ON OPTIMIZATION OF COLLIMATOR SYSTEMS USED FOR CONTROL OF BEAM LOSSES IN LINEAR ACCELERATORS

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Abstract

A theoretical study is presented which is concerned with the purification of a proton beam from particles which may be lost at high energies and thus give rise to activation and radiation damage. Systems of collimator blocks are investigated with regard to their capability to eliminate such unwanted particles from the beam. Any attempt to purify a high energy beam in this way is partly counteracted by multiple scattering within the collimator material giving rise to new "bad" particles. The practical consequences of this effect, however, can be minimized by proper arrangement and dimensioning. Results are presented for a collimator doublett positioned in a linear accelerator at a proton energy of 100 MeV. The first collimator acts as a beam scraper which purifies the beam from bad particles, the second one is arranged at a certain distance downstream to absorb particles which have been scattered at the aperture edge of the primary collimator. By optimizing the arrangement of the collimators an overall removal ratio for undesired particles may be attained, which exeeds two orders of magnitude.

1. Introduction

The projected linear accelerator for the spallation source SNQ will be designed to carry high beam currents with an average value of 5 mA and a peak value of 200 mA. Under these conditions particle losses must be taken into account which are large enough to give rise to radiation damage and activation of sensitive components of the accelerator structure. These losses may result from residual misalignments, field imperfections and from the growth of the transverse emittance caused by space charge effects. Particle losses which can be tolerated from considerations of accessibility decrease rapidly with increasing particle energy. In the energy range above 100 MeV, for instance, tolerable losses are as low as 10^{-5} to 10^{-6} per meter of beam line, if the waiting time for access after shut down shall not exceed 24 hours.

Prediction of such small losses with a reliabiliy sufficient for the final design, however, is regarded to be not possible with presently available methods. A conservative approach, therefore, must be based on the assumption that particle losses cannot be reduced by conventional methods of beam optics to such an extent that the consequences remain tolerable.

The present study is an investigation on the possibilities to overcome the problem be arranging collimators within the beam line at one or several positions which act as beam scrapers. These devices will have to be designed to remove those particles from the beam which otherwise would be lost further downstream. Unavoidable activation and radiation damage would thus be concentrated to the collimator material and kept away from components which should be protected.

Any attempt to remove "bad" particles from a beam by collimators, however, cannot be perfect. Mainly multiple scattering processes within the collimator material will give rise to new particles with large angle and momentum errors with regard to the local transport properties of the beam line. The present study, however, gives evidence that these effects can be minimized to a sufficient degree.

Practical experience with beam purification by collimators has been gained with the storage ring ISR at CERN. Risselada et al. /1/ report successful application of collimator systems in this circular machine. Proper design and precise positioning of the collimators obviously reveal to be important for effective control of beam losses.

2. Investigated collimator system

The system considered in the following consists of a collimator doublett arranged in a proton linac at an energy of 100 MeV. For the projected SNQ-accelerator this corresponds to the transition section between the Alvarez part and the subsequent high energy accelerating structure.

The first collimator is designed as a beam scraper which purifies the beam from bad particles, the second one is arranged to absorb particles which are scattered at the aperture edge of the primary collimator.

2.1 Modelling assumptions

The effect of collimators on the beam quality has been analyzed by means of the computer programme REVMOC /2/. This programme is a multi particle Monte Carlo code which simulates the interaction of protons with a target of solid material. The target geometry can be specified in such a manner that collimator blocks with different types of inner apertures can be represented. In the present study rectangular, circular and elliptical aperture shapes have been investigated.

Particle transport in free space is calculated by means of second order optics, particle interaction with solid material includes multiple scattering, energy loss due to ionization, nuclear absorption and nuclear elastic scattering. In the Monte-Carlo simulation of multiple scattering particle displacements and scattering angles are randomly chosen in such a manner, that they are in agreement with distributions deduced by Molière /3/. Energy losses due to ionization are also evaluated in a manner that takes the statistical nature of these processes into account. The distribution of the energy losses is calculated in such a manner that it corresponds to approaches deduced by U. Fano /4/ and L. Landau /5/.

2.2 Effect of the primary collimator

Results obtained for 100 MeV protons and copper as collimator material are represented in Fig. 1. The cross section of the incident beam was assumed to be elliptical and the maximum angular divergence was chosen to be 5 mrad. The aperture area of the collimator was chosen in such a manner that 15 % of the primary particles hit the collimator face.

The fraction of particles which is scattered from the collimator block into the beam with angles larger than the maximum angular divergence of the primary beam has been determined and compared with the fraction of primary protons captured in the collimator block. These

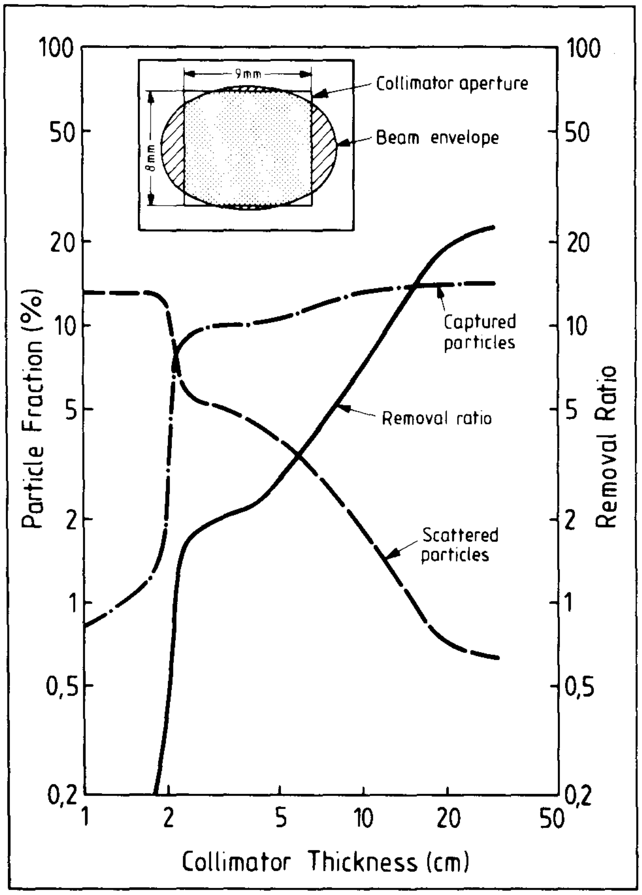

Fig. 1: Removal ratio and particle fractions vs. collimator length for a copper collimator positioned at a proton energy of 100 MeV

fractions are shown in Fig. 1 as a function of collimator thickness. The term "removal ratio" appearing in this figure is used for the ratio of protons removed from the primary beam by capture to the fraction of those protons which are scattered into the beam channel behind the collimator. The removal ratio characterizes the effectiveness of the collimator to eliminate bad particles. The figure shows that the removal ratio is small at a collimator thickness below about 1.8 cm. It increases rapidly beween 1.8 and 2.5 cm and less steep beyond this value. The main reason for this behaviour is the decrease of the amount of particles which are scattered into the beam line if the collimator thickness increases. To attain a removal ratio of 10, for instance, a collimator thickness of about 13 cm is required at this energy.

2.2 Effect of the secondary collimator

Scattered particles emerge from the downstream face of the primary collimator mainly at the edge of the aperture because most of the multiple scattering processes are located within a thin materials layer. The REVMOC-code predicts that the scattered particles cover a broad range of energies below the energy of the primary particles and may have large angular divergence.

The optimum position for the antiscattering collimator is given by that distance behind the primary collimator where the fraction of scattered particles which hit its front face has a maximum for a given aperture. The aperture, in turn, should on one hand be small to keep transmission of scattered particles small, on the other hand large enough to avoid additional capture of particles from the bulk of the beam.

The optimum distance between the primary and the secondary collimator depends essentially on the beam optics between. The high energy accelerating structure of the SNQ-linac will consist of a series of unit cells of identical design, each cell containing four HF-accelerating gaps and a pair of quadrupole lenses which act as a FODO-system. Particle transport codes predict that for this structure an optimum distance is given if both collimators include four unit cells. This corresponds to a distance of about 12 m. The optimum is not very distinct. A distance including one cell more or less is almost as good.

The removal efficiency of scattered particles as a function of collimator aperture is shown in Fig. 2 for two collimator thicknesses. The removal ratio includes particles which experience scattering at the aperture edge of the secondary collimator.

For small apertures the removal ratio increases steeply with increasing aperture. At an aperture of about 1.35 cm it attains a distinct maximum and decreases monotonically for apertures beyond this maximum. The position for the maximum is only weakly dependent on the collimator thickness.

The phenomenon may be understood with the help of Fig. 3. It shows schematically the influence of the antiscattering collimator on particles which have been subject to scattering at the primary collimator. Most of the particles with a large angle divergence will hit the front face of the collimator but a certain fraction will be transmitted through the aperture. This latter fraction is roughly determined by a cone formed by the aperture and the thickness of the secondary collimator. Particles which do not move inside this cone will either hit the front face of the secondary collimator or the inner surface of its aperture. Part of these particles will enter the beam line after multiple scattering in the secondary collimator.

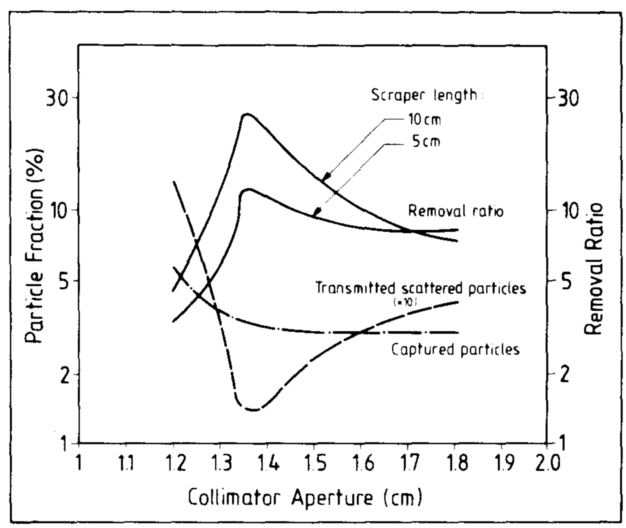

Fig. 2: Removal ratio and particle fractions behind a collimator doublett vs. secondary collimator aperture for a proton energy of 100 MeV

Transmitted scattered particles appearing behind the antiscattering collimator, therefore, arise partly from scattering at the primary and partly from scattering at the secondary collimator. The first contribution to the transmittance increases with increasing aperture

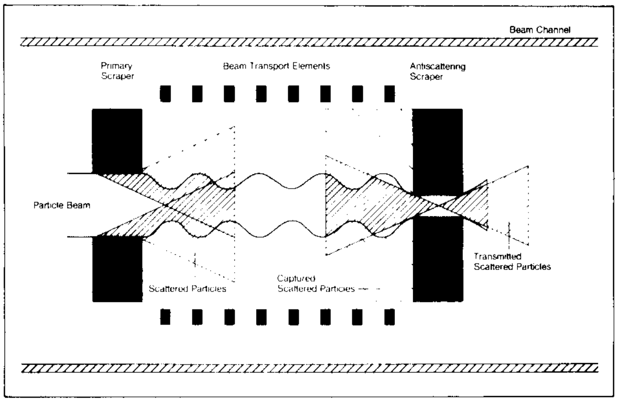

Fig. 3: Schematic representation of the generation and removal of scattered particles in a collimator doublett

of the antiscattering collimator whereas the second contribution decreases with increasing aperture. The observed maximum of the removal ratio appears at the point where both counteracting effect are in balance.

3. Collimator materials

The SNQ-accelerator certainly requires several collimator systems along the high energy accelerating part. It is expected that one collimator system will be able to suppress undesired particle losses over a limited distance only. The dominating counteracting mechanism is probably transverse emittance growth and halo formation due to space charge effects. The study performed for 100 MeV protons gives evidence that an efficient purification of the beam requires that the collimator thickness should exceed the penetration depth of protons considerably. The optimum collimator thickness at 100 MeV is still moderate (in the order of several ten centimeters) but at 1000 MeV the penetration depth will be in the order of one meter.

Short penetration depth at high proton energies, therefore, is an important requirement for collimator materials in addition to a low scattering cross section. Another important aspect comes from the heat deposited in the collimator material as a consequence of the capture of high energy particles. An adequate cooling system will, of course, have to be provided. Nevertheless a high melting point and large heat storage capacity is favourable to avoid melting in case of an accidental transverse displacement of the beam from the beam line axis.

Materials which may be taken into consideration are listed in table I together with some of their relevant properties. The table contains as a measure for the scattering properties of the material the quantity $\sqrt{Z}/\rho$ (denoted as "scattering power") where Z is the atomic number and ρ the density. Fig. 4 shows the penetration depth for protons in several materials as a function of energy.

4. Conclusions

The present theoretical study gives evidence that proper dimensioning of a collimator doublett will provide efficient purification of a proton beam from particles which otherwise would cause activation of the accelerator structure. The undesired consequences of multiple scattering within the collimator material can be minimized to a degree that an overall removal ratio for "wrong" particles can be attained which amounts to more than two orders of magnitude.

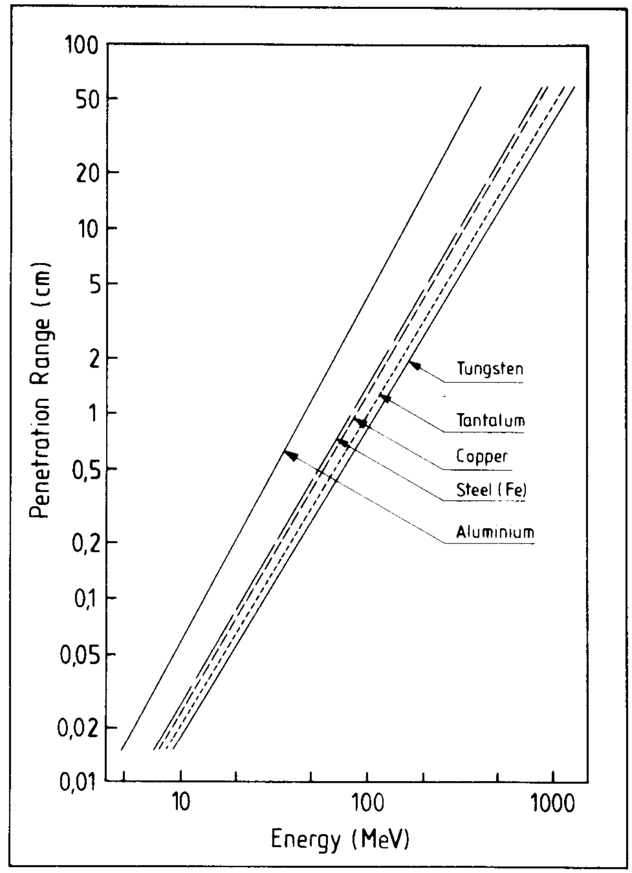

Fig. 4: Penetration range of protons for various materials vs. proton energy

TABLE I

PROFERTIES OF MATERIALS FOR SCRAPERS AND COLLIMATORS

Material	Atomic Weight	Density g/cm³	Scattering Power	Heat Capacity (J/cm³·K)	Melting Point (°C)	Penetration Range (100 MeV) (cm)
Copper	63	8.96	0.60	3.45	1083	1.350
Steel(Fe)	56	7.8	0.65	3.59	1500	1.488
Tungsten	184	19.3	0.44	2.58	3380	0.854
Molybdenum	96	10.2	0.63	2.60	2625	1.325
Titanium	48	4.5	1.04	2.39	1800	2.540
Tantalum	181	16.6	0.51	2.50	3000	0.987
Nickel	58	8.9	0.59	3.91	1455	1.287

5. References

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