UC National Laboratory Fees Research Program – 2025 Workshop

University of California Initiative for Fusion Energy: Workshop Report

The UC National Laboratory Fees Research Program (LFRP) sponsored a workshop to advance innovative research and strengthen collaborations between the University of California (UC) and the (UC) national laboratories, in the field of research advancing fusion energy. Participation was open to researchers at the ten UC campuses and the three UC-affiliated national laboratories (Lawrence Livermore, Los Alamos, and Lawrence Berkeley National Laboratories).

Workshop Structure

The workshop series consisted of a two-day hybrid convening on December 10-11, 2024, at the San Diego Supercomputer Center on the UC San Diego campus. The workshop highlighted the current research landscape and challenges in three key areas for advancing fusion energy: materials under extreme conditions, fusion diagnostics in extreme conditions, and tritium breeding. The workshop also included panels on industry engagement, intellectual property, public policy, and UC-national lab partnership opportunities.

The workshop was organized by a team representing five UC campuses and three national laboratories, and the attendees (85 in-person, plus hybrid attendees) spanned eight campuses, three national laboratories, the Department of Energy, and California businesses.

Workshop Report

The attached workshop report was prepared by the organizing team, and presents the content of the workshop and a wide range of recommendations for ensuring UC-NL collaborations are at the forefront of advancing fusion energy to commercialization.

The research investments recommended in the report highlight specific opportunities in materials science, both for basic research and development and for application to fusion energy. However, overall the research investments recommended across the three key areas focused on research infrastructure: databases, convenings, and other coordinated support necessary to identify partners across the UC-NL ecosystem and leverage LFRP for future funding opportunities in fusion.

The report also recommended a variety of mechanisms for building and sustaining partnerships between UC and the national labs in this area, from utilizing sabbaticals for cross-fertilization to creating fusion-specific versions of existing fellowships and internships. Finally, the report recommended looking beyond UC and the national labs, and exploring partnerships with industry, policymakers, and communities.

Workshop Title: The University of California Initiative for Fusion Energy
Host/Coordinating Institution: UC San Diego
Workshop PI Name: Beg, Farhat
Workshop Report Authors: Beg, Farhat, UCSD; Bernstein, Lee, UCB/LBNL; Bibeau, Camille, UCOP; Campbell, Mike, UCSD; Dollar, Franklin, UCI; Fratoni, Massimiliano, UCB; Garay, Javier, UCSD; Kline, John, LANL; Marian, Jaime, UCLA; Ma, Tammy, LLNL; Schumm, Bruce, UCSC; Schwegler, Eric, LLNL

Executive Summary

In the last several years, there have been significant advances in science and technology for fusion energy generation and milestone achievements by both government laboratories and private industry. Due to these recent results and the growing need to eventually “decarbonize” central power production and meet growing energy demands, there is a renewed interest in fusion energy, and significant investment has been made by private investors. However, there are several imposing scientific and engineering challenges that need to be addressed before fusion energy becomes suitable for the power grid.

The University of California is an ideal place to address these challenges and has the largest number of engineers and scientists in fusion energy and related fields than any other US academic institution. Faculty and scientists at UC campuses are recognized leaders on various aspects of fusion energy. Many of the UC campuses are also strongly connected to industry, which includes significant industrial funding. Three national laboratories affiliated with UC – Lawrence Livermore (LLNL), Los Alamos (LANL) and Lawrence Berkeley (LBNL) – are playing pivotal roles in fusion energy. Therefore, of all institutions, UC has the greatest potential for tackling these challenges and training the fusion energy workforce.

The goal of the workshop was to bring together fusion energy experts from three UC-affiliated national laboratories (LLNL, LANL and LBNL) and UC campuses. The workshop was held in hybrid mode at the San Diego Supercomputer Center (SDSC) at UC San Diego on December 10-11, 2024. The workshop was well attended by students, postdoctoral scholars, research scientists and faculty from eight UC campuses (UC Berkeley, UC Davis, UC Los Angeles, UC Irvine, UC Merced, UC San Diego, UC Santa Barbara, and UC Santa Cruz) and UC-affiliated national laboratories.

The UC has significant strength in myriad topics pertinent to fusion energy and these topics would benefit from UC-wide collaborations but a down selection to three topics was necessary for budgetary and time constraints. Each topic had a review talk covering the current status and state-of-the-art research followed by three talks to discuss strengths and opportunities. The technical sessions were followed by breakout sessions where extensive discussion took place and areas of collaborations were identified on below topics.

- Materials under extreme conditions, including plasma facing first wall integrity
- Fusion diagnostics in extreme conditions
- Tritium breeding (non-proliferation)

Materials and diagnostics systems Research & Development (R & D) are already a strength of UC and UC-affiliated national laboratories, and work done to advance fusion energy delivery should be performed in concert with discovery science, which is often a necessary precursor to technical advances. It is recommended that both these R&D domains be supported in pursuit of commercially viable fusion energy. UC resources that can be brought to bear on the problem of tritium breeding include expertise in fission reactors, fluids expertise for molten salts, and system engineering to examine full system needs. The UC system’s vast human resources and capabilities are its greatest strength, and a systemic initiative to marshal and focus these resources should be undertaken.

In addition to the technical session, there were four panel discussions on i) Fusion policy/Regulations/Public perception, ii) Partnership with industry, iii) IP issues and iv) Partnership with UC-affiliate national laboratories. A number of recommendations arising from the panel discussions can be found in the body of the report.

Background and Current Status

There is a growing need to decarbonize central power production to meet the goals set by federal and California state governments. This need has prompted interest in clean energy sources such as fusion energy. In the last several years, there have been significant advances in fusion energy Research and Development and milestone achievements by both government laboratories and private industry. The fusion industry has now attracted over $7 billion in investment. Fusion energy holds great promise to provide an abundant and clean energy source for the foreseeable future. In addition to its potential to supply energy to the grid, spin-offs from fusion energy can be very beneficial to society. Spin-off applications include high temp superconducting magnets for wide number of applications, high energy lasers for defense and added manufacturing, and EUV has enabled Moore's law on semiconductor manufacturing to continue.

The US government also has an increasing interest in fusion energy. In March 2022 and June 2024, the White House held summits hosted by the U.S. Department of Energy and the Office of Science and Technology Policy, titled “Bold Decadal Vision for Commercial Fusion Energy.” The vision discusses building multiple fusion pilot plants operating as part of new fusion technology hubs around the country within the next ten years. In addition, in early November 2022, the White House announced its “Net-Zero Game Changers Initiative.”

Figure 1: The Venn diagram illustrates the strengths of various UC campuses and UC-affiliated national laboratories in the three technical areas of the workshop, all of which are essential for realizing fusion energy for the power grid. Workforce training and community engagement are also vital components of the fusion ecosystem.

While there has been great progress, important questions pertinent to fusion research still need to be addressed. Significant engineering and design challenges remain before fusion energy can successfully transition from the laboratory to a commercially viable power source. Addressing and solving these challenges calls for a coordinated effort between academia, national laboratories, and industry.

The University of California is an ideal institution to lead the effort to address these challenges, having the largest number of engineers and scientists in fusion energy and related fields than any other US academic institution. The faculty and scientists at UC campuses are the leaders on various aspects of fusion energy. Therefore, UC has the greatest potential for pushing the realization of fusion energy forward, while at the same time training its required technical workforce.

To date, there are only a few large fusion facilities in the country. Two of the largest facilities (NIF at LLNL and DIIID at General Atomics in San Diego) are in California, and UC faculty and scientists are heavily involved in fusion energy R&D at both of these facilities. Many of the UC campuses are also strongly connected to industry and receive significant industrial funding. Three national laboratories affiliated with UC – Lawrence Livermore (LLNL), Los Alamos (LANL) and Lawrence Berkeley (LBNL) – are playing pivotal roles in fusion energy.

With the demonstration of fusion gain in the laboratory, a shift towards engineering a commercially viable power plant presents fresh challenges to solve and opportunities that require new collaborations that would benefit from the vast experience across the UC system and national laboratories.

The goal of the workshop was to bring together fusion energy experts from three UC-affiliated national laboratories (LLNL, LANL, and LBNL) and UC campuses. The workshop was held in hybrid mode at the San Diego Supercomputer Center (SDSC) at UC San Diego on December 10-11, 2024.

The workshop was well attended by students, postdoctoral scholars, research scientists and faculty from eight UC campuses (UC Berkeley, UC Davis, UC Los Angeles, UC Irvine, UC Santa Cruz, UC Santa Barbara, UC San Diego and UC Merced) and UC-affiliated national laboratories. The workshop was also attended by the Department of Energy fusion energy advisor and various fusion companies (Kronos Fusion Energy, General Atomics, Longview Fusion, Blue Laser Fusion, TAE Technologies, Pacific Fusion, and Caminno Energy Inc.). The focus of the workshop was on topics where significant expertise exists within UC campuses and UC-affiliated national laboratories, but no prior collaboration existed of the sort presented above. The primary goal of the workshop was to jump-start the formation of collaborations on these topics that will begin to meet the challenges associated with fusion energy commercialization, while at the same time provide outstanding opportunities not only to faculty and research scientists but also to postdoctoral scholars and graduate students.

The workshop opening session had remarks from Professor and Vice Chancellor for Research and Innovation, Corinne Peek-Asa (UCSD), Professor and Dean of the Jacobs School of Engineering, Al Pisano (UCSD), Program Officer for UC Research Initiatives, Dr. Rebecca Stanek-Rykoff (UCOP) and Fusion Energy Coordinator, Dr. Scott Hsu (US Department of Energy). The UC has significant strength in myriad topics pertinent to fusion energy and these topics would benefit from UC-wide collaborations but a down selection to three topics was necessary for budgetary and time constraints, and to provide a nucleating focus for future activity. The three topics listed below were chosen for inclusion in the workshop due to the importance for future fusion energy-based power plants:

- Materials under extreme conditions including first wall
- Fusion Diagnostics in extreme conditions
- Tritium Breeding (Non-proliferation)

Each topic's session began with a review talk addressing the state-of-the-art of current technology, and the status of current research, followed by three talks to discuss institutional strengths and opportunities. The technical sessions were followed by breakout sessions where extensive discussion took place and areas of collaborations were identified.

In addition to the technical sessions, there were four panel discussions on the following topics:

- Fusion policy/Regulations/Public perception
- Partnership with industry
- IP issues
- Partnership with UC-affiliated national laboratories

The Fusion policy/Regulations/Public Perception panel discussed the regulatory framework and public perception, and how UC can participate in guiding these towards an evidence-based stance. The industry panel discussed partnership opportunities between UC campuses and industry. IP issues were discussed in panel format by experts from UC, industry and national laboratories. The panel focused on finding solutions to IP challenges. The panel on partnership explored pathways for fostering collaboration between UC campuses and national laboratories on fusion energy. A brief summary of each panel discussion is included below.

Research Priorities to Advance the Field

Before and during the workshop, there was an extensive discussion about UC and UC-affiliated national laboratories strengths in the field of fusion energy research. The workshop's series of invited overview and technical talks in each of the three focus areas were followed by hybrid breakout sessions, where colleagues attending the workshop in person and attending remotely extensively participated in the discussion. Below we give a summary of discussion on three technical topics, as informed by the invited talks and breakout sessions, and of the panel discussions.

Materials Under Extreme Conditions:

The realization of a fusion energy power plant will require accelerated development of next-generation materials for the chamber and components that can withstand the unique issues of irradiation by high energy neutrons, charged particles, debris, x-rays, and high heat-flux thermomechanics. There is a need to develop a modeling-informed, experimentally verified understanding of structural materials at the macro- and microscopic levels, including neutron damage. Lifetimes and disposal pathways of chamber materials, final optics, and consumables will also require investigation.

Prior to the breakout session, several talks laid out the materials challenges in fusion energy environments and provided an overview of the current status of fusion materials research. These talks were provided by Prof. Jaime Marian (UCLA), Dr. Bassem El-Dasher (LLNL), Dr. Nithin Mathew (LANL), and Prof. George Tynan (UCSD).

Fusion plasma-facing and structural materials face the most extreme environment imaginable, and must withstand extreme temperatures, irradiation, and stress (see Fig.2). Plasma facing materials (PFM) are those used to construct the plasma-facing components such as the first wall or divertor region of a magnetic fusion energy (MFE) reactor vessel, and are thus, exposed to the plasma where nuclear fusion occurs. These PFM thus must meet requirements of:

- long lifetime
- low activation

- low tritium retention

The structural materials must operate under a set of well-defined, extremely strict requirements, including:

- structural stability to intense fusion neutron exposure (including transmutant H/He)
- reduced activation mandate
- resistance to corrosive environments (under radiation enhanced corrosion conditions)
- large time-varying thermomechanical stresses and high temperatures
- loss of coolant accidents and/or air ingress due to structural failure/loss of vacuum

Also, functional requirements associated with fusion plant operation include:

- minimize the tritium inventory in blanket structures, plasma facing components, etc.
- efficiently extract tritium from hot coolant
- thermohydraulic and magnetohydrodynamic instabilities

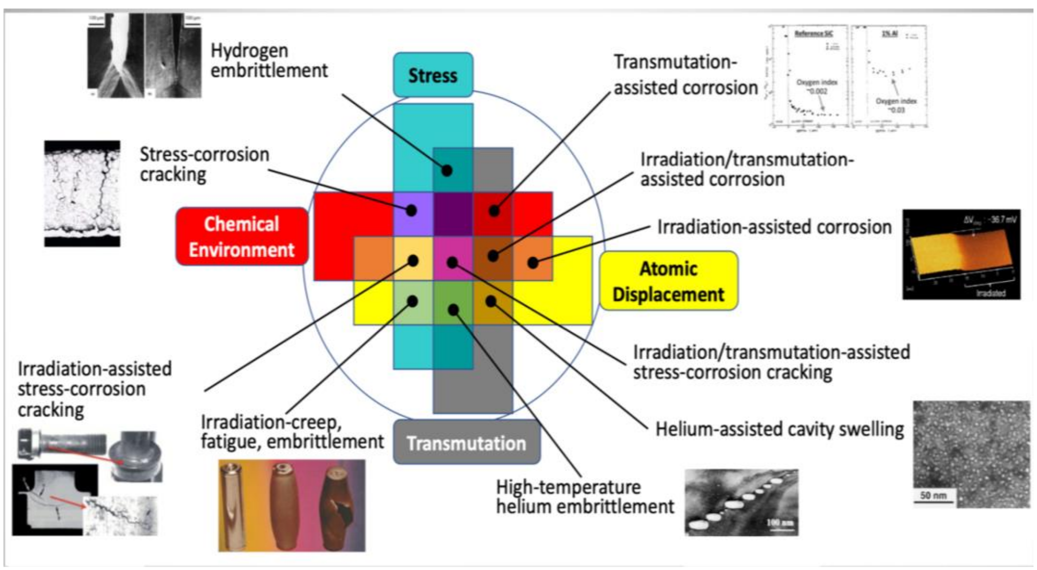

Figure 2: An example of challenges associated with materials facing extreme conditions. Fusion plasma facing and structural materials face the most extreme environments imaginable. Virtually no materials system currently used are reactor viable (figure courtesy of Yutai Katoh, ORNL).

__Current status of fusion materials research and opportunities for innovation and technological development in the United States:__

The current status of development as it relates to fusion structural materials presents a mixed bag of mature technologies with relatively high TRLs (technology readiness level) as well as persistent knowledge gaps with little or no research performed to address critical needs for the safe and reliable operation of fusion reactors. For example, an extensive database of irradiation effects on steels has been compiled over the last three decades, both using surrogate fission neutron sources and ion beam experiments. These primarily include measurements of hardening, fracture toughness, and dimensional stability at temperatures ranging from room temperature to 30% of the melting point. This has helped the fusion materials community build a substantial understanding on the response of austenitic stainless steels and ferritic/martensitic steels to high levels of displacements per atom (dpa).

Conversely, much less is known about helium effects in these materials, particularly at high temperatures when He-induced embrittlement is the dominant failure mechanism under fusion reactor operation. However, uncertainties remain due to the differences between available irradiation sources and actual fusion neutron conditions, both in terms of spectral differences as well as in terms of achievable cumulative irradiation doses (of 100s of dpa in some cases). Other aspects of fusion operation, such as compatibility with liquid breeder/coolants and tritium transport and retention are comparatively much less known.

By contrast, our understanding of other material systems such as W, SiC, advanced V alloys, and heat transfer materials such as CrCuZr alloys is much more limited, even as it relates to fundamental mechanical properties such as stiffness and strength. Clearly, significant effort will have to be directed at filling these knowledge gaps before we can start to gain a sufficient understanding of materials response under fusion operation conditions relevant to public fusion research programs and Milestone Program partners.

In this context, theory, modeling, and simulation are poised to play a crucial role in bridging the knowledge gap between what we can study using existing irradiation facilities and expected operational environments in fusion energy. Careful validation and calibration of models with existing and available data will by necessity become an unnegotiable part of advanced fusion materials research, as validated models can help us gain an approximate idea of how materials will perform under actual operational scenarios until such time as a prototypic fusion neutron source is built and made available to the fusion materials community.

Finally, through a series of workshops and meetings, DOE-FES commissioned a "Fusion Materials Roadmap" to the 'Fusion Materials Coordinating Committee' (FMCC) with broad participation from the US fusion materials community. This resulted in a detailed materials roadmap that typifies existing materials technologies into of a classification of TRLs for potential deployment in a demonstration fusion concept and identifies research and development pathways for materials to be used in a 'next-of-a-kind' fusion reactor with materials constraints and specifications representative of prototypic fusion reactors. The document culminates with a series of 'priority research objectives' intended to guide research efforts and direct public and private sector resources towards specific goals. The FMCC has released a draft of the materials roadmap for public comment (under the auspices of the Electric Power Research Institute, EPRI, which can be accessed [1]) that can be used to identify challenges and opportunities that California institutions could potentially address.

Main outcomes of LFRP Workshop for the materials section:
During the breakout session, the following findings were identified by the participants:

- There are currently many fusion materials bottlenecks. These include:
    - Test facilities. The US needs more facilities that can provide representative nuclear environments with adequate neutron dose such that materials testing and measurements can be carried out. Test stands in relevant ecosystems that could test corrosion, creep, fatigue, and other materials properties would be hugely beneficial in advancing the field.
    - Materials processing. We need a faster testbed for materials screening and downselection. Such tools would allow us to take advantage of faster materials prototyping.
    - Data organization. A coordinated fusion materials database that could maintain metadata and its provenance would be enormously valuable in pooling together valuable materials data from across different facilities, fusion concepts, testbeds, and simulation work.

- Fusion materials development cannot be done in a silo. Instead, it will need to be an iterative discussion between the designers/systems engineers and the materials scientists where fusion power plant requirements need to converge with materials realities. The UC, with its multidisciplinary and expansive expertise can be a platform to facilitate this.
- Emerging technologies can be applied to significantly advance fusion materials. A few examples include:
  - Materials discovery with AI
  - The integration of AI to facilitate high throughput discovery, screening, synthesis, characterization, experimentation, and testing
  - New diagnostic tools to allow for high-fidelity capture of materials microstructure and interfaces, and the interplay
  - Big data integration of materials data to generate cheap surrogate models for materials discovery

Recommendations:

- ➢ The UC and affiliated-national laboratories should exploit existing facilities to make in-situ measurements. For relatively small amounts of funding, existing facilities could be upgraded to look at: high-throughput microstructural characterization, high-throughput thermo-mechanical assessment, high-throughput multi-effect irradiation, magnetic properties. These would be unique, and world-leading diagnostic tools.
- ➢ Materials R&D is already a strength of the UC. In the fusion realm, the UC should maintain a component of discovery science - not all the R&D necessarily needs to be directed toward the commercial end use-case.
- ➢ As fusion materials requirements will need to flow down from an integrated power plant design, UC should facilitate cross-fertilization and extend efforts across the UC system and across departments to enable holistic development of fusion power plant designs and systems.
- ➢ The US is lacking a coordinated fusion materials effort. UC could be the custodian of a fusion materials database, thus filling a crucial gap in materials research, while cementing UC as a leader in this space.
- ➢ Emerging technologies such as AI can rapidly advance fusion materials R&D. UC should look to leverage its innovative ecosystem, including its powerful supercomputing and data centers, to apply the latest emerging technologies in novel ways for fusion.

Fusion Diagnostics Under Extreme Radiation Conditions:

Diagnostics will play a central role in the development and operation of fusion power and science facilities. One of the most visible successes in the field - the creation of a robustly burning plasma [2] and the achievement of nuclear ignition [3] - came as the result of a long, broad program of diagnostics development, associated with advanced readout, acquisition and analysis systems. This could not have been achieved without a comprehensive suite of diagnostics approaches and systems. Researchers at LLNL, LANL, LBNL and the UC campuses have understood the need for robust diagnostic systems and have pioneered the development of these systems at the National Ignition Facility. As an example, Figure 3 below from [4] shows the broad range of diagnostics developed for the NIF. Similarly, the DIII-D tokamak facility at General Atomics is the longest running Magnetic Confinement Fusion facility in the US and hosts particle and photon diagnostics developed from faculty at UCLA, UCD, UCI, LLNL, and UCSD. Such capabilities, as well as platforms to characterize and commission diagnostics will be critical to the deployment of commercially viable fusion power plants.

Workshop Report Authors: Beg, Farhat, UCSD; Bernstein, Lee, UCB/LBNL; Bibeau, Camille, UCOP; Campbell, Mike, UCSD; Dollar, Franklin, UCI; Fratoni, Massimiliano, UCB; Garay, Javier, UCSD; Kline, John, LANL; Marian, Jaime, UCLA; Ma, Tammy, LLNL; Schumm, Bruce, UCSC; Schwegler, Eric, LLNL

Future advances in commercial-scale fusion power will similarly depend on the continued evolution of diagnostic systems and approaches. Of particular concern is the orders-of-magnitude increase in the radiation field (especially neutron fluxes and fluences) that will need to be tolerated by diagnostic systems in any fusion scheme, whether ICF

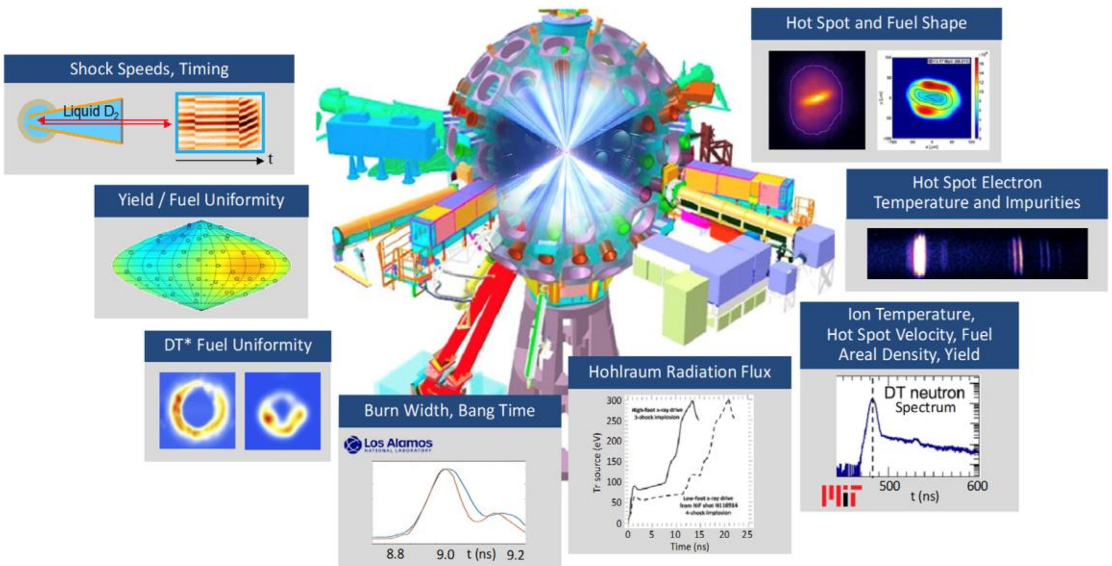

Figure 3. An example [4] of the broad range of diagnostics brought to bear in advancing Fusion Energy Science, in this case at the NIF at Lawrence Livermore National Laboratory.

or MCF. Additionally, advances in diagnostic rates, whether particle-by-particle spectroscopy measurements, or advancement of ICF burn rates to the 10-100 Hz range, need to be made in order to envision the operation of commercial-scale fusion power plants. Certain key fusion diagnostics, such as 3D neutron and X-ray imaging with direct line-of-sight to the burning plasma, making them particularly susceptible to damage and necessitating the development of a more robust operational capability.

In addition to ionizing-particle diagnostics, a breadth of other diagnostic needs will need to be met, a number of which are in the very early stages of consideration. Examples of these include materials integrity diagnostics for the “first wall” containment structure, tritium contamination detection, in-situ laser damage assessment, and superconducting-to-normal transition in magnet structures. In addition, the development of advanced simulation capabilities, including "digital twins" of potential reactor designs, will rely on validation provided by diagnostics capable of operating in such environments.

Prior to the breakout session, several talks discussed challenges in fusion diagnostics under extreme conditions, and provided state-of-the-art research being carried out at UC and affiliated national laboratories. These talks were given by Dr. Maurice Garcia -Sciveres (LBNL), Prof. Penghui Cao (UCI), Dr. Andy MacKinnon (LLNL), and Prof. Eleanor Tubman (UCB).

Discussion during the breakout session suggested that many of the diagnostic needs for ICF can be anticipated, and the community may be in a position to identify these needs and cohere around a program to accelerate their development. For the case of MCF, though, diagnostic requirements seem somewhat less well-defined and could benefit from an effort to assess them and define the most pressing needs.

Breakout-session discussion also revealed that significant expertise in the development of ionizing particle detection, including operation in high-radiation environments, exists within the UC campuses and laboratories, and the community is already relatively well connected. However, many of the system's experts are not yet enmeshed in the fusion energy community, and providing a forum that can help further connect them and focus their efforts on areas of promise to the fusion energy field would be a great benefit to the overall presence and impact of UC in the fusion energy ecosystem. Communities addressing other diagnostic areas required for the transition to commercial-scale energy production are not as well defined but are important to define and start to bring together and focus on problems critical to the advancement of the field.

It should be noted that these diagnostic capabilities will enable a much broader range of applications since the radiation fields in a fusion energy system are similar to those experienced by electronics in particle accelerators, spacecraft traveling beyond the earth's magnetic field and satellites that are crucial to the economic welfare and security of the nation in general. These concerns are well-understood by many researchers in UC and the two NNSA laboratories it helps manage, which host numerous facilities and capabilities to simulate and test electronics in high-intensity neutron environments such as the Berkeley Accelerator Space Effects (BASE) facility at the LBNL 88-Inch cyclotron [5], the Megajoule Neutron Imaging Radiography Experiment (MJOLNIR) [6] at LLNL, the McClellan nuclear reactor at UC Davis [7], the Berkeley Center for Magnet Technology [8] and the UC Berkeley Nuclear Technology Innovation Laboratory [9]. In addition to these neutron sources there are intense X-ray/electron facilities including BELLA at LBNL [10] and the other facilities that comprise LaserNetUS [11] and ZNetUS [12]. There are also other non-UC facilities that can provide radiation testing capabilities in support of fusion energy such as the Linac Coherent Laser Source (LCLS) at Stanford [13]. Facilitating better access to these facilities to researchers across the University of California, the UC-affiliated national laboratories and California-based fusion start-ups would greatly benefit the entire fusion effort.

The scale of funding that would be offered in a Lab Fees award would be unlikely to enable a holistic advancement in the state of field-wide diagnostic capabilities, yet that remains the ambition of the UC fusion initiative. Thus, more than funding specific R&D and commissioning projects, the goal of a prospective Lab Fee-funded fusion award program should be the formation of collaborations that will enhance their competitiveness in appealing for larger-scale, ongoing funding from government agencies and private foundations.

A successful initiative will enable a community that can provide the following service to the UC fusion community:

- An interdisciplinary forum that will
    - Incorporate the full spectrum of the California fusion energy community, including both the public and private sector
    - encourage the ready exchange of ideas between and among field experts and trainees
    - allow for the vetting of potential diagnostic opportunities by experts familiar with the needs of the field
- A network of UC-run or UC-adjacent facilities with a commitment to providing characterization capabilities for prototype systems (a list of potential participating facilities is included above)

- A professional development component that will advance the training environment for students and early career professionals interested in careers in fusion energy science and production

It should also be borne in mind that elements of a diagnostics development program, such as those associated with materials integrity, may require close communication or collaboration with experts in other domains of fusion science research. A successful initiative will incorporate these where appropriate.

***Recommendations**:*

- A survey of groups and institutions be undertaken to assess the most critical diagnostic needs, and the gaps in current technology that will need to be addressed to bridge those gaps
- An enumeration of accelerator, and other advanced characterization, facilities within the UC system and its affiliates be made. Area leaders within these facilities should be consulted about specific modes of support they can provide for fusion energy research, and letters of support expressing the availability and interest of these facilities be solicited
- A workshop to pull together the members of the UC community pursuing, or interested in pursuing, development of fusion-oriented diagnostics be hosted on an annual basis
- Regular updates about funding opportunities, facilitating collaborative applications among members of the broad UC community, be generated

Tritium Breeding:
One of the major thrusts for the success of fusion power is the ability to self-sustain the fusion fuel cycle. Deuterium-tritium (D-T) fusion, indeed, requires the continuous production of tritium, since T has a short half-life (12.3 years) and cannot be stockpiled for a long time. This requires a fusion power plant to produce, recover, and store tritium while accounting for all quantities of this radioactive gas. An accurate design of the fusion blanket is crucial for the successful commercialization of DT fusion energy, particularly for sustaining tritium breeding. In D-T fusion systems, the blanket typically encloses the fusion source and its key roles include breeding tritium to sustain the fuel cycle, and recovering the energy of neutrons from fusion by converting it to thermal energy. In addition to enabling the fuel cycle and energy recovery, the blanket must be engineered to withstand the radiation and stress from the plasma. Research for fusion blankets has been ongoing for a long time, leveraging mostly modeling and simulation work. Blanket designs mostly rotate around the choice of a coolant, a tritium breeding material (that often is also the coolant), a neutron multiplier, and a structural material. Tritium is produced from ^{6}Li by absorbing a neutron (some additional breeding can also occur in ^{7}Li); therefore, a common choice for fusion blankets is to use a coolant containing Lithium such as LiPb or a molten salt like Flibe (LiF-BeF_2). Since each fusion reaction generates one neutron, in order to obtain a breeding ratio greater than one (more tritium produced than those consumed) most blankets incorporate a neutron multiplier such as Be or Pb that increase the number of neutrons available for tritium breeding by means of (n,2n) reactions. In addition to the challenge of obtaining an adequate fuel production, tritium must be recovered and stored, two complex operations due to the ability of hydrogen gas to diffuse through metals.

The overall process will need to be executed at industrial scales, which has never been attempted. Success will require a multi-disciplinary team to develop these processes and to operate such a facility. The research challenges to ensure a closed fuel cycle involves basic physics around the breeding process with relevant property data, development of efficient recovery and storage systems, assessment of safety requirements, and understanding the

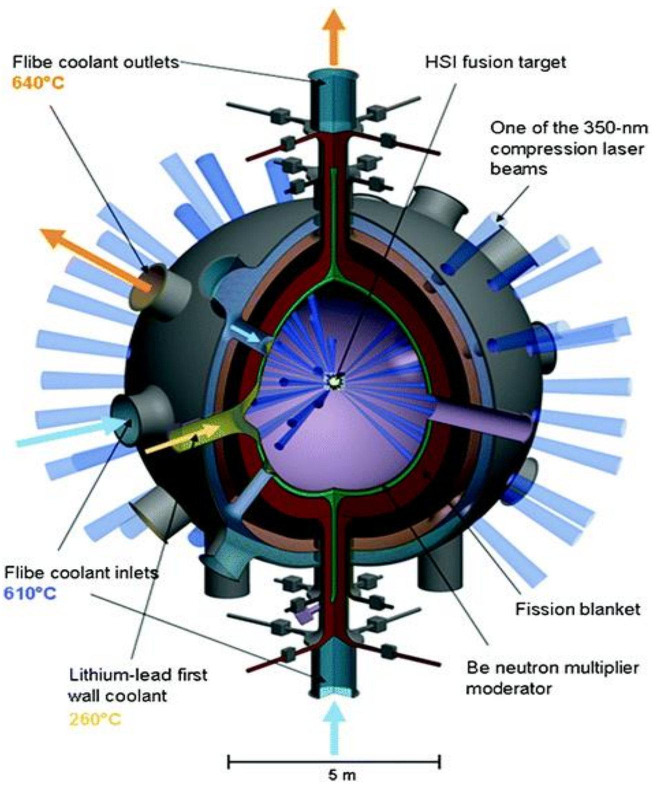

Figure 4. Schematic of fusion power plant showing important aspects of the plant.

workforce needs. The future fusion power plant (see Fig.4) can take advantage of the knowledge that already exists pertinent to fission power plants including modeling and simulations, tritium management, materials under extreme conditions, and sensors.

Talks and breakout-session discussion in the Tritium Breeding session described ongoing research in the UC system, scientific needs and system engineering capabilities for future power plants. Preceding the breakout session, talks were given by Prof. Massimiliano Fratoni (UCB), Prof. Raluca Scarlat (UCB), Dr. Victoria Hypes-Mayfield (LANL), and Dr. Renkun Chen (UCSD). The collection of presentations covered topics including the overlap of needs between fission and fusion energy production, the use of molten salts for cooling and tritium production such as FLiBe (Florine, Lithium, and Beryllium), tritium breeding and capture approaches, and the fluid properties of molten salts. During the breakout discussion the following findings were identified:

- The blanket design and tritium breeding research efforts are currently limited.
- The University of California system and its affiliated national laboratories have a small number of dispersed capabilities addressing tritium fuel cycle issues.
- The critical need combined with the limited number of institutions working on tritium creates an opportunity to have a large impact.
- The limited number of institutions working with tritium leads to a limited workforce for research and operations of systems.
- Impactful facilities for tritium research can be done in a relatively small space and create training opportunities

Recommendations:

- ➢ Since the number of researchers within the UC ecosystem working on tritium is small and independent at present, an inventory of capabilities and people interested in this research area needed to align themselves with identified gaps on the national tritium working groups.
- ➢ A broader look at how the UC can tap into its resources to bring unique capabilities for the problem such as experts in fission reactors, fluids expertise for molten salts, and system engineering to examine full system needs. The vast people's resources and capabilities are a strength.

Panel on Fusion Policy/Regulations/Public Perception:
While significant strides still need to be made in the development of scientific and engineering solutions to the challenges of producing commercial fusion power, the political landscape of regulatory policy and public perception provides an additional constraining framework that will also need to be addressed. The panel was moderated by Prof. Bruce Schumm (UCSC), and panel members were Dr. Scott Hsu (DOE), Dr. Anne-Marie Riitsaar (LLNL) and Zabrina Johal (GA). The panel offered perspectives on what these constraints are, what forces might be in play to address them, and how specifically the UC and its partners might act to augment or amplify efforts to address the regulatory framework (including both safety and security) and to address potential public misconceptions about the nature of fusion energy production.

Led by the US and UK in the West, there is a significant push to have fusion power plants regulated more similarly to accelerator and nuclear medical facilities than to fission power plants. In the US, the Nuclear Regulatory Commission (NRC) is currently heading in this direction, aiming to have a framework in place by 2027 that will classify fusion power plants in this manner, and additionally allow states significant latitude to establish their own local regulatory environment. In anticipation of this emerging framework, California has identified its Department of Public Health (DPH) as the regulatory agency for the State's prospective fusion power industry. Little expertise in the benefit/risk profile of fusion power currently exists within the California DPH. As such, the UC is likely the ideal partner in acting as an "honest broker" to the State's regulatory effort, helping to craft policy that optimally balances the needs to safeguard the public against the public benefit of fusion power.

Additionally, the UC can carry an "honest broker" role into the arena of public outreach and education, presenting a balanced and dispassionate enumeration of fusion energy's benefits and risks. UC can play this role in a number of public arenas, including state and local legislative outreach, talks at professional societies outside the immediate sphere of Fusion Energy Science, and community venues such as Rotary Clubs and Chambers of Commerce. This role can be particularly helpful in supporting the practice of "consent-based siting", an approach supported by members of the panel. An admonition presented by the panel was the avoidance of demonizing fission energy in the process of promoting the fusion energy industry - a practice the panel thought would be counterproductive, generally working against the ambitions of fusion power proponents, and of carbon-free energy production in general.

Recommendations:
- ➢ Through a high-level delegation, form an alliance with the appropriate regulatory office in the State government, and partner to develop optimal regulatory policy
- ➢ Particularly in areas amenable to fusion power plant siting, act as an "honest broker" to mediate discussions between community members and interested commercial partners to develop, in an environment of trust, an informed public view of the risks and benefits of fusion power

Panel on Bridging the Gap: Overcoming IP Challenges to Enhance Collaboration
This session brought together intellectual property (IP) experts from academia, industry, and national laboratories to discuss the critical IP issues that often act as barriers to collaboration between these sectors. The session explored how differing IP strategies, ownership rights, and licensing expectations could hinder innovation and impede the development of fruitful partnerships. The session focused on finding solutions that create mutually

beneficial frameworks for collaboration. The panel was moderated by Priya Sinha Cloutier (UCSD) with two panelists, Prof. Toshi Tajima (UCI) and Shelley Couturier (LANL).

Prof. Tajima gave a history of Tri Alpha Energy, which started as a start-up out of UC Irvine. Now, it is a more than 1-billion-dollar company. The company shared IP with UC. This could be used as an example moving forward collaboration between UC campuses, industry and UC-affiliated national laboratories. Shelley Couturier pointed out contrasting ownership perspectives at the national laboratories, industry and academia. Between the three, industry protects R & D investments and has exclusive licensing issues. However, with initial planning, IP issues could be overcome.

Recommendations:

- ➢ Consider regulatory and compliance requirements
- ➢ Plan for technology transfer and licensing
- ➢ Develop a clear value of proposition
- ➢ Leverage funding partnership

Panel on collaboration with industry:

This session explored partnership opportunities between the UC and national lab research/educational activities and industry end users. The session was moderated by Prof. Javier Garay (UCSD) with three panelists from industry: Dr. Anantha Krishnan (General Atomics), Dr. Keith LeChien (Pacific Fusion), and Dr. Paul Ruby (Blue Laser Fusion). The focus of the discussion was to explore ideas as to how industry can help provide guidance, ensuring relevance of educational activities and research directions. It was concluded that an early alignment between interested UC and industry partners can accelerate progress toward achievement of commercial fusion energy.

Recommendations:

- ➢ Opportunities for collaboration between UC, national laboratories and industry are important to make fusion energy successful.
- ➢ UC and industry should work together to train the next generation of scientists and engineers in fusion energy.
- ➢ Industry should leverage the facilities and capabilities that exist at UC campuses and national laboratories

Partnerships and Training Opportunities

The workshop had a diverse participation from eight UC campuses and UC-affiliated national laboratories including graduate students, postdoctoral scholars, research scientists and faculty. The participants were from engineering, physics, nuclear, chemistry and public policy backgrounds. The organizing committee collectively agreed upon the three main technological thrusts. Speakers were identified from the campuses and labs. In addition to the invited speakers, there were opportunities to make contributed talks. At the workshop, representatives from the national labs presented existing partnerships in a dedicated session. The panel was moderated by Prof. Mike Campbell (UCSD). The panelists were Dr. Eric Schwegler (LLNL), Dr. Brad Beck (LANL) and Dr. Bill Johansen (LBNL). They talked about established deep partnerships between the UC and UC-affiliated national laboratories. For example, greater than 20% of LLNL scientists and engineers have their highest degree from UC and 30-40% of LLNL publications are co-authored by UC faculty and staff. Academic partnerships (including UC) are essential for attracting and retaining a world-class workforce. Opportunities for student engagement at national laboratories include Science Undergraduate Laboratory Internship (SULI). SULI supports interns by providing 10–16-week internships. Some existing programs that were identified:

Lawrence Livermore National Laboratory:
Approximately 1,200 students participate in intern programs each year. Two thirds of the students come during the summer and one third during the academic year. LLNL offers approximately 15 different summer programs. About 43% typically will return for a second summer. Some of the 14 internal summer programs are: the NIF & PS Student Cybersecurity Summer Institute, Data Science Summer Institute, Materials and Chemistry Institute Computational Chemistry and Materials Science. LLNL also offers a Faculty Mini-Sabbatical Program.

Los Alamos National Laboratory:
There are opportunities to connect with LANL through the University Collaborations Office. Opportunities for students, faculty, and LANL staff include Student internships and fellowships, Targeted Summer Schools and Postdoctoral appointments and fellowships. There are mechanisms and collaborative tools including Informal intellectual commerce, agreements between institutions, Contracts, Conferences, workshops, colloquia, Joint proposals to sponsors, Joint Appointments, Joint Institutes, sabbaticals/ extended visits.

Lawrence Berkeley National Laboratory:
The LBNL has 224 joint appointments with UC faculty and has about 300 graduate students. LBNL also has the Visiting Faculty Program (VFP), which supports current faculty members through scientific research collaborations with US Department of Energy (DOE) laboratory scientists. Faculty members may invite up to two undergraduates or graduate students. Applications are solicited annually for the summer term. LBNL's Market Energy Innovation Programs encourages laboratory research to market.

***Recommendations**:*

- Existing partnership mechanisms should be leveraged. In addition, fusion specific opportunities should be established. Some possibilities are fusion specific summer schools at UC campuses and national labs, internship/co-op opportunities for students at national labs and companies.
- Fusion specific curricula that lead to certificates and UC undergraduate/graduate degrees. Curricula can be initiated within the lab fees program, but other resources will likely need to be leveraged to fully develop and deliver curricula.
- Recommendations for ensuring diverse participation and genuine collaboration in future research that leverages complementary expertise and perspectives, and engages graduate students, postdoctoral researchers, early career research and others in research activities that will foster long-term partnerships.
- It is recommended that plans be made to host an early career workshop for engaging early-stage researchers including postdocs. In addition, there should be annual meetings that not only discuss technical accomplishments but give opportunities for presentations from early career stage researchers working in tangential fields, but not currently collaborating in fusion research.

Sustaining and Extending Partnerships beyond the Workshop

Significant time was devoted at the workshop on the discussion about partnership between UC campuses and UC-affiliated national laboratories. All the key players working on fusion energy were present at the workshop. This facilitated discussion of collaboration and a session on "Partnering with national laboratories" also helped to identify directions after workshop convening.

Collaborations: As mentioned above, the workshop facilitated an opportunity to discuss collaboration with various UC campuses and UC-affiliated national laboratories on opportunities to work together on fusion energy. Potential collaborators were identified to pursue the Lab Fees Research Program funding. The technical topics described above provide a roadmap for any future proposals. UC Fee Lab funding will be used as seed funds to leverage large Center grants from the Department of Energy or other funding sources.

Early career faculty and Scientists: Early career faculty and scientists play a pivotal role in defining future research directions. It is recommended that significant attention should be paid to engage them on a regular basis so that they are part of solving challenging scientific and engineering problems pertinent to fusion energy.

Student Fellowships: One of the outcomes of the panel discussion was a recommendation that the Lab Fee program and UC-affiliated national laboratories should set aside funding to support fellowship for graduate students specifically in fusion energy. It was also recommended to reach out to industry based in California to start a dialogue for student fellowship and internship opportunities.

Access to facilities and capabilities: There was significant discussion on facilities and capabilities that exist at UC campuses and at the UC-affiliated national laboratories; it was pointed out that UC is in a unique place due to several fusion energy related facilities and capabilities exist which could be used to train students, postdoctoral fellows and research scientists. Several experimental facilities, computing facilities, codes and diagnostics were identified.

Sabbatical Program: UC-affiliated national laboratories have sabbatical programs, which has been used by some of UC faculty members. However, there is a need to advertise the program broadly to particularly attract early career faculty and research scientists. It was highlighted that lab scientists have not used this program to do sabbaticals at UC campuses. Sabbaticals will help lab scientists to interact with students and potentially offer seminars and teach courses, which will facilitate engagement of young scientists in research at national laboratories.

Curriculum in Fusion Energy: UC campuses offer a variety of graduate courses on fusion energy. On each campus these courses are taken by a small number of students ranging from 5-10. It is highly recommended that faculty at UC campuses coordinate these courses and offer them at other UC campuses. The UC Office of President has already established a mechanism to transfer credit for courses between UC campuses. It is highly recommended that these courses should be open to national laboratories and Industry scientists and engineers. UC campuses have extension programs, which could be leveraged to offer these courses for certificates.

The Department of Energy has been putting significant emphasis on workforce development in fusion energy. The UC system can take advantage of this initiative to offer a Master's degree in Fusion Energy. Interested UC campuses may participate in this program. Students have to spend six months on one campus, then they can take courses in person or remotely to fulfill requirements. Joint appointments offered to Lab scientists enable a new route of incorporating cutting edge fusion research and expertise into UC curriculum.

Industry Engagement: It is highly recommended that UC should engage with industry. The UC is in an ideal position compared to any other university system to offer expertise in a variety of fusion related technologies. Moving forward, it is anticipated that DOE focus will be on public-private collaboration for an ultimate goal of putting fusion energy on the grid. The UC and the national laboratories have historic success in public-private partnerships and knowledge transfer; for instance, the underpinning technology for EUV lithography light sources resulted from a virtual national lab structure in partnership with industry. Similarly, UC Faculty and fusion company TAE Technologies have numerous joint patents in fusion energy and related fields, as well as in tertiary areas such as radiation oncology and imaging. Structures that facilitate opportunities between UC and Lab scientists with industry would be broadly beneficial to all parties.

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[11] https://lasernetus.org/
[12] https://znetus.eng.ucsd.edu/
[13] https://lcls.slac.stanford.edu/

Report Authorship

Author Name	Title	Institutional Affiliation
Farhat Beg	Professor	UCSD
Lee Bernstein	Professor	UCB/LBNL
Camille Bibeau	Senior Scientific Staff	UCOP
Mike Campbell	Professor	UCSD

Franklin Dollar	Professor	UCI
Massimiliano Fratoni	Professor	UCB
Javier Garay	Professor	UCSD
John Kline	Senior Scientific Staff	LANL
Jaime Marian	Professor	UCLA
Tammy Ma	Physicist	LLNL
Bruce Schumm	Professor	UCSC
Eric Schwegler	Director of Academic Engagement Office & Science Education	LLNL

Appendix: Workshop Agenda

University of California Initiative for Fusion Energy Workshop Agenda
December 10-11, 2024
UC San Diego, San Diego Supercomputer Center Conference Center

Workshop Themes:

- Materials Under Extreme Conditions
- Tritium Breeding
- Radiation Hardened Electronics for Fusion Diagnostics
- Fusion Policy/Regulations/Public Perception

Virtual sessions (except the breakouts):
https://ucsd.zoom.us/j/97003521214?pwd=MXuvN8oOWn70oc65kMOnb4lqgMbfLa.1
ID: 970 0352 1214
Password: 241327

Day 1: Tuesday, December 10, 2024
7:30 - 8:15 a.m. **Check-in and Networking Breakfast**

8:30 - 8:55 a.m. **Welcome Session**

- Cori Peek-Asa (recording) (5 min)
- Al Pisano- Eng. School Overview on Fusion (5 min)
- Scott Hsu - U.S. Department of Energy (5 min)
- Rebecca Stanek-Rykoff - LFRP Program overview (10 min)

8:55 - 10:25 a.m. Materials Under Extreme Conditions Session

The realization of a fusion energy power plant will require accelerated development of next-generation materials for the chamber and components that can withstand the unique issues of irradiation by high energy neutrons, charged particles, debris, x-rays, and high heat-flux thermomechanics. There is a need to develop a modeling-informed, experimentally verified understanding of structural materials at the macro-and microscopic levels, including neutron damage. Lifetimes and disposal pathways of chamber materials, final optics, and consumables will also require investigation.

- Session chair: Tammy Ma (LLNL)
- Overview talk on opportunities and challenges (30 min) - Jaime Marian (UCLA)
- Talk 1: (20 min) Nithin Mathew (LANL)
- Talk 2: (20 min) Bassem El-Dasher (LLNL)
- Talk 3: (20 min) George Tynan (UCSD)

10:25 - 10:45 a.m. Break

10:45 a.m. - 12:15 p.m. Tritium Breeding Session

One of the major thrusts for the success of fusion power is the ability to self-sustain the fusion fuel cycle. This requires a fusion power plant to produce, recover, and store tritium while accounting for all quantities of this radioactive gas. The process will need to be executed at industrial scales which has never been attempted. Success will require a multi-disciplinary team to develop these processes and to operate such a facility. The research challenges to ensure a closed fuel cycle involves basic physics around the breeding process with relevant property data, development of efficient recovery and storage systems, assessment of safety requirements, and understanding the workforce needs. This session discussed both scientific needs, as well as system engineering capabilities for future power plants.

- Session chair: John Kline
- Overview talk on opportunities and challenges (30 min) - Massimiliano Fratoni (UCB)
- Talk 1: (20 min) - Victoria Hypes-Mayfield (LANL)
- Talk 2: (20 min) - Renkun Chen (UCSD)
- Talk 3: (20 min) - Raluca Scarlat (UCB)

12:15 - 1:30 p.m. Networking Lunch

1:30 - 2:30 p.m. Fusion Policy/Regulations/Public Perception Session

While significant strides still need to be made in the development of scientific and engineering solutions to the challenges of producing commercial fusion power, the political landscape of regulatory policy and public perception provides an additional constraining framework that will also need to be addressed. This panel discussion dives into what these constraints are, what forces might be in play to address them, and how specifically the University and its partners might act to augment or amplify efforts to address the regulatory framework (including both safety and security) and to address potential public misconceptions about the nature of fusion energy production.

- Panel Discussion (3-4 panelists with short intro followed by discussion)
- Session chair: Bruce Schumm (UCSC)
- Scott Hsu (DOE)
- Anne-Marie Riitsaar (LLNL)

- Zabrina Johal (GA)

2:30 - 2:45 p.m. Break

2:45 - 4:15 p.m. Radiation Hardened Electronics for Fusion Diagnostics

Sustained, neutron-rich, fusion plasmas pose numerous challenges for diagnostic design and survivability. This session identifies the requirements for fusion diagnostics with an eye towards identifying opportunities for collaboration between researchers at UC, industry, and the national laboratories. The session also explores crosscutting needs for radiation hardened electronics in related fields including space exploration, national security, accelerator operation, and aerospace engineering.

- Session chair: Lee Bernstein (UCB/LBNL)
- Overview talk on opportunities and challenges (30 min) - Maurice Garcia-Sciveres (LBNL)
- Talk 1: (20 min) - Penghui Cao (UCI)
- Talk 2: (20 min) - Andy MacKinnon (LLNL)
- Talk 3: (20 min) - Eleanor Tubman (UCB)

4:15 - 5:15 p.m. Lightning Talks

- 5-6 min presentations

5:30 - 7:00 p.m. Networking Reception

<u>Day 2: Wednesday, December 11, 2024</u>

7:30 - 8:15 a.m. Networking Breakfast

8:30 - 9:30 a.m. Industry Panel

This session explores partnership opportunities between the UC and national lab research/educational activities and industry end users. Industry experts can help provide guidance, ensuring relevance of educational activities and research directions. In turn, UC and national lab research breakthroughs can be leveraged by industry. Early alignment between interested UC and industry partners will accelerate the implementation of research findings, provide employment opportunities for students/researchers, and workforce for the fusion energy industry.

- Moderator: Javier Garay (UCSD)
- Anantha Krishnan (GA)
- Keith LeChien (Pacific Fusion)
- Anika Stein (Caminno Energy Inc)
- Paul Rudy (Blue Laser Fusion)

9:30 - 10:30 a.m. Bridging the Gap: Overcoming IP Challenges to Enhance Collaboration

This session brings together intellectual property (IP) experts from academia, industry, and national laboratories to discuss the critical IP issues that often act as barriers to collaboration between these sectors. The session explores how differing IP strategies, ownership rights, and licensing expectations can hinder innovation and impede the development of fruitful partnerships. By addressing these challenges, the session focuses on finding solutions that create mutually beneficial frameworks for collaboration.

- Moderator: Priya Sinha Cloutier (UCSD)
- Talk 1: (25 min) Shelley Lynn Couturier (LANL)
- Talk 2: (25 min) Toshi Tajima (UCI)
- 10 min Q&A

10:30 - 10:45 a.m. **Break**

10:45 - 11:45 a.m. **Partnering with the National Laboratories (Panel)**

This session discusses the pathways for fostering collaboration between the academic community and the national laboratories.

- Moderator: Mike Campbell (UCSD)
- Talk 1: (10 min) Eric Schwegler (LLNL)
- Talk 2: (10 min) Bradley Beck (LANL)
- Talk 3: (10 min) Bill Johansen (LBNL)
- 30 min Q&A session

11:45 a.m. - 12:45 p.m. **Networking Lunch**

12:45 - 3:15 p.m. **Breakout Sessions**

- Materials Under Extreme Conditions (Tammy Ma and Jaime Marian)
  - In-person: Main Auditorium (green name badge sticker)
  - Virtual: https://ucsd.zoom.us/j/94929005307?pwd=6UFF7eRjyM77PoVb4nA5xKUI0LbhXx.1
    - Meeting ID: 949 2900 5307 and Password: 800224
- Tritium Breeding (John Kline and Mike Campbell)
  - In-person: Room E145 (blue name badge sticker)
  - Virtual: https://ucsd.zoom.us/j/99837797151?pwd=dbUzG8QfJBpKPF7rzlheC7SHBK7aL9.1
    - Meeting ID: 998 3779 7151 and Password: 961842
- Radiation Hardened Electronics for Fusion Diagnostics (Lee Bernstein and Bruce Schumm)
  - In-person: Synthesis Center Room E143 (orange name badge sticker)
  - Virtual: https://ucsd.zoom.us/j/94720261285?pwd=wmR7DpkcJqMRJjsHi6TWpZF7JwuUq3.1
    - Meeting ID: 947 2026 1285 and Password: 260254

3:15 - 3:30 p.m. **Break**

3:30 - 4:30 p.m. **Report Out from Breakout Sessions**

- Moderator: Franklin Dollar (UCI)
- Each session moderator will take 10-15 min to share the discussion

4:30 - 5:00 p.m. **Next Steps**

- Farhat Beg

5:00 p.m. **Conference Ends**

Appendix: Organizing Team, Invited Speakers, and Workshop Attendees

First Name	Last Name	Career Stage	Email	Institution	Workshop Role
Felicie	Albert	Lab Staff Scientist	albert6@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Alexey	Arefiev	Full Professor	aarefiev@ucsd.edu	UC San Diego	Attendee
Prab	Bandaru	Full Professor	pbandaru@ucsd.edu	UC San Diego	Attendee
Saumyabrata	Banerjee	Lab Senior Staff Scientist	banerjee9@llnl.gov	LLNL	Attendee
Debra	Bass	Research Communications Director	dbass@ucsd.edu	UC San Diego	Attendee
Bradley	Beck	Student	beckj@lanl.gov	Los Alamos National Laboratory	Attendee
James	Beck	Lab Senior Staff Scientist	beckj@lanl.gov	Los Alamos National Laboratory	Speaker
Farhat	Beg	Full Professor	fbeg@ucsd.edu	UC San Diego	Attendee
Lee	Bernstein	Full Professor	labernstein@lbl.gov	UC Berkeley/LBNL	Attendee
Camille	Bibeau	Lab Senior Staff Scientist	surfingday101@gmail.com	Lawrence Livermore National Laboratory	Attendee
Mike	Campbell	Full Professor	mike.campbell.sd8@gmail.com	UC San Diego	Speaker
Penghui	Cao	Associate Professor	caoph@uci.edu	UC Irvine	Speaker
Edwin	Casco	Grad Student	casco2@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Renkun	Chen	Full Professor	rec001@ucsd.edu	UC San Diego	Speaker
Lifang	Chiang	Staff	Lifang.Chiang@ucop.edu	UCOP	Attendee
Woon-Seng	Choong	Lab Staff Scientist	wschoong@lbl.gov	Lawrence Berkeley National Laboratory	Attendee

Priya	Cloutier	Staff	pcloutier@UCSD.EDU	UC San Diego	Speaker
Shelley Lynn	Couturier	Lab Staff Scientist	shelley@lanl.gov	Los Alamos National Laboratory	Speaker
David	Crandall	Staff	crandalldh@gmail.com	University of California	Attendee
Xiaofan	Cui	Assistant Professor	cuixf@seas.ucla.edu	UCLA	Attendee
Artur	Davoyan	Associate Professor	davoyan@seas.ucla.edu	UC Los Angeles	Attendee
Ahmed	Diallo	Lab Staff Scientist	ahmed.diallo@hq.doe.gov	ARPA-E	Attendee
Franklin	Speaker	Full Professor	fdollar@uci.edu	UC Irvine	Attendee
Xiangfeng	Duan	Full Professor	xduan@chem.ucla.edu	UCLA	Attendee
Thomas	Dugger	Staff	Thomas.Dugger@ucop.edu	UCOP	Attendee
Eric	Duoss	Lab Senior Staff Scientist	duoss1@llnl.gov	LLNL	Attendee
William	Dyer	Staff	wdyer@ucsd.edu	UC San Diego	Attendee
Bassem	El-Dasher	Lab Senior Staff Scientist	eldasher2@llnl.gov	Lawrence Livermore National Laboratory	Speaker
Heather	Erpenbeck	Lab Senior Staff Scientist	hawk14@lanl.gov	Los Alamos National Laboratory	Attendee
Roger	Falcone	Full Professor	rwf@berkeley.edu	UC Berkeley	Attendee
Jonathan	Forstater	Grad Student	jforstater@ucdavis.edu	UC Davis	Attendee
Massimiliano	Fratoni	Full Professor	maxfratoni@berkeley.edu	UC Berkeley	Speaker
Yichen	Fu	Postdoc	fu9@llnl.gov	LLNL	Attendee
Javier	Garay	Full Professor	jegaray@ucsd.edu	UC San Diego	Speaker
Maurice	Garcia-Sciveres	Lab Staff Scientist	MGarcia-Sciveres@lbl.gov	Lawrence Berkeley National Lab	Speaker
Maitrayee	Ghosh	Postdoc	maitree@slac.stanford.edu	SLAC National Accelerator Laboratory	Attendee

Siegfried	Glenzer	Full Professor	glenzer@slac.stanford.edu	SLAC, Stanford	Attendee
Clément	Goyon	Lab Staff Scientist	goyon1@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Peter	Hosemann	Full Professor	peter.hosemann@gmail.com	UC Berkeley	Attendee
Scott	Hsu	Gov. Offical	scott.hsu@hq.doe.gov	U.S. DOE	Speaker
Chengkun	Huang	Lab Staff Scientist	huangck@lanl.gov	Los Alamos National Lab	Attendee
Victoria	Hypes-Mayfield	Lab Staff Scientist	vhm@lanl.gov	Los Alamos National Laboratory	Speaker
Zabrina	Johal	Industry	Zabrina.Johal@ga.com	General Atomics	Speaker
William	Johansen	Lab Senior Staff Scientist	wejohansen@lbl.gov	Lawrence Berkeley National Lab	Speaker
Boubacar	Kante	Full Professor	bkante@berkeley.edu	UC Berkeley	Attendee
Abby	Kavner	Full Professor	akavner@ucla.edu	UC Los Angeles	Attendee
John	Kline	Lab Senior Staff Scientist	jkline@lanl.gov	Los Alamos National Laboratory	Speaker
Keller	Kramer	Campus Research Scientist	kgkramer@ucdavis.edu	UC Davis	Attendee
Anantha	Krishnan	Other	anantha.krishnan@ga.com	General Atomics	Speaker
David	Larson	Lab Senior Staff Scientist	larson6@llnl.gov	LLNL	Attendee
Keith	LeChien	Industry	keith@pacificfusion.com	Pacific Fusion	Speaker
Dongwook	Lee	Full Professor	dlee79@ucsc.edu	UC Santa Cruz	Attendee
Victoria	Lee	Staff	victoria.e.lee@ucop.edu	UC Office of the President	Attendee
Xiaoliang	Li	Student	Xiaoliang Li <bxlli@ucdavis.edu>	UC Davis	Attendee
Dongyu	Liu	Assistant Professor	dyuliu@ucdavis.edu	UC Davis	Attendee

Vincenzo	Lordi	Lab Senior Staff Scientist	lordi2@llnl.gov	LLNL	Attendee
Neville	Luhmann	Full Professor	ncluhmann@ucdavis.edu	University of California, Davis	Attendee
Tammy	Ma	Lab Staff Scientist	ma8@llnl.gov	Lawrence Livermore National Laboratory	Speaker
Andy	MacKinnon	Lab Staff Scientist	mackinnon2@llnl.gov	Lawrence Livermore National Laboratory	Speaker
Jaime	Marian	Full Professor	jmarian@ucla.edu	UC Los Angeles	Speaker
Alessandro	Marinoni	Assistant Professor	amarinoni@ucsd.edu	UC San Diego	Attendee
Nithin	Mathew	Lab Staff Scientist	mathewni@lanl.gov	Los Alamos National Laboratory	Speaker
Simone	Mazza	Campus Research Scientist	simazza@ucsc.edu	UC Santa Cruz	Attendee
Scott	McCormack	Assistant Professor	sjmccormack@ucdavis.edu	UC Davis	Attendee
Daniel	Mumm	Full Professor	mumm@uci.edu	University of California, Irvine	Attendee
Jeremy	Munday	Full Professor	jnmunday@ucdavis.edu	UC Davis	Attendee
Arish	Naim	Grad Student	anaim@ucdavis.edu	UC Davis	Attendee
SungWoo	Nam	Full Professor	sungwoo.nam@uci.edu	UC Irvine	Attendee
Cody	Noghera	Staff	cnoghera@ucsd.edu	UC San Diego	Attendee
Luis	Ocampo Giraldo	Lab Staff Scientist	Luis.OcampoGiraldo@nnsa.doe.gov	U.S. DOE	Attendee
Daniel	Oropeza	Assistant Professor	oropeza@ucsb.edu	University of California, Santa Barbara	Attendee
Albertine	Oudin	Postdoc	oudin1@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Rene	Padilla	Grad Student	remopadi@ucsc.edu	UC Santa Cruz	Attendee
Aurelien	Perron	Lab Staff Scientist	perron1@llnl.gov	Lawrence Livermore National Laboratory	Attendee

Mai	Phan	Staff	ntp227@ucsd.edu	UC San Diego	Staff Planner
Patrick	Poole	Lab Staff Scientist	poole11@llnl.gov	Lawrence Livermore National Laboratory	Attendee
John	Post	Industry	john@longviewfusion.com	Long View Fusion	Attendee
Robert	Powell	Other	rlpowell@ucdavis.edu	UC Davis	Attendee
Soren	Prestemon	Lab Senior Staff Scientist	soprestemon@lbl.gov	Lawrence Berkeley National Laboratory	Attendee
Andrew	Reddie	Associate Professor	areddie@berkeley.edu	UC Berkeley	Attendee
Christopher	Reis	Grad Student	reisch@berkeley.edu	UC Berkeley/LBNL	Attendee
Sean	Riedel	Grad Student	sriedel@ucsc.edu	UC Santa Cruz	Attendee
William	Riedel	Postdoc	riedel1@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Anne-Marie	Riitsaar	Lab Senior Staff Scientist	riitsaar1@llnl.gov	Lawrence Livermore National Laboratory	Speaker
Paul	Rudy	Industry	paul@bluelaserfusion.com	Blue Laser Fusion	Speaker
Raluca	Scarlat	Full Professor	scarlat@berkeley.edu	UC Berkeley	Speaker
Carl	Schroeder	Lab Senior Staff Scientist	cbschroeder@berkeley.edu	LBNL	Attendee
Bruce	Schumm	Full Professor	baschumm@ucsc.edu	UC Santa Cruz	Speaker
Eric	Schwegler	Lab Senior Staff Scientist	schwegler1@llnl.gov	Lawrence Livermore National Laboratory	Speaker
Raspberry Antonia	Simpson	Lab Senior Staff Scientist	simpson56@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Ken	Skulina	Lab Senior Staff Scientist	kenskulina@gmail.com	Lawrence Livermore National Laboratory	Attendee
Joseph	Spears	Lab Senior Staff Scientist	spears20@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Alexander	Spokoyny	Full Professor	spokoyny@ucla.edu	UC Los Angeles	Attendee

Rebecca	Stanek-Rykoff	Campus Research Scientist	rstanek@ucop.edu	UC Office of the President	Speaker
Anika	Stein	Industry	anika@caminno.energy	Caminno Energy Inc	Speaker
Thomas	Strohmer	Full Professor	strohmer@math.ucdavis.edu	UC Davis	Attendee
David	Strubbe	Associate Professor	dstrubbe@ucmerced.edu	UC Merced	Attendee
Toshiki	Tajima	Full Professor	ttajima@uci.edu	UC Irvine	Speaker
Holly	Trellue	Lab Senior Staff Scientist	trellue@lanl.gov	LANL	Attendee
Mani	Tripathi	Full Professor	smani@ucdavis.edu	UC Davis	Attendee
Devon	Tolliver	Staff	dntolliver@ucsd.edu	UC San Diego	Staff Planner
Eleanor	Tubman	Assistant Professor	e.r.tubman@berkeley.edu	UC Berkeley	Speaker
George	Tynan	Full Professor	gtynan@ucsd.edu	UC San Diego	Speaker
Osita	Udekwu	Campus Research Scientist	IK.Udekwu@ucop.edu	UC Office of the President	Attendee
Bruno	Van Wonterghem	Lab Senior Staff Scientist	vanwonterghem1@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Jean-Luc	Vay	Lab Senior Staff Scientist	jlvay@lbl.gov	Lawrence Berkeley National Laboratory	Attendee
Alan	Wan	Lab Senior Staff Scientist	alan.wan@ucop.edu	UC Office of the President	Attendee
Xizheng	Wang	Assistant Professor	xizhengw@uci.edu	UC Irvine	Attendee
Yong	Wang	Lab Senior Staff Scientist	yqwang@lanl.gov	Los Alamos National Laboratory	Attendee
Jeph	Wang	Lab Senior Staff Scientist	zwang@lanl.gov	Los Alamos National Laboratory	Attendee
Anna	Ward	Full Professor	anna.ward@ucop.edu	UC Office of the President	Attendee
Ian	Webster	Other	iwebster@ucsd.edu	University of California San Diego	Attendee

Xishuo	Wei	Campus Research Scientist	xswei@uci.edu	UC Irvine	Attendee
Paul S.	Weiss	Full Professor	psw@cnsi.ucla.edu	UCLA	Attendee
Scott	Wilks	Lab Senior Staff Scientist	wilks1@llnl.gov	Northwind contract with LLNL	Attendee
Weronika	Wolszczak	Lab Staff Scientist	wwols@lbl.gov	LBNL	Attendee
Mary	Woollen	Grad Student	mjwoollen@msn.com	Longview Energy Fusion	Attendee
Frank	Wuerthwein	Full Professor	fkw@physics.ucsd.edu	UC San Diego	Attendee
Glen	Wurden	Lab Senior Staff Scientist	wurden@lanl.gov	Los Alamos National Laboratory	Attendee
Xiaoxing	Xia	Lab Staff Scientist	xia7@llnl.gov	Lawrence Livermore National Lab	Attendee
Jasmine	Yang	Grad Student	jasminey@g.ucla.edu	UC Los Angeles	Attendee
Amani	Zalzali	Campus Research Scientist	amani.zalzali@ga.com	General Atomics	Attendee
Mingwei	Zhang	Assistant Professor	mwwzhang@ucdavis.edu	UC Davis	Attendee
Jian-Xin	Zhu	Lab Senior Staff Scientist	jxzhu@lanl.gov	Los Alamos National Laboratory	Attendee
Ben	Zhu	Lab Staff Scientist	zhu12@llnl.gov	Lawrence Livermore National Laboratory	Attendee
Yilun	Zhu	Associate Professor	amzhu@ucdavis.edu	University of California, Davis	Attendee

Appendix: Workshop Photo