PROBLEMS CONNECTED WITH PARTICLE EXTRACTION FROM ACCELERATORS OF SUPER-HIGH ENERGIES

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1. INTRODUCTION

The efficiency of modern accelerators operating for experimental purposes depends to a great extent on a proper choice of the general layout and characteristics of their ejection systems, particle beam parameters included. The higher the energy, the more complicated is the problem to construct ejection systems that satisfy the requirements of the physics experiments. The problem becomes even more complicated due to radiation influence of the ejected beam on the accelerator components. As is shown further on, these problems acquire a qualitatively new character at energies above 1 TeV and their solution requires new approaches which, in the majority of cases, determine the constructional features of the ejection system and the accelerator itself, and what is even more, determine upper limits for the particle beam intensity. In the present work some of these problems are treated. Some numerical values given here for illustrative purposes, are for the IHEP accelerating-storage complex (UNK) with a design energy of 3 TeV/1/.

2. FACTORS IMPOSING LIMITATIONS ON THE EJECTION EFFICIENCY

When the particle energy is less than hundreds of GeV, the application of an electrostatic septum ES with a screen made of 0.08-0.1 mm wires allows one to obtain an efficiency of slow ejection not worse than 99%. Some fraction of the beam, not more than 1%, interacts with the material of the electrostatic septum, thus warming it up and producing a source of secondary radiation. At this level of energies the main types of interactions are multiple Coulomb and elastic scattering. The situation is quite different at energies of the order of thousands of GeV. Figures 1 and 2 show the characteristics of 3000 GeV proton interactions with Cu target nuclei. The distributions for other atomic nuclei are of the same character. These quoted distributions are peculiar for the very strong anisotropy of the angular distributions and for the large values of the mean energies of the secondary hadrons. These features lead to high densities of energy deposition in the material near the beam axis. Less than 10% of the particles hitting the septum will leave the wires due to multiple Coulomb and elastic scattering. Thus at super-high energies almost all the particles hitting the wires of the ES will inelastically interact with nuclei. Consequently, the best way to reduce energy deposition on the septum is to reduce the beam losses on it. Let us consider this possibility in detail.

The density of particle beam losses on the electrostatic septum at the excitation of the third order resonance is $\rho = \delta\,(\frac{1}{\Delta A} + \frac{1}{A_c})$ where δ is the septum thickness, ΔA is the step in the amplitude increase, A_c is the distance from the septum to the beam centre. The value of A_c is limited by the accelerator aperture and can be increased at the location of the electrostatic septum by increasing the amplitude function β_c. The beam dimensions in the regular part of the accelerator will be smaller than in the long straight section by a factor $\left(\frac{\beta_c}{\beta_k}\right)^{\frac{1}{2}}$, where β_k is the amplitude function for the regular part. When slow ejection is performed this allows one to have a sufficient clearance between the beam edges, during

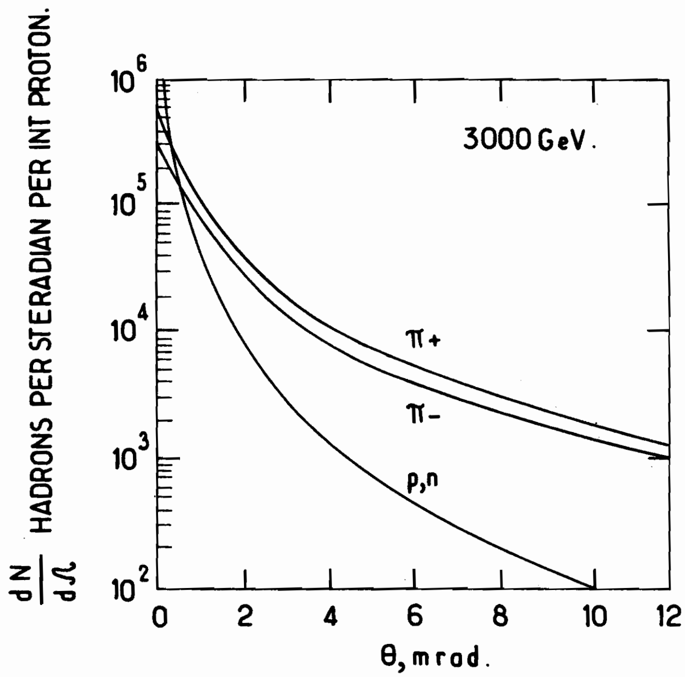

Fig.1 Angular distributions of hadrons produced in interactions of 3 TeV protons with Cu nuclei

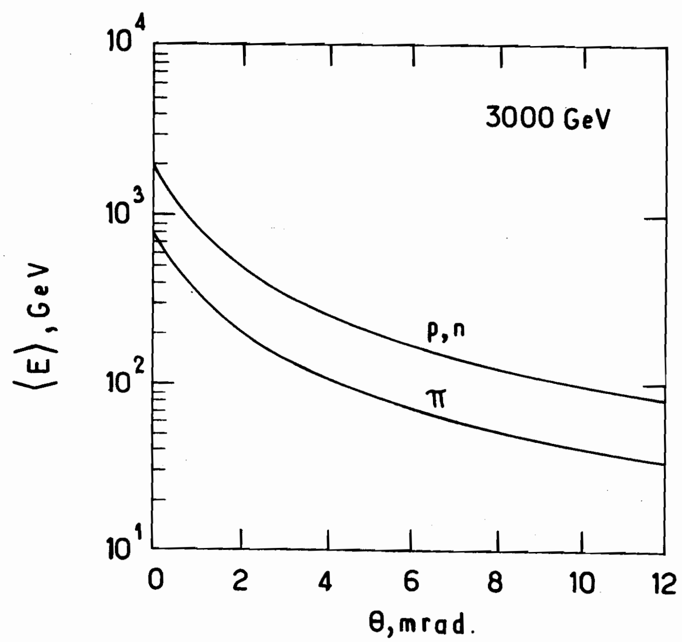

Fig.2 Angular dependence of average hadron energy in interactions of 3 TeV protons with Cu target.

resonance, and the vacuum chamber. To make the beam losses on the electrostatic septum less than 1% (the wires are ∿ 0.1 mm thin) the step size ΔA should be more than 10 mm. For the UNK we adopted ΔA = 20 mm. A further increase of ΔA does not give us any appreciable gain in efficiency, but would nevertheless result in a considerable increase of the voltage of the electrostatic septum.

In the regular part of the UNK ring β_k = 150 m and the radius of the aperture of the vacuum chamber is equal to 35 mm. In order to have $A_c \approx$ 35 mm at the point of location of the ES the quantity β_c was chosen to be equal to 1200 m. In this case the clearance between the resonant beam and the chamber is about 15 mm. Though the value for β_c of 1200 m is not the maximum one, it seems not to be expedient to make it larger since in this case the aperture and forces of the quadrupole lenses of the long straight section become larger alongside with higher requirements for the accuracy in manufacturing and tuning and greater power of the resonance system. From what was said it follows that the values for the losses in the wire septa quoted above i.e. 1% or a little bit less - may be considered as very close to the real ones.

At 3000 GeV the length of the free path in the ejection straight section should not be less than 150 - 200 m at reasonable forces and lengths of the elements of the extraction system. The calculations show that an increase in the value of β_c is accompanied by a shortening of the length of the free path. At β_c = 1200 m one can have a free path of ~ 160 m. The structure for the long straight sections of the UNK chosen on the basis of the above arguments is shown in fig. 3. Further increase of the accelerated beam energy will cause a considerable increase in the length of the straight sections.

The power of the ejection units, which occupy quite a great part of the straight section, increases linearly with the energy.

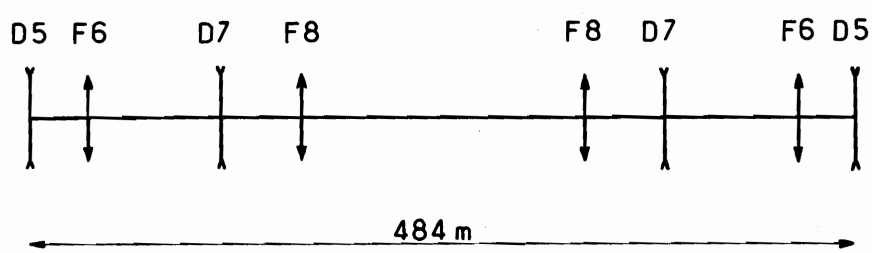

Fig.3 Layout of the quadrupoles in the long straight section of the UNK

3. RADIATION HEATING

Many problems in particle extraction from accelerators of super-high energy are connected with radiation problems. These result from the nuclear cascade, initiated by interactions of intense high energy particle beams with matter : residual gas, wire septa, vacuum chamber, magnetic elements, external targets, and absorbers. Energy deposition during cascade development is the factor which leads to the undesirable consequences.

Hadrons and the accompanying electron-photon cascades are calculated in the present work with a Monte-Carlo method using the program MARS-4 [2,3]. The modelling scheme, the physical models used here and possibilities of the program are described in the works quoted above. When calculating the heating the thermal physical parameters are assumed to be independent of temperature. The initial temperature of the system is 27°C. The parameters of the considered materials used for our calculations are presented in Table I.

TABLE I

Parameters of materials used in heating calculations

Material	Be^9	Ti^{48}	W^{184}
$\rho (\frac{g}{cm^3})$	1.85	4.54	19.20
$C_p (\frac{J}{g°C})$	1.8	0.5	0.14
t_m(°C)	1283	1668	3380

It should be noted that the temperature increases of the materials given below, calculated without taking into account phase transitions have a physical meaning only up to the temperatures below the melting point t_m (Table 1).

Heating above t_m, which cannot be permitted, is given here only to make clear how serious the situation is. Due to greatly non-uniform temperature fields arising in the course of heating of the ejection system units, there may occur mechanical stresses exceeding the limit of elasticity, which lead to mechanical destruction of the constructional elements. Assuming that the admissible heating is not very large ($t_o + \Delta T < 0.6\ t_m$) we do not treat this problem in the present paper.

4. HEATING OF THE WIRE SEPTA

Beam losses on the ES result in considerable heating of the wire septa. Estimations of the wire septa heating were made for two materials: tungsten and titanium, the proton energy being 3000 GeV and beam losses on the ES wire septa in resonance ejection 1% as indicated above. The wires of the ES wire septa are 0.1 mm diameter, 40 mm long and the distance between them is 1 mm. The distribution of the incident particles on the front face of the ES is assumed in our calculations to be uniform in the horizontal plane and Gaussian in the vertical plane with dispersions σ = 2.5 mm and 5 mm. The maximum heating takes place near the beam axis at a distance of about 75 cm from the beginning of the ES wire septa for tungsten and 300 cm for titanium. The estimates of the maximum temperature rise of the ES wire septa at instantaneous ejection of 5.10^{13} protons are given in Table 2.

TABLE 2

Estimates of the maximum ΔT of the wire septa at instantaneous extraction of 5×10^{13} protons

σ_V	2.5 mm	5 mm
W	22000°C	10000°C
Ti	840°C	550°C

As is seen in manufacturing the wire septa one can use only very light and sufficiently heat-resistant materials. Furthermore the vertical dimensions of the beam on the wire septa should be as large as possible. The higher the energy of the ejected beam the more difficult it is to solve the problem of the septum heating. Similar estimates made for slow ejection show that the situation with the heating of the ES wire septa will be somewhat better, since during slow ejection heat is carried away by the mechanisms of heating conduction and heat emission from the surfaces of the wires. However, the problem of radiation heating of the splitter in the target station in the slow ejection system remains very serious, if no special measures are taken to reduce the losses on it.

5. PROTECTION AGAINST RADIATION IN THE EJECTION SECTION

One of the main problems with the accelerators of super-high energies is the one connected with the radiation heating of the superconducting magnetic systems (SMS) caused by the incident particles hitting it. Instantaneous energy deposition in the materials of the superconducting magnets caused by the influence of high energy particles leads to their heating and quench. It follows from the calculations[4,5] that the level of losses must be reduced to extremely low values to avoid quenching of the superconducting magnets.

A very serious situation arises in the ejection straight section, since the electrostatic septum is an important source of secondary radiation. Secondaries generated on the ES wire septa irradiate the downstream SMS. The hadronic constituent of the secondary radiation initiates the development of the extranuclear cascade in these elements, while photons from π^0 meson decay produce electromagnetic showers. During fast ejection the time of irradiation of the SMS is less than 1 ms. This results in a practically instantaneous rise of temperature of the superconductor of the constructional units of the SMS corresponding to the spatial distribution of the energy deposition. This is the most dangerous mode of radiation, since in the slow ejection some part of the heat release may be taken away by the coolant.

To reduce the radiation influence on the superconducting elements downstream of the ES in the ejection straight section and in the ring tunnel down to some tolerable level some particular protection measures should be taken [5]. For instance, the increase up to 5-7 mm thickness of the vacuum chamber walls in the area of the superconducting elements suffering the highest irradiation reduces greatly (up to an order of magnitude) the energy deposition from the electron-photon shower, which constitutes the main contribution to the total energy deposition at energies in the TeV region.

Steel 6 m long collimators situated in front of each superconducting quadrupole of the ejection straight section can reduce the level of the quadrupole irradiation almost four times.

When the beam energy is higher than 1000 GeV the deflection of the beam before the ES by an angle of a few mrad is also an effective way of protection. This measure allows one to weaken quite considerably the contribution from the neutral component to the total energy deposition in the long straight section quadrupoles as well as in the bending magnets immediately downstream of the long straight section. The maximum distance between the superconducting magnet systems and radiation sources plays also an important role in the processes of reducing the energy deposition. As is shown in [5] all these measures together give the possibility to realize slow ejection of the beam with an intensity of 10^{14} ppp and fast ejection with 10^{13} ppp at E = 3 TeV. The higher the energy of the ejected beam the more complicated is the problem concerning radiation heating of the superconducting elements in the ejection straight section.

6. EMERGENCY BEAM EJECTION. HEATING OF THE EXTERNAL ABSORBER

The energy stored in the proton beam during the acceleration process is of the order of hundreds of MJ at the super-high accelerators. Even if a fraction of the beam hits the accelerator elements it may cause the failure of the systems. To avoid such a situation there should be some special systems for emergency beam evacuation. In their structure these resemble conventional beam ejection systems which can evacuate the beam during not more than one turn if an emergency situation occurs. The system of emergency evacuation should be designed for the maximum emittance and maximum energy of the beam. If the energy variation range is rather large during the acceleration process, it will be more expedient to divide the abort system into two or even more stages thus making the efficiency and reliability of the system higher. The first stage must evacuate the beam of lower energy but larger size. The second one is for the beam of higher energy and smaller size. The optimal division with respect to the energy is such when the power of the parts is almost equal.

The beam extracted from the accelerator with the help of the abort system, is guided onto special external absorbers, the number of which corresponds to the number of emergency evacuation systems. In a general case the beam absorber consists of a cylindrical core, designed to absorb the main fraction of the beam energy. It also contains a heat-resistant insertion made of some light material. To reduce the level of the residual radiation down to a tolerable level and to protect the earth and ground water against radiation this core should be shielded. It is expedient to use beryllium or carbon as material for the heat-resistant insertion and iron for the cylindrical core. The shield should be heavy concrete.

To estimate the heating of the absorber under the influence of the ejected beam we made calculations of the nuclear cascade in a beryllium insertion, whose diameter is 25 cm and length is 600 cm. Figure 4 presents the radial distributions of the temperature field

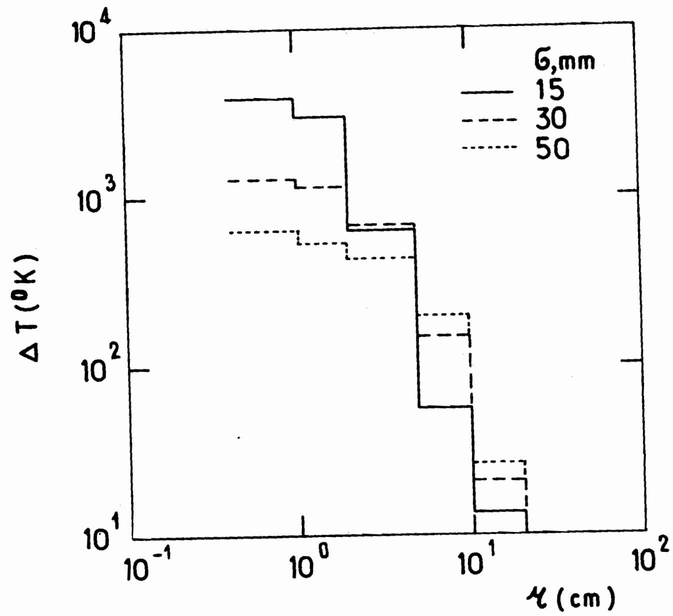

Fig. 4 Radial distribution of the maximum heating in the Be insertion of the abort system absorber when $5 \cdot 10^{14}$ protons with energy of 3 TeV are instantaneously stopped on it. Dispersion for beam density distribution σ = 15,30 and 50 mm.

at the cascade maximum at a depth of 275 cm for protons with an energy of 3 TeV and three values for the dispersions of the beam density distribution. As is seen the temperature when dumping a beam with an intensity of 5×10^{14} ppp remains below the melting point only when σ = 50 mm. Table 3 gives the maximum heating at instantaneous stopping of 5×10^{14} protons of various energies with a dispersion σ = 30 mm on a beryllium absorber.

TABLE 3

Maximum instantaneous heating when stopping 5×10^{14} protons with beam size σ = 30 mm and various energies in a beryllium dump

E_0 (TeV)	0.4	1.5	3	20
ΔT(°C)	140	750	1400	12000

If the energy increases above 3000 GeV the transport system should provide still larger dimensions of the beam on the absorber of the abort system.

From the calculations it follows that with increasing energy the problem of heating the beam absorber becomes still more complicated. The simplest way out is beam defocusing during its transport to the absorber.

7. EXTERNAL TARGETS

One of the very important problems is the problem connected with heating of the external targets. In the majority of the cases the physical experiments require very small transverse dimensions of the beam on the target. At high energies and large intensities this results in large temperatures and very unhomogeneous heating of the target.

For illustration we have calculated the temperature field in a beryllium target 150 cm long and with a radius of 1 cm irradiated instantaneously by a proton beam of 0.4, 3 and 20 TeV. The protons have a Gaussian density distribution with dispersions 1 and 2.5 mm. The beam axis coincides with that of the target. The maximum heating is observed along the beam axis at the end of the target. Maximum heating has been calculated for an intensity of 5×10^{13} protons (see Table 4).

TABLE 4

Instantaneous temperature rise in a 1.5 m long beryllium target with 10 mm radius irradiated by 5×10^{13} protons

E_0 (TeV)	0.4	3	20
$\Delta T(^{\circ}C)$ for σ = 1 mm	220	9100	1.5×10^5
$\Delta T(^{\circ}C)$ for σ = 2.5 mm	145	4800	6×10^4

The heating reaches about 1600°C for a 50 cm long target at a beam energy of 3000 GeV and σ = 1 mm. According to the estimations in the case of the slow ejection of a beam with an intensity of 10^{13} pps at E = 3000 GeV the heating will be about 400°C for σ = 1 mm onto a target of 150 cm length. Using a cooling system in the target one can reach high intensities in the case of slow ejection.

From the estimates quoted it is clear that fast ejection imposes certain limitations onto the intensity of the beam. This level is the one that will not result in the heating of the target up to the melting point. Another way out is to use targets only once.

From the above estimates it becomes evident how important the problem is when the beams of high energies and intensities are ejected. Many problems require further detailed study, search for new materials and techniques. Counter and bubble chamber experiments need slow and fast ejection. The best way for slow ejection is a resonance one using resonances of betatron oscillations of the third order. High efficiency of such an ejection with application of special measures on protecting the superconducting elements in the ejection SS makes it possible to reach an intensity of the order of 10^{14} ppp at 3000 GeV. With fast ejection of the beam the difficulties become even more serious. However, the requirements of the majority of the foreseen experiments can be satisfied if only a fraction of the beam intensity will be ejected. Thus the ejection may be realized in parts several times during the flat top of the magnetic field cycle. Fast resonance ejection can conveniently be used in simultaneous operation of the fast and slow ejection. This permits to eject into the same beam channel without readjustment of the focusing system and also allows to adjust the ejected intensity within the required limits so that the radiation level in the ejection SS and external target heating will remain within the admissible levels of irradiation.

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