THERMO MECHANICAL CALCULATIONS OF A CYCLOTRON DEFLECTOR*

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Abstract
We discuss in this paper finite element calculations that simulate the thermal and mechanical effects on the deflector septum of a cyclotron. The energy deposited by the beam is cooled by radiation and conduction to a water cooled plate. The deformation of the septum due to the thermal expansion and electrical pressure is calculated in the model.

1 INTRODUCTION

The experimental program at the NSCL is shifting toward radioactive beams produced by the projectile fragmentation method. An upgrade of the facility is under way with the purpose of increasing the intensity of secondary beams. In the new regime intense primary heavy ion beams (10^{12} ions/sec of Ar at 8 GeV) will be extracted. The extraction process starts with an electrostatic deflector that peels off the last turn from the internal beam. No real separation exists between them, just a lower current density region. Power losses of 400 W will be absorbed and dissipated by the deflector septum. The usual difficulties of cyclotron deflectors are compounded in the superconducting cyclotron case because of the small vertical gaps where the deflector must be placed.

Traditionally, the cyclotrons accelerating high intensity beams have accelerated protons. Some high intensity radioisotope producing cyclotrons accelerate negative H ions and extract the beam by stripping to positive H. The highest intensity cyclotron beams are extracted from the PSI accelerators where intensities higher than 1.5 mA have been achieved [1]. These accelerators are separated sector cyclotrons, where more space is available to include large electrostatic deflectors, and due to their large size the separation between turns is significantly larger than in compact machines like our superconducting cyclotrons.

When the beam is intercepted by the extraction system septum, protons will deposit the energy in a much larger volume than a heavy ion of the same energy per nucleon. For example a 200 MeV proton has a range of 25.8 mm in Tungsten while a 200 MeV/u Ar beam has a 3.3 mm range, see Figure 1. This much shorter range creates unique problems for high intensity heavy ion cyclotrons.

Cyclotron septa have been designed for many years with a V notch in their leading edge to increase the boundary area of the region where the beam deposits the energy [2].

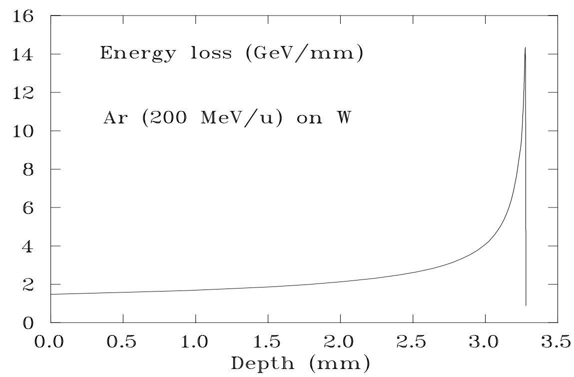

Figure 1 Energy loss as a function of the penetration depth for an 8 GeV Ar ion (200 MeV/u).

2 MECHANICAL DESCRIPTION

The first electrostatic deflector of the K1200 cyclotron consists of three sections approximately 35 cm long, connected with hinges that allow the deflector to adapt to the orbit shape of the different ions being extracted. Most of the losses occur at the entrance edge of the first section [3]. Our calculations are then restricted to this first segment. A cross section of the deflector is shown in Figure 2. The top and bottom plates are made of Cu to assure good thermal conductivity and the bottom one is water cooled. The high voltage electrode is cooled only by conduction through the insulators. The model includes the copper housing but not the high voltage electrode.

The septum is positioned by top and bottom clamps. These clamps can prevent the motion in all directions, or alternatively, provide a sliding guide that allows displacements of the septum, but maintaining some alignment while constraining the angle between the septum and the guides. When the clamps are “loose” the heat transmission to the cooled support housing is decreased.

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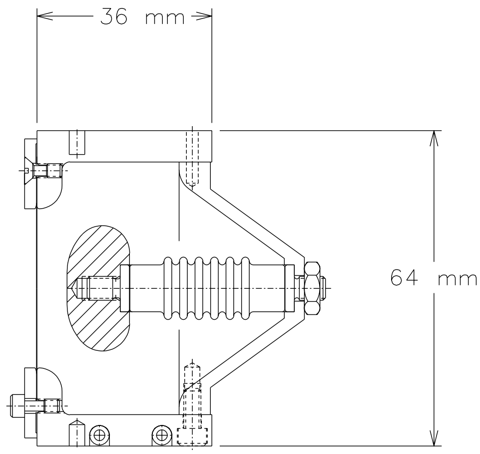

Figure 2 Cross section of the K1200 cyclotron electrostatic deflector. The gap between the septum on the left and the high voltage electrode is 6 mm.

3 THE MODEL

Thermal and mechanical analyses were accomplished using the general purpose finite element analysis (FEA) program COSMOS/M [4] using 3 node or 4 node shell elements for the septum and 8 node solid elements for the housing. All thermal analyses used nonlinear, transient analysis with temperature dependent material properties. Transient analysis was more efficient because of the difficulty in convergence of a static analysis with the high temperatures and gradients present and T^4 radiation dependency.

Mechanical analysis was done on full septa to investigate the effects of pressure on the septum due to electrostatic forces. For thin septa nonlinear dynamic analysis was done because of the relatively large displacements and initial instability of thin materials. For thicker septa linear static analysis could be used. The electric field in the gap (80 kV over 6 mm) will deform the septum, increasing the apparent thickness that the beam will see. We considered first a Molybdenum septum with thicknesses from 0.05 to 0.25 mm, like the septa used in the cyclotron at the present reduced power levels. These calculations showed that if the electric field started on the edge of the septum, the deformations were 0.5 and 0.016 mm respectively. If the electric field is displaced 1 cm away from the edge (extending the septum upstream of the high voltage electrode) the corresponding displacement was reduced to 0.04 mm for the 0.05 thick septum and a 0.12 mm thick septum had a displacement of 0.015. The electric field was then included in the following calculations starting 1 cm from the edge.

Thermal mechanical analysis was then done investigating the effects of both temperature and pressure along with methods to spread the power dumped in the septum over a larger area. The thermal analysis was first performed with the resulting temperature profile loaded into the mechanical problem, accomplished in COSMOS/M by simply specifying a reference temperature and issuing a command to read the calculated temperatures as a load case. Linear static analysis was used for the mechanical analysis. Different boundary conditions were investigated on both the thermal and mechanical analyses.

Radiation cooling from only one side of the septum has been considered. This gives us a more conservative evaluation of the result. The emission toward the high voltage electrode side has been neglected .

4 MATERIALS

Our study was restricted to the two materials that are more likely to succeed in handling the high power: pyrolytic graphite (PG) and tungsten (W). In the past we have used mostly molybdenum as septum material in the cyclotron because the power requirements were lower and the residual radioactivity is less than with tungsten. Pyrolytic graphite is more expensive and more difficult to obtain than Mo or W.

The thermal conductivities of PG and W are shown in Figure 3. The thermal conductivity of PG in the plane parallel to the layers is very much higher than in the perpendicular direction.

An important difference between PG and W is the ion range. For example the 8 GeV Ar ion mentioned above has a range of 3.3 mm in W, but almost 16 mm in carbon. This much lower energy density deposition is a big advantage that favors PG, besides its lower residual radioactivity.

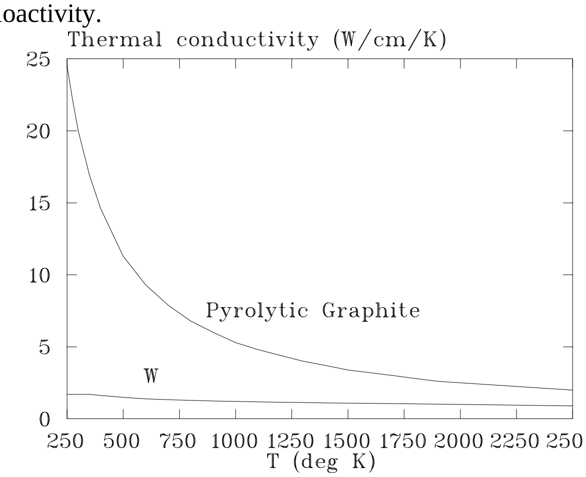

Figure 3 Thermal conductivites of pyrolytic graphite and W used in the COSMOS model.

5 RESULTS

Multiple thermal and mechanical boundary conditions were considered. We have performed all the calculations with an 8 GeV Ar beam depositing 400 W in a 0.25 mm thick septum. This beam characterizes our worst power deposition case. The power density near the end of the range is 130 W/mm^3 for PG and 510 W/mm^3 for W. A beam height of 4mm was assumed in the calculations.

For a PG septum constrained with both (top and bottom) clamps and good conductivity to the Cu plates the maximum temperature reached 1230 deg. K. We found that the septa buckled significantly under these conditions. The expansion of the material produced a bulging that could reach 2.4 mm. Obviously this is not acceptable, because any small increase of the apparent septum thickness will increase the amount of power deposited on it and increase the problem even more. If we modify the boundary conditions, allowing the septum to "float" inside the guiding clamps, the heat transmission to the cooled Cu plates is decreased but a significant fraction of the heat is still dissipated by radiation and the temperature does not increase significantly. The buckling in this case is reduced to 0.08 mm. A plot of the temperature distribution is shown in Figure 4. The corresponding displacement plot is shown in Figure 5.

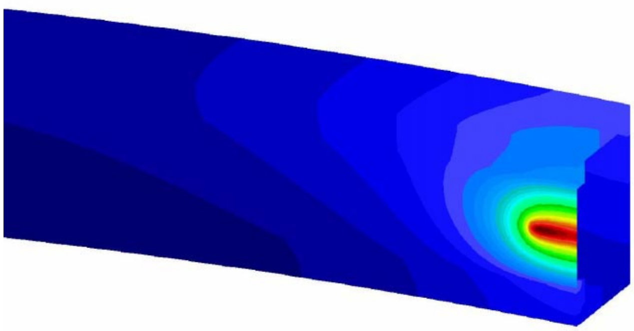

Figure 4 Thermal distribution in the pyrolytic graphite septum. Maximum temperature is 1230 deg. K. The beam comes from the right.

The higher thermal conductivity of PG helps to expand the radiation emission area, improving its cooling efficiency. In the case of W we have used a V notch on the leading edge as described in the Introduction. Under this conditions, the W septum reaches a maximum temperature of 2000 deg. K approximately, see Figure 6. This is a very comfortable margin of safety for a melting point temperature of 3400 deg. C.

6 SUMMARY

We have modelled the behavior of the electrostatic deflector in a heavy ion cyclotron, including the forces due to electric fields, temperature dependence of heat conduction coefficients and radiative cooling. The model predicts temperatures of less than 1300 deg K for the pyrolytic graphite septum and of 2000 deg. K for a W septum with a V notch. The deformations calculated do not indicate a serious buckling problem if appropriate support systems are used.

7 ACKNOWLEDGEMENTS

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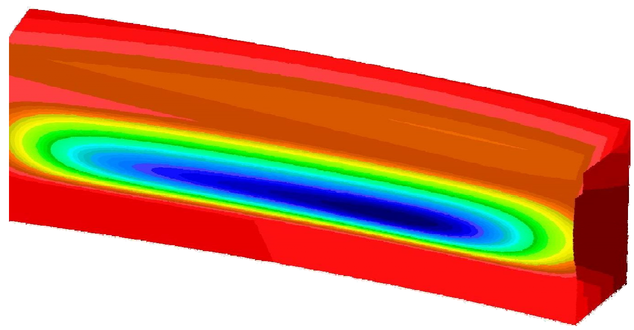

Figure **5** Displacement map for the septum in Figure 4. The septum is allowed to move inside the guides. The maximum displacement is 0.08 mm.

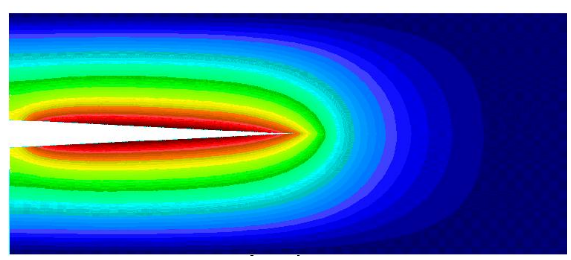

Figure 6 Temperature distribution in a 0.25 mm thick W septum with notch. The beam comes from the left. The maximum temperature is 2000 deg. K.