General User Access Proposal 013093

Cycle 37 (Jan-Jun 2023)

Rocking Curve Scans of GlueX Photon-Beam-Production Diamonds

General User Access

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Abstract

The proposed experiment centres on the characterization of diamond wafers at CLS-BMIT, used to carry out fundamental nuclear physics (properties of the strong nuclear force) at Jefferson Lab, USA. Thin diamond targets with narrow whole-crystal rocking curves are needed to produce 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 crystal structure factor that determines the peak intensity and polarization in coherent bremsstrahlung at such energies 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.

Single-crystal rocking curve measurements of large-area CVD diamonds are proposed to be carried out at CLS-BMIT. This proposal requests a brief run to test three new samples, ranging in thickness from 80-250 microns. 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 (thinning) process.

Scientific Description

The GlueX experiment at Jefferson Lab, 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 12-GeV polarized photons from protons in a liquid hydrogen target, and detects the decay particles from reactions. The experiment is able to seek exotic-matter mesons with specific quantum numbers that are associated with gluonic excitations.

The photon beam used by GlueX is generated from the electron beam using the process of coherent bremsstrahlung in an oriented crystal radiator. Inside the radiator, high-energy electrons from the 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 diamonds' 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.

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 GlueX beam spot. Relaxing the thickness requirement from 20 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.

The GlueX group brought four samples to CLS for rocking curve scans on the BMIT beamline in December 2021 to characterize the crystal defect structure of single-crystal diamonds in order to evaluate their suitability. The diamonds need to be very thin (50 microns) while maintaining a near-perfect crystal structure over a large area of 7mm x 7mm transverse size. A detailed analysis procedure has been developed by our group which allows rocking curve data collected at CLS to be converted directly into predictions for polarization and spectral intensity in the GlueX beamline. In June 2019 our group measured the rocking curves of five new Element Six diamonds, and determined that none of them were as good as those we had measured in the past, and just one out of the five would pass the acceptance test for GlueX. In response, the GlueX group opened two parallel tracks to investigate possible causes for the degraded sample quality, one looking at the original raw diamond material from which the samples are cut, and the other looking at the details of the cutting and polishing procedures. The purpose of the run in December, 2021 was to look at the quality of the original raw material from Element Six, and to compare it with a sample from Microwave Industries whose product has an order of magnitude lower concentration of impurity. Four samples were studied: three brand new Element Six CVD (type II) samples as delivered 1.2mm thick from the manufacturer, uncut and never epoxied to a mount, and one Microwave Industries low-impurity (type III) sample 300 microns thick. The analysis showed conclusions on the quality of diamonds from the two manufacturers and hinted at which parts of the process cause performance degradation.

We are requesting a brief run at CLS in 2023 prior to further polishing down to the final 50 microns thickness. This step-wise approach should allow GlueX to conclusively determine where along the production chain the degradation is occurring.

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 $10M ($1.5M transferred to ZP's group) 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 (JETSET, 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 former 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 and the soil microbiome. 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. Three members (ZP, RJ, AT) are leaders in various experimental endeavours, manage their own labs, and contribute to GlueX Run Coordination and Management. AT and ZP lead experimental and detector development and are actively contributing to CLS, Fedoruk and TRIUMF research activities.

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.

Benefits to Canada

Technologies developed together with industry for GlueX, such as large-area 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. The Regina members have pioneered that direction with the photonics industry. This collaboration then spawned a new applied research direction in the department, with the Fedoruk Centre as a partner, in the area of nuclear imaging of plants. Two successive five-year bridged-funded Fedoruk Chairs have been placed in the Department of Physics at the U of Regina. The associated research areas currently pursued include nuclear radiation detector development and instrumentation, plant imaging, and material science, all of direct economic relevance to Canada and Saskatchewan.

Materials & Methods

BMIT-BM – Biomedical Imaging and Therapy (BM)

6 Shifts

Suitability and Justification:

The measurements in the previous four 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

Source	Bending Magnet
Spectral Range	12.6 – 40.0 keV
	<10^-3 mono, ~0.1 filtered

Biomedical Imaging and Therapy (BM) (BMIT-BM)

BMIT bending magnet (BM) beamline generates X-rays in the energy range 12.6-40 keV which is optimal for 2D and 3D imaging of small animals, such as mice, and well-established (by now) methods, which have been optimized over a series of run periods in 2016, 2017, 2019 and 2021. The methodology and steps have been meticulously logged in Google Docs, which facilitates the smooth running of the experiment.

Resolution	white beam
Spot Sizes	200 mm horizontal (flat); 4 mm vertical (FWHM) for mono @ 20 keV and 3 mm vert. (FWHM) for filtered white beam
Photon Flux	10^9 ph/s/mm2 @ 20 keV mono, 10^12 ph/s/mm2 peak @ 20 keV filtered white beam

lightweight materials. Imaging with spatial resolution down to 2 microns and CT scans in several seconds are possible. Propagation-based phase contrast and imaging with crystal-based optics can be utilized to achieve better sensitivity to low contrast features which are normally invisible in ordinary X-ray scans http://bmit.lightsource.ca/

Experimental Procedure:

Rocking Curve/Diffraction Enhanced Imaging

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 relatively fast. 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 4-6 hours.

Based on these estimates, the entire program requested in this proposal is expected to fit within 6 shifts, including beamline setup time by CLS scientific staff and out group, plus time set aside for safety walk-throughs and user training that might be required prior to beginning of work in the experimental area.

Date Preferences

Preferred dates:

Undesirable dates:

Scheduling considerations: No ancillaries or materials are requested, besides the a BMIT 0.8mm Al absorber followed by a silicon double down-bounce monochromator and the high-resolution X-ray BMIT camera. We bring our own tools to mount the diamonds on thin, Aluminum target holders. The GlueX experiment has been running at the current Jefferson Lab cycle since June 2022 and will conclude in Match 2023. After a scheduled large-scale upgrade, it will continue to run for several years from 2024 and on. Thus, if this proposal is successful, beam time in the first half of 2023 is optimal for the diamond scans at CLS-BMIT to allow time for processing and shipment of the diamonds to Jefferson Lab, as well as for installation on the GlueX radiator holder. Due to running shifts at GlueX, Jan 15-30, 2023 are keep-out dates. Otherwise our group's schedule is flexible.

Number of Samples: 3

Review Status	Name	Description	Hazards
Pending	JD80-210 Diamond (1)	JD80-210 : 250 microns thickness, polished one side	☑
Pending	JD80-220 Diamond (1)	JD80-220 : 80 microns thickness, polished both sides	☑
Pending	JD80-230 Diamond (1)	JD80-230 : 250 microns thickness, polished one side	☑

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:

No decontamination or disposal is needed. After scanning, the diamonds will shipped to the USA for installation in the GlueX target holder.