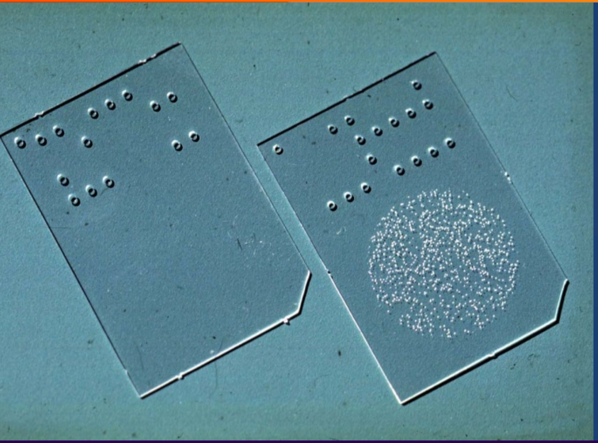
Charged particle LET threshold determinations with the HPA neutron PADC dosemeter

L G Hager, R J Tanner, J S Eakins

WRMISS 15, Frascati, September 2010

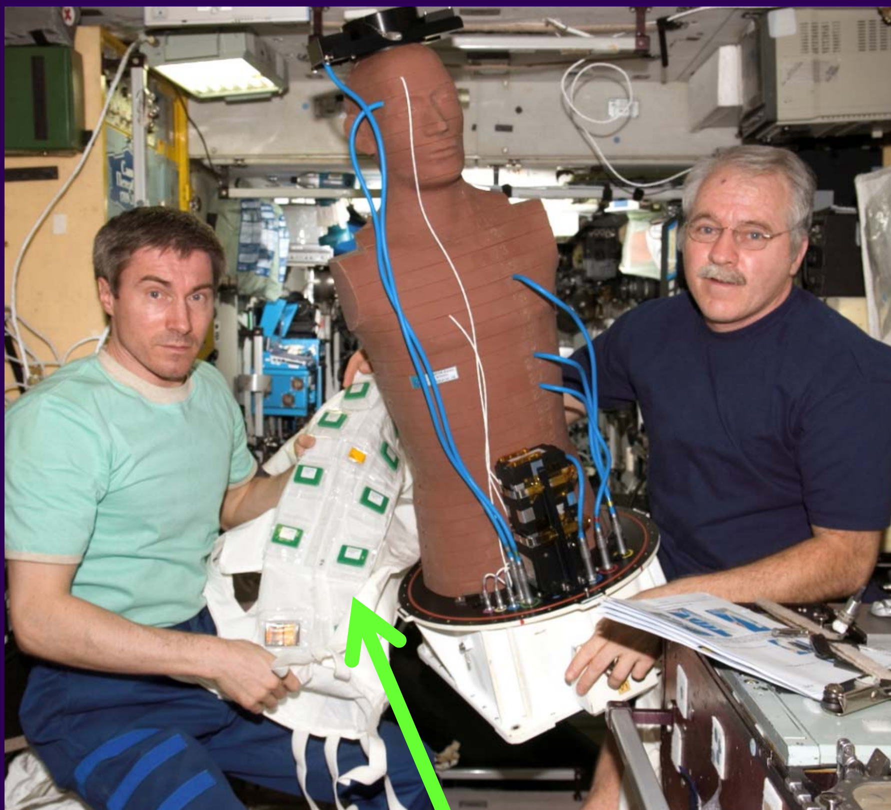
HPA PADC dosemeter

Health Protection Agency



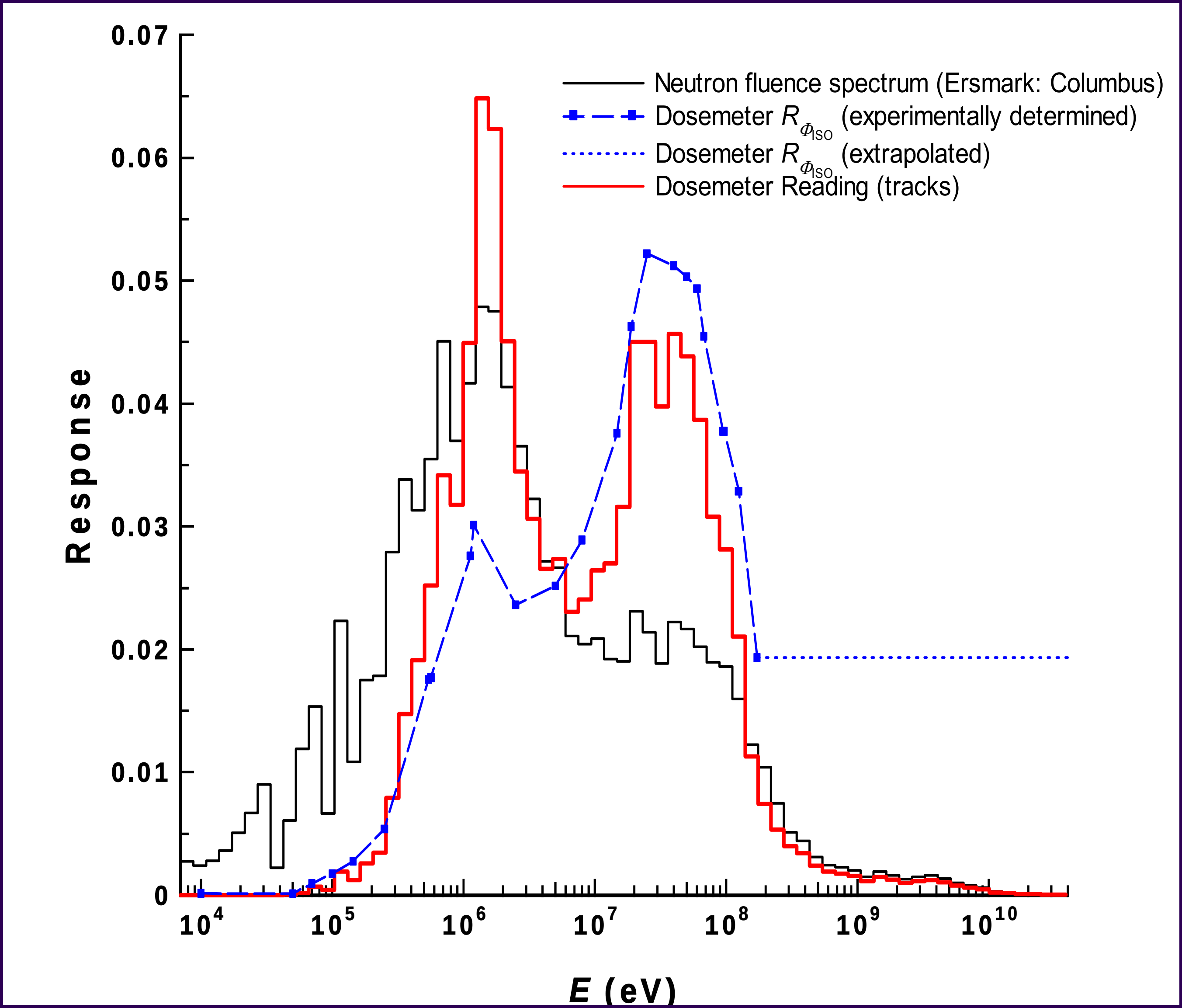
- Routine issue for neutron personal dosimetry – electrochemical etch rear face
- Calibrated for neutrons ≤ 173 MeV
- Electrochemical etch produces indistinguishable tracks for neutrons, direct protons, and heavy ions

Poncho jacket on MATROSHKA phantom

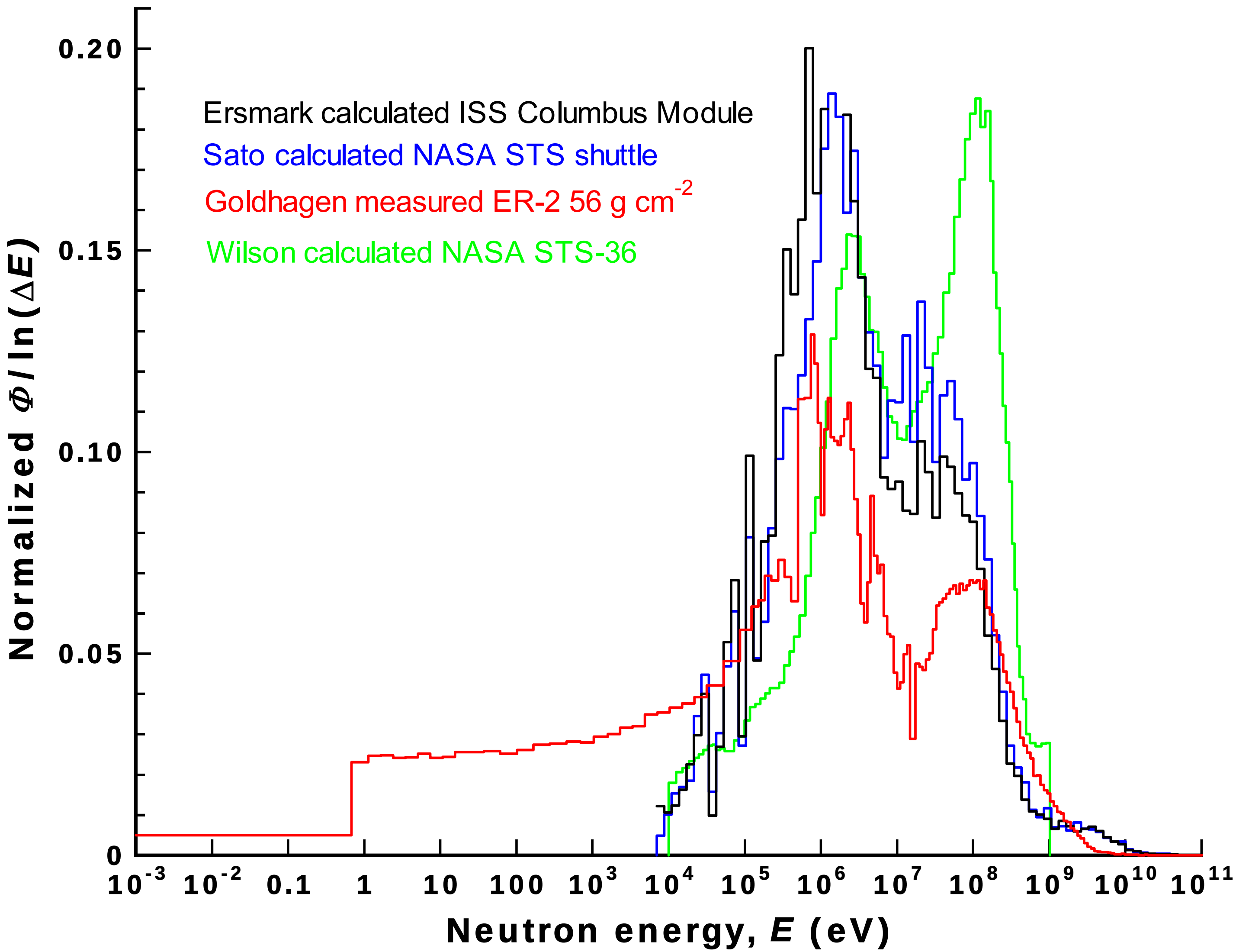


HPA PADC dosemeters attached to poncho

PADC dosemeter neutron response in Columbus module ISS
(using T Ersmark's neutron spectrum)



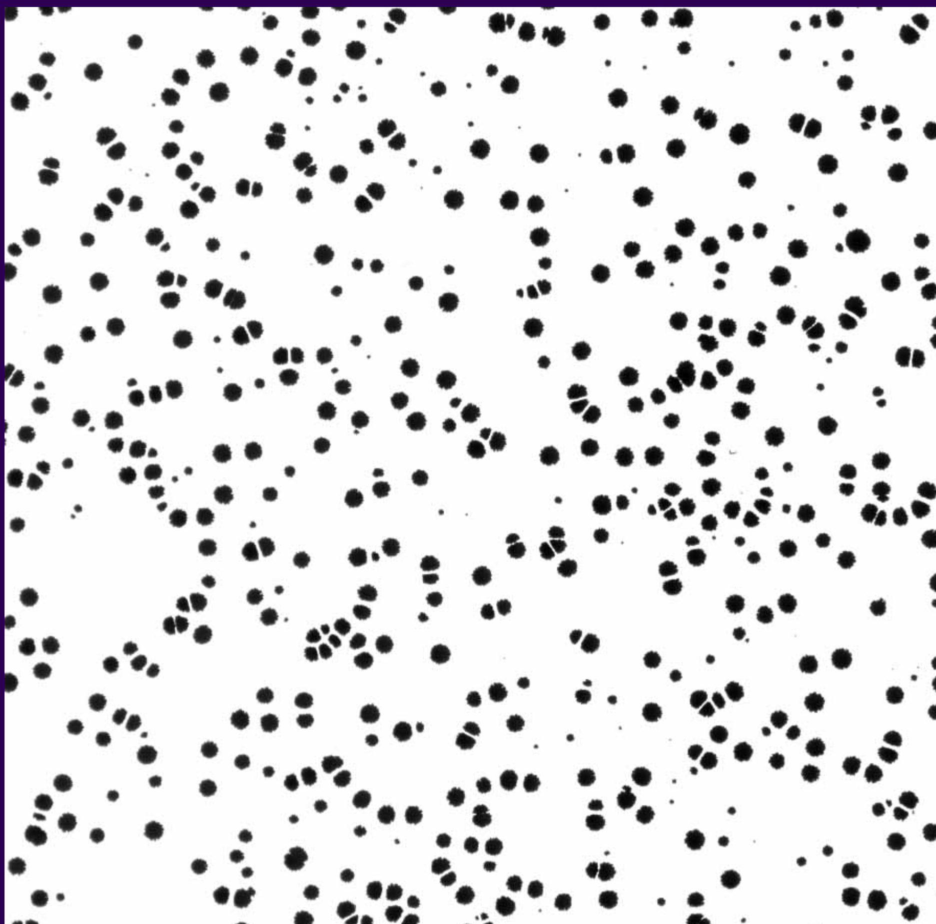
Representative neutron energy distributions



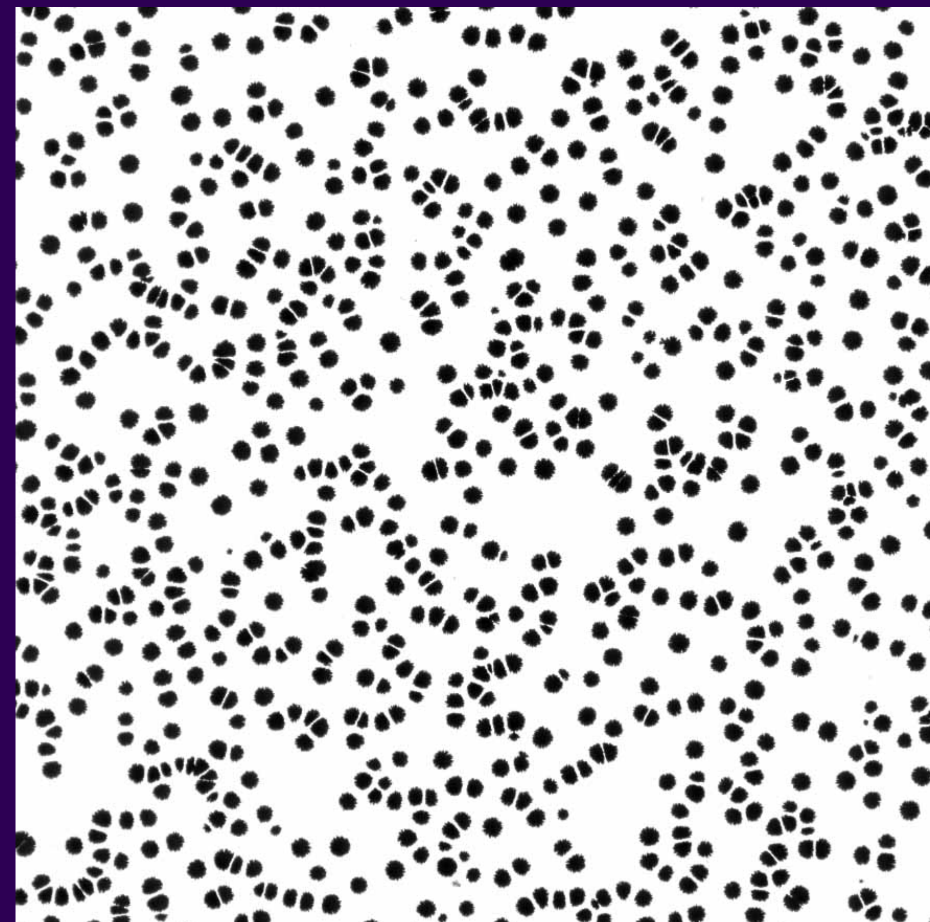
HPA PADC Dosemeter
Calculated response in different neutron energy distributions

Neutron energy distribution	E_{ISO}/Φ (pSv cm^2)	R_{Φ} (10^{-6} cm^2)	$R(E_{iso})$ (mSv^{-1})
Ersmark Columbus module ISS	228	30.7	134 (16)
Wilson NASA STS-36	304	35.4	116 (14)
Sato NASA STS with water	284	34.3	121 (15)
Goldhagen *et al*. ER-2 plane	167	19.6	117 (14)
Mean	246 (31)	30.0 (3.6)	122 (14)

ELECTROCHEMICAL etch problem - Tracks similar for all charged particle types



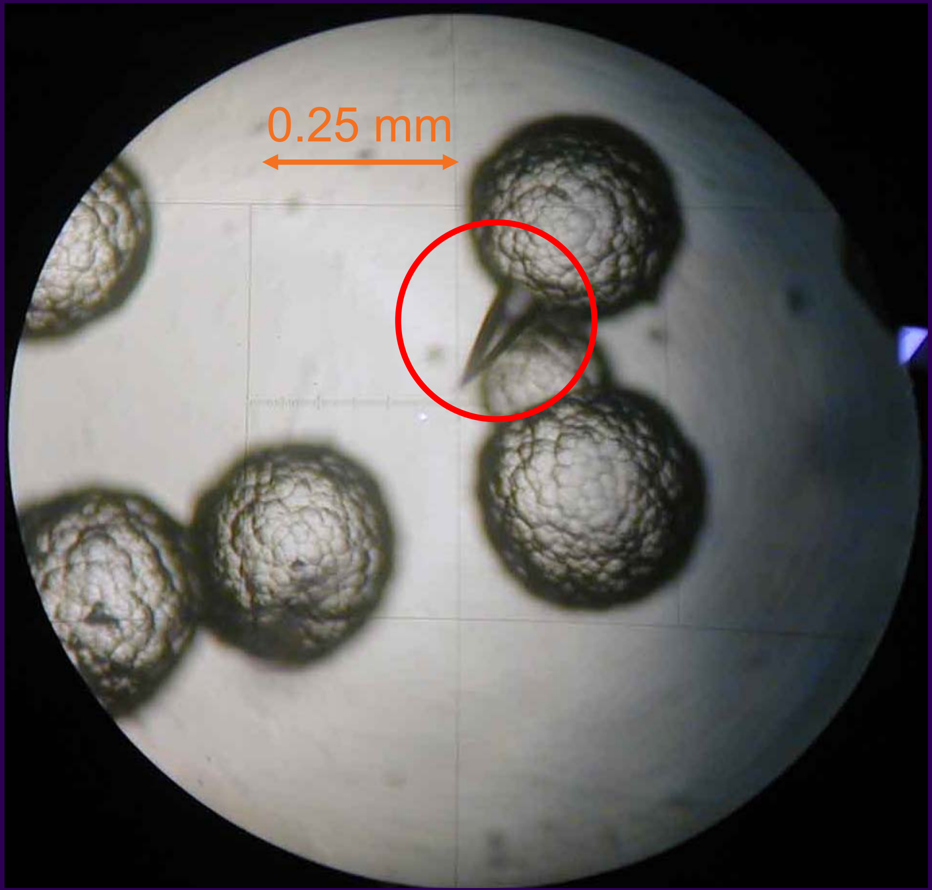
^{241}Am-Be Neutron induced tracks



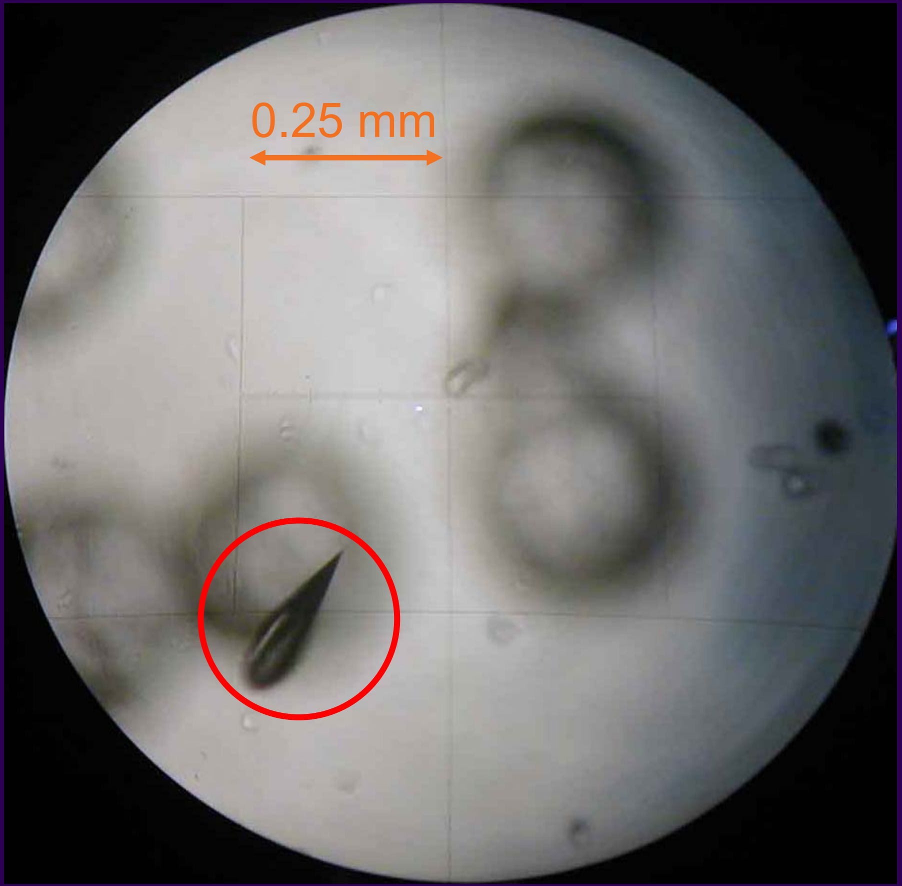
^{12}C tracks

Secondary chemical etch shows long range charged particle tracks

Heavy charged particle track subtraction for Z ≥ 3

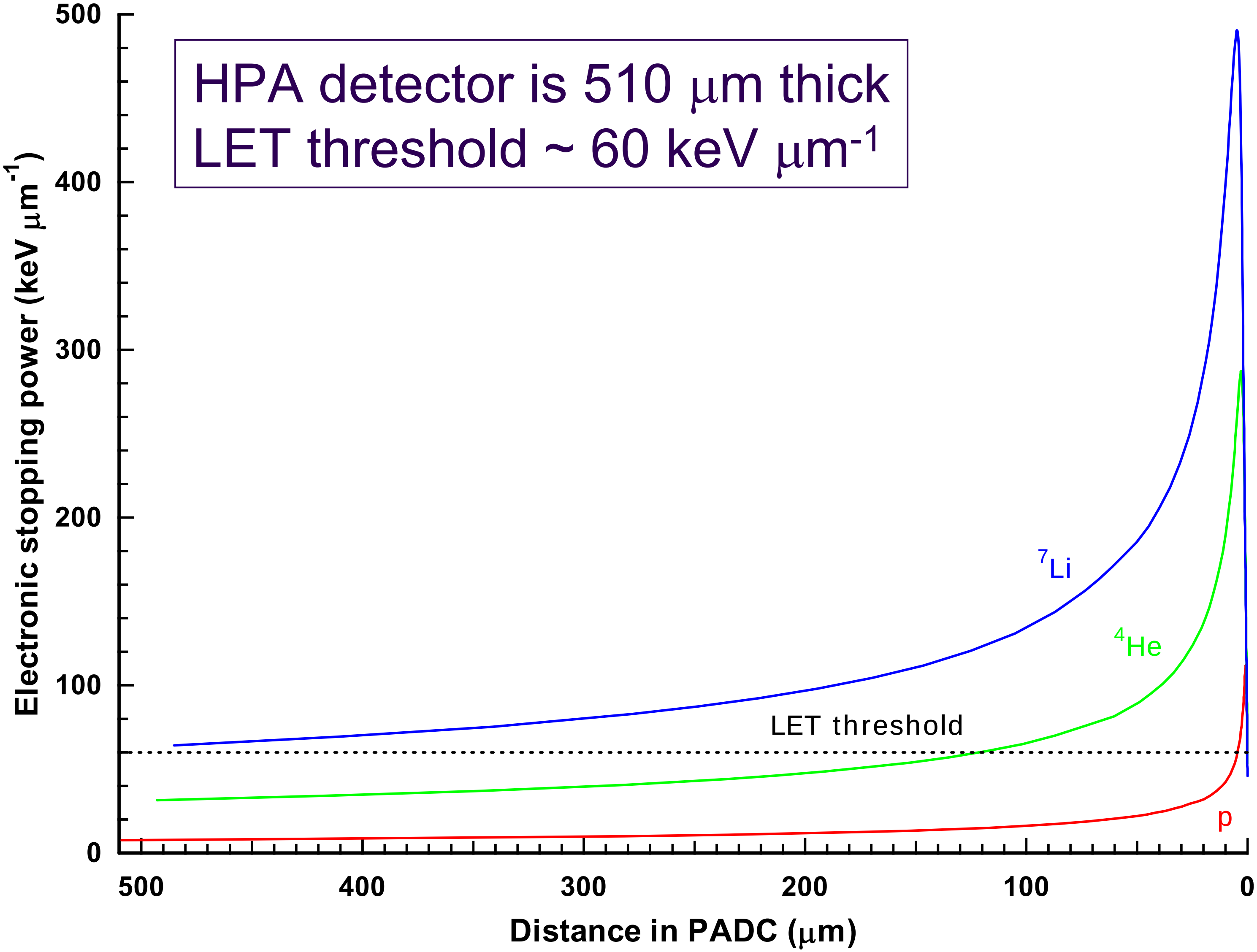


Focus on Back Face of detector

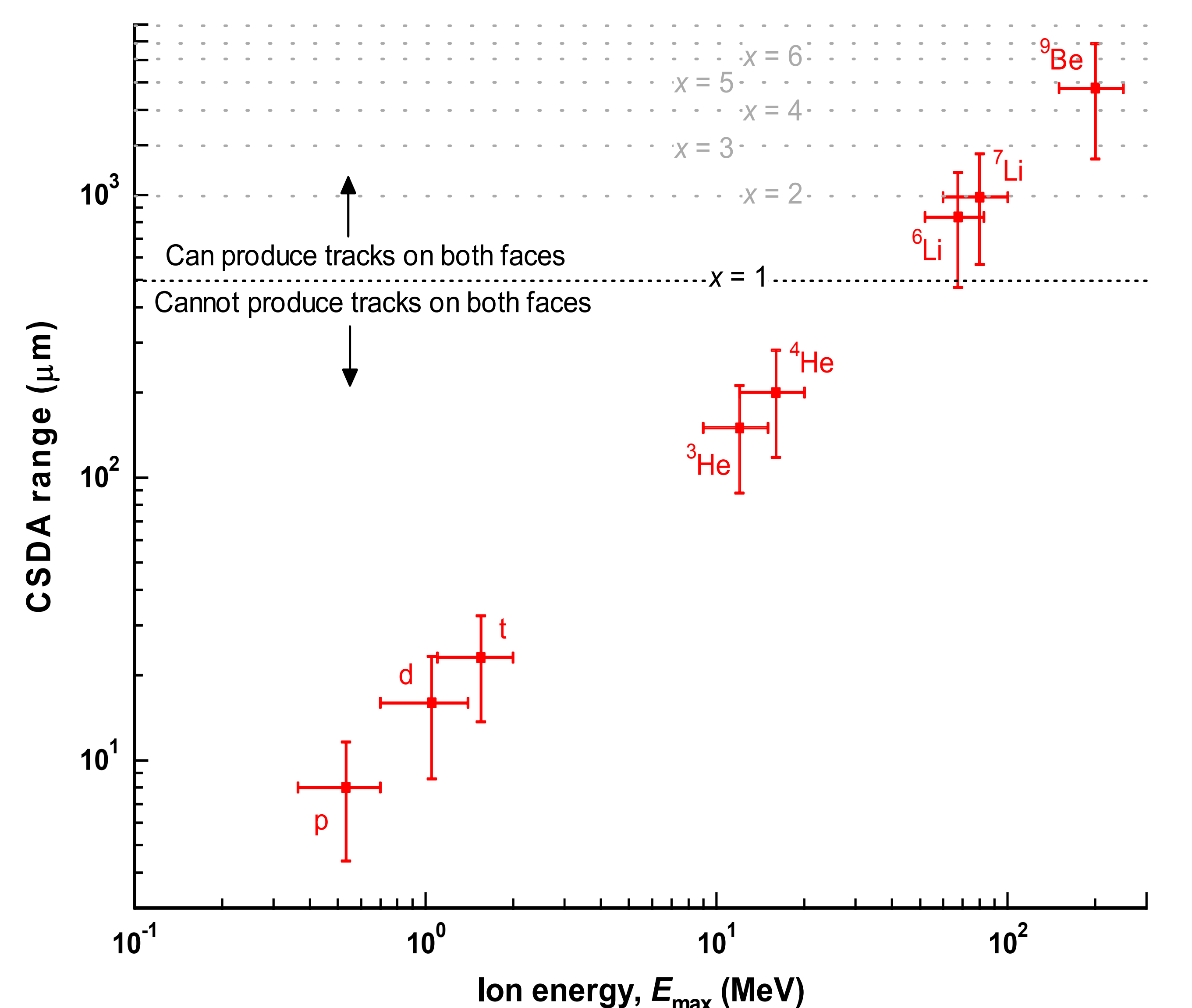


Focus on Front Face of detector

LET in 1 detector thickness



Residual range for charged particles in PADC



Z< 3 particle contribution to the total counted tracks

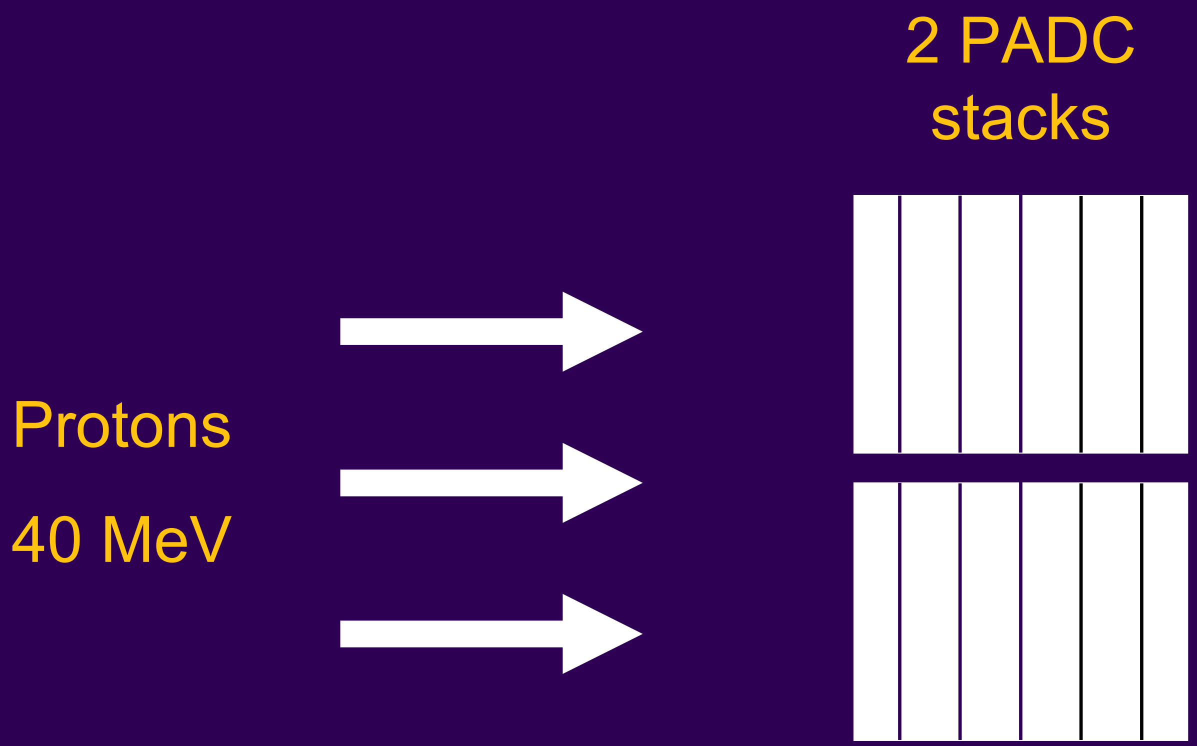
Have to calculate the Z< 3 particle contribution to the counted tracks on the dosemeter

We need

- Measured LET threshold for the Z< 3 particles
- Fluence energy distributions for Z< 3 particles inside ISS

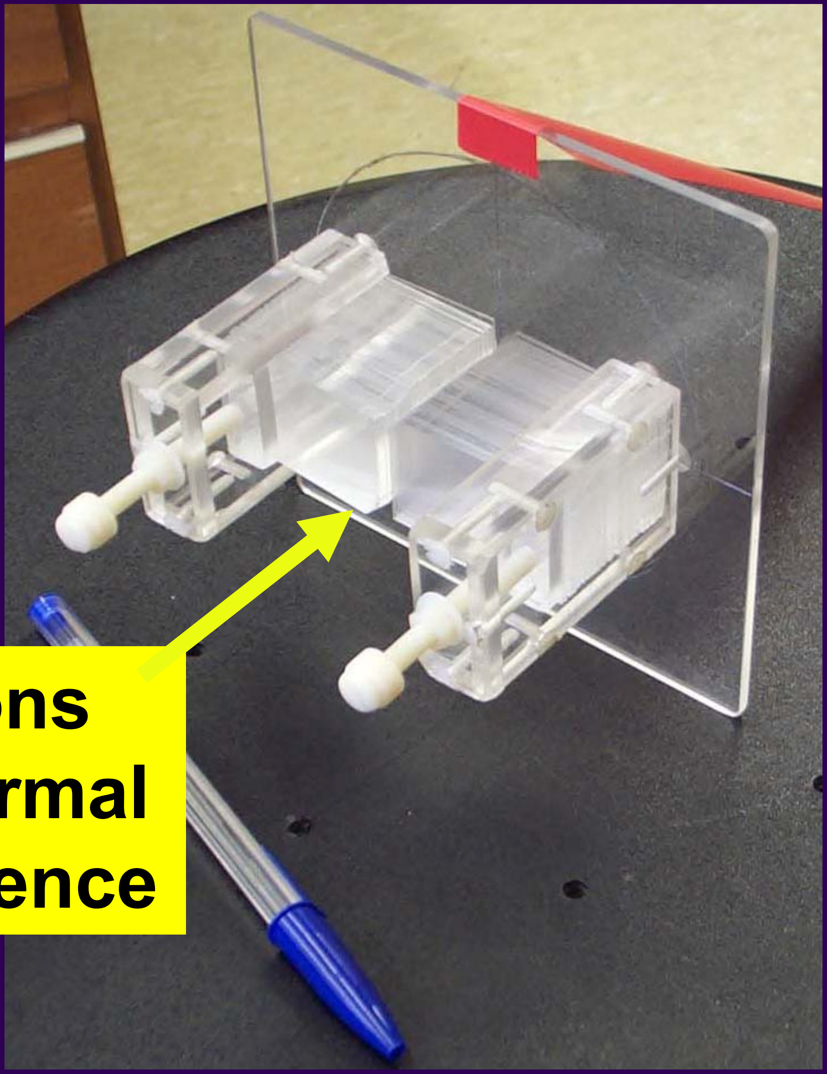
HIMAC Proton irradiations of PADC

(Performed in collaboration with NIRS)



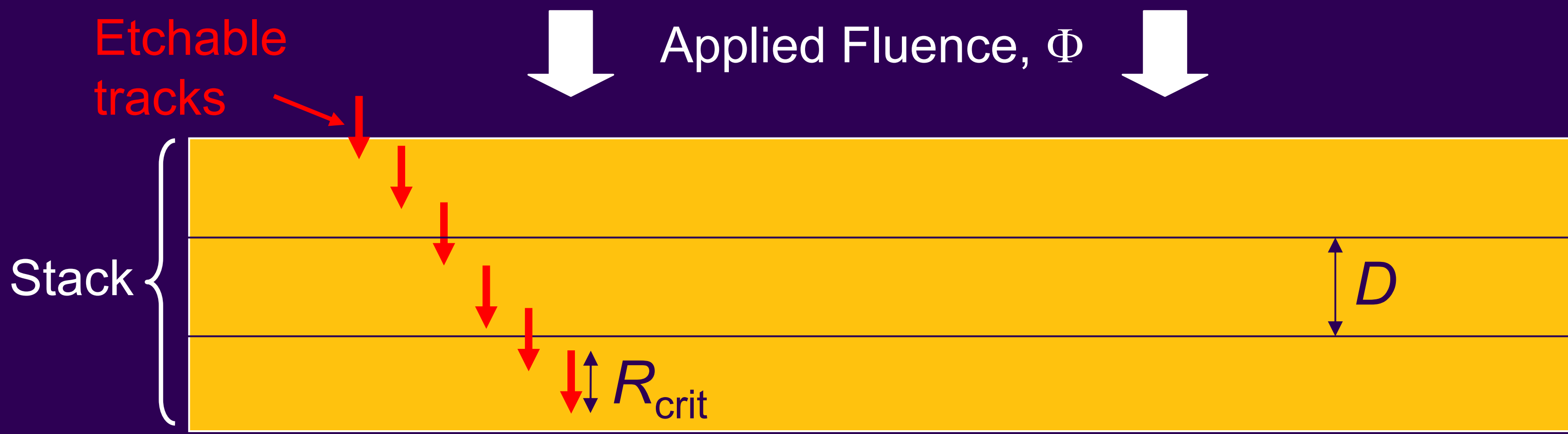
2nd set: Repeat for 70 MeV protons

Proton LET threshold
(Calibration performed at HIMAC in collaboration with NIRS)



protons at normal incidence

Etchable range in PADC



$$R_{crit} = \frac{DN}{\Phi}$$

D = detector thickness

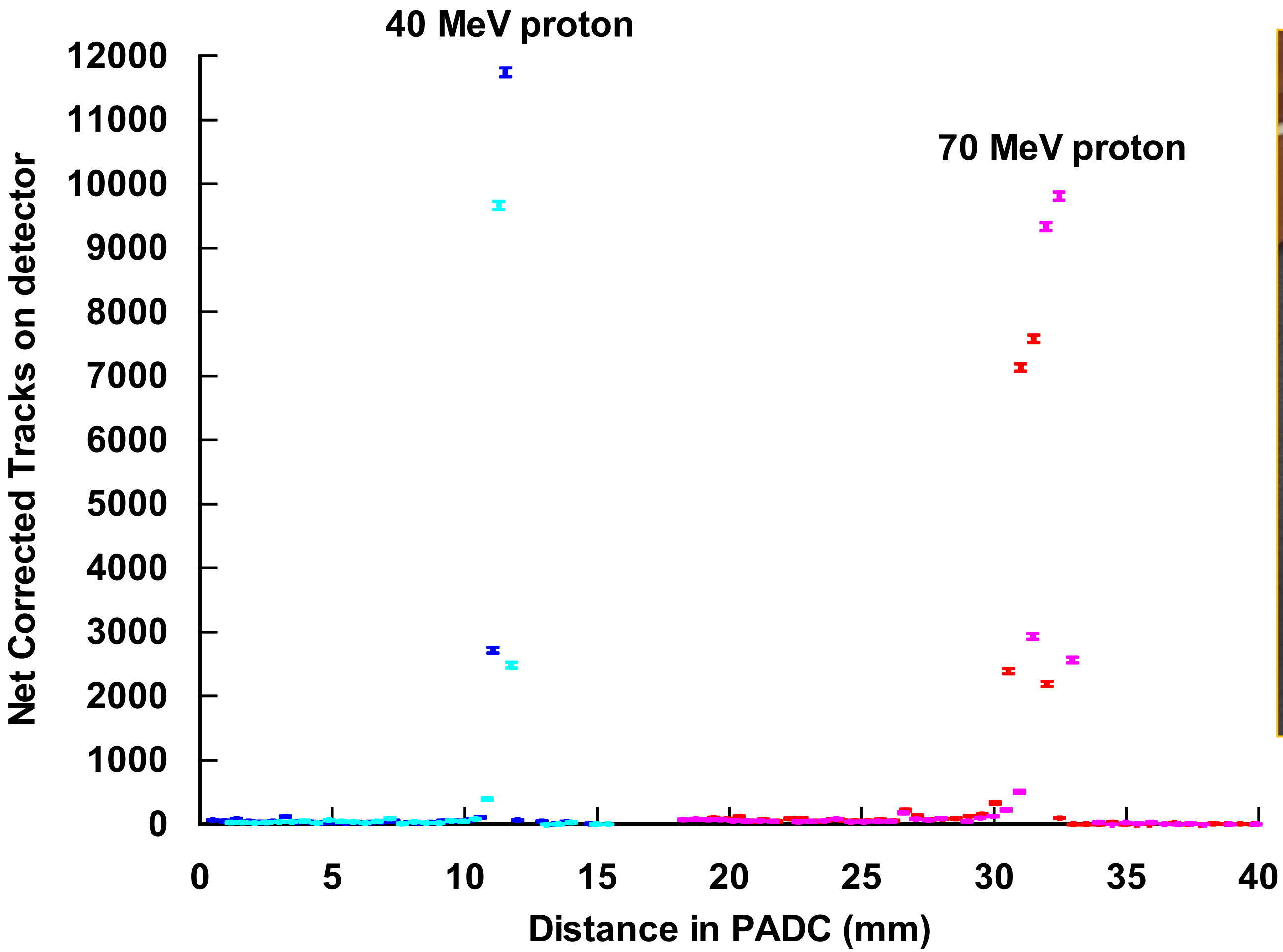
N = measured tracks summed for peak distribution

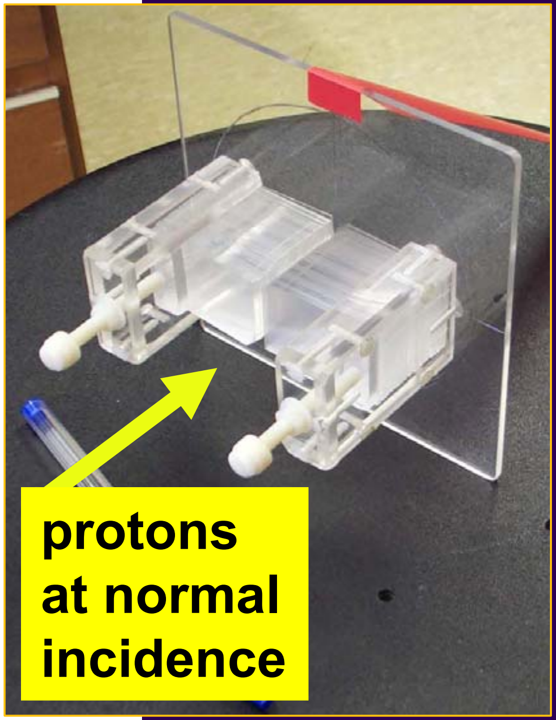
Φ = Applied fluence

R_{crit} = etchable length of track (i.e. LET > LET_{crit})

If R_{crit} = D measured tracks = applied fluence

Proton LET threshold
(Calibration performed at HIMAC in collaboration with NIRS)





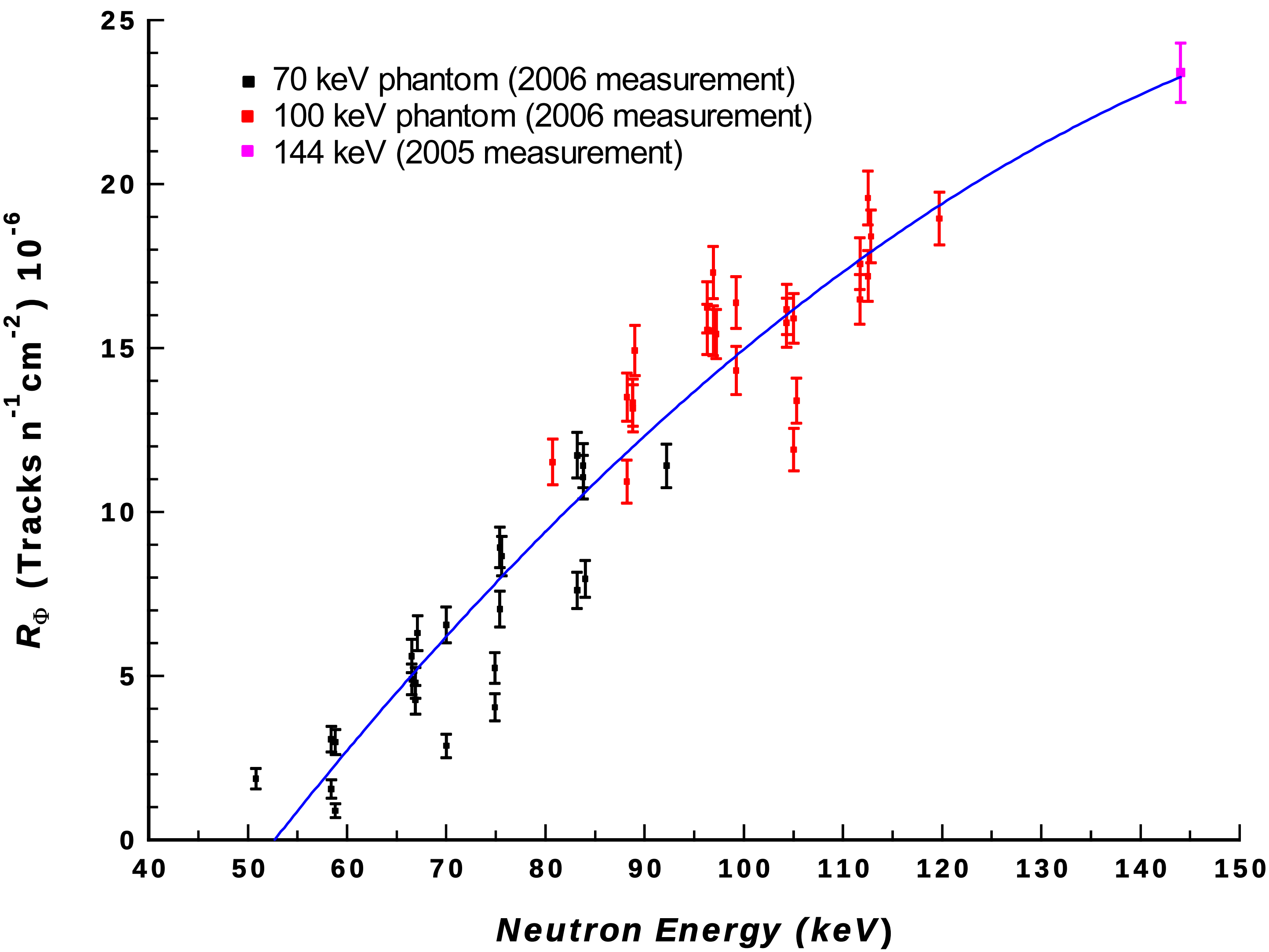
Assessed proton LET thresholds in PADC

Ion used	Angle of incidence	Etchable track length, R_{crit} (μm)	Maximum Energy (keV)	LET_{∞} PADC (keV/μm)	LET_{∞} water (keV/μm)	#LET_{200} PADC (keV/μm)
^{1}H 40 MeV	Normal 0°	8.7 (0.5)$	589	45 (1)$	33 (1)$	24 (1)$
^{1}H 70 MeV	Normal 0°	10.0 (0.5)$	645	43 (1)$	31 (1)$	22 (1)$

$ 1 standard uncertainty

Using: $\log(LET_{\infty}\ \text{water}) = 0.1689 + 0.984\log(LET_{200}\ \text{CR-39})$ (*E.Benton*)

70, 100, 144 keV
Low energy Neutron calibrations
(National Physical Laboratory, UK)

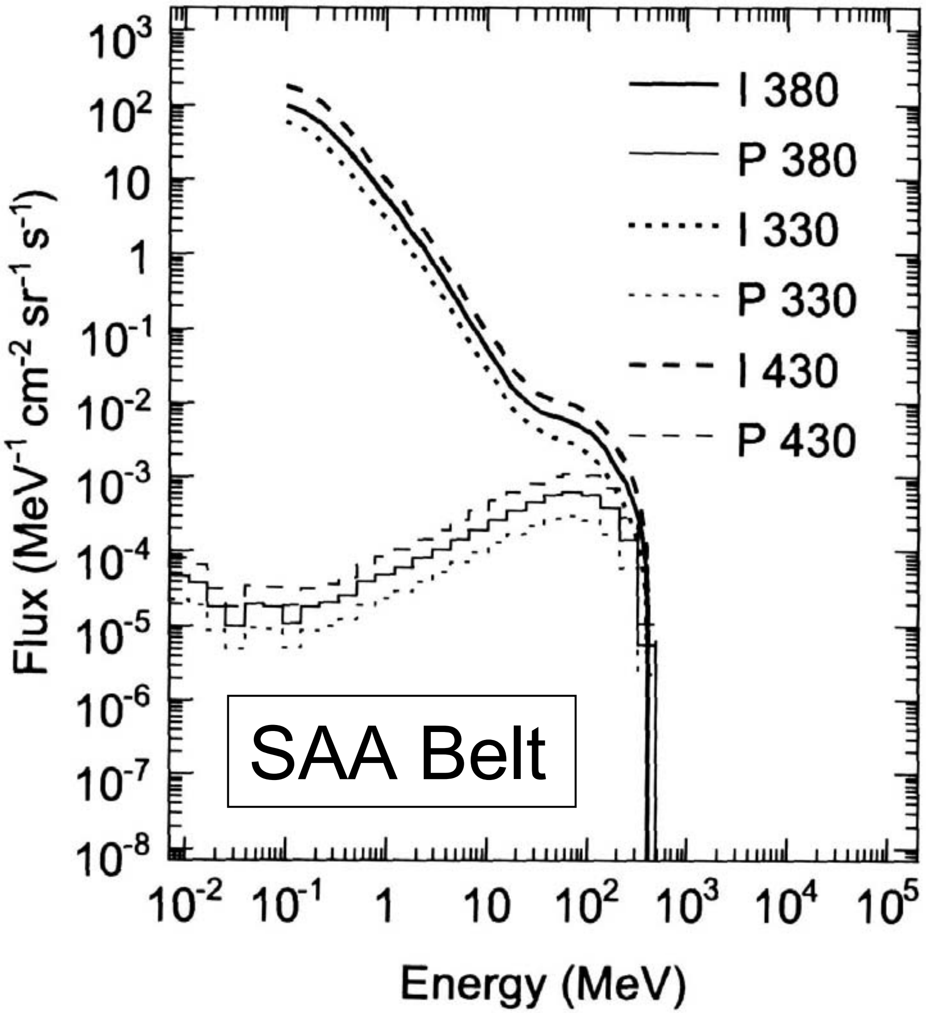


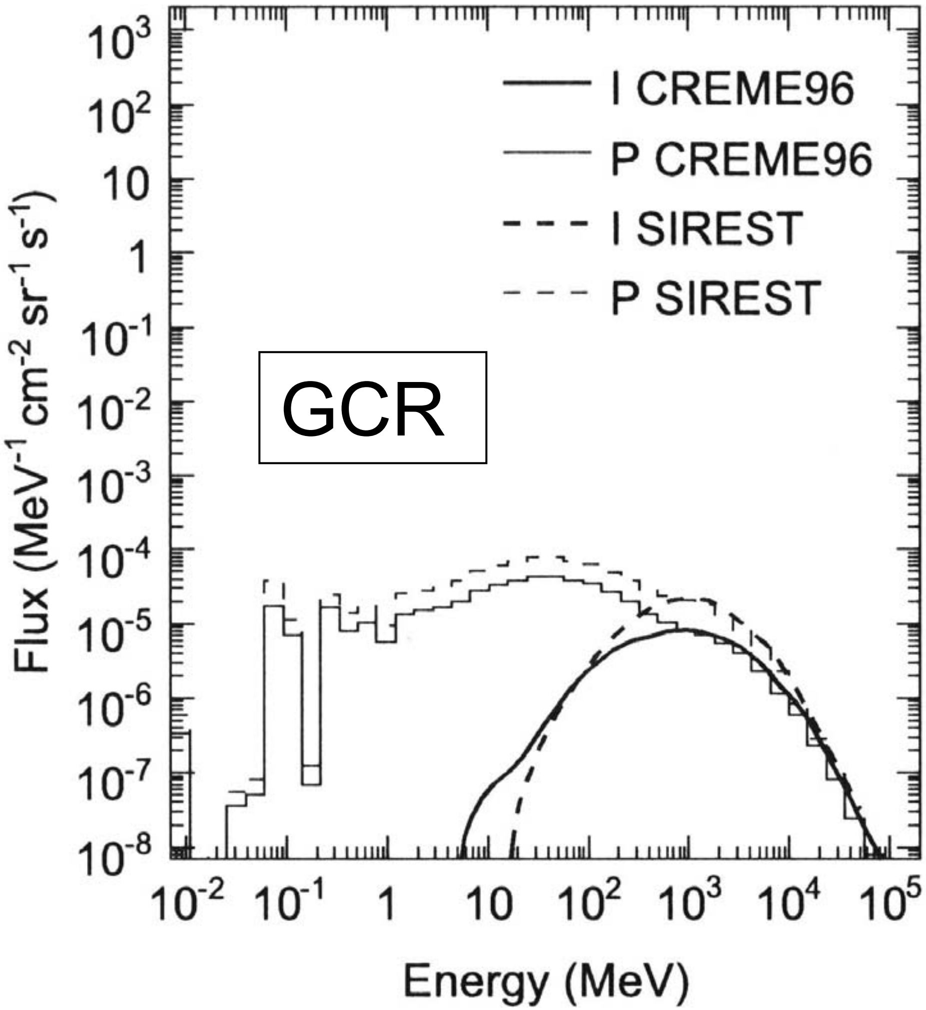
Detection criteria for protons in PADC

- Measured proton $LET_{\infty\ PADC}$ threshold ~ 44 keV / μm
- Measured neutron response threshold ~ 50 keV
- At 50 keV, response dominated by proton recoils
- Range of 50 keV proton in PADC ~ 0.6 μm

➢ Protons detected at the surface of the PADC when $LET_{\infty\ PADC}$ > 44 keV / μm and range > 0.6μm: in the direction normal to the detector surface

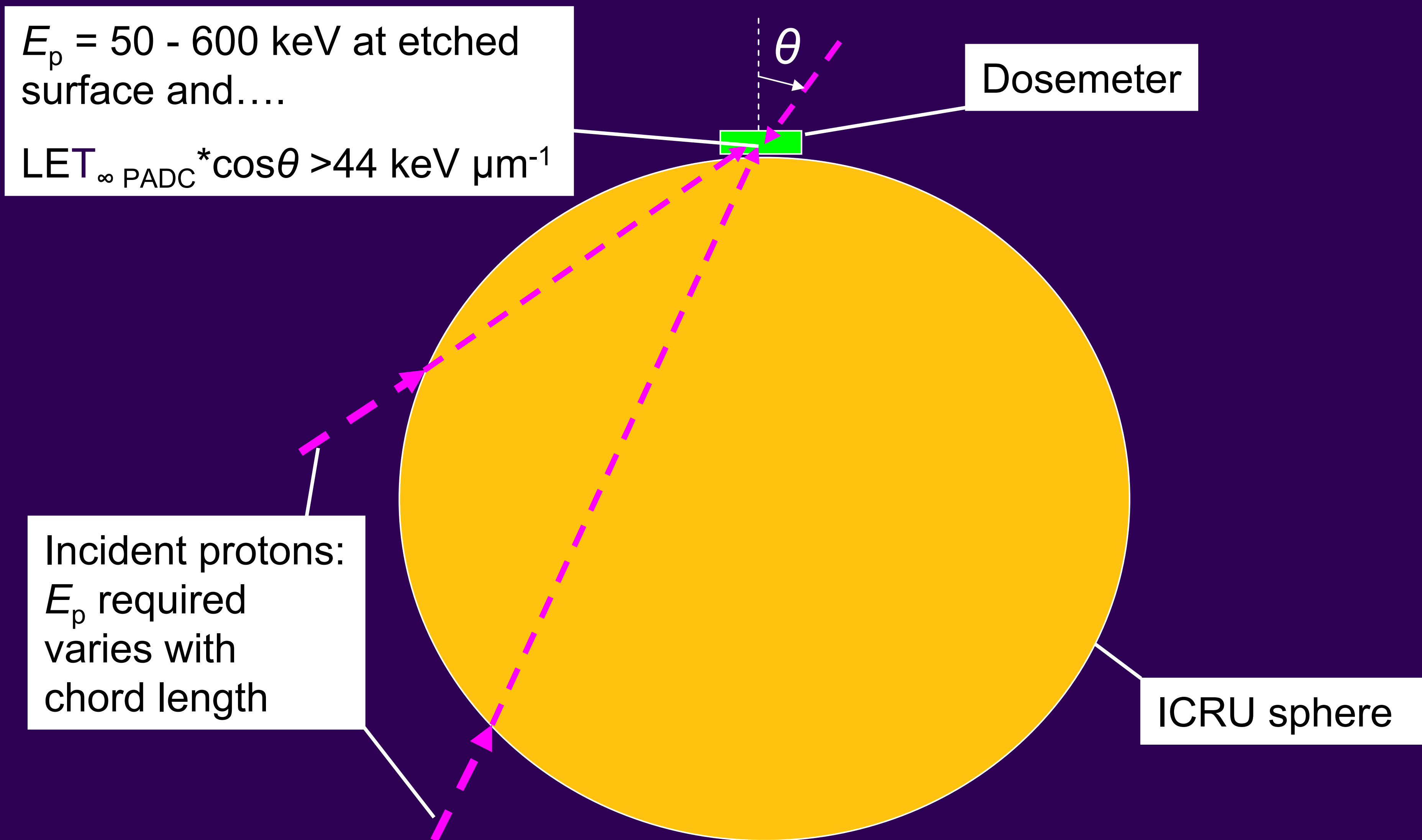
Calculated protons inside ISS Columbus module
(GEANT4)



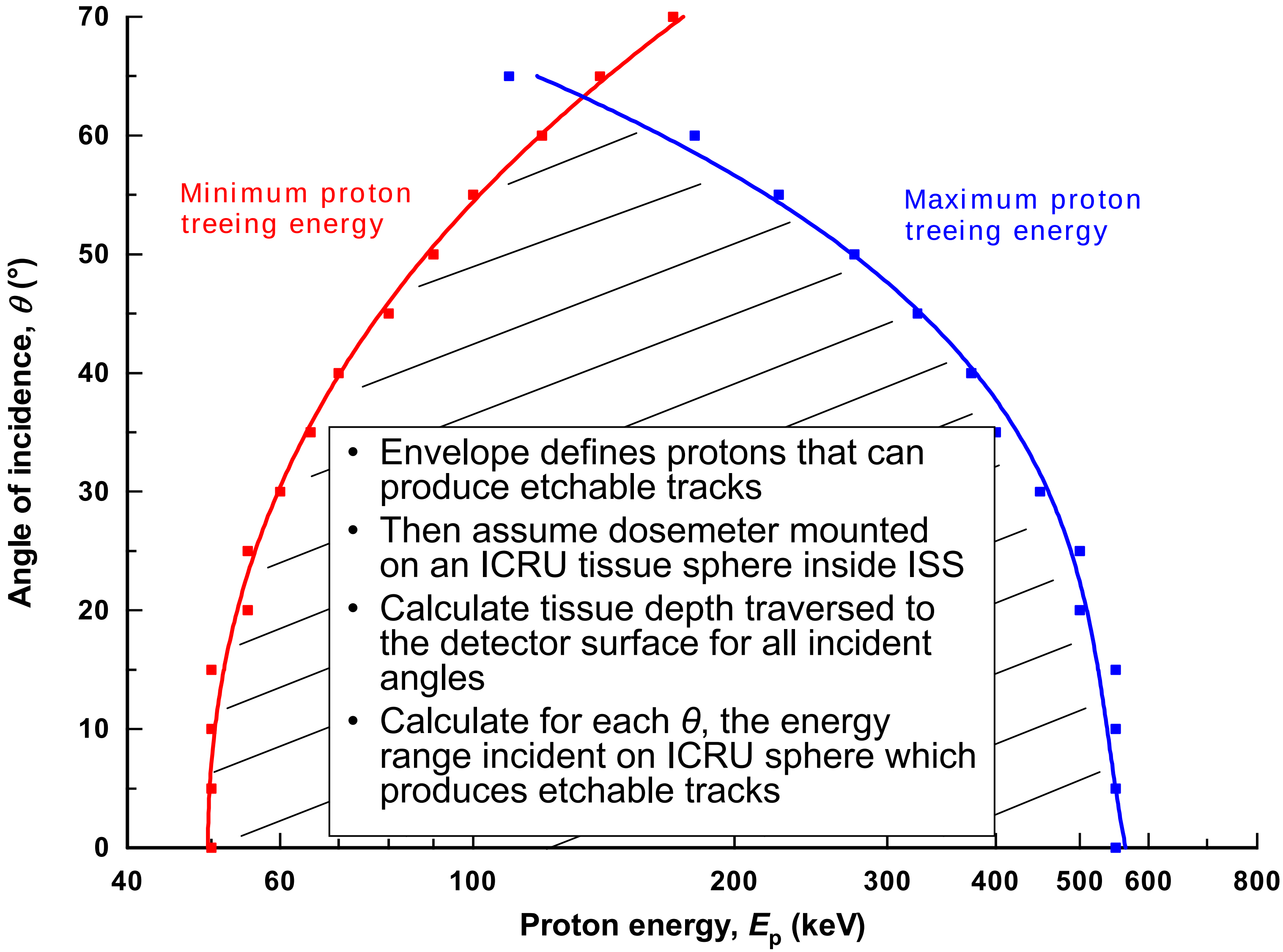


(T Ersmark PhD thesis, June 2006, Royal Institute of Technology, Stockholm)

Analytical method to determine the direct proton response
Dosemeter mounted on 30 cm diameter ICRU tissue sphere



Angle of incidence, θ vs E_p to produce etchable tracks



- Envelope defines protons that can produce etchable tracks
- Then assume dosemeter mounted on an ICRU tissue sphere inside ISS
- Calculate tissue depth traversed to the detector surface for all incident angles
- Calculate for each θ, the energy range incident on ICRU sphere which produces etchable tracks

Estimated etchable proton tracks for inside ISS

Origin	Etchable proton tracks ($cm^{-2}\ d^{-1}$)
SAA belt	1.09
GCR	0.11
TOTAL	1.20 (0.35)#

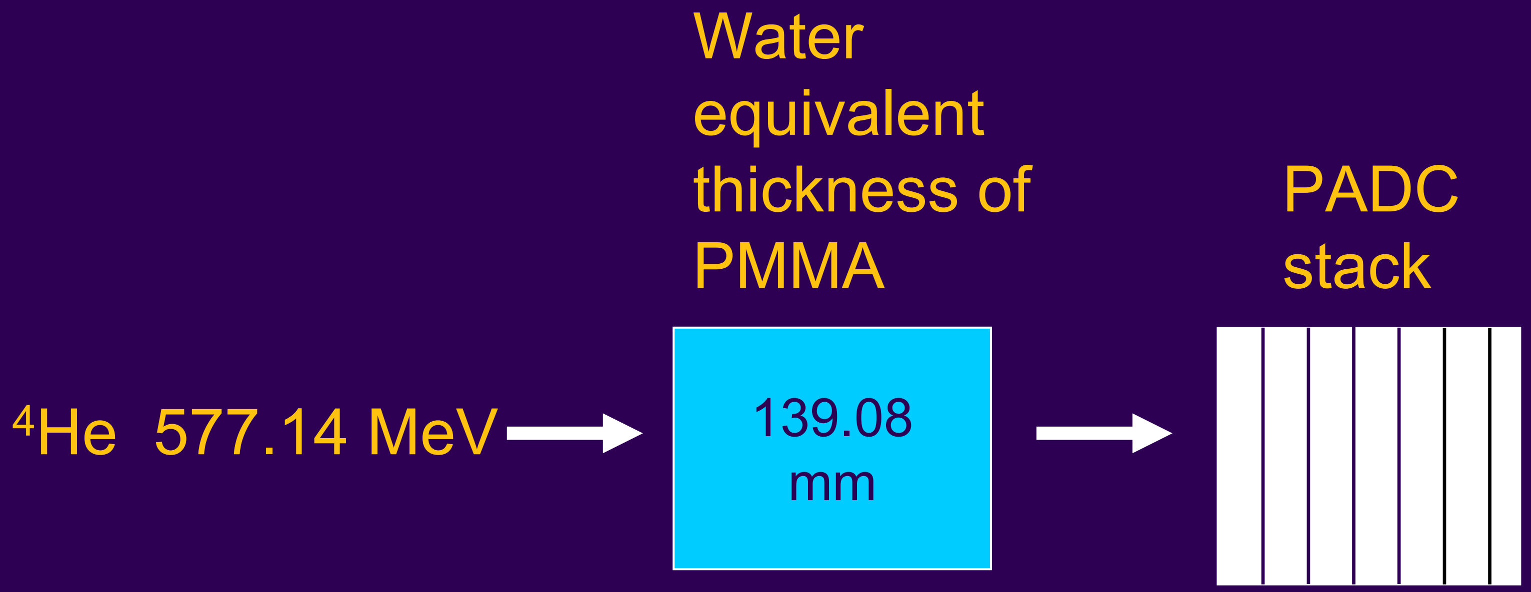
1 standard uncertainty in brackets

Neutron dose estimate outside ISS using PADC dosemeter

For inside ISS the 'direct' proton contribution to the total tracks recorded by the dosemeter is currently calculated to be ~ 8%.

For outside of ISS the 'direct' proton contribution to the total tracks on the dosemeter is expected to be significantly higher than inside due to the higher fluence. This would swamp the neutron contribution. Consequently, an accurate estimate of the neutron dose using the HPA dosemeter is unlikely for exposures outside the ISS.

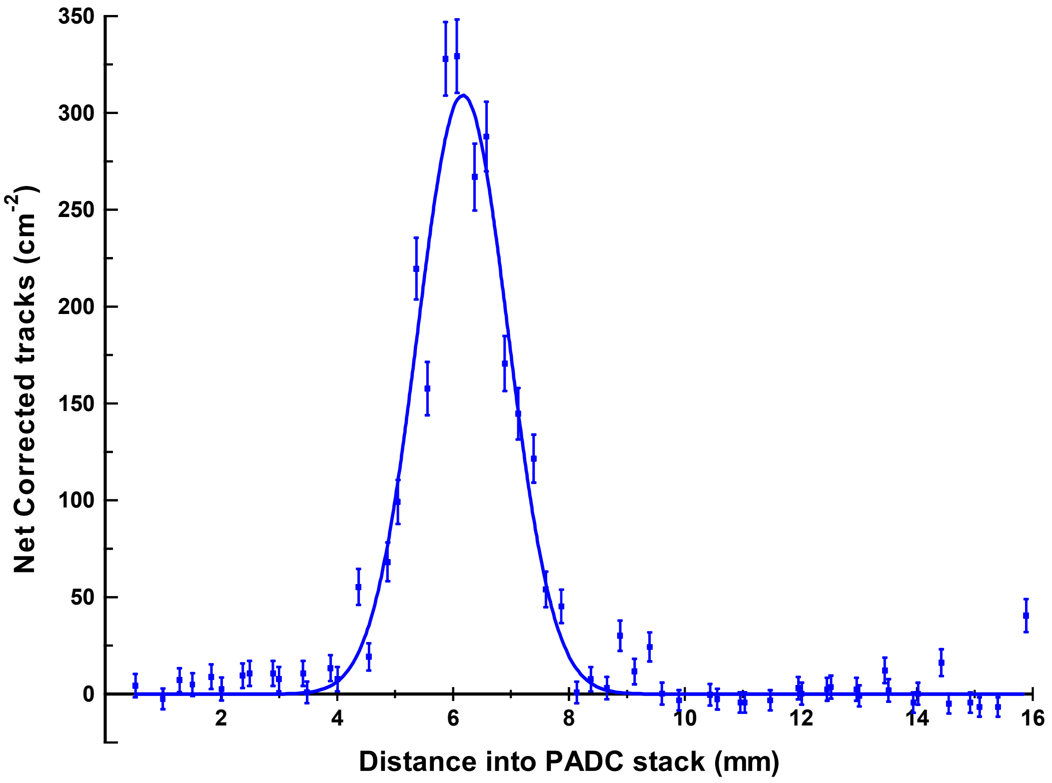
^{4}He LET threshold
PADC detector stacks at HIMAC



HIMAC ^{4}He: 577.14 MeV

+ 139.08 mm water equiv PMMA

(performed under EC funded HAMLET project)

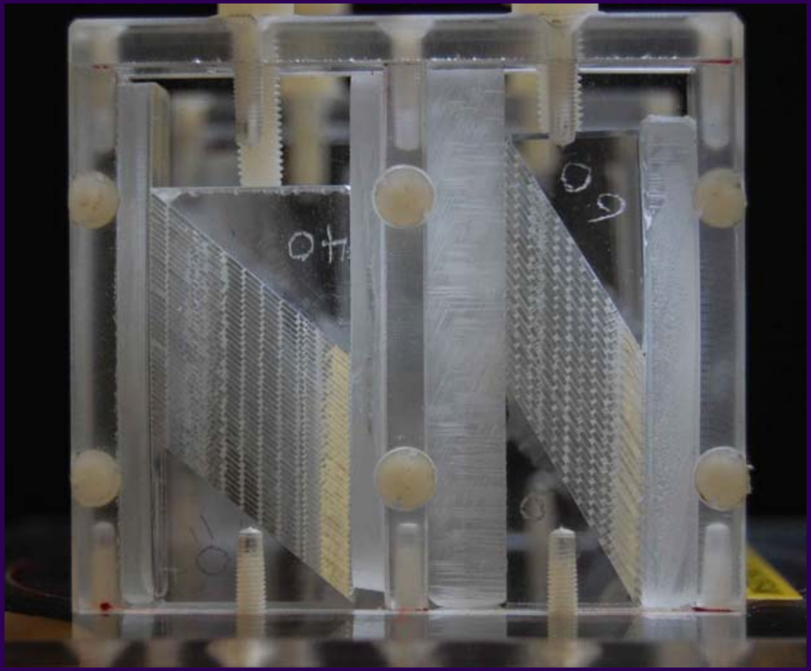


HIMAC ^{4}He 577.14 MeV

+ 139.08 mm water equiv PMMA

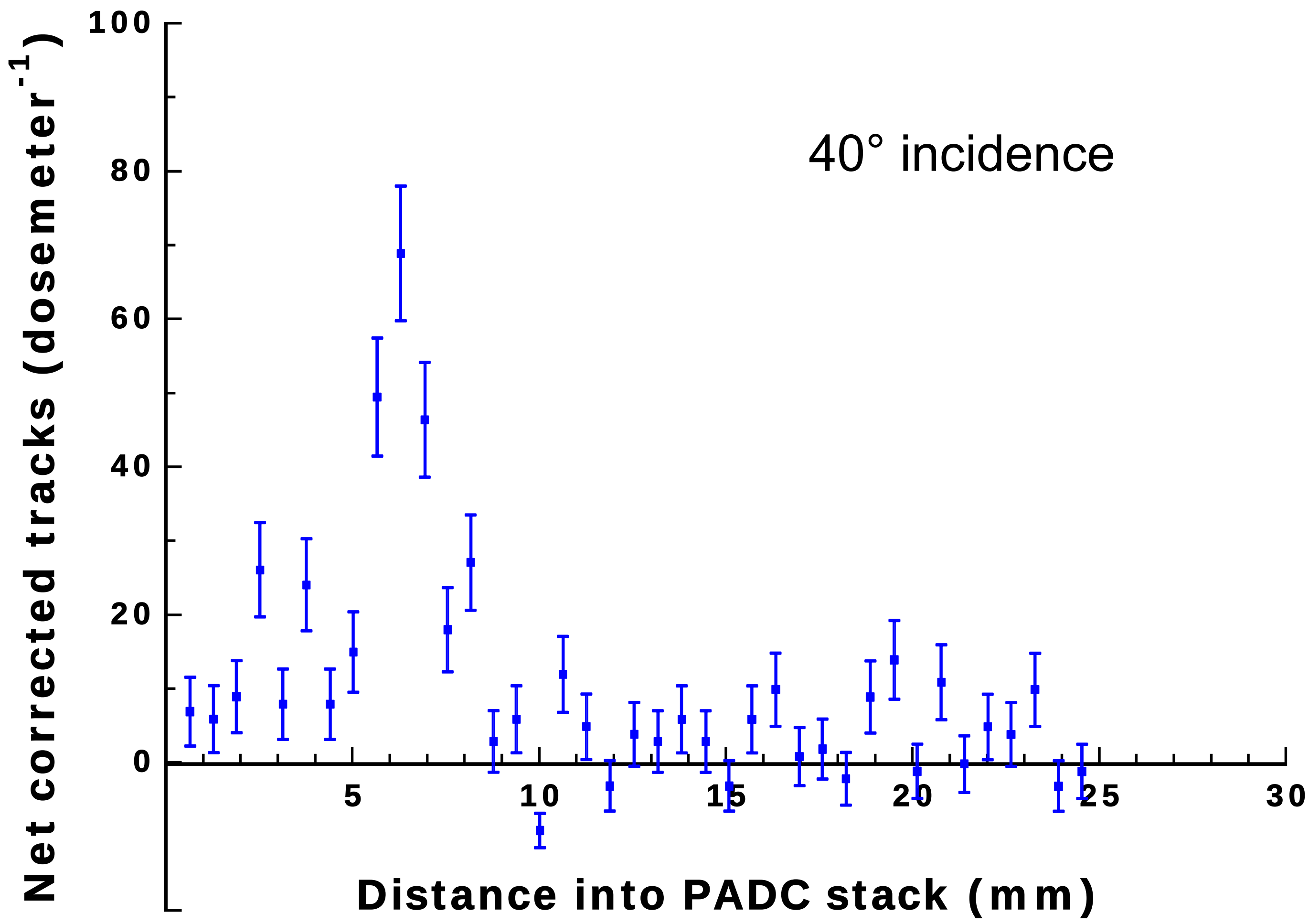
(performed under EC funded HAMLET project)

PADC stacks: 40°, 50°, 60° incidence



Unfortunately this time the fluence used was a little low resulting in poor statistics ……….

HIMAC ^{4}He 577.14 MeV
+ 139.08 mm water equiv PMMA
(performed under EC funded HAMLET project)



HIMAC ^{4}He 577.14 MeV
+ 139.08 mm water equiv PMMA
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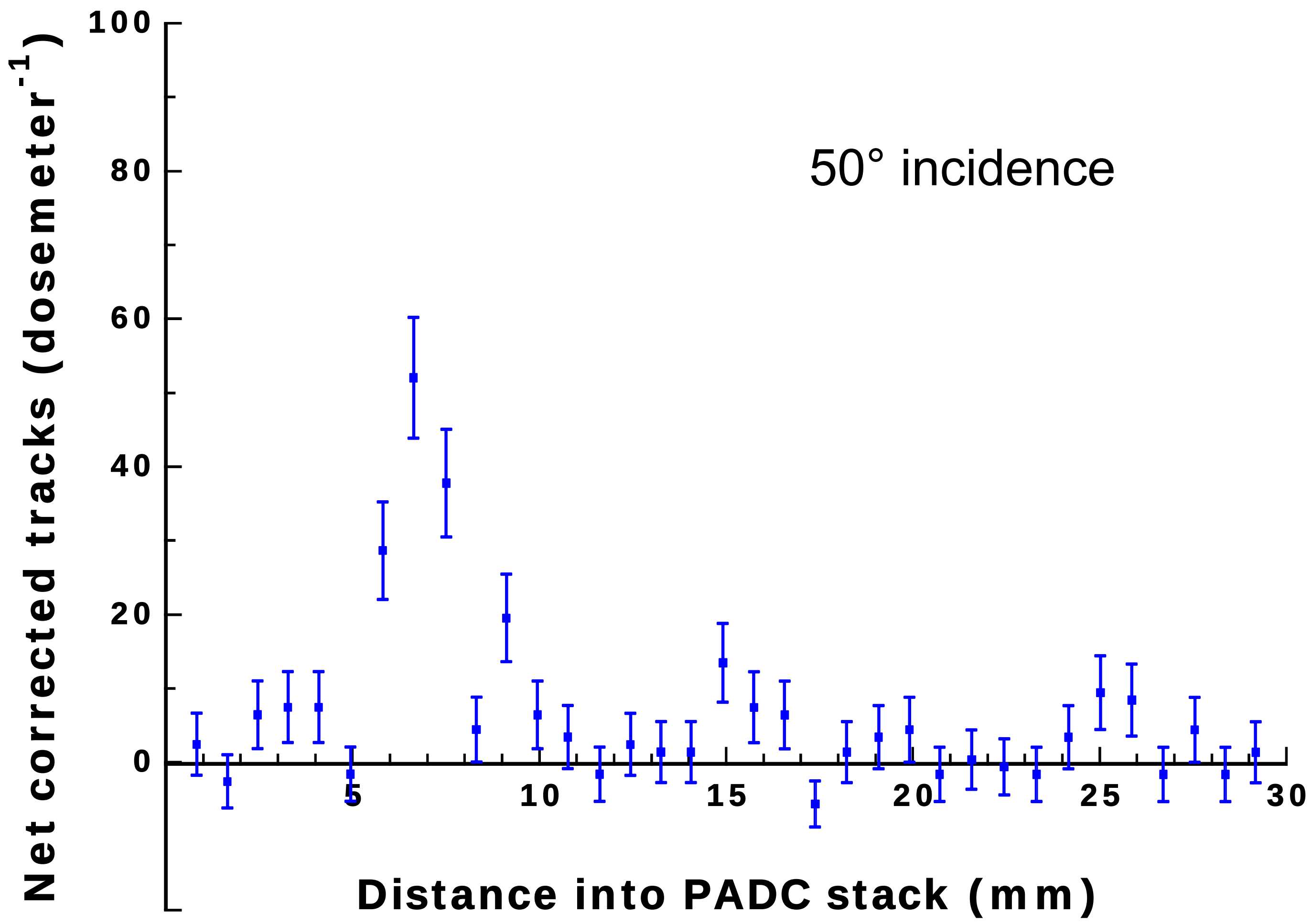

HIMAC ^{4}He 577.14 MeV
+ 139.08 mm water equiv PMMA
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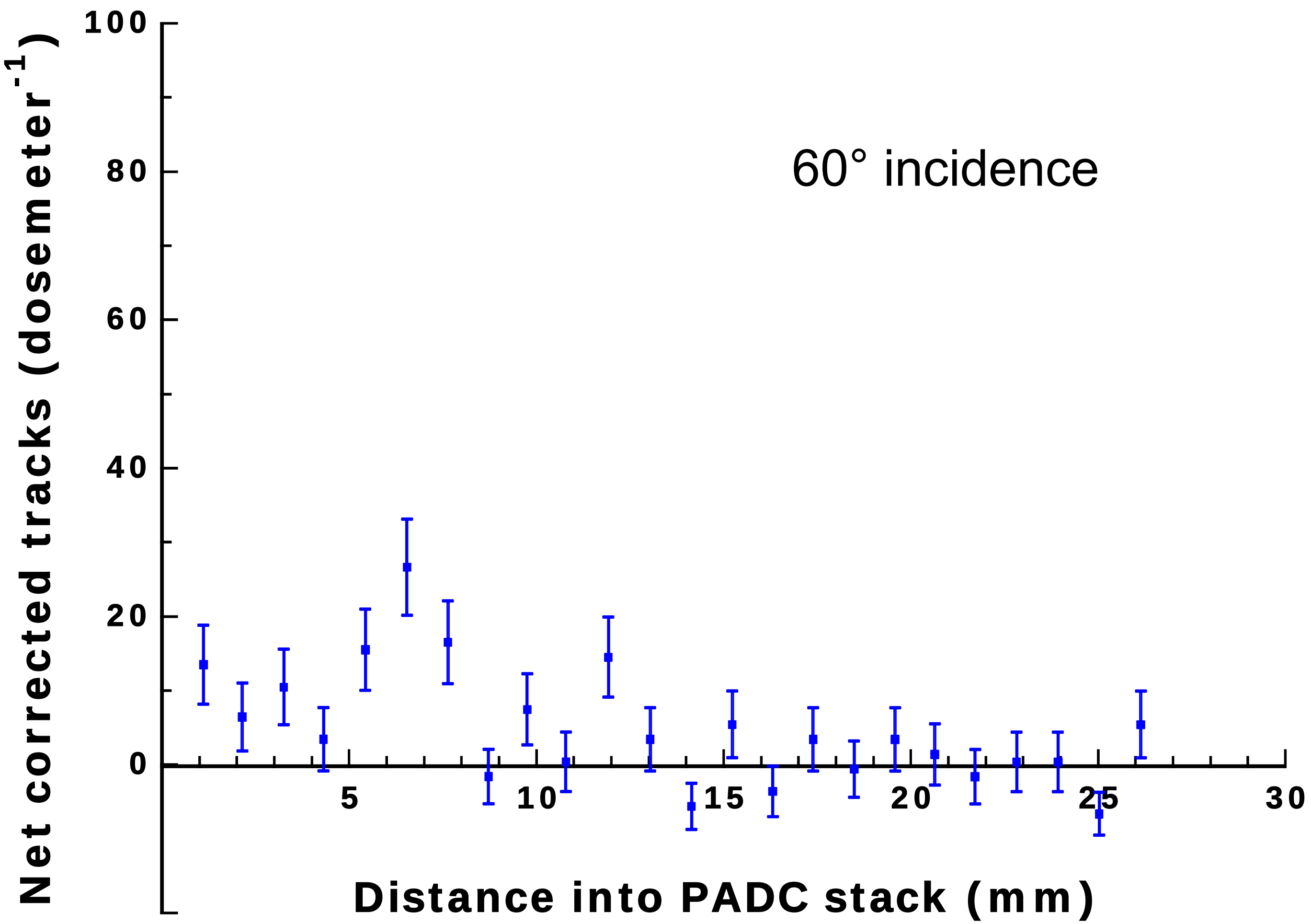


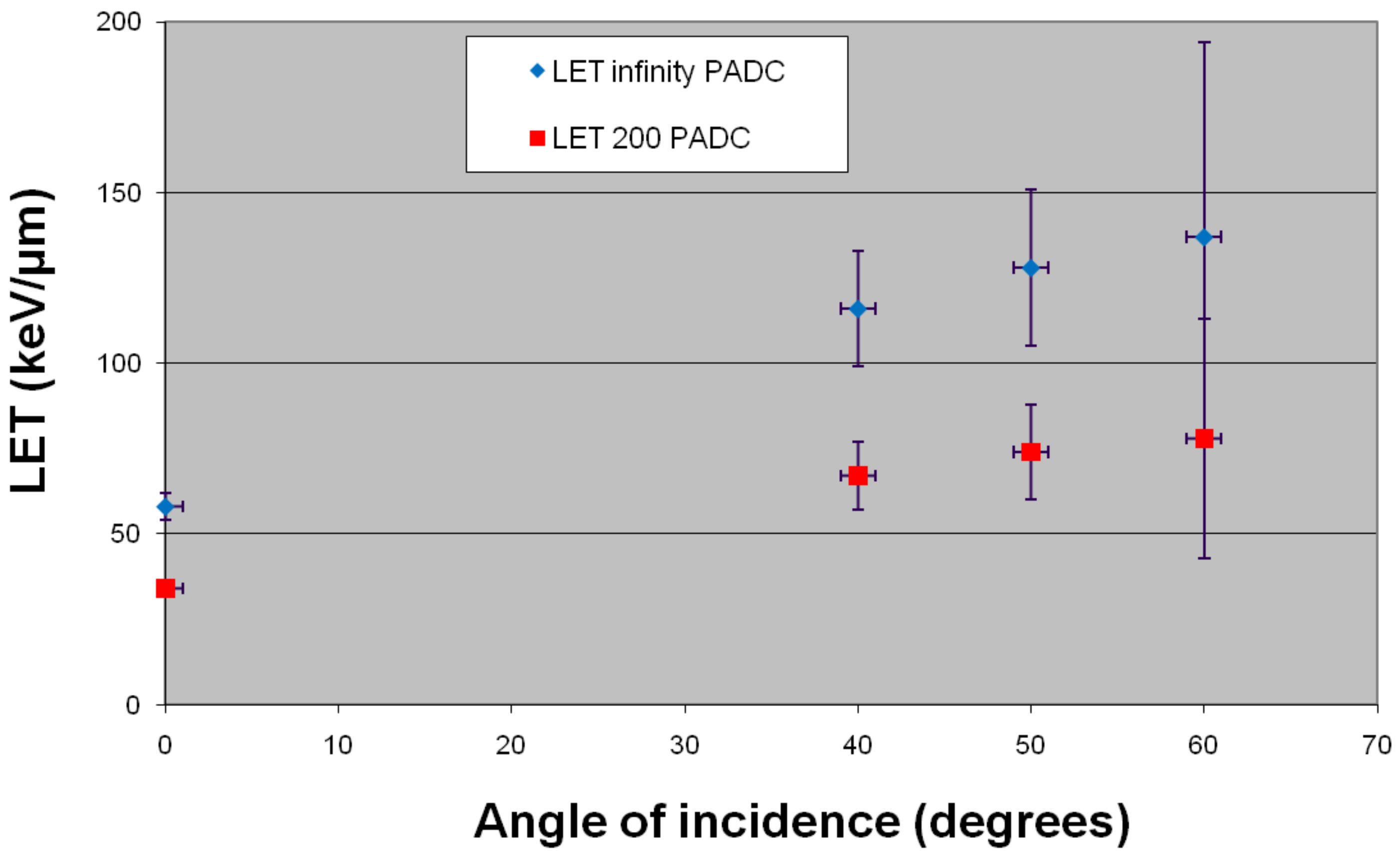
Assessed ^{4}He LET thresholds in PADC

Ion	Angle	Etchable track length, R_{crit} (µm)	Energy, *E* (MeV)	LET_{∞} PADC (keV/µm)	LET_{∞} water (keV/µm)	#LET_{200} PADC (keV/µm)
^{4}He	0°	130 (16)	12.8 (1.0)	58 (4)	47 (3)	34 (2)
	40°	28 (8)$	5.0 (1.0)$	116 (17)$	92 (13)$	67 (10)$
	50°	23 (8)$	4.3 (1.1)$	128 (23)$	102 (19)$	74 (14)$
	60°	20 (13)$	3.9 (1.9)$	137 (57)$	108 (47)$	78 (35)$

$ 1 standard uncertainty

Using: $\log(LET_{\infty}\ \text{water}) = 0.1689 + 0.984\log(LET_{200}\ \text{CR-39})$ *(E. Benton)*

^4He LET $_{PADC}$ threshold vs. angle of incidence



LET thresholds in PADC

Ion	$LET_{\infty,\ PADC}$ (keV/μm)
^{1}H	44
^{4}He	58
^{12}C	77
^{20}Ne	44

HAMLET HIMAC 2010 ^{56}Fe
PADC stack multiple angles of incidence
0° and 55° to 85°

HAMLET HIMAC 2010 ^{56}Fe
PADC stack multiple angles of incidence
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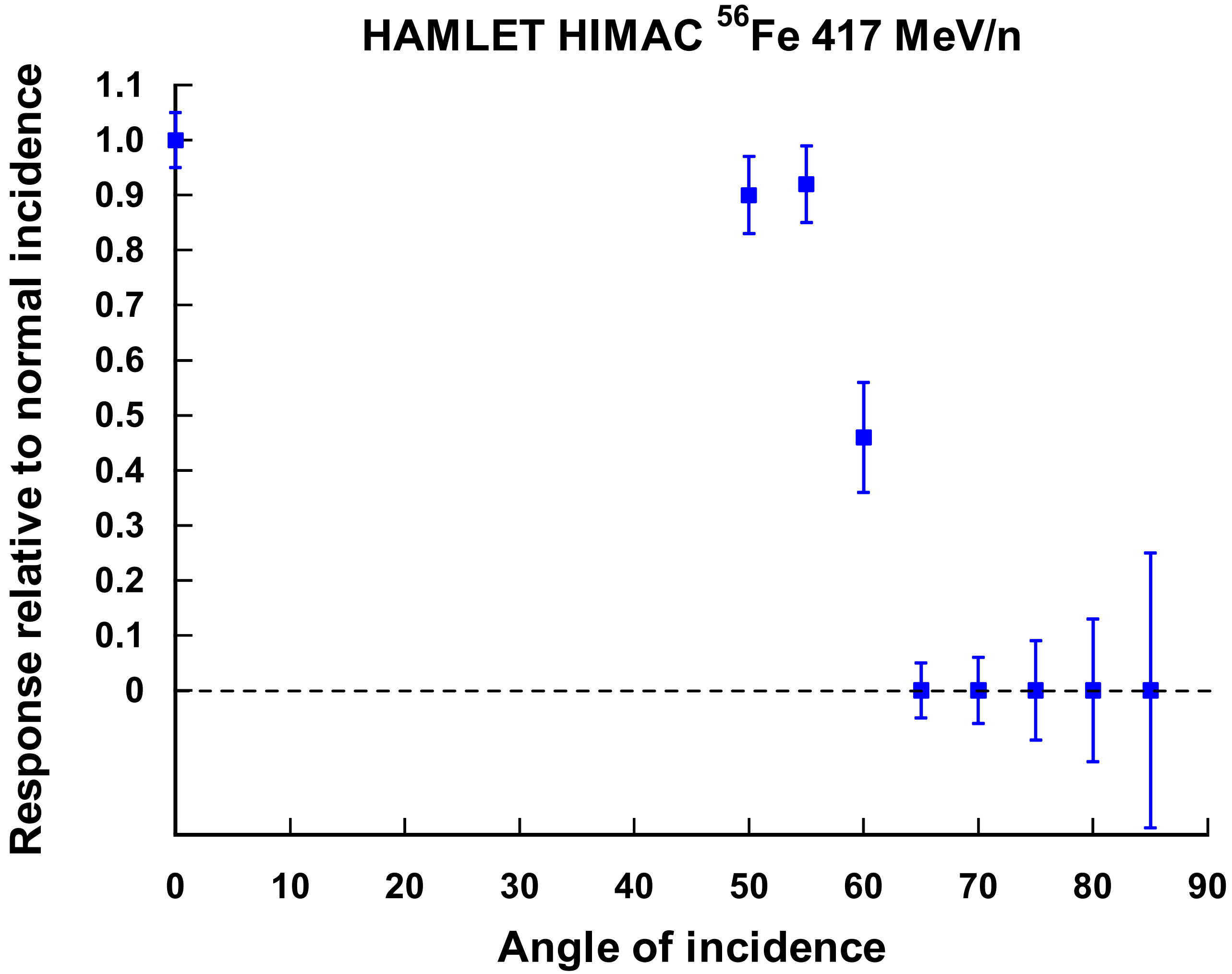
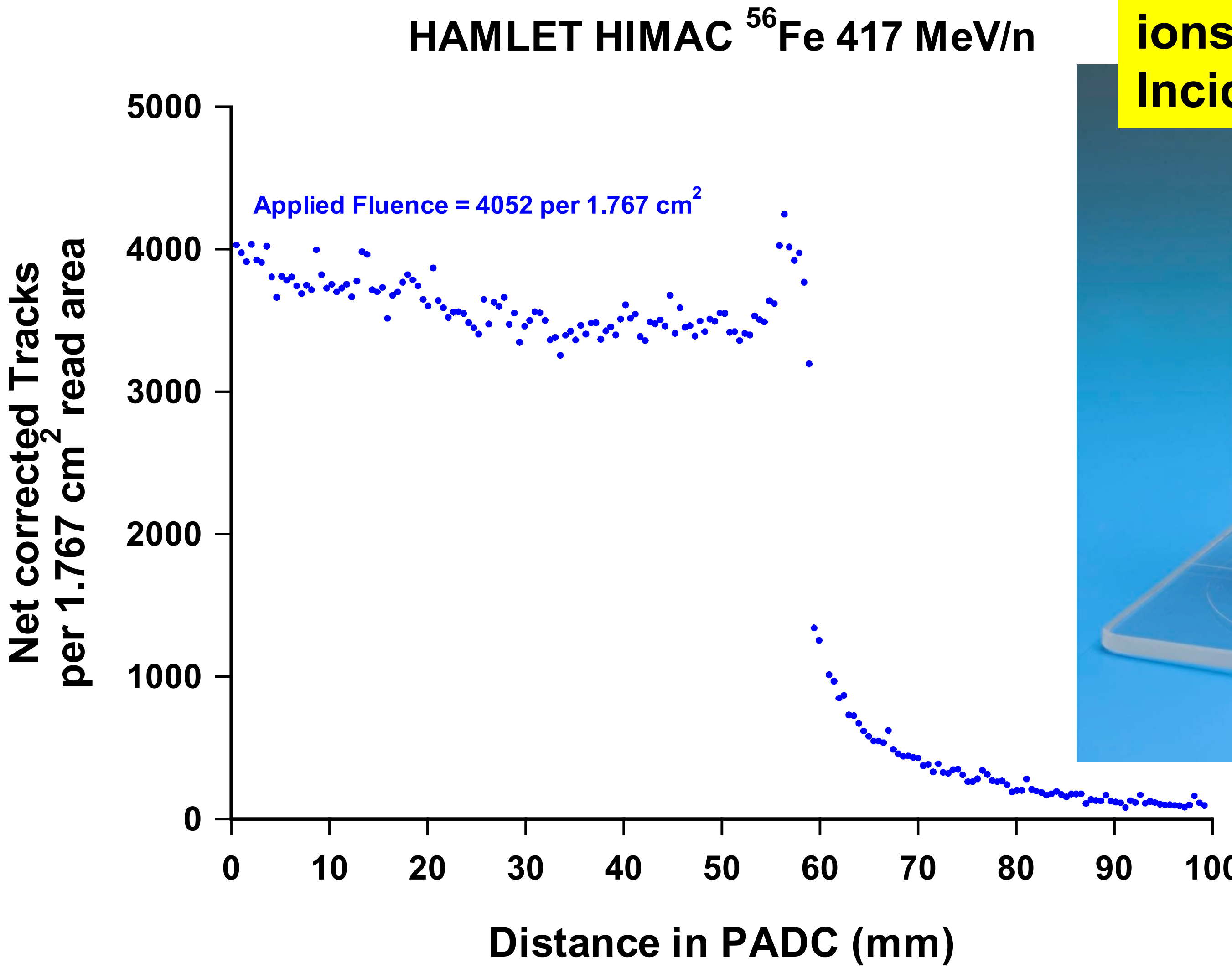
Health Protection Agency



HAMLET HIMAC 2010 ^{56}Fe
100 mm thick PADC stack

ions at normal Incidence
417 MeV/n

HAMLET HIMAC 2010 ^{56}Fe



Future work

- Determine fluence energy spectra - protons inside ISS

  - ^{4}He inside ISS
- CREME-96 spectra + 20g/cm^2 shielding + MCNPX

- Proton calibration at Heidelberg - to obtain LET threshold vs. angle of incidence

Acknowledgements

- Yukio Uchihori and colleagues at Radiation Measurement Research Section, Fundamental Technology Center, National Institute of Radiological Sciences, Chiba, JAPAN, for providing irradiations during HAMLET HIMAC and proton ICCHIBAN.

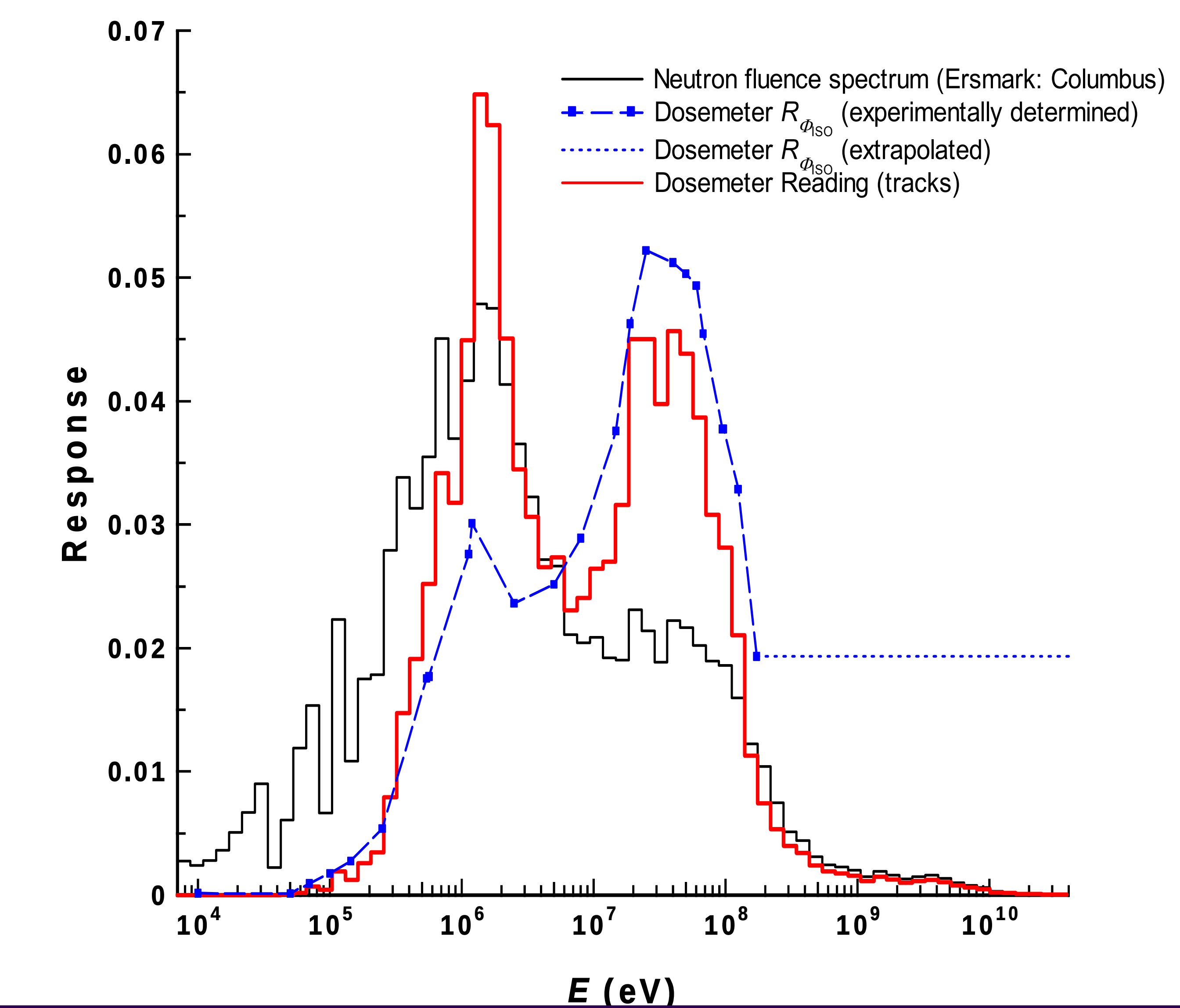
- Part of the irradiations at NIRS were performed in the framework of HIMAC Research Project 20P-240 "Space Radiation Dosimetry-Ground Based Verification of the MATROSHKA Facility".

- Part of the research leading to these results has been performed within the HAMLET project (http://www.fp7-hamlet.eu/) which has received funding from the European Community's Seventh Framework Programme (FP7) under project No. 218817, and is coordinated by the German Aerospace Center (DLR)

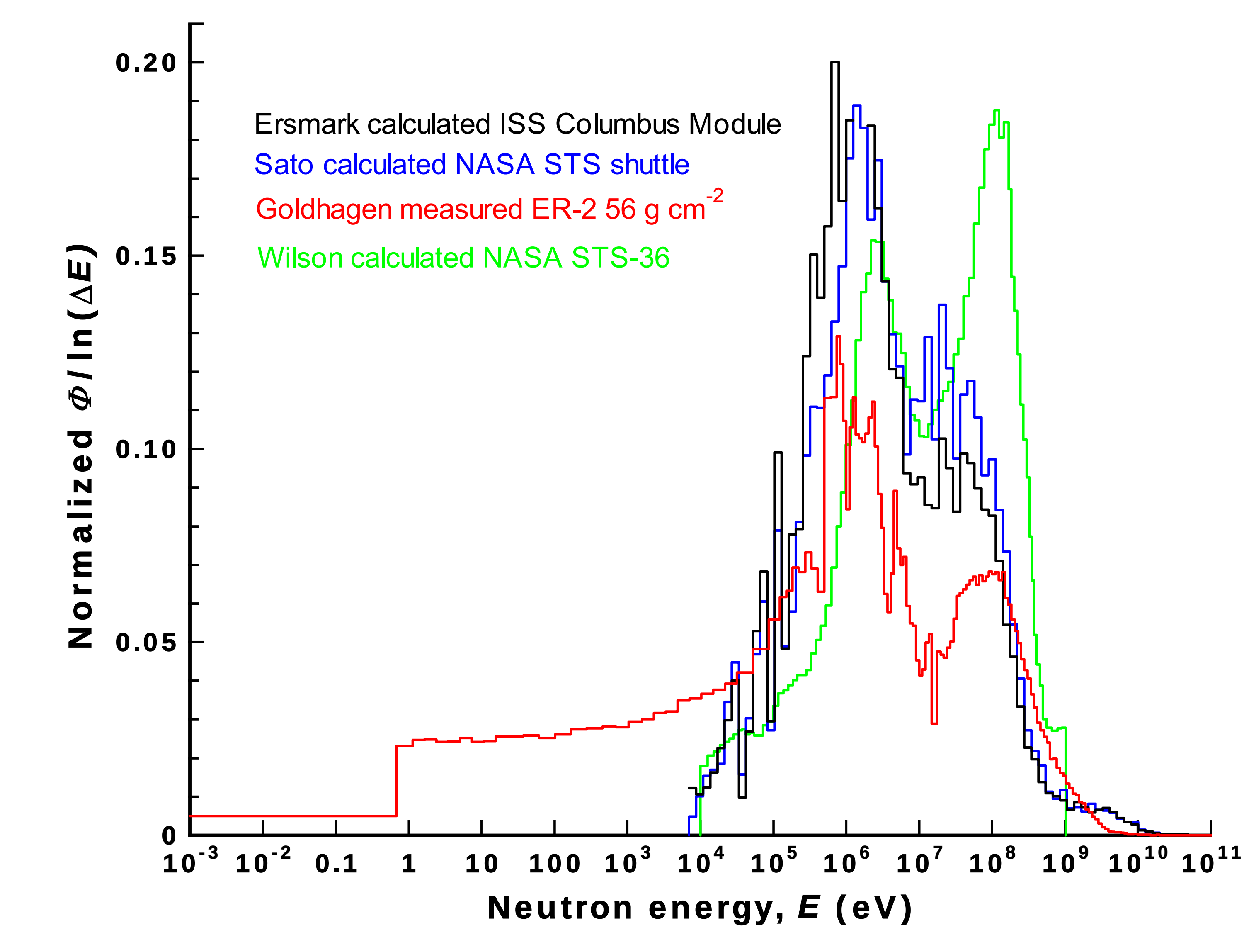
HAMLET internal meeting
HPA Neutron dose assessment

- How advanced is calibration ?
- What needs to be done ?
- What's achievable in 3rd year ?
- When to expect neutron dose values ?

PADC dosemeter neutron response in Columbus module ISS (using Ersmark's neutron spectrum)



Representative neutron energy distributions



Calculated response in different neutron energy distributions

Question – Is the neutron energy distribution correct

Answer – Table below shows that variation in our dose equivalent response to selected cosmic ray spectra is not large, so choice of neutron spectra is not too critical

Neutron energy distribution	E_{ISO}/Φ (pSv cm^2)	R_{Φ} (10^{-6} cm^2)	$R(E_{iso})$ (mSv^{-1})
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Proton LET threshold
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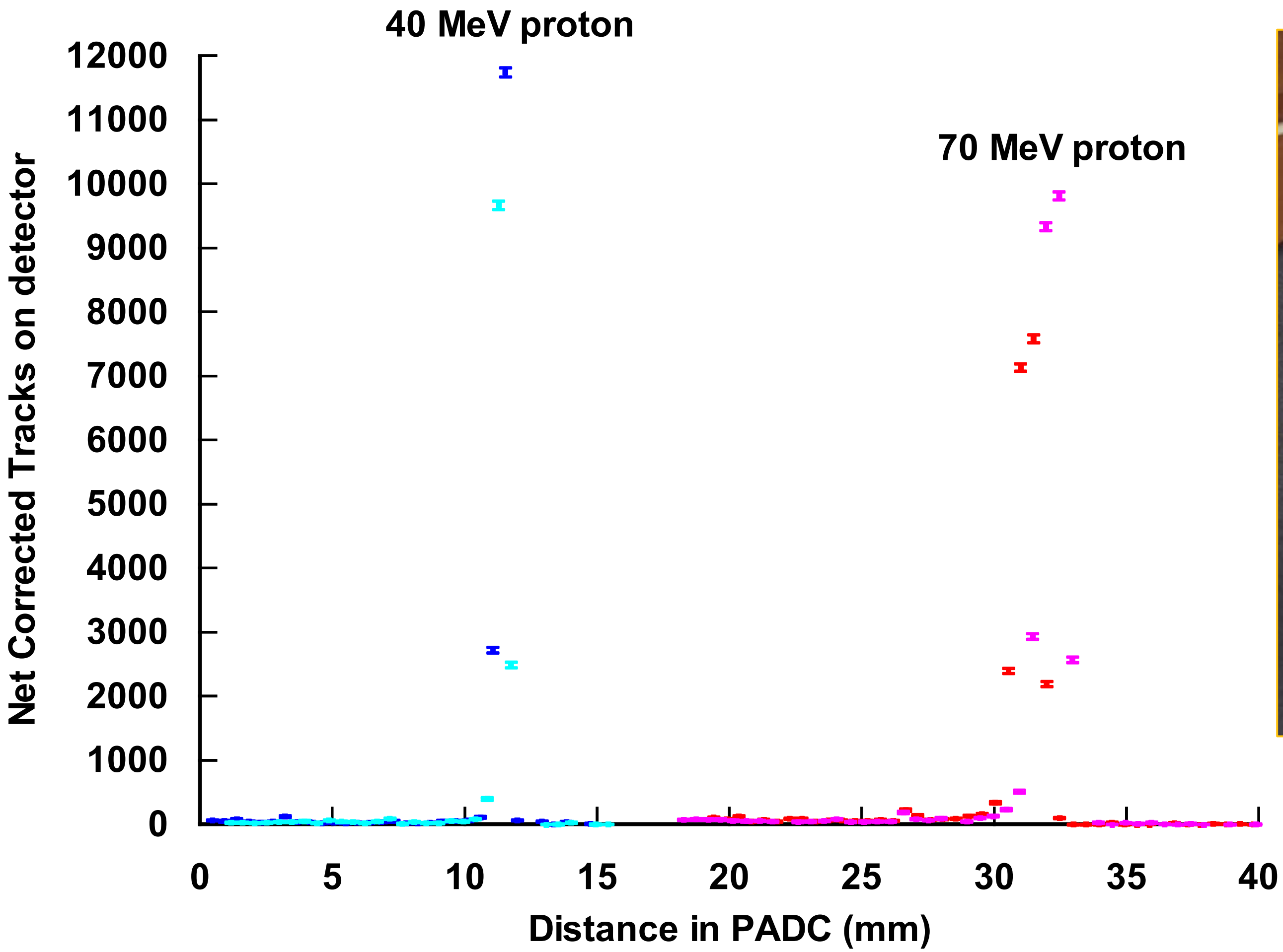

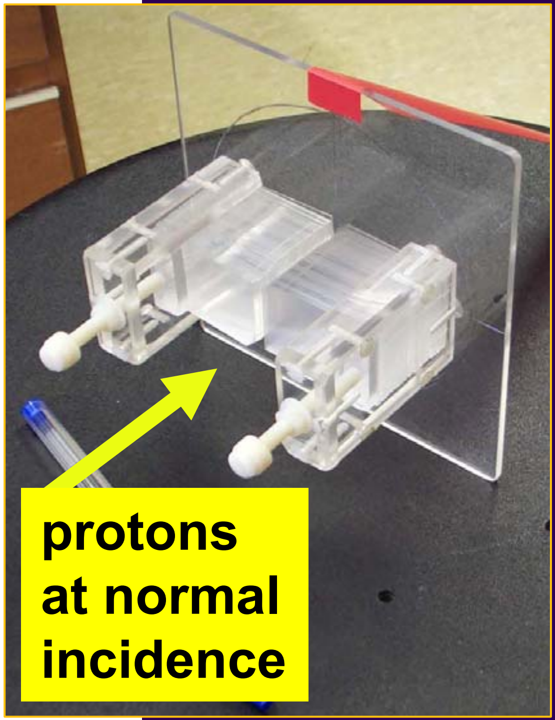

Assessed proton LET thresholds in PADC

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$ 1 standard uncertainty

Using: $\log(LET_{\infty}\text{ water}) = 0.1689 + 0.984\log(LET_{200}\text{ CR-39})$ (*E.Benton*)

Proton critical angle

$LET_{\infty PADC} * \cos\theta \geq 44 keV/\mu m$

$Range * \cos\theta \geq 0.6 \mu m$

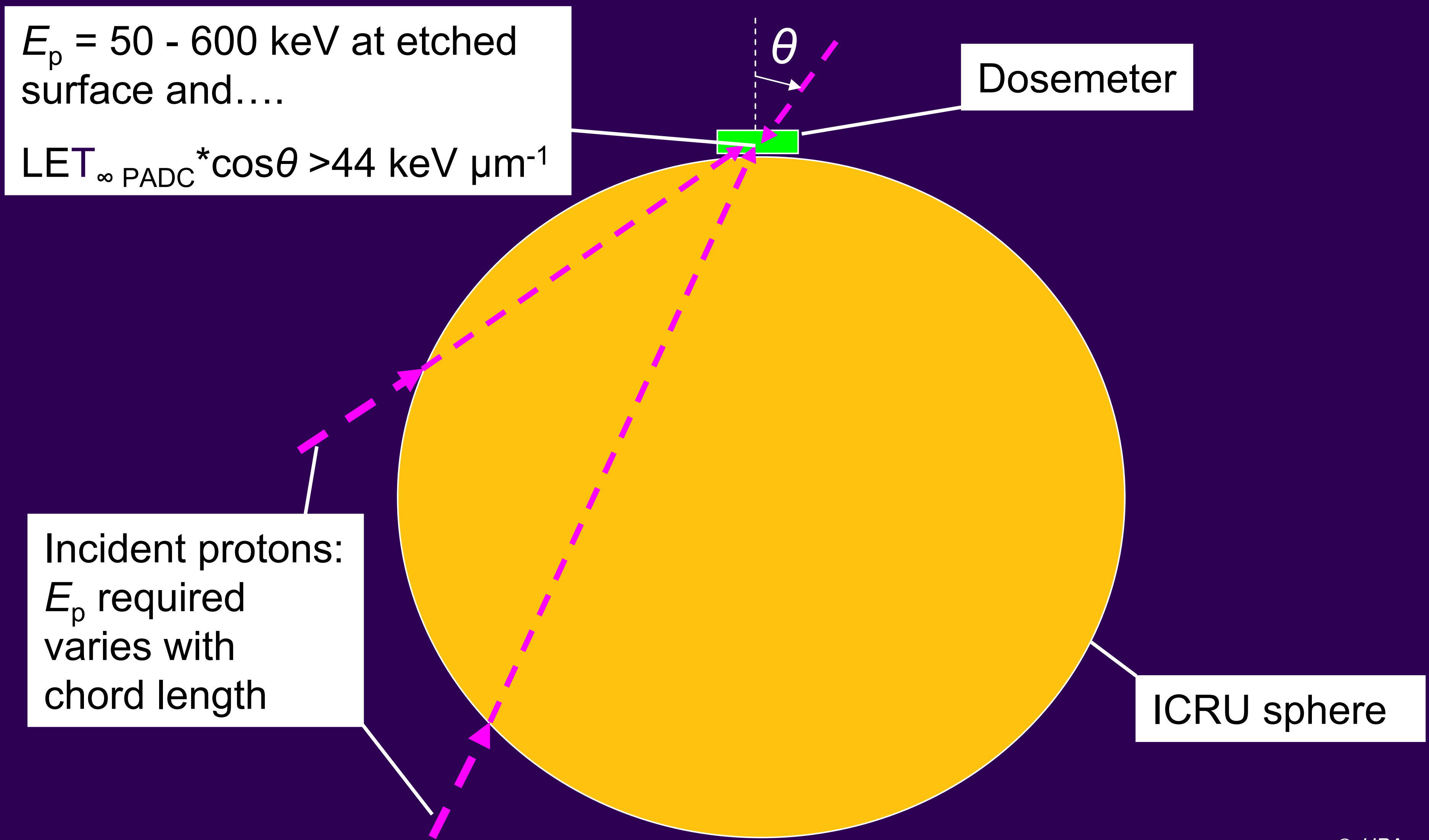
LET_{min} 44 keV μm^{-1} d_{min} 0.60 μm

Angle (°)

E (keV)	R (µm)	L	0 d	0 L	5 d	5 L	10 d	10 L	15 d	15 L	20 d	20 L	25 d	25 L	30 d	30 L	35 d	35 L	40 d	40 L	45 d	45 L	50 d	50 L	55 d	55 L	60 d	60 L	65 d	65 L	70 d	70 L	75 d	75 L	80 d	80 L	85 d	85 L
30.0	0.44	92		92		91		90		89		86		83		79		75		70		65		59		53		46										
32.5	0.47	94		94		94		93		91		88		85		81		77		72		66		60		54		47										
35.0	0.49	96		96		96		95		93		90		87		83		79		74		68		62		55		48										
37.5	0.52	98		98		98		97		95		92		89		85		80		75		69		63		56		49										
40	0.54	100		100		99		98		96		94		90		86		82		76		71		64		57		50										
45	0.59	103		103		102		101		99		96		93		89		84		79		73		66		59		51										
50	0.64	105	0.6	105	0.6	105	0.6	103	0.6	101		99		95		91		86		80		74		67		60		52		44								
55	0.68	107	0.7	107	0.7	106	0.7	105	0.7	103	0.6	100	0.6	97		92		87		82		75		69		61		53		45								
60	0.73	108	0.7	108	0.7	107	0.7	106	0.7	104	0.7	101	0.7	98	0.6	93		88		83		76		69		62		54		46								
65	0.77	109	0.8	109	0.8	108	0.8	107	0.7	105	0.7	102	0.7	99	0.7	94	0.6	89		83		77		70		62		54		46								
70	0.82	109	0.8	109	0.8	109	0.8	108	0.8	105	0.8	103	0.7	99	0.7	95	0.7	89	0.6	84		77		70		63		55		46								
80	0.91	109	0.9	109	0.9	109	0.9	108	0.9	106	0.9	103	0.8	99	0.8	95	0.7	90	0.7	84	0.6	77		70		63		55		46								
90	1.00	108	1.0	108	1.0	108	1.0	107	1.0	105	0.9	102	0.9	98	0.9	94	0.8	89	0.8	83	0.7	77	0.6	70		62		54		46								
100	1.09	107	1.1	107	1.1	107	1.1	105	1.1	103	1.0	101	1.0	97	0.9	93	0.9	88	0.8	82	0.8	76	0.7	69	0.6	61		54		45								
110	1.19	105	1.2	105	1.2	105	1.2	104	1.1	102	1.1	99	1.1	95	1.0	91	1.0	86	0.9	81	0.8	74	0.8	68	0.7	60		53		44								
120	1.28	103	1.3	103	1.3	103	1.3	101	1.2	99	1.2	97	1.2	93	1.1	89	1.0	84	1.0	79	0.9	73	0.8	66	0.7	59	0.6	51										
130	1.38	101	1.4	101	1.4	100	1.4	99	1.3	97	1.3	94	1.3	91	1.2	87	1.1	82	1.1	77	1.0	71	0.9	65	0.8	58	0.7	50										
140	1.48	98	1.5	98	1.5	98	1.5	97	1.4	95	1.4	92	1.3	89	1.3	85	1.2	80	1.1	75	1.0	69	1.0	63	0.8	56	0.7	49	0.6									
150	1.58	96	1.6	96	1.6	95	1.6	94	1.5	92	1.5	90	1.4	87	1.4	83	1.3	78	1.2	73	1.1	68	1.0	61	0.9	55	0.8	48	0.7									
160	1.69	93	1.7	93	1.7	93	1.7	92	1.6	90	1.6	88	1.5	84	1.5	81	1.4	76	1.3	71	1.2	66	1.1	60	1.0	53	0.8	47	0.7									
170	1.79	91	1.8	91	1.8	90	1.8	89	1.7	88	1.7	85	1.6	82	1.6	79	1.5	74	1.4	70	1.3	64	1.2	58	1.0	52	0.9	45	0.8		0.6							
180	1.90	88	1.9	88	1.9	88	1.9	87	1.8	85	1.8	83	1.7	80	1.6	77	1.6	72	1.5	68	1.3	63	1.2	57	1.1	51	1.0	44	0.8		0.6							
200	2.14	84	2.1	84	2.1	84	2.1	83	2.1	81	2.0	79	1.9	76	1.9	73	1.8	69	1.6	64	1.5	59	1.4	54	1.2	48	1.1		0.9		0.7							
225	2.44	79	2.4	79	2.4	79	2.4	78	2.4	76	2.3	74	2.2	72	2.1	68	2.0	65	1.9	61	1.7	56	1.6	51	1.4	45	1.2		1.0		0.8		0.6					
250	2.76	75	2.8	75	2.7	74	2.7	73	2.7	72	2.6	70	2.5	68	2.4	65	2.3	61	2.1	57	2.0	53	1.8	48	1.6		1.4		1.2		0.9		0.7					
275	3.11	71	3.1	71	3.1	70	3.1	70	3.0	68	2.9	66	2.8	64	2.7	61	2.5	58	2.4	54	2.2	50	2.0	45	1.8		1.6		1.3		1.1		0.8					
300	3.47	67	3.5	67	3.5	67	3.4	66	3.4	65	3.3	63	3.1	61	3.0	58	2.8	55	2.7	51	2.5	47	2.2		2.0		1.7		1.5		1.2		0.9		0.6			
325	3.85	64	3.9	64	3.8	64	3.8	63	3.7	62	3.6	60	3.5	58	3.3	55	3.2	52	2.9	49	2.7	45	2.5		2.2		1.9		1.6		1.3		1.0		0.7			
350	4.25	61	4.3	61	4.2	61	4.2	60	4.1	59	4.0	57	3.9	55	3.7	53	3.5	50	3.3	47	3.0		2.7		2.4		2.1		1.8		1.5		1.1		0.7			
375	4.66	59	4.7	59	4.6	58	4.6	58	4.5	57	4.4	55	4.2	53	4.0	51	3.8	48	3.6	45	3.3		3.0		2.7		2.3		2.0		1.6		1.2		0.8			
400	5.09	56	5.1	56	5.1	56	5.0	56	4.9	54	4.8	53	4.6	51	4.4	49	4.2	46	3.9		3.6		3.3		2.9		2.5		2.2		1.7		1.3		0.9			
450	6.01	52	6.0	52	6.0	52	5.9	52	5.8	51	5.6	49	5.4	47	5.2	45	4.9		4.6		4.2		3.9		3.4		3.0		2.5		2.1		1.6		1.0			
500	6.99	49	7.0	49	7.0	49	6.9	48	6.8	47	6.6	46	6.3	44	6.1		5.7		5.4		4.9		4.5		4.0		3.5		3.0		2.4		1.8		1.2		0.6	
550	8.0	46	8.0	46	8.0	46	7.9	45	7.8	45	7.6		7.3		7.0		6.6		6.2		5.7		5.2		4.6		4.0		3.4		2.7		2.1		1.4		0.7	
600	9.2	##	9.2		9.1		9.0		8.8		8.6		8.3		7.9		7.5		7.0		6.5		5.9		5.2		4.6		3.9		3.1		2.4		1.6		0.8	
650	10.3	42	10.3		10.3		10.2		10.0		9.7		9.4		8.9		8.5		7.9		7.3		6.6		5.9		5.2		4.4		3.5		2.7		1.8		0.9	
700	11.6	40	11.6		11.5		11.4		11.2		10.9		10.5		10.0		9.5		8.8		8.2		7.4		6.6		5.8		4.9		4.0		3.0		2.0		1.0	
800	14.2	36	14.2		14.1		14.0		13.7		13.3		12.9		12.3		11.6		10.9		10.0		9.1		8.1		7.1		6.0		4.8		3.7		2.5		1.2	
900	17.0	34	17.0		17.0		16.8		16.4		16.0		15.4		14.7		13.9		13.0		12.0		10.9		9.8		8.5		7.2		5.8		4.4		3.0		1.5	
1000	20.1	32	20.1		20.0		19.8		19.4		18.9		18.2		17.4		16.4		15.4		14.2		12.9		11.5		10.0		8.5		6.9		5.2		3.5		1.7	

Analytical method to determine the direct proton response

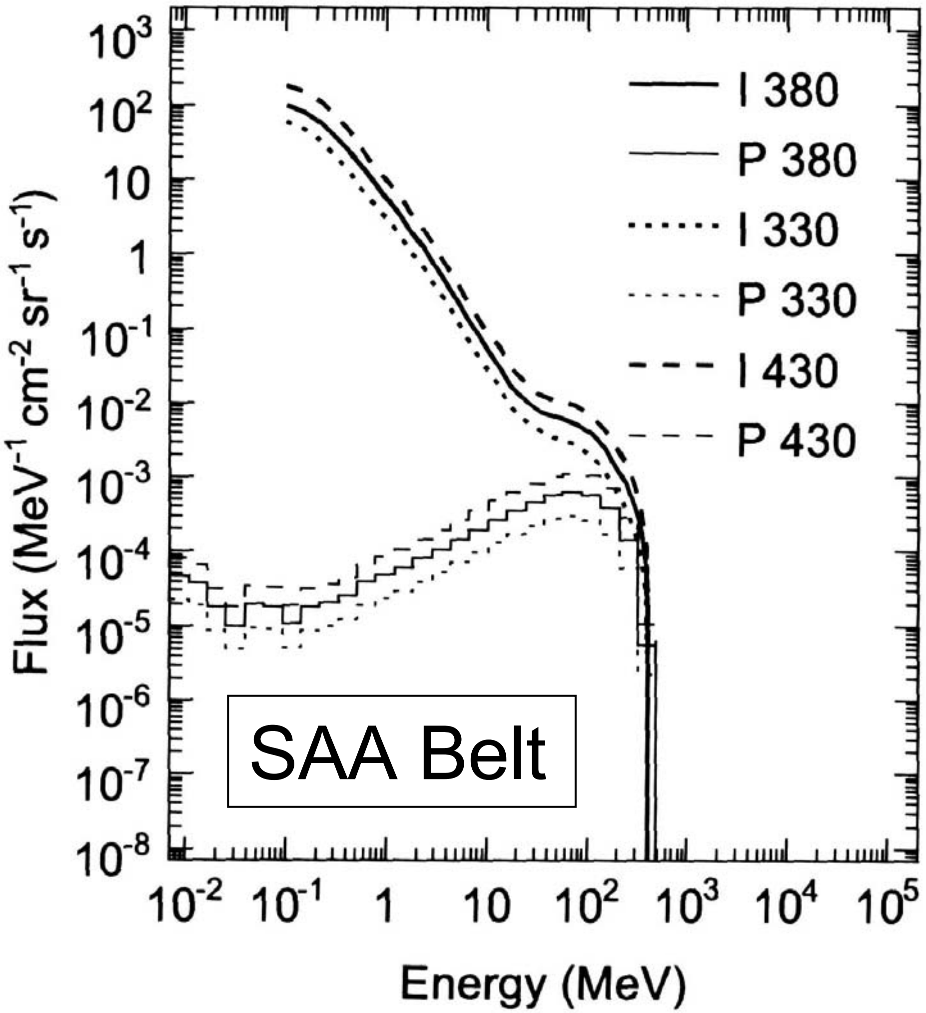
Dosemeter mounted on 30 cm diameter ICRU tissue sphere

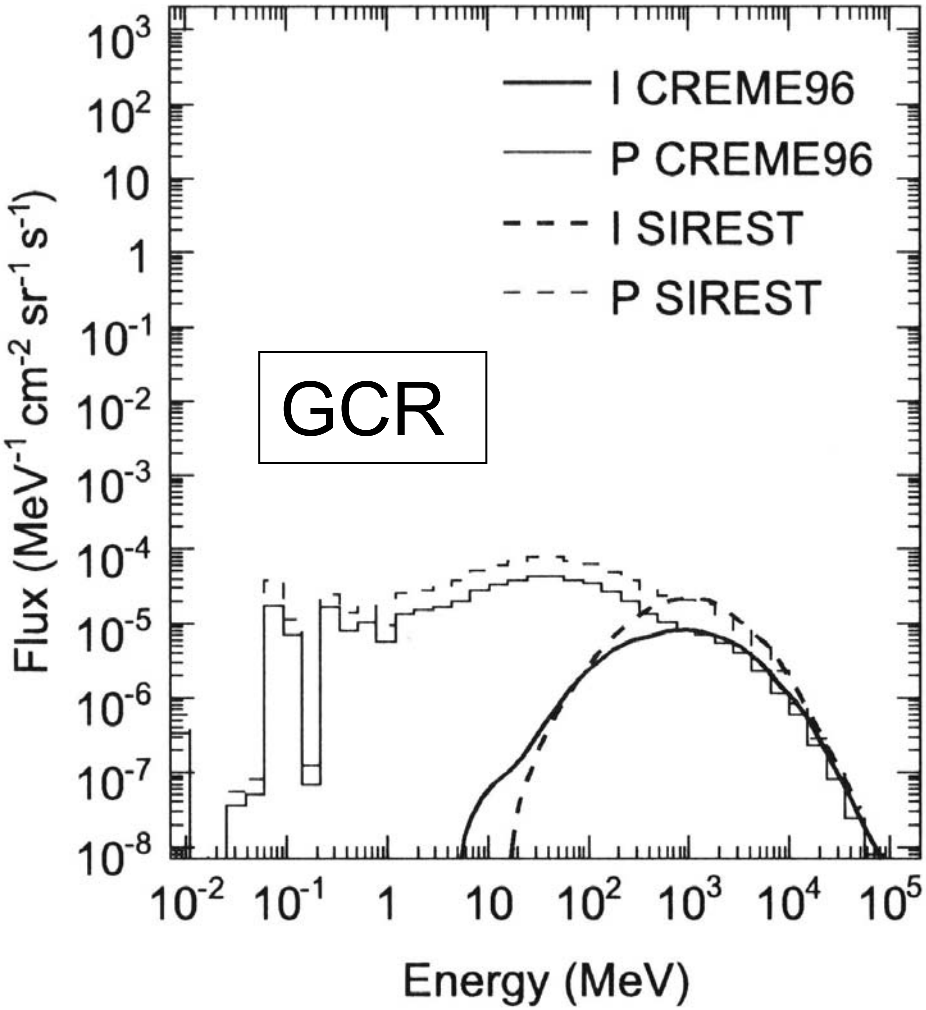


Detectable proton energy ranges

			Lowest energy detected				Highest energy detected						
θ (°)	θ (rad)	Ω (sr)	r_{ICRU} (mm)	$\ln(r)$	$\ln(E(r))$	$E(r)$ (MeV)	r_{PADC} (µm)	r_{ICRU} (µm)	$r+\delta$ (mm)	$\ln(r+\delta)$	$\ln(E(r+\delta))$	$E(r+\delta)$ (MeV)	ΔE (MeV)
0	0.000	0.006	5.00	1.610	3.067	**21.48**	9.20	11.51	5.012	1.612	3.068	**21.51**	0.0251
5	0.087	0.048	5.02	1.613	3.069	**21.53**	8.00	10.01	5.029	1.615	3.070	**21.55**	0.0216
10	0.175	0.095	5.08	1.625	3.076	**21.66**	7.90	9.89	5.087	1.627	3.076	**21.68**	0.0212
15	0.262	0.142	5.18	1.644	3.086	**21.89**	7.80	9.76	5.186	1.646	3.087	**21.91**	0.0207
20	0.349	0.187	5.32	1.672	3.101	**22.22**	6.60	8.26	5.329	1.673	3.102	**22.24**	0.0170
25	0.436	0.232	5.52	1.708	3.121	**22.67**	6.30	7.88	5.525	1.709	3.122	**22.68**	0.0159
30	0.524	0.274	5.77	1.753	3.146	**23.24**	5.20	6.51	5.780	1.754	3.146	**23.25**	0.0125
35	0.611	0.314	6.10	1.809	3.176	**23.96**	4.20	5.26	6.109	1.810	3.177	**23.97**	0.0096
40	0.698	0.352	6.53	1.876	3.213	**24.85**	3.60	4.50	6.532	1.877	3.213	**24.86**	0.0077
45	0.785	0.388	7.07	1.956	3.257	**25.96**	2.70	3.38	7.074	1.956	3.257	**25.97**	0.0052
50	0.873	0.420	7.78	2.051	3.309	**27.35**	2.00	2.50	7.781	2.052	3.309	**27.35**	0.0033
55	0.960	0.449	8.72	2.165	3.371	**29.11**	1.40	1.75	8.719	2.166	3.371	**29.11**	0.0017
60	1.047	0.475	10.00	2.303	3.446	**31.38**	1.00	1.25	10.00	2.303	3.446	**31.38**	0.0008
65	1.134	0.497											
70	1.222	0.515											
75	1.309	0.529											
80	1.396	0.540											
85	1.484	0.546											
90	1.571	0.548											
95	1.658	0.546											
100	1.745	0.540											
105	1.833	0.529											
110	1.920	0.515											
115	2.007	0.497											
120	2.094	0.475	150.00	5.011	4.958	**142.32**	1.00	1.25	150.00	5.011	4.958	**142.32**	0.0007
125	2.182	0.449	172.07	5.148	5.037	**153.98**	1.40	1.75	172.07	5.148	5.037	**153.98**	0.0009
130	2.269	0.420	192.84	5.262	5.102	**164.41**	2.00	2.50	192.84	5.262	5.102	**164.42**	0.0012
135	2.356	0.388	212.13	5.357	5.157	**173.71**	2.70	3.38	212.14	5.357	5.157	**173.72**	0.0016
140	2.443	0.352	229.81	5.437	5.204	**181.95**	3.60	4.50	229.82	5.437	5.204	**181.95**	0.0021
145	2.531	0.314	245.75	5.504	5.243	**189.15**	4.20	5.26	245.75	5.504	5.243	**189.15**	0.0023
150	2.618	0.274	259.81	5.560	5.275	**195.36**	5.20	6.51	259.81	5.560	5.275	**195.36**	0.0028
155	2.705	0.232	271.89	5.605	5.301	**200.59**	6.30	7.88	271.90	5.605	5.301	**200.60**	0.0034
160	2.793	0.187	281.91	5.642	5.322	**204.86**	6.60	8.26	281.92	5.642	5.322	**204.86**	0.0035
165	2.880	0.142	289.78	5.669	5.338	**208.17**	7.80	9.76	289.79	5.669	5.338	**208.18**	0.0041
170	2.967	0.095	295.44	5.688	5.350	**210.53**	7.90	9.89	295.45	5.689	5.350	**210.54**	0.0041
175	3.054	0.048	298.86	5.700	5.356	**211.95**	8.00	10.01	298.87	5.700	5.356	**211.96**	0.0041
180	3.142	0.006	300.00	5.704	5.359	**212.42**	9.20	11.51	300.01	5.704	5.359	**212.43**	0.0048

Calculated protons inside ISS Columbus module
(GEANT4)





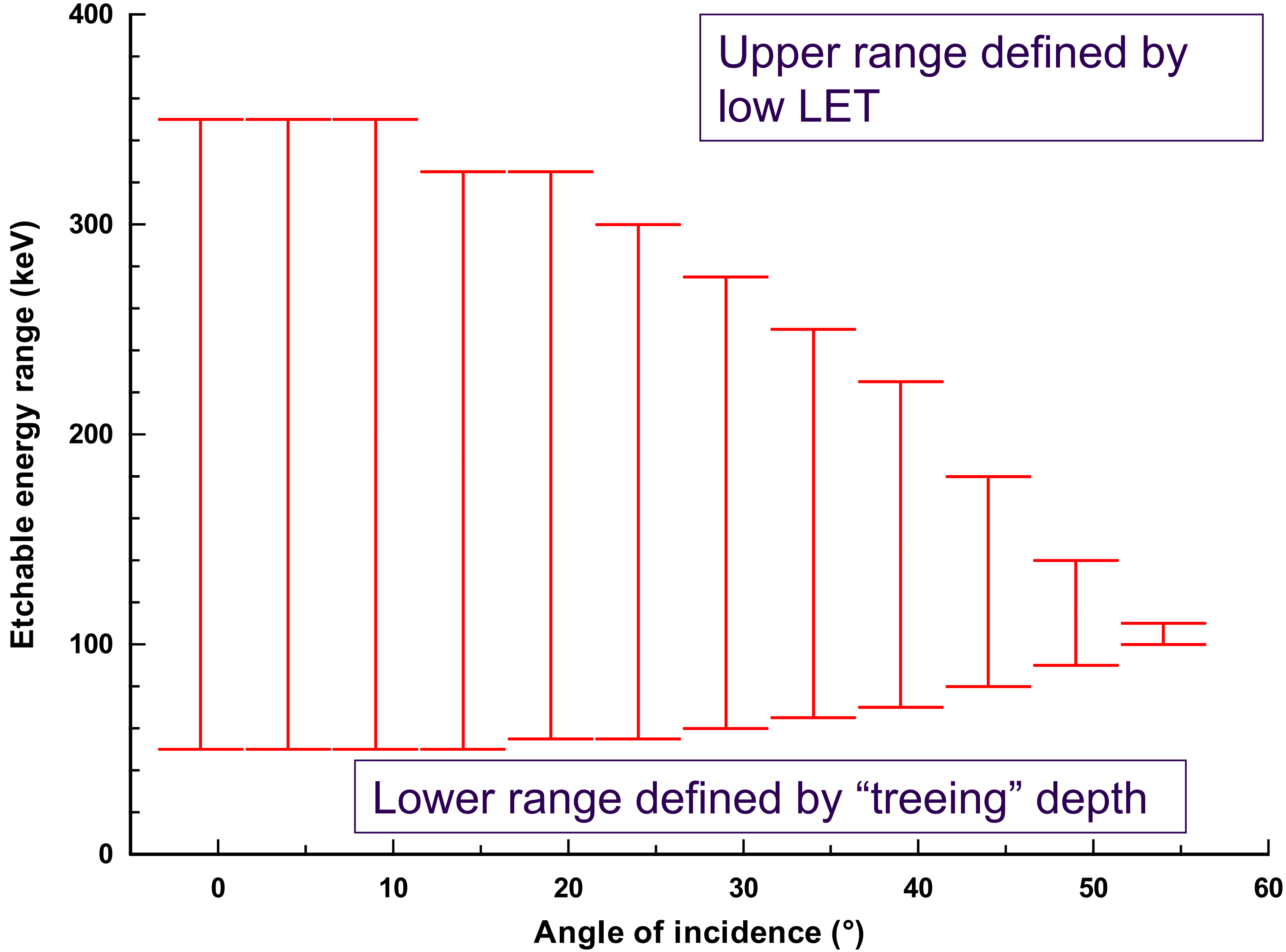
(T Ersmark PhD thesis, June 2006, Royal Institute of Technology, Stockholm)

Estimated etchable proton tracks for inside ISS

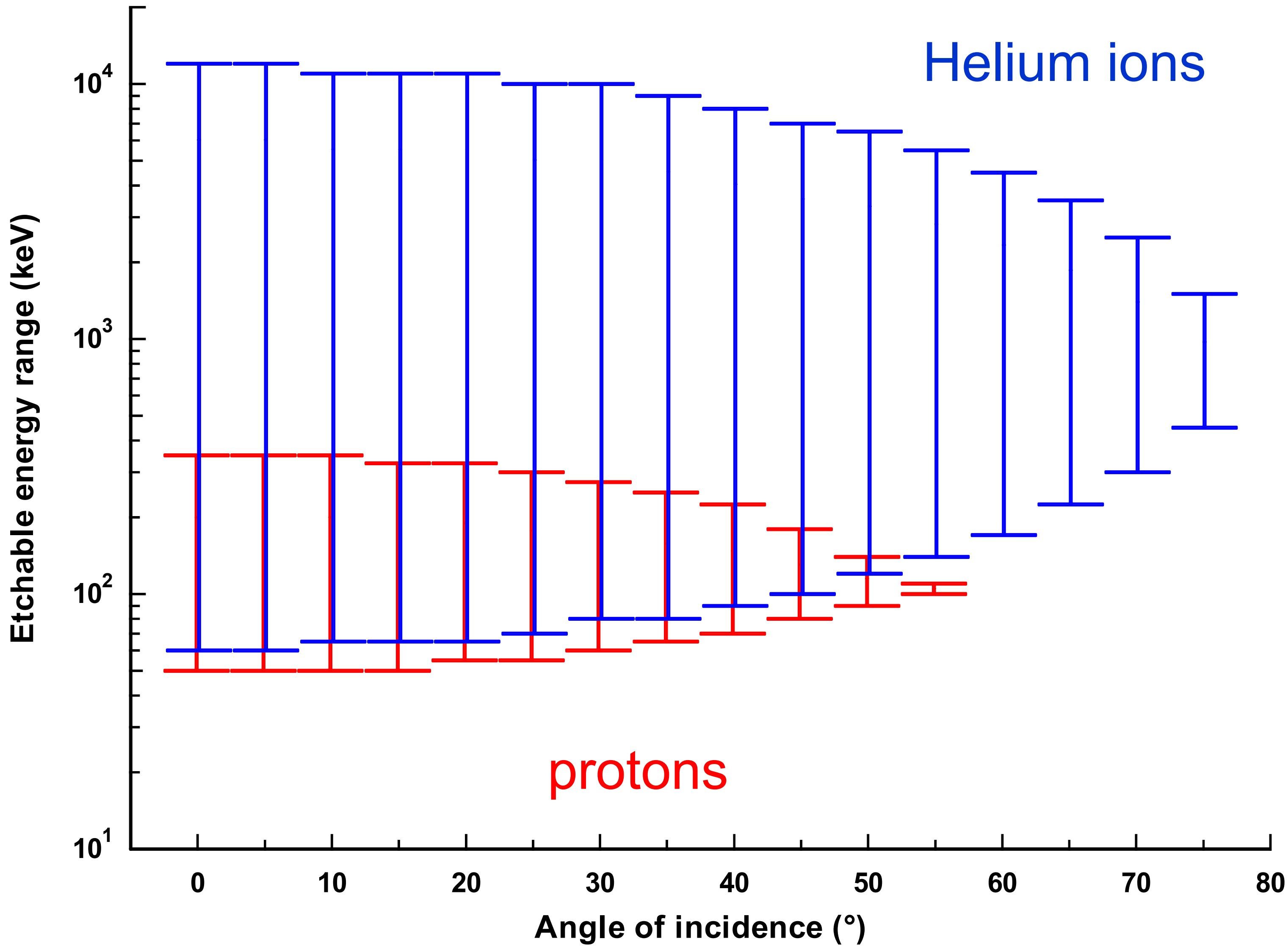
Origin	Etchable proton tracks ($cm^{-2}\ d^{-1}$)
SAA belt	1.09
GCR	0.11
TOTAL	1.20 (0.35)#

1 standard uncertainty in brackets

Etchable energy windows for protons



Etchable energy windows for helium ions



Future work

- How advanced is calibration ?

- Neutron calibration good, un-finalised contribution to signal mainly from protons, ^{4}He.

- What needs to be done ?

- Use MCNPX_2.6 to determine the fluence-energy-angle distributions of the particle fields inside the ISS. Use CRÈME-96 to produce incident spectra. Assume shielding of 20 g/cm^{2}.

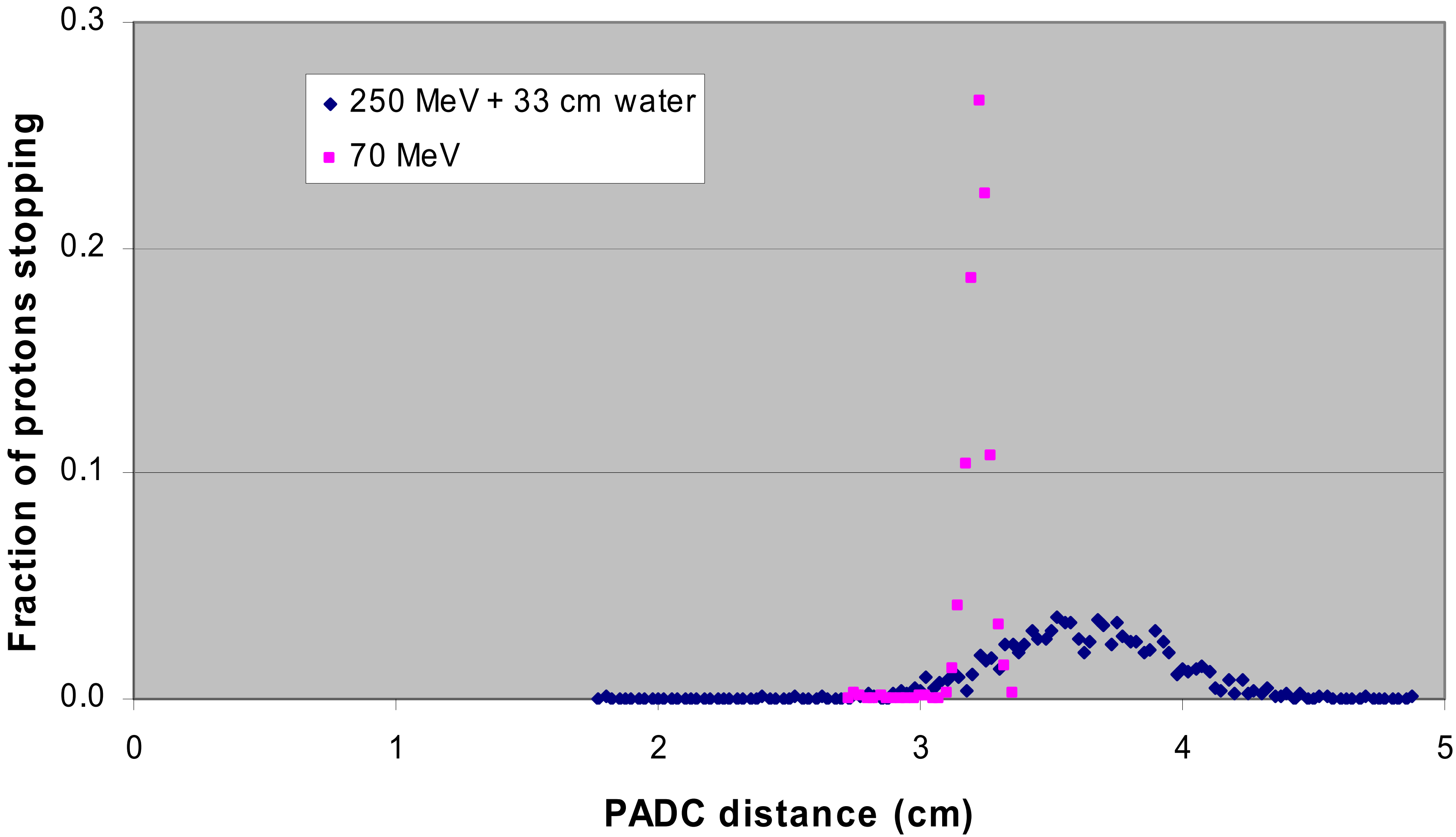
- What's achievable in 3rd year ?

- Assuming the fluence energy distributions are derived (at least for proton and ^{4}He), then a more reliable estimate of the unwanted contribution to the dosemeter signal, and a better neutron dose estimate.

- When to expect neutron dose values ?

- Realistically this is probably 4 - 6 months away.

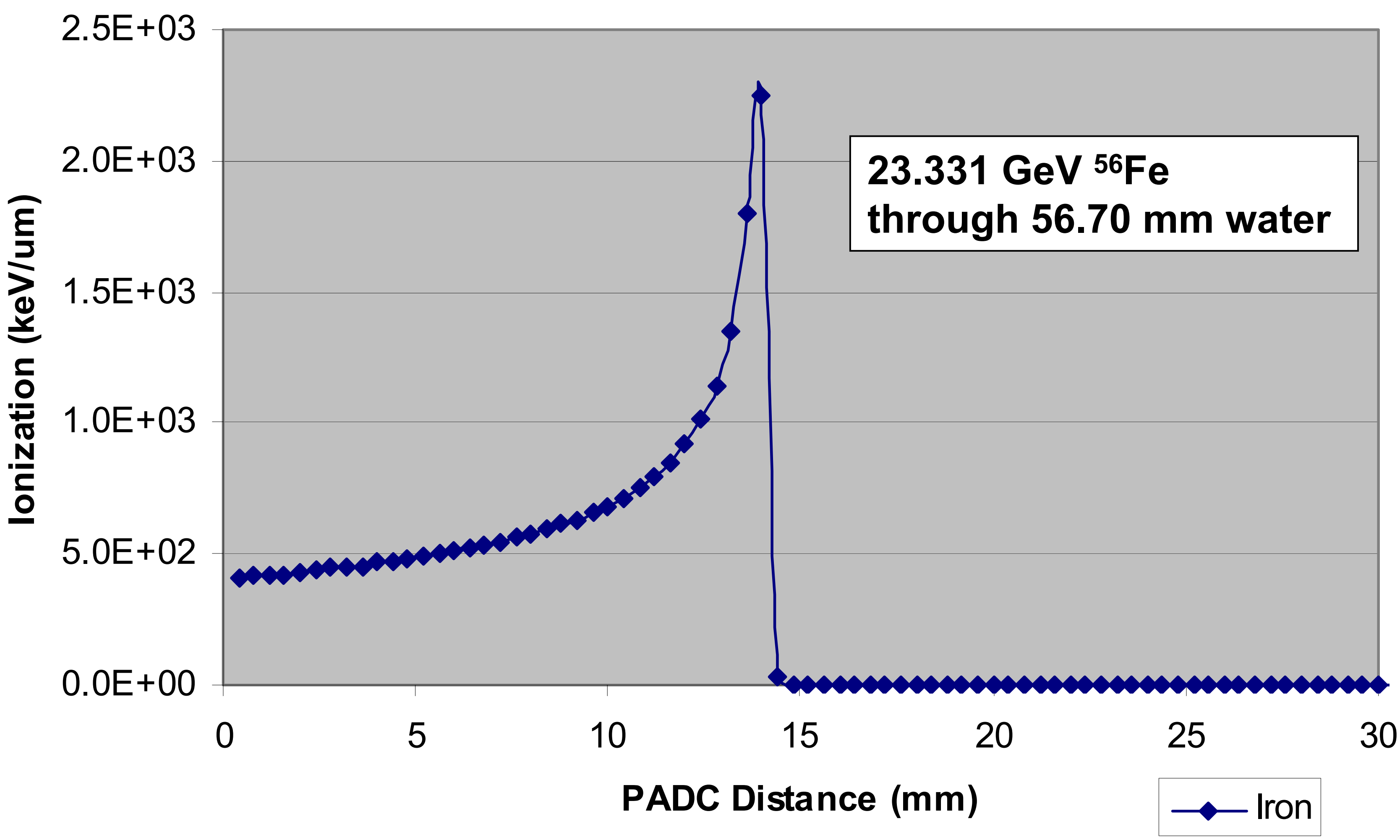
Ranges of protons in PADC for different initial energies
TRIM calculation



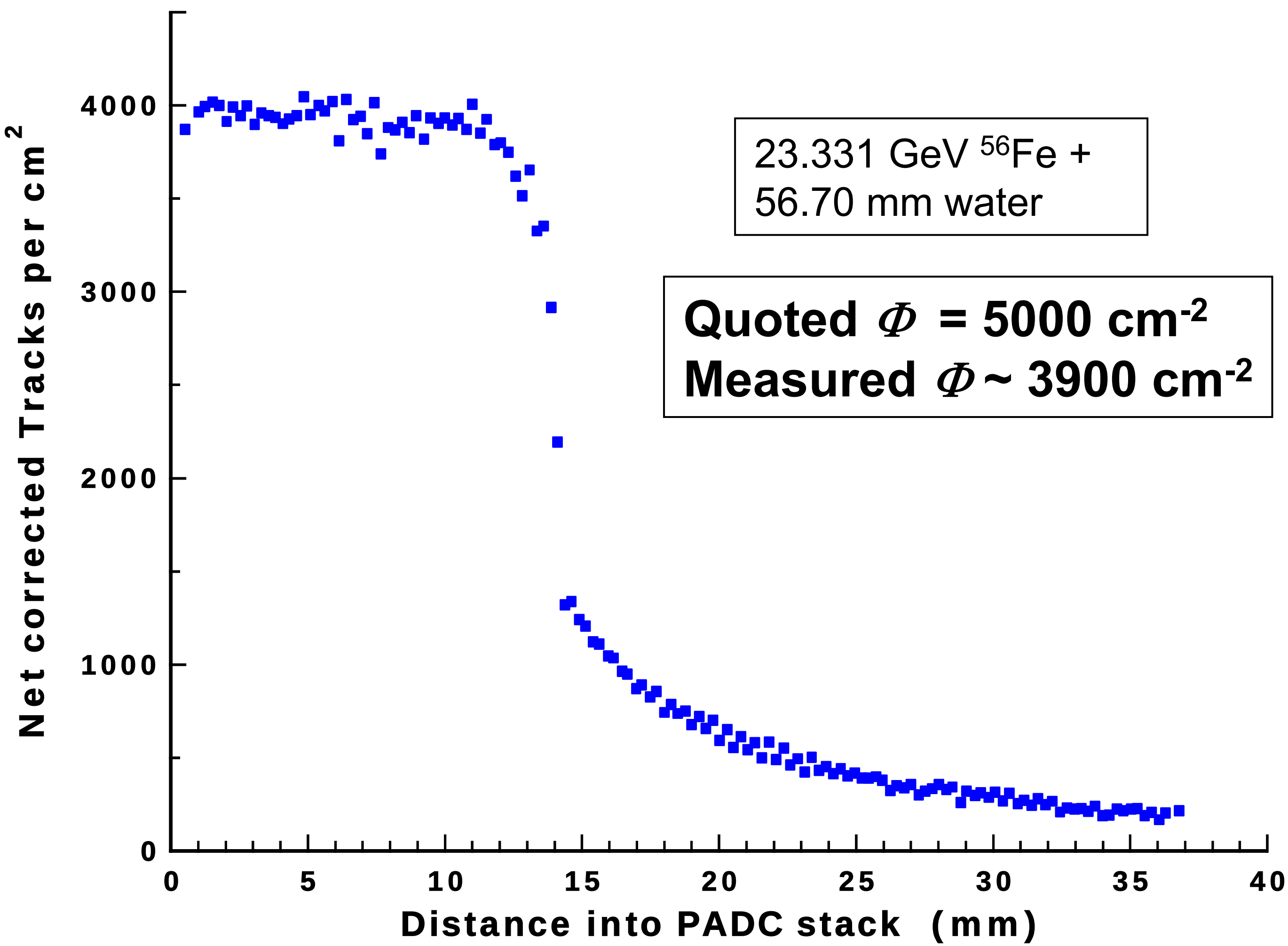
Galactic Cosmic Radiation at top of atmosphere

Protons	86 %
Helium nuclei	12 %
Electrons Positrons	2 %
Heavier nuclei	< 1%

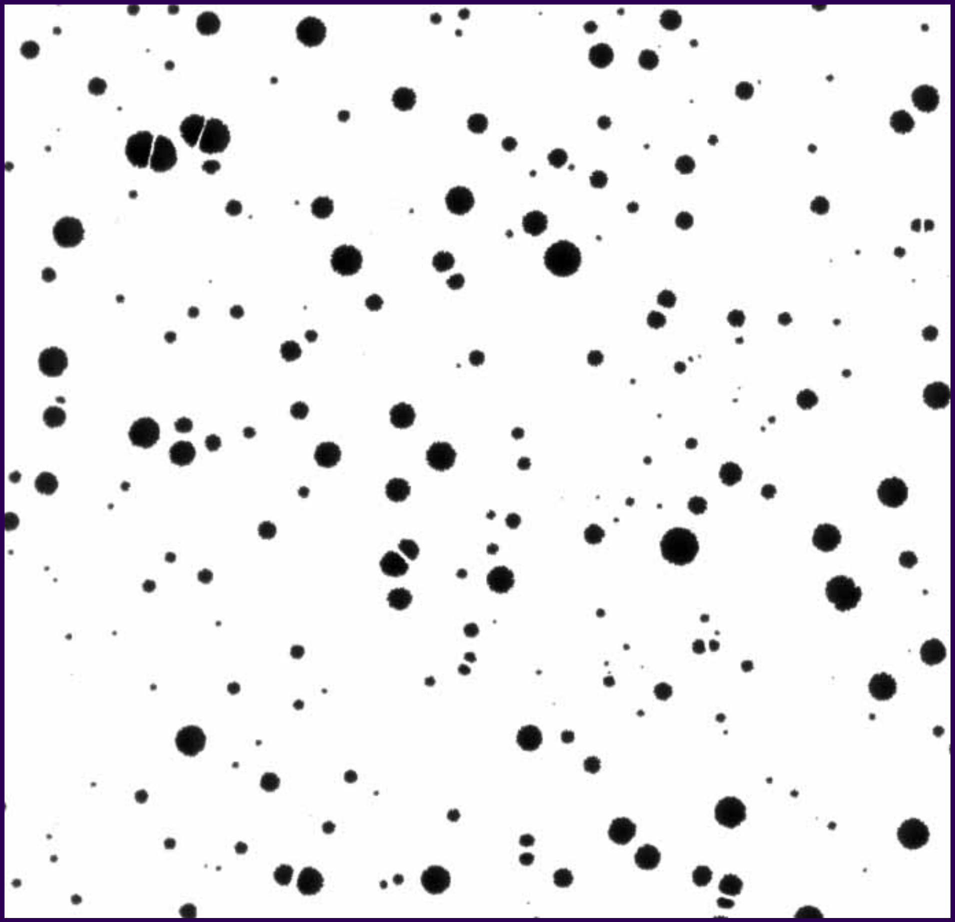
TRIM calculation of ionization
^{56}Fe



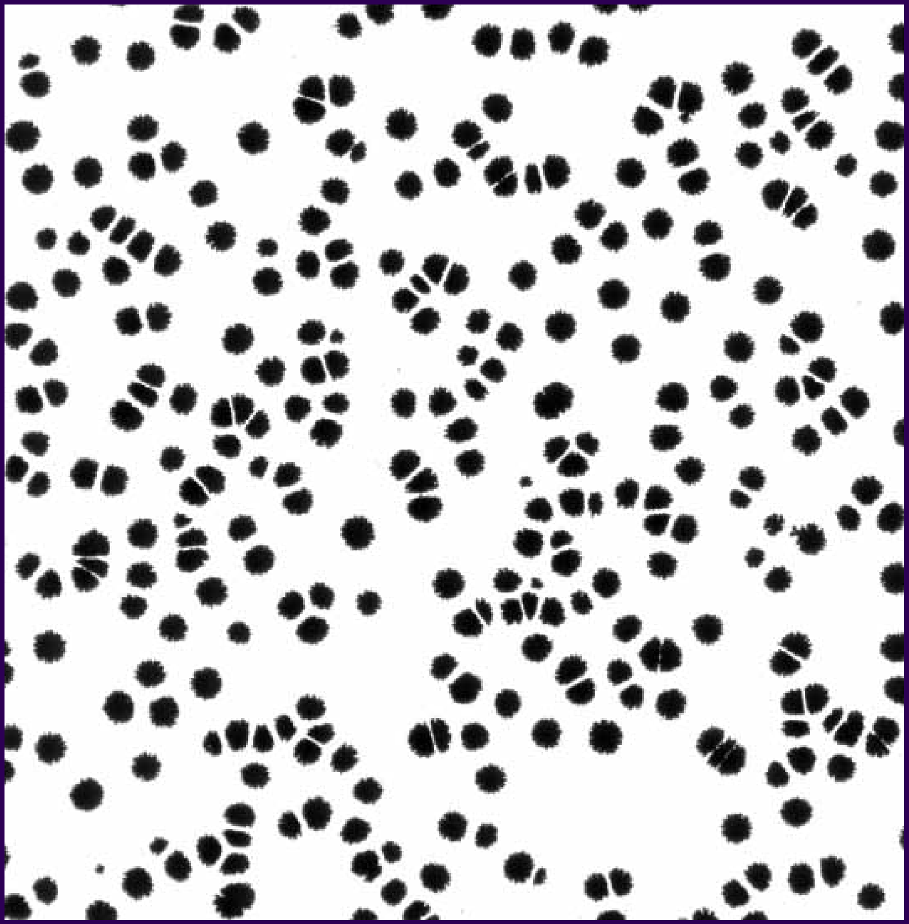
HIMAC ^{56}Fe: 23.331 GeV
+ 56.70 mm water equiv PMMA



HIMAC ^{12}C: 4.582 GeV
+ 220.37 mm water equiv PMMA

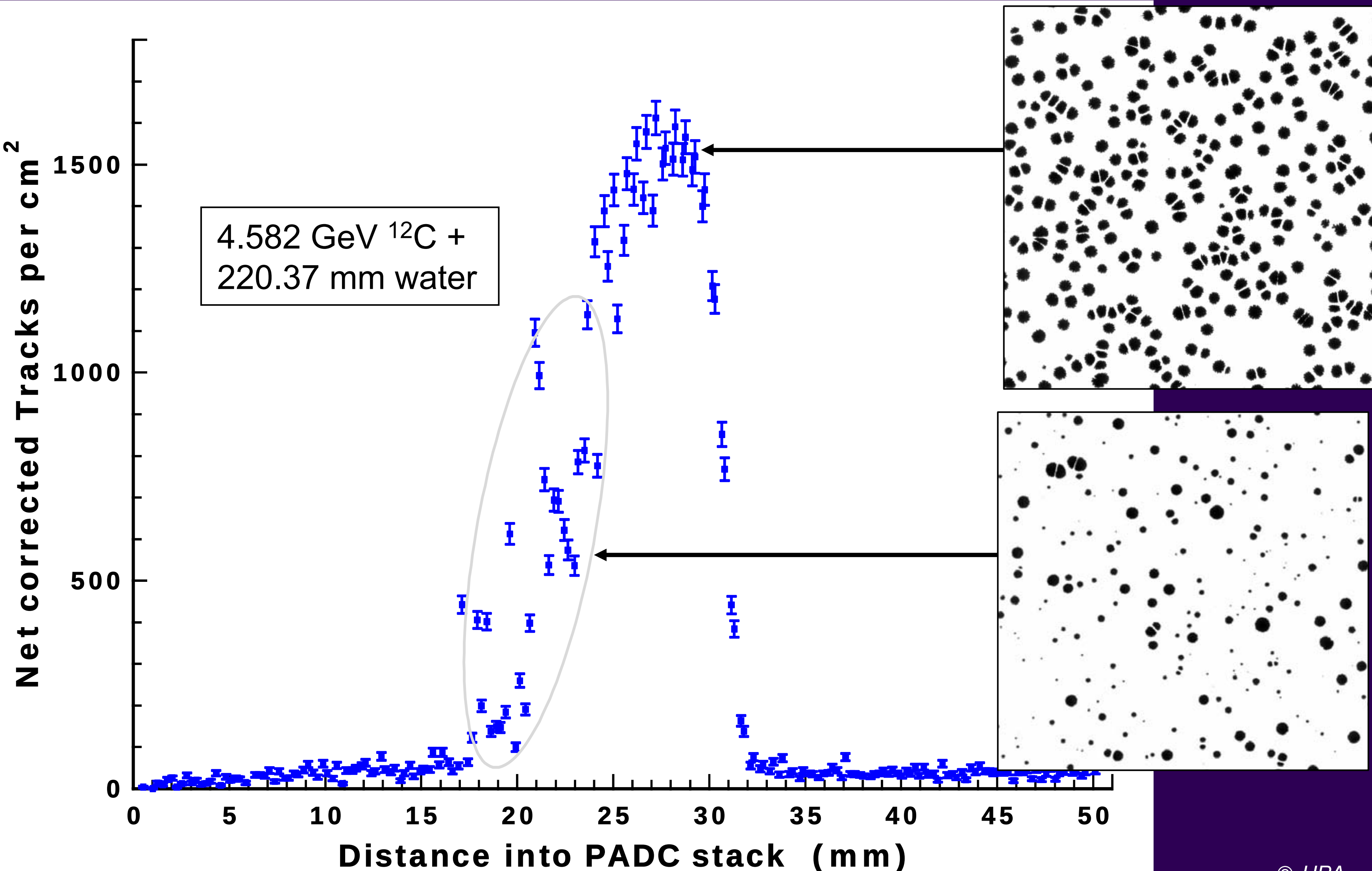


BEFORE PEAK of measured response - highly variable track sizes

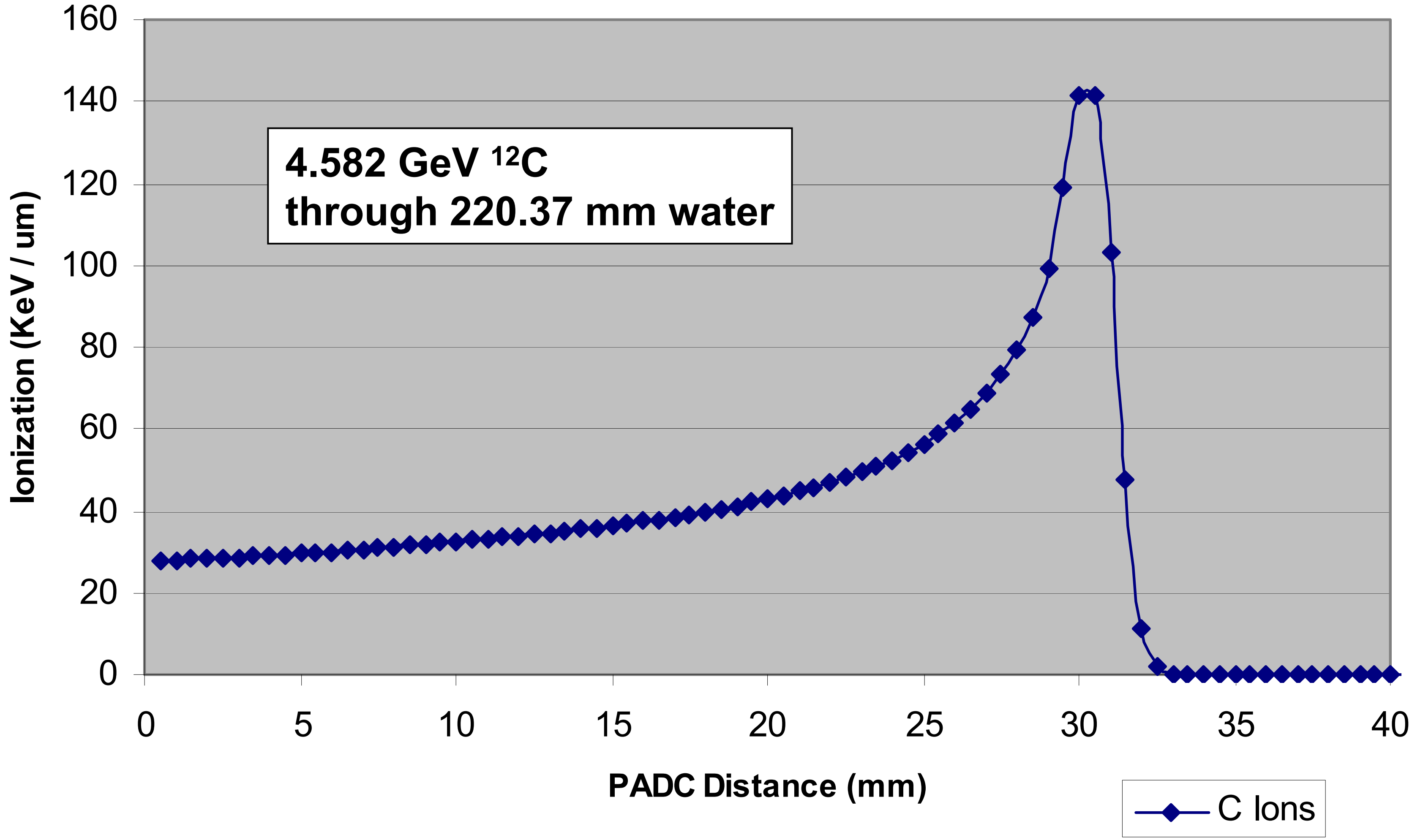


AT PEAK of measured response - uniform track sizes

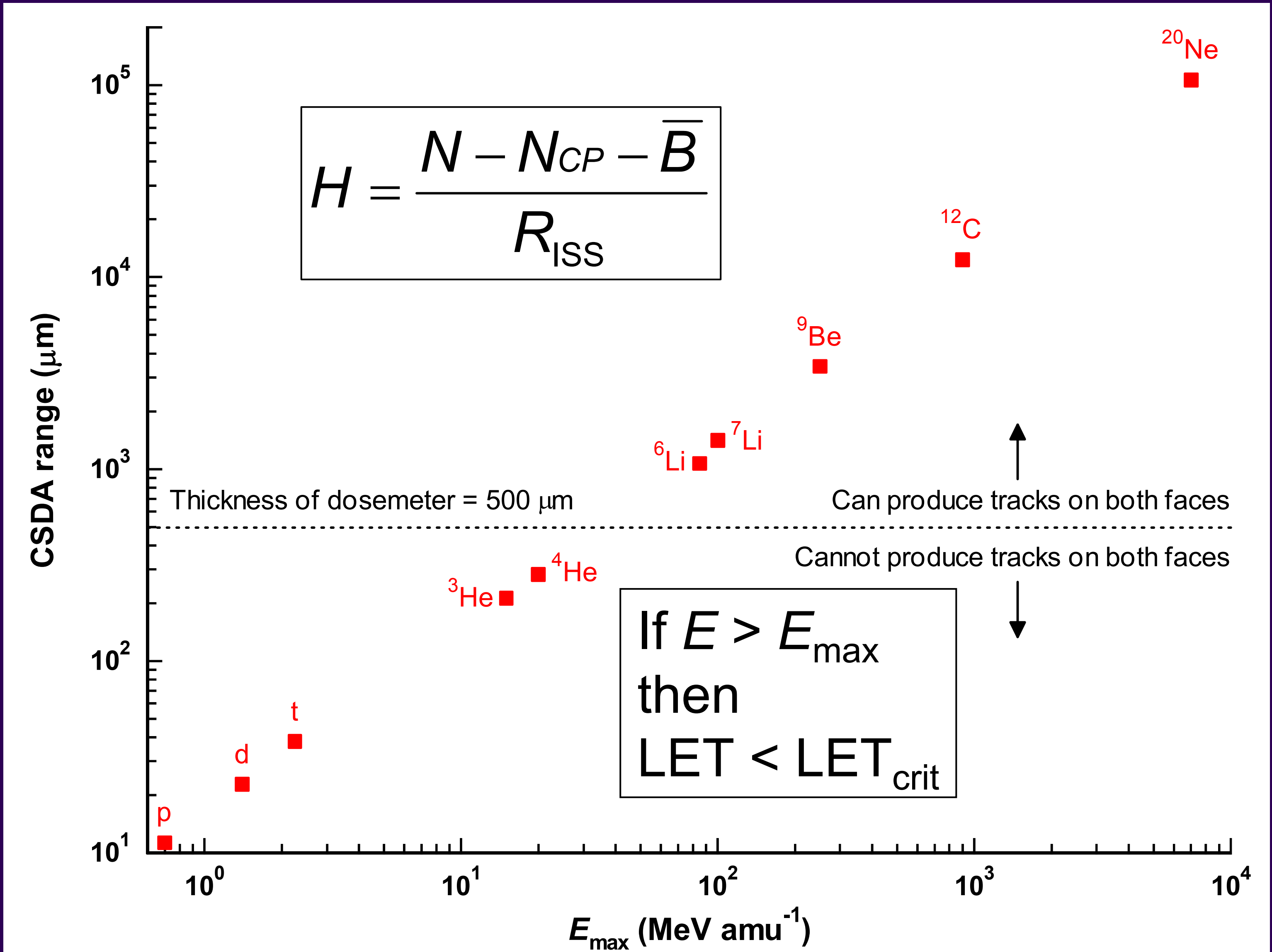
HIMAC ^{12}C: 4.582 GeV
+ 220.37 mm water equiv PMMA



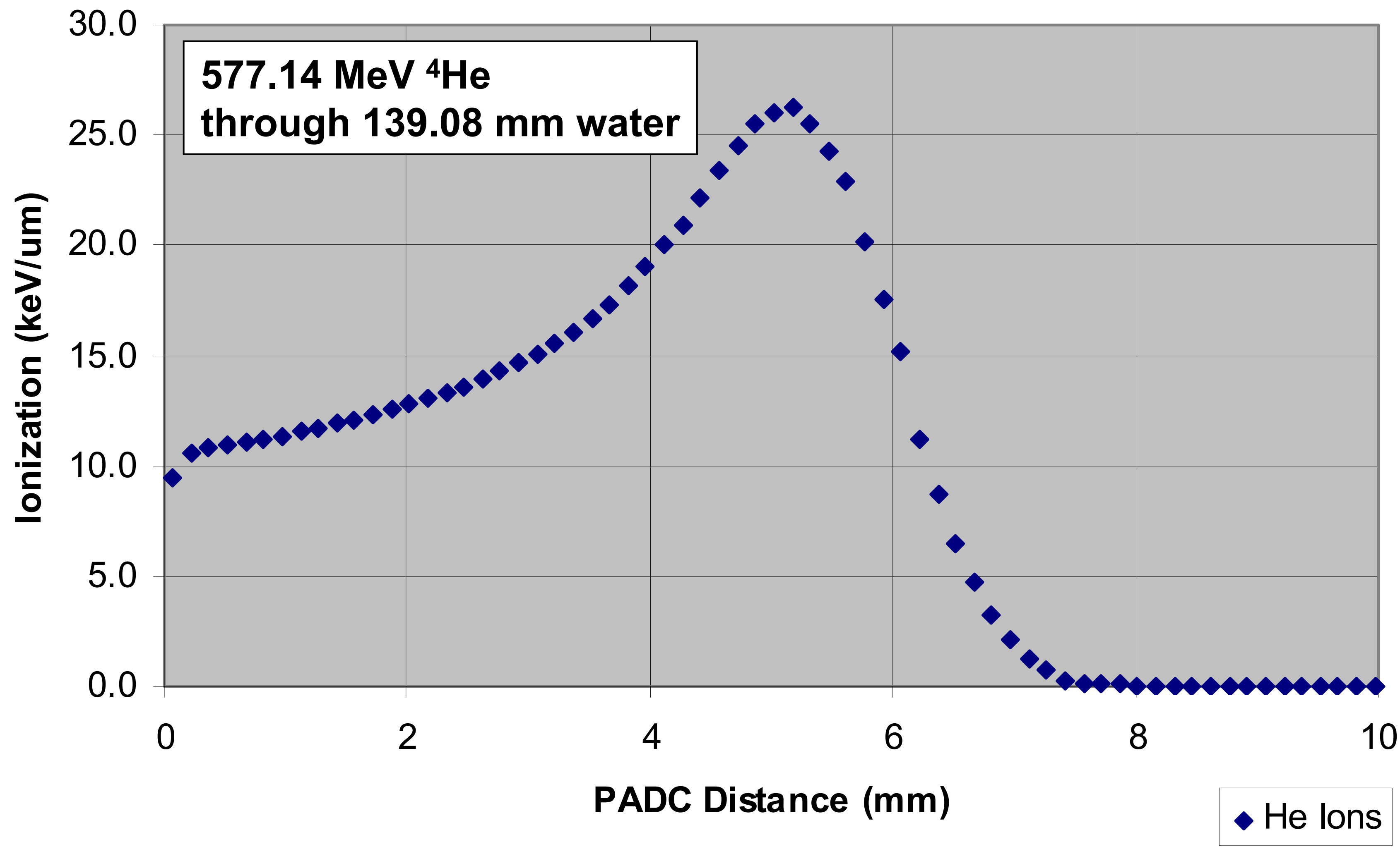
TRIM calculation of ionization ^{12}C

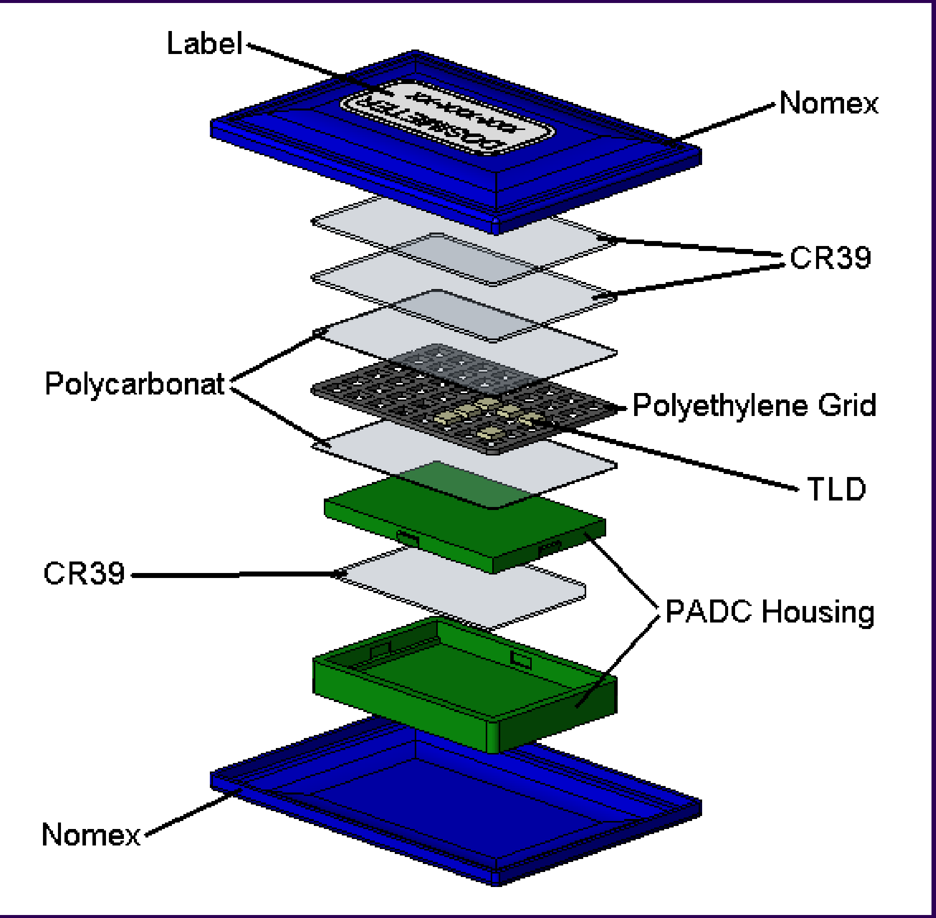


Residual range vs E_{max} in PADC



TRIM calculation of ionization
^{4}He




Label
Nomex
CR39
Polycarbonat
Polyethylene Grid
TLD
CR39
PADC Housing
Nomex

Proton calibrations to determine LET_{crit}

Options available: PSI 62 MeV, 250 MeV
TSL 200 MeV
Heidelberg 250 MeV?

62 MeV: range in water = 32 mm
straggling 1.3 mm (SRIM 2008)

250 MeV range in water = 300 mm
straggling 12 mm (SRIM 2008)

Preferred arrangement: 250 MeV through build-up to give a lot of straggling
Several angles would be desirable
High enough fluence to give good statistics

Methods – need to get rid of the charged particles

Simple method to get neutron dose

$$H = \frac{N - \overline{B}}{R_{ISS}}$$

H = Dose equivalent

N = Total Tracks counted

B = Background tracks

R_{ISS} = Dosemeter dose equivalent response for ISS

But, unwanted charged particles are also recorded by the PADC dosemeter – these need to be removed

$$H = \frac{N - N_{CP} - \overline{B}}{R_{ISS}}$$

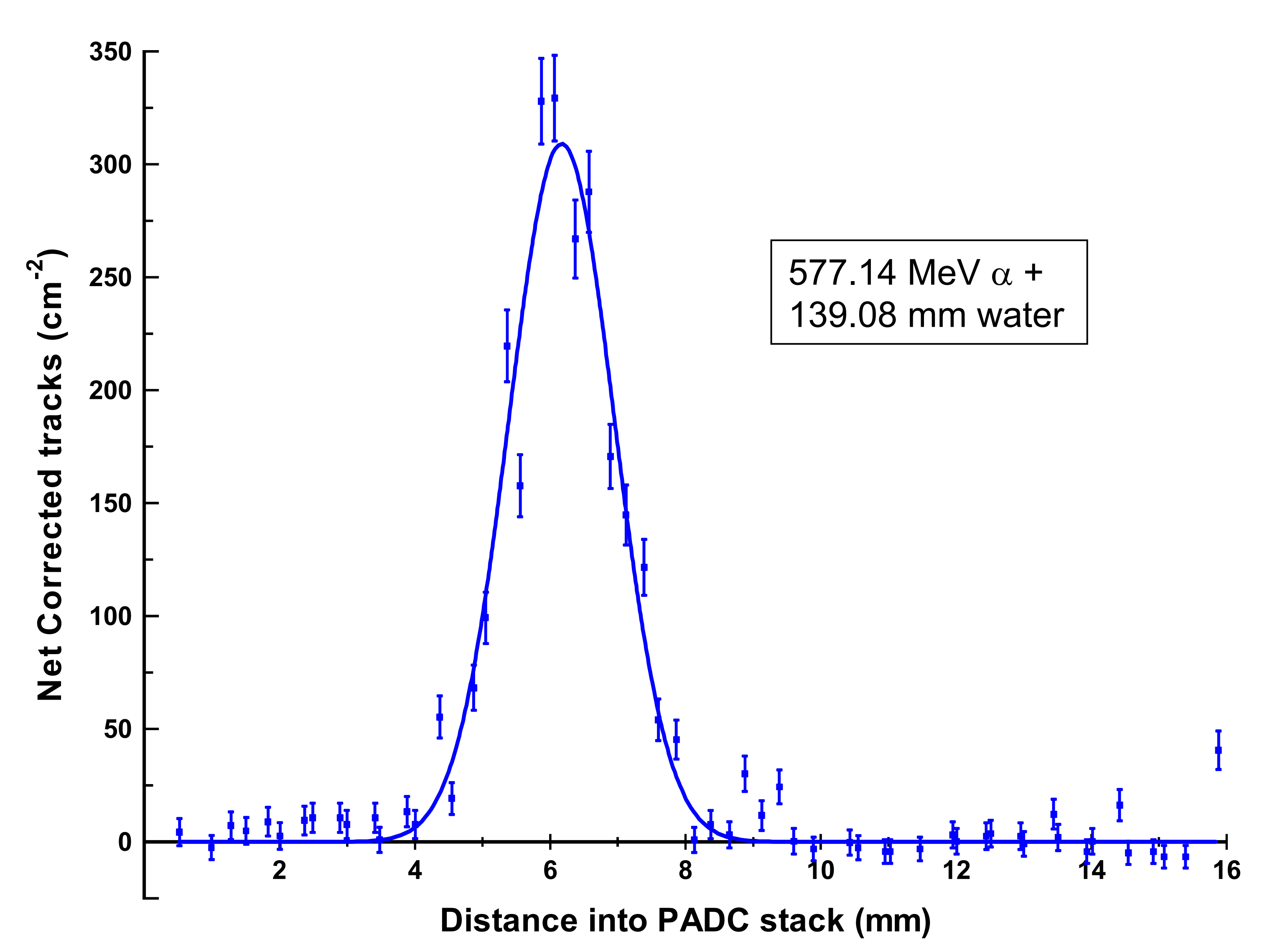
N_{CP} = Tracks from charged particles

HIMAC irradiation of PADC stacks

	Water equivalent thickness of PMMA	PADC stack
^{4}He 577.14 MeV	139.08 mm	
^{12}C 4581.9 MeV	220.37 mm	
^{56}Fe 23.331 GeV	56.70 mm	

HIMAC ^{4}He: 577.14 MeV

+ 139.08 mm water equiv PMMA



Assessed LET thresholds in PADC

Ion	Angle	Etchable track length, R_{crit} (μm)	Energy, E (MeV)	LET_{∞} PADC (keV/μm)	LET_{∞} water (keV/μm)	#LET_{200} PADC (keV/μm)
^{4}He	0°	130	12.8	**(58)**	47	33
	40°	37 (8)$	5.8 (0.8)$	105 (11)$	83 (8)$	60 (6)$
	50°	33 (15)$	5.3 (1.7)$	118 (27)$	93 (21)$	68 (16)$
	60°	29 (19)$	4.6 (2.3)$	141 (50)$	112 (40)$	82 (30)$
	70°	24 (14)$	4.1 (1.8)$	146 (45)$	116 (36)$	85 (27)$
^{12}C	0°	2.886 mm	403.6	77	62	44
^{56}Fe	0°	> 3 m	-	-	-	-
^{20}Ne	0°	-	6020	**(44)**	35	25

$ 1 standard uncertainty

Using: $\log(LET_{\infty}\ \text{water}) = 0.1689 + 0.984\log(LET_{200}\ \text{CR-39})$

Incident Proton spectra at ISS orbit