Dynamic experiment using IMPULSE at the Advanced Photon Source

B J Jensen1, K J Ramos1, A J Iverson2, J. Bernier3, C A Carlson2, J D Yeager1, K Fezzaa4 and D E Hooks1

1Los Alamos National Laboratory, WX-9, Los Alamos, NM 87544, USA.
2National Security Technologies LLC, Los Alamos, NM 87544, USA.
3Lawrence Livermore National Laboratory, Livermore, CA 94551, USA.
4Argonne National Laboratory, Advanced Photon Source, Argonne, Illinois 60439, USA.
E-mail: bjjensen@lanl.gov

Abstract. The ability to examine the dynamic response of materials at extreme conditions requires diagnostics that can provide real-time, in situ, spatially resolved measurements at the appropriate length scale. Recent advances in synchrotron sources and diagnostics coupled to dynamic loading platforms are transforming the dynamic compression field to allow for such investigations. In the current work, recent experimental efforts on the IMPULSE (IMPact System for ULtrafast Synchrotron Experiments) capability at the Advanced Photon Source (Argonne, IL) will be highlighted to describe its development and use to examine phenomena including jet-formation in metals, compaction, crack formation and propagation, and material strength and failure. These experimental results have relied in part on: 1) the development of a robust optically multiplexed intensified detector configuration to obtain the first shock movies and 2) gun system improvements to better synchronize the impact event with the 80-ps width X-ray bunch. The IMPULSE capability is expected to continue to reveal novel phenomena for materials subjected to high strain rate loading while developing the required knowledge base to ensure success for future facilities including the Dynamic Compression Sector at the Advanced Photon Source and LANL’s MaRIE.

1. Introduction

Dynamic compression experiments are well suited for examining material response at high pressures, and have been widely used to study shock induced phenomena such as phase transitions [1–4], elastic-plastic deformation [5, 6], and material strength [7]. Although there has been considerable success over the years in relating the shock wave evolution to the material response, traditional diagnostics provide indirect information about the underlying mechanisms for deformation, and have difficulty when the processes and/or materials are heterogenous. More advanced diagnostics are needed to examine the dynamic response of complex materials such as foams, powders, high explosives, and complicated processes such as hot-spot formation in explosives or formation of jets from metal surfaces. Developments in synchrotron facilities and in X-ray diagnostic methods provide unique opportunities for ultrafast, high resolution, spatially resolved measurements to examine materials during impact loading. In this manuscript, we highlight the experimental efforts leading to the development of the IMPULSE capability at the Advanced Photon Source (APS), and describe how these efforts support the development of
Figure 1. (a) Model view of the IMPULSE launcher system consisting of the gas breech, barrel, and target chamber (support structure not shown). The target chamber consists of a diagnostic feed through flange and several X-ray ports and vent flanges. (b) Schematic of the standard experimental configuration for plate impact experiments at the synchrotron. The X-ray beam from the synchrotron is shown as a red line entering and exiting the target chamber.

future signature facilities such as the Dynamic Compression Sector (DCS) at the APS and the MaRIE concept at Los Alamos National Laboratory (LANL) [8].

2. IMPULSE Capability at the APS

Over the years, significant efforts have focused on the development of X-ray diffraction techniques for shock wave experiments. These efforts have proven successful in examining phenomena including phase transitions in KCl [9] and elastic-plastic deformation in LiF [10, 11], but are limited because they have relied in part on the divergent, monochromatic X-ray beams generated using standard flash X-ray systems. To take advantage of diagnostics currently available at synchrotron sources, such as phase contrast imaging and Laue X-ray diffraction, shock wave experiments must overcome key challenges including: (1) synchronization of the impact event with the detectors and the X-ray bunch and (2) the detection of the X-rays from a single photon bunch. Although there are several examples of research coupling gun systems to synchrotrons [12, 13], routine measurements have not been possible. The IMPULSE system (IMPact System for ULtrafast Synchrotron Experiments) was designed specifically for conducting routine plate impact experiments at synchrotron sources to take advantage of
In October 2011, the first dynamic experiments were performed on IMPULSE demonstrating the ability to obtain images of dynamic compression using a single 80-ps width X-ray pulse. The typical experimental configuration for X-ray imaging experiments is shown in figure 2. The x-ray beam is shown passing through a series of fast/slow shutters, mechanical slits, interacting diagnostics such as phase contrast imaging (PCI) and Laue X-ray diffraction [14, 15]. The system (figure 1-a) consists of a 12.6 mm bore launcher capable of accelerating projectiles to velocities up to 1 km/s, a mobile support structure that allows for quick insertion/removal from the X-ray beam, and a target chamber that contains various diagnostic ports and can withstand detonation of up to 750 mg of explosives (TNT equivalent). The target chamber can rotate up to 30 degrees to position the sample in the X-ray beam. The system includes a complete suite of standard shock physics diagnostics including VISAR [16], Photonic Doppler Velocimetry (PDV) [17], impact pins, and optical beam interrupts. A schematic of an experimental configuration for plate impact experiments at the synchrotron source is shown in figure 1(b). X-rays enter the target chamber through a side port, diffract or transmit through the target located on the muzzle of the gun, and exit the chamber through the detector flange. The basic operation of the gas gun system is described elsewhere [15].

Figure 2. (a) Experimental configuration for phase contrast imaging measurements using the IMPULSE system. (b) Image of jet formation in cerium metal. The false-color image is a convolution of multiple detector frames to show the evolution of the jet with time. (c) Single frame showing impact of a 300 μm copper cylinder onto a vitreous carbon plate [14, 18]. (d) Single frame showing opening of a crack generated during interaction of two release waves in the vitreous carbon sample. (e) Compression of large cell micro-lattice foam. (inset) shows the static image before the experiment [14].
Figure 3. Back reflection experiment configuration for Laue X-ray diffraction using the white X-ray beam. Example static X-ray diffraction data for iron single crystals are shown for two exposure durations of 15 and 0.300 $\mu$s.

with the sample, and finally incident on a scintillator in the detection system. A wide a variety of experiments have been conducted to date and four examples are shown in figure 2 to illustrate the X-ray imaging capability. In figure 2(b), X-ray images show the evolution of jets from cerium metal caused when a shock wave interacted with grooves at the rear surface of the sample. The images show a convolution of three separate detector frames with an estimated 2-3 micron spatial resolution. Frame 0 is the static image of the grooves before the experiment. Frames 1 and 2 show the jet position and shape later in time. The jet heights combined with velocimetry data (not shown) provide an estimate of the yield stress. Figure 2(c) shows a single image of a 300-micron copper cylinder impacting a vitreous carbon plate to study crack formation [18]. Figure 2(d) shows a crack opening and the formation of a damage region in vitreous carbon caused by the interaction of two release waves with an arrested crack [18, 19]. Figure 2(e) shows the dynamic compression of micro-lattice foams [14]. Additional experiments are underway applying X-ray imaging to examine detonator performance, directly observed the shock wave propagation through aerogels, study the process of high strain rate polymer extrusion [20], and observe compaction of idealized 100 micron borosilicate spheres, for example.

At the same time as the X-ray imaging experiments were underway, efforts began to obtain Laue X-ray diffraction using a single photon bunch. Initial experiments were promising [21] with high quality images obtained on low-Z molecular crystals (such as Tylenol or explosives) and some data on shocked single crystal iron. One of the experimental configurations used in these tests is shown in figure 3 for Laue X-ray diffraction from iron single crystals. X-rays are shown incident on the sample at an approximate 25 degree angle. Back reflected X-rays are incident upon an LSO crystal phosphor which is then imaged onto the intensified CCD using a lens. Two example images are shown in figure 3 for a long exposure of 15 microseconds and 300 nanoseconds. These results are promising and clearly demonstrate the ability to obtain Laue XRD data using a single X-ray bunch from the synchrotron. Future experiments at the
Dynamic Compression Sector (Sector 35 at the APS) will be further improved through the use of focusing optics and more advanced undulators to increase the photon flux.

3. Innovations: Detection, Synchronization, Velocity Amplification

The success of IMPULSE, and the ability to perform routine X-ray imaging experiments during dynamic compression, has relied in part on two essential innovations: (1) the development of a robust optically multiplexed intensified detector configuration and (2) gun system improvements to better synchronize the impact event with the 80-ps width X-ray bunch. These are discussed in the following paragraphs.

Detector feasibility tests [22] had shown that it was possible to capture an X-ray image from a single photon bunch using standard intensified CCD detectors (Princeton Instruments PI-MAX series). The detectors included a triggering capability to synchronize it with the shock event and micro-channel plate gating to limit exposure of the scintillator to a minimum number of X-ray bunches [14, 21]. The current IMPULSE detector system [23] used four separate ICCDs (PI-MAX II) each independently secured to a stackup of motorized stages that provide three degrees of freedom. The detectors were optically coupled to the scintillator using a combination of optical splitters, light tubes, and microscope objectives to image the 1-2 mm square X-ray image from the scintillator onto the detector. The scintillator stage was also equipped with resolution grids and a white light source to optimize the system without X-rays. The current detector system is shown in figure 4 (top). An example of X-ray images using the system are shown in figure 4 (bottom) for an experiment where a copper cylinder impacted a vitreous carbon plate to study crack dynamics [18, 19]. The four images were taken at subsequent times showing the deformation of the cylinder as it penetrates the plate and the generation of cracks within the plate. This prototype detector system is currently being used as the starting point for developing multi-frame X-ray diffraction (MXRD) and simultaneous MPCI and MXRD measurements for IMPULSE and the Dynamic Compression Sector (DCS) at APS.

Synchronization of the impact event with the detectors and X-ray beam remains a key challenge in performing dynamic compression experiments at the synchrotron. The IMPULSE system was designed with a gas-breech which had the advantage of eliminating some of the hazards associated with powder guns while presenting limitations on the projectile velocity and large uncertainty in the system time (launch initiation to impact). The difficulties were overcome by: (1) developing a new millisecond launch valve which reduced the system time from 200±60 ms to 20±4 ms [15], (2) developing a novel velocity amplification concept that used an extruding die to increase the velocity of the flyer by up to 50 percent or more [24], and (3) development and testing of a new low-jitter breech concept presented here for the first time. The low-jitter breech concept is shown in figure 4 and consists of a breech body, a front flange, rupture disc assembly, a barrel, and a rear flange that accommodates a high-pressure, high voltage feedthrough (not shown). The high voltage feed through was used to connect the RP-87 (Teledyne-RISI) detonator to the fireset. The breech operates by filling the breech volume with helium to a pressure close to the rating of the burst disc. A detonator epoxied to the rupture disc is then used to burst the rupture disc and launch the projectile. A total of three experiments were conducted to test this concept for breech pressures of 950 psi using an Oseco rupture disc (1000 PSI rating). PDV was used to observe the operation of the rupture disc and to measure the system time which is the time delay between detonator initiation and bursting of the disc. A signal from the fire-set that initiates the detonator was used as a trigger for the PDV diagnostics to measure this total system time. For the three experiments, the system times were 3.145, 3.538, and 3.463 µs resulting in an average opening time of 3.382±0.209 µs which represents a significant improvement in gun performance and synchronization overall. Work continues to develop this concept to determine the system time for a range of burst pressures and breech volumes that will span the operating range of the standard gas gun system.
Figure 4. (A) Side view of the IMPULSE MPCI detection system in place next to the target chamber of the IMPULSE gun. The four CCDs are indicated along with the gun barrel and the target chamber. (B) Top-view of the MPCI detector system (C) Images obtained using the MPCI system to monitor impact of a 300-micron Cu cylinder onto a vitreous carbon plate to image crack formation [18]. Times shown are referenced to a pre-impact trigger pin and the scale bar shown is 500 µm. Experimental configuration is described elsewhere [14].

4. Summary and Path-Forward
The main objective of the IMPULSE project was to design, fabricate, qualify, and install a mobile plate impact facility at the APS and to perform the first dynamic compression experiments using a single X-ray photon bunch for phase contrast imaging and Laue X-ray diffraction. Key challenges in using a gun system to acquire dynamic data at the APS were: synchronization (or bracketing) of the impact event with the detectors and single 80-ps width X-ray bunch, detection of the diffracted or transmitted X-rays, and the design of appropriate shock wave experiments compatible with these new diagnostics. The IMPULSE team worked to develop a new launch initiation system that significantly reduced the system time of the gun by an order of magnitude [15], successfully tested a low-jitter breech concept for improved synchronization in future experiments, and improved gun performance by developing a velocity amplification method for any gun system. In addition, a novel multi-frame detector system was developed for
Figure 5. (a) Partial schematic of the low-jitter breech. The detonator position is indicated and the rear flange and high-voltage feed through are not shown. (b) Example PDV data. (c) The components that make up the rupture disc assembly. (c) A photo of the rupture disc with the RP-87 detonator epoxied to the inner surface. (d) Recovered rupture disc following one of the experiments.

PCI which resulted in the first “shock movies” of X-ray imaging at a synchrotron source with an unprecedented 1-2 micron spatial resolution. Efforts are underway to develop a qualified explosive vessel for explosive drive experiments, to use X-ray imaging to examine detonator performance and shock propagation through aerogels, and to develop a simultaneous PCI and XRD detector system based on our current prototype. In early 2014, the IMPULSE capability will be available at the new Dynamic Compression Sector (Sector 35 at the APS), along with its complete suite of shock wave diagnostics. IMPULSE will continue to play a central role in capability development by performing novel experiments while developing the user knowledge base needed to ensure success of future facilities including the Dynamic Compression Sector and LANL’s MaRIE.

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References

[1] Hayes D B 1974 J. Appl. Phys. 45 1208-1217.
[2] Dolan D H, Knudson M, Hall C and Deeney C 2007 Nature Phys. Lett. 3 339-347.
[3] Jensen B J, Gray III G T and Hixson R S 2009 J. Appl. Phys 105 013502.
[4] Jensen B J, Cherne F J, Cooley J, Zheruokletov M and Kovalyev A 2010 Phys. Rev. B 81 214109.
[5] Asay J R, Fowles G R, Duvall G E, Miles M and Tind M 1972 J. Appl. Phys. 43 2132.
[6] Taylor J W 1965 J. Appl. Phys. 36 3146.
[7] Huang H and Asay J 2007 J. Appl. Phys. 101 063550.
[8] Sarrao J 2012 Marie 1.0: A flagship facility for predicting and controlling materials in dynamic extremes Los Alamos National Laboratory Tech. Rep. LA-UR 12-00500.
[9] d’Almeida T and Gupta Y M 2000 Phys. Rev. Lett. 85 330.
[10] Jensen B J and Gupta Y M 2006 J. Appl. Phys 100 053512.
[11] Jensen B J and Gupta Y M 2008 J. Appl. Phys. 104 013510.
[12] Dolan D H 2007 Characterizing the emissivity of materials under dynamic compression Sandia National Laboratory Tech. Rep. SAND2007-6376.
[13] Gupta Y M, Turneaure S J, Perkins K, Zimmerman K, Arganbright N, Shen G and Chow P 2012 Rev. Sci. Instrum. 83 123905.
[14] Jensen B H, Luo S N, Hooks D E, Fezzaa K, Ramos K J, Yeager J D, Kwiatkowski K, Shimada T and Dattelbaum D M 2012 AIP Advances 2 012170.
[15] Jensen B J, Owens C T, Ramos K J, Yeager J D, Saavedra R A, Iverson A J, Luo S N, Fezzaa K and Hooks D E 2013 Rev. Sci. Instrum. 84 013904.
[16] Barker L M and Hollenbach R E 1974 J. Appl. Phys. 45(11) 4872-4887.
[17] Strand O T, Berzins L V, Goossen D R, Kuhlow W W, Sargis P D and Whitworth T L 2004 Proceedings of SPIE ed Paisley D L, Kleinfielder S, Snyder D R and Thompson B J (Virginia: SPIE) p 593.
[18] Ramos K J, Jensen B J, Yeager J D, Bolme C, Iverson A J, Carlson C A and Fezzaa K 2014 Conf. Proc. of the Society for Experimental Mechanics Series: Dynamic Behavior of Materials vol 1 ed Song B, Casem D and Kimberley J (Springer International Publishing) pp 413-420.
[19] Ramos K J, Jensen B J, Yeager J D, Bolme C, Iverson A J, Carlson C A and Fezzaa K 2014 submitted to these conference proceedings.
[20] Brown E, Furmanski J, Ramos K J, Dattelbaum D M, Jensen B J, Iverson A J, Carlson C A, Fezza K, Gray III G T, Patterson B, Trujillo C and Martinez D 2014 submitted to these conference proceedings.
[21] Luo S N, Jensen B J, Hooks D E, Fezzaa K, Ramos K J, Yeager J D, Kwiatkowski K and Shimada T 2012 Rev. Sci. Instrum. 83 073903.
[22] Yeager J D, Luo S N, Jensen B J, Fezzaa K, Montgomery D and Hooks D E 2012 Composites Part A: Applied Science and Manufacturing 43 885-892.
[23] Iverson A J, Carlson C A, Jensen B J, Ramos K J, Montgomery J and Fezzaa K 2014 submitted to these conference proceedings.
[24] Anderson W W, Jensen B J, Cherne F J, Owens C T, Ramos K J and Lieber M 2014 submitted to these conference proceedings.