TRANSPORT SYSTEMS FOR HIGH INTENSITY BEAMS*

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Summary

High intensities pose new problems in the design of transport systems. Induced radioactivity, radiation damage to materials, radiation induced chemical reactions, and heating problems are discussed. Proposed solutions to these problems for the Stanford Linear Accelerator transport systems in the beam switchyard are outlined.

Introduction

Recent years have seen increasing emphasis placed on the beam current capabilities of accelerators in all energy ranges. For high energy accelerators where increases in design current are occuring together with considerable energy increases, the resultant power levels are spectacular. Figure 1 gives the energy-current coordinates of several machines now under construction, or proposed, together with a sample of machines already in operation. Difficult technical problems arise for high power levels, and also for extremes of energy or current at relatively low power levels. Although many of the presently operating machines have problems directly related to intensity, I believe it is fair to say that neither design nor cost have been greatly affected. Problems begin to occur as the power level of proton machines approaches 1 KW and at somewhat higher levels in electron machines. The power levels of the new high energy machines, and many of the lower energy machines exceed these figures by orders of magnitude.

This paper is a discussion of the impact of these new power levels on the design of beam transport systems. The Stanford Linear Accelerator can operate in the megawatt range. I shall review the problems encountered in the design of the "switchyard" for this accelerator, and describe some of the solutions which we hope will allow us to cope with these intensities. At the same time I will attempt to point out the variations in similar effects which will arise for other machines of different energy, current, and type of accelerated particle.

The switchyard at SLAC will consist of two transport systems which will deliver energy analyzed electron beams to two separate target areas. The parameters of the systems are shown in Table I. A collimator determines the size of the input beam, but no control of initial angular divergence is included, since we expect this to be very small. The systems should produce achromatic beam spots at various locations in the target areas. A special requirement imposed on each system is a high degree of isochronicity to preserve the 3000 Mc rf structure of the accelerated beam.

TABLE I

PARAMETERS FOR THE TRANSPORT SYSTEM OF THE SLAC SWITCHYARD

	Electron-Photon Area	Secondary Beam Area
Maximum energy	25 GeV	25 GeV (expands easily to 40 GeV)
Input conditions:		
Beam radius	0.3 cm	0.3 cm
Angular divergence	$< 10^{-4}$ rads.	$< 10^{-4}$ rads.
Energy spread	< 2%	< 6%
Total bend	24.5°	12.5°
"Resolution"	0.1%	0.2%
"Dispersion" at slit	0.15%/cm	0.3%/cm
Isochronicity (3000 Mc rf)	$< 10^\circ$	$< 10^\circ$
Achromatic	Yes	Yes

A final spot size of 2 mm radius is obtained by a set of quadrupoles ~ 15 meters from the target.

The basic optical configuration for both systems is shown in Fig. 2. A pulsed magnet is used to deflect the initial beam into one or the other transport system, and has no optical significance. Each system is arranged to be double focussing between the collimator and the slit, at which point the momentum dispersion is 0.15%/cm. The second bend and Q_4-Q_5 produce an almost parallel achromatic beam, which can then be allowed to drift for long distances and focussed as desired by the moveable quadrupole pair Q_6-Q_7. (Figure 3.) A complete account of the optics can be found in SLAC Report No. 29.[1] A computer code (TRANSPORT) was developed for the treatment of these optical systems. Figure 4 shows the configuration of magnets used to obtain a system similar to the basic system of Fig. 2. In order to use such a system effectively a good deal of instrumentation is required to monitor performance and supply information to the accelerator. Figure 5 shows the complexity of the final system. (The dumping magnets and beam dump in the high resolution beam are for the production of γ-ray beams.)

The difficulties brought on by high intensity obviously arise from the interception of beam particles in the system. Machine designers have been able to minimize the difficulties for the accelerator proper by paying close attention to beam loss during acceleration, and where this is insufficient, to localization of the stopped particles. For

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example, it has been estimated that only 3% of the total beam power at SLAC will be lost in the two miles of acceleration--designs for the very high energy proton synchrotrons are predicated on the use of external targets for most experiments, greatly reducing the beam loss in the accelerator ring. There is an important moral here for transport system designers--the best thing to do with unwanted particles is to not accelerate them. Every opportunity to reduce beam loss in the transport system by improving the properties of the input beam should be carefully explored. At SLAC, a small, stable beam of very narrow momentum spread will greatly reduce the problems in the switchyard. Efforts have been made to accomplish this, and early running experience should allow further improvements, but it is unlikely that the momentum spread can be reduced to values comparable with the resolution capabilities of the transport system.

The most important problems which may arise due to beam intensity are:

1) Induced radioactivity
2) Shielding
3) Radiation damage to materials, and induced chemical reactions
4) Heating, thermal shock and fatigue, heat transfer.

The physics involved in the interaction of particles of different kinds and with different energies, and the dependence of the locations and intensities of beam loss on the details of a given transport system, greatly affect the relative importance of these factors in a given case. Design reports and proposals for the various high power machines consider these problems in exhaustive detail.[2,3,4,5,6,7,8]

1. Induced Radioactivity

Problems of induced activity and shielding are quite familiar, since they exist on a reduced scale at almost every accelerator. In reactor technology levels similar to those which will arise in the high power machines already exist and techniques for dealing with such levels have been developed. Since accelerators and transport systems usually cover a very large area and a high degree of accessibility is demanded, the problems from induced activity will be similar to, but not identical with reactor problems.

The nuclear physics involved in the production of radioactive isotopes has been extensively investigated, although many cross sections of interest for calculating incuded activities are unknown and must be estimated rather crudely. The number of disintegrations per second dN/dt for an isotope of mean life τ, produced at the (constant) rate of R nuclei/sec is given by

$$\frac{dN}{dt} = -R\left(1-e^{-T/\tau}\right)e^{-t/\tau}$$

where T is the irradiation time and t is the time after shut down. It can be seen that isotopes with very short or very long half lives do not greatly contribute.

It is very simple, if somewhat discouraging to write down a list of potentially hazardous isotopes by estimating the disintegration rate for reasonable T and t in the periodic table near or below the position of the bombarded material. A very striking feature of activation is the frequency of cases in which a dominating activity comes from a relatively rare chemical or isotopic constituent, or a reaction with relatively low cross section. One should also consider those isotopes which are particularly serious when ingested. Tritium is a particularly nasty example which can build up in circulating water systems to the point where the evaporation will be a hazard in case of spill. In estimating the production rates of the various isotopes it is usually convenient to distinguish between the (relatively) high energy reactions which take place close to the beam, and neutron capture reactions which account for most of the activiation at some distance from the beam.

In electron machines, the electromagnetic shower develops in a short distance, and activation away from the beam takes place due to neutron capture reactions, and to a lesser degree, relatively low energy γ's (~ 30 MeV). The problem of activiation is much less severe for electron machines than proton machines of equal power, because the cross sections for nuclear interaction or for producing strongly interacting secondaries is of the order of (1/137) times smaller than for protons. In spite of this, we have serious activation problems at SLAC. The nucleonic cascade for high energy protons is much larger transversely than the electromagnetic case, so that localization of the activities is less pronounced.

In addition to identifying the most important reactions and estimating the relevant cross sections, perhaps the most difficult problem which must be met in the design of a transport system is the pattern of beam loss throughout the system. Where the high power beam is deliberately absorbed, it is clear that intense activation will exist, but slit penetration, slit scattering or energy spectrum "tails" may produce activation at other locations in the system. Although beam loss is difficult to predict, it can be measured early in the life of the machine before activities have built up, and appropriate measures taken.

In the SLAC transport systems the slits and collimator are designed to absorb several hundred kilowatts each. At these power levels H. DeStaebler has calculated saturation activities of ~ 100 rads with a relatively slow decrease to the order of 5 rads.[9] Low Z materials should be used to keep the activity down, and although the determining problem in slit and collimator design is heat transfer, and not activity, the major stopping materials, Al and water, meet this low Z requirement. The water which cools these devices will contain curies of Be^7 and H_3, so that the heat exchangers located outside the switchyard shielding must be shielded also. The major active nuclides will be Na^{22} (2.6 years) and Na^{24} (15 hours) from the aluminum, Be^7 (54 days) in the water, together with Na^{24} (15 hours) and Fe^{59} (45 days) from the concrete and supports through neutron capture. Dose rates of hundreds of rads would be expected from the Na^{24} in concrete and rad dosages from Fe^{59} in the reinforcing steel, except that all of the high power devices are surrounded by special boron loaded concrete which will reduce these levels by more than an order of magnitude. Dose rates in the rest of the system are very hard to predict before the beam is turned on and studied, but will no doubt be somewhat lower. (The very much smaller beam loss will be compensated somewhat by the presence of heavier stopping materials, and the absence of boron loaded concrete.)

In the design of the housing structure we have assumed that any point may be orders of magnitude above tolerance. The tunnels for the transport systems are designed in two levels. (Figure 6.) All components of the transport system will be mounted in the lower tunnel, and can be separated from the access tunnel above by a layer of iron or concrete shielding. The upper tunnel will be safe for entering personnel, so that significant exposures will occur only when the shielding between layers is removed for work in the lower tunnel.

Rails have been provided to support a heavy shielded cab which can operate independently of the crane, and which could house complicated remote handling gear. Initially, a modest L-shaped shielded trolley will be provided which will protect an operator from direct radiation either from below, while the shielding blocks have been removed, or transversely when a hot device has been lifted into the upper tunnel by the crane and is being transported along the tunnel. Each device in the switchyard is equipped with quick vacuum disconnects and electrical disconnects which can be operated by rods through holes in the floor of this trolley. More complicated systems will be devised as the radioactivity builds up and the patterns of beam loss are established. It is also possible to mount shielded cabs on the crane rails separately from the crane itself.

This two layer type of structure results in a flexible system. Since any housing must provide space either above or beside the device making up the transport system, to allow removal and replacement of components, the total cross sectional area of the tunnel is not greatly increased from that for an unseparated tunnel. The major inconvenience which results from this structure is the feeding of services from the access tunnel to the lower level. This is accomplished in chases in the wall behind the rails at regular intervals, and these services, while not likely to fail, will be difficult to replace. The one thing that is likely to become impossible as the levels build up, is extensive modification or repair of the housing itself in the lower level near the beam absorbers.

Each absorber is provided with a catch basin sunk in the floor of the lower tunnel which will hold the radioactive water from the device in the event of a major leak. Another hazard in the SLAC switchyard arises from activation of the air near the beam absorbers. DeStaebler has calculated that concentrations of approximately 100 times radiation worker tolerance will exist at shut down, providing the air in the switchyard has been thoroughly mixed. Without this mixing, serious exposures could result from a few minutes spent near a slit or collimator.

In order to provide quick access to the switchyard, we have provided for high speed venting of the structure (which is unvented during operation). When operating near maximum intensity, it will probably be sensible to delay this venting for 20 minutes or so to allow decay of O^{15} (3 minutes) and N^{13} (15 minutes) thus reducing the activity by approximately a factor of three. After these isotopes have decayed the dominating activity is A^{41} (2.6 hours) from neutron capture on A^{40}. Under very adverse meteorological conditions one can delay venting for half a day, by which time the levels will have dropped to tolerance, and will be due to Be^7 (54 days). These activities would be considerably increased if the slits and collimators had not been designed to contain all but a small fraction of the shower development.

Other papers at this conference deal with problems of induced activity for proton accelerators where problems are more severe for comparable power levels.

2. Radiation Damage and Induced Chemical Reactions

Radiation Damage to Materials

A rather clear distinction can be made between organic materials where covalent bonds can be broken by ionization, and crystalline materials, metals and ceramics where ionization damage is much less severe and most damage occurs as a result of the displacement of atoms. Fast neutrons are very efficient at producing displacements, so that for the latter materials the fast neutron flux is the most important factor. (This does not always hold for material in which the beam is actually stopped.) Table II shows the dosage required to damage several representative types of material.

Damage problems appear to be most severe for the "meson factories" as they produce a localized, intense source of fast neutrons. For beam powers of ~ 1 MW levels over 10^{19} n/cm^2/year will exist in a volume of 1000 cm^3 near a thick target, so that these accelerators approach the region in which metals show damage.

High energy proton machines have a less serious problem as the fast neutron production, though intense, is spread over a relatively large volume.

An electron machine's production of fast neutrons is approximately two orders of magnitude smaller than for a proton machine of comparable power, but the ionizing radiation fields are much larger for electrons. It is impossible to use organic materials near beam absorbers. The flux of electrons encountered by a metal in the beam will be near the damaging region, but the high temperatures produced simultaneously will be the major problem and will help anneal the defects.

Up to the point where metal damage occurs solutions can be obtained by constructing systems of metals and ceramics only. This is expensive but localization of the radiation and shielding of components away from beam stoppers can be used to restrict the amount of this expensive construction. For higher levels even more stringent localization

TABLE II

INTEGRATED DOSAGE FOR DAMAGE TO VARIOUS MATERIALS

Integrated Dose n/cm^2	Integrated Dose ergs/gm	rads	Material	Change	Integrated Ion.Dose* ergs/gm
10^{22}			Concrete	None	10^{19}
10^{22}			Copper	0.1% Growth in volume	10^{19}
10^{20}			Metals	Embrittlement. Increase in tensile strength.	10^{17}
10^{20}			Ceramics	Mechanical failure	10^{17}
~ 10^{20}	~10^{14}	~10^{12}	SLAC Epoxy	Mechanical failure	
10^{19}			Copper	10% drop in conductivity	10^{16}
10^{19}			Soft Iron	20% loss in permeability	10^{16}
10^{18}	10^{12}	10^{10}	Epoxy	Mechanical failure	
	10^{11}	10^{10}	Polyethelyne Polystyrene	Mechanical failure	
	10^{10}	10^{8}	Teflon Butadiene Polyurethane	Mechanical failure	
	10^{9}	10^{7}	Neoprene Rubber	Mechanical failure	
	10^{8}-10^{6}	10^{6}-10^{4}	Semiconductors	Electrical characteristic	

*The last column indicates the dose of 80 MeV electrons required to produce the same number of dislocations as the indicated fast neutron dose in column 1.

and frequent replacement of damaged components will be necessary.

At SLAC we will construct our transport systems as all-metal in the lower tunnel, except for insulation for cables and magnets and the vacuum chamber of the pulsed magnet. The cables are insulated with MgO in the critical areas, and with mineral or glass fiber elsewhere. Early in the design phase we considered magnet insulation in the light of predicted "worst case" dose rates between 10^{12} and 10^{13} ergs/gm/10 years. Since ceramic insulation is both expensive and inefficient because of the reduction in packing fraction and ordinary epoxies were very nearly sufficiently radiation resistant, H. Brechna[10] decided to experiment with different epoxies and loadings to improve their performance. The results of this work are being reported at this conference. At the same time we minimized the stray radiation lost in the magnets by providing thick copper collimators at various locations in the system. Present estimates by D. Neet[11] of levels in the switchyard predict dose rates of less than 2 times 10^{11} ergs/gm/10 years for all magnets except the pulsed magnet. The pulsed magnets sweep out degraded electrons from the main collimator and receive dosages up to 10^{13} ergs/gm/10 years, although the level at the coils is probably considerably lower than this figure. All of the magnets are built in a conventional manner with the alumina loaded epoxy used for coil insulation, which should support these radiation levels. Water paths in the magnets are ceramic insulated.

The vacuum chambers for the pulsed magnets must also be insulating since, at 360 cps, eddy currents in conducting chambers will distort the magnetic field and heat conducting chamber walls to high temperatures. Several tests are underway to evaluate different ceramics, which must also stand heating by electrons and possible charge storage. If no satisfactory material is found the magnets can be "canned" with a vacuum envelope surrounding the entire magnet. Dosages sufficient to cause metal damage can only be observed if the absorbing metals receiving 10^{18}ergs/gm/yr($\simeq$10 kw/gm). Cooling problems are great and thermal and corrosion problems are likely to dominate. These arguments apply to the SLAC slits and collimators, and equally to windows for low energy high current accelerators.

Induced Chemical Reactions

Irradiated gases and liquids may undergo chemical reactions which do not occur in the absence of radiation. Simple examples are the ionization of water leading to formations of H_2 and O_2 or H_2O_2, and the ionization of air with the consequent formation of NO_2 and O_3. Much more complicated reactions will occur if organic materials are bombarded.

The reactions in air can lead to high levels of toxicity if much of the beam escapes into the air. This is most likely to occur in the low energy electron accelerators. In the shielded enclosures around the SLAC slits and collimators ozone concentrations of 30 ppm will be produced in one day. N_2O levels of perhaps 5 times this concentration are likely. N_2O will combine with water or water vapor to form nitric acid. Most of the water and HNO_3 will condense on the walls of the tunnel. It may become necessary to circulate the air from these enclosures into the switchyard to avoid corrosion.

Water in the slits and collimators will be decomposed. Experimental numbers at the high dose rates encountered are lacking, but simple calculations and extrapolation from (10^6 times) lower currents seem to agree on H_2 evolution rates as high as 1.5 liters/sec per megawatt of beam power absorbed in the water. The concentration of H_2O_2 is expected to increase to high levels before O_2 evolution reaches half the H_2 value. These conclusions are still tenative. So far no serious problems have arisen in plans for disposing of the gas.

Several other problems may arise owing to radiation. Irradiation may change the behavior of the cooling water-metal interface resulting in decreased heat transfer or increased corrosion. Thermal fatigue behavior may be modified in very high radiation fields. These "second order" problems which complicate already existing problems are under investigation.

We have considered using liquid metal coolants and streams of liquid metal as beam absorbers. Such systems tend to corrode vigorously if impurities are present, even in very low concentrations. In some cases production of isotopes may be great enough to greatly increase corrosion, in addition to the very high induced activities in the liquid metal.

3. Shielding

The shielding of a transport system to protect personnel or experiments outside the housing structure from radiation is determined by the accelerator energy rather than by beam power, as the required thickness of material to reduce a given kind of radiation to a certain level increases only logarithmically. Intensity can cause qualitative differences in shielding if intensities are low enough so that some types of secondary particles can be ignored, and there is a large difference in the absorbtion lengths for the remaining radiations. I will not consider these "classical" shielding problems except to mention the particular solutions at SLAC. DeStaebler[12] has calculated the transverse shielding required for the SLAC switchyard to be 32 feet of compacted earth. (Figure 2.) This calculation does not include the usual large safety factor, since the two story structure will allow us to add up to 4 feet of steel over any insufficiently shielded region. This transverse shielding is determined by the absorption of neutrons in the few hundred MeV energy range. In the forward direction the most penetrating radiation will be μ-mesons. μ-mesons lose energy in material almost entirely by ionization loss, so that for minimum ionizing μ's the shield thicknesses necessary to stop the particles is a linear function of energy. A 20 BeV μ will be stopped by 50 feet of iron, or ~ 200 feet of earth. Enormous shields will be required for the high energy proton synchrotrons. The μ-mesons from the slits in the SLAC transport systems cannot escape into the target area for the high resolution system except after one or more large angle scatterings. In the other transport system μ-mesons from the slit impinge on a wall separating the target area from the experimental area which must be thick enough to stop the μ-mesons.

With the increasing power levels, shielding for protection of components which make up an accelerator or a transport system becomes important. Shields are also necessary to protect personnel against induced radioactivity, and where possible to absorb the inducing radiations in a favorable material. These have been discussed above.

4. Heating, Thermal Shock and Fatigue, Heat Transfer

When a beam of particles impinges on material heating results from the ionization loss of the particles. If this heating occurs suddenly, as in a pulsed machine, shock waves may be generated in the material. Cyclical heating and cooling may cause thermal fatigue. If the bombardment is continuous some means for removing heat from the material is necessary to limit the temperature rise.

Heating

The calculation of the spatial deposition of energy in a given material is a complicated physics problem. For high energies it is usually necessary to use Monte Carlo calculations, and in the case of proton machines in new energy regions to estimate relevant cross sections. It is very simple to obtain the energy deposition at the input surface:

$$\Delta T_{av} = \frac{\Delta Q_{av}}{C_p} = \frac{k\, i_{av}\left(\frac{dE}{dx}\right)_{ion}}{A\, C_p}$$

where

ΔT_{av} = average temperature rise, ^{o}C/sec

ΔQ_{av} = average energy deposited, (cal/gm)/sec

C_p = specific heat, (cal/gm)/^{o}C

i_{av} = average current, amps

$\frac{dE}{dx}_{ion}$ = ionization loss, MeV/(gm/cm^2) per incident particle

A = area of the beam, cm^2

k = 2.3×10^5 (particles/sec)/amp/cal/MeV

For a 1 cm diameter 100 μA beam of minimum ionizing particles the temperature rise in copper will be around 400°C/sec with no cooling. In pulsed machines the temperature rise per pulse may be great enough to melt the material, even though cooling for the average level is sufficient.

In the material the situation is much more complex. The production of secondary particles and showers by the primary beam changes the number and type of particles as a function of depth in the material, and the radial spread due to scattering and secondary production angles changes the effective area of the beam.

Figure 6 shows the fractional power deposited by electrons in a block of copper for different electron energies. The increase in loss due to shower buildup is evident at the higher energies. The maximum energy loss is approximately independent of energy above 1 BeV. The radial development results in shower sizes of approximately 1/30 of a radiation length. For beam sizes greater than this, the deposition of energy for a beam of particles will scale inversely as the area. For a 1 MW beam of 10 BeV and 1 cm^2 radius 100 kW are deposited in 12.8 gms/cm^2 for copper (1 radiation length = 12.8 gms/cm^2 for copper). At low energies the maximum loss at constant power scales as 1/E. Therefore, for low energy machines windows are very difficult while for high energy machines the problems occur deep inside a stopper.

The maximum multiplicity (number of charged particles per incident electron) in an electron shower can be obtained from the following formula (not good for very low Z)

$$N = \frac{1}{2} Z^{3/4} E \text{ (in BeV)}$$

Variations in Z of stopping metals will increase the temperature-rise (not the energy deposition) at shower maximum approximately as Z^2, since the specific heat varies roughly as 1/A.

Figure 7 shows similar curves for protons. The nuclear cascade process is evident for the high energies, but is not so pronounced as in the electron case. A very significant difference in the two cases is the extent of the lateral spread in the cascades. For the electron case the radial extent is small compared with usual spot sizes, and the peak heating is several radiation lengths inside the stopper. For protons the cascade products are spread over distances large compared to beam spot sizes, and the peak of energy deposition per unit volume occurs at the point of entry into the block. At lower energies the rise in $(dE/dx)_{ion}$ and 1/E scaling (for constant beam power) make proton window problems even more difficult than for electrons.

The problems of instantaneous heating of intercepting components may eventually limit the power levels possible. For accelerators used in a conventional way this limit is probably not far off. With streams of liquid metal for collimators and targets it is probably possible to approach 100 MW.

Thermal Shock and Fatigue

Thermal shock phenomena have received relatively little attention to date for high energy machines although accelerators like Astron, which can supply 200 A in a 0.25 μsec pulse at 4 MeV, can show spectacular shock effects. For the higher energy machines the need to keep the temperature rise/pulse small has minimized this problem to date.

Thermal fatigue is caused by cyclical stressing of a metal under the bombardment-cooling cycle, as the bombarded portion of the metal repeatedly expands and contracts. Failures will occur under such conditions at much lower stresses than predicted by by simple stress-strain relations. The significance of these for SLAC collimators has been discussed by D. Walz.[13, 14]

Heat Transfer

The high energy deposition rates present in high intensity systems require substantial cooling to prevent catastrophic temperature rise.

Cooling of the bombarded material can take place either by radiation to a larger surface area, or by conduction in which the heat is transferred to a coolant. In addition, the bombarded material may be physically moved out of the beam to increase the area over which transfer takes place.

Cooling by radiation requires that the beam be stopped in highly refractory materials. To transfer 100 $watts/cm^2$ a temperature of at least 2000°C is required.

The National Bureau of Standards is designing collimators of rotating tungsten disks which will radiate power to re-entrant water cooled fins. Such devices were considered by SLAC but the factor of 5 increase in power over NBS made them impractical. A disadvantage of such systems is the high vapor pressure of materials at elevated temperatures leading to considerable loss rates for the bombarded materials. A rough calculation for graphite discs at 3000°C showed loss rates of gms/day.

A stationary surface cooled by flowing water is the common system for cooling bombarded materials. Transfer rates of 1-2 kW/cm^2 are obtainable by careful design. The maximum rates before burnout lie between 5 and 10 kW/cm^2. Gas cooling is much less efficient. Liquid metal coolants can probably be used to increase these figures somewhat but suffer from severe activation problems. Water cooled Al surfaces are used in the collimators and slits at SLAC. The requirement of a vacuum tight surface forming the edge of the slit led first to stressed membranes and then to the design shown in Figs. 8&9 where water flows through Al tubes at high velocity. The walls of the tubes are as thin as possible so that a large fraction of the power is actually absorbed in the water, which is continuously moving. Design heat transfer rates of 2 kW are required at the shower maximum.

The beam dumps at SLAC are illustrations of a system in which the beam is absorbed in a moving coolant (Fig.10). Circulating water forms a vortex and the beam is absorbed by the water. Well after shower maximum copper plates are inserted to shorten the system.

Corrosion in these systems may be important with the intense exposure to ionization. The literature on radiation effects on corrosion are incomplete and often conflicting.

Conclusions

Problems of high intensity have led to rather complicated and expensive transport system designs. No system has yet operated over 100 kW.

High energy proton machines have the most severe activation problems but will have minimal problems in heating and radiation damage. High energy electron machines have the worst problems of heat transfer, and non-neglible activation and damage problems. Medium energy proton machines suffer from all three problems, but localization in space is straight-forward. At low energies heating becomes the dominant problem, and is worst for proton machines. Operations will probably uncover several problems not considered here. Unless these problems are more difficult than those foreseen, it should be possible to extend the power range to even higher levels.

Acknowledgements

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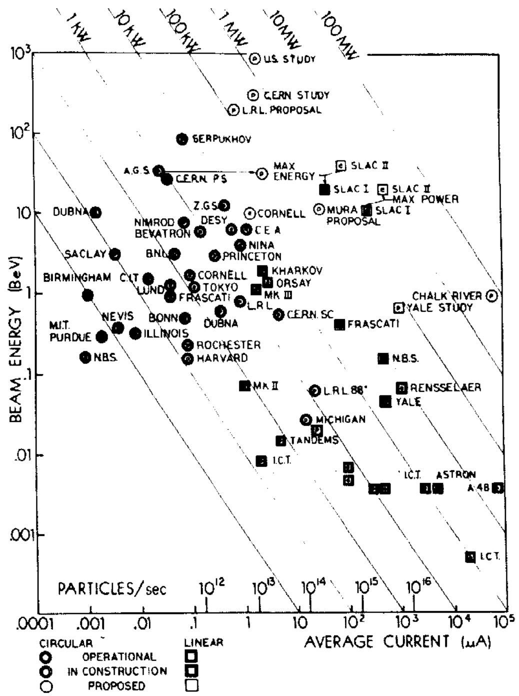

Fig. 1. Energies, currents and power levels of a selection of accelerators now operating, under construction, or proposed. (Several machines are not included, but are represented by other machines with closely corresponding parameters.)

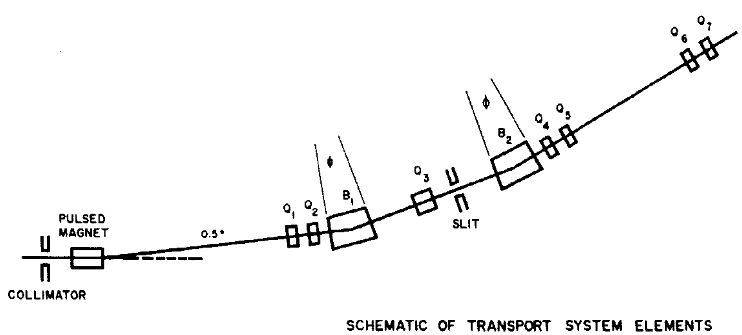

Fig. 2. A schematic of the optical system used in the transport systems at SLAC.

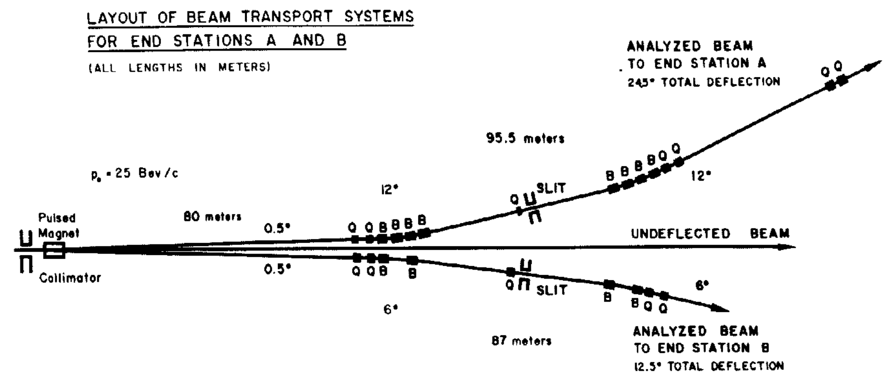

Fig. 3. Basic components of the SLAC transport system.

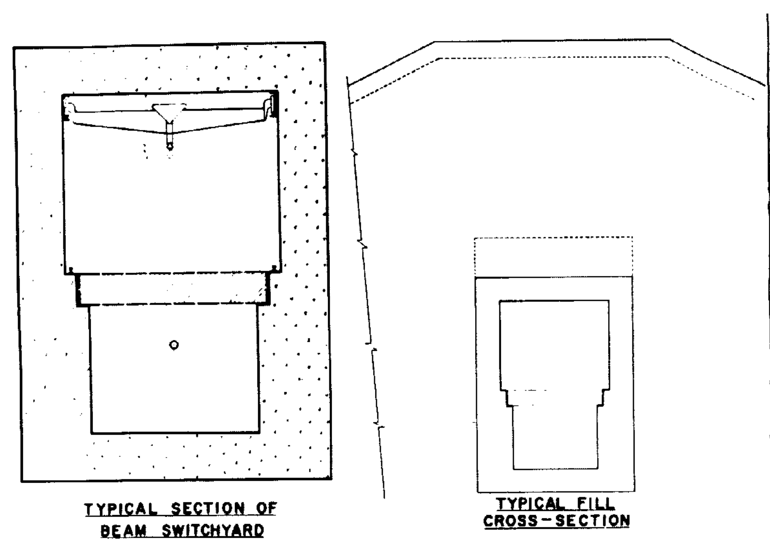

Fig. 4. Beam transport system and experimental areas at SLAC. The 24.5° deflection system is over 1000 feet long.

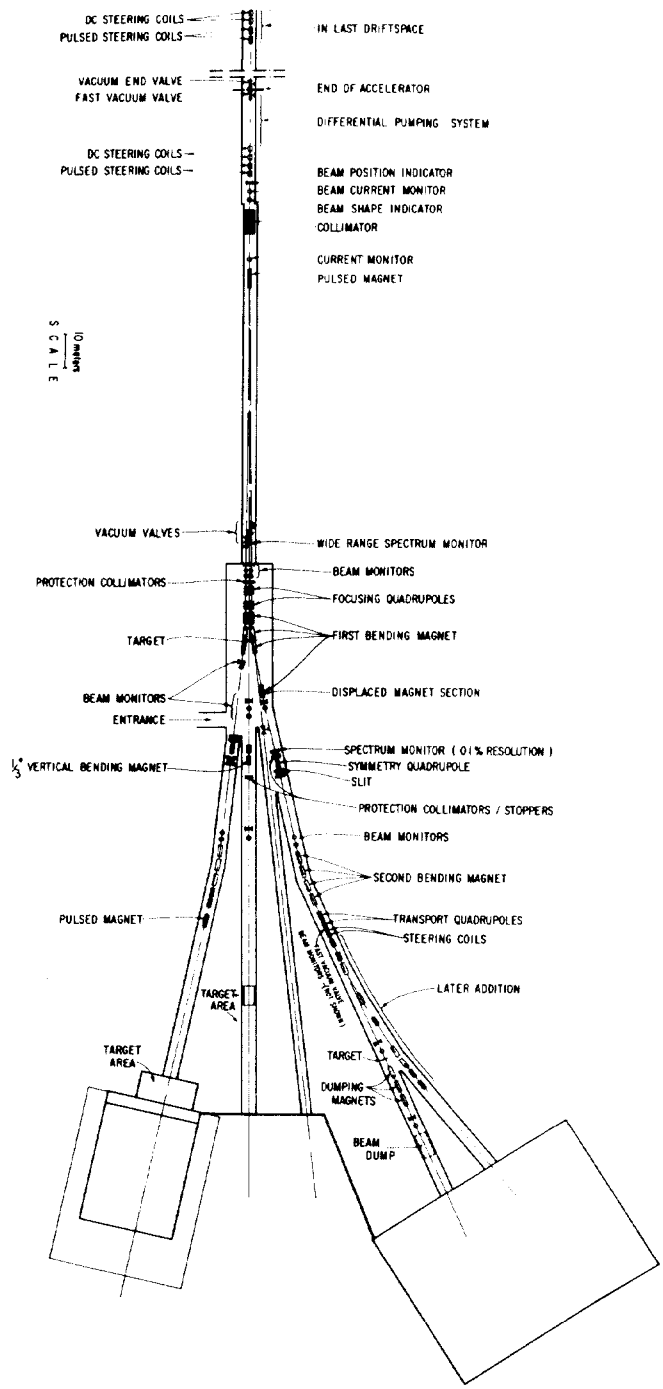

Fig. 5. Typical sections of the beam switchyard tunnel.

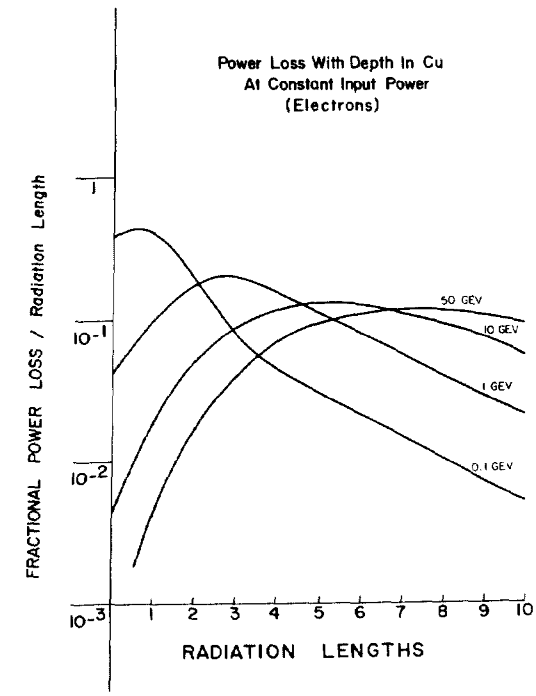

Fig. 6. Fractional power loss for electrons in copper.

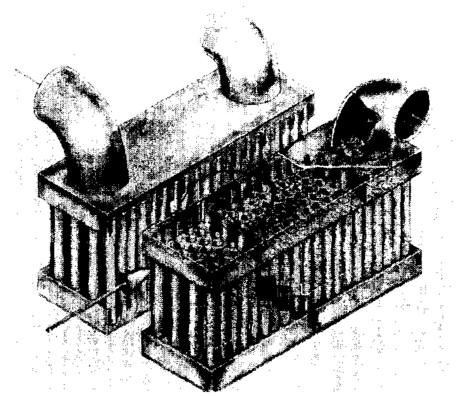

Fig. 8. Schematic of a module of the SLAC slits.

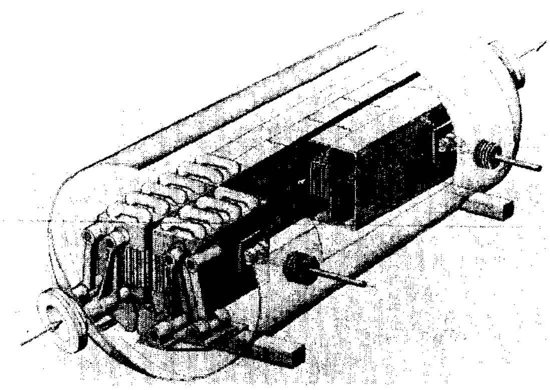

Fig. 9. Artist's conception of a SLAC slit. Two such units with one rotated 90° with respect to the other from the collimator.

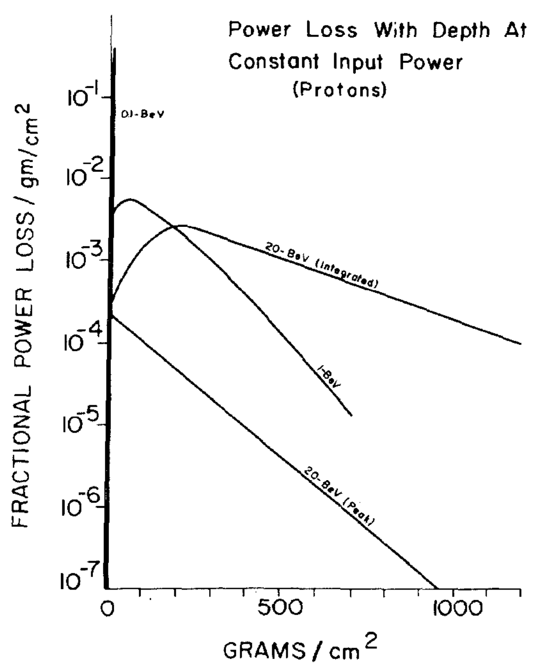

Fig. 7. Fractional power loss for protons in copper. (The lower curve represents the peak power loss as a function of depth.)

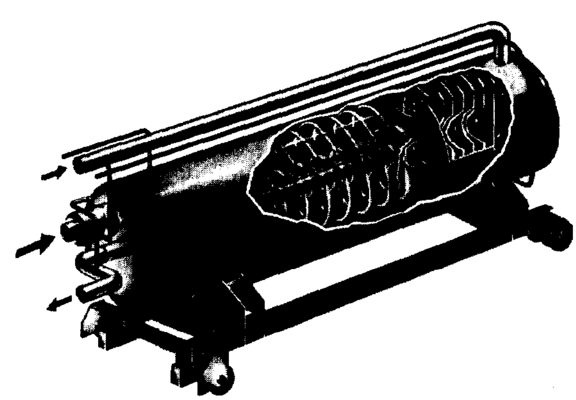

Fig. 10. Artist's conception of the SLAC Dump.