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RADAITION PROTECTION FOR THE RELATIVISTIC HEAVY ION COLLIDER AT THE BROOKHAVEN NATIONAL LABORATORY*

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ABSTRACT

The Relativistic Heavy Ion Collider (RHIC) is a high energy particle accelerator built to study basic nuclear physics. It consists of two counter-rotating beams of fully stripped gold ions that are accelerated in two rings to an energy of 100 GeV/nucleon. The rings consist of a circular lattice of superconducting magnets 3.8 km in circumference. The beams can be stored for a period of five to ten hours and brought into collision for experiments during that time. The first major physics objective when the facility goes into operation is to recreate a state of matter, the quark-gluon plasma, that has been predicted to have existed at a short time after the creation of the universe. There are only a few other high energy particle accelerators like RHIC in the world. The rules promulgated in the Code of Federal Regulations under the Atomic Energy Act do not cover prompt radiation from accelerators, nor are there any State regulations that govern the design and operation of a superconducting collider. Special design criteria for prompt radiation were developed to provide guidance for the design of radiation shielding.

INTRODUCTION

The scope of the RHIC Project was to design, construct, and bring into operation a colliding beam facility, which will enable studies of nuclear phenomena in relativistic energy heavy ion collisions. The collider, which consists of two concentric rings of superconducting magnets, was constructed in a tunnel of ~3.8 km circumference located in the northwest section of the Brookhaven National Laboratory (BNL) site. Figure 1 depicts the layout of the facility. The collider is to be able to accelerate and store counter-rotating beams of ions, ranging from hydrogen (protons) to gold, up to kinetic energies of 100 GeV/u (GeV per nucleon) for gold ions and 250 GeV for protons. The store duration for gold in the energy range of 30 to 100 GeV/u is expected to be approximately 10 h. The layout of the tunnel and the magnet lattice enables the two rings to intersect at six locations along their circumference where the counter-rotating beams collide.

For the scientific mission of the complex four of the six intersection regions have been developed with experimental particle detectors for the "Day-1" facility. The other two regions are for future development, if and when the physics needs justify expansion. Four experiments have been constructed in the intersection regions, two "large" and two "small" detectors systems. One of the large detectors, PHENIX, will be discussed in this paper.

Normal beam loss in a superconducting collider such as RHIC must be small for the collider to efficiently operate. However, some potential for worst-case faults exists which may dominate the passive shielding requirement in a given location. In practice, the radiological controls and posting employed to mitigate the hazards caused by beam loss will be consistent with regulatory requirements (USDOE 1993).

However, at most locations surrounding a superconducting accelerator, the maximum possible radiation field corresponds to the improbable occurrence of losing an entire beam at full energy due to a fault. Unfortunately, standards, such as those used for protection of the general public, were not intended to apply to this type of (short duration) radiation field or scenario. They are more appropriately applied when the dose equivalent is delivered over long time frames with high probabilities of occurrence; i.e., the regulations do not set limits on the definition of an uncontrolled area for accelerator "accidents". Because the existing regulatory and guidance documents do not explicitly address fault scenarios for RHIC beam loss, a scheme to provide guidance for shielding design and a means to classify a hierarchy was developed (Stevens et al 1994).

DESIGN CRITERIA FOR PROMPT RADIATION

Beam Loss in the RHIC Facility

Systematic beam losses in a superconducting accelerator are limited by the ability of the magnets to sustain their superconducting state in the presence of particle losses. Particles leaving the beam pipe of the accelerator deposit energy in the form of a cascade of hadronic and electromagnetic particles. These interactions typically give rise to a significant temperature rise, which is, at a maximum, several meters from the initial interaction point. A temperature rise of more than 0.5° K is sufficient to destroy the superconducting state of the Nb-Ti wire (a quench). Several hours are then required to cool the magnets back down to the 4° K operating temperature. During this time, the accelerator is non-operational. The amount of energy needed to initiate a magnet quench is ~4 mJ/g of superconductor and can be achieved by a loss of as little as 1 part in 10^4 of the circulating beam. Since such a small amount of beam loss can cause significant disruption to the operating program, superconducting accelerators are effectively loss free during normal operations. Small amounts of particle losses are intercepted by collimators, beam scrapers and a rapid acting (<1 ms) beam removal system that is used to protect the magnets from the onset of beam loss by directing the beam onto a well shielded external beam dump.

It should be noted that when beam loss occurs, there is typically 3.97 m of sand shielding over the Collider and Transfer Line. An additional 1.8m of sand is over the Collider in the vicinity of the Collider Center, which is occupied by non-radiation workers, 0.6 m over the Collimators and 1.5 m over the Collider Beam Dump.

Design-Basis Accident Fault

A worst-case fault in the collider would be the loss of the full beam at full energy at an arbitrary point (any magnet or device which intrudes into the physical aperture). Although it was concluded that the maximum credible fault would be full beam loss at points which are near the limiting aperture of the collider and loss of one-half of the full beam at other locations, and that such occurrences should be allowed for at a rate of once in several years, for the purpose of evaluating necessary shielding and access restrictions as applied to a specific location, the design-basis accident (DBA) will be assumed to be the maximum credible fault once per year.

Controlled and Uncontrolled Area Classifications

Existing DOE regulatory requirements do not explicitly consider low probability fault situations for accelerators (USDOE 1993; USDOE 1998). The RHIC criteria uses the International Commission on Radiological Protection (ICRP) concept of dose averaging (ICRP 1990) and adopts the philosophy that both low occupancy and low probability of faults mitigate allowable dose in a single year, if a multi-year average dose for a given individual is acceptably low. Four area classifications are defined where personnel are allowed without restriction by physical barriers. These areas are categorized according to whether or not personnel allowed access have been trained as radiation workers (areas posted as controlled) and according to whether the occupancy is expected to be "high" (i.e., continuous as defined by 2000 h per year) or "low", defined as a region with an occupancy factor (OF) of 1/16 (1/2 h per 8 h day) or below (NCRP 1976). Regions with intermediate occupancy will be treated as if they are high occupancy areas.

Design Criteria

I. Classification "A": Radiation workers; high occupancy

Normal loss 0.002 mSv h^{-1}, DBA Fault 5 mSv y^{-1} limit

II. Classification "B": Radiation workers; low occupancy

Normal loss 0.032 mSv h^{-1}, DBA Fault 10 mSv y^{-1} limit

III. Classification "C": Non-radiation workers; high occupancy

Normal loss 0.15 mSv y^{-1}, DBA Fault 0.1 mSv y^{-1} limit

IV. Classification "D": Non-radiation workers; low occupancy

Normal loss 2.4 mSv y^{-1},DBA Fault 1.6 mSv y^{-1} limit

Normal loss is typically from beam-gas, intra-beam scattering, limiting aperture collimators, and small losses that successfully trigger the collider beam abort.

Four of the eight criteria are for regions accessible without restriction by physical barriers. The classifications are distinguished by occupancy and by whether radiation worker training is required for entry. Each classification is specified by limits on dose equivalent resulting from both anticipated beam loss and from design basis accident faults. Although no explicit regulatory requirements exist for low probability faults, the highest proposed fault limits, 10 mSv y^{-1} in low occupancy regions restricted to radiation workers and 1.6 mSv y^{-1} in low occupancy uncontrolled regions, are compatible with several recommendations (Shleien 1992) that consider infrequent exposures and multi-year dose averaging for given individuals.

In anticipation of a future regulatory change to the mandated Neutron Quality Factor to convert absorbed dose-to-dose equivalent, the weighted Quality Factors were doubled for the purpose of design. Operational controls for prompt radiation; e.g., posting, will be based on existing regulations (USDOE 1998).

Modeling of Shielding

A variety of tools were used, including empirical formulae, in making estimates of dose equivalent due to prompt radiation. The principal tools were the hadron cascade Monte Carlo programs CASIM (Von Ginneken 1975) and MCNPX (Hughes et al 1997). Neither of these codes is "complete" when considered by themselves, but they nicely complement one another. CASIM transports hadrons to only ~50 MeV, and requires the assumption of an "equilibrium spectrum" to estimate dose. The lack of low energy neutron transport implies that CASIM is not useful for penetrations. On the other hand, CASIM has a non-analog transport technique that permits "deep penetration" calculations and has magnetic field capability, attributes missing in MCNPX. Figures 2 and 3 show a comparison between the two codes in a very simple target-in-a-cave geometry. The quantity plotted is the dose per primary after 10 ft. transverse shielding thickness of BNl soil for 100 GeV protons[1] incident on thin targets with varying atomic weight. Although some atomic weight dependence is clearly visible in these figures, the most noticeable difference is that CASIM obtains a much higher dose estimate in the forward direction and a much lower estimate in the backward direction when compared to MCNPX. This reflects a difference in the physics models used in the two codes which has been noted before (Tesch and Dinter 1986). At RHIC, the shield block configuration at any location (typically each of the Intersection Regions (IRs)) is designed for a DBA fault on *any magnet*. In general, this required several CASIM calculations with the fault assumed on upstream magnets until the worst case was found. If the MCNPX code is "more correct" than CASIM in relation to the forward/backward difference, the IR shield may be somewhat "over-designed." The only places on the collider site which would be affected by a CASIM underestimate in the backwards direction are the fence locations upstream of the internal dumps in both rings. These locations will be closely monitored.

The differences in Figs. 2 and 3 are one type of systematic error associated with prompt radiation estimates in complex configurations. The table below summarizes such errors by type.

SYSTEMATIC ERRORS

Topic	Magnitude	Comments
Physics	20% → Large	Small angle problems difficult
Knowledge of Materials	50% → Large	Deep Penetrations What is BNL Soil, for example, anyway
Dose (Equivalent) Conversion	10% → Large	Especially where not dominated by low E neutrons
Approximation of Geometry	20% → Large	Experience needed

In addition to differences in physics models illustrated by Figs. 2 and 3, systematic errors arise from a lack of precise knowledge of materials properties, uncertainties in how dose equivalent is obtained from the

[1] For the purpose of shielding estimates, the heavy ion "primaries" are simply considered to be a collection of independent nucleons. In making estimates of both energy deposition close to a primary interaction or detector backgrounds, the distinctive properties of ions must be taken into account. However, at large distances from the primary interaction, the approximation of an ion as independently interacting nucleons is a good one.

quantities actually calculated, and myriad approximations which must be made in creating a computer representation of a physical configuration.

These tools were also applied to evaluate cracks between blocks in single layer concrete shield walls. The results indicated that there should be no cracks within 2° of the mid-plane of the beam line, and no vertical cracks greater than 1 cm wide. All larger cracks were required to be shimmed with low Z material.

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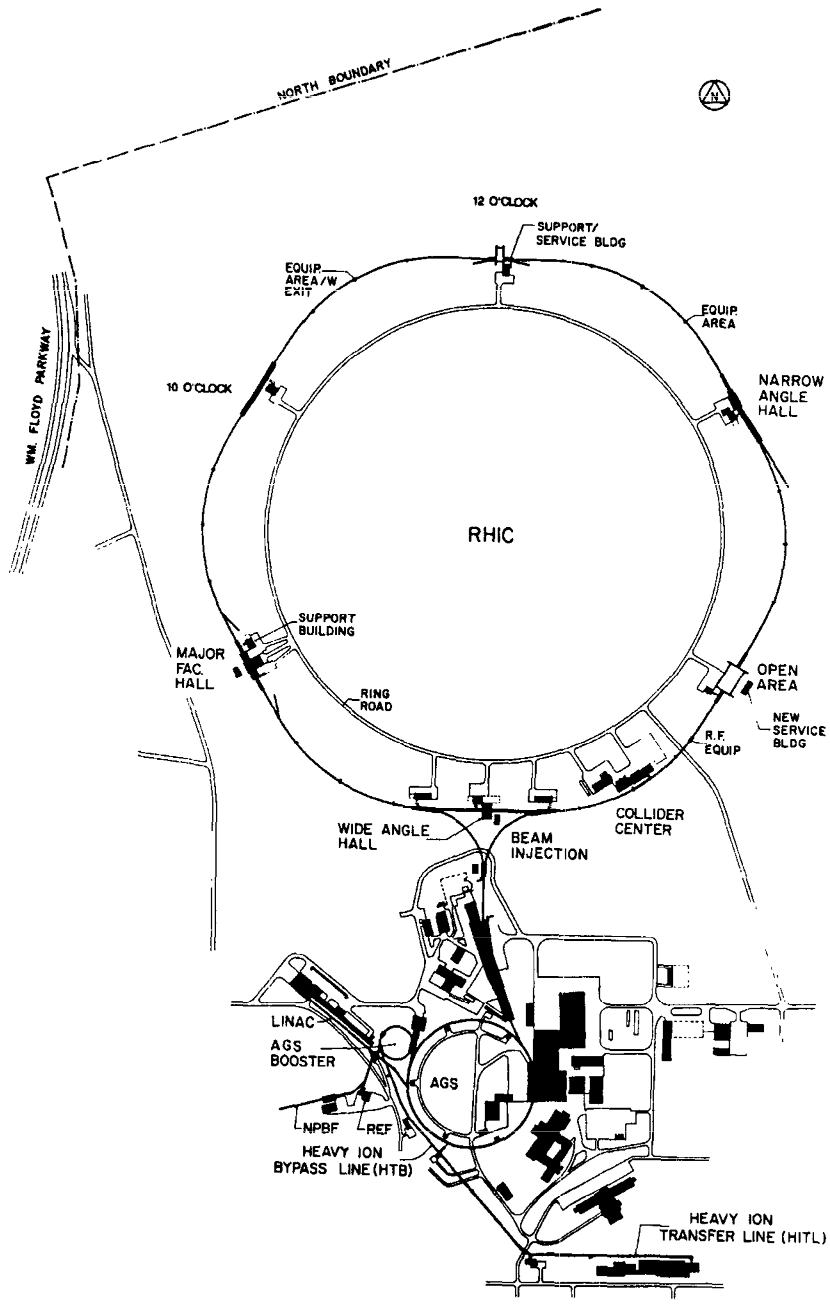

SITE MAP

Fig. 1

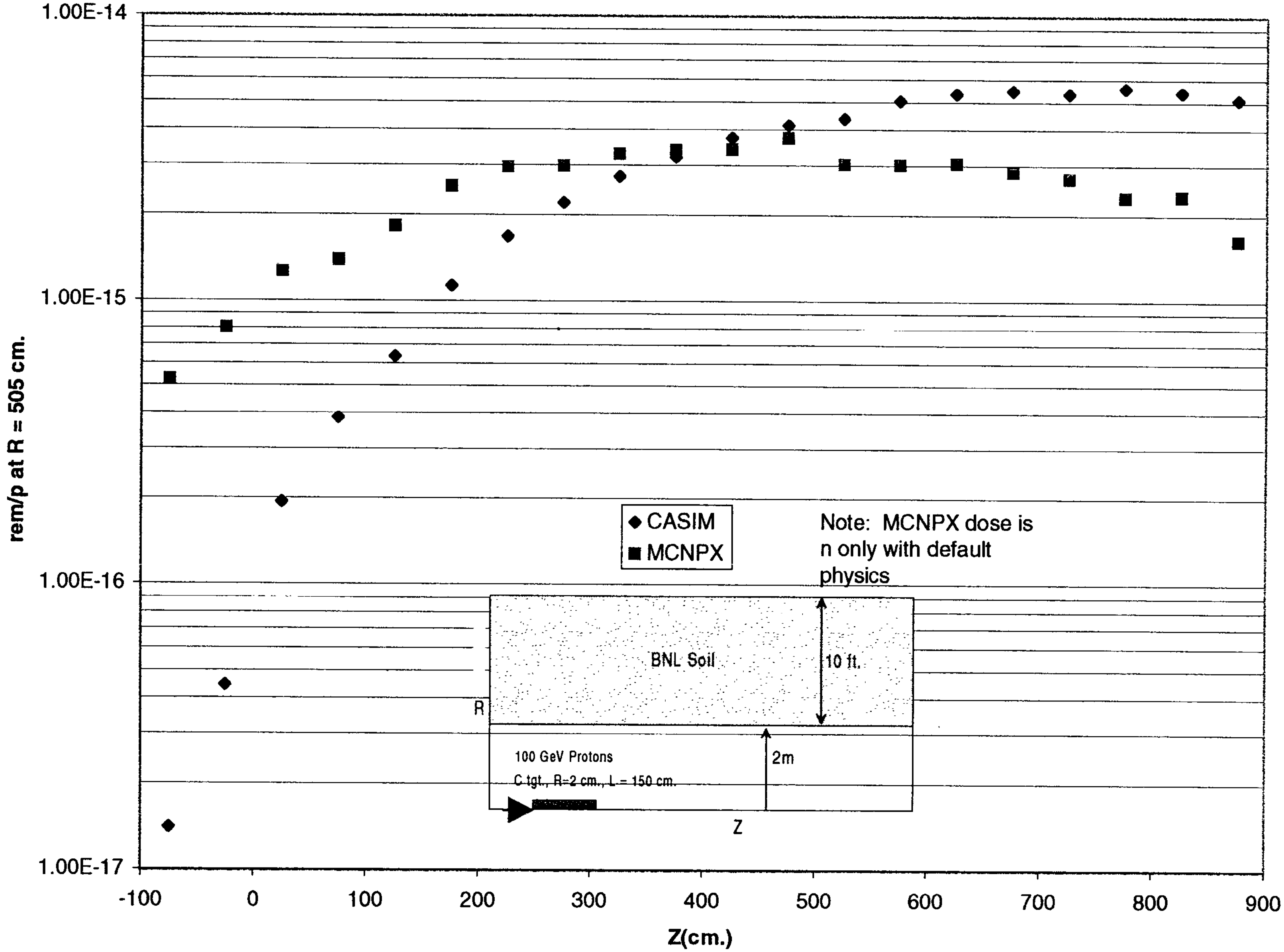

Fig. 2 Results for a Carbon Target

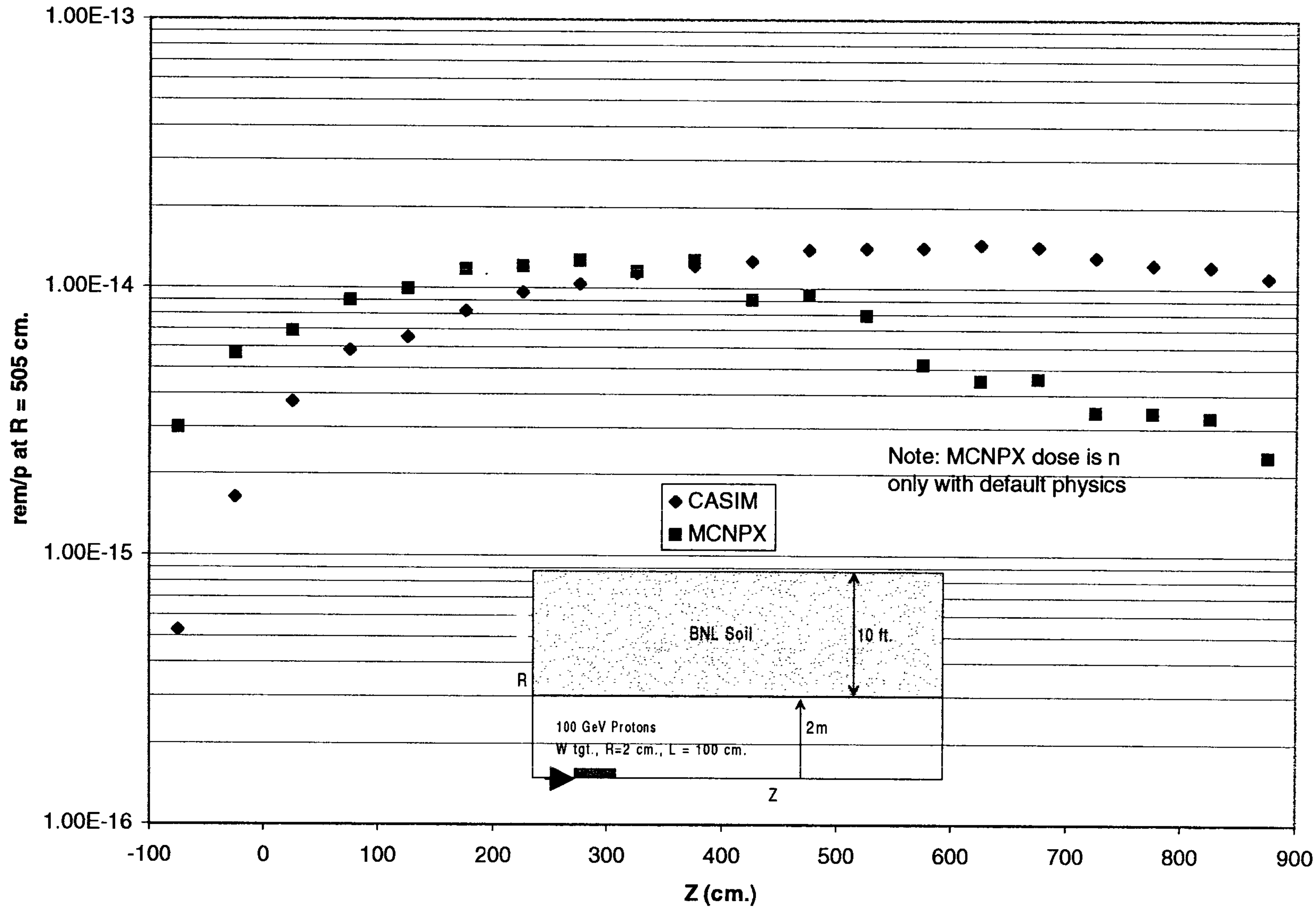

Fig. 3 Results for a Tungsten Target