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Research perspectives at Jefferson Lab: 12 GeV and beyond

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Abstract. The plans for upgrading the CEBAF accelerator at Jefferson Lab to 12 GeV are presented. The research program supporting that upgrade is illustrated with a few selected examples. The instrumentation under design to carry out that research program is discussed. Finally, a conceptual design of a future upgrade which combines an electron-ion collider facility at a luminosity of up to 10^{35} cm^{-2}s^{-1} and a CM energy of up to 65 GeV with a 25 GeV fixed-target facility.

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1 Introduction

The design parameters of the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLab) were defined nearly two decades ago. In that period our understanding of the behaviour of strongly interacting matter has evolved significantly, providing important new classes of experimental questions which can be optimally adressed by a CEBAF-type accelerator at higher energy. The original design of the facility, coupled to developments in superconducting RF technology, makes it feasible to triple the initial design value of CEBAF's beam energy to 12 GeV in a cost-effective manner (at about 15% of the cost of the initial facility).

The research program with the 12 GeV upgrade will provide breakthroughs in two key areas: (1) gluonic excitations of mesons and the origin of quark confinement and (2) the unified description of the quark-gluon content of the nucleon. The upgrade will provide important advances in two additional areas: (1) a unified description of high-density cold nuclear matter and (2) measurements which test the Standard Model. A detailed overview of the upgrade research program is given in the recent pre-Conceptual Design Report [1].

2 Research program

The dynamics of quarks and gluons leading to the phenomenon of confinement are among the outstanding unsolved problems in physics. Theory and computation in lattice QCD have led to the concept of quarks interacting through the development of flux tubes. These flux tubes contain the gluonic degrees of freedom, which can be excited to generate "hybrid" states. Whereas a few experimental indications for the gluonic excitation of mesonic states have been reported, the 12 GeV upgrade would be the unique facility for a systematic search of such states. It would provide a hitherto unavailable combination of kinematical reach and statistics.

Recent theoretical advances [2] have established, within the framework of QCD, the impact of Generalized Parton Distributions (GPD), which are accessible through deeply virtual and exclusive reactions. These GPDs contain the correlations between quark states of different momenta and thus reach beyond the standard parton distributions. They provide, among other properties, a simultaneous determination of the longitudinal momenta of quarks and of their transverse position within the nucleon: for the first time it will become possible to build a three-dimensional picture of the nucleons from experimental data. It also promises to determine the contribution of the quark orbital angular momentum to the nucleon spin. Exclusive reactions, such as deeply virtual Compton scattering and meson production, will be measured with unprecedented precision and kinematical range with the 12 GeV upgrade.

With the 12 GeV upgrade Jefferson Lab will be unique in its ability to attain in nuclear reactions very high values of Q^2 and x_B along with an excellent resolution. This ability represents a unique tool for studying high-density configurations in the nuclear ground state. Such studies will determine the limits of hadron-based nuclear physics from a comparison to results from ab-initio nucleon-based calculations. Short-range nucleon-nucleon correlations can be studied with great sensitivity in quasi-elastic electrodisintegration of light nuclei, in deep-inelastic electron-nucleus scattering at x_B-values greater than 1, in semi-inclusive measurements of a nucleon from the target fragmentation region and in the elastic form factors of few-nucleon systems. In reactions at high momentum transfer the color-singlet nature of strongly interacting matter will be emphasized. Examples of such experiments are photo-disintegration of the deuteron, studies aimed at identifying point-like configurations (color transparency) in nuclei and nuclear hadronization processes.

Precision parity-violating electron scattering experiments with the 12 GeV upgrade have the sensitivity to search for deviations from the Standard Model that could signal the presence of new gauge bosons, of leptoquarks or of particles predicted by supersymmetry. Of clear importance will be a new measurement of the weak charge of the electron. A Møller scattering experiment similar to the SLAC E158 experiment could achieve half the uncertainty achieved in E158. An 11 GeV measurement of parity-violating DIS could easily attain the precision required to determine whether the NuTeV result is a true indication of new physics. The present program of measuring the $\pi^\circ \to \gamma\gamma$ decay width via the Primakoff effect can be extended at 11 GeV to include the η and $\eta\prime$ mesons. Such measurements will significantly enhance our knowledge of the u and d quark mass ratio.

3 Accelerator

At present CEBAF accelerates electrons to 6 GeV by recirculating the beam four times through two superconducting linacs, each producing an energy gain of 600 MeV per pass. Both linac tunnels provide sufficient space to install five additional newly designed cryomodules. The new cryo-modules will each provide over 100 MV (compared to the 28 MV from the existing ones), by increasing the gradient to 20 MV/m and the number of cavity cells from five to seven. This will result in a maximum energy gain per pass of 2.2 GeV, providing a maximum beam energy to Halls A, B and C of 11 GeV. The new Hall D will be provided with the desired maximum energy of 12 GeV by adding a tenth arc and recirculating the beam a fifth time through one linac. A total of 90 μA of CW beam can be provided at the maximum beam energy. Further modifications required are changing the dipoles in the arcs from C-type to H-type magnets, replacing a large number of power supplies and doubling the central helium liquifier capacity to 10 kW. An overview of the upgrade of the accelerator is shown in Fig. 1.

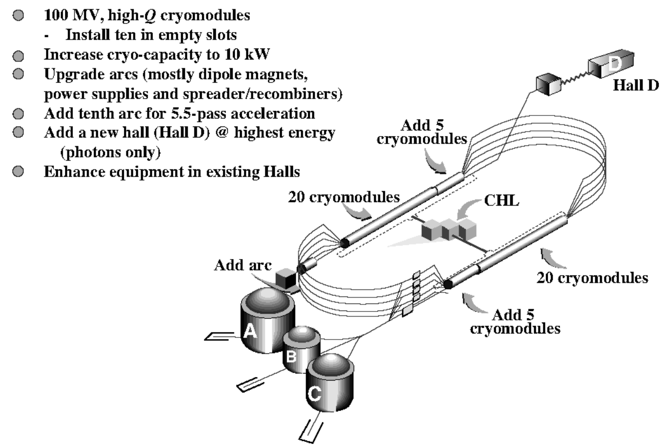

Fig. 1. Overview of the accelerator upgrade to 12 GeV

Two instrumentation upgrades are proposed to allow an optimal study of the intended experiments: a magnetic spectrometer, dubbed MAD (Medium Acceptance Detector), and an electro-magnetic calorimeter. The proposed MAD device is a magnetic spectrometer built from two combined-function (quadrupole and dipole) superconducting magnets. The design provides a maximum central momentum of 7.5 GeV/c at a total bend angle of 20°. It is expected that even higher momenta can be accommodated for specific experiments by decreasing the deflection of the second magnet. MAD has a momentum resolution of better than 10^{-3} and an angular resolution of better than 1 mrad. A pointing accuracy of better than 0.5 mrad required for an accurate L/T separation can be obtained. The angular acceptance is 28 msr at angles larger than 35° and decreases linearly to 6 msr at an angle of 12°. An angle as small as 5° can be reached by using one of the existing septum magnets. This design has resulted in the characteristics shown in Table 1.

Table 1. The design characteristics of the MAD spectrometer shown along with the HRS performance

Parameter	MAD design	HRS performance
Central momentum range	0.4 - 7.5 GeV/c	0.2 - 4.3 GeV/c
Scattering angle range	5° - 130°	6° - 150°
Momentum acceptance	±15%	±5%
Momentum resolution	0.1%	0.02%
Angular acceptance	28 msr (≥35°)	6 msr (standard)
	4-6 msr ($5^\circ - 12^\circ$)	12 msr (forward)
Angular resolution (hor)	1 mrad	0.5 mrad
Angular resolution (ver)	1 mrad	1 mrad
Target length acc. (90°)	50 cm	10 cm
Vertex resolution	0.5 cm	0.1 cm
Maximum DAQ rate	20 kHz	5 kHz
e/h Discrimination	0.5×10^5 at 98%	1×10^5 at 98%
π/K Discrimination	1000 at 95%	1000 at 95%

The basic detector package for the MAD spectrometer, covering the full momentum and angular acceptance, includes: fast high-resolution tracking chambers, a hydrogen-gas Čerenkov counter, trigger scintillator counters and a lead-glass hadron rejector. For the detec-

4 Hall upgrades

4.1 Hall A

The present base instrumentation in Hall A has been used with great success for experiments which require high luminosity and high resolution in momentum and/or angle of at least one of the reaction products. The central elements are the two High Resolution Spectrometers (HRS). Both devices provide a momentum resolution of better than 2×10^{-4} and an angular resolution of better than 1 mrad with a design maximum central momentum of 4 GeV/c.

tion of hadrons a variable-pressure gas Čerenkov counter, two diffusely reflecting aerogel counters, a Ring Imaging Čerenkov counter and a Focal Plane Polarimeter will also be available. The data acquisition system is designed with a new generation of pipeline digitizing front-end electronics in order to handle event rates up to 20 kHz.

In combination with the MAD spectrometer, a 100 msr lead-glass calorimeter is available for studies of nucleon form factors and of Real Compton Scattering. A large acceptance, high granularity calorimeter with a 1296 element array of PbF_2 crystals is proposed to optimally study Generalized Parton Distributions through Deep Virtual Compton Scattering. It would also benefit other experiments, such as photo-production of neutral mesons at large transverse momenta.

With the cross section dropping rapidly with increasing Q^2, a large acceptance spectrometer that can operate at a high luminosity is crucial for precision measurements. In combination with the existing HRS or calorimeter in Hall A, MAD will open up a window to a rich research program, including measurements of:

- Polarized and unpolarized quark distributions up to large x, using polarized proton and ^3He targets. Values of x larger than 0.8 can be probed once spin duality has been established;
- Semi-inclusive $\pi^{\pm}$ and $K^{\pm}$ electroproduction in order to separate the spin and flavor components of the sea quark distributions up to $x \approx 0.65$;
- Nucleon form factors to significantly larger Q^2-values, over 5 $(\mathrm{GeV/c})^2$ for G_E^n and over 14 $(\mathrm{GeV/c})^2$ for G_E^p;
- Real Compton Scattering up to $s \approx 20$ $(\mathrm{GeV/c})^2$ and $|t| \approx 15$ $(\mathrm{GeV/c})^2$ and Deep Virtual Compton Scattering up to $Q^2 \approx 7$ $(\mathrm{GeV/c})^2$ and $x \approx 0.5$;
- Deuteron photo-disintegration up to photon energies of 7 GeV over a large range of CM angles, with recoil polarization up to a photon energy of 4 GeV;
- Few-body elastic form factors to Q^2-values of over 10 $(\mathrm{GeV/c})^2$;
- Parity violation in deep inelastic scattering with very high accuracy to probe possible extensions of the Standard Model,
- Threshold ψ photoproduction to study the color Van der Waals-type component of the NN force.

4.2 Hall B

The CEBAF Large Acceptance Spectrometer (CLAS) in Hall B is used for experiments that require the detection of several, loosely correlated particles in the hadronic final state at a limited luminosity. CLAS is a magnetic toroidal multi-gap spectrometer. Its magnetic field is generated by six superconducting coils. The detection system consists of drift chambers to determine the track of a charged particle, gas Čerenkov counters for particle identification, scintillation counters for the trigger and for measuring time-of-flight and electromagnetic calorimeters to detect showering particles like electrons and photons. CLAS presently operates at a luminosity of 10^{34} $\mathrm{cm^{-2}s^{-1}}$.

The CLAS upgrade CLAS++ incorporates two major improvements: (1) increasing the luminosity by an order of magnitude to account for the lower cross section values, (2) providing a more complete detection of the hadronic final state. The use of major components (torus magnet, scintillators, Čerenkov counters and EM calorimeters) will be retained. The tracking chambers will be replaced and a new central detector added. Table 2 summarizes the expected performance of CLAS++.

Table 2. CLAS++: acceptance and resolution

	Forward detector	Central detector
Angular coverage		
Tracks (inbending)	8° - 37°	40° - 135°
Tracks (outbending)	5° - 37°	40° - 135°
Photons	3° - 37°	40° - 135°
Track resolution		
$\delta p/p$	$0.003 + 0.001p$	$\delta p_T/p_T = 0.02$
$\delta\theta$ [mrad]	1	8
$\delta\phi$ [mrad]	2 - 5	2
Photon detection		
Energy range [MeV]	> 150	> 60
$\delta\theta$ [mrad]	4 at 1 GeV	15 at 1 GeV
Neutron detection		
η_{eff}	0.5 ($p > 1.5$ GeV/c	NA
Particle ID		
Electron/pion	> 1000 ($p < 4.8$ GeV/c)	NA
	> 100 ($p > 4.8$ GeV/c)	NA
π^+/π^-	full range	< 0.65 GeV/c
K/π	full range	< 0.65 GeV/c
$K^+/p, K^-/\bar{p}$	< 4.5 GeV/c	< 0.90 GeV/c
$\pi^\circ \to \gamma\gamma$	full range	full range
$\eta \to \gamma\gamma$	full range	full range

With these modifications and additions to the existing CLAS components, CLAS++ will be able to carry out a core program for the study of internal nucleon dynamics and hadronization processes as listed here:

- Quark-gluon dynamics and nucleon tomography through measurement of deeply virtual Compton scattering and deeply virtual meson production, both with unpolarized and polarized hydrogen and deuterium targets;
- Polarized and unpolarized valence quark distributions at high x_B, using polarized hydrogen and deuterium targets, and by employing a novel technique of neutron tagging. Values of x_B up to 0.85 can be accessed in deep inelastic processes. A broad program of semi-inclusive measurements will allow quark-flavor tagging and give access to transverse quark structure functions;
- The magnetic structure of the neutron will be probed through magnetic form factor measurements up to $Q^2 \approx 14$ $(\mathrm{GeV/c})^2$, and the C2/M1 ratio for the $N \to \Delta(1232)$ up to $Q^2 \approx 12$ $(\mathrm{GeV/c})^2$. Higher mass resonance transitions can be studied in multiple meson decays at high Q^2 as well;
- Space-time characteristics of quark hadornization and color transparency can be studied in nuclei in highly sensitive processes;

– Meson spectroscopy on $^{3,4}He$ with a small-angle quasi-real photon tagger allows to eliminate baryonic background. Heavy baryon spectroscopy (*e.g.* Ξ) can be studied on hydrogen targets.

4.3 Hall C

The Hall C facility has generally been used for experiments which require high luminosity at moderate resolution. The core spectrometers are the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS). These two devices have been used flexibly as either electron or hadron arms, at times in coincidence with each other, at times in coincidence with a third experiment-specific arm. The HMS has a maximum momentum of 7.6 GeV/c, the SOS a value limited to only 1.7 GeV/c.

For the upgrade the SOS spectrometer will be replaced by the so-called Super High Momentum Spectrometer (SHMS). The SHMS design consists of two superconducting quadrupoles and one combined-function magnet. It will have a maximum momentum of 11 GeV/c, a minimum scattering angle of 5.5°, a momentum acceptance (resolution) of ±20 (0.2)% and an angular acceptance (resolution) of 2 msr (2 mrad). The basic configuration of the detector stack would consist of DC tracking chambers, trigger scintillator hodoscopes and a lead glass calorimeter. The overall specifications of the Hall C spectrometer set-up for 11 GeV running are summarized in Table 3.

Table 3. Summary of the design specifications for the SHMS and the HMS performance

Parameter	SHMS Specification	HMS Performance
Central momentum range	2.5 - 11 GeV/c	0.4 - 7.3 GeV/c
Scattering angle range	5.5° - 25°	10.5° - 90°
Momentum acceptance	-15 to +25%	±10%
Momentum resolution	<0.2%	0.1%
Angular acceptance	2 msr (SSA tune)	6.7 msr
	4 msr (LSA tune)	
Angular resolution (hor)	2-4 mrad	0.8 mrad
Angular resolution (ver)	1-1 mrad	1 mrad
Target length acc. (90°)	50 cm	10 cm
Vertex resolution	0.2-0.6 cm	0.3 cm
Maximum DAQ rate	10 kHz	2 kHz
e/h Discrimination	10^3 at 98%	10^3 at 98%
π/K Discrimination	100 at 95%	100 at 95%

With the new equipment Hall C will be able to deliver, amongst others:

– A charged pion from factor measurement up to $Q^2 \approx 6$ (GeV/c)^2;
– Deep exclusive pion and kaon electroproduction up to $Q^2 \approx 10$ (GeV/c)^2, including precise longitudinal-transverse separations and spin-dependent measurements;
– Nucleon elastic and transition form factors to $Q^2 \approx 18$ (GeV/c)^2;
– Real Compton Scattering up to $s \approx 20$ (GeV/c)^2;
– Complete separation of the F_L, F_T, g_1 and g_2 inclusive structure functions of the proton (in the valence quark region) up to $Q^2 \approx 10$ (GeV/c)^2;

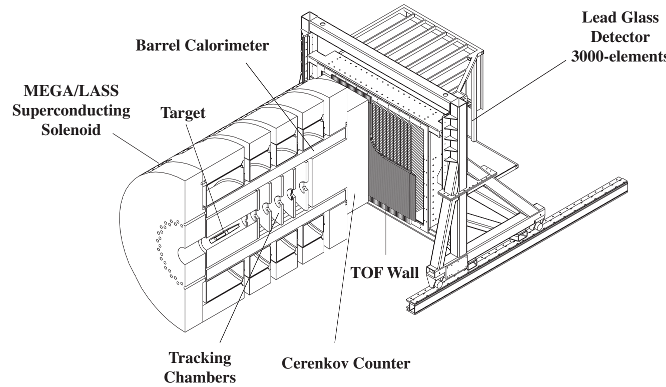

Fig. 2. Schematic view of the detector in Hall D

– Precision measurements of the Q^2-dependence of nuclear effects in both inclusive structure functiuons and (deep) exclusive scattering, crossing the charm threshold;
– A parity violation deep inelastic scattering experiment with unprecedented precision, to search for extensions of the Standard Model.

4.4 Hall D

The GlueX experiment in Hall D will be focused on a definitive measurement of the spectrum of exotic hybrid mesons, which are expected in a mass range from 1 to 2.5 GeV/c^2. Lattice QCD calculations have convincingly illustrated [3] the linear quark-quark potential necessary for confinement. However, very little is still known about the direct excitation of the flux tube. The observation of such direct manifestations of gluonic degrees of freedom will provide understanding of confinement [4]. The quantum numbers of the flux tube, added to those of a $q\bar{q}$ meson, can produce exotic hybrids with unique J^{PC} quantum numbers. These excitations can be probed far more effectively with photons than with π^- or K-mesons, because the quark spins are aligned in the virtual vector-meson component of the photon. For a full partial-wave analysis of such excitations linearly polarized photons are a requisite.

The optimum photon energy for production of exotic hybrids in its expected mass range is between 8 and 9 GeV. Linearly polarized photons in this energy range are optimally produced by coherent bremsstrahlung with 12 GeV electrons. The Hall D detector provides a nearly hermetic acceptance for both charged and neutral particles and includes several particle identification systems. Figure 2 is a schematic representation of the proposed detector. Momentum analysis of charged particles is achieved with a superconducting solenoid and tracking chambers. The final planned photon flux is 10^8 photons/s. At this flux the experiment will acumulate in one year of running a factor of 100 more meson data than are presently available even from pion production. The primary characteristics of the detector are given in Table 4. Its hermetic design makes it an ideal tool to:

– Determine the masses and quantum numbers of mesons in the mass range of 1.5 to 3.5 GeV/c^2;
– Study properties of hybrid mesons produced at rates as low as a few percent of that of normal mesons;
– Map out the poorly known spectra of $s\bar{s}$ mesons.

Table 4. Summary of the GlueX detector's characteristics

	Range
Charged particles	
Coverage	$1 \le \theta \le 170°$
Momentum resolution	$\sigma_p/p \approx 1 - 2\%$
Position resolution	$\sigma \approx 150 - 200\mu$m
dE/dx measurements	$20 \le \theta \le 140°$
Vertex detector	$\sigma \approx 500\mu$m
Time-of-flight scintillators	$\sigma_t \approx 50$ ps
Čerenkov for π/K separation	$\theta \le 14°$
Barrel time resolution	$\sigma_t \approx 250$ ps
Photon detection	
Energy measurements	$1 \le \theta \le 120°$
Veto capability	$\theta \ge 120°$
Lead glass energy resolution	$\sigma_E/E \approx 2 + 5\%/\sqrt{E}$
Barrel energy resolution	$\sigma_E/E \approx 4.4\%/\sqrt{E}$
Barrel position resolution	$\sigma_z \approx 1$ cm
DAQ/ trigger	
Level 1	200 kHz
Event rate	15 kHz to tape
Data rate	100 MB/s

5 Electron-ion collider

Conceptual design studies [5] have indicated that the JLab facility can be further upgraded to provide a high-luminosity Electron Light-Ion Collider (ELIC) in the 20-65 GeV center-of-mass energy range. Such a facility would uniquely address the following research goals: (1) to complete our understanding of how quarks and gluons provide the binding and the spin of the nucleon, (2) to understand how quarks and gluons evolve into hadrons via the dynamics of confinement and (3) to refine our understanding of how the nuclear binding arises from QCD. A schematic lay-out of the ELIC collider is shown in Fig. 3. Longitudinally polarized electrons are injected into the CEBAF accelerator and accelerated to 5-7 GeV in a single pass (after all of the remaining 20 MV cryo-modules have been replaced by new 100 MV modules). The electrons are then injected into a circulator ring, in which they collide with the ions. After appr. 100 revolutions they are extracted and transported back for deceleration and energy recovery. ^1H, ^2H and ^3He ions are injected longitudinally polarized and accelerated in a conventional RF linac to a maximum energy of 200 MeV. After pre-boosting to 2-3 GeV the ions are stacked and accelerated in a "Fig. 8" ring to a maximum of 150 GeV. The "Fig. 8" ring provides flexible spin manipulation and preservation. This design results in a maximum CM energy of appr. 65 GeV. A luminosity of 5×10^{34} cm^{-2}s^{-1} appears feasible through the use of electron cooling and crab crossings. Ions of up to mass 40, albeit unpolarized, will also be available. This design will also provide a 25 GeV beam in fixed-target mode.

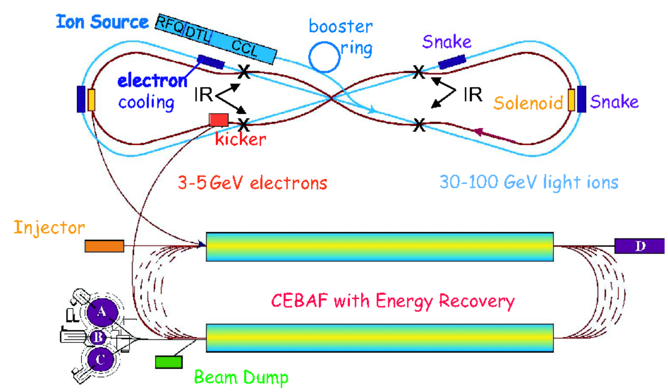

Fig. 3. Schematic view of ELIC

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