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## COLLIMATOR DESIGN FOR THE NSNS ACCUMULATOR RING

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## I. INTRODUCTION

Collimators are used to remove halo or off-momentum particles from the main proton beam. Off-momentum particles are removed by situating collimators 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. Thus, collimators reduce uncontrolled losses around the ring and reduce activation of the accelerator components.

Requirements and performance goals for the collimator are summarized below:

1. Halo proton attenuation by a factor of  $10^{-4}$ ,
2. Minimize production of secondary radiation, and its subsequent leakage,
3. Remove heat (1 kW),
4. Mechanically compatible with ring operation (mitigate fatigue failures due to cyclic heating), and
5. Minimize radiation damage and secondary activity.

In order to meet these goals a self-shielding collimator configuration will be designed. An arrangement consisting of a layered structure will be considered. The initial layers (in the direction of the proton beam) are transparent to protons, and become progressively less transparent (blacker) with depth into the collimator. In addition, a high density (iron) shield will be added around this structure, particularly in the backward direction, to attenuate any reflected protons. The protons are stopped in the approximate center of the collimator, and thus the bulk of the secondary particles will also be generated there. Since these secondary particles are primarily produced isotropically their leakage path length will be maximized in

this manner (high probability of capture or attenuation). In the case of neutrons a black layer is included at each end in order to further minimize their leakage in the direction of the beam. This design will therefore minimize the activation of surrounding accelerator components.

## II. CONCEPTUAL DESIGN

A series of preliminary scoping studies were carried out using slabs of iron and tungsten. These calculations were carried out to understand the interactions of 1 GeV protons with possible collimator materials. Results from these calculations indicated that:

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

The conceptual design, based on the above results and ring constraints, is shown on Figure 1. The protons travel from left to right, with the beam confined primarily to the inner diameter of the collimator. Halo particles are found between the collimator inner diameter and the beam tube inner diameter, and are assumed to pass into the collimator

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volume. On their way into the collimator the halo particles will first encounter a graphite transition piece between the beam-tube diameter and the collimator diameter. This piece is 20 cm long, and has a conical front end. Protons at the operating energy pass through graphite with relative ease, and hardly produce any secondary particles. The collimator containment vessel wall fits behind the graphite piece, it is 1 cm thick and made of steel. The next 15 cm consist of a borated light-water volume. This region is relatively transparent to high energy protons, but lower energy neutrons, such as those which might result from a spallation reaction, would be thermalized in this region and be absorbed by the boron. It would thus be black to low energy neutrons. The use of borated light water to thermalize and absorb neutrons is a common practice in the light water reactor industry.

All the zones to this point have the same composition in the radial direction. The following two zones have a radial variation at a radius of 20 cm. Within the 20 cm radius they consist of randomly packed spheres cooled by borated light water, and outside this radius they consist of solid iron plates. This arrangement is chosen to ease the assembly of the collimator, ensure heat removal, and minimize the cost. Randomly packed beds of particles are particularly efficient at heat transfer, since their area per unit volume is greater than any other practical arrangement of the same characteristic dimension. Furthermore, the cost of small spheres of either stainless steel or tungsten is lower than machined discs of the same material. The void (coolant in this case) fraction of randomly packed spheres is approximately 35%, thus the solid fraction in these zones will be 65%. The first particle bed zone will consist of 3 mm diameter stainless steel particles, with a length of 80 cm. The protons will lose the bulk of their energy in this zone, and since the production of neutrons per proton is modest for stainless steel at these energies, the secondary production of neutrons is relatively low. Once the protons have lost the bulk of their energy in the stainless steel particle bed zone they will enter a 45 cm long tungsten particle bed zone. The tungsten particles in this zone are not truly spherical in shape, but consist of crushed irregular shapes with an average dimension of 3 mm. This choice is driven by a desire to further reduce the material cost, and the reduced heat removal requirements at this depth into the collimator. In this zone the protons give up most of their remaining energy. In addition, their energy is low enough that the neutron production is modest. However, there is a probability of generating secondary protons in addition to the neutrons. Fortunately the yield of secondary protons is low compared to the neutron yield, due to the fact that the protons have to overcome the potential barrier before escaping the excited nucleus.

Finally, the back 15 cm of the collimator consists of the same borated light water used in the first 15 cm of the collimator. This volume will ensure that many of the remaining spallation neutrons are slowed down and captured. The collimator is encased in 20 cm of solid iron on all sides except the front, where the thickness is increased to 45 cm. The collimator thus has an overall radius of 75 cm and a total length of 222 cm (including the iron shield). The thick iron shield acts to stop/attenuate any protons which are reflected or are created within the collimator. In addition, any high energy neutrons which may escape the collimator will be attenuated in these shields, thus minimizing the activation of the surrounding (upstream and downstream) ring components. In addition, the thick shields should minimize the activation of the air and tunnel walls. Table 1 summarizes the masses and overall dimensions for the collimator configuration described above.

### III. ANALYSIS AND RESULTS

The above collimator configuration was analyzed using the Monte Carlo codes LAHET<sup>1</sup>, for particles above 20 MeV; and MCNP<sup>2</sup> for particles below 20 MeV. In addition, a suitably modified version of the ORIGEN<sup>3</sup> code was used to estimate the buildup of spallation products during machine operation, and their decay following shutdown. The LAHET code is based on the high energy transport code HETC<sup>4</sup>, which transports nucleons, pions and muons. Neutron and photon histories with energies below 20 MeV are stored on a source file and used as input to MCNP. Nuclear interactions are represented by an intranuclear cascade model due to Bertini<sup>5</sup>. MCNP is used for transporting all neutrons and photons below 20 MeV. It uses a continuous point-wise nuclear data base, and a combinatorial surface/cell geometric representation. Both LAHET and MCNP use the same geometric representation of the collimator. ORIGEN is a point depletion and decay code for determining activation products and decay heat. It solves the relevant equations using the matrix exponential method. The primary modifications made to this version of ORIGEN were to make it compatible with a nuclear data library used with CINDER'90<sup>6</sup>. Most of the spallation products of interest are on this library in a 63-group format. The specific one-group cross sections suitable for ORIGEN are created using spectra determined by MCNP for the specific geometry and composition of interest. The proton beam is assumed to be traveling from left to right, parallel to the collimator tube. The source plane is situated at the graphite transition piece (20 cm from the front of the collimator). Radially the proton beam is assumed to have a Gaussian shape.

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The performance of the above collimator design is shown in Table 2. These results show the backward (opposite to the direction of the proton beam) and forward (in the direction of the proton beam) proton currents in the halo zone of the beam (radius greater than 5 cm) at various axial positions along the collimator. It is seen that the halo constitutes a fraction of 0.001 (surface 25.0 cm, forward direction). This fraction decreases monotonically to the back end of the collimator. In addition, the leakage out of the front end of the collimator is also seen to be vanishingly small (surface 0.0 cm, backwards direction). Within the collimator it is seen that the proton current in the backward direction varies, with a maximum at the interface between the shield and the collimator containment vessel. The need for the thick iron shield is thus demonstrated. Thus, the proton leakage out of the back and front of the collimator meets the design goal set for it. Neutron currents at the same locations and directions as those for the proton currents are also shown in Table 2 (neutrons with energies above 20 MeV). It is seen that in the forward direction the neutron current increases initially and then decreases monotonically to a low value at the outer surface. In the backwards direction the current peaks at the interface between the front shield and the collimator body. Leakage out of the front face is also seen to be acceptably low.

The thick shield should minimize neutron leakage, which in turn will minimize the activation of the tunnel air. Activation levels can be further reduced by venting the tunnel air. The only other activated material which can leave the collimator is the cooling water. Potentially  $^7\text{Be}$  and  $^3\text{H}$  are formed and circulate in the coolant. If contained, the  $^3\text{H}$  should be undetectable, since it emits an electron upon decaying to  $^3\text{He}$ . However, the  $^7\text{Be}$  decays via a gamma ray (477.6 keV) and a half-life of 53.28 days. This poses a potential problem, particularly for maintenance work. For the above reason the cooling water will be cooled in a closed loop via an intermediate heat exchanger. The maximum heat load from a collimator is 1 kW. If a temperature rise of  $5^\circ\text{C}$  is assumed ( $T_{\text{in}}=30^\circ\text{C}$ , and  $T_{\text{out}}=35^\circ\text{C}$ ) a flow rate of approximately  $1.3(-4)\text{m}^3/\text{s}$  is required. This implies a moderate heat removal system for the design basis condition.

Estimates of the energy deposition in the collimator indicate the bulk of the power will be generated in the inner 20 cm of the front borated light water zone (9%), the front iron shield (10%), the stainless steel particle bed (52%), and the graphite transition piece (20%). All these zones need to be cooled by the cooling water system. The stainless steel particle bed zone is inside the collimator and is cooled by the borated water system. The graphite transition piece and the iron shield will be cooled by a cooling jacket

positioned between them. They will thus be cooled on one surface by cooling water, and conduction within the body of the respective pieces. Preliminary estimates of the temperature in the two pieces indicate that they are well within their operating limits.

In addition to the estimates of energy deposition in bulk components, an estimate of the axial and radial variation of energy deposition was made in the collimator tube, and front shell. The energy deposition was found to be quite modest, with the maximum ( $2.2 \times 10^5 \text{ W/m}^3$ ) occurring at the leading edge behind the graphite transition piece. Preliminary estimates of the temperature distribution were made, based on these energy deposition values. The tube and containment shell are subject to the most challenging thermal environment, since they are cooled on one surface, and the coolant flow pattern in the leading edge corner can be ambiguous if sufficient attention is not paid to channeling the coolant flow using appropriate vanes. Assuming a heat transfer coefficient of  $350 \text{ W/m}^2\text{-}^\circ\text{C}$  on the surface the maximum temperature rise per pulse is estimated to be approximately  $15^\circ\text{C}$ , and the implied maximum thermal stress is estimated to be  $4.0(7)\text{N/m}^2$ . These values appear to be within the operating limits of the containment shell material. However, it should be pointed out that the above estimates do not account for the cyclic nature of the beam, and the possible effects due to thermal-mechanical shock enhancement of the stresses.

The activation of selected zones within the collimator is shown in Table 3. The values shown on this table assume that the machine has operated for 180 days at full power (1 MW, with 0.001 of the beam being captured in the collimator). Activation levels are shown for 1 day, 7 days, and 30 days following shutdown. It is seen that the quadrupole magnets have a low activation. The primary activation products being  $^{51}\text{Cr}$ ,  $^{54}\text{Mn}$ ,  $^{56}\text{Mn}$ ,  $^{55}\text{Fe}$ ,  $^{59}\text{Fe}$ ,  $^{65}\text{Ni}$ ,  $^{62}\text{Cu}$ , and  $^{66}\text{Cu}$ . In the iron zones of the magnet structure the same activation products are important, except Cu and Ni. The dipole magnets behind the collimator have a vanishingly small amount of radioactive buildup. The energy spectrum due to decay gamma rays was found to peak in the energy range between 0.85 MeV and 1.25 MeV. The number of radioactive isotopes contributing to the overall activity is substantially reduced if only those isotopes are considered which decay by emitting a gamma ray with an energy between 0.85 MeV and 1.25 MeV. Thus, if only these isotopes are considered the activity in curies shown on Table 3 is reduced by approximately 50%. The activity of the solid components within the collimator is well shielded, and the gamma ray leakage out of the cylindrical surfaces of the shield is approximately six orders of magnitude below the source intensity.

Furthermore, the activity is contained within the collimator structure. If for some reason the radiation levels should be too high (for maintenance work) then it is possible to arrange for the placement of movable shields around the collimator. It is seen that the air activity is quite modest, and is initially dominated by argon activation, for longer times carbon is the dominant contributor. The stainless steel particle bed is the most activated part within the collimator.

Finally, it has been estimated that the number of electrons produced in the collimator aperture tube is approximately  $10^{-3}$ /circulating proton. This estimate was made by carrying out a combined neutron, photon and electron transport calculation. Neutrons below 20MeV and gamma rays due to  $\pi^0$  decay and nuclear de-excitations were included in this calculation. These electrons are essentially isotropic in angular distribution, and have an energy spectrum which peaks at 5.0 MeV. The effects of grazing protons due to a realistic proton beam have not been studied in great detail. However, off-setting the angle of the proton beam by approximately 3 mrad. relative to the collimator tube increased the number of electrons by about 25%.

Additional shielding might be required to minimize radiation levels during periods of maintenance. This will be accomplished by movable shielding blocks, which will be placed around the collimators should this be necessary.

#### ACKNOWLEDGMENTS

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**TABLE - 1 – MASSES AND OVERALL DIMENSIONS FOR COLLIMATOR**

<u>Component</u>	<u>Masses (kg)</u>	<u>Mass</u>
Graphite transition piece		18
Front iron shield		8939
Collimator vessel		900
Graphite/Borated water		800
Molybdenum/Borated water		618
Iron		5212
Tungsten/Borated water		623
Iron		2852
Radial iron shield		10240
Back iron shield		<u>2770</u>
<u>Total</u>		32972

**Dimensions (cm)**

Graphite transition piece		20 (L)
Front iron shield		45 (L)
Collimator vessel		150 (OD)
Borated water		15 (L)
Steel particle bed/Borated water	80 (L) x 20 (OD)	
Iron		80 (L)
Tungsten particle bed/Borated water	45 (L) x 20 (OD)	
Iron		45 (L)
Radial iron shield	155 (L) x 190 (OD)	
Borated water		15 (L)
Back iron shield		20 (L)

**TABLE - 2 – PERFORMANCE OF COLLIMATOR**

**Protons Crossing Surface Per Source Proton**

<u>Surface (cm)</u>	<u>Backwards</u>	<u>Forwards</u>	<u>Remark</u>
0.0	~	~	Front
25.0	3.2(-6)*	1.0(-3)	Source
45.0	4.1(-6)	7.4(-4)	Front of Coll.
61.0	3.0(-6)	6.3(-4)	Front of s/s bed <sup>+</sup>
141.0	~	1.2(-6)	Front of W bed
186.0	~	1.2(-7)	Back of W bed
201.0	~	2.3(-7)	Back of Coll.
222.0	~	~	Back

**Neutrons Crossing Surface Per Source Proton**

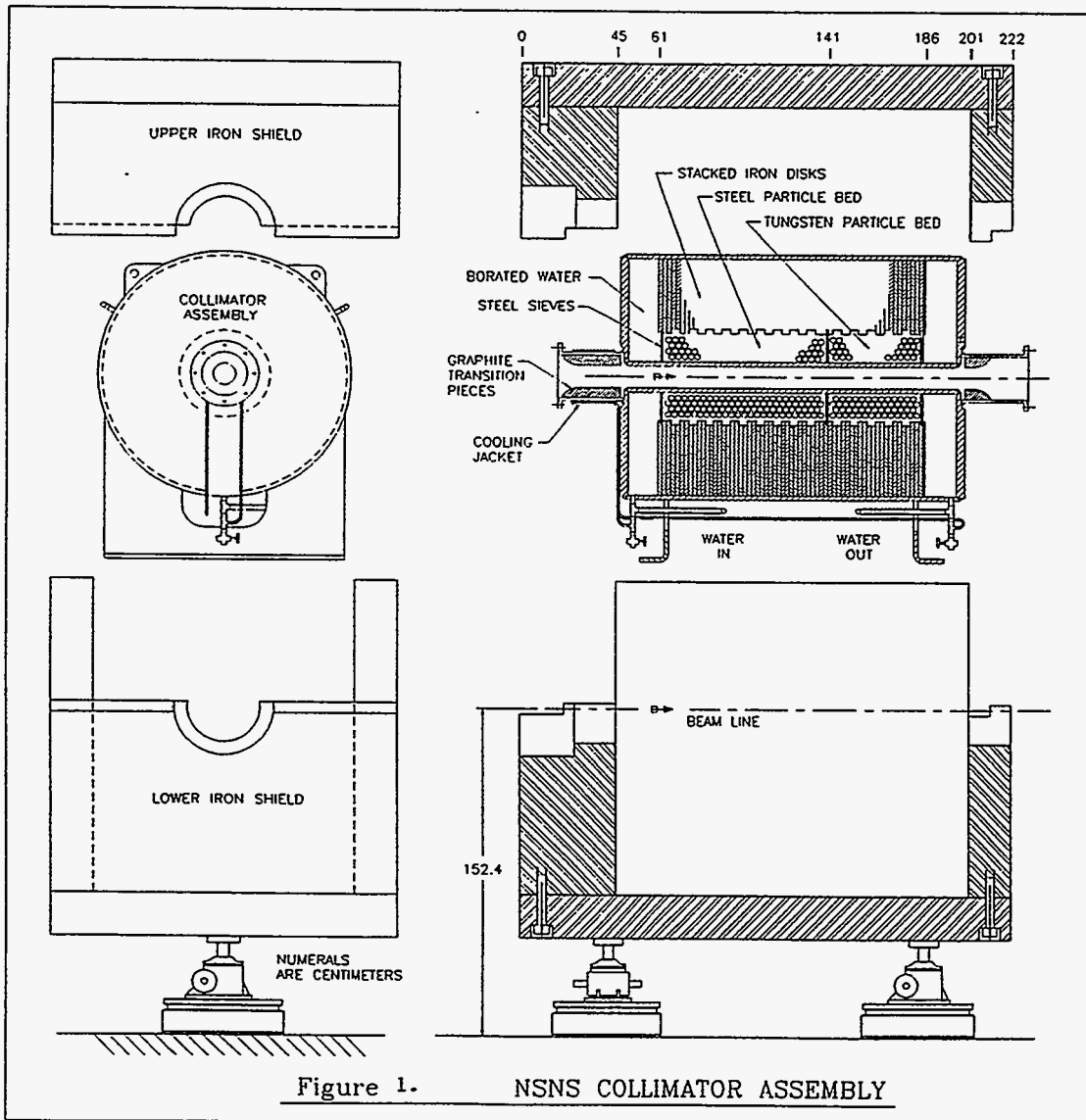
<u>Surface (cm)</u>	<u>Backwards</u>	<u>Forwards</u>	<u>Remark</u>
0.0	1.3(-6)	~	Front
25.0	1.8(-5)	1.6(-4)	Source
45.0	5.9(-5)	4.7(-4)	Front of Coll.
61.0	4.8(-5)	5.1(-4)	Front of s/s bed
141.0	7.0(-6)	5.9(-5)	Front of W bed
186.0	1.3(-6)	7.7(-6)	Back of W bed
201.0	2.3(-7)	5.3(-6)	Back of Coll.
222.0	~	1.3(-6)	Back

\* 3.2(-6)=3.2x10<sup>-6</sup>

<sup>+</sup> s/s bed=stainless steel particle bed

**Table - 3 – ACTIVATION OF SELECTED COMPONENTS AFTER SHUTDOWN  
(CURIES)**

Component	Time after shutdown			
	0 days	1 day	7 days	30 days
Quadrupole (Cu/Fe)	6.5	1.5	0.1	0.1
Quadrupole (Fe)	0.4	0.1	0.1	0.1
Air front	0.03	~	~	~
Graphite transition	123.0	24.0	21.0	16.0
H <sub>2</sub> O- <sup>10</sup> B (20 cm rad.)	28.0	2.5	2.4	2.0
s/s part. bed	250.0	174.0	145.0	100.0
W part. bed	58.0	24.0	10.0	7.5



**Figure 1. NSNS COLLIMATOR ASSEMBLY**