Investigating Sonoluminescence as a Source of Alternative Energy

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Presented at
GRC GREEN Forum
August 14, 2009

Outline

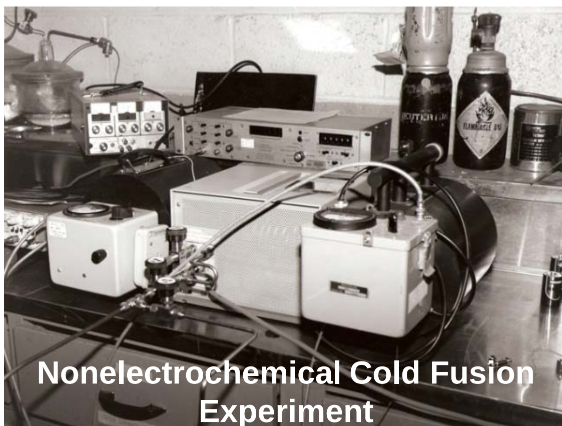
"Star in a Jar"

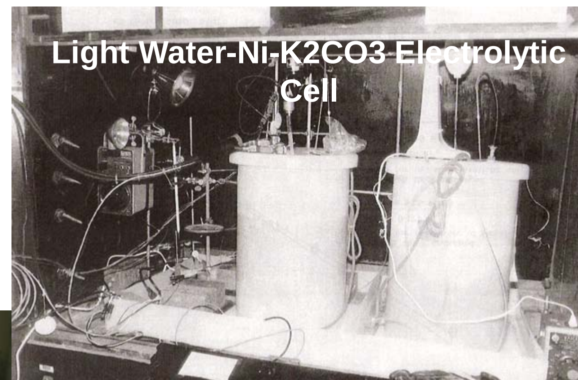
– W. Moss, LLNL

- Introduction
- Sonofusion
- Apparatus & Imaging
- Indications of High Temperature
- Concepts
- Summary

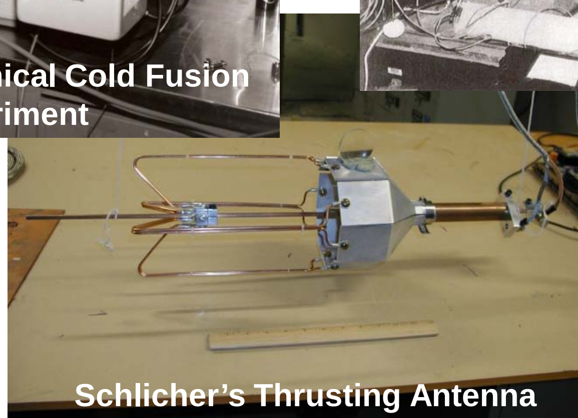
GRC History of Revolutionary Research

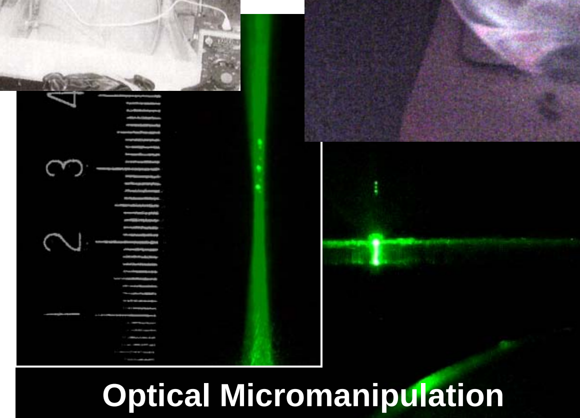
- Nonelectrochemical Cold Fusion Experiment
- Light Water-Ni-K_2CO_3 Electrolytic Cell
- Schlicher's Thrusting Antenna
- Optical Micromanipulation
- **NanoStar: Sonoluminescence**


Nonelectrochemical Cold Fusion Experiment


Light Water-Ni-K2CO3 Electrolytic Cell

NanoStar: Sonoluminescence


Schlicher's Thrusting Antenna

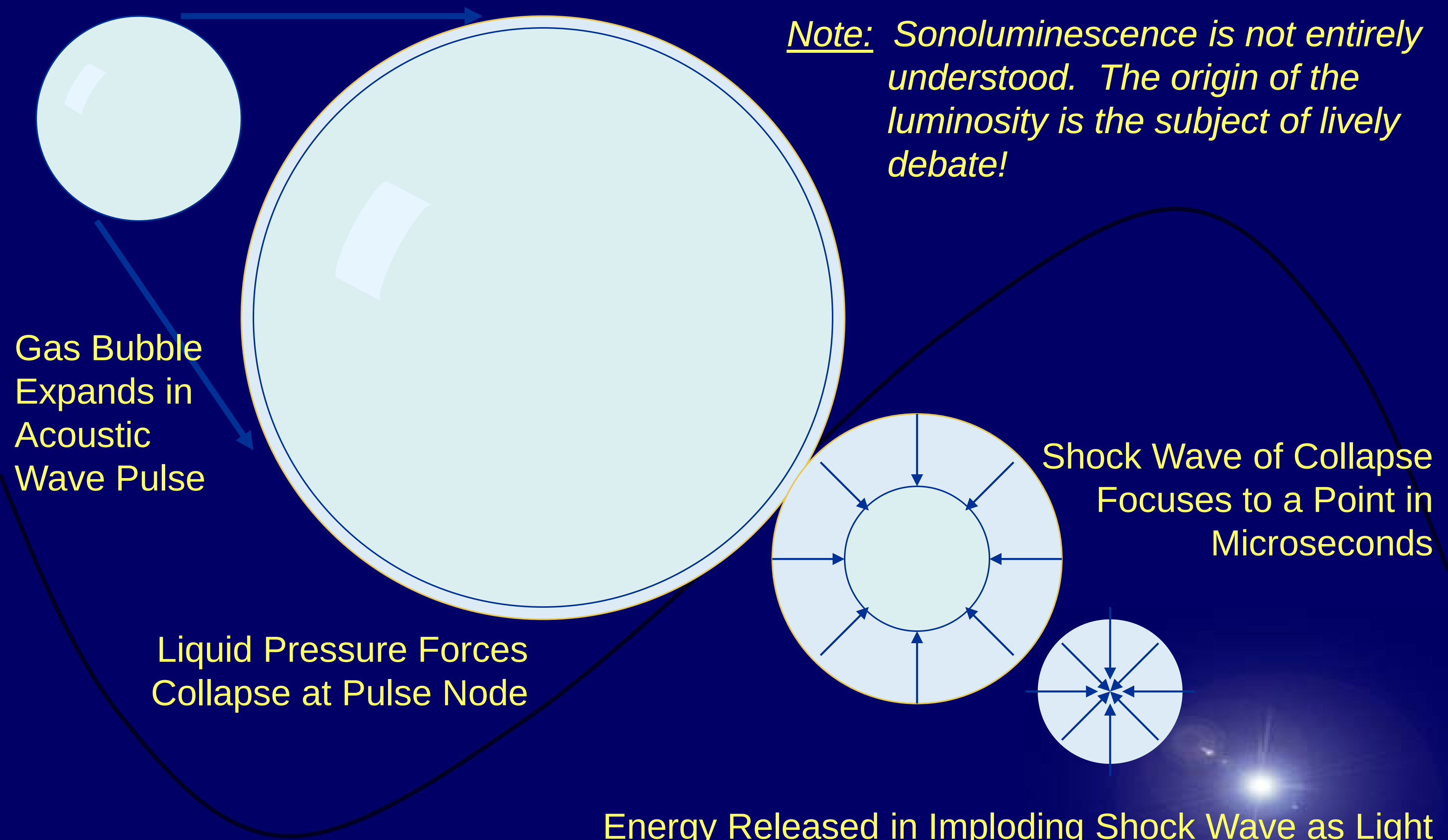

Optical Micromanipulation

A Short History Of Sonoluminesence

- 1920's and 30's: Chemists discovered that strong acoustic fields could catalyze chemical reactions.
- 1934: H. Frenzel & H. Schultes, U. of Cologne, discovered sonoluminescence in a bath of water excited by sound waves.
  - Thought it was an electrical discharge phenomenon, similar to static electricity
- 1990: Gaitan and Crum, U. of Washington, succeeded in trapping a single light emitting bubble in partially degassed water.
  - Demonstrated bubbles can emit repeatable flashes at minimum of bubble collapse
- 1991: Putterman, UCLA, also begins systematic study
  - Putterman's article on Sonoluminescence appears in Feb. 1995 *Scientific American*
- 1997: NATO Advanced Study Institute on Sonochemistry and Sonoluminescence (a conference in Leavenworth, WA)
- 2002: Taleyarkhan, Purdue U. publishes "Evidence for Nuclear Emissions During Acoustic Cavitation", *Science*, 8 March 2002 ("Sonofusion")
  - Widespread publicity begins public debate over results, Empirical Science vs. Pathological Science
- 2005: Young's "Sonoluminescence" (CRC Press)

The Sonoluminescence Process

Note: *Sonoluminescence is not entirely understood. The origin of the luminosity is the subject of lively debate!*



Energy Released in Imploding Shock Wave as Light

Calculations show that the Collapsed Bubble Temperature is Millions of Degrees

Bubble Collapse

- Bubble begins expanding at minimum wave pressure (rarefaction)
  - Bubble Growth/Collapse is adiabatic ($P \cdot V^{\gamma}$=constant)
- Bubble expands to a radius of 30 to 60 µm, then collapses suddenly
  - Mach 4 wall velocity (10^{11}g acceleration)
- Bubble collapses to a radius of ~0.5 µm (Van der Waals radius) for <20ns
  - Flash of light at collapse (how?) for <50 picoseconds
- “Afterbounces” of bubble amplitude after collapse ~3 MHz
  - Instabilities in afterbounces can destroy the bubble

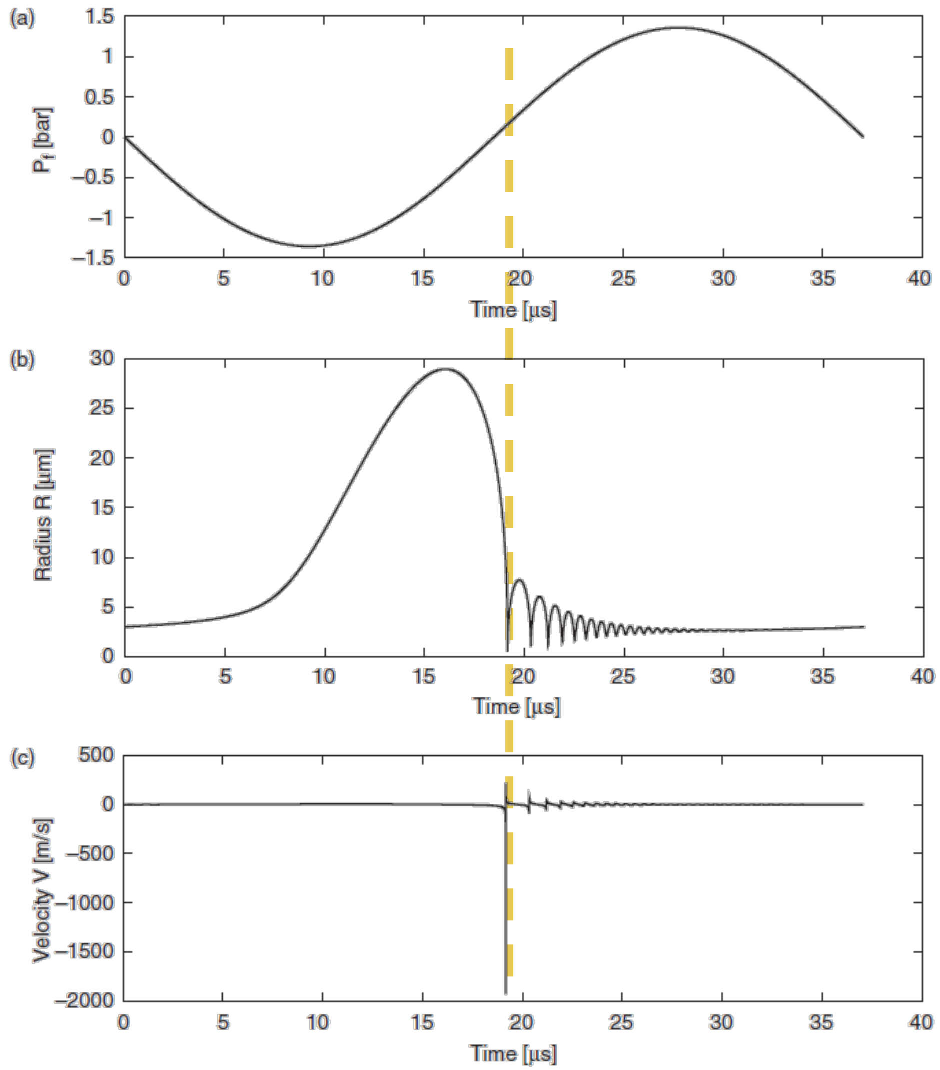


Figure 2. The driving pressure (*a*), the radius of the bubble (*b*), and the velocity of its interface (*c*) as a function of time for one acoustic cycle. The parameters are $P_a = 1.36$ bar, $R_0 = 3\,\mu m$, $\gamma = 5/3$, and $\omega/2\pi = 27$ kHz.

Graphs from Simon, et al., *Nonlinearity* **15** (2002) 25–43

Theories of Sonoluminescence

- Shock Wave Theory-S. Putterman, UCLA
  - Bubbles remain perfectly spherical as they collapse
  - Pressure increases to as much as 200 Mbar at minimum radius
  - Bubble stops collapsing, but shock wave continues, creating plasma & light emission in broad spectrum
  - Doesn’t account for reports that cold water works better than warm water, and water infused with a noble gas works better than not
- Jet Formation-A. Prosperetti, U. of Mississippi
  - Bubble does not remain spherical as it collapses, but caves in & propels a small jet across the bubble
  - The jet hits the opposite wall of the bubble at high speed and fractures the water at the point of impact; the light is due to fracto-luminescence.
  - Noble gases would disturb the crystalline form of the hammered water, and provide fracture points.
- Collision Induced Emission-A. Frommhold & A. Atchley, U. of Texas
  - Colliding molecules induce oscillating dipoles in each other.
  - Collisions occur on short time scale, so radiation is broad band, as is observed.
  - Effect is supposedly strongest when collisions occur between N or O and Ar.
  - Doesn’t appear to explain water or temperature dependence of sonoluminescence.
- Quantum Vacuum Radiation-C. Eberlein, U. of Illinois
  - Radiation is due to dynamic Casimir effect: Photons are created whenever the interface between a dielectric and a vacuum or between two dielectrics moves non-inertially.
  - The medium can be regarded as an assembly of dipoles, excited by zero point fluctuations; when an interface moves non-inertially, fluctuations no longer average to zero and real photons are emitted.
  - The effect is normally very feeble; but the acceleration of the wall of the sonoluminescent bubble is enormous.
  - This theory makes a specific prediction: there are no photons emitted in the x-ray transparency range of water, $232\ \text{Å} < \lambda < 437\text{Å}$.

Sonofusion: Why do we care?

Burning Coal:

- $C + O_2 \rightarrow CO_2$ (4 eV)

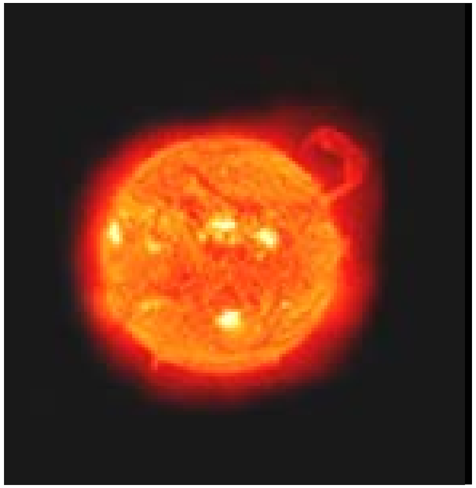
Fission:

- $^{235}U + n \rightarrow {}^{236}U$

  $\rightarrow {}^{141}Ba + {}^{92}Kr + 3{\cdot}n$ (170 MeV)

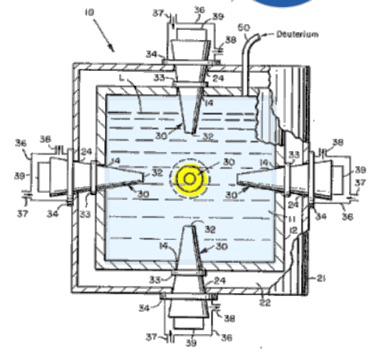
Fusion Processes:

- $D + D \rightarrow T$ (1.01 MeV) + p (3.02 MeV)
- $D + D \rightarrow {}^{3}He$ (0.82 MeV) + n (2.45 MeV)
- $D + D \rightarrow {}^{4}He$ (73.7 keV)+ γ (23.8 MeV)
- $D + {}^{3}He \rightarrow {}^{4}He$ (3.6 MeV) + p (14.7 MeV)
  - $D = {}^{2}H$, $T = {}^{3}H$; D available from D_2O, “heavy” water and from deuterated solvents
  - At least 13% more productive per mass of fuel

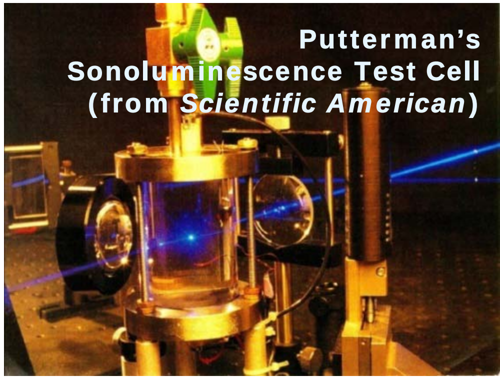


“Sonofusion”

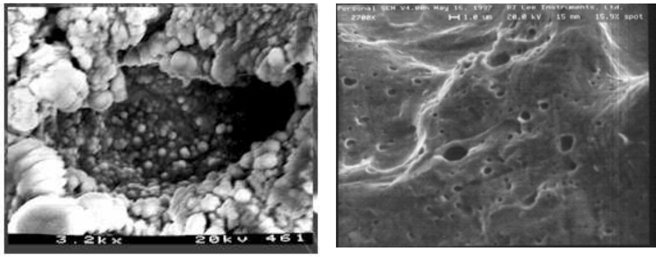
- Cavitation Fusion Reactor (CFR) - Hugh Flynn (U. of Rochester) (1982) – Concept (never built)
  - Six acoustic horns to cavitate liquid lithium metal with hydrogen, deuterium or helium gas
  - Liquid metal used due to high speed of sound and thus higher energy cavitations
  - Fusion reactions would be intiated by cavitation
  - Case would heat a heat exchanger for energy harvesting
- Seth Putterman (UCLA) & W. Moss (LLNL) examined D-D and D-T fusion possibilities in Sonoluminescence (“Sonofusion”)
  - UCLA patented Putterman’s apparatus for converting acoustic power to other useful forms of energy, including D-T fusion reactions (1997)
  - No method of extracting the energy from fusion was outlined
- Roger Stringham & Russ George (D2Fusion, Inc.) published claims of “Cavitation-Induced Micro-Fusion” (1996-)
  - Metal foil (Cu, Ag, Ti, NiTi, Pd) in heavy water (D_2O) cavitated by an acoustic horn
  - Up to 15 watts output with 10 acoustic watts input
  - Micro-eruptions seen in Pd claimed indicative of localized nuclear reactions



Flynn’s Cavitation Fusion Reactor (from Patent)



Putterman’s Sonoluminescence Test Cell (from *Scientific American*)



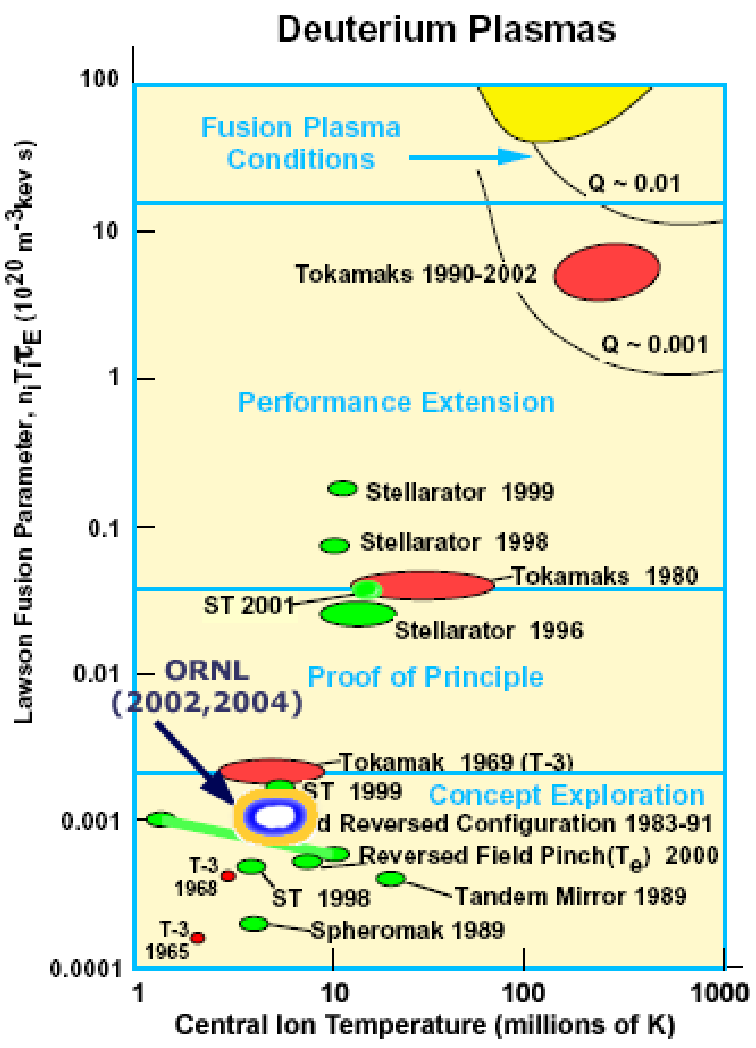
Stringham & George’s “Micro-eruptions” on the surface of Pd foil (from George’s 2005 APS Presentation)

Taleyarkhan's Sonofusion

- R. P. Taleyarkhan, et al. (ORNL/Purdue) "Evidence for Nuclear Emissions During Acoustic Cavitation," *Science* **295**, 1868 (2002) outlined results of cavitation experiments in deuterated acetone
  - Cavitation sites were initiated with a 14 MeV pulsed neutron source and driven with a PZT ring
  - Sonoluminescence was not single-bubble, but formed clusters of a thousand bubbles at the cavitation site.
  - Observed tritium decay activity above background, neutron emission near 2.5 MeV coinciding with sonoluminescence flash
  - Control experiments with normal acetone did not result in tritium activity or neutron emissions.
  - Hydrodynamic shock code simulations supported the observed data and indicated highly compressed, hot (10^6 to 10^7 K) bubble implosion conditions
  - The results imply that higher cavitation temperatures are found in liquids with higher vapor pressure rather than liquids with higher speed of sound, surface tension or viscosity
  - A different ORNL group repeated the experiment, but no coincidence of neutrons with sonoluminescence flash was found
- Taleyarkhan's group repeated experiment with uranyl nitrate in a mix of benzene, tetrachloroethene and acetone (normal and deuterated)
  - Reported an increase in neutron and gamma ray flux using the deuterated acetone mixture; this flux was not seen in the other mixtures, including heavy water (*Phys. Rev. Lett.* **96**(3), January 2006)
  - Edward Forringer and his group from LeTourneau University were able to reproduce the experiment and results (*Transactions of the American Nuclear Society*, November 2006)
  - Criticism of the results range from neutron flux is too weak for definitive evidence or that the reported neutron energies are consistent with Cf-252 emission, a common lab source

Lawson Diagram Metric to Track Fusion Development

- Conditions for D-D Fusion:
  - $T \geq \sim 4 \times 10^8$ K
  - $n\tau \geq 10^{16}$ s/cm^3 (Lawson Criterion)
- ORNL/Purdue claims that thermonuclear fusion using sonochemistry is possible ("Sonofusion" or "Bubble Fusion")
  - Results supported by LeTourneau University
  - Discounted by UCLA
- The Lawson Criterion metric suggests that Sonofusion is at the point that Tokamaks were 40 years ago



Sonoluminesence as a Power Source?

- As a new Practical Power Source, needs to be scalable to as small as possible
  - Power supply for the transducers is most of the mass
  - An array of cells like a battery pack can distribute required mass for larger specific power
  - >>20 ml for cell size realistic criterion
- First Order Estimate of Cell Size:
  - free oscillation frequency of a bubble in a liquid:

$$\omega = \frac{1}{a}\sqrt{\frac{3\gamma P}{\rho}}$$

  - resonance frequency of the test cell:

$$\omega = \frac{k\pi c}{r}$$

  - smallest test cell (with *k*=1):

$$\frac{r}{a} = \sqrt{\frac{k^2\pi^2 c^2 \rho}{3\gamma P}} = 230$$

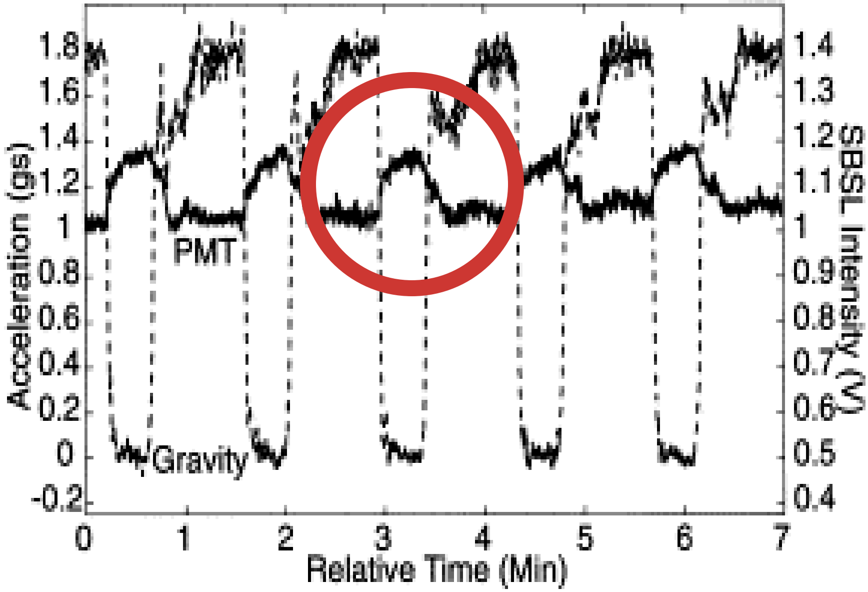
  - If *a*=10 µm, *r*=2.3 mm, so V=0.013 ml, but f=325 kHz

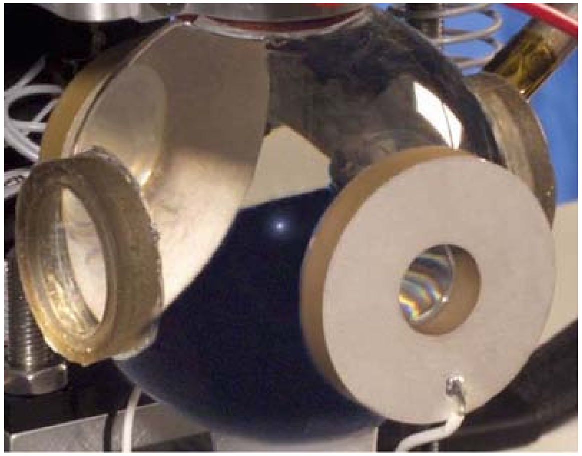
ISS Battery Cell Pack
~316 W/kg specific power (peak)
350 ml per Ni-H cell

Star in a Jar
1 kW/kg specific power (?)

Sonoluminescence in Microgravity

- KC-135 Flight in 1998 by University of Washington
- Single-Bubble Sono-luminescence (SBSL) promptly brightened 20% and continued brightening under microgravity conditions
- ISS experiment was scheduled for launch April 2005
- Flight hardware under development in 2003
- Experiment cancelled in the redirection of space exploration efforts





NanoStar: Sonoluminescence

Gus Fralick (PI - RIS), John Wrbanek (RIS), Susan Wrbanek (RIO)

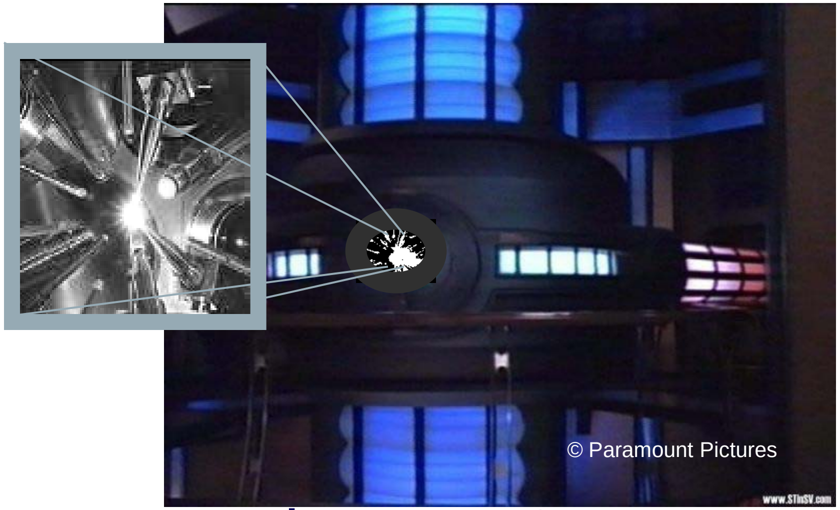
From a "Star in a Jar"…

Task Summary

- **Sonoluminescence: The phenomenon in which acoustic energy is concentrated into collapsing bubbles that emit picosecond pulses of broadband light.**
- **Calculations indicate that peak temperatures inside the SL bubbles may exceed 12 million K, that peak pressures may reach 100 million atmospheres, could initiate D-D fusion.**
- **Harnessing the high energy release would lead to the development of revolutionary propulsion and power systems.**
- **Developing instrumentation and measurement techniques to investigate power generation using sonoluminescence.**
- **Initially determine whether there is any difference in the emission spectrum of radiation from bubbles in heavy water (D_2O) and light water (H_2O).**

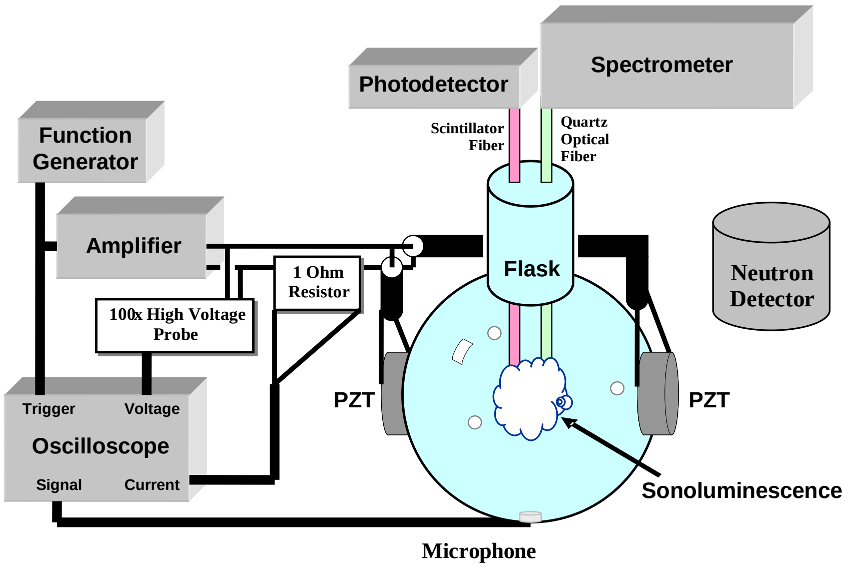
Advancing the Existing State of the Art

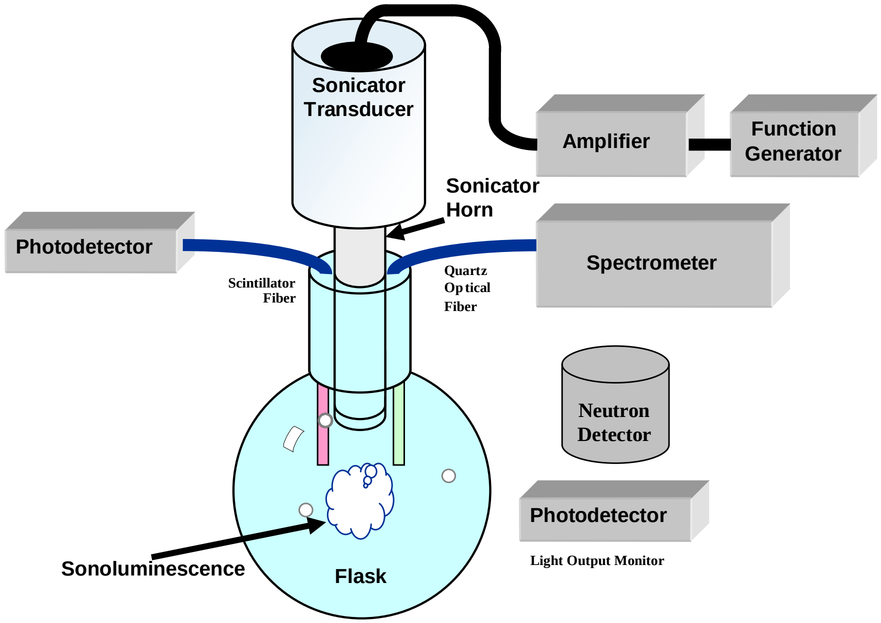
- **The claims and theories being examined predict a net gain of power resulting from atomic interactions at the high temperatures and pressures present in SL.**
- **SL-based power generation has been only recently reported in the main-stream academic press (*Science*, 8 Mar 02).**
- **The development of measurement techniques to verify and further develop this technology is a necessity.**



…to the Future?

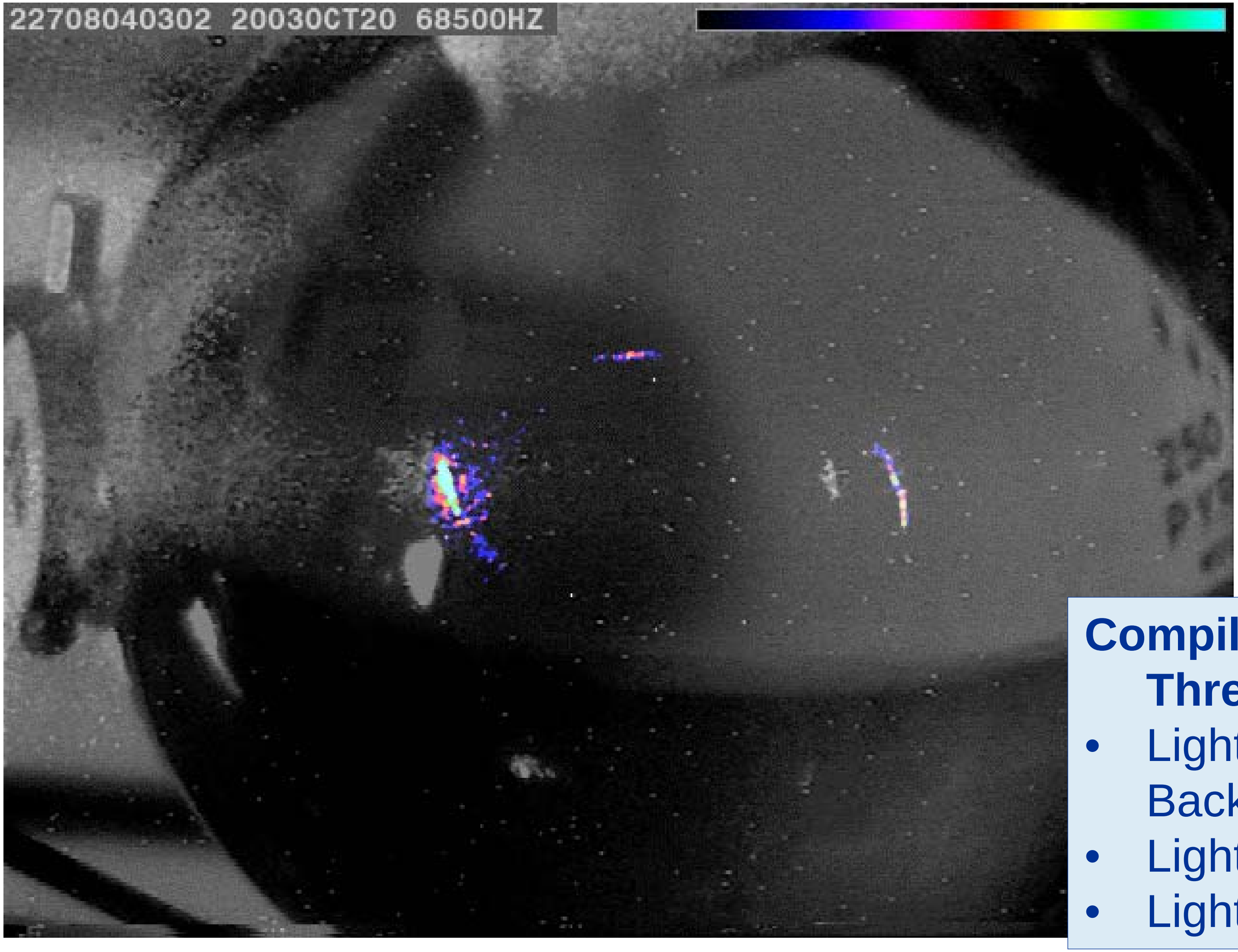
Apparatus





- Ultrasonic transducer induces cavitation in a test cell
- Piezoelectric amplifier drives transducer from signal generator
- Two types of transducer setups
  - Resonating Test Cell
  - “Sonicator” Cell Disruptor in Flask or Beaker
- Photodetectors, Spectrometers, Neutron Detectors can be used
  - Monitor with Lights Out!

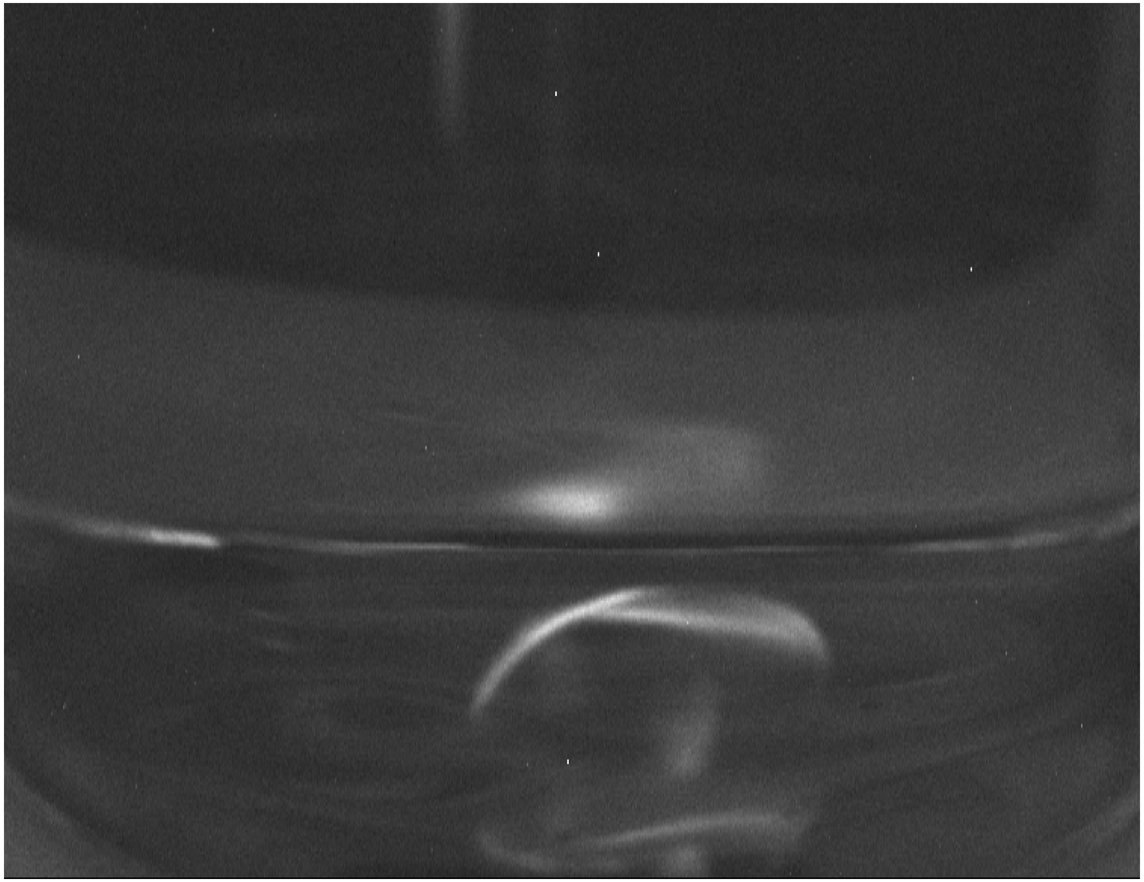
Ring of Multi-Bubble Sonoluminescence (MBSL) Imaged with Low Lux Video Camera



Compilation of Three Images:

- Lights Off Background
- Lights On Flask
- Lights Off MBSL

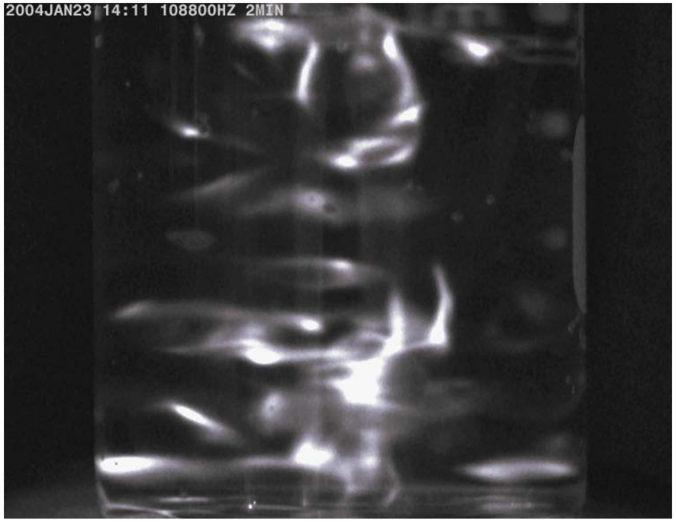
Multi-Bubble Sonoluminescence (MBSL) Imaged using Astrophotography Camera

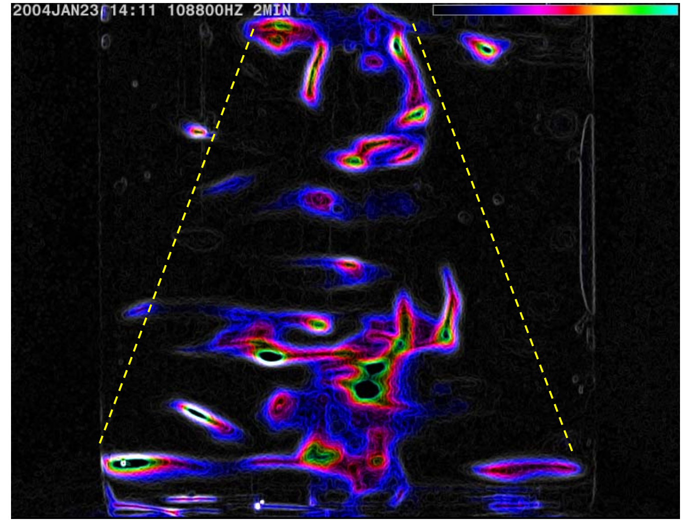


- Image quality allows better placement of instrumentation
- Improved image of MBSL over video camera
  - – Enhanced contrast only

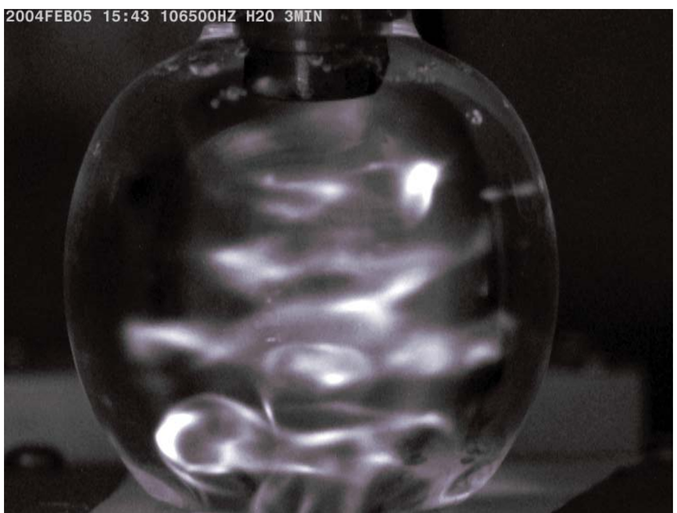
MBSL using Sonicator Test Cell

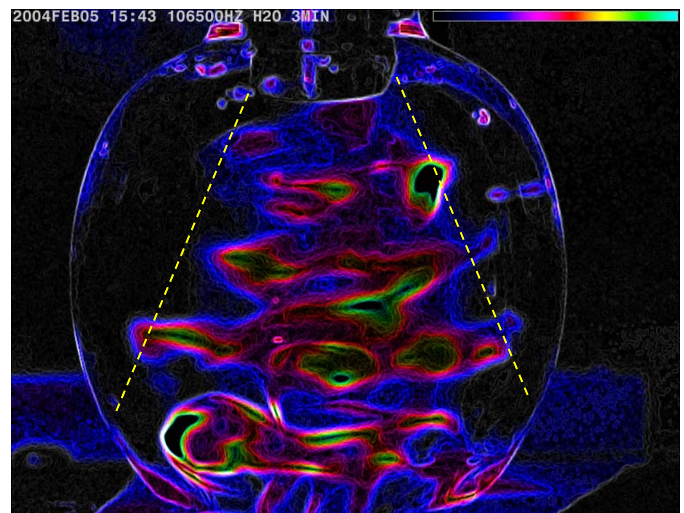
- 100 ml Beaker





- 50 ml Quartz Flask

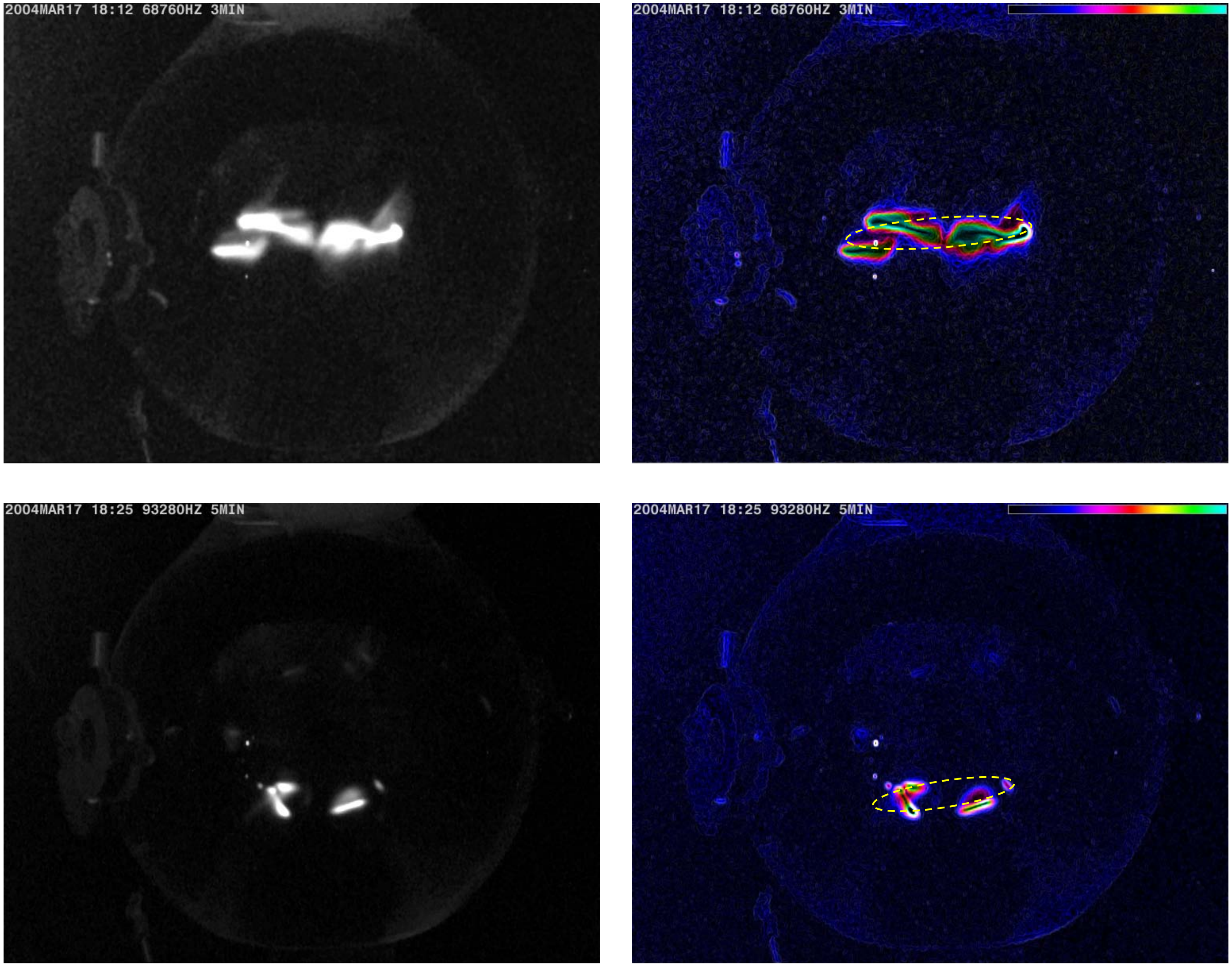




False Color Images Showing Structure

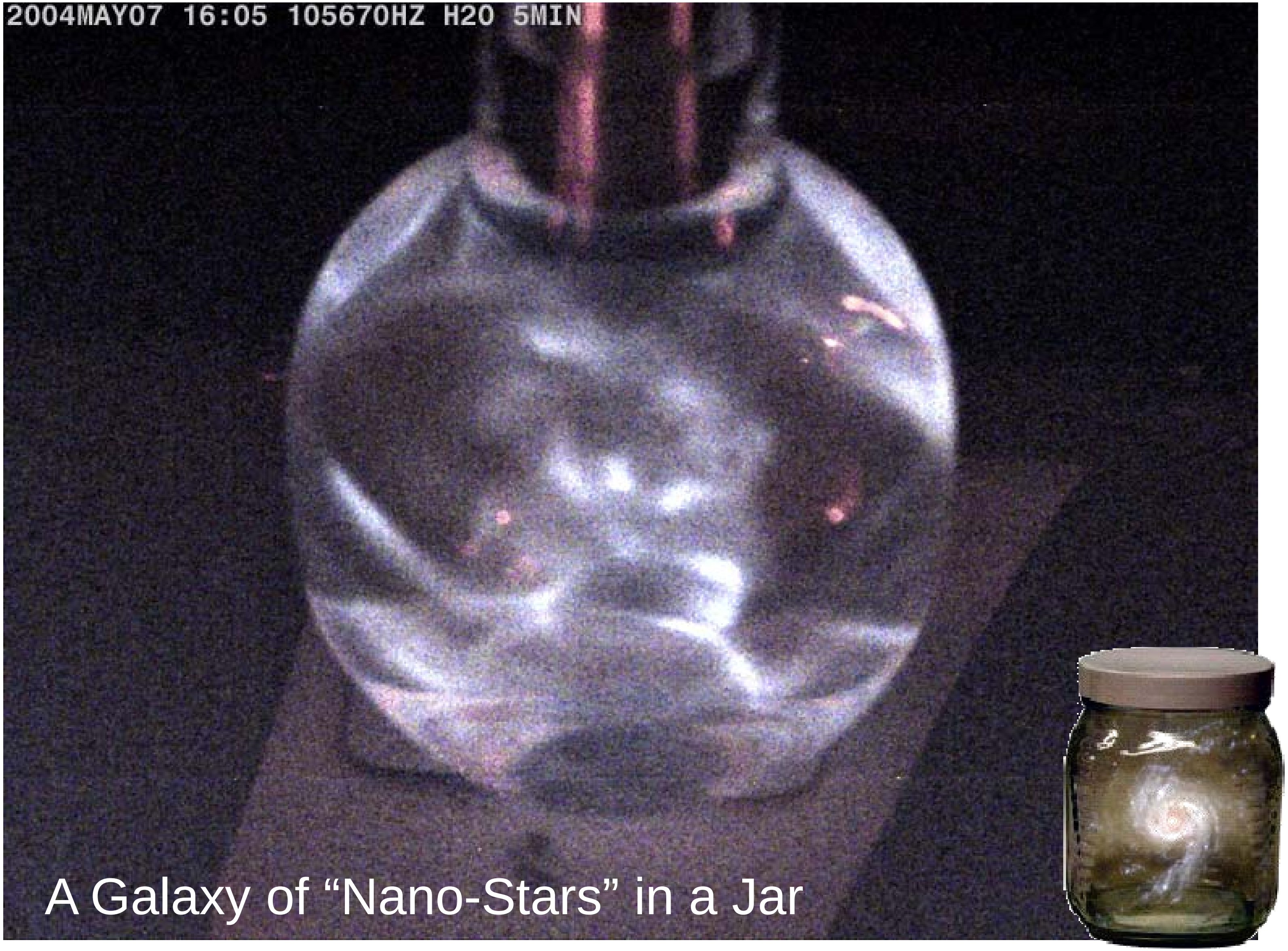
MBSL in Resonating Test Cell

- 68.76 kHz
- 93.28 kHz



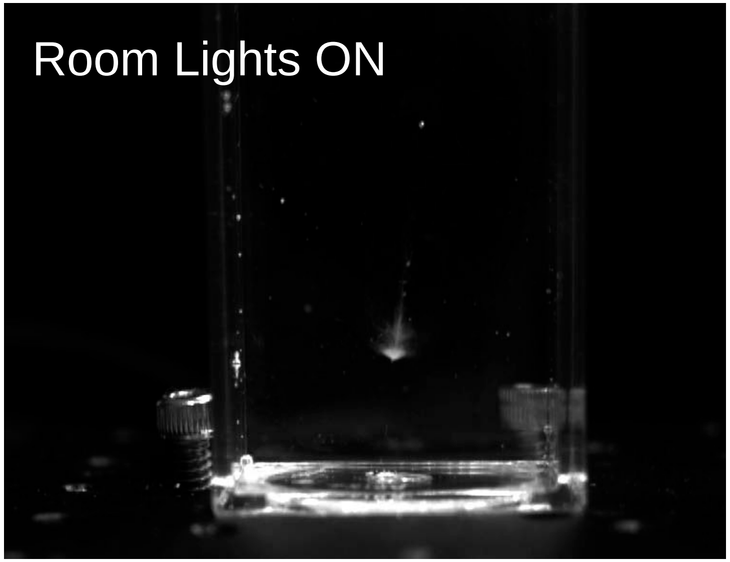
False Color Images Showing Structure

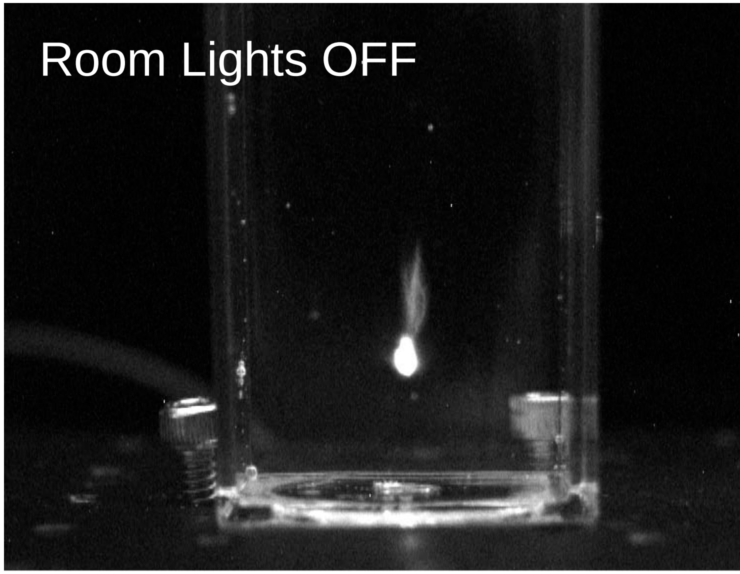
True-Color MBSL in H_2O



Sonoluminescence in Solvents

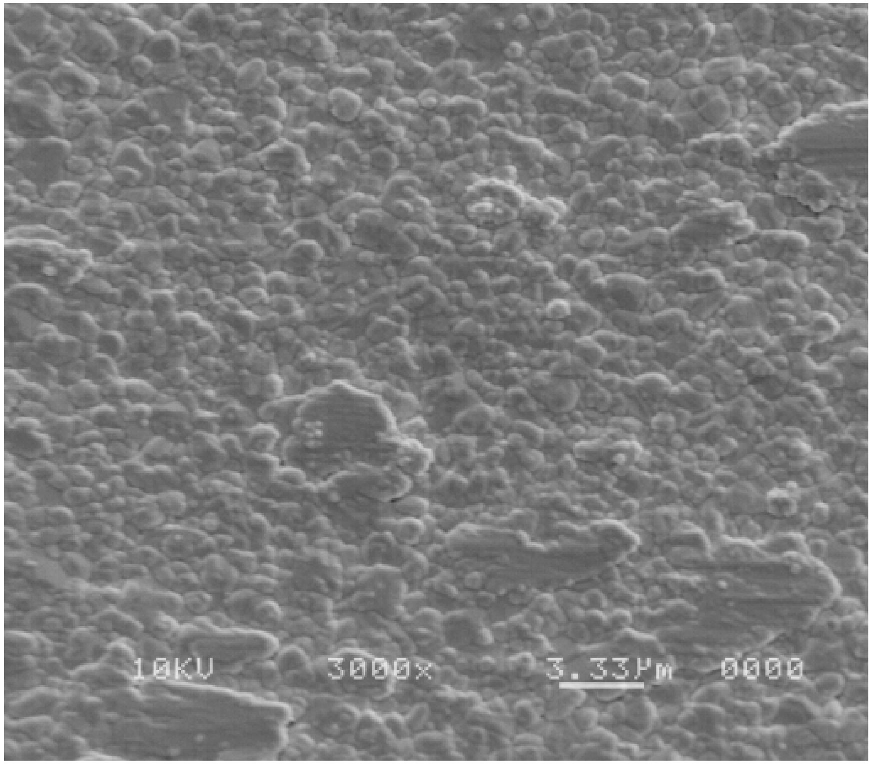
- Empirical relationships correlate SL brightness with:
  - the liquid's viscosity,
  - surface tension,
  - inverse of the vapor pressure, or
  - a combination of properties
- Brighter sonoluminescence should be seen in the solvents with higher boiling points (>100°C)
- Glycerin is an attractive solvent for use in sonoluminescence studies
  - Notoriously hydroscopic
  - Stabilizes as the 80% glycerin to 20% water mixture in air
  - Relatively safe and readily available
- Generated cavitation in Glycerin with a Sonicator setup corresponding to bright MBSL
  - Cavitation was particularly localized
  - Provides a promising target for spectroscopy and radiation studies



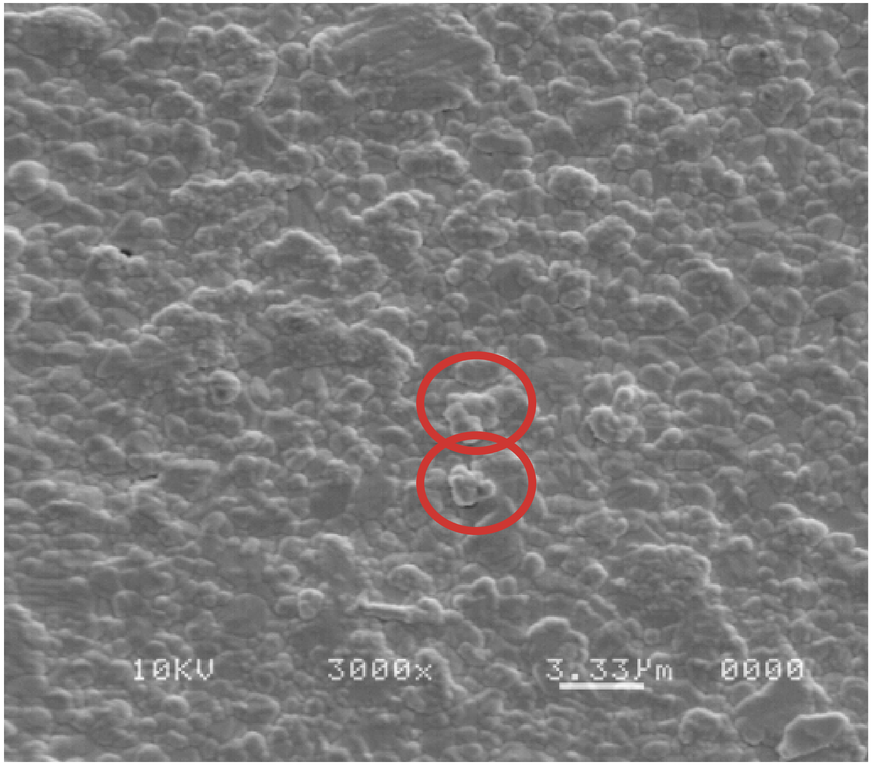


Indications of High Temperature

- Modifications of films can indicate high temperature environments
  - Comparison can reveal temperature differences
- Initial platinum (Pt) films on alumina exposed to MBSL in H_2O and D_2O showed little difference
  - Globules in D_2O run? Not conclusive

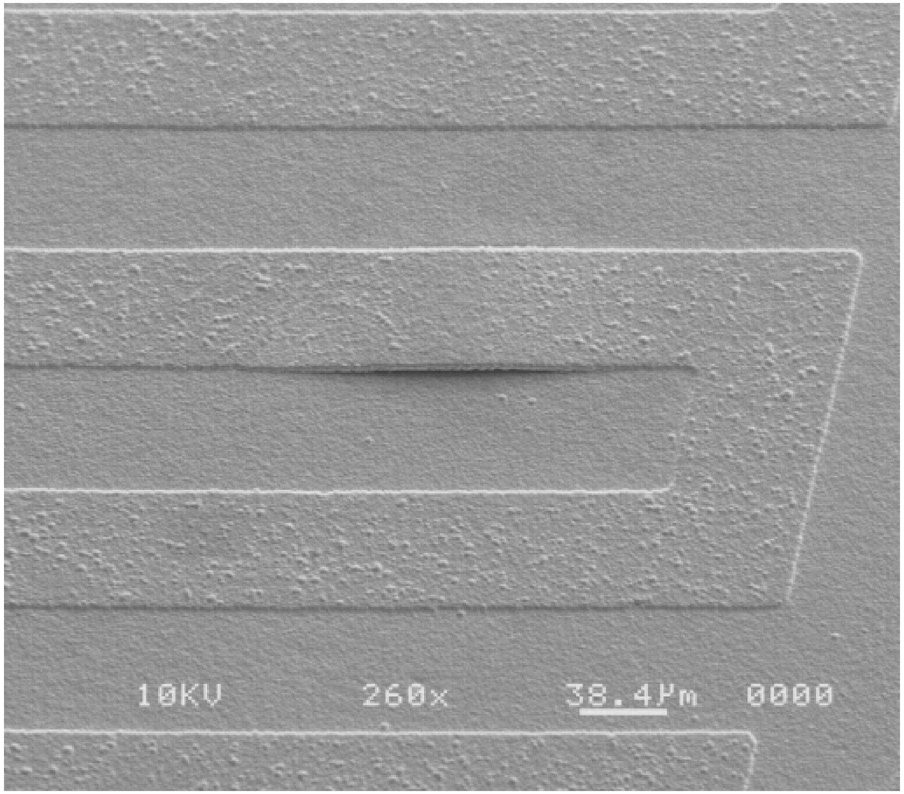


- Pt Film after exposure to MBSL in H_2O

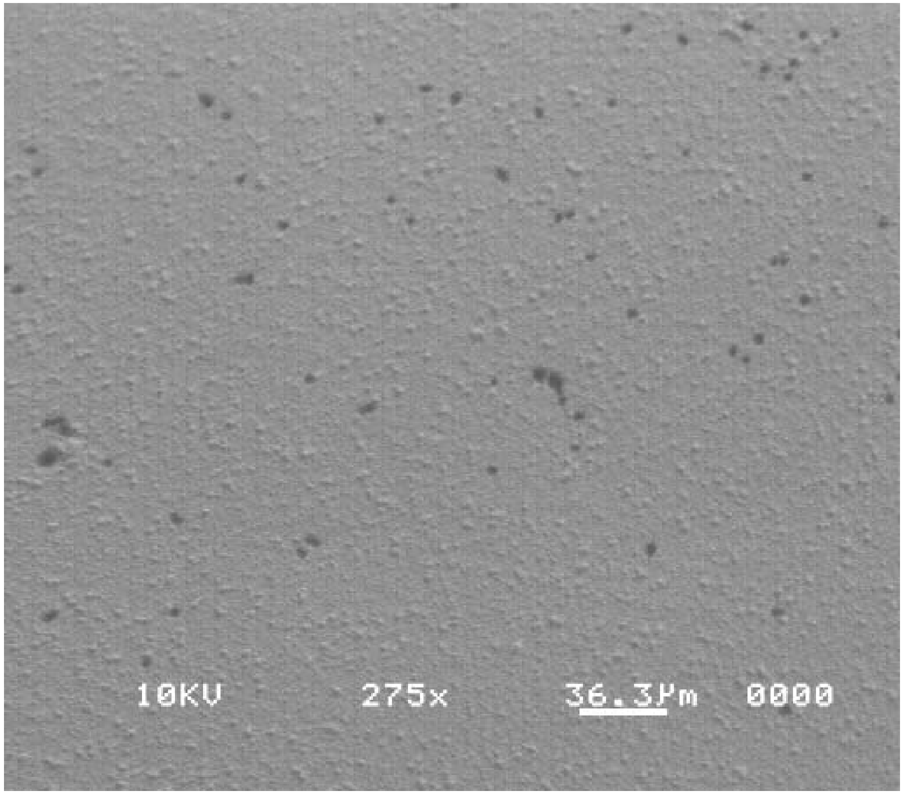


- Pt Film after exposure to MBSL in D_2O

PdCr Thin Films Over Pt Traces on Alumina



- No Crater Formation seen after exposure to MBSL in H_2O



- Crater Formation seen after exposure to MBSL in D_2O

- Large Grain Failures usually seen in thin films due to CTE mismatches at high temperature (~1000°C)

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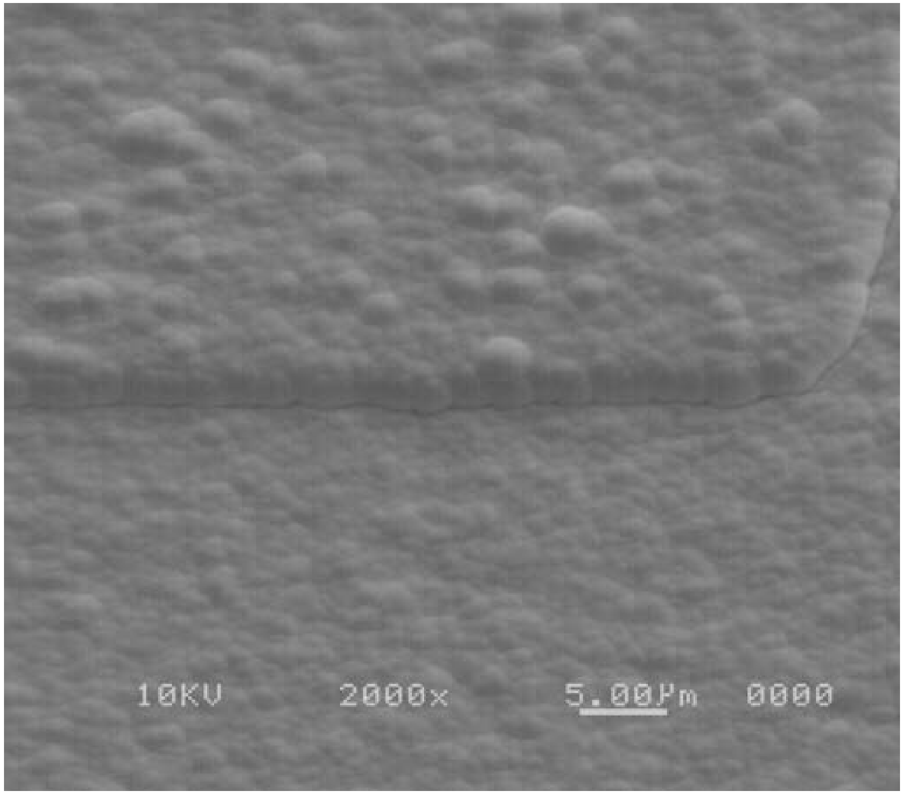

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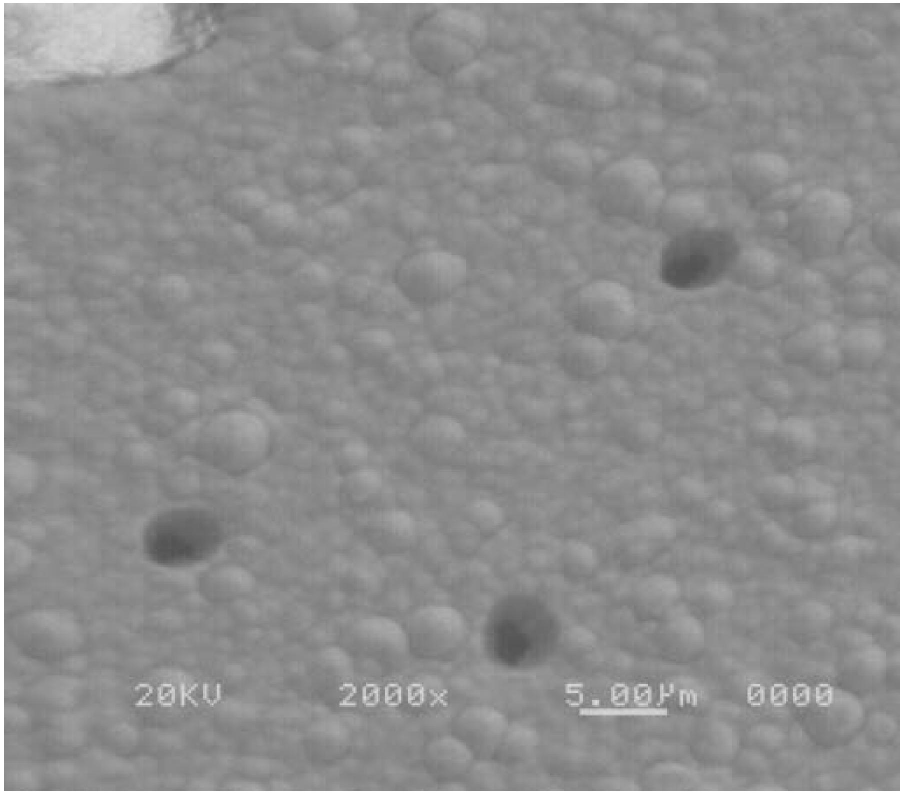

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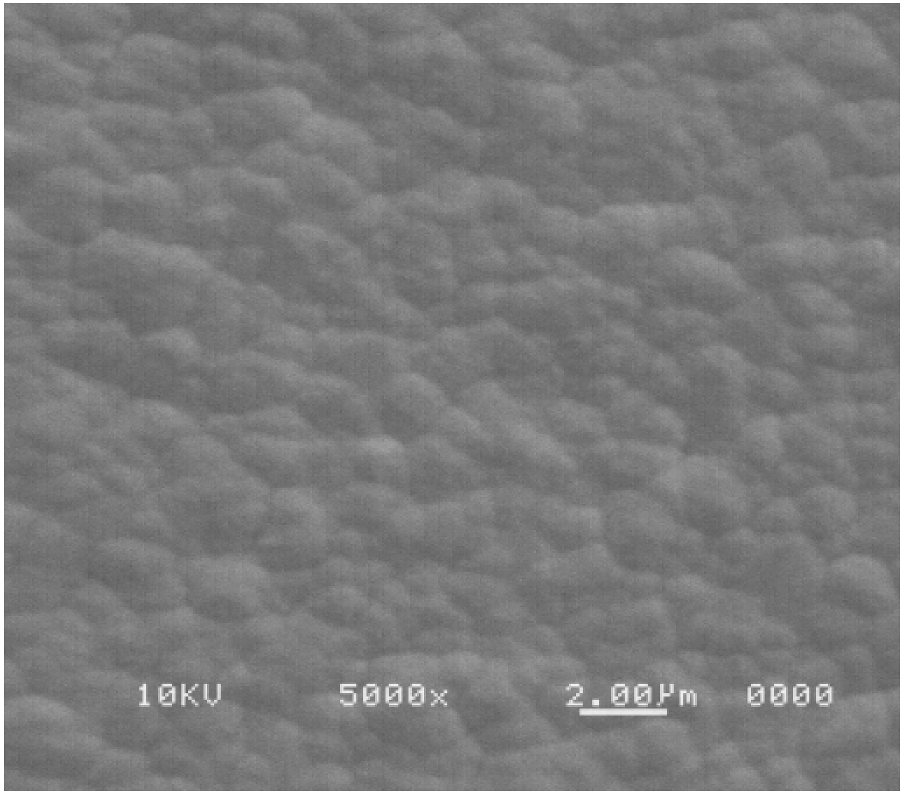

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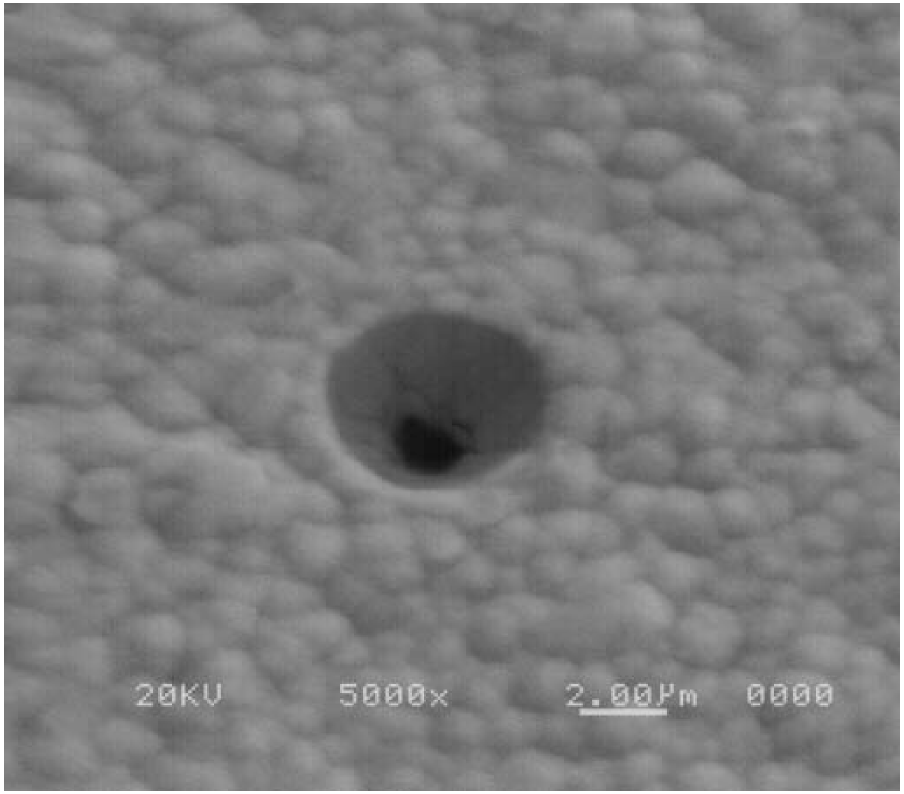

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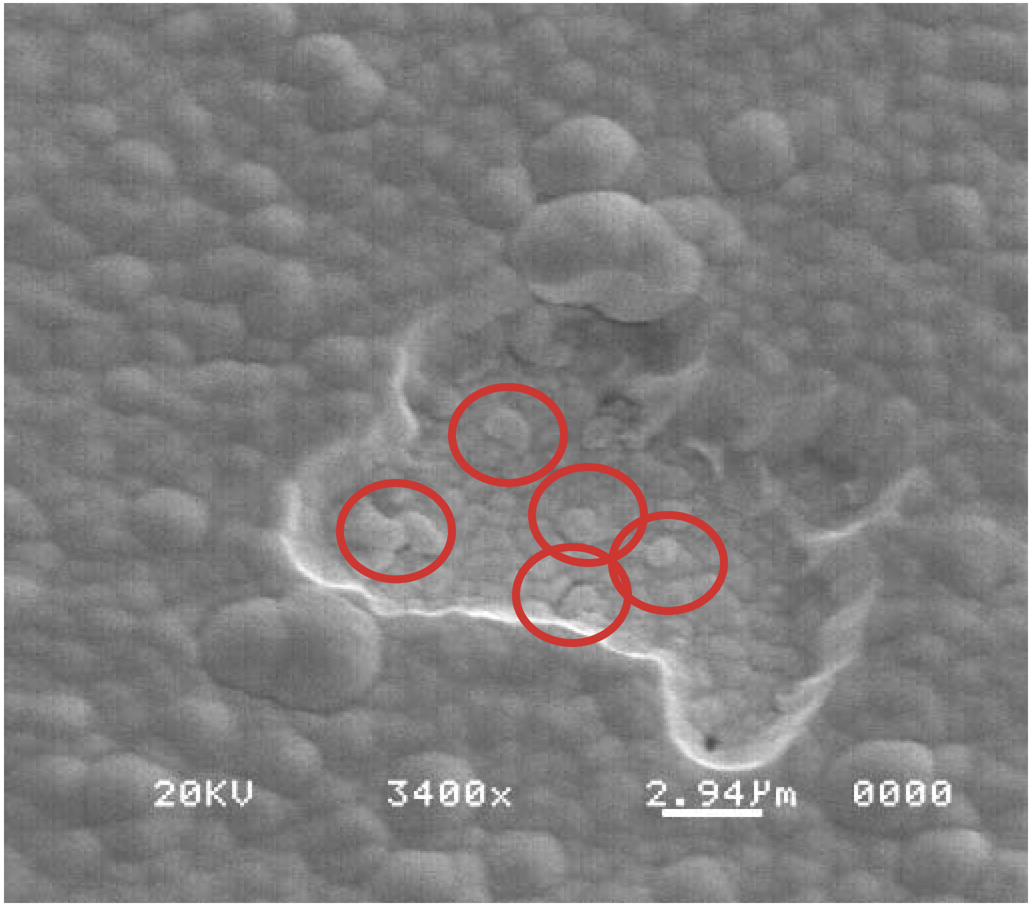
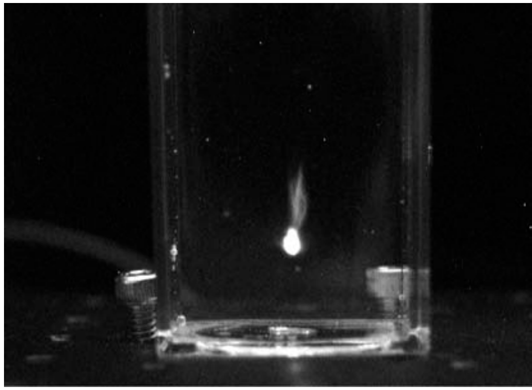
PdCr Thin Films Over Pt Traces on Alumina

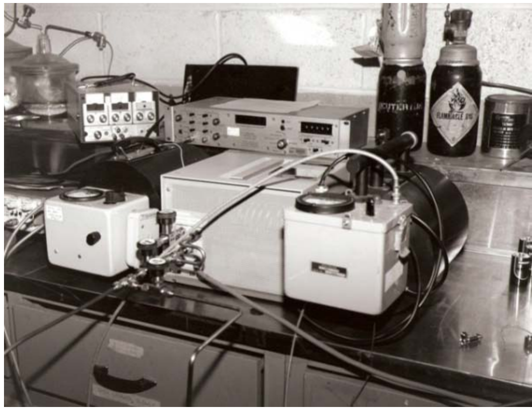
- Large failure areas also seen in PdCr film over Pt exposed to MBSL in D_2O
  - PdCr nodules appear on the bottom in failure areas
- Failures not seen in PdCr directly on alumina, or when exposed to MBSL in H_2O runs

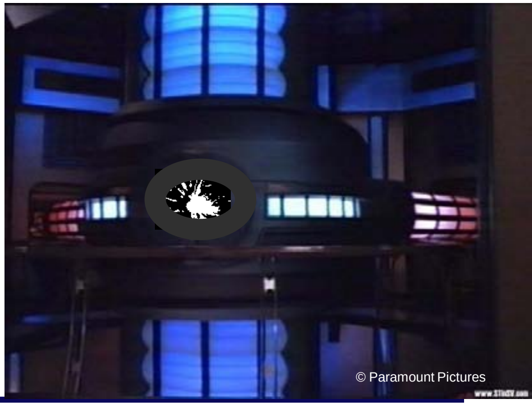


Concepts

- Localized sonoluminescence a first step for including in-situ instrumentation
- Sonofusion claims of neutron production should be detectable
  - Miniature radiation detectors inside cells complementing or replacing large detectors outside of the test cells
- Bubble temperature of millions of degrees should be harvestable
  - In-situ energy harvesting based on thermal gradient between liquid and hot bubbles

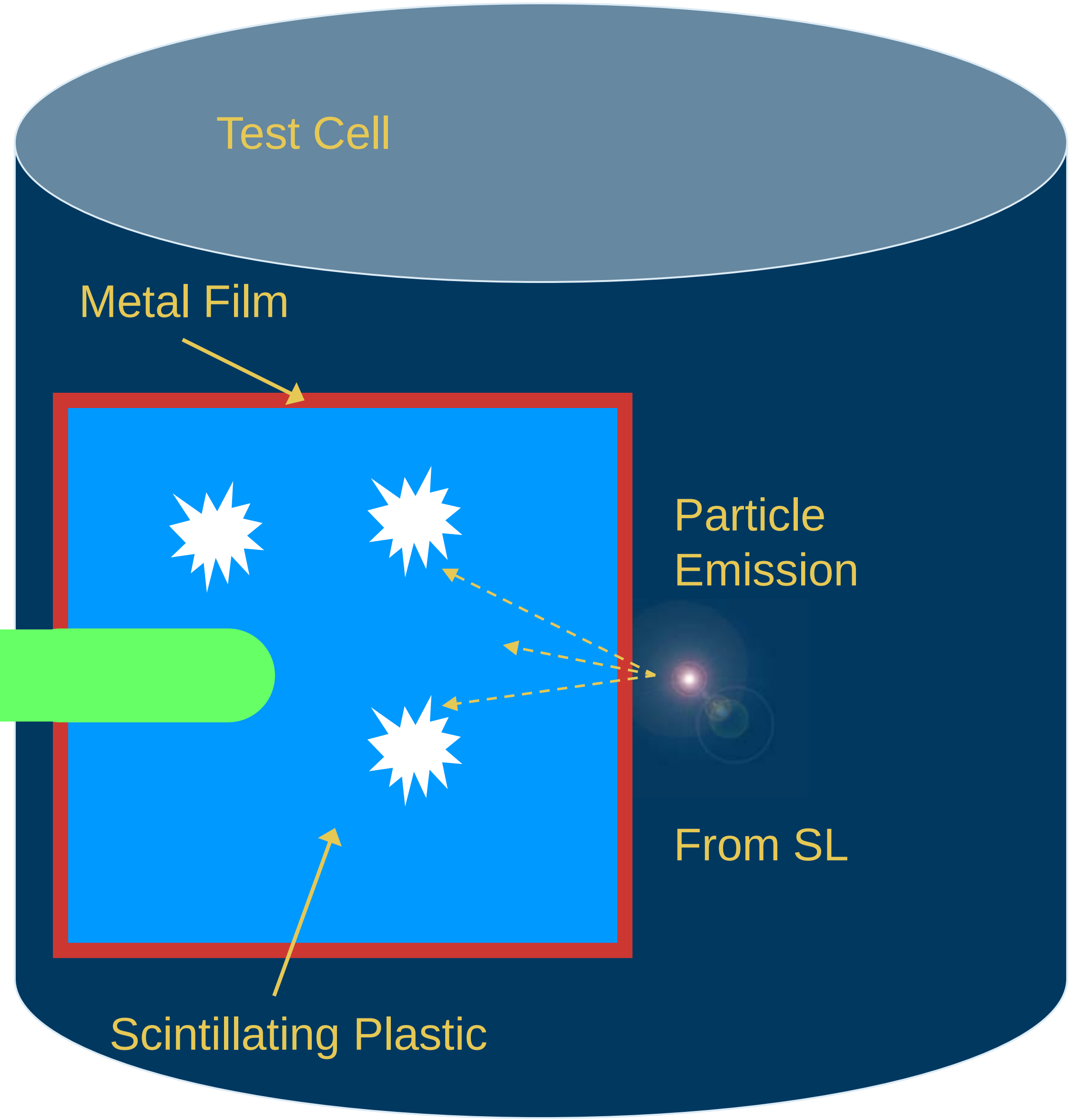






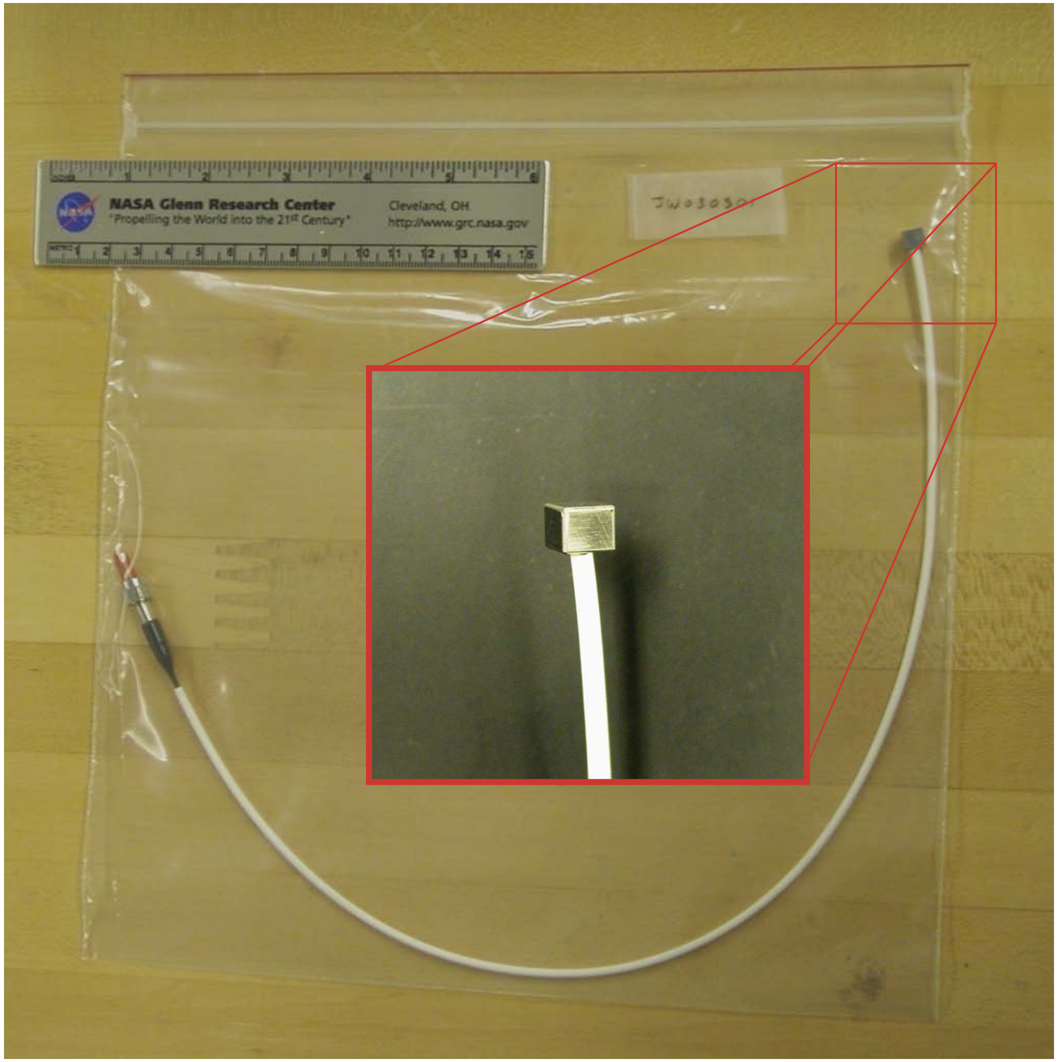
Thin Film Coated Scintillating Detectors

- Fiber optic-based scintillator detector under development
- Particle emissions react with metal film
  - Results react with the scintillator
- Thin film coatings allow identification of processes that may be occurring

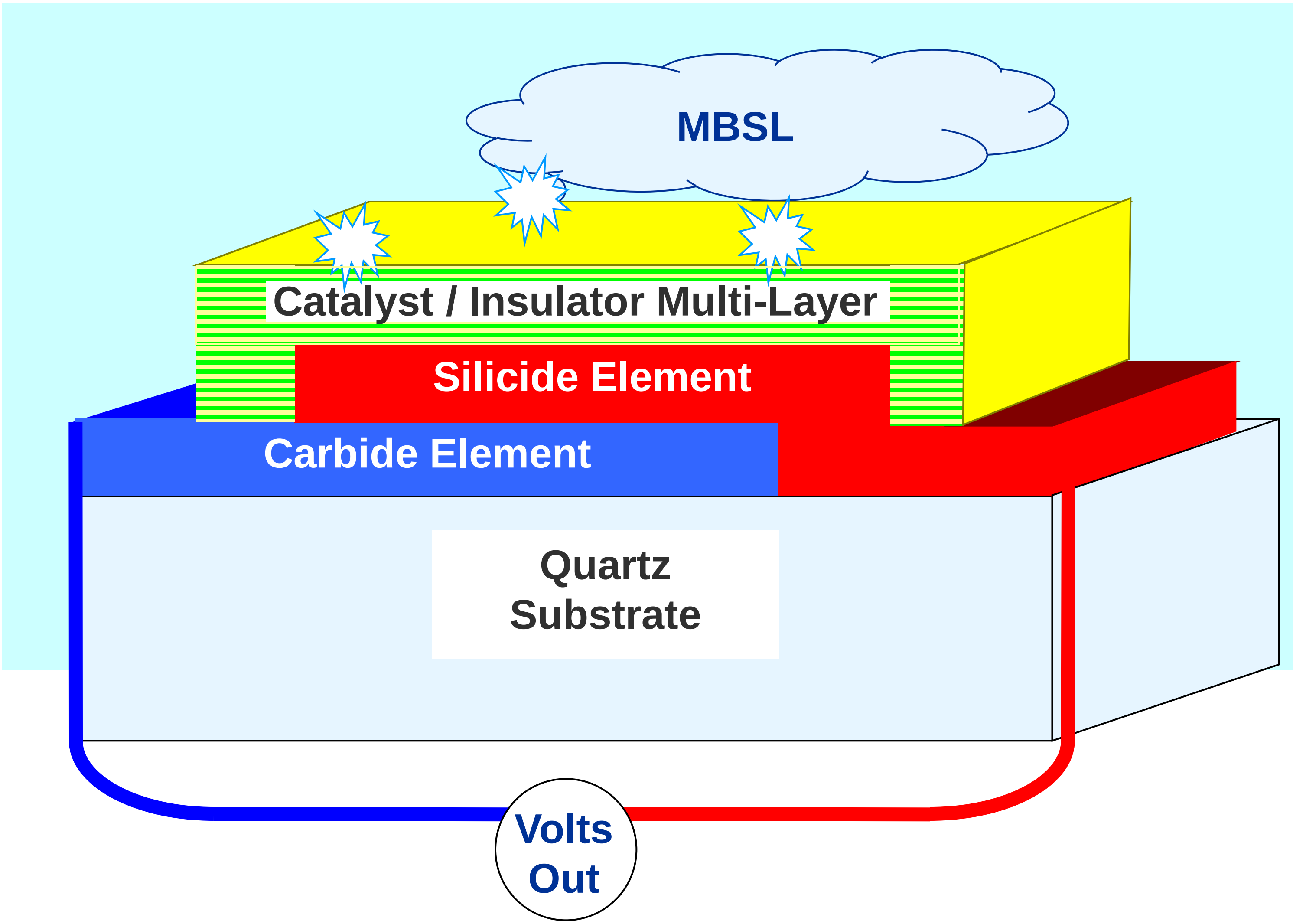


Thin Film Coated Scintillating Detectors

- Prototype detectors fabricated
  - Rhodium for neutron detection
  - Copper as an attenuator,
  - Palladium as a possible catalyst based on thin film experiments
- Relative responses modeled using Monte Carlo program SRIM
- Very sensitive to external light noise
- Leveraging work as detectors for space missions



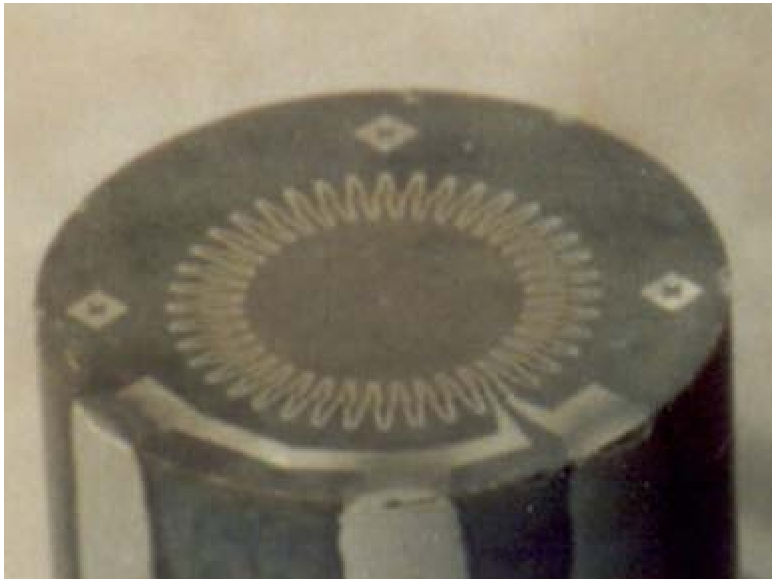
Energy Harvesting Concept



- Recent results in ceramic thin films suggest this concept is possible

Energy Harvesting Concept

- Initial test of concept to use thin film thermopile for heat flux measurements



6 mm diameter, 40-pair thermopile thin film heat flux sensor

- Estimate of power generation:

  100µV/°C × ΔT => 200 mV/junction

  200 Ω/junction => 0.2 mWatts/junction

  50% efficiency => 0.1 mWatts/junction

  40 junctions => 4 mWatts

  – Input electrical power of Sonicator => 350 Watts
- Improvements needed
  – Thermoelectric materials
  – Sonocator/PZT arrays

Sonoluminesence as a Power Source?

- As a new Practical Power Source, needs to be scalable to as small as possible
  - Power supply for the transducers is most of the mass
  - An array of cells like a battery pack can distribute required mass for larger specific power
  - >>20 ml for cell size realistic criterion
- First Order Estimate of Cell Size:
  - free oscillation frequency of a bubble in a liquid:

$$\omega = \frac{1}{a}\sqrt{\frac{3\gamma P}{\rho}}$$

  - resonance frequency of the test cell:

$$\omega = \frac{k\pi c}{r}$$

  - smallest test cell (with *k*=1):

$$\frac{r}{a} = \sqrt{\frac{k^2\pi^2 c^2 \rho}{3\gamma P}} = 230$$

  - If *a*=10 µm, *r*=2.3 mm, so V=0.013 ml, but f=325 kHz

ISS Battery Cell Pack

~316 W/kg specific power (peak)

350 ml per Ni-H cell

Star in a Jar

1 kW/kg specific power (?)

Summary

- The high temperatures and pressures measured in sonoluminescence have generated claims and theories that predict a net gain of power resulting from atomic interactions.
  - Success has been recently reported in the mainstream academic press, and if practical, could revolutionize aerospace power systems.
- NASA Glenn Research Center (GRC) conducted a preliminary investigation of the technologies and techniques to characterize sonoluminescence.
- Apparatus to produce sonoluminescence were built to generate the effect with both a resonating container and a Sonocator inserted in a flask
- Images have been produced of sonoluminescence in a variety of containers and with a variety of liquids
- The modification of palladium-chromium alloy (PdCr) thin films suggests the generation of high temperature from sonoluminescence in heavy water.
- Concepts for in situ radiation detection and energy harvesting were presented.

Acknowledgments

- Alternate Fuel Foundation Technologies (AFFT; Leo Burkardt, Dave Ercegovic) Subproject of the Low Emissions Alternative Power (LEAP) Project and the Breakthrough Propulsion Physics (BPP; Marc Millis) Project at the NASA Glenn Research Center (GRC) for sponsoring this work.
- Nancy Rabel Hall of the Fluid Physics and Transport Branch at NASA GRC, for providing references and information on sonoluminescence in microgravity and for reviewing this report.
- José Gonzalez of Gilcrest Electric as part of the NASA GRC Test Facilities Operation, Maintenance, and Engineering (TFOME) organization at NASA GRC for thin film deposition support.
- Tim Bencic of the Optical Instrumentation & NDE Branch at NASA GRC for providing support in a student's attempt to look at the glycerin spectrum.

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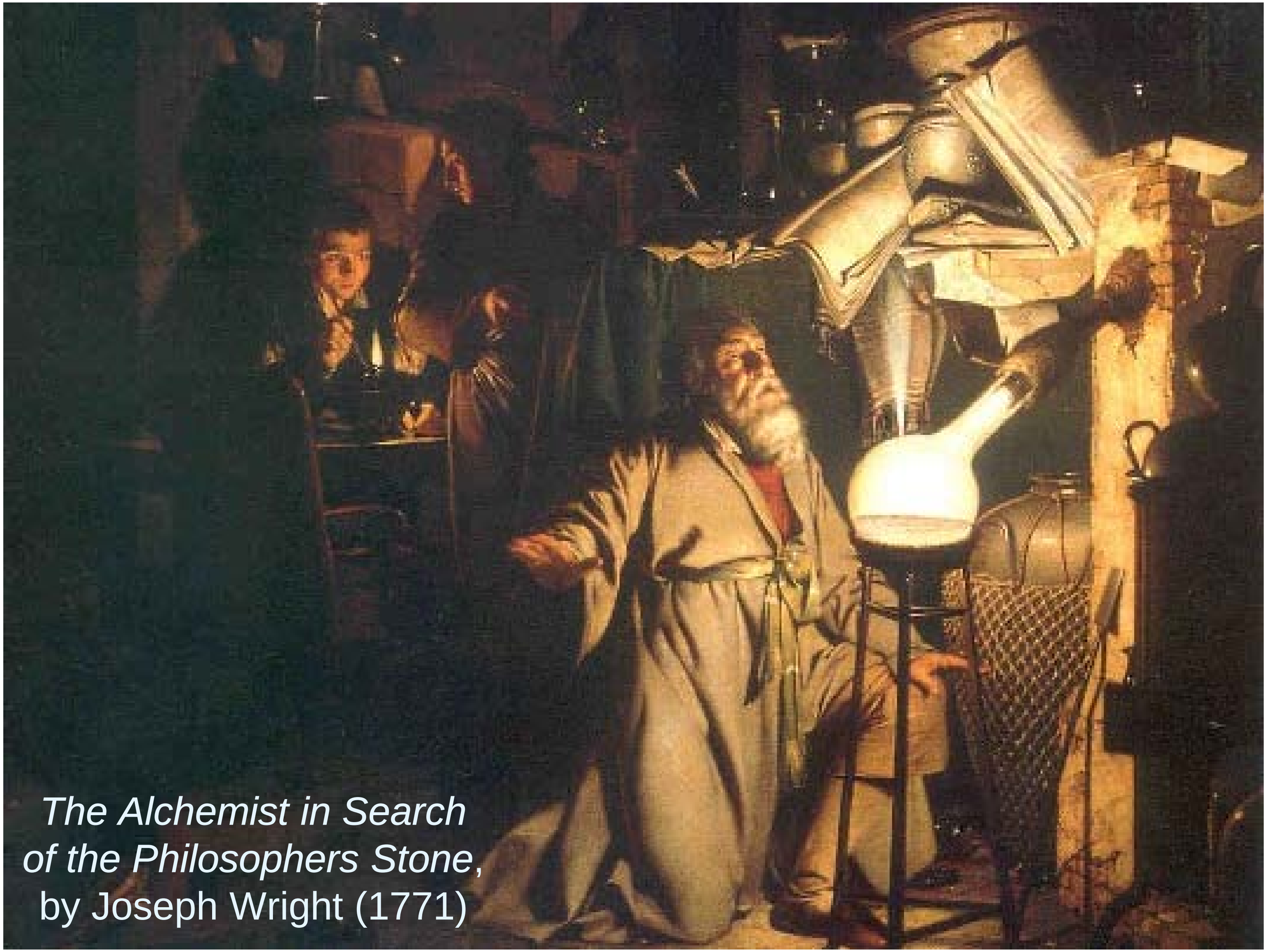
Questions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