THE CATHOLIC UNIVERSITY of AMERICA

Jefferson Lab

Update on the Neutral Particle Spectrometer (NPS)

Vladimir V. Berdnikov
on behalf of the NPS collaboration

HallC Users Meeting
Jefferson Lab; January 28-29 2020; Newport News; Virginia

NPS collaboration

- Consist of members involved in NPS construction plus additional collaborators on the four 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)

NPS Scientific program overview

- The neutral-particle spectrometer (NPS) offers **unique scientific capabilities** for studies of the transverse spatial and momentum structure of the nucleon in Hall C

- Five experiments have been fully approved by the JLab PAC to date:

NPS ERR 2019

  - **E12-13-007:** Measurement of Semi-inclusive π^0 production as Validation of Factorization
  - **E12-13-010:** Exclusive DVCS and π^0 Cross Section Measurements in Hall C
  - **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 CS at large s, t and u

- One conditionally approved experiment

  - **C12-18-005:** Timelike Compton Scattering off a transversely polarized proton

- Total of **160 PAC days** approved: **~ 20%** of all **approved beam time in Hall C**!

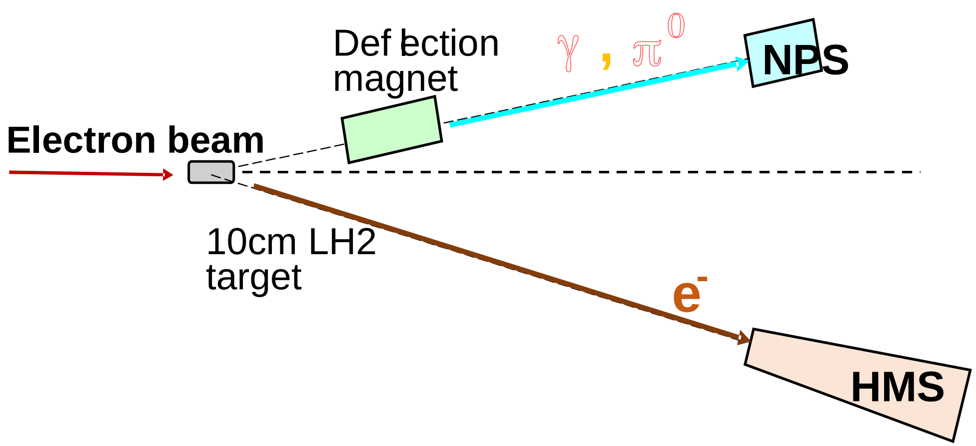
- Scheduling request for **E12-13-010/E12-13-007** (run group) has been submitted

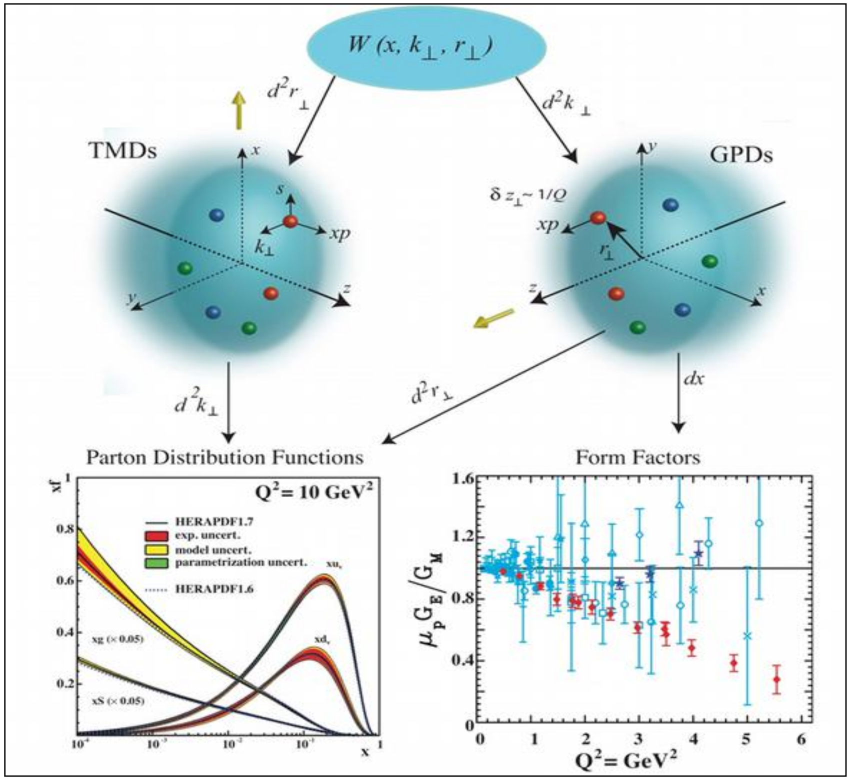
Details on NPS ERR: https://wiki.jlab.org/cuawiki/index.php/NPS_ERR

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

E12-13-010 and E12-13-007





- **E12-13-010** - provides precision measurements of the deeply-virtual Compton scattering cross section at different beam energies to extract the real part of the Compton form factor without any assumptions. Also provides π^0 L/T cross section data to validate the exclusive meson production mechanism – if σ_L large, access to regular GPDs, if σ_T large, then access to transversity may become possible

- **E12-13-007** - measure the basic semi-inclusive neutral-pion cross section in a kinematical region where the QCD factorization scheme is expected to hold, crucial to validate the foundation of this cornerstone of 3D transverse momentum imaging

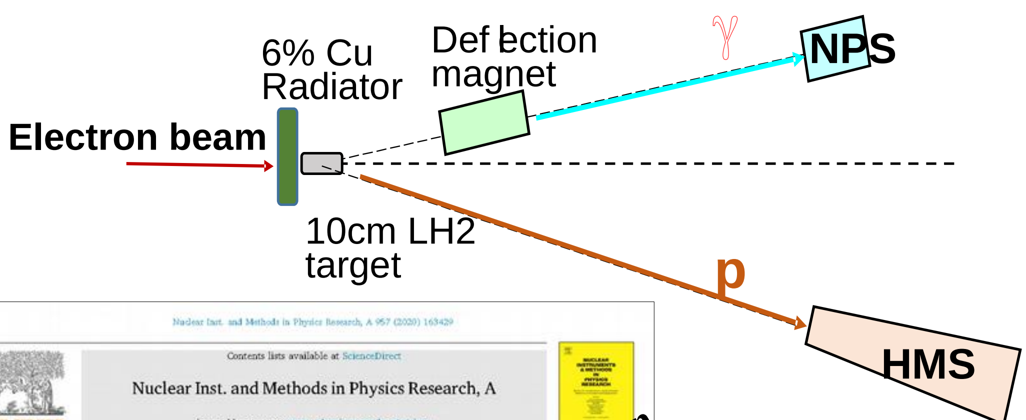
Combine NPS with Compact Photon Source (CPS)

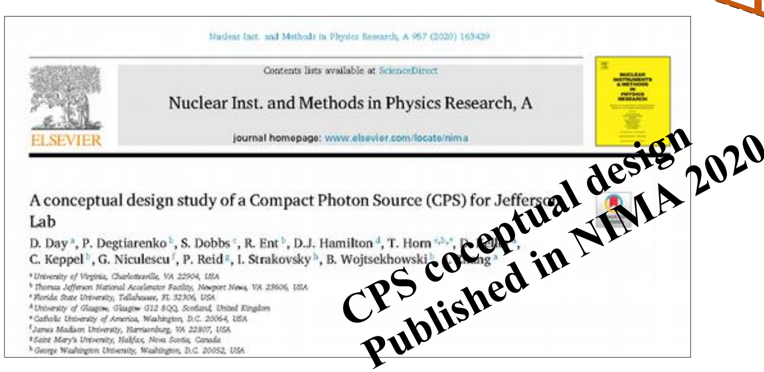
- Much progress in imaging nucleon structure can be made with electron-scattering reactions, yet experiments with high-energy photons play a unique complementary role

- Small scattering probabilities of exclusive reactions demand high-intensity photon beams

- Understanding strengthened by imaging longitudinally-polarized and transversely-polarized nucleons

E12-14-003, E12-14-005 and E12-17-008




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

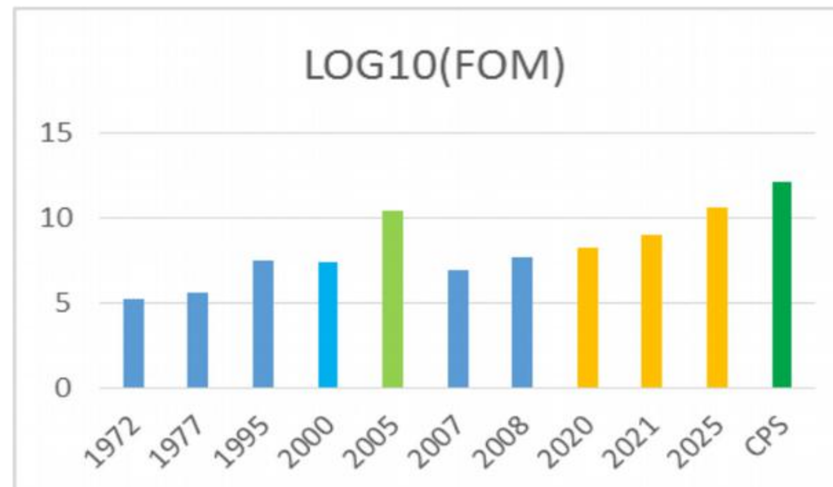
Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

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

D. Day, P. Degtiarenko, S. Dobbs, R. Ent, D.J. Hamilton, T. Horn, ...
C. Keppel, G. Niculescu, P. Reid, I. Strakovsky, B. Wojtsekhowski, ...



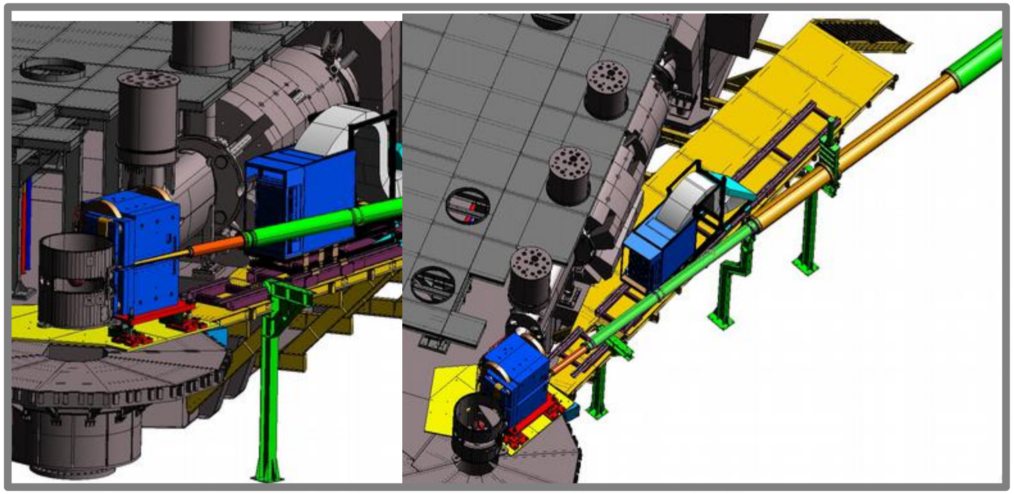
CPS enables a gain of a factor of 30 in figure-of-merit! Enables a new suite of high-energy photon scattering experiments to image and understand the dynamical nucleon structure

- **E12-17-008** - investigate the mechanisms behind RCS – provides crucial insight into the nature of exclusive reactions and proton structure

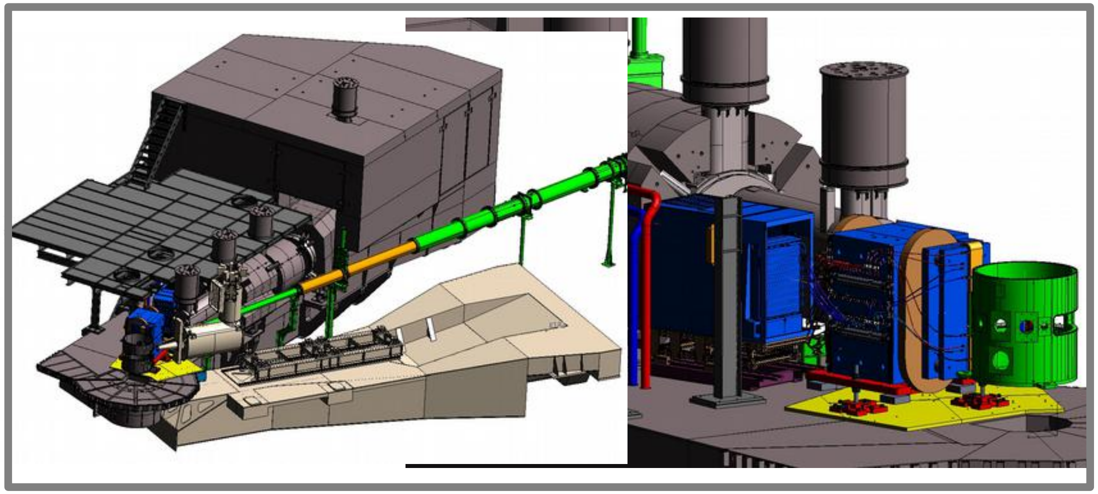
- **C12-18-005** - first fundamental test of the universality of the GPDs, as the GPDs extracted from TCS should be comparable with those extracted from the analogous space-like (electron) scattering process - DVCS

The Neutral Particle Spectrometer

Supported by NSF MRI PHY-1530874



Small angles (6°-23°) configuration



Large angles (23°-57.5°) configuration

- ~25 msr neutral particle detector consisting of ~1080 $PbWO_4$ crystals (30x36 matrix) in a temperature controlled frame including gain monitoring and curing systems
- HV distribution bases with built in amplifiers for operation in a high rate environment
- Essentially deadtime less digitizing electronics to independently sample the entire pulse form for each crystal Jlab developed Flash ADCs
- A 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. For NPS angles from 6 to 23 degrees, the platform will be on the left of the SHMS carriage for NPS angles 23-57.5 degrees it will be on the right
- A beam pipe with as large opening/critical angle for the beam exiting the target/scattering chamber region as possible to reduce beamline-associated backgrounds

The NPS sweep magnet

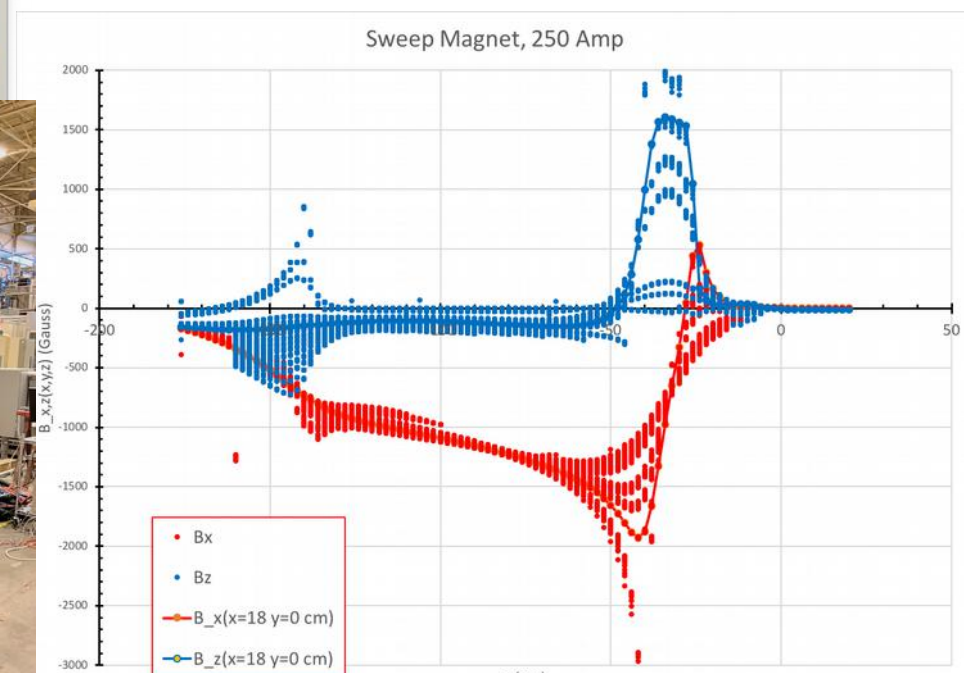
Supported by NSF MRI PHY-1530874

NPS magnet and power supply in test lab

- Normal resistive iron dominated magnet provided by CUA and ODU
- Fully assembled and being tested at JLAB
- Completed fringe field mapping at 25% of full current – next: compare to calculation
- Planning full current tests in Hall C – will there be an opportunity this year (2020)?

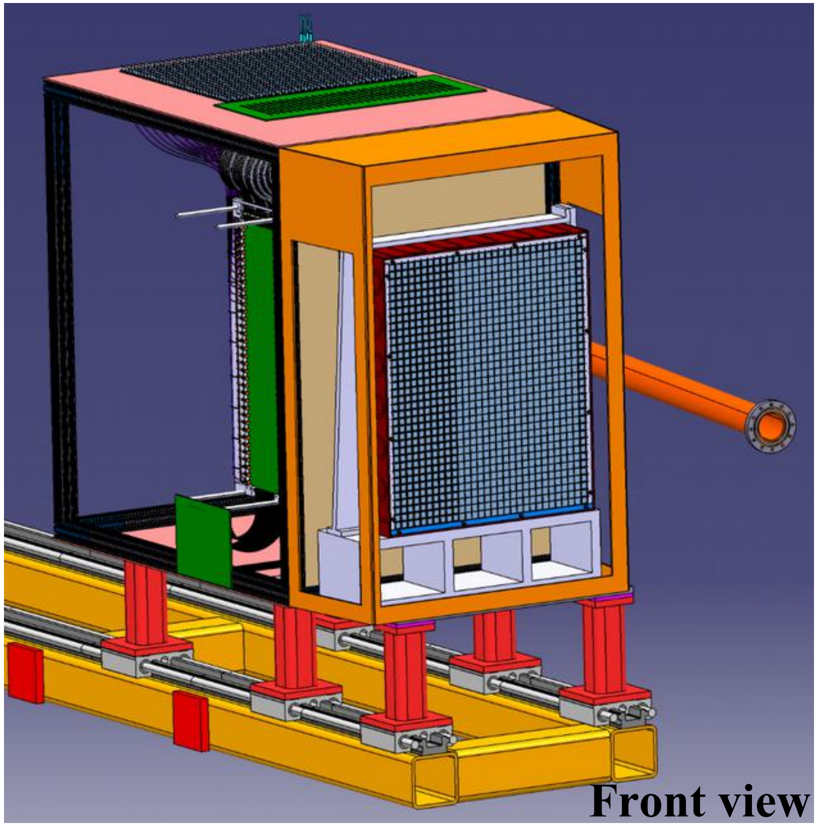
Max Current (Amp)	990
R @ 20°C (Ohm)	0.1
ΔV Max (V)	110
Cooling medium	LCW
ΔP (psi) ΔT (°C)	130 30
Corrector Max (Amp)	520

Mapping equipment



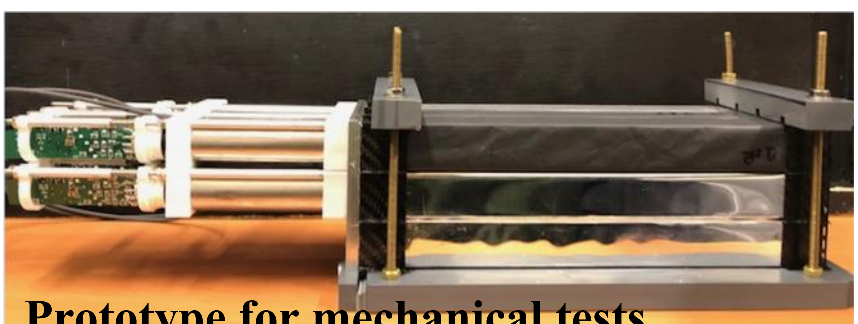
Results from mapping – lots of data acquired!

Calorimeter conceptual design

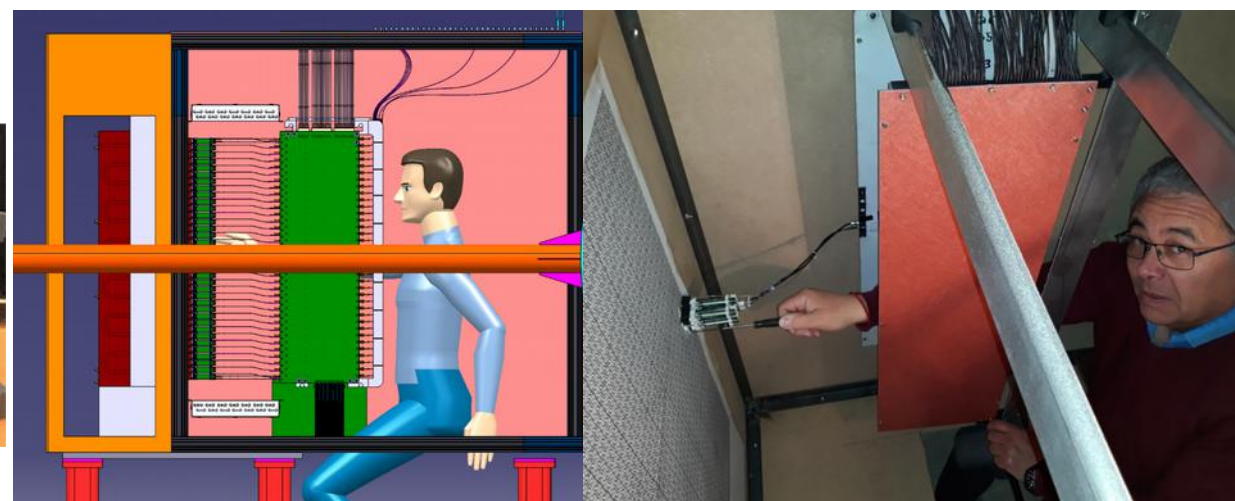


Front view

- 30x36 (1080) $PbWO_4$ crystals of size: 2x2x20 cm3
- Hamamatsu R4125 PMTs with custom active HV bases provided by Ohio U.
- Design completed at IPN Orsay
  - Crystals placed in a 0.5 mm-thick carbon frame to ensure good positioning
  - PMTs accessible from the back side to allow for maintenance
  - Calibration and radiation curing with blue LED light though quartz optical fibers (concept originally designed by Yerevan)



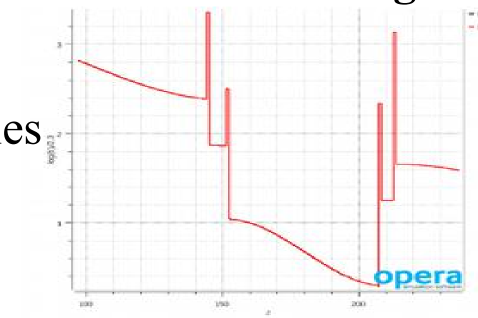
Prototype for mechanical tests



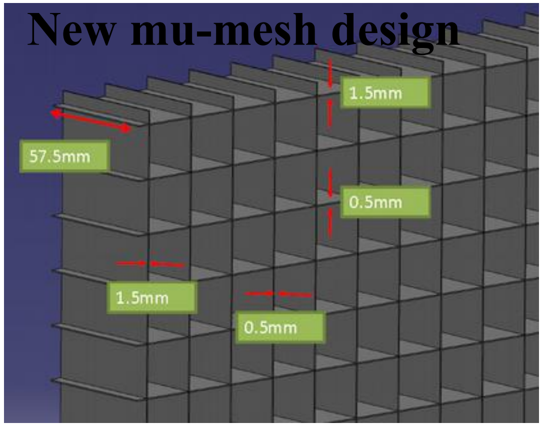
Human size detector!

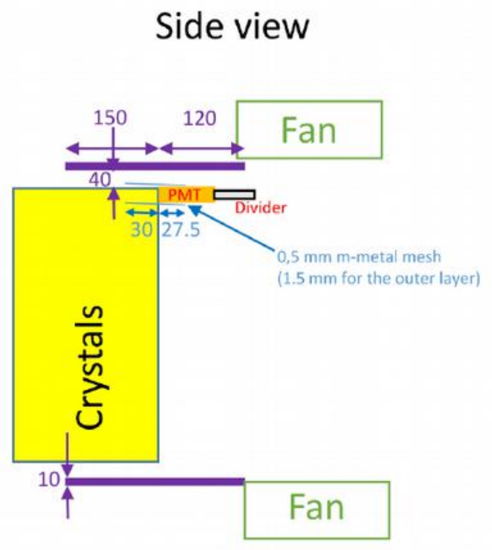
Magnetization studies

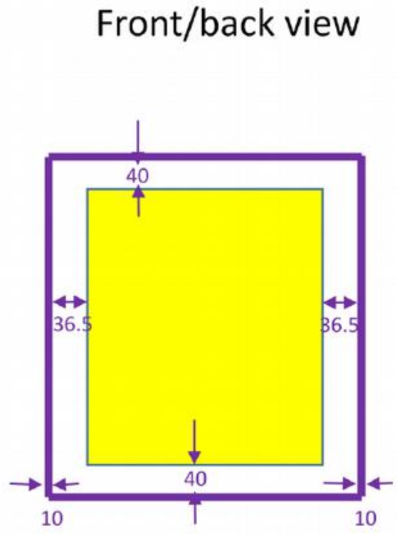
Old shielding

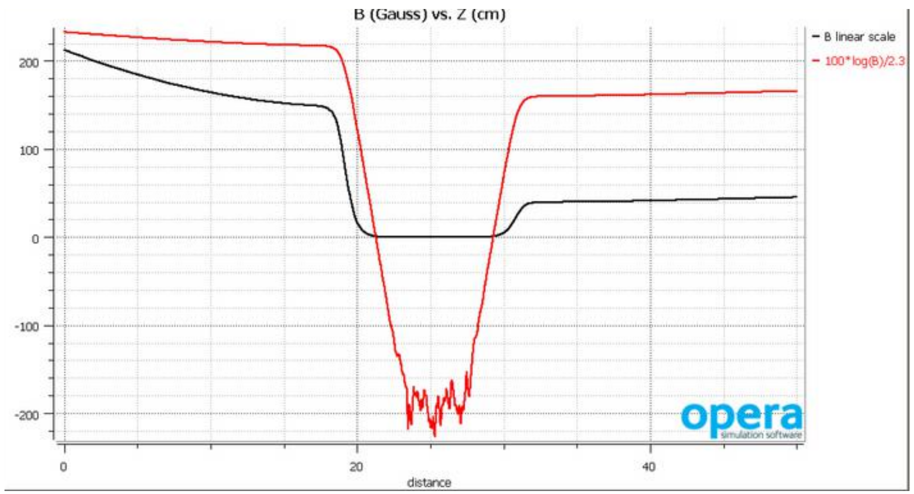


- Found that the magnetic field is large at PMT locations for NPS at small angles (~200 Gauss)
- Adjusted NPS design concept to include
  - a mu-metal mesh around PMTs (30mm in front, 27.5mm towards PMT dynode)
    - Inside 0.5mm thick
    - Outside 1.5mm thick
  - A soft iron (1006) shield box with 10mm thickness
- With the new shielding concept the magnetic field is negligible at the PMT location
  - Field is below 1 Gauss along the 8cm from the PMT front face





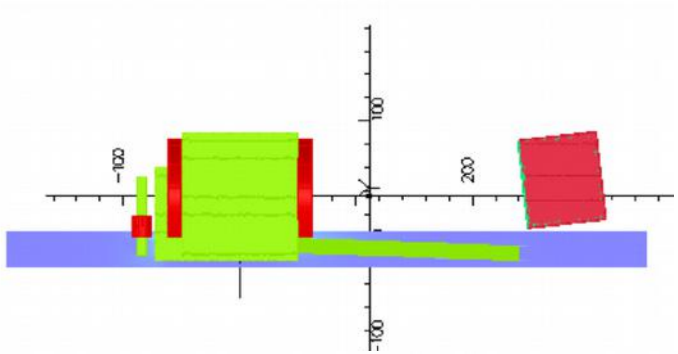


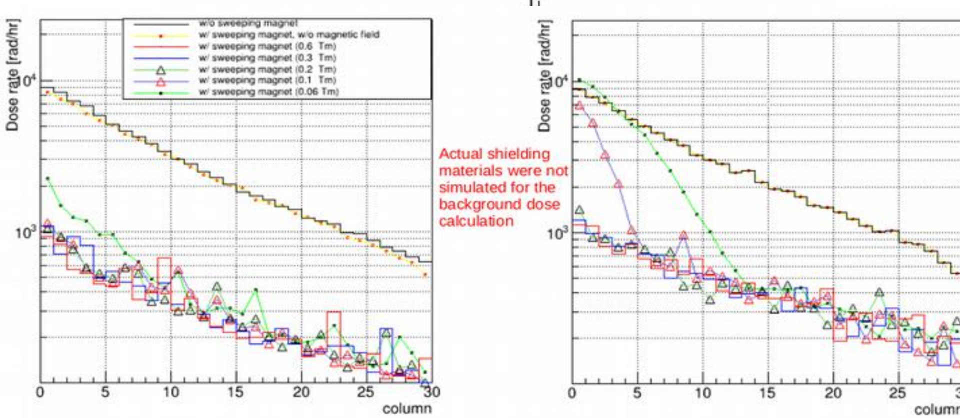


Background simulations

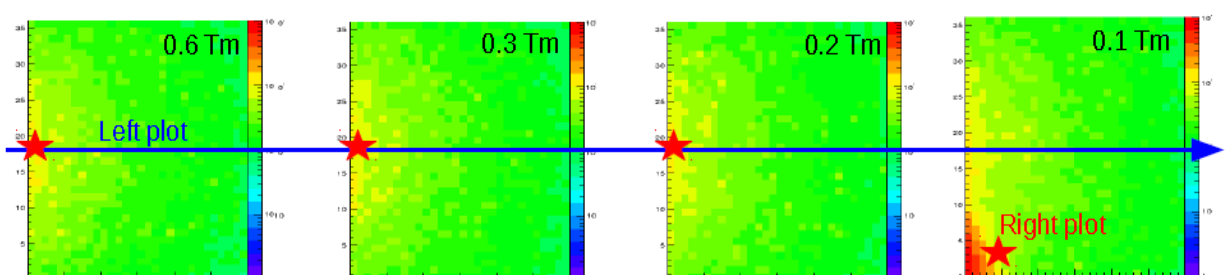
- Simulations of energy and dose distribution of background in NPS shows that particles with energy <10 MeV constitute ~20% of the total energy deposited in the detector – need shielding, magnet field strength doesn’t help

- With the new NPS shielding 0.2Tm is enough to reduce the charged particle backgrounds





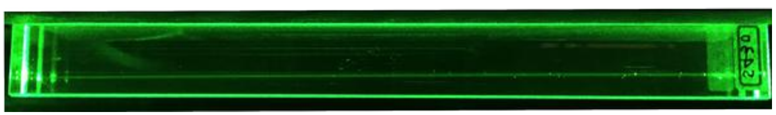
- Magnetic field center: 1.57m from the target
- Magnetic field center: 2.2 deg from the beam-pipe
- Physical magnet`s center: 1.6m from the target
- Physical magnet`s center: 2.3 deg from the beam-pipe
- Magnetic field`s z-axis: goes through the target
- Calorimeter: 4m away from the target
- Calorimeter: 8.5 deg from the beam-pipe
- Calorimeter`s magnetic shielding:
  - iron 1mm+mu-metal 1mm in the front face
  - iron 5mm+mu-metal 1mm in the other 5 faces



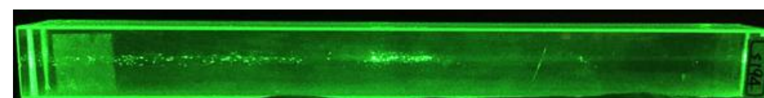
NPS calorimeter: PbWO4 crystals

Supported by NSF MRI PHY-1530874

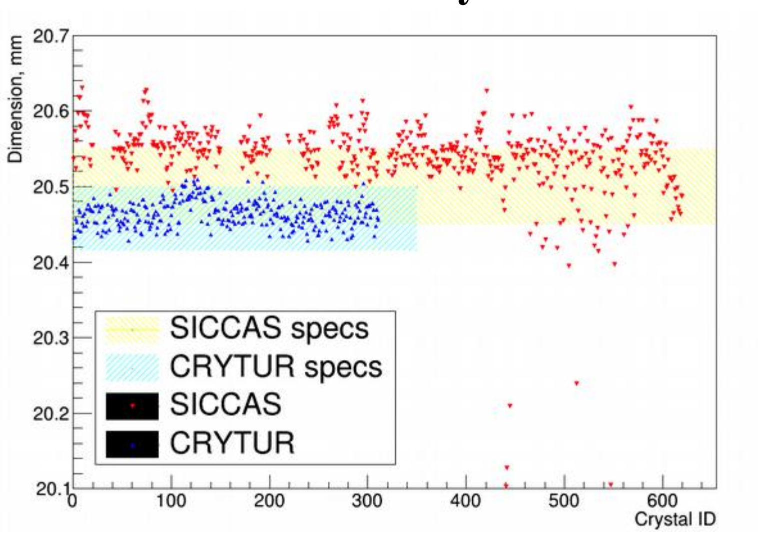
- Only two vendors of PbWO4 crystals available worldwide
- SICCAS/China: failure rate ~30% of crystals produced in 2014-19 due to major mechanical defects
- CRYTUR/Czech Republic: Strict quality control procedures – so far 100% of crystals accepted
- NPS calorimeter crystal coverage:
  - CRYTUR crystals will cover 78.7% of the active volume
  - SICCAS crystals will cover 21.3% (edges)



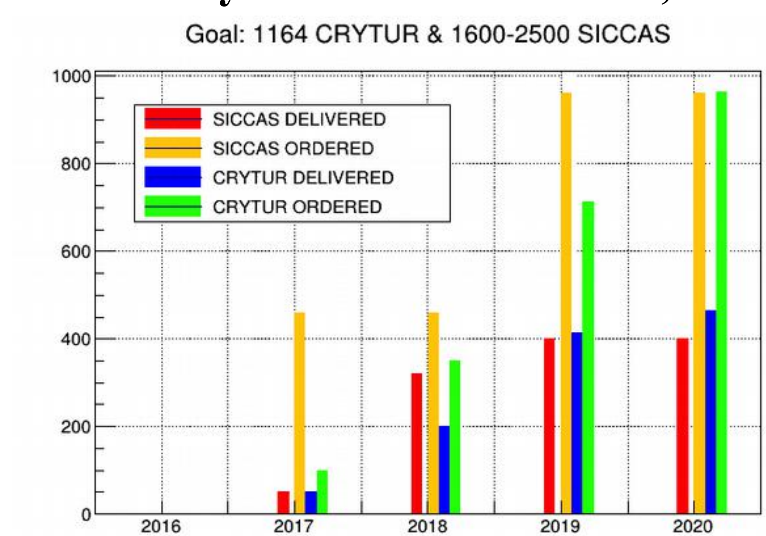
Good crystal



Bad crystal: bubbles in bulk, old labels ...

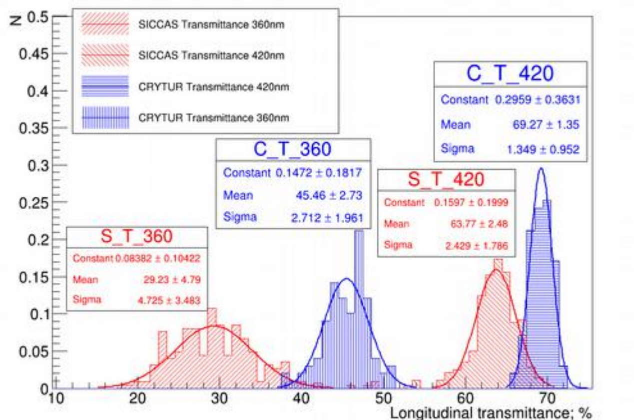


Quality check: dimension uniformity

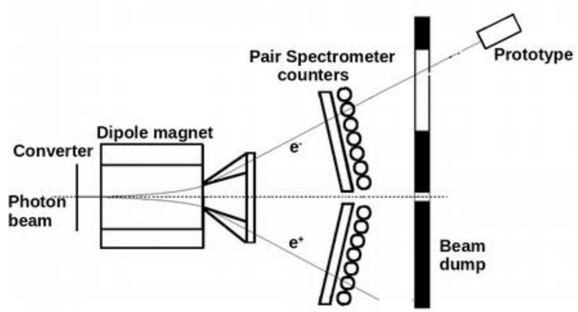


Crystal delivery timeline

PbWO4 crystal properties and performance tests



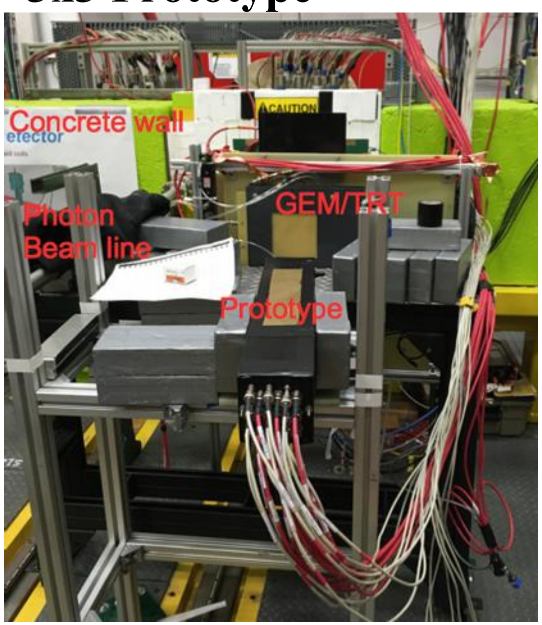
Longitudinal transmittance



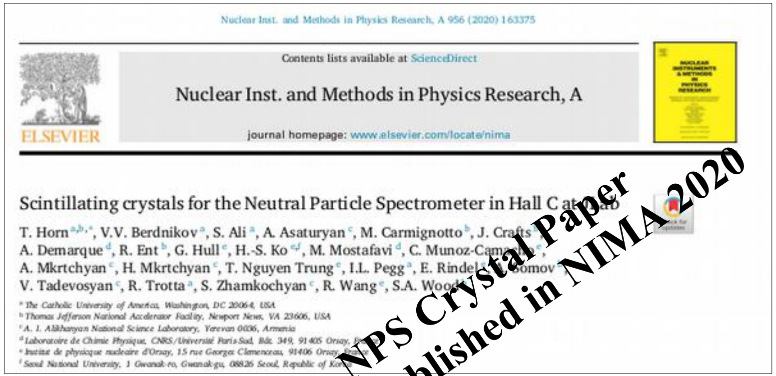
- **Primary quality assurance of the crystals:**
  - Precise dimension measurements and visual inspections
  - Optical transmittance measurements
  - Light yield measured using a radioactive source Na-22 and 2in PMT inside of thermo-controlled darkbox

- **Crystal/glass beam test program in HallD:**
  - Installed the 3x3 prototype behind the PS (2018,2019,2020)
  - Energy resolution measurement
  - Readout chain optimization
  - Glass-ceramic scintillator tests
  - Streaming readout
  - Crystal test stand 12 crystal measured at the same time (2020)
  - Studies of crystal defects, light guides, cookies and etc.

3x3 Prototype



Crystal test stand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Nuclear Inst. and Methods in Physics Research, A

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

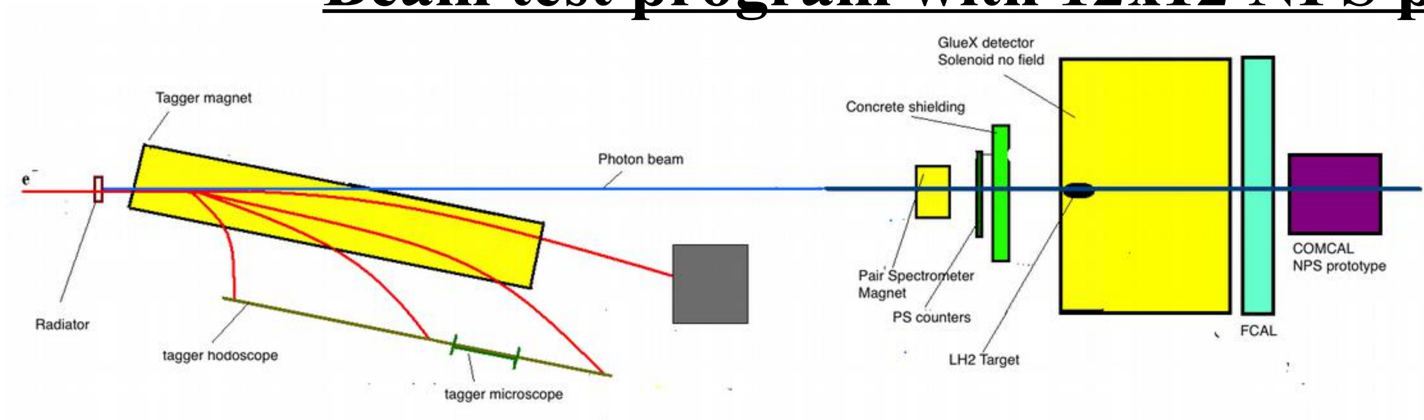
ELSEVIER

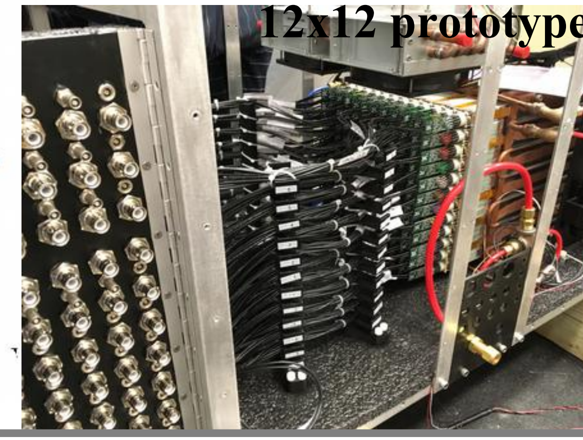
Scintillating crystals for the Neutral Particle Spectrometer in Hall C at JLab

T. Horn, V.V. Berdnikov, S. Ali, A. Asaturyan, M. Carmignotto, J. Crafts, A. Demarque, R. Ent, G. Hull, H.-S. Ko, M. Mostafavi, C. Munoz-Camacho, A. Mkrtchyan, H. Mkrtchyan, T. Nguyen Trung, I.L. Pegg, E. Rindel, A. Somov, V. Tadevosyan, R. Trotta, S. Zhamkochyan, R. Wang, S.A. Wood

NPS Crystal Paper Published in NIMA 2020

Beam test program with 12x12 NPS prototype



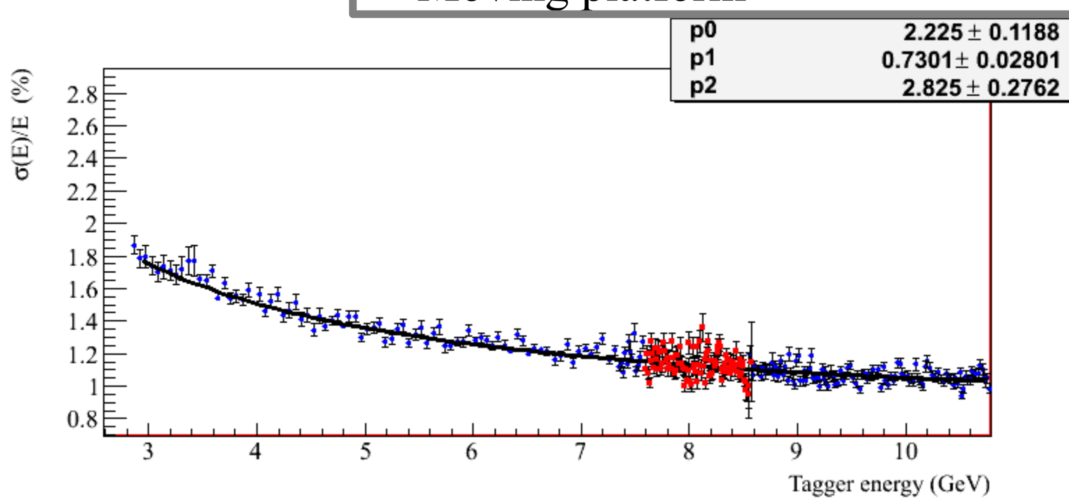


- Built a 12x12 detector for more detailed studies compared to quick checks with the 3x3 prototype
  - Allows for studies of energy resolution in wide energy range, stability, rate dependence, etc.
  - But, not as flexible as 3x3 since cannot run in parasitic mode and has to be installed in the beamline - requires scheduling, crane installation, alignment, slow controls, integration to data stream...

Detector design major components:

- 12x12 Matrix (140 crystals)
- NPS HV divider
- 250 fADC readout
- Environment control:
  - Temperature, humidity, light sensors
- Monitoring system consisting of LED and α-source
- Moving platform

- Beam test program completed in 2019
  - Initial results show energy resolution: ~**2.83%/E+2.23%/√E+0.73%**
  - Ongoing studies to improve linearity
  - Preparing publication on beam test results – to be submitted to NIMA in next few months



Outlook

- NPS experiments (E12-13-007, E12-13-010, E12-14-003, E12-14-005) passed ERR in May 2019 and beam time scheduling request has been submitted
- Sweeper magnet ready for full current test in Hall C
- Frame scheduled to be on-site at the end of summer 2020
- >700 PMT`s received and spot checked 25% - no rejections
- All (1100) active bases assembled
- Calorimeter assembly scheduled for Fall 2020
- Details will be discussed at NPS collaboration meeting Feburary 3 2020

Agenda

3 February 2020 - CC RM L210A

9:00 -9:30 - Welcome – NPS History, Overview and Meeting Goals - *Tanja Horn (CUA)*
9:30 -9:50 - NPS in Hall C – Design Status (platforms, moves) - *Mike Fowler/Paulo Medeiros (JLab)*
9:50 -10:10 - Magnet Status – Field Mapping - *Charles Hyde (ODU)*
10:10 -10:40 - Detector Frame and Infrastructure - *Emmanuel Rindel (IPN Orsay)*
BREAK
11:00 -11:30 - Crystal characterization - *Vladimir Berdnikov (CUA)*
11:30 -11:45 - HV Divider Status - *Julie Roche (Ohio U.)*
11:45 -12:00 - HV Divider Optimization and Results - *Fernando Barbosa (JLab)*
12:00 -12:30 - Simulations and software development - *Ho-San Ko (IPN Orsay)*
LUNCH BREAK
13:30 -13:50 - Hall C Infrastructure – HV, Electronics, DAQ - *Brad Sawatzky (JLab)*
13:50 -14:10 - Hall C Infrastructure – Patch Panels, Cabling, LCW, Power, etc - *Joe Beaufait (JLab)*
14:10 -14:30 - NPS Installation Planning - *Walter Kellner (JLab)*
14:30 -15:00 - NPS Assembly Plan Discussion (magnet, platform and rails, detector, cabling, ...)
15:00 -15:30 - NPS Calorimeter Assembly Discussion
BREAK
16:00 -16:30 - NPS To-Do List Discussion (Gain Monitoring, Calibrations, Software) - *Hamlet Mkrtchyan (ANSL)*
16:30 -17:30 - TCS Conditional Approved Experiment – Plans and To-Do List - *Marie Boer, Dustin Keller, Vardan Tadevosyan*
17:30 - Adjourn

Summary

- 3D Hadron Imaging, encapsulated in the GPDs and TMDs, is one of the key programs at the 12 GeV Jlab
- NPS allows for validation of the exclusive electroproduction reaction mechanism – required for accessing the GPDs and TMDs
- Adding a real photon beam (Compact Photon Source) allows for accessing complementary high-energy photoproduction processes

General requirements of the NPS experiments

Ee=6.6,8.8,11 GeV

	E12-13-010	E12-13-007	E12-14-003	E12-14-005
Angular resolution(mrad)	0.5-0.75	0.5-0.75	1-2	1-2
Energy resolution(%)	(1-2)/√E	(1-2)/√E	5/√E	5/√E
Photon energies	2.6-7.6	0.5-5.7	1.1-3.4	1.1-3.4
Luminosity (cm-2cm-1)	~1038	~1038	~1.5x1038	~1.5x1038
Acceptance	60%/25msr	(10-60)%/25msr		
Beam current (uA)	5-50	5-50	~40;+6% Cu radiator	~40;+6% Cu radiator
Targets	10cm LH2	10cm LH2	10cm LH2	10cm LH2

- Suppress and eliminate charged background - sweeping magnet
- Resolution for photon detection – high light yield; fine granularity
- Expected rates: up to 1MHz- fast response PMT, active base with gain to reduce anode current
- Radiation hardness- integrated doses 20-30kRad, monitoring and curing systems