HANDLING HIGH POWER ELECTRON BEAMS

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Summary

In recent years accelerators have been designed and built which produce beams of extremely high power, current, and charge-per-pulse. The handling of these beams presents a number of difficult problems. Among these problems are: removal of large heat flux, fatigue failure of components due to pulsed nature of the beam, radiation damage of materials, corrosion, residual radioactivity, and chemical effects such as radiolysis of water and production of noxious gases. Consideration of these problems strongly influences the overall design of beam handling systems, as well as the designs of specific components. Examples of the problems encountered and the solutions adopted in various electron accelerator labatories will be discussed.

Introduction

The development in recent years of electron linacs with extremely high beam powers has presented the accelerator designer with a whole new class of beam handling problems. Among these problems are: removal of large heat flux from such components as beam windows and collimators, fatique failure of components due to the pulsed nature of the beam, radiation damage to materials, corrosion, residual radioactivity, and chemical effects such as radiolysis of water and production of noxious gases. Consideration of these problems strongly influences the overall design of beam handling systems. For example, a compromise must be made between interlocking and beam monitoring on the one hand, and use of components which can withstand high-power beam impingement on the other hand. Optimizing this compromise could easily affect the total cost of the beam handling system by a factor of two or more, besides having a large effect on the reliability and ease of operation of the system.

From the point of view of power handling the most significant beam parameters are total power, average current, and charge-per-pulse. Serious problems can be expected when the magnitudes of these parameters exceed 10 kw beam power, 100 μa average current, or one microcoulomb per pulse respectively. Beam energy, per se, is not a fundamental parameter because of the long ranges of minimum ionizing electrons. Of course, at high energies the power handling components become larger and therefore the engineering problems become more difficult. In addition one must take into account the fact that the current produced in a thick target at high energies far exceeds the incident current due to the multiplication of secondaries in the electromagnetic shower generated in the target. Of the many high powered linacs in operation or being built two representative examples of design parameters are the 20 Gev SLAC machine (2 MW, 100 μA, .3 μC/pulse)[1/] and the 100 MeV NBS machine (100 kW, 1 mA, 3 μC/pulse)[2/].

Since current density is the determining factor in heat flux and fatigue problems we must include beam cross-sectional area among the significant parameters in power handling. Unfortunately, beam area cannot be defined with the same accuracy as the parameters mentioned above can be for any given machine. The reason for this uncertainty is that the good beam emittance of most linacs allows the strong focussing elements of the beam transport system to produce extremely small beam spots at many locations through the system. Due to operator error, inadequate monitoring, beam energy changes, etc., it is quite likely that a well focussed beam will sometimes impinge on a component where it is neither desired nor expected. The usual result at high power levels is the very sudden appearance of a hole in the vacuum system. If one is lucky, air rather than water is on the other side of the hole. We do not know of any operating high power machine in which some such incident has not occurred. The problem of determining an effective beam size will be discussed further below.

In the following sections we will discuss the main power handling problems mentioned above. We will then give examples of specific designs of power handling components, and finally we will look at the influence of power handling problems on overall system design.

Beam Impingement

Calculation of the power deposited by an electron beam in any given component, and the resulting temperature rise, heat flux and thermal stress is not difficult. The real problems are finding a heat transfer process which can remove the heat in a particular geometry and selecting materials which can withstand the environment. We will proceed to outline the calculation of the various parameters of the heat transfer problem.

Consider an electron beam of current i and cross sectional area A passing through some uniform material. The power deposited per unit volume of material W, is given by

$$W = \frac{i}{A} \rho \frac{\partial E}{\partial X} , \qquad (1)$$

where ρ is the density of the material and $\frac{\partial E}{\partial X}$ is the rate of energy loss (MeV $g^{-1}cm^2$) in the material. The value of $\frac{\partial E}{\partial X}$ is nearly independent of electron energy and varies only slightly with atomic number. Determination of the current density $(\frac{i}{A})$ depends on the particular problem being considered. Assuming that the current produced by the accelerator and the emittance of the beam are known, the current density at subsequent points throughout the beam transport system is determined by application of the methods of beam transport optics. In addition, if the beam passes through any appreciable thickness of material the current density is further modified by multiple scattering and production of secondaries. For low energy (~ 100 MeV) beams, scattering is dominant and the current density rapidly decreases as the beam penetrates the material. At higher energies, and particularly in high atomic number materials, secondary production becomes increasingly important. For example, in the SLAC machine the greatest current densities occur at depths of the order of five radiation lengths.[1] In any event, one can determine current densities throughout the medium by application of shower theory[3] or experimental data.[4] Simple approximate shower calculations have been made for particular geometries[5-8].

Having obtained the deposited power density (equation 1), the remaining thermal parameters may be easily calculated. We consider only the typical example of a beam impinging on the thin metal wall of a vacuum chamber as shown in figure 1. This wall could represent, for example, the surface of some collimating element, or part of a window where the beam is to be removed from the vacuum system. Behind the wall is a water channel, to which the deposited heat must be removed. We wish to calculate the heat transfer H to the water per unit surface area, and the maximum temperature in the wall. In most cases the beam size is large compared to the wall thickness t. This results in two useful (but not essential) simplifications: (a) the angle of incidence of the beam does not enter into the calculation, and (b) transverse heat flow can be neglected. The results of the calculation are that the heat transfer rate is just

$$H = tW \tag{2}$$

and the temperature difference between the cooled and uncooled surface of the wall is

$$\Delta T = \frac{Wt^2}{2k}\ , \tag{3}$$

where k is the thermal conductivity of the medium. As an indication of the magnitudes of the above quantities, consider a 1 mA beam 5mm in diameter (these are design values for the NBS linac). This beam, incident on a 1-1/4 mm thick copper wall deposits about 66 kW/cm^3 (equation 1). The heat transfer rate to the water must be 8.2 kW/cm^2 (equation 2) in thermal equilibrium, and the temperature difference across the copper is 130°C (equation 3). The required heat transfer rate is extremely difficult to achieve as will be discussed below and the temperature rise, already large, would cause materials of lower thermal conductivity (such as stainless steel) to melt.

Up to this point we have treated the thermal problem as if the electron beam were continuous, using the average beam current in our calculations. This is always acceptable because the thermal relaxation times for all structural materials in any reasonable geometry is very much larger than the maximum pulse lengths (a few microseconds) of any existing linac. At large repetition rates, when the average power deposited can be large, thermal relaxation times are usually also large compared to the inter-pulse time. The only significant effect of the pulsed nature of the beam is that the temperature at any point in the material varies cyclicly as shown in figure 2. Because of the long thermal relaxation time, the temperature rise during a pulse ΔT_p, is simply given by the energy deposit per unit mass per pulse, divided by the specific heat. That is

$$\Delta T_p = \frac{q}{A}\left(\frac{\partial E}{\partial X}\right)/C, \tag{4}$$

where q is the charge delivered per pulse, and C the specific heat. In table I we list the temperature rise per pulse for several common materials subject to a 3 μC per pulse beam of 5mm diameter. (These are the maximum design values of the NBS linac.) Specific heats at room temperature are used in the calculation.

Heat Removal

In designing collimators, targets, and beam windows careful consideration must be given to obtaining adequate heat transfer. The commonly used methods of heat removal are by transfer to water flowing in channels within the structure and by thermal radiation from materials with high melting points. Careful design of components can serve to reduce the heat transfer requirements. From inspection of equations 1 and 2 two obvious ways of accomplishing this are using low density materials and making the structural members thin. In some applications a component may be designed to have a rotating or oscillating motion which serves to increase the effective beam area. An example of this is the adjustable aperture collimator composed of two rotating tantalum wheels shown in figure 3. Because the thermal relaxation times are of the order of the revolution period of the wheels, the entire surface area of the wheel can radiate heat. The heat transfer rate is reduced by the ratio of beam area to wheel surface area, a factor of about 4000.

Water Cooling

The most commonly employed heat transfer method is by turbulent water flow[9]. The ordinary case in which the water is not heated to its boiling point, even locally, is well understood. This method is capable of removing heat fluxes up to about 300 watts/cm^2, although achieving this requires water flow velocities of the order of 30 ft/sec and the temperature difference between the cooled surface and the bulk water may be of the order of 50°C. An order of magnitude larger heat transfer is obtained in the nucleate boiling regime. The mechanism is the formation of small steam bubbles on the hot surface which quickly condense in the bulk liquid. In this case the difference between the surface temperature T_s, and the boiling temperature T_B is[10]

$$T_s - T_B = AH^{1/4}\exp\ (-p/900), \tag{5}$$

where p is the absolute water pressure in psi. If the heat flux H is expressed in watts/cm^2, the constant A has the value of 7.9 to obtain the temperature difference in Centigrade degrees. The maximum heat flux H_{max} which can be removed by the nucleate boiling process has been measured as a function of water flow parameters in several experiments, and in each case the results have been collated in an empirical equation. Unfortunately, the predictions of the several equations differ widely[11], suggesting that not all of the variables which influence the limiting heat flux have been recognized and controlled. Only one of these empirical equations will be presented here, with the warning that while the dependence on the listed parameters is probably fairly reliable, the absolute magnitudes should be treated skeptically:[12]

$$H_{max} = \frac{4.0\ (T_B - T_W)\sqrt{v}}{.76 + .027\ \ell/D}, \tag{6}$$

where T_B and T_W are the boiling temperature at the ambient pressure and the actual water temperature expressed in degrees centigrade, v the water velocity in ft/sec, ℓ the length of the heated region, D the hydraulic diameter of the cooling channel, and H_{max} the limiting heat flux in watts/cm^2. We believe equation 6 to be rather conservative for the particular case of the small diameter pulsed beam produced by a linac. In one set of tests performed with the 500 µA beam of the Yale University linac, heat fluxes of about 1.4 times the values predicted by equation 6 were achieved with both copper and stainless steel samples[13]. The bombardment times were only a few hours so that no information on long-term effects was obtained. However the catastrophic burnout failure which occurs when H_{max} is exceeded (due to the formation of a macroscopic steam bubble at the hot spot) was not observed.

Radiation Cooling

Thermal radiation is a useful mechanism for heat transfer when the heat flux to be removed is not too large. It has the distinct advantage that a failure does not result in spilling water into the vacuum system. This feature was the reason for the use of the rotating wheels shown in figure 3 as the entrance collimators of the NBS beam handling system. However, several words of caution about radiant heat transfer are in order. First, the component design must allow for extreme differential thermal expansions. Second, for most materials as the temperature is increased the specific heat and strength decrease while the coefficient of thermal expansion increases. These variations all tend to make the fatigue problem, discussed below, more serious.

Fatigue

The pulsed nature of a linac beam results in cyclic thermal stresses to bombarded components. The magnitude of the temperature cycle, ΔT_p is given by equation 4 above. Parts of the structure not hit by the beam will have much smaller temperature fluctuations. The thermal stress S_T in the bombarded region will thus be approximately given by

$$S_T \simeq \alpha\ E\ \Delta T_p, \tag{7}$$

where α is the coefficient of thermal expansion, and E the Youngs modulus of the material. An accurate calculation of S depends on several geometrical factors, such as the variation of ΔT_p within the bombarded region[14]. Most linacs yield about 10^6 pulses per hours, so for reasonable life expectancy the thermal stress should be well below the long term fatigue limit of the material. The problem may be mitigated to some degree by self-annealing, although it is difficult to estimate the effect quantitatively. Fatigue effects were clearly the cause of failure of several thin window foils in some tests carried out at Yale University[15]. Materials tested included copper, molybdenum, tantalum, and titanium. The beam intensity was about 2 µC per pulse with an area of order .2 cm^2.

Radiation Resistance

Radiation damage to materials is one of the class of problems whose seriousness depends primarily on the total beam power of the accelerator. The problem is serious at power levels as low as a few kilowatts. Because of the penetrating nature of the x-rays and neutrons produced by machines of even 20 or 30 MeV, the effect of beam energy is minor. A large amount of experimental information is available on the radiation resistance of various materials[16], so we will confine our discussion to a few general remarks. Organic materials are to be avoided to the greatest degree possible along all beam paths. This implies all-metal vacuum systems using for example copper or gold gaskets. (Indium gaskets have caused trouble by melting due to heating by beam spray.) Vacuum valves subject to a high radiation flux must be of all metal construction. Many types, including gate valves with up to 4 inch aperture are now available commercially, although they are extremely expensive and in some cases not highly reliable under repeated operation. Asbestos or mineral insulated electrical cable are used exclusively in the NBS beam switchyard, with the latter preferred for most applications. Ceramic materials only are used as insulators on electrical vacuum feedthrus, magnet cooling water lines, and so forth. Magnet coils are usually insulated with glass tape, potted in epoxy. Various epoxy materials exhibit vastly different radiation resistances, usually in inverse relationship to their mechanical strength and ease of fabrication[17]. Anodized aluminum foil coils have also been used successfully in high radiation environments.

Corrosion

The subject of corrosion is an extremely complicated one which we obviously cannot discuss fully here. Corrosion problems are not unique to the high-powered accelerator, but should nevertheless be mentioned here for three reasons. First, the corrosion rates may be adversely affected by the presence of radiation. Second, many of the chemical species produced by the passage of a charged particle beam through air or water are highly corrosive. (This will be discussed in the section on chemical effects.) Third, corrosion resistance is one of the considerations in choosing materials for power handling components.

Corrosion rates in water cooled power handling components depend on a great many factors including: materials employed, water purity, oxygen content, pH value, temperature, radiation, and water flow velocities. Aluminum and copper are incompatible because of electrolytic corrosion[18]. If both metals are used, separate water systems should be seriously considered. In closed-loop recirculating water systems, water purity can be controlled by the use of chemical demineralizers, a variety of which are available to meet specific requirements. At NBS, mixed-bed demineralizing and oxygen removal resins are employed in our copper-stainless steel systems. We have not been in operation long enough to be certain of the adequacy of these measures. Furthermore, since environmental conditions vary widely, it is not clear that the same techniques would be effective in other systems.

Stress corrosion can be a serious problem with many metals including aluminum alloys, copper and stainless steels[18,19]. The seriousness of the effect varies widely between different alloys and depends strongly on the environment. Among the steels, low-carbon alloys such as 304L and 316L (which is better, but not readily available) are preferred. Chlorides in particular greatly enhance stress corrosion in stainless. At NBS we have seen stress-corrosion cracking particularly of forged or spun components, flexible bellows, and near welded joints. The influence of a zinc-chloride bearing flux used in the soldering of water cooling lines is suspected to have contributed substantially to these failures.

Erosion of metal surfaces in contact with flowing water can in some cases be significant. Erosion rates depend on the metal employed and the water velocity. In the nucleate boiling heat-transfer regime, erosion rates are greatly enhanced, presumably due to the impact of microscopic steam bubbles collapsing near the metal surface. Under these conditions, metal removal rates exceeding 0.5 mils per hundred hours of operation have been observed[20].

Residual Radioactivity

Residual activity levels of several roentgens per hour are observed ~8 hours after the end of a beam run in the vicinity of collimators which have absorbed as little beam energy as 100 kilowatt-hours from the NBS linac. No matter how carefully we design and build these components, occasional failures and the need for some maintenance work will never be completely eliminated. The necessity of allowing people to work near beam handling components must therefore be anticipated. The amount of personnel exposure can be reduced by the use of remote handling equipment, but these techniques are complicated and expensive[22]. It is therefore clear that attention must be paid to minimizing residual activity levels in the beam switchyard. We have found it highly desirable to dump as much of the beam power as possible in water, since the predominant activity is the short-lived O^{15}. The long-lived product of water are tritium[21] and Be^7. The Be^7 (produced by a γ,n2α reaction) is effectively collected in the system demineralizers where it can be easily shielded or disposed of if necessary. In selecting other materials for beam absorbers, we must consider the half-lives and intensities of the daughter products in relation to our estimates of time between failures, time needed to make repairs, and whether remote handling equipment is available. Half-lives less than 12 or 15 hours can be ignored since half-lives of this order are inevitable from such reactions as (γ,n) on Cu^{65}, (n,α) on aluminum, or (n,γ) on sodium (in concrete). This magnitude of half-life is tolerable because we are willing to wait a few days before working on damaged components, particularly in a system where very few component failures can prevent all operation. The longer half lives are often produced by 'exotic' reactions such as (γ,nα), (γ,n2α), and (γ,α2n), especially at higher energies[23]. For low energy ($\lesssim$ 50 MeV) linacs, aluminum is a very desirable material because of the absence of long-lived daughter products. Above 50 MeV, this advantage is not so obvious because the (γ,nα) reaction leading to the 2.2 year Na^{22} activity becomes increasingly important. For high energy accelerators there are no ideal materials (except perhaps water), and residual activity ceases to be a major factor in material selection. There remain a few materials which are particularly bad and should be avoided, such as antimony (present in lead alloys) and bismuth.

Chemical Effects

Chemical reactions are induced by radiolysis when a charged particle beam passes through gases or liquids. In air, the major products are nitrous oxides (which combine with water vapor to form nitric acid) and ozone[24], both of which contribute substantially to corrosion problems. The nitric acid production rate has been estimated to be about 70 grams per kilowatt-hour of beam dissipated in air[25]. Methods have been suggested for handling the nitric acid, but so far none of these have been actually employed. In water, radiolysis by the beam liberates hydrogen and oxygen gas, and produces substantial quantities of hydrogen peroxide. The hydrogen gas production rate is estimated to be about 5 liters per kilowatt-hour of beam dissipated in water[1]. At SLAC, the possibility of recombining the hydrogen and oxygen catalatically has been considered. The present NBS solution is to vent the hydrogen from our water systems, and to remove the oxygen chemically. We have not been in operation long enough to gather lifetime information on the oxygen-removal resins used, but should this prove to be a problem other solutions are available.

Component Design

We will attempt to illustrate some of the general principles of component design by means of a few specific examples. A few preliminary comments should be made concerning material selection. A number of factors must be considered including corrison properties, residual radioactivities, strength, and thermal properties, particularly for components subject to direct beam impingement. In these cases fatigue, high heat flux, and large temperature rise may all be limiting factors. The resistance of a given material to fatigue failure requires that

$$\frac{\alpha E}{S_F C}\left(\frac{q}{A}\right)\left(\frac{\partial E}{\partial X}\right) < 1, \qquad (8)$$

where S_F is the fatigue stress limit of the material (the remaining quantities have been defined previously). From the standpoint of minimizing heat flux and/or temperature rise, the best material depends on the particular geometry, and especially on the function of the component. This is illustrated in Table II. In developing Table II, we have ignored the slow variation of $\frac{\partial E}{\partial X}$ with atomic number, and have assumed that radiation lengths (in /cm^2) are simply proportional to 1/Z. We have included in Table I for easy reference a listing of properties of common structural materials. We have not attempted to include fatigue limits or working stresses because these parameters differ widely among various alloys of the same metal and of course also depend on the treatment given the material.

The NBS Thin Window

In designing the NBS beam window[26], the major concern was to reduce energy loss and scattering of the beam to an absolute minimum. The only possible cooling method is by direct water flow since for any foil strong enough to hold atmospheric pressure over the desired two inch diamter, the heat deposited by a well focussed 1 mA beam is too large to be removed by any other process. A conventional water cooled window consists of two concentric foils with water flowing between them. Since one of the foils is subject to forces tending to buckle it, it must be rather thick. The alternative of bowing the two foils in opposite directions is worse since the water thickness would be prohibitive. In the NBS window, four foils are used as shown in figure 4. Water flows between each pair of concentric foils. Helium gas at a pressure exceeding the water pressure is introduced into the central chamber so that all foils are in tension and may be of minimum thickness. In designing this window, model studies were necessary to insure reasonably uniform water flow over the foil surfaces. It was found that inlet and outlet water orifices must be carefully designed if regions of near-zero water velocity are to be avoided. Windows of this type are in routine use with the NBS linac. A photograph of one is shown in figure 5. Beam currents up to 600 μA average and 2 μC per pulse have been transmitted for long periods with no sign of difficulty. The windows we have built have a total thickness of less than .4 g/cm^2, or about .015 radiation lengths. Since calculated safety margins against all types of failure (fatigue, static stress, boiling burnout, and melting) are at least a factor of 5, a considerably thinner version of this window is feasible. It is interesting to note that for equal safety factors, windows made with aluminum alloys, titanium, or stainless steel foils would have very similar total thicknesses (in radiation lengths). We actually used titanium because aluminum is not compatible with our copper-stainless water systems, and we are afraid of stress corrosion effects in stainless.

Fixed Aperture Collimator

The classical water-cooled fixed aperture collimator consists of two concentric tapered metal tubes with high-velocity water flow in the annular region between the tubes. The wall thickness of the inner tube must be large enough to withstand the (inward-directed) water pressure. (This geometry is not inherently stable mechanically.) For the beam parameters of the NBS linac and the desired aperture sizes of one to two centimeters, aluminum is the only common material in which the heat transfer rates and hot-spot temperatures would be within reason. Because of its relatively low density and large radiation length, aluminum collimators do not provide a sharp definition of the edge of a collimated beam in the energy region where multiple scattering is the dominant process in removing particles from the beam. For this reason, among others, we wanted to use copper collimators. For the wall thicknesses needed in the concentric tube geometry ($\gtrsim$ 1 mm) the required heat transfer rates ($\gtrsim$ .5 kW/cm^2) are prohibitive. We therefore developed collimators of the design shown in figures 3 and 6. The collimating aperture is defined by a bundle of copper tubes arranged in a circle around the beam axis. The axes of the tubes are slightly skewed with respect to the beam axis, providing a nearly circular aperture to the beam. The small diameter of the tubes (1/4 in. O.D.) and the fact that the water pressure acts outward (which is mechanically stable) permits the use of small wall thickness (0.5 mm) reducing the required heat transfer rate to a tolerable value (3.2 kW/cm^2).

Unfortunately this type of collimator is difficult and expensive to build. We have had one failure, which could be attributed to poor brazing techniques. Several collimators of this type are in use at NBS. Operating experience to date has been at levels up to about 140 μA average current, and 1 μC per pulse.

Figure 3 serves to illustrate the general philosophy of power-handling component design adopted at NBS. The geometry of the system limits direct beam impingement to the rotating wheels and to the thin-walled tubing bundle which are capable of handling the full current density. Beam hitting the back-up section (which is cooled by a sheath of water flowing in the annulus between two concentric pipes) is much reduced in intensity by multiple scattering in the wheels and tubes. Finally, the beam absorber and radiation shield is subject only to highly degraded beam.

Adequate cooling is provided by a modest amount of water flowing in copper tubing inside the lead casting. The same design philosophy is also employed in collimators with water cooled adjustable elements (used to define the energy spread of a momentum-analyzed beam), fixed-aperture collimators, and the vacuum chambers of deflecting magnets where the beam energy has not previously been defined well enough to prevent impingement on the chamber walls.

System Design Considerations

The many difficult problems in attempting to handle high power electron beams will strongly influence the overall design of beam transport systems and experimental facilities. Some of the considerations which have been mentioned or implied above are: Selection of materials is largely determined by heat transfer properties, radiation resistance, residual radioactivities, and corrosion resistance. The need for a high degree of component reliability and the possible need for remote manipulating equipment is implied by the high residual radiation levels which are expected. Mechanically complex collimators with large radiation shields must be considered in the optical design of beam transport systems.

Perhaps the strongest influence of power-handling problems on system design is the interplay between the number and complexity of power handling components needed and the amount of beam monitoring instrumentation employed. A certain minimum number of power handling elements will always be needed, including: (1) adjustable collimators which are needed to define the energy and limit the energy spread of momentum analyzed beams, since user requirements on energy stability and spectrum will often exceed the intrinsic capability of the accelerator; (2) beam dumps at the end of each high power beam path; (3) one or two collimators (of which at least one may have to have variable aperture) between the accelerator and the beam switchyard, depending on the optics of the transport system, unless the definition of beam size and location provided by the linac aperture itself is sufficient to eliminate the influence of steering and focussing conditions on the performance of the momentum analysis system; (4) vacuum chambers in and downstream of all deflecting magnets preceeding the momentum-selecting collimator, unless the energy stability and spectrum of the accelerator can be guaranteed to be good enough to prevent impingement; (5) beam windows, if the beam is to be removed from the primary vacuum system; and (6) any targets which are intended for high power beam impingement (such as positron converters). Beyond these essentials, power handling components may be eliminated in favor of detecting equipment which senses for example the current, position, or size of the beam, or the radiation levels at selected points throughout the transport system. These monitors are used to detect loss of beam from its desired path or impingement on unprotected components, and operate interlocks which turn off the injector (or reduce its repetition rate to a harmlessly low value) until the dangerous condition can be corrected. Carrying the interlock philosophy too far could result in a completely safe system which never produces a useful beam, but not carrying it far enough results in a system which is unduly expensive, complicated, and unreliable.

As a final example of the savings which can be achieved in power handling components by favorable system design, consider the two beam switchyards shown in figures 7a and 7b. In figure 7a we show a conventional switchyard having three beam paths, each with its own momentum defining collimator. The system of figure 7b also provides three beam paths, but the momentum analysis is always done at the same location. The savings realized by eliminating two collimators and two power handling vacuum chambers could be a significant fraction of the total system cost.

Conclusions

Reasonably well understood techniques are available for handling the high power beams of modern electron accelerators. For the most powerful present accelerators, the procedures required are complicated and expensive. The various problems which we have discussed are fairly well understood, so that with sufficient care in the design and construction of power handling components a reasonable degree of system reliability can be achieved.

In future accelerators we can anticipate even larger beam power and current. Many of the problems we have referred to will become even more serious. The most serious difficulties are to be expected in the areas related to direct beam impingement; i.e. fatigue effects and high-flux heat transfer problems. With present day current and charge-per-pulse values we are already near the limit of conventional mechanical engineering techniques. Any major increases in these parameters will require radically new methods of power handling. Some of the ideas already being considered include: intentional beam defocussing to drastically reduce power densities; non-intercepting magnetic collimators[27], which essentially accomplish the same end; and jets of liquid metals in vacuum, to be used for targets and collimators.

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TABLE I

THERMAL PROPERTIES OF COMMONLY USED MATERIALS

Material	Atomic Number Z	Stopping Power, $\frac{\partial E}{\partial X}$	Radiation Length	Density ρ	Thermal Conductivity k	Specific Heat C	ΔT_p (a)
		MeV cm^2/g	g/cm^2	g/cm^3	watt/cm°C	watt sec/g	°C
Water	-	1.75	37.1	1.00	-	4.18	6
Aluminum	13	1.58	24.5	2.71	2.09	0.91	26
Titanium	22	1.52	16.1	4.52	0.17	0.47	48
Stainless Steel (304)	-	1.49	14.2	7.86	0.16	0.44	51
Copper	29	1.45	13.1	8.9	3.94	0.39	56
Tantalum	73	1.22	7.1	16.6	0.54	0.15	121
Lead	82	1.17	6.5	11.3	0.34	0.13	137

(a) ΔT_p is the temperature rise per pulse due to a 3 μC per burst beam, 5mm in diameter, according to equation 4.

TABLE II

	For Equal			
	Thickness	Energy Loss	Scattering or Radiation	Strength
Heat flux is proportional to	ρ	1	Z	ρ/S_s
Temperature rise is proportional to	ρ/k	$1/\rho k$	$Z^2/\rho k$	ρ/kS_s^2

ρ = density

k = thermal conductivity

S_s = safe working stress

Z = atomic number

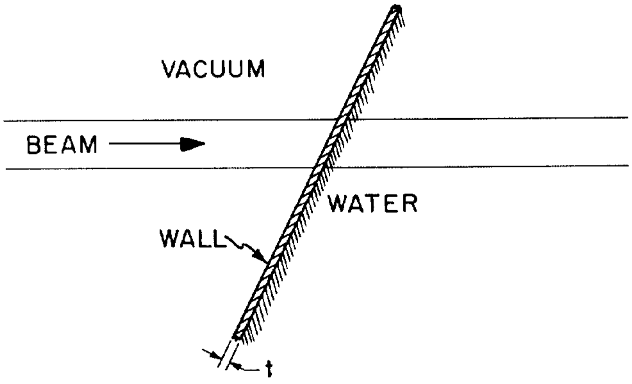

Fig. 1. Electron beam in vacuum impinging on a water cooled wall.

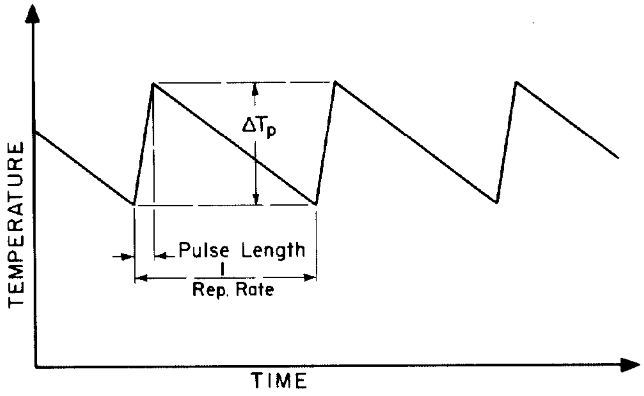

Fig. 2. Temperature cycle of material subjected to a pulsed beam.

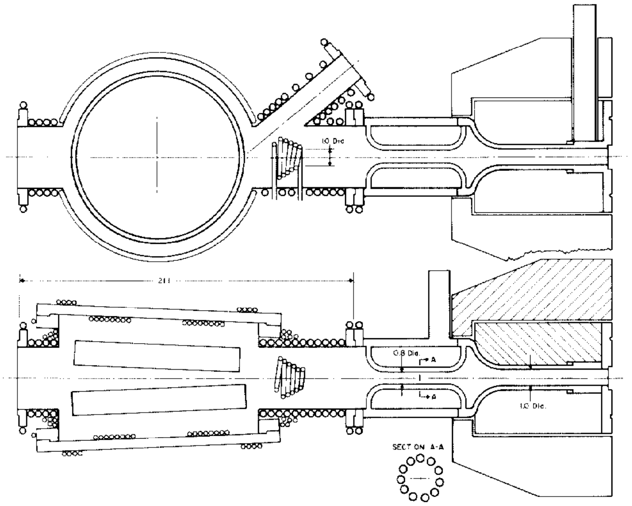

Fig. 3. Adjustable collimator assembly for the NBS linac. The beam enters from the left. The first section contains two tantalum-tungsten alloy cylindrical rings, one on each side of the beam. The rings are rotated about axes approximately perpendicular to the beam direction. They may be moved in and out along their axes of rotation to vary the aperture presented to the beam. The drive mechanisms are not shown. The second section contains the tubing-bundle type fixed aperture described in the text along with a sheath cooled back-up section and a lead radiation shield.

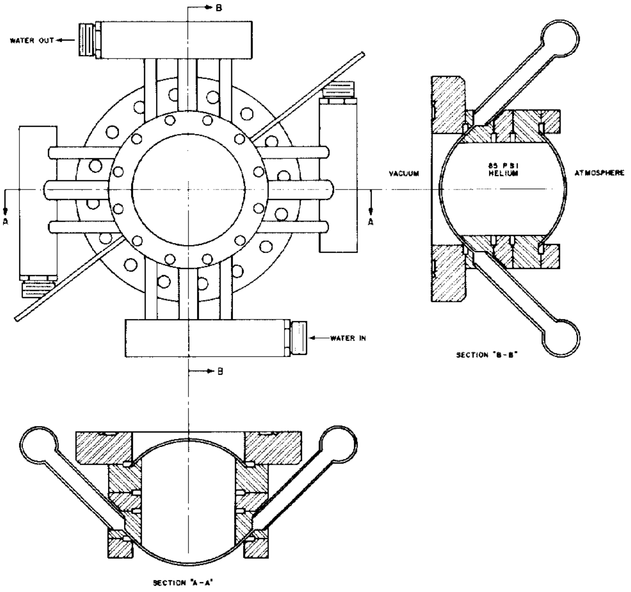

Fig. 4. The NBS four-foil beam window. For description, see text.

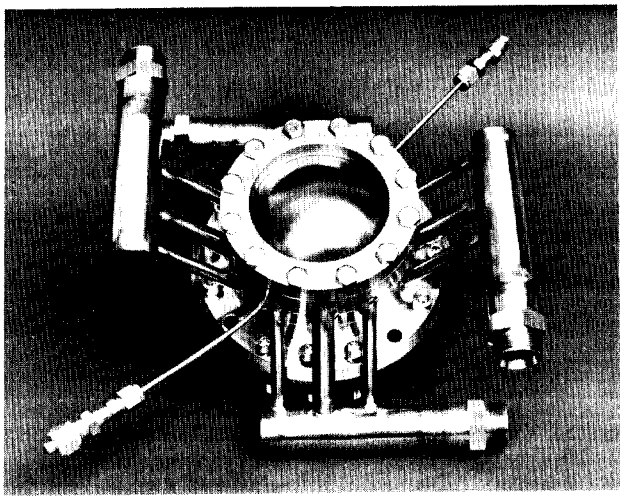

Fig. 5. Photograph of the complete assembly of the window shown in Figure 4.

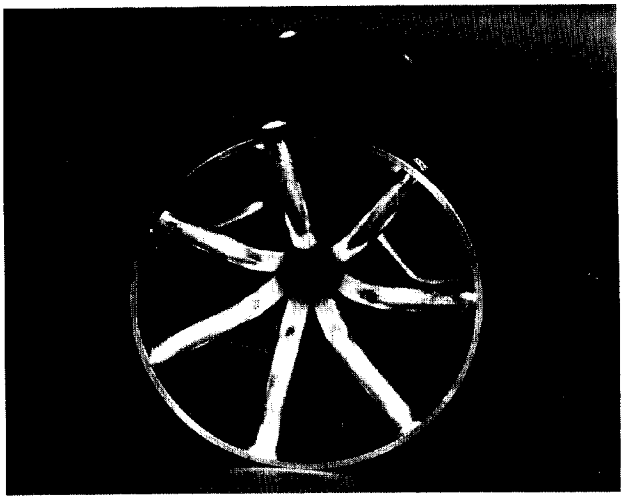

Fig. 6. Photograph of the fixed aperture section of the collimator shown in Figure 3.

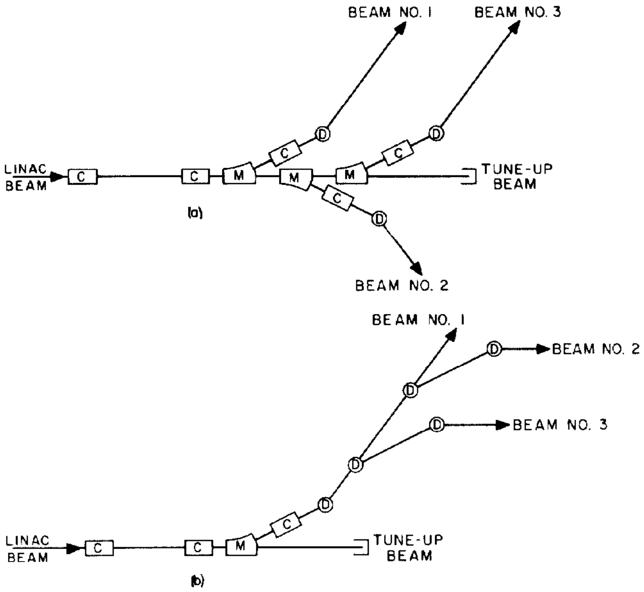

Fig. 7. Arrangement of major power handling components in beam switchyard. C-represents a collimator assembly, M-represents a deflecting magnet requiring a significant degree of power handling ability in its vacuum chamber, and D-represents a deflecting magnet needing little or no power handling. A conventional switchyard is shown in (a), while (b) provides very similar beam properties with fewer power handling components.