ESRF	**Experiment title:** Time-resolved, high-resolution X-ray radiography of shock-compressed planetary powders	**Experiment number:** MI-1224
Beamline: ID19	**Date of experiment:** from: 14^{th} Sept 2015 to: 18^{th} Sept 2015	**Date of report:** 3^{rd} Feb 2016
Shifts: 15	**Local contact(s):** Alexander Rack	*Received at ESRF:*

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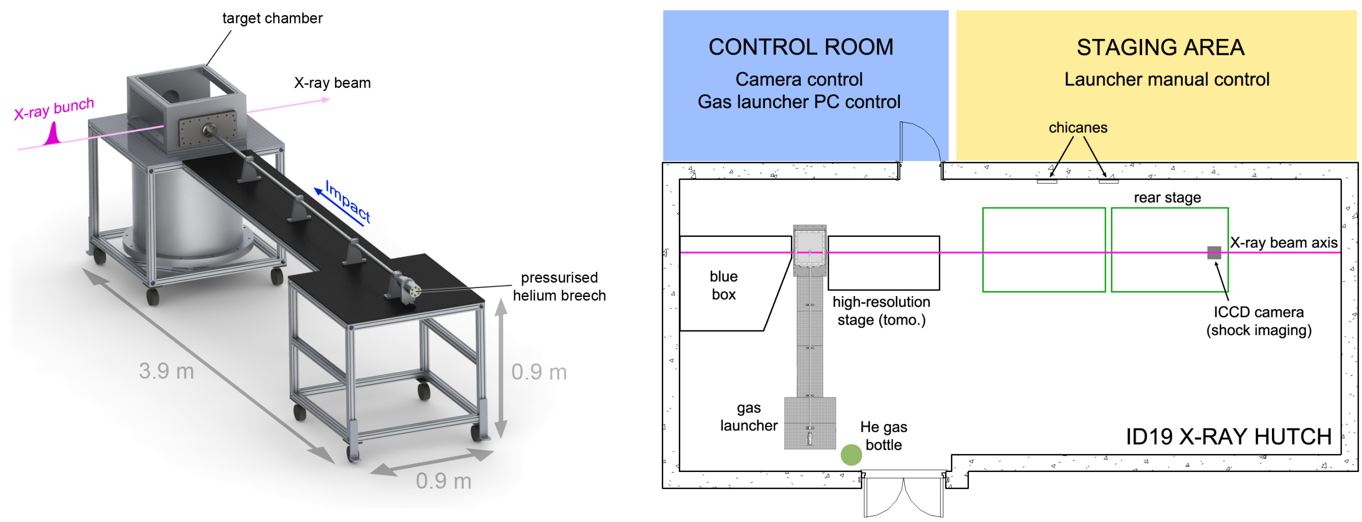
Report:

The purpose of experiment MI-1224 was to study the role of high-speed impact in the early formation of asteroids and planetary bodies in the early solar system. Building upon a dynamic X-ray radiography method developed at the Diamond Light Source, we sought to employ the much higher X-ray flux on beamline ID19 to perform multi-frame, single-bunch X-ray imaging of a powder specimen subjected to high-velocity impact. The primary challenges of this work were in the installation and synchronisation of a gas-gun based impact system at ESRF, coupled with fielding of a new multi-frame imaging capability for the first time.



(a) (b)

Figure 1: (a) Model of the portable gas gun impact system installed on ID19. The impact and resulting shock wave propagates transverse to the X-ray beam. (b) Illustration of the set-up in and around the hutch, with control of the gas gun, synchronisation and ICCD camera taking place remotely.

Shown in Figure 1a is an illustration of the portable single-stage gas gun used in this work. The gas gun was transported to ESRF from Imperial College London and installed in the rear hutch of Beamline ID19. Figure 1b shows the relative placement of the gun in the ID19 hutch between the ‘blue box’ and high-resolution detector stage, with the impact direction aligned normal to the X-ray beam path. Although assembly of the gun was fairly straightforward, alignment of the impact axis to the X-ray beam was an extended process, owing to the lack of fine vertical translation in the gun frame.

Complete operation of the gun, e.g. charging, firing, and venting, was accomplished using a remote LabVIEW interface. Connections between the gun, LabVIEW control system and diagnostics were fed through chicanes on the near side of the control room. During an experiment, high-pressure He gas (supplied by ESRF) was used to accelerate a projectile to speeds $\sim$650 m/s, generating dynamic compression upon impact with the sample. A large expansion tank, located adjacent to the target chamber, ensured the system maintained at vacuum even at the highest firing pressures ($\sim$200 bar).

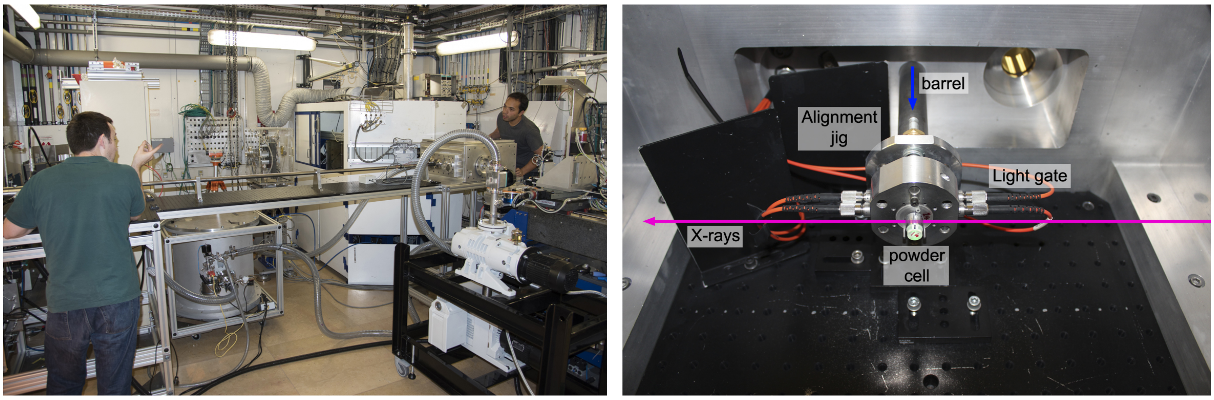


Figure 2: (Left) Photograph showing the Imperial College mesoscale gas gun installed on Beamline ID19. (Right) View inside the target chamber, showing a powder cell sample aligned to the barrel and X-ray beam.

Synchronisation of the impact event with the X-ray bunches was accomplished in a manner similar to that described in [1], using a variety of signals from the gas-gun, the remote LabVIEW control system, and synchrotron. When the gun was fired, a signal from the control system opened the fast X-ray shutter for a period of 200 ms, limiting the heat load into the sample and scintillator, however sufficient to bracket the entire impact event (typically 170 ms after firing). Arrival of the projectile $\sim$250 mm from the end of the barrel was detected by a surface-mounted strain-gauge, which provided an early trigger to the PI-Max camera needed to initialise the double-frame mode. Finally, passage of the projectile through the light gates just prior to the sample satisfied the first condition of an 'AND' gate to trigger the camera, with the 4-bunch signal from the Beamline BCDU8 serving as the second. In this way, up to two phase contrast X-ray radiographs were obtained in each experiment, with imprecision of less than 704 ns. In practice, it was found that delaying the second frame by 3 bunch spacings (2.11 μs) provided sufficient time for decay of the YAG:Ce phosphor in the camera, with two sequential impact experiments staggered to complete the time series of radiographs.

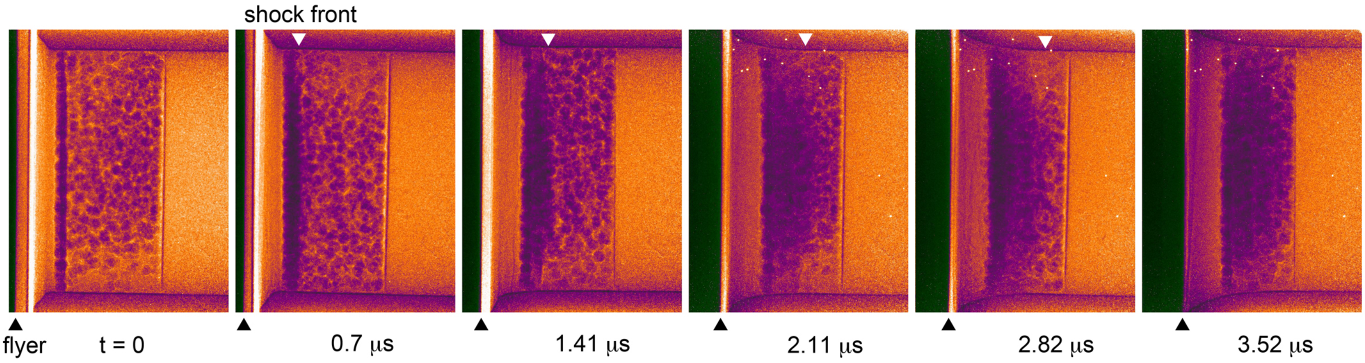


Figure 3: Time-series of phase contrast radiographs showing the first dynamic compression experiments carried out at ESRF using the gas gun developed by Eakins and Chapman [1]. Impact loading was performed on 10 mm dia. cells containing asteroid powder simulant, with sequences of single-bunch X-ray images clearly resolving the progress of the shock wave through the bimodal powder bed. These preliminary results demonstrate the capability for multi-frame, high resolution phase-contrast imaging of extreme physical behaviour.

A total of 19 experiments were performed on two distinct SiO_2 powder configurations representing the preconsolidated state of asteroids and other protoplanetary bodies. The configurations comprised a 30 vol.% mixture of solid density SiO_2 chondrules (either 190 or 450 μm diameter) and 70 vol.%

nanometer-scale SiO_2 matrix, where the matrix itself was 50 vol.% porous. Impacts were performed at 650 m/s in all cases, with the loading pressure varied by using either polycarbonate or copper driver plates. Sequences of images were obtained by increasing the delay between the BCDU8 signal and camera trigger in multiples of the bunch spacing, yielding snapshots of the transient compaction states of the powder mixtures every 704 ns. An example of such a time series is shown in Figure 3 for the mixture containing 450 μm chondrules. The dynamic compaction of the porous mixture and propagation of a shock wave can be clearly seen over the ~3.5 μs after impact.

In addition to the impact experiments, high-resolution tomography was performed to capture the precise configuration of the chondrules and matrix in each powder cell. This information will be used to initialise a faithful 3D hydrocode simulation of the compaction process, and in turn generate snapshots of the mesoscale matched to the X-ray radiograph times. In this way, models of dynamic material strength and component interaction may be validated at the mesoscale for the first time, leading to an overall improvement in multi-scale predictive capability. Figure 4 shows the first attempt at simulating the compaction of the coarse powder mixture. A 2D central slice of the tomography dataset has been successfully imported into the iSALE multi-material Eulerian hydrocode, and dynamic compaction simulated via movement of a piston at 650 m/s. The modelling results reveal significant nonuniformities in density and temperature, with the majority of deformation energy deposited into the initially porous matrix. Further work is needed to enable import of the 3D microstructure before quantitative comparisons can be made to the dynamic radiographs.

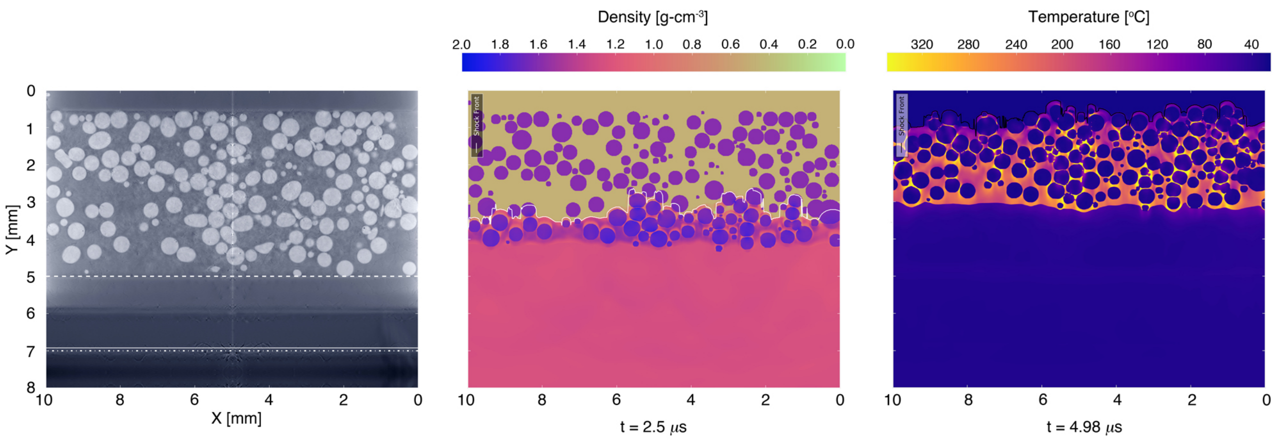


Figure 4: 2D iSALE simulation of the dynamic compaction of the coarse chondrule mixture impacted at 650 m/s. The model was initialised from a 2D central slice of an X-ray tomography dataset, with particles approximated at circles.

In conclusion, this experiment has successfully demonstrated the first precision impact loading experiments at the European Synchrotron Radiation Facility, and a new capability for revealing the subsurface details of dynamic compaction in astrophysical powders. The results of this work are currently being prepared for publication, with an extended paper planned following completion of the 3D modelling. Future areas of improvement include introducing multiple ICCD cameras to extend the number of frames per experiment to 4 or 8; experimenting with high light output, faster-decay scintillators to reduce interframe times for potential exploitation of the ESRF 16BM [2]; and exploring single-bunch diffraction to access quantitative strain/structure information during rapid, high-pressure loading.

[1] D. E. Eakins and D. J. Chapman. X-ray imaging of subsurface dynamics in high-Z materials at the Diamond Light Source. *Review of Scientific Instruments*, 85(1):123708, Dec. 2014.

[2] M. E. Rutherford, D. J. Chapman, T. G. White, M. Drakopoulos, A. Rack, and D. E. Eakins. Evaluating scintillator performance in time-resolved, hard X-ray studies at synchrotron light sources. *Journal of Synchrotron Radiation*, in press.