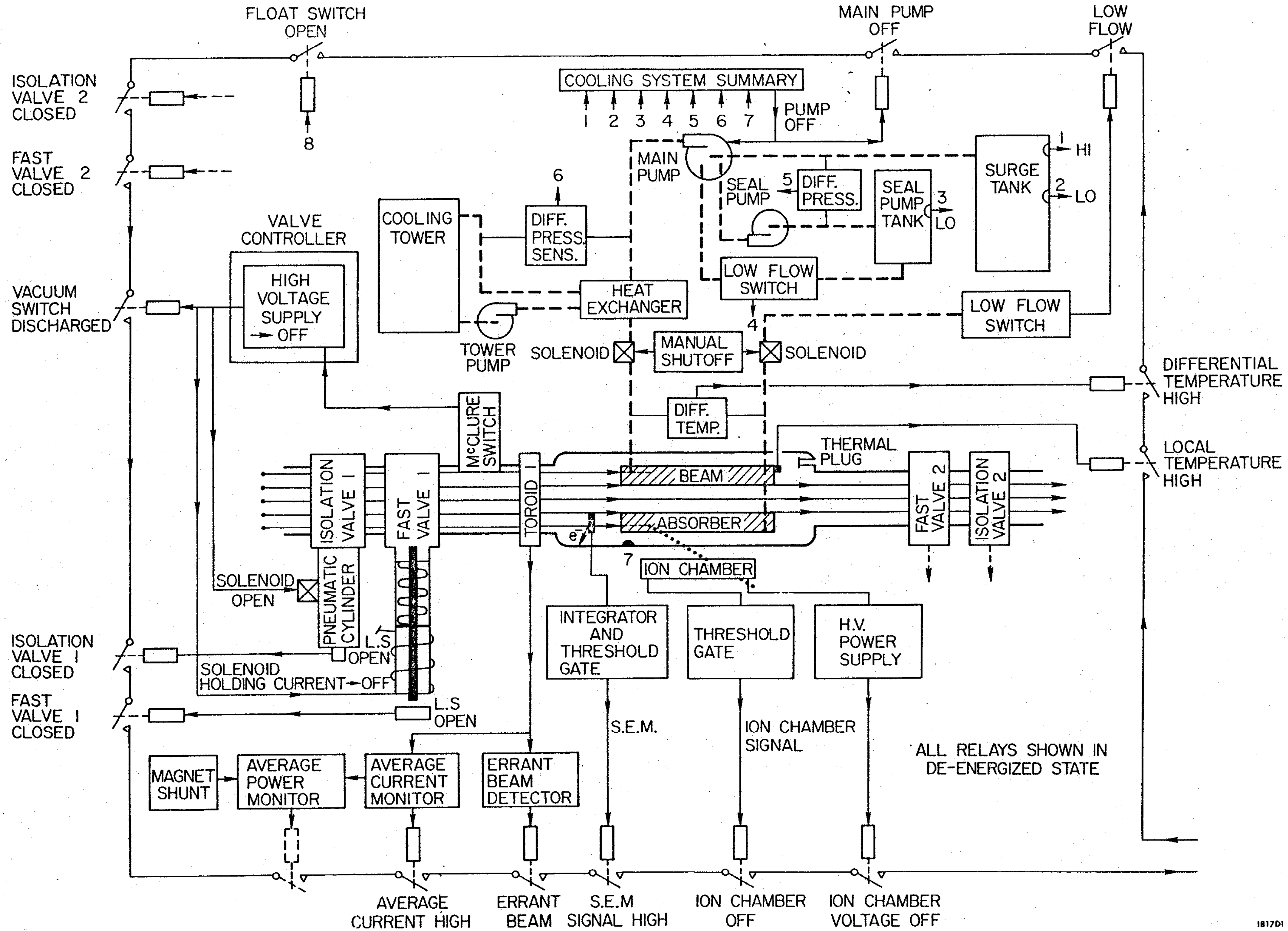

FIG. 1--General interlock scheme for high power beam absorber.

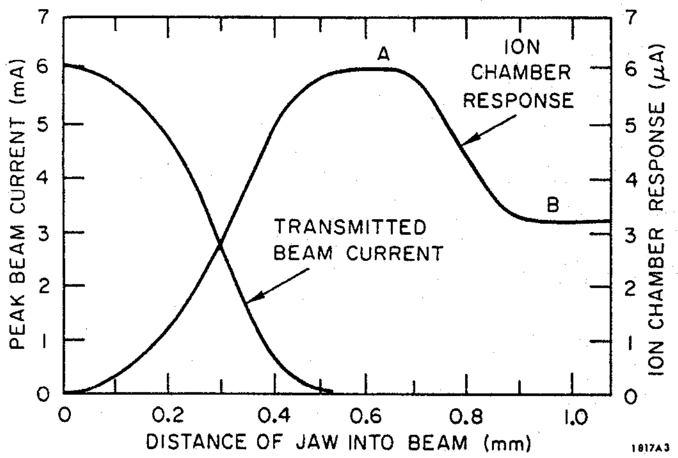

FIG. 2--Self-shielding effect at collimator ion chamber.

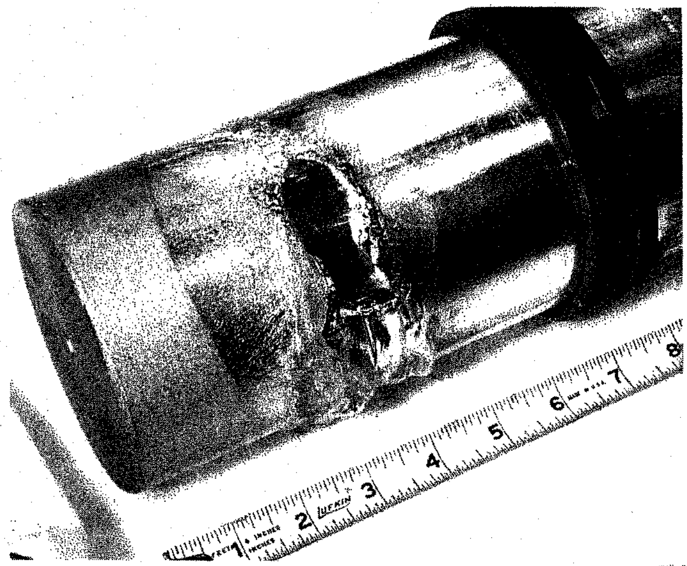

FIG. 3--Failure at shower maximum in uncooled copper beam stopper.

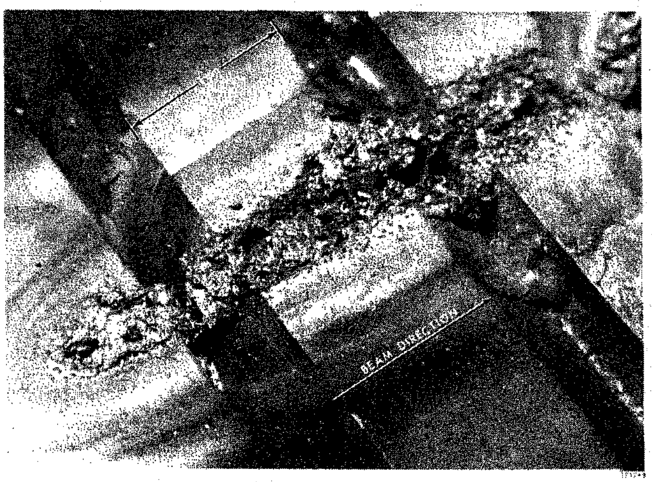

FIG. 4--Tungsten alloy collimator jaw.

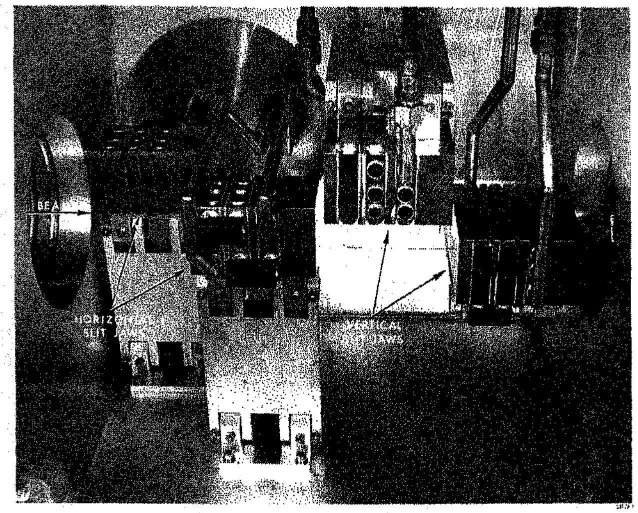

FIG. 5--Collimator assembly.