The NPS Calorimeter & Experiment Requirements

T. Horn & H. Mkrtchyan

(for NPS collaboration)

NPS Collaboration Meeting, Jlab, 1-2 February, 2021

Overview Scientific Program

- Approved experiments to date

NPS ERR 2019

Run group 1

- E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
- E12-13-007: Measurement of Semi-inclusive π^0 production as Validation of Factorization
- E12-06-114 – DVCS – days moved from Hall A

Run group 2

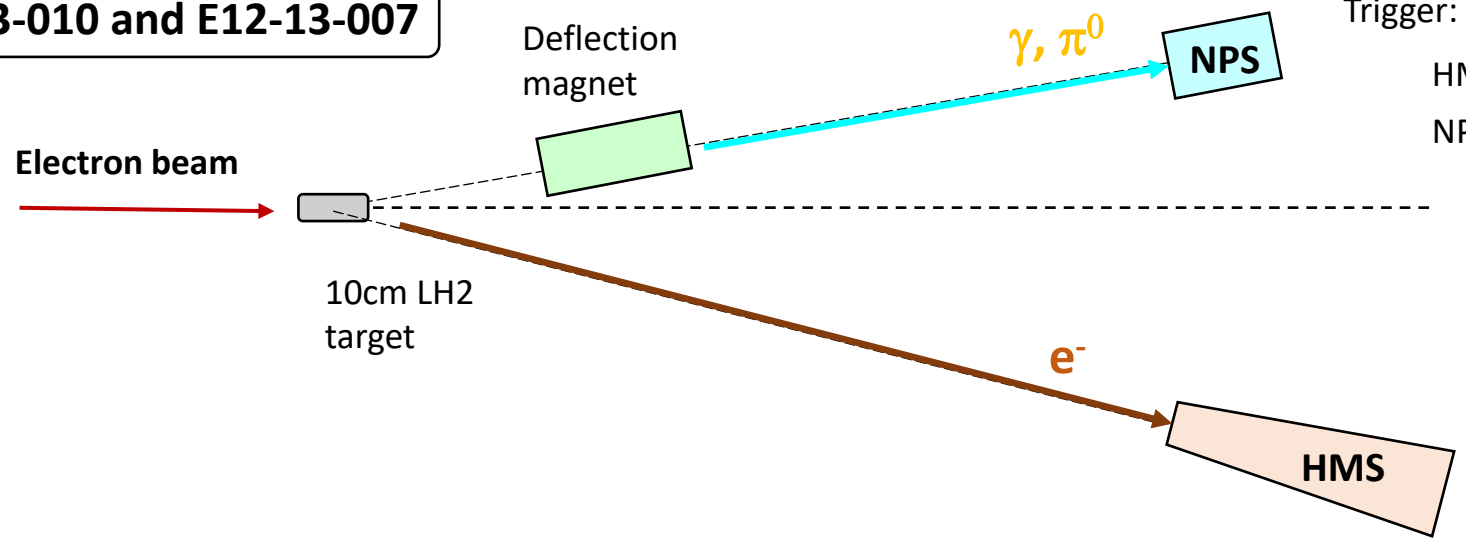
- E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
- E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons

- E12-17-008 – Polarization Observables in Wide-Angle Compton Scattering

- Conditionally approved experiments: TCS with transverse target

Experimental Techniques

E12-13-010 and E12-13-007

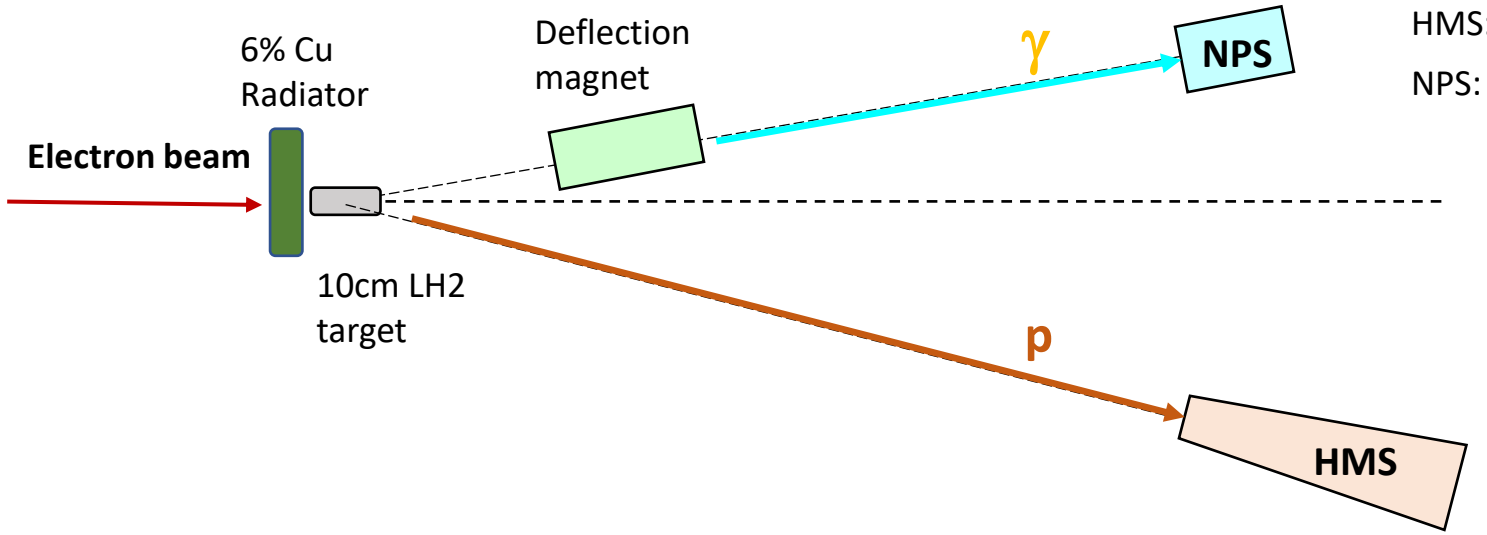


Trigger: HMS, HMS+NPS

HMS: 1 MHz (max)

NPS: 86 MHz (max)

E12-14-003 and E12-14-005



Trigger: HMS

HMS: ~47 kHz (max)

NPS: ~1MHz (max)

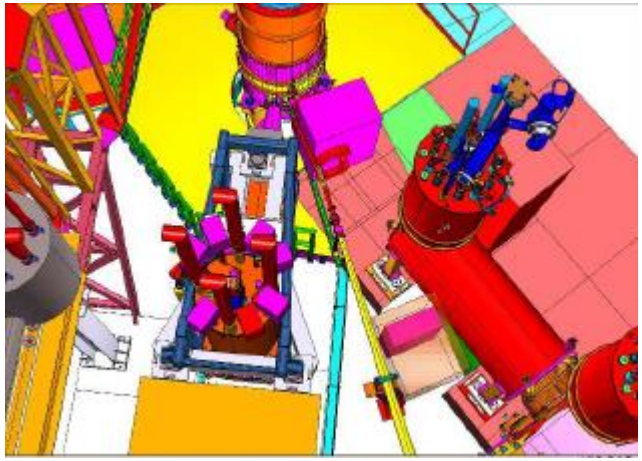
Semi-Inclusive π^o Production kinematics

E12-13-007, Measurement of Semi-Inclusive π^0 Production as Validation of Factorization. (25 days, PAC40 approved, A- rating). **$e + p \rightarrow e' + \pi^o + X$**

Spokespersons: R. Ent, T. Horn, E. Kinney, H. Mkrtchyan, V. Tadevosyan

HMS + NPS

Kinematics	E (GeV)	E' (GeV)	θ_e (deg)	ε	Q^2 (GeV^2)	W (GeV)	θ_γ (deg)	q_γ (GeV/c)	$\pi^o - eff$ (%)	z	k-counts/h expected	k-counts/h detected
A	11.0	5.67	10.27	0.20	2.00	2.98	10.57	5.513	1.0	0.30	26.11	0.261
									9.3	0.40	29.89	2.780
									19.9	0.50	30.37	6.109
									29.5	0.60	27.23	8.033
									38.0	0.70	21.15	8.037
									45.4	0.80	12.37	5.616
B	11.0	6.56	11.70	0.36	3.00	2.49	16.21	4.767	0.0	0.30	10.87	0.054
									3.0	0.40	12.66	0.380
									11.1	0.50	13.06	1.450
									19.9	0.60	11.83	2.354
									28.0	0.70	9.30	2.604
									35.3	0.80	5.99	2.114
C	11.0	5.08	15.38	0.36	4.00	2.83	12.44	6.250	3.0	0.30	3.92	0.118
									14.1	0.40	4.45	0.627
									25.5	0.50	4.46	1.137
									35.3	0.60	3.93	1.387
									43.8	0.70	3.00	1.314
									51.1	0.80	1.86	0.950
D	11.0	2.86	24.14	0.36	5.50	3.26	7.93	8.472	15.6	0.30	0.68	0.106
									30.6	0.40	0.73	0.223
									42.7	0.50	0.70	0.299
									52.8	0.60	0.58	0.306
									61.0	0.70	0.42	0.256
									68.2	0.80	0.25	0.171
E	11.0	5.88	15.65	0.50	4.80	2.38	16.57	5.565	0.5	0.30	2.10	0.011
									7.7	0.40	2.45	0.189
									17.9	0.50	2.47	0.442
									27.3	0.60	2.21	0.603
									35.7	0.70	1.71	0.610
									43.0	0.80	1.08	0.464
F	11.0	5.67	17.84	0.60	6.00	2.21	17.23	5.865	1.0	0.30	0.75	0.008
									9.3	0.40	0.86	0.080
									20.0	0.50	0.87	0.174
									29.6	0.60	0.77	0.228
									38.0	0.70	0.59	0.224
									45.4	0.80	0.37	0.168



- Beam: E = 11 GeV, I ≈ 1-2 μA electron
- Target: 10 cm LH2
- Rate per crystal: 1-2 MHz
- Luminosity: ~1.0×10^{36} /cm^2/s
- Calorimeter minimum angle: ~8.0^o
- Calorimeter minimum distance: 4m
- Total dose: ~30-40 krad

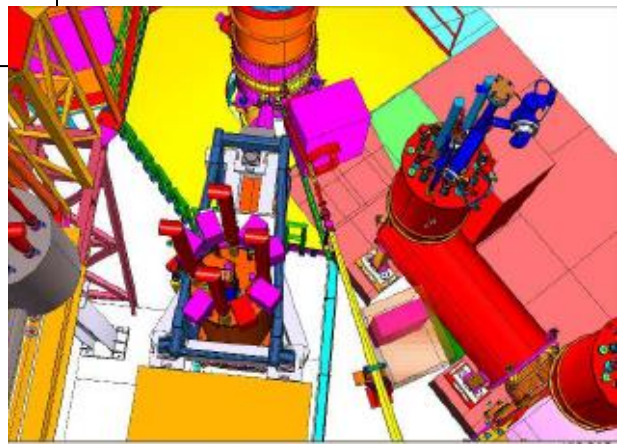
DVCS and π^o kinematics

E12-13-010, Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C. (53 days, PAC40 approved, A rating). ***Spokespersons: C. Munoz-Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche***

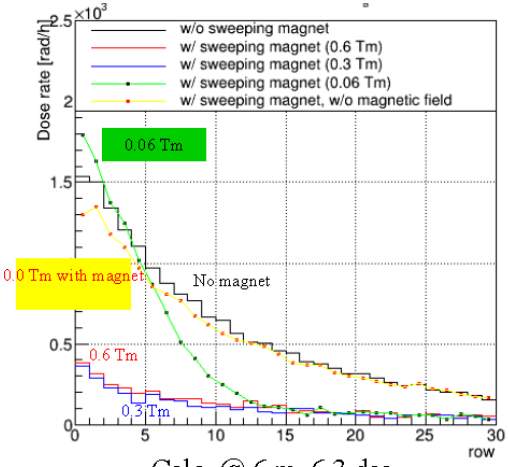
e+p→e+p+γ

- Beam: E = 8.8 & 11 GeV, I ≈ 10-50 μA electron
- Target: 10 cm LH2
- Rate per crystal: 1-2 MHz
- Luminosity: ~3.0×10^{37} /cm²/s
- Calorimeter minimum angle: ~6.3º
- Calorimeter minimum distance: 3 m
- Total dose: 300-400 krad

HMS + NPS



PMT gain 10^5, anode current ~1.3 mA
(Ho San KO, NPS meeting, 07 May 2020)



Calo. @ 6 m, 6.3 deg
(low-xB 11uA)

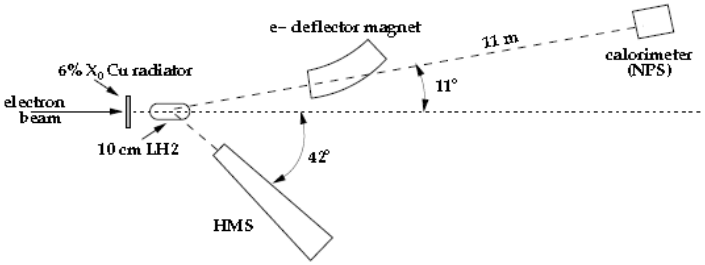
	Energy Dependence at fixed (Q^2, x_B)												Low-x_B				High-Q^2		
x_B	0.36					0.50			0.60				0.2				0.36	0.50	0.60
Q^2 (GeV)^2	3.0			4.0		3.4	4.8		5.1			6.0	2.0			3.0	5.5	8.1	10
k (GeV)	6.6*	8.8	11	8.8*	11	8.8	11	11	6.6	8.8*	11	11	6.6	8.8	11	11	11		
k' (GeV)	2.2	4.4	6.6	2.9	5.1	5.2	7.4	5.9	2.1	4.3	6.5	5.7	1.3	3.5	5.7	3.0	2.9	2.4	2.1
θ_{Calo} (deg)	11.7	14.7	16.2	10.3	12.4	20.2	21.7	16.6	13.8	17.8	19.8	17.2	6.3	9.2	10.6	6.3	7.9	8.0	8.0
D_{Calo} (m)	3	3	3	4	3	3	3	3	3	3	3	3	6	4	4	6	4	4	4
I_{beam} (μA)	28	28	28	50	28	28	28	28	28	28	28	28	11	5	50	11	50	50	50
N_{evt} (10^5)	1.5	8.8	8.2	2.1	7.9	7.3	11	5.1	0.2	0.2	2.7	2.6	3.5	3.6	64	3.4	6.1	0.8	0.4
$\sigma_{M_X^2}$ (GeV^2)	0.13	0.13	0.12	0.15	0.15	0.09	0.09	0.11	0.09	0.09	0.09	0.09	0.17	0.17	0.17	0.22	0.19	0.15	0.13
Days	1	2	1	1	3	3	2	5	5	1	5	10	1	1	1	1	5	5	12

Wide-Angle Compton Scattering kinematics

E12-14-003, Wide-angle Compton Scattering at 8 and 10 GeV photon energies. (18 days, PAC42 approved, A- rating).
Spokespersons: B. Wojtsekhowski, D. Hamilton, S. Sirca

γ+p→γ+p

HMS + NPS



- Beam: E = 8.8 & 11 GeV, I ≈ 60 μA electron
- Radiator: 6% Cu (E_γ= 5-10 GeV)
- Target: 10 cm LH2
- Rate per crystal: ~1.0 MHz
- Luminosity: 1.58×10^{38} /cm²/s
- Calorimeter minimum angle: ~11.0º
- Calorimeter minimum distance: 3.3 m
- Total dose: ~150 krad

Table 2: Kinematics variables for WACS in five settings with a 4-pass, 8.8 GeV electron beam (4A–4E) and five settings with a 5-pass, 11 GeV electron beam (5A–5E).

Kin	E_{in} [GeV]	θ_γ [°]	E_γ [GeV]	θ_p [°]	p_p [GeV/c]	θ^{cm} [°]	s [GeV²]	$-t$ [GeV²]	$-u$ [GeV²]
4A	8	14.2	6.347	40.1	2.416	55.8	15.89	3.10	11.03
4B	8	17.9	5.663	33.7	3.138	67.6	15.89	4.39	9.75
4C	8	22.5	4.851	27.8	3.978	80.4	15.89	5.91	8.22
4D	8	26.9	4.161	23.7	4.684	90.9	15.89	7.20	6.93
4E	8	34.0	3.255	18.9	5.605	104.8	15.89	8.90	5.23
5A	10	11.0	8.362	41.7	2.399	48.9	19.65	3.07	14.81
5B	10	13.8	7.647	35.3	3.154	59.5	19.65	4.41	13.47
5C	10	16.9	6.848	30.0	3.981	70.1	19.65	5.91	11.97
5D	10	19.7	6.158	26.3	4.687	78.7	19.65	7.21	10.68
5E	10	29.9	4.135	17.8	6.739	103.2	19.65	11.01	6.88

Table 3: Calorimeter and deflector magnet distances, deflector magnet field settings, calorimeter hit difference position resolutions, electron deflection at the calorimeter front face and estimates for the ratios $R_{ep\gamma}$, R_{π^0} and $R_{RCS} \equiv N_{RCS}/N_{tot}$.

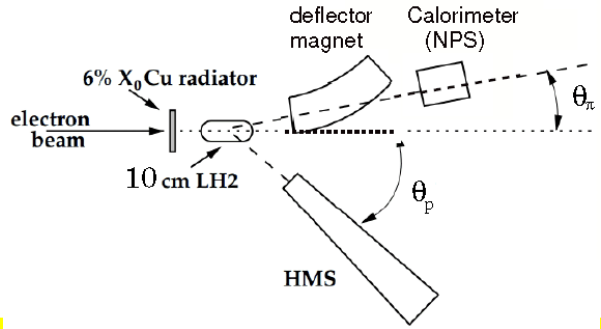
Kin	D_{calo} [m]	D_{mag} [m]	B [T]	$\int B\cdot dl$ [Tm]	σ_x [cm]	σ_y [cm]	Δy_e [cm]	$R_{ep\gamma}$	R_{π^0}	R_{RCS}
4A	9.0	2.45	0.75	0.3	2.93	0.73	9.02	0.61	0.12	0.27
4B	7.0	1.65	1.00	0.4	2.21	0.75	10.74	0.37	0.33	0.30
4C	5.0	1.65	1.25	0.5	1.61	0.71	9.55	0.18	0.60	0.22
4D	3.5	1.10	1.50	0.6	1.36	0.79	9.24	0.08	0.76	0.16
4E	3.0	1.10	1.50	0.6	1.21	0.86	8.72	0.03	0.89	0.08
5A	11.0	2.45	0.625	0.25	3.42	0.70	7.53	0.78	0.05	0.17
5B	9.0	2.45	0.875	0.35	2.63	0.71	8.71	0.64	0.15	0.21
5C	7.5	1.65	1.00	0.4	2.30	0.77	9.75	0.38	0.39	0.23
5D	6.0	1.65	1.25	0.5	2.18	0.79	9.91	0.34	0.49	0.17
5E	3.25	1.10	1.50	0.6	1.26	0.92	8.07	0.03	0.90	0.07

Wide-Angle Exclusive π^o kinematics

E12-14-005, Wide Angle, Exclusive Photoproduction of π^0 Mesons. (18 days, PAC42 approved, B rating). $\gamma + p \rightarrow \pi^o + p$

Spokespersons: D. Dutta, M. Amaryan, H. Gao, M. Kunkel, S. Sirica, I. Strakovski

HMS + NPS



- Beam: E = 11 GeV, I ≈ 60 μA electron
- Radiator: 6% Cu (E_γ= 5-10 GeV)
- Target: 10 cm LH2
- Rate per crystal: 1.2 MHz
- Luminosity: 1.6×10^{38} /cm²/s
- Calorimeter minimum angle: ~8.0º
- Calorimeter minimum distance: 3 m
- Dose rate: 840 rad/h (for kin 4D)
- Total dose: ~150 kRad

TABLE I. Table of kinematics for the $p(\gamma,\pi^0 p)$ reaction at E_{beam} of 11.0 at pion c.m. angle of 90° and 6.6 GeV at pion c.m. angle of 70, 90 and 105°. These settings are in addition to the setting used in the WACS proposal.

	E_γ	$\theta^*_{\pi^o}$	$\sqrt{s}$	$\lvert t\rvert$	θ_p (lab)	θ_{π^o} (lab)	P_p	P_{π^o}
3A	6.0	70	3.48	3.44	35.6	21.2	2.602	4.170
3B	6.0	90	3.48	5.21	26.7	30.1	3.595	3.218
3C	6.0	105	3.48	6.98	21.1	38.5	4.334	2.50
3D	5.0	70	3.20	3.14	37.6	23.1	2.251	3.497
3E	5.0	90	3.20	4.81	28.3	32.5	3.079	2.716
3F	5.0	105	3.20	5.32	22.5	41.6	3.691	2.125
5F	10.0	90	4.43	8.01	22.1	23.9	5.632	5.227

TABLE II. Table of parameters for the experimental setup for the E_{beam} = 8.8 and 11 GeV settings where the π^0 cross section will be extracted. These are reproduced from the WACS proposal, except for the additional setting 5F to cover the 90° c.m. angle at the highest photon energy.

Label	D_{NPS}	D_{mag}	B	σ_x	σ_y	e-defl	$N_{qp\gamma}/N_{\pi^o}$	$N_{\pi^o\pi^o}/N_{\pi^o}$	N_γ/N_{π^o}	N_{RCS}/N_{π^o}
	(m)	(m)	(T)	(cm)	(cm)	(cm)				
4B	7.0	1.65	1.00	2.21	0.75	10.74	1.12	0.022	0.006	0.90
4C	5.0	1.65	1.25	1.61	0.71	9.55	0.29	0.013	0.004	0.37
4D	3.5	1.10	1.50	1.36	0.79	9.24	0.11	0.021	0.004	0.21
4E	3.0	1.10	1.50	1.21	0.86	8.72	0.03	0.022	0.006	0.1
5B	9.0	2.45	0.875	2.63	0.71	8.71	4.13	0.012	0.012	1.39
5C	7.0	1.65	1.00	2.30	0.77	9.75	0.97	0.012	0.004	0.56
5D	6.0	1.65	1.25	2.13	0.79	9.91	0.69	0.012	0.003	0.36
5E	3.25	1.10	1.50	1.26	0.92	8.07	0.03	0.017	0.006	0.09
5F	5.0	1.10	1.50	2.16	0.82	9.57	0.43	0.015	0.006	0.22

Polarized Wide-Angle Compton Scattering kinematics

E12-17-008, Polarization Observables in Wide-angle Compton Scattering at large s, t and u. (48 days, PAC45 approved, A-rating). ***Spokespersons: D. Hamilton, D. Day, D. Keller, G. Niculescu, B. Wojtsekhowski, J. Zhang***

$\gamma + p \rightarrow \gamma + p$

BigBite + NPS

- Beam: Polarized (~80%) electron, E = 8 & 11 GeV, I ≈ 2.5 μA
- Radiator: 10% Cu (N_γ ~1.5×10^{12} /s)
- Target: 3 cm polarized (~75%) NH3
- Rate per crystal: 50 kHz
- Luminosity: 2.5×10^{35} /cm²/s
- Calorimeter minimum angle: ~17.4º
- Calorimeter minimum distance: 1 m
- Total dose: ~10 krad

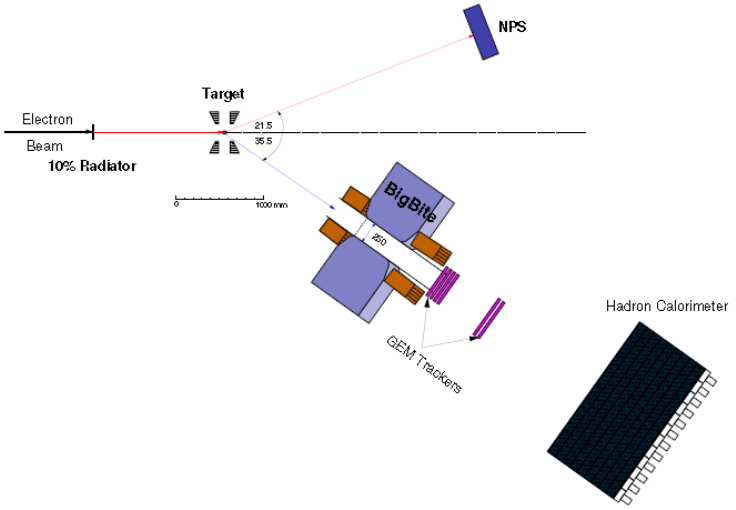


Table 2: Kinematics variables for WACS in four settings with a longitudinally polarized target (L1–L4) and two settings with a transversely polarized target (S1 and S4).

Kin	E_{Beam} [GeV]	P_{Target}	E_{in} [GeV]	θ_γ [º]	E_γ [GeV]	D_{NPS} [m]	θ_p [º]	p_p [GeV/c]	D_{BB} [m]	θ^{cm} [º]
L1	8.8	L	6.0	21.5	4.16	3.0	35.5	2.62	1.5	70.0
S1	8.8	T	6.0	21.5	4.16	3.0	35.5	2.62	1.5	70.0
L2	11.0	L	9.5	17.4	6.49	3.0	30.5	3.82	1.5	70.0
L3	8.8	L	6.0	30.2	3.22	3.0	26.5	3.63	2.5	90.0
L4	8.8	L	6.0	42.3	2.25	1.0	19.4	4.55	3.5	110.0
S4	8.8	T	6.0	42.3	2.25	1.0	19.4	4.55	3.5	110.0

Requirements of the experiments

Parameterfor	SIDIS π^o (E12-13-007)	DVCS (E12-13-010)	WACS (E12-14-003)	DES π^0 (E12-14-005)	WACS (NH3) (E12-17-008)
Min. dist. From. Tgt. (m)	3.0-4.0	3.0-6.0	3.0-5.0	4.0	1.0-3.0
Coordinate res. (mm)	2-3	3-4	3-4	2-3	~3
Photon angl. Res. (mrad)	0.5-0.75	1-2	1-2	0.5-0.75	~1.0
Energy res. (%)	(2-3)/√E	(5-6)/√E	~5/√E	(2-3)/√E	< 3/√E
Sweeping magnet (Tm)	0.3	0.3	0.6	0.6	?
Second arm	HMS	HMS	HMS	HMS	BigBite
Photon angle (degrees)	8.0-23.0	6.0-22.0	22-60	10-25	17.4-42.3
Photon energies (GeV)	0.5-5.7	1.3-7.4	1.1-3.4	3.1-5.7	2.25-6.49
Acceptance (msr)	~25	~25	~25	~25	~25
Beam current (μA)	1-2	~5-50	~60, +6%Cu	60, +6% Cu	2.5
Targets	10cm LH2	10cm LH2	10cm LH2	10cm LH2	3cm pol NH3
Luminosity ($cm^{-2}s^{-1}$)	$\sim 1\times10^{36}$	$\sim 3\times10^{37}$	$\sim 1.6\times10^{38}$	$\sim 1.6\times10^{38}$	$\sim 2.5\times10^{35}$
Rates & Timing	~1 MHz, <100ns	1MHz, <100ns	~1 MHz, <100ns	~1 MHz, <100ns	~50 kHz <100ns
Beam Time (hours)	~600	1200	~440	~440	1100
Expected total rad. Dose (Krad)	~30-40	~300-400	~150	~150	~10

- **Energy resolution - (2-3)%/√E, high light yield, PbWO4 is the best, cost effective available crystal**
- **Coordinate resolution - 2--3 mm, granularity 2.05×2.05 cm^2, small Møller radius**
- **Angular resolution - 0.5-2.0 mrad, combine fine granularity with distance from the target**
- **Good Timing - Fast signal with short tail to minimize pile-up at high rates**
- **Radiation hardness - Modest damage for total doses ~50 krad (significant damage for doses 1.0-1.5 Mrad)**

Thanks !

NPS Science Motivation

A Neutral Particle Spectrometer (NPS) is required to carry out the JLab 12 GeV Hall C program of precision cross section measurements and L/T separations, extending the charged-particle (p, $\pi^{+/-}$, $K^{+/-}$) measurements to neutral particles (γ and π^0). It will open new opportunities in Hall C, utilizing the HMS, SHMS or BigBite spectrometers

Proposals benefitting from the NPS facility, so far:

- E12-13-007, Measurement of Semi-Inclusive π^0 Production as Validation of Factorization. (25 days, PAC40 approved, A- rating, running with E12-13-010).

- E12-13-010, Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C. (53 days, PAC40 approved, A rating).

- E12-14-003, Wide-Angle Compton Scattering at 8 and 10 GeV photon energies. (18 days, PAC42 approved, A rating).

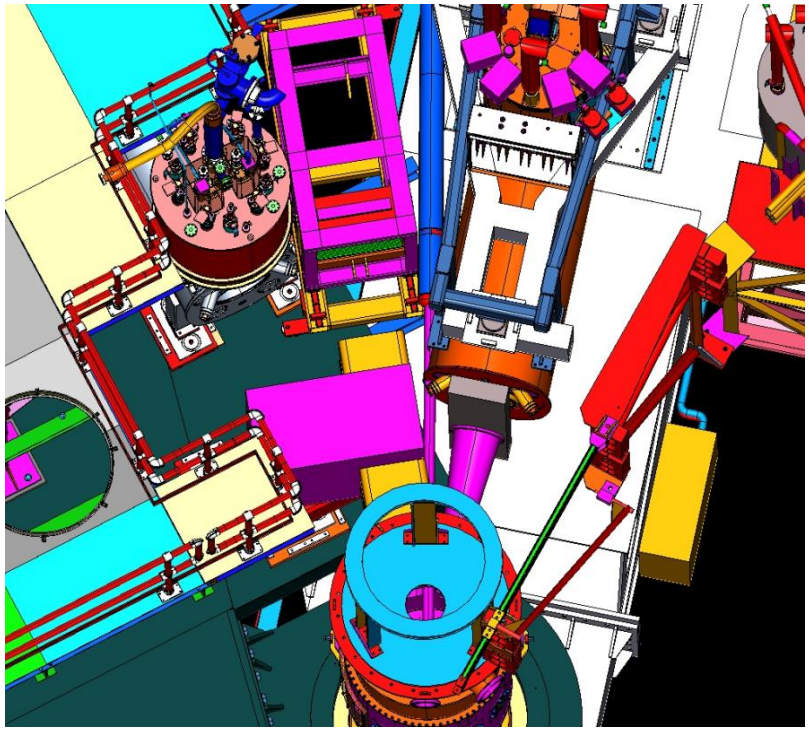
- E12-14-005, Wide Angle, Exclusive Photoproduction of π^0 Mesons. (18 days, PAC42 approved, B rating).

- E12-17-008. Polarization Observables in Wide-Angle Compton Scattering at large s, t and u. (46 days, PAC45 approved, A- rating).

NPS Facility

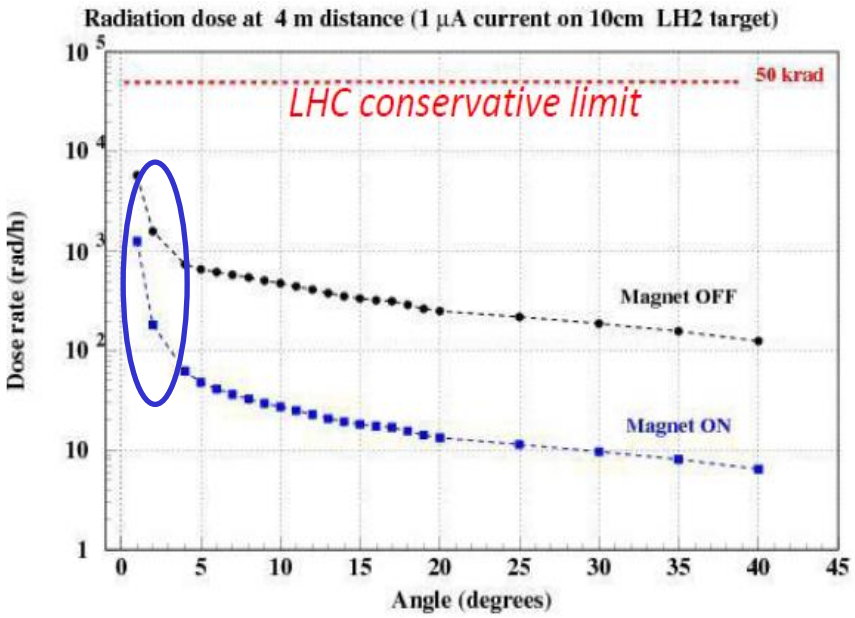
The NPS is an efficient and economical way to meet all of the presently known experimental requirements. It will consist of the following components:

- Solid angle ~25 msr at distance 4 m
- ~1200 $PbWO_4$ crystals, each $2.05 \times 2.05 \times 20$ cm^3
- Temperature controlled frame (18 ± 0.1 °C)
- HV distribution bases (without amplifiers ?) for operation in a high-rate environments with reduced number dynodes
- Essentially dead-time-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs (fADC)
- Sweeping magnet of ~0.3-0.6 Tm field strength
- Cantelevered platforms to allow for precise, remote rotation in the range 5.5°-30° (on the SHMS carriage), and between 25° and 60° range
- A light monitoring (and curing) system to monitor (and restore) crystal optical properties
- Energy resolution ~(2-3)%/√E
- Position resolution ~2-3 mm



Radiation conditions in Hall C

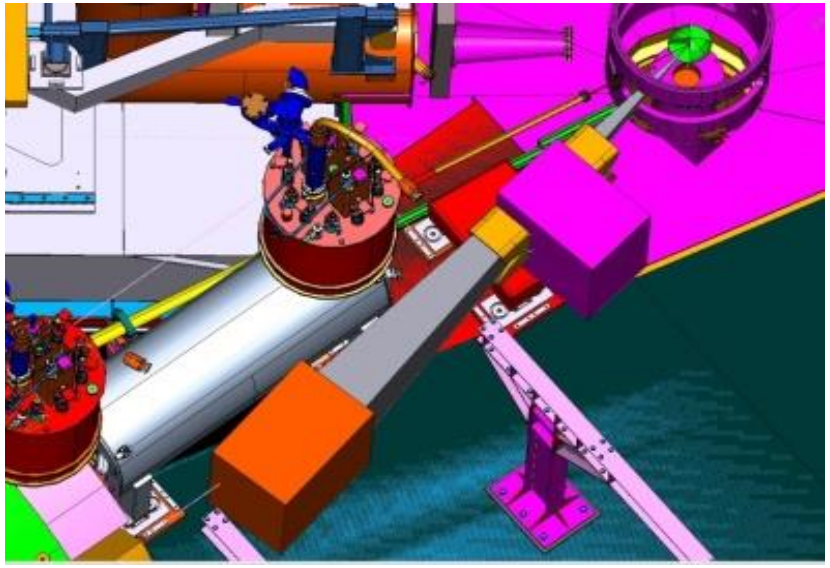
The damage to crystals is a limiting factor for beam current !



Expected dose rate versus angle

(Based on P. Degtiarenko's simulations.)

- **The radiation background is strongly angular (and energy) dependent.**
- **The magnet will sweep off most of the charged background below 300 MeV.**
- **Remaining low energy photon flux is capable to damage crystals (darkening, mostly in the first few cm).**



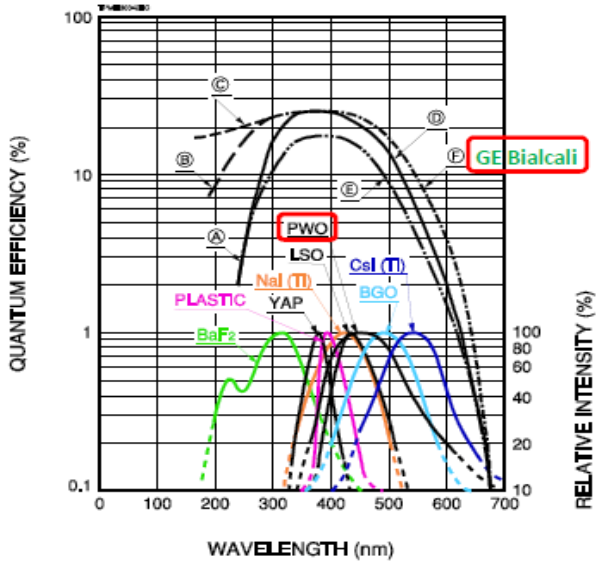
- **NPS calorimeter will be operated in open geometry, prone to radiation damage.**
- **Degradation of the crystal properties depends on dose rate, accumulated dose and type of the radiation particles.**

- **How often curing of the crystals are needed ? What are the best and suitable methods for curing in our experiments ? These are main questions to finalize before we can start experiments with NPS.**

Choice of PMT and $PbWO_4$

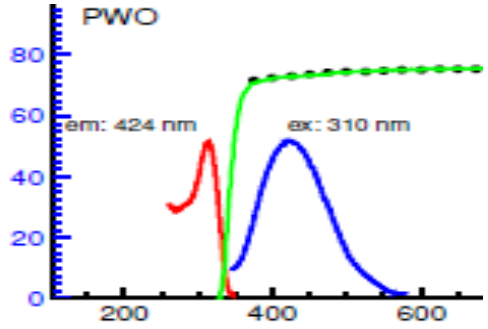
Hamamatsu R4125 PMT

Parameter	Value
diameter	18.6 mm (3/4'')
No. of stages	10
Photocathode	Bialkali, Green Ext.
Sensitivity range	300 – 650 nm
QE_{MAX} at ~400nm	27 %
Supply voltage	1500 V
Gain	8.7×10^5
Dark Current	10 nA
Rise Time	2.5 ns
Transit Time	16 ns



PbWO4 crystal

Property	Value
Density (g/cm^3)	8.3
Radiation length (cm)	0.89
Moliere radius (cm)	2.00
Interaction length (cm)	20.7
Refractive index (420 nm)	2.20
Hygroscopicity	No
Luminescence (nm), slow and fast components	425, 420
Decay time (ns) slow and fast components	30, 10
Light yield (% of NaI) slow and fast components	0.30, 0.077
dLY/dT (%/C) at room temp.	-2.5



Emission spectrum (blue) is in the transparent region (green).

General properties of heavy crystals for calorimetry

Parameter	Lead Tungsten ($PbWO_4$)	Lead Fluoride (PbF_2)	Bismuth Germanate (BGO)	Luterium-Yttrium (LSO/LYSO)
Density (g/cm^3)	8.28	7.66-7.77	7.13	7.2-7.4
Rad. length (cm)	0.89	0.93-0.95	1.10-1.12	1.16
Refraction index	2.20	1.82	2.15	1.82
Emission peak (nm)	420	~310, ~280	480	420
Moliere radius (cm)	2.19	2.22	2.15	2.07
Radiation type	Scint. (~13% Č)	Pure Čer.	Scint. (~1.6% Č)	Scintillation
Timing property τ (ns, %)	5(73%), 14(23%), 110(4%)	Fast, <30	300	40-50
Effective Z	73	77	83	65
Hydroscopicity	No	No	No	No
Interact. length (cm)	~20.7	~21	~22.7	~20.9
Rad. hardness (krad)	~20-50	~50	~1,000	>1,000
Light yield LY (photon/MeV)	~140-200	~2-6	~5,000-10,000	~5,000-30,000
d(LY)/dT (%/°C)	-2.0-2.5	No	-0.9	-0.2
Critical energy (MeV)	~9.6	8.6-9.0	7.0	9.6

BGO, $PbWO_4$, PbF_2 and LSO/LYSO are among the good candidates

But BGO is too slow and LSO/LYSO are very expensive.

Our choice would be to use $PbWO_4$ or PbF_2, or their combination