A REACTOR-BASED INTENSE POSITRON SOURCE (IPS)

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AMARILLO COLLEGE
TRTR WORKSHOP
30-SEPT-2024

MOTIVATION

1. POSITRONS NEEDED

2. EXOTIC MATTER RESEARCH

3. PROPULSION

4. MATERIALS SCIENCE (PALS)

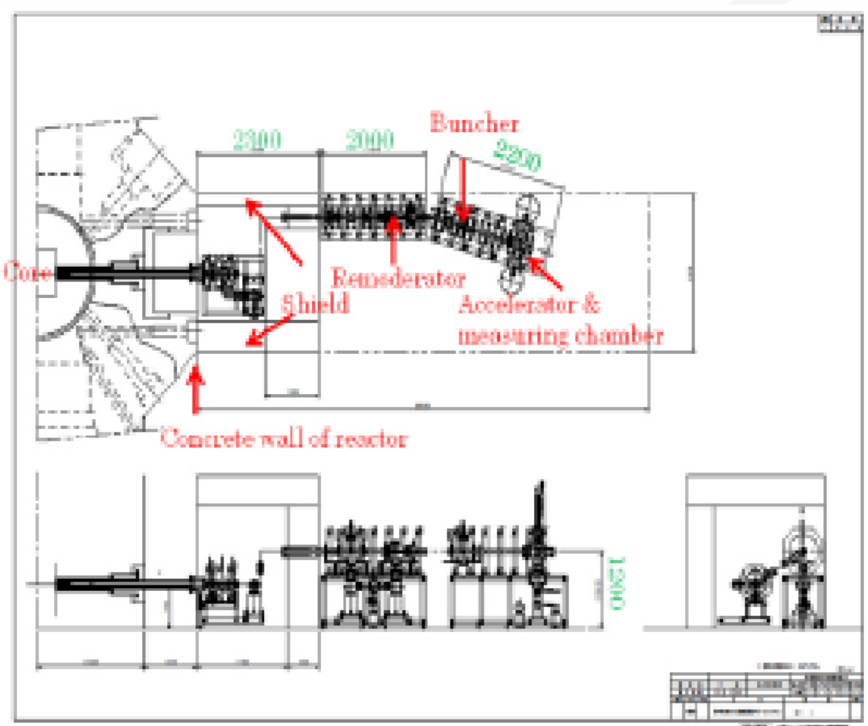
5. BIOMEDICAL
   A. THERANOSTIC APPLICATIONS
   B. MICRO-ORGANISMS

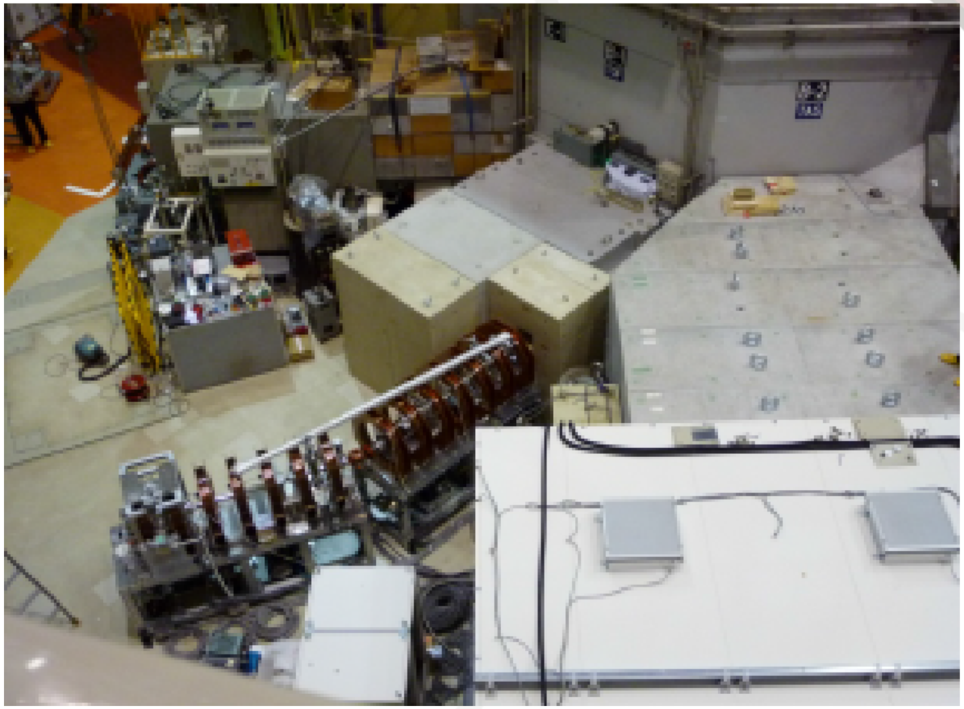
6. DECREASING β+ RESEARCH

1. IN-PILE POSITRON SOURCE: EM

The positron beam is magnetically guided to the confinement system in a solenoid field of 5-7mT, as well as compensation fields.

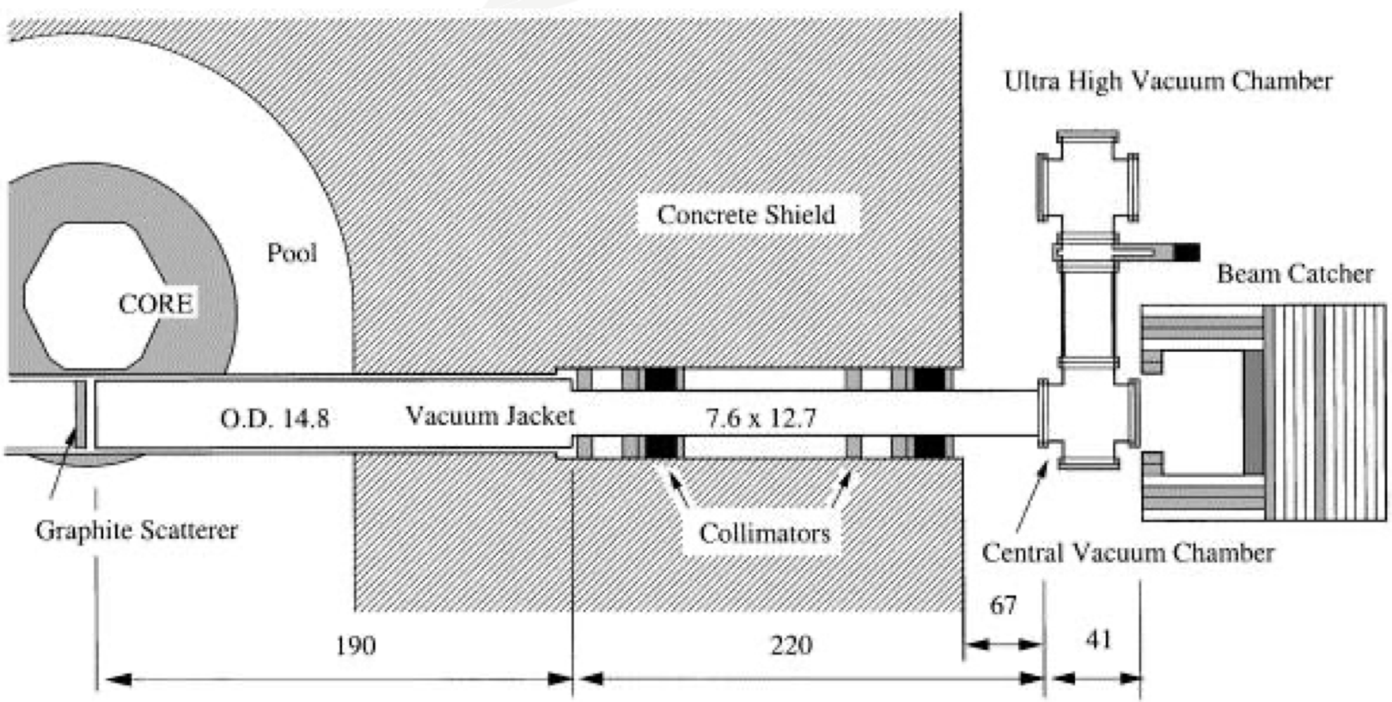
Kyoto Model after Xu, *et al*. 2013



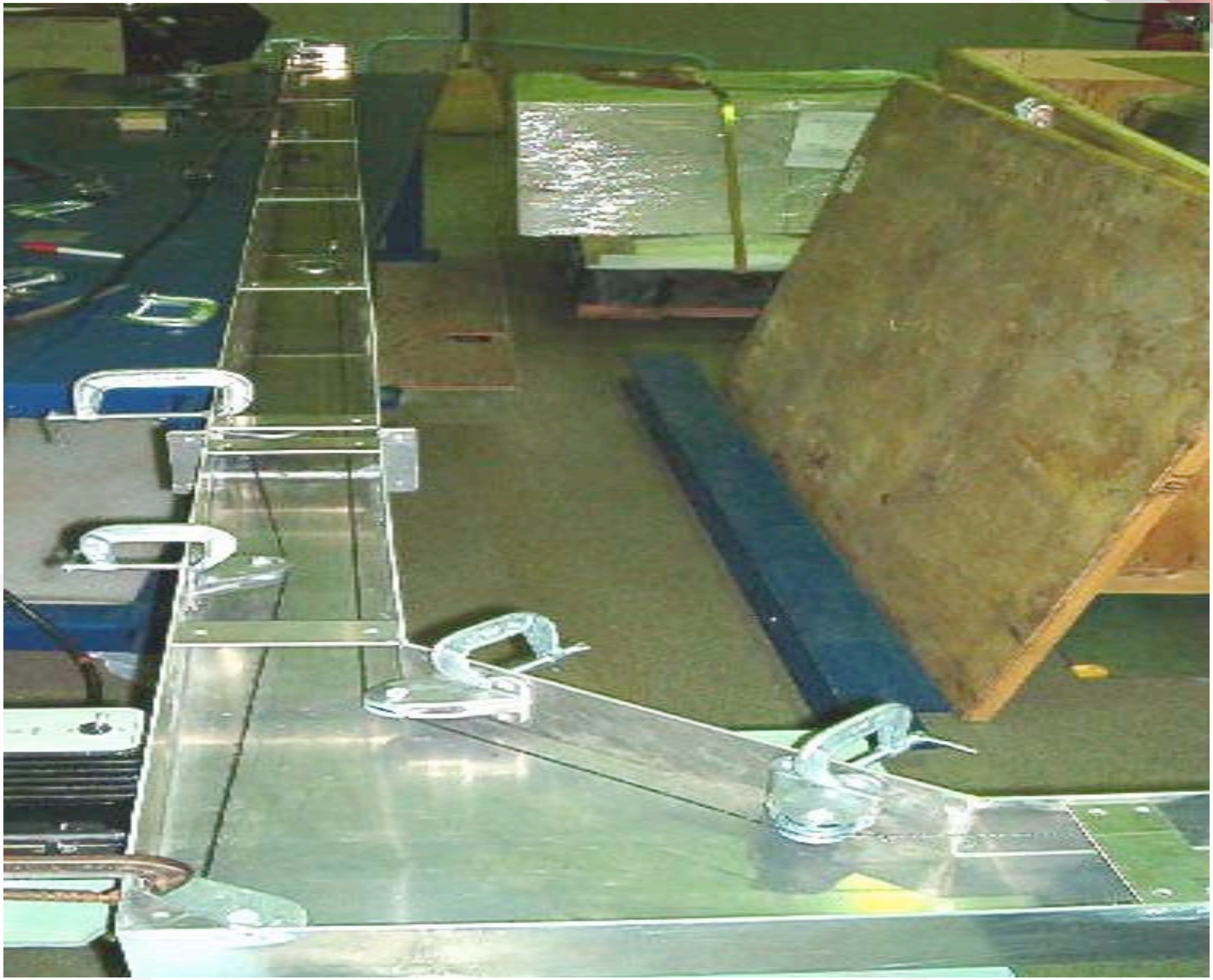


2. IN-PILE POSITRON SOURCE: TIPS

Note that the beam traverses collimators and a vacuum jacket. Moreover, gamma radiation is further attenuated by absorption into an Al beam catcher where it is captured by a Cu transport system. (Image from Köymen et al., 1999.)

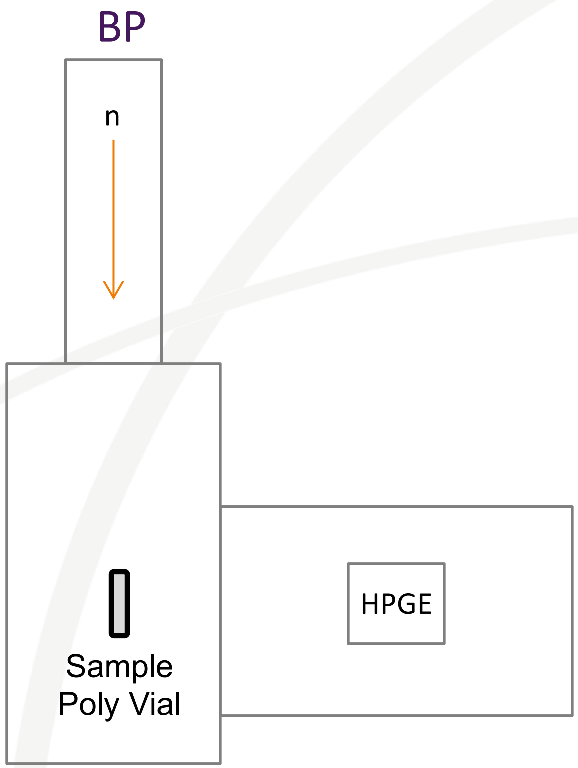


2. IN-PILE POSITRON SOURCE: TIPS MECHANICAL TRANSPORT



Doron, 2004

INITIAL BENCHMARK EXPERIMENTAL SETUP



1. Experimental verification run using rx PGAA system

2. Flux assumed to be 1E7 n/cm^2/sec (see Table 1)

3. HPGe detector used to measure 511keV annihilation peak

TABLE I

Power (watts)	Total flux ($_0n^1/cm^2/sec$)	Thermal flux ($_0n^1/cm^2/sec$)
0.1	7.13×10^6	$(5.81 \pm .12) \times 10^6$
0.1	7.29×10^6	$(5.95 \pm .12) \times 10^6$
1	6.73×10^7	$(5.48 \pm .11) \times 10^7$
1	7.02×10^7	$(5.72 \pm .11) \times 10^7$
10	6.44×10^8	$(5.25 \pm .10) \times 10^8$
10	6.41×10^8	$(5.22 \pm .10) \times 10^8$
100	6.45×10^9	$(5.26 \pm .10) \times 10^9$
100	6.50×10^9	$(5.30 \pm .11) \times 10^9$
750	4.61×10^{10}	$(3.75 \pm .08) \times 10^{10}$
750	4.70×10^{10}	$(3.83 \pm .08) \times 10^{10}$

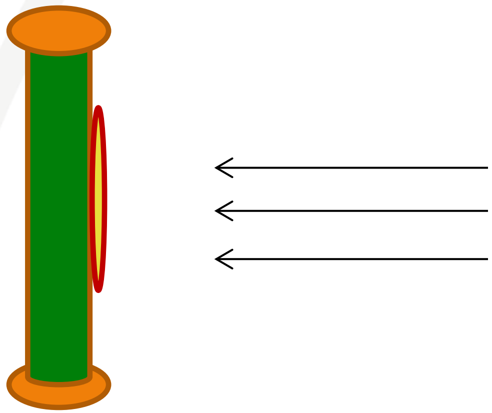
Perry (1963): https://hdl.handle.net/10945/11541

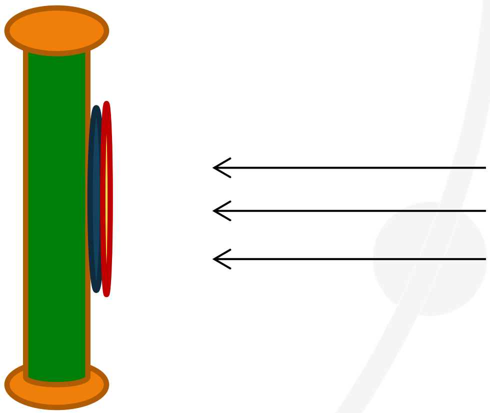
β+ Source Experimental Setup

Element	Purity [%]	Weight [g]	Thickness [in]	Diameter [in]	Density [g/cc]
Cd	99.97	2.23662	0.02	0.5	8.65
W	99.9608	0.3189	0.005	<0.5	19.3

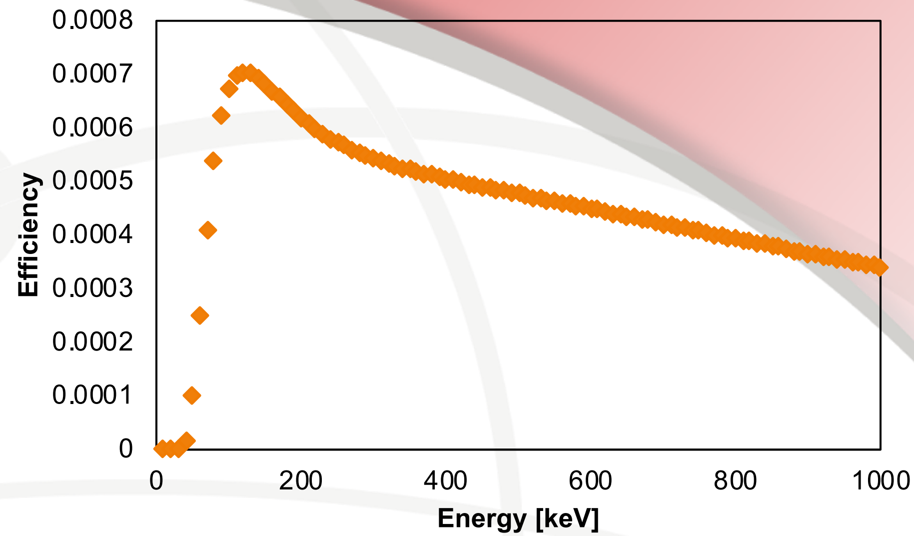
Two variations were run:

1. Cd half cap alone (a)
2. Cd half cap over W foil (b)


(a)


(b)

Efficiency Calculation



Reference Date	1-Apr-13
Measurement Date	21-Nov-14
Time Difference (secs)	51753600
Live Time (secs)	172800

Nuclide	Gamma Ray Energy	Activity	Activity Uncertainty	Net Area	Area Uncertainty	Efficiency	Efficiency Uncertainty
Pb-210	46.5	5.796E+02	1.9477E-02	6.51E+03	182.92	6.498E-05	1.827E-06
Am-241	59.5	3.988E+02	1.7454E-02	1.56E+04	237.54	2.269E-04	3.447E-06
Cd-109	88	2.355E+02	9.5781E-03	2.80E+04	201.6	6.879E-04	4.953E-06
Co-57	122.1	6.866E+01	4.4498E-03	7.89E+03	1.59E+02	6.648E-04	1.343E-05
Ce-139	165.9	2.183E+01	9.5409E-04	2.39E+03	144.29	6.326E-04	3.826E-05
Hg-203	279.2	1.281E-01	2.5711E-06	0.00E+00	0	0.000E+00	0.000E+00
Sn-113	391.7	1.681E+01	5.2896E-04	1.61E+03	109.34	5.531E-04	3.764E-05
Cs-137	661.7	3.933E+02	1.9258E-02	2.76E+04	1.82E+02	4.064E-04	2.682E-06
Y-88	898	3.034E+01	3.9674E-04	1.88E+03	91.22	3.585E-04	1.740E-05
Co-60	1173.2	6.047E+02	1.6120E-02	3.19E+04	194.99	3.049E-04	1.866E-06
Co-60	1332.5	6.048E+02	1.6120E-02	3.02E+04	184.43	2.887E-04	1.765E-06
Y-88	1836.1	3.211E+01	4.0691E-04	1.23E+03	46.51	2.215E-04	8.383E-06

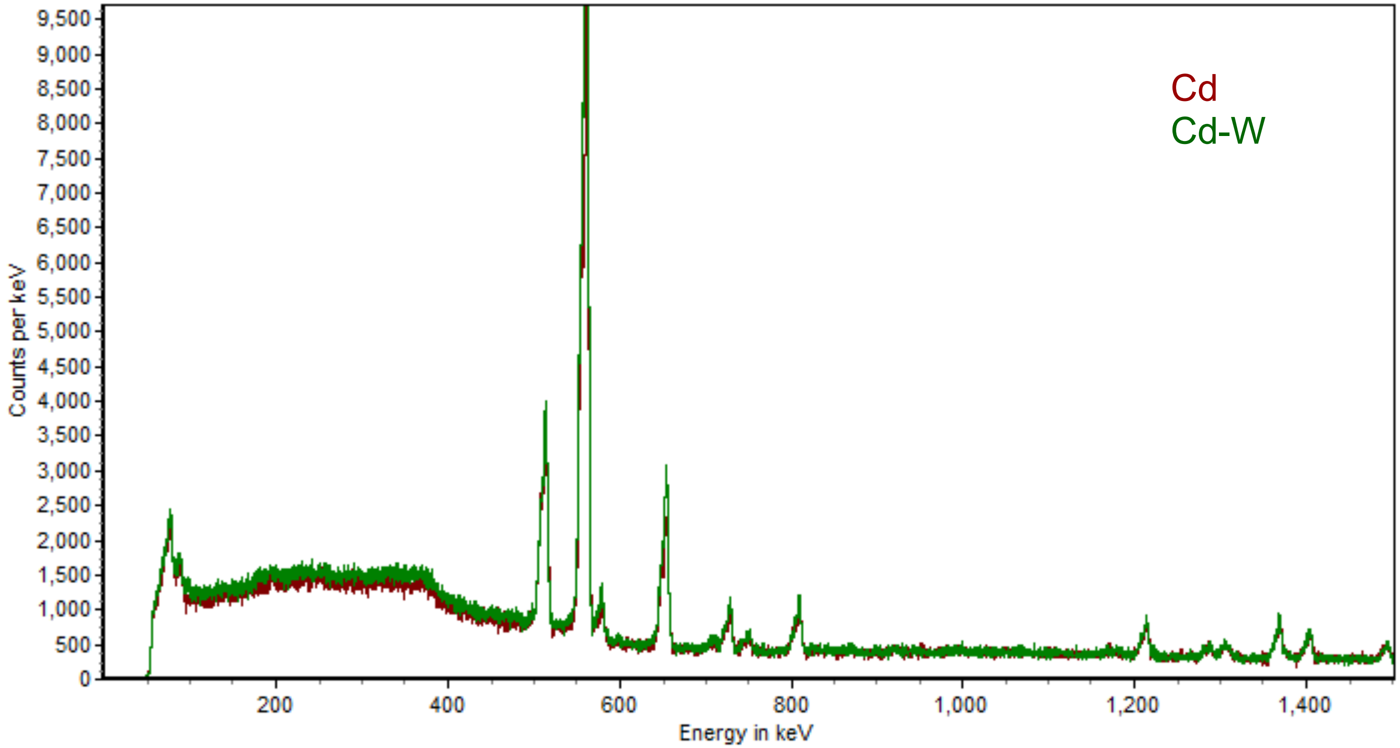
$$\varepsilon = e^{0.078\ln(511)^5 - 2.383\ln(511)^4 + 28.92\ln(511)^3 - 174.2\ln(511)^2 + 520.4\ln(511)}$$

$$= 4.7399\text{E} - 4$$

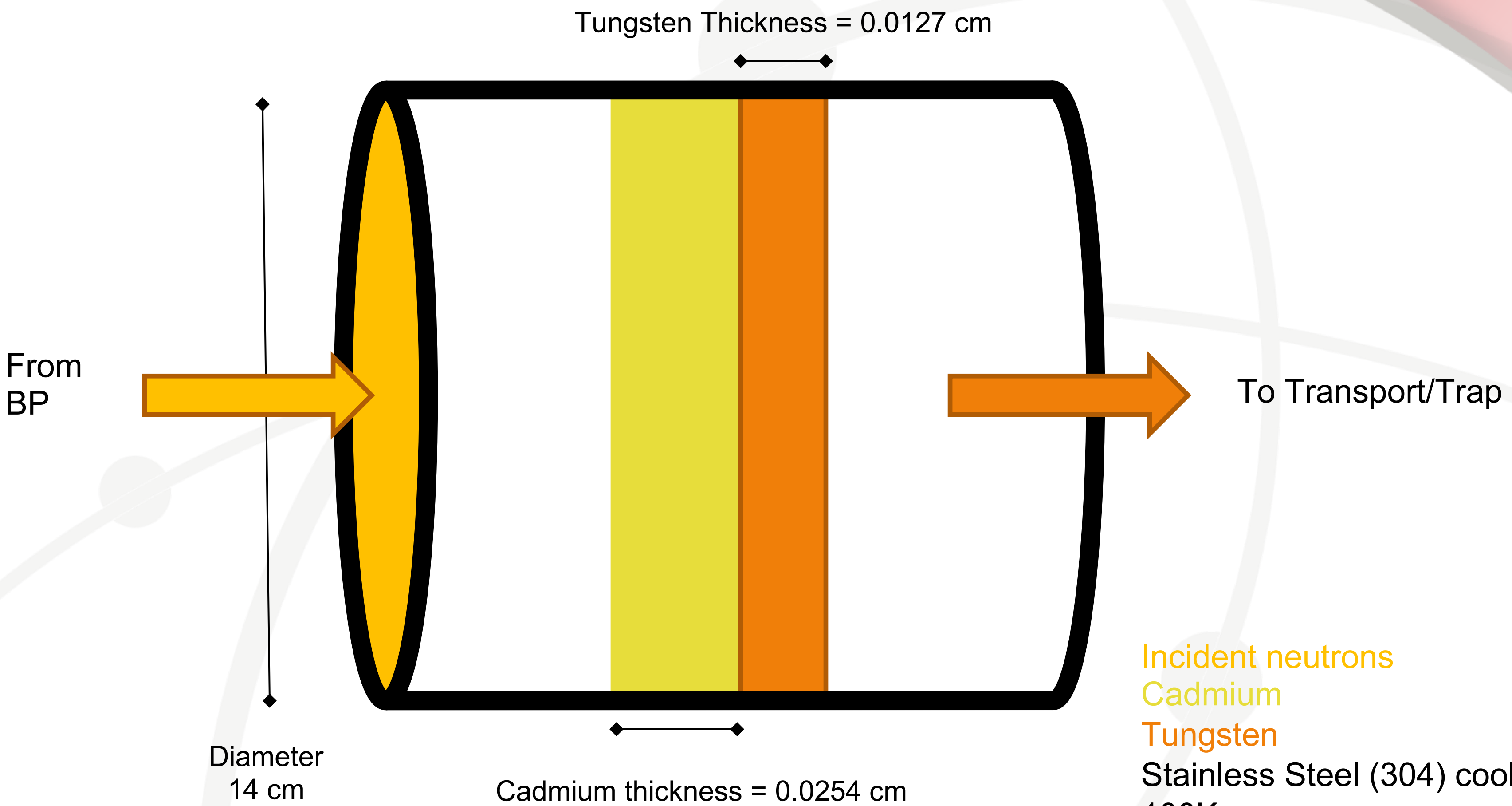
Experimental Results

$$\text{Counts}/_{\varepsilon}/_{t_L}$$

Material	Live Time [s]	Positrons/sec
Cd	300	1.90E+05
	600	1.89E+05
	Mean	1.89E+05
Cd-W	300	1.80E+05
	600	1.79E+05

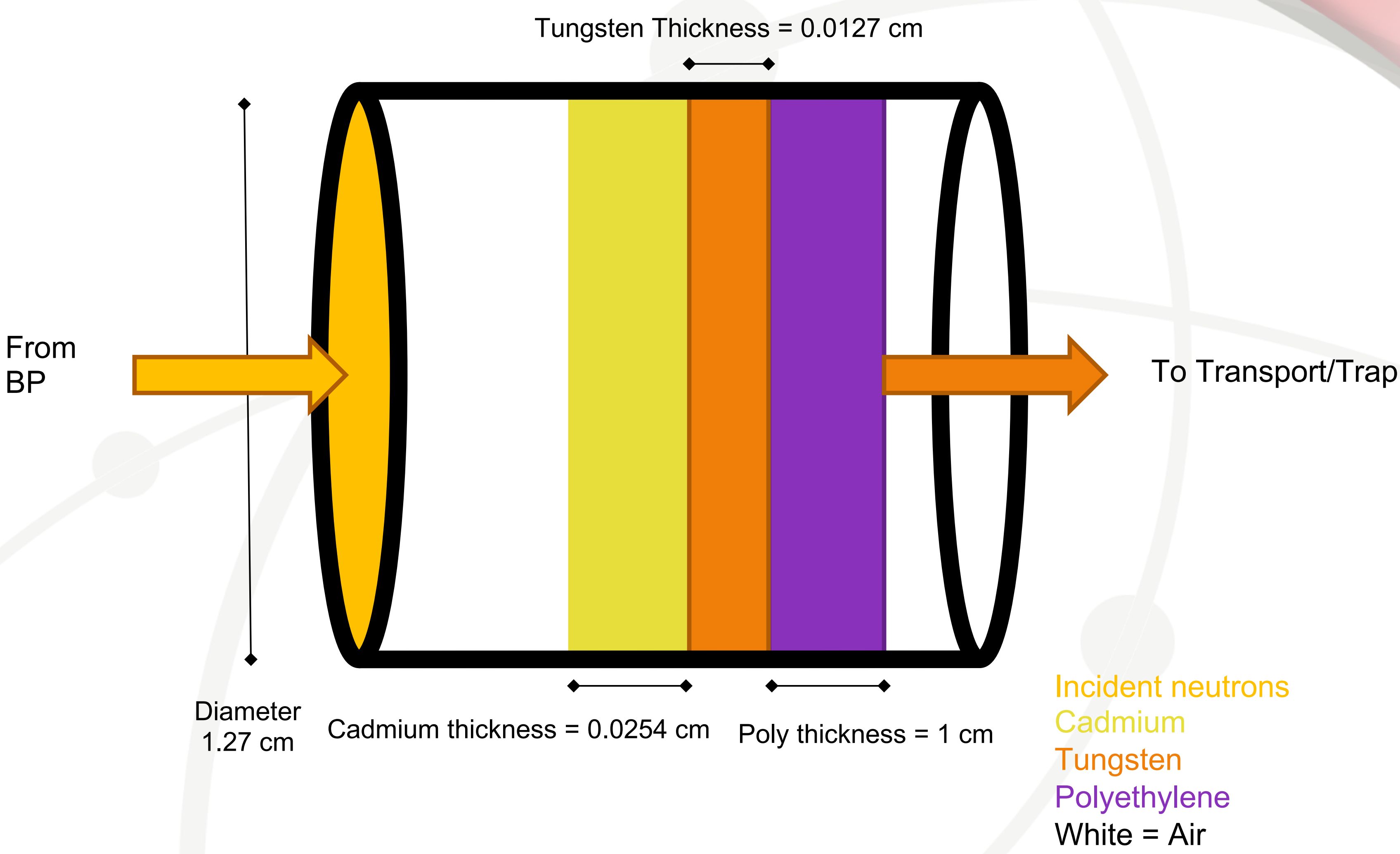


MCNP Model

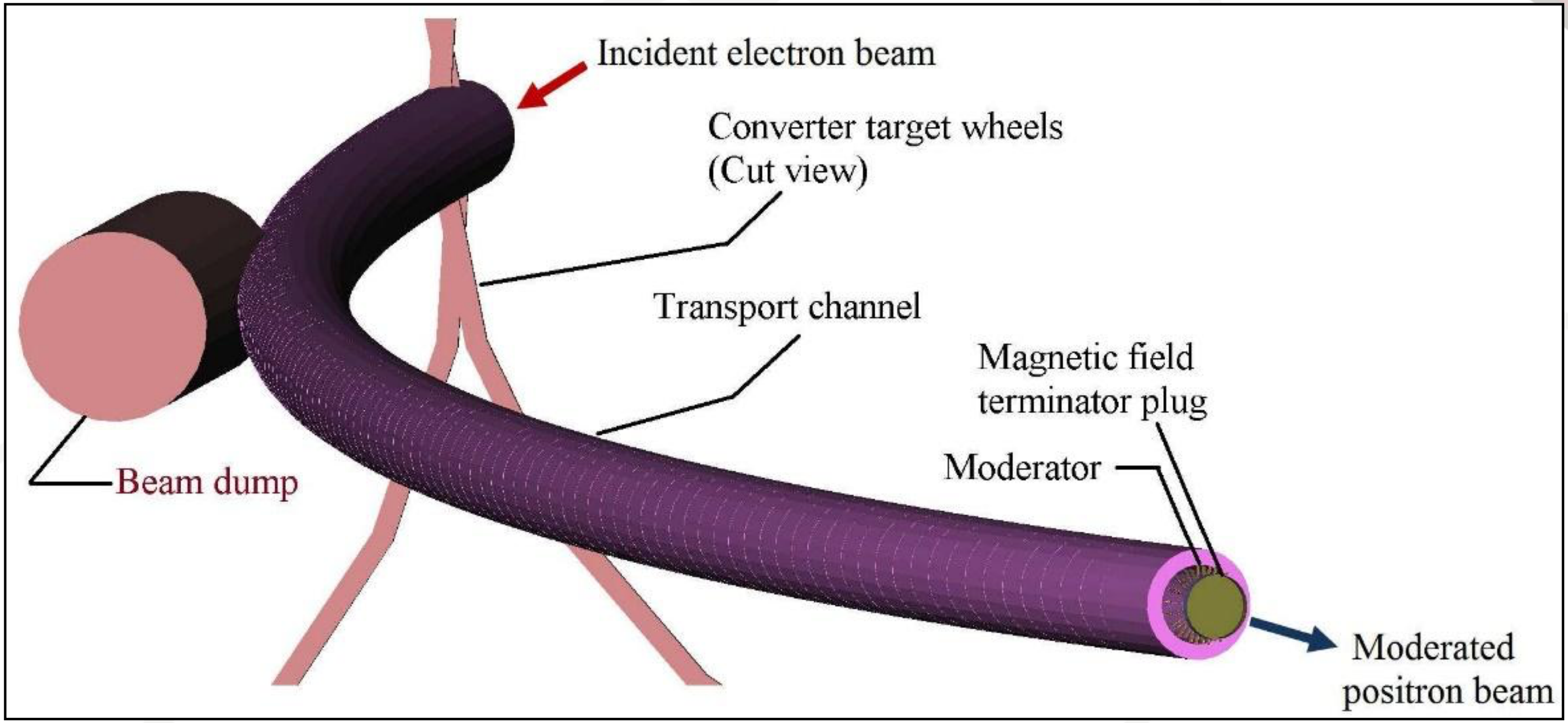


Incident neutrons
Cadmium
Tungsten
Stainless Steel (304) cooled to 100K
White = Vacuum

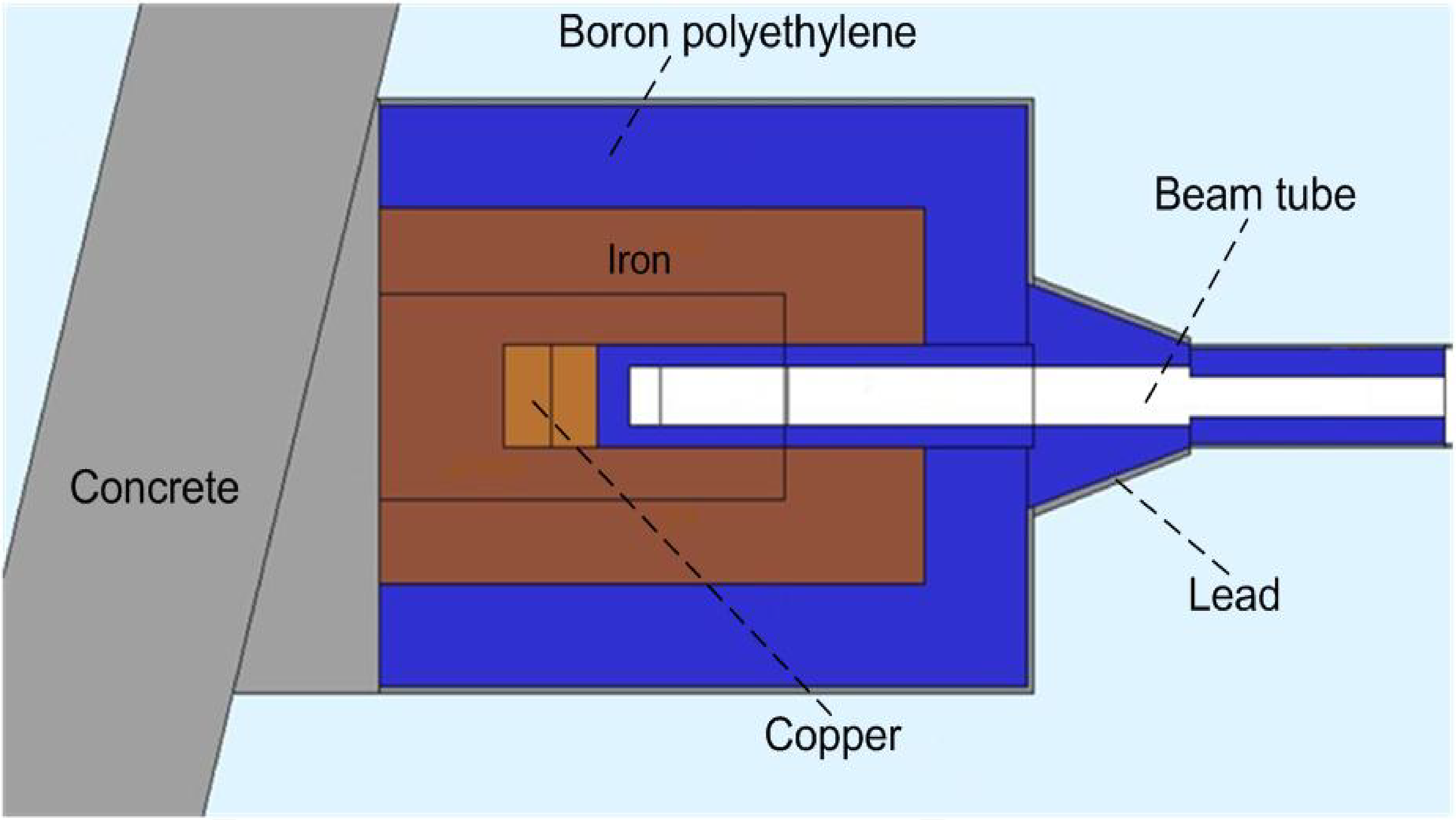
MCNP Model for Experiment



POSITRON CONTINUOUS WAVE BEAM DUMP: SCHEMATIC

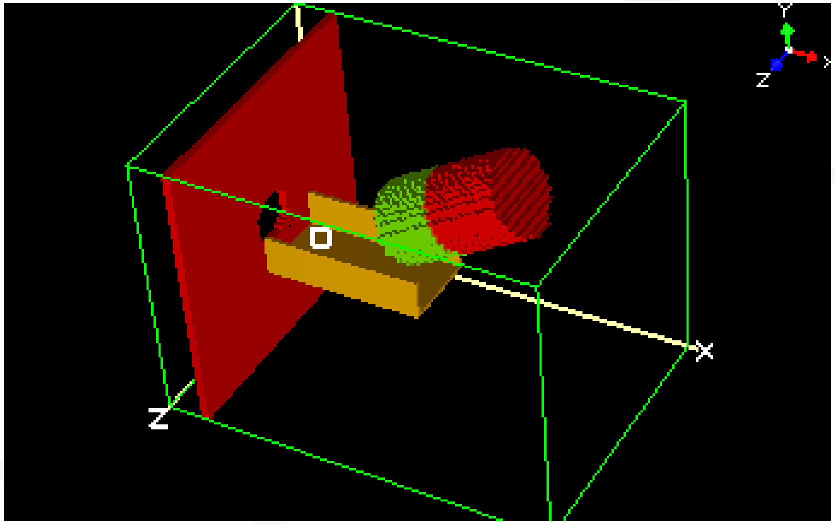


POSITRON CONTINUOUS WAVE BEAM DUMP: SHIELDING



SIMULATION: BEAM DUMP

3-D



POSITRON

strike rate = 58 / 2.79 sec

E = 512 KeV

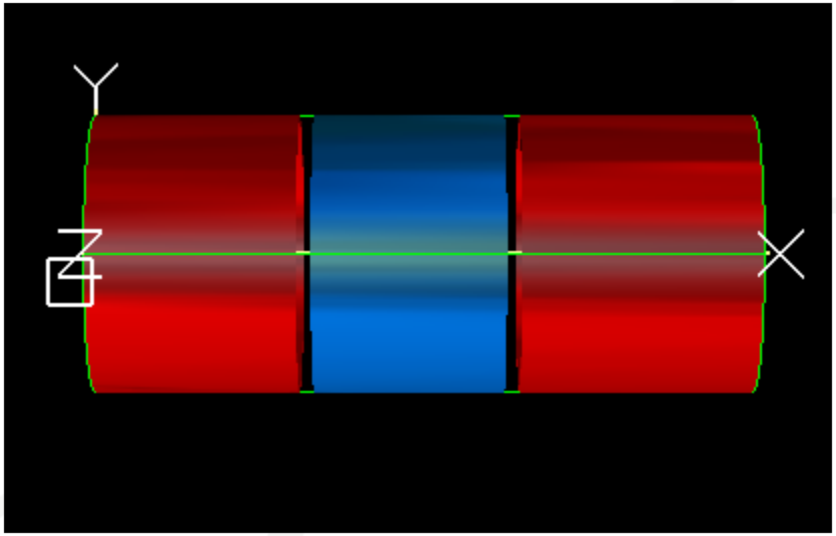
t = 1.89 sec

error = 1.6 x 10^{-2} V

v = 18.791 mm/ µsec

DATA – BEAM LINE

3-D



POSITRON

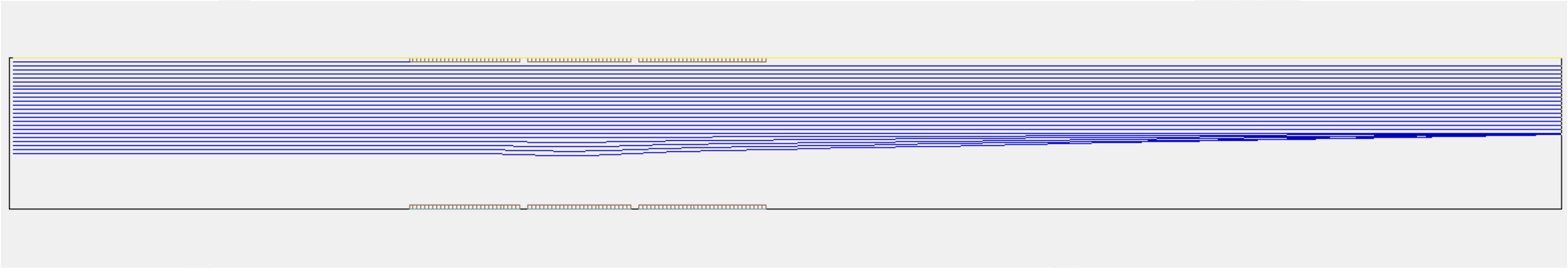
strike rate = 25 / 1.89 sec

E = 512 KeV

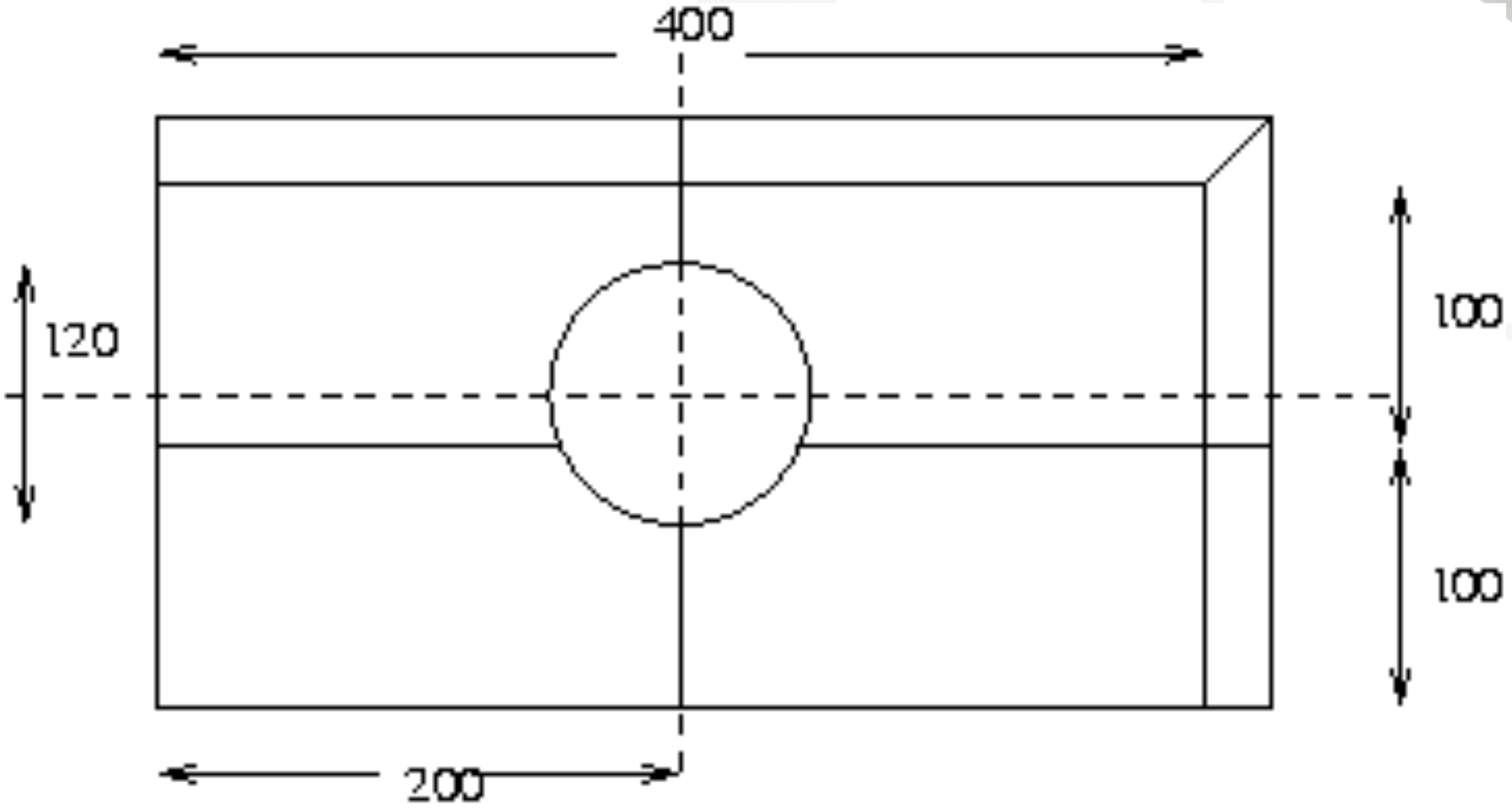
t = 1.89 sec

error = 0

v = 19.701 mm/ μsec

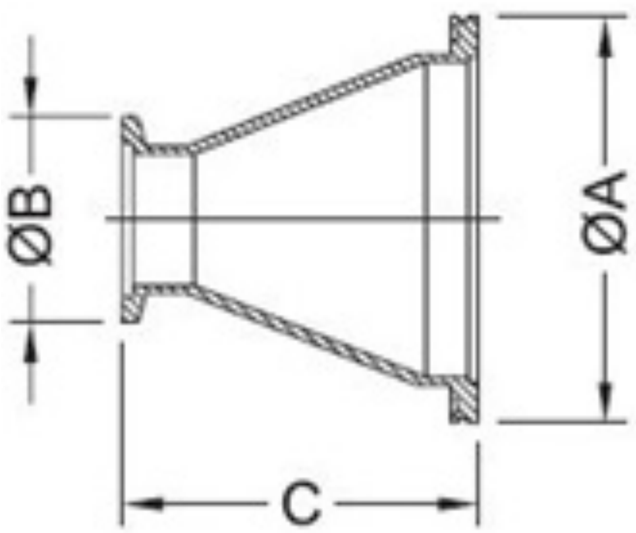


AGN BEAM PORT: ELEVATION



https://www.hzdr.de/db/Cms?pOid=11150&pNid=69

AGN BEAM PORT: REDUCER

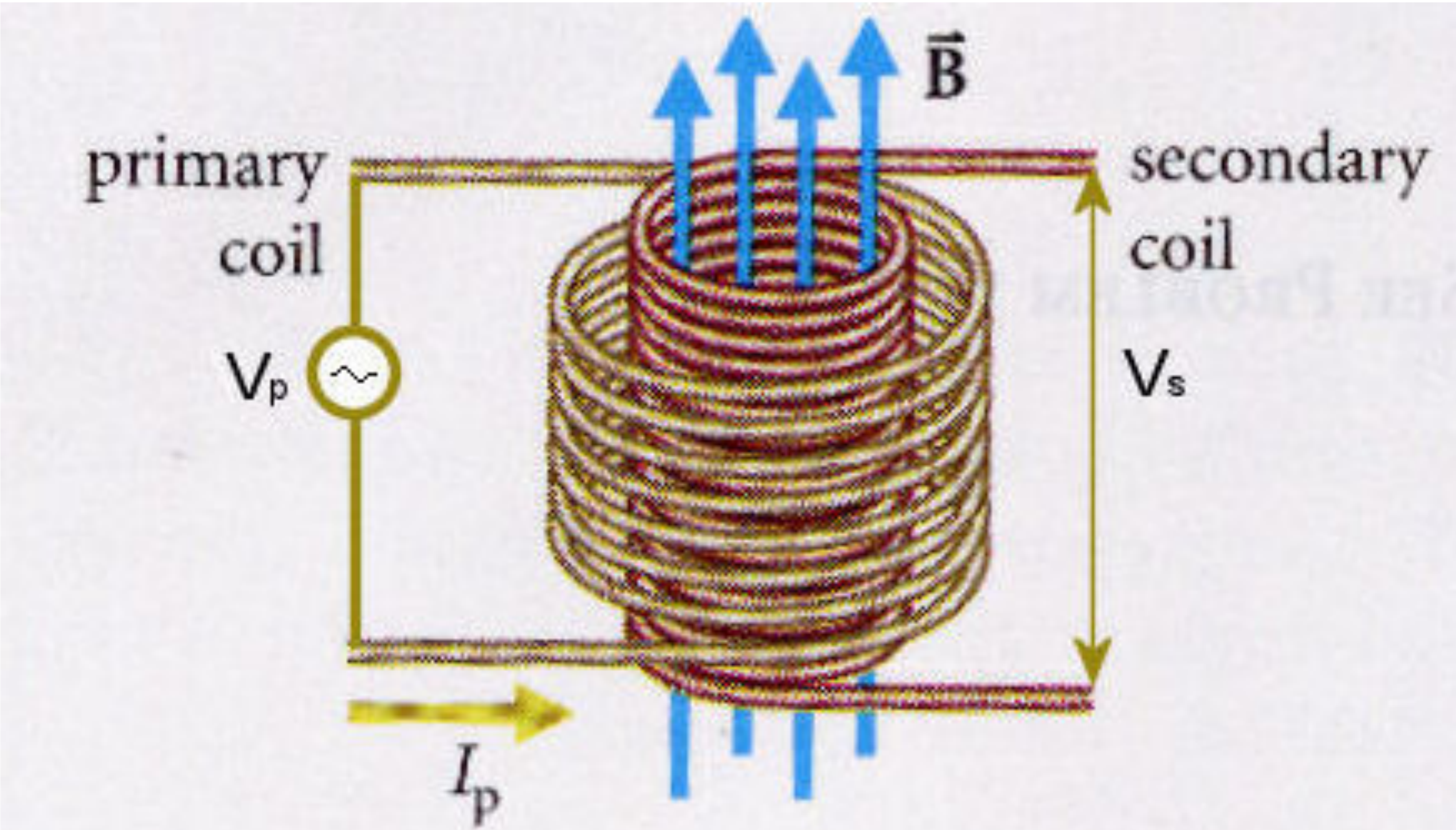


A = 105 mm   B = 12 mm C = 63 mm

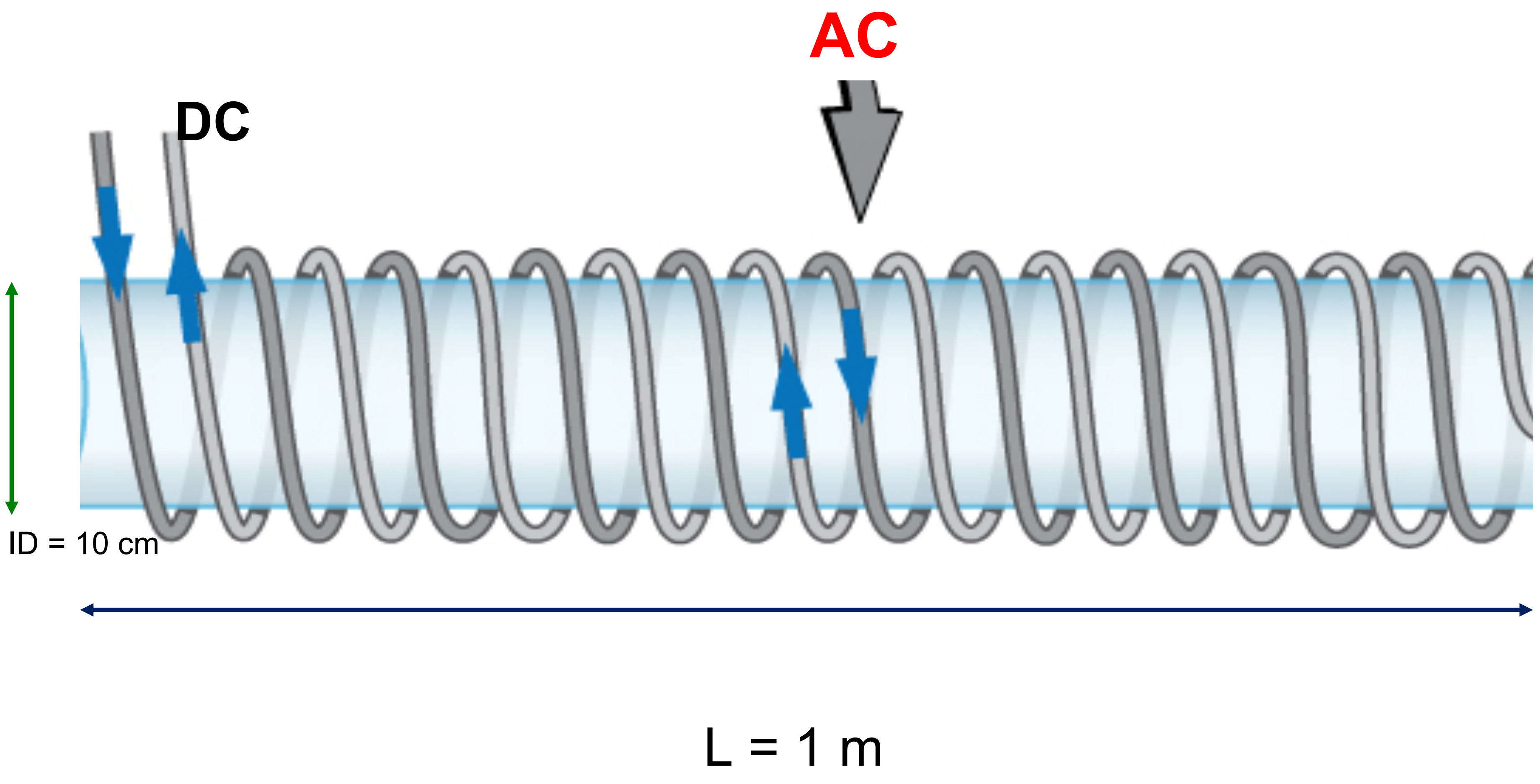
https://www.ajvs.com/product_info.php?products_id=7790

BEAM LINE

BEAM LINE



BEAM LINE: SECONDARY



BEAM LINE: SECONDARY

POSITRON TRANSPORT THEORY

BACKGROUND

1. VACUUM
2. INVISCID FLUIDS
3. A. Air
   B. Gases
4. VISCOUS, COMPRESSIBLE FLUIDS
5. CURRENT (I) (β+ CONFINEMENT)
   A. High
   B. Low

POSITRON TRANSPORT THEORY

VERIFICATION EXPERIMENTS: Part 1

1. Little is known about positronic transport in air under adiabatic conditions.
2. Positrons previously have not been transported using an air core beam guide.
3. What is the activity (A) at the reaction chamber into which the fomites will be introduced?

A. Marker: Eesa catalyzed a reaction between NO and O to form the paramagnetic NO_2.[1] This reaction produces a brown-colored gas, thus rendering the boundary front in the reaction chamber visible. It also provides visual verification of the calculated values for the Froude, Stokes, Reynolds, and other scalar quantities by observing these regimes in the clear tube demarcated by the brown vapor. In this case, however, it is proposed to employ iodine (MW 254 g/mol at AW 127) that evaporates under adiabatic conditions. Moreover, iodine exhibits diamagnetic properties that will simulate the behavior of the positively charged positrons within the air coil solenoid beam guide.[2] The diffusivity of iodine through air is 1.13 x 10^{-5} m^2/s and its saturation vapor pressure is 2.6 kPa. The iodine solid(s) are emplaced in a three-neck flask, into which a variable, incurrent air flow comes into the vessel, carrying the resultant vapor with it (Figure 2).[3] The middle neck of the flask carries a thermometer to verify the temperature of the reaction, T_{min} = 298K. The third neck functions as the air and vapor discharge, to which the excurrent air will be piped into the source chamber. This flask has the added functionality of being placed in a water bath to control T_{min} thus ensuring the maintenance of the adiabatic conditions under which the initial verification experiments are to be conducted. If it is determined to go beyond the adiabatic into other temperature and pressure regimes, this component will accommodate many of those specifications, including boiling (Figure 3).[4]

POSITRON TRANSPORT THEORY

VERIFICATION EXPERIMENTS: Part 2

Source and Source Chamber

This verification experiment would carry the I_2 vapor from the vapor chamber into the source chamber containing ^{22}Na. It and its transport fluid (air) would there pick up the positrons emitted by the ^{22}Na and would transport the positrons, positronic swarms, and Ps complexes thence into the beam guide where they would then be guided toward the fomite reaction chamber. It should be understood that ^{22}Na is here adopted for reasons of financial and experimental economy and that there is a radioisotope of iodine (^{124}I) that could be used directly that is a strong positron (β+) emitter that could visualize and verify the experimental aims of this project as well, $t_{1/2}$ = 4.18 d

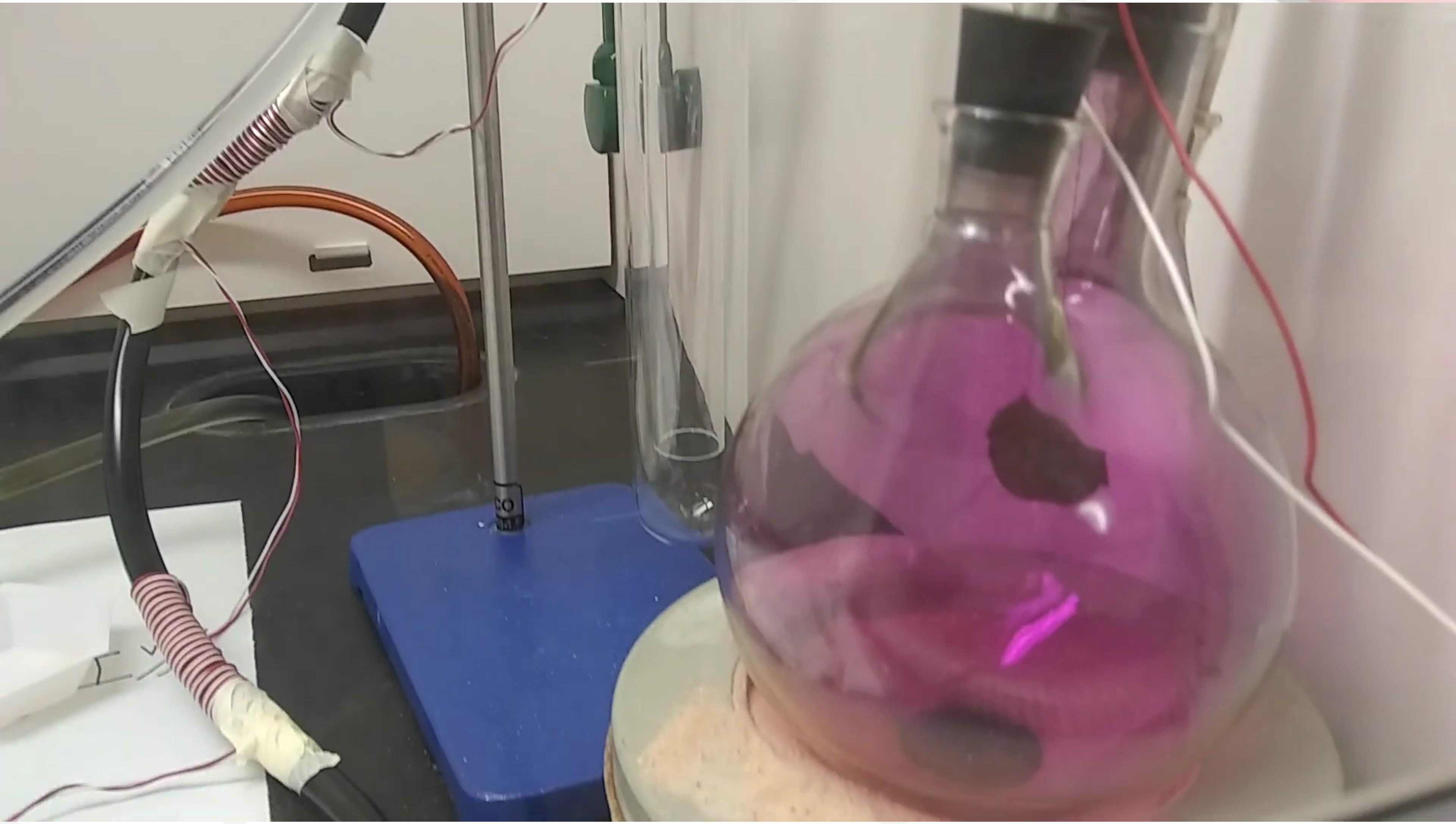
POSITRON TRANSPORT THEORY

VERIFICATION EXPERIMENTS: Part 3

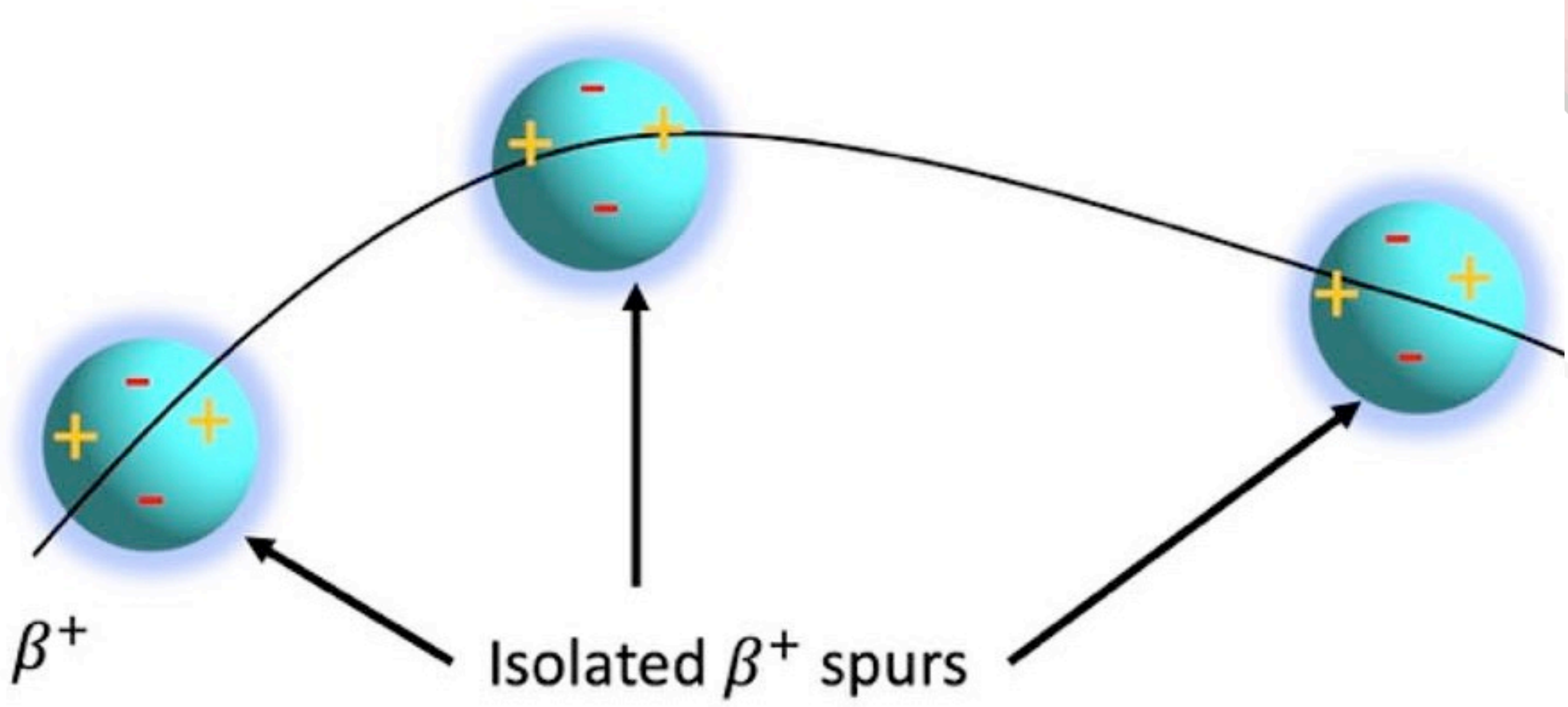
Laminar (Re < 3000) Flow of I-Ps Vapor through PVC Beam Guide

POSITRON TRANSPORT THEORY

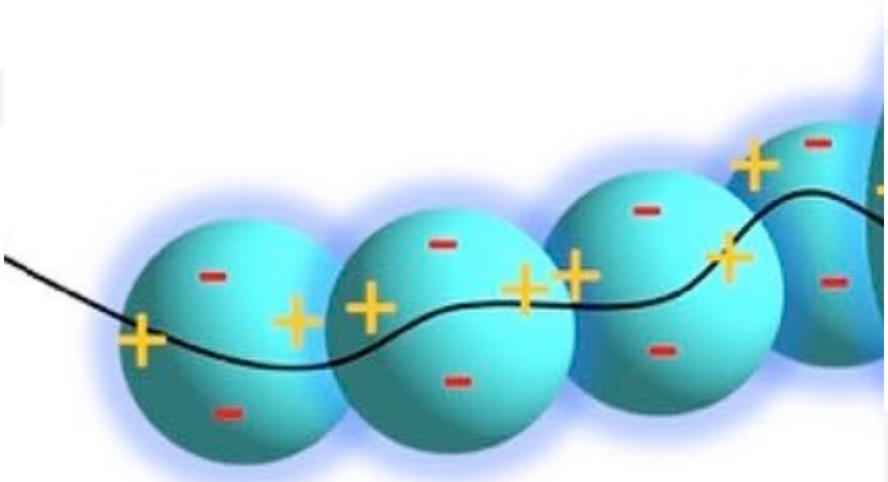
VERIFICATION EXPERIMENTS: Part 2



β+ energy deposition in water through "spur" formation



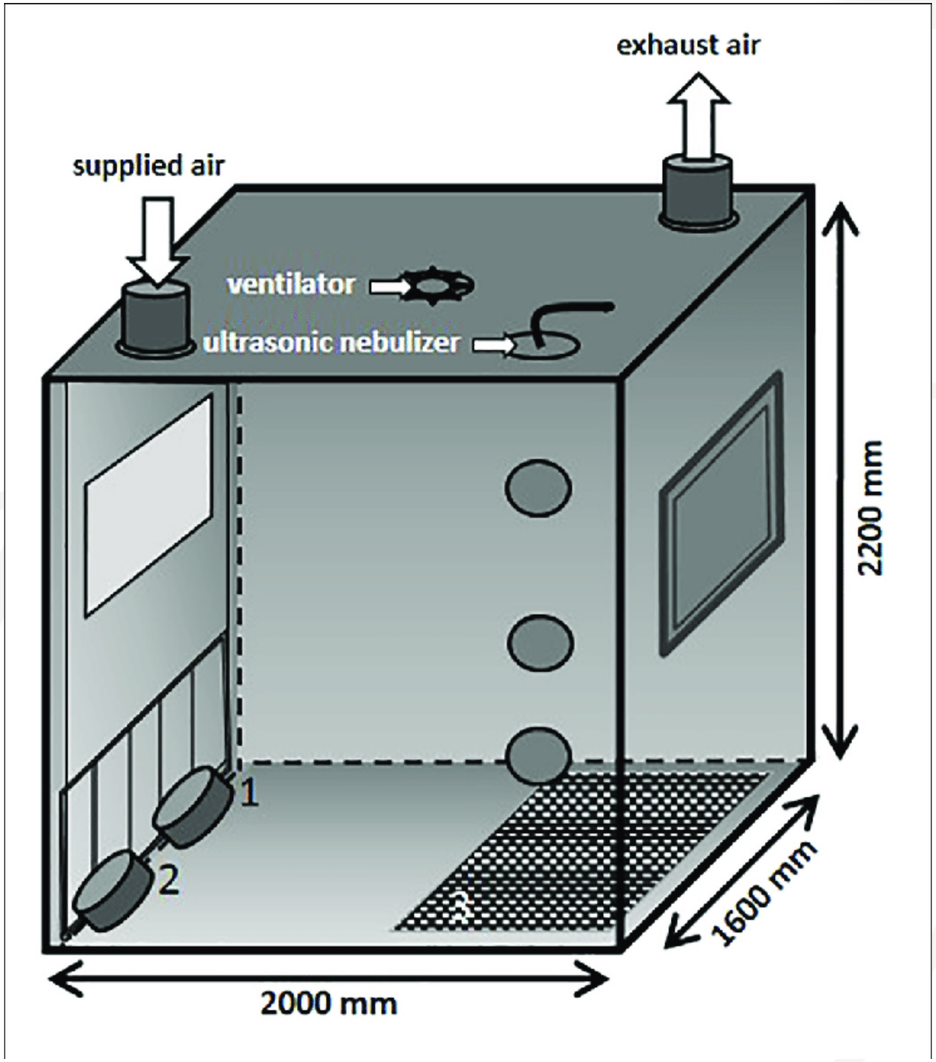
The “Spurs” collocate into a string.



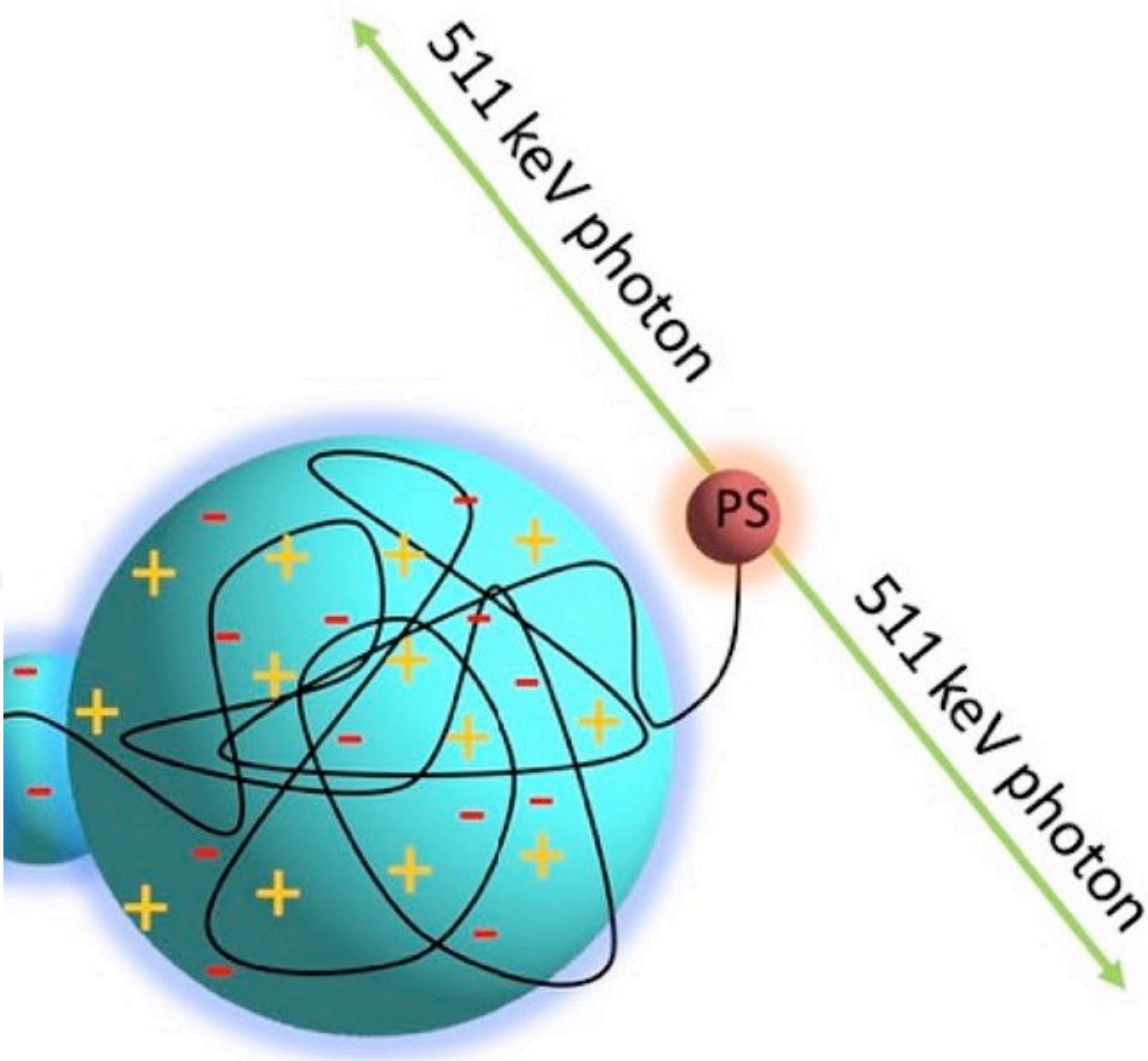
BEAM LINE: SECONDARY (DC)

Voltage (V)	Current (Amp.)	Air Velocity (m/sec)	Air Flow rate (m3/sec)
3.00	0.90	0.20	0.0015
4.50	0.90	1.10	0.0083
6.00	1.25	1.60	0.0120
7.50	1.25	2.00	0.0150
9.00	1.28	2.20	0.0165
12.00	1.28	2.40	0.0180

DESTINATION: VIRUCIDE



FORMATION OF TERMINAL BLOB τ = 1100 ns



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Prof. Chris Rylander, UT-Austin

INAUGURAL MEETING OF THE SOUTHWEST INSTITUTE FOR POSITRON AND ELECTRON STUDIES (SWIPES)

2025-2026

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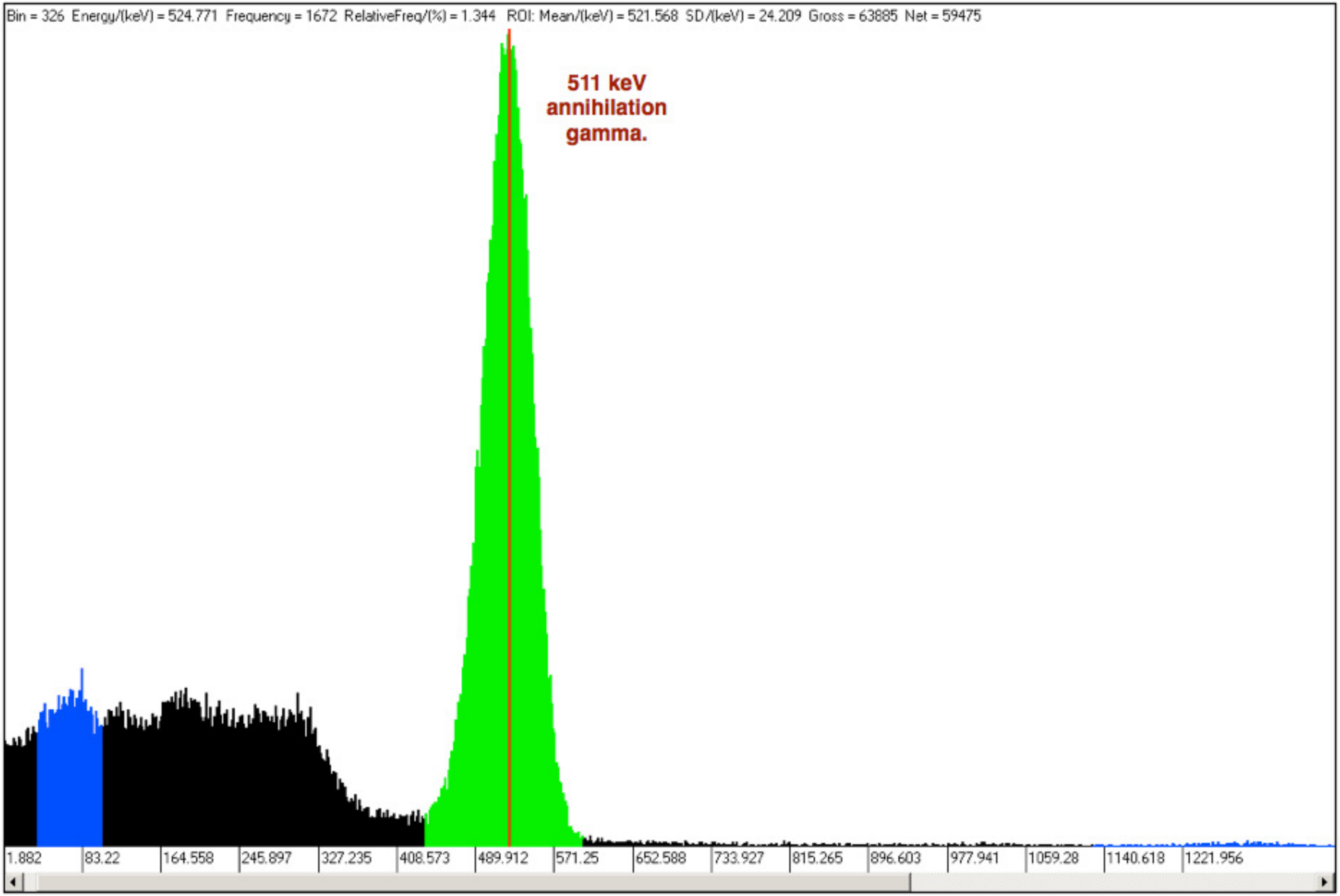
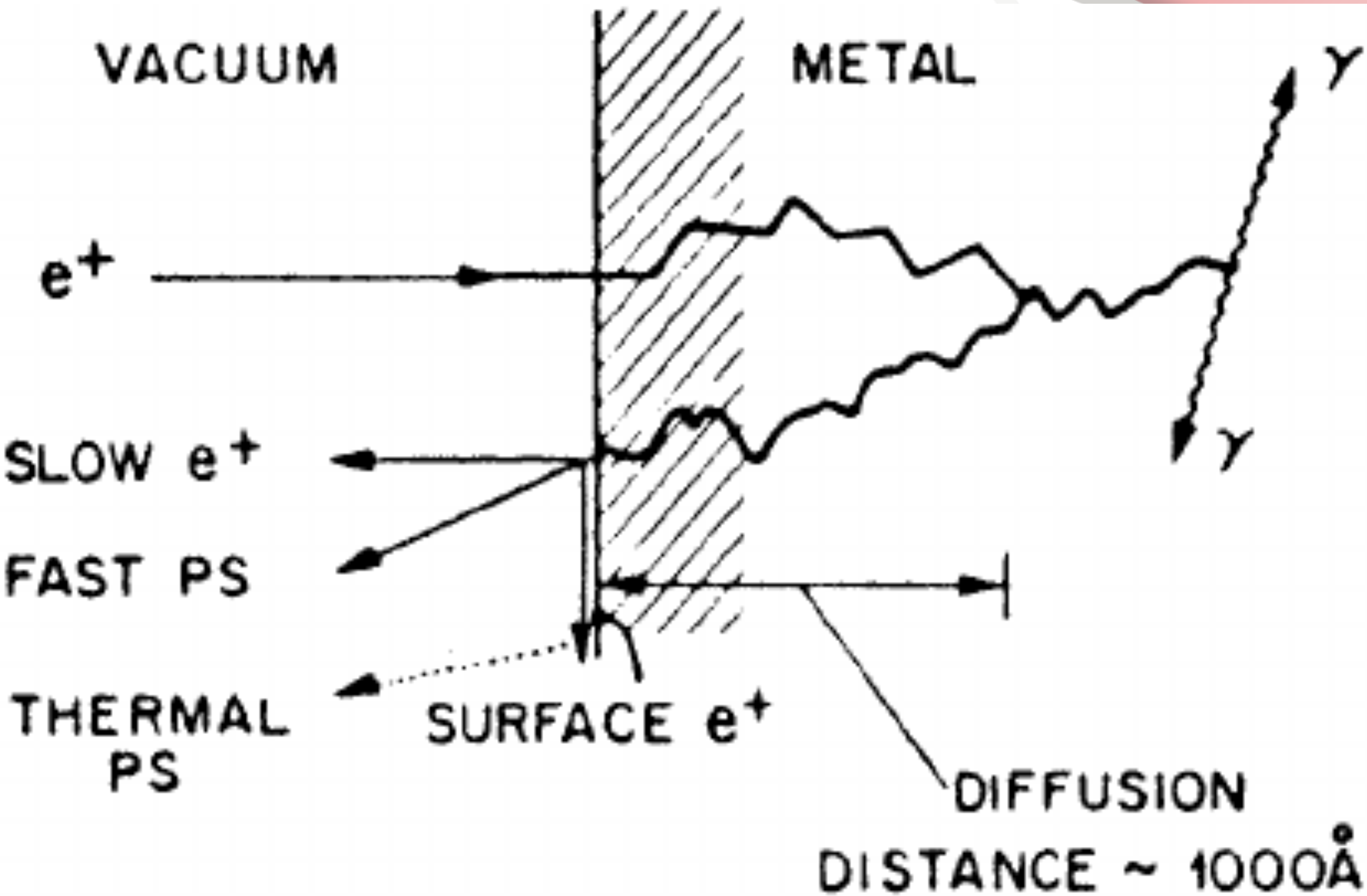
ANNOUNCEMENT

APPENDIX

• **Na-22 Gamma Spectrum**



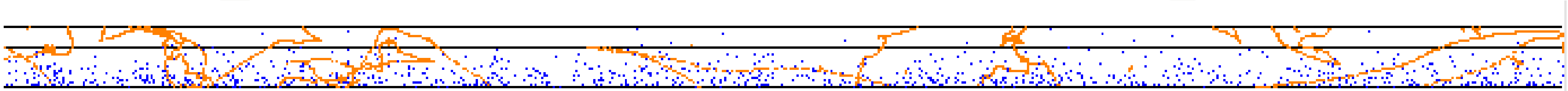
- **Positron Moderation**



MCNP e Tracks

electron creation	tracks	weight (per source particle)	energy (per source particle)
source	0	0.	0.
nucl. interaction	0	0.	0.
particle decay	0	0.	0.
weight window	0	0.	0.
cell importance	0	0.	0.
weight cutoff	0	0.	0.
e or t importance	0	0.	0.
pair production	589044	2.2863E-01	1.3437E+05
compton recoil	43757	1.6990E-02	1.0446E-01
photo-electric	360663	5.7423E-02	3.0075E-03
photon auger	3562	1.3833E-03	2.6544E-05
electron auger	7490	2.9094E-03	5.5829E-05
knock-on	11713539	4.5473E+00	2.9267E-02
(gamma,xelectron)	0	0.	0.
total	12718055	4.8546E+00	1.3437E+05

electron loss	tracks	weight (per source particle)	energy (per source particle)
escape	207818	8.0659E-02	7.0857E-01
energy cutoff	11867990	4.6072E+00	4.3346E-03
time cutoff	0	0.	0.
weight window	0	0.	0.
cell importance	0	0.	0.
weight cutoff	0	0.	0.
e or t importance	0	0.	0.
scattering	0	0.	8.1210E-02
bremsstrahlung	0	0.	4.7625E-02
p-annihilation	4024	1.5637E-03	5.6214E-09
atomic excitation	0	0.	0.
electroionization	0	0.	0.
total	12079832	4.6895E+00	8.4174E-01



MCNP Results

f1 current tally with an elc card used to determine source strength
Flux obtained by using an f2 neutron tally and scaling with a known reactor flux

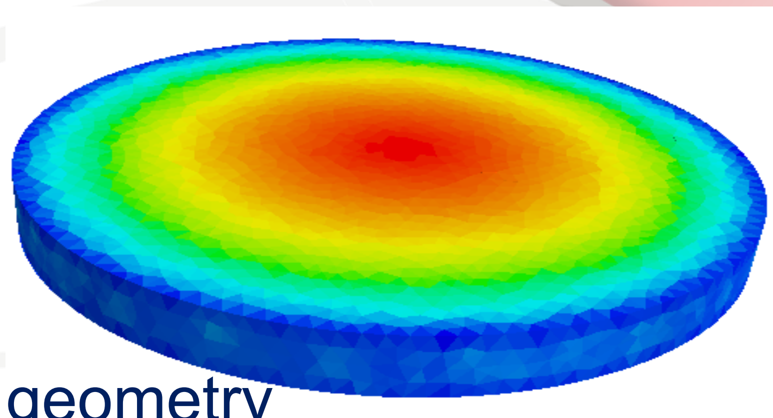
	p-annihilation [per source particle]	$e^+/cm^2/sec$	
		MCNP	Experimental
Cd	8.02E-03	8.02E+04	1.89E+05
Cd-W	2.67E-03	2.67E+04	1.80E+05

Cd-only and Cd-W designs compared

Cd		
Source Strength	5.40E+07	e^+/sec
	8.90E+07	e^-/sec
Positrons Produced	3.70E+08	e^+/sec
Cd-W		
Source Strength	1.00E+08	e^+/sec
	4.00E+08	e^-/sec
Positrons Produced	7.30E+08	e^+/sec

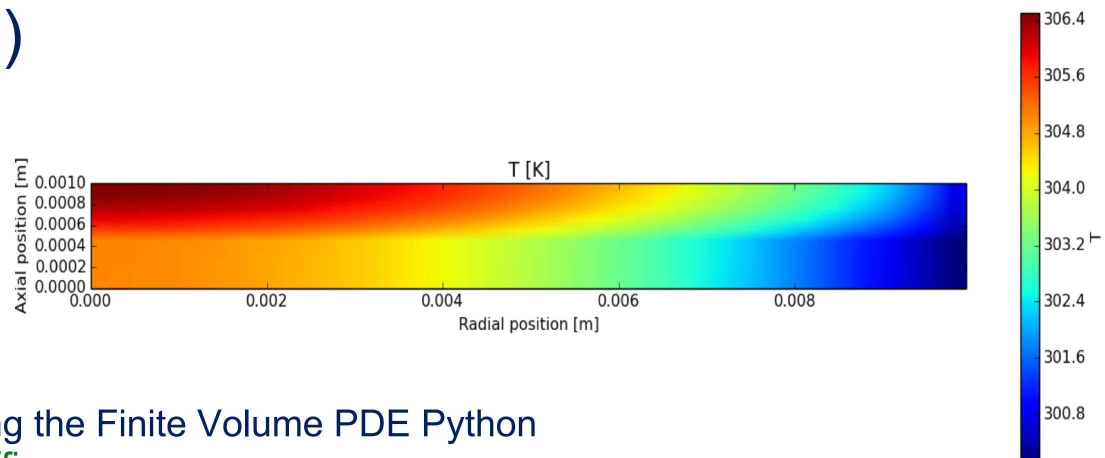
Final design used a target radius of 7 cm
Cd – 0.0254cm thick
W – 0.0127cm thick

Heat Transfer



Capabilities:

1. Time dependent
2. 1D, **2D axis-symmetric** or 3D geometry
3. Volumetric Heat source [Fn(t, r, z, theta)]
4. Handle 2 material layers with different thermal properties (Cd & W foil)



Heat transfer solver developed using the Finite Volume PDE Python Toolkit: FiPy: https://ctcms.nist.gov/fipy

Heat Source and Material Properties

Table 1. Material Properties

	Cadmium	Tungsten
Thermal Conductivity [W/m-k]	97	173
Density [g/cc]	8.65	19.3
Cp [J/kg-K]	0.23e-3	0.134e-3
Tmelt [K]	595	3695
Macroscopic Absorption Xsec [1/cm]	113.6	1.195

Table 2. Thermal Neutron Flux vs. Reactor Power

Power [kW]	Thermal Flux [n/cm^2-s]
0	0.0
100	2.04e11
400	8.16e11
500	1.02e12

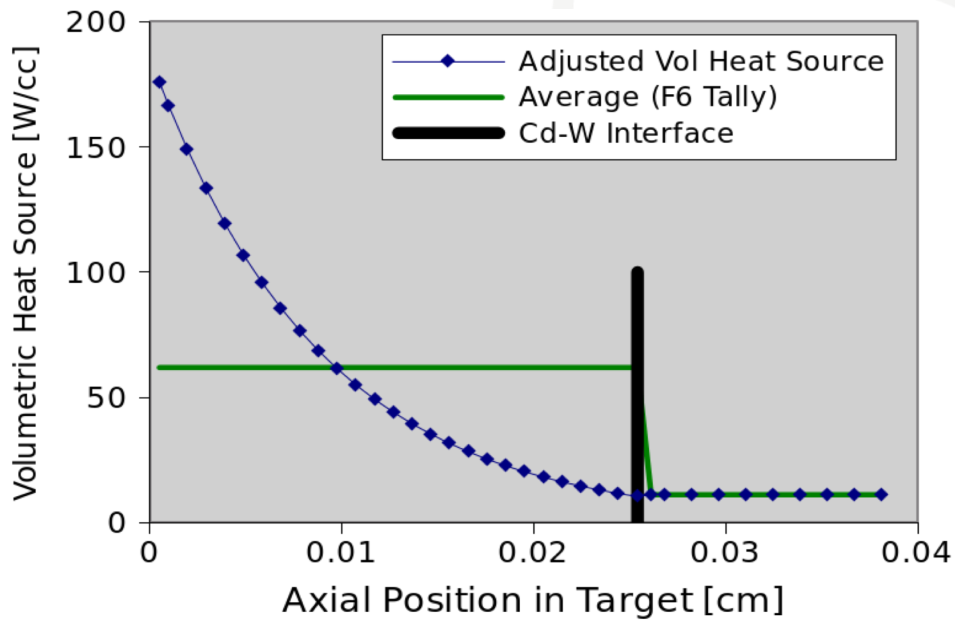
- Heating tally (f6) is averaged over entire cell. Assuming local deposition of gammas, heating profile may be adjusted by:

$$\phi(z) = \frac{\bar{\phi}\Sigma_a t}{(1 - e^{-\Sigma_a t})} e^{-\Sigma_a z}$$

(This correction is not necessary for thin, well conducting geometries)
t=thickness, z=axial location

- Flux scaling done with data in Table
- Addition of W improves thermal performance of composite target.

Attenuation Adjusted Heat Flux and Vol Avg Heat flux profiles. Thermal flux = 1.02e12 [n/cm^2-s]



Target Radius Study

- 2D axis symmetric geometry used. Cd and W modeled.
- Cd thickness = 0.0254 [cm]. W thickness = 0.0127 [cm].
- Boundary and Initial Conditions
  - T0=100K
  - Radial Edge T set to 100K (What we might achieve with LN cooling).
  - Tinf set to 350K for rad heat transfer from target to surroundings.

Target Radius [cm]	Reactor Power [kW]	Cd Vol Heat source [W/cc]	Cd Steady State Max Temp [K]	Time to T=550K [s]
9.0	500	60.89	856.7	26
8.0	500	60.87	705.7	30
7.0	500	60.84	565.4	58
9.0	400	48.71	712.0	24
8.0	400	48.69	585.8	58
7.0	**400**	**48.67**	**472.4 (472.62)***	**inf**

* With beam attenuation adjusted axial heat profile

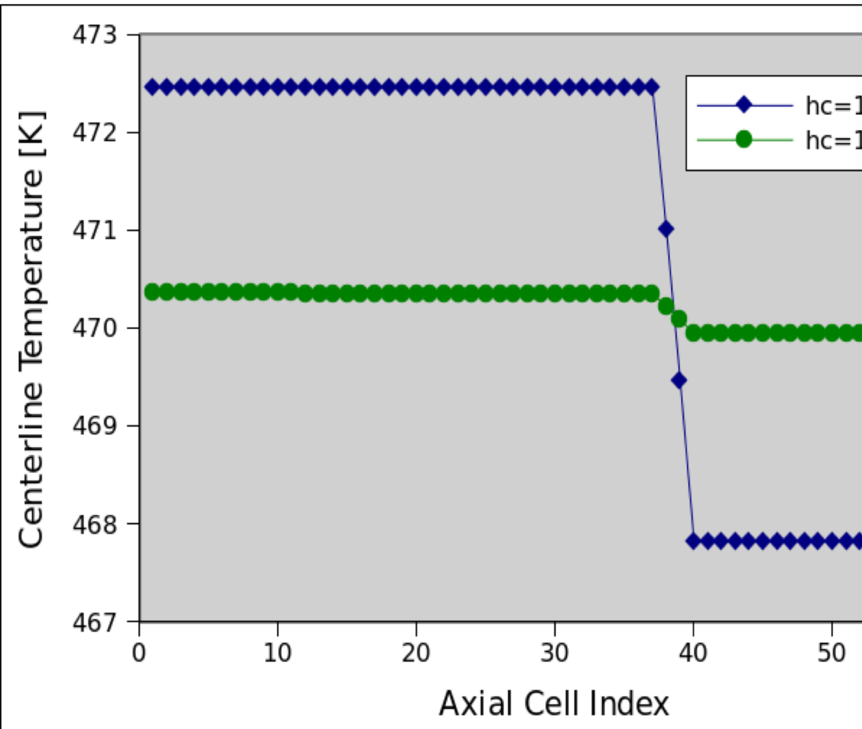
Cd Thickness Study

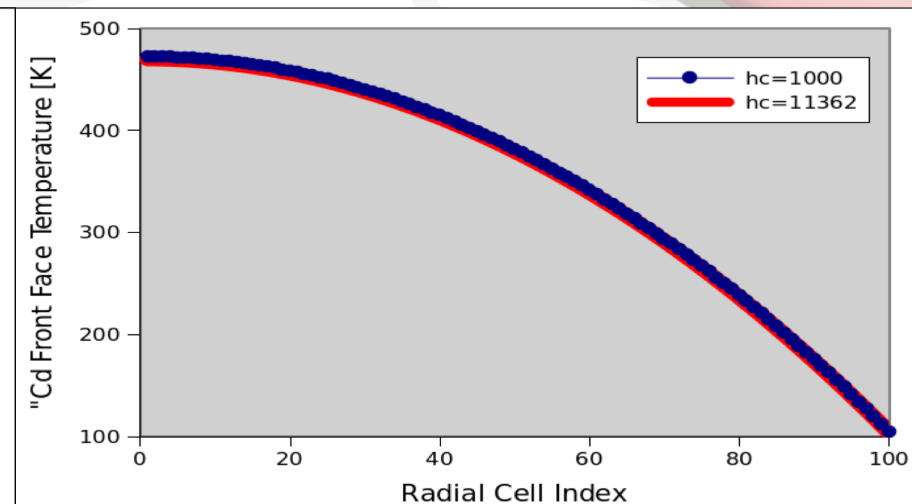
- 2D axis symmetric geometry used. Cd and W modeled.
- **Disk radius = 10.2 cm**
- Boundary Conditions
  - T0=100K.
  - Edge T set to 100K (What we might achieve with LN cooling).
  - Tinf set to 350K for rad heat transfer from target to surroundings
- **CONCLUSION:**
  - Changes to Cd thickness have some small effect target temperature.
    - Vol heat source actually increases with thinner target – due to beam attenuation.
    - Effective area available for conduction out of the target decreases.
  - Best to reduce target radius to lower centerline temperature.

Cd thickness [cm]	W thickness [cm]	Reactor Power [kW]	Cd Vol Heat source [W/cc]	Cd Steady State Max Temp [K]	Time to T=550K [s]
0.0254	0.0127	500	60.9	1033	30
0.0229	0.0127	500	65.8	1068	24
0.0203	0.0127	500	71.7	1076	22

Temperature Profiles Sensitivity to Gap Conductance

Cd thickness = 0.0254 [cm]. W thickness = 0.0127 [cm]. Target Radius = 7[cm]. Tedge = 100K. Reactor Pwr = 400[kW].





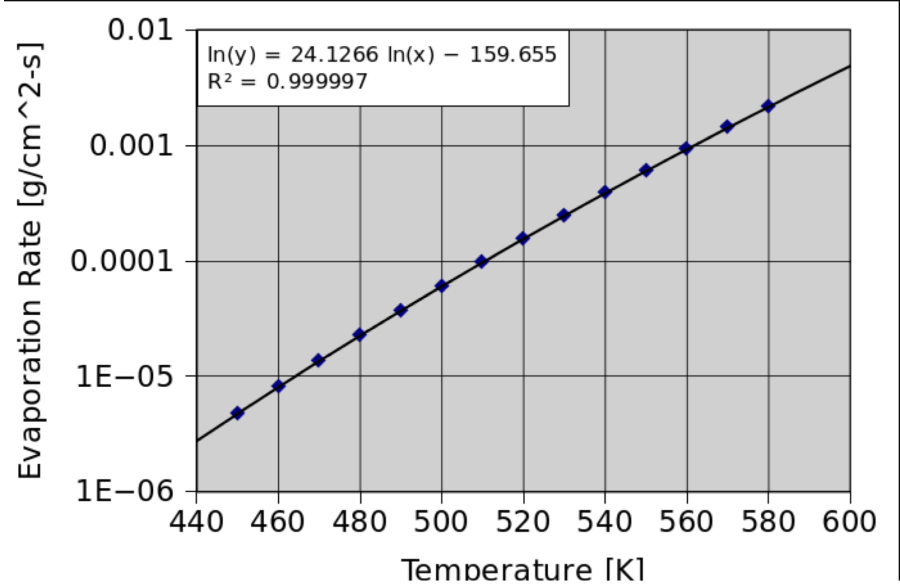
hc [W/m^2K]	T max [K]	roughness [um]	Note
11363	470.3	2.54	Ground Al on Cu
3787	470.8	2.54	SS on SS
1000	**472.4**	**N/A**	**Design Value**
500	474.7	N/A	Worst case

- Jump seen in axial temperature profile due to low gap conductance estimated by parallel conduction model:

$$h_c = \frac{1}{L_g}\left[\frac{A_c}{A}\left(\frac{2k_a k_b}{k_a + k_b}\right) + \frac{A_v}{A}k_f\right]$$ [W/m^2-K]

Ka/b = metal conductance
Kf = void conductance (vacuum: 0.00 W/m-k)
Ac = conducting area
Av = void area
A = total interface area
Lg = Interface width

Target Damage



- Cd has relatively high vapor pressure.
- At temperatures >450K, material loss due to evaporation is significant.
- At 400kW: Predicted centerline temp of 472.4K
  - Allows approximately 3 hrs of continuous operation until 80% target loss at the centerline.

T Cd [K]	Vapor P [Torr]	Evap Rate [g/cm^2*s]	80% Material Evap [hours]
400	5.86E-06	2.90E-07	168.6332
430	3.62E-05	1.61E-06	30.28961
450	0.000114007	4.78E-06	10.22473
460	0.000198397	8.08E-06	6.039236
470	0.000341165	1.35E-05	3.604665
480	0.000580013	2.25E-05	2.173424
490	0.000975344	3.69E-05	1.323332

$$\Phi_e = \frac{\alpha_e N_A (P_v - P_h)}{\sqrt{2\pi MRT}}$$ [#/m^2-s]

Na=Avagadros Const
Pv=Vapor Presssure
Ph=Chamber Pressure
Alpha_e=evaporation const (~0.9)
wfu.edu/ucerkb/Nan242/L06-Vacuum_Evaporation.pdf

Thermal Design Summary

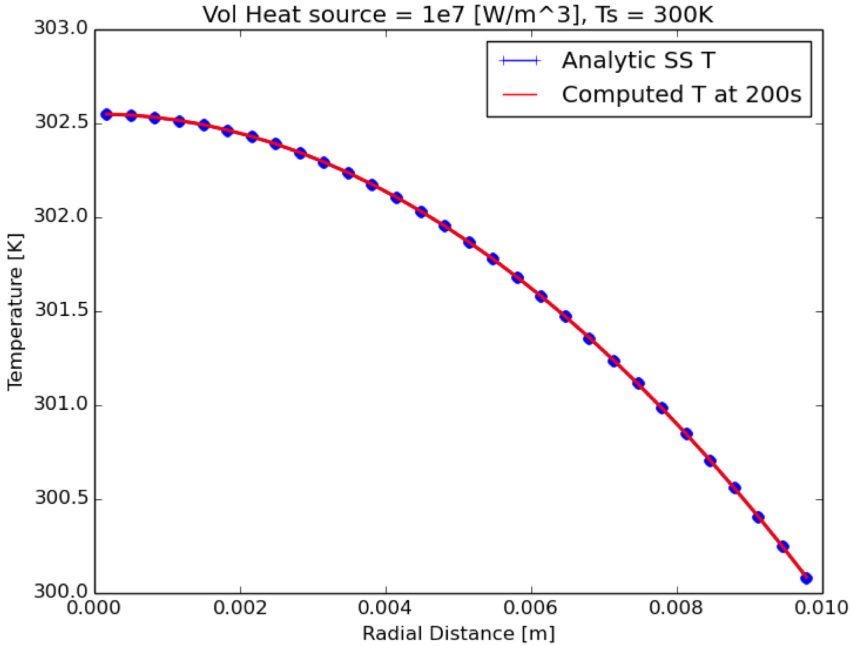
- To meet thermal performance requirements:
  - **Actively cool target edges**
    - **Target Tedge = 100K**
  - Rotate larger target / spread out heat load
  - **Control flux**
  - **Quality Cd-W interface contact**
    - **Obtain contact coefficient of > [1000 W/m^2-K]**
- Target Dimensions & Estimated performance summary:

Parameter	Value
Target Radius [cm]	7.0
Cadmium Thickness [cm]	0.0254
Tungsten Thickness [cm]	0.0127

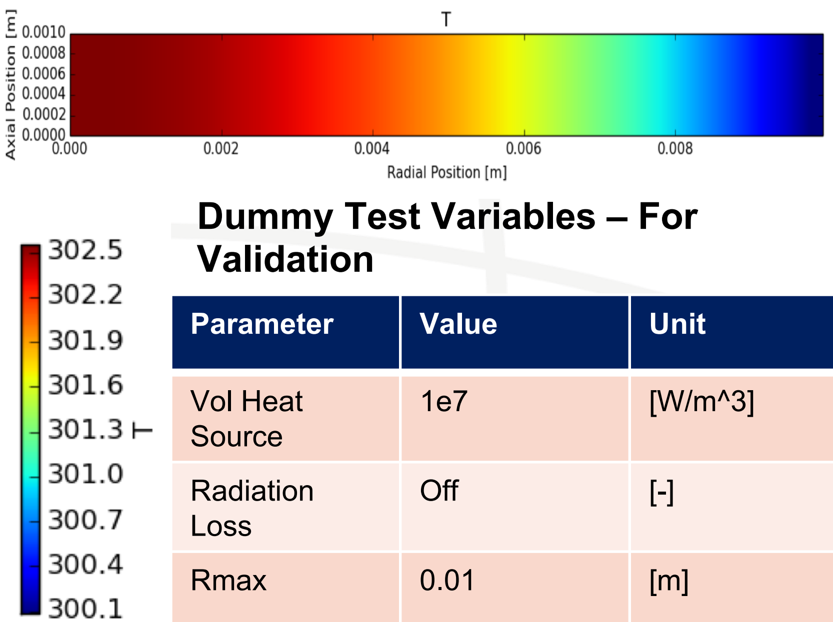
Reactor Power	400 kW	500 kW
Max Temperature [K]	472.4	565.4
Aprox. time to failure.	3 [hrs]	190 [s]
Qv Cadmium [W/cc]	48.67	60.84

Appendix: Heat Transfer Validation

- Simple 2D/1D Steady State Solution Validation



T|t=0 = 300K



Dummy Test Variables – For Validation

Parameter	Value	Unit
Vol Heat Source	1e7	[W/m^3]
Radiation Loss	Off	[-]
Rmax	0.01	[m]
Fixed T BC	300	[K]

PRELIMINARY DATA

ELECTRON (e-)

strike rate = 1 / 1.0 x 10^{-2} sec

error = 0

E = 2.8 eV

v = 187.554 mm/ μsec

POSITRON (e+)

strike rate = 1 / 3.0 x 10^{-2} sec

error = 0

E = 2.8 eV

v = 187.554 mm/ μsec

DATA COMPARISON

ELECTRON (e-)

strike rate = 1 / 1.0 x 10^{-2} sec

error = 0

v = 187.554 mm/ µsec

POSITRON (e+)

strike rate = 53 / 1.44 sec

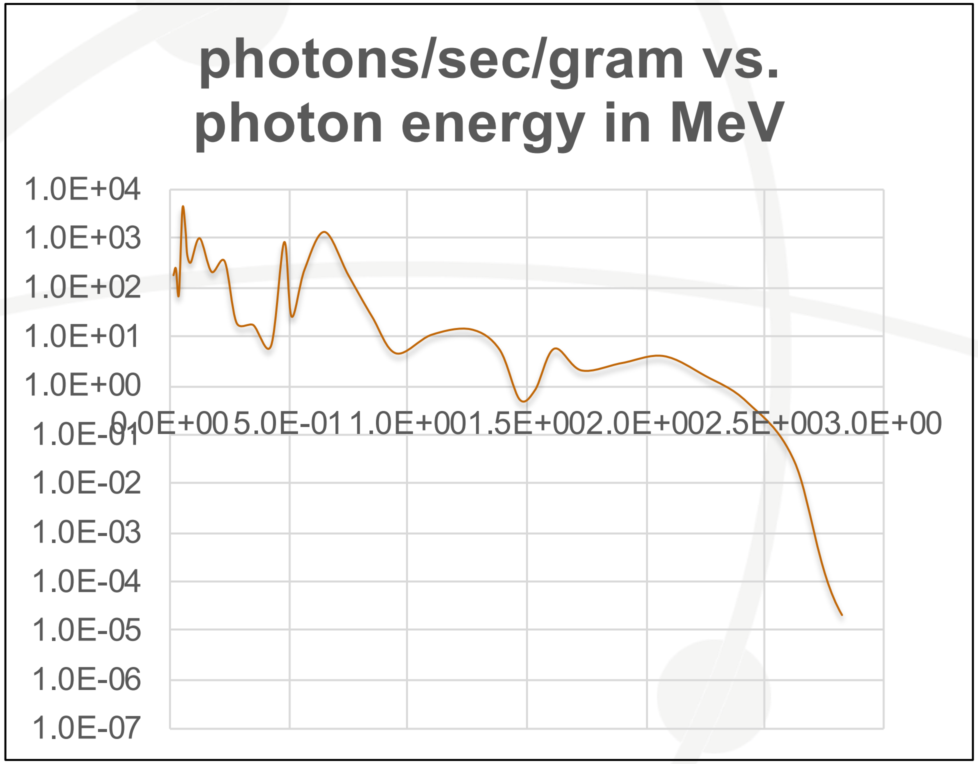
E = 512 KeV

error = 0 V

v = 993.983 mm/ µsec

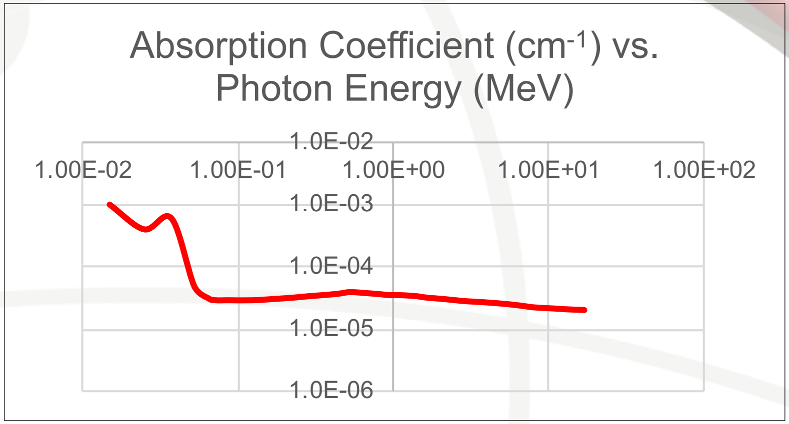
Radiation and Shielding Concerns

- By Irradiating Cd and W, Gamma radiation is produced
- The following Gamma spectrum is produced for 1 gram of Cd and 1 gram of W



Radiation and Shielding Calculations

- Using a rough plot of the Linear Absorption coefficient in air;
- Then taking the exposure rate to be flux*E*Absorption coefficient/density of air at STP;
- Exposure rate on contact can be calculated easily (which conservatively assumes all photons are traveling towards personnel from a point source, and assumes no self-shielding.



Intensity at a distance can be roughly extrapolated from the on-contact value using:

$$I(d) = S/(4*pi*d^2)$$

Radiation and Shielding Conclusions

- Personnel should not be closer to the device than 250 cm while operating

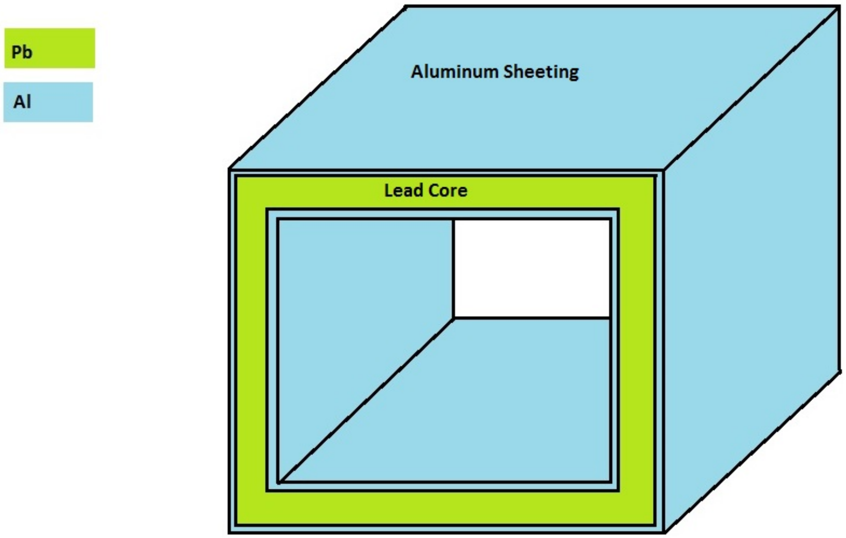
- For 1 gram of Cd and 1 gram of W:
  - on-contact exposure rate is **<0.10 mR/hr**
  - At >250 cm, personnel exposure is **< 2E-129 mR/hr** (negligible)

- For 33.8 g Cd and 37.7g W:
  - on-contact exposure rate is **<3.8 mR/hr**
  - At >250 cm, personnel exposure is **<3E-100 mR/hr** (Still negligible)

- Shielding is already required for reactor and beam-port operation. <u>No additional shielding, beyond that already required, should be necessary for this device</u>.

Idealized Shielding Box

If desired for reducing other radiation emanating from Beam Port, a box built from lead and aluminum could be used:



Exposure Refinement and Shielding Calculations

1. Further refinement of the exposure calculations are unnecessary as seen.
2. If shielding is needed, the following equations and build-up factors could be used.

Linear Attenuation Shielding Formula With Buildup:

$$I_B = I_A * b * e^{-\mu x}$$

Where:

I_B = the shielded dose rate
I_A = the initial dose rate
b = the buildup factor for one energy at the shield thickness x
μ = the linear attenuation coefficient in –cm
x = the shield thickness in cm

Linear Attenuation Shielding Formula With Buildup for Multiple Photon Energies:

$$I_B = I_A * (b_1 * f_1 * e^{-\mu_1 x} + b_2 * f_2 * e^{-\mu_2 x} + b_3 * f_3 * e^{-\mu_3 x} ... + b_i * f_i * e^{-\mu_i x})$$

Where:

I_B = the shielded dose rate
I_A = the initial dose rate
b_i = the buildup factor for each energy (up to the i^{th} energy) at the shield thickness x
μ_i = the linear attenuation coefficient for each energy (up to the i^{th} energy) in –cm
f_i = the fraction of I_A that comes from each photon energy (e in MeV) = $\frac{e_i * n_i}{\sum_i e_i * n_i}$
n_i = the yield or probability of emission factor for each atomic decay for each energy
x = the shield thickness in cm

Aluminum Build-Up Factors

	Energy (MeV)												
R (mfp)	15	10	8	6	5	4	3	2	1.5	1	0.8	0.6	0.5
0.5	1.13	1.18	1.21	1.25	1.28	1.31	1.34	1.39	1.42	1.49	1.53	1.6	1.75
1	1.23	1.32	1.39	1.48	1.57	1.62	1.7	1.83	1.93	2.10	2.22	2.41	2.57
2	1.41	1.59	1.72	1.91	2.03	2.21	2.43	2.79	3.09	3.59	3.94	4.49	4.87
3	1.58	1.85	2.05	2.33	2.53	2.8	3.18	3.82	4.37	5.35	6.04	7.14	7.91
4	1.76	2.12	2.37	2.75	3.03	3.4	3.95	4.92	5.78	7.37	8.51	10.3	11.6
5	1.95	2.4	2.71	3.18	3.53	4.02	4.75	6.08	7.3	9.64	11.3	14.1	16.1
6	2.15	2.68	3.04	3.62	4.04	4.64	5.57	7.3	8.62	12.1	14.6	18.4	21.3
7	2.35	2.97	3.39	4.06	4.56	5.28	6.42	8.57	10.6	14.1	18.1	23.3	27.3
8	2.55	3.26	3.74	4.51	5.09	5.92	7.28	9.9	12.5	17.9	22.1	28.9	34.2
10	2.97	3.86	4.44	5.43	6.16	7.22	9.05	12.7	16.3	24.5	31	41.8	50.5
15	4.11	5.45	6.27	7.79	8.91	10.6	13.7	20.3	27.2	44.3	59.2	84.9	107
20	5.36	7.15	8.18	10.3	11.8	14	18.6	28.5	39.4	68.4	95.4	143	189
25	6.71	8.96	10.1	12.8	14.7	17.5	23.6	37.4	52.7	96.2	139	217	296
30	8.15	10.9	12.2	15.2	17.6	21.1	28.8	46.8	67.1	127	190	306	430
35	9.63	12.8	14.2	17.5	20.6	24.8	34.1	56.6	82.3	162	247	410	591
40	11.1	14.8	16.2	19.5	23.3	28.4	39.4	66.6	98.2	199	310	529	780

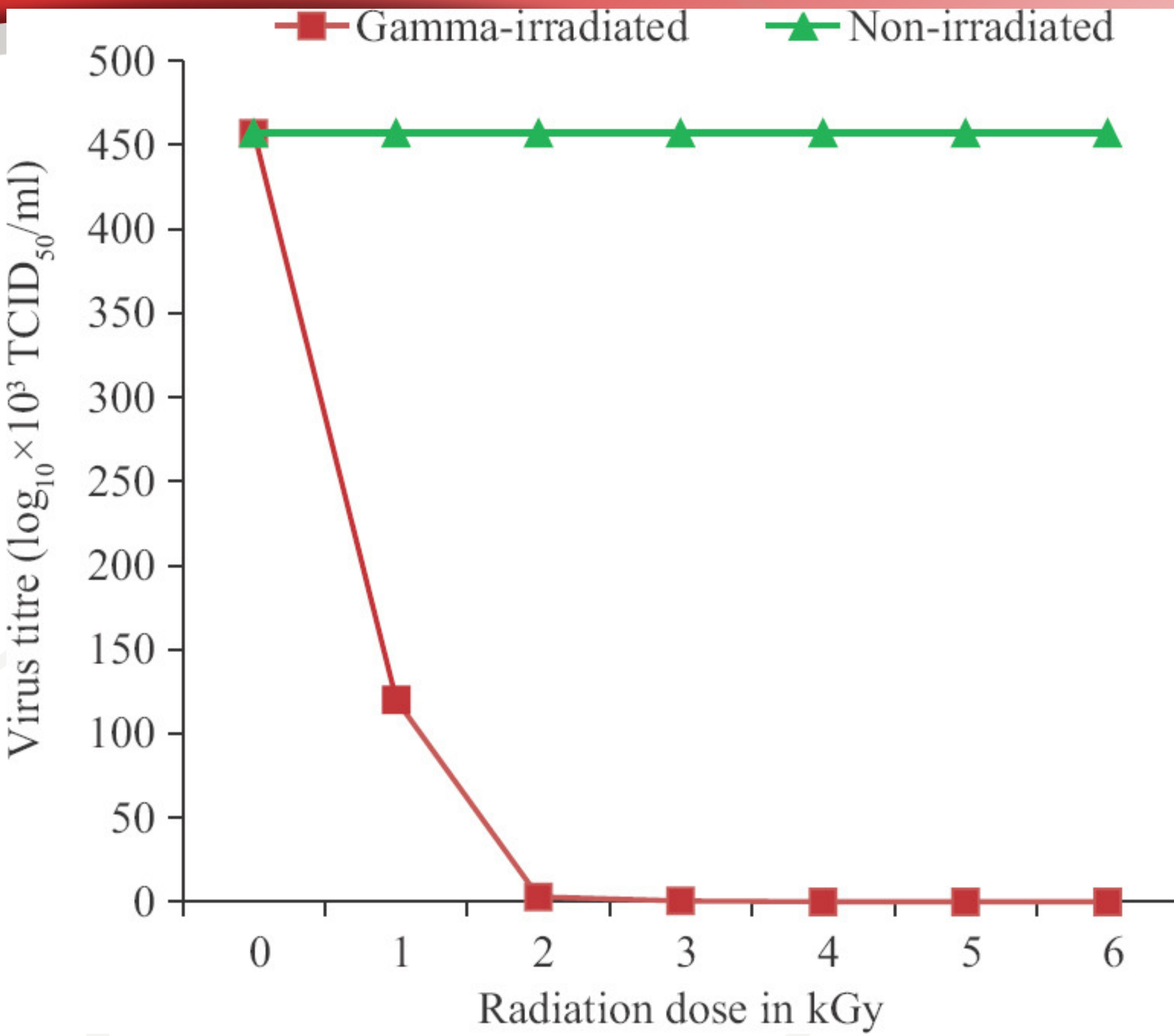
	Energy (MeV)											
R (mfp)	0.4	0.3	0.2	0.15	0.1	0.08	0.06	0.05	0.04	0.03	0.02	0.015
0.5	1.76	1.85	2.1	2.36	2.43	2.24	1.85	1.61	1.33	1.16	1.05	1.02
1	2.77	3.06	3.64	4.12	4	3.41	2.46	1.9	1.5	1.23	1.07	1.03
2	5.46	6.35	7.76	8.5	7.44	5.66	3.44	2.52	1.77	1.32	1.10	1.04
3	9.06	10.8	13.2	14	11.2	7.87	4.31	2.94	1.97	1.39	1.12	1.05
4	13.5	16.3	19.8	20.5	15.2	10.1	5.13	3.32	2.12	1.45	1.13	1.05
5	19	23	17.9	28.2	19.6	12.4	5.91	3.68	2.26	1.5	1.14	1.06
6	25.4	31.1	37.5	37.1	24.4	14.7	6.67	4.01	2.38	1.54	1.15	1.06
7	32.9	40.6	48.8	47.3	29.6	17.1	7.41	4.33	2.5	1.57	1.16	1.07
8	41.5	51.7	61.8	58.8	35.2	19.6	8.14	4.63	2.6	1.61	1.17	1.07
10	62.5	78.8	93.9	86.3	47.7	24.9	9.59	5.2	2.79	1.67	1.18	1.08
15	139	181	215	184	86.7	39.6	13.2	6.5	3.2	1.78	1.21	1.09
20	253	342	407	331	137	56.2	16.7	7.67	3.53	1.87	1.23	1.1
25	410	572	688	534	198	74.1	20.2	8.75	3.81	1.94	1.25	1.1
30	614	882	1070	801	271	94.8	23.5	9.76	4.06	2	1.26	1.11
35	867	1280	1580	1140	356	117	26.5	10.6	4.25	2.05	1.27	1.11
40	1170	1780	2220	1560	451	140	28.9	11.3	4.39	2.08	1.28	1.11

Lead Build-Up Factors

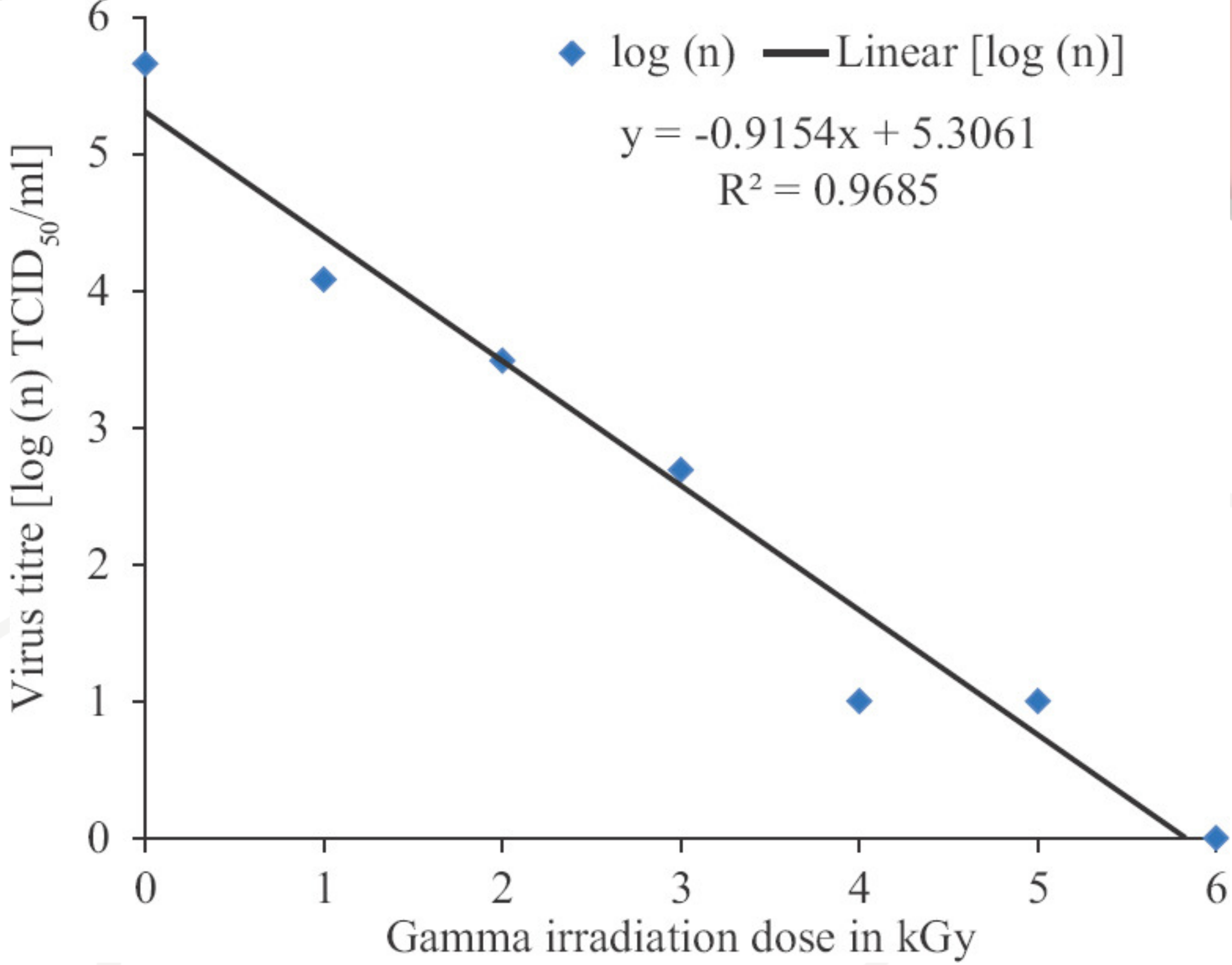
	Energy (MeV)																	
R (mfp)	15	10	8	6	5	4	3	2	1.5	1	0.8	0.6	0.5	0.4	0.3	0.2	0.16	0.15
0.5	1.32	1.35	1.4	1.41	1.44	1.43	1.49	1.48	1.43	1.46	1.43	1.36	1.48	1.45	1.47	1.45	1.45	1.45
1	1.55	1.54	1.59	1.58	1.62	1.6	1.71	1.78	1.75	1.76	1.7	1.56	1.67	1.58	1.6	1.69	1.72	1.77
2	1.99	1.88	1.89	1.84	1.89	1.91	2.11	2.28	2.29	2.23	2.09	1.85	1.92	1.76	1.66	1.91	2.03	2.20
3	2.58	2.3	2.24	2.15	2.22	2.28	2.56	2.82	2.82	2.64	2.43	2.07	2.11	1.88	1.68	2	2.2	2.52
4	3.42	2.85	2.66	2.5	2.59	2.68	3.03	3.35	3.31	2.99	2.7	2.25	2.26	1.98	1.69	2.05	2.32	2.81
5	4.61	3.54	3.17	2.91	3	3.12	3.55	3.9	3.81	3.32	2.95	2.41	2.40	2.06	1.7	2.08	2.42	3.10
6	6.26	4.4	3.79	3.4	3.48	3.61	4.12	4.5	4.34	3.68	3.22	2.58	2.53	2.15	1.72	2.09	2.49	3.39
7	8.56	5.5	4.53	3.94	4.02	4.15	4.72	5.08	4.85	4.00	3.45	2.72	2.65	2.22	1.73	2.1	2.56	3.72
8	11.8	6.87	5.41	4.56	4.6	4.73	5.34	5.68	5.36	4.30	3.67	2.85	2.76	2.28	1.75	2.11	2.64	4.11
10	22.6	10.8	7.76	6.08	6.01	6.06	6.73	6.95	6.4	4.90	4.1	3.11	2.97	2.41	1.77	2.13	2.8	5.14
15	117	338	19	12.1	11.1	10.4	10.8	10.3	9.08	6.26	5.03	3.65	3.41	2.66	1.83	2.15	3.28	9.52
20	594	105	45.9	23.1	19.1	16.4	15.7	13.9	11.8	7.44	5.82	4.08	3.77	2.87	1.87	2.16	3.85	21.7
25	2930	319	108	42.6	31.3	24.3	21.2	17.7	14.6	8.48	6.49	4.44	4.07	3.04	1.91	2.16	4.5	56.6
30	14100	944	249	75.7	49.3	34.4	27.4	21.5	17.2	9.41	7.09	4.75	4.33	3.18	1.94	2.17	5.45	160
35	66200	2730	562	131	75.1	47	34.1	25.5	19.7	10.3	7.64	5.03	4.56	3.3	1.97	2.17	6.89	473
40	305000	7750	1240	221	111	62.4	41.4	29.1	22.2	11.1	8.13	5.28	4.76	3.41	1.99	2.18	9.1	1440

	Energy (MeV)												
R (mfp)	0.14	0.13	0.12	0.11	0.1	0.09	0.089	0.088	0.08	0.06	0.05	0.04	0.03
0.5	1.46	1.43	1.46E+00	1.45E+00	1.44E+00	1.48E+00	1.48E+00	1.07	1.05	1.02	1.02	1.01	1.01
1	1.81	1.51	1.85E+00	1.88E+00	1.89E+00	2.00E+00	2.01E+00	1.1	1.08	1.04	1.02	1.01	1.01
2	2.41	1.61	2.62E+00	2.85E+00	3.05E+00	3.49E+00	3.54E+00	1.12	1.1	1.05	1.03	1.02	1.01
3	2.96	1.67	3.52E+00	4.20E+00	4.92E+00	6.24E+00	6.39E+00	1.14	1.11	1.06	1.04	1.02	1.01
4	3.59	1.72	4.71E+00	6.30E+00	8.25E+00	1.18E+01	1.22E+01	1.15	1.12	1.06	1.04	1.02	1.01
5	4.33	1.76	6.40E+00	9.71E+00	1.44E+01	2.31E+01	2.41E+01	1.16	1.13	1.06	1.04	1.02	1.01
6	5.23	1.8	8.77E+00	1.52E+01	2.54E+01	4.59E+01	4.85E+01	1.18	1.14	1.07	1.05	1.03	1.01
7	6.41	1.84	1.23E+01	2.41E+01	4.50E+01	8.78E+01	9.38E+01	1.19	1.15	1.07	1.05	1.03	1.01
8	7.68	1.87	1.72E+01	3.77E+01	7.67E+01	1.66E+02	1.79E+02	1.19	1.16	1.08	1.05	1.03	1.02
10	12.2	1.92	3.39E+01	9.20E+01	2.32E+02	6.11E+02	6.71E+02	1.21	1.17	1.08	1.05	1.03	1.02
15	45.7	2.03	2.34E+02	1.08E+03	4.33E+03	1.75E+04	2.00E+04	1.24	1.19	1.09	1.06	1.04	1.02
20	220	2.12	2.06E+03	1.55E+04	9.54E+04	5.66E+05	6.71E+05	1.26	1.21	1.1	1.06	1.04	1.02
25	1190	2.19	2.01E+04	2.49E+05	2.33E+06	1.99E+07	2.44E+07	1.28	1.22	1.11	1.07	1.04	1.02
30	6680	2.25	2.04E+05	4.19E+06	6.02E+07	7.40E+08	9.36E+08	1.3	1.24	1.11	1.07	1.04	1.02
35	38500	2.3	2.10E+06	7.20E+07	1.61E+09	2.86E+10	3.74E+10	1.31	1.25	1.12	1.08	1.05	1.02
40	225000	2.35	2.18E+07	1.25E+09	4.35E+10	1.12E+12	1.53E+12	1.32	1.26	1.12	1.08	1.05	1.02

Equations from http://www.hps.org/documents/shielding_of_gamma_radiation.pdf, tables from Nucleonica.com

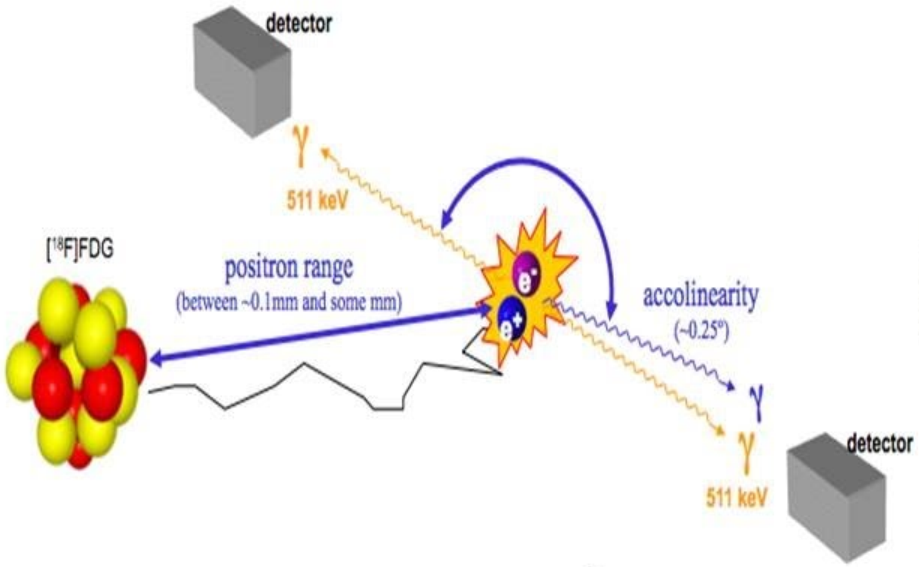


Gamma-irradiated
Non-irradiated
Virus titre (log10×10^3 TCID50/ml)
500
450
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
Radiation dose in kGy



log (n)
Linear [log (n)]
y = -0.9154x + 5.3061
R² = 0.9685
Virus titre [log (n) TCID50/ml]
0
1
2
3
4
5
6
Gamma irradiation dose in kGy

Interaction of Positron and Electron capture and their Energy loss



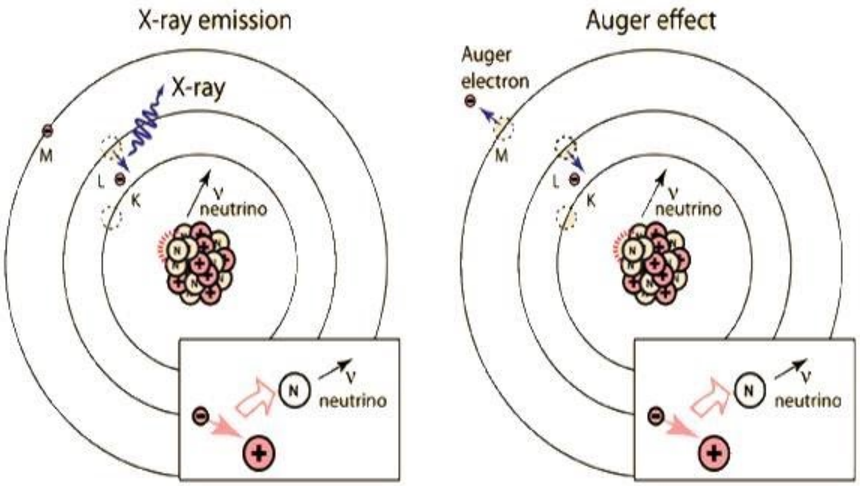


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Image 24: https://www.hzdr.de/db/Cms?pOid=11150&pNid=69

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