Neutral Particle Spectrometer (NPS)

Vladimir V. Berdnikov
on behalf of the NPS collaboration

Hall A/C Collaboration Meeting
June 16-17 2022

NPS collaboration

- Consist of members involved in NPS construction plus additional collaborators on the six experiments

1. Ibrahim Albayrak (Akdeniz Univ/Turkey)
2. Salina Ali (CUA)
3. Moskov Amaryan (ODU)
4. Vladimir Berdnikov (CUA)
5. William J. Briscoe (GWU)
6. John R.M. Annand (U Glasgow)
7. Arshak Asaturyan (AANL, YerPhI)
8. Vincenzo Bellini (INFN-Catania)
9. Kai Brinkmann (Giessen U.)
10. Marie Boer (CUA)
11. Alex Camsonne (JLab)
12. Marco Carmignotto (JLab)
13. Donal Day (UVa)
14. Dipangkar Dutta (MSU)
15. Stefan Diehl (Giessen U.)
16. Rolf Ent (JLab)
17. Michel Guidal (IPN-Orsay)
18. David J. Hamilton (U Glasgow)
19. Tanja Horn (CUA)
20. Charles Hyde (Old Dominion University)
21. Dustin Keller (UVa)
22. Cynthia Keppel (JLab)
23. Mitchell Kerver (ODU)
24. Edward Kinney (U. of Colorado)
25. Greg Kalicy (CUA)
26. Ho-San Ko (IPN-Orsay)
27. Mireille Muhoza (CUA)
28. Arthur Mkrtchyan (AANL, YerPhI)
29. Hamlet Mkrtchyan (AANL, YerPhI)
30. Carlos Munoz-Camacho (INP-Orsay)
31. Pawel Nadel-Turonski (Stonybrook)
32. Gabriel Niculescu (James Madison U.)
33. Rainer Novotny (Giessen U.)
34. Rafayel Paremuzyan (NH)
35. Ian Pegg (CUA)
36. Hashir Rashad (Old Dominion University)
37. Julie Roche (Ohio University)
38. Oscar Rondon (UVa)
39. Simon Sirca (U Ljubljana)
40. Alex Somov (JLab)
41. Igor Strakovsky (GWU)
42. Vardan Tadevosyan (AANL, YerPhI)
43. Richard Trotta (CUA)
44. Hakob Voskanyan (AANL, YerPhI)
45. Rong Wang (IPN-Orsay)
46. Bogdan Wojtsekhowski (JLab)
47. Steve Wood (JLab)
48. Simon Zhamkochyan (AANL, YerPhI)
49. Carl Zorn (JLab)
50. Jixie Zhang (UVa)

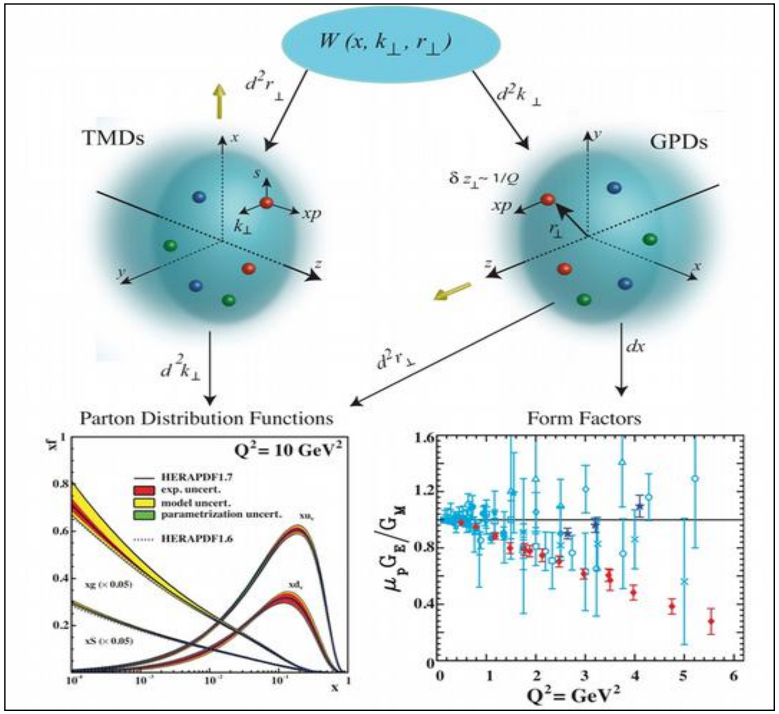
- **Collaboration meetings since 2012**

Experiments overview

Experiment	Exp #	Beam	Target	PAC Days	Rating
π^0 SIDIS	E12-13-007	$\vec{e}^-$	L H_2	(26)	A^-
DVCS and Exclusive π^0	E12-13-010	$\vec{e}^-$	L H_2	53	A
Wide Angle Compton Scattering (WACS)	E12-14-003	e^-, γ	L H_2	18	A^-
Wide Angle Exclusive π^0 photoproduction	E12-14-005	e^-, γ	L H_2	(18)	B
DVCS – days moved from Hall A	E12-06-114	$\vec{e}^-$	L H_2	35	A
A_{LL} & A_{LS} Polarization Observables in WACS at large s, t, and u	E12-17-008	CPS: $\vec{\gamma}$	$N\vec{H}_3$	46	A^-
Timelike Compton Scattering (TCS) off a Transversely Polarized Proton	C12-18-005	CPS: $\vec{\gamma}$	$[N\vec{H}_3]_T$	35	C2

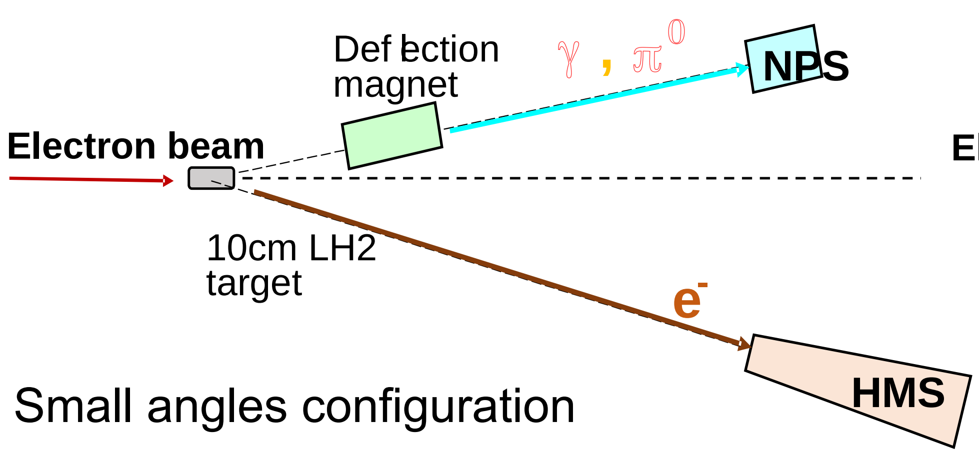
- Scheduling request submitted for E12-13-010/E12-13-007 (NPS Phase-1)
- Detector assembly out of the hall now ongoing in EEL-108
- Hall C Run period July 2023 to March 2024 (see Mark Jones`s talk)
  - Experiments:
    - E12-13-010 and E12-13-007
    - E12-06-114

Motivation of NPS Experiments: Validation of Reaction mechanism



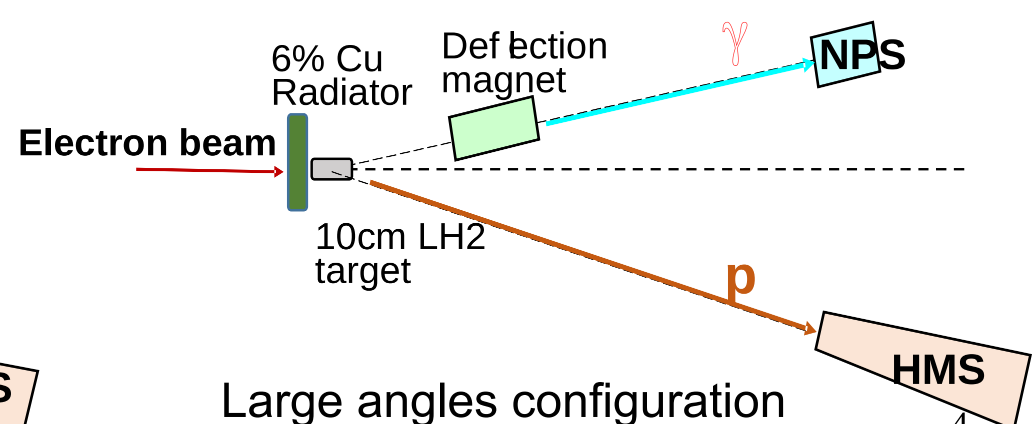
- To extract the rich information on nucleon structure encoded in **GPD** and **TMD**s one needs to show that the scattering process is understood
  - Neutral final states offer unique advantages
- Two arm combination of high resolution neutral particle spectrometer and a magnetic spectrometer offers unique scientific capabilities for studies of the transverse spatial and momentum structure of the nucleon in Hall C

E12-13-010 and E12-13-007



Small angles configuration

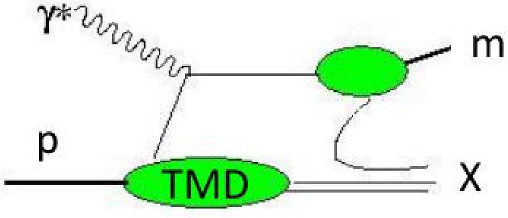
E12-14-003 and E12-14-005



Large angles configuration

E12-13-007: SIDIS basic (e,e´π) cross sections

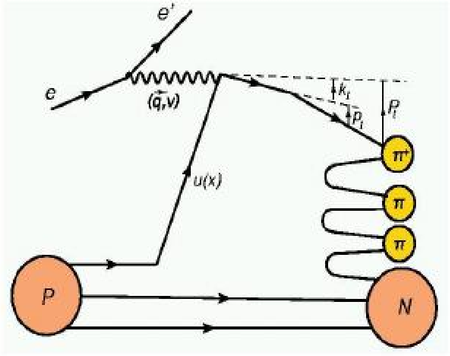
Linked to framework of *Transverse Momentum Dependent Parton Distributions*



- Validation of factorization theorem needed for most future SIDIS experiments and their interpretation
- Need to constrain TMD evolution w. precision data
- Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

$TMD^q(x,k_T)$

Transverse momentum widths of quarks with **different flavor (and polarization)** can be different



$P_T = p_t + z\,k_t + O(k_t^2/Q^2)$

E12-13-007 goal: Measure the basic SIDIS cross sections of π^o production off the proton, including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Requires new ~25 msr Neutral-Particle Spectrometer

Advantages of $(e,e'\pi^o)$ beyond $(e,e'\pi^{+/-})$

- Many experimental and theoretical advantages to validate understanding of SIDIS with neutral pions
- Can verify: $\sigma^{\pi^o}(x,z) = ½\,(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition/k_T dependence

PAC: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon."

E12-13-010: precision DVCS cross sections

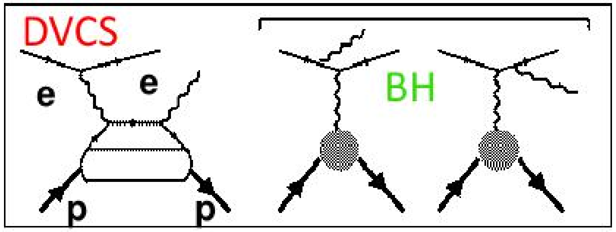
Simplest process: **e + p → e′ + p + γ (DVCS)**

E12-13-010 DVCS measurements follow up on measurements in Hall A:

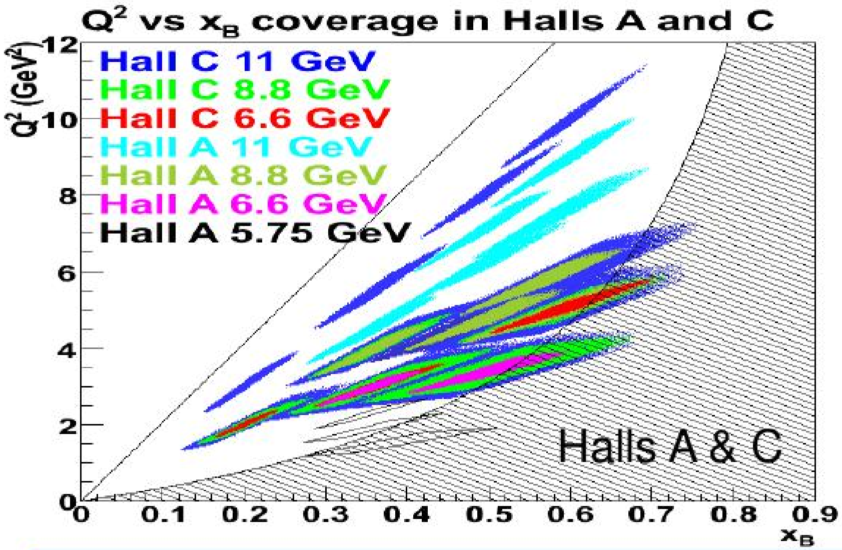
- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \underbrace{\mathrm{Re}\left[DVCS^{\perp}\ BH\right]}_{\sim E^2_{beam}} + \underbrace{|DVCS|^2}_{\sim E^3_{beam}}$$

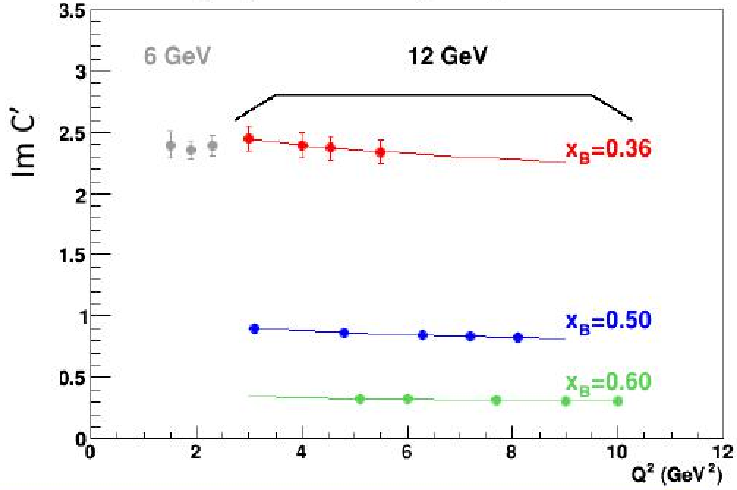
- L/T separation of π^0 production



Hall A data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering

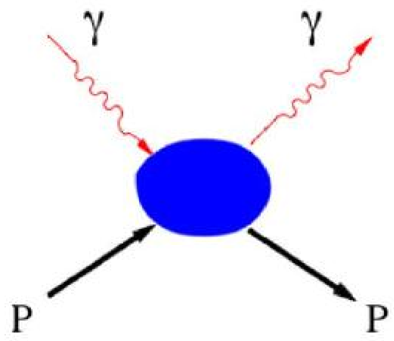


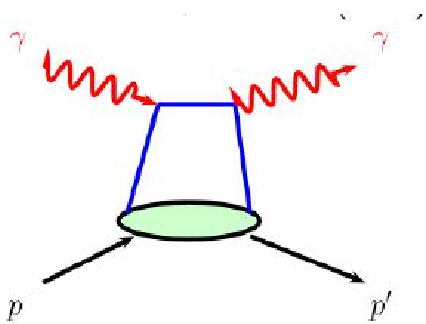
12 GeV projections: confirm formalism



Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies ($DVCS^2$–Interference separation)

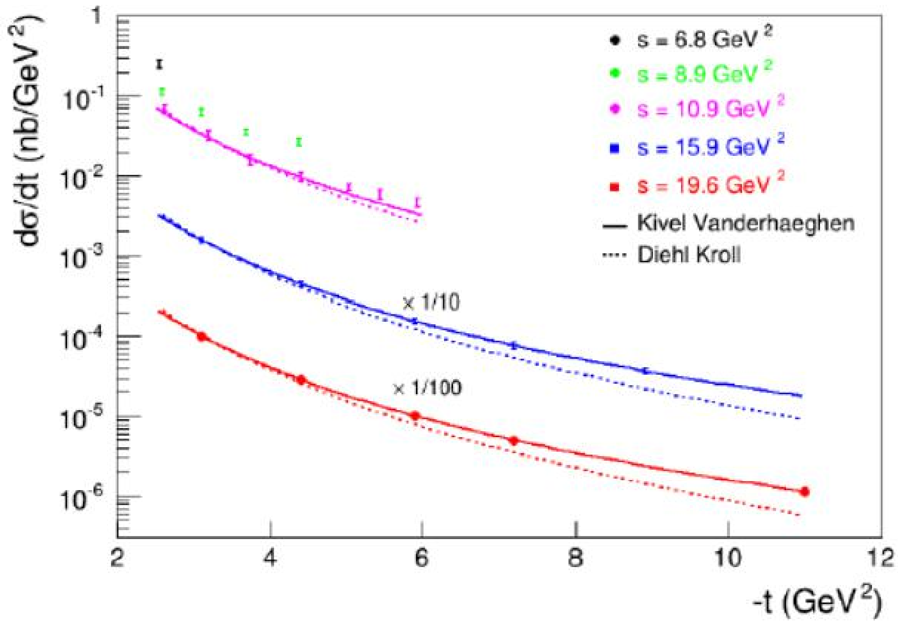
E12-14-003: Wide Angle Compton Scattering





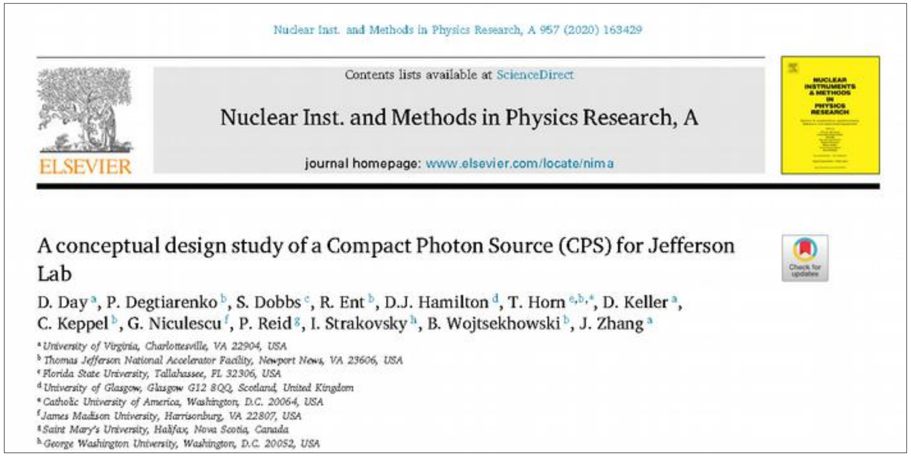
- ❑ Arguably the least understood of the fundamental reactions in the several-GeV regime
- ❑ Wide-Angle Compton Scattering cross section behavior was a foundation leading to the GPD formalism
- ❑ Reaction mechanism intrinsically intertwined with basics of hard scattering process (handbag diagram), yet also sensitivity to transverse structure like high-Q^2 form factors

- ➢ Perhaps (6-GeV data) factorization valid for *s, -t, -u > 2.5 GeV²*
- ➢ 12-GeV data for $-u > 2.5$ and $-t$ up to ~ 10, s up to ~ 20 GeV²



Combine NPS with Compact Photon Source (CPS)

- Much progress in imaging nucleon structure can be made with electron-scattering reactions, yet experiments with high-energy photons play a unique complementary role
- Small scattering probabilities of exclusive reactions demand high-intensity photon beams
- Understanding strengthened by imaging longitudinally-polarized and transversely-polarized nucleons


Nuclear Inst. and Methods in Physics Research, A 957 (2020) 163429

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

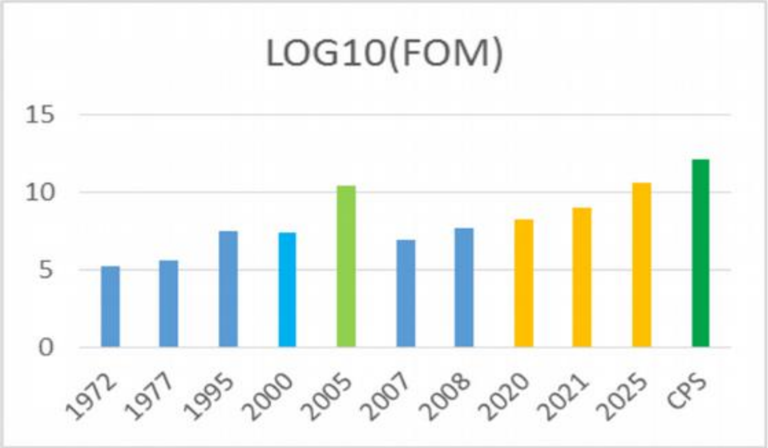
ELSEVIER

A conceptual design study of a Compact Photon Source (CPS) for Jefferson Lab

D. Day[a], P. Degtiarenko[b], S. Dobbs[c], R. Ent[b], D.J. Hamilton[d], T. Horn[e,b,*], D. Keller[a], C. Keppel[b], G. Niculescu[f], P. Reid[g], I. Strakovsky[h], B. Wojtsekhowski[b], J. Zhang[a]

[a] University of Virginia, Charlottesville, VA 22904, USA
[b] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[c] Florida State University, Tallahassee, FL 32306, USA
[d] University of Glasgow, Glasgow G12 8QQ, Scotland, United Kingdom
[e] Catholic University of America, Washington, D.C. 20064, USA
[f] James Madison University, Harrisonburg, VA 22807, USA
[g] Saint Mary's University, Halifax, Nova Scotia, Canada
[h] George Washington University, Washington, D.C. 20052, USA

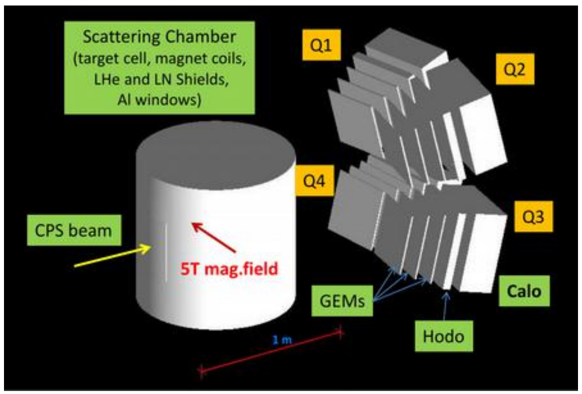
CPS conceptual design Published in NIMA 2020



CPS enables a gain of a factor of 30 in figure-of-merit! Enables a new suite of high-energy photon scattering experiments to image and understand the dynamical nucleon structure

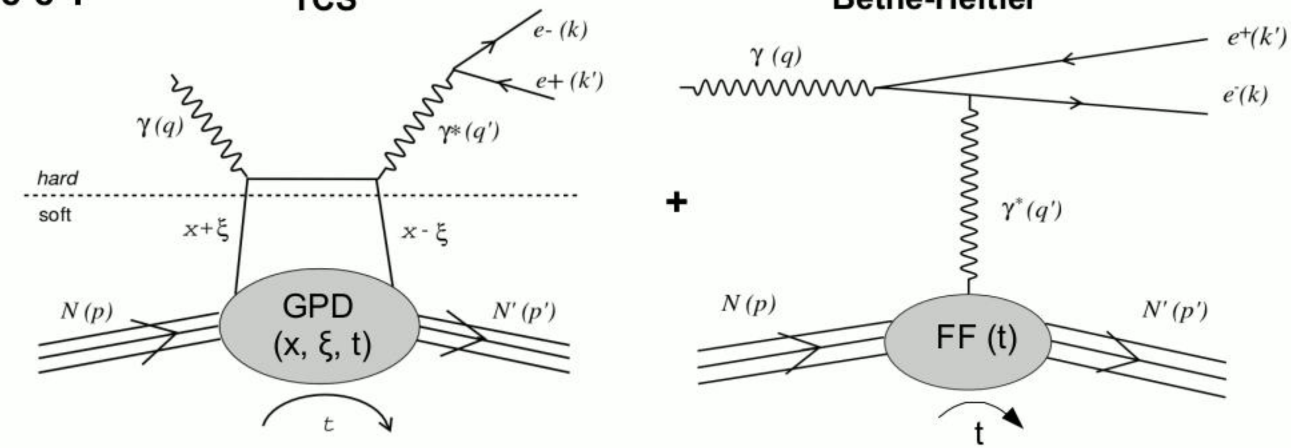
- **E12-17-008** - investigate the mechanisms behind RCS – provides crucial insight into the nature of exclusive reactions and proton structure
- **C12-18-005** - first fundamental test of the universality of the GPDs, as the GPDs extracted from TCS should be comparable with those extracted from the analogous space-like (electron) scattering process - DVCS

C12-18-005: Time-like Compton Scattering

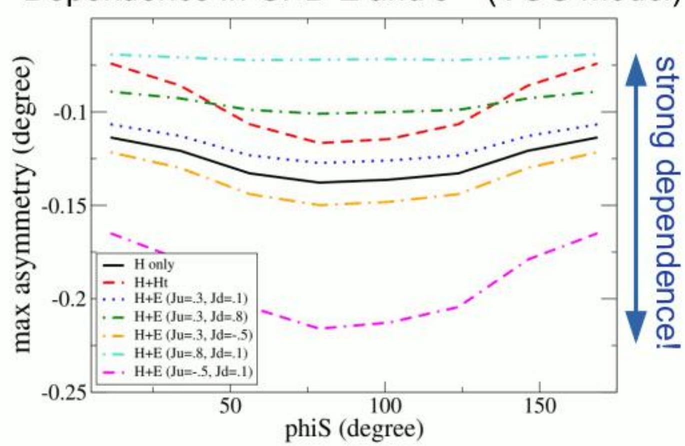


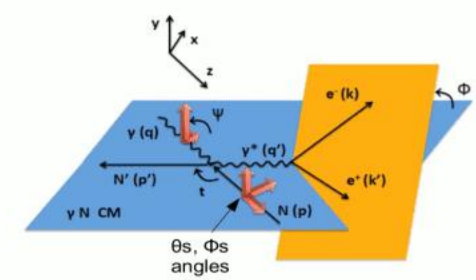
Physics goals

$\gamma P \rightarrow e^+e^- P' =$



Sin(φ) moment of transverse spin asymmetry vs φ_S,
Dependence in GPD E and $J^{u,d}$ (VGG model)

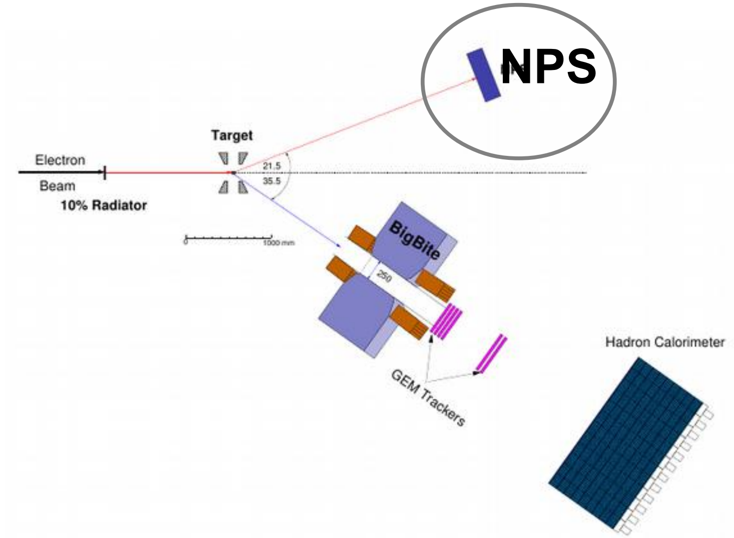




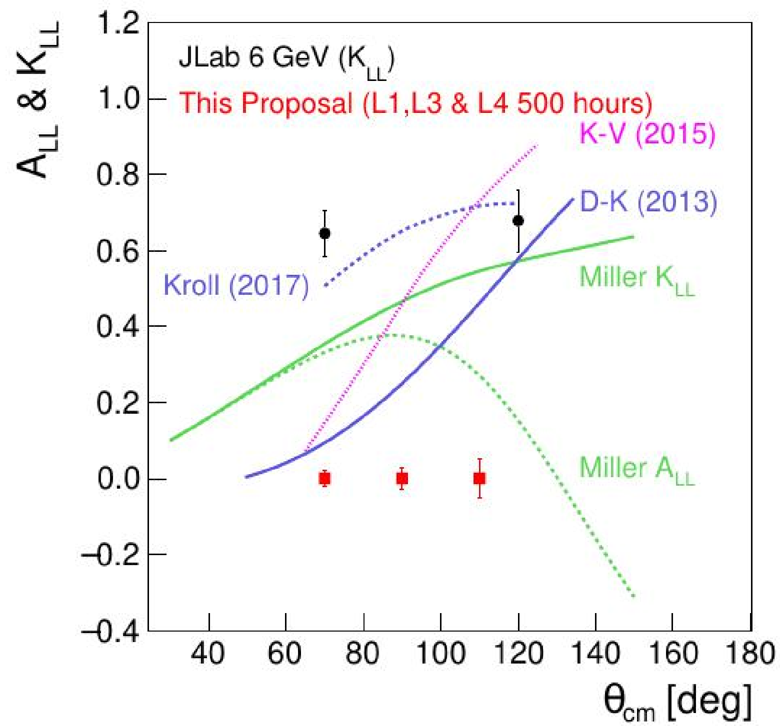
TSA as a function of φ and φ_S

- Sensitive to Im(interference), BH cancels
- Strong dependence in angular momenta,
Sensitivity to GPD E (also to H, Ht)

E12-17-008: Polarized Wide-angle Compton Scattering



The use of the CPS and BigBite results in a significantly improved figure-of-merit over all previous experiments and opens up a new range of polarized physics opportunities at JLab.



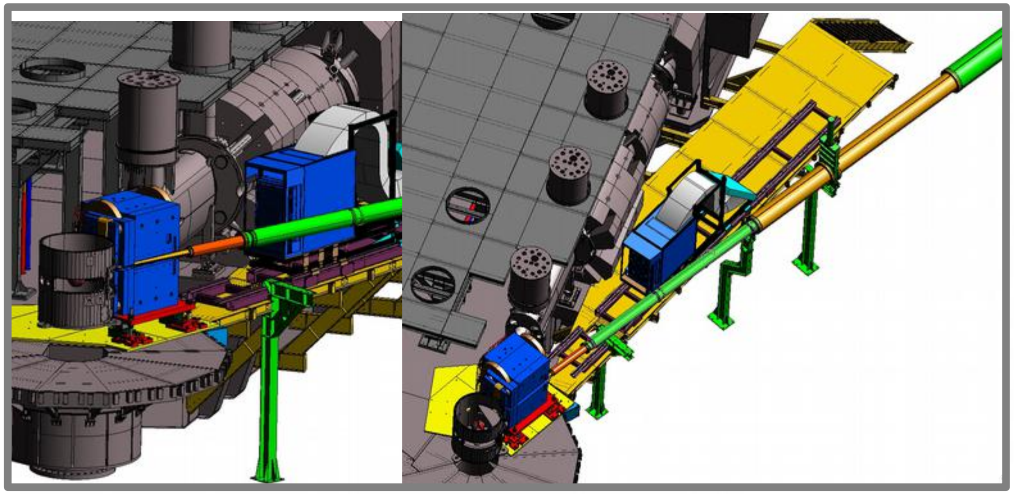
- Make an explicit, model-independent test of factorization by measuring the s-dependence of the polarization observables at fixed θ_p^{cm}, and verify that target mass corrections and higher twist effects are small.

- Constraining the GPDs $\tilde{H}$ and E at high $-t$ and comparing with the Axial and Pauli form factors will have a significant and broad impact in the fields of electron and neutrino scattering.

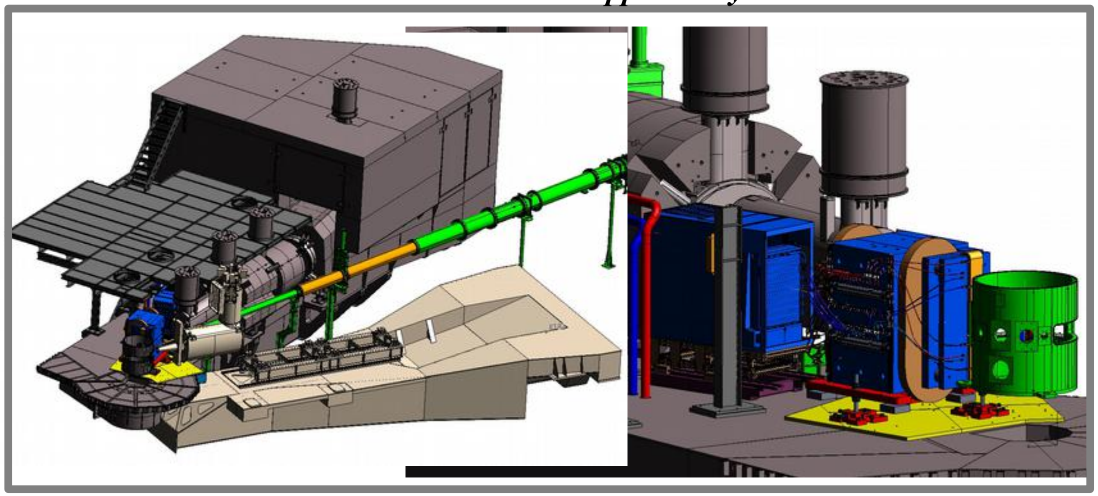
The Neutral Particle Spectrometer

- Neutral particle detector - lead tungstate electromagnetic calorimeter consisting of 1080 crystals placed in a temperature controlled frame including gain monitoring and crystal curing systems
- Crystals read by photomultipliers. HV distribution bases with external power amplifiers for operations in a very high rate environment
- Essentially dead time less digitizing electronics to independently sample the entire pulse form for each crystal. JLab developed readout electronics
- Beam pipe with as large as possible opening/critical angle for the beam exiting the target/scattering chamber region to reduce beam line associated backgrounds
- Vertical-bend sweeping magnet with integrated field strength of 0.3 Tm to suppress an eliminate charged background
- Cantilevered platforms off the Super High Momentum Spectrometer (SHMS) carriage to allow for remote rotation.

Supported by NSF MRI PHY-1530874



Small angles (6°-23°) configuration (Left)



Large angles (23°-57.5°) configuration (Right)

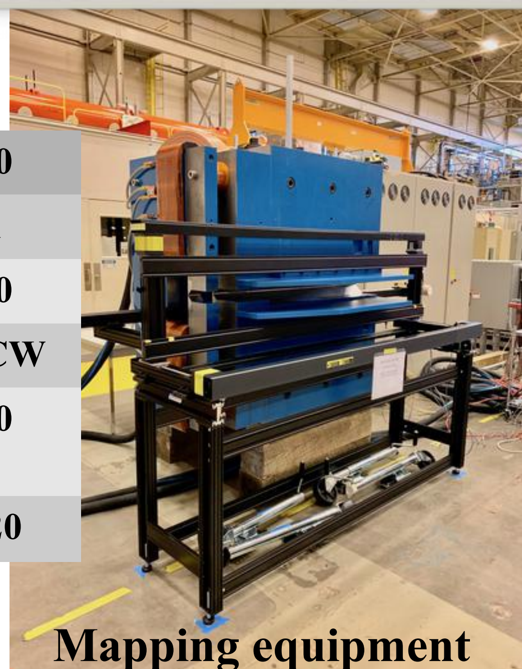
NPS sweeper magnet

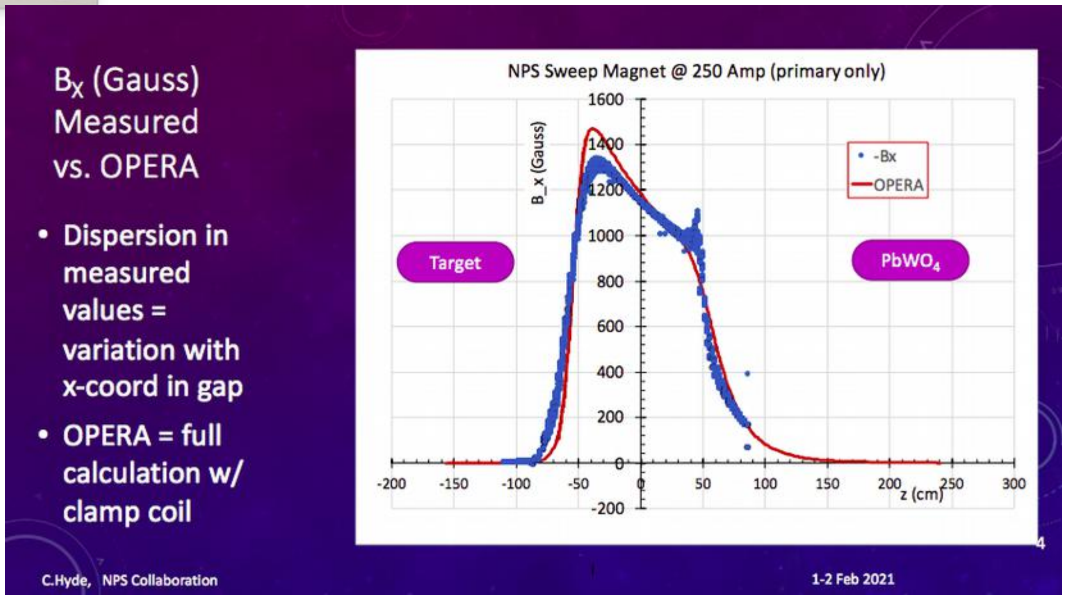
Supported by NSF MRI PHY-1530874


NPS magnet and power supply in test lab

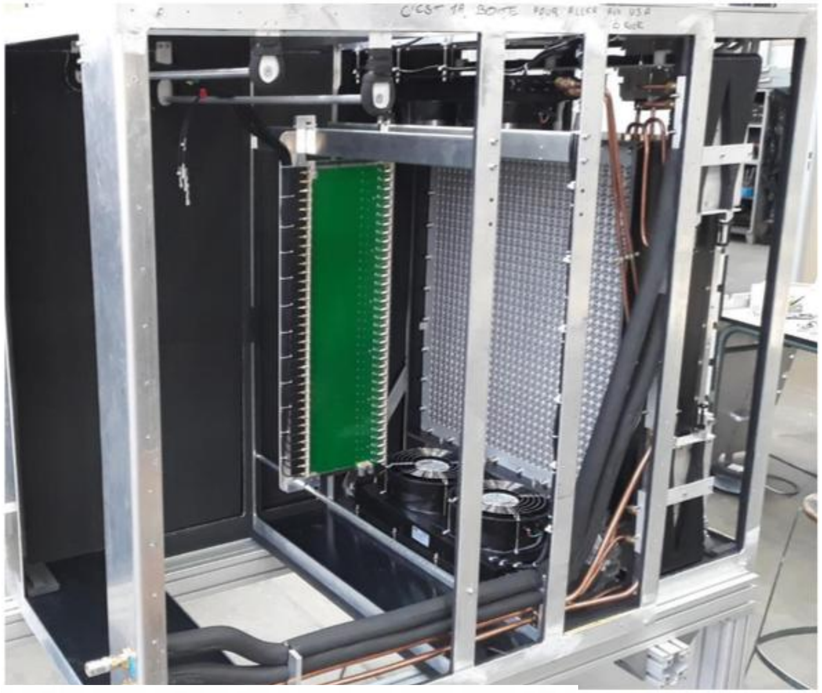
- Normal resistive iron dominated magnet provided by CUA and ODU
- Fully assembled,tested and awaiting installation for full field test in the hall
- Completed fringe field mapping at 25% of full current and compared to calculation

Max Current (Amp)	990
R @ 20°C (Ohm)	0.1
ΔV Max (V)	110
Cooling medium	LCW
ΔP (psi) ΔT (°C)	130 30
Corrector Max (Amp)	520

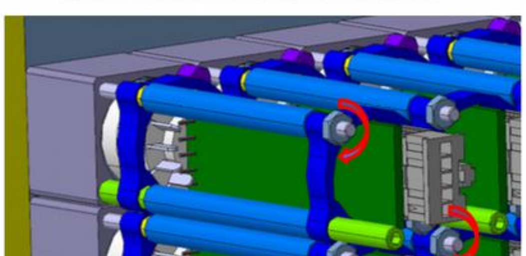

Mapping equipment

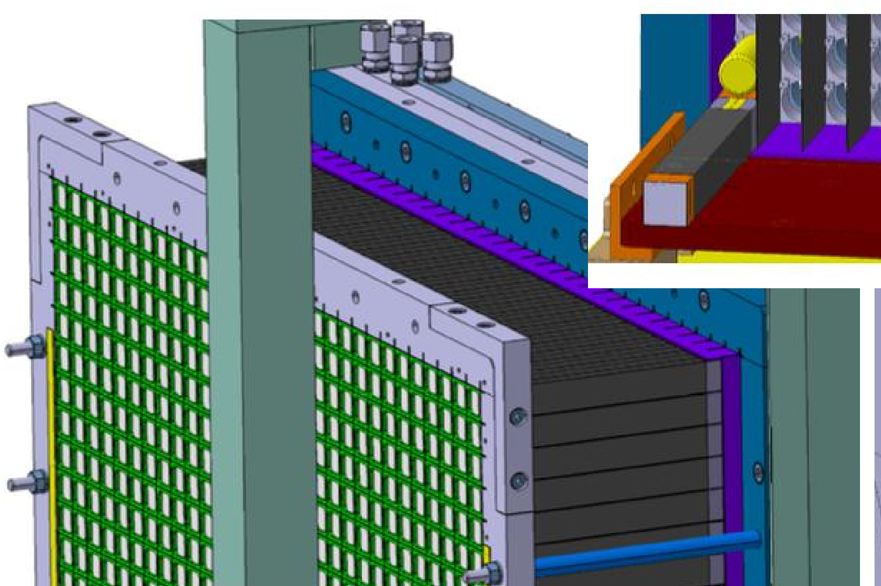


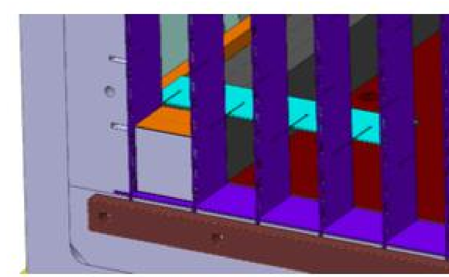
NPS calorimeter structure overview

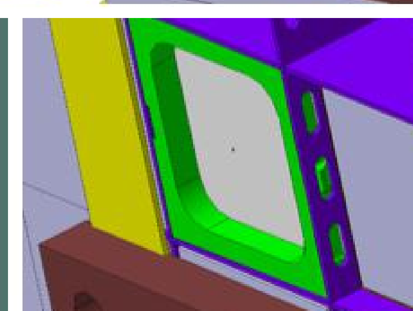


- 30x36 (1080) PbWO4 crystals of size: 2x2x20 cm3
- Hamamatsu R4125 PMTs with custom HV bases
- Design by IJCLab - Orsay
- Crystals placed in a 0.5mm thick carbon frame to ensure good positioning
- PMTs accessible from the back side for maintenance
- Calibration and radiation curing with blue LED light though quartz optical fibers (concept originally designed by AANL Yerevan)
- Frame onsite since 2021



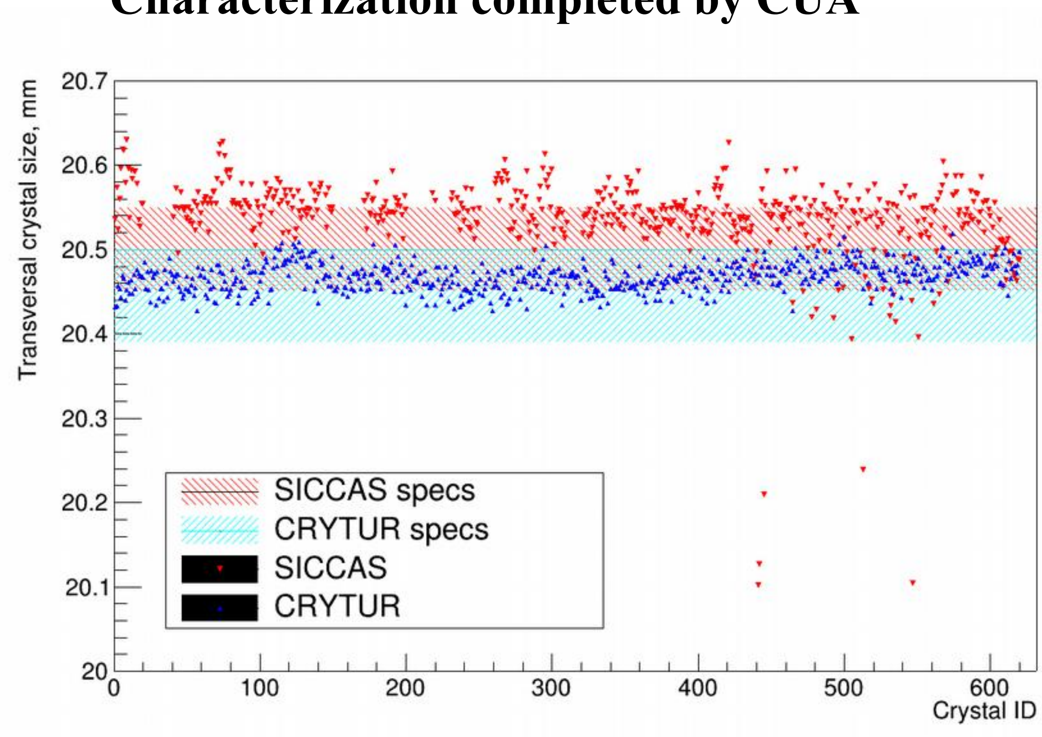






Characteristics of PWO crystals

Characterization completed by CUA

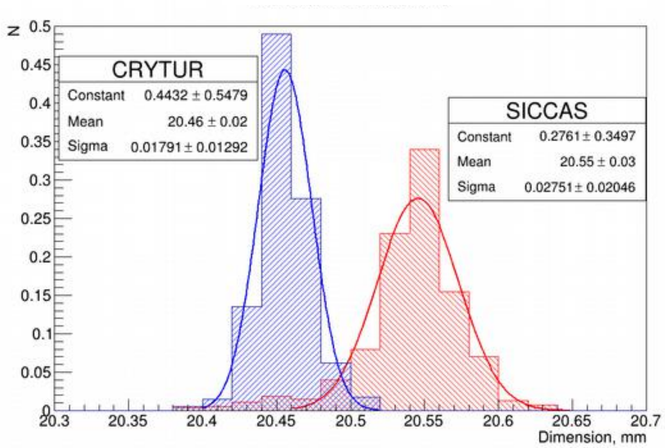


CRYTUR crystals are excellent quality

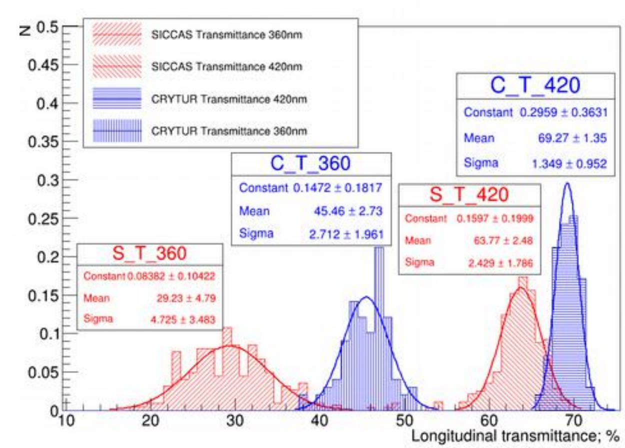
- Great transmittance
- Uniform LY and light collection
- Characteristics within specification
- Rejection rate 0%

SICCAS crystals are low medium quality

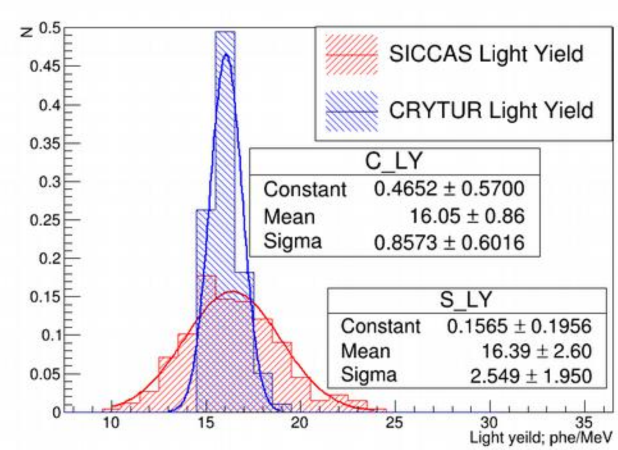
- Lower transmittance compare to CRYTUR
- Non-uniform LY and light collection
- Characteristics outside of specification for significant portion of crystals
- Preselection required
- Rejection rate 30%



Crystal size



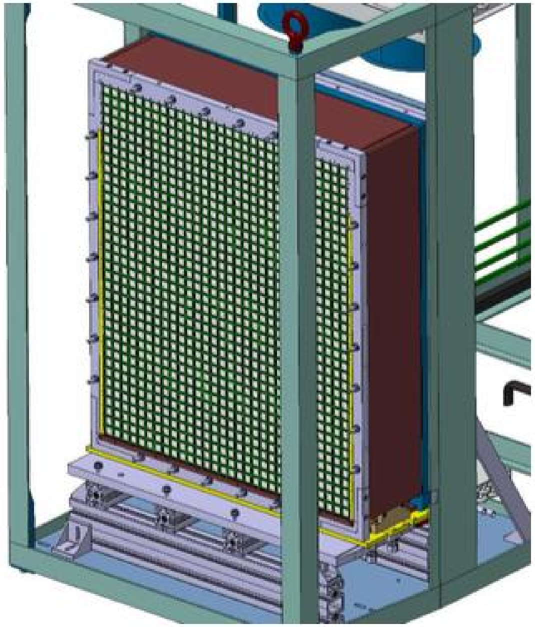
Transmittance

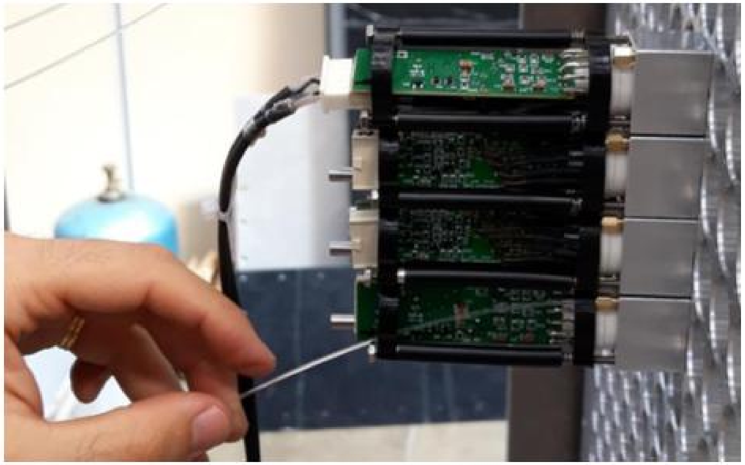


Light yield

NPS calorimeter stacking

- NPS Collaboration decision is to stack NPS with all **CRYTUR** crystals
  - Satisfied to quality requirements
  - All crystals have uniform characteristics
  - Radiation hard
  - Crystal preselection not needed
  - Good control of the constant term
- NPS Calorimeter will consist of 1080 towers, matrix of 36 vertical and 30 horizontal crystals

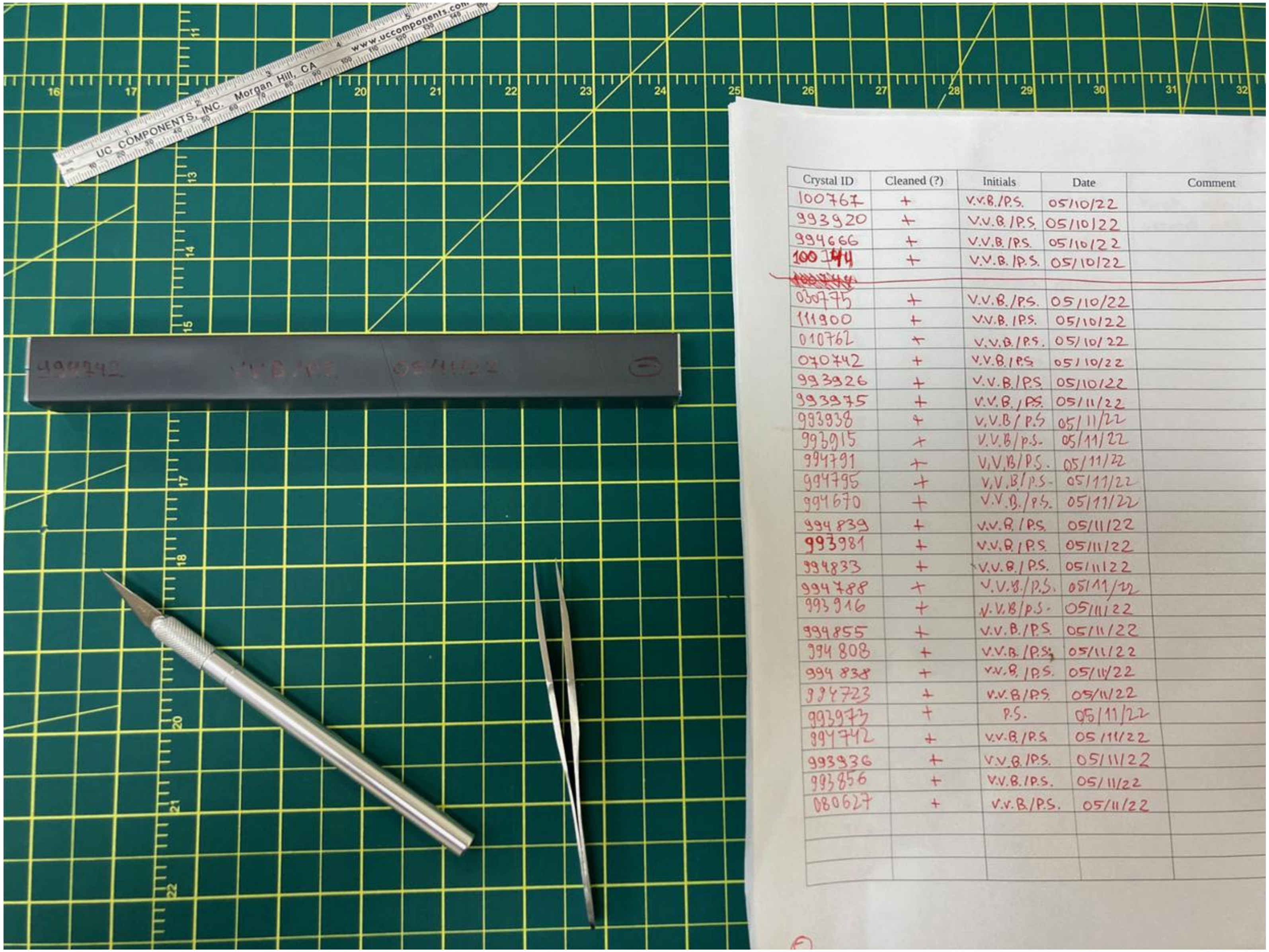




NPS crystals module preparation

Institutions: CUA, AANL, MSU, UIC

NPS crystals module preparation

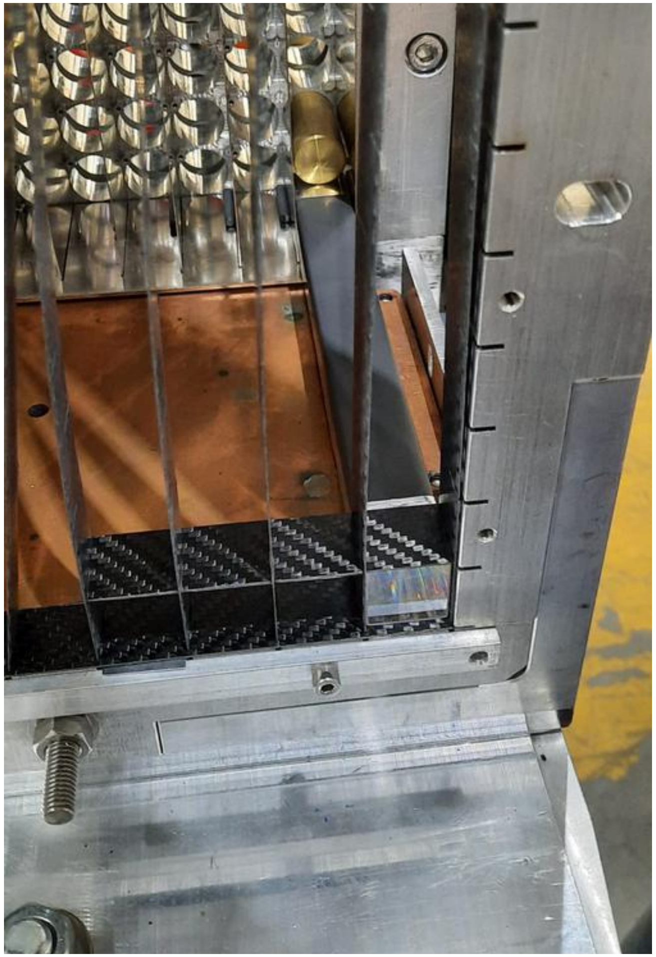


NPS crystals modules storage and transportation

NPS crystals modules ready for assembly

1080 crystals in one spot !!! Finished within one month

NPS frame preparation

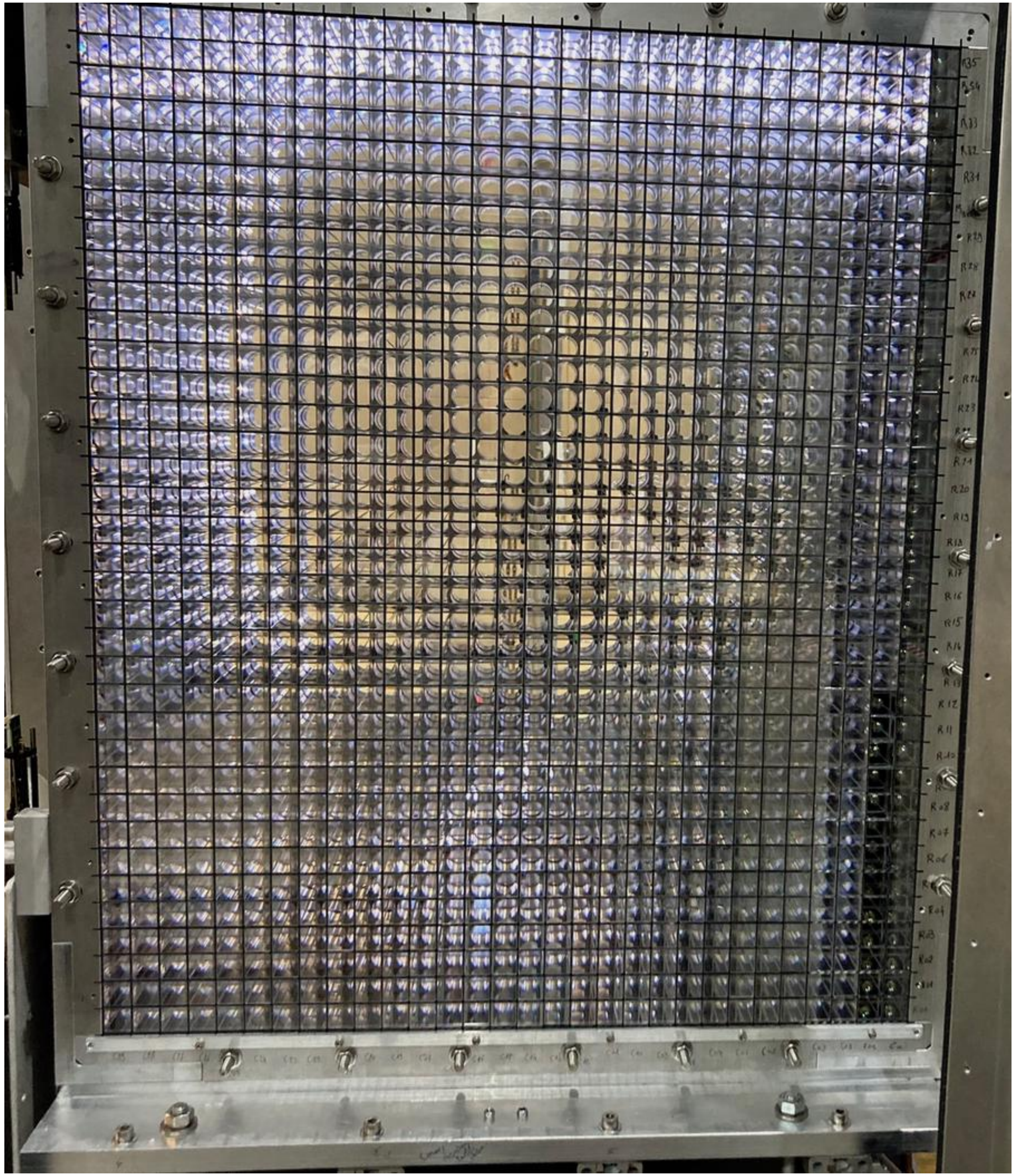


IJCLab – Orsay team

NPS crystals stacking

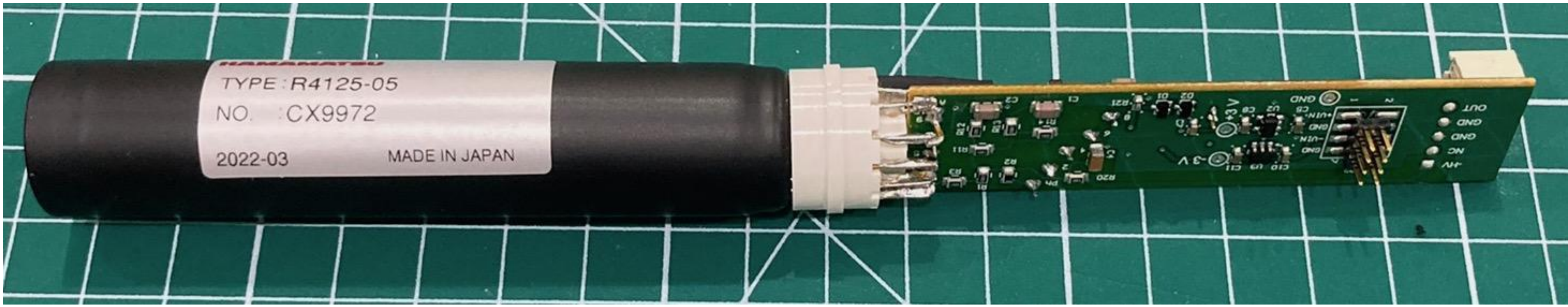
IJCLab – Orsay team

NPS crystal stacking completed



Major step completed by NPS collaboration

PMTs and HV dividers



NPS 8-Stage Active Divider FJ Barbosa

NPS 8-Stage Active HV Divider - Summary

Table 2: Measured divider ratios

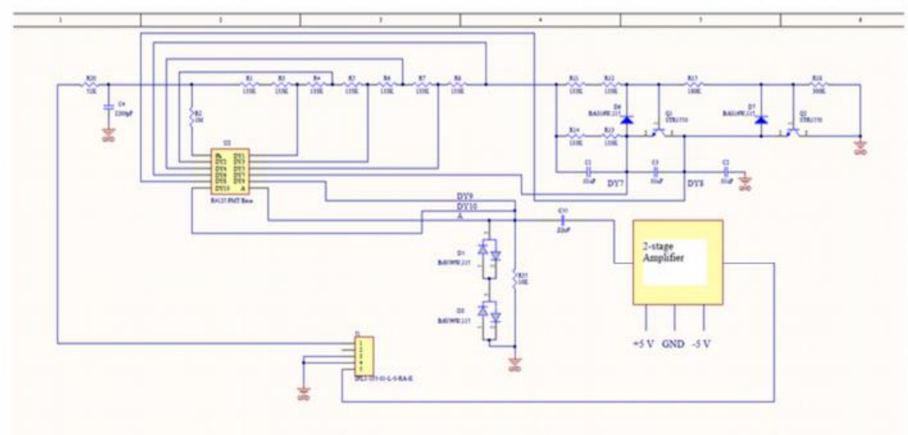
	K–Dy1	Dy1-Dy2	Dy2-Dy3	Dy3-Dy4	Dy4-Dy5	Dy5-Dy6	Dy6-Dy7	Dy7-Dy8	Dy8-Dy9	Dy9-Dy10	Dy10-GND
Active	1.8	1	1	1	1	1	1	1	2	4.3	3.5
Hamamatsu	1.4	1	1	1	1	1	1	1.2	1.8	3.3	3.1

- *Dynodes 9 and 10 are connected to Anode and no amplifier for the following tests.*
- *Preserved PMT biasing of other electrodes (see above table).*
- *Test Results (Vladimir, Carlos, Chris):*
  - *PMT Gain ~ 2 x 10^3 (with reference to Hamamatsu divider: 10^5 @1.1kV).*
  - *HV: 630 V @ 405 uA.*
  - *Source (LED, Laser): set at 10% of maximum expected in the experiment.*
    - *Signal Amplitude = 7 mV nominal (10% of maximum).*
    - *Residual Noise = 2.5 mV peak.*

8 May 2021 Jefferson Lab 1

NPS 8-Stage Active Divider FJ Barbosa

- *Proposed divider simplified:*

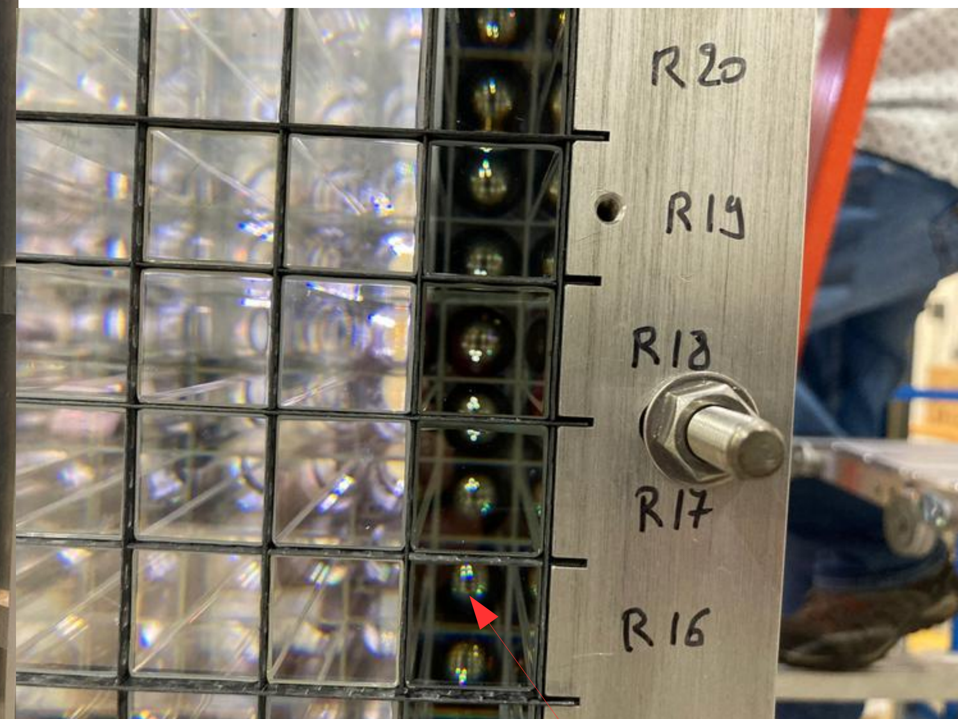


8 May 2021 Jefferson Lab 5

PMTs in preparation for assembly

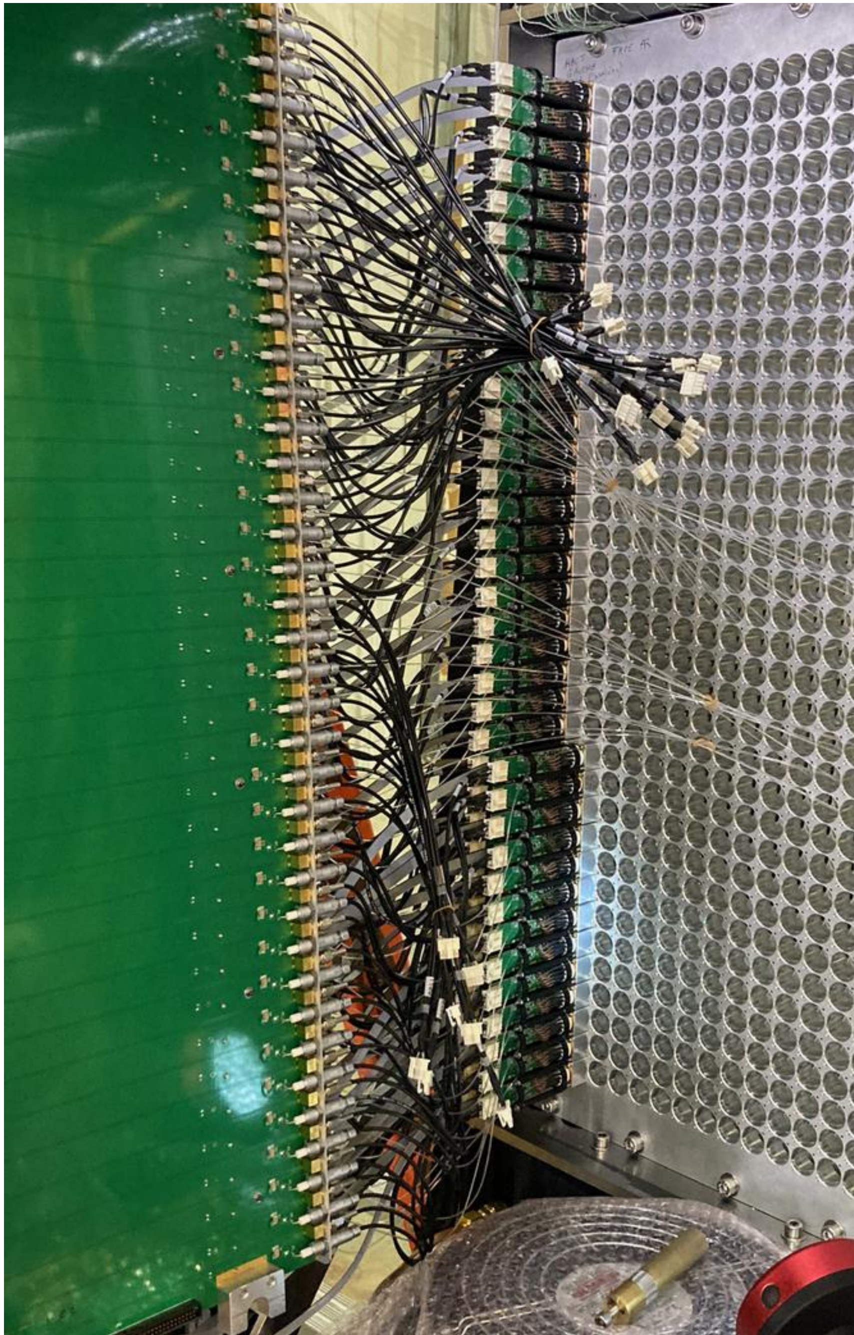
Readout PCBs preparation

NPS PMT installation and cabling



PMTs visible by looking through the crystal

NPS cabling



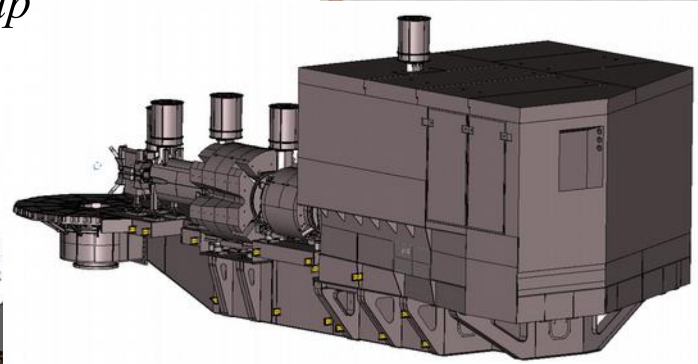
Hall C mechanical infrastructure preparations overview

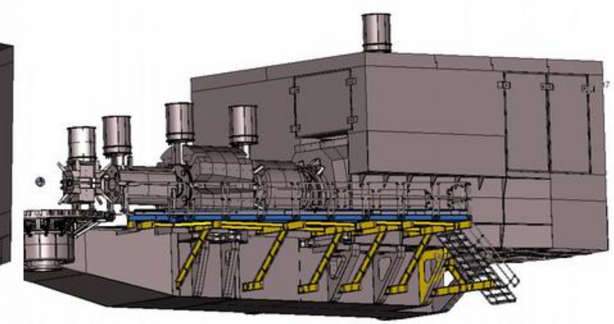
Platform was completely installed and removed Leaving behind the welded mounts so platform can be remounted

Detector rail track was fitup and removed

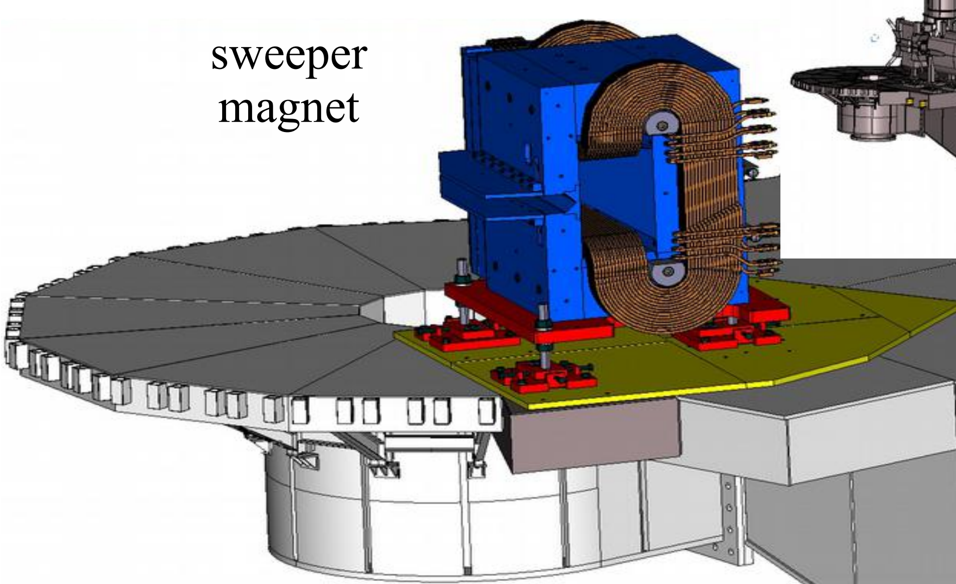
New detector deck section is installed permanently

Design by HallC engineering group





sweeper magnet



All hardware components for detector support structure on site

Pictures from Paulo Medeiros pictures

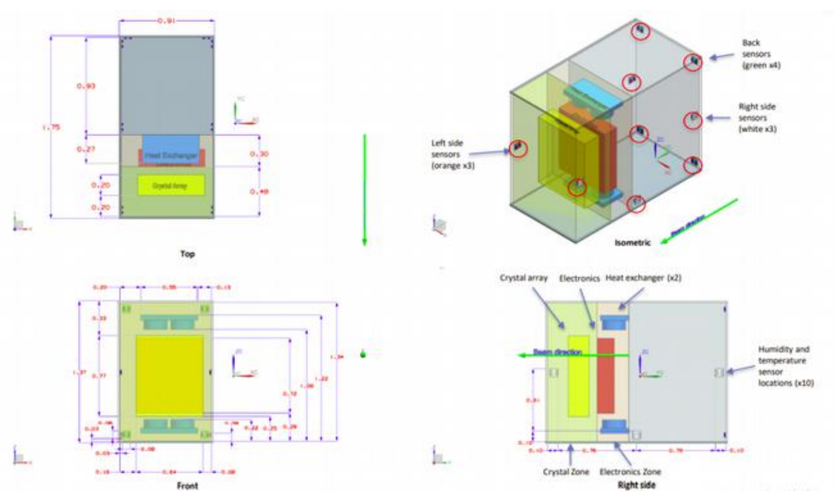
Detector Support Group (DSG) contributions

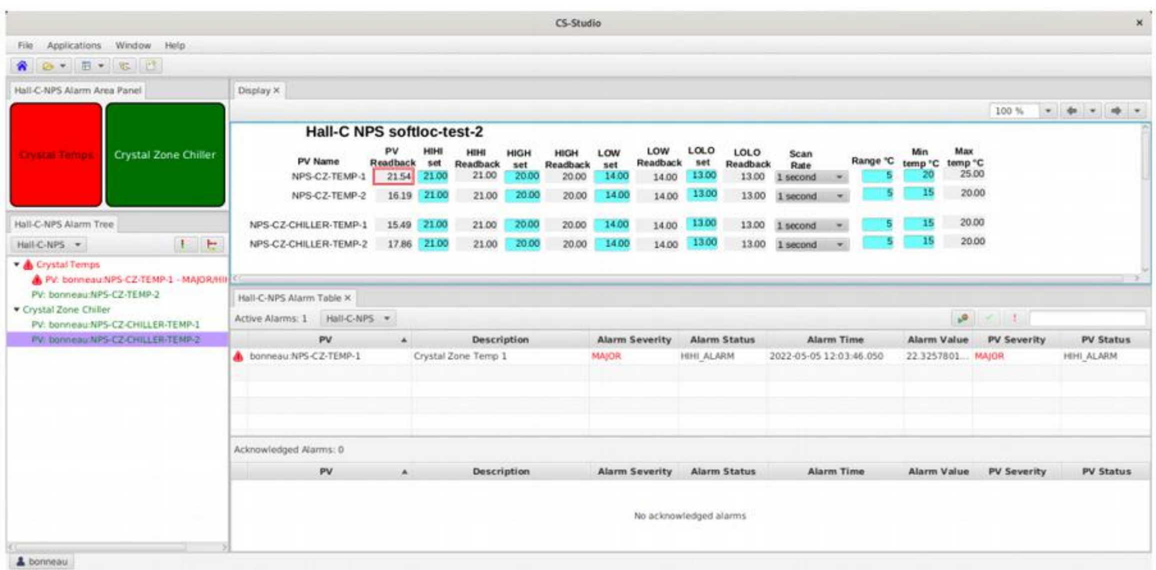
- Controls & Monitoring systems progressing well
  - Developing EPICS Phoebus monitoring and alarm system
  - Developing engineered interlocks system

- Ansys Thermal Analysis
  - Steady-state analysis for central zone crystals
  - Fluent analysis in progress for electronics, PMTs and crystal

- High Voltage Supply Cables preparation and tests

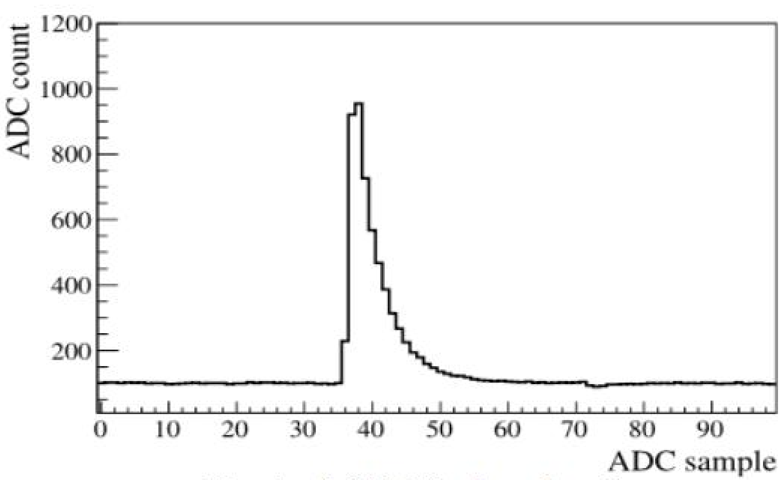
- ESR reflector foils pre-shaping process completed





DAQ / Electronics / Analyzer team

- The team:
  - Coordination: Brad Sawatzky
  - Software lead: David Hamilton
  - Contributors: Steve Wood, Paul King, …
- Action items:
  - DAQ and firmware
  - Slow controls
  - Decoding software (FADC mode 10, VTP data, unblocking)
  - Online software (raw displays, GUI, interface with ET system)
  - Offline reconstruction (clustering algorithm, multi-threading)



Typical fADC signal pulse

Summary and Outlook

- NPS scientific program includes includes 6 fully approved experiments (E12-13-007, E12-13-010, E12-14-003, E12-14-005, E12-06-114, E12-17-008) and one conditionally approved experiment (C12-18-005) and 3 new proposals at PAC 2022

- All components on site and ready

- Major progress with NPS assembly

    - Crystals modules prepared and installed into the NPS calorimeter frame
    - Frame being prepared for initial tests in EEL108
    - HallC infrastructure becoming real

- NPS DAQ/Electronics/Analyzer group working towards detector check-out and commissioning

- NPS Phase-1 scheduled for 2023 and 2024

- Many opportunities to contribute for students, postdocs and new collaborators