Nuclear heating and radiation damage studies for a compact superconducting proton cyclotron


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Nuclear heating and radiation damage studies for a compact superconducting proton cyclotron

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Abstract

Radiation effects on the superconducting magnet system are critical considerations in the design of ultracompact, high energy, high current ion cyclotrons, especially when control of the full power beam is lost during operation. Nuclear particle cascades caused by the ion beam striking materials inside the cyclotron can result in nuclear heating of the cryogenic magnet and radiation damage to the superconductor, potentially causing permanent magnet damage or failure. To predict the expected radiation effects for Megatron, a proposed experimental 250 MeV, 1 mA superconducting proton cyclotron, Geant4 was used to model the nuclear heating and radiation damage resulting from two loss-of-beam-control scenarios: the beam impacting the cryogenic cold masses; and the proton beam impacting the copper beam extraction aperture. Results of the nuclear heating and radiation damage calculations for both scenarios are presented, and their implication for the design of the Megatron cyclotron is discussed.

Keywords: Superconducting cyclotron, Nuclear heating, Radiation damage, Geant4

1. Introduction

Superconducting magnets in strong radiation fields experience two deleterious effects: radiation induced damage to the current carrying elements in the magnet and nuclear heating of the magnet cryogenic system. The full characterization of the radiation field of a proposed cyclotron is, therefore, a critical component of the design phase. The radiation in cyclotrons may be broadly classified into two categories: primary radiation refers to the beam of particles that are injected at low energy and extracted from the cyclotron after acceleration; secondary radiation refers to particles that are induced by the primary particles.

The dominant radiation effect on materials is caused when the accelerated beam strikes a material surface and induces nuclear particle cascades inside the cyclotron. The primary and secondary radiations are stopped in the cyclotron structure and deposit their kinetic energy as heat. Other forms of secondary radiation, such as synchrotron radiation, may be safely neglected, since the total radiated power

\[ P = \frac{2e^2c \beta^4 \gamma^4}{3r^2} \]

is negligible compared to the kinetic power of an accelerated particle. This is especially true for ion cyclotrons, since the radiated power scales inversely to the fourth power of the particle rest mass. For instance, a 250 MeV, 1 μA proton cyclotron beam with a 1 m radius contains 250 W of kinetic power compared to approximately 0.1 μW of radiated power.

Megatron is a proposed compact (2.0 m) isochronous cyclotron for experimentally demonstrating the feasibility of high energy (250 MeV) high current (1 mA) superconducting proton cyclotrons in order to assess the present technological limits on high power cyclotron operation [1]. A cross section of the Megatron engineering model is presented in Figure 1; the key engineering parameters are presented in Table 1. The critical limits on the radiation damage and cryogenic temperature of the superconductor in the magnets, coupled with the high beam energy and current, require careful study of the radiation fields in Megatron and their effect on the superconducting magnets.

This paper is structured as follows: Section 2 describes the critical radiation effects and design challenges for compact su-
perconducting cyclotrons; Section 3 presents a Geant4 model for simulating radiation transport and effects in the Megatron cyclotron, as well as several results from the verification and validation of the model; Section 4 presents the results of nuclear heating effects on the Megatron superconducting magnetic coils, while Section 4.2 presents the results of radiation damage to the superconductor and electrical insulator of the Megatron superconducting coils; finally, Section 5 concludes with a discussion of the effects of radiation on the design of Megatron.

2. Radiation challenges in ultracompact superconducting cyclotrons

Historically, the large size and/or relatively small beam power of ion cyclotrons have ensured that nuclear heating and radiation damage in the superconducting magnets did pose serious operational limits. Recently, however, in response to demands from the medical and security industries, cyclotron technology is being developed that will be capable of achieving high energy (~ 250 MeV to ~ GeV) [2, 3] and high beam current (~ µA to mA) [4], increasing the impact of radiation effects.

For primary ions that collide with materials inside the cyclotron, high kinetic energies open many nuclear reaction channels while high beam currents result in substantial nuclear reaction rates for the accessible reaction channels. Aggravating the radiation issues in ultracompact cyclotrons is the constrictive geometry. With diameters on the order of a meter, the superconducting coils in ultracompact cyclotrons are exposed to much higher radiation fluences than found in larger cyclotrons. The compactness of the cyclotron, coupled with the high-energy nature of the secondary neutron and gamma radiation hinders the implementation of an effective radiation shield.

Two radiation effects must be considered: nuclear heating of the cryogenic superconducting magnets; and radiation damage to the superconductor within the magnets. Nuclear heating of the magnets occurs when high energy primary or secondary particles deposit their kinetic energy into the bulk mass of the magnet as heat, either through direct ionization (in the case of ions) or through the production of secondary ions within the magnet itself (in the case of neutrons and gamma rays). To prevent a quench of the superconducting magnet, which can permanently damage or destroy the magnet, the deposition of heat in the cold mass (superconducting magnet plus other cryogenic volumes such as magnet supports) must be commensurate with the heat-removal capabilities of the cryocooler used to keep the magnet below the superconducting critical temperature.

Radiation damage to the magnet occurs when the superconducting windings are exposed to high particle fluences. For example, due to neutron-induced elastic collisions causing microstructure defects (displaced atoms, dislocations), the fast neutron fluence (> 0.1 MeV) linearly decreases the critical temperature of Nb3Sn superconductor and ultimately prevents superconducting operation for fluences above 4.5 × 10^23 m^-2 [5]. For NbTi superconductor, fast neutron fluences (¿1 MeV) on the order of 10^23 m^-2 have been shown to decrease the critical currents by up to 20 % [6]. Furthermore, the accumulated radiation dose from neutrons and gammas embrittle and weaken the electrical insulator and copper stabilizer used in the construction of the superconducting windings, resulting in a potential failure mechanism for the magnet. Experiments have shown that epoxy-based insulators, such as G10-CR, degrade significantly after gamma and neutron doses on the order of 10^7 rads and 10^8 rads, respectively, while polyimide-based insulators can withstand total doses of 10^9 to 10^10 rads without compromising the structural properties [7].

3. Cyclotron radiation studies with Geant4

Monte Carlo particle transport codes such as Geant4 [8] have been extensively employed in the design of particle accelerators and the study of the radiation fields they produce e.g [9, 10]). Other Monte Carlo codes such as MCNPX [11], PHITS [12] and FLUKA [13] have been used for the same purpose and would have also been suitable for the study of Megatron. Geant4 was selected because the extensive physics packages, such as particle transport through electromagnetic fields and modelling of scintillation physics, enable the present simulation to be extended for comprehensive future design studies, such as particle injection, particle extraction, and external detectors for beam diagnostics. In addition, the modular C++ nature of Geant4 enhanced the ability to perform automated parameter sweeps (e.g. for shielding studies) and allowed customized data formatting and output (e.g. for input into finite element analysis codes).

3.1. Overview of the relevant Geant4 physics models

When using Geant4 to model nuclear heating and radiation damage studies in cyclotrons, care should be taken in the selection of neutron transport and hadronic cascade models. While the standard electromagnetic models in Geant4 are capable of handling the gamma transport and charged particle energy deposition required, different neutron transport and hadronic cascade models, however, can significantly affect the calculated result.

For the transport of neutrons, Geant4 uses parameterized, or theory-driven, models for computationally efficient treatment of
neutrons, although with some penalty in accuracy. This is especially necessary in the high energy region (~150 MeV to ~1 TeV) where essentially no neutron cross section data is available. For applications where neutron transport and neutron-induced reactions are critical, the parameterized model may be replaced by the high-precision (HP), data-driven neutron transport model in the 0 to 20 MeV neutron energy range. With extensive cross section data from the ENDF-VI and ENDF-VII nuclear data libraries, the HP model accounts for neutron elastic, inelastic, capture, and fission reactions.

For the production of secondary radiation, Geant4 contains three principle hadronic cascade models that are valid for the energy range of interest in Megatron, all of which have been extensively validated against experimental data: the Bertini cascade [14], the binary ion cascade [15], and the Liège cascade-ablation model [16].

The Bertini cascade (BERT) models the nucleus as an average nuclear medium in which primary and secondary hadrons collide with nucleons according to the free-particle cross section data, which are used to generate the final state of the nucleus. Deexcitation of the nucleus is handled by pre-equilibrium, nucleus explosion, fission, and evaporation models. The BERT model has been validated in the 0 to 10 GeV energy range for incident hadrons.

The binary ion cascade (BIC) models the nucleus as a three-dimensional nucleon assembly; primary and secondary hadrons are transported through the nuclei using two particle (binary) collisions in the nuclear force field with a Runge-Kutta stepper. The BIC model has been validated from 0 to 10 GeV for incident protons and neutrons, and it is the most accurate of the three hadronic models at reproducing experimental results in the ≲ 1 GeV range.

The Liège cascade-ablation model (INCL/ABLA) models the nucleus as an isotropic nucleon target, with the primary and secondary hadrons transported in straight line trajectories to binary collisions with randomly sampled nucleons. Deexcitation of the excited nucleus is handled by an implementatio of the ABLA code. The INCL/ABLA model has been validated in the 0.2 to 3.0 GeV energy range for incident neutrons and light ions, making it less suitable for Megatron studies due to its 0.2 GeV energy cutoff.

3.2. Benchmarking Geant4 against MCNPX

In order to qualify Geant4 as a tool for radiation studies in Megatron, as well as to optimize the selection of neutron transport and hadronic cascade models and parameters, Geant4 (version geant4.9.4.p02) was compared as directly as possible to MCNPX (version 2.60) for three different benchmark cases: spallation by 250 MeV protons in copper; heating of copper by neutrons and gammas; and heating of copper by 250 MeV proton spallation particles. In all three cases, care was taken to ensure that the geometry and materials were identical.

In Geant4, the standard parameterized model and the neutron HP model, which used the G4NDL3.14 neutron data library for neutron physics below 20 MeV, were used for neutron transport; the BERT, BIC, and INCL/ABLA models were used for simulating the hadronic cascades. The inclusion of the physics was accomplished with the standard prepackaged physics list included with the Geant4 source code: QGSP_BERT, QGSP_BERT_HP, QGSP_BIC, QGSP_BIC_HP, and QGSP_INCL_ABLA.

In MCNPX, neutron transport was data driven below 150 MeV using the ENDF/B-VI.8 neutron data libraries and parameterized above 150 MeV. The simulation of hadronic cascades was carried out with three available models, two of which are MCNPX equivalents of the hadronic cascade models found in Geant4: the Bertini cascade, the Liège cascade-ablation model, and the ISABEL model. All three MCNPX hadronic models were used with their default settings on the LCA and LBC physics cards with the exception that the maximum applicable energy was set to 255 MeV.

3.2.1. Benchmarking 250 MeV proton spallation

To benchmark the production of spallation particles from 250 MeV protons impacting copper, a geometry consisting solely of a 5 × 5 × 7 cm copper target was used. A one-dimensional pencil beam of 1 × 10^5, 250 MeV protons was directed into the target along the axial direction. The dimensions of the target were chosen using SRIM [17] to ensure that 250 MeV protons would be fully stopped within the target.

The normalized spallation particle yields (spallation particle yields per incident 250 MeV proton) were tabulated for the hadronic cascade models of interest. In Geant4, yields were aggregated by using the G4UserStackingAction class to count new particle tracks during the simulation run; in MCNPX, the spallation particle yields are automatically banked in the MCNPX output file at the end of the simulation run. The tabulated results appear in Table 2.

<table>
<thead>
<tr>
<th>Cascade model</th>
<th>n</th>
<th>p</th>
<th>d</th>
<th>t</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCL/ABLA</td>
<td>0.990</td>
<td>0.695</td>
<td>0.023</td>
<td>0.004</td>
<td>0.074</td>
</tr>
<tr>
<td>BERT</td>
<td>1.012</td>
<td>0.711</td>
<td>0.026</td>
<td>0.004</td>
<td>0.074</td>
</tr>
<tr>
<td>ISABEL</td>
<td>0.990</td>
<td>0.698</td>
<td>0.025</td>
<td>0.004</td>
<td>0.072</td>
</tr>
<tr>
<td>Geant4/BERT</td>
<td>1.024</td>
<td>0.586</td>
<td>0.059</td>
<td>0.015</td>
<td>0.154</td>
</tr>
<tr>
<td>INCL/ABLA</td>
<td>1.192</td>
<td>0.697</td>
<td>0.017</td>
<td>0.003</td>
<td>0.027</td>
</tr>
</tbody>
</table>

3.2.2. Benchmarking the nuclear heating of copper

To benchmark the nuclear heating of copper, a simplified cyclotron-like geometry consisting of a copper “magnet coil” cylinder (r_{inner} = 0.6 m, r_{outer} = 0.8 m, r = 0.3 m) contained within a hollow iron “magnet yoke” cylinder (r_{inner} = 0.5 m, r_{outer} = 1.0 m, h = 0.5 m). An isotropic, monenergetic point source was placed at the center midplane of the geometry in order to investigate the energy deposition by gammas and neutrons in the copper coil.

The energy deposited in the copper coil per incident particle was scored over the energy range of interest of gammas (0–
20 MeV) and neutrons (0–250 MeV). In Geant4, the energy deposition was scored by using a sensitive detector attached to the volume representing the copper coil; the energy deposited in the coil was accumulated over the entire run and then normalized. In MCNPX, the energy deposition was scored by using the +F6 collision heating tally for all particles. The tabulated results for gammas appear in Table 3 and for neutrons in Table 4.

### 3.2.3. Benchmarking nuclear heating from spallation

To benchmark the nuclear heating of the copper “magnet coil” from secondary radiation generated by proton spallation on copper, the same simplified cyclotron geometry described above was used. A pencil beam of monoenergetic protons was incident along the axis of a 5 × 5 × 7 cm copper target, which was placed at the center midplane of the geometry.

#### Table 4: Normalized heating (energy deposited per source gamma) of the copper coil for an isotropic, monoenergetic gamma source placed in the center of the benchmark geometry.

<table>
<thead>
<tr>
<th>Gamma energy (MeV)</th>
<th>Geant4</th>
<th>MCNPX</th>
<th>Geant4/MCNPX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0040</td>
<td>0.0040</td>
<td>1.0000</td>
</tr>
<tr>
<td>3</td>
<td>0.0425</td>
<td>0.0426</td>
<td>0.9977</td>
</tr>
<tr>
<td>5</td>
<td>0.0857</td>
<td>0.0854</td>
<td>1.0035</td>
</tr>
<tr>
<td>7</td>
<td>0.1231</td>
<td>0.1216</td>
<td>1.0123</td>
</tr>
<tr>
<td>9</td>
<td>0.1570</td>
<td>0.1535</td>
<td>1.0228</td>
</tr>
<tr>
<td>11</td>
<td>0.1871</td>
<td>0.1832</td>
<td>1.0213</td>
</tr>
<tr>
<td>13</td>
<td>0.2143</td>
<td>0.2115</td>
<td>1.0132</td>
</tr>
<tr>
<td>15</td>
<td>0.2378</td>
<td>0.2396</td>
<td>0.9925</td>
</tr>
<tr>
<td>17</td>
<td>0.2595</td>
<td>0.2684</td>
<td>0.9668</td>
</tr>
<tr>
<td>19</td>
<td>0.2883</td>
<td>0.2974</td>
<td>0.9694</td>
</tr>
</tbody>
</table>

### 3.3. Discussion of benchmarking results

#### 4. Nuclear heating and radiation damage in Megatron

In the present study, two scenarios are considered that may lead to significant nuclear heating and radiation damage in Megatron, both of which occur when control of the full power primary proton beam is lost. The first scenario (Scenario I) occurs when the primary proton beam crosses the radial inner wall of the cryostat, depositing a small amount of energy in the cryostat wall and thermal shielding before impacting the cryogenic stainless steel magnet support bobbin. Primary and secondary radiation contribute significantly to the nuclear heating of the magnet, as well as radiation damage to the G10CR insulation surrounding the magnet windings. The second scenario (Scenario II) occurs when the primary proton beam directly impacts the copper aperture used for beam extraction. Only secondary radiation contributes to radiation effects in the superconducting magnets since it has been assumed that primary protons are fully stopped in the copper aperture. Furthermore, because the copper aperture is immersed in the strong cyclotron magnetic field, secondary charged particles produced in the aperture will spiral inwards before reaching the cryostat and, therefore, not contribute to the nuclear heating or radiation damage of the magnet.

A realistic mockup of the proposed Megatron geometry was constructed in Geant4, including the magnet yoke, magnet dees, cryostat, thermal shielding, superconducting magnets, and magnet support bobbins. The top superconducting magnet, radially innermost layer of G10CR magnet insulation, and steel magnet support bobbin were overlaid with high resolution, 3D cylindrical meshes in order to score the nuclear heating and radiation dose due to particles sources representing Scenarios I and II. The particle source for Scenario I consisted of $1 \times 10^8$, 250 MeV protons tangentially incident upon the cryostat at the full power extraction radius of 42 cm, while the particle source for Scenario II consisted of $1 \times 10^8$ 250 MeV protons incident upon a 5 × 5 × 7 cm copper target at the full power extraction radius of 42 cm to simulate the primary proton beam impacting the copper extraction aperture.

#### 4.1. Nuclear heating of the cryogenic masses

The energy deposited in each voxel of the mesh (units of MeV) was converted into volumetric and total heat deposition...
Two conclusions may be drawn:

- There is significant difference in the total heat deposition profiles between cases I and II, especially for the important cold masses. The conclusion of this study is that full power beam impact into the cryostat must be avoided at all costs. If such an event occurs, at least 7cm of high-Z radiation shielding must be built into the design in order to stop primary radiation from reaching the cold masses. The shield material must be chosen carefully to minimize the secondary radiation produced in the shield that may reach the cold masses and cause additional heat deposition.

- There is strong azimuthal localization of the power deposition for case I versus the smeared out distribution of power deposition in case II. The principle factor is the nuclear kinematics in scenario II. The dissipation of the primary particle energy into secondary particles occurs over a much greater solid angle in scenario II compared to the direct deposition of energy in the cold masses by both primary and secondary particles. The result is both lower power deposition in case I versus the smeared out distribution of power deposition in case II. The principle factor is the nuclear kinematics in scenario II. The dissipation of the primary particle energy into secondary particles occurs over a much greater solid angle in scenario II compared to the direct deposition of energy in the cold masses by both primary and secondary particles. The result is both lower total and peak power deposition in scenario two. The conclusion is that, if peak heating in the magnets is a concern, the extraction aperture must be located as far away from the magnets as possible to leverage the increased solid angle to reduce nuclear heating.

(Units of mW cm$^{-3}$ and mW) per microamp of primary proton beam. A view of the simulation geometry, as well as the two dimensional volumetric heat deposition profiles in a 1 cm planar slice closest to the cyclotron midplane for Scenarios I and II, appear in Figures 2 and 3, respectively.

Future work will entail importing the three dimensional heat deposition profiles into a multiphysics analysis tool, such as COMSOL, in order to assess temperature rise and cooling requirements during steady state and pulsed operation. However, two conclusions may be drawn:

- There is strong azimuthal localization of the power deposition for case I versus the smeared out distribution of power deposition in case II. The principle factor is the nuclear kinematics in scenario II. The dissipation of the primary particle energy into secondary particles occurs over a much greater solid angle in scenario II compared to the direct deposition of energy in the cold masses by both primary and secondary particles. The result is both lower total and peak power deposition in scenario two. The conclusion is that, if peak heating in the magnets is a concern, the extraction aperture must be located as far away from the magnets as possible to leverage the increased solid angle to reduce nuclear heating.

4.2. Radiation damage to the magnet insulation

Calculated radiation damage profiles in the superconducting magnets are shown in Figures 4 and 5. The relatively low accumulated dose rates do not pose significant damage to the superconducting magnets during the predicted lifetime of the cyclotron, even considering steady-state operation during a majority of its lifetime.

5. Conclusion

The deleterious effects of nuclear heating and radiation damage have been examined for two loss-of-beam-control incidents in compact, superconducting cyclotron. We first performed a series of verification and validation studies comparing Geant4 with MCNPX for the physics and energy ranges of interest to this study; the outstanding agreement between the two codes shows the validity of using Geant4 in this work. We then performed a serious of detailed radiation studies using a high-fidelity model of a proposed high-power, compact cyclotron. While radiation damage to the magnets appears to be a non-issue for the lifetime of the cyclotron, we have shown that allowing the 250 MeV primary proton beam to directly impact the cryostat leads to unacceptably high levels of both peak and total heating of the cryogenic cold masses, potentially damaging or destroying the the superconducting magnets through quenching. However, the peak and total heat deposition in the superconducting coil is substantially reduced if the beam first impacts a dedicated shield layer or the beam extraction aperture. A summary of the key results are presented in Table 5.

References

Figure 4: (a) Neutron flux > 0.1 MeV, (b) gamma flux, and (c) accumulated dose rate to the top superconducting coil resulting from the primary proton beam entering the cryostat and being fully stopped by the steel coil bobbin.

Figure 5: (a) Neutron flux > 0.1 MeV, (b) gamma flux, and (c) accumulated dose rate to the top superconducting coil resulting from the primary proton beam impacting the copper beam extraction aperture.


[10] F. Jones, R. Baartman, Y.-N. Rao, Using Geant4-based tools to simulate a proton extraction and transfer line, ICAP09 - 10th International Computational Accelerator Physics Conference 2009.


