Utilization of Acoustically Tensioned Metastable Fluid Detectors in Health Physics

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HPS Conference Poster Presentation; Madison, WI; July 8th, 2013

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System Description and Capabilities

Fluid Metastability
Cavitation and Triggering

It has been shown that fluids may be placed under tensile forces, just as solids can [1]. The application of these tensile forces induces negative pressures, which places the fluid in a region of metastability.

Metastable fluids exhibit some interesting and useful characteristics. Of particular interest to our application is the significantly reduced energy required to cause localized boiling. Energy imparted by ions moving through the fluid can easily cause localized boiling. These ions may be induced by neutron-nucleus collisions, as well as alpha particles.

Once the ion has imparted enough energy to the metastable fluid, a localized boiling event, or cavitation, will occur. This cavitation will then grow, and if it exceeds a threshold size (r_c), can grow to visible sizes. The collapse of these cavitations creates pressure waves which can be detected by the human ear. Thus, the presence of nuclear particles may be detected by sight or sound.

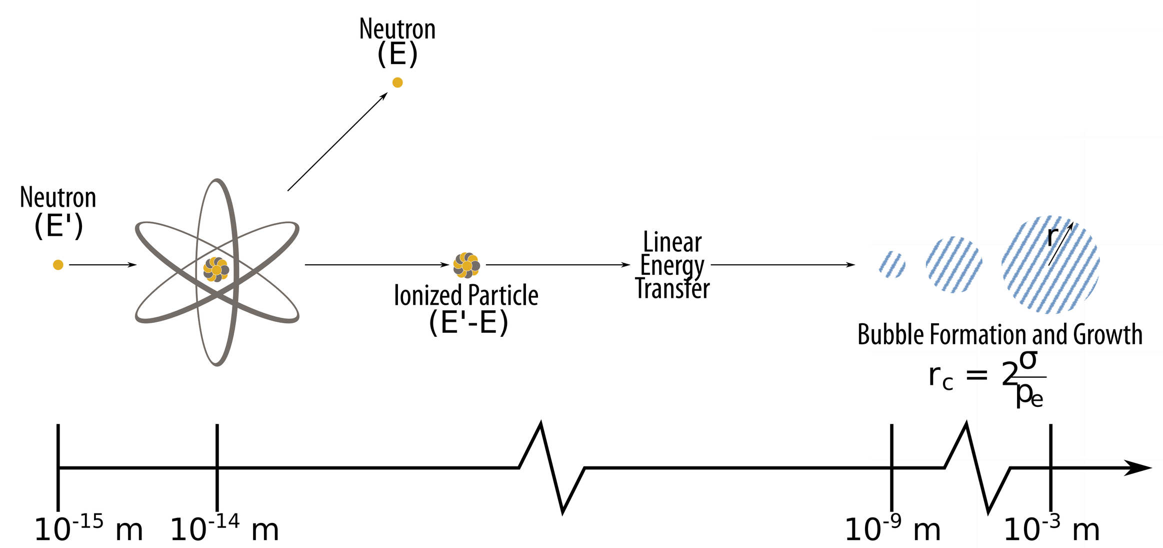


Figure 1: Size Scales and Description of Cavitation Trigger Process

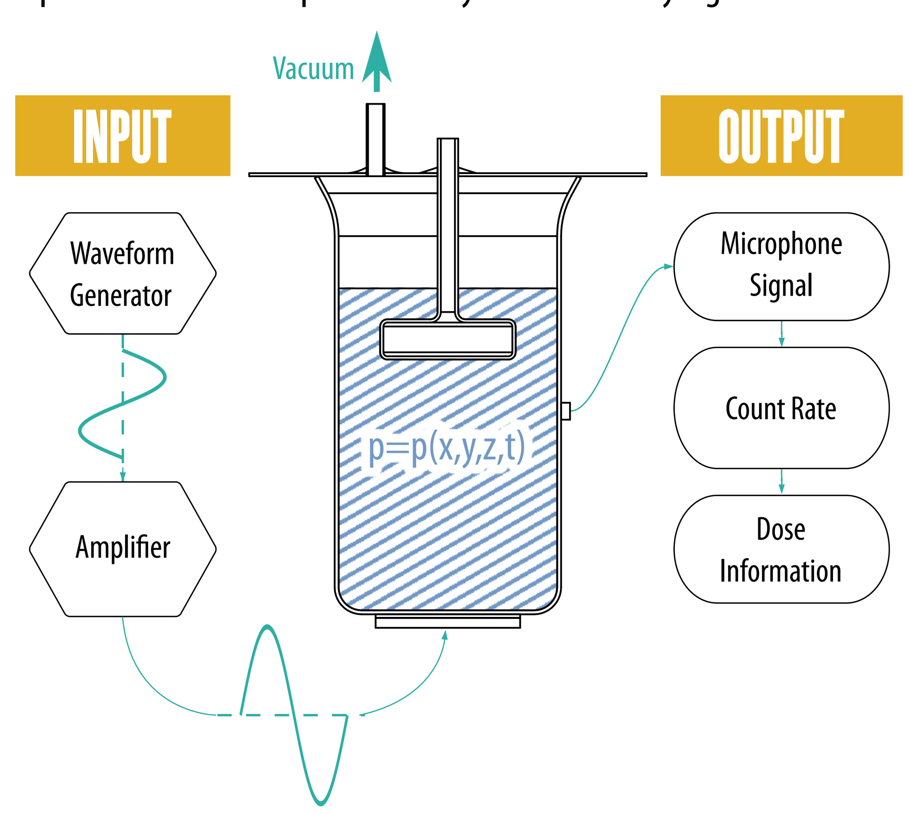


Figure 2: ATMFD Operation Schematic

Creation of Metastability
Acoustic Field Induction

Induction of tensile pressures in fluids is currently done by centrifugal force, surface tension, or acoustic fields. For the system described, the Acoustically Tensioned Metastable Fluid Detector (ATMFD), the tensile pressures are induced by an acoustic field.

The system includes a glass resonant acoustic chamber, a glass acoustic power reflector, and a piezoelectric transducer used to drive the chamber. By applying resonant frequency sine waves to the transducer, a resonant mode of vibration can be imparted into the fluid. This causes the fluid to switch between compression and tension many thousand times a second. The system also includes a lid for sealing and structural integrity, and a microphone to impart signals which are used to ensure resonance and to detect events.

Because of the simplicity of the concept and the ability to create the chamber out of commonly obtainable components, the system competes favorably with state of the art systems in terms of capabilities, and well exceeds state of the art systems in affordability.

Comparison to State of the Art
He3 and BF3 Tube System vs. ATMFD Comparison

The benefits of the ATMFD when compared to state of the art systems come in two forms; the ATMFD system competes or exceeds the state of the art in capabilities, yet still vastly outperforms the state of the art in affordability and simplicity.

Table 1: Comparison Between ATMFD System and ^{3}He and ^{3}BF systems - Operational Characteristics and System Cost

Parameter	Conventional System	ATMFD System
Intrinsic efficiency	~0% (MeV neutrons) ~90% (0.01 eV neutrons) (3cm x 30cm tube)	~90% (MeV neutrons) ~90% (0.01 eV neutrons) (10cm x 10cm volume)
On-Off times	Minutes, saturation during pulsed interrogation	Microseconds, adaptable for pulsed systems
Gamma blindness?	Limited; Saturation in high gamma fields	Yes; No gamma saturation issues
Neutron Directionality?	No with single systems; Yes if arrays are used	Yes (to within 10^{o}) with single system
Can system detect neutrons and alphas?	No; neutron spectroscopy requires Bonner spheres and spectrum unfolding	Yes. Same system can be adapted to detect neutrons and alphas with spectroscopy
Cost	High (~$5k-$10k for single tube systems)	Low-to-Modest ($50-$1k+)

Current System Development Thrusts

Directionality
Source Position Sensing

The physics involved with the ATMFD detection process enables the system to ascertain the direction in which the source is located. By determining the probability that a neutron cavitation event will occur in each position in the chamber, the source direction can quickly be calculated to within several degrees. The source location probability distribution shown below was determined after 2000 events (~5 minutes) with a cylindrical detector setup (shown to right). A previous design of the ATMFD (the D-ATMFD) was used for this analysis. The probability surface plot below shows that the ATMFD system can quickly and accurately predict source location [2].

In contrast to thermal neutron imaging applications, the neutron fluence needed in this application is very low, position sensing is very fast, and standoffs may be rather long (on the order of meters). Because of this, the imaging quality is lower, providing only direction information. It would be ideal for use to determine leakage in containment walls, to determine the location of leaks, or many other applications.

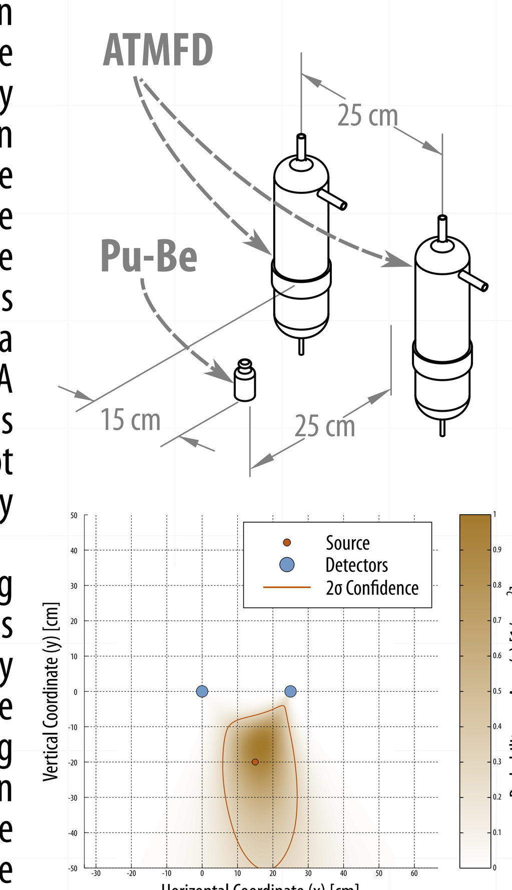


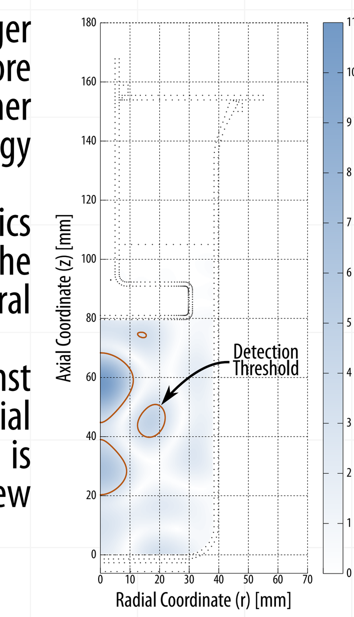
Figure 3: (a) TOP - Experimental Setup for Directionality Analysis, (b) BOTTOM - Results given in probability per area for DIrectionality Analysis

Detector Optimization
Multiphysics Simulation Based Parameter Studies

Optimization of the ATMFD system will provide larger sensitive areas, which in turn will provide more directional information per detection event, higher detection efficiencies, and even a lower neutron energy threshold required for detection.

Optimization is accelerated by using a multiphysics simulation platform, which accounts for the electromagnetics, piezoelectric response, structural mechanics, and acoustics in the system.

The simulation has been benchmarked against experimental data both in the frequency and spatial domains, and has good agreement in both. It is considered a leadership tool for optimization and new design iterations [4].



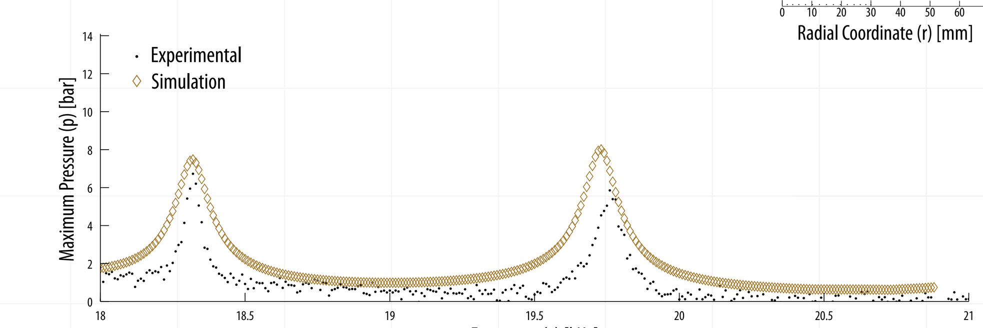


Figure 4: (a) TOP - Simulated Pressure Profile at Detection Resonance of E-ATMFD, (b) BOTTOM - Frequency Response of D-ATMFD System, Experimental and Simulation Comparison

System Applications

Dose Monitoring
ATMFD Based Persistent Dose Monitor

The ATMFD system has characteristics that place it well as a persistent dose monitor for neutrons. The charts below show count rates with two different sources, showing detection over time at a variety of distances. These response curves were taken by filtering the microphone response in one second windows on an EATMFD system at 15cm, 30cm, 50cm, and 70cm with a Pu-Be or ^{252}Cf source [4]. Through simple calculation, these count rates could be converted into dose rates. The total amount of detections would easily be tallied, providing the persistent dose measurement desired in an area.

The system has several operational advantages to state of the art systems for dose monitoring applications. Current ATMFD implementations may be portable, and in these configurations is much lighter than Bonner Sphere type detectors. Also, ATMFD piezoelectric elements currently require only ~200 V, much lower than the dangerously high voltages in other detector applications. ATMFDs' simplicity provides hope for ruggedization, as opposed to the fragile electronics in state of the art systems.

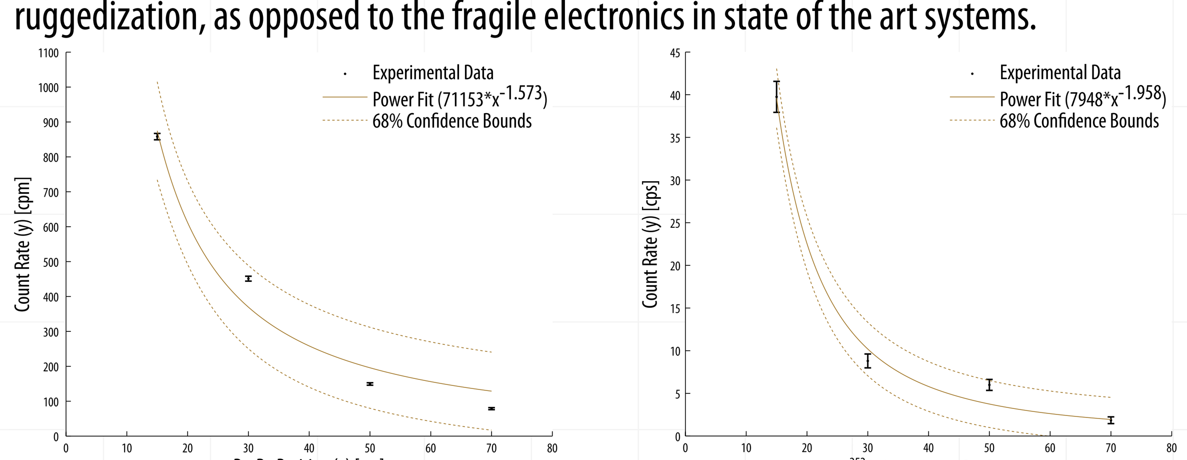


Figure 5: (a) LEFT - Count Rate vs. Distance using Pu-Be as Source in E-ATMFD System, (b) Right - Count Rate vs. Distance using ^{252}Cf as Source in E-ATMFD System [4]

The ATMFD system is gamma-blind; it will not detect any gamma, regardless of intensity of field or energy. This has been tested up to a 3 Ci ^{137}Cs source with no detections [3]. Gamma-blindness may be an advantage in Nuclear Power Plant applications. Because state of the art detectors often get saturated in gamma fields and thus provide no information on neutron dose, the ATMFD could be used to replace or supplement those detectors in order to provide information on the neutron dose.

The final benefit of the ATMFD system is the ability to detect from thermal to fast neutrons. Neutron absorbers may be added to the detection fluid. Reactions on these absorbers can yield secondary ions, which in turn are detected. This has been shown in Tri-Methyl Borate on a consistent basis. Boron has a large cross section for neutron capture, and the $^{10}B + n \rightarrow {}^{7}Li + \alpha$ reaction occurs upon absorption, where the α or Li is detected. The fluid properties of Tri-Methyl Borate also allow for detection of fast neutrons, alongside the thermal detections on ^{10}B [5]. In all, the ATMFD system provides thermal to fast, gamma blind neutron detection with a more portable and rugged system than state of the art.

Acknowledgements

This project is funded in part by the U.S. Department of Energy. Special thanks to Sagamore Adams Laboratories, LLC for their support and help in the development of tensioned metastable fluid detectors. Acknowledgement should be given to other members at the MFARL Lab at Purdue University who gave advice and contributed some time such as Jeffery Webster and Stefan Rogers. Purdue Radiological and Environmental Management deserves recognition as well for the use of their equipment and services.

References

[1] B.C. Archambault, T.F. Grimes, J.A. Webster, N.W. Wilson, A. Hagen, K.F. Fischer, R.P. Taleyarkhan, "Development of a 4π directional fast neutron detector using tensioned metastable fluids," Homeland Security (HST), 2012 IEEE, pp.423,428, 13-15 Nov. 2012, doi: 10.1109/THS.2012.6459886
[2] B.C. Archambault, J.A. Webster, J.R. Lapinskas, T.F. Grimes, R.P. Taleyarkhan, "Development of a novel direction-position sensing fast neutron detector using tensioned metastable fluids", Nuclear Instruments and Methods in Physics Research, Volume 673, 1 May 2012, Pages 89-97, ISSN 0168-9002.
[3] T.F. Grimes, B.C. Archambault, J.A. Webster, A. Sansone, R.P. Taleyarkhan, "Gamma-blind transformational nuclear particle sensors," Homeland Security (HST), 2012 IEEE, pp.417,422,13-15 Nov. 2012,doi: 10.1109/THS.2012.6459885
[4] K.F. Fischer, A. Hagen, T.F. Grimes, B.C. Archambault, R.P. Taleyarkhan, "Economical, High-Efficiency SNM Detection via Gamma-Beta Blind Acoustically Tensioned Metastable Fluid Detectors as He-3 Sensor Replacements," Homeland Security (HST), 2013 IEEE,12-14 Nov. 2013, To Be Published
[5] J. Lapinskas, P. Smagacz, Y. Xu, R.P. Taleyarkhan, "Tension metastable fluid nuclear particle Detector—Qualification and comparisons", Nuclear Engineering and Design, Volume 239, Issue 10, October 2009, Pages 2152-2159, ISSN 0029-5493.