RADIATION DAMAGE PROBLEMS IN SLOW EXTRATION AREA AND INTERNAL BEAM DUMP OF SIS100

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1. Introduction

SIS100 is a to-be-built superconducting synchrotron of FAIR facility [1]. It should accelerate proton beams to energies up to E = 27 GeV and intensities up to $N = 2.5 \cdot 10^{13}$ particles per cycle and wide range of heavy ion beams, like for example U ion beam up to E = 2.7 GeV/u and $N = 5 \cdot 10^{11}$ ions/shot.

Unavoidable particle losses of such high-energetic and high-intensity hadron beams lead to serious radiation damage problems in the synchrotron, like quench danger, degradation of material properties, mechanical stability and residual activation of the machine components.

In the present work we consider the problems in the most critical parts of the synchrotron from the radiation damage point of view: beam losses in the slow extraction area and emergency beam dump into the internal beam dump of SIS100. Due to the restricted volume of the paper we mostly state the nature of the radiation damage problems and technical solutions and for more detailed information we direct the reader to GSI internal notes and other publications [2-5].

2. Radiation problems in the slow extraction area

Unavoidable beam losses of the order of about 5% are expected in the slow extraction area of SIS100. The main beam loss mechanism is the change of the rigidity of beam particles hitting the wires of the electrostatic septum. Simulations showed that the particles with changed rigidity end up lost into the quadrupole doublet situated right downstream the septum [2]. Numerous radiation damage problems are invoked due to the lost particles:

- mechanical stability of the septum wires [3]
- quench danger in the quadrupole doublet [2]
- insulation degradation in the quadrupole doublet [2]
- residual activation in the slow extraction area [4]
- total ionisation dose (TID) problems and single event upsets (SEU) in the electronics [5]
- degradation of optical cables [5]

The septum wires are very effectively heated by lost U ions from one side and very poorly cooled from the other side. Due to the small diameter of the wires the heat conductivity along the wire is negligible and the only cooling mechanism is radiation cooling from the surface of the wires. The energy deposition into the wires increases with the volume of the wire and radiation cooling increases with the surface area of the wire. Thus the wires with small diameter are preferable [3]. The simulations showed that for spill length of the order of one second, Ti wires should have the diameter as small as few micrometers in order to keep the temperature below the comfortable value of 1500 K. Mechanical stability of such thin wires is a big technical problem.

U beam losses of 5% out of the nominal intensity $N = 5 \cdot 10^{11}$ ions/shot at beam energy $E = 2.7$ GeV/u make about 1.5 kW of energy deposition into the quadrupole doublet. In order to evacuate this heat via the cryogenic system of the superconducting magnets, one needs a liquid He cryoplant with power of about 1.5 MW, which is unrealistic. One should consider a possibility to evacuate this heat load by other means, for example, using liquid N in the spots without superconducting wires. That would require a special non-standard design of the doublet. Or one should replace this particular quadrupole doublet with normal conducting one. The superperiodicity of the machine beam optics will be distorted in both cases.

Another unpleasant peculiarity of the lost beam is its non-uniform distribution in the transverse plane. Most of the lost beam particles hit the quadrupole coil in the horizontal direction. Simulations [2] showed that the energy deposition into the Kapton insulation of the coil would be of the order of 100 MeV/cm^3 per lost ion. Even if one assumes very optimistic value 100 MGy for the radiation hardness of Kapton, this limit would be exceeded just in 100 hours of synchrotron operation in slow extraction regime. One should take special care about the design of the quadrupole coils. Either the coil should be shielded by some metal plate or a special gap should be introduced in the coil design in order to avoid the direct hit of the cables by lost particles.

In order to insure safe hands-on maintenance of the machine the losses of U beam should not exceed few Watts per meter [4]. Otherwise the induced residual activity would not allow any access to the hot spots for many hours or even days. Simulations [2] showed that the 1.5 kW of U beam loss is distributed in the slow extraction area over a length of about 10m. This is by far above the comfortable few Watts per meter value. And this problem of the residual radioactivity is very conservative and cannot be avoided at any special design of the doublet. One needs to work out a special access scenario in case of urgent need of maintenance.

The secondary particles from the lost beam create very high radiation field in the tunnel of SIS100 downstream of the slow extraction point. This results in danger to the electronics and optical cables. According to estimates [5] it is possible to organise the ditches in the tunnel in such a way that the cables receive 0.6 kGy/y. Cables with radiation hardness of 25 kGy would survive for about 40 years. From the other hand the radiation tolerance of the electronics to TID is 200 Gy/y only. So, they would survive in the ditches for few months only. Even in the niche nearest to the slow extraction point the electronics would receive 130 Gy/y. Also the neutron flux of $5 \cdot 10^{11}$ n/cm^2 per year would lead to about 5 faults of electronics per year. So, installation of electronics in more distant points is required.

3. Internal beam dump in SIS 100 synchrotron

Internal beam dump in SIS 100 synchrotron is being developed for an emergency situation when the power supply fails during the acceleration of the beam. It is intended to be used primarily for heavy-ion operation (e.g. uranium beam). Main purpose of the beam dump is to protect an extraction channel of the SIS 100 synchrotron. The beam dump is designed to be very compact. It is assumed to be installed directly in the beam pipe and located in its bottom part. Position in the SIS 100 is assumed to be in Sector 5 (extraction section). The beam dump consists of the carbon-composite core (absorber) which is surrounded by the stainless steel (see Fig. 1). The carbon-composite was chosen for its good thermal and mechanical stress resistance [6]. Total length of the internal beam dump is 24 cm.

The internal beam dump is not designed for permanent irradiation during operation. It has to withstand only one shot of the beam in case of emergency and then the machine is shut down. However SIS 100 is designed for acceleration of the high-intensity heavy-ion beams. This means that very high energy deposition is expected in the carbon absorber even per one single shot after dumping of the beam.

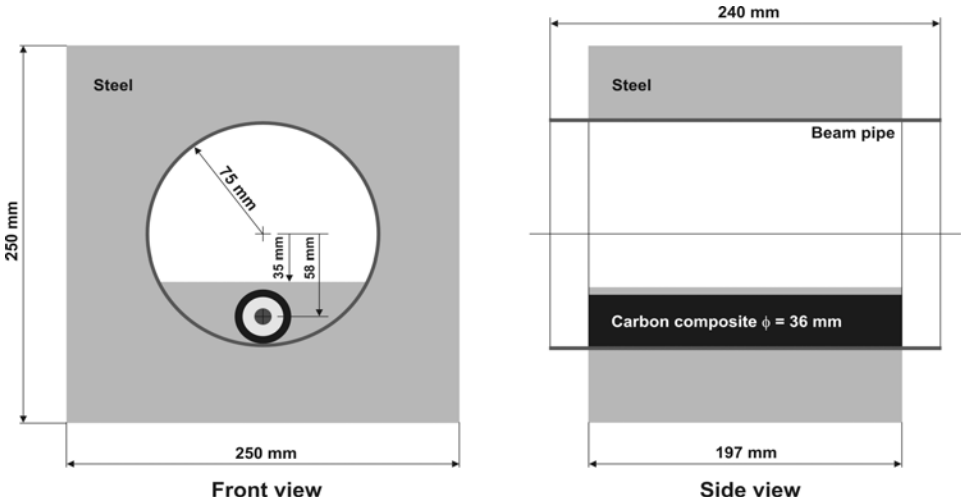

Fig.1: *Front and side view of the internal beam dump. Light and dark circle on the absorber is the beam size at injection (200 MeV/u) and extraction energy (2.7 GeV/u), respectively.*

The power of the uranium beam to be accelerated in SIS 100 is assumed to be in order of tenths of kilowatts. High energy deposition in the absorber causes specific issues such as high temperature rise and mechanical stress. Other important issues are activation of the beam dump and its surroundings as well as a possible quench of the superconducting quadrupoles located about 1 m downstream.

Energy deposition of the uranium beam at energies from 200 MeV/u up to 2.7 GeV/u in the carbon-composite absorber was simulated using Monte Carlo code FLUKA [7]. The beam profile used in simulations was assumed to be a Gaussian distribution. Diameter of the beam corresponds to the 2 σ of the distribution and varies from 26 mm (200 MeV/u) to 11 mm (2.7 GeV/u). It relates with the beam geometrical emittance which decreases with increasing beam energy. Energy deposition profile was calculated in a cylinder of diameter which corresponds to 0.5 σ of the beam distribution and is localized in the centre of the carbon absorber. Energy deposition ΔE in certain volume can be then recalculated to the temperature rise ΔT using following formula:

$$\Delta T = \Delta E \frac{N}{\rho \cdot c_p}, \tag{1}$$

where N is the total number of particles, ρ is density of the material and c_p is specific heat capacity of the material. The total number of particles in SIS 100 pre one shot is assumed to be $N = 5{\cdot}10^{11}$ ions. For the carbon-composite material $\rho = 1.65\ \mathrm{g{\cdot}cm^{-3}}$ and $c_p = 0.71\ \mathrm{J{\cdot}g^{-1}{\cdot}K^{-1}}$. Results of the energy deposition simulation and the temperature rise calculation in the carbon composite are presented in Fig. 2.

It can be seen that maximum of the energy deposition profile at low beam energies occurs in the Bragg peak area. But energy deposition in the Bragg peak area decreases with increasing beam energy. Maximum of the energy deposition profile at high energies (above 1.5 GeV/u) occurs at the beginning of the target instead of the Bragg peak area. This can be explained by the fact that heavy primary-ions at low energies are stopped mostly by Coulomb interaction with the target electrons and only a minor part of them interacts with the target nuclei. In other words, the Coulomb stopping range of these particles is shorter compared to their mean-free path for nuclear interaction. In contrary, the heavy ions at high energies have their ranges longer than the mean-free path. This means that the probability of nuclear interaction increases with their increasing energy [4].

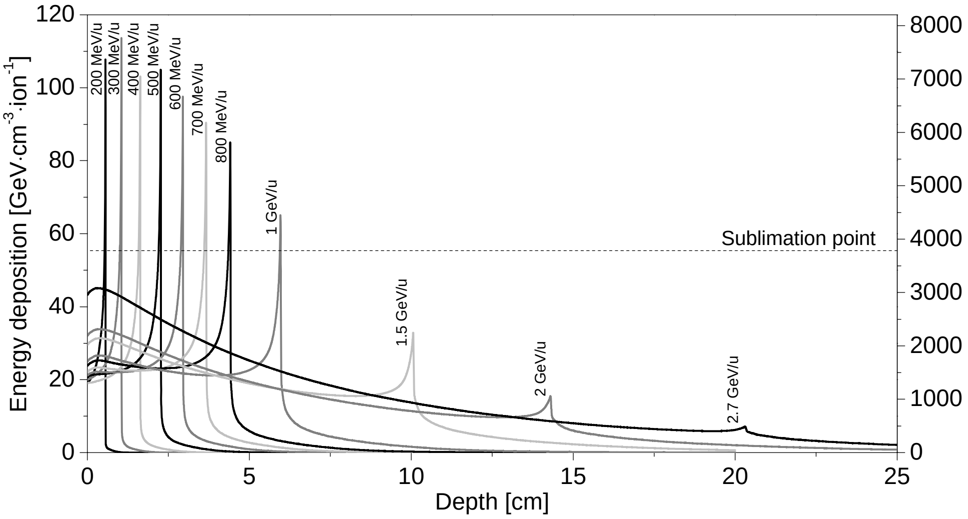

Fig.2: *Energy deposited by uranium beam normalized per one incident particle (left axis) and the temperature rise in the carbon-composite absorber induced by $5{\cdot}10^{11}$ ions (right axis) for various energies from 200 MeV/u up to 2.7 GeV/u.*

In the interaction process primary ions undergo nuclear fragmentation and electromagnetic dissociation. Energy deposition is proportional to the Z^2 (proton number). That is why maximum of the energy deposition profile at high beam energies is localized in the beginning of the target where the most of primary ions is not yet fragmented. Due to fragmentation of the primary ions and consequently different range of the fragments energy deposition in the Bragg peak area decreases with increasing energy of the beam.

It was also found out that the temperature rise at high beam energies is below sublimation point of the carbon-composite along the whole profile. However the temperature rise at lower energies significantly exceeds the sublimation point in the Bragg peak area. The highest temperature almost 8000 K was observed at 300 MeV/u and corresponds to the top of the Bragg peak. Already from the temperature rise calculation, it is evident that this concept of the internal beam dump will not work for the maximum designed uranium beam intensity which is $5{\cdot}10^{11}$ ions. In order to be safely below the sublimation point the beam intensity has to be decreased at least by factor of three. Another critical issue is a thermal shock or mechanical stress caused by a temperature gradient in the carbon-composite absorber. Thermal shock can damage the absorber even at considerably lower temperatures than the sublimation point. Assessment of the thermal stress requires further analysis and calculation of the pressure in the absorber due to temperature change is needed.

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