1 Target Cells

1.1 Cell Construction

The construction of the target cells is a lengthy process involving many details which critically affect the maximum achievable polarization of ^{3}He.The whole process can be divided into three basic steps: glassblowing of the target cell and the glass string to which it is attached, vacuum system bake out, and gas filling.

1.1.1 Glassblowing

The glass surface is very critical to the relaxation properties of tha polarized ^{3}He ,since it is the interaction of the helium nuclear spins with the paramagnetic surface atoms that forms one of the possible nuclear relaxation channels. There has been evidence that surface microfissures enhance this interaction by trapping the helium nuclei at the surface for a longer time.Therefore, the glass tubing that has been used for the construction of the cell body has been resized, in order to smoothen the glass surface.

1.1.2 Vacuum System

The string is mounted on the vacuum system ,the layout of which is shown in Figure 1. It consists of the gas handling system,the pumping system, and the glass string. The pumping system is driven by a diffusion pump (with a liquid nitrogen pump on the inlet) ,which is backed by a mechanical pump. Several hot ion gauges placed throuhout the vacuum system measure pressure, whereas a mass sprectrometer provides a continuous monitoring of the bake out. The cell is baked out at a temperature of about 460 ^oC for a period of four days, in order for volatile impurites on the glass walls to be removed. During that period, Rb from the ampule is chased with a glassblowing torch into the little recess on the left of the retort. Rb is chased into and out of the recess a few times ,in order to evaporate the oxidized surface formed by the initial contact of the ampule with the atmosphere. The retort is finally pulled off.

1.1.3 Cell Filling

By the end of the bake out , the pressure in the vacuum system, is a few times 10^{-9} torr, and one can proceed with the filling. Before that, the Rb has to been chased from the recess into the cell. The next step is the nitrogen filling. Nitrogen is flown through its purifier (grenn path) until the pressure in the string is about 40 torr. The target chamber of the cell is then cooled down to about 10 ^oK by flowing liquid helium through a dewar that encloses the target chamber. The nitrogen accumulates in the cold cylindrical target chamber, and the string pressure of about 40 torr is chosen so that the final room temperature N_2 pressure will be the desired 60-70 torr. The most important though effect of the cooling is the fact that the pessure in the string is always kept below 1 atmosphere. Thus the glass can collapse under the atmosphere when the time comes to seal off the cell. The last step is filling with ^{3}He. This is a repetitive process, during which a 'fill' volume is charged up to a known pressure for a number of times. The fill volume consists of the calibrated volume and the manifold volume. The volume of the latter is measured using the known volume of the former. By opening the manifold valve, this volume can be charged up to a certain pressure (measured by baratron 1) , by flowing helium from the ^{3}He tank through the helium purifier (blue

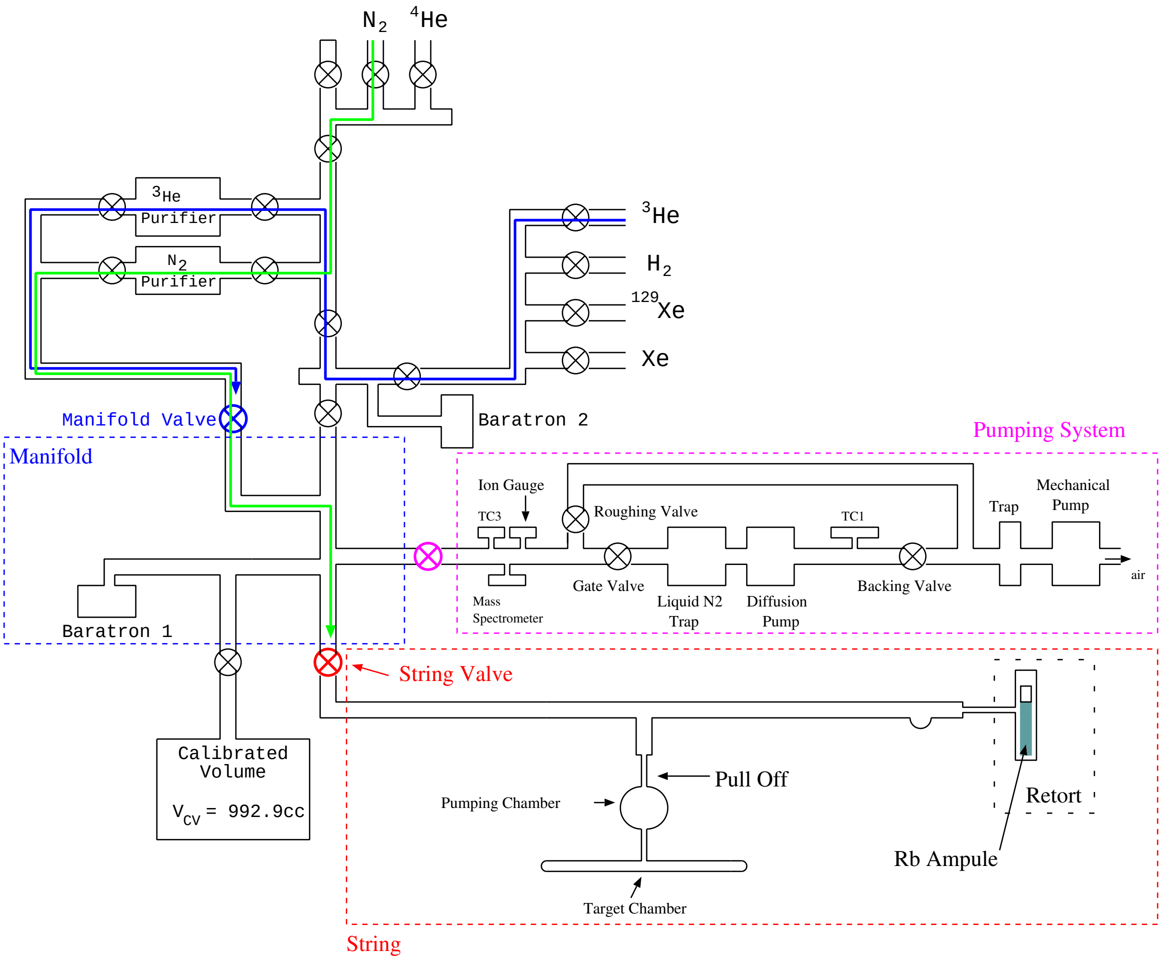

Figure 1: Vacuum system and String

path). By opening the string valve, helium from the fill volume flows into the cold target chamber. This is repeated until the desired ^{3}He density in the cell is achieved (9-10 amagats). The cell is then sealed off with a torch at the 'pull off' constriction.

1.2 Cell Volumes

The total volume of the cell is needed in order to extract the ^{3}He density from the vacuum system gas filling data. Moreover, the volumes of the individual parts of the cell, namely the pumping chamber, the transfer tube and the target chamber, are necessary for density calculations when a temperature gradient is present. There are three ways to measure the cell volume: at the vacuum system ,the buoyancy method, and the geometrical measurement. The last is the only method to measure the volumes of the three parts of the cell individually. The glass thickness has aslo to be known for that method to give the inside cell volume. When the cell is attached on the vacuum system, one can measure the volume of the string in the following way: The calibrated volume is filled at a known pressure, wheras the manifold and the string are pumped out.Then the gas in the calibrated volume is let into the manifold and into the string. From the pressure drop ,the string volume can be measured. The same procedure is repeated after the cell is pulled off, so the difference of the to volumes is the inside cell volume, appart from a very small correction (¡ 1cc) due to the pull-off volume. The buoyancy method rests on Archimede's principle. It measures the outside volume of the cell, so the glass volume has to be substracted. If the mass of the cell is m_{cell} and the density of the glass ρ_{glass} ,then the glass volume is :

$$V_{glass} = \frac{m_{cell} - m_{^3He}}{\rho_{glass}} \tag{1}$$

where $m_{^3He}$ is the mass of the gas ($\approx$ 0.3 g) A metal block suspended from an accurate scale is submerged in water. If the weight with just the block is W_{block} and the weight with the block and the cell attached to it is $W_{block+cell}$, then the inside cell volume will be :

$$V_{cell} = \frac{W_{block} - W_{block+cell} + m_{cell}}{\rho_{water}} - \frac{m_{cell} - m_{^3He}}{\rho_{glass}} \tag{2}$$

The overall accuracy of the method is estimated to be 0.5%. An independent check was performed ,using a sphere made out of pyrex glass (ρ_{pyrex}=2.23g/cc). By measuring the mass of the sphere when empty and when filled with water ,its volume is found to be 303.1 cc. The following table gives the results of the two measurements.

True Volume	Vacuum System	Buoyancy
303.1±0.1 cc	298±1.2 cc	303±1.5 cc

Figure 2 shows the geometry of a typical target cell. The geometrical measurement provides the outside volume of the cell, so the glass volume has to be substracted. This can be done either by assuming a value for the glass thicknes of the various parts, and correcting the outside dimensions,or by substracting the glass volume given by (1). This seems more reliable, and that's what has been done here. To get the inside volumes of the three individual parts of the cell, we scale the outside volumes by the ratio of total inside and outside volumes. The following table summarizes all the above.

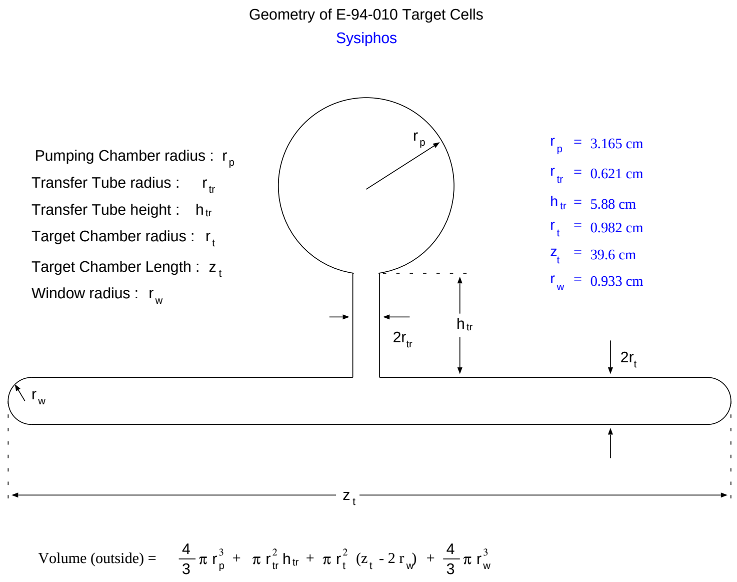

Figure 2: Cell geometry

Cell	Pumping Chamber Volume (OD)	Transfer Tube Volume (OD)	Target Chamber Volume (OD)	Total Volume (OD)	Glass Volume	Geometr. Volume	Vacuum System	Buoyancy
DontWorry	194.4	8.59	103.0	244.39	48.48	195.91	-	197.1
Armageddon	118.85	6.45	107.27	232.57	50.18	182.39	189.71	188.5
BeHappy	139.85	6.03	104.73	250.61	47.05	203.56	200.0	217.2
Nepheli	123.46	7.93	109.35	240.74	42.75	198.0	-	201.5
Sysiphos	132.8	7.12	117.72	257.64	46.31	211.3	204.3	212.4
Jin	123.58	10.37	110.2	244.15	43.6	200.55	187.73	199.5

1.3 Cell Densities

1.3.1 Vacuum system density

Let $P_j^{initial}$ be the pressure in the fill volume after charging it up for the j-th time, and $P_j^{initial}$ the equilibrium pressure after opening the string valve for the j-th time. Let P_{final} be the pressure in the fill and string volume when the string valve is opened after the cell has been pulled off. If N is the number of fill-volume charges, then the number density of ^{3}He in the cell will be:

$$n_{^3He} = \frac{1}{k_B T_{fill} V_{cell}} \left(\sum_{j=1}^{N-1} (P_j^{initial} - P_j^{final}) + P_N^{initial} \right) V_{fill} - P_{final}(V_{fill} + V_{string-cell}) \qquad (1)$$

where T_{fill} and V_{fill} are the temperature and volume of the 'fill volume', respectively, and $V_{string-cell}$ is the vloume of the string after the cell has been pulled off.

1.3.2 Pressure Broadening Measurement

The most precise method to determine the ^{3}He density relies on the broadening of the absorbtion lines (D1 and D2) of Rb due to the presence of ^{3}He, which acts as a high pressure perturber of these lines. One can consider the collision :

$$Rb(i) + \hbar\omega + {}^3He \rightarrow Rb(f) + {}^3He \tag{1}$$

to result in a radiating oscillator (Rb) with a varying phase. In the impact approximation ([1]) , i.e. when the collision can be assumed to be instantaneous, the Fourier spectrum of the oscillating amplitude is just a lorentzian:

$$L(\omega) = \frac{\gamma}{2\pi} \frac{1}{(\omega - \omega_0 - \Delta)^2 + (\gamma/2)^2} \tag{2}$$

where both the width ,γ ,and the line shift,Δ , are proportional to the ^{3}He density. The proportionality constants, as well as their temperature dependence have been measured by [2]. In our case, we use the widths of the D1 and D2 lines to extract the ^{3}He density. For convenience, we reproduce the relevant constants in the following table.

	^{3}He	N_2
D1 full width GHz/amg	18.7±0.2	17.8±0.3
D2 full width GHz/amg	20.8±0.2	18.1±0.3

To the measured width of the absorbtion lines, there are three contributions : the main one come from the broadening due to collisions with ^{3}He. However, there is a roughly 1% contribution due to N_2, the density of which is only about 0.1 amg. Finally, when there is no perturbing gas, the width γ of (2) reduces to the Doppler width at the particular temperature at which the measurement is done. The full Doppler width is ([3]) :

$$\delta f_{Doppler} = 29.23\sqrt{T} MHz \tag{3}$$

At T=100 oC , $\delta f_{Doppler}$=565 MHz, which amounts to only 0.3% of the total, pressure broadened, width.

The following figure shows the setup used for the measurement.

Cell	D1	D2	Average	Fill	Total Average
DontWorry	10.03±0.17	9.94±0.15	9.99±0.22	9.71±0.03	9.90±0.23
Armageddon	10.09±0.17	10.25±0.15	10.17±0.22	10.09±0.03	10.14±0.23
BeHappy	9.28±0.15	9.39±0.14	9.34±0.20	9.23±0.02	9.30±0.21
Nepheli	11.47±0.19	11.32±0.17	11.40±0.25	10.95±0.02	11.25±0.25
Sysiphos	8.31±0.14	8.14±0.12	8.23±0.18	8.00±0.02	8.15±0.19
Jin	8.46±0.14	8.42±0.13	8.44±0.19	8.25±0.02	8.39±0.19

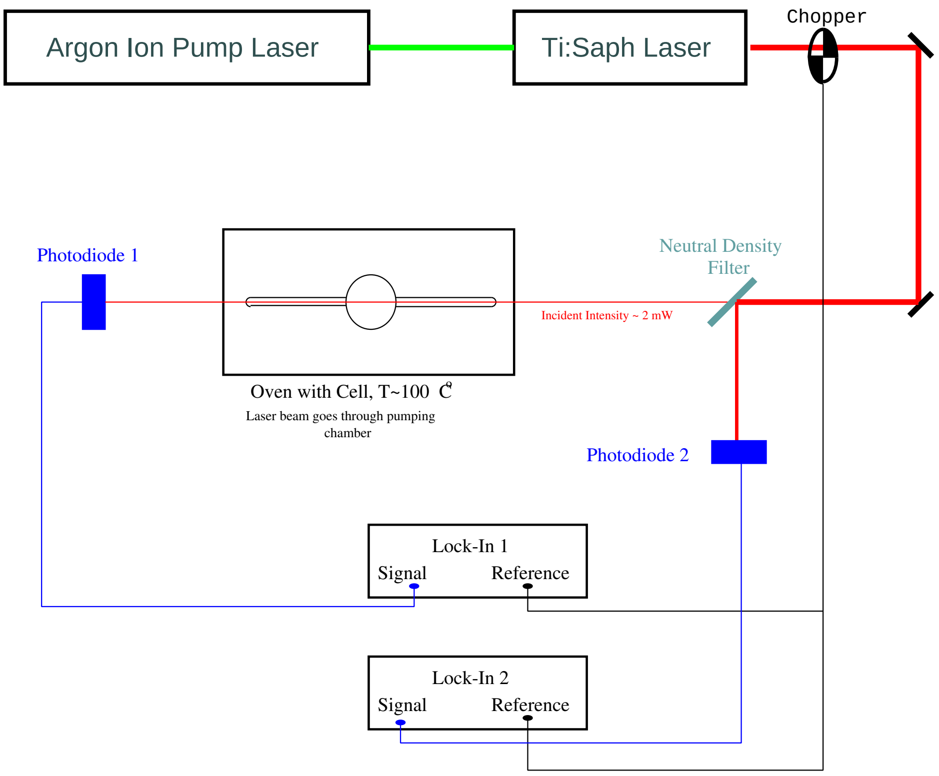

Figure 3: Setup for pressure broadening measurement.

1.4 Target Chamber Window Thicknesses

1.4.1 Interferometric Measurement

The most accurate method to determine the thickness of a target cell window, is the interferometric measurement, a schematic setup of which is depicted in Figure 1. The beam from a scannable

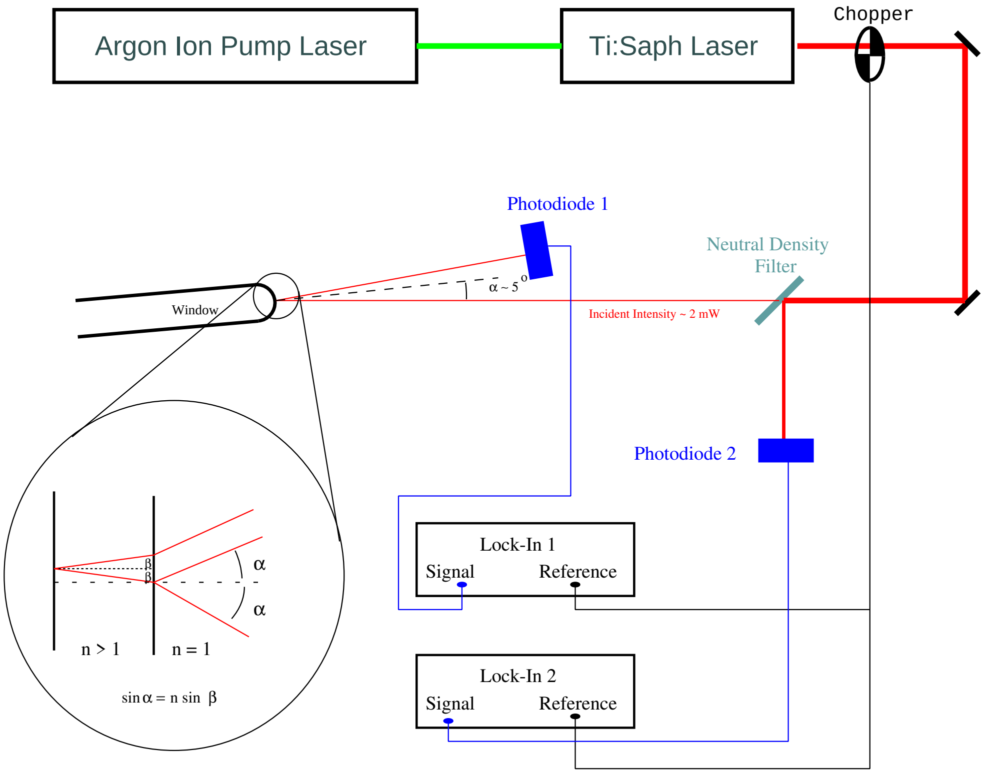

Figure 4: Setup for optical measurement of window thickness

Ti:Saph laser is reflected on the surface of the window to be measured. If the angle of incidence is α, the index of refraction of the glass n and the angle of refraction β then the reflectance ,R, is given by ([1]):

$$R = \frac{F sin^2(\phi/2)}{1 + F sin^2(\phi/2)} \tag{1}$$

where F is the finesse, and

$$\phi = \frac{4\pi f}{c} nd\sqrt{1 - sin^2\beta} + \Delta\phi \tag{2}$$

For an angle of incidence of about 5^o,

$$\sqrt{1 - sin^2\beta} \approx 1 \tag{3}$$

so that

$$\phi/2 = \frac{2\pi f}{c} nd + \Delta\phi \tag{4}$$

By scanning the frequency (we usually scan over 3000 GHz) and fitting the resulting R vs f pattern to the above form, one can very accurately determine the window thickness d. Figure 2 shows an example of the measured reflectance and the corresponding fit. The abscissa is a normalized frequency, namely $\frac{f-f_0}{f_1-f_0}$, where $[f_0, f_1]$ is the scan interval.

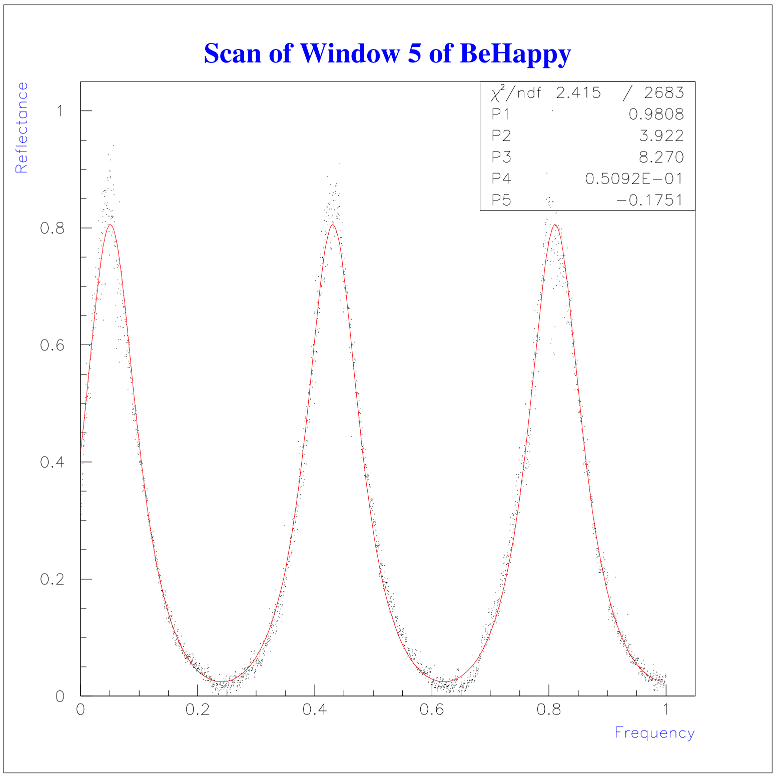

Figure 5: Reflectance versus frequency

1.4.2 Mechanical Measurement

Before connecting the windows to the target chamber, we measured them with a micrometer of 1.3 μm resolution. The following table contains the measurements with both methods, while figure 3 show the ratio of the two numbers for all windows. For most of the windows, the two numbers agree within 5%.

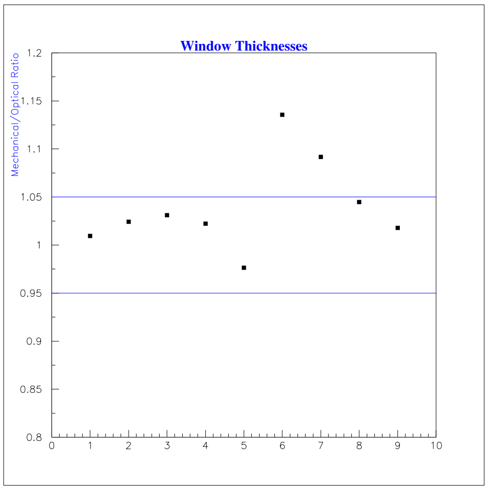

Figure 6: Reflectance versus frequency

Target Cell	Window	Thickness [μm]	
		Mechanical	Optical
DontWorry	2	137.2±1.3	135.9±0.6
	21	143.5±1.3	140.1±0.5
Armageddon	VII	125.7±1.3	121.9±0.6
	XVIII	142.2±1.3	139.1±0.7
BeHappy	4	129.5±1.3	-
	5	132.1±1.3	135.3±1.6
Nepheli			-
			-
Sysiphos	9	152.4±1.3	134.2±1.0
	18	132.1±1.3	121.0±1.0
Jin	14	142.2±1.3	136.1±1.2
	15	137.2±1.3	134.8±0.8

1.5 Target Chamber Wall Thicknesses

The target chamber cylinder is produced by resizing a glass tube of known inner and outer radii. By assuming that the volume of the wall of the cylinder stays the same , one can estimate its thickness, since its outer radius is also known. The following table shows the inner and outer radii of the two types of glass tubing used to construct the target cells.

Glass	r_i [cm]	r_o [cm]
1720	0.630	0.741
GE 180	0.621	0.788

If $r_i^/$ and $r_o^/$ are the inner and outer radii of the target cylinder ,respectively, then the wall thickness will be :

$$w = r_o^/ - \sqrt{r_o^/ - (r_o^2 - r_i^2)} \tag{1}$$

Thus we obtain the following wall thicknesses :

Cell	Target Chamber Wall Thickness [mm]
DontWorry	0.86
Armageddon	1.35
BeHappy	0.87
Nepheli	0.84
Sysiphos	0.80
Jin	0.84

1.6 References

[1] : J.Szudy, W.E.Baylis, Profiles of line wings and rainbow satellites associated with optical and radiative collisions, Physics reports 266 (1996).
[2] : M.V.Romalis, E.Miron, G.D.Cates, Phys.Rev. A ....
[3] : W.Demtröder, Laser Spectroscopy, Springer Verlag 1995.