The Conceptual Design of the PXIE Beam Dump. Radiation Shielding and PXIE Complex Enclosure

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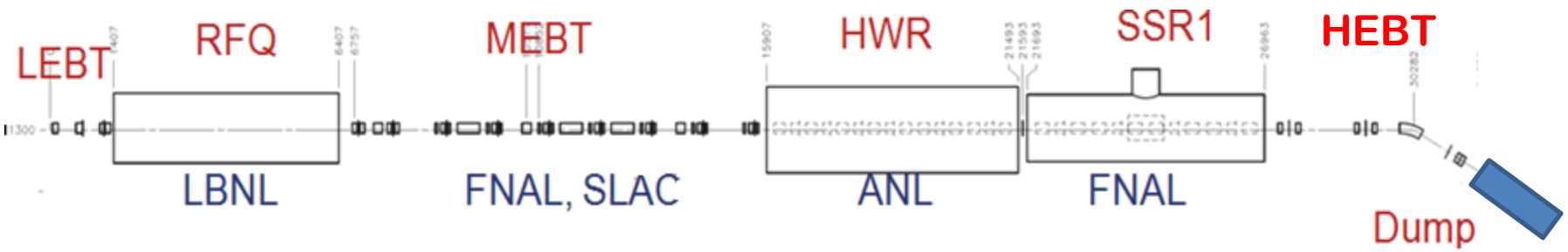
Outline:

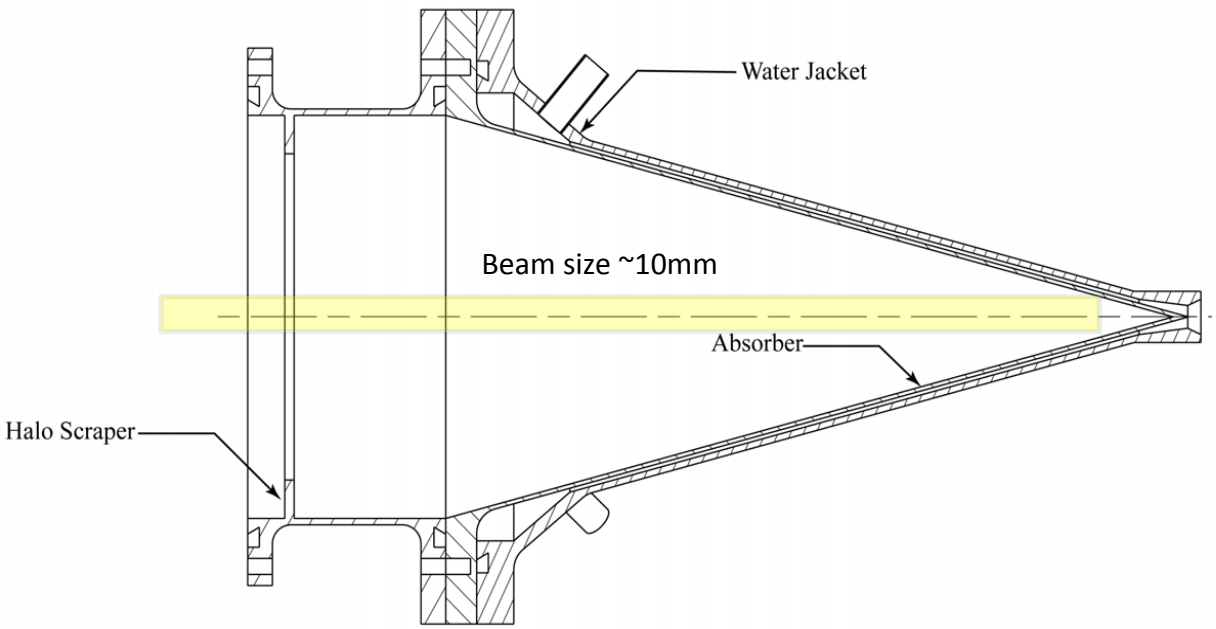
- Prototypes
- Beam Dump Layout
- Data for Beam Dump Materials
- Back Scattering (*TRIM* Simulation)
- Sputtering (*TRIM* Simulation) and Blistering
- Water Cooling
- Radiation Shielding (*MARS* Simulation)
    - *Beam Dump Attenuation*
    - *Exits from Labyrinth*
    - *Roof*
    - *Tritium Production in soil*
- Future Work

PXIE Beam Parameters



Parameter	Nominal Energy	Max Energy	Units
Energy	25	30	MeV
Beam current (H^-)	2	1.7	mA
Beam power	50	50	kW
H^- flux	4.5×10^{19}	3.8×10^{19}	Ions/hr
Operation time	2300	2300	hrs/year
Total particles to absorber	1×10^{23}	8.8×10^{22}	Ions/year

Prototypes: SNS Beam Stop

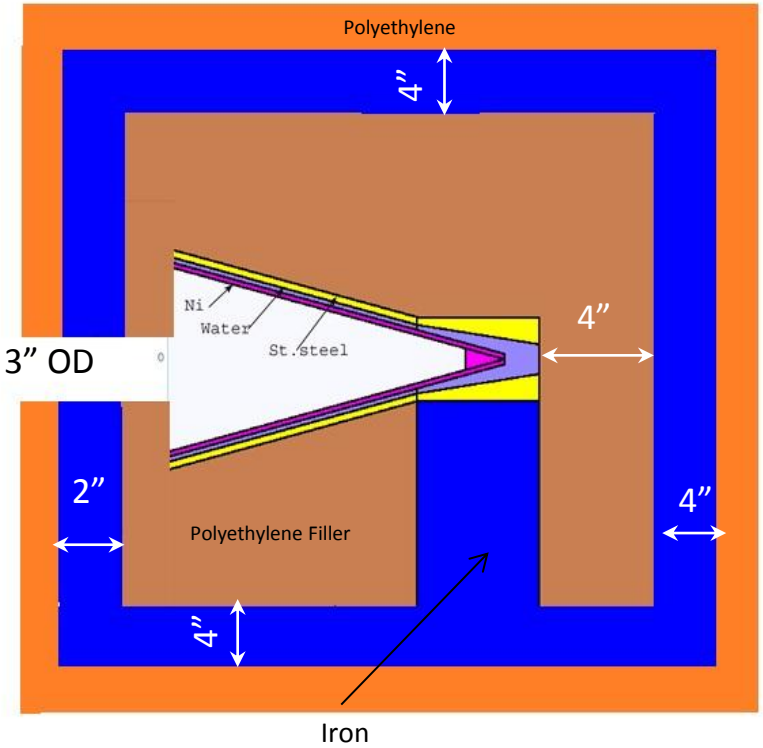


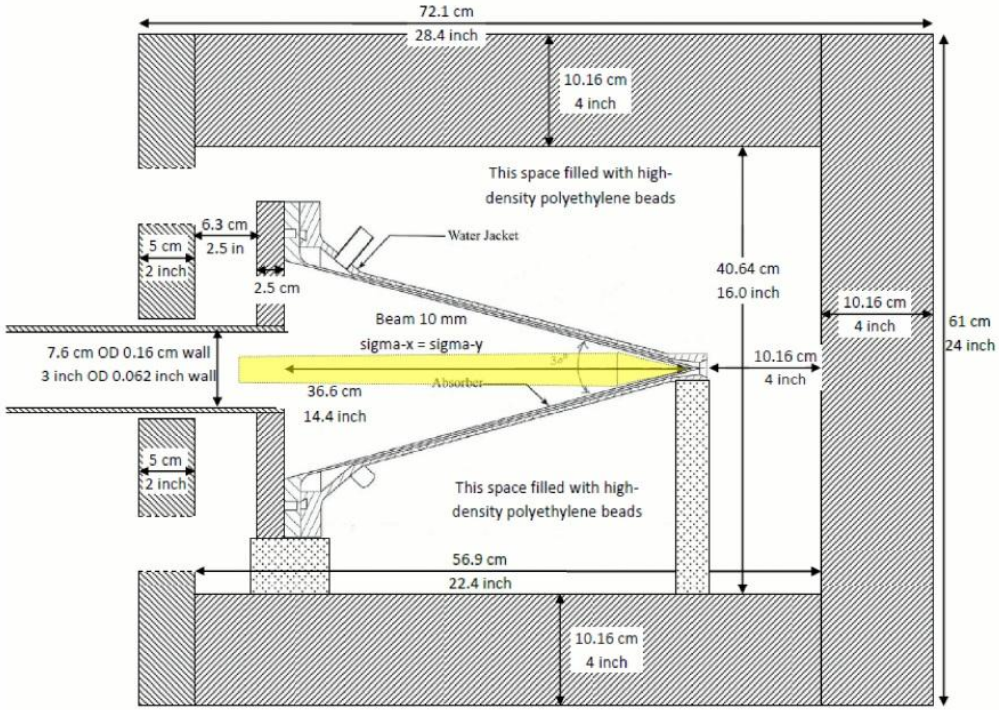
Beam Characteristics	
Operation Pulse	60 Hz
Energy and current	7.5 MeV at 36mA, Gaussian
Duration	1 ms
Physical Features	
Dimensions	30.5cm ODx 44cm Length
Beam Centerline length	35 cm
Beam stop geometry	Axisymmetric cone
Beam stop Dimensions	20cm ID 35cm Length
Beam stop Material	Nickel 200
Coolant	DI Water
Coolant flow direction	Rotational and counterflow to beam direction
Thermal Management	
Total heat removed	16 kW
Maximum Average Heat Flux	277 W/cm^2 (at the tip of the cone)
Water flow rate	0.00063 m^3/s (10 gpm)
Water pressure	2.34 MPa (340 psi)
Water velocity	6.2 m/s
Temperature rise	6.5 C
Slope of the beam stop	3.5 cm/cm

References:

1. Steve Ellis. "SNS DTL D-Plate Beam Stop Engineering Review".http://projectx-docdb.fnal.gov/cgibin/RetrieveFile?docid=572;filename=Ellis_Beam_stop_engineering_review_6Feb02.pdf;version=1
2. "Thermal and Structural Analysis af a Beam Stop". SNS01_PUB_0547. http://www.sns.gov/diagnostics/papers/Physics%20-%20Model/Publications%20and%20Presentations/Thermal%20and%20Structural%20Analysis%20of%20a%20Beam%20Stop.pdf

Prototypes: HINS Beam Absorber

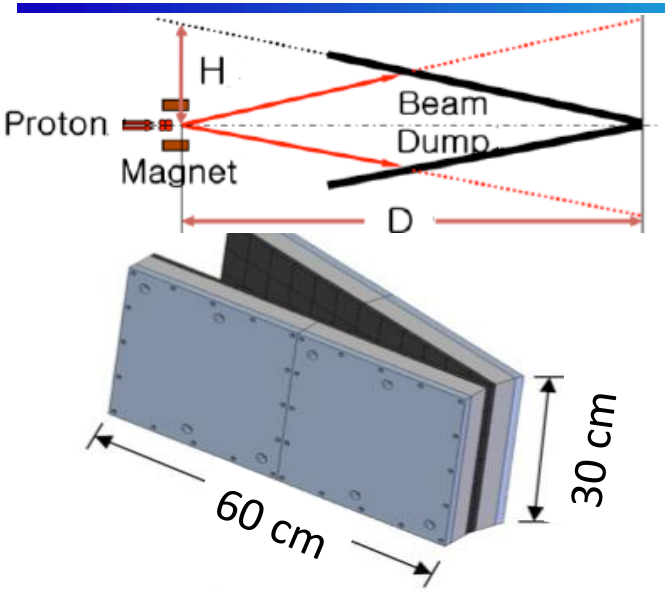




Energy Beam: 3 - 10 MeV
Intensity: 1% of 25 mA ($5 \cdot 10^{18}$ p/hr)
Power: 0.75 – 2.5 kW
Operation: 500 hr/year

References:
N. Mokhov. “HINS Beam Absorber MARS15 Simulations”. http://beamdocs.fnal.gov/AD/DocDB/0035/003597/002/HINS_mokhov_042810.pdf
P. Kasper. “The HINS Linac Shielding Assessment”. http://projectx-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=655

Prototypes: 20 MeV Beam Dumps for A Korean Proton Accelerator



- Beam dump material **: Graphite (IG 430), Copper (OFHC), SUS 304**
- Brazing filler metal : TiCuSil (Ti: 4.5 %, Cu : 27.7%, Silver 68.8%) : tails= 5cmx5cmx1cm
- Two plates (30 cm x 60 cm, angle 15°)
- Power : **96kW (20 MeV, 4.8mA)**
- Peak heat flux : **200 W/cm^2**
- Maximum Temperature : **Graphite : 223 ℃, Copper : 146 ℃, Cooling Water : 85 ℃**

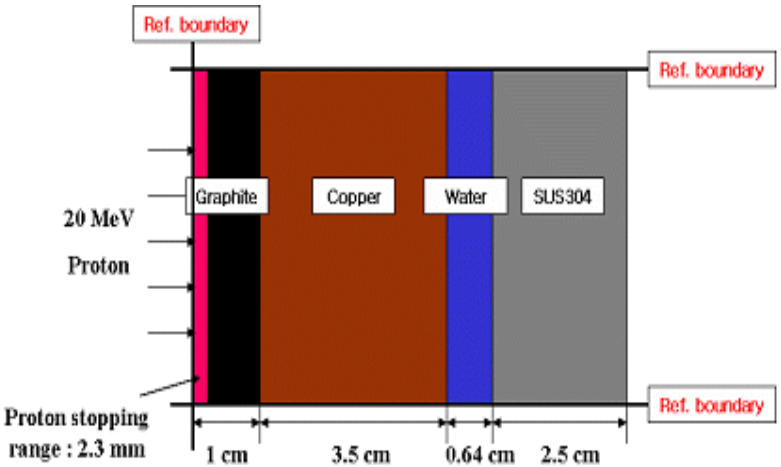
References:

1. C-S. Gil et al. "Beam Dump Development for a Korean Proton Accelerator". Proceedings of HB2010, Morschach, Switzerland. THO2A02. http://epaper.kek.jp/HB2010/papers/tho2a02.pdf ; http://hb2010.web.psi.ch/talks/THO2A02_talk.pdf

Prototypes: 20 MeV Beam Dumps (details)

Activation analysis:

- MCNP Calculation;
- Table shows residual activity after 3 hours operation with 20 MeV, 4.8 mA proton beam

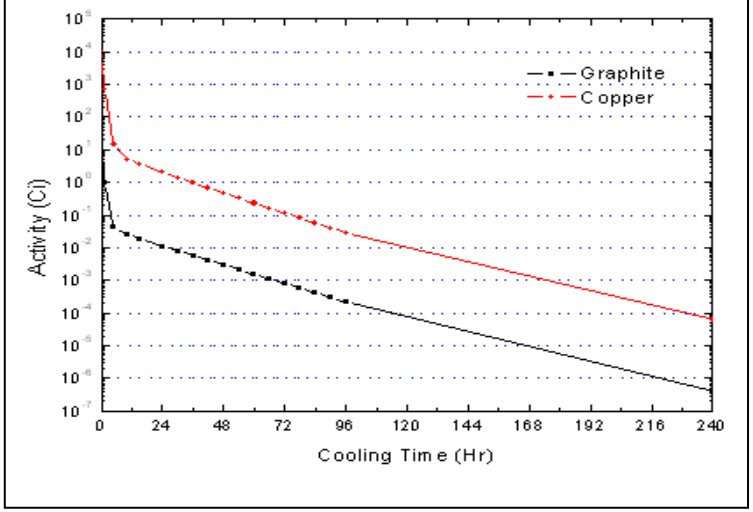


Comparison of the Residual Activities in Graphite and Copper Beam Dump

	Particle	Activity (Ci)			
		Graphite	Copper	SUS	Total Activity (Ci)
Graphite + Copper	Proton	25.6	-	-	35.7
	Neutron	-	9.9	0.2	
Copper	Proton	-	9751		10276.9
	Neutron		521	4.9	

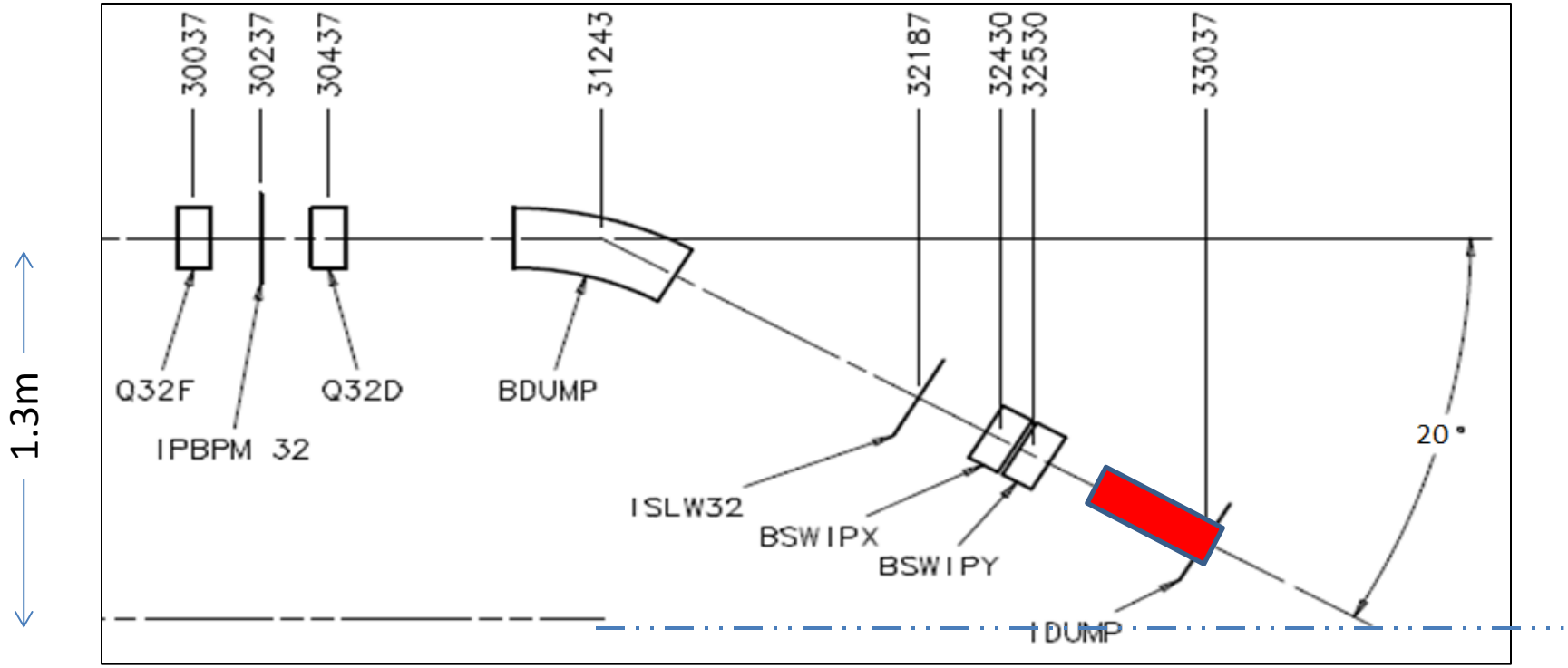
Note: 100 MeV dump was designed using copper

Model for MCNP Calculation



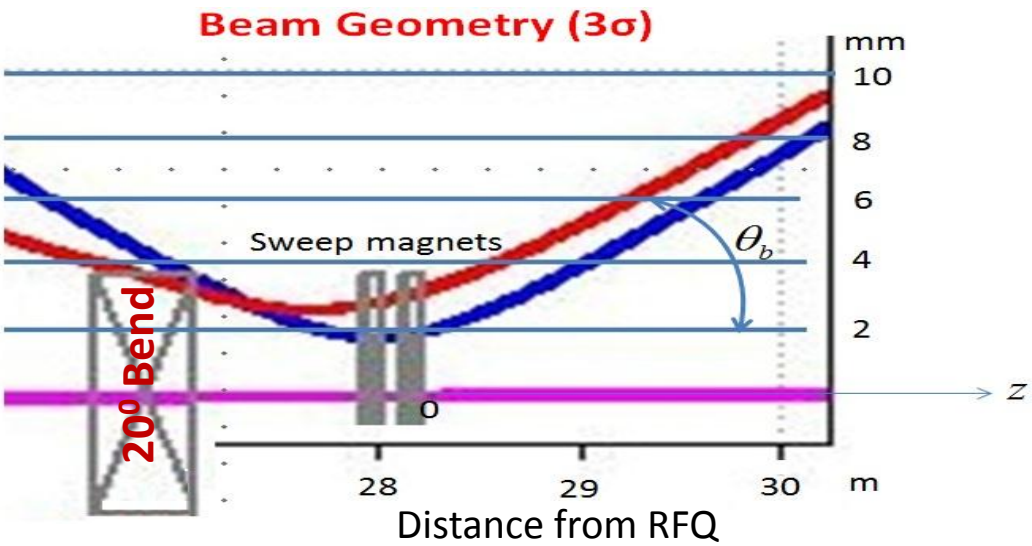
PXIE Beam Dump Layout

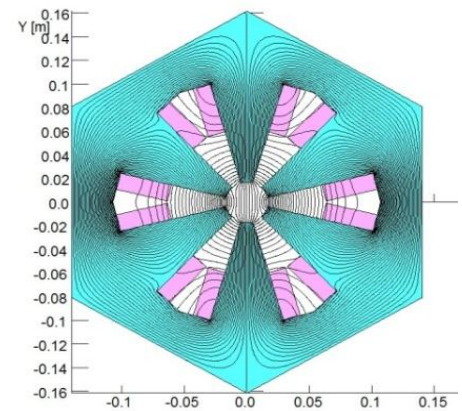
The primary beam absorber (dump) for the PXIE 30 MeV CW H^- accelerator is located at the end of the diagnostics line downstream of a 20° vertical bending magnet.



Mechanical Engineering layout of the end of the diagnostics line and the beam dump (not updated).

PXIE Beam Dump Layout (2)



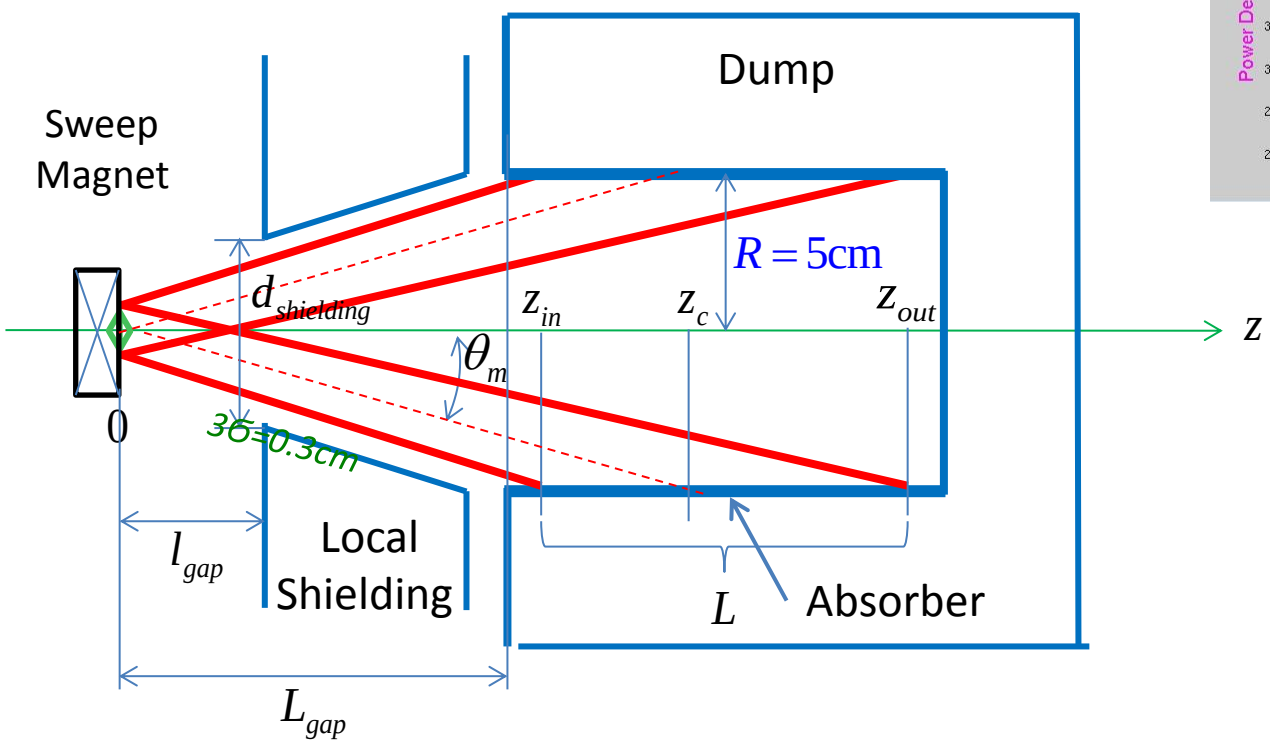


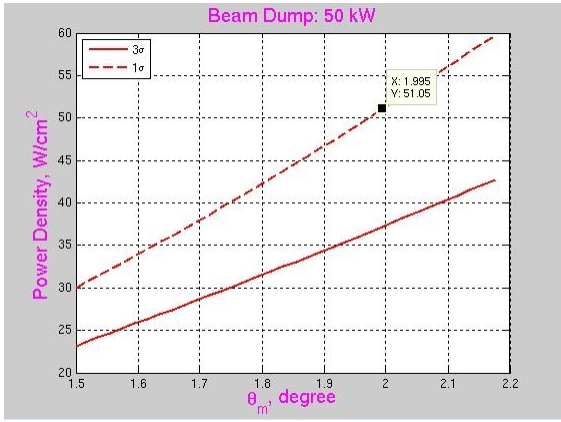
sweeping magnet cross-section

$\Theta_{beam} = 3mrad = 0.175°$

Parameter	Unit	Value
Magnet aperture (diameter)	mm	34
Integrated dipole peak field	T-m	0.04
Magnet effective length	mm	200
Good field area diameter	mm	23
Field homogeneity at 11.5 mm radius	%	± 16
Peak dipole field in the magnet center	T	0.2
Peak / R.M.S. current at 60 Hz	A	250 /177
Total power	W	810
Copper conductor with the cooling hole	mm	6.5x6.5 dia. 3.0
Coil number of turns		12
Power source		AC, 3-phase, 60 Hz
Magnet width / length	mm	280 / 260
Water pressure drop	MPa	0.4
Water temperature rise	°C	24

PXIE Beam Dump Layout (4)





$\Theta_m = 2°$
$L_{gap} = 120$ cm
$Z_c = 143.6$ cm
$Z_{in} = 123.8$ cm
$Z_{out} = 166.4$ cm
Ldump=43 cm

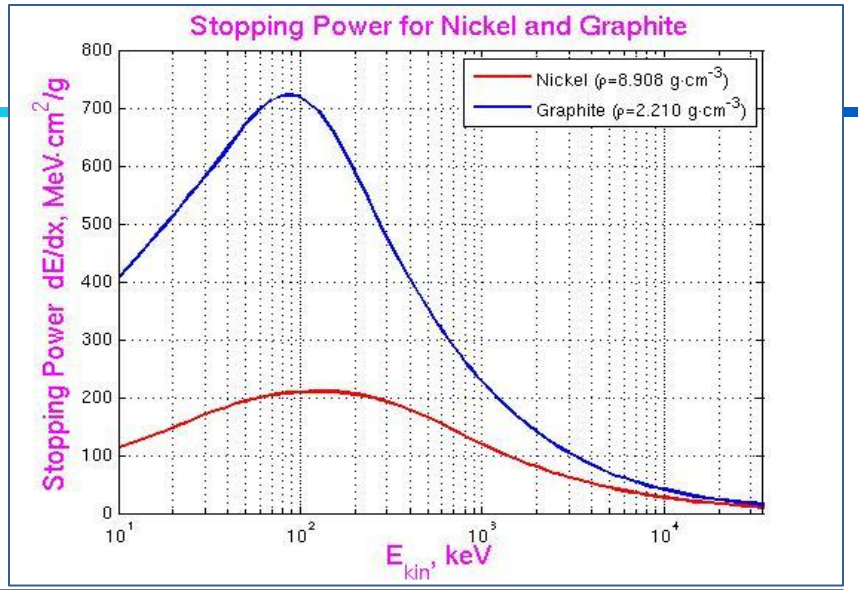
Beam Dump Materials

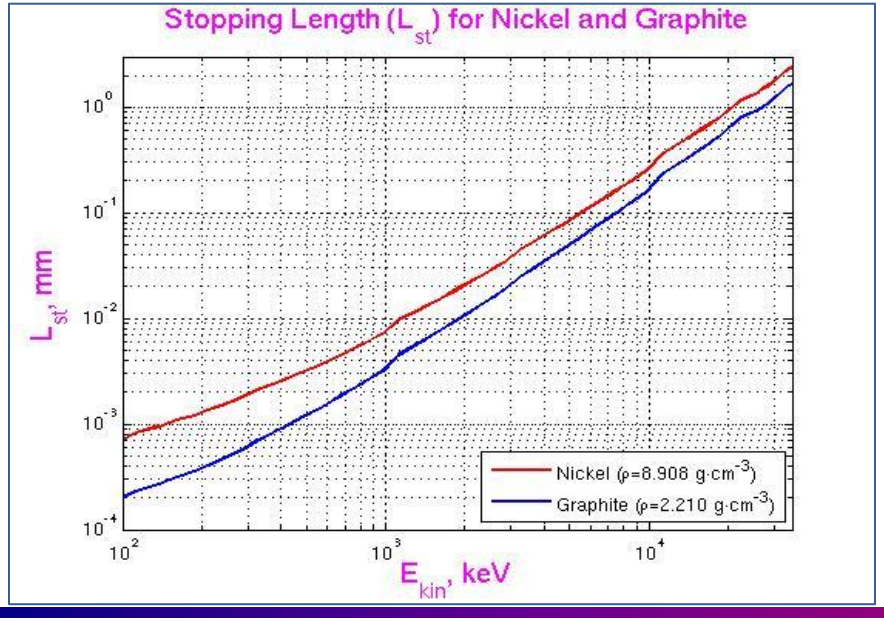
Multiple Scattering: Nickel vs. Graphite

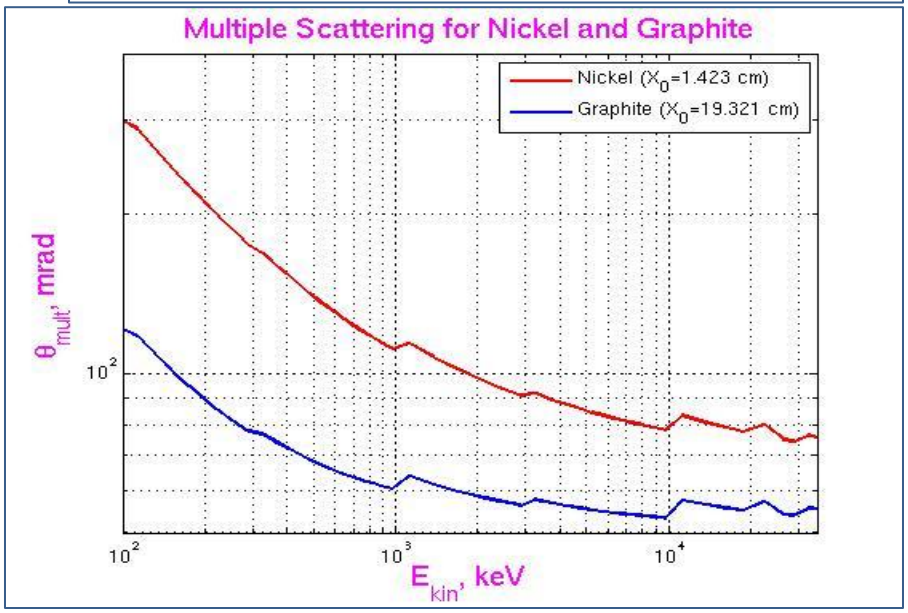
$$L_{st}(E_{kin}) = \int_0^{E_{kin}} \left(\frac{dE}{dx}\right)^{-1} dE;$$

$$\beta cp = E_{kin}\frac{E_{kin}+2m_p}{E_{kin}+m_p};$$

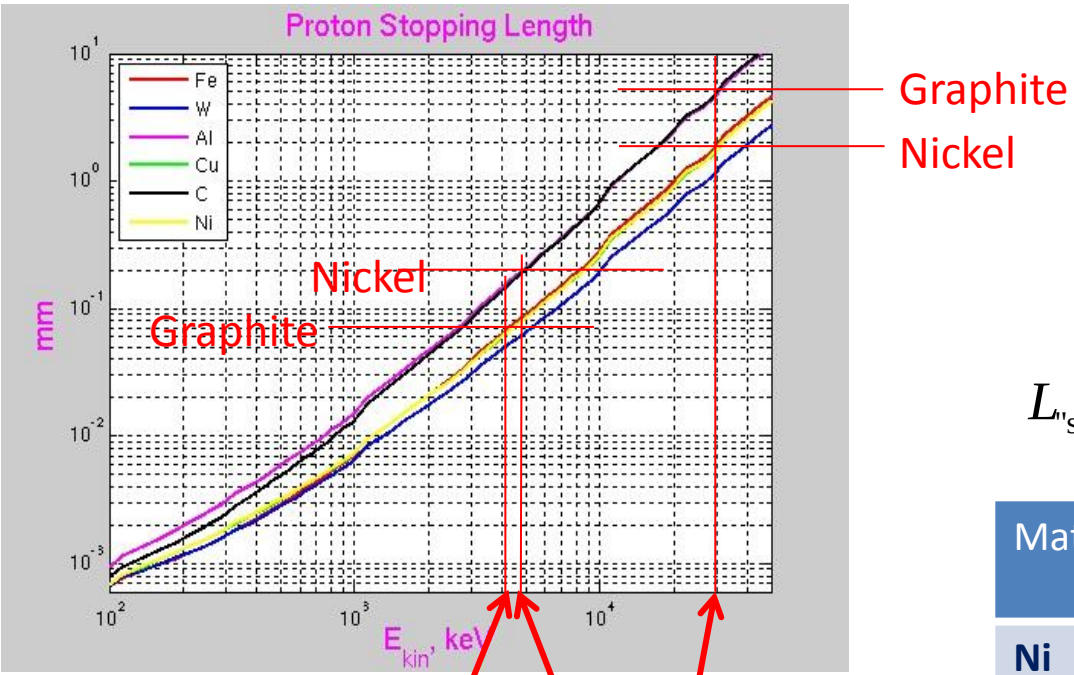
$$\theta_{mult}(E_{kin}) = \frac{13.6\ \text{MeV}}{\beta cp}\sqrt{\frac{L_{st}}{X_0}}\left(1+0.038\cdot\ln\frac{L_{st}}{X_0}\right).$$







Data for Beam Dump Materials

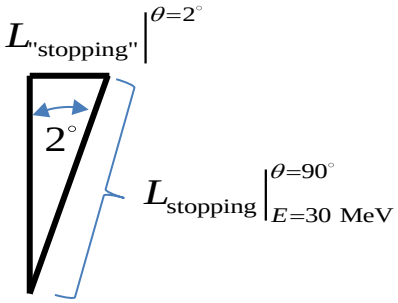


"Effective" $E_{stopping}$ (MeV):

≈4.0

≈4.75

30 MeV



$$L_{"stopping"}\Big|^{\theta=2^\circ} \approx \sin 2^\circ \cdot L_{stopping}\Big|^{\theta=90^\circ}_{E=30\ \mathrm{MeV}}.$$

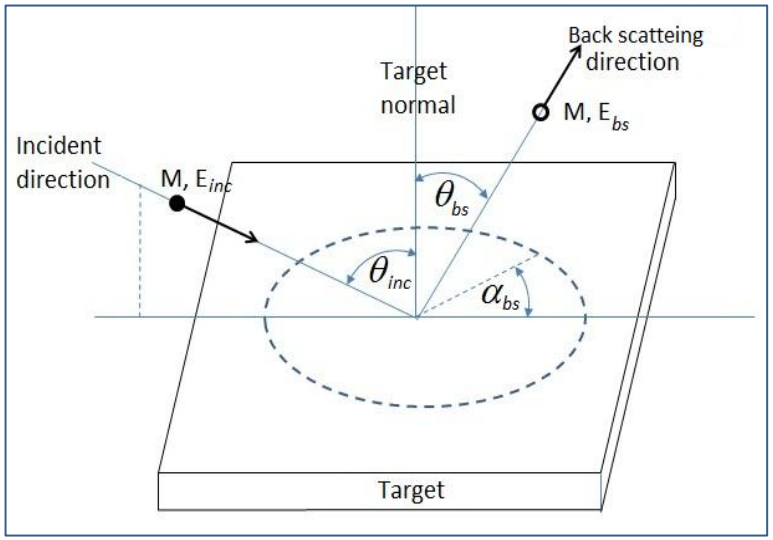
Material	L_{st} (90°) µm	L_{st} (2°) µm	E_{eff} MeV
Ni	1950	70	4.0
C	5440	200	4.75
Cu	1950	70	4.0
Fe	1950	70	4.0
Al	5440	200	4.75

Back Scattering (1)

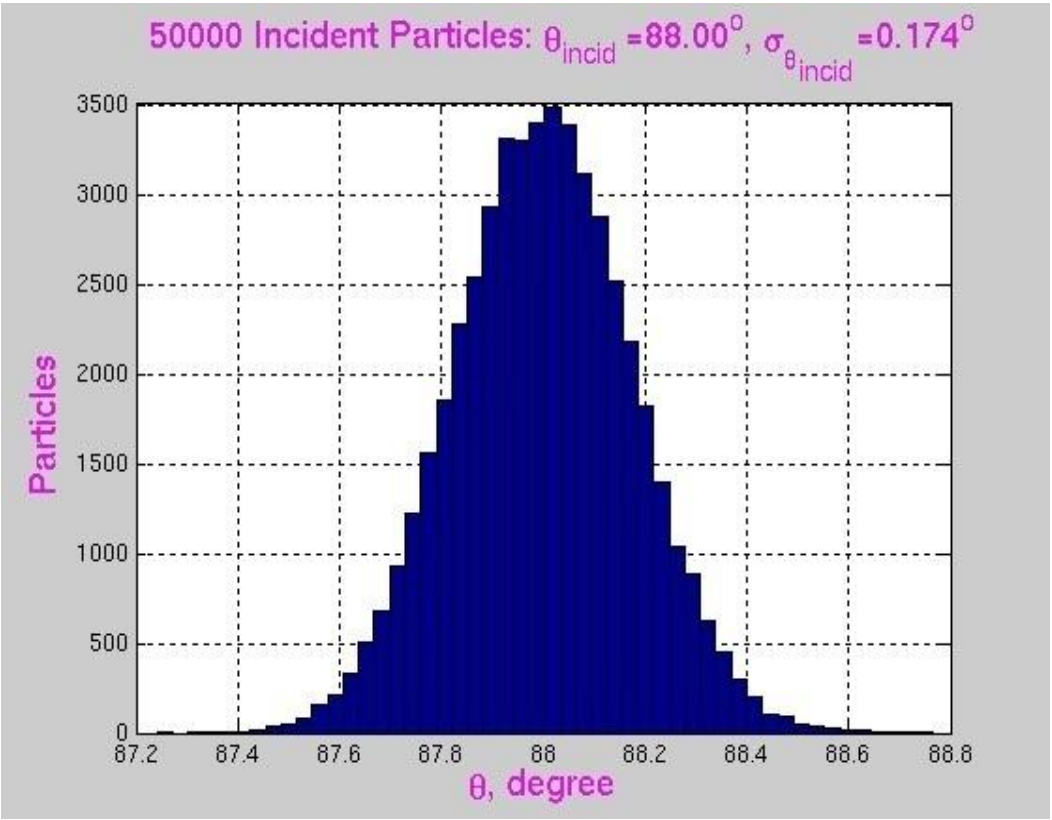
Back Scattering Simulation: Code *SRIM*

50,000 Incident Particles

Back Scattering Geometry



Distribution of Incident Particles

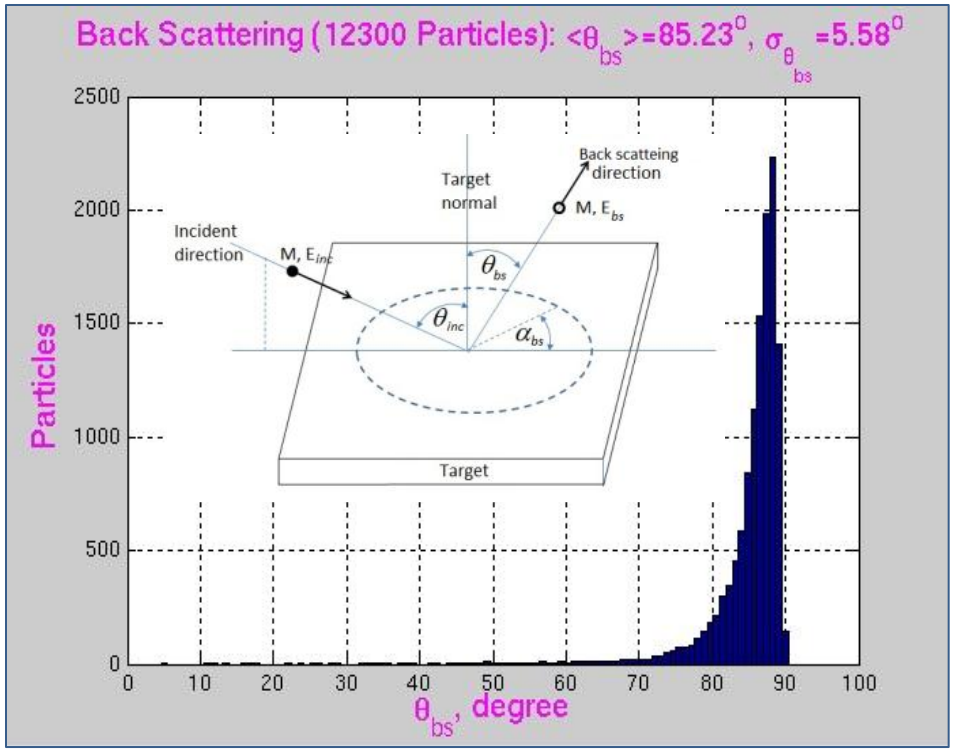


Back Scattering (2)

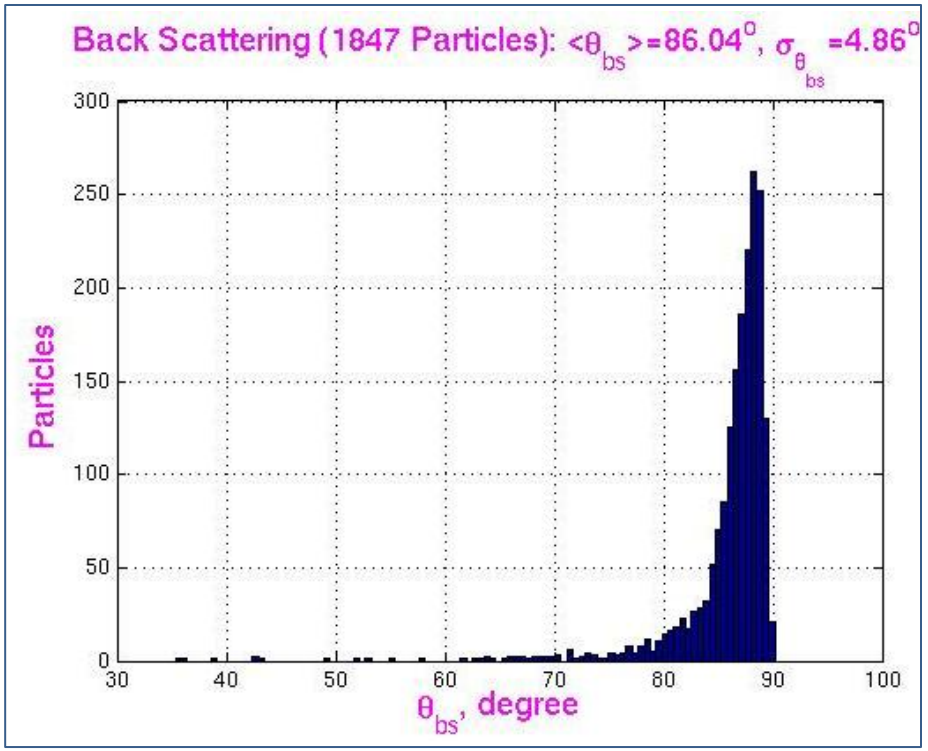
Particle Distribution vs. Back Scattering Angle

50,000 Incident Particles

Nickel



Graphite

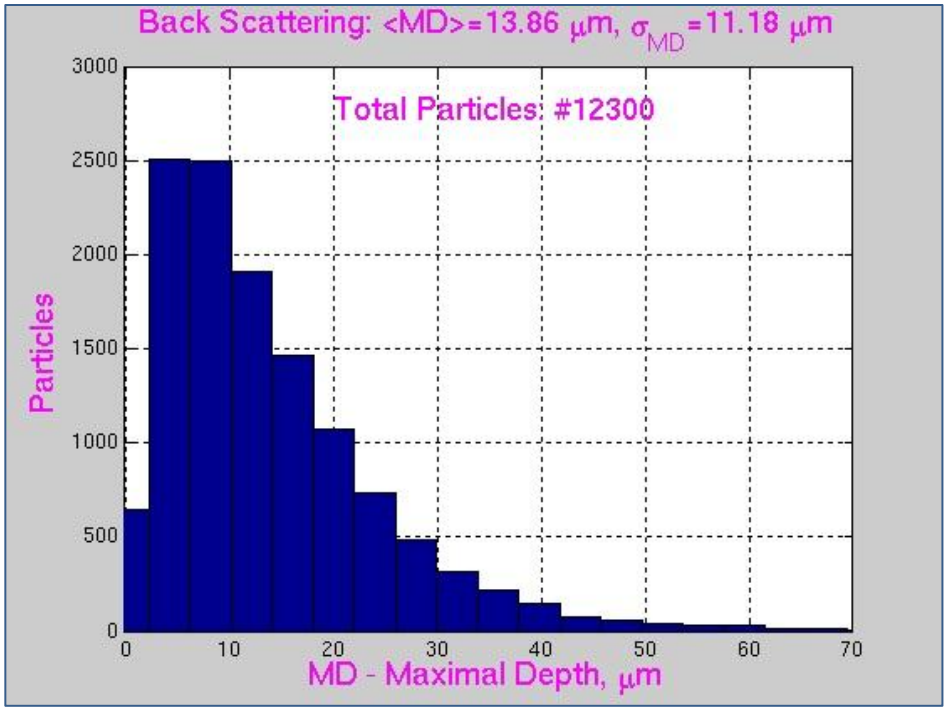


Back Scattering (3)

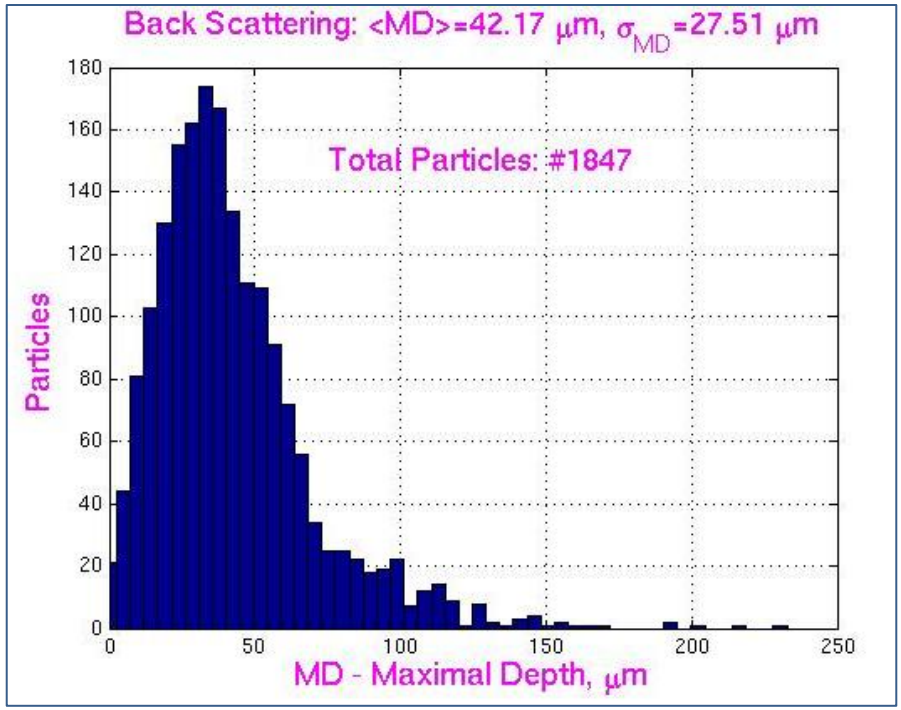
Penetration of the Back Scattered Particles to the Beam Dump

50,000 Incident Particles

Nickel



Graphite (Carbon)



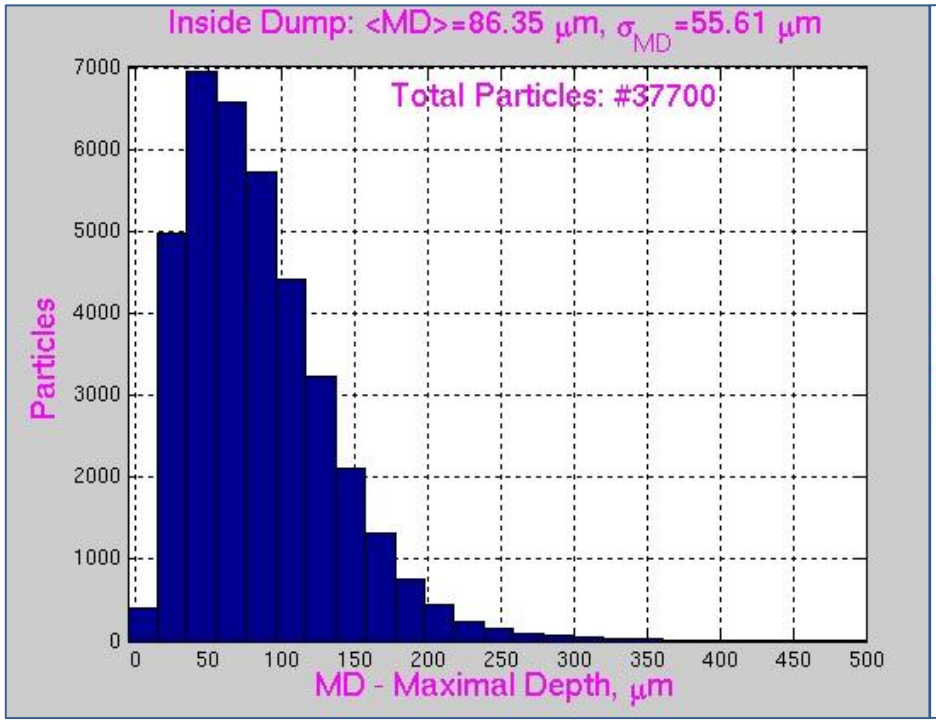
Back Scattering (4)

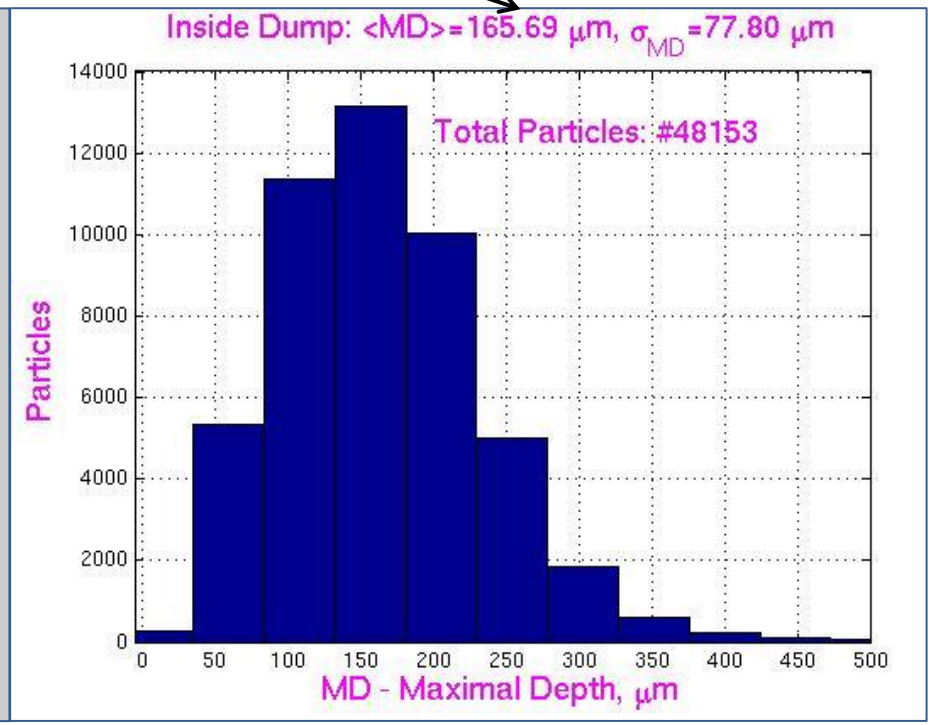
Penetration of the Incident Particles to the Beam Dump

Data for Beam Dump Materials :

70 µm — Nickel

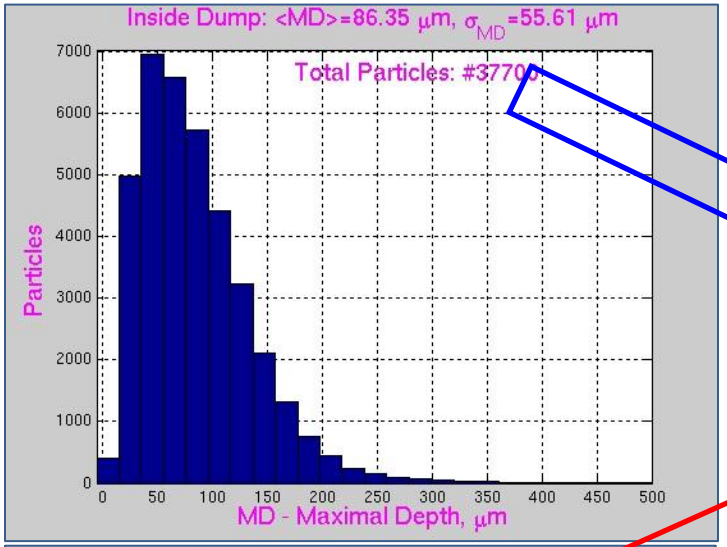
200 µm — Graphite (Carbon)

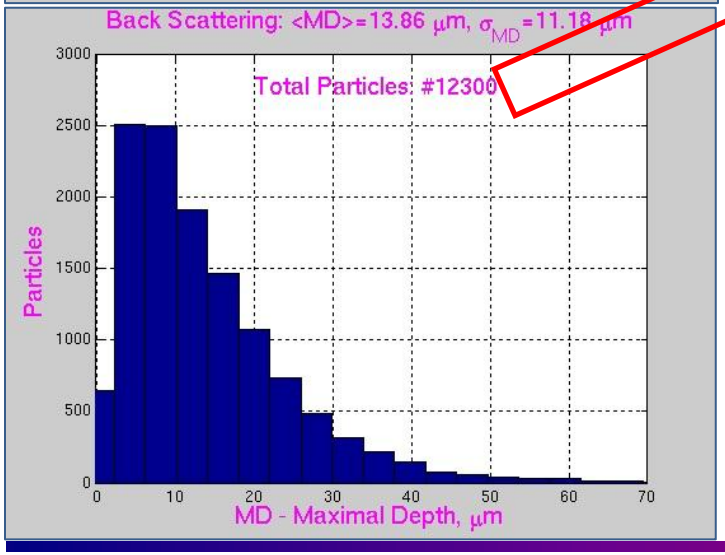


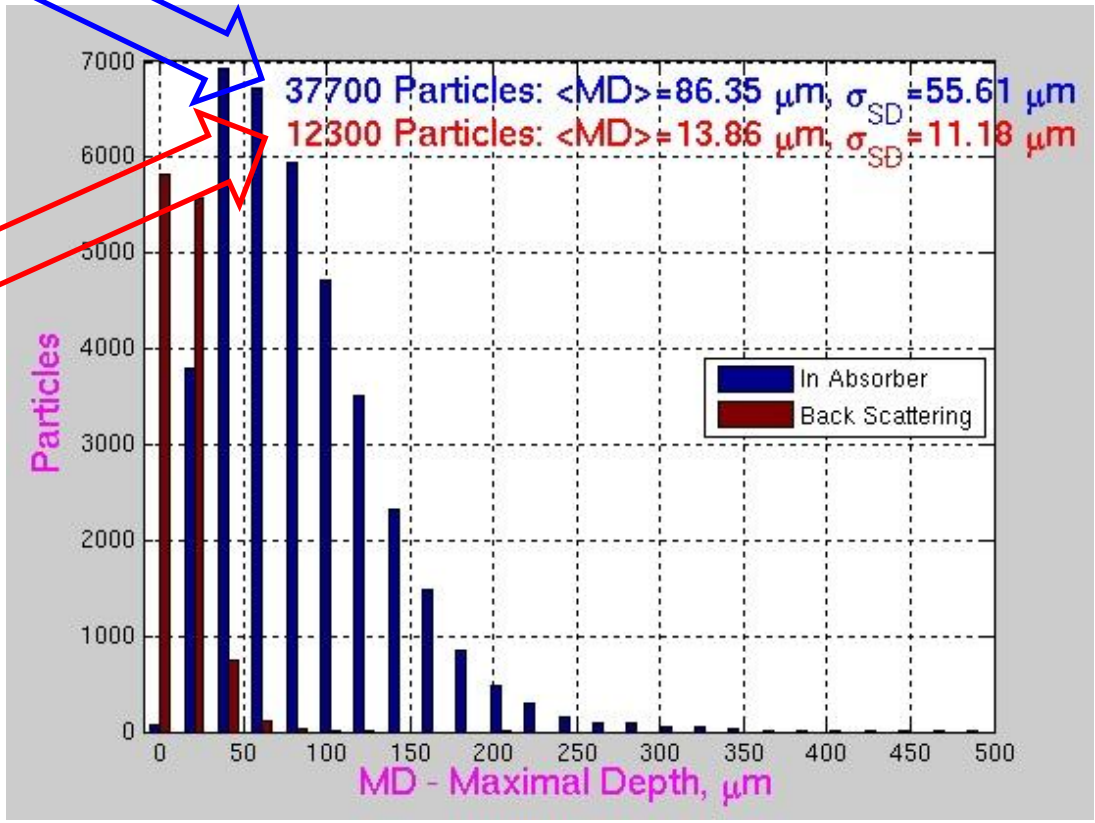


Back Scattering (5)

Comparison of the Penetration to the Beam Dump of Incident and Back Scattered Particles (Nickel)





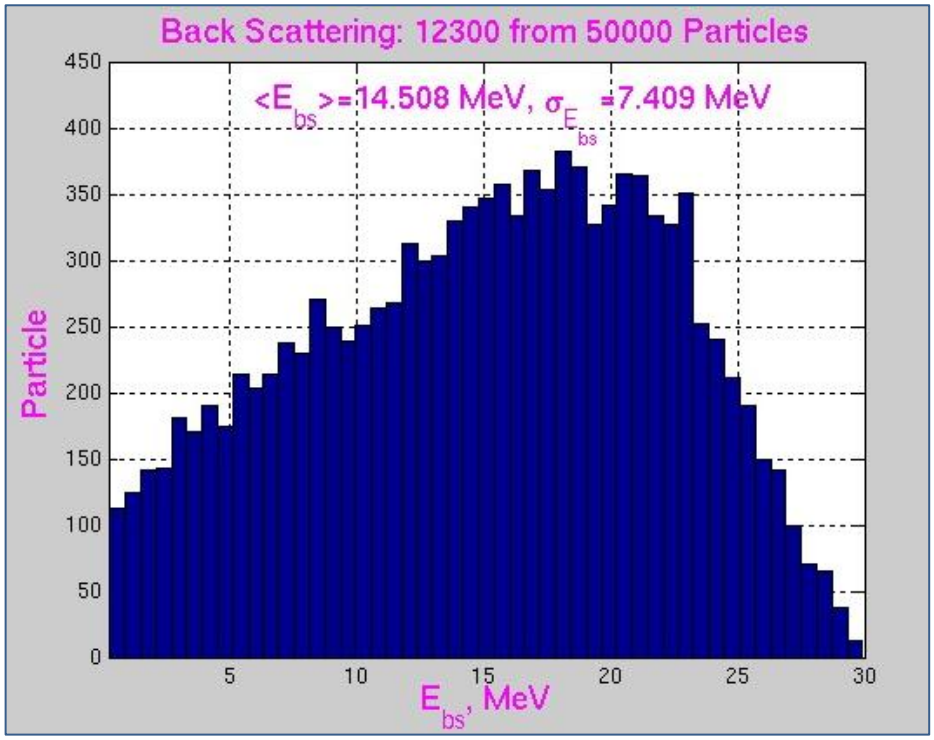


Back Scattering (6)

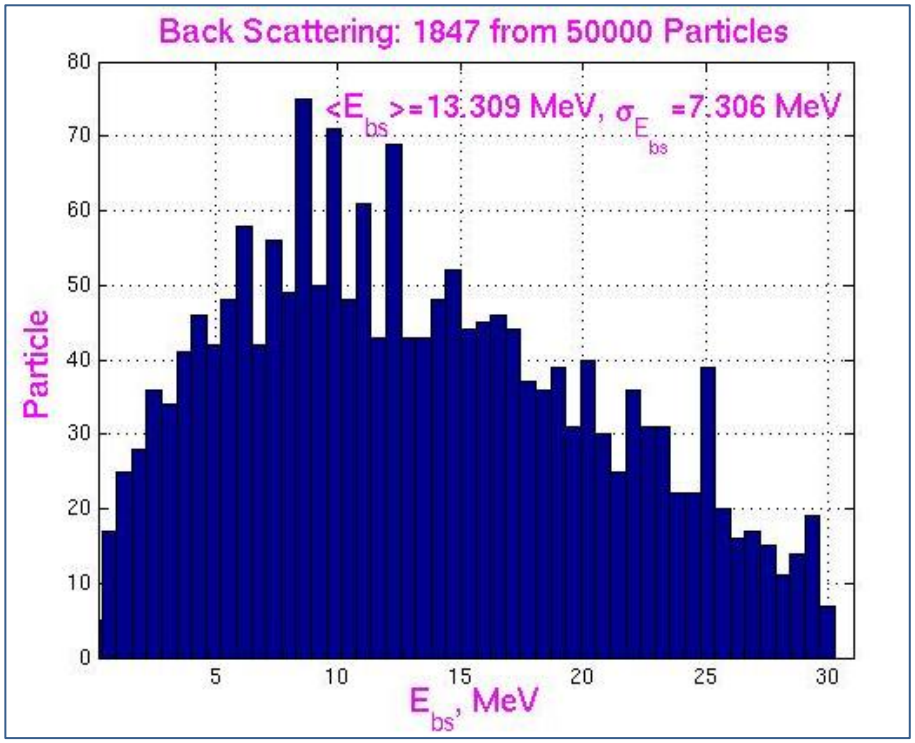
Particle Distribution vs. Energy

50,000 Incident Particles

Nickel



Graphite (Carbon)

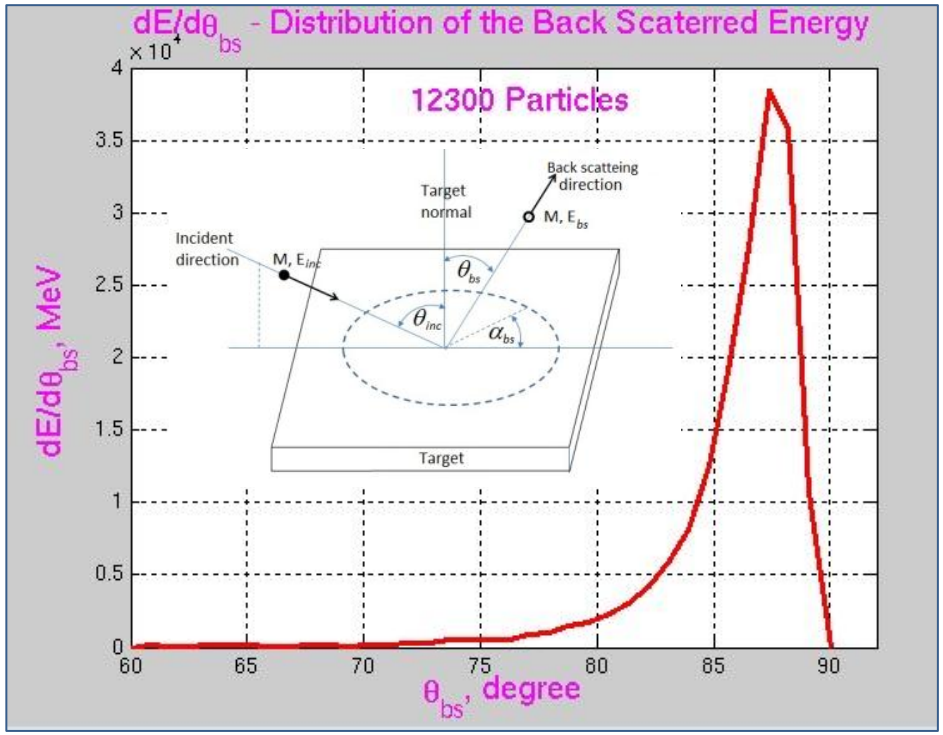


Back Scattering (7)

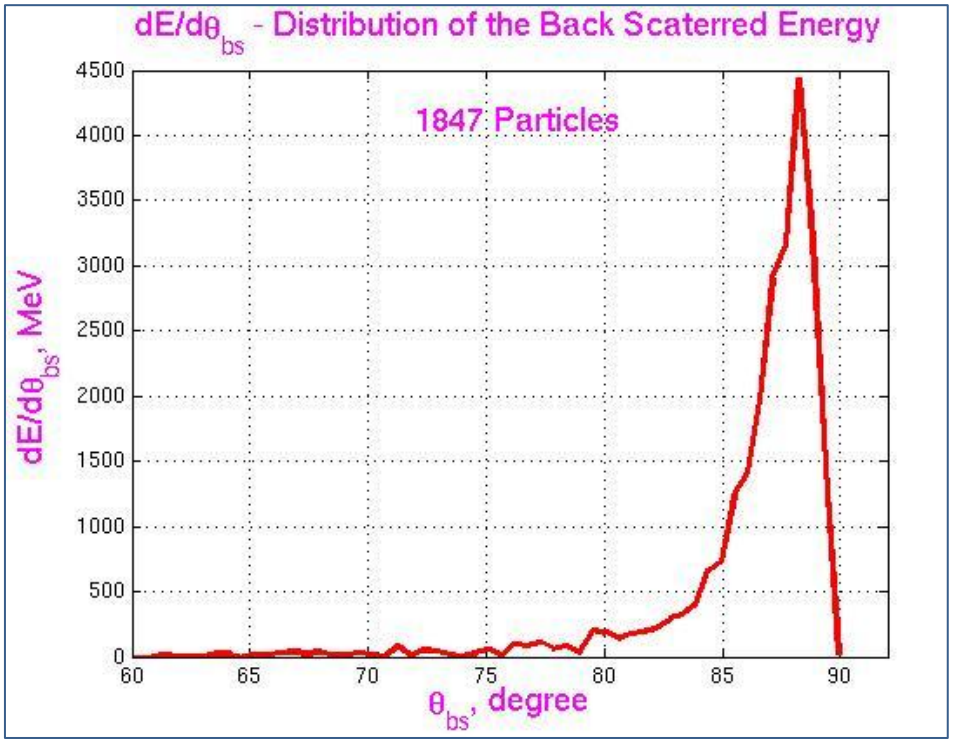
Energy Distribution vs. Back Scattering Angle

50,000 Incident Particles

Nickel



Graphite (Carbon)

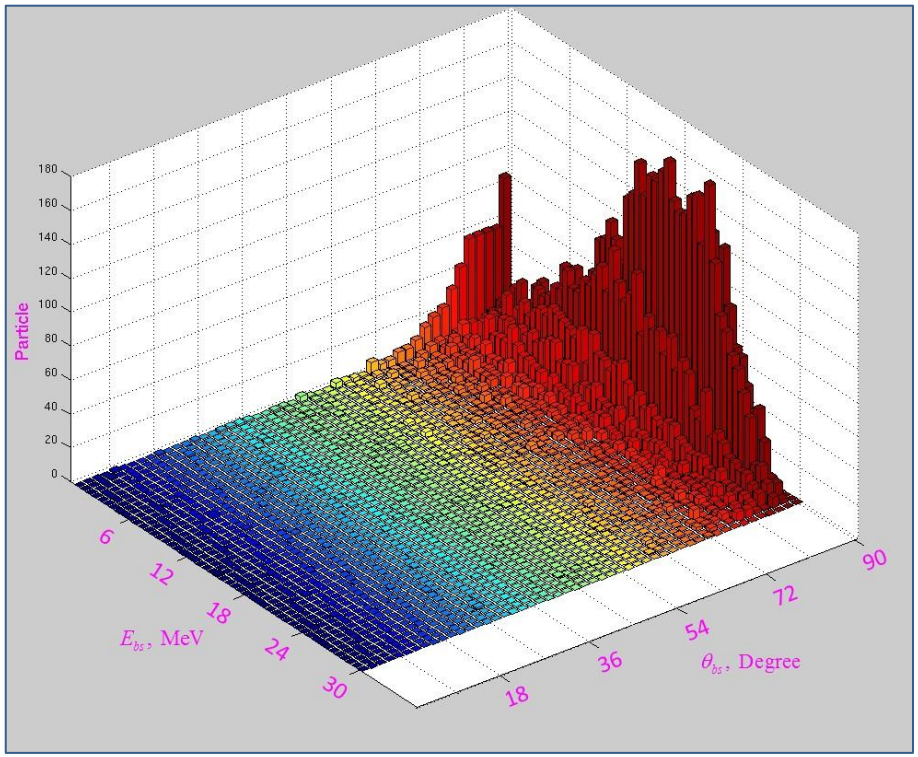


Back Scattering (8)

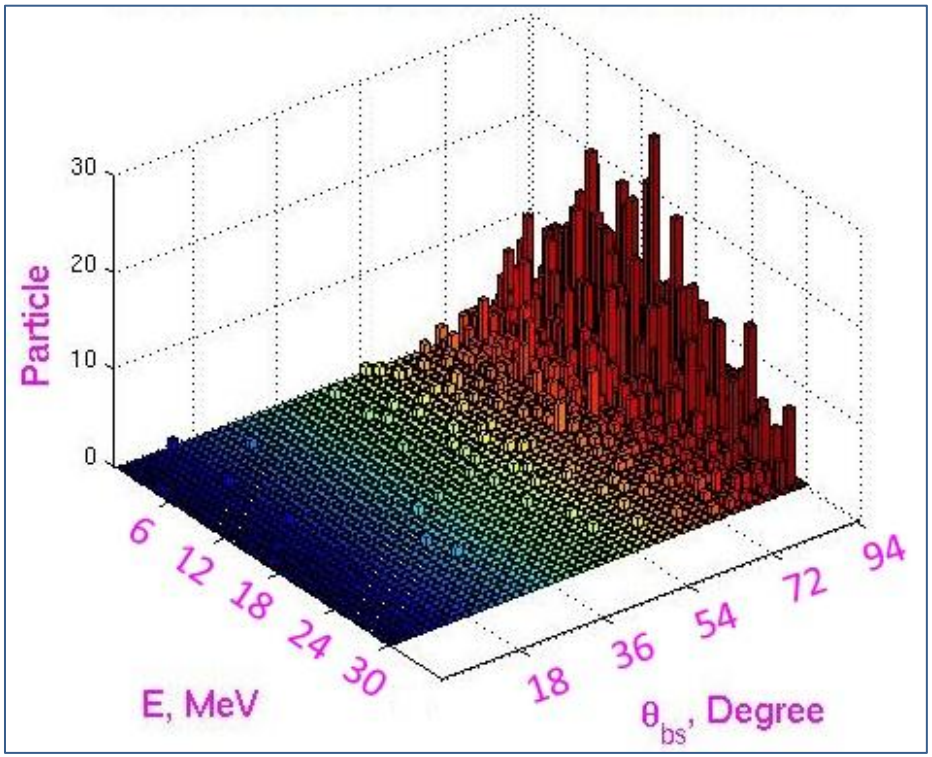
Particle Distribution vs. Energy and Back Scattering Angle

50,000 Incident Particles

Nickel (12,300 Particles)



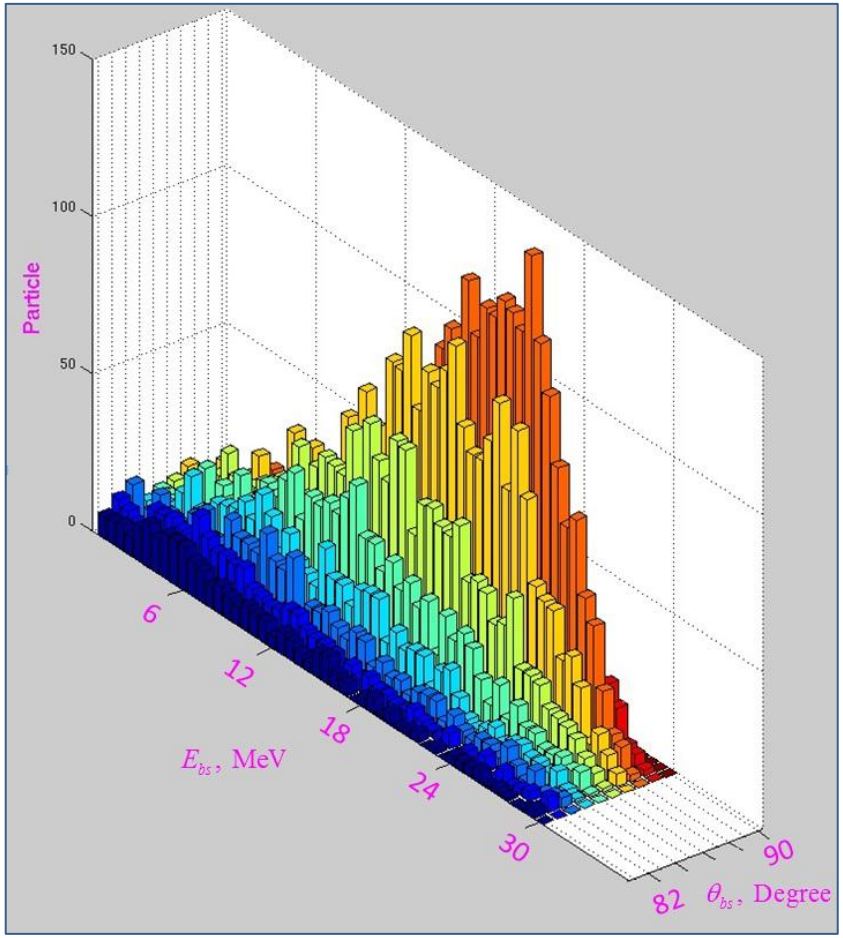
Graphite (1,247 Particles)



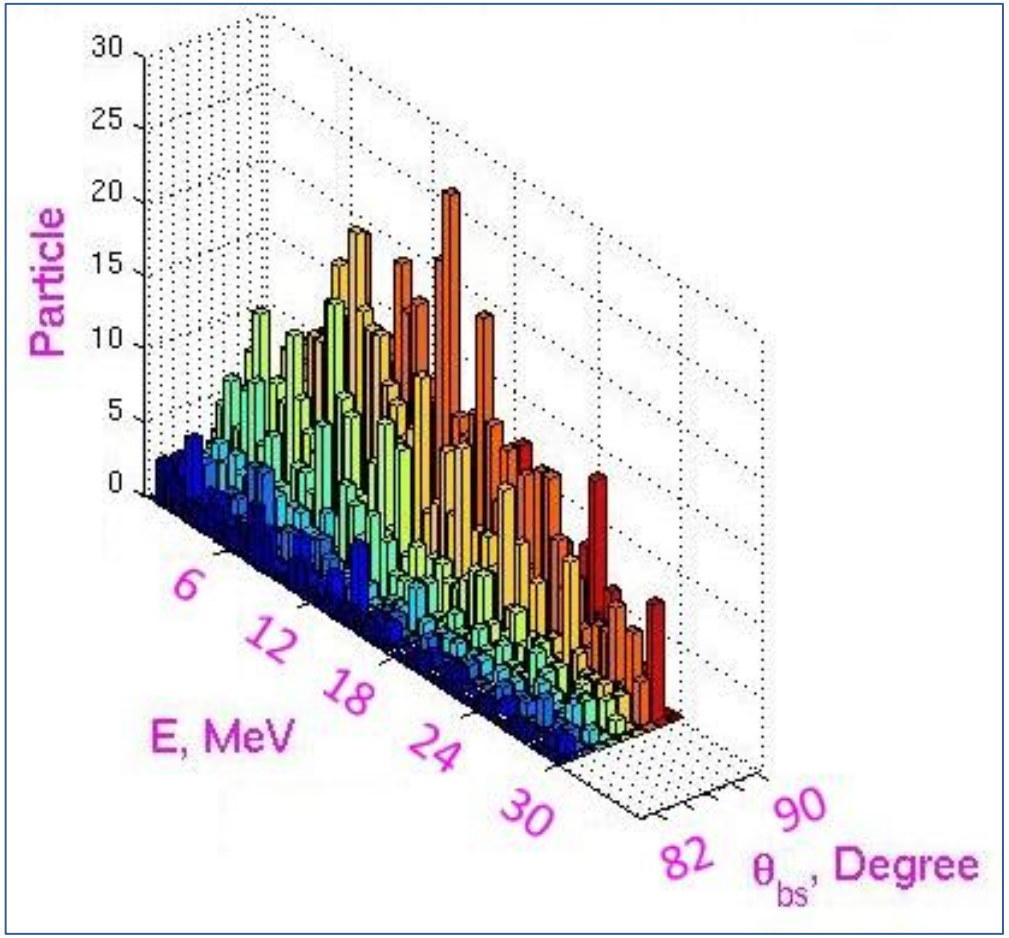
Back Scattering (9)

Particle Distribution vs. Energy and Back Scattering Angle (Near the Grazing Angle)

Nickel (10940 Particles)



Graphite

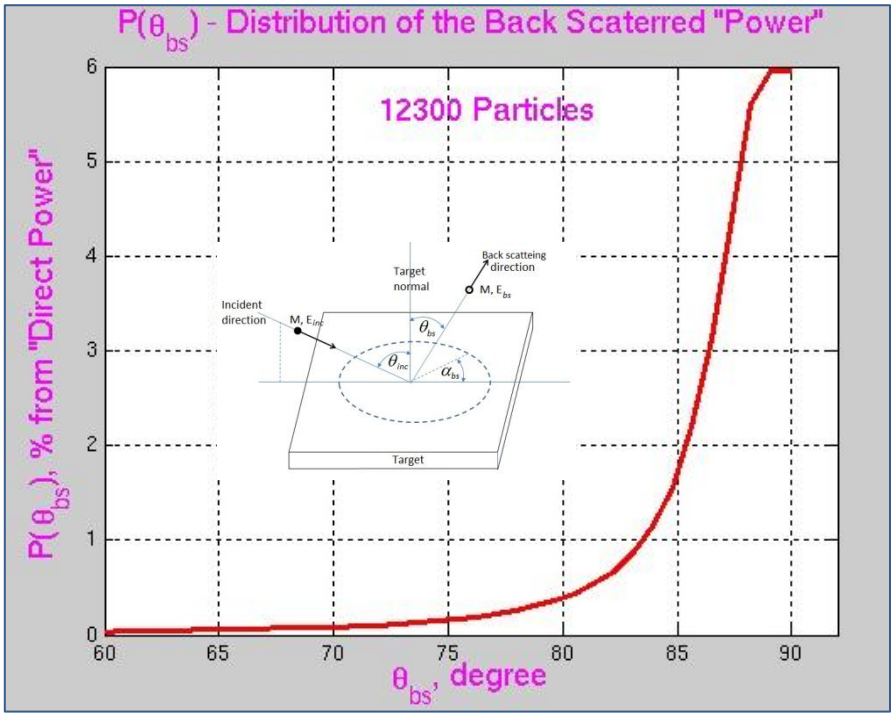


Back Scattering (10)

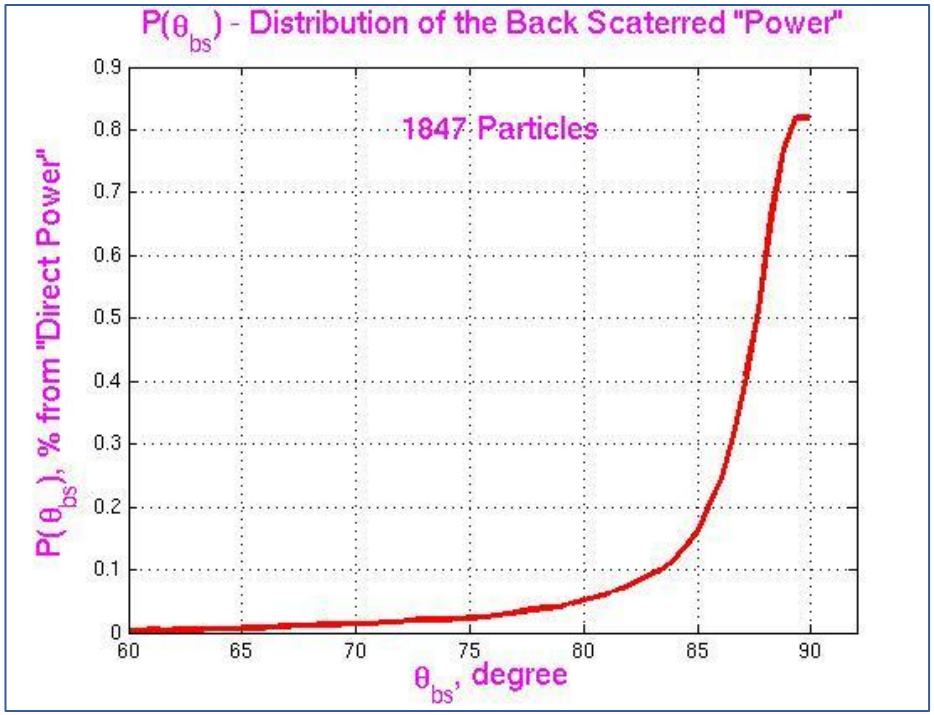
"Power" Distribution vs. Back Scattering Angle

$$P(\theta_{bs}) = \frac{1}{P_{Direct}} \cdot \int_0^{\theta_{bs}} \frac{dE_{bs}}{d\theta'} d\theta' ; \qquad \text{where:} \qquad P_{Direct} = \sum_{Incident} E_i$$

Nickel



Graphite (Carbon)



Back Scattering (11)

Resume:

For 2° of incident angle ~25% (nickel) and ~4% (graphite) of the particles are forward scattered from the surface with much wider energy and angular distributions (σ_E ~ 7 MeV and σ_ϑ ~ 6°). They carry out ~6% (nickel) and ~1% (graphite) of the power of the incident beam.

Penetration depth in the material of the absorber is different for the forward scattered (MD_{fs}=13.9±11.2 μm for nickel and MD_{fs}=42.2±27.5 μm for graphite) and stopped in material particles (MD_{stop} =86.3±55.6 μm for nickel and MD_{fs}=165.7±77.8 μm for graphite).

Sputtering (1)

- The absorber material must have at least a 5 years lifetime under assumed irradiation conditions. It must not create a large neutron flux. The blistering and sputtering properties of the primary absorber material is a concern.
- Several materials were considered as candidates for the inner surface of the absorber: nickel, graphite, aluminum, and copper. The current choice for the primary absorber material is nickel [SNS,HINS].

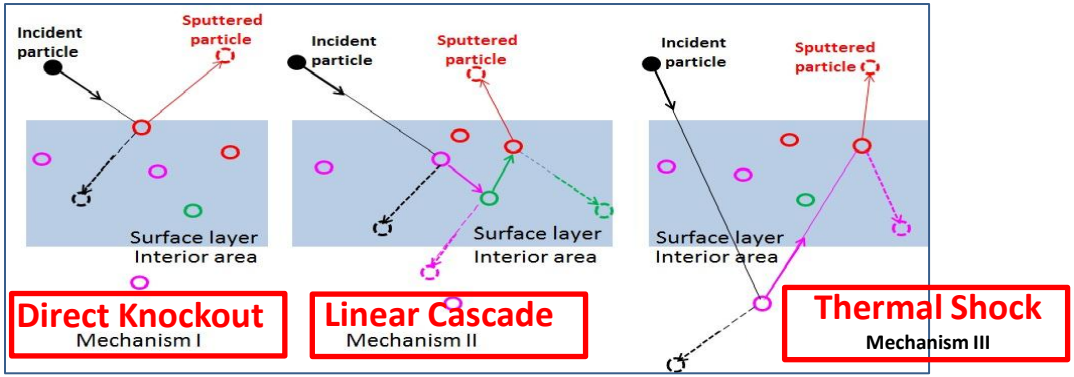
Nickel:

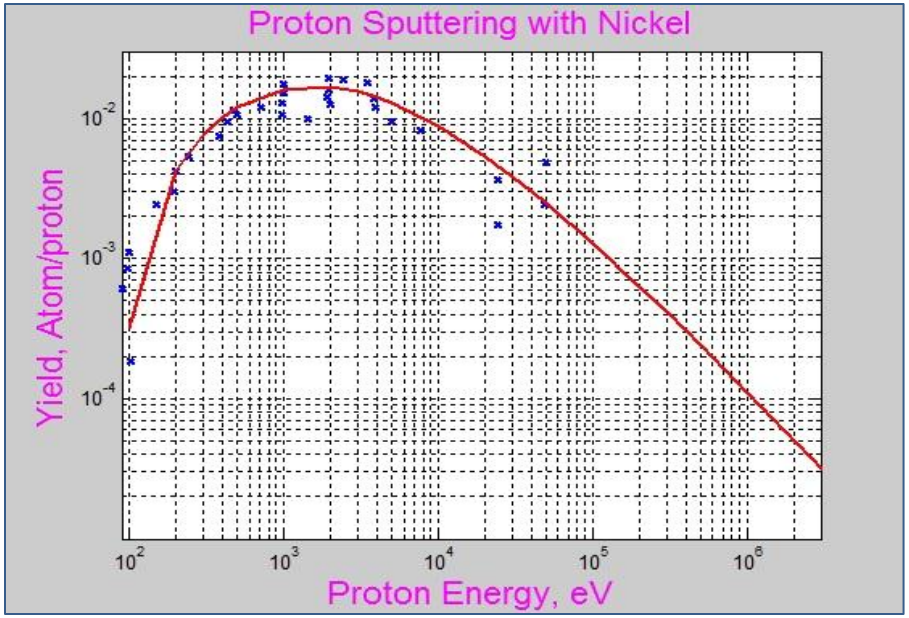
- Has good thermal properties,
- Low residual activation,
- Can be brazed to copper,
- Small value of a stopping range. At the proposed incident angle of 2° the stopping depth from the surface is ~70 µm (consistent with SRIM simulations).

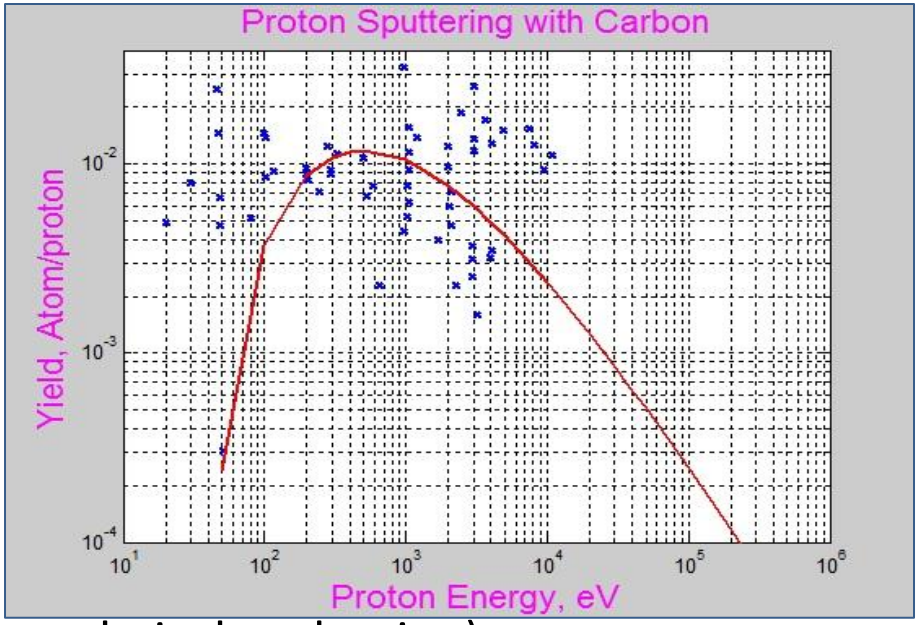
Sputtering (2)

Three mechanism of sputtering:

Incidence	Normal	Oblique	Grazing
Light Ions	III	II and I	I and II
Heavy Ions	III	II and I	II and I







Normal incidence (red line — analytical evaluation)

Sputtering (3)

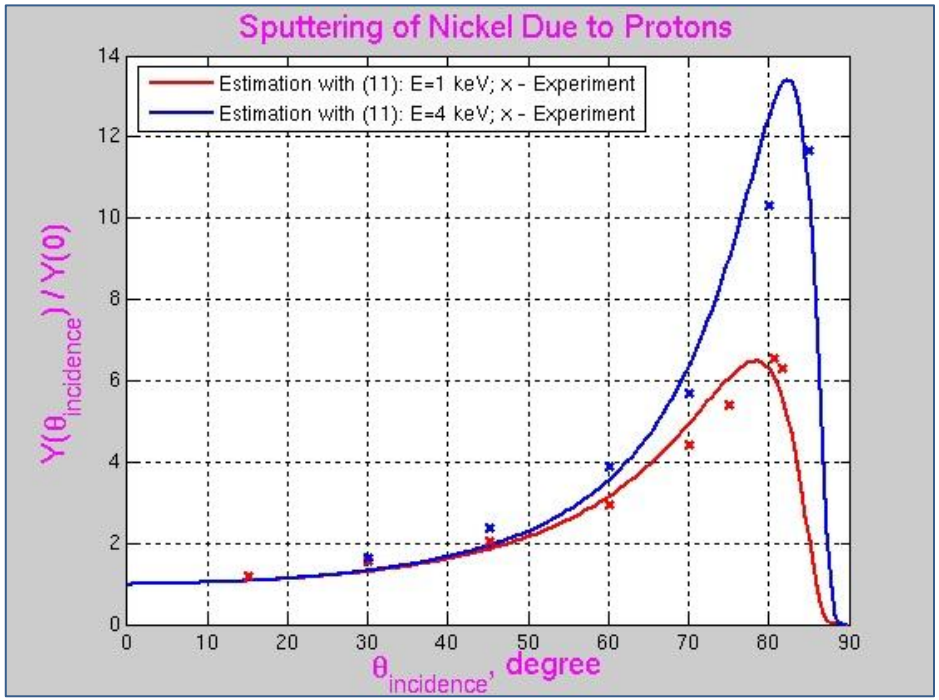
Angular dependence of sputtering yield incident for light ions

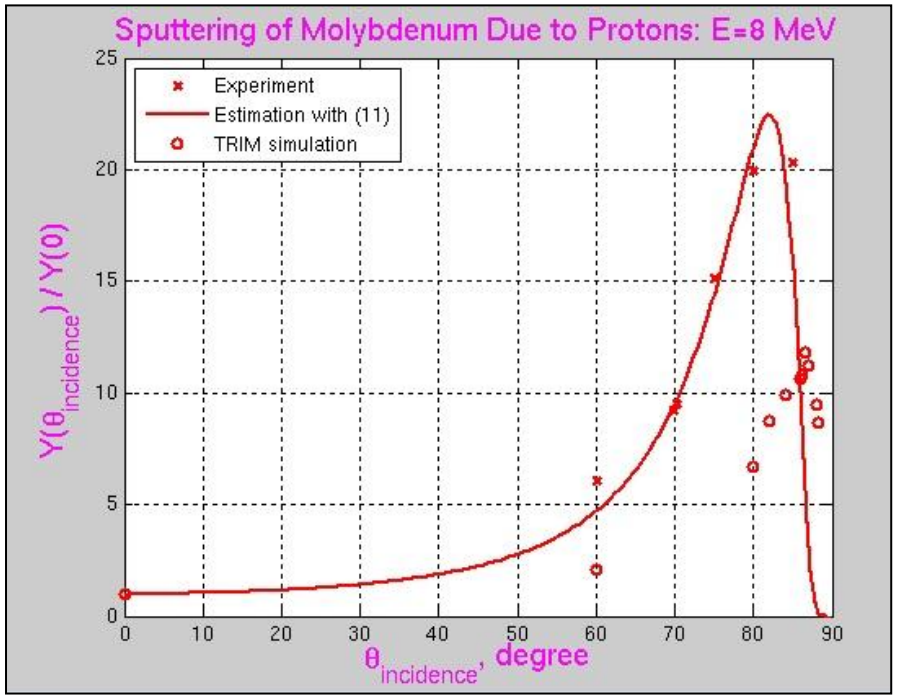
E_{acc}, keV	Target	f	θ_{opt}
2	Mo	2.40	81.8^0
8	Mo	2.80	82.0^0
1	Ni	2.34	78.3^0
4	Ni	2.27	82.3^0

$$Y(\theta) = Y(0)\frac{\exp(-(1/cos\theta - 1)\cdot S)}{(cos\theta)^f},$$

$$where: \quad S = f \cdot cos\theta_{opt}$$

Comparison of the Experimental Data, Analytical Estimation, and *TRIM* Simulation





Sputtering (4)

Summary of Sputtering for some Materials

Value/Material	Nickel	Copper	Carbon	Aluminum	Iron
d, Density, g/cm^3	7.81	8.92	2.267	2.7	7.874
M_{atom}, Weigth of atom, aum	58.69	63.55	12.01	8.27	55.847
V_{atom}, Volume of atom, cm^3	$1.26\cdot10^{-23}$	$1.19\cdot10^{-23}$	$8.9\cdot10^{-24}$	$1.67\cdot10^{-23}$	$1.18\cdot10^{-23}$
Y, Yield, atom/proton	$2.2\cdot10^{-6}$	$4.9\cdot10^{-6}$	$3.4\cdot10^{-7}$	$7.6\cdot10^{-7}$	$1.6\cdot10^{-6}$
$S_{[sec]}$, Sputtering, atom/sec	$2.2\cdot10^{11}$	$4.9\cdot10^{11}$	$3.4\cdot10^{10}$	$7.6\cdot10^{11}$	$1.6\cdot10^{11}$
$S_{[year]}$, Sputtering, atom/year	$6.8\cdot10^{17}$	$1.5\cdot10^{18}$	$1.1\cdot10^{17}$	$2.4\cdot10^{17}$	$5.2\cdot10^{17}$
$S_{[mm]}$, Sputtering, mm/year	$4.8\cdot10^{-5}$	$1.0\cdot10^{-4}$	$5.3\cdot10^{-6}$	$2.2\cdot10^{-5}$	$3.4\cdot10^{-5}$
Maximal values (for corresponding proton energy, keV)					
Y, Yield, atom/proton	$1.7\cdot10^{-2}(\approx 2)$	$3.6\cdot10^{-2}(\approx 2)$	$1.2\cdot10^{-2}(\approx .5)$	$1.8\cdot10^{-2}(\approx .5)$	$1.4\cdot10^{-2}(\approx 2)$
$S_{[sec]}$, Sputtering, atom/sec	$1.7\cdot10^{14}$	$3.6\cdot10^{14}$	$1.2\cdot10^{14}$	$1.8\cdot10^{14}$	$1.4\cdot10^{14}$
$S_{[year]}$, Sputtering, atom/year	$5.2\cdot10^{21}$	$1.1\cdot10^{22}$	$3.7\cdot10^{21}$	$5.6\cdot10^{21}$	$4.4\cdot10^{21}$
$S_{[mm]}$, Sputtering, mm/year	0.367	0.747	0.184	0.524	0.293

Beam:

E_0=30 MeV; I=1.7 mA;

➔$N_p=10^{16}$ p/sec; $\sigma_x=\sigma_y$= 1mm

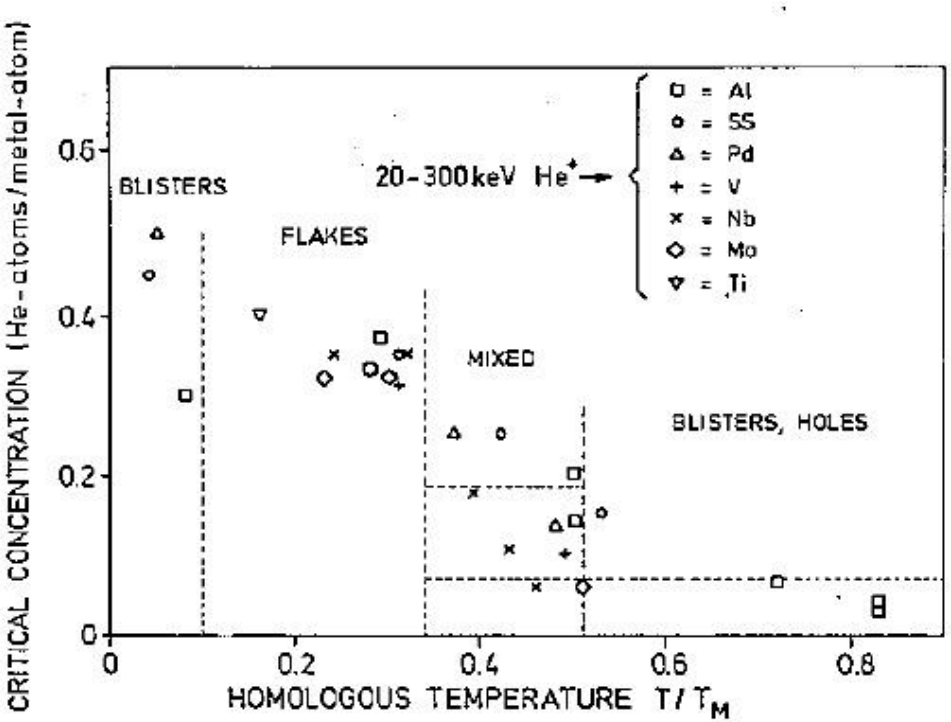
Resume: Parameters of the proton beam in the fall it on the nickel PXIE beam dump the phenomenon of sputtering is negligible in terms of expected duration of operation of this device.

Blistering (1)

- Protons penetrating inside a material are trapped and form gas molecules clustered near defects. The gaseous ions create bubbles with high pressure causing blistering and flakes. Bad thermal contact with surface causes material evaporation with higher exposition. This is the mechanism for surface erosion.
- Typically, first blistering is observed at deposition in the range of ~10^{21}- 10^{24} ions/cm^2; above 10^{23} ions/cm^2 flakes and blisters are eroded by sputtering. Nickel is one of the best materials considered as material for reactors; blistering in nickel starts later than in many other materials (Cu, AL, Nb, Mo etc.).
- Taking into account this rate, surface of dump ~0.1 m^2 and total expected particle per year in absorber we estimate that the lifetime of an absorber with 5 mm nickel thickness is ~10 years. We assumed penetration length in Nickel ~70 microns for 2° incident angle and this layer will be removed when fluence exceeds 10^{23} ions/m^2.

Blistering (2)

Different Types of Surface Deformation



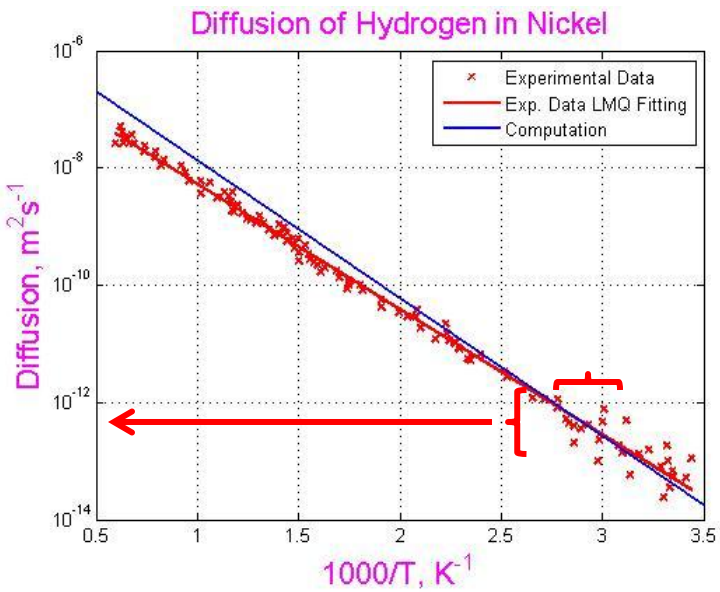
Threshold for a Blistering Start

Material	Ion	*E*, MeV	T, K	D_{cr}, 10^{18} cm^{-2}
Steel	H^+	25	300	0.6
Al, Ni, Mo	**H^+**	**20**		**1.0**
V	**H^+**	**20**		**20**
Nb	D^+	250	970	12.0
Cu	D^+	200	350	7.0
W	H^+	1760	300	5.0
Au	H^+	1760	300	8.0
Ta	H^+	1760	300	>10.0
Amorphous alloy $Ni_{40}Fe_6Co_{20}Cr_{12}Mo_6B_{16}$	**H^+**	**250**		**>15.0**
Ni	H_3^+	900	450	>1.2

Beam 1 mA/cm^2 ≈6.25·10^{15} cm^{-2}·s^{-1} exposed during 160” provides fluence D ~ 10^{18} cm^{-2}

Blistering (3)

Evaluation for Nickel Beam Dump



$$D \approx 10^{-13} \div 10^{-12}\,\mathrm{m^2 s^{-1}}, \quad \tau_{diff} \approx \frac{\overline{\Delta x^2}}{2D} \approx \frac{<MD>^2}{2D};$$

$$\tau_{diff} \approx \frac{70^2}{2(10^{-13} \div 10^{-12})} \frac{\mu\mathrm{m}^2}{\mathrm{m^2 s^{-1}}} \approx (2.5 \div 25) \cdot 10^3 \mathrm{s};$$

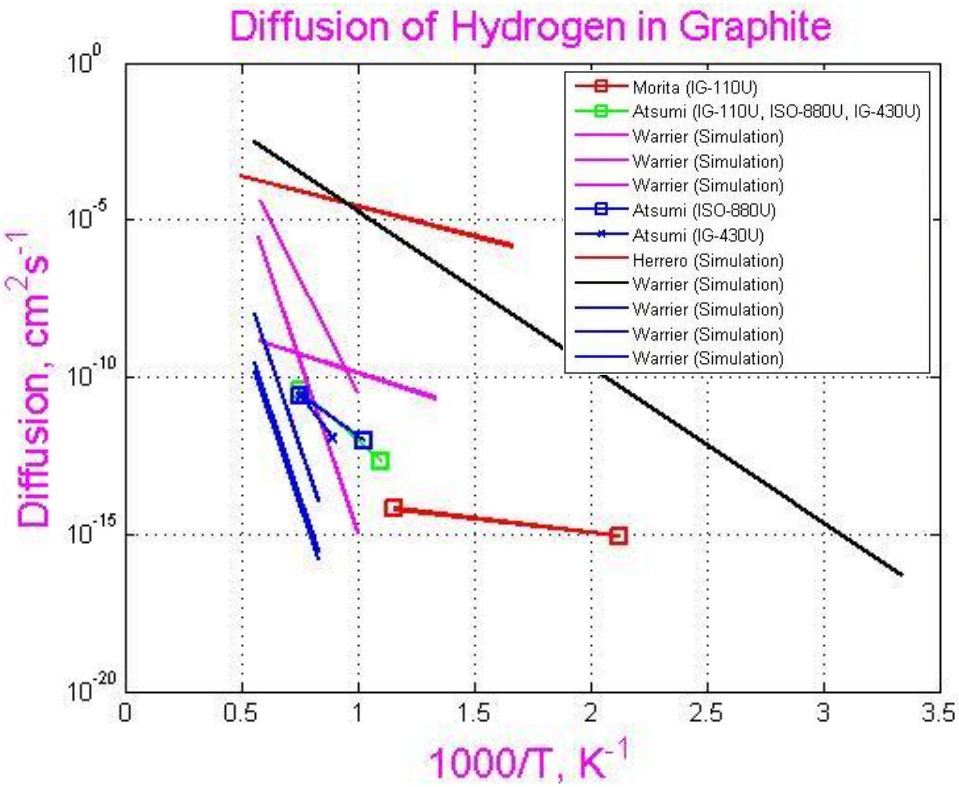
$$j \approx \frac{I_{H^-}}{S_{Dump}} \approx 7 \cdot 10^{12} \frac{\mathrm{prtcl}}{\mathrm{cm}^2}, \quad \Phi_{\tau_{diff}} \approx j\tau_{diff} \le (1.7 \div 17) \cdot 10^{16} \mathrm{cm}^{-2};$$

$$\Phi << \Phi_{blistering}$$

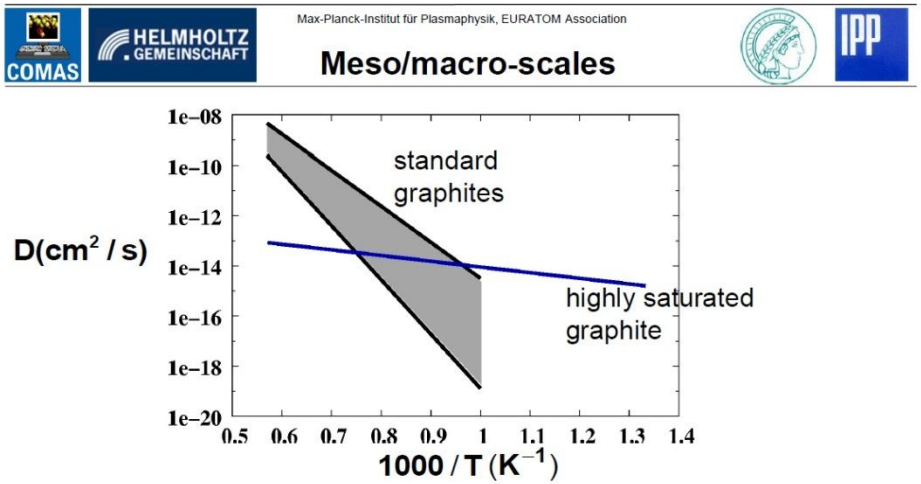
Resume: Parameters of the proton beam in the fall it on the nickel PXIE beam dump the phenomenon of blistering is negligible in terms of expected duration of operation of this device.

Blistering (4)

Evaluation for Graphite Beam Dump



R.Schneider at al. "Plasma-Wall Interaction – A Multi-Scale Problem"



Large variation in observed diffusion coefficients

Strong dependence on void sizes and not void fraction

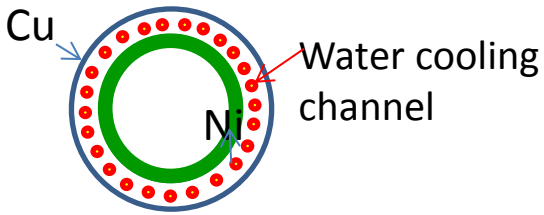
Diffusion coefficients without knowledge of structure are meaningless

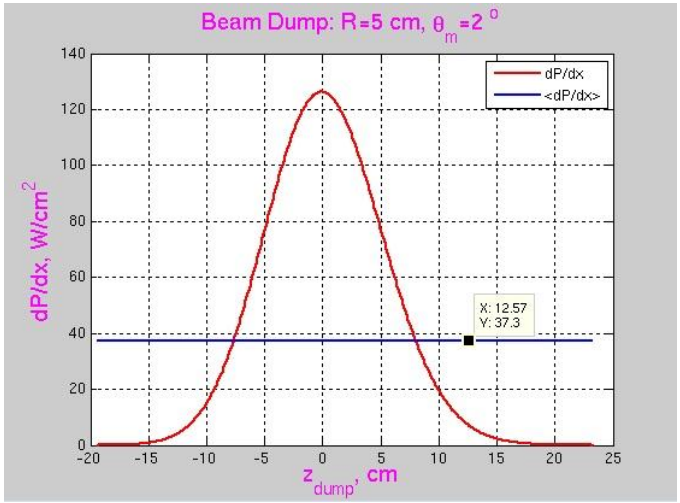
$$D \approx 10^{-15}\,\mathrm{m^2 s^{-1}}, \quad \tau_{diff} \approx \frac{200^2}{2\cdot 10^{-15}} \frac{\mu\mathrm{m}^2}{\mathrm{m}^2\mathrm{s}^{-1}} \approx 2\cdot 10^7\,\mathrm{s};$$

$$j \approx \frac{I_{H^-}}{S_{Dump}} \approx 7\cdot 10^{12} \frac{\mathrm{prtcl}}{\mathrm{cm}^2}, \quad \Phi_{\tau_{diff}} \approx j\tau_{diff} \le 1.4\cdot 10^{20}\,\mathrm{cm}^{-2};$$

$$\Phi >> \Phi_{blistering}$$

Water Cooling (1)





$$Re = \frac{\rho v D}{\mu}; \qquad Pr = \frac{C_p \mu}{\lambda};$$

$$Nu = 0.023 \cdot Re^{0.8} Pr^{0.33}; \text{ or}$$

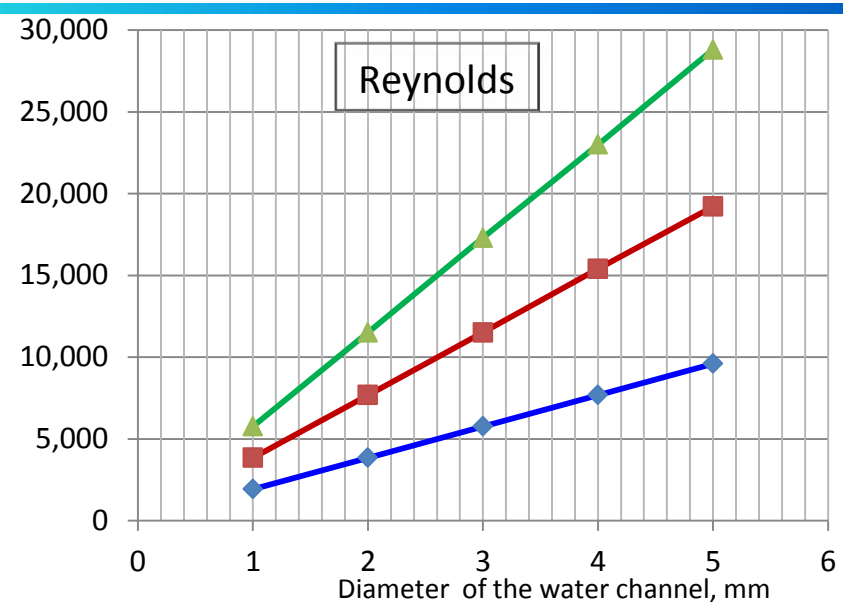
$$Nu = \frac{(f/8)\,(Re - 1000) \cdot Pr}{1 + 127 \cdot (f/8)^{1.2} (Pr^{2/3} - 1)}$$

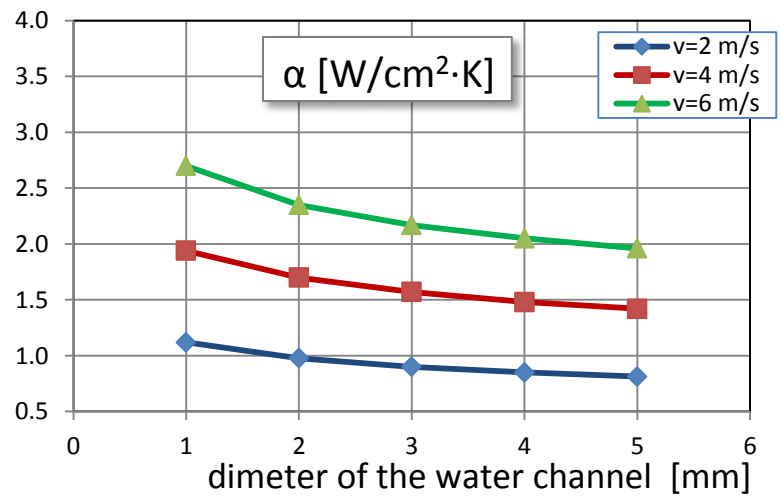
$$where: \; f = (0.79 \cdot \ln(Re) - 1.64)^{-2}$$

$$\Rightarrow \quad \alpha = \frac{Nu \cdot \lambda}{D}$$

Parameters:

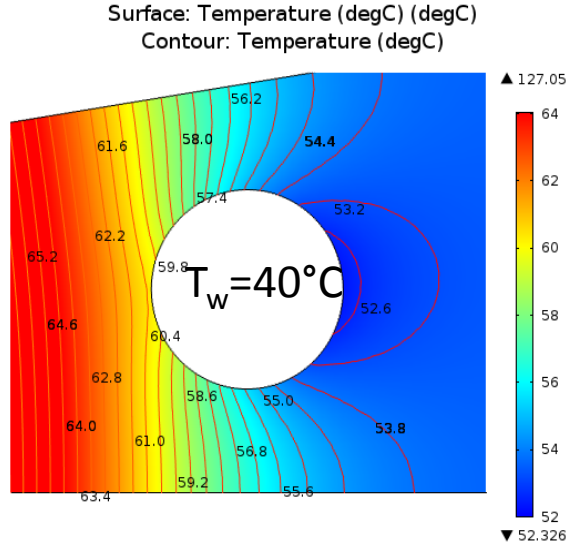
Re ~ 30,000
Velocity = 6m/s
Flow ~1.2 g/s
ΔP ~ 4 psi
α ~ 2 W/cm²·K

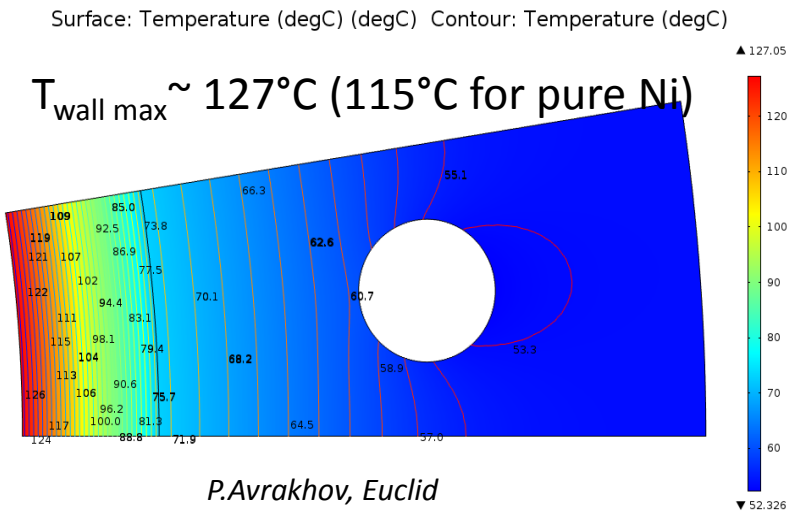




Cooling (1)

Nickel: Temperature & stresses (Code *Comsol*)

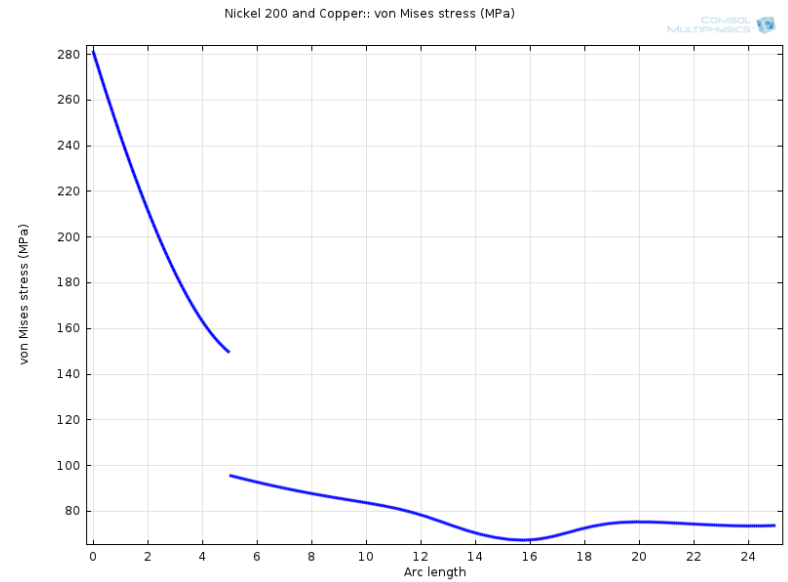




P.Avrakhov, Euclid

Example of temperature analysis:

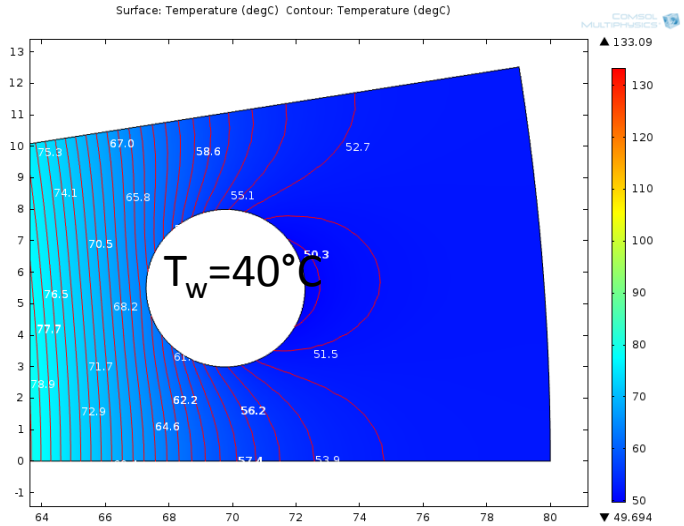
- Power 50 kW, Heat flux max = 80 W/cm^2
- Nickel200 5mm (SNS-like) -5mm + copper 30mm
- cooling channels Ø5mm, N=40; T_{w_in} = 30°C;

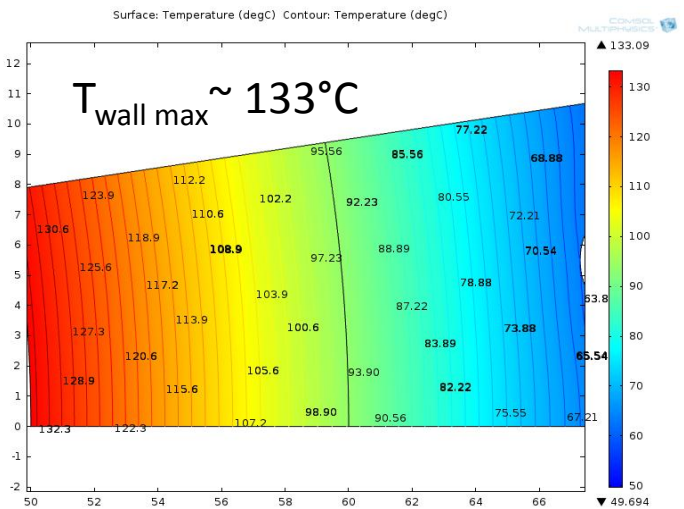


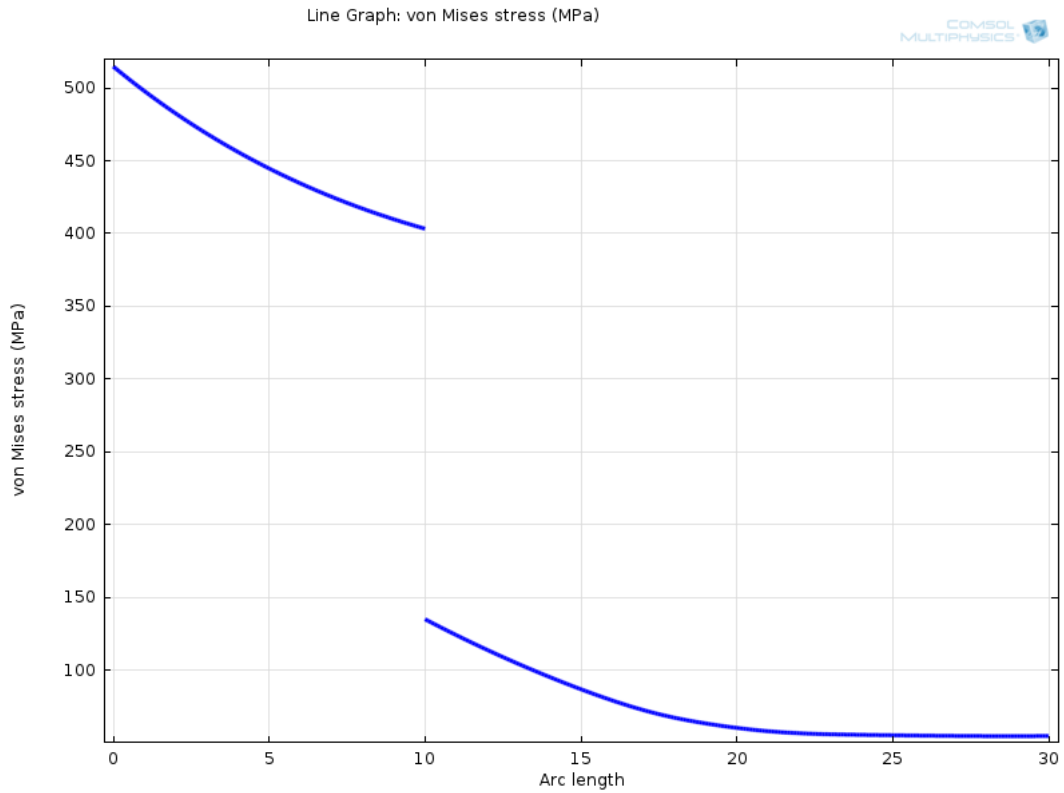
Stress, MPa	Ni, min	Cu, max	Ni - Cu
Ni(100%)	164.66069	95.74645	68.914
Nickel-200	149.47525	95.73952	53.736
Duranickel 301	207.72645	108.00045	99.726

Cooling (2)

Graphite: Temperature & stresses (Code *Comsol*)

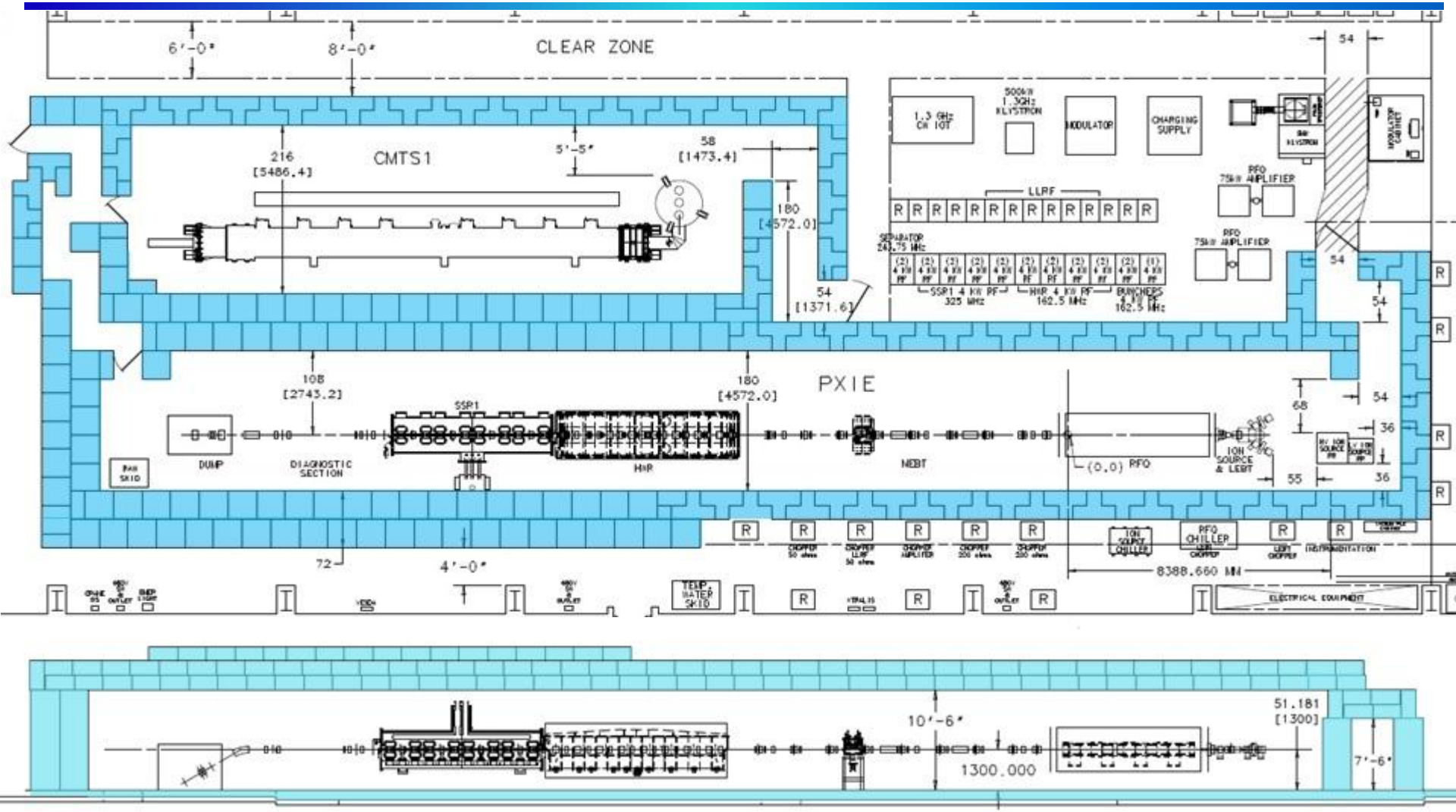






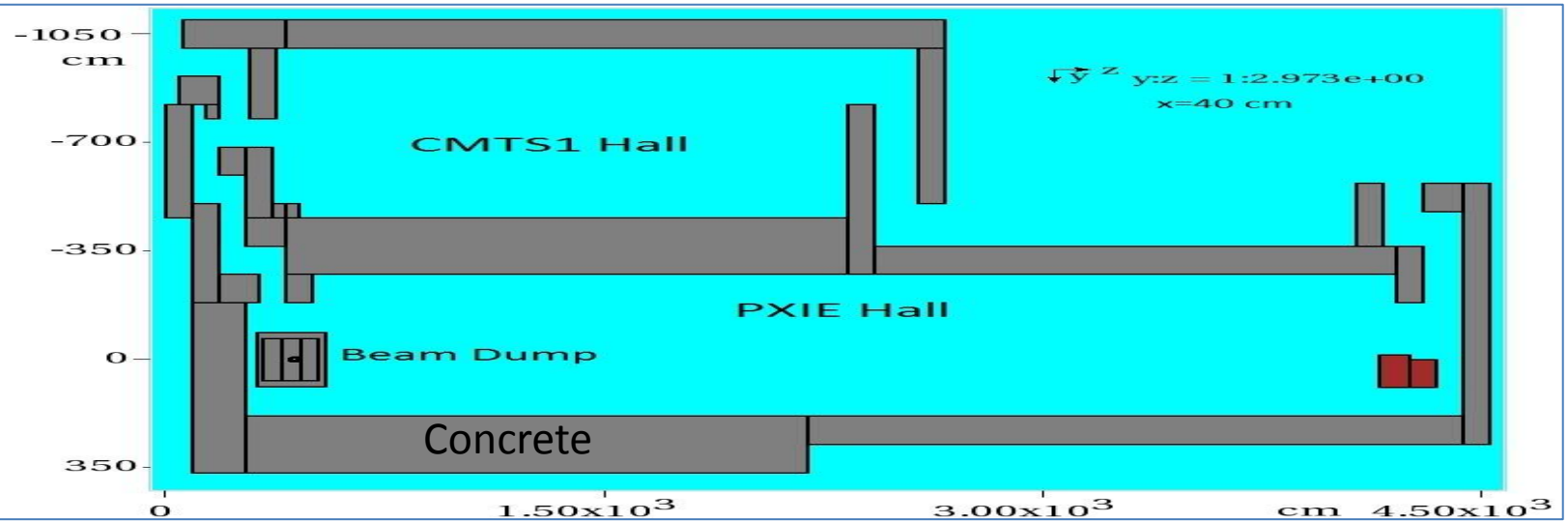
Radiation Shielding (1)

PXIE Enclosure

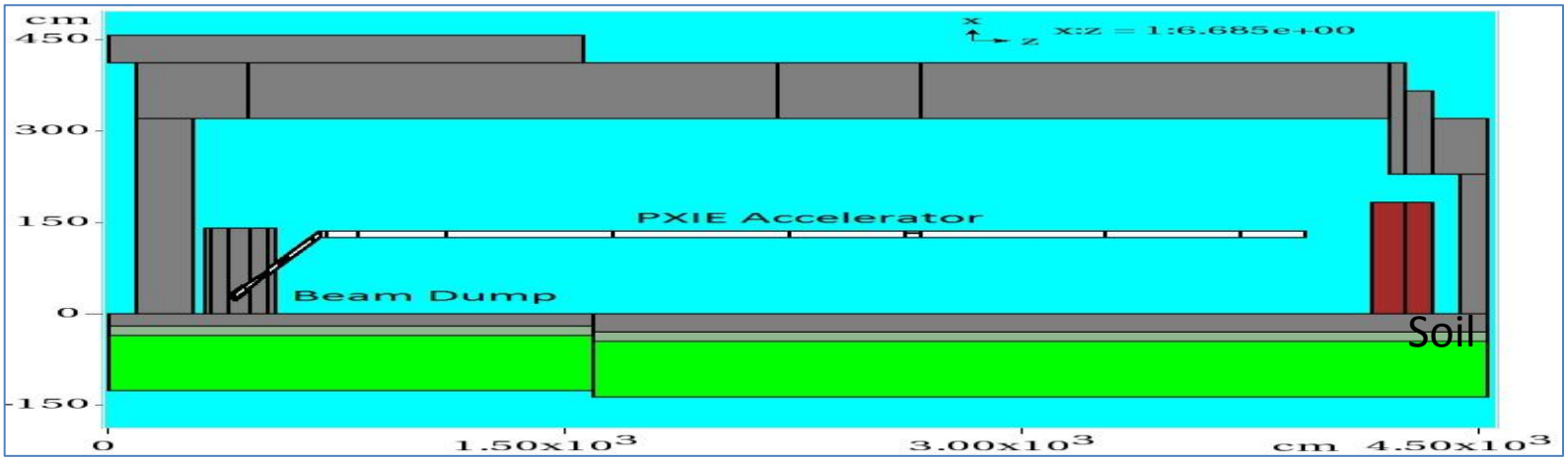


Radiation Shielding (2)

MARS Model of PXIE Enclosure



Plan view



Side view

Radiation Shielding (3)

Radiation Shielding Requirements

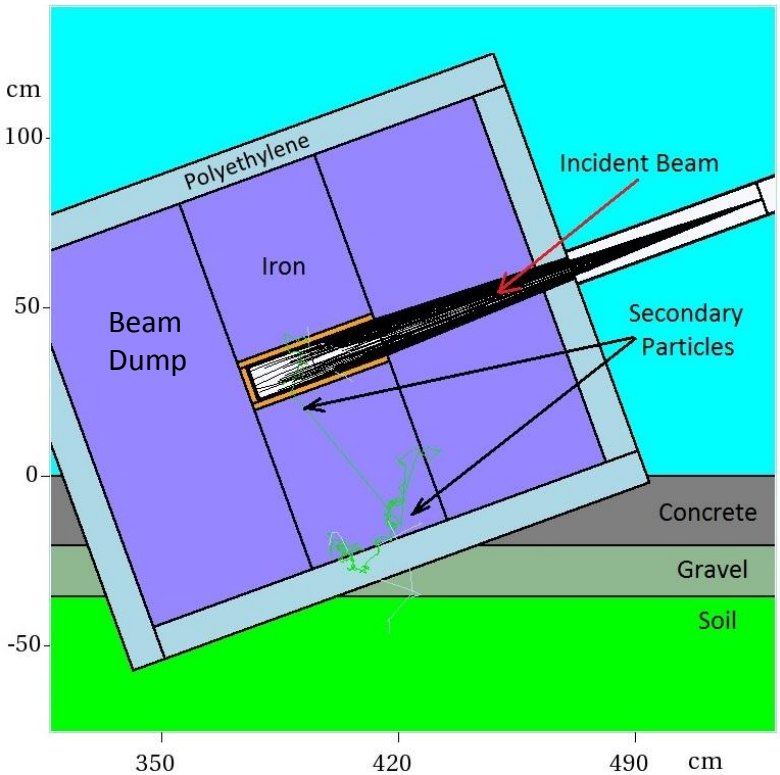
Radiation shielding of the PXIE cave and local shielding of the beam dump must meet the following main requirements:

- *The beam dump shielding has to provide suppression of the radiation originated from the beam dump surface by no less than 10^{-3};*
- *The beam dump shielding and PXIE enclosure shielding has to provide the level of total prompt dose at the exits of the both (downstream and up upstream) labyrinths and the entrance to the CMTS1 hall of no more than 0.05 mrem/hr ($5\cdot10^{-4}$ mSv/hr);*
- *To provide the level of total prompt dose on the roof of the PXIE cave no more than 0.25 mrem/hr ($2.5\cdot10^{-3}$ mSv/hr);*
- *To provide the level of the contact residual dose for walls of the halls (PXIE and CMTS1), and equipment no more than 0.05 mrem/hr ($5\cdot10^{-4}$ mSv/hr);*
- *To provide a yield of dangerous radionuclides in the soil under PXIE cave no more than 20 pCi/($cm^3\cdot$year).*

Radiation Shielding (4)

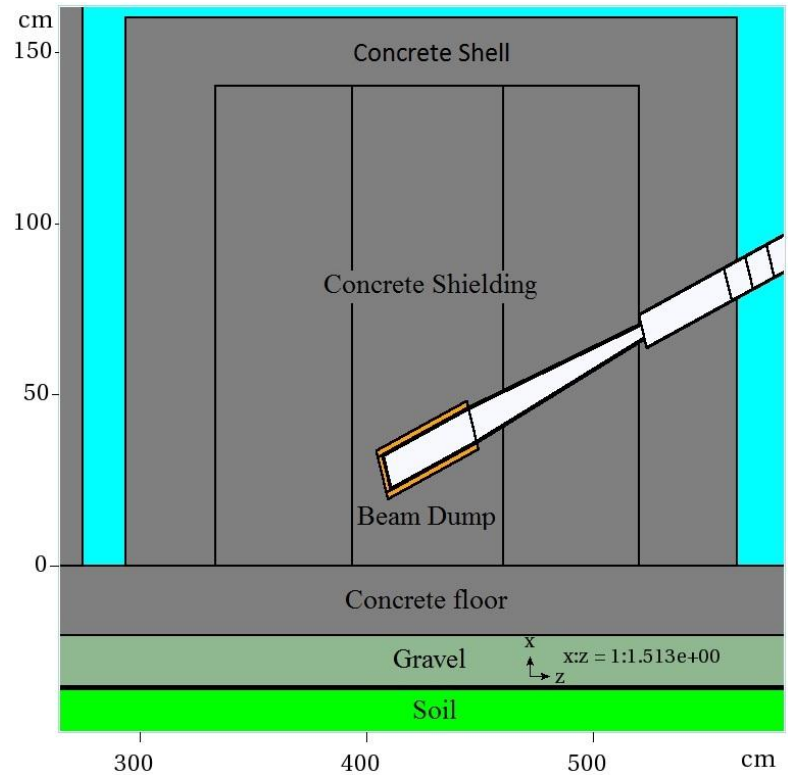
MARS Model of the Beam Dump

"Sandwich type" Local Shielding
(+ Primary and Secondary Particles)



Case_05-fin

Concrete Local Shielding



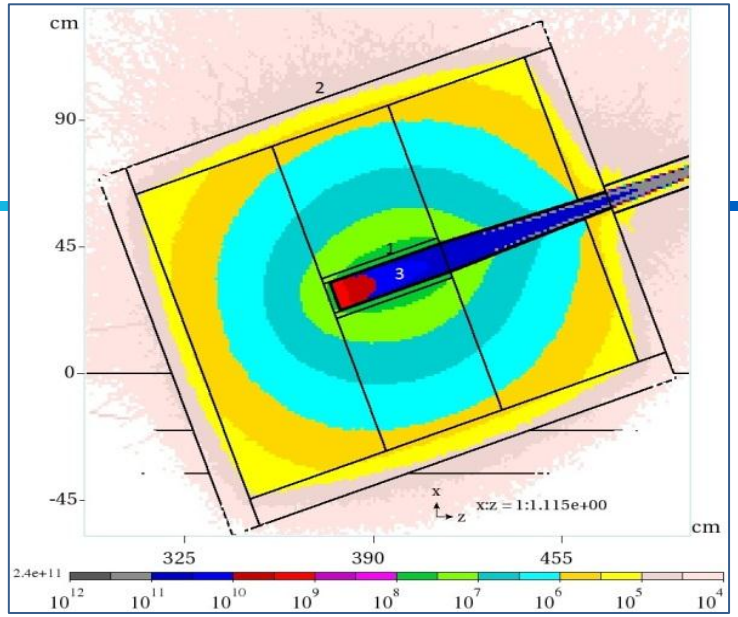
Case_09

Radiation Shielding (5)

Beam Dump Cases Simulated

Beam Dump	Beam Dump Materials		Shielding Material	Shell Material	Beam Dump configuration
	Absorber	Cooler			
05-fin	Nickel	Cooper	Iron 60 cm	Polyethylene 20 cm	Oblique
06-2					
06-3			Concrete 60 cm	Concrete ~50 cm	Horizontal
07					
09	Carbon	Aluminum			

Radiation Shielding (6)



Beam Dump Attenuation

Typical Prompt Dose (mSv/hr) Distribution (case_05-fin):

Table: Beam Attenuation Results:

Beam Dump Case	Total Prompt Dose				Attenuation: "2"/"1"
	Point "1"		Point "2"		
	Value, mSv/hr	Accuracy, %	Value, mSv/hr	Accuracy, %	
05-fin	$4.5\cdot10^{7}\pm3.9\cdot10^{4}$	±0.1	$2.1\cdot10^{4}\pm1.0\cdot10^{3}$	±4.8	$47\cdot10^{-5}$
06-2	$4.3\cdot10^{7}\pm8.5\cdot10^{4}$	±0.2	$5.5\cdot10^{3}\pm7.5\cdot10^{2}$	±13.6	$13\cdot10^{-5}$
06-3	$4.8\cdot10^{7}\pm\cdot4.410^{4}$	±0.1	$7.5\cdot10^{2}\pm\cdot3.510^{2}$	±46.7	$1.6\cdot10^{-5}$
07	$7.7\cdot10^{8}\pm1.3\cdot10^{6}$	±0.17	$5.8\cdot10^{3}\pm1.6\cdot10^{3}$	±26.7	$0.8\cdot10^{-5}$
09	$3.0\cdot10^{6}\pm1.1\cdot10^{4}$	±0.39	33.0±10.0	±30.3	$1.1\cdot10^{-5}$

Resume: *Local shielding provides the required level of the attenuation (item 1 of the requirements)*

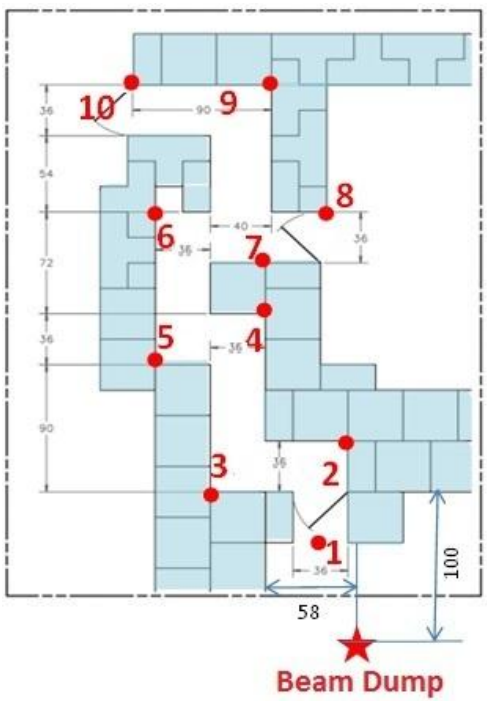
Radiation Shielding (7)

Exit from Downstream Labyrinth (1)

Unfortunately *MARS* simulation during a 3-7 days provides an unacceptable statistical accuracy of the prompt dose calculation at the exits of the labyrinth (estimated accuracy ±100%). Due to the analytical evaluation of the decreasing *U* of the prompt dose for single "leg" of labyrinth was used *) (*L* is a length of leg and *S* is a cross section of the labyrinth; X=L/√S):

$$U(X) = (1+X)^{-(2.275+0.384\ln(1+X))}$$

Downstream Labyrinth (Sizes in Feet)



Attenuation coefficients of each Leg (Comparison with the *MARS* Simulation Data; Case_06-2):

Point, P_i	*MARS* simulation		Attenuation: $U=P_{i+1}/P_i$	
	Prompt Dose, mSv/hr	Statistical Error, %	*MARS* simulation	Analytical Formulae
1	956 ± 81	8.5	–	–
2	348 ± 51.4	14.8	0.364	0.156
3	37.9 ± 10.6	28.0	0.109	0.110
4	2.21 ± 0.30	13.6	0.058	0.059
5	1.32 ± 0.29	22.0	0.757	0.156
6	1.14± 0.525	46.4	0.856	0.080
7	$0.18 \pm 7.4\cdot10^{-2}$	41.0	0.138	0.144
8	$1.06\cdot10^{-2} \pm 5.5\cdot10^{-3}$	51.5	0.0094	0.0176
9	$1.27\cdot10^{-2} \pm 1.2\cdot10^{-2}$	100	0.071	0.059
10	$2.29\cdot10^{-3} \pm 1.23\cdot10^{-3}$	53.7	0.180	0.102

Resume: Analytical estimation can be used to evaluate prompt doses at the exits of labyrinth

Radiation Shielding (8)

Exit from Downstream Labyrinth (2)

*) I. Baishev, N. Mokhov. "Firming Up the SSC Access Shaft Calculations". SSCL-521, September 1992.

So, the total attenuation coefficients for exits from downstream labyrinth are:

$$U_{1-10} = U_{1-2} \cdot U_{2-3} \cdot U_{3-4} \cdot U_{4-5} \cdot U_{5-6} \cdot U_{6-7} \cdot U_{7-9} \cdot U_{9-10} \approx 1.1 \cdot 10^{-8}$$

and

$$U_{1-8} = U_{1-2} \cdot U_{2-3} \cdot U_{3-4} \cdot U_{4-5} \cdot U_{5-6} \cdot U_{6-8} \approx 9.6 \cdot 10^{-7}$$

These two coefficients of attenuation were used to estimate the prompt dose value at the exits of upstream labyrinth:

Beam Dump Case	Labyrinth's Prompt Dose, mSv/hr		
	Entrance of Labyrinth	Main Exit (Point 10)	Exit to CMTF1 (Point 8)
05-fin	$2.31 \cdot 10^{3}$	$2.54 \cdot 10^{-5}$	$2.22 \cdot 10^{-3}$
06-2	$9.56 \cdot 10^{2}$	$1.05 \cdot 10^{-5}$	$9.18 \cdot 10^{-4}$
06-3	$4.38 \cdot 10^{1}$	$4.82 \cdot 10^{-7}$	$4.21 \cdot 10^{-5}$
07	$2.31 \cdot 10^{3}$	$2.54 \cdot 10^{-5}$	$2.22 \cdot 10^{-3}$
09	$2.98 \cdot 10^{1}$	$3.28 \cdot 10^{-7}$	$2.86 \cdot 10^{-5}$

Resume:

Local shielding provides the required level of the prompt doses outside the PXIE shielding enclosure (item 2 of the requirements)

Radiation Shielding (9)

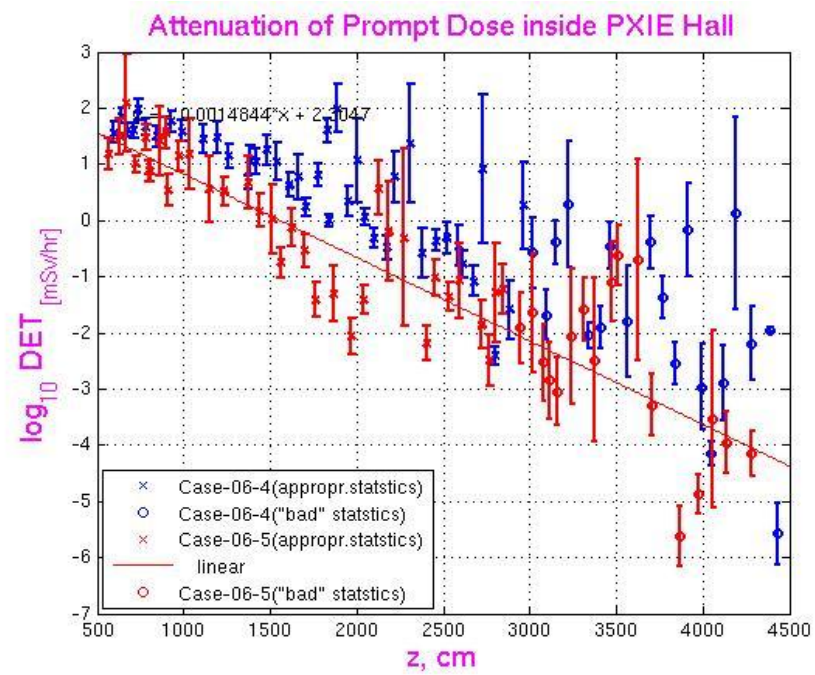
Exit from Upstream Labyrinth (1)

Another approach was used to estimate the level of the prompt dose at the exit of the upstream labyrinth. Firstly, the dependence of the prompt dose on the distance from beam dump was found from *MARS* simulation. Two sets of data were analyzed: Case_06-4 and case_06-5. First set was received as a "typical" *MARS* data. For the second set a much smaller number of the primary particle was used, but a special "smoothing" allowed provide much better statistics of the results (this approach is always used in subsequent simulations).

Both sets od data divide into two arrays each: first is characterized by an acceptable level of collected statistics (statistical errors ≤50%), while for the second array statistical errors can reach 100% ("bad" statistics).

Linear fitting of the "appropriate" data (red crosses) corresponds exactly to a diffusion propagation of the neutrons inside PXIE hall:

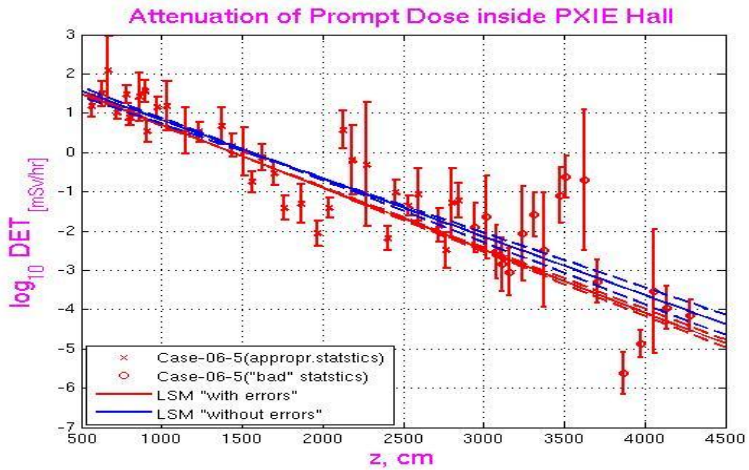
$$DET(z) = DET_0 \cdot e^{-\bar{\alpha} z} \equiv 10^{-\alpha z + \beta}$$



Radiation Shielding (10)

Exit from Upstream Labyrinth (2)

Two least square methods (LSM) to fit the "appropriate" arrays: with (red line) and without (blue line) taking into account the statistical errors of the data:



Dashed lines correspond to the fitting parameters, which increase the minimized quadratic functional on 1

Results based on "red" fitting: $\alpha = (1.59054 \pm 0.03509) \cdot 10^{-3}, \quad \beta = 2.28441 \pm 0.05213$

For $z_{entrance} = 4251.96 \text{ cm}$ $\quad DET_{entrance} = (2.1 \div 5.3) \cdot 10^{-5} \text{ mSv/hr}$

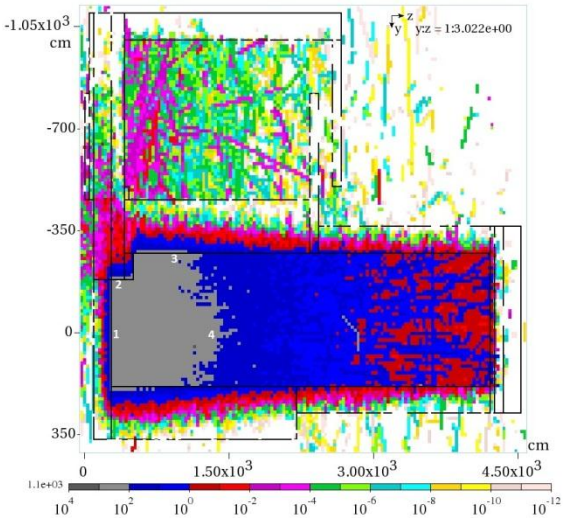
And using (*) with $X = 2.7067$: $\quad DET_{exit} = (5.7 \div 14.3) \cdot 10^{-7} \text{ mSv/hr}$

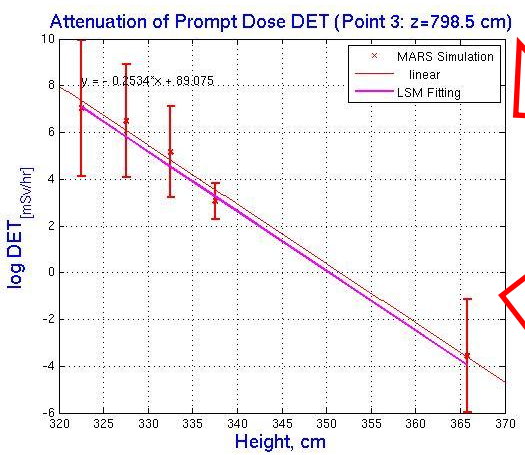
Resume: *Local shielding provides the required level of the prompt doses outside the PXIE shielding enclosure (item 2 of the requirements)*

Radiation Shielding (11)

Evaluation of the Prompt Dose Above the Roof (1)

Typical Prompt Dose Distribution Above the Roof (Case_06_2)





Problem: 100% statistics errors

Solution: interpolation based on the data obtained, where errors are small

MARS Data for 5 Layers Inside the Concrete Roof

(Case_07, beginning of the roof: x_0=320.04 cm)

Layer	x-coordinate, cm	DET, mSv/hr	ΔDET, mSv/hr	δDET, %
1	322.54	1135.0	341.6	30.1
2	327.54	660.0	125.6	19.0
3	332.54	172.6	48.58	28.1
4	337.54	21.13	4.53	21.4
5	365.76	0.0283	0.0079	27.9

Exponential decreasing of the prompt dose inside the roof:

$$DET = e^{-ax+b} = D_{init} e^{-x/\lambda}, \quad \text{where}$$

$$\lambda = a^{-1}, \quad D_{init} = e^{-ax_0+b}$$

Radiation Shielding (12)

Evaluation of the Prompt Dose Above the Roof (2)

Parameters $a,\ b,\ \lambda,\ D_{init}$ are found from *MARS* data and determine the attenuation coefficient $r = D_{req} / D_{init}$ and the required thickness of the concrete roof $\Delta H = -\lambda \log(r)$

$$D_{req} = 5 \cdot 10^{-3}\ \text{mSv/hr}$$

$$\Delta H_{PXIE} = 130\ \text{cm}$$

Point	Parameter	Case_06-2	Case_06-3	Case_07
"1"	a, cm	0.06119	0.07352	0.20260
	λ, cm^{-1}	16.34	13.82	4.94
	b	25.822	27.702	72.648
	D_{init}	512.4	94.30	4221.0
	$r=D_{req}/D_{init}$	$9.8 \cdot 10^{-6}$	$5.3 \cdot 10^{-5}$	$2.0 \cdot 10^{-6}$
	$\Delta H = -\lambda \log(r)$	**188.6**	**136.1**	**64.7**
"2"	a, cm	0.07323	0.13178	0.23696
	λ, cm^{-1}	13.66	7.59	4.22
	b	29.211	46.307	82.860
	D_{init}	322.1	62.31	1124.1
	$r=D_{req}/D_{init}$	$1.6 \cdot 10^{-5}$	$8.0 \cdot 10^{-5}$	$4.4 \cdot 10^{-6}$
	$\Delta H = -\lambda \log(r)$	**151.2**	**71.6**	**52.0**
"3"	a, cm	0.09013	0.16811	0.25558
	λ, cm^{-1}	11.10	5.95	3.91
	b	33.549	57.464	89.516
	D_{init}	110.5	38.94	2254.9
	$r=D_{req}/D_{init}$	$4.5 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$2.2 \cdot 10^{-6}$
	$\Delta H = -\lambda \log(r)$	**111.0**	**53.3**	**50.9**
"4"	a, cm	0.12746	0.12581	0.23702
	λ, cm^{-1}	7.85	7.95	4.22
	b	45.187	44.807	82.743
	D_{init}	81.0	93.95	978.2
	$r=D_{req}/D_{init}$	$6.2 \cdot 10^{-5}$	$5.3 \cdot 10^{-5}$	$5.1 \cdot 10^{-6}$
	$\Delta H = -\lambda \log(r)$	**76.0**	**78.2**	**51.4**

Resume: PXIE shielding enclosure provides the required level of the prompt doses above the roof (item 3 of the requirements)

Radiation Shielding (13)

Tritium Production (1)

Channels for tritium production:

- ✗ From beam dump materials with their subsequent migration into the soil;
- Irradiation of the soil's lithium by the neutrons produced in the beam dump.

Due to "low" energy (30 MeV) of the primary beam

Concentration of the $^{6}Li_3$ in the soil: $$N_{^6Li_3} = 6.03 \cdot 10^{23} \frac{\rho_{soil}}{\mu_{soil}} \eta_{Li_natural} \cdot \eta_{^6Li_3} \cdot \nu_{Li}$$

Parameter		Value
ρ_{soil}	Density of the soil	2.25 g·cm^{-3}
μ_{soil}	Molecular weight of the soil	20.4857 g·mol^{-1}
$\eta_{Li_natural}$	Abundance of the lithium in the soil	29 mg/kg
η_{6Li3}	Part of $^{6}Li_3$ in the natural lithium	7.59%
ν_{Li}	Part of soluble lithium in the natural lithium	5%

In Chicago area

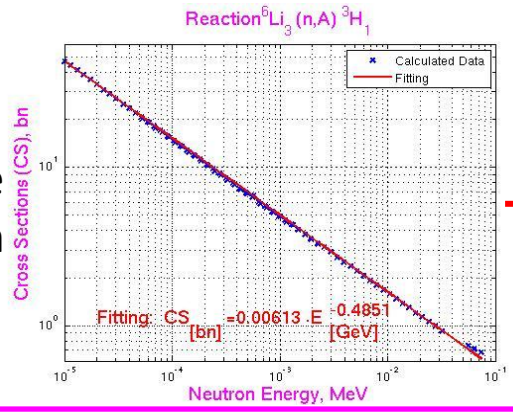
$$N_{^6Li_3} \approx 7.45 \cdot 10^{15} \text{ cm}^{-3}$$

Radiation Shielding (14)

Tritium Production (2)

Cross section of the reaction $^{6}Li_{3}\ (n,A)\ ^{3}H_{1}$ was estimated based on the data for ratio of the cross sections of the desired and "reference" reactions, and data for cross section of the "reference" reaction $^{10}B_{5}\ (n,A)\ ^{7}H_{3}$

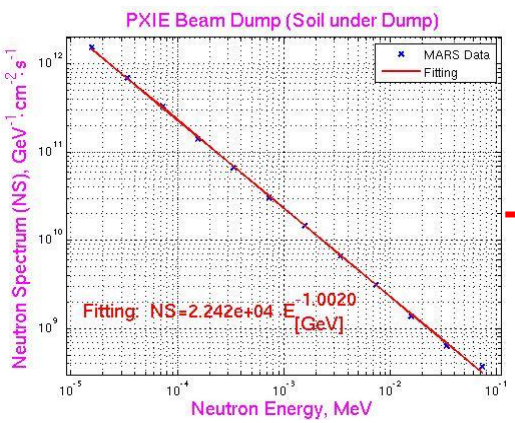
Calculated dependence of the cross section on neutron energy:



Linear Fitting →

$$\sigma_{Li\to T} = A_{Li\to T}\cdot E^{-\alpha_{Li}}_{[GeV]};$$
$$A_{Li\to T} = 0.00613\ \text{nb},$$
$$\alpha_{Li\to T} = 0.4851$$

Neutron spectrum (*MARS* simulation):



Linear Fitting →

$$\frac{dN_n}{dE} = A_{spectrum}\cdot E^{-\alpha_{spectrum}}_{[GeV]};$$
$$A_{spectrum} = \frac{2.242\cdot 10^{4}}{GeV\cdot cm^{2}\cdot s},$$
$$\alpha_{spectrum} = 1.0002$$

Radiation Shielding (15)

Tritium Production (3)

Rate of the tritium production (atoms per cm^3·s):

$$Q_T = N_{^6Li_3} \cdot \int_{E_{min}}^{E_{max}} \sigma_{Li\to T} \frac{dN_n}{dE} dE = N_{^6Li_3} \cdot A_{Li\to T} \cdot A_{spectrum} \frac{E_{max}^{1-(\alpha_{Li\to T}+\alpha_{spectrum})} - E_{min}^{1-(\alpha_{Li\to T}+\alpha_{spectrum})}}{1-(\alpha_{Li\to T}+\alpha_{spectrum})}$$

The interval selected neutron energy: $10^{-5} \div 10^{-1}$ MeV

Equation for $N_T(t)$: $\frac{dN_T}{dt} = -\lambda N_T + Q_T$,

where $\tau_{1/2} = \log 2 / \lambda = 13.35\ year$

Tritium Activity (pCi per cm^3·year):

$$Y_T(t) = f \cdot \lambda \cdot N_T(t)$$

where f =1/037 disintegrations per s

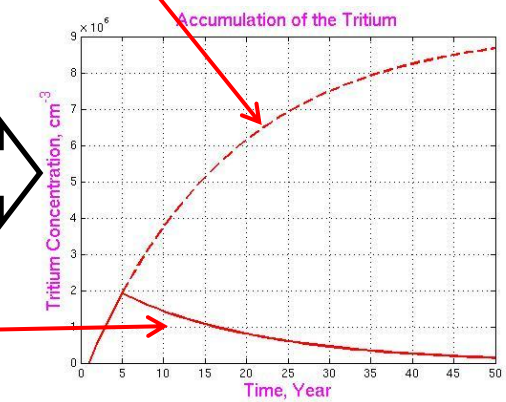
Solution:

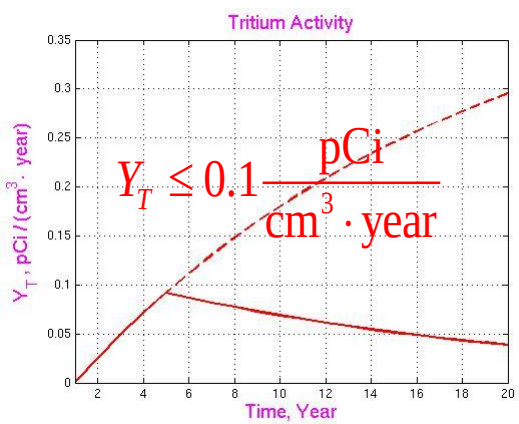
$$N_T(t) = \frac{Q_T}{\lambda}\left(1-e^{-\lambda t}\right) = \frac{Q_T \tau_{1/2}}{\log 2}\left(1-2^{-t/\tau_{1/2}}\right)$$

PXIE Life Operation:

$$\tau_{PXIE} = 5\ year$$

$$\tau_{PXIE} = 50\ year$$





Resume:

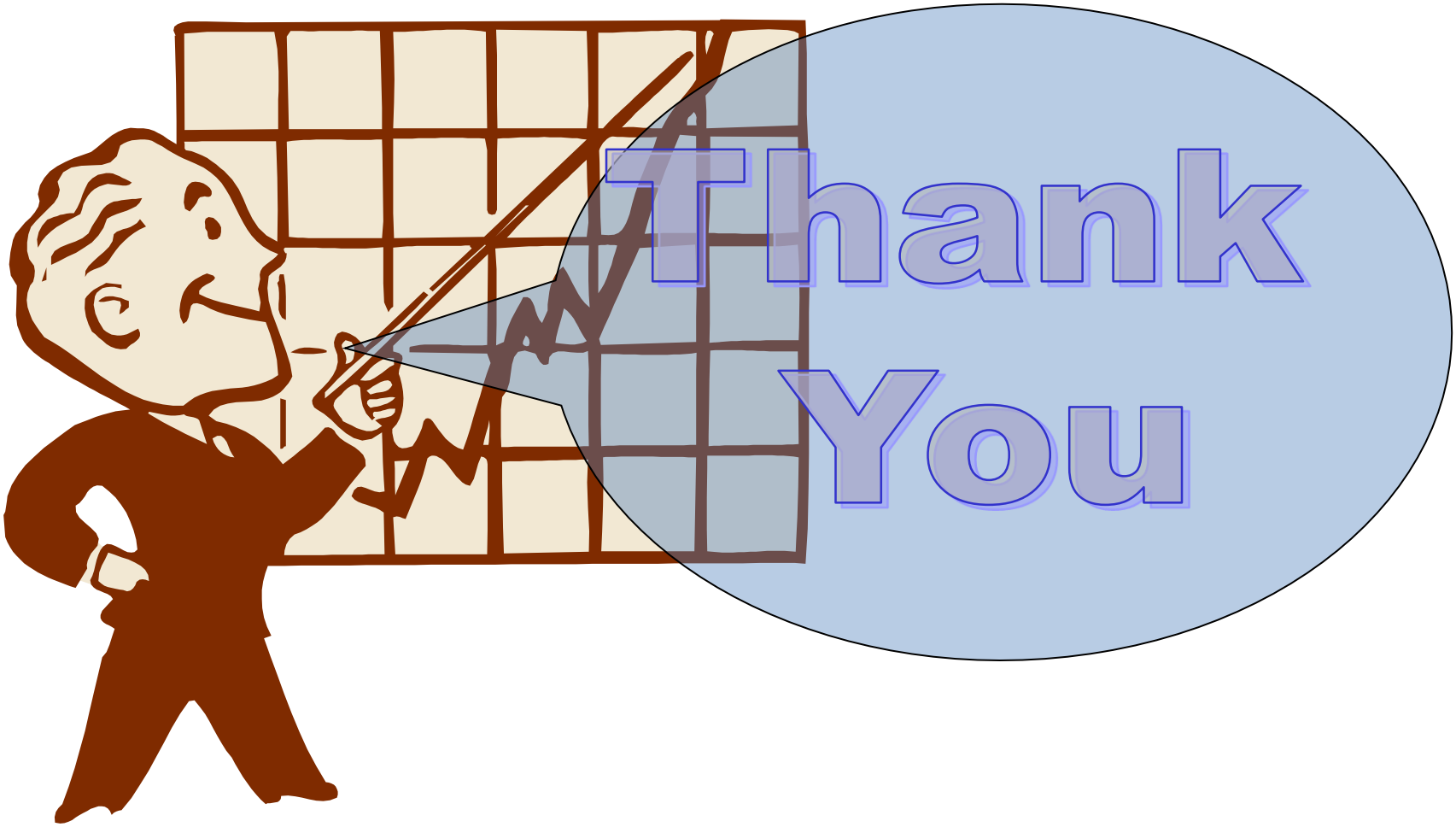
An estimate of tritium activity in the soil under the PXIE absorber yields significantly smaller value than the maximum acceptable value determined by Fermilab safety regulations (20 pCi/(cm^{3}year))

Summary

- Conception of beam dump layout is selected
- ~25% (nickel) and ~4% (carbon) of the particles are forward scattered from the surface. They carry out ~6% (nickel) and ~1% (carbon) of the power of the incident beam
- The phenomenon of sputtering is negligible in terms of expected duration of operation of this device
- The phenomenon of blistering is negligible in terms of expected duration of operation of this device in the case with nickel beam dump. Case with graphite requires further study
- No serious problems with cooling of the beam dump
- Local shielding provides the required level of the attenuation of the beam dump and required level of the prompt doses outside the PXIE shielding enclosure (both labyrinths and roof)
- An estimate of tritium production in the soil under the PXIE absorber yields significantly smaller value than the maximum acceptable value determined by Fermilab safety regulations (20 pCi/(cm^{3}year))

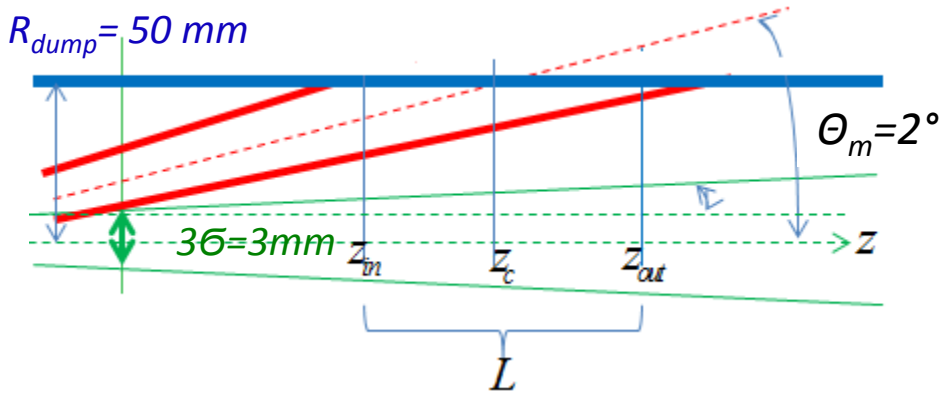
Future Work

- Final selection of material: *Nickel or Graphite*
- For normal operation mode and incident scenario:
  - Distribution of absorbed dose associated with type of particle;
  - Levels of induced activity in accelerator components
- ? ? ?

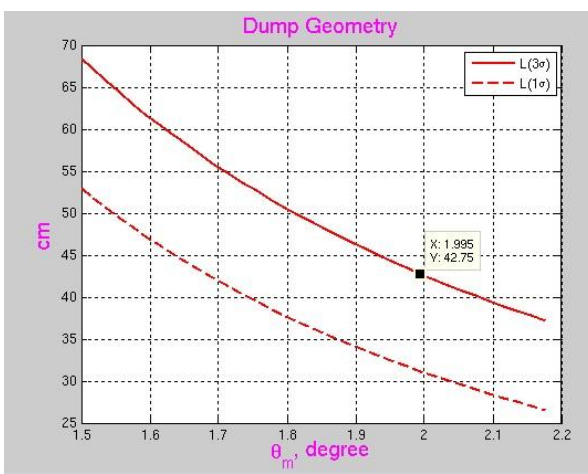

Thank
You

Back-up slides

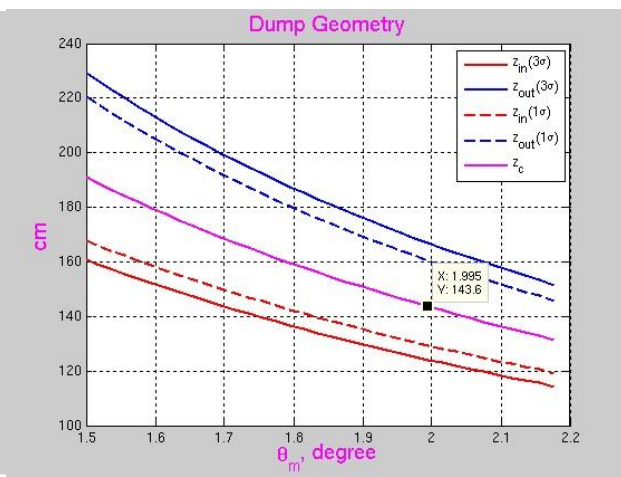
PXIE Beam Dump Layout (1)



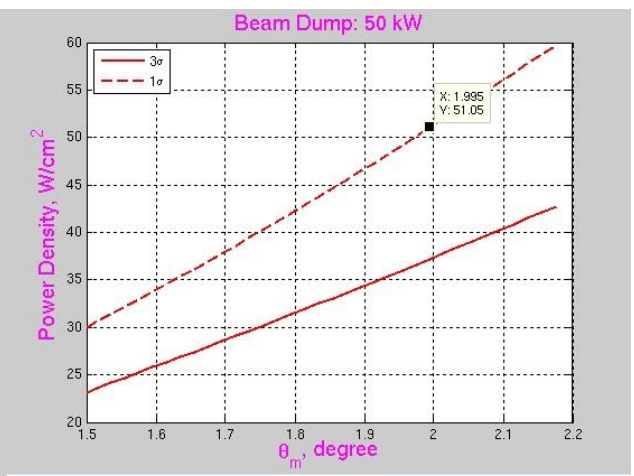
Length of the Beam Dump



Location of the Beam Dump



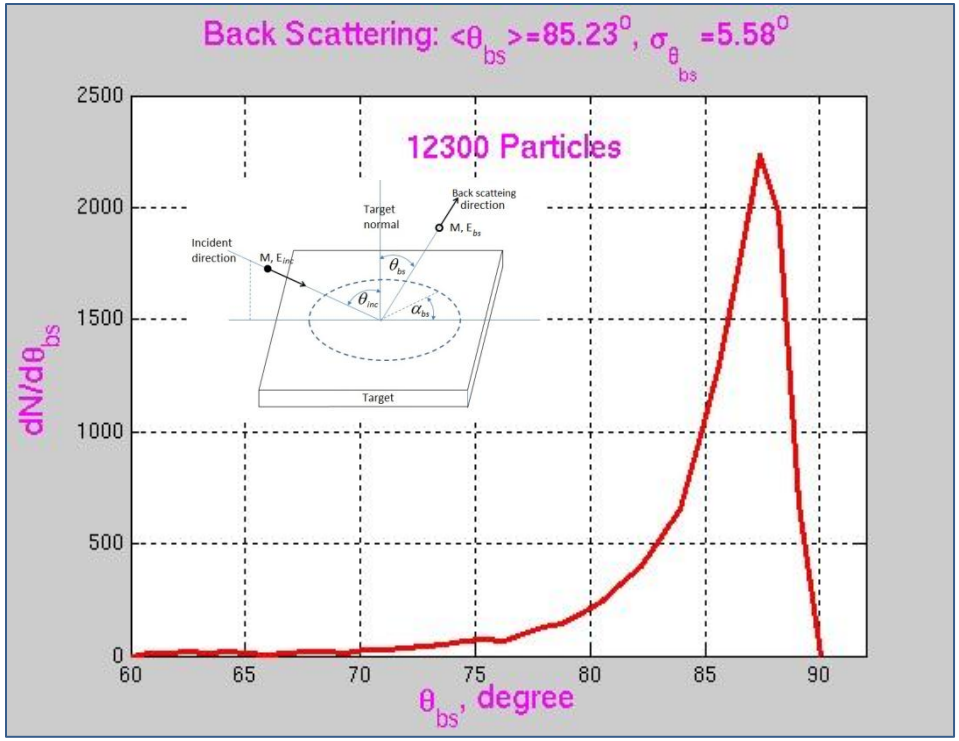
Power Density



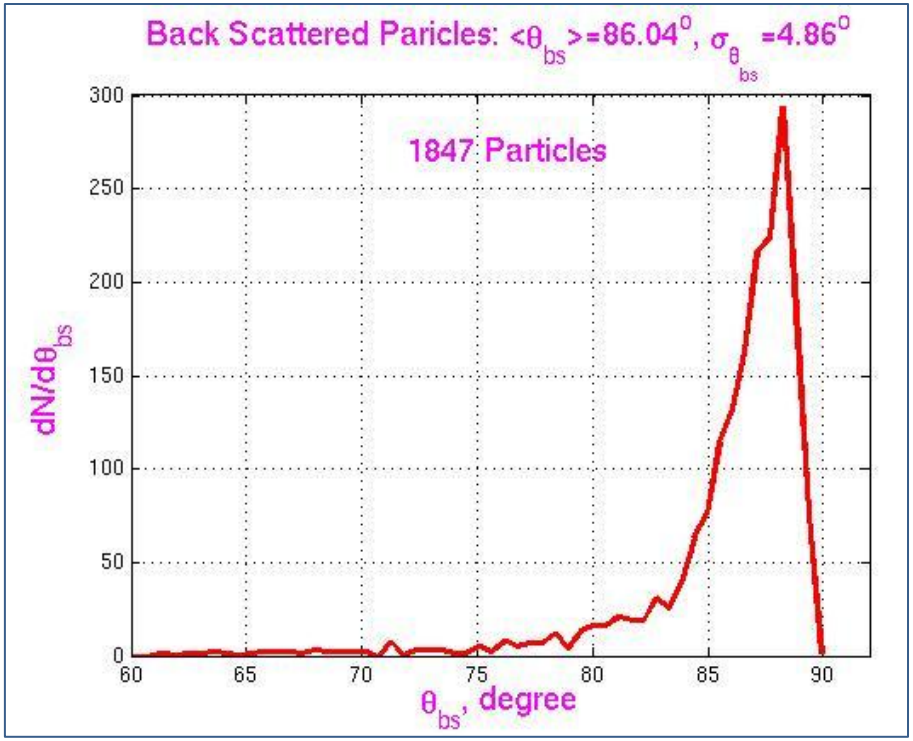
Back Scattering (1)

Particle Distribution vs. Back Scattering Angle

Nickel

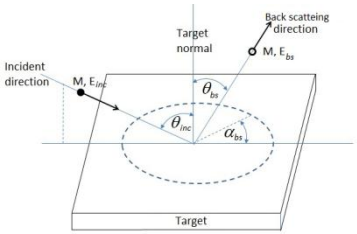


Carbon

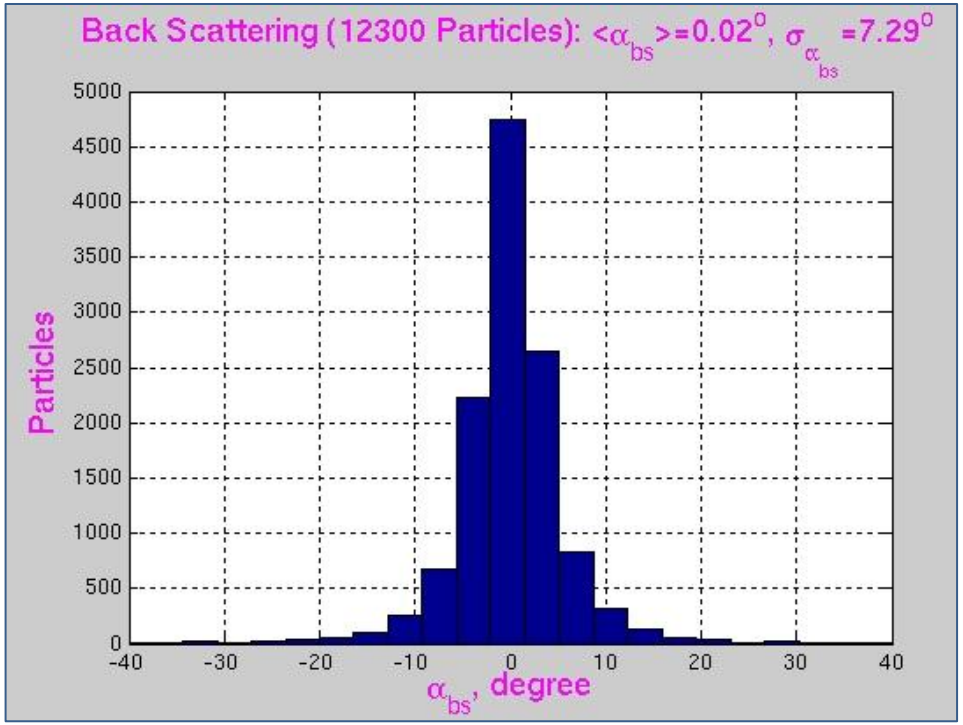


Back Scattering (2)

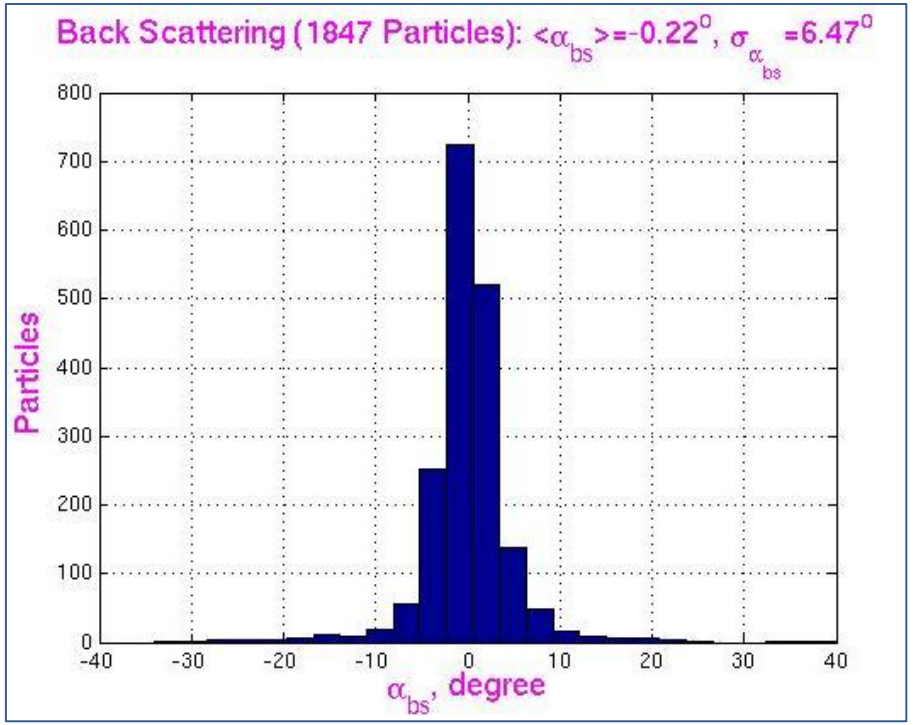
Particle Distribution vs. Transversal Back Scattering Angle



Nickel



Carbon



Sputtering (1)

Preferred mechanisms of sputtering for light/heavy ions:

Incidence	Normal	Oblique	Grazing
Light Ions	III	II and I	I and II
Heavy Ions	III	II and I	II and I

I — Direct Knockout; II — Linear Cascade; III — Thermal Shock

<u>Empirical formulas for normal incidence</u>

The following parameters and empirical formulas are used to describe the sputtering at normal incidence of particles of mass M_1, charge Z_1, and kinetic energy E on the surface of material with M_2, Z_2:

1) Energy transfer factor $\gamma = \dfrac{4M_1M_2}{M_1+M_2}$;

2) Coefficient to factorize the cross section

$$\alpha^*(M_2/M_1) = \begin{cases} 0.249\cdot(M_2/M_1)^{0.56} + 0.0035\cdot(M_2/M_1)^{1.5}, & \text{for } M_1 \le M_2, \\ 0.0875\cdot(M_2/M_1)^{-0.15} + 0.165\cdot(M_2/M_1), & \text{for } M_1 \ge M_2 \end{cases};$$

3) Lindhart electronic stopping coefficient

$$k_e = 0.079\frac{(M_1+M_2)^{3/2}}{M_1^{3/2}M_2^{1/2}}\frac{Z_1^{2/3}Z_2^{1/2}}{(Z_1^{2/3}+Z_2^{2/3})^{3/4}};$$

Sputtering (2)

4) Reduced energy $\varepsilon(E) = \dfrac{0.03255}{Z_1 Z_2 \sqrt{Z_1^{2/3} + Z_2^{2/3}}} \dfrac{M_2}{M_1 + M_2} E;$

5) Reduced nuclear stopping cross section (Fermi-Tomas model)

$$S_n^{TF}(\varepsilon) = \frac{3.441\sqrt{\varepsilon} \cdot \ln(\varepsilon + 2.718)}{1 + 6.355\sqrt{\varepsilon} + \varepsilon(6.882\sqrt{\varepsilon} - 1.708)};$$

6) Reduced nuclear stopping cross section

$$S_n(E) = 84.78 \frac{Z_1 Z_2}{\sqrt{Z_1^{2/3} + Z_2^{2/3}}} \frac{M_1}{M_1 + M_2} S_n^{TF}(\varepsilon);$$

7) Values U_s (surface binding energy), $Q(Z_2)$, $W(Z_2)$ (fitting parameters) and $s(Z_2)$ (yield power factor) can be found for selected material from the following table:

target	Z_2	U_s	Q	W	s
Be	4	3.32	1.66	2.32	2.5
B	5	5.77	2.62	4.39	2.5
C	6	7.37	1.70	1.84	2.5
Al	13	3.39	1.0	2.17	2.5
Si	14	4.63	0.66	2.32	2.5
Ti	22	4.85	0.54	2.57	2.5
V	23	5.31	0.72	2.39	2.5
Cr	24	4.10	0.93	1.44	2.5
Mn	25	2.92	0.95	0.88	2.5
Fe	26	4.28	0.75	1.20	2.5
Co	27	4.39	1.02	1.54	2.5

Sputtering (3)

target	Z_2	U_s	Q	W	s
Ni	28	4.44	0.94	1.33	2.5
Cu	29	3.49	1.0	0.73	2.5
Ge	32	3.85	0.59	2.08	2.5
Zr	40	6.25	0.54	2.50	2.8
Nb	41	7.57	0.93	2.65	2.8
Mo	42	6.82	0.85	2.39	2.8
Ru	44	6.74	1.31	2.36	2.5
Rh	45	5.75	1.14	2.59	2.5
Pd	46	3.89	0.85	1.36	2.5
Ag	47	2.95	1.08	1.03	2.8
Sn	50	3.14	0.47	0.88	2.5
Tb	65	4.05	0.90	1.42	2.5
Tm	69	2.42	0.65	0.85	2.5
Hf	72	6.44	0.65	2.25	2.5
Ta	73	8.1	0.56	2.84	2.8
W	74	8.9	0.72	2.14	2.8
Re	75	8.03	1.03	2.81	2.5
Os	76	8.17	1.11	2.86	2.5
Ir	77	6.94	0.96	2.43	2.5
Pt	78	5.84	1.03	3.21	2.5
Au	79	3.81	1.08	1.64	2.8
Th	90	6.2	0.63	2.79	2.5
U	92	5.55	0.66	2.78	2.5

Sputtering (4)

8) Coefficient

$$\Gamma = \frac{1}{1+(M_1/7)^3} W;$$

9) Sputtering threshold energy

$$E_{th} = U_s \cdot \begin{cases} 6.7\gamma^{-1} & \text{for } M_1 \geq M_2, \\ \dfrac{1+5.7\cdot(M_1/M_2)}{\gamma} & \text{for } M_1 \leq M_2 \ . \end{cases}$$

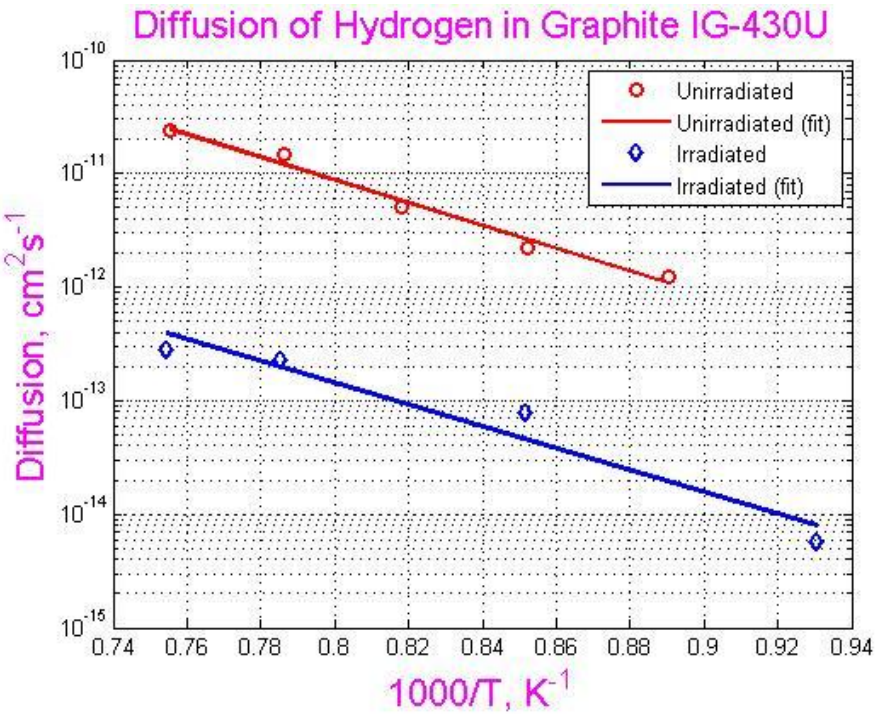
After that the yield sputtering is determined from the following expression:

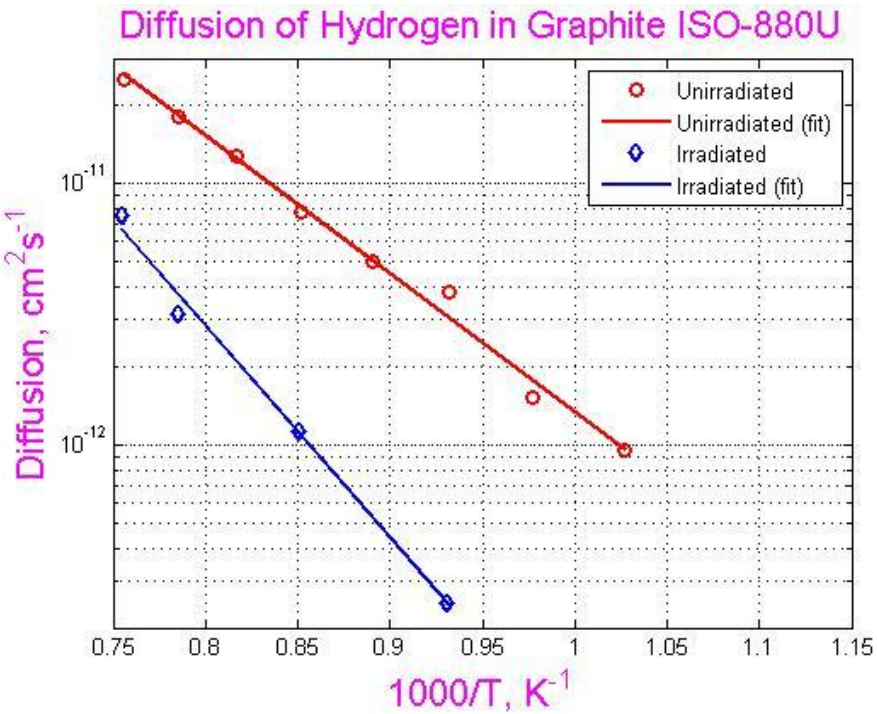
$$Y(E) = 0.042 \frac{Q(Z_2)\cdot\alpha^*(M_2/M_1)}{U_s(Z_2)} \frac{S_n(E)}{1+\Gamma(W)\cdot k_e\cdot\varepsilon(E)} \left[1-\sqrt{\frac{E_{th}}{E}}\right]^{s(Z_2)}$$

Reference: "Sputtering of Materials for MEBT Absorber and PXIE Beam Dump",
PX Doc DB ID: Project X-doc-1091 v-1

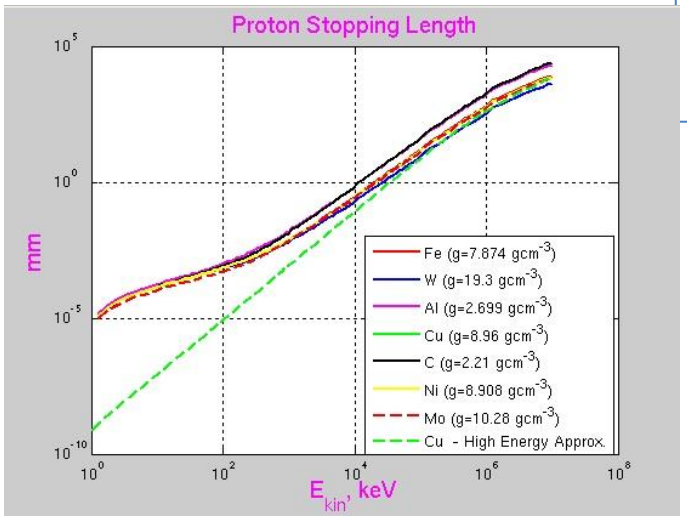
Diffusion of Hydrogen in Graphite

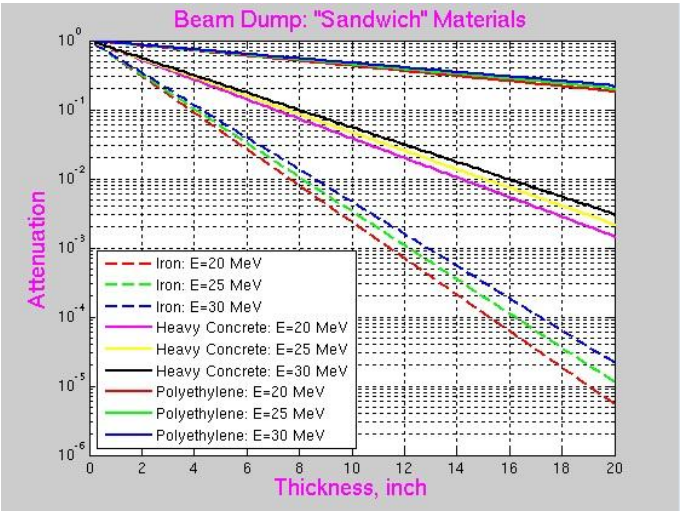
Influence of Neutron Irradiation: $\Phi_n = 3.9 \cdot 10^{19}$ n/cm^2





Attenuation of Materials





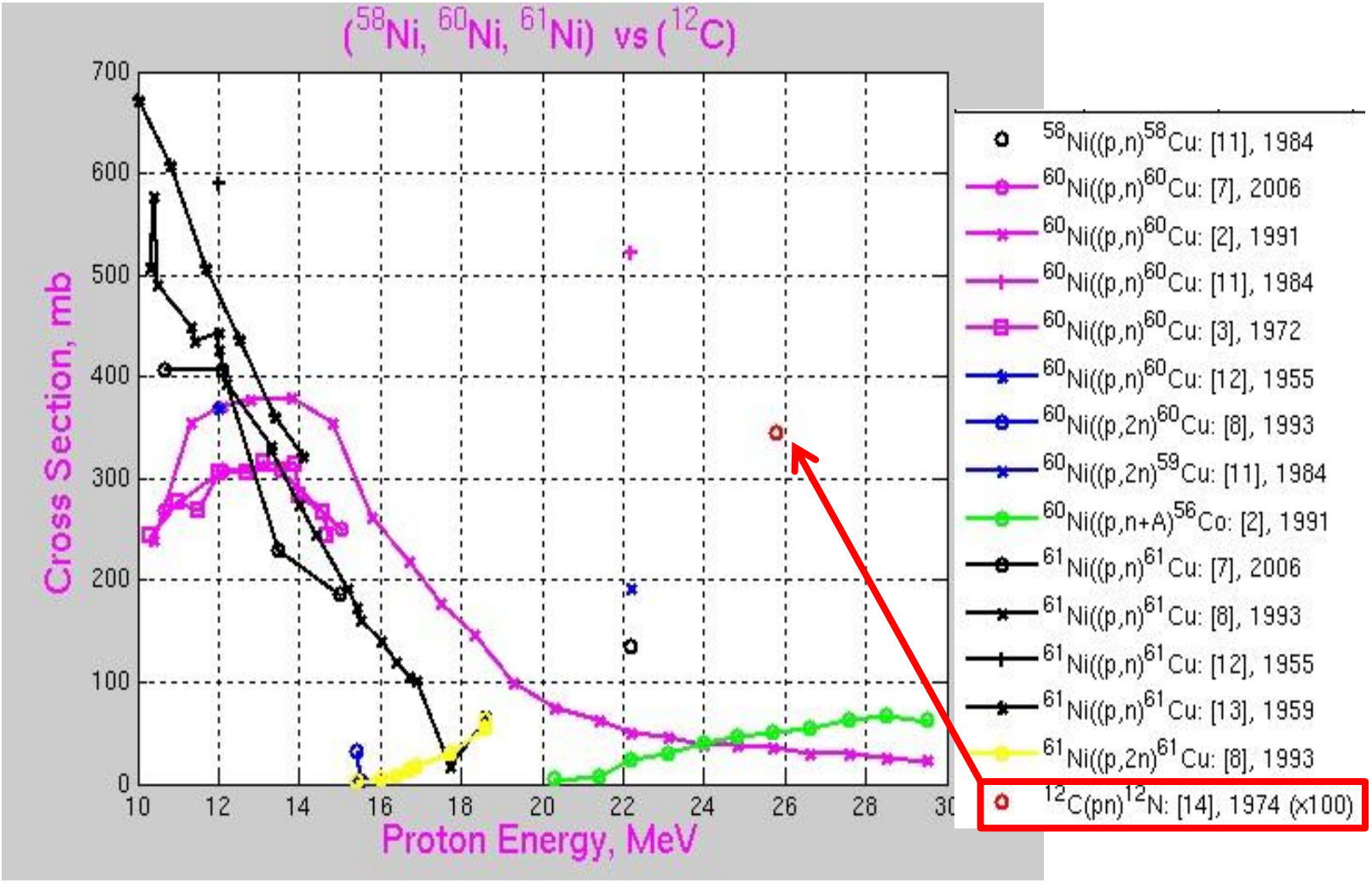
Data were received from PSTAR code:
http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

Attenuation *A* as function of thickness *d* of material and energy *E (GeV)* of the beam (high energy approximation):

$$A(d,E) = 10^{-\frac{d}{\lambda[1-0.8\exp(-5E)]}};$$

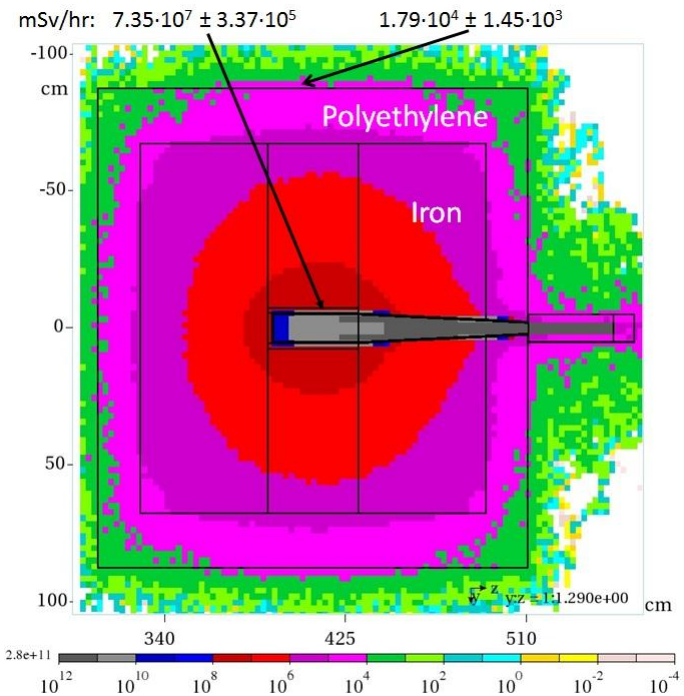
Material:	$\rho, \frac{\text{g}}{\text{cm}^3}$	λ, cm
Iron	7.84	35
Heavy concrete	3.6	65
Concrete	2.35	100
Polyethylene	0.95	250
Polyethylene filler	0.8	290

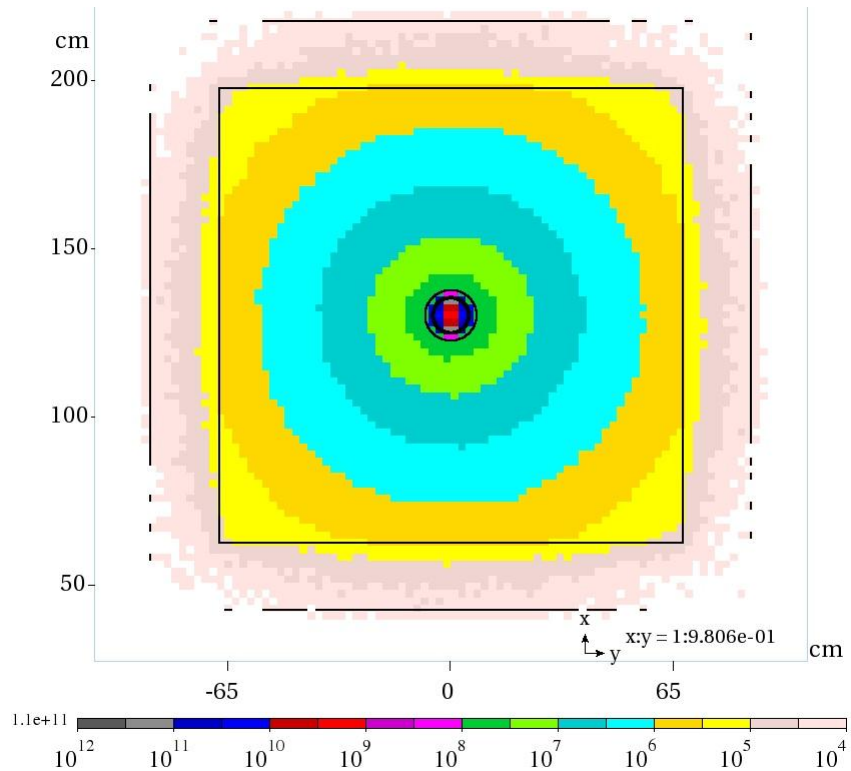
Cross Section for Nickel and Graphite



MARS Simulation (1)

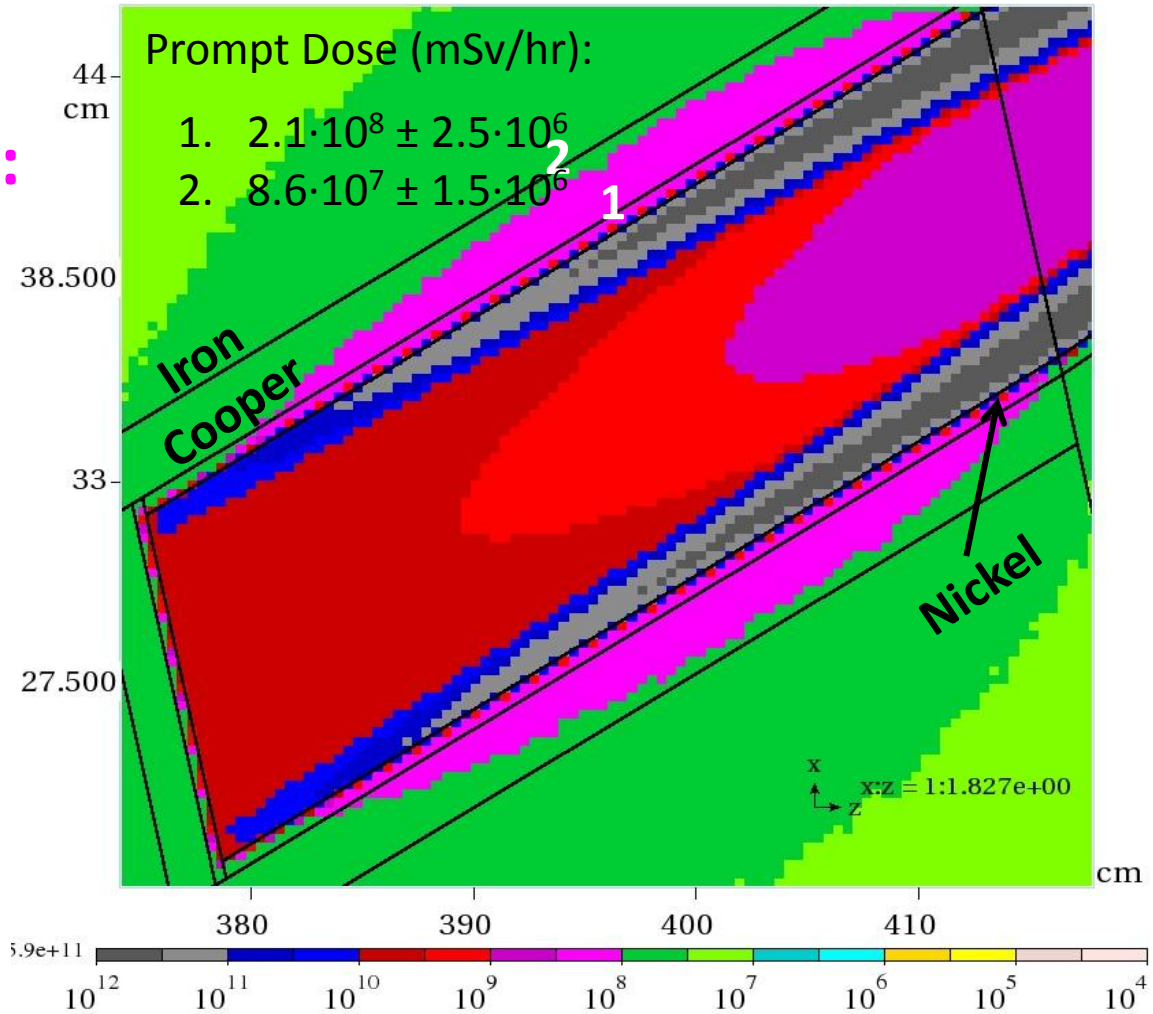
Case_05-fin





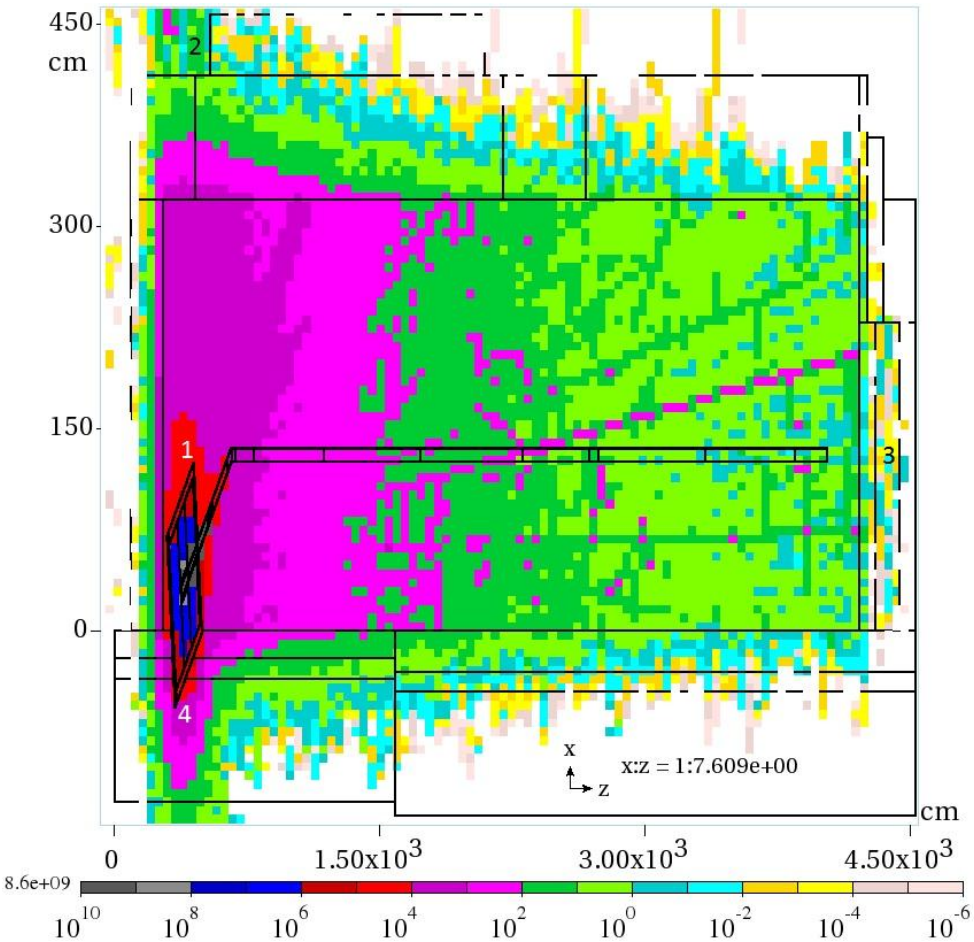
MARS Simulation (2)

Protons(case_05-3):
E=30 MeV,
I=1.7 mA,
W=50 kW



MARS Simulation (3)

Protons: E=30 MeV, I=1.7 mA, W=50 kW (case_05-5)



PXIE Cave

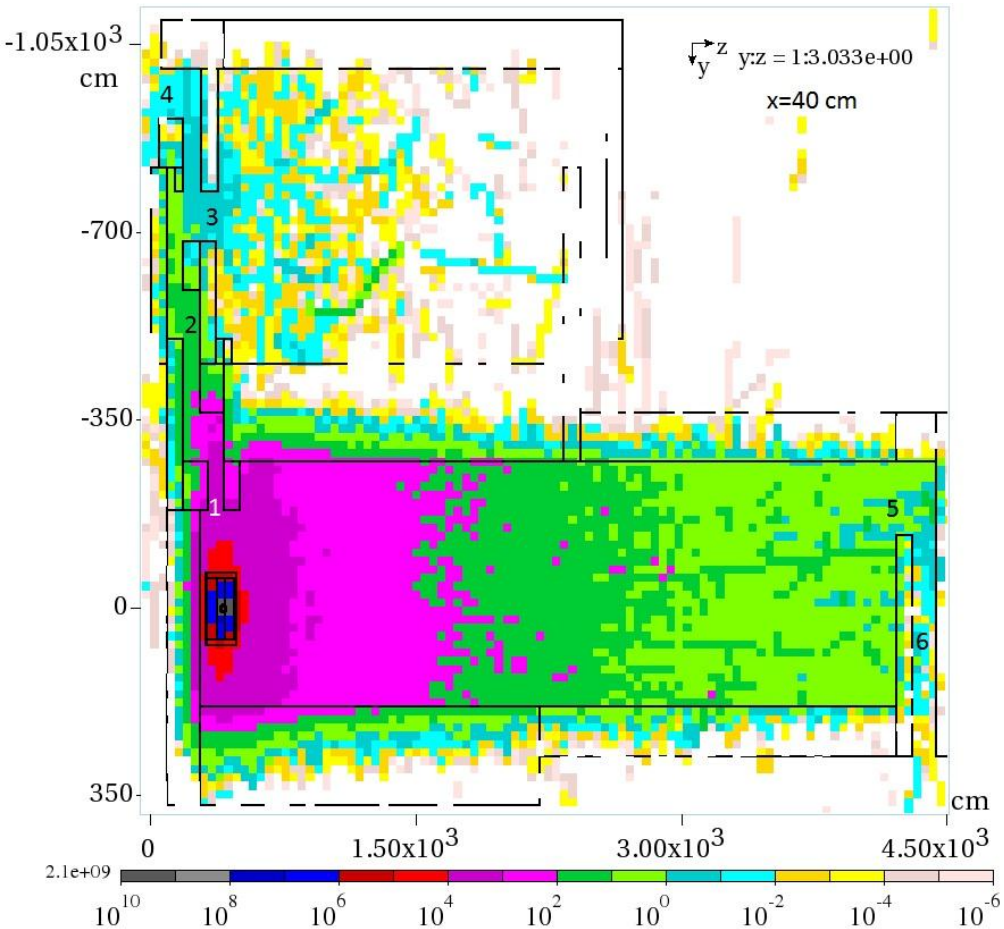
Prompt Dose (PD, mSv/hr)

1. $(1.92 \pm 0.205)\cdot 10^{4}$
2. 39.1 ± 23.3
3. $(1.25 \pm 1.25)\cdot 10^{-4}$
4. $(3.28 \pm 0.04)\cdot 10^{3}$

1mSv → 100 mrem

MARS Simulation (4)

Protons: E=30 MeV, I=1.7 mA, W=50 kW (case_05-5)



PXIE Cave

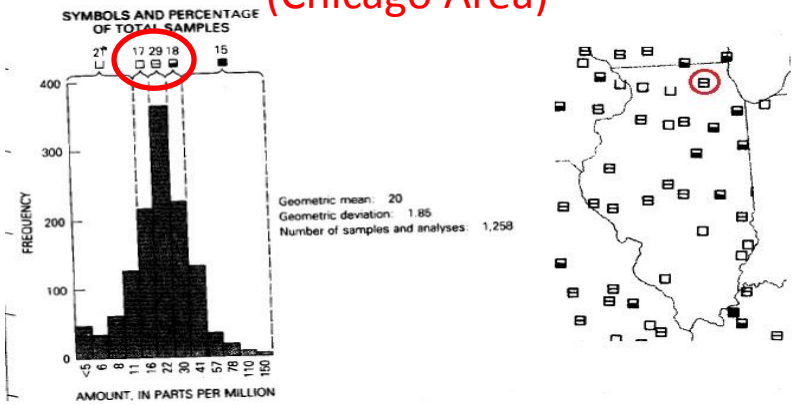
Prompt Dose (PD, mSv/hr)

1. $(4.11 \pm 0.13)\cdot 10^{3}$
2. 24.91 ± 3.94
3. $(4.37 \pm 1.17)\cdot 10^{-1}$
4. $(4.92 \pm 2.81)\cdot 10^{-2}$
5. 1.96 ± 0.63
6. $(3.03 \pm 1.39)\cdot 10^{-2}$

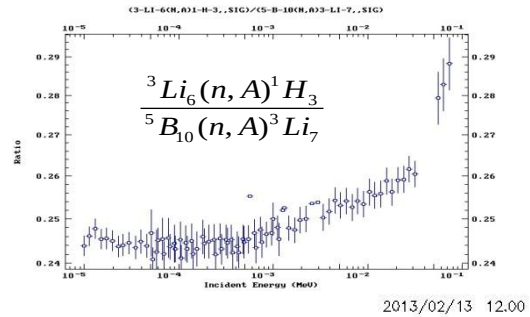
1mSv → 100 mrem

Tritium Production (1)

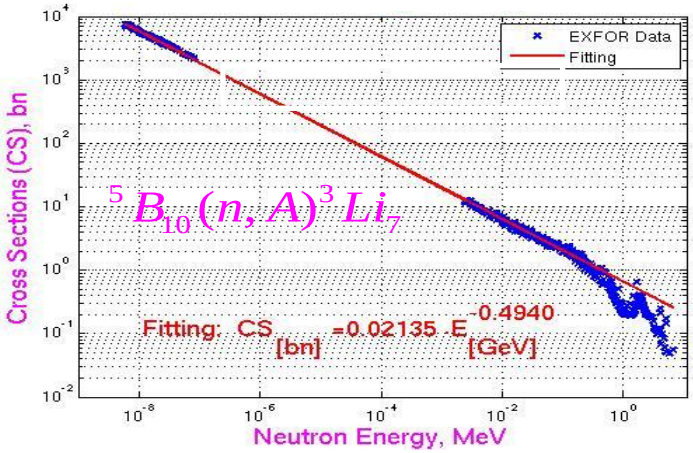
Abundance of the lithium in the soil (Chicago Area)



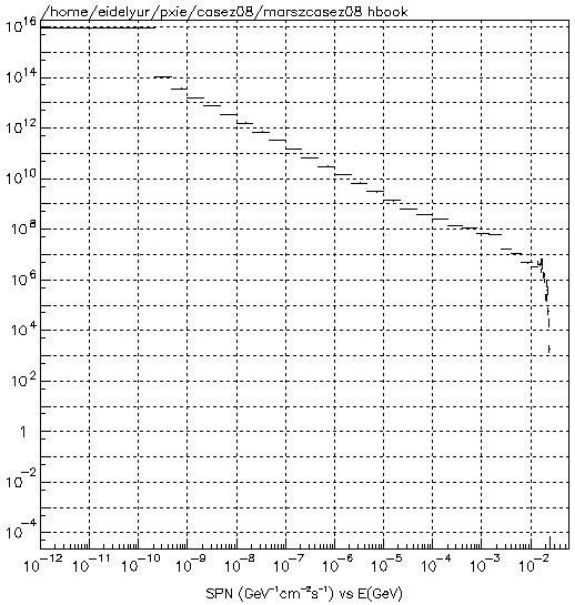
Ratio of Cross Sections of the Reference and Required Reactions



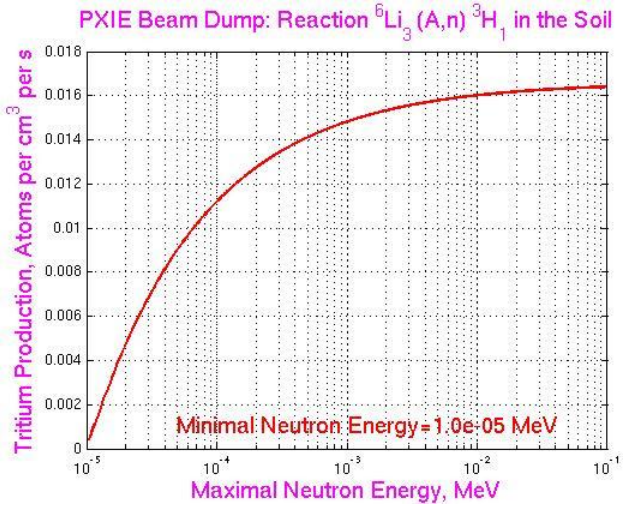
Reference Reaction

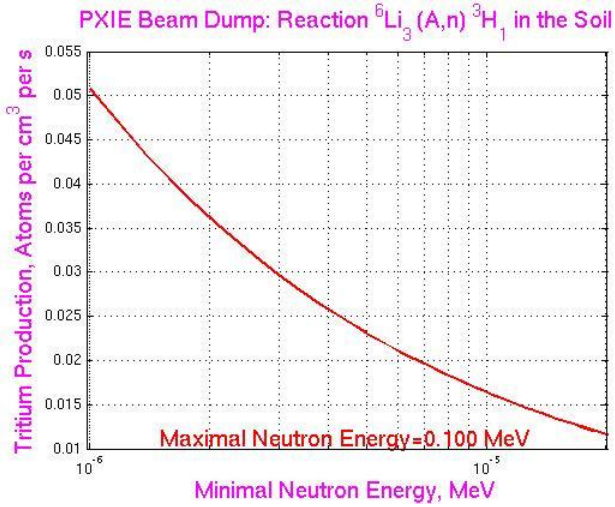


Neutron Spectrum in the Soil (*MARS* Simulation)



Tritium Production (2)





Radiation Shielding (1)

The normal and accident beam loss conditions

Section	Energy	Current	Normal condition losses	Accident condition losses
Ion source	30 keV	10 mA	-	100%
LEBT	30 keV	10 mA	Up to 90%	100%
RFQ	2.1 MeV	10 mA	5%	100 %
MEBT	2.1 MeV	10 mA	Up to 90%	100 %
HW	10.8 MeV	1 mA	Up to 0.1%	Up to 18% *
HW/SSR1 interface	11 MeV	2 mA	Up to 0.1%	100%
SSR1	30 MeV	1.7 mA	Up to 0.1%	0.1% *
Diagnostic section	30 MeV	1.7 mA	Up to 0.1%	100%
Beam dump	30 MeV	1.7 mA	100%	100%

*Sustained, high percentage beam loss under accident conditions may not be possible due to limitations of cryogenic systems.

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Radiation Shielding (2)

The normal and accident beam loss conditions

- The 2.1 MeV H^- beam losses upstream of the HW cryomodule do not present any known radiological concerns. Materials selected for use in the construction of the low energy section of PXIE have been checked to verify that there is no potential for production of neutrons .
- The HW and SSR1 cryomodules are intended to be operated with very high efficiency and extremely low losses. A machine protection system will be developed to limit losses between the upstream end of the HW cryomodule and the downstream end of the Diagnostic Section to 0.1%. Beam losses in the HW and SSR1 cryomodules must be limited to prevent damage to those cryomodules. Losses even approaching 0.1% will lead to degraded cryomodule performance and must be prevented for machine protection.
- The diagnostic section losses are expected to be very low. The beam quality established in the HW and SSR1 cavities is expected to survive through the diagnostic section. Losses no higher than 1:1000 or 0.1% are anticipated in the diagnostic section for normal conditions. Since the diagnostic section is warm, the accident condition of 100% beam loss must be considered.
- The beam dump is to be designed for continuous operation at 50 kW. The normal condition is the most severe condition for the beam dump. The beam dump will be designed such that the beam directed to the dump would not generate more radiation than a 0.1% beam loss in the diagnostic section.
- No beam transmission beyond the beam dump will be possible.

Radiation Shielding (3)

PXIE Radiation Dose Rate Design Goals

Location	Condition	Radiation Dose Rate limit (mrem/hr)	Permitted FRCM Occupancy	Required FRCM Radiological Postings
Perimeter at floor level around PXIE enclosure	Normal	<0.05	No precautions needed.	No posting required
Perimeter at floor level around PXIE enclosure	Accident	< 1	No precautions needed.	No posting required
PXIE enclosure ceiling	Normal	<0.25	No occupancy limits imposed.	Controlled Area
PXIE enclosure ceiling	Accident	<1	No precautions needed.	None

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