Development of NPS for the DVCS experiments in Hall C at Jefferson Lab

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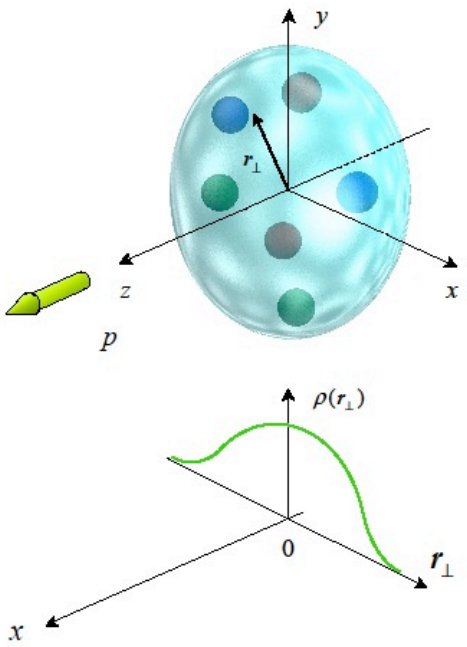
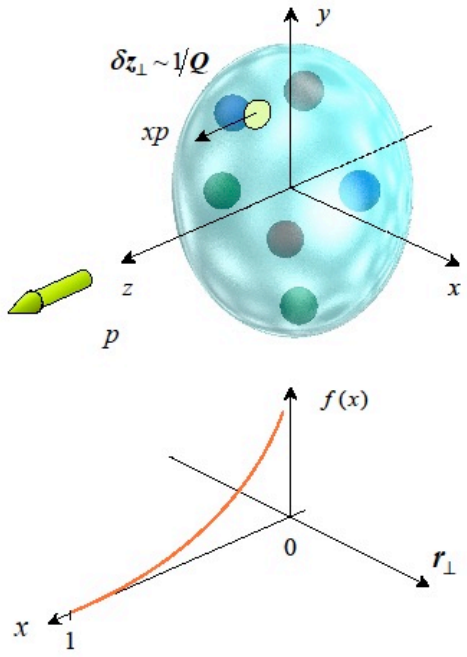
Parallel 1 : Hadronic structure - GPDs

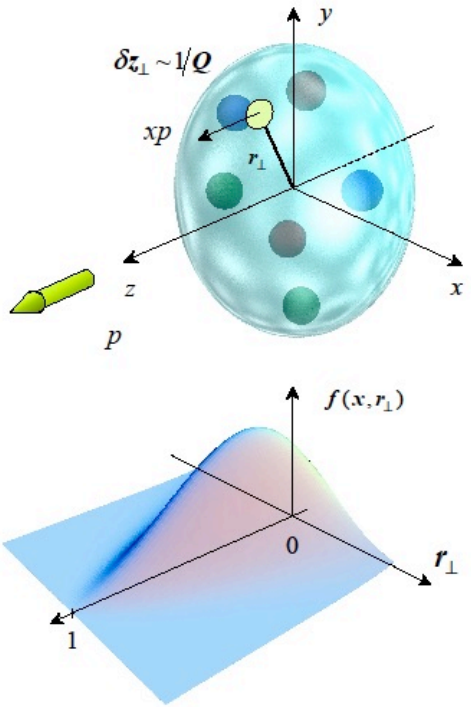
Outline

- Deeply Virtual Compton Scattering(DVCS) for GPDs
- Neutral Particle Spectrometer(NPS) for DVCS experiments in Hall C
- NPS simulations and crystal optical properties measurement

Generalized Parton Distributions







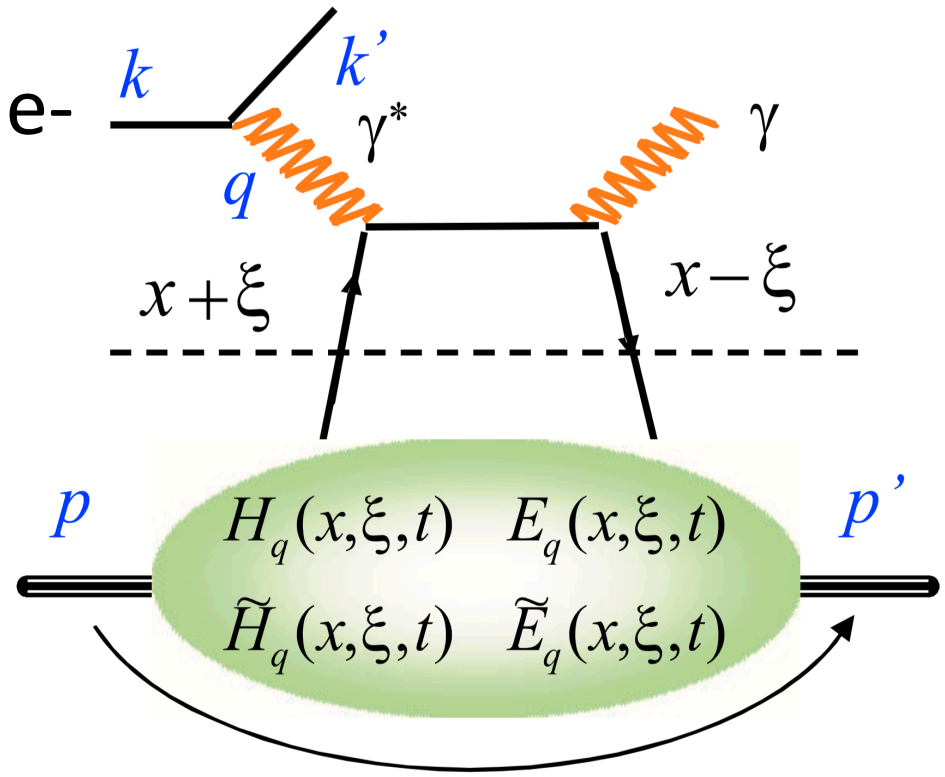
Form Factors:
<u>via elastic scattering</u>
-charge & magnetization spatial distribution

Parton distribution:
<u>via deep inelastic scattering</u>
-Longitudinal momentum & helicity distribution of partons

Generalized Parton Distributions:
<u>via exclusive reactions</u>
-Transverse position distribution and longitudinal momentum of partons

Deeply Virtual Compton Scattering

$$\gamma^* p \rightarrow p' \gamma$$



$$t = (p' - p)^2$$

Hard Part

Soft Part

Bjorken limit

$$Q^2 \rightarrow \infty$$

$$\nu \rightarrow \infty$$

$$x_B = \frac{Q^2}{2M\nu}$$

$$Q^2 = -q^2$$

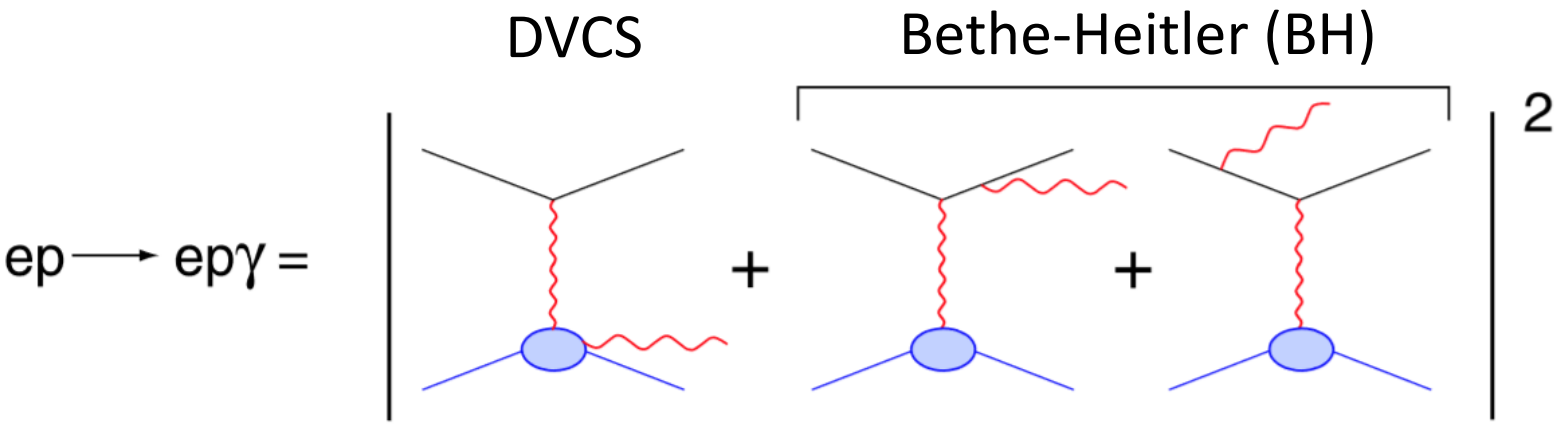
$$\nu = \frac{p \cdot q}{M}$$

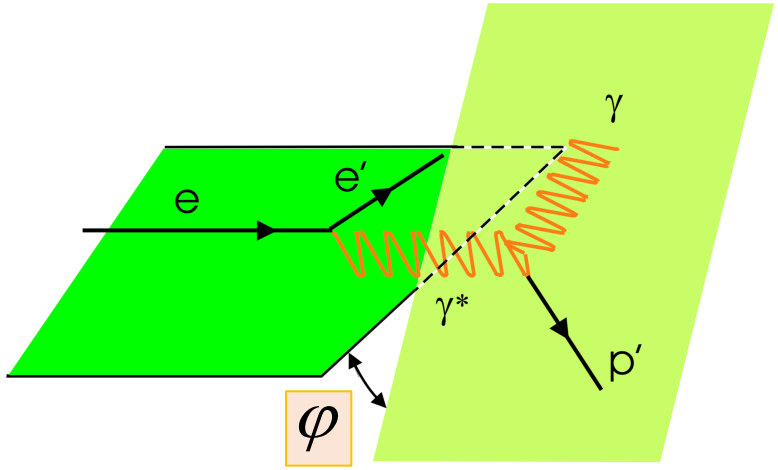
$$\xi \sim \frac{x_B}{2 - x_B}$$

At high Q^2, DVCS amplitudes can be factorized into 2 parts
«Hard Part» : Perturbatively calculable
«Soft Part» : Nucleon structure → Parameterized by GPDs

Deeply Virtual Compton Scattering

<<pictures from thesis of C.Munoz Camacho>>





DVCS process and BH process entangle → Need to separate each term to extract the GPDs

$$\sigma \propto |\mathrm{BH}|^2 + |\mathrm{DVCS}|^2 + \mathit{Interference}$$

Calculable from QED

~ 1

$$\sim \frac{1+\cos\varphi}{P_1(\varphi)P_2(\varphi)}$$

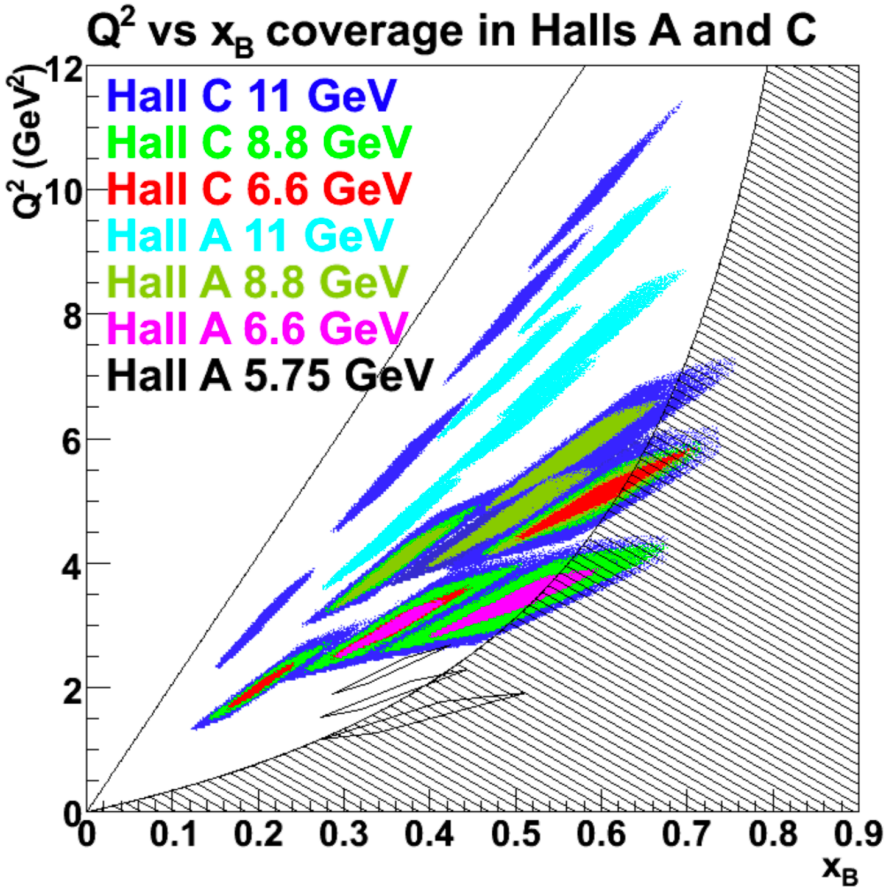
$$I \propto (E_b/\nu)^3$$

$$|\mathrm{DVCS}|^2 \propto (E_b/\nu)^2$$

At fixed Q^2 and $\nu = Q^2/(2Mx_B)$

DVCS experiments in Hall C

Thomas Jefferson National Accelerator Facility(Jefferson Lab), Virginia, USA.
12 GeV continuous electron beam. 4 experimental halls with different setups



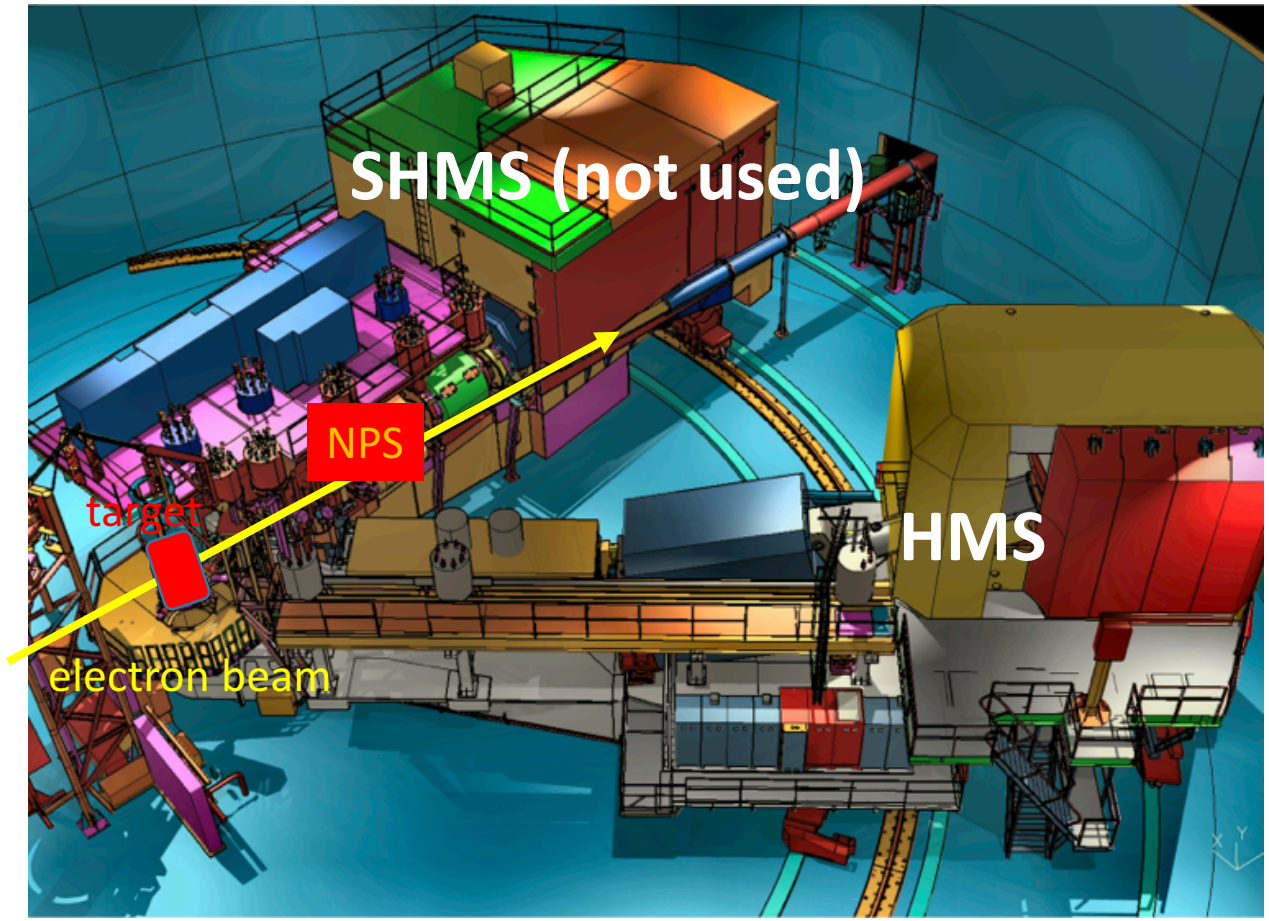
<<Kinematic region accessible by JLab 11GeV beam>>

Need a full kinematic region to better understand the GPDs

- Reach higher Q^2
  : further test the Q^2 dependence of the observables
- Different beam energies
  : separate $|\mathrm{DVCS}|^2$and *Interference* term
- Reach lower value of x_B
  : Cross-check with CLAS, CLAS12 and COMPASS

→Highest precision data in the kinematic domain accessible with an 11GeV beam

Neutron Particle Spectrometer(NPS) in Hall C



$$e\ p \rightarrow e' p' \gamma$$

$$\gamma^{*} p \rightarrow p' \gamma$$

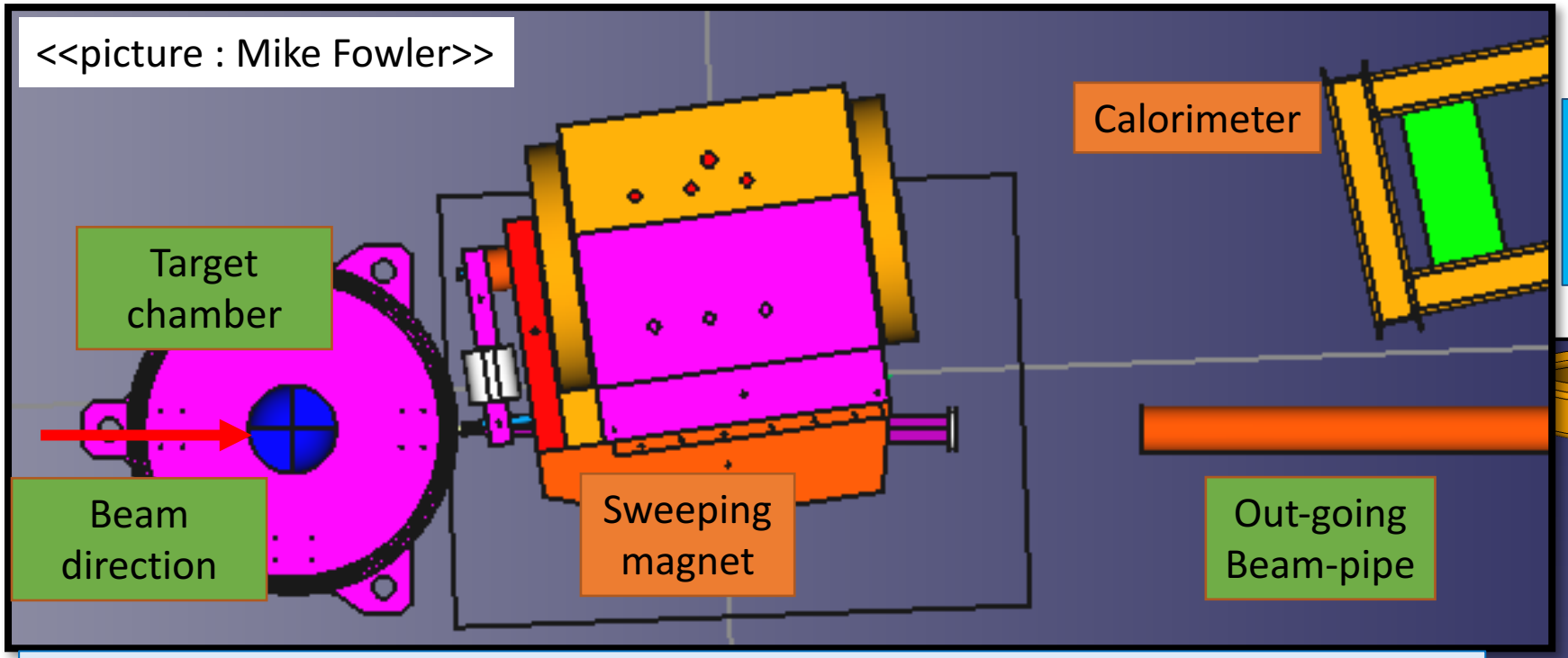
(Exclusive process)

To detect neutral particles (γ , π_0),
NPS will be installed on to the SHMS
SHMS will be used as a cantilever

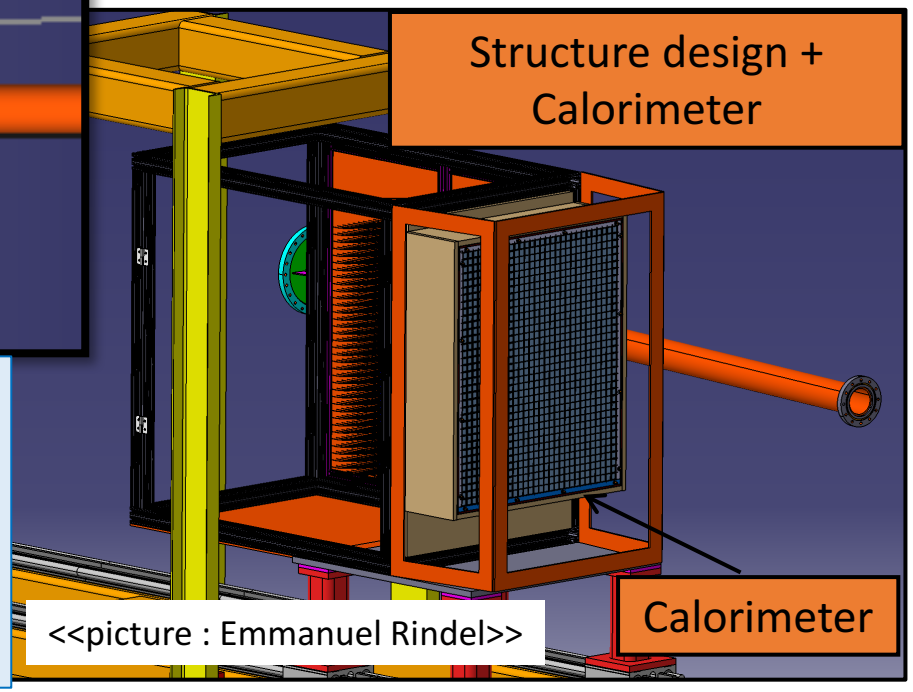
HMS detects scattered electrons
NPS detects neutral particles

HMS : High Momentum Spectrometer
SHMS : Super High Momentum Spectrometer

Neutron Particle Spectrometer(NPS) in Hall C



Calorimeter :
1080 (30X36) $PbWO_4$ blocks
each crystals : 2X2X20 cm3, ~670 gram



Highest luminosity($\sim 10^{38} cm^{-2} s^{-1}$) of DVCS ever before with smallest angle(for the high Q^2 data) possible

- Creates big amount of background to the calorimeter

→ Introduce sweeping magnet to reduce the background

Contributions for the NPS

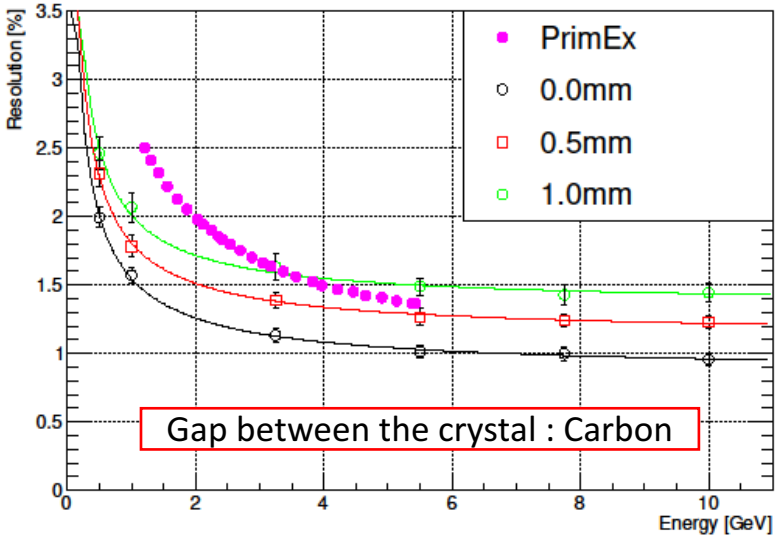
- Geant4 simulation
  - Energy resolution simulation
  - Dose rate calculation
  - Acceptance calculation

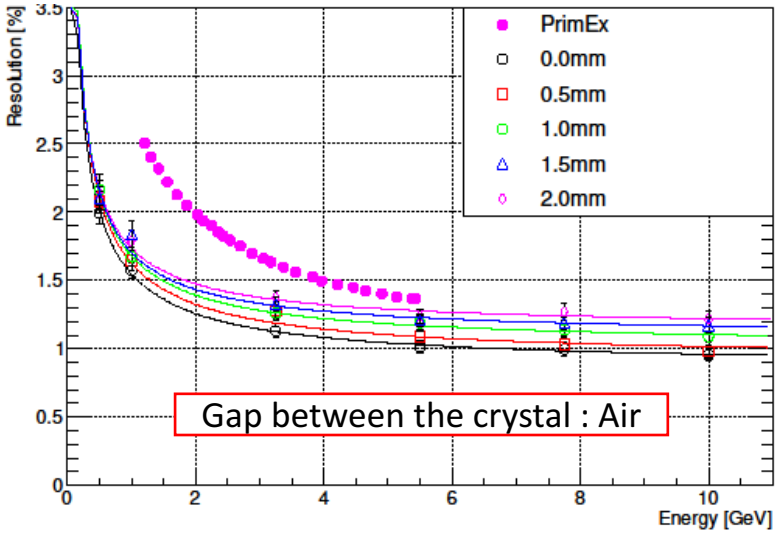
- Optical properties measurement of $PbWO_4$ crystals
  - Radiation hardness measurement
  - Optical bleaching

Geant4 NPS Simulation

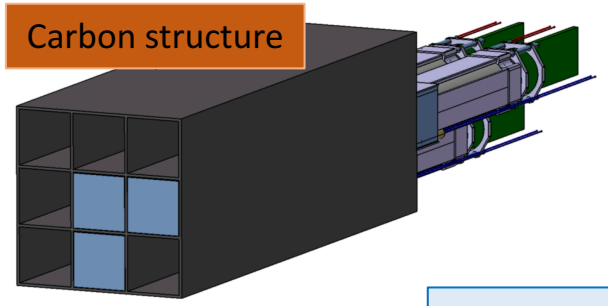
- Energy resolution simulation
  - Decision of the design of the NPS
- Radiation dose rate calculation
  - Estimate dose rate on the NPS to take the radiation damage into account
    - How often we need to cure the crystals
    - What is the maximum luminosity we can tolerate
    - Effect of background on detector resolution
- Precise calculation of the detector acceptance
  - Work in progress

NPS Energy Resolution Simulation



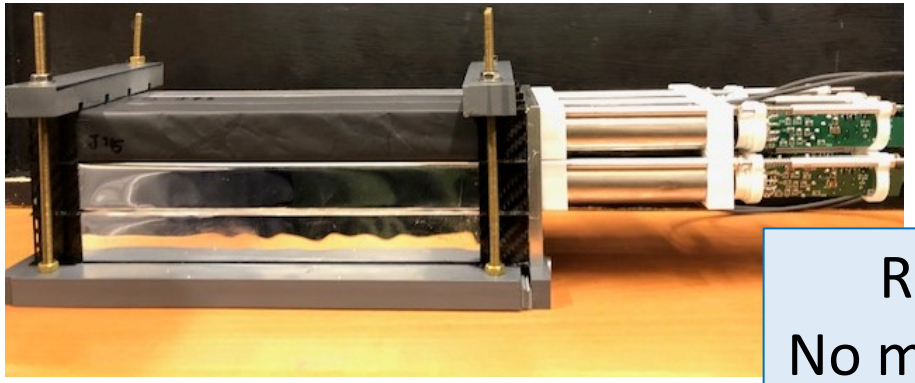


$$\frac{\sigma}{E} = A \oplus \frac{B}{\sqrt{E}} \oplus \frac{C}{E}$$



- Purpose :
  - -NPS is made of 1080 crystals (30X36, stacked)
  - -Need structures for uniform arrays → Better energy resolution
  - -More structure between crystals → Worse energy resolution

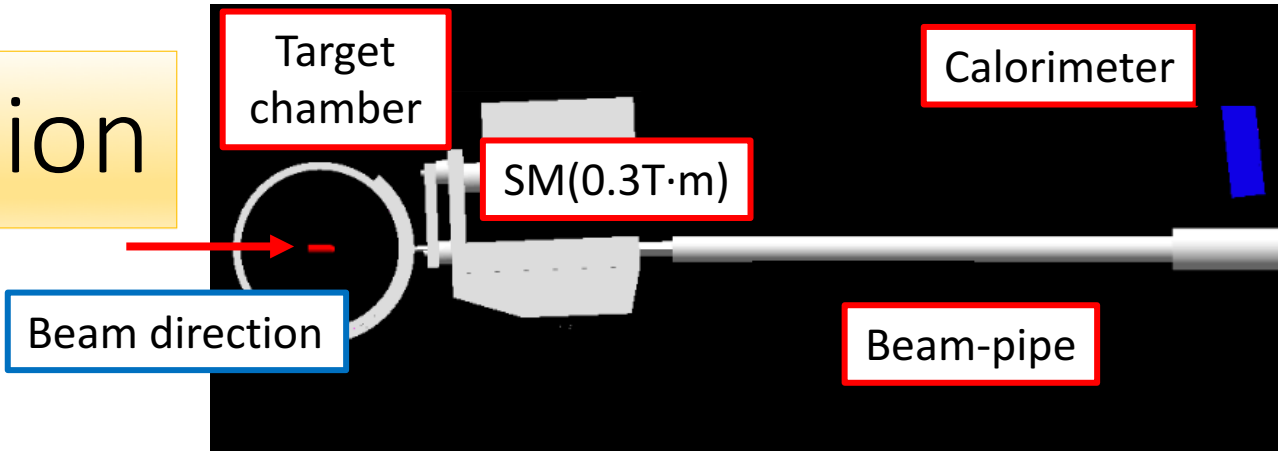
➔Check the dependency of the energy resolution of the NPS on the distance between the crystals(gap)



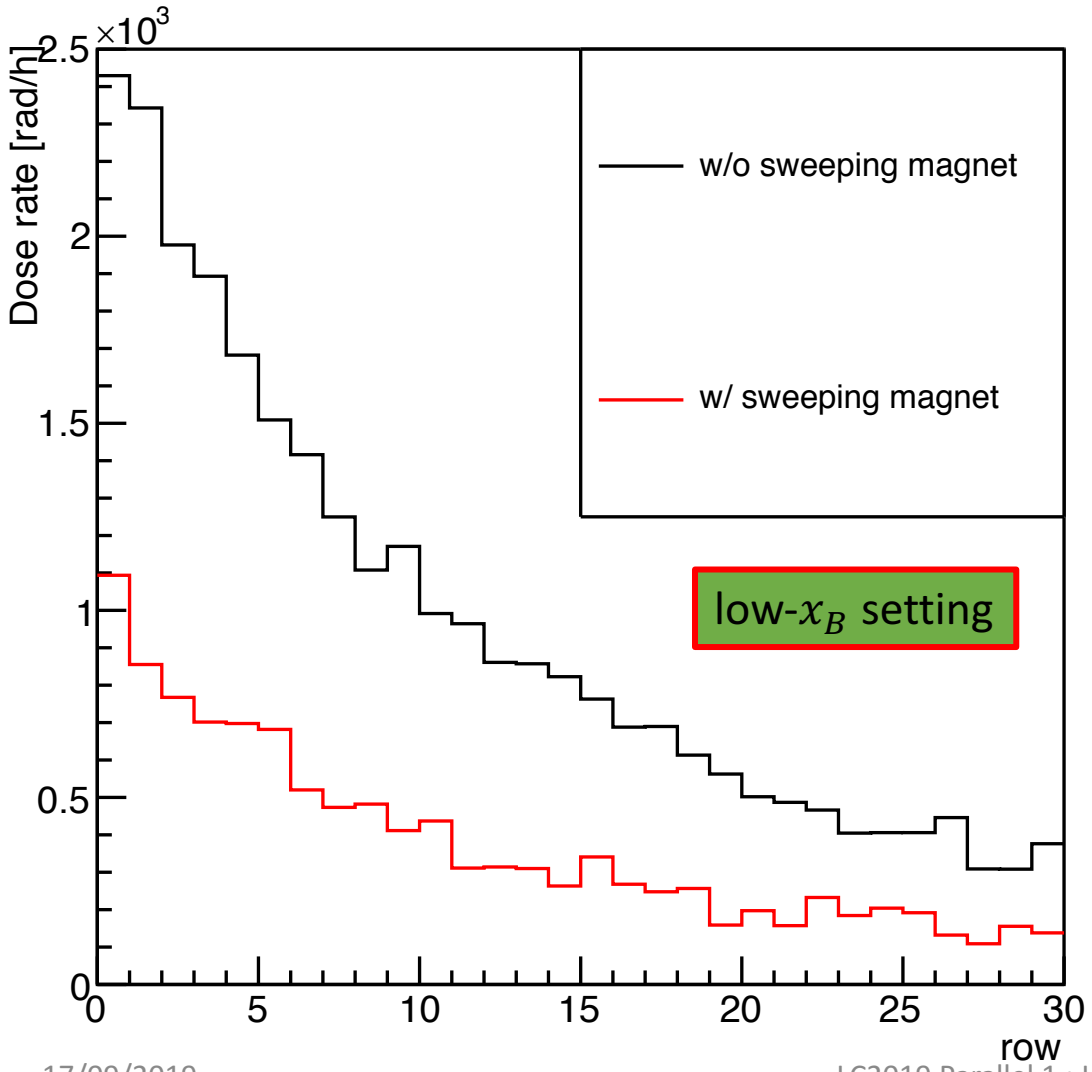
Recent NPS prototype :
No material in the middle part

<<PrimEx also used $PbWO_4$ crystals for the calorimeter>>

NPS Dose Rate Calculation



<<picture : Geant4 simulation>>



11μA beam in 15cm Liquid hydrogen target (approximate luminosity : $\sim 2\times10^{37} cm^{-2} s^{-1}$)
NPS placed 6m away from the target, 6.3°

Sweeping Magnet (SM) :
- Reduces the dose rate a factor of 3 or more
→ Reach smaller angle
→ Tolerate higher luminosity

Geant4 NPS Simulation Conclusions

- Energy resolution simulation
  - Detector structure : 0.5mm carbon material only in the front and the back side, 2cm each of the crystals

- Radiation dose rate calculation
  - Sweeping magnet : reach smaller angle for the high Q^2 and tolerate higher luminosity

- Full package of experimental setup is ready for the NPS acceptance calculation

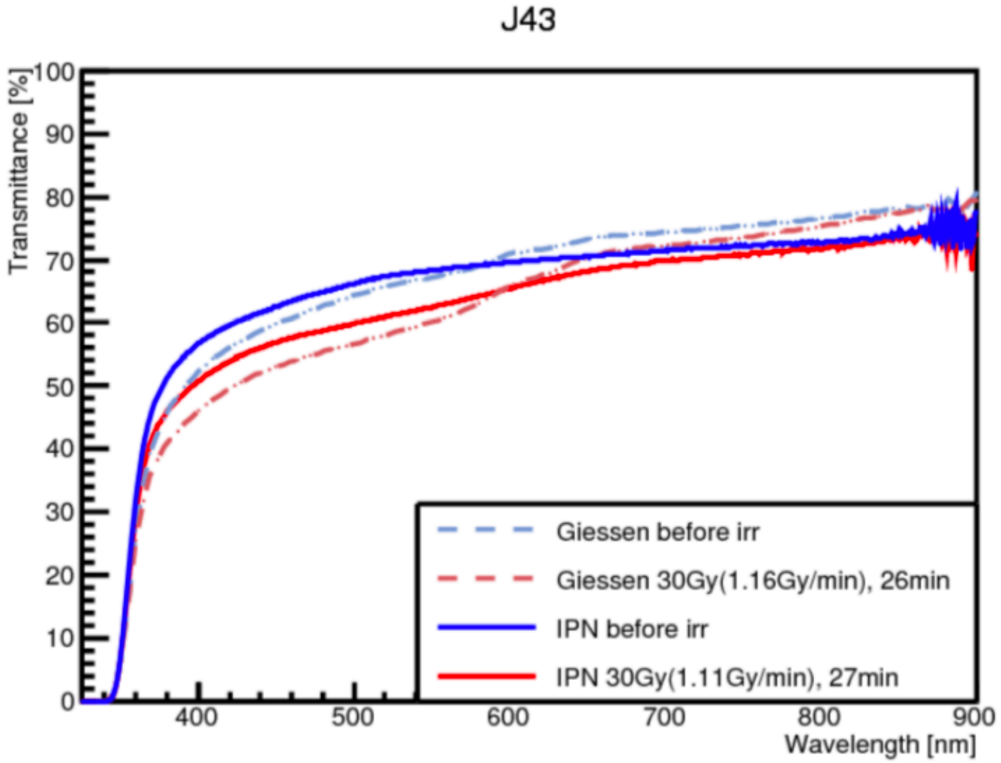
$PbWO_4$ Optical Properties Measurements

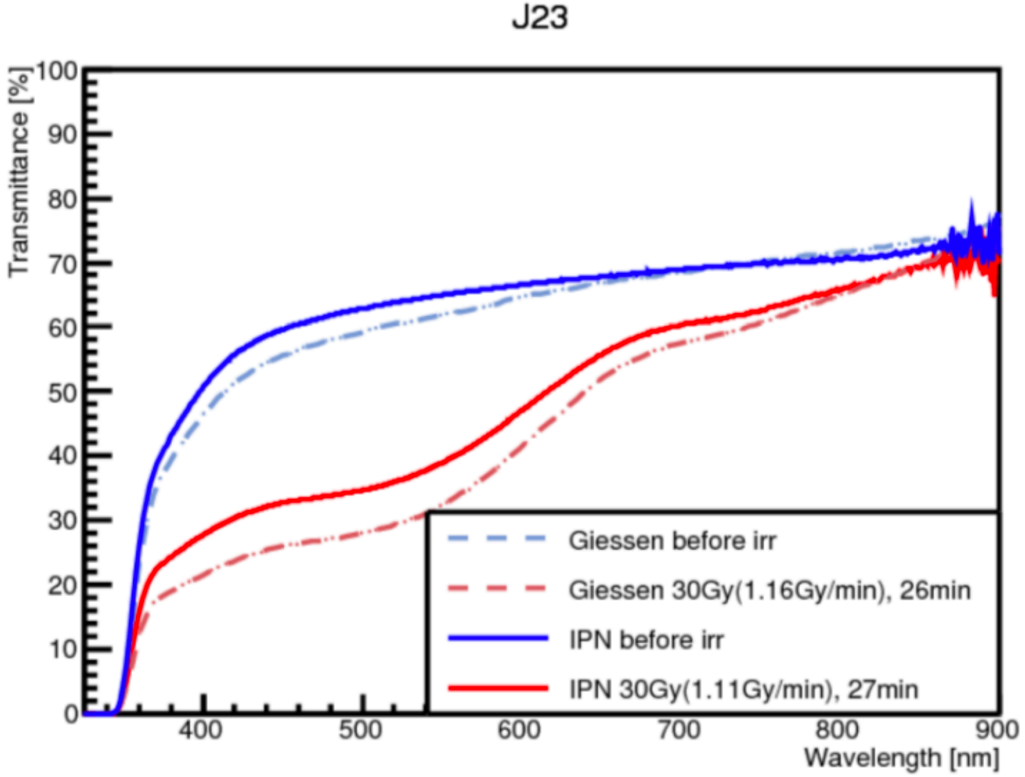
- Radiation hardness measurement
  - Check crystal performance in high radiation environment
  - Impact of radiation on crystal resolution
  - Study the needs for curing

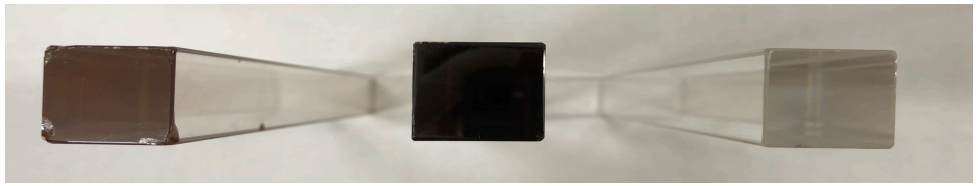
- Optical bleaching
  - Method to recover the optical properties of the crystals after the irradiation damage

$PbWO_4$ Irradiation Test

Light transmittance measurement







Picture : ~20Gy/min ~4hrs with ^{60}Co
at Laboratoire de Chimie Physique

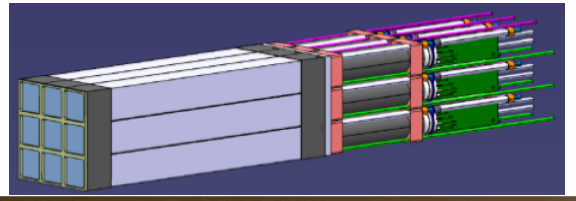
The radiation damage differs for every crystal

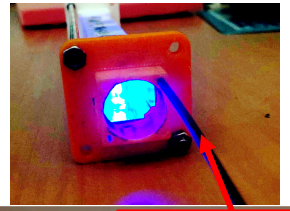
$PbWO_4$ Radiation Damage Recovery

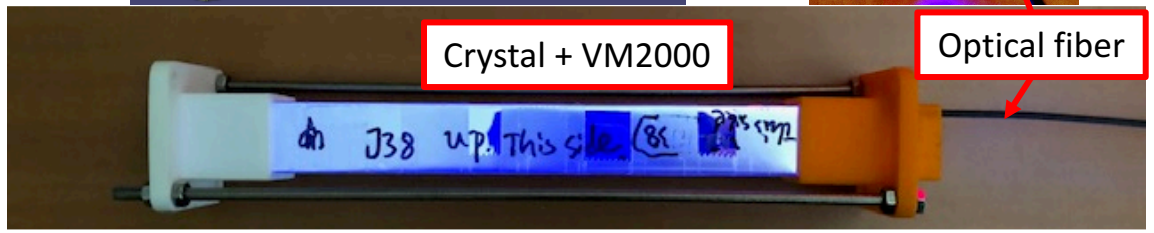
- Ionizing radiation creates color centers
  - By electron traps or point structure defects

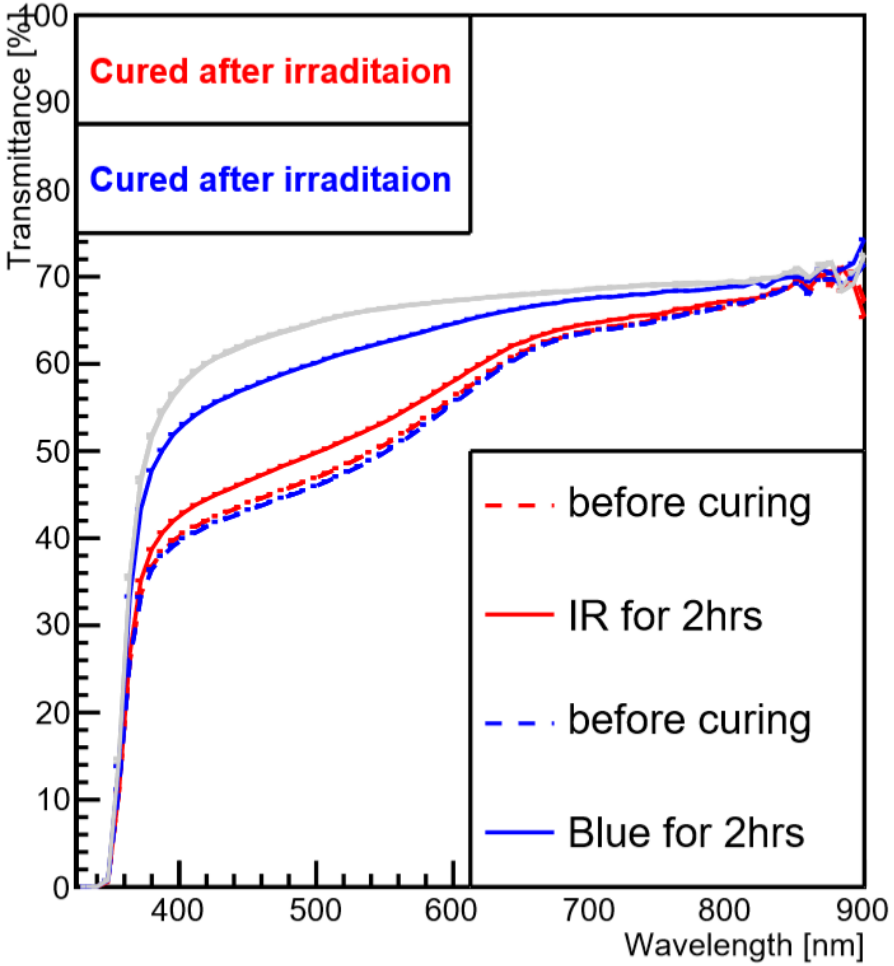
- Relaxation of color centers
  - Thermo-activation
  - Injection of specific energy
    - Blue light : PMT sensitive
    - Infrared light : PMT insensitive → possibility of curing during data taking

$PbWO_4$ Optical Bleaching









-The crystal was irradiated with 30Gy of dose
-Applied two types of light illumination recovery

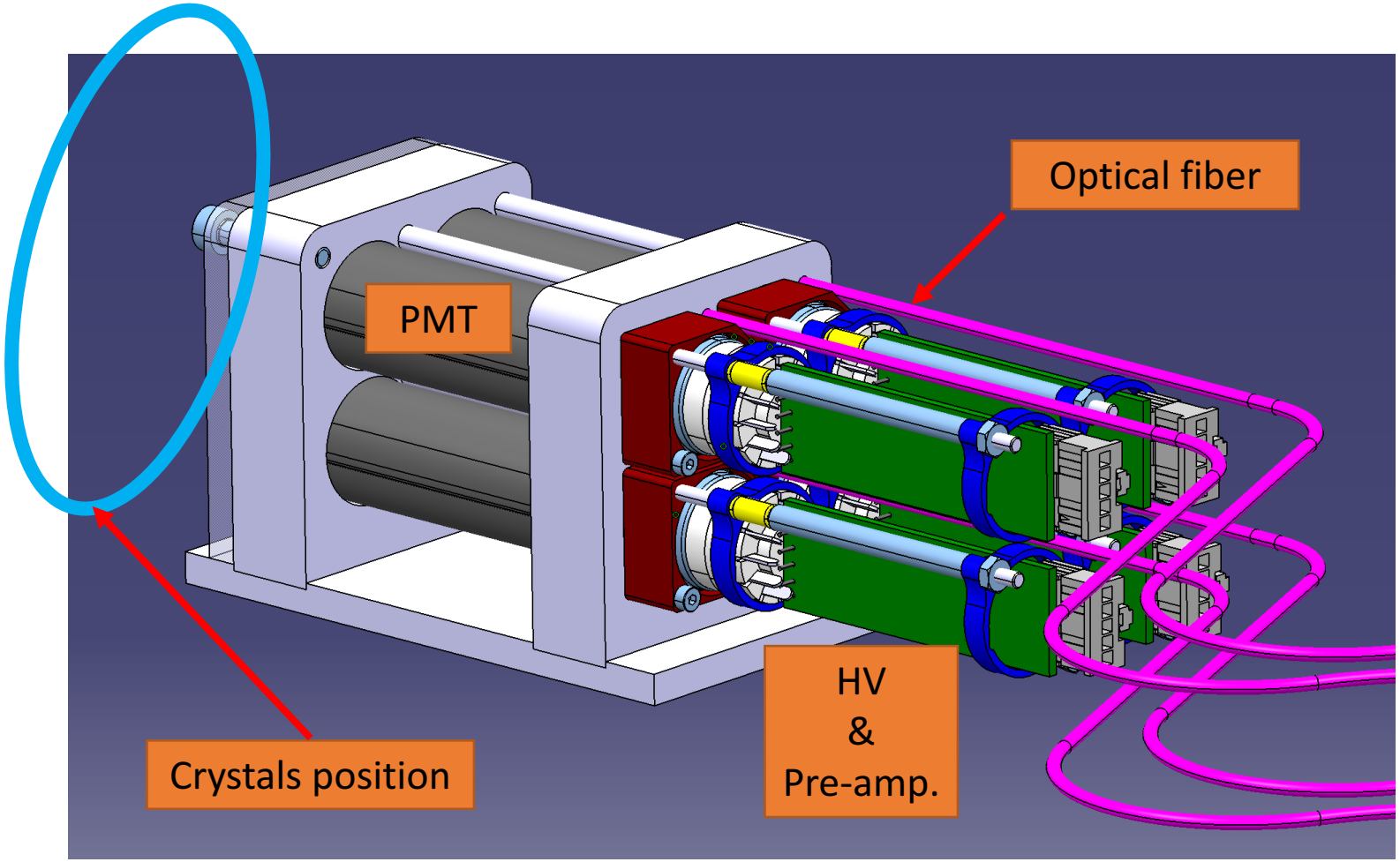
-Infrared(IR) light with optical fiber for 2hrs
-Blue light with optical fiber for 2hrs

→Blue light works better in recovering the transmittance

→Blue light for the crystal optical property damage recovery system of NPS

Optical Bleaching

$PbWO_4$ Optical Properties Measurements Conclusion



- Radiation damage exists and varies with crystals
- Crystals radiation damage can be cured

  - Blue light curing (optical bleaching) via optical fiber to be used for the NPS

<<picture : Emmanuel Rindel>>

Summary

- DVCS access to the GPDs
- DVCS experiments in Hall C will exploit vast kinematic region and cross check Hall A, CLAS, HERMES and COMPASS data
- NPS is needed in Hall C in order to perform the DVCS experiment
- NPS energy resolution and dose rate calculation with Geant4
- Optical bleaching method for maintaining calorimeter's energy and position resolution

Time Line of the NPS

- Detector construction in the 2nd half of 2019
- Delivery of NPS to Jefferson Lab at the beginning of 2020
- NPS tests at Jefferson Lab in 2020
- DVCS experiment expected in 2021

Ongoing projects

- Additional measurements on the prototype
  - Finalize the NPS design
- Software reconstruction for the NPS and acceptance calculation

Backups

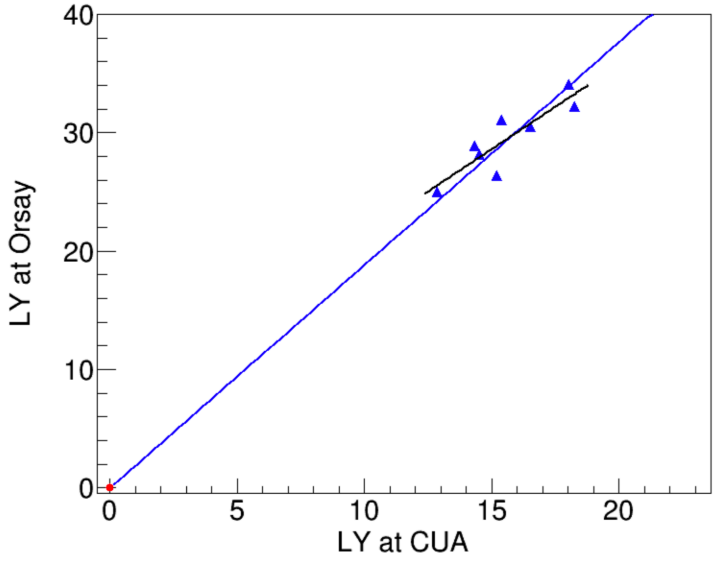
Approved Science Program with the NPS

EXP. NO.	Hall	Title	Spokespersons	Institutions	Beam Days	Rating	PAC	Run Group
E12-13-007	C	Measurement of Semi-Inclusive π^0 Production as Validation of Factorization	R. Ent	JLab	25	A-	40	A
			T. Horn	CUA				
			H. Mkrtchyan	Yerevan				
			V. Tadevosyan	Yerevan				
E12-13-010	C	Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C	C. Munoz Camacho	IPN Orsay	53	A	40	A
			R. Paremuzyan	UNH				
			T. Horn	CUA				
			C. Hyde	ODU				
			J. Roche	Ohio U				
E12-14-003	C	Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies	B. Wojtsekhowski	JLab	18	A-	42	B
			D. Hamilton	Glasgow				
			S. Sirca	Ljubljana				
E12-14-005	C	Wide Angle Exclusive Photoproduction of π^0 Mesons	D. Dutta	Miss. State	18	B	42	B
			M. Amaryan	ODU				
			H. Gao	Duke				
			M. Kunkel	ODU				
			S. Sirca	Ljubljana				
			I. Strakovsky	GWU				
E12-14-006	C	Initial State Helicity Correlation in WideAngle Compton Scattering	D. Keller	UVa	15	B	42	C
			D. Day	UVa				
			J. Zhang	UVa				

Parameter	Lead Tungsten ($PbWO_4$)	Lead Fluoride (PbF_2)
Density (g/cm3)	8.28	7.66-7.77
Radiation length Xo (cm)	0.89	0.93-0.95
Refraction index	2.36 (λ = 420 nm) 2.24 (λ = 600 nm)	1.8-2.0 (depending on λ)
Transmission range (nm)	340-1000	250 -- 1100
Moliere radius (cm)	2.19	2.22
Radiation type Sensitivity to low en. bckgr.	Scintillation (~13% Čerenkov) Sensitive	Pure Čerenkov Insensitive (no scintillation)
Timing property (slow/fast) τ_{sc}, ns (%)	≈30 ns / 10 ns 5 (73%) 14 (23%) 110 (4%)	Very fast, Total pulse width < 20 ns
Lead content (% by weight)	> 85	85
Hydroscopicity	No	No
Energy resolution σ_E/E (%)	~2.4/√E	5.3/√E
Position resolution σ (mm)	~2.5/√E	~1.5/√E
Photon yields per 1 MeV	~140-200	~1.0-2.0
Temperature dependence of Light Yield	~ -2%/°C at room temperature	No need of temperature stabilization
Critical Energy (MeV)	--	8.6--9.0

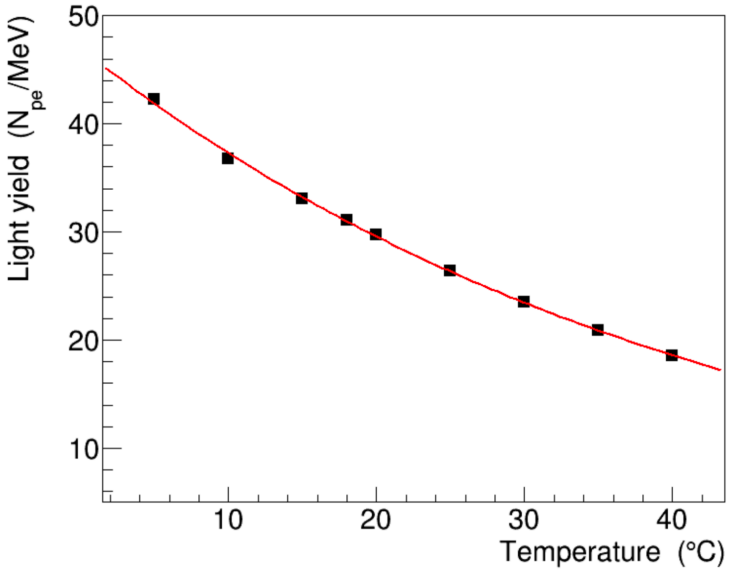
	Energy Dependence at fixed (Q^2, x_B)												Low-x_B				High-Q^2		
x_B	0.36					0.50			0.60				0.2				0.36	0.50	0.60
Q^2 (GeV)^2	3.0			4.0		3.4		4.8	5.1			6.0	2.0			3.0	5.5	8.1	10
k (GeV)	6.6*	8.8	11	8.8*	11	8.8	11	11	6.6	8.8*	11	11	6.6	8.8	11	11	11		
k' (GeV)	2.2	4.4	6.6	2.9	5.1	5.2	7.4	5.9	2.1	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

$PbWO_4$ Light Yield Measurements



Cross checking the measured LY between two different lab.

<<measurements done by Rong WANG>>



Measurement of the temperature dependence of the crystals light yield

Also, light yields differ in each crystals.