Analysis of Potential Radiation Hazards from the PXIE RFQ

Jim Steimel, Lionel Prost

Revision History

Revision	Date	Section No.	Revision Description
0	1/21/2014	All	Initial Release.
1	5/14/2014	2-b	Removed section 2-b, X-rays from Proton Impact

TABLE OF CONTENTS

1. Introduction:

The PXIE project is designed to test continuous, high current proton accelerator technology. This experiment focuses on the low energy components of the accelerator, up to the first 30MeV of beam energy. One of the key components of the experiment is a Radio Frequency Quadrupole (RFQ) cavity that focuses and accelerates low energy H^- ions from 30keV to 2.1 MeV. This paper analyzes the possible sources of ionizing radiation that the RFQ could generate and confirms that the PXIE beam line enclosure provides adequate shielding from this radiation. The analysis covers radiation generated by H^- impacting the RFQ components and x-rays generated by sparks due to the RF generated fields.

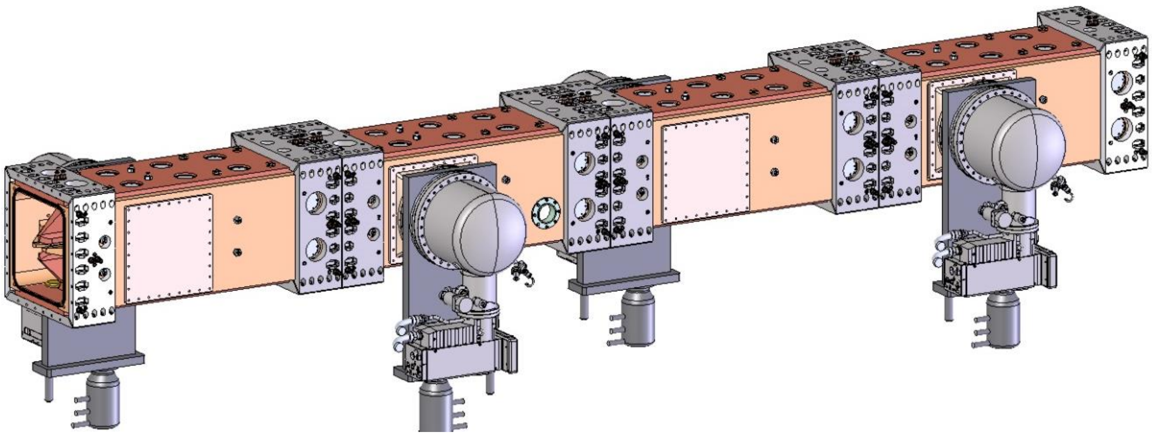

Figure 1: Solid model of RFQ.

2. Specifications & Assumptions

The following table summarizes the important specifications for the RFQ that impact the shielding calculations. These values are derived from the PXIE RFQ FRS [2] and presentations from the RFQ design review.

Table 1. Summary of RFQ Specifications

Beam		
	Ion type	H^-
	Nominal Input energy (kinetic)	30 (+/- 0.5%) keV
	Nominal output energy (kinetic)	2.1 (+/- 1%) MeV
	Beam Current Operating Range	1- 10 mA
RF		
	Frequency	162.5 MHz
	Duty factor (CW)	100%
	Total available RF power from amplifiers	150 kW
	Design potential across vanes	60 kV
	Simulated power consumption at design potential	~75 kW

a. X-rays from RF Fields:

X-ray yields from high RF fields are based on the highest energy that electrons can receive from the RF potential. Adjacent vane tips are the largest source of potential difference on the RFQ. Beam acceleration efficiency is optimized for 60 kV potential between the vanes, and simulations estimate the power consumed to maintain this potential is about 75kW [3]. The amplifiers could theoretically drive the potential up to about 85 kV (60 kV * 1.414), because they have twice the available power.

If all of the available power from the power amplifiers went into a spark across the vane tips, the current across the tips could be as high as 1.75A (150 kW / 85 kV). The spark electrons impact the copper vanes and produce x-ray brehmstrallung. Most of the electron energy is disipated in heat. The total x-ray power generated by the electron impact can be estimated by the following formula [4]:

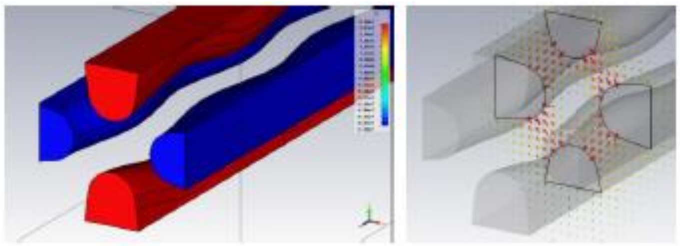

Figure 2: Simlation of RFQ vanes, setting potential between vanes to 60kV. Right illustration shows static field strength is highest between vane tips.

$$P_{x-ray} = i \cdot a' \cdot Z_{\text{target}} \cdot E_k \cdot (E_k + 16.3 \cdot Z_{\text{target}}), \quad (1)$$

with $i \equiv$ electron current in A, $E_k \equiv$ electron energy in V, and $a' \equiv$ a constant = 1.2×10^{-9}. P_{x-ray} is the total X-ray power in W. Of the 150kW of estimated electron current impacting the copper (Z=29), only 442W is converted to x-rays.

We make the conservative assumption of equating the average energy of these x-rays to the electron impact energy of 85keV. The absorbed dose rate in air one meter from the source is given by [5] and can be written as:

$$D_{air} = 100 \left(\frac{\overline{\mu_{en}}}{\rho}\right)^{air} \frac{P_{x-ray}}{4\pi} \ \ (\text{rad-cm}^2\text{s}^{-1}) \quad (2)$$

with $(\mu_{en}/\rho)^{air}$ = 23 cm^2/kg at 100 keV [6]. This gives a total dose rate of 2.9e4 rad-m^2/hr due to the electron impact of a spark on the copper vanes.

b. Neutrons from Proton Impact:

The RFQ is an enclosed, copper cavity vacuum chamber, so accelerated protons will only impact copper within the RFQ. The maximum proton energy of 2.1 MeV is below all of the kinetic energy thresholds for neutron production in copper [8].

3. Shielding:

The PXIE shielding plan must protect personnel from potential radiation sources in the beam line enclosure. The prompt dose rate from a RFQ spark must be kept under 1 mrem/hr outside the enclosure for unrestricted occupancy [9]. The RFQ copper and the concrete enclosure blocks are the two main forms of x-ray shielding from the RFQ spark. The formula for calculating the effect of shielding is given by [6]:

$$\frac{I}{I_0} = e^{-\mu t} \qquad (3)$$

where I/I_0 is the intensity reduction, t is the thickness, and μ is the mass attenuation coefficient times the material density (ρ); μ for copper is 4.12 cm^{-1} for 100 keV x-rays.

Most of the RFQ vacuum chamber is surrounded by at least 4cm of solid copper, and the vane tips have a minimum distance of 20cm to outside of the chamber. This leads to an x-ray dose of 60 mrem/hr, just outside the RFQ. However, there are a number of holes on the RFQ copper structure. The most significant points are the vacuum pump ports and the input coupler port.

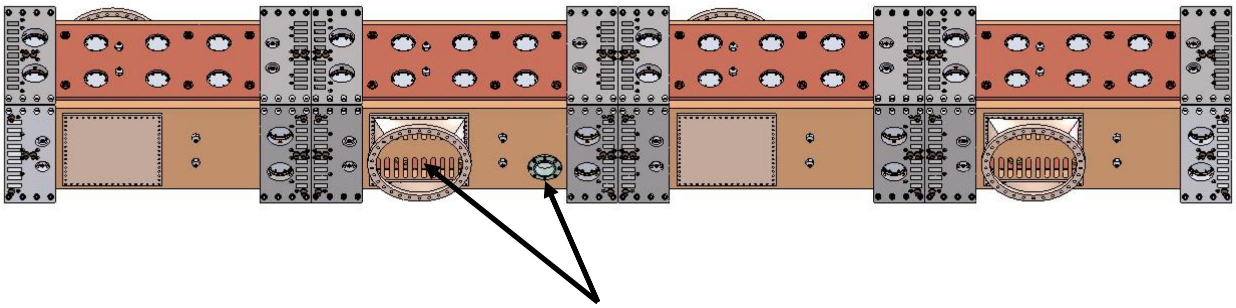

Figure 3: Solid model of RFQ showing openings for vacuum ports and input couplers.

a. Direct Path

The first analysis assumes that the vacuum ports are open and that a spark occurs directly adjacent to the port. X-rays will shine through the port holes on to the concrete shielding. The shielding wall in the neighborhood of the RFQ is 36" thick, comprised of interleaved T-blocks shown in Figure 4. The orientation of adjacent T-blocks is flipped, so that there is no clear seam through the wall. Thus, this analysis also assumes that the x-rays shine through one of these seams between T-block boundaries, so that the effective shielding is only the half the width of a T-block i.e. 18". The minimum distance between the RFQ vanes and the outside surface of the shielding wall is 2.7 m and μ of concrete is 0.462 cm^{-1}. This leads to a dose rate outside the shielding wall of 0.064 mrem/hr, well under the 1 mrem/hr requirement.

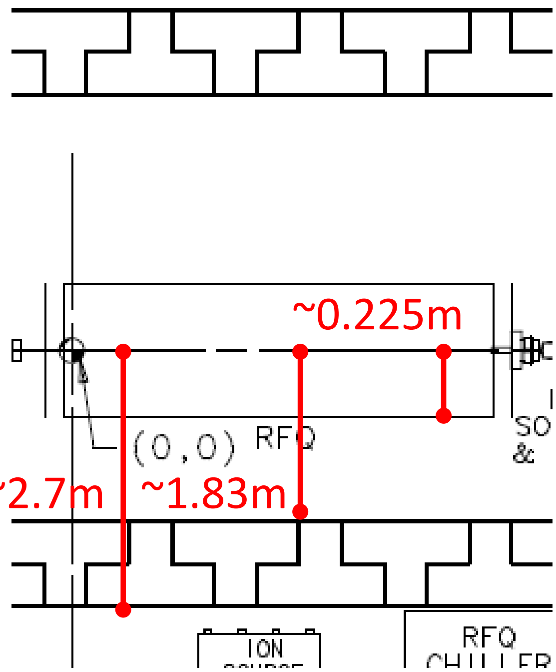

Figure 4: Layout of RFQ relative to enclosure shielding. Distance between beam line and outside of enclosure is about 2.7m. Distance between beam line and inner wall is about 1.83m, and distance between beam line and outer RFQ walls is about 0.225m.

b. Reflection Path

This analysis follows the shortest path that x-rays can travel, reflecting off the walls of the enclosure, to reach the outside of the labyrinth. The dose rate outside the labyrinth from reflected x-rays can be expressed as [7]:

$$\dot{D}_r = \frac{\dot{D}_0 \alpha_1 A_1 (\alpha_2 A_2)^{j-1}}{(d_1 \cdot d_{r1} \cdot d_{r2} \cdots d_{rj})^2} \quad (4)$$

- α_1 is the reflection coefficient for x-rays on first reflecting material.
- α_2 is the reflection coefficient for x-rays on subsequent reflecting materials.
- A_1 is the area struck by x-rays on the first reflecting material.
- A_2 is the cross-section of the labyrinth.
- d_{rj} are the centerline distances along each maze length.

The calculation of A_1 assumes that x-rays are generated from a point source on a RFQ vane. In the worst case, this source is located directly behind the middle of a vacuum port, and the vacuum pumps do not provide extra shielding.

Figure 5 shows the design of the RFQ vacuum port. The port consists of 20, 80mm x 16 mm slits that are just over 40mm deep. These narrow and deep slits limit the effective solid angle of x-ray distribution that can escape the RFQ. The rectangle on the figure shows the effective x-ray escape area for an isometric point source on the vane. This rectangle is projected on to the concrete wall to determine A_1. The effective exposed wall area is given by:

$$A_1 = A_{rfq}\left(\frac{d_1}{d_{rfq}}\right)^2 \tag{5}$$

where A_{rfq} is the escape area on the RFQ vacuum port (290cm^2), and d_{rfq} is the distance from the point source to the outside of the RFQ (0.225m).

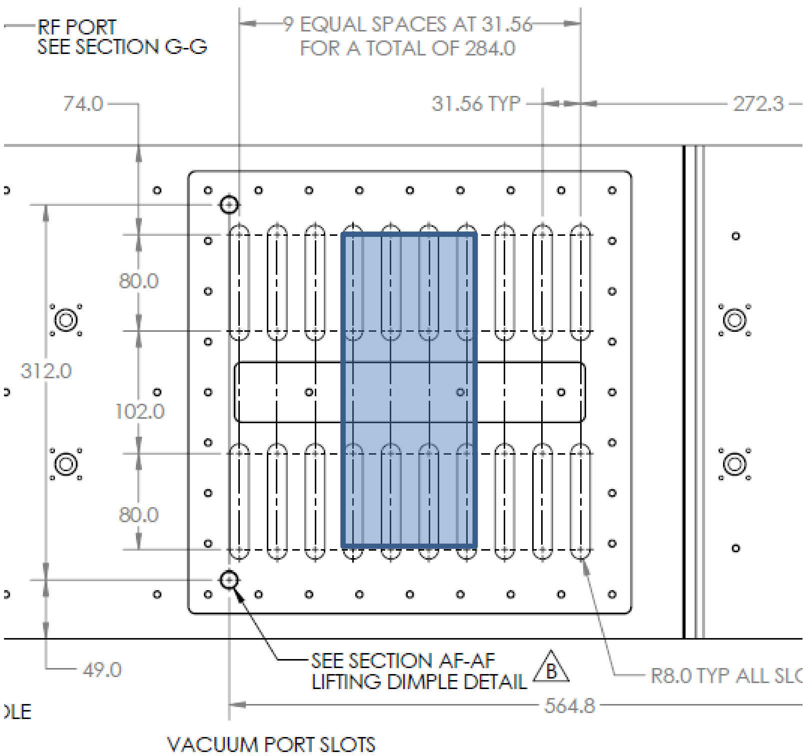

Figure 5: Drawing of RFQ vacuum port showing the effective escape area of point source x-rays.

Figure 6 shows the x-ray path used to estimate the dose outside the labyrinth gate. The reflection coefficient for 85 keV x-rays off of concrete is estimated at 3%, and the area of the labyrinth hall is 4-1/2 ft by 7-1/2 ft. The total estimated dose rate at the exit of the labyrinth is 0.17 mrem/hr.

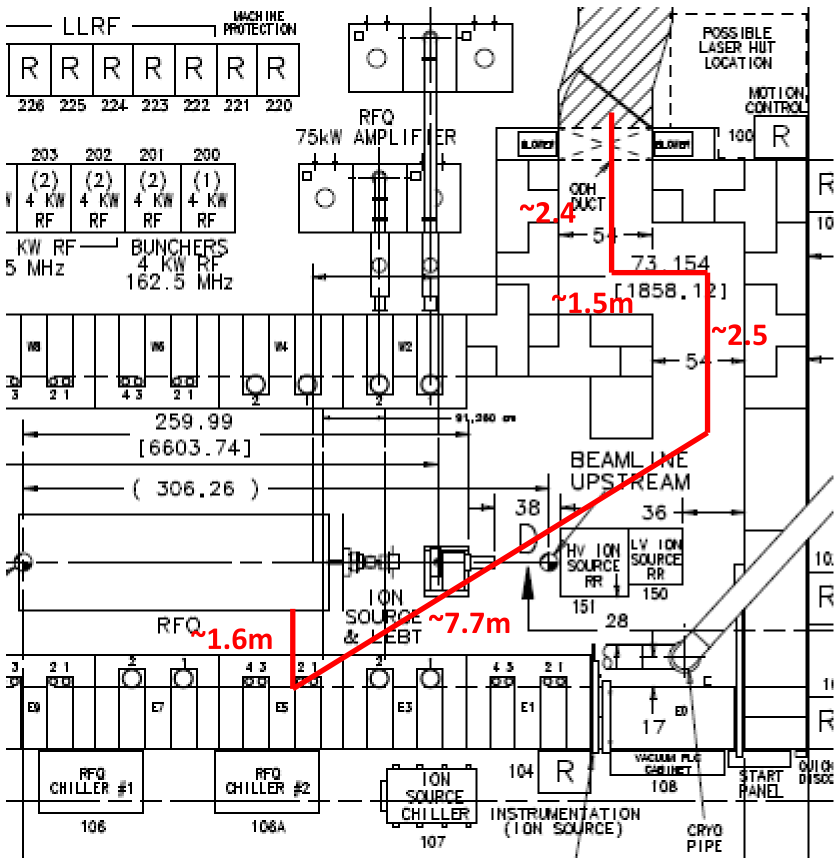

Figure 6: Worst case reflection path for RFQ generated xrays.

4. Conclusions:

Using very conservative estimates on unlikely accident scenarios, we have shown that the enclosure design provides adequate shielding from RFQ generated x-rays. Calculations show that the dose rate outside the enclosure will never exceed 0.2 mrem/hr due to RFQ operations.

5. References:

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