CLS Proposal for GlueX Diamond Rocking Curve Measurements

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Abstract

Single-crystal rocking curve measurements of several large-area CVD diamonds are proposed to be carried out at the Canadian Light Source BMIT facility. Thin large-area diamond targets with narrow whole-crystal rocking curves are needed to produce secondary beams of linearly polarized photons in the 8-10 GeV energy range at Jefferson Lab for the GlueX experiment, in which the authors of this proposal are active participants. The challenging part of producing these targets is machining them down to the desired thickness without too much degradation of the rocking curve width. Such measurements were first carried out at BMIT in 2016 and 2017 on a set of diamonds that had a thin window machined out of the center using UV laser ablation. That technique was successful in achieving the optimum target thickness of 20 microns, but the rocking curves measured at CLS showed large plastic deformation over the thin region of the target, explaining why the polarization observed in the GlueX photon source was sub-optimal. In 2019, the GlueX group returned to CLS with a new set of CVD samples which had been machined down to 50 microns using a IR laser cutting technique followed by mechanical polishing. Once again, the rocking curve results showed extensive broadening from plastic deformation, with just one of the six samples tested being sufficiently narrow to support running of the GlueX experiment in 2020.

This proposal requests a brief run to test 4 new samples. One is a different type of CVD diamond with very low nitrogen impurity, already thinned to 50 microns and polished by the manufacturer. The other three samples are standard type-II diamonds that are still 1.3mm thick. The rocking curves of the thick samples will show whether the plastic deformation is intrinsic to the material or whether it is introduced during the machining process, while the rocking curve of the low-impurity (electronic-grade) sample will show whether this material has any advantage in reduced plastic deformation seen in the earlier type-II samples studied. These results will determine whether there is a significant advantage in the use of electronic grade diamond, and whether the degradation seen in the earlier results is intrinsic to the CVD raw material or if it was induced by the thinning process.

Scientific Description

The GlueX experiment at Jefferson Lab, in Newport News Virginia, is an international nuclear physics experiment designed to search for evidence of gluonic excitations in the spectrum of light mesons, as predicted by the theory of Quantum Chromodynamics. The experiment scatters a beam of high-energy polarized photons from protons in a liquid hydrogen target, and detects the decay particles from reactions where a significant fraction of the beam photon energy is converted into the mass of an excited meson. By studying the momentum and angular distributions of the decay products, the experiment is able to distinguish the contributions from individual mesons with specific quantum numbers that are associated with gluonic excitations, and disentangle them from the decays of familiar mesons that are predicted by the quark model in which the gluonic field remains in its ground state.

The photon beam used by GlueX is generated from a 12 GeV electron beam using the process of coherent bremsstrahlung in an oriented crystal radiator. Inside the radiator, high energy electrons from the CEBAF accelerator scatter coherently from the planes of carbon atoms in a diamond crystal, so as to produce bremsstrahlung radiation that is highly focused in the forward direction, with a polarized intensity that peaks at a particular energy that depends in a critical way on the incidence angle of the electron beam with respect to the crystal planes. The crystal structure factor that determines the peak intensity and polarization in coherent bremsstrahlung at the scale of 8-10 GeV is the same one that is measured in X-ray diffraction at 10-20 keV, which makes X-ray diffraction imaging an ideal way to determine the performance that a radiator will have in the high-energy photon source. Moreover, the high intensity of the X-ray beam at a synchrotron light source, coupled with a high-resolution X-ray camera, provides topographic images of the crystal rocking curve across the face of a sample within a matter of hours that would require weeks of dedicated running with the high-energy CEBAF beam to measure directly using the coherent bremsstrahlung beam. Analysis of the rocking curve topography measured at CLS has provided detailed deformation maps of the radiator crystals that, when fed into a simulation of the GlueX photon source, directly predict the intensity and polarization spectrum that crystal will generate.

Besides the rocking curve width of the crystal, there are other effects that degrade the polarization profile of a crystal in the coherent bremsstrahlung source, the most important being multiple-scattering of the high-energy electron beam in the crystal. Unlike X-ray, the incident electrons are scattered prior to radiation of the polarized photon, and this scattering degrades the alignment of the incident electron momentum relative to the crystal planes that is required by the coherent scattering condition. For this reason, it would be no use to have a crystal with a very narrow rocking curve unless at the same time it is thin enough to minimize the effects of multiple scattering. Matching the Darwin width of the (2,2,0) reflection of diamond with the effects of multiple scattering of 12 GeV electrons in diamond leads to an optimal radiator thickness less than 20 microns. The big challenge that GlueX faces is to find a way to manufacture such thin diamonds with sufficient area (6mm x 6mm active region to contain the CEBAF beam) whose rocking curve is within a small factor of the Darwin width.

Standard diamond machining techniques are capable of producing large-area single crystals with thickness as small as 10 microns, but GlueX experience so far has shown that these invariably have whole-crystal rocking curve widths that are a factor 20-50 larger than the Darwin width. X-ray measurements have shown that this is due almost entirely to plastic deformation, i.e. the local rocking curves in micron-sized regions of the target remain close to the ideal limit, but smooth variations across the face of the diamond produce very broad rocking curves when averaged over the active region that is covered by the CEBAF beam spot.

Relaxing the thickness requirement from 20 microns to 50 microns makes the crystal much more stiff and resistant to internal stress that produces the plastic deformation, while at the same time relaxing the rocking curve width that is required to match the broadening from multiple scattering. Based on that reasoning, the GlueX group produced six new 50 micron samples and brought them to CLS in 2019 for rocking curve imaging. Unfortunately only one of them gave results close to the desired goal, the others having rocking curves a factor of 2-3 worse.

GlueX experiment is in the middle of a shutdown period in 2021, with plans to resume running of the polarized beam program in the second half of 2022 through 2025. If a means could be found to produce a regular supply of 50 micron radiators with rocking curves a factor of 3 smaller than what was seen in the samples measured at CLS in 2019, this would result in significant improvement in the systematic errors associated with GlueX polarization observables. Two avenues to achieve this goal are entailed in this proposal. The first is to use a single-crystal material that has a low level of nitrogen impurities. Nitrogen is a dominant impurity present in diamond crystals, but special CVD growth techniques have been developed specifically to produce crystals with a low nitrogen content. This material is marketed for electronic applications because of the much longer mean free path that it has for conduction band electrons, but it is plausible that the reduced concentration of impurities might also lead to a lower intrinsic strain, and it might suffer less plastic deformation when thinned down to 50 microns. One such sample of electronic-grade diamond has been obtained by the PI's, in order to test this hypothesis.

The second avenue to achieve the goal of a factor 3 reduction in rocking curve relative to the 2019 results is to start with bulk material and carefully control the manufacturing process at every step in the slicing and polishing of the samples to 50 microns. Three uncut samples of 1.3mm thickness each will be assessed with rocking curve measurements to ensure that the bulk material meets the expected rocking curve criteria before the thinning process starts. Assuming this is the case, optical techniques will be used to watch for relative changes in the strain throughout the thinning process, followed by final rocking curve measurements at a future date.

Capability & Productivity of Research Team

The UofR/UConn team (Papandreou, Jones, Teymurazyan) has had a long-track record and considerable productivity in subatomic physics projects in terms of publications, technical reports, invited talks and presentations at conferences, workshops, and collaboration meetings. The team has developed nuclear physics instrumentation and analysis methodology and techniques, related to a broad spectrum of sensitive detectors. Members have worked in the design, construction, and delivery of a large complement of detectors to several subatomic physics labs for experiments employing hadronic and electromagnetic probes.

- Dr. Zisis Papandreou has significant experience in subatomic physics experimentation and large-scale project management. He has participated and led experiments on three continents, among which is GlueX, which his group joined in 1998. One of the most critical detector components of GlueX is a $10.5M, 30-ton, 48-segment, electromagnetic, lead-scintillating-fiber calorimeter, charged with the detection of neutral and charged particles. This detector was designed and built by his group, with funding of $1.5M from the USA Department of Energy and over $600K from NSERC, and it involved the hiring and training over 50 highly qualified Personnel. The group has also made innovative and significant contributions to the development of large-area SiPM-arrays, by initiating and carrying out R&D efforts with a European photonics company (SensL) in the period 2006-2008. His group established the initial testing and evaluation protocols, eventually resulting in functional units, which are now offered commercially by several firms in formats based on the GlueX standard.

- Dr. Richard Jones is a beamline expert for the GlueX/Hall D facility, including the diamond radiators, tagger hodoscope/microscope, and active collimator. He is the author of the GEANT4-based simulation package for GlueX. His expertise also includes: RICH detector using a solid radiator and a pixel MWPC readout; thin diamond monocrystals for use as coherent bremsstrahlung targets; high resolution X-ray topography of diamond using synchrotron light; active collimator for high energy coherent bremsstrahlung source; silicon photomultiplier devices for scintillating fiber detector readout; shaped diamond milling using UV laser ablation; open GEM detector for ambient radon decay rate measurement. He has also worked in detector systems integration, advanced Monte Carlo, has been data analysis manager for several experiments (JESET, RADPHI), and author of Partial Wave Analysis formalism and code for Jetset.

- Dr. Aram Teymurazyan is an assistant professor at the Department of Physics of the University of Regina and the Fedoruk Research Chair in Nuclear Imaging Technologies. One aspect of his current research is the investigation of advanced detectors and implementation of novel modalities for diagnostic imaging in the field of medical physics. Amongst others, he has been exploring advanced detector concepts for x-ray imaging for external beam radiotherapy. A more recent and very exciting addition to his research program is the development of nuclear imaging detectors dedicated to nuclear imaging of plants. In collaboration with biologists and radio-chemists from UofR and UofS these detectors will be used to study plants and soil cores at a molecular level to improve the understanding of plant productivity, nutrient and water use efficiency, plant-microbe interactions, response to environmental stress and injury, and others.

The team’s expertise includes beam-profile and 3D-detector simulations and event reconstruction. All three members are leaders in various experimental endeavours, manage their own labs, and contribute to GlueX Run Coordination and Management.

Societal, Economic and Industrial Relevance

The GlueX Experiment is foundational in nature and has been rated by several international advisory panels and the Long Range Planning in USA Science as having "discovery" potential. Canadians, at the Universities of Regina and Connecticut, have played a leading role in this experiment since its inception in the late 1990s. Many HQPs have been educated and trained during the R&D and now the running phase of the GlueX project. Technologies developed together with industry for GlueX, such as silicon photomultiplier arrays, have already made an impact in particle physics and are now being researched for use in the medical and agriculture sectors, in Positron Emission Tomography of humans, small animals, and plants.

Materials & Methods

BMIT — BioMedical Imaging and Therapy Facility

Suitability and Justification:

The measurements in the previous three runs were successful in that they provided detailed rocking curves for the diamonds, which allowed the GlueX Collaboration to select the best ones for experimental running. No deviations are planned from our well-established (by now) methods, which have been optimized over a series of run periods in 2016, 2017, and 2019.

Experimental Procedure:

The experimental goal is to take high-resolution topographic images of the 2,2,0 reflection of our diamond samples in Laue geometry in steps of 2.5 microradians in the Bragg angle, covering the full range in Bragg angle over which the scattered X-ray intensity from any point on the surface of the target is above the noise floor of the camera. One such rocking-curve scan consists of between 100 and 600 steps, depending on the total rocking curve width. A complete set of measurements for each sample consists of 4 complementary scans: one with the (2,2,0) direction in the Bragg scattering (vertical) plane, one with (2,-2,0) in the scattering plane, followed by repeats of each of the above with the target flipped by 180 degrees. The (2,2,0) and (2,-2,0) scans are complementary because they cover the two reciprocal lattice vectors in the radiator that are used in complementary runs of high-energy polarized photon source to generate beams with opposite linear polarization. The repeated scans with the target flipped by 180 degrees are necessary in order to distinguish two possible sources of variation in the rocking curve peak centroid across the surface of the crystal: d-spacing variations, and curvature of the planes. Shifts in the Bragg peak due to d-spacing variations are even under this inversion of the target, whereas shifts due to plastic deformation of the crystal are odd under inversion. These two scans are combined during data analysis to produce separate maps of the d-spacing variation and variation of the surface normal direction across the surface of the sample.

Initial setup of the BMIT beamline is normally carried out by CLS scientific staff. The beamline is configured with a 0.8mm Al absorber followed by a silicon double down-bounce monochromator set to the 2,2,0 reflection at 20 keV. To minimize the dispersion correction, the diamond target is also set to reflect in the downward direction. Once the camera is mounted on the rotation stage downstream of the target station, it is moved to the approximate Bragg scattering angle 2-theta = 28 degrees below the horizontal. The camera is instrumented with the GADOX-20um scintillator, which has been found to give very good resolution and sensitivity to 20 keV X-rays. For initial setup, a known diamond target is placed on the target mount, using a level to adjust the Bragg angle to near the diffraction maximum for 2,2,0 in Laue geometry, and a scan of theta using the stepping motor on the target mount is used to find the center of the diffraction peak. Then the camera focus is optimized using a tungsten pin target in front of the camera aperture.

The data acquisition settings are verified and the stepping motor is adjusted for micro-stepping such that each micro-step is 2.44 microradians. A full scan is then taken with the test sample to make sure that the target height is set to fully expose the entire crystal in a single rocking curve scan.

Barring significant hardware failures, the above setup steps would take 4-6 hours to complete, including reviewing any changes to the data acquisition and stepping motor configurations that may have changed since the last run. After setup is complete, the running of rocking curve scan proceeds one-after-another until a full set of 4 rocking curves have been taken of each sample on the work list. The scans themselves are automated by the data acquisition software that coordinates the stepping motor motion with the acquisition of images between each step. One image is acquired every 3-5 seconds, so a typical scan only requires between 20 and 30 minutes. Most of the time during a run is taken up with the tasks of mounting and rotating the samples between scans, and finding the Bragg reflection each time the target has been mounted or rotated. During the last run, on average we were able to complete the 4 complementary scans and swap out the next target once every 4 hours.

As soon as the complete set of images and metadata for each scan have been recorded, the transfer of these data is initiated over the internet to a computer cluster at the University of Connecticut, where parallelized software is running to perform fits of the rocking curves for each pixel in the images in real time and save the results in the form of rocking curve topographic images. These are false-color images of the sample, representing the rocking curve peak and width, as well as peak intensity and background coming from the fits, as functions of x,y position on the face of the target. These images still need to be corrected for dispersion and shifted into alignment with their quad-scan counterparts to produce a single unified picture of the d-spacing and curvature of the sample planes, and extract the whole-crystal rocking curve width. But these initial rocking curve peak and width topographs already give a sufficiently detailed view of the data to show whether the data are sound or whether something went wrong and the scans should be repeated.

Based on these estimates, the entire program requested in this proposal is expected to fit within a single 24-hour period, not including beamline setup time by CLS scientific staff, plus time set aside for safety walk-throughs and user training that might be required prior to beginning of work in the experimental area. Expanding that estimate by a factor of 2 for contingency, this request would easily fit into any 2-day slot that might be available in the BMIT schedule.

Ancillary Requirements:

Labs: BMIT Lab

Equipment: Dry Laboratory (1070)

Name	Description	Type	Quantity	Hazards
Diamond crystals		other	4 * 1	none

Mechanical Equipment:

Review Status	Type	Name	Manufacturer	Model
Pending	Mechanical — None required;		N/C	N/C

Electrical Equipment:

Review Status	Type	Name	Manufacturer	Model
Pending	Electrical — None required		N/C	N/C

Sample Preparation:

The UConn/UofR team will bring the diamond and ancillary materials and handle all materials. No handling is required by CLS. Diamonds are variable thickness and 7mm x 7mm in area, mounted on simple frames and aluminum bars. The target frames can be mounted easily in the BMIT setup with the CCD camera, as we have done in the past runs.

Waste Generation:

The following types of waste will be generated:

- No Waste
- Waste Disposal: None.

Following the rocking curve measurements at BMIT, the diamonds will be shipped to the USA for further machining and eventual use in the GlueX experiment starting in the second half of 2022.