Introduction to the Campaigns

Our search for LENR embodied a variety of campaigns, focused on trying to generate nuclear reactions (via combinations of loading, materials, and stimulation) and/or developing sensitive methods to detect them.

These will each be discussed, in detail, in the following sections of this report.

But first, here's a brief synopsis of what the campaigns were, and why we did them.

Let's first introduce two campaigns which did not directly try to make or detect LENR, but instead developed the technical infrastructure which was essential for the other campaigns to do so.

Synergy : Software and data-handling are ubiquitous parts of any modern scientific effort. But, in a fast-paced, parallel-track, program like ours, these usually become bottlenecks, retarding progress. A major reason is siloing; each experimenter, and often each of their key instruments, uses their own computers and codes, and retains its own data. Synergy was developed to address these issues. It provided a common platform to document all experiments, the materials used in them, and the data collected by them[7]. It was designed to make operation and interactivity as easy and seamless as possible; user-to-user, user-to-equipment, and user-to-the-past.

Loading : The most basic precondition necessary for PdD-based LENR, is loading deuterium into palladium. Callisto's primary route to do so, used high pressure D_2 gas. And, since we wanted loadings all the way to 100%, this meant we needed D_2 pressures as high as 500,000 psi. This is not an off-the-shelf capability, particularly since hydrogen embrittles almost all structural metals. This campaign had to develop the pumps to pressurize D_2, as well as vessels which were strong enough to host experiments at these pressures. In addition to developing the pressure hardware, we learned how to load deuterium into palladium without disrupting it, and how to measure near-stoichiometric loadings.

The next seven campaigns were focused on investigating different way to generate LENRs.

Thermal Ignition : After our early room-temperature experiments showed no signs of LENR, we searched for some form of successful stimulation. Temperature was the choice, but at a given pressure (e.g., 150 ksi) there is a strong tradeoff between loading and temperature, they can't both be high. This campaign was designed to give us both high loading and high temperature at the same time. We would load deuterium into Pd at room temperature (or even cryogenic), reaching 96-99% values. Then we would quickly heat the target with a laser. For a short time, 10 seconds or so, the loading would remain high; we looked for LENR during this high loading, high temperature period. Due to the nature of these experiments, we had to use temperature

[3] One guide to the reader; throughout the discussions there will be frequent references to BE#s or BD#s, e.g., BE4131. These are Synergy "pages" documenting our experiments (BE#) or devices (BD#).

measurements as the diagnostic. As a result, very careful controls (usually PdH vs PdD) became essential, and these evolved into our most complex LENR experiments.

Staring : This campaign was launched out of our desire to look for LENR using finer spacetime resolution than possible with full-target sensors (such as a calorimeter or a single temperature probe). Our approach was still temperature sensing, but done using a fast IR camera. Remote imaging allowed us to sense the temperature of thousands of small spatial pixels every millisecond or so. Our stimulation of choice was thermal, implemented by a programmable series of short laser pulses. Spatial control of the irradiation allowed us to heat different regions of the target separately. In the later stages of the project we used Staring's laser irradiation as a controllable, albeit fairly gentle, stimulation source for a variety of archaeology measurements

Chips : The most effective knob to turn, in order to detect ever fewer numbers of LENR events, is to reduce the size of the target being tested. The Chips campaign was focused on doing this, by using modern lithographic techniques to make small Pd targets, usually with integral stimulation sources and LENR detectors. We designed and fielded a variety of different systems. The canonical one involved a thin layer of Pd mounted above a Pt RTD-heater combination. In operation, the system would be placed in high pressure D_2 gas, thus loading the Pd; then current in the Pt would apply a short heat pulse to the PdD, and the RTD would record the resultant temperature history; this process would be repeated tens of thousands of times. Among the other Chips experiments were Estim ones, using micro-capacitors to apply electric field stimulation to Pd or rare-earth films; a fundamentally different type of stimulation than our normal thermal one. We also fielded Chips experiments using nanopillars and nanofilms for archaeological detection, as well as ones testing electric-field-concentrating Pd nanostructures such as bowties and THz metamaterials.

Ultra-Short Pulse : As we've discussed, most forms of thermal stimulation are fundamentally, on the atomic scale, very similar. However, once energy is applied on timescales comparable to, or much shorter than, the oscillation period of deuterons within the palladium lattice, things change; we can drive more intense deuteron motion, and can move neighboring deuterons coherently. The timescale needed is about 100 fsec; although this is short, there are many commercially available lasers with shorter pulses. We used both single pulses and resonant chains of pulses to attempt to stimulate LENRs. We used a variety of diagnostics for these experiments, including pump-probe sensing, thermal probes, and archaeology.

Terahertz : The outcome of thermal stimulation is predicted to be enhanced hopping of deuterons out of their octahedral traps, so that they can encounter each other and have the opportunity to undergo LENRs. Terahertz stimulation has the potential to enhance this hopping much more directly, by generating phonons tuned to resonantly drive deuteron oscillations. Since PdD is a metal, very little of arriving terahertz radiation can penetrate below the surface and cause hopping; hence intense terahertz sources are required. We tried to deliver strong enough terahertz power in two different ways, by nonlinear generation in plasma above the PdD surface, and by lithographically creating resonant terahertz metamaterials on the surface.

High Pressure Electrolysis : We have used our high-pressure capability to improve electrolytic loading. Doing so, required different (in some ways greater) hardware challenges than gas loading, notably due to the corrosive nature of strong electrolytes. We were able to demonstrate 98% PdD loadings at pressures as high as 400 ksi. However, we found that the advantages of pressure leveled off; 150 ksi pressures worked as well as 400 ksi, and involve considerably more convenient hardware and electrolyte mixtures. With these systems, we performed high pressure electrolytic experiments, using our commercial calorimeters to look for LENR.

Replications : We are not the only LENR researchers to use D_2 gas in order to load Pd. Only a couple of efforts explored the very high pressure regime that we have, and they did not report seeing any sign of LENRs. There have, however, been a number of notable lower pressure experiments that have claimed to see LENRs, and so we have attempted to replicate two of these. One effort was carried out by Les Case in the early 2000s. He used commercial Pd-catalytic material (Pd nanoparticles on a carbon substrate), and cyclically loaded/deloaded this with D_2 gas at temperatures of around 200ºC; LENR detection comprised comparing temperatures reached with D_2 gas to those with H_2. Another was pioneered by Yoshiko Arata in the 1990s, and was extended after his death by other Japanese researchers. These experiments also use nanoparticles, typically PdNi combinations embedded in a ZrO_2 matrix, and exposed to elevated temperatures and pressures. In both of our replication attempts, we first tried using apparatus similar to theirs, and then migrated to our standard calorimeters; in neither case did we detect signs of LENR. In another, unrelated effort, we examined the 1989 LLNL electrolytic experiment. Here, we were not trying to look for LENR (Callisto electrochemical loading is performing replications experiments for that), but instead tried to identify possible non-LENR explanations for its results.

The final five campaigns concentrated on different ways of detecting LENRs.

Calorimetry : This is traditionally the gold-standard for thermal detection of LENR. Our main "wrinkle" was the exclusive use of commercial calorimeters, rather than custom-built ones. As previously discussed, this choice gave us sensitive, well-characterized calorimeters, while providing easier traceability and replicability of our measurements for other researchers. We used these calorimeters in a wide variety of high pressure LENR experiments. The most sensitive usage was in passive experiments, with no stimulation; these included bulk Pd targets, as well as Pd nanoparticles and aerogels. Since LENR likely requires some form of stimulation, we also performed experiments using resistive heating pulses. A final, quite different, use of our calorimeters, was to perform high pressure liquid-based electrolysis in them.

Physical Archaeology : This was our most sensitive LENR detector, and should be able to record single localized LENR events. It worked by using arrays of very small Pd nanostructures; each one thin enough so that energy from even a single LENR would permanently damage the nanostructure, in a way that would be visible in SEM images taken after the experiment. We fielded two different types of these structures; nanopillars, which were vertical Pd cylinders about 60-100 nm wide, and nanofilms, which were 20-30 nm thick films of Pd. Most of our nanopillar experiments occurred in the Staring and Chips campaigns. Later, because of their versatility and ease of fabrication, we concentrated on nanofilm detectors. In addition to use in Staring and Chips, we also used these in the Ultra High Pressure apparatus with both long and ultra-short laser stimulation, as well as in high-pressure electrolysis. Furthermore, we were able to field nanofilms using not just Pd, but also a wide variety of Pd alloys, and some other metals.

Magnetic Archaeology : This form of archaeology did not rely on permanently damaging a Pd target, but rather on the transient thermal spike from a LENR event changing the magnetic field in a nearby magnetic material. This is a novel, and very-fast-acting form of a thermal history sensor; it tells us what's most important (that a given temperature was reached) without having to determine exactly when that occurred (a fact that we care much less about). Implementing these detectors was technologically quite challenging; we learned to fabricate arrays of magnetic nanodots, and to image magnetic changes in them using either magnetic force microscopy or tunneling magnetoresistance read-heads.

Seismology : This was an attempt to measure the vibrations induced within materials by the sharp thermal impulse caused by a LENR event. Basically, it's an analog to how one detects earthquakes or underground nuclear tests; abrupt impulses launch waves which persist long after, and far away from, the event itself. We faced two key challenges: One, was detecting the weak electrical signals from an event's wave given the background electrical noise in our facility. The other, was the presence of non-LENR impulses as the Pd was interacting with the high pressure D_2 gas. This campaign was begun in the last year of our project; as a result, we were still working to resolve the two challenges, and have not determined the final sensitivity of this approach.

Nuclear Detection : Since the only products of conventional deuterium-deuterium reactions are energetic particles, we devoted some resources towards detecting nuclear products, postulating that they may at least constitute a side reaction to LENR's heat channel; and, crucially, that nuclear products would be a much less ambiguous sign of nuclear reactions than heat. We used two main approaches; using scintillators to look for γ-rays, neutrons, or charged particles escaping the sample during an experiment, and placing samples in gamma well detectors after experiments to look for delayed γ-rays resulting from nuclear transmutation.