D-line Upgrade and New Science Capabilities

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CHESS's popular D1 station, utilizing synchrotron radiation from a hard-bend dipole magnet and a multilayer monochromator, has both a versatile optical system and a 5-meter long hutch (Figure 1). Sharing the smallest x-ray source size at CHESS with C-line, D1 has been extensively used for small and wide angle scattering as well as microbeam experiments with glass capillaries to create x-ray beams on the scale of 50 nanometers to 50 microns. Recent applications include grazing-incidence small- and wide-angle x-ray scattering on thin films of soft materials such as block copolymers[1], conjugated polymers[2], nanocrystal assemblies[3] and nanoporous films[4] as well as high-energy small-angle scattering in conjunction with diamond anvil cells[5], and microbeam SAXS and WAXS studies[6]. D1 has also supported a development program for new experimental techniques such as an evaluation of the potential of Laue diffraction for structure determination of protein microcrystals[7] or fluorescence imaging of large-scale paintings[8] and Roman tombstones[9].

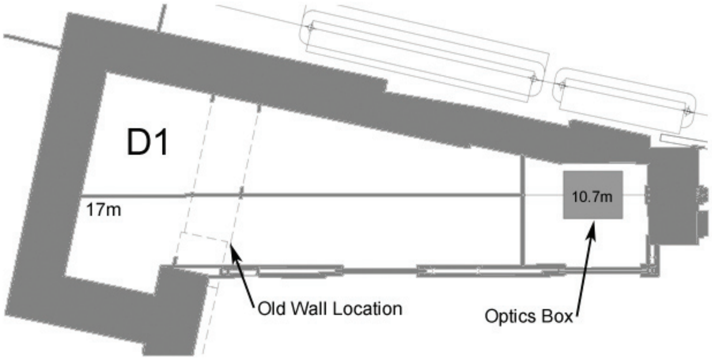

Fig. 1: Conceptual plan to improve the D1 experimental program by lengthening the user space by 2 meters (old wall position shown). The new high-vacuum x-ray optics box is already installed and commissioned, and D1 has delivered a total of 12 weeks of user operation within the old experimental hutch (dashed).

A few years ago, during an exercise to identify strategic long-term plans to improve CHESS stations and beamlines, it became clear that the size and scope of the soft-matter science program being supported at D1 was "bursting at the seams." For example, new demand has been growing steadily to study thin-films either in static specimens or *in-situ* during solvent vapor conditioning. Technically, the beamline front-end and optics had not been upgraded in almost two decades. In particular, the helium monochromator box that housed the synthetic multilayer mirrors was in poor shape and the unclean environment led to carbon-like deposits on the multilayer surfaces that needed to be cleaned off periodically.

This exercise resulted in replacing the old helium optics box with a high-vacuum enclosure and a conceptual design to lengthen the experimental hutch (see figure 1). The extra space became available with the demise of the high-energy physics program at the decommissioned CLEO detector. The longer hutch would allow access to SAXS studies with higher resolution and/or at higher beam energies. A new optics box was designed to provide rapid changeover between multiple multilayer optics with different wavelength ranges, thus cutting down on set-up and realignment time.

At about the same time the accelerator physics group was proposing to use the CESR storage ring as a "test accelerator" (TA) for part of the R&D aimed at the international linear collider (ILC). Using the flexible lattice of CESR the TA group wanted to create a prototype ultralow emittance positron and electron damping ring of the sort that might become part of the injector system for the ILC. In this study they needed to setup a pinhole camera to image the electron and positron bunches, using the CHESS x-ray beamlines C1 and D1 close to the former interaction region. Using a fast detector, the group hoped to be able to measure the size and shape of individual bunches of charged particles, with photons emanating from a single pass of the bunches through the bend magnet source. Because this work would be done with a machine energy of 2.0 GeV, where the x-ray flux is peaked at 1 keV, the accelerator physicists requested that the targeted beamlines have all beryllium vacuum windows removed, in order to avoid absorption of low-energy x-rays coming down the line.

Marrying the needs for better x-ray science capabilities with the accelerator group requests, the CHESS design, technical and vacuum groups designed an upgrade plan to accomplish these goals. Pictured in figure 2, the upstream D beamline was almost completely replaced with ultra-high-vacuum compatible flight tubes, apertures, a differential pumping stage to separate storage

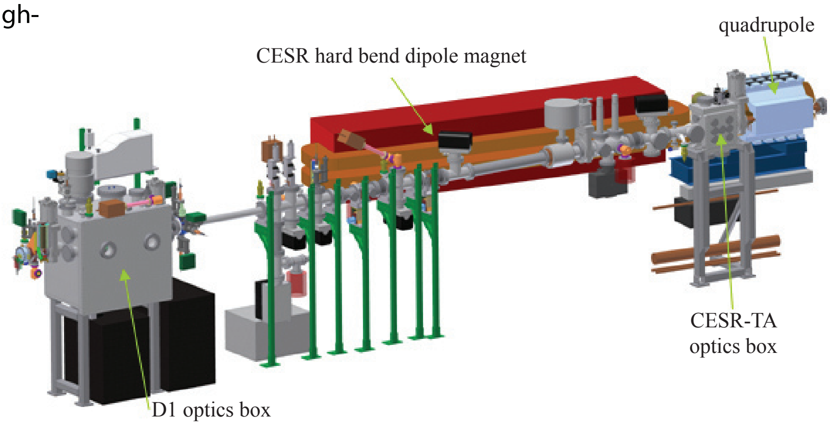

Fig. 2: The new windowless D1 front-end. The x-ray beam enters from the right, traveling downstream to the left through a series of beamstops, a beam viewer, and differential pumping chambers. The D1 optics box is described in more detail in the text and in Figure 3.

ring ultra-high vacuum from the high vacuum typically achieved in optics boxes, as well as removable thin diamond foil x-ray beam viewers to assist line-up.

For the CESR-TA project a small vacuum optics box as close to the storage ring as possible was added. This small box is used by the accelerator group to hold a small pinhole, Fresnel zone plate, or coded aperture that will create an image of the positron source. During these special "TA" runs, all D1 hutch equipment (two full CHESS optical tables) is removed and the CESR-TA group rolls into the x-ray station a large vacuum detector box that has an ultra-thin diamond window with a pressure balance system designed by CHESS. This box houses a high-speed pin-diode linear array detector that measures the projected size of the x-ray source.

The old D1 x-ray optics box was replaced by a high-vacuum chamber with all vacuum-compatible motors, a large turbomolecular pump, gate valves before and after the optics for isolation of vacuum cells, a set of adjustable white beam slits, and a second downstream thin diamond foil x-ray beam viewer (figures 2 and 3). When the x-ray beam passes through the diamond foil beam viewer it creates a visible light image that is recorded by a video camera. Coupled with custom software designed by CHESS scientist Peter Revesz, the *in-situ* video images of the x-ray beam are extremely helpful for diagnostics on beam shape, position, and stability.

The new D1 multicrystal monochromator contains three pairs of multilayers of varying properties. The first set is the tried and true 30Å Mo:B_4C multilayer made by the APS optics group that has been D1's workhorse monochromator over the past four years[10]. Although somewhat damaged by prolonged operation in the old helium box, there are still good parts left. In the last running period of Spring 2009, the x-ray beam remained at a single spot, and it showed no signs of degradation over an initial four week user-mode operations period. Typically this multilayer covers the 8 keV to 15 keV energy range, but can get as low as 6 keV at increased offset. The second multilayer set is again a matched set, 21Å W:B_4C by Osmic. This multilayer was chosen to cover the hard x-ray range from 15 keV to 30 keV. Originally conceived for fluorescence imaging, it is now also being tested for high-pressure SAXS and GIWAXS for an extended scattering range.

The third multilayer set is an experimental one for exploring new optics configurations. The d-spacings of the Mo:B_4C multilayers were purposely mismatched with 21 Å for the upstream multilayer and 25 Å for the downstream multilayer, resulting in a beam that is somewhat bent down from the horizontal. A third optical element, a rhodium-coated mirror, is used to bend the beam back up to the horizontal plane, working close to the Rh critical angle. Since multilayer scattering angles and the critical angle of the mirror both scale inversely proportional with energy, this configuration can be maintained throughout the energy range of 10-20 keV. The Pd mirror generates an appropriate energy cut-off for higher harmonics, so that the third and higher orders cannot pass. This will result in a D1 beam with much less higher-energy contamination.

As an additional option, the mirror can be slightly detuned towards lower incident angles, resulting in a slightly bent down beam that could enable grazing incidence experiments from liquid surfaces. Again, as multilayer Bragg angles and relevant critical angles have the same energy dependence, this mode can be maintained throughout the energy range. A future upgrade could add a bender to this mirror to increase flux on the samples at the cost of a small extra angular divergence, while maintaining a well-defined incident angle on samples. The advanced mirror options still remain to be commissioned at the time of writing.

The multilayer set-up rests on a solid internal x-translation table so that different multilayers can be brought into the beam via remote computer control. This avoids the problem of having to re-align the optical tables in the hutch after changing multilayers. All monochromator motions use vacuum-compatible motors and bearings. Vacuum of better than 10 nanoTorr was maintained under beam and motor moving after careful conditioning. The whole monochromator assembly can be leveled by an external 3-point actuator set.

Additional optical elements are a set of white beam slits limiting the incident beam to the beam that is needed. These internally water-cooled slits are controlled by external actuators via bellows, and maintain a clean vacuum even under heat load. Finally, a set of fixed slits behind the multilayer optics will be used to clean up the beam exiting the monochromator; in particular, to remove small amounts of diffuse scattering from the multilayers. This slit set, to be installed before the upcoming run, is also controlled through an external actuator via bellows.

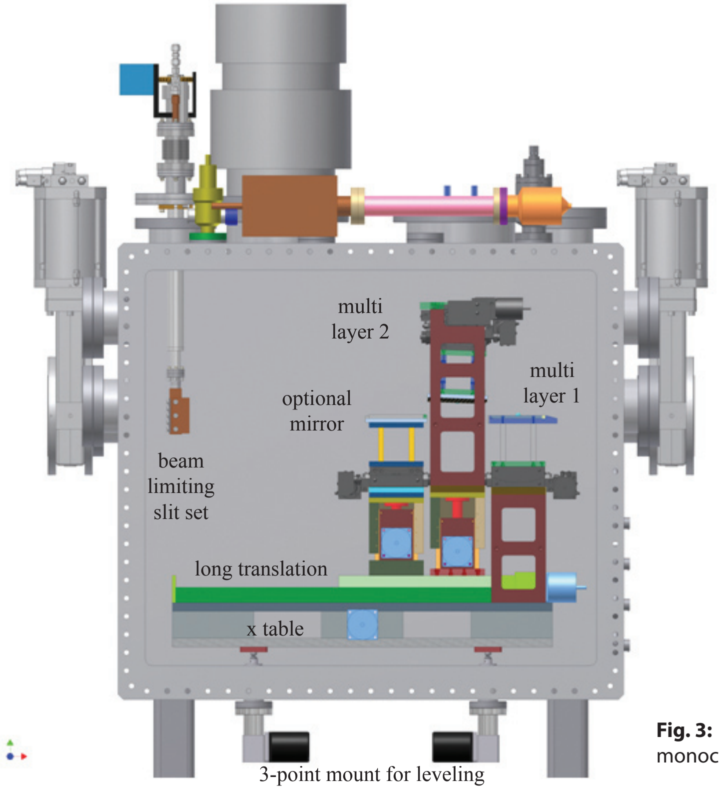

Fig. 3: Inside detail of the new D1 vacuum multicrystal monochromator. Details given in text.

One aspect of the upgrade that has not yet been tackled is to lengthen the experimental hutch. This will require a significant restructuring of the thick and heavy shielding walls, as well as moving some quantity of wiring. Short of moving those walls, though, the downstream-most wall of the hutch had a 12-inch hole bored through it. This was done as an optional, alternate means to locate the "TA" beam size detector as far as possible from the storage ring source. This option has not yet been exploited. Another option under discussion is adding a full second D-line hutch at the far end of the CLEO enclosure, that would serve for USAXS, microbeam scattering, or coherent scattering applications as well as for CESR-TA at higher resolution.

We thank the members of the CHESS Mechanical Design Group headed by Jim Savino, the Operations Group headed by Chris Conolly, and the Vacuum Group headed by Bob Seeley for all their great work. Particular thanks to Aaron Lyndaker who designed the bulk of the vacuum system including the new monochromator box, and Tom Krawczyk who designed, assembled, and commissioned the complex insides of the multi-crystal monochromator.

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In conclusion, during this upcoming Fall 2009 x-ray running period the technical and scientific staff at CHESS will commission new beamline, optics and station equipment that promise to significantly update and enhance the scientific capabilities of the flexible C-line experimental station. Our ambitious plans to produce low-energy x-ray optics and expand the size of the experiment hutch are still being developed. Look for more innovations during the coming year and contact the station scientist, Ken Finkelstein, with any questions or suggestions.

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