Final Report

**Studies of Limits on Uncontrolled Heavy Ion Beam Losses for
Allowing Hands-On Maintenance**

(DE-FG02-07ER41475)

Final Report

Studies of Limits on Uncontrolled Heavy Ion Beam Losses for Allowing Hands-On Maintenance

(DE-FG02-07ER41475)

Funding received in k\$

	FY 07/08
Michigan State University (R. M. Ronningen)	103
Oak Ridge National Laboratory (I. Remec)	87
Total	190

Table of Contents

1. Overview of Efforts	4
1.1. Introduction.....	4
1.2. Purpose	4
1.3. R&D Collaboration.....	5
1.3.1. Expertise in Collaboration	5
1.3.2. Facilities and Resources used in the R&D Efforts	6
1.3.3. Execution of Collaborative Effort.....	6
2. Executive Summary	7
3. Project Publications	7
4. Background.....	8
4.1. Overview.....	8
4.2. Beam-Loss Mechanisms.....	9
4.2.1. Controlled Beam Losses	9
4.2.2. Uncontrolled Beam Losses	9
4.3. Previous Work at Other Labs and the Hands-on Maintenance Limit.....	9
4.4. Relationship to Regulatory Requirements	10
4.5. Neutron Production Overview	10
4.5.1. From Proton Interactions	10
4.5.2. From Heavy Ion Interactions	11
5. Dose Rates from Uncontrolled Proton Beam Losses Obtained Using Sullivan’s Semi-phenomenological Equations	14
6. Dose Rates from Uncontrolled Proton and Heavy Ion Beam Losses from Monte Carlo-based Simulations	15
6.1. Code Descriptions.....	15
6.1.1. PHITS	15
6.1.2. MCNPX	16
6.1.3. DCHAIN-SP 2001	17
6.2. Validation of Methods	20
6.3. Results for a Long Beam Pipe	24
6.3.1. Radiation Transport Results	24
6.3.2. Calculations of Activation using DCHAIN-SP 2001	26
6.4. Simulations using a Drift-Tube-Linac (DTL) Geometry.....	28
6.4.1. Radiation Transport Results	29
6.4.2. Calculations of Activation using DCHAIN-SP 2001	30
6.5. Simulations using a Superconducting Linac (SCL) Geometry.....	35
6.5.1. Radiation Transport Results	38
6.5.2. Calculations of Activation using DCHAIN-SP 2001	38
7. Conclusions and Recommendations	44
8. References.....	45

1. Overview of Efforts

1.1. *Introduction*

This report is the Final Report for the project “Studies of Limits on Uncontrolled Heavy Ion Beam Losses for Allowing Hands-On Maintenance”, (DE-FG02-07ER41475). The report is organized in the following way. First, a brief overview of the overall purpose of the R&D efforts will be given together with a presentation of the collaboration and resources. This will be followed by a detailed description of the achieved R&D results. To keep the report concise it was assumed that the reader is familiar with linear accelerator basics. Within the report the specific energy of an ion in a beam is specified in units of MeV/u, taken to mean MeV per nucleon.

1.2. *Purpose*

The US nuclear physics community’s effort towards realizing a next-generation facility for rare isotope ion beams [NSAC07] has resulted in DOE Critical Decision 0 for Facility for Rare Isotope Beams (FRIB). This has been accompanied with substantial research and development work involving many institutions in the US. FRIB is to be based on a driver linac capable of accelerating light and heavy ions with a beam power up to 400 kW and a specific energy of 200 MeV/u for uranium. There are possibilities for energy upgrades, to ~ 1 GeV protons, ~ 500 MeV/u for heavy ions such as Xe, and 400 MeV/u for uranium. Uncontrolled losses of high beam power at these energies may pose significant personnel safety challenges.

This report summarizes a one-year collaborative R&D project carried out by Michigan State University (MSU), Oak Ridge National Laboratory (ORNL), and Scientific Investigation and Development (SID).

There is significant overlap in the radiation effects issues and methods used to address them between this project and the following previously completed DOE-funded RIA R&D collaborative efforts performed between 2003 and 2007:

- “Development of a Concept for High Power Beam Dumps and Catchers, and the Pre-separator Area Layout for Fragment Separators for the Rare Isotope Accelerator Project (funded under DE-FG02-04ER41313);”
- “Development of a Concept for the ISOL Target Areas for RIA (funded under DE-FG02-04ER41322);”
- “Determination of Component Activation and Radiation Environment in the RIA Second Stripper Region (funded under DE-FG02-05ER41403).”

1.3. R&D Collaboration

The R&D Collaboration for this project consisted of members of Michigan State University (MSU), Oak Ridge National Laboratory (ORNL), and Scientific Investigation and Development (SID).

1.3.1. Expertise in Collaboration

Rare isotope beam production and neutronics experts at MSU, ORNL, and SID have established a strong collaboration regarding the calculations of radiation fields, shielding, and material damage.

Full and part-time members of the present R&D collaboration:

- Inseok Baek, Georg Bollen, Mikhail Kostin, and Reginald M. Ronningen, Michigan State University, National Superconducting Cyclotron Laboratory
- Igor Remec, Oak Ridge National Laboratory

- Tony Gabriel, Scientific Investigation and Development, 9608 Lyttleton Lane, Knoxville, TN 37922

1.3.2. Facilities and Resources used in the R&D Efforts

ORNL has extensive analytical, computational, and experimental resources available to support this project. A wide range of computer codes, including MCNPX, PHITS, MARS and ORIHET are licensed and were used in this work. There is access to two clusters of high-end PC's operating under LINUX with a distributed processing capability.

MSU has extensive experience in accelerator design (cyclotrons, superconducting linear accelerator components), rare isotope production, and the design of fragment separators. Detailed knowledge exists of the effects of radiation on the facility components and impact on facility operation and design. MSU also has experience with several of the relevant computer codes (MCNPX, PHITS, MARS, DCHAIN-SP 2001) and access to adequate computational resources to perform the work. Within the previous DOE-funded RIA R&D efforts the NSCL purchased a 16-node/32-processor computing cluster dedicated to DOE-funded R&D calculations. In addition, MSU has an established high-performance computing center, which is available to the NSCL. Both computing capabilities were extensively used within this work.

1.3.3. Execution of Collaborative Effort

Efficient and frequent communication between the collaborating partners has been of particular importance for a project. The collaboration is small enough that frequent phone conferences and e-mail exchanges between the MSU and ORNL PIs to address project and data management issues have taken place at regular intervals.

2. Executive Summary

Dose rates from accelerator components activated by 1 W/m beam losses are obtained semi-empirically for a 1 GeV proton beam and by use of Monte Carlo transport codes for the proton beam and for 777 MeV/u ^3He , 500 MeV/u ^{48}Ca , ^{86}Kr , ^{136}Xe , and 400 MeV/u ^{238}U ions. The dose rate obtained by the semi-empirical method, 0.99 mSv/h (99 mrem/h) at 30 cm, 4 h after 100 d-irradiation by a 1-GeV proton beam, is consistent with studies at several accelerator facilities and with adopted hands-on maintenance dose rate limits. Monte Carlo simulations verify this result for protons and extend studies to heavy ion beam losses in drift-tube linac and superconducting linac accelerating structures. The studies indicate that the 1 W/m limit imposed on uncontrolled beam losses for high-energy proton beams might be relaxed for heavy ion beams. These studies further suggest that using the ratio of neutrons produced by a heavy ion beam to neutrons produced by a proton beam along with the dose rate from the proton beam (for thin-target scenarios) should allow an estimate of the dose rates expected from heavy ion beam losses.

3. Project Publications

The collaboration produced the following publications during the project:

- *Estimated Limits on Uncontrolled Beam Losses of Heavy Ions for Allowing Hands-On Maintenance at an Exotic Beam Facility Linac*, Reginald Ronningen, Georg Bollen, Igor Remec, ICRS-11 (11th International Conference of Radiation Shielding) and RPSD-2008 (15th Topical Meeting of Radiation Protection and Shielding Division, American Nuclear Society) April 13-18, 2008, Pine Mountain Georgia.
- *Estimated Limits on Uncontrolled Beam Losses of Heavy Ions for Allowing Hands-On Maintenance at an Exotic Beam Facility Linac*, Reginald Ronningen, Georg Bollen, Igor Remec, invited paper in the session "Best of RPSD 2008" at the 2008 winter meeting of the American Nuclear Society, Reno, NV, November 10 - 14, 2008.
- *Prediction Of Doses From Uncontrolled Beam Losses In Heavy Ion Linacs*, R. M. Ronningen, G. Bollen, and I. Remec, 54th Annual Meeting of the Health Physics Society, July 12-16, 2009, Minneapolis, MN
- *Estimated Limits on Uncontrolled Beam Losses of Heavy Ions for Allowing Hands-On Maintenance at an Exotic Beam Facility Linac*, Reginald Ronningen, Georg Bollen, and Igor Remec, Nuclear Technology 168, pp. 670-675(2009).

4. Background

4.1. Overview

The purpose of this study is to obtain estimates of limits on uncontrolled beam losses of heavy ions for allowing hands-on maintenance at a heavy ion linac for a rare isotope beam facility. Semi-empirical formulae are used to estimate dose equivalent rates from activated accelerator components for 1 W/m uncontrolled losses of protons up to 1 GeV. The estimated dose rates after 100 d irradiation time 4 h post-shutdown cooling time are compared to a hands-on maintenance limit of 1 mSv/h (100 mrem/h) at 30 cm. The transport codes PHITS and MCNP5, and activation code DCHAIN-SP 2001 are used to verify the estimate for proton losses and to obtain limits on heavy-ion beam losses that will satisfy the hands-on maintenance dose rate limit. Radiation doses to personnel at accelerators are obtained predominately while performing maintenance on components activated generally by beam losses during operations. Beam losses may be classified as either controlled (*e.g.* at collimators, scrapers, dumps, and stripping regions) or uncontrolled (*e.g.* from gas stripping and beam halo). Controlled losses are better understood and local shielding and remote handling techniques can be employed to minimize doses.

It is therefore desirable to estimate dose rates from uncontrolled losses and to compare these to personnel dose criteria so that conventional facility design, accelerator design, maintenance, and operations can be optimized to minimize doses and to allow hands-on maintenance over as much of the accelerator as possible.

The next-generation facility for rare isotope ion beams [NSAC07] will have a driver linac that can accelerate ions of any stable atom to 0.2 – 1 GeV per nucleon with expected beam power of up to 400 kW.

Although activation by uncontrolled losses of energetic proton beams has been previously studied, to our knowledge activation by losses of heavier ions has not. It is important to verify dose rates from proton losses and to obtain limits on heavy-ion beam losses that dose rates will satisfy the hands-on maintenance limit.

4.2. Beam-Loss Mechanisms

J. Wei has surveyed the design and operational experience of existing and proposed proton facilities, and provides summaries of beam loss mechanisms [Wei03]. Beam losses are categorized into two classes: controlled and uncontrolled.

4.2.1. Controlled Beam Losses

Controlled beam losses include losses at beam dumps, scrapers, collimators, stripping regions, and beam windows. In general, controlled losses are better understood and local shielding and remote handling techniques can be employed to minimize doses.

4.2.2. Uncontrolled Beam Losses

Wei has categorized uncontrolled beam loss as those losses linearly proportional to the beam's intensity (*e.g.*, Coulomb scattering and nuclear scattering at injection foils, magnetic stripping, gas scattering, kicker malfunction, noises from rf systems and magnet power-supply systems), and those losses that grow progressively with intensity (*e.g.*, space-charge-induced tune spread and coherent resonance crossing, instability, electron-cloud effects) [Wei03]. In the case of uncontrolled losses the magnitudes and locations of uncontrolled beam losses are difficult to know *pre hoc*.

4.3. Previous Work at Other Labs and the Hands-on Maintenance Limit

Published literature containing estimates of maintenance doses at high energy proton linacs include that of [Wan98, Wa08]. Operating experience and design studies at Los Alamos National

Laboratory [Har99] and at the Spallation Neutron Source at Oak Ridge National Laboratory [Gala01, Gall01, Rem00] determined that dose rates from activated accelerator components for 1 W/m losses of ~ 1 GeV protons are below the requirement for hands-on maintenance: 1 mSv/h (100 mrem/h) at 30 cm ($\sim$ one foot). At FNAL the requirement [Mok99] is that anywhere in the machine, residual photon dose rates are less than 1 mSv/h at 30 cm from the component surface, at $t = 4$ h after the end of $T = 100$ days of accelerator operation, and furthermore the dose rates averaged over all the components must be $\leq 0.10 - 0.20$ mSv/h.

4.4. Relationship to Regulatory Requirements

This hands-on maintenance limit is reasonable for several safety and administrative reasons. It avoids a “High Radiation Area” classification according to U.S. radiation regulations (≥ 1 mSv in an hour at 30 cm from the source or the surface from which radiation emanates) and the attending strict requirements on monitoring and access control. In addition, maximum permissible occupational exposure in the US is 50 mSv per year. However, lower limits likely are administratively in place, typically 5 mSv in a year. Thus significant fractions of radiation dose limits could be obtained in short work periods, even within one work-shift. It is also prudent to let very short-lived activities (*e.g.* ^{11}C in activated air) decay after accelerator shut-down and before personnel commence work, hence 4 hours.

4.5. Neutron Production Overview

4.5.1. From Proton Interactions

The number of secondary neutrons produced from Cu and Fe targets as a function of proton energy can be estimated from the data shown in Figure 1 and by using the equation developed by Broome [Bro00] for the yield of high-energy neutrons produced by protons of different energies interacting with nonfissionable target materials:

(1)

$$Y(E, A) = 0.1(E_{\text{GeV}} - 0.12)(A + 20)$$

where E_{GeV} is energy of the incoming proton in GeV and A is the mass number of the target.

Figure 1: Neutron production as a function of proton energy [Bro00].

4.5.2. From Heavy Ion Interactions

Kurosawa *et al.* [Kur00] have measured the angular and energy distributions of neutrons produced from thick C, Al, Cu, and Pb targets bombarded by 400 MeV/u Ar, Fe, Xe ions and 800 MeV/u Si ions. The total neutron yields above 5 MeV were integrated over a hemisphere from 0° to 90° and were parameterized by the following formula that roughly represents the projectile-like neutron yields from a thick target:

(2)

$$Y = \frac{1.5 \times 10^{-6}}{N_T^{\frac{1}{3}}} E_P^2 (A_P^{\frac{1}{3}} + A_T^{\frac{1}{3}})^2 N_P \frac{A_P}{Z_P^2}$$

where A_P and A_T are the mass numbers of projectile and target, N_P is the neutron number of projectile, and Z_P is the atomic number of projectile. N_T is the neutron number of target and E_P is the incident particle energy per nucleon (specific energy, MeV/u).

As described by Kurosawa *et al.* [Kur00], the term $(A_P^{\frac{1}{3}} + A_T^{\frac{1}{3}})^2$ represents the geometrical cross section σ_G , and when σ_G is multiplied by the neutron number of projectile N_P , it represents the projectile-like neutron production cross section. The term $\frac{A_P}{Z_P^2}$ represents the range of projectiles. For two isotopes having equal velocities, their ranges are directly proportional to their mass numbers. For two isotones having equal velocities, their ranges are inversely proportional to the square of their atomic numbers.

Figure 2 displays the yields of produced neutrons from ^{48}Ca beams, obtained by using (2) interacting with a thick target having $A=60$, $Z=26$, as a function of beam specific energy. These yields are compared to yields from proton beams, obtained by using (1). The ratio of produced neutrons from ^{48}Ca beams to produced neutrons from proton beams as a function of beam specific energy, each for 1 W/m loss, is shown in Figure 3.

Figure 2: Yields of neutrons from ^{48}Ca beams interacting with a thick target having A=60, Z=26, as a function of beam specific energy. These yields are compared to yields from proton beams.

Figure 3: The ratio of produced neutrons from ^{48}Ca beams to proton beams as a function of beam specific energy, each for 1 W/m loss.

5. Dose Rates from Uncontrolled Proton Beam Losses Obtained Using Sullivan's Semi-phenomenological Equations

Accelerator materials become activated through spallation interactions with protons lost from the primary beam and through interactions with secondary particles (mainly neutrons for proton beam energies below 1 GeV). Doses result from residual, material-dependant radioactive nuclides such as $^{58,60}\text{Co}$, ^{64}Cu , ^{54}Mn , ^{47}Sc *etc.*

Sullivan's semi-empirical formula [Sul92] for the activity produced in spallation reactions between a proton beam and a target of a medium-mass material (*e.g.* Cu, Fe) is:

$$S = 0.031 \times \ln\left(\frac{T+t}{t}\right) \text{ Bq per spallation interaction per second.} \quad (3)$$

T is the irradiation time and t the cooling time.

The number of secondary neutrons produced from Cu and Fe targets as a function of proton energy can be estimated using the equation developed by Broome [Bro00] for the yield of high-energy neutrons produced by protons of different energies interacting with nonfissionable target materials:

$$Y(E, A) = 0.1(E_{\text{GeV}} - 0.12)(A + 20) \quad (4)$$

For Fe or Cu materials, the mass number A may be taken as 60.

Therefore, the activity normalized to lost beam current is given by:

$$S = 0.25(E_{\text{GeV}} - 0.12) \ln\left(\frac{T+t}{t}\right) \text{ Bq}\cdot\text{s/proton.} \quad (5)$$

Or, in terms of power loss per unit length:

(6)

$$S = 1.6 \frac{E_{GeV} - 0.12}{E_{GeV}} \ln\left(\frac{T+t}{t}\right) \text{ GBq}\cdot\text{m/W}.$$

The activity should be increased [Sul92] by approximately 50% due to radioactivity produced by evaporation and thermal neutrons, which presumably are not included in Eqn. 2. This increase strongly depends on material composition and accelerator geometry. Assuming that personnel are exposed to the activity within accelerator structures closest to surfaces (about 10% of the total) [Sul92] that provides dose, and using a dose conversion constant [Sul92] of 220 fSv/h per Bq at 1m, the dose rate, D , is:

(7)

$$D = 52 \frac{E_{GeV} - 0.12}{E_{GeV}} \ln\left(\frac{T+t}{t}\right) \text{ }\mu\text{Sv/h at 1m (per 1 W/m loss)}.$$

For $T = 100$ d and $t = 4$ h and for 1 GeV, the expected dose rate at 30 cm (for US regulatory purposes; linear scaling was assumed) is 981 $\mu\text{Sv/h}$ (98.1 mrem/h). This satisfies the hands-on maintenance criterion presented in section 4.1.1.3 and is in agreement with previous studies [Gala01, Gall01, Har99, Rem00, FRCM]

6. Dose Rates from Uncontrolled Proton and Heavy Ion Beam Losses from Monte Carlo-based Simulations

6.1. Code Descriptions

6.1.1. PHITS

PHITS [Iwa01, Iwa02, Iwa03] is a three dimensional radiation transport code system with the capabilities of transporting heavy ions as well as protons, neutrons, charged pions, electrons, positrons, gamma rays, *etc.* The main transport module and the proton, neutron, and charged pion collision modules of PHITS were originally obtained from the ORNL code NMTC [Ber63] and have been modified with various upgrades and improvements. For high-energy neutrons and

other particles, Jet AA Microscopic Transport Model (JAM) [Nar99] and JAERI Quantum Molecular Dynamics (JQMD) [Nii01] are used to simulate particle induced reactions up to about 200 GeV, and nucleus–nucleus collisions up to about 100A GeV, respectively. Fission and evaporation processes are treated by the Generalized Evaporation Model (GEM) [Fur00]. The GEM code calculates the final yields of light nuclei produced from the de-excitation of residual nuclei. Neutrons which emerge from the nucleus below about 20-MeV are then transported in the same manner as in the MCNP4C radiation transport code [Bre97]. PHITS employs the cross sections from evaluated nuclear data libraries such as ENDF-B/VI [McL96] and JENDL-3.3 [Shi02] up to 20 MeV and LA150 up to 150 MeV [Cha99]. PHITS also uses evaluated nuclear data for photon and electron transport below 1 GeV in the same manner as the MCNP4C code. The geometry input to PHITS may be either Combinatorial Geometry (CG) or Generalized Geometry (GG). It is possible to import directly any MCNPX-type geometry definition.

6.1.2. MCNPX

MCNPX [Pel05] is a general-purpose radiation simulation code that transports up to 34 particle types and, in addition, heavy ions. Physics models are used from 1 TeV down to energies where tabular data are available (most generally below 20 MeV, and below 150 MeV in some cases). Currently, MCNPX is a merger project of MCNP 4C [Bre97] and LAHET 2.8 [Pra89]. There are several intra-nuclear cascade, fission, and evaporation physics models that may be used in combinations. These combinations are: Bertini/Dresner, CEM2K, ISABEL/Dresner, Bertini/ABLA, ISABEL/ABLA, INCL4/Dresner, and INCL4/ABLA. MCNPX uses an enhanced Combinatorial Geometry (CG) to treat arbitrary three-dimensional configurations of geometric cells, bounded by first- and second-degree surfaces and fourth-degree elliptical tori that contain

materials of interest. MCNP also provides a “macrobody” capability, where basic shapes such as spheres, boxes, cylinders, *etc.*, may be combined using Boolean operators.

6.1.3. DCHAIN-SP 2001

For activation analysis purposes, PHITS was coupled with DCHAIN-SP 2001 code [Kai01]. This code uses specific output from PHITS to calculate residual activity, decay heat and photon spectra via decay data libraries for all isotopes. The calculational flow is shown in Figure 4.

Figure 4: The calculational flow of decay and build-up of spallation products for DCHAIN-SP 2001 coupled to PHITS.

DCHAIN-SP 2001 estimates the nuclide inventories and radiation environment of high energy accelerator related facilities and was designed to resolve issues regarding spallation neutron facilities. DCHAIN-SP 2001 solves the time evolution of decay and build-up of nuclides in decay chains by the Bateman-equation method [Bat10]. It can calculate the nuclide inventory, radioactivity, heat accompanying decay (i.e. α , β , γ) and gamma-ray energy spectra on the basis of the nuclide production rates calculated by the heavy-ion transport code system PHITS (or by

several other codes such as NMTC/JAER197 [Tak98], NMTC/JAM [Nii01], and MCNPX [Pel05]). Cycles of irradiation and cooling can be treated in the calculation.

DCHAIN-SP 2001 is an update to DCHAIN-SP [Tak99]. DCHAIN-SP was developed on the basis of DCHAIN2 [Tas80] for analyzing the decay and build-up characteristics of spallation products by revising decay data and implementing neutron cross section data. In DCHAIN-SP the decay data are processed from the data libraries of EAF 3.1 [Kop92], FENDL/D-1 [Pas93] and ENSDF [Tul87].

Nuclear reactions induced by the neutrons with energies below 20 MeV in the radiation field produced in the spallation target are taken into account in the code. Due to the lack of available cross section data, however, the nuclear reactions above 20 MeV are not treated in the present code but they are included in the nuclide yield data obtained by PHITS. In order to calculate the neutron reactions, the group-wise neutron cross section data are prepared as a data library. These data are collapsed with the group-wise neutron flux calculated by the MCNP code functionality supplied within NMTC/JAERI97, NMTC/JAM, or with PHITS.

Neutron reaction cross section data libraries are used to take account of the transmutation of nuclides in a neutron field. The cross section data were taken from FENDL/A-2.0 [Pas96], JENDL/Act-96, JENDL-2.0, JENDL-3.2, JENDL-3.3, JENDL/Dosimetry-99 libraries [Nak92, Nak95, Nak96], with revisions as found necessary, and compiled in the 175 energy group structure defined by VITAMIN-J. The present library contains 13005 reactions for 735 nuclides. The nuclides produced with neutron reactions include the isomer states.

Fission yield data are included to allow application to experimental facility design for nuclear transmutation of long-lived radioactive waste where fissionable materials are treated. Attention is given to activation cross section data below 20 MeV which have close relation to facility safety,

in particular cross section data of i.e. mercury, lead and bismuth, and tritium production cross sections. The fission yields produced in reactions with thermal, fast, and fusion neutron fields, and by spontaneous fission, may be calculated after choosing from the desired evaluated nuclear data libraries, ENDF/B-VI or JNDC/FP-2.

The radioactive decay data of all nuclides used in the DCHAIN-SP 2001 code were checked and updated in comparison with experiment. As a result, the present decay data library contains the data of 3139 nuclides within the atomic number range of $1 \leq Z \leq 100$ including 261 stable nuclides.

The decay data library for the DCHAIN-SP 2001 code comes from the evaluated nuclear data file EAF-3.1, FENDL/D-1, and FENDL/D-2 [For97]. For the other nuclides excluded from these data files, the decay data have been obtained from ENSDF [Tul87], Table of Isotopes 8th edition [Fir96], and Chart of the Nuclides 1996 [Hor96].

The DCHAIN-SP 2001 code assumes a single γ -ray emission with average γ -decay energy for nuclides without γ -ray energy spectrum data. For the nuclide having β^+ -decay modes with electron capture decay (EC), an electron capture decay ratio data library is prepared on the basis of the data in the ENSDF. The DCHAIN-SP 2001 code treats the β^+ -decay accompanied with EC as two annihilation γ -rays with energy of 511 keV emitted with the weight of β^+ decay ratio. The β^+ -decay ratio given in the ENSDF is used as a weight of the annihilation γ -rays. For the nuclides whose β^+ -decay ratio is unknown, the β^+ -decay ratio has been estimated by the interpolation with the existing data.

The present decay data library for DCHAIN-SP does not contain the energy spectrum data of the characteristic X-rays.

6.2. Validation of Methods

To validate the use of PHITS in this project the geometry of the straight section in the SNS 1.3 GeV-compatible 248-m accumulator ring was obtained and used in PHITS and MCNPX simulations for a 1 GeV proton beam. Beam was “lost” uniformly in the section and all results given are normalized per source particle. The average neutron, photon, and proton fluences were tallied in the air region in the tunnel, and results from the two codes were compared. The results are shown in Figure 5-12. In general, the results from the two codes agree very well. The largest differences are noted at highest “particle” energies. However, even there ratios of results are less than about 1.75.

Figure 5: Average neutron fluence, normalized to one source proton, in the air in the accelerator tunnel, as calculated by MCNPX and by PHITS, as a function of neutron energy.

Figure 6: The ratio (PHITS/MCNPX) of the average neutron fluences in the air in the accelerator tunnel, as calculated by MCNPX and by PHITS, as a function of neutron energy.

Figure 7: Average neutron dose rates, normalized to one source proton per second, in the air in the accelerator tunnel, as calculated by MCNPX and by PHITS, as a function of neutron energy.

Figure 8: The average photon fluence in the air in the accelerator tunnel, normalized to one source proton, as calculated by MCNPX and by PHITS, as a function of photon energy.

Figure 9: The ratio (PHITS/MCNPX) of the average photon fluences in the air in the accelerator tunnel, as calculated by MCNPX and by PHITS, as a function of photon energy.

Figure 10: The average photon dose rate in the air in the accelerator tunnel, normalized to one source proton per second, as calculated by MCNPX and by PHITS, as a function of photon energy.

Figure 11: The average proton fluence in the air in the accelerator tunnel, normalized to one source proton, as calculated by MCNPX and by PHITS, as a function of proton energy.

Figure 1: The ratio (PHITS/MCNPX) of the average proton fluences in the air in the accelerator tunnel, as calculated by MCNPX and by PHITS, as a function of proton energy.

6.3. Results for a Long Beam Pipe

6.3.1. Radiation Transport Results

Proton and heavy ion interactions with one of the simplest of possible accelerator structures, a stainless steel beam pipe, here 11.76-m long and having 9 cm inner and 10 cm outer diameters, were studied using the heavy ion transport code system PHITS [Iwa01, Iwa02, Iwa03].

In the calculations the sources were assumed to be distributed uniformly along the axis of the beam pipe with uniform divergence of 2.5 degrees from the nominal beam direction. The length for each source was 30.58 m. Each source was normalized to provide losses of 1 W/m.

Table 1 gives the ions, their specific energies and the number of produced neutrons per ion from interactions with the pipe (provided by PHITS) relative to that from the 1-GeV proton beam (1.8 neutrons per proton). Fully-stripped ions were assumed. The ions and energies chosen are those expected at a next generation facility for radioactive ion beams [NSAC07].

Table 1: Beam ions, specific energies, and secondary neutron production per ion.

Ion	Specific Energy [MeV/u]	Neutrons/ion relative to that for 1-GeV proton beam [%]
H	1000	100
³ He	777	221
⁴⁸ Ca	500	478
⁸⁶ Kr	500	517
¹³⁶ Xe	500	616
²³⁸ U	400	417
⁸⁶ Kr	1000	2065

Measurements of secondary neutrons produced in heavy ion interactions have been summarized by Nakamura and Heilbronn [Nak05]. Thick target data show that thick-target neutron yields, for a given ion beam-target combination, increase as the square of the ion's specific energy ($E_{\text{ion}}/\text{nucleon}$). The simulations for ⁸⁶Kr at two different energies reflect this observation.

Table 2 gives the numbers of produced neutrons per second for 1 W/m losses in the beam pipe, for the beams under consideration.

Table 2: Beam ions and specific energies, and secondary neutron production for 1 W/m losses.

Ion (Specific Energy in MeV/u)	Neutrons/s for 1 W/m loss	Neutrons/s for 1 W/m loss relative to that for 1-GeV proton beam [%]
H (1000)	3.4E+11	100.0
³ He (777)	3.2E+11	94.6
⁴⁸ Ca (500)	6.7E+10	19.9
⁸⁶ Kr (500)	4.1E+10	12.0
¹³⁶ Xe (500)	3.1E+10	9.1
²³⁸ U (400)	1.7E+10	4.9
⁸⁶ Kr (1000)	8.1E+10	24.0

6.3.2. Calculations of Activation using DCHAIN-SP 2001

For each ion, nuclide production yields and fluxes of neutrons having energies below 20 MeV were obtained from the PHITS simulations. The yields, fluxes, and the pipe elemental composition and volume were used as input to DCHAIN-SP 2001 [Kai01].

6.3.2.1. Normalizations

DCHAIN requires the particle current (in particle-mA), the total energy of the ion (in GeV) and the number of ions per second (to normalize the neutron flux spectra). The normalization factors for each ion were calculated using the relationship between lost power, the total energy of the beam and the beam current:

$$\text{Power} = \text{Total Energy} \times \text{Particle Current}$$

where

$$\text{Total Energy} = \text{Specific Energy} \times \text{Mass}, \text{ and } 1 \text{ pmA} = 6.24 \times 10^{15} \text{ ions/s}.$$

Table 3 presents the information used in the calculations and the resulting values for the particle currents and number of ions per second.

Table 3: Beam ions, specific energies, and particle currents and number of source ions per second for 1 W/m losses.

Ion	Specific Energy [MeV/u]	Particle Current for 1 W/m [pA]	Source [ions/s]
H	1000	3.06E-05	1.91E+11
³ He	777	1.31E-05	8.19E+10
⁴⁸ Ca	500	1.27E-06	7.95E+09
⁸⁶ Kr	500	7.11E-07	4.44E+09
¹³⁶ Xe	500	4.50E-07	2.81E+09
²³⁸ U	400	3.21E-07	2.00E+09
⁸⁶ Kr	1000	3.56E-07	2.22E+09

6.3.2.2. Irradiation Time, Cooling Time Assumptions

The pipe was assumed irradiated for 100 days and then allowed to “cool” for 4 h after the irradiation.

6.3.2.3. MCNP5 Calculations

Energy-grouped photon fluxes at 4 h after irradiation were obtained from DCHAIN-SP 2001 output. The photon energy distribution was grouped according to DCHAIN-SP 2001’s 42-group “VITAMIN-J” (0.001 MeV to 50.0 MeV) option. The fluxes were part of the source specifications for MCNP5 [Bre97, MCNP05] calculations. MCNP “built-in” functions were specified to distribute the sources. The source was assumed to be uniformly distributed radially and axially within the pipe. The pipe material was assumed to be “stainless steel” having density 8.02 g/cm^3 and constituents chromium (18%w), iron (74.46%w) and nickel (7.54%w). The pipe was assumed to contain vacuum and to be surrounded by air (specified to have “ORNL air composition”). A “ring” tally (F5Z:p) was made on photon fluxes to obtain dose rates at 30 cm from the pipe and axially located at the middle of the pipe. The tally was modified by the value of the weight from the DCHAIN-SP 2001 photon file. The dose equivalent rate (rem/h) at 30 cm was obtained using the ICRP-21 photon flux to dose conversion factors from Vol.1, Appendix H, Table H.2 of the MCNP5 manual.

6.3.2.4. Activation Results

Table 4 gives the calculated dose rates relative to that obtained for the proton beam (989 $\mu\text{Sv/h}$). The dose rate from proton-beam activation agrees well with the result from the simple estimate. The ratios of dose rates from the heavy-ion beams to the dose rate from the proton beam are very nearly the same as the ratios of the produced neutrons.

Table 4: Beam ions (specific energies), dose rates 30 cm from the beam pipe relative to the dose rate produced by the proton beam (98.9 mrem/h), and neutron production relative to neutron production by the proton beam, for 1 W/m losses.

Ion (Specific Energy in MeV/u)	Dose rate relative to that from proton beam (%)	Neutrons/s for 1 W/m loss relative to that for 1-GeV proton beam [%]
H (1000)	100.0	100.0
³ He (777)	75.9	94.6
⁴⁸ Ca (500)	19.2	19.9
⁸⁶ Kr (500)	12.1	12.0
¹³⁶ Xe (500)	9.4	9.1
²³⁸ U (400)	5.2	4.9
86Kr (1000)	21.8	24.0

6.4. Simulations using a Drift-Tube-Linac (DTL) Geometry

A geometric model of a drift tube linac (DTL) was obtained from a large-scale model used in beam loss studies at SNS [Gall01]. The tunnel houses DTL, coupled-cavity linac (CCL) and superconducting linac (SCL) sections. Such linac components will likely comprise the driver accelerator for the next generation exotic beam facility [NSAC07].

The concept for a drift-tube linac layout is shown in Figure 2 [Gall01]. The model includes drift tubes placed inside of a DTL tank. The accelerator structure is placed inside of an accelerator tunnel with concrete walls. The accelerator tunnel contains air outside of the accelerator structure. For the transport and activation calculations a simplified model shown in Figure 3 with reduced number of cells and homogenized materials was used.

Figure 4: Section of the DTL model housing the drift tubes placed in a DTL tank. The figure is taken from [Gall01].

Figure 5: Section of the DTL model housing the drift tubes placed in a DTL tank with materials shown. The concrete regions are not shown but were included in the PHITS transport calculations.

6.4.1. Radiation Transport Results

Proton and heavy ion interactions with the DTL model were studied using the heavy ion transport code system PHITS.

In the calculations the sources were assumed to be distributed uniformly along the axis of the beam pipe with uniform divergence of 2.5 degrees from the nominal beam direction. The length for each source was 36.649 m. Each source was normalized to provide losses of 1 W/m.

6.4.2. Calculations of Activation using DCHAIN-SP 2001

For each ion, nuclide production yields and fluxes of neutrons having energies below 20 MeV were obtained from the PHITS simulations. The yields, fluxes, and the material elemental compositions and volumes were used as input to DCHAIN-SP 2001 [Kai01].

6.4.2.1. Normalizations

DCHAIN requires the particle current (in particle-mA), the total energy of the ion (in GeV) and the number of ions per second (to normalize the neutron flux spectra). Just as in section 5.3.2.1 the normalization factors for each ion were calculated using the relationship between lost beam power, the total energy of the beam and the beam current:

$$\text{Power} = \text{Total Energy} \times \text{Particle Current}$$

where

$$\text{Total Energy} = \text{Specific Energy} \times \text{Mass}, \text{ and } 1 \text{ pmA} = 6.24 \times 10^{15} \text{ ions} / \text{s}.$$

Table 5 presents the ion information used in the calculations and the resulting values for the particle currents and number of ions per second.

Table 5: Beam ions, specific energies, and particle currents and number of ions per second for 1 W/m beam power losses along the DTL.

Ion	Specific Energy [MeV/u]	Particle Current for 1 W/m [pA]	Number of Ions per Second [s ⁻¹]
H	1000	3.66E-05	2.29E+11
³ He	777	1.57E-05	9.81E+10
⁴⁸ Ca	500	1.53E-06	9.53E+09
⁸⁶ Kr	500	8.52E-07	5.32E+09
¹³⁶ Xe	500	5.39E-07	3.36E+09
²³⁸ U	400	3.85E-07	2.40E+09

6.4.2.2. Irradiation Time, Cooling Time Assumptions

The DTL model was assumed irradiated for 100 days and then allowed to “cool” for 4 h after the irradiation.

6.4.2.3. MCNPX Calculations

The activation and decay calculations performed with DCHAIN-SP 2001 provided the intensity and energy spectrum of the photon source for each geometry cell included in the calculation. The photon sources were used in subsequent MCNPX [Pel05] calculation of photon dose rates in the accelerator tunnel. The geometry model was the same as for the simulation of the proton and ion beams interactions with the accelerator structures.

The photon source description took advantage of the great flexibility provided by the MCNPX code, and was quite elaborate. For each source photon the origination point, the energy, and the direction need to be selected. This was performed as follows. First the geometry cell was selected. The probability to select a cell, which was proportional to the intensity of the photon source in a cell, was biased, so that the cells were picked with equal probability. The coordinates of the origination point were determined by uniformly selecting a point inside a cell-specific rectangular parallelepiped, which dimensions were defined so that it contained the selected cell. A point was re-sampled if it wasn't inside the cell. The photon energy was selected from the

histogram distribution specific for the selected cell. The photon direction was sampled from an isotropic distribution. The weight of a source photon was made equal to the total strength of the photon source (summed over all energies and cells), so that the dose rates were properly normalized.

A cylindrical surface placed at the selected distance from the beam, coaxial with the beam direction, and segmented in 50 cm intervals was used to tally the photon fluxes. The ICRP-21 photon-flux-to-dose-rate conversion factors were used to calculate photon dose rates. Mesh tallies, superimposed on the geometry, were employed to determine the spatial distribution of photon dose rate in horizontal and vertical planes through the beam direction as well as in planes perpendicular to the beam at selected locations.

6.4.2.4. Activation Results

Figure 15 shows a cross section of the tunnel and DTL, and the residual dose rates at 4 h after a 100 d-irradiation with 1 W/m loss of 1 GeV protons. The calculated maximum dose rate within the beam pipe (see Figure 16) was 45.8 mSv/h (4.58 rem/h). Figure 17 shows the same for 1 W/m loss of ^{48}Ca ions having specific energy 500 MeV/u. The calculated maximum dose rate in this case, within the beam pipe, was 18 mSv/h (1.8 rem/h).

Figure 15: Photon dose rates superimposed on the cut through DLT tunnel perpendicular to the beam direction at 4 h after a 100 d-irradiation by 1 W/m-loss of 1 GeV protons. Dose rates are in units of rem/h (0.01 Sv/h). Scales on the right and the bottom edges are dimensions (in centimeters).

Figure16: Detail from Fig. 15, enlarged to show dose rates in the vicinity of the DTL tank.

Figure 17: Photon dose rates superimposed on the cut through DLT tunnel perpendicular to the beam direction at 4 h after a 100 d-irradiation by 1 W/m-loss of 500 MeV/u ^{48}Ca ions. Dose rates are in units of rem/h (0.01 Sv/h). Scales on the right and the bottom edges are dimensions (in centimeters).

Figure 18 shows the calculated residual dose rates at 30 cm from the DTL tank walls 4 h after a 100 d-irradiation by 1 W/m losses of protons and ^3He , ^{48}Ca , ^{86}Kr , ^{136}Xe , and ^{238}U ions. The residual dose rates were averaged over 11 m length along the DTL (from 11.5 m to 22.5 m; see Fig. 18). The ratio of those average dose rates from the heavy ion beams to the proton beam are shown in Table 6 and agree well with the result presented in Table 4 for the case of simple steel pipe.

Figure 18: Comparison of dose rates at 4 h after a 100 d-irradiation by 1 W/m-losses of 1-GeV protons and of 777 MeV/u ^3He and 500 MeV/u ^{48}Ca , ^{86}Kr , ^{136}Xe and ^{238}U ions.

Table 6: Beam ions and specific energies, and dose rates 30 cm from the DTL tank relative to dose rates produced by the 1-GeV proton beam. Losses of 1 W/m were assumed. For reference, in the case of the proton beam, the average dose rate at 30 cm from the DTL tank between 11.5 m and 22.5 m along the DTL is 53.5 mrem/h.

Ion (Specific Energy in MeV/u)	Dose rate relative to that from proton beam for the DTL (%)
H (1000)	100.0
^3He (777)	85.3
^{48}Ca (500)	20.5
^{86}Kr (500)	13.1
^{136}Xe (500)	10.1
^{238}U (400)	5.4

6.5. Simulations using a Superconducting Linac (SCL) Geometry

To study another complex accelerating structure that may be more appropriate for accelerators for high energy applications, a geometric model of a tunnel containing superconducting linac (SCL) sections was obtained from a large-scale tunnel model used in beam loss studies at SNS [Gall01]. A detailed conceptual layout of the tunnel and SCL elements

are shown in Figure 19 [Gall01]. The layout includes geometries of “medium-beta” cavities and physically longer, high-beta cavities, placed inside of helium-filled stainless steel cryomodules. Pairs of normal-conducting magnets are located between cryomodules. The accelerator structure is placed inside of a concrete accelerator tunnel. The accelerator tunnel contains air outside of the accelerator structure.

Figure 20 shows simplified model of the tunnel section with dimensions that was employed in the Monte Carlo and activation calculations. Figure 21 shows some details of the materials and densities used in the simplified model.

Figure 19: The left panel shows the section of the detailed SCL model showing medium-beta cryomodules. The right panel shows the section of the SCL model showing high-beta cryomodules.

Figure 20: The section of the SCL model employed in PHITS calculations showing medium-beta and high-beta cryomodules.

Figure 21: Section of the SCL model used in PHITS calculations housing the low-beta SCL cryomodules and the magnets between them. Material descriptions and densities are shown.

6.5.1. Radiation Transport Results

Proton and heavy ion (500 MeV/u ^{48}Ca) interactions with the SCL model were studied using the heavy ion transport code system PHITS.

In the calculations the sources were assumed to be distributed uniformly along the axis of the beam pipe with uniform divergence of 2.5 degrees from the nominal beam direction. The length for each source was 129.372 m. Each source was normalized to provide losses of 1 W/m.

6.5.2. Calculations of Activation using DCHAIN-SP 2001

For each ion, nuclide production yields and fluxes of neutrons having energies below 20 MeV were obtained from the PHITS simulations. The yields, fluxes, and the material elemental compositions and volumes were used as input to DCHAIN-SP 2001.

6.5.2.1. Normalizations

DCHAIN requires the particle current (in particle-mA), the total energy of the ion (in GeV) and the number of ions per second (to normalize the neutron flux spectra). The normalization factors for each ion were calculated using the relationship between lost power, the total energy of the beam and the beam current:

$$\text{Power} = \text{Total Energy} \times \text{Particle Current}$$

where

$$\text{Total Energy} = \text{Specific Energy} \times \text{Mass}, \text{ and } 1 \text{ pmA} = 6.24 \times 10^{15} \text{ ions} / \text{s}.$$

Table 6 presents the information used in the calculation and the resulting values for the particle currents and number of ions per second.

Table 7: Beam ions, specific energies, and particle currents and number of ions per second for 1 W/m losses along the SCL.

Ion	Specific Energy [MeV/u]	Particle Current for 1 W/m [pA]	Number of Ions per Second [s ⁻¹]
H	1000	1.29E-04	8.07E+11
⁴⁸ Ca	500	5.36E-06	3.36E+10

6.5.2.2. Irradiation Time, Cooling Time Assumptions

The SCL model was assumed irradiated for 100 days and then allowed to “cool” for 4 h after the irradiation.

6.5.2.3. MCNPX Calculations

The activation and decay calculations performed with DCHAIN-SP 2001 provided the intensity and energy spectrum of the photon source for each geometry cell included in the calculation. The photon sources were used in subsequent MCNPX calculation of photon dose rates in the accelerator tunnel. The method used was the same as that for the DTL model, described in section 6.4.2.3.

6.5.2.4. Activation Results

Figure 22 shows the horizontal section of the tunnel and SCL, and the residual dose rates at 4 h after a 100 d-irradiation with 1 W/m loss of 1 GeV protons. Figure 23 shows the horizontal section of the tunnel and SCL, and the residual dose rates at 4 h after a 100 d-irradiation with 1 W/m loss of 500 MeV/u ^{48}Ca ions. It is noted that the level of activation by 1 W/m line-losses of 1 GeV protons is significantly higher than the level of activation produced by 1 W/m losses 500 MeV/u ^{48}Ca ions.

Figure 22: Horizontal section through tunnel containing a SCL as used in beam loss simulations and dose rate calculations. Photon dose rates are shown for 4 h after a 100 d-irradiation by 1 W/m-loss of 1 GeV protons. Dose rates are in units of rem/h (0.01 Sv/h). Scales on the right and the bottom edges are dimensions (in centimeters).

Figure 23: Horizontal section through tunnel containing a SCL as used in beam loss simulations and dose rate calculations. Photon dose rates are shown for 4 h after a 100 d-irradiation by 1 W/m-loss of 500 MeV/u ^{48}Ca ions. Dose rates are in units of rem/h (0.01 Sv/h). Scales on the right and the bottom edges are dimensions (in centimeters).

It is noted that there is significant activation of the copper magnet pairs located between the cryomodule tanks. Figure 24 shows the gamma dose rate in a plane perpendicular to the beam direction, at $z = 166$ m, which is representative of the region in the vicinity of the magnets. The residual dose rates are at 4 h after a 100 d-irradiation with 1 W/m loss of 1 GeV protons. Figure

25 shows the gamma dose rate in a plane perpendicular to the beam direction, at $z = 170$ m. Here the dose rate level is significantly lower than the dose rate level near the magnet pairs. Figures 26 and 27 show calculated dose rates for the 500 MeV/u ^{48}Ca ion beam. The irradiation conditions and locations are the same as those shown in Figs 24 and 25 for the proton beam.

Figure 24: Cross section of tunnel at 166 m (see Figure 22), containing the SCL as used in beam loss simulations and dose rate calculations. Photon dose rates are shown for 4 h after a 100 d-irradiation by 1 W/m-loss of 1 GeV protons. Dose rates are in units of rem/h (0.01 Sv/h). Scales on the right and the bottom edges are dimensions (in centimeters).

Figure 25: Cross section of tunnel at 170 m (see Figure 22), containing the SCL as used in beam loss simulations and dose rate calculations. Photon dose rates are shown for 4 h after a 100 d-irradiation by 1 W/m-loss of 1 GeV protons. Dose rates are in units of rem/h (0.01 Sv/h). Scales on the right and the bottom edges are dimensions (in centimeters).

Figure 26: Cross section of tunnel at 166 m (see Figure 22), containing the SCL as used in beam loss simulations and dose rate calculations. Photon dose rates are shown for 4 h after a 100 d-irradiation by 1 W/m-loss of 500 MeV/u ^{48}Ca ions. Dose rates are in units of rem/h (0.01 Sv/h). Scales on the right and the bottom edges are dimensions (in centimeters).

Figure 27: Cross section of tunnel at 170 m (see Figure 22), containing the SCL as used in beam loss simulations and dose rate calculations. Photon dose rates are shown for 4 h after a 100 d-irradiation by 1 W/m-loss of 500 MeV/u ^{48}Ca ions. Dose rates are in units of rem/h (0.01 Sv/h). Scales on the right and the bottom edges are dimensions (in centimeters).

Figure 28 shows the calculated residual dose rate distribution along the SCL at 30 cm from the SCL cryomodule tank walls for the protons and ^{48}Ca ion beams and the irradiation conditions as previously described in this section. The linac sections exhibiting the highest dose rates are near the exposed magnets. For the proton beam the dose rates there exceed the recommended hands-one maintenance level; however they are well below the recommended level for the ^{48}Ca beam. Along the SCL outside of cryomodule tanks, the levels of activation are similar to those for the DTL structure. In the SCL case, like the DTL case, the ratio of the maximum dose rates from the ^{48}Ca ion beam losses to those due to proton beam losses agree well with the results presented in Tables 4 and 6.

Figure 28: Comparison between dose rates along the SCL at 4 h after a 100 d-irradiation by 1 W/m-losses of 1-GeV protons and of 500 MeV/u ⁴⁸Ca ions.

7. Conclusions and Recommendations

Dose rates from accelerator components activated by 1 W/m beam losses are obtained semi-empirically for a 1 GeV proton beam and by Monte Carlo transport codes for the proton beam and for 777 MeV/u ³He and 500 MeV/u ⁴⁸Ca, ⁸⁶Kr, ¹³⁶Xe and ²³⁸U ion beams. The dose rate obtained by the semi-empirical method, 0.99 mSv/h (99 mrem/h) at 30 cm, 4 h after 100 d-irradiation by a 1-GeV proton beam, is consistent with studies at several accelerator facilities and with adopted hands-on maintenance dose rate limits. Monte Carlo simulations verify this result for protons and extend studies to heavy ion beam losses in drift-tube linac and superconducting linac accelerating structures. Monte Carlo simulations indicated that the 1 W/m limit imposed on uncontrolled beam losses for high-energy proton beams might be relaxed for heavy ion beams. These studies further suggest that using the ratio of produced neutrons by a heavy ion beam to that by a proton beam along with the dose rate from the proton beam should allow an estimate of the dose rates expected from heavy ion beam losses.

Our results are in very good agreement with a similar study by Strasik *et al.* [Str08], presented at ICRS-11/RPSD-2008; we also presented our first results at the same conference.

8. References

- [Bat10] H. Bateman, "The solution of a system of differential equations occurring in the theory of radio-active transformations", Proc. Cambridge Philos. Soc. 15, 423-427 (1910)
- [Ber63] H.W. Bertini, "Monte Carlo Calculations on Intranuclear Cascade", ORNL-pp.3833, Oak Ridge National Laboratory (1963)
- [Bre97] J.F. Briesmeister, "MCNP – a General Monte Carlo N-Particle Transport Code", Los Alamos National Laboratory, LA-12625-M (1997)
- [Bro00] Tim Broome, "The Production of Useful Neutrons, The ISIS Lectures", www.isis.rl.ac.uk/accelerator/lectures/, (April 17, 2000)
- [Cat01] N. Catalan-Lasheras, J. Galambos, N. Holtkamp, D. Raparia, R. Shafer, J. Staples, J. Stovall, E. Tanke, T. Wangler, and J. Wei, ORNL Technical Note SNS/AP/7 (2001)
- [Cha99] M.B. Chadwick *et al.*, "LAI50 Documentation of Cross Sections, Heating, and Damage", Los Alamos National Laboratory, LA-UR-99-1222 (1999)
- [For97] R.A. Forrest, F.M. Mann, "FENDLID-2.0, Decay Data Library for Fusion Applications", Summary Documentation by A.B. Pashchenko and H. Wienke, Report IAEA-NDS-178 (1997)
- [Fir96] R.B. Firestone, V.S. Shirley (eds.): Table of Isotopes Eighth Edition (1996)
- [Fur00] S. Furihata, Nucl. Instr. Meth. B171, 251 (2000)
- [Gala01] John Galambos, N. Catalan-Lasheras, D. Raparia, R. Shafer, E. Tanke, and J. Wei, "SNS beam loss, activation, and collimation", M6 Working Group Meeting, Snowmass CO (July 7, 2001)
- [Gall01] Franz X. Gallmeier, "Calculations of Operational and Residual Doses for the SNS Linac", AccApp'01 and ADTTA'01 Nuclear Applications in the New Millennium, Reno, NV (US), November 11-15, 2001
- [Har99] R. A. Hardekopf, "Beam Loss and Activation at LANSCE and SNS", LA-UR-99-6825, Los Alamos National Laboratory, Los Alamos, NM (September, 1999)
- [Hor96] T. Horiguchi, T. Tachibana J. Katakura, "Chart of the Nuclides 1996," JAERI/NDC (1996)
- [Iwa01] H. Iwase, T. Kurosawa, T. Nakamura, N. Yoshizawa, J. Funabiki, "Development of heavy ion transport Monte Carlo code", Nucl. Inst. Meth. B183, pp. 374 (2001)
- [Iwa02] H. Iwase, K. Niita, and T. Nakamura, "Development of General-Purpose Particle and Heavy Ion Transport Monte Carlo Code", Journal of Nuclear Science and Tech. 39, pp. 1142-1151 (2002)

- [Iwa03] H. Iwase, Ph.D. Thesis, Tohoku University (2003)
- [Kai01] T. Kai, F. Maekawa, K. Kosako, Y. Kasugai, H. Takada, and Y. Ikeda, "DCHAIN-SP 2001: High Energy Particle Induced Radioactivity Calculation Code", JAERI Data/Code-2001-016 (February 2001)
- [Kop92] J. Kopecky and D. Nierop, "Contents of EAF-3, " ECN-1-92-023 (1992)
- [Kur00] T. Kurosawa *et al.*, "Neutron yield from thick C, Al, Cu and Pb targets bombarded by 400 MeV/nucleon Ar, Fe, Xe, and 800 MeV/nucleon Si ions," Phys. Rev. C, 62, 044615 (2000)
- [McL96] V. McLane, et al., "ENDF/B-VI Summary Documentation", BNL-NCS-17541 (1996)
- [MCNP05] X-5 Monte Carlo Team, "MCNP – A General Monte Carlo N-Particle Transport Code Version 5", Diagnostics Applications Group, Los Alamos National Laboratory, LA-UR-03-1987 (Revised 10/3/05)
- [Mok99] N. V. Mokhov and W. Chou, Eds., Workshop on Beam Halo and Scraping, Lake Como, Wisconsin (FNAL, Batavia, IL) (1999)
- [Nak05] Takashi Nakamura and Lawrence Heilbronn, Handbook on Secondary Particle Production and Transport by High-Energy Heavy Ions, World Scientific Publishing Co., Singapore (2005)
- [Nak92] M. Nakazawa, K. Kobayashi, S. Iwasalu, T. Iguchi, K. Sakurai, Y. Ikeda T. Nakagawa, "JENDL Dosimetry File", JAERI, pp. 1325 (1992)
- [Nak95] T. Nakagawa, K. Shibata, S. Chiba, T. Fukahori, Y. Nakajima, Y. Kikuchi, T. Kawano, Y. Kanda, T. Ohsawa, H. Matsunobu, M. Kawai, A. Zukeran, T. Watanabe, S. Igarasi, K. Kosako, T. Asami, "Japanese Evaluated Nuclear Data Library Version 3 Revision-2: JENDL-3.2", J. Nucl. Sci. Technol., 32, 1259 (1995)
- [Nak96] Y. Nakajima, "Status of the JENDL Activation File", JAERI-Conf 96-008, p.50 (1996)
- [Nar99] Y. Nara, N. Otuka, A. Ohnishi, K. Niita, S. Chiba, "Study of relativistic nuclear collisions at AGS energies from p + Be to Au + Au with Hadronic Cascade Model", Phys. Rev. C 61, 024901 (1999)
- [Nii01] K. Niita, H. Takada, S. Meigo, Y. Ikeda, "High-energy transport code NMTC/JAM", Nucl. Instr. Meth. B 184, pp. 406 (2001)
- [NSAC07] DOE/NSF Nuclear Science Advisory Committee Report, Robert Tribble (Chair), "The Frontiers of Nuclear Science" (December 2007)
- [Pas93] A.B. Pashchenko, "Status of FENDL Activation File and Plans for the Future Developments", Proc. Int. Workshop on Nucl. Data for Fusion Reactor Technol., Del Mar, California, USA, pp. 3-6 (1993)
- [Pas96] A.B. Pashchenko, "Summary Report for IAEA Consultants' Meeting on Selection of Evaluations for the FENDLIA-2 Activation Cross Section Library", INDC(NDS)-341, International Atomic Energy Agency (1996)
- [Pel05] D.B. Pelowitz, ed., "MCNPX User's Manual Version 2.5.0," Los Alamos National Laboratory, LA-CP-05-0369 (April 2005)

- [Pra89] R.E. Prael, H. Lichtenstein, "User guide to LCS: The LAHET Code System", Los Alamos National Laboratory, LA-UR-89-3014, Revised (September 15, 1989)
- [Rem00] Igor Remec, "Calculation of Dose Rate in the Ring South Access Tunnel", Oak Ridge National Laboratory, SNS 106100200-TR0021-R00 (September 2000)
- [Shi02] K. Shibata *et al.*, "Japanese Evaluated Nuclear Data Library Version 3 Revision-3: JENDLE-3.3", J. Nucl. Sci. Technol. 39, 1125 (2002)
- [Str08] I. Strasik, E. Koslova, I. Hofmann, E. Mustafin, A. Smolyakov, N. Sobolevskiy, and L. Latysheva, "Simulation of the residual activity induced by high-energy heavy ions", Proc. ICRS-11/RPSD-2008, Pine Mountain, GA, (April 13-18, 2008)
- [Sul92] A. H. Sullivan, "A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators", Nuclear Technology Publishing, Ashford, Kent, United Kingdom (1992)
- [Tak98] H. Takada, N. Yoshizawa, K. Kosako, K. Ishibashi, "An Upgrade Version of Nucleon Meson Transport Code, NMTC/JAERI97," JAERI-Data/Code 98-005 (1998)
- [Tak99] H. Takada, K. Kosako, "A Code System for Analyzing Decay and Build-up Characteristics of Spallation Products," JAERI-Data/Code-99-008 (March 1999)
- [Tas80] K. Tasaka, "DCHAIN2: A Computer Code for Calculation of Transmutation of Nuclides", JAERI-M 8727 (1980)
- [Tul87] J.K. Tuli, "Evaluated Nuclear Structure Data File," BNL-NCS-5 1655-Rev.87 (UC-32c) (1987); The data set used was taken from the version released in 1997.
- [Wei03] Jie Wei, "Synchrotrons and accumulators for high-intensity proton beams", Reviews of Modern Physics 75, pp. 1383-1432 (2003)
- [Wan98] Thomas P. Wangler, "Principles of RF Linear Accelerators", (Wiley, New York) (1998)
- [Wan08] Thomas P. Wangler, "RF Linear Accelerators", John Wiley & Sons, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany (2008)