SULI PPPL Internship 2016

Advanced Superheated Bubble Detector Test Bench for Zero-Knowledge Warhead Verification

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<u>Abstract:</u> Superheated droplet detectors, or bubble detectors, are emulsions of fluorocarbon droplets homogeneously dispersed in an aqueous gel matrix. These non-electronic detectors can be manufactured to be sensitive only to neutrons above a certain energy threshold without being sensitive to gamma rays, and have the ability to record the total fluence at which they were exposed during multiple exposures. Recently, bubble detectors have been used in the first experimental demonstration of a physical zero-knowledge protocol for nuclear warhead verification. Such a protocol can confirm that two objects are identical without revealing their geometry or composition, and could play an important role in the next round of nuclear arms control agreements that may require inspection of individual warheads. A follow up experiment to discriminate special nuclear materials of identical geometry but different isotopic composition, without learning what these properties are, is currently being developed at PPPL.

As part of this experiment, we are developing a test bench to implement advanced optical and laser bubble counting techniques for the careful characterization of bubble detectors. In particular, we are looking to increase our capacity to adequately measure greater detector exposure (~1000 bubbles) in order to increase the statistics of our measurements, as well as study the physical mechanisms of bubble aging. Such system should be able to take high-resolution videos of the detectors including during exposure to 14-MeV neutrons.

Concurrently to the development of the test bench and further work in the development of the main experiment, which require the careful characterization of the neutron field produced by our new 14-MeV DT neutrons generator shielded in a large collimator. This work involves both Monte Carlo simulations and experimental measurements using fast neutron scintillator detectors.

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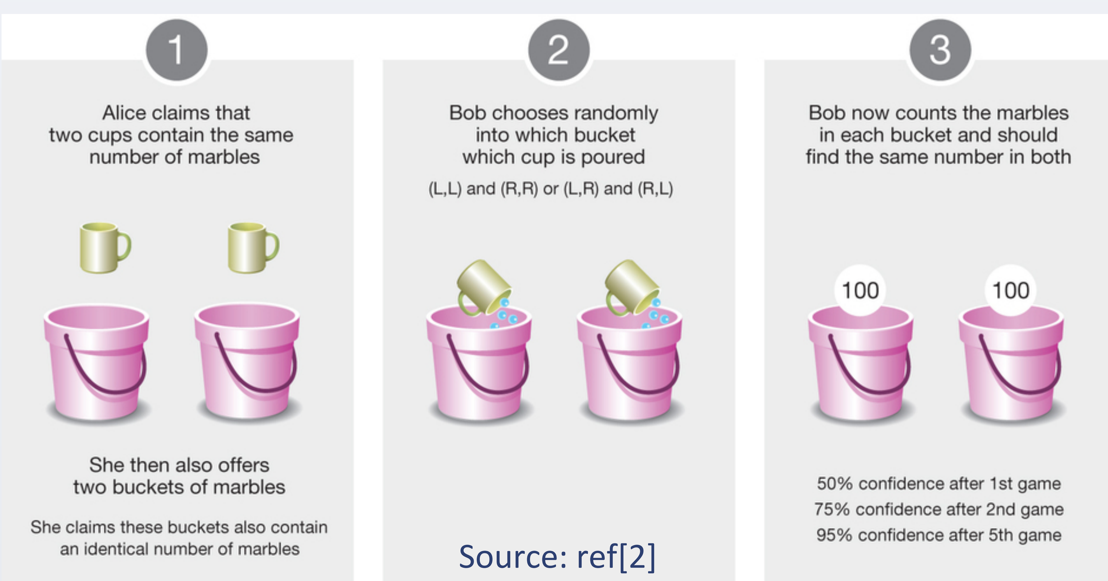
Zero-Knowledge Protocol, a Definition [1]

A proof in which the "prover" can demonstrate to the "verifier" that a statement is true without revealing any other information about the statement itself.

Zero Knowledge Proof using Marbles[2]



Source: ref[2]

Application to Nuclear Disarmament

Future arms reduction agreements may place numerical limits on deployed and non-deployed nuclear warheads. The verification of such agreements could require the authentication of thousands of treaty accountable items declared as nuclear weapons. To do so, it is important to develop inspection systems that can confirm the authenticity of true warheads while being able to detect potential spoofs. The sensitive nature of nuclear weapons require at the same time not to reveal any secret design details of the weapon itself. Previous efforts have been focusing on the development of electronic information barriers that measure but sanitize data. They require, however, both parties to trust the hardware and software so that the host cannot modify the result of an inspection and the inspector cannot secretly acquire data, a problem that has yet to be solved.

To address this conundrum, Glaser, Barak and Goldston have proposed a physical zero-knowledge protocol for warhead verification [2] using non-electronic superheated droplet detectors where sensitive information is never measured. Key aspects of this approach were recently demonstrated by Philippe et al. at PPPL[3].

Current Verification Experiment and Motivation for Improved Counter

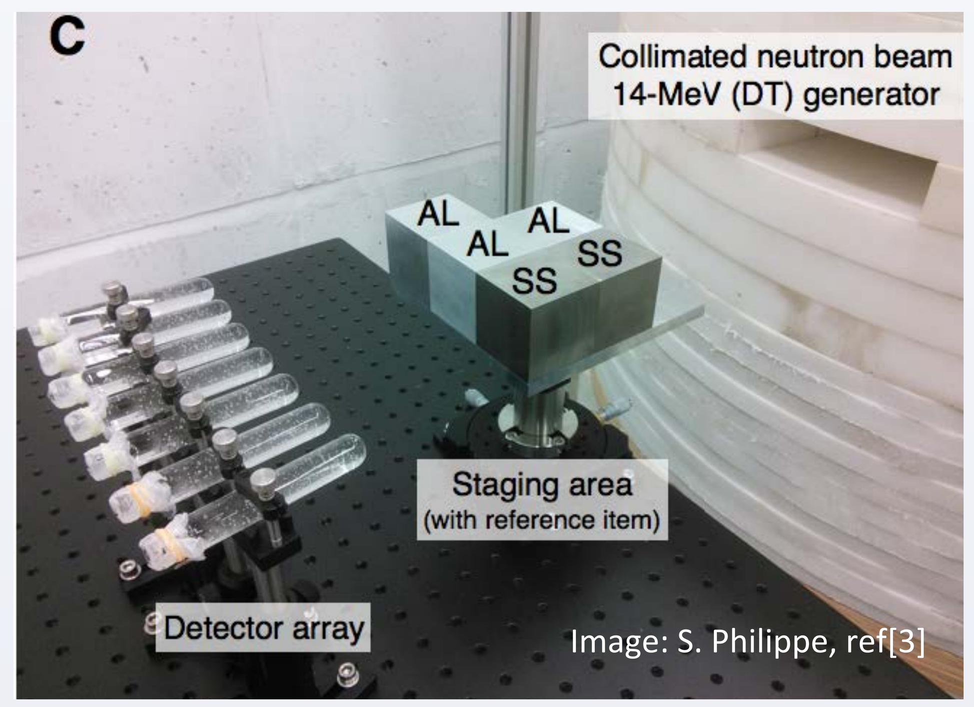
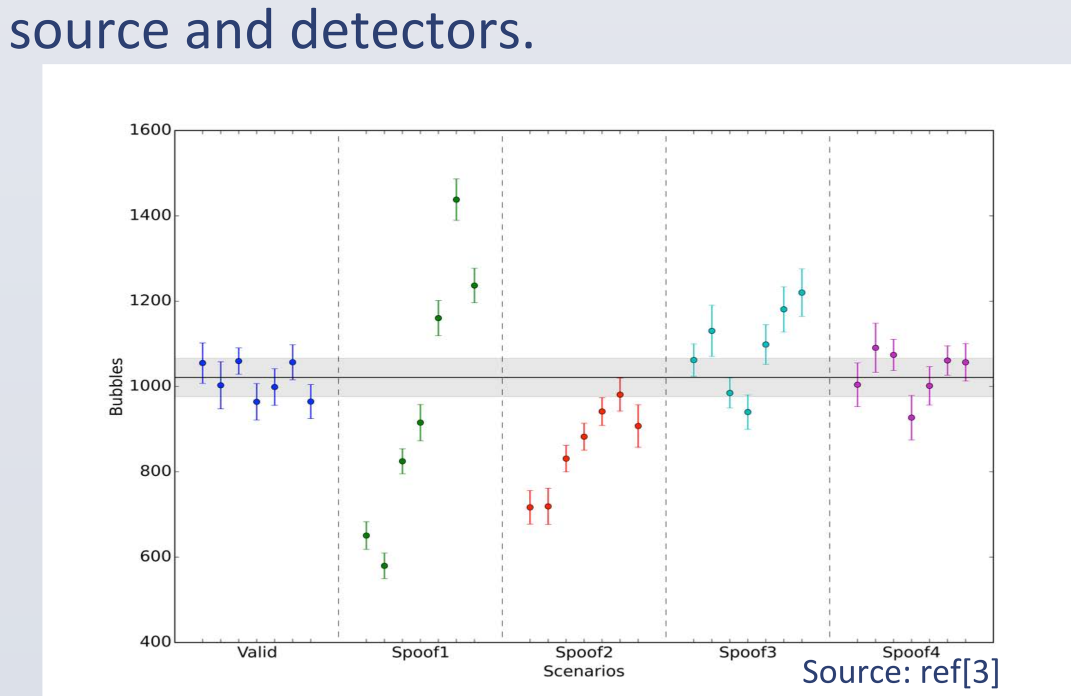


Image: S. Philippe, ref[3]

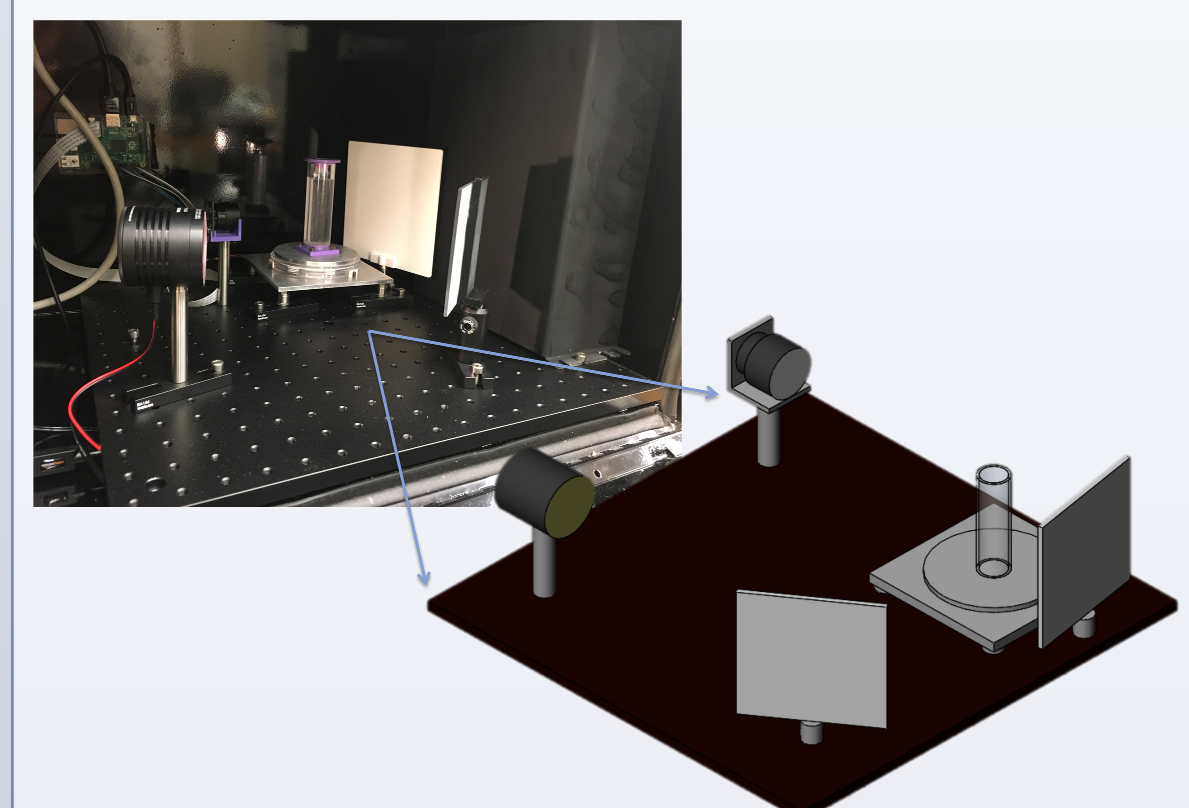
The approach consists of performing neutron transmission radiography of treaty accountable items. The objects are illuminated with a collimated neutron beam and the resulting signal is recorded on the bubble detectors. The detectors are then preloaded with the complement radiograph of a reference item trusted by the inspectors such that the resulting signal (sum of preload and radiograph), following the inspection of an item identical to the reference, is Poisson-distributed with parameter N_{max}. N_{max} can be defined as the expected number of bubbles if no object had been present between the source and detectors.



Source: ref[3]

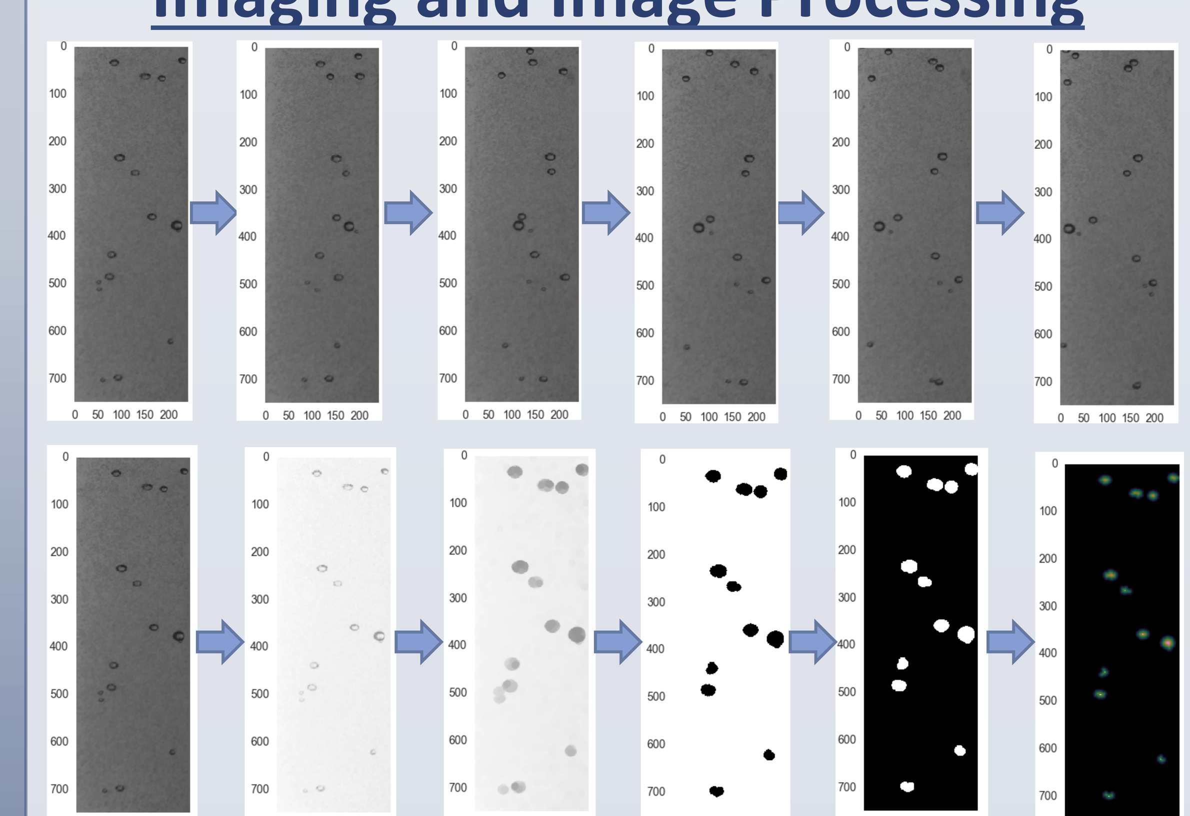
The higher N_{max} is the better the inspection system can detect attempts at cheating. It is therefore necessary to be able to count a large amount of bubbles in the detectors accurately.

Experimental Test Bench Set Up



The test bench is designed to perform 360deg optical tomography of bubble detectors by rotating them around the z axis while taking pictures or videos. This technique allows in theory to count and distinguish a large number of bubbles by improving segmentation and tracking of individual bubbles. The bench is built on an optical bread board using a lamp shinning onto a mirror and diffusor which illuminate the detector. The detector sits on a turn table in front of a camera. The entire device is controlled by a Raspberry Pi.

Imaging and Image Processing



The first challenge faced when making this test bench was developing a set up that had the ability to capture pictures and videos of high enough quality to preform image processing on them. Once this was accomplished, image processing could be conducted through a series of steps to calculate the centroid of each bubble in the detector. This was needed to track each bubble.

Method Behind Tracking the Bubbles

Tracking bubbles through rotation of the bubble detector:

Here $\Delta\theta$ is the amount rotated between each picture, x_n is the projected radius of a bubble from the central axis of rotation on the nth rotation of $\Delta\theta$ as viewed from a head on flat profile view of the detector, θ_{ref} is the reference angle from the initial position of the angle and r_0 is the true radius of a bubble from the central axis of rotation constant over all angles. Note: z coordinate remains constant throughout rotation

$$x_n = r_0 \cos(\theta_{ref} + n\Delta\theta)$$

Using the trig identity

$$\cos(u+v) = \cos(u)\cos(v) - \sin(u)\sin(v)$$

Expanding x_n and taking x_n/x_0

$$\frac{x_n}{x_0} = \cos(n\Delta\theta) - \tan(\theta_{ref})\sin(n\Delta\theta)$$

Solving for θ_{ref} and r_0 *in* the most general case

$$\theta_{ref} = tan^{-1}\left(\frac{\cos(n\Delta\theta) - \frac{x_n}{x_0}}{\sin(n\Delta\theta)}\right)$$

$$r_0 = \frac{x_n}{\cos(\theta_{ref} + n\Delta\theta)}$$

References

- [1] Goldwasser, S., Micali, S. & Rackoff, C. "The knowledge complexity of interactive proof-systems." SIAM J. Comput. 18, (1989): 186–208.
- [2] Glaser, A., Barak, B. & Goldston, R. J. "A Zero-knowledge Protocol for Nuclear Warhead Verification." Nature 510.7506 (2014): 497-502.
- [3] Philippe, S., Goldston, R. J., Glaser A. & d'Errico F. "A physical zero-knowledge object comparison system for nuclear warhead verification." Nature Communications, forthcoming.

Acknowledgements

This work was made possible by funding from the Department of Energy for the Summer Undergraduate Laboratory Internship (SULI) program. This work is supported by the US DOE Contract No. DE-AC02-09CH11466.

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