THE CONCEPTIONAL DESIGN OF THE SHIELDING LAYOUT AND BEAM ABSORBER AT THE PXIE*

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Abstract

The Project X Injector Experiment (PXIE) is a prototype of the Project X front end. A 30 MeV, 50 kW beam will be used to validate the design concept of the Project X. This paper discusses a design of the accelerator enclosure radiation shielding and the beam dump.

INTRODUCTION

Project X is a high intensity proton facility conceived to support a world-leading physics program at Fermilab [1]. Project X will provide high intensity beams for neutrino, kaon, muon, and nuclei based experiments and for studies supporting energy applications. PXIE will be a prototype of linear accelerator frontend. The construction and successful operation of PXIE will validate the concept for the Project X front end, thereby minimizing a large portion of the technical risk within Project X.

Main sections of the PXIE accelerator are shown in Fig. 1. They are: Ion Source (IS), Low Energy Beam Transport (LEBT), Radio Frequency Quadrupole (RFQ) accelerator, Medium Energy Beam Transport (MEBT), Half Wave (HWR) and Single Spoke Resonator 1 (SSR1) superconducting cryomodules, Diagnostic Section (DS), and Beam Dump (BD) area.
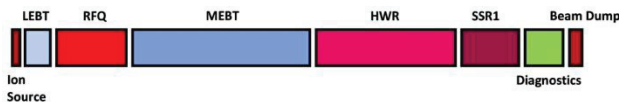

Figure 1: PXIE accelerator concept.

Each of PXIE accelerator section is characterized by different values of the beam current and energy (Table 1).

Table 1: PXIE Beam Power Summary

Section	Energy, MeV	Current, mA	Power, kW
IS	0.03	10	0.3
LEBT	0.03	10	0.3
RFQ	2.1	10	21
MEBT	2.1	10	21
HWR	11	2	22
SSR1	30	1.7	50
DS	30	1.7	50
BD	30	1.7	50

PXIE will be installed and operated inside a new concrete enclosure in the building for Cryomodule Test Facility (CMTF) located near the New Muon Lab (NML)

building. A plan view of the enclosure is shown in Fig. 2.
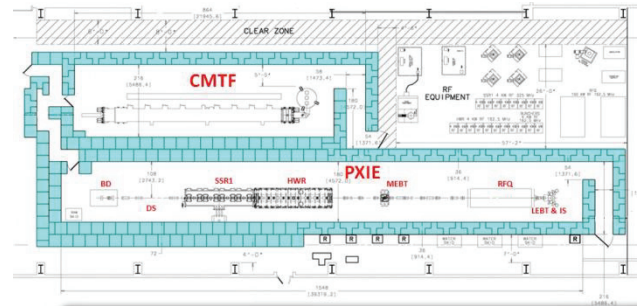

Figure 2: Plan view of PXIE accelerator in concrete enclosure within CMTF.

The PXIE enclosure includes two entrances through labyrinths located at the high and low energy end. The low energy entrance will serve as the main entrance to the PXIE enclosure. Two cryogenic penetrations will enter the enclosure vertically through the ceiling upstream of the HWR and SSR1 cavities. RF transmission lines and supporting signal and instrumentation cables will enter the PXIE enclosure through labyrinths designed for adequate radiation attenuation at both sides of the enclosure low energy end.

The concrete enclosure will be built with overlapping, prefabricated concrete shielding blocks. The low energy end walls and the entire enclosure ceiling will be a minimum of 3 feet thick. A section of the ceiling above the SSR1 cryomodule and diagnostic section where prolonged beam loss may be feasible is 4.5 feet thick. The high energy end walls will be 6 feet thick.

PXIE SHIELDING REQUIREMENTS

The design goals for shielding in normal and accident conditions are variable for different PXIE sections and defined by section assignment in the structure of accelerator. Functionally, each section differs. Some sections, having beam dumps and collimators, are designed to accept high current beam loss while other sections are expected to have very low losses. Significant losses in these sections cannot be tolerated due to damage to accelerator components.

Normal and accident beam loss conditions

The normal and accident beam loss conditions are defined in Table 2.

The HWR and SSR1 accident condition losses are driven by the limitation of the cryogenic cooling specified to be 50 W at 2 K.

The losses at the high energy part are expected to be below 0.1% at normal operations. The 100% beam loss is envisaged as the accident condition in the DS.

Table 2: Normal and accident beam loss conditions

Section	Normal condition losses	Accidental condition losses
IS	-	100%
LEBT	Up to 90%	100%
RFQ	Up to 90%	100%
MEBT	Up to 90%	100%
HWR	<< 0.23%	<< 0.23%
HWR/SSR1 interface	0.1%	100%
SSR1	<<0.1%	<0.1%
DS	0.1%	100%
BD	100%	100%

The beam dump is to be designed for continuous operation at 50 kW and 30 MeV so that the beam directed to the dump would not generate radiation exceeding 0.1% of radiation corresponding to 100% loss in the DS end.

Radiation Dose Rate Design Goals

Table 3 shows locations and intended Radiation Dose Rates Limits (RDRL) for normal and accident conditions.

Table 3: Dose Rate Limits for Normal and Accident Beam Condition Losses

Location	Condition	RDRL, mrem/hr	Permitted FRCM [2] Occupancy	Required FRCM [2] Posting
Perimeter at floor level around PXIE enclosure	Normal	<0.05	No precautions needed	No posting required
	Accident	<1		
PXIE enclosure ceiling	Normal	<0.25	No occupancy limits imposed	Controlled area
	Accident	<1	No precautions needed	None

SHIELDING ASSESSMENT RESULTS

The main results of the shielding assessment of the PXIE enclosure are as follows:

- The PXIE accelerator preliminary shielding assessment is for a maximum power of 50 kW.
- The proposed shielding wall thicknesses, ceiling thicknesses, labyrinths, and various penetration designs are acceptable for the anticipated normal, 50 W beam loss.
- Three interlocked radiation detectors are necessary to provide protection against any accident conditions, e.g., > 0.1% beam loss.

- The building in which the PXIE accelerator is to be contained is not large enough to add sufficient passive shielding to negate the need for interlocked radiation detectors.
- Intended occupancy on the ceiling of the PXIE enclosure is minimal occupancy with a peak dose rate of 0.25 mrem/hr. The ceiling area will require the Controlled Area posting and would have no occupancy limitations.
- Occupancy at the perimeter of the PXIE enclosure walls is unlimited since calculated normal dose rates are below 0.05 mrem/hr.
- A radiation safety system will be required to exclude personnel access to the PXIE enclosure whenever operation may produce significant ionizing radiation. This will include the operation of the RFQ, HWR cryomodule, and the SSR1 cryomodule.

BEAM DUMP DESIGN

High Intensity Neutrino Source (HINS) beam absorber [3] was considered as a PXIE beam dump prototype.

Table 4: Beam Parameters for HINS and PXIE Beam Dumps

Parameter	HINS	PXIE
Energy Beam, MeV	3 - 10	30
Beam Intensity, mA or protons/hr	0.25 5.4×10^{18}	1.7 3.7×10^{19}
Time Operation, hr/year	500	2300

The parameters of beams for both dumps are shown in Table 4. The power density of PXIE beam is much higher than for the HINS beam. High reliability of the beam dump requires the beam power density on the beam receiving surface to be sufficiently small (≤ 150 W/cm^2). To achieve this for a compact beam size design we plan to use beam sweeping and a small grazing angle of incoming beam. Two orthogonal sweeping magnets are used to redistribute the beam on the inner cylindrical surface of the beam dump. Fig. 3 presents corresponding details of the geometry and Fig. 4 shows power beam power distribution over this surface.
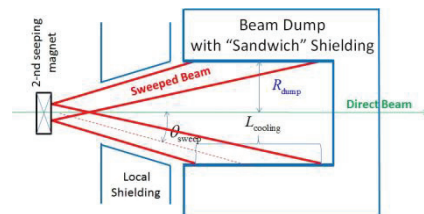

Figure 3: Sketch of geometry of the PXIE beam dump.

The following main characteristics of the dump were chosen: nickel as absorber material, the cylinder inner

radius $R_{dump} = 5$ cm, the sweeping angle $\theta_{sweep} = 2^o \approx 35$ mrad, the surface area of beam absorption $S_{dump} \approx 1250$ cm^2, and the average power of the beam on this surface $<P_{beam}> \approx 40$ W/cm^2. Evaluations of the water cooling system for this geometry confirmed an absence of serious problems in the implementation of such a device.
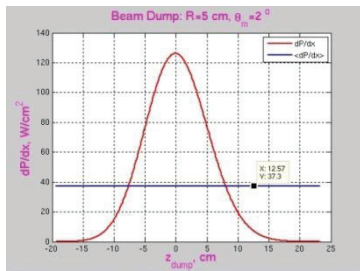

Figure 4: Beam power distributions on the absorber surface; total power of the beam 50 kW.

The oblique (almost grazing) incidence of the beam on the surface of the absorber is accompanied by beam reflection – due to single multiple scattering. Code SRIM [4] was used to analyze this effect. Simulations showed that about 25% of the initial protons are reflected. These particles carry away about 6% of the total beam power. The distribution of the "reflected power" presented in Figure 5 shows that the main part of this power is located in about 7^0 ranges.
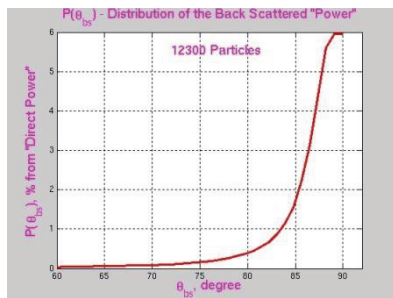

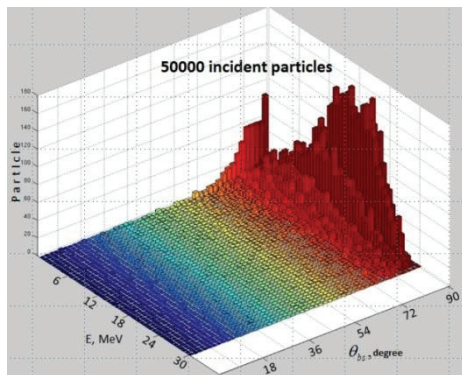Figure 5: Distribution of the back scattered "power" of the beam due to multiple scattering effect.

Figure 6: Distributions of the back scattered protons. Incident beam: $\theta_{grazing} \approx 35$ mrad, $\theta_{beam\ spread} \approx 3$ mrad.

Figure 6 shows the distributions of the reflected particles over their energy and back scattering angle. As can be seen all values of the energy are presented in the reflected beam.

In the case of high intensity beam the sputtering and blistering, if not properly addressed, can severely affect the beam dump lifetime. Figure 7 presents the maximum depth (MD) of particle penetration into the beam dump surface for absorbed and back scattered particles.
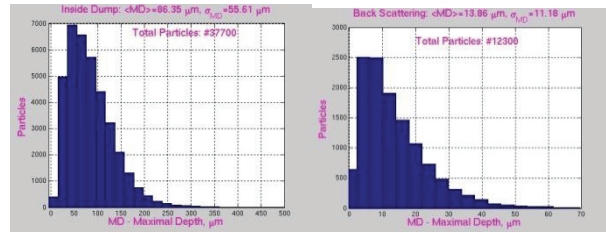

Figure 7: Distributions of the absorbed and back scattered protons.

The distributions show that $MD_{ab} \approx 86 \pm 56$ µm for absorbed and $MD_{bs} \approx 14 \pm 12$ µm for back scattered particles. It means that the absorbed particles are distributed almost homogeneously in the surface layer of the absorber. This confirms the importance of examining the sputtering and blistering during the accumulation of absorbed particles in the absorber material. These processes are under progress in more details.

As mentioned earlier the beam directed to the dump should not generate radiation exceeding 0.1% of radiation corresponding to 100% loss in the DS end. The different kind of local enclosure of the beam dump has been investigated.
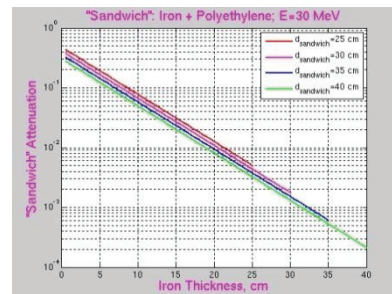

Figure 8: Comparison of "sandwich" type of local enclosure of the beam dump.

Data in Fig. 8 shows that "sandwich" from ≈ 40 cm of iron and about 10 cm of polyethylene will ensure the desired level attenuation 0.1% of the radiation due to beam absorption in the beam dump.

REFERENCES

[1] Project X Front End R&D Program – PXIE, Project X document 966-v3.

[2] "Fermilab Radiological Control Manual": Section 2.3 (2010).

[3] R. C. Webber et al., "Overview of the High Intensity Neutrino Source Linac R&D Program at Fermilab," LINAC08, Victoria, Sept. 2008, MO301.

[4] "SRIM – the Stopping and Range of Ions in Matter"; http://www.srim.org