The Solid Polarized Target Group at the University of Virginia

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Contents

1 Summary

The solid polarized target group began in 1990 with the preparation of a solid polarized proton target, intended for Jefferson Lab, first used at SLAC in E143 and ultimately in a set of 3 spin structure experiments which generated, collectively, more than 2800 citations. At Jefferson Lab we have led five polarized target experiments. The first two have both earned the 100+ top citation designation at HEP-inspire (inspirehep.net/). Both Day and Crabb have impressive h-indices, according to hep-inspires and World of Science.

Until 2015 years the principles have been Donal Day, Donald Crabb and Oscar Rondon. Rondon retired in June of 2015. Crabb is retiring at the end of the 2018 Spring semester. It is unlikely that Day will be active in this area much past the start of the next decade.

The group concentrates on experiments that use spin degrees of freedom (i.e. using polarized targets and beams) in electron-nucleon/nucleus interactions to extract new information about the properties of these fundamental building blocks of nature and lend

new insights into their structure. We are **alone** among domestic university-based research groups that have the capability of developing, building and maintaining the cryogenic polarized targets critical for this research.

Since 2000 the group has produced 16 Ph.Ds and 3 M.S. graduates and there are 3 more students in training. See Table 1. Among our graduates, four have tenured or tenure track positions (Renee Fatemi, Dustin McNulty, Nadia Fomin and Jonathan Mellor) and two are staff scientists at national labs (Josh Pierce and James Maxwell). Our lab has been a very attractive place for undergraduates and we have engaged very many. A significant fraction of these students have gone on to graduate or professional school.

Former postdocs have also done well, often remaining in the field. These include Karl Slifer, now a tenured professor at the University of New Hampshire and a trailblazer in spin structure measurements, a research associate with us from 2004-2008. Dr. Benedict Zilhman was a member of our group for 4 years as a research associate in the late 1990's and is now a leading staff scientist in Hall D at Jefferson Lab. Stephen Bueltmann, a tenured professor at Old Dominion University, was our research associate in the mid-1990s.

Our funding from the DOE has been very steady in good times and bad, a total of $12.4M since 2000. Our most recent renewal proposal with a 3-year budget (Dec. 01, 2016 - Nov. 31 2019) was awarded $2.16M. See Figure 1 for our funding profile since 2000.

Our program manager at DOE, Gulshan Rai, and the Associate Director for Physics at Jefferson Lab, Rolf Ent, have expressed their willingness to discuss support for our group's future. We also have strong support for our succession plan from LANL and TUNL.

Our success has arisen, to a large part, because the University had the wisdom to allow faculty to be fully dedicated to research with minimal teaching and service responsibilities. This contribution and the results of these special circumstances have not gone noticed or unrewarded by the funding agencies. Our contribution to the department's reputation has been substantial and can continue. The dismantling of the group would be a material mistake; not only would it result in the loss of substantial external research funds but also opportunities for graduate and undergraduate students alike. It would immediately diminish the standing of the department.

2 General Focus

Our laboratory work, since the formation of the group in 1990 has largely been focused on the polarized targets used world-wide. We intend to continue exploring the technology to deliver the best figure of merit for polarized fixed target experiments. We are among the leadership of several approved polarized target experiments at Jefferson Lab which rely on developments from our target lab. Two of these are: "Measurements of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries", PR12-15-005, and "The Deuteron Tensor Structure Function b_1^d", E12-13-011. Both require a robust tensor po-

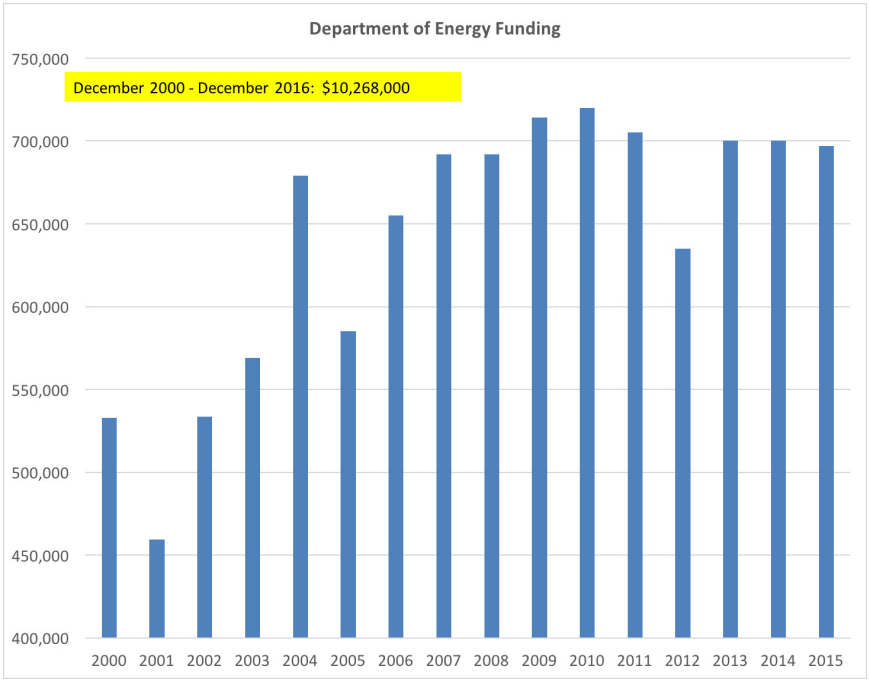

Figure 1: Since 2000 we have been awarded a total of $12.4M. Year 2017 (in purple) is for the period Dec 01, 2017 - Nov. 30, 2018 and 2018 (in blue) is for the period Dec 01, 2018 - Nov. 30, 2019. Note the suppressed zero. The funds represented by colored bars have not yet been spent.

larized deuteron target and pioneering methods to improve both the magnitude and the precise determination of the tensor polarization have come from our lab. The third, Wide Angle Compton Scattering (E12-17-008) is conditionally approved for 45 days and has as its goal to measure the initial state helicity asymmetry in Compton scattering from a proton polarized target. A_{LL} provides access to the the E and H Generalize Parton Distributions (GPDs), with a different weighting than one obtains from other exclusive processes, eg. elastic proton scattering. This latest success was made possible by our efforts designing a pure real photon source making it feasible to increase the photon flux intensity by more than a factor of 30.

Our group is deeply engaged at the TUNL facility (Duke) and two polarized target experiments have been approved - the target itself is being developed here.

We are responsible for the polarized target for the polarized SeaQuest at Fermilab (E1039) where the measurement of polarized Drell-Yan interactions is a major milestone in the hadronic physics community, motivated by a fundamental prediction of QCD that postulates that a naively time-reversal-odd distribution function, such as the Sivers function, measured in Drell-Yan production, must change sign if measured in semi-inclusive deep inelastic scattering (SIDIS). This experiment is expected to run in early 2019. A measure of the community and agency support for this experiment is made concrete by the DOE's commitment of $2M, largely to support the polarized target infrastructure at FermiLab.

3 Education

We commit a tremendous amount of time teaching and training undergraduate and graduate students enrolled at UVA as well as at other institutions. Our facility is the only fully functioning educational laboratory in the country serving solid polarized target experiments. Because our research and development in polarized targets is pivotal to the experimental effort in nuclear physics we are in the unique position to offer students opportunities in research, leading to critical work in which they have played a major role[1] Over a calendar year we will have 5-10 different undergraduates working with us. Some stay for a semester, some stay for 3 years. They all work assisting essential research projects. Table 1 provide listings of our graduate students - their current positions are included.

Our group is dedicated to the education and training of young scientists and at the same time we are committed to the training and assistance of seasoned researchers. Our relationship with UNH, TUNL, LANL, ORNL, Fermilab, and JLab have allowed us to introduce and prime scientists to construct/operate specialized cryogenic refrigerators, DNP microwave systems, superconducting magnets, and NMR systems. We are promised a continuing relationship with the national labs as only we can provide the facilities to test

[1] We employ high vacuum and low temperature techniques as well as millimeter microwaves and RF NMR.

materials and specialize instrumentation.

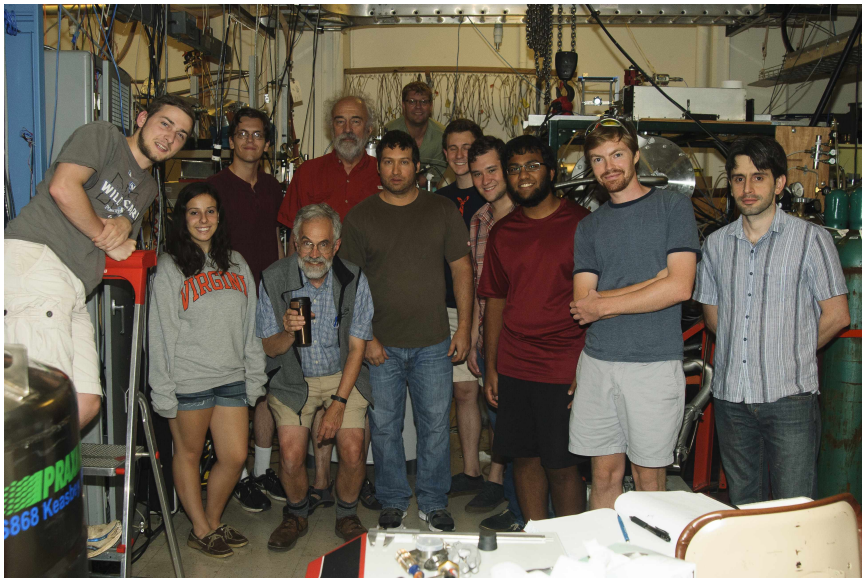

Figure 2: The Drell-Yan magnet and cryostat obscured by the UVA polarized target group and LANL staff in our lab in July 2015 where the new magnet rotation was tested successfully. Left to right: Jack Beatty, Brianna Biessecker, Ian Johnson, Richard Raymond (UMich), Donald Crabb, Dustin Keller, David Kleinjan (LANL), Jacob Higgins, Matt Biondi, Senthil Kannan, Ethan Scott and Mikhail Yurov. Photo by Andi Klein (LANL).

Much of our lab research is in low temperature physics and solid-state spin dynamics for nuclear experiment applications. UVA is the only domestic university conducting research and development in this field. Jefferson Lab has an excellent target group with an international reputation. However their group is dedicated to service and not research and development or the training of students. It is not a surprise that the JLAB target group staff has included our graduates - Josh Pierce (2008 Ph.D) left Jefferson Lab for ORNL in 2013 and James Maxwell (2012 Ph.D.) was subsequently hired as his replacement.

4 Nuclear and Particle Physics Research - the next decade

We believe the future holds more than 10 years of work at accelerator facilities both providing, improving and exploiting solid polarized targets. We have a unique facility and unequaled experience in spin physics that has been accumulated over almost 3 decades. Our facilities and our knowledge should be fully exploited.

It is useful to have a sense of how the community views our program. Here are some selected (and highlighted) comments taken from the reviews of our 2013 and 2016 DOE

Name	Advisor	Graduated	Degree	Pres. Inst.	Pres. Position
Paul McKee	Day	2000	Ph.D	QIM LLC	Chief Technical Officer
Chris Cothran	Day	2000	Ph.D	Georgetown University	Director of Instr. Labs
Al Tobias	Crabb	2001	Ph.D	Univ. Virginia	Physics Staff
Hongguo Zhu	Day	2001	Ph.D	Defense Threat Reduction Agency (DTRA)	Physical Scientist
Chris Harris	Day	2002	Ph.D	Vanderbilt University	Director of Licensing
Rene Fatemi	Crabb	2002	Ph.D	U. Kentucky	Associate Professor
Dustin McNulty	Crabb	2002	Ph.D	U. Idaho	Associate Professor
Yelena Prok	Crabb	2004	Ph.D	VCU	Assistant Professor
Svyatoslav Tkachenko	Crabb	2004	M.S.	NA	NA
Jonathan Mellor	Crabb	2006	M.S.	Univ. Conn.	Assistant Professor, CE & ME
Justin Wright	Day	2006	M.S.	US Army Night Vision Lab	Staff Scientist
Nadia Fomin	Day	2008	Ph.D	Univ. Tenn.	Assistant Professor
Josh Pierce	Crabb	2008	Ph.D	ORNL	Staff Scientist
Vahe Mamyan	Day	2011	Ph.D	UCLA	Medical Physics Certification
K. Kovacs	Crabb	2010	Ph.D	UCSB	Instructor
James Maxwell	Day	2012	Ph.D	Jefferson Lab	Staff Scientist
J. Mulholland	Day	2012	Ph.D	Booz Allen	Staff Scientist
Nicholas Kvaltine	Crabb	2013	Ph.D	MHKKG (Austin)	Patent Technical Advisor
Zhihong Ye	Day	2014	Ph.D	Argonne Natl. Lab.	Research Associate
Mikhail Yurov	Day	2017	Ph.D	Los Alamos National Lab (Jan. 2018)	Research Associate
Dien Nguyen	Day	2018	Ph.D		
Dan Abrams	Day	2020	Ph.D.		

Table 1: Listing of graduate students since 2000 along with current positions.

renewals.

Comments from Reviewer #1 (2013):

> The target group .... has an outstanding record in building and maintaining polarized targets and is internationally highly recognized. ... The group has a long-term expertise, a sound foundation of technical equipment and local facilities and is, to my knowledge the only one in the US to develop solid polarized targets on a systematic and academic level.

Comments from Reviewer #2 (2013):

> ... the group has a unique facility in their target lab and they take full advantage of having this technology. Their past performance is excellent. The only concern might be that this group is run by three senior PIs who are at, or close to, retirement age and may not be able to continue this work for another decade. The group has provided important and unique contributions to polarized target development, and it would be good to see such work continue well into the next (few) decades.

Comments from Reviewer #1 (2016):

> Two world experts are guiding the work. They have a long experience in polarized target developments and have largely proven to be highly qualified for

the work proposed. They have provided polarized targets for many physics experiments with great success.

The PI has already endorsed several responsibilities proving wide interest in physics experiments and accelerators. He has been involved in the research and development of polarized target since long, and thus has the full expertise to lead the research program.

Another physicist is already anticipated as future Principal Scientist and co-PI. He is presently in charge of planning and day to day activity for the target research development labs, oriented towards the plans at JLab, Fermilab and Duke, in full coherence with the proposed research.

The team has access to the full hardware highly specialized resources needed thanks to extensive work in this domain in the past. Several relevant hardware installations have been successively and wisely refurbished and upgraded, and so will be with within the present grant.

Finally, it must be noted that the research is essential for unique large facilities in US. Indeed within the experimental physics program of the newly available 12 GeV electron beam of JLab, many experiments based on polarized targets have been approved by the scientific committee. To make use of such a unique beam, high performance targets are mandatory.

Comments from Reviewer #2 (2016):

The innovation in this proposal is, for the most part, leveraged on the development of solid, polarized targets. This is the leading group in the US, and probably the world, for the development of these types of targets. As a reminder, laser optical pumping cannot provide a competitive polarized gaseous hydrogen or deuterium target, and frozen spin butanol targets cannot survive beam heating from the incident electron beam. For the JLab experimental program, the target technology being developed at UVa is the main (only?) path forward. The impact of this research is deeply woven through the JLab spin-physics program.

To my knowledge, there are no other university groups in the US so heavily involved in polarized target development, and the running of target-spin-dependent electron scattering experiments. The UVa group operates within a unique niche.

5 Succession Plan

Don Crabb is retiring in May of this year and it is unlikely that Donal Day will be engaged in this work past the turn of the decade. Oscar Rondon has already retired. We are unique among domestic university groups with regard to building and developing these targets and training other researchers and students, however we are not a service group and our focus is most generally on spin physics research. Our infrastructure has been built up over a very long time and will hardly be reproduced elsewhere in the short term. We were able to come into existence largely because of state support for both Donal Day's and Donald Crabb's positions as full-time research faculty for more than a quarter of century. This, along with direct state and DOE support over many years, has made our success possible. Without faculty fully dedicated to research it is unlikely our success would have happened - nor is it likely to happen elsewhere without the same.

Dustin Keller's transition from principal scientist to the research professor track is a necessary step that both our group and the DOE agree to in order to keep this grant and research activities alive. Once formalized with the assistance of Donal Day he will become lead PI on our grant and be able to recruit students for the many future projects he has proposed. He has for the last 5 years taken the largest role in the lab and nearly all the progress in our novel target developments of late are due to his leadership. He has spokesperson positions on several polarized target experiments and indeed has generated several proposals at different facilities listed below. Both Donal Day and Donald Crabb are completely in support of him becoming the PI and taking over our research and strongly encourage this transition to the research professor track. The DOE has also shown considerable support for this transition and gave strict permission to promote him to principal scientist until Crabb's retirement at which point we are committed to make the transition to the research professor track. We have already received support from our reviewers of our previous renewal on this succession with regard to the DOE's support. We have had preliminary discussions with our chair, and the chair with our dean, and with the DOE about our future and we are optimistic that all parties are on the same page with our succession plan. Below we present some of Dustin Kellers research in his own words.

5.1 Research Statement

I have a broad interest in Spin Physics. I have ongoing analysis projects in the spin physics of photoproduction hadronic spectroscopy using Jefferson Labs (Hall B) CLAS6 and have a keen interest in trying to understanding the nature of confinement using the spectrum of resonances and the search for exotic states. I also have an interest in the development of machine learning algorithms to use in conjunction with polarized observables where a broad phase-space can be exploited using multilayers of classification giving a great deal more information on the contributing partial waves. I also believe the next phase of nuclear physics analysis evolution will entail the use of increasingly sophisticated pattern recognition tech-

niques to use in signal extraction. Incorporating experimental covariance information into these types of analyses can improve resolving power even further. Recently, I have published work on U-Spin symmetry tests of the strange sector electromagnetic decays, and have extracted transition magnetic moments, branching ratios, and cross sections with the use of these types of covariance sensitive tools using photoproduction data from CLAS6. I will be migrating this effort to Hall D with the hope of expanding the GlueX project to use polarized target observables in the search for exotic mesons created by the excitation of the gluonic field. Such an expansion to the GlueX experiment would allow clear determination of the single spin (beam or target), double spin (beam-target, beam-recoil, target-recoil) and tensor polarized asymmetries in pseudoscalar and vector meson production. Spin dependent measurements will complement the existing GlueX program by allowing for the determination of complete isospin amplitudes and assisting in the search for exotic mesons.

I am also interested in Nucleon Tomography and using processes like Deeply Virtual (DVCS), Time-like (TCS), and Wide-angle Compton scattering (WACS) to explore the internal nucleon structure. I am involved in exploring ways to impose more theoretical, analytical, and experimental constraints on the extraction framework with the intention of improving the resolution of the 3D nucleon picture as well as to improve and expand the method of proposing experiments to add to this picture. This work involves deep study on the phenomenological level but also exploiting all components of the helicity amplitudes for each type of process at higher twist. Once this has been achieved it will be possible to propose more well define experiments that are sensitive to each of these components. At the moment the goal for DVCS and TCS is to run future experiments in Hall A and C with polarized beam and target. I have also proposed, with collaborators, an experiment to study the initial state helicity correlation in WACS in JLab Hall C. The measured longitudinal polarization transfer parameter is inconsistent with predictions of pQCD, yet consistent with calculations of the handbag mechanism. The WACS experiment will be able to discriminate between the various models and help to clarify the role of the power suppressed helicity flip contribution and hopefully confirm the method of factorization and connection to the generalized parton distributions. In order for this experiment to be feasible a high intensity photon beam (well over $10^{12}\gamma/sec$) had to be developed to work in combination with a new rotating target (raster) to maximize luminosity and reconstruction resolution. Our high intensity photon source collaboration is working on a publication of this configuration. There are many more photon beam, and photon beam with polarized target physics ideas of this nature that I would like to explore.

I am in a leadership role in several polarized target experiments and assist on a contributing level on several others. I am highly involved in all aspects of a major experimental effort at Fermilab in the SeaQuest polarized Drell-Yan experiment E1039. This project has received full funding and is the first experiment to measure not only the sign, but also the magnitude and shape of the Sivers function with sub-percent precision directly using the dynamics of the sea quarks. E12-13-011 is an experiment to measure the deuteron tensor structure function b_1 and E12-15-005 is proposed to measure the quasielastic tensor

asymmetry. Both of these experiments are conditionally approved requiring a tensor polarization of about 30%. I have recently developed an optimized solid tensor polarized target along with a polarization measurement technique directed at the necessity of these experiments. This advancement required a completely new type of target that rotates in the holding field while receiving RF irradiation to optimize quadrupole polarization in the target material. The new technology will increase the figure of merit for tensor polarized experiments by nearly a factor of 4 allowing for previously inaccessible asymmetries at Jefferson Lab. There are additional observables to explore using a tensor polarized target, such as the three additional spin-1 structure functions. The generalized deep inelastic tensor spin structure of the deuteron can only be obtained from deeply virtual Compton scattering and meson production experiments on a tensor polarized target. There are interesting connections to the total quark angular momentum sum rule for a spin-1 hadronic system within a gauge invariant decomposition of hadronic spin. In addition, polarized proton-deuteron Drell-Yan processes can be explored by studying the tensor-polarized antiquark distributions accessible only by a tensor polarized target. In general I very much enjoy research that opens the door to new types of experiments that can access information not otherwise achievable.

5.2 Current Polarized Target Experiments and Proposals

The present dirction of the groups research focus can be seen in the polarized target proposals listed below for experiments to run in the near future at Jefferon Labs, TUNL, and Fermilab.

- E12-06-109 *The Longitudinal Spin Structure of the Nucleon (JLab Hall B)*
  (Full Approval) Spokespersons: K. Griffioen, M. Holtrop, D. Keller, S. Kuhn, Y. Prok, T. Forest
- HIGS-P-12-16 *Tensor Analyzing Power in Deuteron Photodisintegration (Duke TUNL)*
  (Full Approval) Spokespersons: D. Keller (Contact), P. Seo, B. Norum
- E1039 *SeaQuest with a Transversely Polarized Target (Fermilab SeaQuest)*
  (Full Approval) Spokespersons: A. Klein, D. Keller
- E12-13-011 *The Deuteron Tensor Structure Function b1 (JLab Hall C)*
  (C1 Approval) Spokespersons: J.P. Chen, N. Kalantarians, D. Keller, E. Long, K. Slifer, P. Solvignon
- E12-14-006 *Initial State Helicity Corellations in WACS (JLab Hall C)*
  (Full Approval (withdrawn)) Spokespersons: D. Day, D. Keller (Contact), J. Zhang
- E12-15-005 *Tensor Asymmetry Quasielastic Region (JLab Hall C)*
  (C1 Approval) Spokespersons: D. Day, D. Higinbotham, D. Keller, E. Long, K. Slifer, P. Solvignon

- E12-17-008 *Polarization Observables in WAC Scattering (JLab Hall C)*
(C1 Approval) Spokespersons: D. Day, D. Hamilton, D. Keller, G. Niculescu, B. Wojtsekhowski, J. Zhang

A Facilities and Resources

Over the last 25 years we have built up a tremendous laboratory infrastructure some of which is listed below. These have been purchased through our previous grants, state support, have been acquired from other laboratories, or are on loan. Recently we acquired many items from the polarized target groups at Argonne National Lab and the University of Michigan Spin Physics Group. Reproduction of this laboratory will not happen elsewhere - the cost is prohibitive.

We have equipment on loan which is helping other groups, e.g a ^{4}He fridge, 2 NMR Q-meters and a 7 T super magnet (obtained from our NMR spectroscopy colleague in the Department of Chemistry) at UNH; a set of Roots pumps (12000 m^3/hr) at JLab (for which we provide back up with our local equipment during experiments there) and a set of Roots pumps (4000 m^3/hr), operating at TUNL at Duke University.

The advantages of an in-house facility are many: students and post-docs and others can be trained in the operation of the polarized target obviating the need for on-the-job training during the particle physics experiment. It is also a facility where our undergraduates have conducted their own research projects. As mentioned above, we use the refrigerator(s) to investigate procedures (e.g. deuteron tensor polarization) which has already lead to new Jefferson Lab proposals and certainly more in the future.

We occupy 1800 ft^2 fully equipped lab space with the following:

- A cold bore superconducting solenoid operating up to 8 T and which has a 1 K ^{4}He evaporation refrigerator integrated into it.
- A warm bore superconducting magnet operating up to 7 T into which our several refrigerators can be inserted.
- Two horizontal ^{4}He refrigerators; one has been loaned to UNH.
- Two horizontal ^{3}He refrigerators.
- Two horizontal ^{3}He/^{4}He dilution refrigerators, one high power, one very low temperature for frozen spin operation, obtained from HZG Germany and to be used at HIGS.
- Four high power EIO microwave tubes, operating around 140 GHz and two matching power supplies, plus matching waveguides and instrumentation for measuring power and frequency.

- Two high power 183 GHz EIO microwave tubes (for 6.55 T) which operate with above power supplies including power and frequency measurement systems, plus appropriate wave guide components.
- Three 70 GHz carcinotron microwave tubes and 1 power supply and four 70 GHz klystrons and matching 70 GHz hardware and one power supply.
- NMR polarization measurement. Have 11 Liverpool Q-meters and matching hardware. Recently acquired 4 more plus components to make two more. Instrumentation plus spares to operate up to 6 Q-meters at a time. One of these has been lent to UNH and one to ODU.
- National Instruments DAQ hardware and robust Labview program to operate or monitor all of the above instruments.
- A chiller for for liquifying gases such as CD_4 and CD_3 and dripping into LN_2 to make beads for our polarized targets.
- Two complete sealed Roots pump sets and pumping lines.One other set is used in our experiments at JLab. Finally a fourth set will be used in polarized target experiments at the HIγS facility at Duke University.
- Infrastructure (other pumps, temperature and pressure monitoring instruments, cryogenic hardware etc.) to support two separate installations.