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NSNS Ring Systgem Design Study - Collimation and Shielding

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DISCLAIMER

NSNS RING SYSTEM DESIGN STUDY

COLLIMATION and SHIELDING

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COLLIMATION AND SHIELDING

INTRODUCTION

Collimators are used to remove halo particles from the proton beam. Off-momentum particles are removed by collimators situated in high-dispersion areas of the beam. In addition to removing halo particles collimators will also act as shielding for the remainder of the accelerator structures. This shielding reduces uncontrolled losses around the ring and reduces activation of the accelerator components. The power dissipation in the collimator structures of the 1 MW NSNS is expected to be in the range of 200 W, or 2×10^{-4} of uncontrolled beam loss. However, the design specification will allow for 1 kW of uncontrolled beam loss. In this way there will be sufficient safety margin to allow an upgrade to 2 MW of beam power. The requirements and performance goals for the collimators are summarized below:

1) Maximize the attenuation of the halo (10^{-4})
2) Minimize dose to and activation of accelerator components due to secondary radiation (neutrons and gamma rays)
3) Remove deposited heat (~1 kW)
4) Maintain stresses in acceptable limits. Since thermal stresses will be cyclic the possibility of fatigue failures must be accounted for. Finally, the possibility of thermal-mechanical enhancement of the stresses must be investigated.
5) Minimize radiation damage due to the protons, neutrons, and gamma rays.
6) Minimize activation of the collimator structure.

The goal of the above design is to allow for hands-on maintenance for most of the accelerator components, except for a few localized high loss areas.

In addition to collimators, beam stops and shielding requirements will be estimated. The beam stops are needed to catch the H^0 and H^- beams resulting from ring injection. Shielding design will be consistent with accepted DOE/EH standards.

INITIAL SCOPING STUDIES

In this section an analysis of a conceptual design, which satisfies the above requirements will be outlined. The preliminary analyses will be used to configure the collimator arrangement. This initial collimator arrangement will then be integrated into a section of the ring, and an estimate of the neighboring magnet activation will be made. In addition, estimates of heating load, temperatures, and thermal stress will be made.

Preliminary analyses using slabs of iron and tungsten have shown that:

1) Back-scattered protons are distributed essentially isotropically, with a slight backward peak,

2) Transmitted protons are highly peaked in the forward direction,
3) Neutron production increases with increasing slab thickness, reaching a maximum at the stopping distance thickness,
4) Intensity of transmitted neutrons increases with decreasing slab thickness until decreasing production out-weighs increasing slab transparency,
5) Most neutrons exit at energies below 20 MeV, and
6) Pion production is approximately 1/30 of neutron production (at the assumed 1 GeV proton beam energy).

Low energy neutrons are responsible for most of the activation of accelerator components and shields, hence their leakage from the collimator must be minimized. Among the possible radionuclides produced in the accelerator and the magnet structures/components are ^{64}Cu and ^{65}Zn in copper, and ^{54}Mn, ^{56}Mn, and ^{60}Co in steel. Shielding can also be activated by radioactive sodium and steel. In addition, ^{7}Be will be generated in the cooling water.

In order to minimize the leakage of low energy neutrons from the collimator it will be desirable to produce the neutrons in the internal zones of the collimator and require them to leak out through a black zone (fully absorbing). Thus the outer zone of the collimator needs to be largely transparent to protons and black to neutrons. In this arrangement protons penetrate the collimator and produce neutrons primarily by spallation reactions internal to the collimator. These neutrons then have to pass through the black zone before leaking back out into the remainder of the accelerator.

In order to test the above design concept a series of four simple configurations were studied. They are illustrated in Figures 1-2 together with a proposed collimator configuration. The first case consists of a tungsten/water mixture (50 cm thick) encased in a steel containment vessel. The second case is similar to the first case with the addition of 15 cm of borated water between the tungsten and the steel containment. In the third case the tungsten/water mixture zone is increased in thickness by 50%. The fourth case consists of an enhanced metal/water region, with the addition of an iron/water region (50 cm thick) in front of the tungsten/water region (75 cm thick). In all the above cases the steel containment is assumed to be 2 cm thick.

Based on the above concepts the proposed configuration was designed. This configuration has a containment shell thickness reduced to 1 cm. A second proposed configuration was also considered, which had a 20 cm thick piece of graphite placed in front of the containment. These configurations were all analyzed using the LAHET SYSTEM CODE[1)], which uses the Monte Carlo code MCNP[2)] to transport neutrons and gamma rays below 20 MeV. Results for transmitted and reflected neutrons and protons (above 20 MeV) per source proton are given on Table 1. These results show that the reflected neutron fraction decreases from case 1 to case 4, indicating that the addition of borated water and an iron/water region reduces the high energy neutron leakage out of the front of the collimator. For protons the reflected fraction does not vary significantly from the value for a bare tungsten slab. This would indicate that the reflection takes place within the first few centimeters of collimator thickness, and suggests that the shell be reduced in thickness for the actual application. Both the transmitted neutron and proton fractions decrease with increasing thickness. In the case of protons essentially no protons are transmitted for case 4. The results for the proposed cases shows that the reflected protons decreases following a reduction in containment shell thickness, and the addition of graphite further reduces the reflected fraction for both neutrons and protons.

Table 1-Number of reflected and transmitted neutrons and protons per source proton (See Fig. 1 and 2)

Case	Reflected		Transmitted	
	n	p	n	p
Tungsten-slab*	0.26	0.0082	0.27	0.064
1	0.22	0.0084	0.075	0.0015
2	0.15	0.0077	0.050	0.0012
3	0.15	0.0074	0.0078	0.00022
4	0.11	0.0074	0.0012	~
Proposed-case	0.03	0.002	0.0004	~
Proposed-case#	0.01	0.00005	~	~

* Slab thickness = 30 cm.
# Includes 20 cm graphite in front of first proposed configuration.

The number of low energy (below 20 MeV) neutrons leaking out of the front face of the collimator are shown on Table 2. These neutrons are created by evaporation from excited nuclei, and thus are emitted isotropically. The production of these neutrons drops off with distance into the target, since the protons are losing energy as they interact with the material of the collimator. Table 2 shows the number of neutrons per proton leaving the face of the collimator, and moving straight back. It is seen that there is a dramatic drop between case 1 and case 2, indicating that the borated water is having the desired effect of reducing the leakage of neutrons from the collimator. The reduction occurs primarily for neutrons in the energy range between 0.625 eV and 0.821 MeV.

Figure 3 shows a possible collimator configuration which incorporates the insights from the four scoping cases. The containment shell is made of steel 1 cm thick in order to minimize the reflection of protons from the front face. Borated cooling water fills the second volume. This water is essentially transparent to high energy protons, but it is very efficient at slowing down neutrons, and the low energy neutrons are absorbed in the boron ($^{10}B(n,\alpha)^{7}Li$), without emitting any penetrating radiation. This layer is 15 cm thick, and is used on both sides of the collimator to essentially prevent the low energy neutrons from leaking into the accelerating structure and activating components. The two following zones contain a metal/borated water mixture, the first being 80 cm thick and the second 45 cm thick. The first zone consists of iron/borated water and is meant to slow the protons down while minimizing the production of neutrons. However, capture gamma rays are produced from neutron capture in the iron. The following layer consists of tungsten/borated water and it is meant to stop all remaining protons and assist in shielding sections of the accelerating structure from the gamma rays generated by radiative capture. The metal/water ratio in these two zones is 85%/15% respectively. Currently a metal plate structure with cooling water flowing between the plates is envisioned as the collimator configuration. The total length of this collimator design is 159 cm and the outside diameter is 200 cm. The central penetration for the proton beam is 10 cm in diameter.

Table 2-Energy spectrum of neutrons below 20 MeV reflected straight back (n/cm^2-str-s-p) (See Fig. 1 and 2)

		Case			
Energy Group (MeV)	W-slab	1	2	3	4
0.0-6.25(-7)*	-	8.9(-4)	7.0(-3)	6.0(-3)	3.1(-3)
6.25(-7)-6.63(-3)	9.8(-3)	1.7(-1)	1.9(-2)	2.0(-2)	1.0(-2)
6.63(-3)-8.21(-1)	2.95	1.19	4.9(-2)	4.4(-2)	3.5(-2)
8.21(-1)-20.0	8.5(-1)	6.2(-1)	1.4(-1)	1.3(-1)	8.8(-2)
Total Flux	3.81	1.97	2.1(-1)	2.0(-1)	1.4(-1)

* = 10^{-7}

ENERGY DEPOSITION

The above model was used to estimate the heat deposited in the various collimator components. A grid of axial and radial volumes were arranged in the collimator and the heat deposition in each volume was estimated. The total power deposited in the collimator was normalized to 1 kw. Figure 4 shows the deposited heat in watts as a function of radius and axial distance in the collimator. Generally the magnitude of the values are not large, and should not pose a cooling challenge, with the exception of the leading edge of the containment shell. Very little heat is deposited in the tungsten/water region, most of the heat is deposited in the iron/water region closest to the containment shell. Interestingly there is some heat being deposited at significant radial distances (40 cm to 150 cm radial grid).

Preliminary estimates of the component temperatures have been made, based on the above power deposition. The steel containment shell is subject to the most challenging thermal environment, since it sees the primary proton beam first, is only cooled on one surface, and the coolant flow pattern in the leading edge corner is ambiguous if a square design as shown is used. Clearly more sophisticated analyses will have to be carried out to achieve an acceptable design for this region. Estimated temperatures for the collimator tube are shown on Table 3. These are seen to be well within the material capabilities. Table 4 shows the estimated temperatures of the steel plates assuming all the power is deposited in the steel plates. The estimated temperatures are well within the material capabilities. An estimate of the implied thermal stress due to the above temperature gradients is shown in Table 5 for the collimator tube. This stress is within the operating limits of the containment shell. However, it should be recognized that the above stress estimate does not account for the cyclic nature of the beam, and thus the possibility of fatigue failure and thermal-mechanical shock enhancement of the stresses both need to be addressed in a final design.

Table 3-Estimated maximum temperatures in collimator tube*
(See Fig. 4)

Axial position	Temperature increase (°C)
1	14
2	11.5
3	9.5
4	7.5
5	5.5
6	7.3
7	4.3
8	2.5
9	1.5
10	0.5
11	0.3
12	~

* Assuming
1) Cooled on one side h=350 w/m^2-K
2) Steel conductivity k=20 w/m-K

Table 4-Estimated maximum temperature in iron plate structure*
(See Fig. 4)

Axial position	Maximum temperature (°C)
1	3.0
2	2.0
3	1.5
4	1.0
5	0.5
6	0.3
7	~

*Assuming
1) Cooled on two sides h=200 w/m^2-K
2) Steel conductivity k=20 w/m-K

Table 5-Estimated thermal stresses in collimator tube*
(See Fig. 4)

Axial position	Thermal stress (psi)
1	5750
2	4710
3	3900
4	3000
5	2250
6	3000
7	1750
8	1000
9	600
10	200
11	100
12	~

Assuming
1) Steel expansion coefficient =1.78(-5)/°C
2) Steel Young's modulus = 2.76(7) psi
3) Steel Poison ratio = 0.305

An integration of the collimator design outlined above into a length of the accumulator ring was carried out in order to estimate the possible level of activity (curies) induced in the adjacent magnets following a reasonable operating period. The integrated configuration is shown in Figure 5, with a quadru-pole magnet on the left and a di-pole magnet on the right. The collimator is approximately mid-way between these two components, which are 3.18 m apart.

BEAM STOPS AND SHIELDING

In addition to collimators, beam stops need to be configured to catch the H° and H^{-} atoms resulting from the injection process. Since the power in these beams will be very low, cooling requirements of these catchers will be minimal. They will consist primarily of a stopping length heavy metal (iron or tungsten) beam stop surrounded by approximately one meter of concrete. This concrete will stop all the neutrons generated in the beam stop.

Shielding provides protection for workers and the general public during operation of the machine. The design limits for new facilities, Art. 128 of DOE/EH 0256T Rev. 1 requires that individual worker dose be less than 5 mSv/yr (500 mrem/yr). The dominating radiation, which determines the necessary shielding thickness for a high energy proton beam is the high energy (> 150 MeV) neutron component formed in nuclear cascades. Thus, designs which attenuate these neutrons will automatically shield against lower energy neutrons and gamma rays. The shielding requirement will be satisfied by using sufficient iron and concrete as bulk shield to ensure adequate attenuation of the high energy neutrons. An earth berm can supplement the concrete, as a perimeter shield.

REFERENCES

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2) MCNP, A General Monte Carlo Neutral-Particle Transport Code, Version 4A, (Nov 1993), J.F. Breismeister ed., LA-12625-M, Los Alamos National Laboratory, Los Alamos, New Mexico.

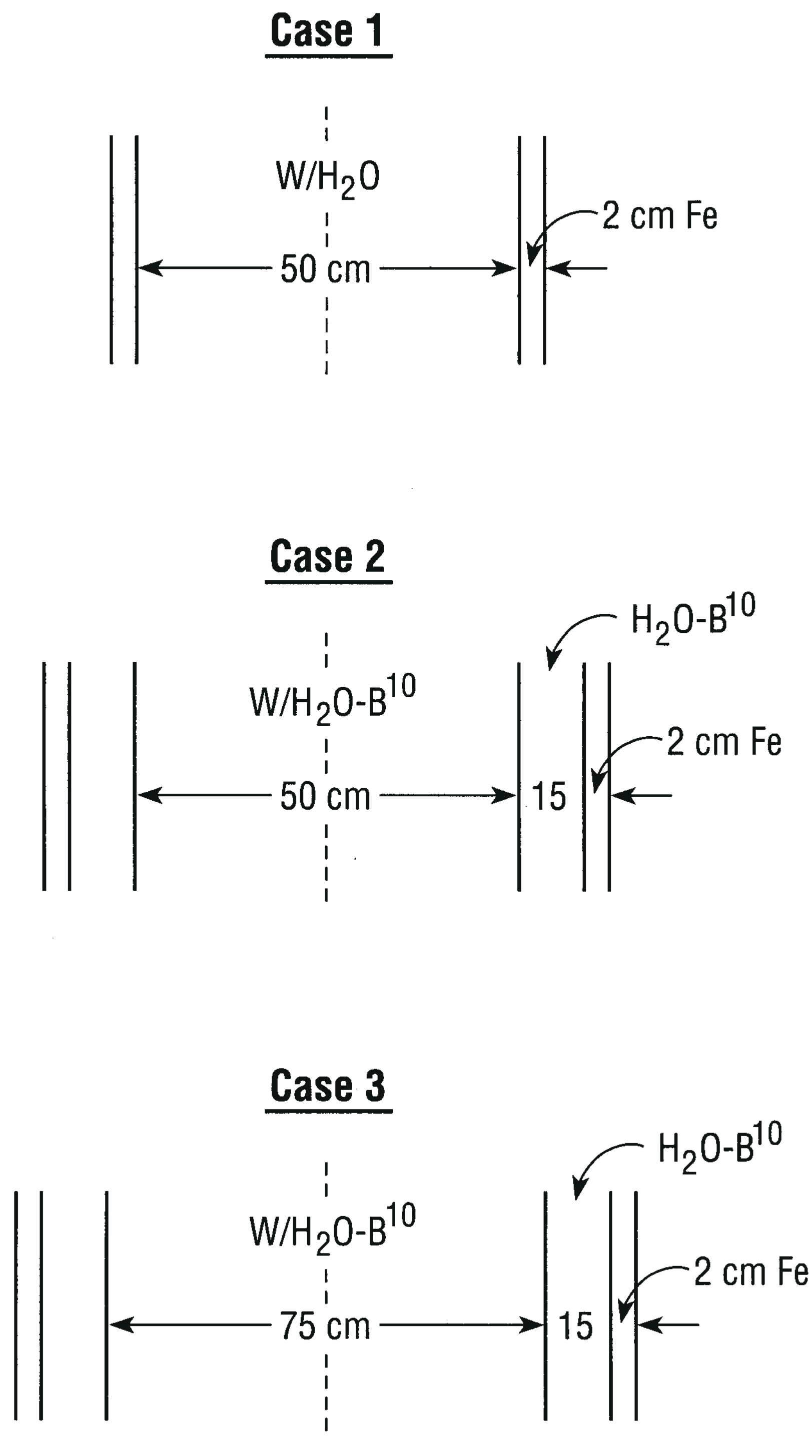
Case 1
W/H2O
2 cm Fe
50 cm
Case 2
H2O-B10
W/H2O-B10
2 cm Fe
50 cm
15
Case 3
H2O-B10
W/H2O-B10
2 cm Fe
75 cm
15

Figure 1

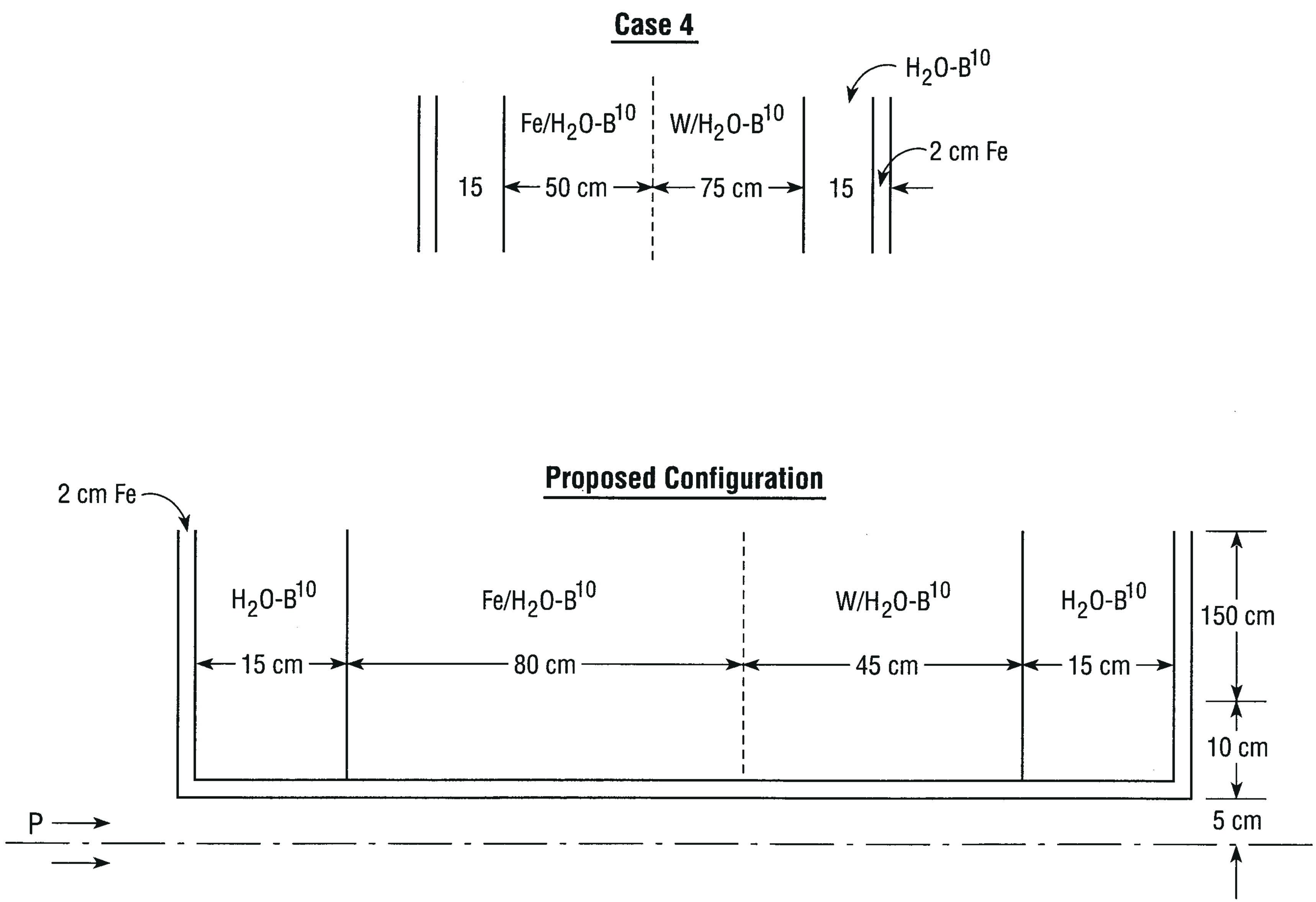
Case 4
H_2O-B^{10}
Fe/H_2O-B^{10}
W/H_2O-B^{10}
2 cm Fe
15
50 cm
75 cm
15
Proposed Configuration
2 cm Fe
H_2O-B^{10}
Fe/H_2O-B^{10}
W/H_2O-B^{10}
H_2O-B^{10}
15 cm
80 cm
45 cm
15 cm
150 cm
10 cm
5 cm
P

Figure 2

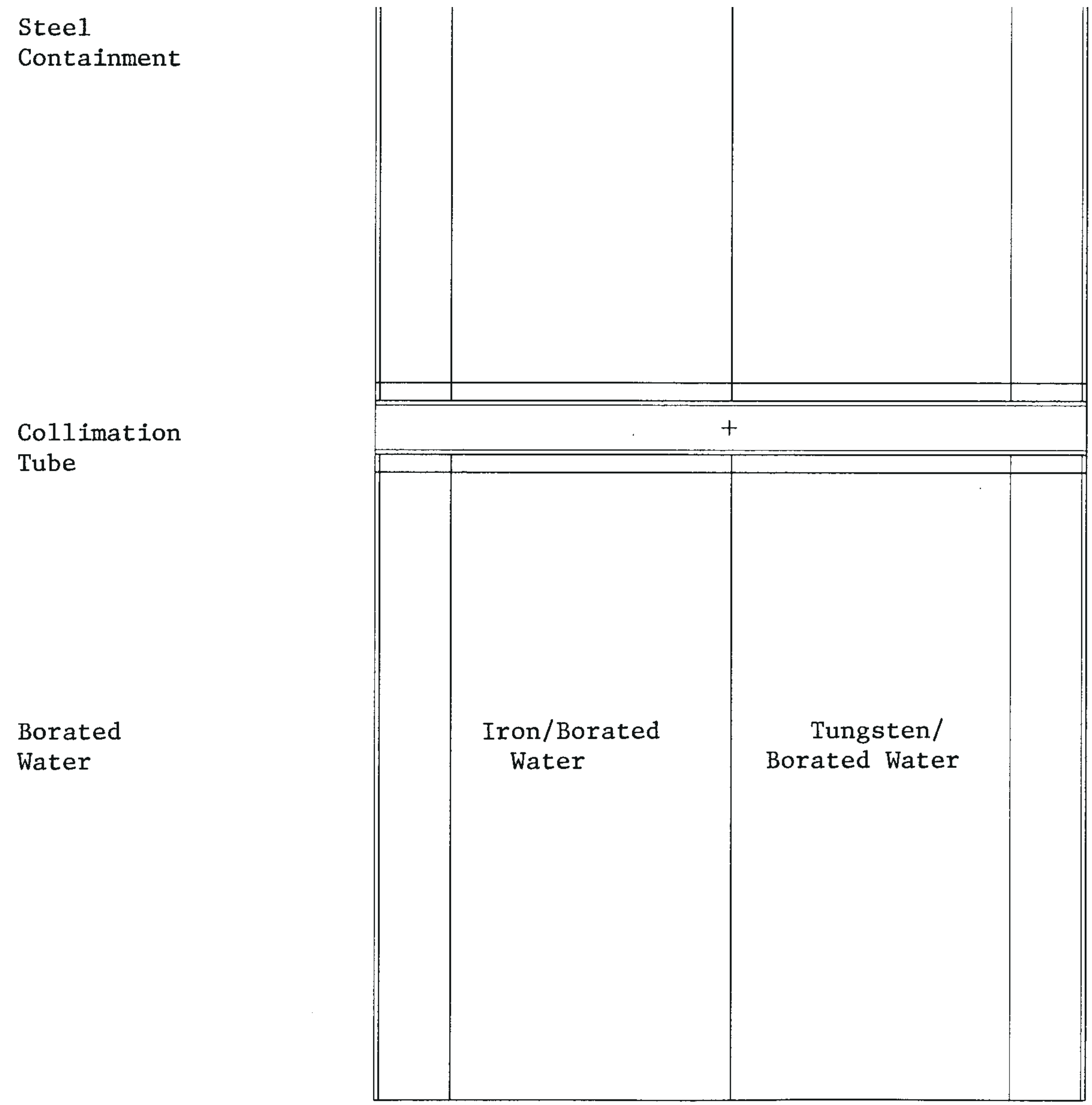

Figure 3 - Collimation Configuration

Power Deposition (watts)

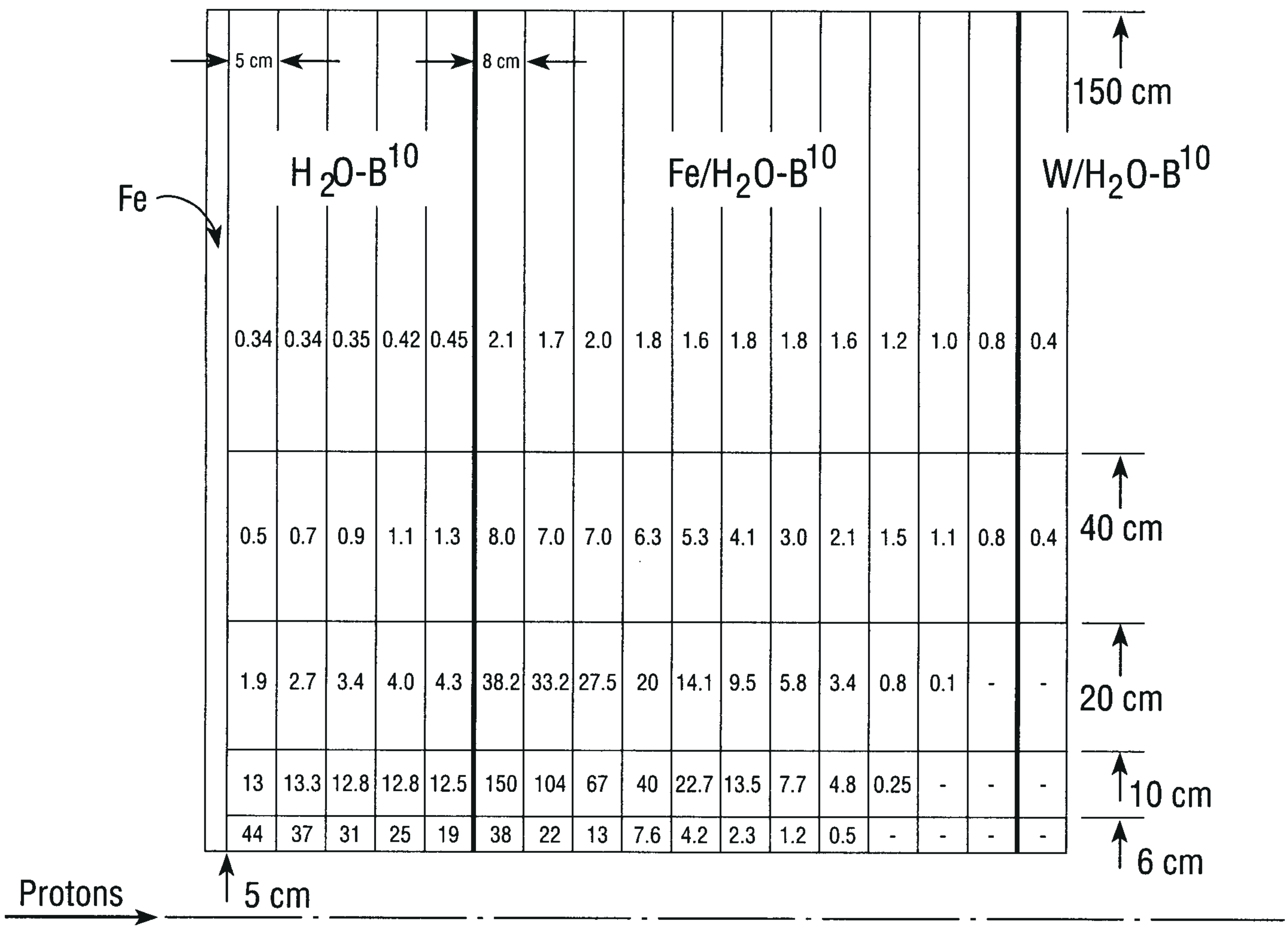

Figure 4

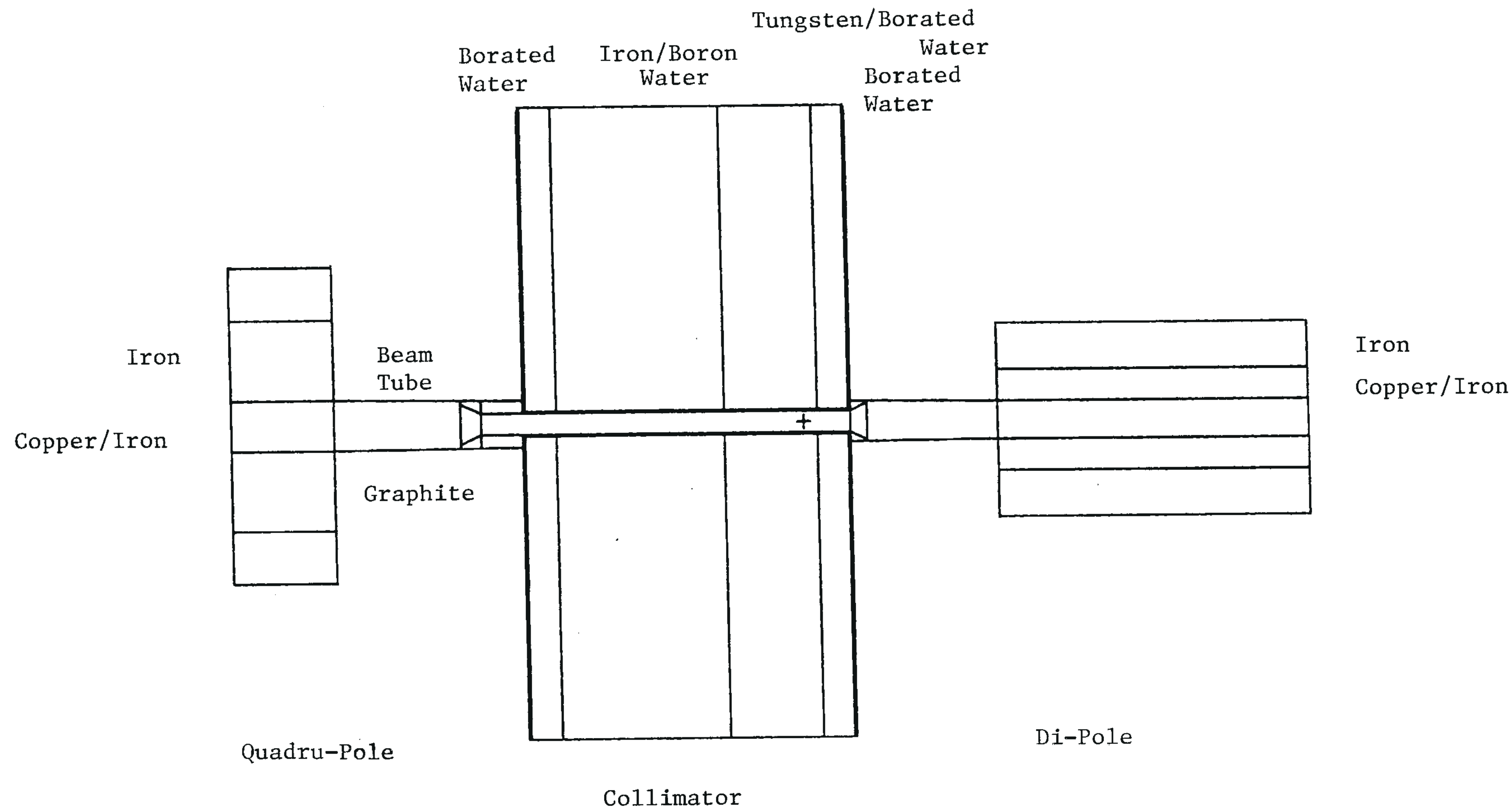
Tungsten/Borated
Water
Borated
Water
Iron/Boron
Water
Borated
Water
Iron
Copper/Iron
Beam
Tube
Graphite
Iron
Copper/Iron
Quadru-Pole
Collimator
Di-Pole

Figure 5