Hall B Physics Program and Upgrade Plan

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Jefferson Lab

- Introduction
- The Equipment Plan
- The 12 GeV Physics Program
- Conclusions

PAC23 Meeting on the 12 GeV Upgrade, January 20, 2003
Physics Program with \textit{CLAS}^{++} at 12 GeV

- **Quark-Gluon Dynamics and Nucleon Tomography**
  - Deeply Virtual Compton Scattering (DVCS)
  - Deeply Virtual Meson Production (DVMP)
  - High-t DVCS and $\pi^0/\eta$ production

- **Valence Quark Distributions**
  - Proton and Neutron Spin Structure
  - Neutron Structure Function $F_{2n}(x,Q^2)$
  - Tagged Quark Distribution Functions
  - Novel Quark Distribution Functions (tranversity, $e(x)$,..)

- **Form Factors and Resonance Excitations**
  - The Magnetic Structure of the Neutron
  - Resonance Excitation Dynamics

- **Hadrons in the Nuclear Medium**
  - Space-Time Characteristics of Hadronization
  - Color transparency

- **Physics with quasi-real Photons**
Requirements for the CLAS upgrade:

- Retain high statistics capabilities for exclusive processes at beam energies up to 12 GeV
  - Complement missing mass techniques by more complete detection of hadronic final state
  - Increase maximum luminosity to $10^{35}\text{cm}^{-2}\text{sec}^{-1}$
  - Extend particle ID to higher momenta ($e^{-}/\pi^{-}$, $\pi/K/p$, $\gamma/\pi^{0}$)

- Complement CLAS detection system with new Central Detector
  - tracking, magnetic analysis, and photon detection in angular range $5^{o} - 135^{o}$
  - veto events with incomplete determination of final state

- Reduce DC occupancies to reach higher luminosities
  - reduce DC cell sizes
  - new magnetic shielding for Möller electrons

- Upgrade the CLAS Forward detection system
  - implement new threshold Cherenkov detector $p_{\pi} \sim 5 \text{ GeV/c}$
  - improve time-of-flight resolution to $\sim 60\text{psec}$
  - increase calorimeter granularity for $\pi^{0}/\gamma$ separation
CLAS++ - 2D CUT

- Drift Chambers
- Forward Electromagnetic Calorimeter
- Preshower Calorimeter
- Central Detector
- High Threshold Cerenkov Counter
- Forward Time-of-Flight Counters
- Repositioned torus coils
- Inner Electromagnetic Calorimeter
- Low Threshold Cerenkov Counter
The CLAS++ Detector
Central Detector

- TOF light guide
- Flux return
- Superconducting solenoid coil ($B_{max} = 5T$)
- Central EC
- Central Tracker
- Central TOF
- TOF lightguide
- Microstrip
Magnetic Field Distribution in Flux Return Iron

Solenoid Coil

Central B-Field
5 Tesla

Flux Return Iron

$B_z$ (Gauss)

15814.5359855537 to 30794.01371107
Möller Electrons in Target Region

$L = 10^{35} \text{cm}^{-2}\text{s}^{-1}, \quad \Delta T = 250\text{nsec}$

Möller electrons are contained within a $3^\circ$ cone around the beam.
CLAS ++ Central Calorimeter

- PMTs
- Axial fibers
- Tungsten-SciFi
- Polar angle fibers
- Fiber readout

axial readout prototype under construction with 5,500 fibers
The CLAS$^{++}$ Detector
Central Time-of-Flight Detector

additional particle id from $\Delta E_{\text{scint}}$
The CLAS++ Detector
Central Drift Chamber - Cathode Pad Readout

Cathode Pad Chambers:
- 20 pads in azimuth/sl
- 40 pads parallel to beam/sl
- 160 anode wires
- 1600 cathode pads read out
The CLAS++ Detector
Central Microstrip Detector

- silicon wafers
- vertex reconstruction
- high rate operation near target
- tracking in full azimuth

silicon strips
- large angle
- forward angle

pitch ~ 300µm

Layer 1
Layer 2

readout
High $Q^2$, low $t$  $ep \rightarrow eK^+\Sigma^0(\gamma\Lambda(p\pi^-))$ event

Central Detector
Forward Detector System Upgrades

- Replace Region 1, Region 2, Region 3 drift chambers
  => similar design as current DCs, factor 2 smaller cell sizes

- Time-of-flight detector with improved timing resolution

- Forward calorimeter => extend $\gamma/\pi^0$ separation to higher momenta
  + instrument coil regions with calorimetry (PbWO$_4$ crystals)

- New Cherenkov Detector with pion threshold $\sim 5$GeV

- Microstrip detector (forward angle portion)
CLAS^{++} - Electron/pion separation

e^{-} and \pi^{-} inclusive cross sections
The CLAS++ Detector
Inner Cerenkov Detector

$\eta > 99.5\%$

Winston cones, PMTs

Split Mirror system

Radiator Gas CO$_2$
Coil Calorimeter in Torus coil region

Torus coils

Inner Calorimeter

e.g. PbWO$_4$ crystals

Readout with APD or magnetic field insensitive PMTs.
Forward TOF Detector - Improved Time Resolution

- reduce scintillator width to 5cm
- add second scintillator layer

$$\delta T \sim 50-60\text{psec}$$
Pre-shower Calorimeter

Scintillator/lead sandwich, with wavelength shifting fiber readout, \( \sim 4 \) rad. length.

3.5cm

method has been tested

Lead sheet: 1mm thick

Wavelength Shifting Fibers embedded in scintillator

![Graph showing comparison between existing and finer granularity calorimeters]
**CLAS ++ - Expected Performance**

<table>
<thead>
<tr>
<th></th>
<th>Forward Detector</th>
<th>Central Detector</th>
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</thead>
<tbody>
<tr>
<td><strong>Angular coverage:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracks (inbending)</td>
<td>8° - 37°</td>
<td>40° - 135°</td>
</tr>
<tr>
<td>Tracks (outbending)</td>
<td>5° - 37°</td>
<td>40° - 135°</td>
</tr>
<tr>
<td>Photons</td>
<td>3° - 37°</td>
<td>40° - 135°</td>
</tr>
<tr>
<td><strong>Track resolution:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>δp (GeV/c)</td>
<td>0.003p + 0.001p²</td>
<td>δp_T = 0.02p_T</td>
</tr>
<tr>
<td>δθ (mr)</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>δφ (mr)</td>
<td>2 - 5</td>
<td>2</td>
</tr>
<tr>
<td><strong>Photon detection:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy range</td>
<td>&gt; 150 MeV</td>
<td>&gt; 60 MeV</td>
</tr>
<tr>
<td>δE/E</td>
<td>0.09 (1 GeV)</td>
<td>0.06 (1 GeV)</td>
</tr>
<tr>
<td>δθ (mr)</td>
<td>3 (1 GeV)</td>
<td>15 (1 GeV)</td>
</tr>
<tr>
<td><strong>Neutron detection:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>η_{eff}</td>
<td>0.5 (p &gt; 1.5 GeV/c)</td>
<td></td>
</tr>
<tr>
<td><strong>Particle id:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e/π</td>
<td>&gt;&gt;1000 (&lt; 5 GeV/c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;100 (&gt; 5 GeV/c)</td>
<td></td>
</tr>
<tr>
<td>π/K (4σ)</td>
<td>&lt; 3 GeV/c</td>
<td>0.6 GeV/c</td>
</tr>
<tr>
<td>π/p (4σ)</td>
<td>&lt; 5 GeV/c</td>
<td>1.3 GeV/c</td>
</tr>
</tbody>
</table>
## Physics processes measured concurrently - I

Target: H₂  
Beam: E = 11 GeV, P_ε > 0.70  
L = 10^{35} cm^{-2} s^{-1}, 2000 hours

All reactions require:  
Forward tracking, HTCC, Forward TOF, Central solenoid

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Description</th>
<th>Physics quantity</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ep → epγ</td>
<td>DVCS, DVMP, internal qq (twist-2), qGq (twist-3), spin dynamics, proton tomography</td>
<td>GPDs, H, x=ξ</td>
<td>central tracker, central TOF, pre-shower EC, inner EC, central EC</td>
</tr>
<tr>
<td>ep → epε⁺ε⁻</td>
<td></td>
<td>GPDs, -ξ&lt;x&lt;ξ</td>
<td></td>
</tr>
<tr>
<td>ep → e(Δ,N*)γ</td>
<td>N* transition GPDs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ep → ep(ρ,ω,φ)</td>
<td>GPDs spin/flavor separation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ep → eN(π⁰,η,π⁺)</td>
<td></td>
<td>central tracker, central EC</td>
<td></td>
</tr>
<tr>
<td>ep → eN(π⁰,η,π⁺)</td>
<td>hard meson production short distance dynamics</td>
<td>GPDs @ high t</td>
<td>central tracker, central TOF, central EC</td>
</tr>
<tr>
<td>ep → e(π⁺,π⁰,η,K⁺)X</td>
<td>quark transverse momentum-dependent distributions (TMD)</td>
<td>e(x) twist-3 distribution function, twist-3 sum rule</td>
<td>central tracker central TOF</td>
</tr>
<tr>
<td>ep → eN(π⁰,π⁺)</td>
<td>NΔ - R_{EM}, R_{SM} high mass N*, pQCD</td>
<td>approach to scaling spectroscopy of high mass N*</td>
<td>central tracker, central TOF, central EC</td>
</tr>
<tr>
<td>ep → eN(η,π⁺π⁻,ω)</td>
<td></td>
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</tr>
</tbody>
</table>
Modeling of the **Generalized Parton Distributions**

\[ H(x, \xi, 0) \]

Cross section difference

Quark distribution \( q(x) \)

Cross section

\( q\bar{q} \) distribution
DVCS/BH projected for CLAS^{++} at 11 GeV

972 data points measured simultaneously + high t (not shown)

Q^2, x_B, t ranges measured simultaneously.

A(Q^2, x_B, t)
Δσ (Q^2, x_B, t)
σ (Q^2, x_B, t)
CLAS$^{++}$: Kinematics for $ep \rightarrow ep\gamma$ (DVCS)

$E = 11$ GeV

$Q^2 = 2.5 \text{GeV}^2$

$Q^2 = 5 \text{GeV}^2$
Separated Cross Section for $ep \rightarrow epp\rho^0(\pi^+\pi^-)$

$\gamma^* + p \rightarrow \rho^0 + p$

$x_B = 0.3-0.4$

$-t = 0.2-0.3\text{GeV}^2$
Axial Compton Formfactor and NΔ(1232) Transition

\( \gamma^* p \rightarrow p \pi^0 \)

\( \gamma^* p \rightarrow p \pi^0(\gamma\gamma) \)

W > 2 GeV

\( (e^2 R_A(t))^2 \)

also: \( E_{1+}/M_{1+} \)
### Physics processes measured concurrently - II

**Target:** D$_2$
**Beam:** $E = 11$ GeV, $P_e > 0.70$
**L** = $10^{35}$ cm$^{-2}$s$^{-1}$, 2000 hours

All reactions require:
- Forward tracking, HTCC, Forward TOF,
- Central solenoid

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<th>Reaction</th>
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</thead>
<tbody>
<tr>
<td>$eD \rightarrow ep_sX$</td>
<td>S.F. of “free” neutron neutron resonances</td>
<td>$F_{2n}(x,Q^2)$ $A^6_{1/2}, A^6_{3/2}(Q^2)$</td>
<td>central tracker, central TOF, central EC</td>
</tr>
<tr>
<td>$eD \rightarrow ep_s(\pi^-p), \Delta^+\pi^-$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$eD \rightarrow eD\gamma$</td>
<td>DVCS, N$^*$VCS</td>
<td>GPD $H(\xi,\xi,t)$ $G_{N^*}(t)$</td>
<td>central tracker, central TOF, pre-shower EC, inner EC</td>
</tr>
<tr>
<td>$eD \rightarrow ep_s(\Delta^0,N^*)\gamma$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$eD \rightarrow e(M,\gamma)X$</td>
<td>twist-3 distribution functions</td>
<td>$e(x)$</td>
<td>central tracker, central TOF, pre-shower EC</td>
</tr>
<tr>
<td>$eD \rightarrow e(n,p)$</td>
<td>neutron magnetic form factor</td>
<td>$G_{Mn}(Q^2)$</td>
<td>central tracker, central TOF</td>
</tr>
<tr>
<td>ep $\rightarrow e\pi^+n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$eD \rightarrow eD(\rho,\omega,\phi)$</td>
<td>color transparency in coherent VM production</td>
<td>$d\sigma(t1)/d\sigma(t2)$ vs $Q^2$</td>
<td>central tracker, central TOF</td>
</tr>
<tr>
<td>$eD \rightarrow e(\rho,\omega,\phi)X$</td>
<td>color transparency at fixed coherence length</td>
<td>$\sigma_A/A\sigma_N$</td>
<td>central tracker, central TOF</td>
</tr>
</tbody>
</table>
Structure of “Free” Neutrons - e.g. $F_{2n}$

Requires detection of a slow recoil proton at backward angles and with momenta $\sim$60-150MeV/c

Measure $Q^2$ dependence simultaneously
Structure of bound Neutrons & Color Transparency

**Bound Neutron**

**Color Transparency**

\[ D(e,e'p_b)X \text{ in CLAS++} \]

500hrs

\[ eD \rightarrow eD\rho^0 \]

\[ E = 11.5 \text{ GeV} \]

2000 hours at \( L = 10^{35} \text{ cm}^{-2} \text{ sec}^{-1} \)
CLAS$^{++}$: Neutron $G_{Mn}$

$E = 11$ GeV

![Graph](image-url)

- $eD \rightarrow en(p_s)$
- $ep \rightarrow e\pi^+n$
Physics processes measured concurrently - III

Target: Polarized H/D
Beam: \( E = 11 \text{ GeV}, P_e > 0.70, P_p = 0.75, P_D = 0.35 \)
\( L = 10^{35} \text{cm}^{-2}\text{s}^{-1}, 1000 \text{hrs NH}_3, 1000 \text{hrs ND}_3 \)

All reactions require:
Forward tracking, HTCC, Forward TOF

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<tr>
<td>( e_p \rightarrow eX, e_T^p \rightarrow eX )</td>
<td>proton spin structure</td>
<td>( A_{1p}, g_{1p}, g_{2p}, \Gamma_{1p} )</td>
<td>transverse target</td>
</tr>
<tr>
<td>( e_D \rightarrow eX, e_T^D \rightarrow eX )</td>
<td>neutron spin structure</td>
<td>( A_{1n}, g_{1n}, g_{2n}, \Gamma_{1n} )</td>
<td>central tracker, central TOF, preshower EC</td>
</tr>
<tr>
<td>( e_p \rightarrow e\gamma )</td>
<td>DVCS/BH target SSA</td>
<td>GPDs ( \tilde{H}, H, E, \bar{H}, \bar{E} )</td>
<td>central tracker, central TOF, preshower EC</td>
</tr>
<tr>
<td>( e_p \rightarrow e\gamma )</td>
<td>DVCS/BH double asym.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( e_p \rightarrow eN(\pi^0, \eta, \pi^+) )</td>
<td>DVMP target SSA</td>
<td>GPDs ( \tilde{H}, \bar{E} )</td>
<td>central tracker, central TOF, preshower EC</td>
</tr>
<tr>
<td>( e_p \rightarrow eN(\pi^0, \eta, \pi^+) )</td>
<td>DVMP/BH double asym.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( e_p \rightarrow e(\pi^+, \pi^0, \eta, K^+)X )</td>
<td>quark flavor tagging</td>
<td>( A_{UL}, \Delta d_v/d_v )</td>
<td>preshower EC, central tracker, central TOF</td>
</tr>
<tr>
<td>( e_D \rightarrow e(\pi^-, \pi^0, \eta)X )</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>( e_p^T \rightarrow e(\pi^+, \pi^0, \eta, K^+)X )</td>
<td>quark transversity</td>
<td>( A_{UT}^{\sin\phi}, \delta u/u )</td>
<td>transverse target, preshower EC</td>
</tr>
</tbody>
</table>
CLAS++: $A_{1p}(x,Q^2)$, $g_{2p}(x,Q^2)$, $A_{1d}(x,Q^2)$, $A_{1n}(x,Q^2)$

Measure $Q^2$ dependence simultaneously

1000 hrs @ $10^{35}\text{cm}^{-2}\text{s}^{-1}$/target

Measure $Q^2$ dependence simultaneously
Semi-Inclusive Deeply Inelastic Scattering

Flavor separation

Quark transversity

twist-3
# Physics processes measured concurrently - IV

**Target:** Nuclear  
**Beam:** \( E = 11 \text{ GeV}, P_e > 0.70 \)  
\( L = 10^{35}\text{cm}^2\text{s}^{-1}, 2000 \text{ hrs} \)

All reactions require:  
Forward tracking, HTCC, Forward TOF

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<tr>
<td>( e^2H \rightarrow e \text{ hadrons } X )</td>
<td>space-time characteristics of hadronization (DIS kinematics)</td>
<td>Hadronization length vs. ( Q^2, v, p_T, z, ) hadron mass and size, and quark flavor; quark energy loss, gluon emission properties, quark-gluon correlations</td>
<td>central tracker, central TOF, central EC, preshower EC</td>
</tr>
<tr>
<td>( e^{14}N \rightarrow e \text{ hadrons } X )</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>( e^{56}Fe \rightarrow e \text{ hadrons } X )</td>
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<td></td>
<td></td>
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<tr>
<td>( e^{84}Kr \rightarrow e \text{ hadrons } X )</td>
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<td></td>
<td></td>
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<tr>
<td>( e^{197}Au \rightarrow e \text{ hadrons } X )</td>
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<tr>
<td></td>
<td>hadrons = ( \pi^0, \pi^+, \pi^-, \eta, \omega, \eta', \phi, K^+, K^- K^0, p, \bar{p}, \Lambda, \Lambda(1520), \Sigma^+, \Sigma^0, \Xi^0, \Xi^- )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( e^{14}N \rightarrow \rho X )</td>
<td>color transparency in ( \rho ) production from complex nuclei</td>
<td>color transparency at fixed coherence length</td>
<td>central tracker, central TOF</td>
</tr>
<tr>
<td>( e^{56}Fe \rightarrow \rho X )</td>
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</tbody>
</table>
Space-Time Characteristics of Nuclear Hadronisation
Physics potentials with forward electron facility

Meson spectroscopy, e.g. with $^4$He - gas targets

Heavy baryon spectroscopy, e.g. $\Xi^*$

Time-like virtual-Compton-scattering “$\gamma$”p -> pe$^+e^-$

Structure functions at very low $Q^2$

$J/\psi$ production

others...
Physics goals with $\textit{CLAS}^{++}$ and $\textit{Hall B}$

The primary goal of experiments using the $\textit{CLAS}^{++}$ detector at energies up to 12 GeV is the study of the internal nucleon dynamics in terms of elementary degrees of freedom, and the QCD structure of hadrons in the nuclear medium. Towards this end, the detector has been optimized for studies of \textit{exclusive} and \textit{semi-inclusive} reactions in a wide kinematic range. \textit{Inclusive} processes, for which the unique properties of the $\textit{Hall B}$ instrumentation are essential (e.g. polarized NH$_3$(ND$_3$), neutron tagger, forward electron tagger), will be measured as well.