RADIATION DAMAGE TO THE ELEMENTS OF THE NUCLOTRON-TYPE DIPOLE OF SIS100*

E.Mustafin#, G.Moritz, G.Walter, GSI, Darmstadt, Germany
L.Latycheva, N.Sobolevskiy, INR RAS, Moscow, Russia

Abstract

Irradiation of various structural elements such as superconducting cables and insulating materials of the Nuclotron-type dipole of SIS100 as a consequence of primary beam losses was calculated. In addition, attention was also turned to high-current by-pass diodes for quench protection. The Monte-Carlo particle transport code SHIELD was used to simulate the propagation of lost ions and protons together with the products of nuclear interactions in the materials of interest. The results for the proton projectiles were cross-checked using the particle transport code MARS, and a good agreement between both codes was found. The calculations have shown that the lifetime of the organic materials under irradiation are a much more restrictive limit for the tolerable level of beam particle losses than the danger of quench events in the superconductor.

INTRODUCTON

The SIS 100 superconducting synchrotron will be part of the GSI future facility FAIR (Facility for Antiprotons and Ion Research) [1]. It is planned to be operated with high energy proton and heavy ion beams of high intensity:

- Protons: intensity $2.5 \bullet 10^{13}$, accelerated from the injection energy of 2.7 GeV up to the final energy of 29 GeV
- U ions: intensity 10^{12}, accelerated from 100 MeV/u up to the final energy of 1 GeV/u

The study of radiation damage in the most irradiation sensitive elements of the SIS100 is mandatory and therefore an important part the superconducting magnet R&D. As a first step, the energy deposition into the structural elements of the SIS100 dipoles is considered in this work: 1) instantaneous energy deposition into the superconducting wires of the dipole – to study the danger of quenches, 2) energy deposition into the organic materials of the cables – to estimate the lifetime of the materials with low radiation hardness and 3) energy deposition and neutron fluxes in the high-current by-pass protection diodes of the dipoles – to estimate the lifetime of the semiconducting diodes.

THE SIMULATION MODEL

The Monte-Carlo transport code SHIELD [2] was used to simulate the propagation of lost beam particles together with the products of nuclear interactions in the structural elements of the SIS100 dipole [3].

Geometry and Materials Composition

The simulation model consists of a 2 m long vacuum chamber in front of a 2.6 m long dipole, the cryostat around the dipole and the dipole itself. It is presented schematically in Fig.1 in the longitudinal cross-section. The detailed simulation model for the dipole is shown in Fig.2 in a transverse cross-section [4].

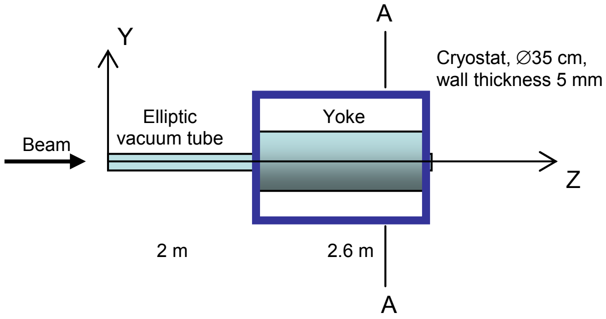

Figure 1: Longitudinal cross-section of the simulation model.

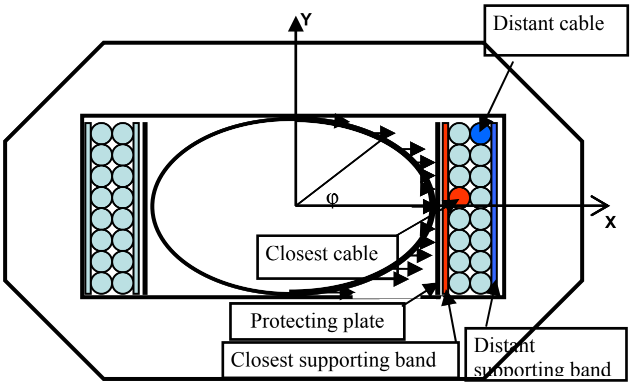

Figure 2: Transverse cross-section of the dipole (A-A in Fig.1).

The hollow-tube superconducting cable was modelled with 7 layers as it is shown in Table 1, where is the mass density of the material, and the contribution of the elements is given either in atomic (at.%) or in weight (wt.%) percentages.

A schematic view of the superconducting cable is shown in Fig.3.

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#E.Mustafin@gsi.de

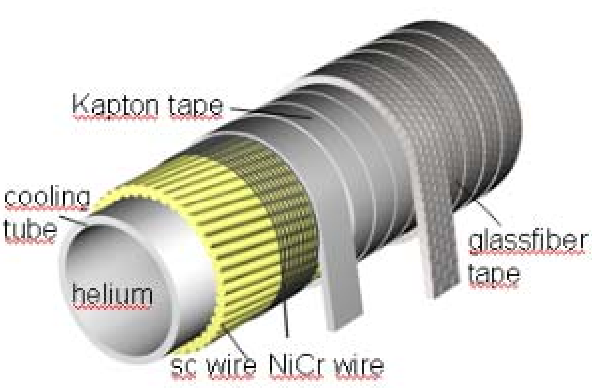

Fig.3 Schematic view of the hollow-tube superconducting cable of the SIS100 dipole.

Table 1 Geometry, element composition and density of the layers of the hollow superconducting wires.

Layer	Outer radius, mm	Element composition	Density, g/cm^3
2-phase He	2.0	100% He	0.07
Cooling tube	2.5	Wt.%: 70 Cu, 30 Ni	8.6
Epoxy	2.6	Wt.%: 76 C, 7 H, 17 O	1.5
s.c. wires	3.0	Wt.%: 68 Cu, 16 Ti, 16 Nb	6.0
NiCr wire	3.2	Wt.%: 76 Ni, 23 Cr, 1 Si	8.4
Kapton	3.36	At.%: 55 C, 26 H, 7 N, 12 O	1.4
Glassfiber	3.56	25 Si, 46 O, 12 Al, 13 Ca, 1 Mg, 3 B	1.9

Irradiation Model

Three different beam-loss regimes were considered:

1. Proton projectiles are lost to the inner surface of the vacuum chamber with 1 mrad angle of incidence relative to the surface. The incidence points are distributed uniformly over the surface of the vacuum chamber. The energies of the projectiles are distributed uniformly in the range from the injection energy of 2.7 GeV and to the extraction energy of 29 GeV.
2. Uranium projectiles of the energy of E=1 GeV/u are lost to the inner surface of the vacuum chamber with 1 mrad angle of incidence relative to the surface. The incidence points are distributed uniformly over the surface of the vacuum chamber.
3. Uranium projectiles of the energy of E=1 GeV/u are lost to the inner surface of the vacuum chamber with trajectories parallel to the horizontal plane and with 17 mrad angle deviation from the axis of the chamber. The incidence points are distributed uniformly over the surface of one half of the vacuum chamber.

The first two regimes represent the so-called "halo" particle losses, i.e. loss of particles with large amplitudes of betatron oscillations. The last regime represents the so-called "vacuum" losses of U ions due to the charge-exchange with the molecules of the residual gas. The average angle of incidence for these kind of lost beam particles is about 1^0 or 17 mrad to the direction of the beam propagation [5]. The direction of beam losses in this regime is shown schematically in Fig.2.

THE RESULTS OF THE SIMULATION

The energy deposition was calculated for three different construction elements of the SIS100 superconducting dipole which are sensitive to radiation damage: the superconducting wires, organic materials and the high-current by-pass quench-protection diodes.

The tolerable beam-loss limits given in Table 2 are obtained assuming a uniform distribution of particle losses along the orbit of SIS100. The quench limit is given in numbers of lost ions per one dipole, whereas for the organic materials and the diode the limits are given in percents of total beam intensity of 10^{12} U ions and $2.5 \cdot 10^{13}$ protons, respectively. The second number in the cells of Table 2 is the energy deposition and neutron flux per lost projectile.

For the organic material the life-time dose limit is chosen to be 10^6Gy [4] in 10 years.

The lifetime limit for the diodes is determined by the neutron flux of $1.5 \cdot 10^{14}$ n/cm^2 in 10 years for the epitaxial type diodes [7].

The quench limit is chosen to be 1.65 mJ/g [6] instantaneous energy deposition into the superconducting wires.

One can see from Table 2 that the quench limit is not a very serious problem in the normal operating regimes of the SIS100: $3 \cdot 10^{10}$ lost ions per length of one magnet (2.6 m) mean about 1% beam loss per meter. This is by an order of magnitude higher than in the case of total beam intensity loss over the whole circumference of the SIS100 synchrotron (1080 m).

The most severe limitation comes from the lifetime of the organic materials (i.e. the material of the supporting band wrapped around the s.c. cables Fig.2): the "vacuum" losses of U ions must not exceed 0.4% of the total beam power distributed uniformly along the orbit. Insertion of a thin (1 mm) stainless steel shielding between the vacuum chamber and the superconducting cables could help to bring the tolerable beam loss limit up to 2%. The calculations for the proton operating regime were re-done with the MARS [8] transport code in order to cross-check the results by the SHIELD code. Discrepancies of the order of few tens of percents were found between the values of energy deposition and neutron flux obtained by the codes.

Table 2. Tolerable beam-loss limits.

	Organic materials	Quench, ions per magnet	Diodes
Protons	~5% of beam intensity, $3.5 \cdot 10^{-5}$ GeV/(g·proton)	$\sim 5 \cdot 10^{+11}$ protons, $3.5 \cdot 10^{-5}$ GeV/(g·proton)	~1%, $7 \cdot 10^{-4}$ neut./cm^2
U ions, 'halo' losses	~2% of beam intensity, $4 \cdot 10^{-4}$ GeV/(g·U)	$\sim 7 \cdot 10^{+10}$ U ions, $1.5 \cdot 10^{-4}$ GeV/(g·U)	~1%, $6 \cdot 10^{-3}$ neut./cm^2
U ions, 'vacuum' losses	~0.4% (2%), $1.8 \cdot 10^{-3}$ ($5 \cdot 10^{-4}$) GeV/(g·U)	$\sim 3 \cdot 10^{+10}$ U ions, $2.5 \cdot 10^{-4}$ GeV/(g·U)	~1%, $6 \cdot 10^{-3}$ neut./cm^2

A few percent of allowed beam loss level is a serious requirement for the operation of the synchrotron. An accurately designed system of collimators will be desirable to intercept the lost particles outside the magnets and make the loss limits more relaxed.

The lifetime dose limits given in [4] are for the irradiation of the organic materials with neutron and gamma-ray beams. Experiments are planned at GSI starting in 2004 to measure the lifetime doses for heavy ions [6]. The spectra of secondary fragments penetrating into the s.c. cables of the SIS100 dipole were calculated in order to provide an input data for these experiments [3]. It was found that the secondary particles are mostly light ions, with only few per mille contribution of fragments heavier than carbon ($Z > 6$).

CONCLUSION

The radiation damage to various construction elements of the superconduting dipole of the SIS100 synchrotron by the lost beam particles was estimated using the Monte-Carlo particle transport code SHIELD.

It was found that the danger of quench events is not the main intensity limiting factor for the SIS100 synchrotron. The most severe limitations come from the lifetime of the materials with low radiation hardness such as the organic materials and the semiconducting diodes: only few percent of beam loss is allowed in normal operation regime of the synchrotron in order to have lifetime in the order of 10 years.

The mass and energy spectra of particles (resulting from the nuclear interaction of the lost particles with the nuclei of the target material) entering the s.c. cable were calculated to provide input data for the experimental investigation of the radiation hardness of the materials.

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