Pre-formed Plasma Channels for Heavy Ion Transport in IFE Reactors: Final Report for Contract #46053410

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R. R. Peterson and M. E. Sawan

Fusion Technology Institute
Department of Nuclear Engineering and Engineering Physics
University of Wisconsin-Madison
1500 Engineering Drive
Madison, WI 53706

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1. Introduction

The propagation of heavy ion beams in pre-formed plasma channels is a potentially attractive option for Inertial Fusion Energy (IFE). The channels would guide ions to a target over long distances, allow a moderate relaxation of beam microdivergence limits, and introduce a target chamber fill gas. These lead to the following:

- Stand-off distance between the final focusing optic and the target. This leads to flexibility in final optic and target chamber design.

- Larger allowable emittance and microdivergence leads to more flexibility and perhaps lower cost in the accelerator.

- Target chamber fill gas allows protection of the target chamber from target explosion generated x rays and debris ions.

A number of reactor studies [1], [2], [3] and [4] have defined consistent sets of beam parameters for heavy ion fusion. Parameters are shown in Table 1 for the Prometheus-H and OSIRIS power plant designs and the HIDIF facility. The parameters that are relevant to transport in plasma channels are listed. Most of the parameters are fairly constant between the designs. The one major exception is the beam emittance, which is very important to transport but is not well known. The value is very high for the OSIRIS design because the value quoted is the maximum that would still allow ballistic transport to be feasible, while the other two use the lowest reasonable value. Emittance growth of the beam during transport in the accelerator or in the target chamber can be very difficult to determine. The emittance of the beam at the final optic determines the minimum size of the beam spot at the entrance to the channel. In both Prometheus-H and OSIRIS the focal spot radius is acceptable for channel transport.

2. Channel Formation

Heavy ion beam transport in pre-formed plasma discharge channels requires channels with small radius, large azimuthal magnetic field, and minimal plasma turbulence. The targets must be irradiated by beams of no more than about 0.5 cm in radius. The azimuthal magnetic field is defined as the ability to turn the transverse motion of the beam ions and force the ions into betatron orbits. The magnetic field is generated by a discharge current flowing in the channel, determined by the expression (in kA):

$$I_{ch} = \frac{1.3\times10^{3}\left(\frac{R}{F}\right)^{2} A_b^{1/2} E_b^{1/2}}{Z_b} \ . \tag{1}$$

R is the aperture of the final optic and F is the focal length, so R/F is approximately the largest angle between beam ions and the channel axis in radians. Z_b is the charge state of the beam ions, E_b in the beam ion energy in MeV, and A_b in the atomic mass number of the beam ions. If the current is uniform in a cylinder of radius r_c, the magnetic field at the edge of the channel is

$$B_\theta = \frac{0.21_{ch}}{r_c} \ , \tag{2}$$

Table 1. Ion Beam Parameters for Three Heavy Ion Concepts

	Prometheus-H	OSIRIS	HIDIF
Ion energy (GeV)	4.0	3.83	10
Ion mass (amu)	208	131	20
β	0.20	0.24	0.31
Ion charge (esu)	2	1	1
No. of beams	18	12	1
Pulse width (ns)	37.3	100	37.5
Ion energy/beam (MJ)	0.433	0.42	1.0
Ion power/beam (TW)	11.6	4.2	26.7
Ion current/beam (kA)	2.9	1.1	2.7
Beam emittance (m-mrad)	.045	4.7	0.05
Transport length (m)	5.6	4.5	?
Beam radius at final optic (cm)	15	14.2	?
Focal spot radius (cm)	0.25	0.23	?
Driver efficiency (%)	20.6	28.2	?

where I_{ch} is the channel current in *A*, r_c is the channel radius in cm and B is in gauss. Ion power transport constraints (see below) predict that a proper *R/F* for Prometheus-H might be 0.04. Using A_b = 208, E_b = 3830 MeV, and Z_b = 40, one sees that a discharge current of 46 kA and an azimuthal magnetic field of 18.4 kG are required.

Channels were designed for the LIBRA [5] light ion beam reactor study that meet these conditions. Computer simulations of the formation of channels for light ion transport were performed as part of the LIBRA study with the ZPINCH code [6]. We have not performed additional computer simulations of the formation of channels for heavy ion fusion, but rely on those older calculations. In the intervening years, we have developed new capabilities which could be used to study this issue.

The LIBRA channels are formed by a double pulse of discharge current shown in Figure 1. The LIBRA channels are formed in 23.7 μg/cm^3 of nitrogen gas. The number density is similar to what is suggested by transportable power considerations (see below), but those arguments are only strictly valid for deuterium gas. The peak discharge current was 100 kA. A study was carried out for LIBRA channels where the time delay, Δt, was varied and the magnetic field was calculated with ZPINCH simulations. In Figure 2, the azimuthal magnetic field is plotted against Δt for channels guided by a laser that has a Gaussian half-width of 0.5 cm. In these calculations radiation transport was included. The magnetic field is taken at 0.5 cm off the axis and at its maximum. At $\Delta t = 1$ μs the field at 0.5 cm is about 20 kG. The maximum field is higher and occurs at large radius because discharge current is flowing at larger radius. As Δt increases the current flows at larger and larger radii, leading to lower magnetic fields. In Figure 3, the azimuthal magnetic field is shown plotted against the laser radius for calculations where radiation transport is included and where it is ignored. The radiation transport has a much more important effect than the size of the laser cross section. It seems that radiation transport spreads the region of hot plasma at the center of the channel, which allows current to flow at a larger radius. Radiation transport dominates the size of the current carrying region, so the magnetic field is not much affected by the size of the laser beam. These calculations show that it is

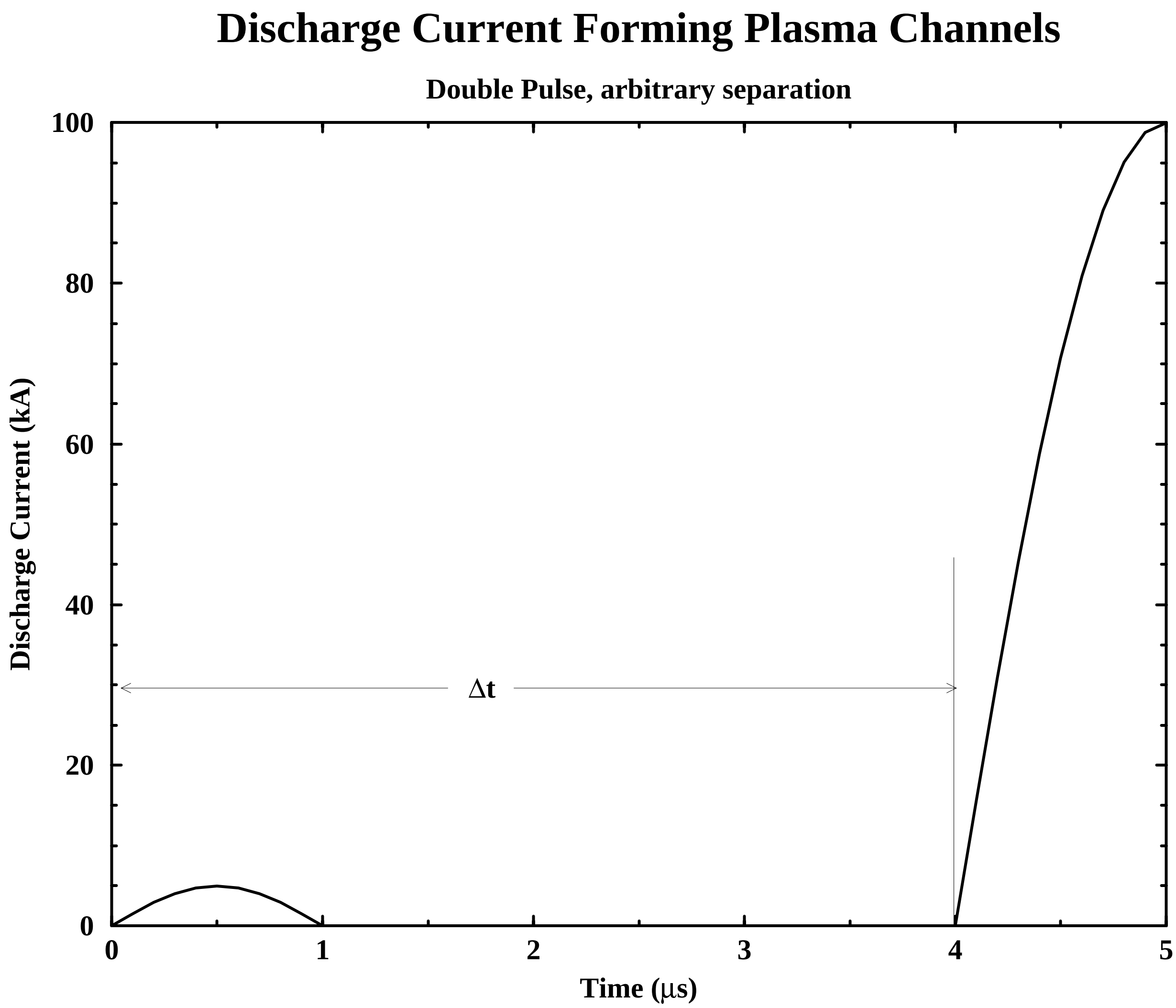

Figure 1. Discharge current history for the formation of plasma channels for LIBRA.

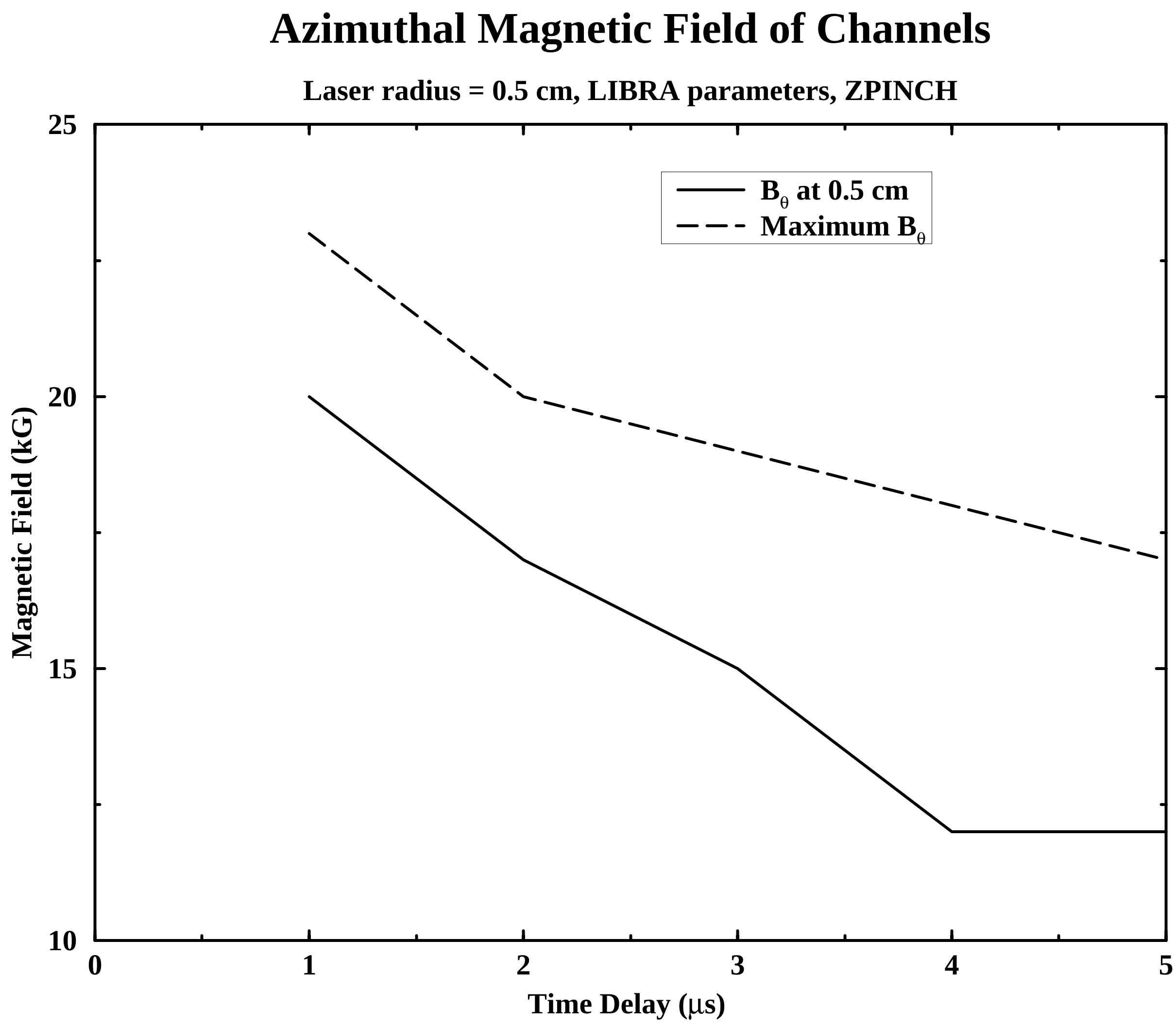

Figure 2. Maximum and peak azimuthal magnetic field at 0.5 cm versus time delay. These calculations with ZPINCH are for laser guided plasma channels in 23.7 μg/cm^3 nitrogen. The laser Gaussian half-width was 0.5 cm.

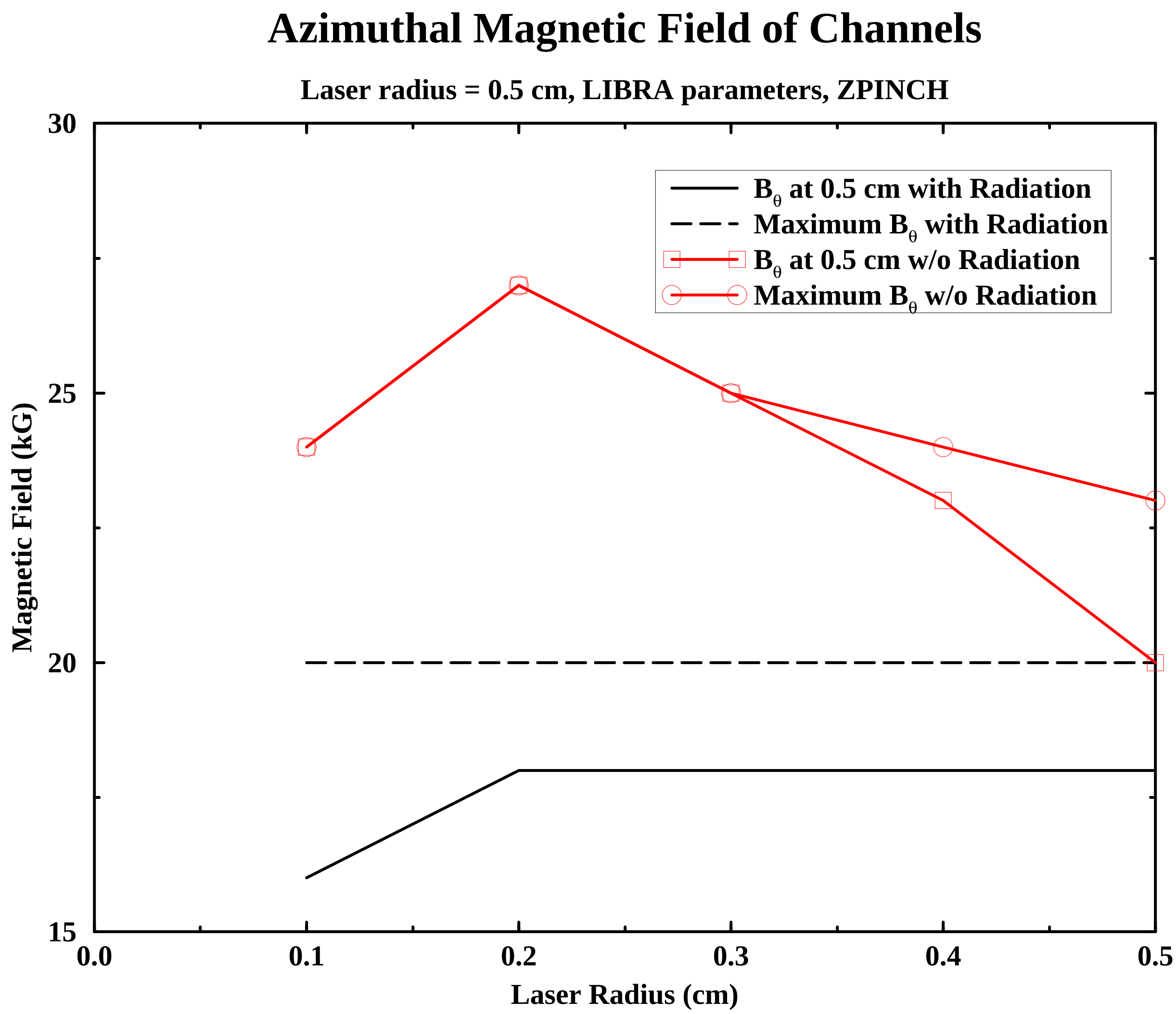

Figure 3. Maximum and peak azimuthal magnetic field at 0.5 cm versus laser Gaussian half-width. These calculations with ZPINCH are for laser guided plasma channels in 23.7 μg/cm^3 nitrogen. ZPINCH calculations with and without radiation transport are compared.

certainly possible to find a set a parameters for the laser and discharge which will form a channel with 18.4 kG at 0.5 cm.

3. Transportable Ion Power

Several plasma physics effects are present in the beam-channel system that can limit the allowable ion power that can be carried by the channel. The following effects have been included in a code called WINDOW [7]. The WINDOW code follows closely on the work of Mosher et al. in the early 1980's at NRL [8]. The following relationships and the WINDOW code are currently only valid for a deuterium target chamber fill gas.

- **Electrostatic Microturbulence.** The two-stream instability can grow into electrostatic microturbulence. This turbulence would increase the microdivergence of the beam while it is in the channel. The two-stream instability is collisionally stabilized if the electron temperature is kept below a critical value. Since the ion beam heats the channel, there is a limit to the ion power allowed in the channel. This power limit is calculated in WINDOW as

$$P_{ES} = 1.6\times 10^{-3}\left[\frac{\left(\frac{\rho}{\rho_{opt}}\right)^{6} r_b^8 \lambda_{ei}^4}{Z_b^{26}\tau_b^3}\right]^{1/7}\left(\frac{R}{F}\right)^{12/7}\frac{E_b^3}{A_b^{1/2}}\ . \quad (3)$$

  Here, ρ/ρ_{opt} is the ratio of the fill gas mass density to the optimum and τ_b is the pulse width of the beam in seconds and P_{ES} is the ion power limit from this effect in TW.

- **Filamentation of Ion Current.** The ion beam will filament if the ion current is high enough. This will add microdivergence to the beam. The instability is damped if the ion trajectories have a wide spread in direction. Therefore, there is a minimum *R/F* to avoid ion filamentation, which is a very weak function of ion power (only through the Coulomb logarithm λ_{ei}):

$$\left(\frac{R}{F}\right)_{BFIL} = 2.5\times 10^{-2}\left[\frac{\lambda_{ei}^4 E^2}{Z_b^8 A_b^6}\right]^{1/8}\ . \quad (4)$$

- **Filamentation of Return Current.** The ion beam generates a return electron current in the channel. This current can also filament, which would result in local variations in the neutralization of the ion beam and a growth of microdivergence. This can be avoided if the ion beam current (and therefore the electron return current) is held below a threshold value. This leads to a limit on transportable ion beam power:

$$P_{CFIL} = 1.76\times 10^{5}\left(\frac{\rho}{\rho_{opt}}\right)^{2}\left(\frac{R}{F}\right)^{4}\left[\frac{E_b^{14}\, 4\,\tau_b^2 A_b^4}{Z_b^{20}}\right]^{1/6}\ . \quad (5)$$

- **MHD Expansion of Channel.** The Lorentz force between the electron return current and the azimuthal magnetic field can expand the channel. This is undesirable and can be avoided by limiting the ion current and power. The allowed power is proportional to the mass density of the gas squared and inversely proportional to the pulse width cubed.

$$P_{MHD} = 1.5\times10^{-21}\frac{\left(\dfrac{\rho}{\rho_{opt}}\right)^2 r_b^4 E_B^2}{Z_b^2\tau_b^3 A_b} \;. \tag{6}$$

- **Energy Loss.** Two energy loss mechanisms to the ion beam are considered: collisional and deceleration in the axial electric field that is generated self-consistently by the ion beam itself. The electric field has a resistive and an inductive component. The WINDOW code assumes that this field is primarily inductive, which is proportional to the electron return current times the magnetic field. The collisional energy loss increases with increasing density, while the axial electric field decreases. Therefore, there is an optimum mass density which is written as,

$$\rho_{opt} = 0.167\frac{E_b^{1/2}P^{1/2}\tau_b^{1/2}\left(\dfrac{R}{F}\right)^2}{r_b^2 Z_b} \;. \tag{7}$$

Here P is the lowest of all the power limits. The ion power limit is also a function of the transport length L, and the allowed fraction of ion energy which can be lost, f_E. The energy loss power limit is a strongly decreasing function of *R/F* because the magnetic field required to trap the beam increases as the square of *R/F*,

$$P_{ELOSS} = \frac{3.5\times10^{-5} f_E^2 E_b^3 r_b^4}{\left(\dfrac{\rho}{\rho_{opt}}+\dfrac{\rho_{opt}}{\rho}\right)^2 A_b^2 Z_b^2 \tau_b L^2\left(\dfrac{R}{F}\right)^4} \;. \tag{8}$$

With the WINDOW code, the maximum allowable ion power is computed for each of the above constraints. This is done for a range of values for the injection angle, *R/F*. At each value of *R/F*, the most limiting constraint on ion power is determined. From this, an allowable "window" in *R/F* - ion power space is plotted. Also, the allowable ion current is calculated. The optimum mass density is calculated as in Eqn. 7. In all of the window plots the gas density is assumed to be the optimum.

A sample of a WINDOW plot is shown in Figure 4. In this plot, the power limits are shown for each phenomenon. It is seen that, for typical heavy ion fusion parameters, electrostatic and channel filamentation limit the power at low *R/F*, while energy loss limits at high *R/F*. Several of these phenomena become more restrictive as the ion beam electrical current increases, so the charge state of the beam ions is quite important. We have not calculated the charge state of the beam ions but will vary its value in this study. This particular plot is for a charge state of the beam ions in the channel of 40. The other parameters are shown in Table 1, under the column marked Prometheus-H, which we have chosen as a representative design. The

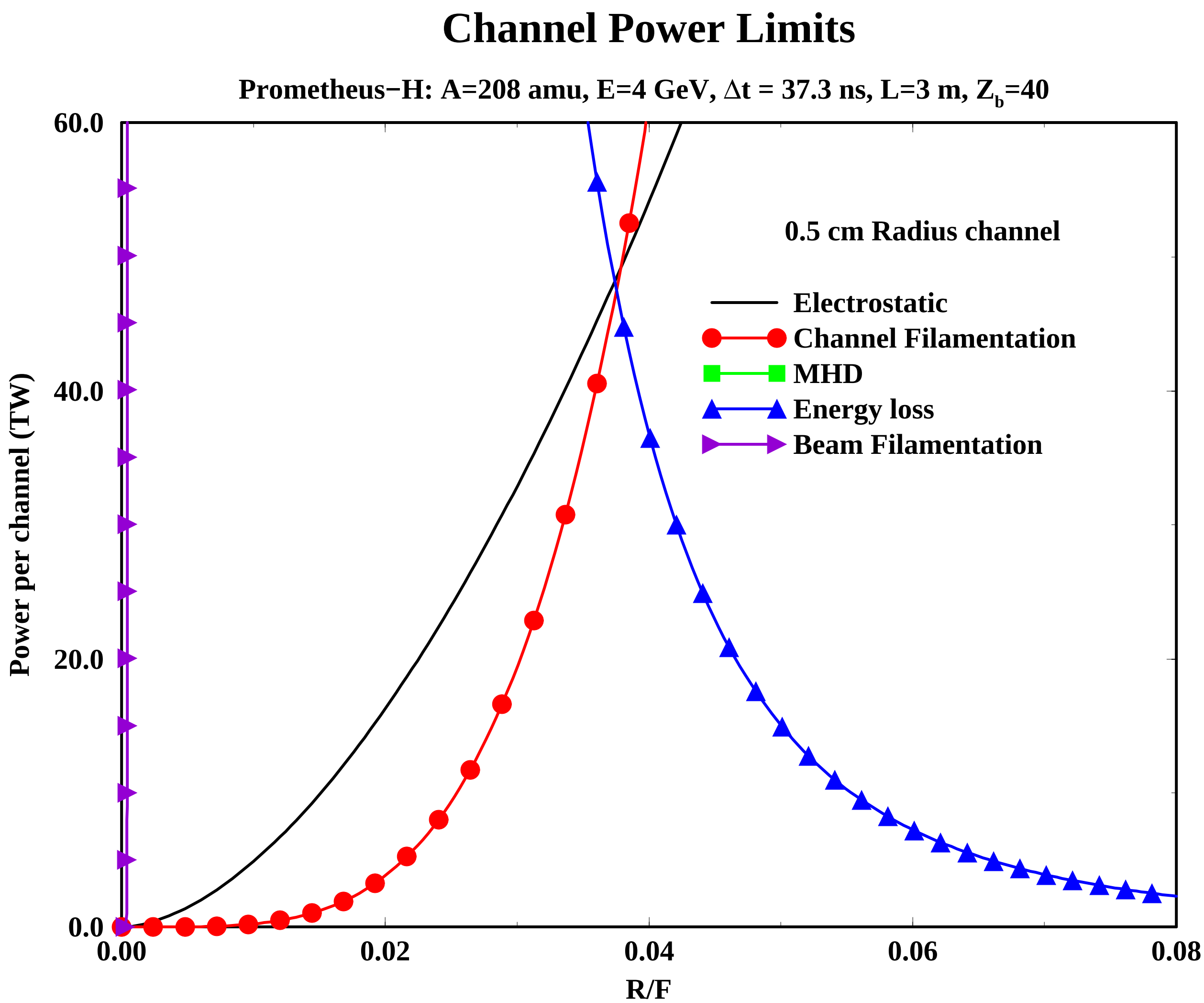

Figure 4. Transportable ion power per channel versus injection angle (R/F). Channel radius = 0.5 cm. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 40.

allowed ion beam particle current is shown in Figure 5, along with the transportable ion power with the specific constraints removed. All of the other cases will be plotted in this way. The beam current peaks at *R/F* = 0.038 with a value of 12 kA. Of course, this is the same place that the ion power peaks at 46 TW. In Figure 6 the optimum mass density is plotted versus *R/F* for this same case. The peak optimum mass density occurs at the same *R/F* as the peak power. The peak is 2.0 μg/cm^3 for this case.

The ion charge state has been varied in increments of 10 up to 70. The results are shown in Figures 5 through 12. The *R/F* of the peak transportable power remains approximately constant at 0.04. The value of the peak power falls as the charge state of the beam is increased. This is shown in Figure 13. The transportable ion power for Prometheus-H parameters and a 0.5 cm radius channel falls steeply as the ion charge state increases; from 47 TW per beam at a charge state of 40, to 8 TW at Z_b of 70. From Table 1, 11.6 TW per channel are injected into each channel, which is allowed except for Z_b = 70. The beam must be time of flight bunched since the unbunched beam would only lead to a peak power on target of 200 TW, so the power per channel leaving the channel would be higher. If the charge state of the ions is 70 or higher, then it will require more channels than the 18 called for in the Prometheus-H design. More work is required to calculate the stripping of the beam in the channel. The charge stage of the beam will change as the beam moves down the channel. The fill gas density (for deuterium at the *R/F* for peak power) is plotted against charge state in Figure 14. As the charge state increases, the optimum mass density decreases, but it only falls by a factor of 2 for Z_b changing from 40 to 70. From this, one sees that the fill gas mass density should be in the range of 1 mg/cm^3, with some minor adjustments to be made as the charge state on the ions becomes better known. If a gas other than deuterium is desired, the formalism needs to be re-derived. Two and/or 3-D computer simulations will be required to verify the results suggested here.

4. Ionization of Chamber Gas by Radioactivity

The structure of a target chamber of a heavy ion fusion reactor will become radioactive from the effects of fusion generated neutrons. The γ-ray emitted by this radioactive structure will, to some degree, ionize the target chamber gas. If the gas is ionized to a high degree, the pre-ionization of the gas in the path of the plasma channels by lasers will be ineffective in guiding the channel formation. To resolve this issue, we have estimated the ionization of a target chamber gas by the γ-rays.

The γ-ray spectrum and spatial dependence of the flux in the LIBRA target chamber are shown in Figures 15 and 16. The spectrum is peaked at about 200 keV, though there is another small peak at about 2.5 MeV. This is the spectrum at the center of target chamber. The flux increases as one moves towards the wall just due to geometrical effects, as is shown in Figure 16. Assuming a source of photons from radioactive decay in a spherical chamber wall and no absorption, the flux inside the chamber is,

$$\phi(R) = \frac{\phi(R_{wall})}{2}\frac{R_{wall}}{R}\ln\frac{1+\frac{R}{R_{wall}}}{1-\frac{R}{R_{wall}}} \quad . \qquad (9)$$

Between the chamber wall and the center of the chamber, the flux falls by a factor of about three. The decay γ source immediately following shutdown was used in the calculation.

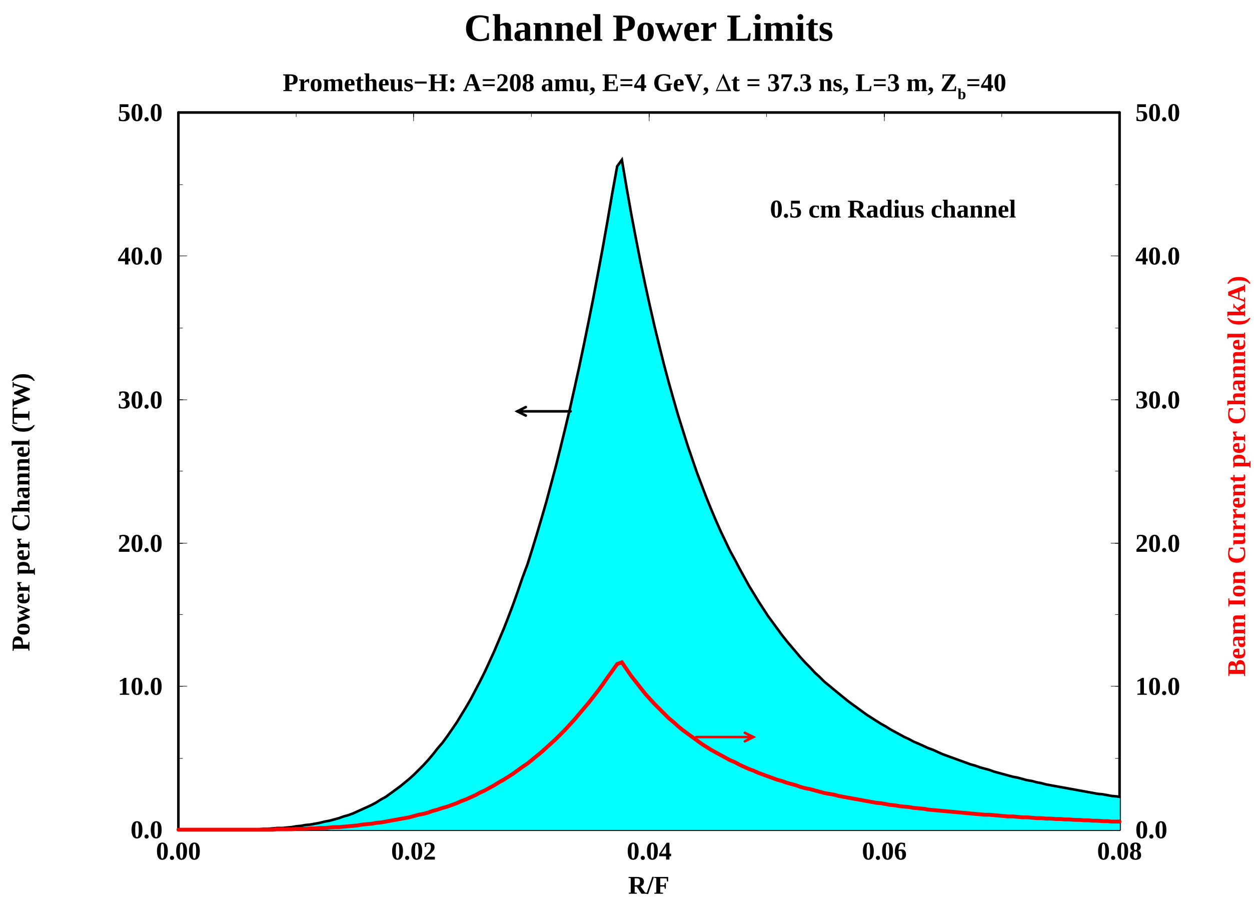

Figure 5. Transportable ion power per channel and ion current versus injection angle (R/F). Channel radius = 0.5 cm. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 40.

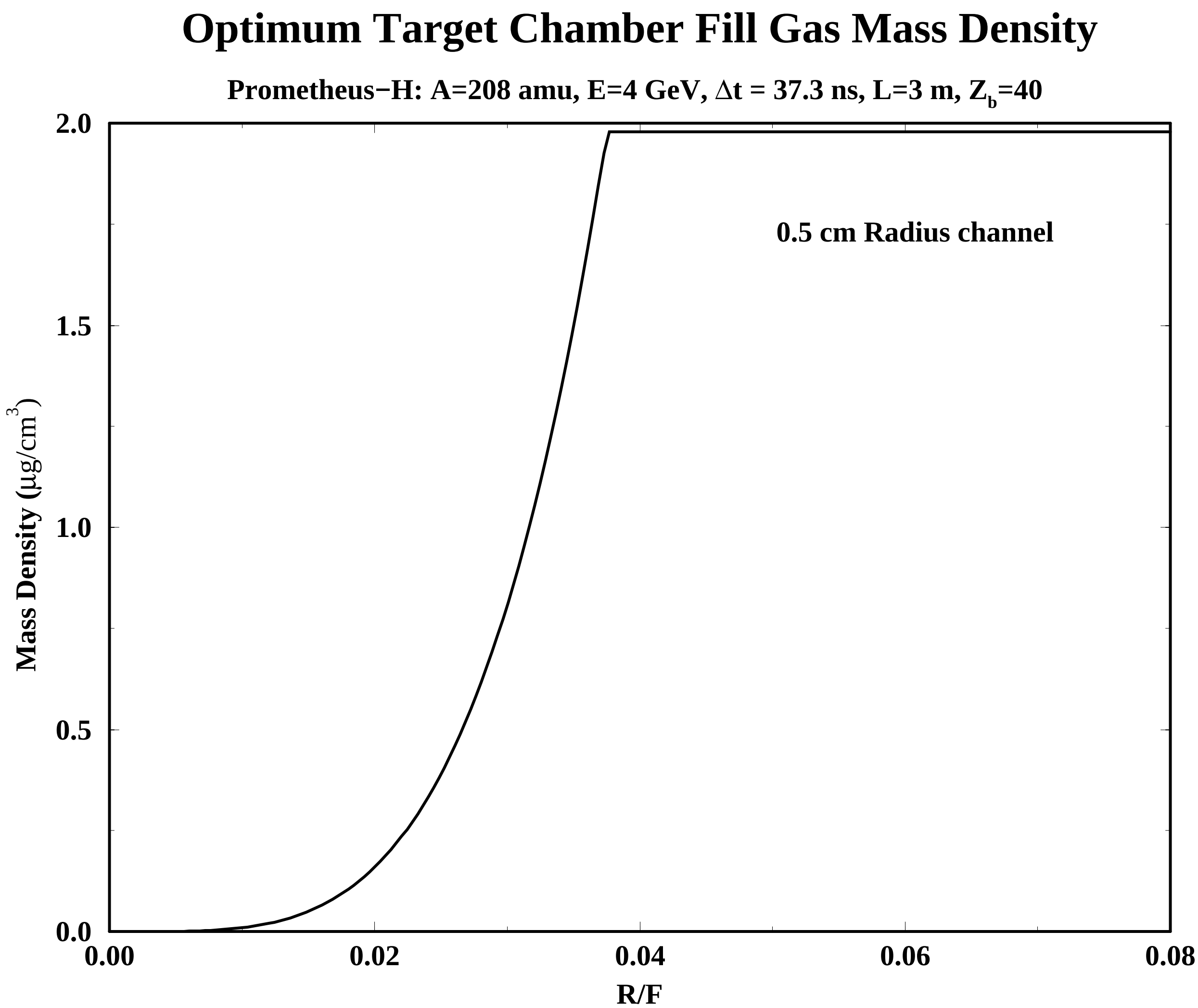

Figure 6. Optimum fill gas density versus injection angle (R/F). Channel radius = 0.5 cm. Deuterium fill gas. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 40.

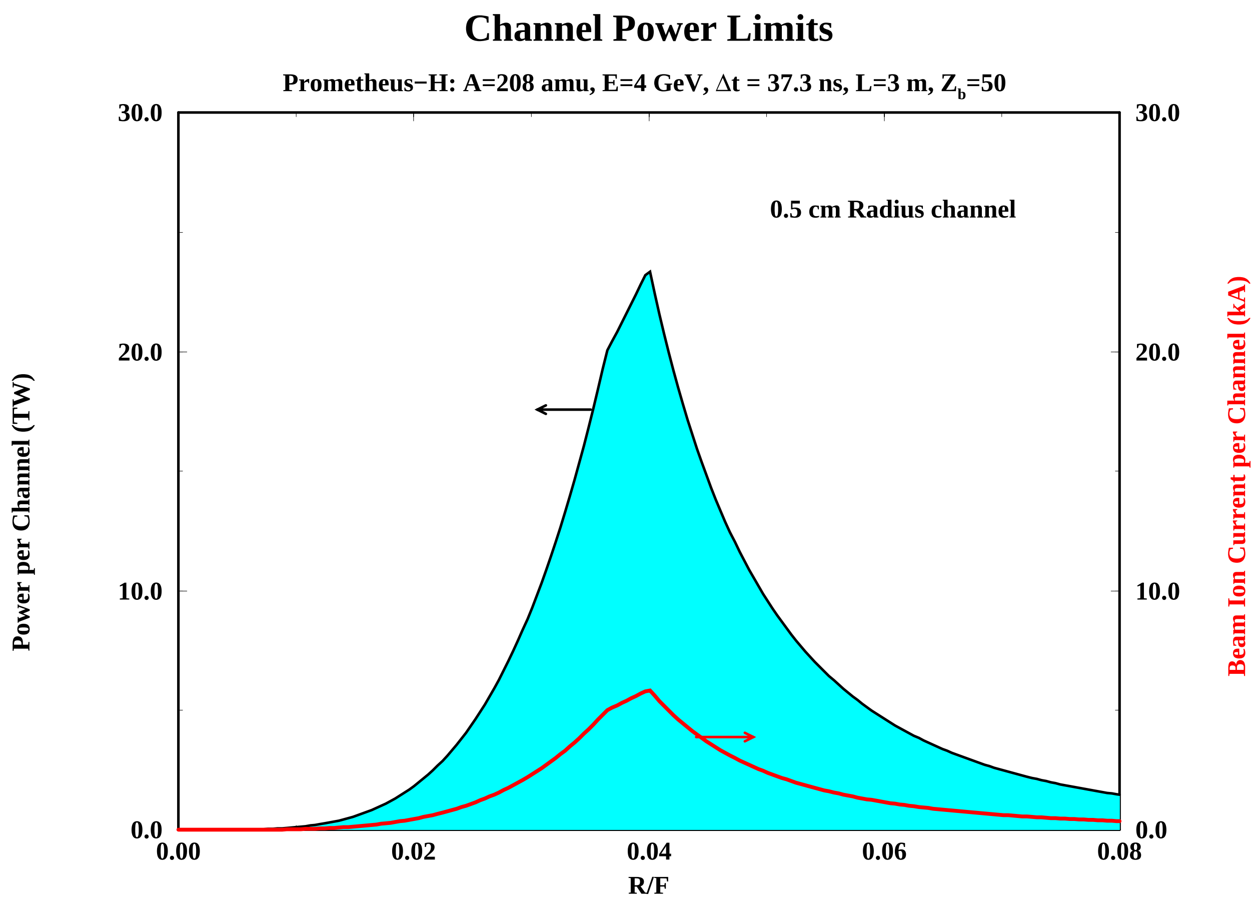

Figure 7. Transportable ion power per channel and ion current versus injection angle (R/F). Channel radius = 0.5 cm. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 50.

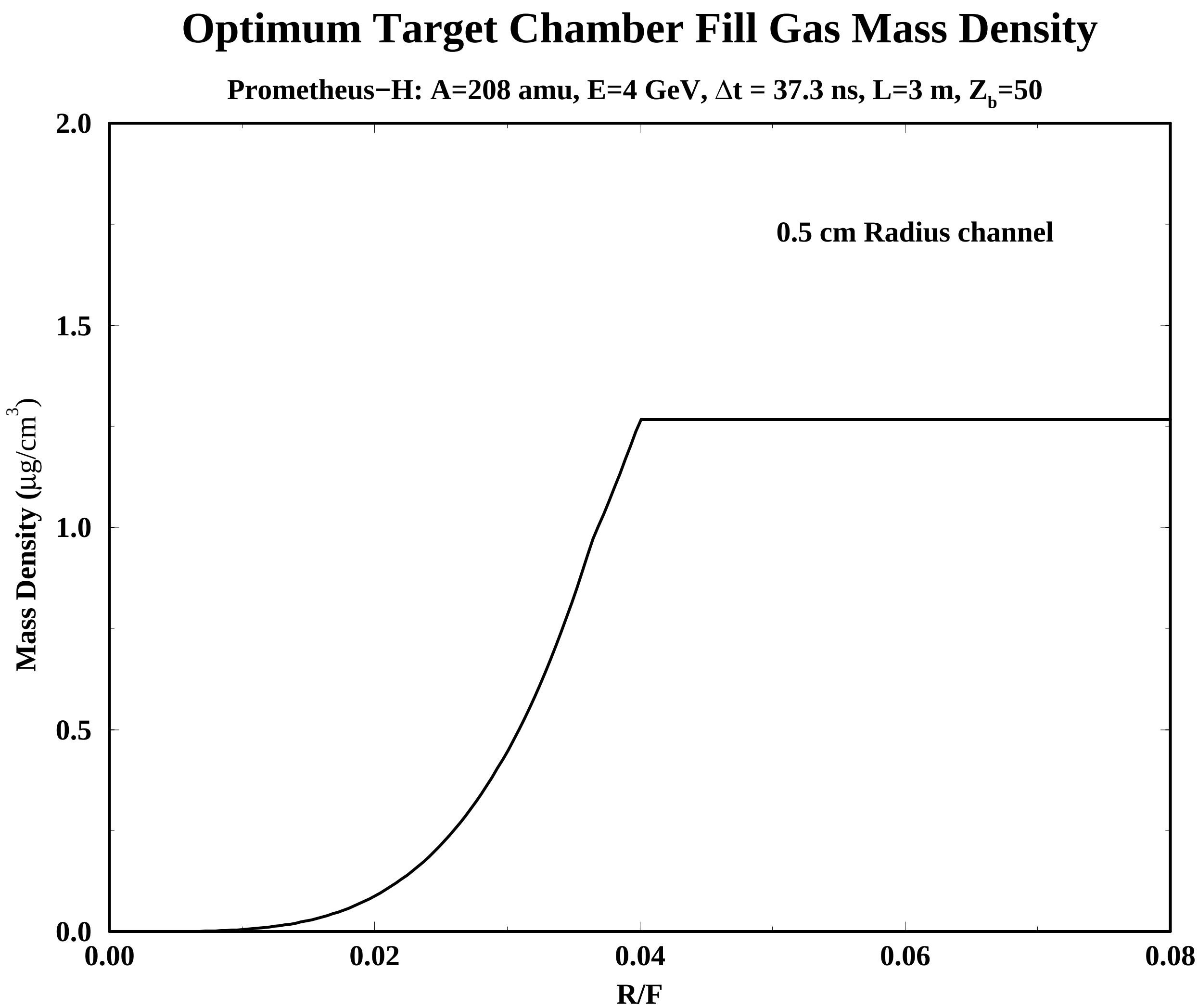

Figure 8. Optimum fill gas density versus injection angle (R/F). Channel radius = 0.5 cm. Deuterium fill gas. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 50.

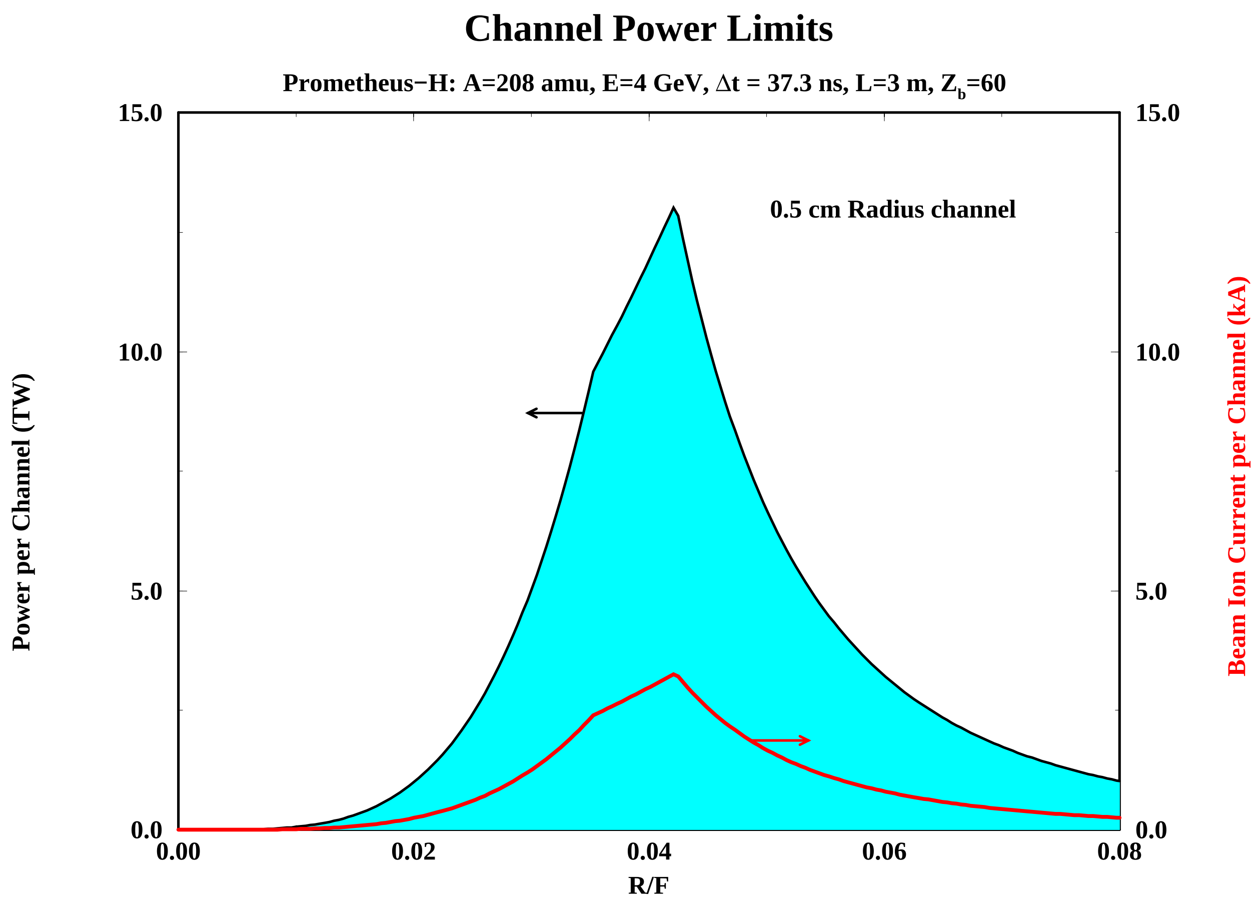

Figure 9. Transportable ion power per channel and ion current versus injection angle (R/F). Channel radius = 0.5 cm. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 60.

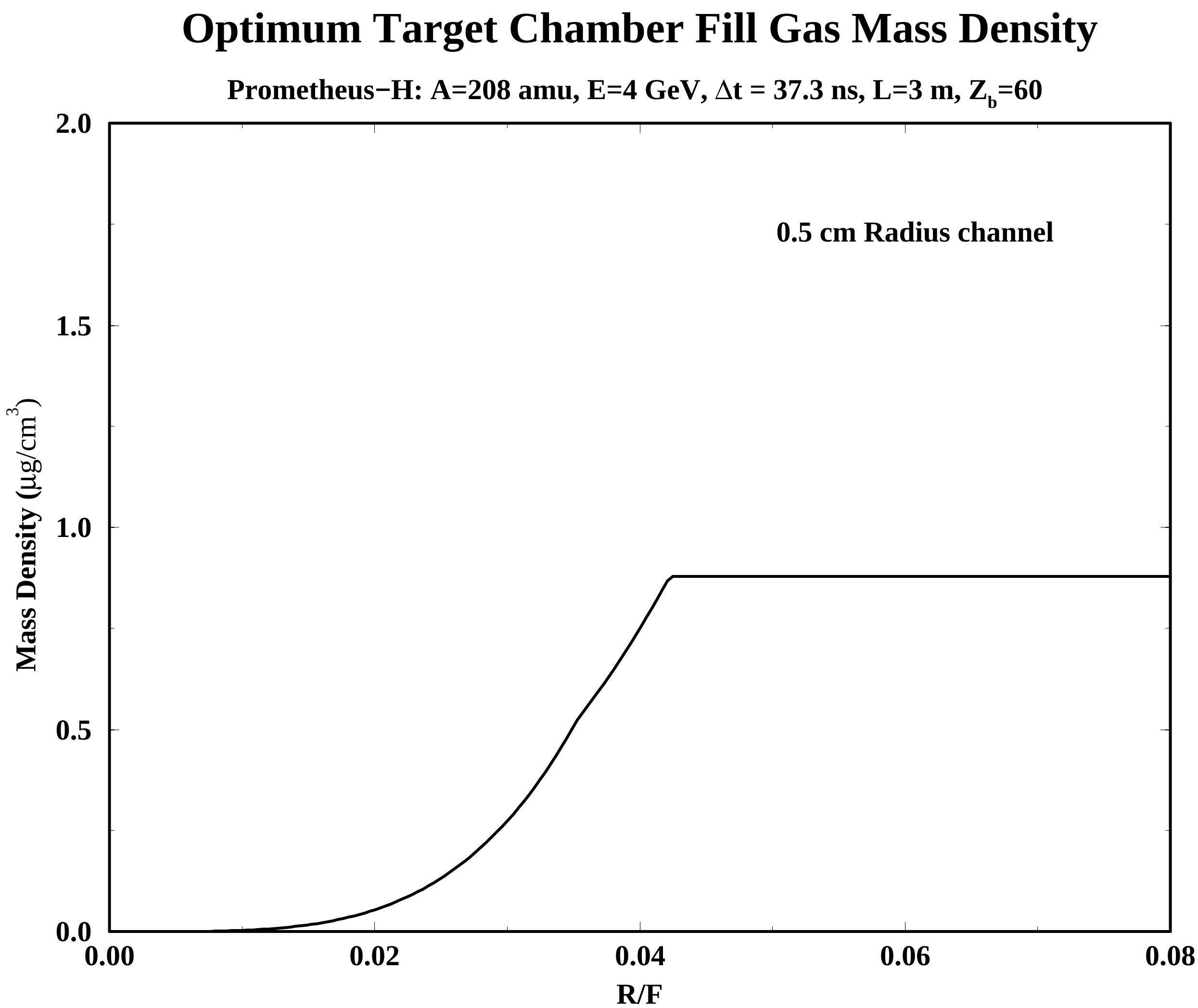

Figure 10. Optimum fill gas density versus injection angle (R/F). Channel radius = 0.5 cm. Deuterium fill gas. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 60.

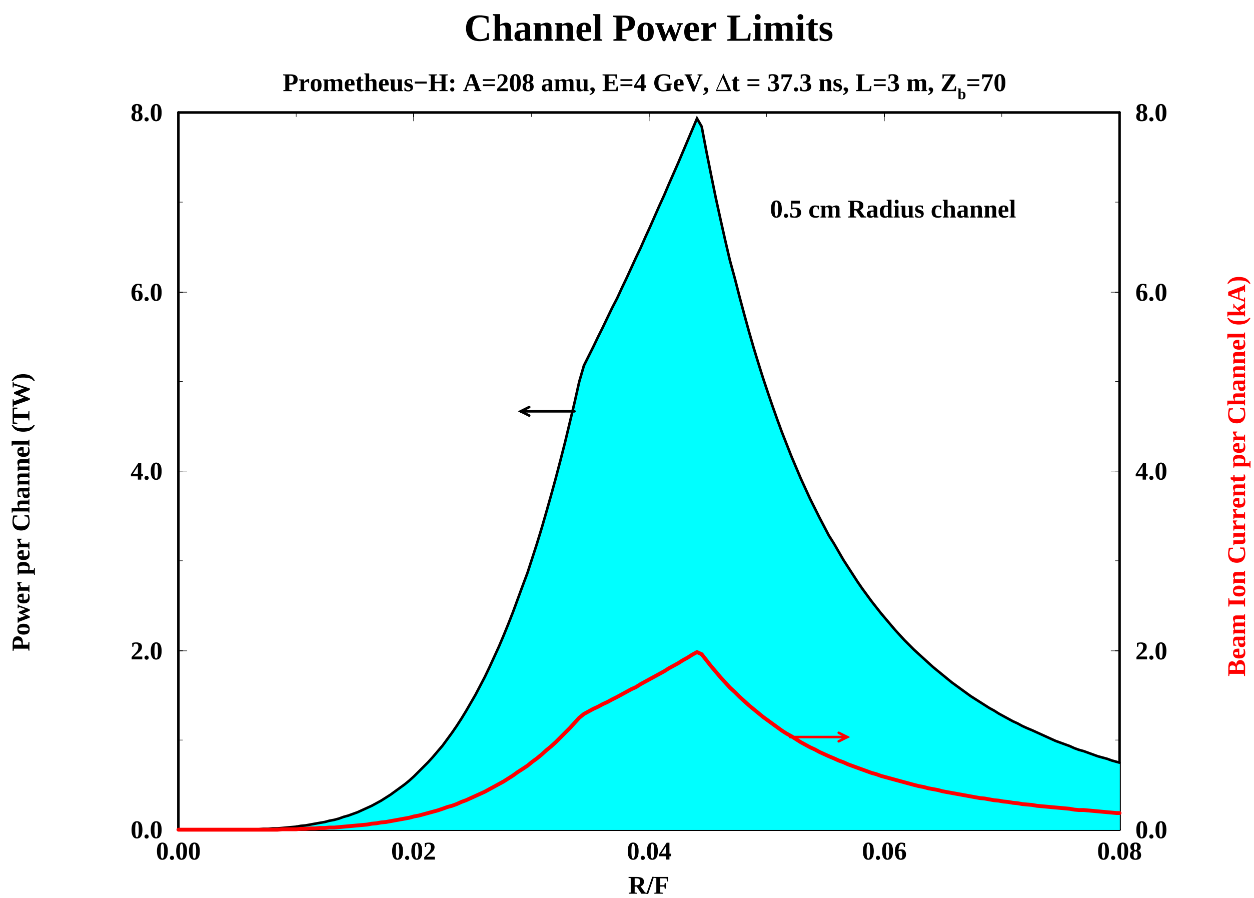

Figure 11. Transportable ion power per channel and ion current versus injection angle (R/F). Channel radius = 0.5 cm. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 70.

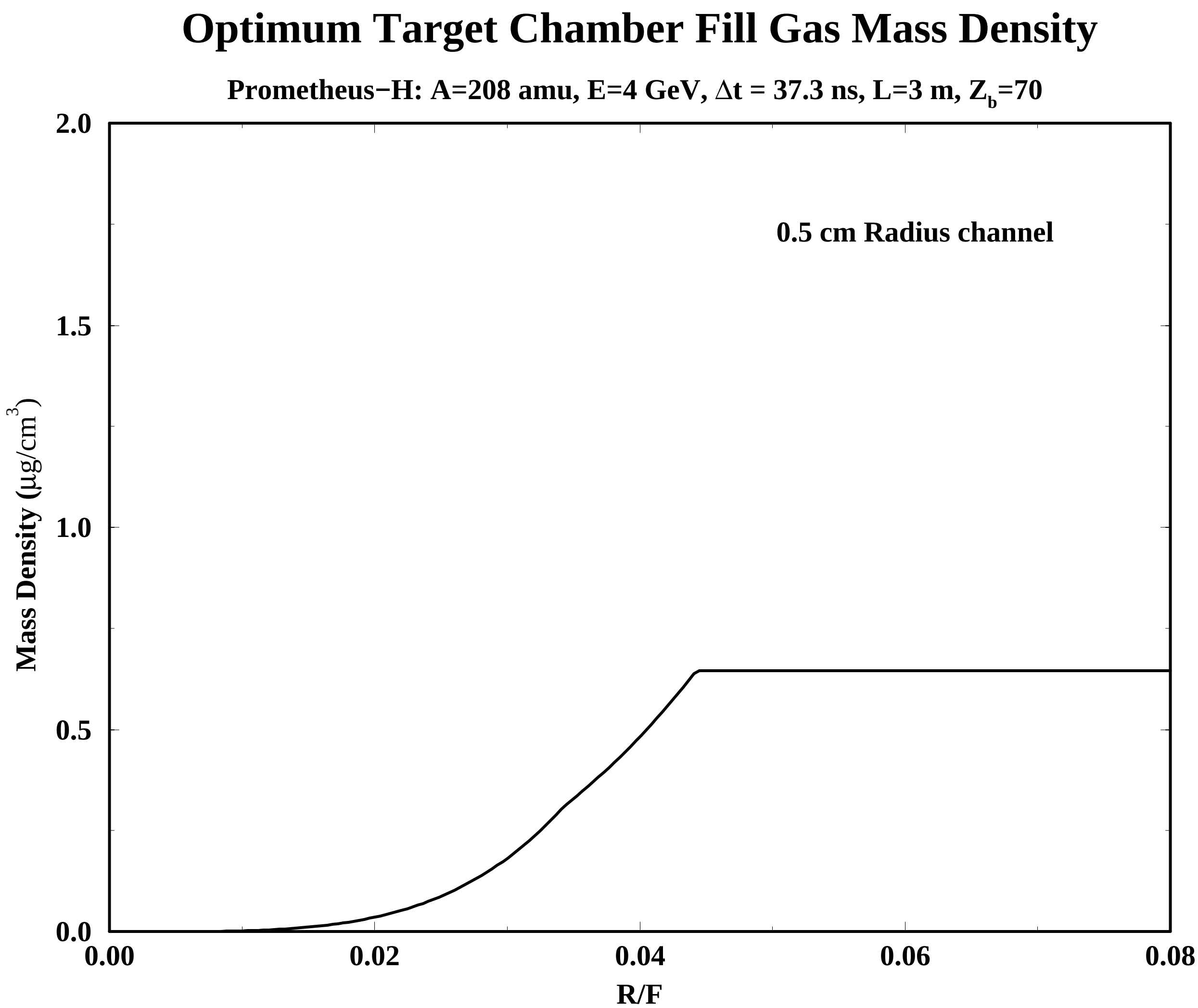

Figure 12. Optimum fill gas density versus injection angle (R/F). Channel radius = 0.5 cm. Deuterium fill gas. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, channel length = 3 m, and ion charge state in the channel = 70.

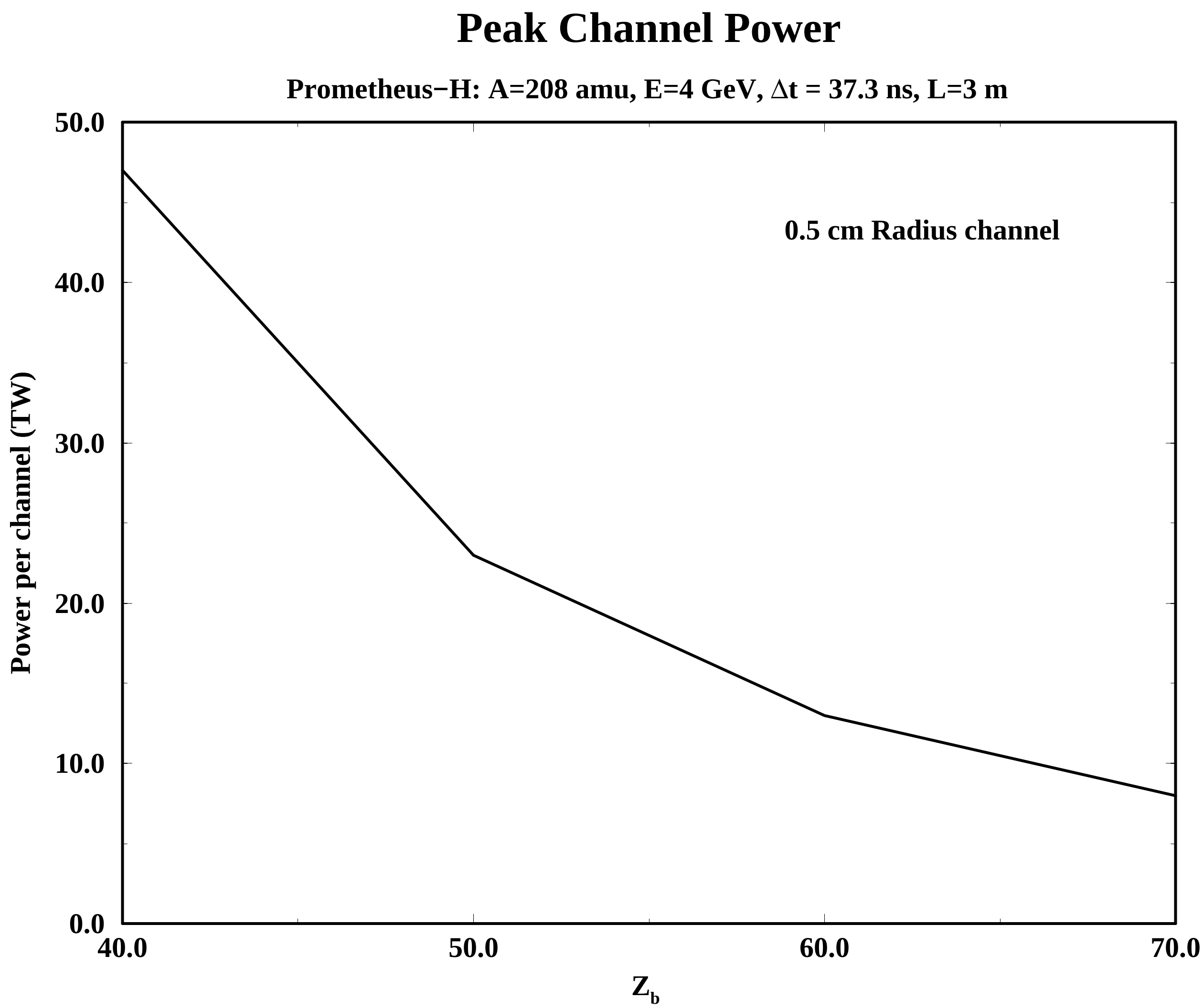

Figure 13. Transportable ion power per channel and ion current versus charge state. Channel radius = 0.5 cm. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, and channel length = 3 m.

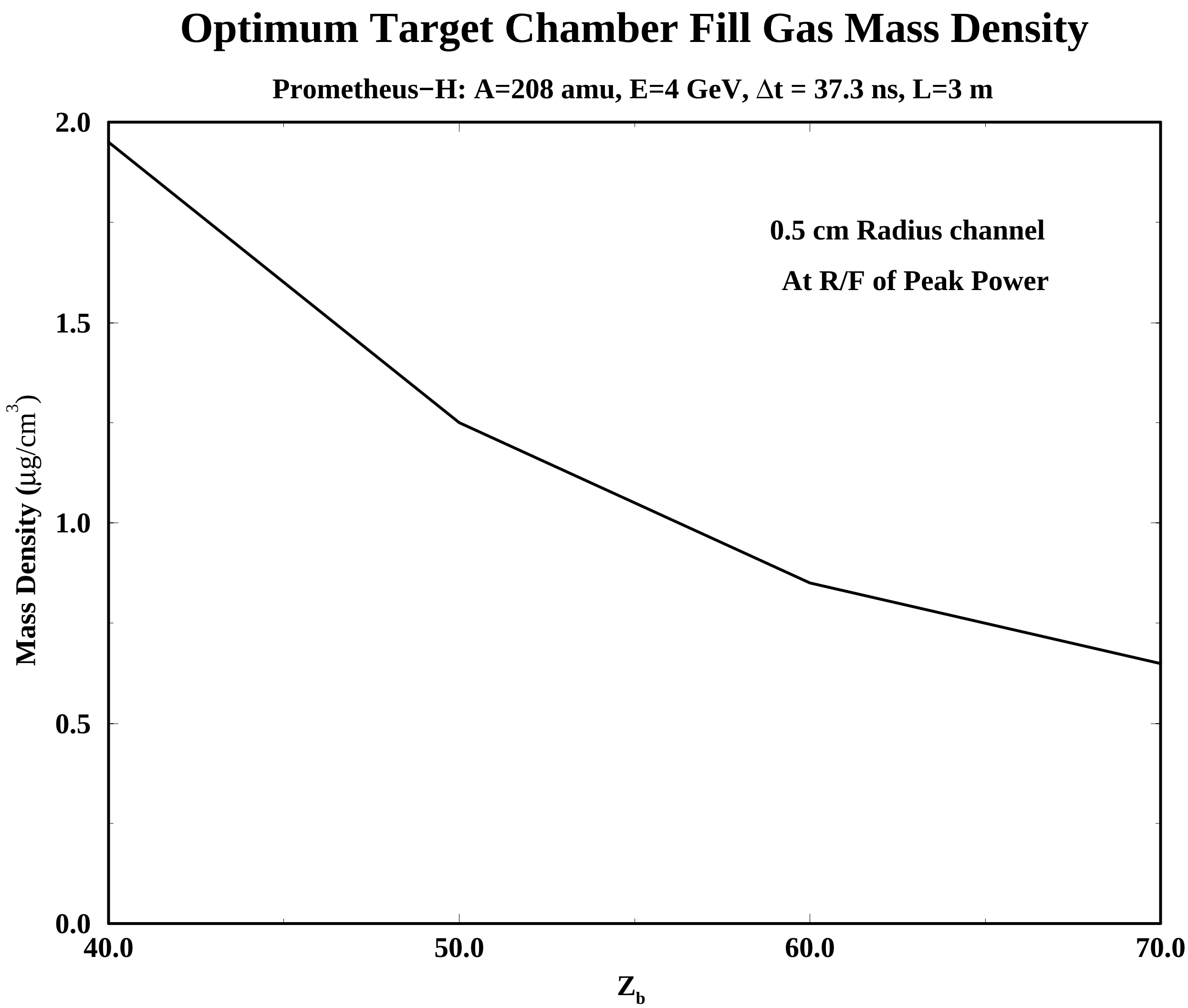

Figure 14. Optimum fill gas density versus injection angle (R/F). Channel radius = 0.5 cm. Deuterium fill gas. At R/F of peak transportable power. Prometheus-H parameters, ion atomic number = 208 amu, ion energy = 4 GeV, ion pulse width = 37.3 ns, and channel length = 3 m.

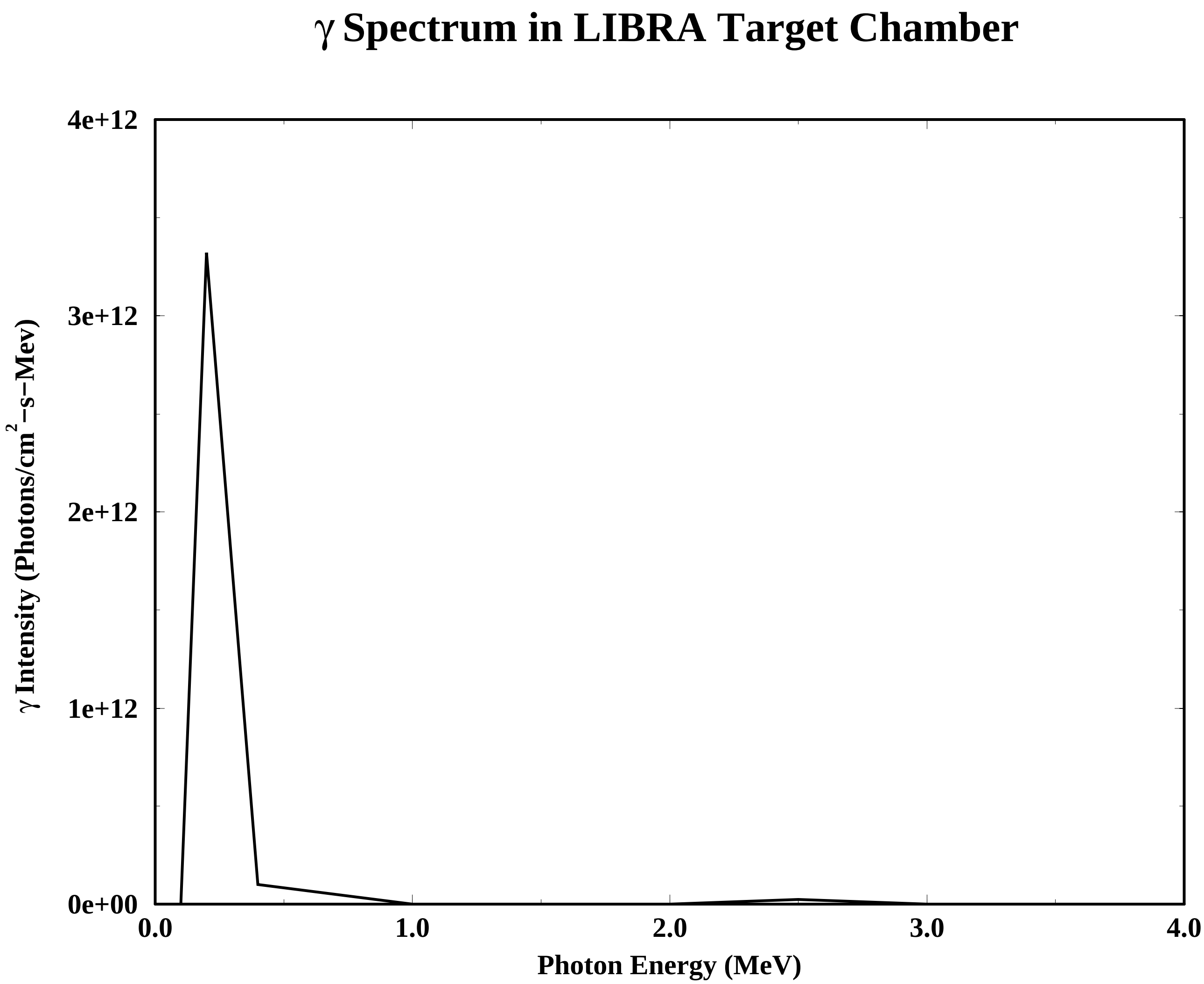

Figure 15. γ-ray spectrum in the center of the LIBRA target chamber.

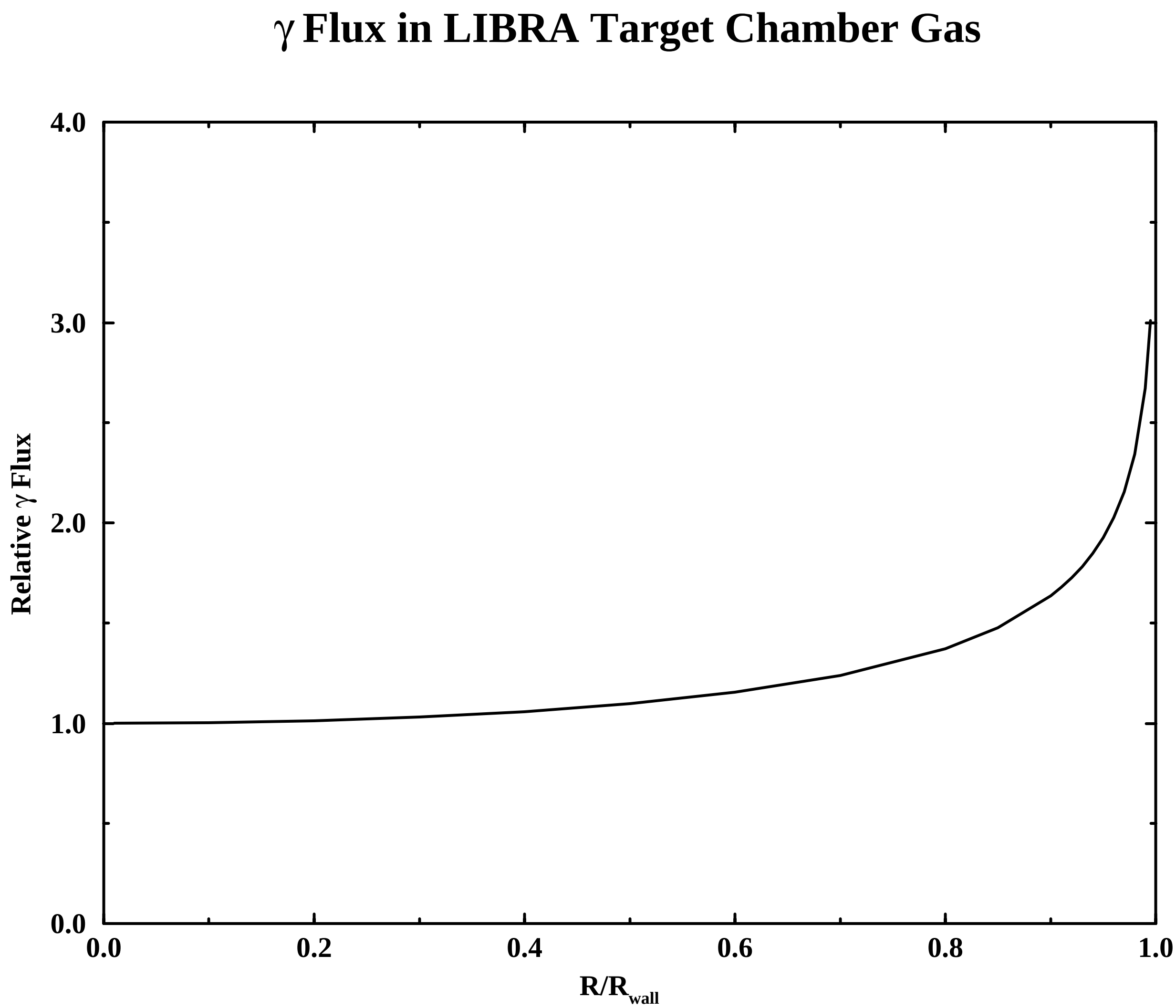

Figure 16. Normalized γ-ray flux versus normalized position in the target chamber fill gas.

Using the γ-ray field described above, we can calculate the rate at which gas atoms are ionized. We have used a γ-ray flux 3 times what is shown in Figure 15, which is what we expect to see at the chamber wall and which is where the ionization would be the worst. The semiclassical expression for the photoionization cross section of an atom [9] is,

$$\sigma_{\nu n} = \frac{64\pi^4 e^{10} m Z^4}{3\sqrt{3} h^6 c \nu^3 n^5} \ . \tag{10}$$

Here ν is the photon frequency, n is the principal quantum number of the electron being removed, and Z is the charge state the ion will have after photoionization. For deuterium, Z is 1. Since the cross section is proportional to ν^{-3}, the photons which will do most of the ionization in Figure 15 are at 200 keV. From this expression, and assuming that the fill gas is deuterium in the ground state (n = 1), $\sigma_{200\ \mathrm{keV},1} = 1 \times 10^{-31}\ \mathrm{cm}^2$. Using the γ intensity near the wall, which is the worst case, of 9×10^{12} photons/cm^2-s-MeV over a band 0.2 MeV wide, we can estimate that each atom is ionized at a rate of 1.8×10^{-19} ionizations/s. If we have 1 μg/cm^3 of deuterium, or a number density of 3×10^{17} atoms/cm^3, electrons are being produced at a rate of 0.06 electrons/cm^3-s. If there is a shot in the target chamber 4 times a second, the number of electrons produced between shots is 0.015 electrons/cm^3. This estimate does not include recombination, which will reduce the number of free electrons. The laser pre-ionization will create a much higher number of free electrons. Residual heat in the target chamber gas after the target explosion, probably contributes more to the ionization state of the gas than does the activation. Therefore, ionization of the gas by the radioactivity of the target chamber doesn't seem to be an important issue.

5. Conclusions

From these considerations, we believe that channel transport is a viable technique for directing heavy ion beams to ICF targets in reactor concepts. In this report, we have examined three general issues. In some cases, these considerations lead to constraints on the ion beam parameters.

- **Minimum Channel Radius.** Radiation transport limits the size of the channels to 0.5 cm or greater in radius, when the channels are in nitrogen. This means that the focal spots should be 0.35 cm in radius to avoid emittance growth in the channel. This seems achievable with Prometheus-H or OSIRIS parameters. The beam spot on the targets will be greater than or equal to 0.5 cm, which will exclude some target designs.

- **Transportable Ion Power (effects of beam on channel).** Transportable ion beam power is determined by plasma instabilities, channel expansion, and energy loss. It is a strong function of the maximum angle between the ion beams and the axis of the channel. For Prometheus-H parameters, the optimum angle is 0.04 radians. The Prometheus-H design needs to have a focal length F of 375 cm for channels to be viable. The power per channel is also very sensitive to the charge state of the ion in the channel. If the charge state of 3.83 GeV Pb in the channel in less than or equal to 60, the channels can carry the 11.6 TW called for in the Prometheus-H design. If the charge state is higher, more channels will be needed.

- **Ionization of Target Chamber Gas by Radioactivity.** The rate at which a chamber fill gas will be ionized by radioactivity from the target chamber structures has been found to be very low and probably not an issue. The LIBRA target chamber was used for this because we have the γ-ray information available and for deuterium gas at 1 μg/cm^3.

6. Future Work

This small study has used already existing channel formation calculations, the existing WINDOW code, and activation calculations from the LIBRA study. Within those limitations, it has shown plasma channels to be viable for heavy ion fusion. Now, better calculations can be done with more developed tools. Also, some issues were not studied in this project. We believe that the next step would be to perform better calculations, making improvements to old codes, verifying new codes, and addressing issues not considered in this project.

- **Channel Formation Simulations.** We have developed a 1-D radiation hydrodynamics code, BUCKY[10], whose radiation transport and hydrodynamics have been verified with comparison with several types of experiments. Recently MHD with magnetic field diffusion and current flow have been added to BUCKY. We believe that this code can give better predictions of channel formation than ZPINCH. We suggest that 1) channel formation calculations be performed with BUCKY for heavy ion fusion power plant conditions, and 2) the BUCKY code be verified by comparing with channel experiments in progress at LBNL.

- **Beam Power Limit Calculations.** As shown in this report, WINDOW code calculations are very useful in designing channels for ion transport. The current version of the code is only valid for deuterium gas. There are certainly good reasons for considering other gases, such as first wall protection. We think that extending the WINDOW code to general gases would be useful. Then WINDOW and BUCKY calculations could be performed in a more consistent way.

- **Other Issues.** Other issues of channel transport have not been addressed in this report. The following is a list of items than should be addressed.

    1. **MHD Stability**. MHD stability of channels remains a puzzle. It has been seen to disrupt some experimental channels and not others. An understanding of this is critical to channels for IFE. Two or 3-D MHD simulations are need to study this issue.

    2. **Gas Conditions Prior to Channel Formation**. We have found that radioactivity in the LIBRA chamber does not cause much pre-ionization of the background gas. There are other issues in the gas conditions that need to be considered, such as residual heat. The radiation hydrodynamic codes at the University of Wisconsin can address the residual heat problem.

    3. **First Wall Protection and Channels**. The gas required for channels will also provide some protection for the target chamber first wall from x rays and debris. The choice of gas and the density will determine how much protection will occur. The channels themselves may provide a pathway of a target explosion generated fireball to vent to the first wall. The University of Wisconsin now has all the tools to address these issues and integrate a chamber design with channels.

Acknowledgment

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