Monday Morning, November 4, 2024

Quantum Science and Technology Mini-Symposium
Room 123 - Session QS1+VT-MoM

Vacuum Systems for Quantum Applications

Moderators: Freek Molkenboer, TNO Science and Industry, the Netherlands, **Russell Gleason**, Infleqtion, **Corey Rae McRae**, National Institute of Standard and Technology, **David Pappas**, Rigetti Computing

8:15am **QS1+VT-MoM-1 High-Precision, Four-Way Comparison of Three Cold Atom Vacuum Standards and an Orifice Flow Standard**, ***Stephen Eckel****, D. Barker, J. Fedchak, J. Scherschligt,* National Institute of Standards and Technology (NIST)

The cold atom vacuum standard (CAVS) is the first primary standard and sensor for vacuum in the ultra-high vacuum regime and below. By measuring the loss rate of ultra-cold atoms from a conservative magnetic trap, the CAVS infers the pressure of the surrounding vacuum from first principles calculations of the scattering cross section. Various CAVSs have been constructed or are under construction, with different sensor atoms, sizes, and technical capabilities. In 2023, we reported the first comparison of two CAVSs – a laboratory-sized version based on ^{87}Rb and a portable version based on ^{7}Li – to a traditional vacuum metrology apparatus, an orifice flow standard. This initial experiment showed agreement between all three at roughly the 2 % uncertainty level. Here, we report a comparison between three different CAVSs – a laboratory-sized version that can use either ^{7}Li or ^{87}Rb and a portable version that uses ^{7}Li – and our orifice flow standard. We anticipate our new comparison will have total uncertainties < 1 %. In combination with other studies, our results represent a stringent test of quantum mechanical scattering theory.

8:30am **QS1+VT-MoM-2 Vacuum Based Quantum Technology with Aluminum Alloys for Space Applications**, ***Klaus Bergner****, F. Löwinger, C. Gruber, L. Gerlach, S. Hüttl, L. Axtmann, A. Trützschler, J. Hertel,* VACOM, Germany*; J. Schneider, L. Kanzenbach, T. Schmidt, S. Wieland, D. Richter,* Fraunhofer Institute for Machine Tools and Forming Technology IWU, Germany*; J. Grosse, M. Warner, M. Elsen,* ZARM Center of Applied Space Technology and Microgravity, Germany

The advancement of quantum technologies has opened new horizons for space applications with capabilities in communication and metrology. This talk explores the potential of vacuum-based quantum technology utilizing aluminum as a pivotal material to enabling access to a wide range of robust and miniaturized turn-key solutions. Vacuum systems used in these quantum physics package solutions often require low form factors, low weight as well as robust and economic design combined with a low magnetic susceptibility and low outgassing rates. But current first demonstrators mainly rely on expensive, bulky, fragile, and unique solutions.

To overcome these limitations, these systems demand the miniaturization as well as increased reliability of used vacuum systems. Optimization and up-scaling of manufacturing processes is key to distinguish competitive technologies for use in commercial applications. One key factor of this approach could be the use of aluminum alloys as base material of vacuum systems. An advantage of aluminum is simpler processing during manufacturing and the associated simpler miniaturization approach. However, the use of aluminum-based ultra-high vacuum (UHV) systems for space applications has not been qualified, nor have the effects of static and dynamic mechanical loads and temperature fluctuations been researched. Due to the complexity of this qualification work, in this joint paper we present the effects of mechanical and thermal influences on the critical system components - the releasable ConFlat (CF) sealing technologies.

The mechanical load of aluminum UHV CF sealing was characterized within a cooperation between Center of Applied Space Technology and Microgravity in Bremen and VACOM. The talk shows results of leakage rate due to static loads. In addition, a disadvantage of aluminum is the temperature limitation of only 120 °C. Within the cooperation between Fraunhofer Institute IWU in Chemnitz and VACOM it was possible to raise this limit up to 200 °C with our newly developed aluminum UHV CF sealing technology. Both results demonstrate the high temperature and mechanical stability of aluminum related CF sealing technology. In summary, this talk is intended to understand the demands of quantum space technology for vacuum systems and allows to develop a proper design of space suitable commercially viable solutions.

8:45am **QS1+VT-MoM-3 Compact UHV Technology for Quantum**, ***Alex Kato****,* IonQ **INVITED**

UHV systems for quantum technology (E.g. sensors, computing) can be made smaller by moving away from conventional vacuum parts. I will review several ways in which size, weight, and power can be significantly reduced without sacrificing on desired system performance. This requires moving away from conventional vacuum components, such as off the shelf conflat flanges and windows, feedthroughs, and gauges.

9:15am **QS1+VT-MoM-5 Quantum-Based Sensors and Standards with the NIST on a Chip Program**, ***Jay Hendricks****,* NIST*; B. Goldstein,* NIST-Gaithersburg

The NIST on a Chip program (NOAC) is briefly introduced as a forward-looking vision of the future of measurement science.The world-wide redefinition of units that occurred on May 20th, 2019, has opened new ways to think about metrology under a "zero-chain-traceability" paradigm.Next generation quantum-based sensors and standards, based on physical constants of nature, are briefly introduced, for pressure, vacuum, mass and more.The re-definition of the SI units enables new ways to realize the units for the kelvin, mass, and therefore the pascal. A new way to realize the pascal is exciting for vacuum technology (VT), will lead to other exciting applications. These quantum-based systems; however exciting, do raise new challenges and several important questions: Can these new realizations enable the size and scale of the sensor to be miniaturized to the point where it can be imbedded into everyday products?What will be the role of metrology institutes in this new ecosystem of measurement?Where will these new quantum-based systems go and what will they do? This talk will begin to explore these important questions.

9:30am **QS1+VT-MoM-6 3D Printed Ion Traps for Quantum Computation**, ***Kristin Beck****,* Lawrence Livermore National Laboratory **INVITED**

Trapped atomic ions are one of the leading qubit candidates for quantum computing. The fidelity of quantum gates and the noise performance of a quantum processor built on this platform depends on the degree of isolation between the classical environment and the ions. One leading noise source is electric field noise. Additive manufacturing has introduced the possibility of generating accurate, replicable and scalable ion traps with geometries that promise to reduce sensitivity to this noise source. In this talk, I will describe miniaturized RF Paul traps that we have fabricated at LLNL using high-resolution 3D printing approach based on two-photon polymerization and share the results of initial tests.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Vacuum Technology
Room 121 - Session VT1-MoA
History of Vacuum Technology

Moderators: Marcy Stutzman, Jefferson Lab, **Alan Van Drie**, TAE Technologies

1:30pm **VT1-MoA-1 Advancements Through the Ages: The Evolution of Vacuum Technology***, **Kurt Lesker IV**,* Kurt J. Lesker Company*; G. Vergason,* Vergason Technology **INVITED**

In this informative presentation, **Kurt J. Lesker IV** and **Gary Vergason** delve into the fascinating journey of vacuum technology. From its humble beginnings to cutting-edge innovations, they explore the pivotal role vacuum science plays in diverse fields. With historical milestones of time, technology, and industry, they discuss how vacuum technology has shaped semiconductor manufacturing, aerospace research, and sustainable energy production. Join them as they unravel the secrets behind vacuum technology and the companies that laid the foundation. Please join us!

Vacuum Technology
Room 121 - Session VT2-MoA
Measurement, Partial Pressure, and Gas Analysis

Moderators: Marcy Stutzman, Jefferson Lab, **Alan Van Drie**, TAE Technologies

2:00pm **VT2-MoA-3 Monitoring Chamber Health with an Optical Plasma Gauge***, **Martin Wüest**, S. Kaiser,* INFICON AG, Liechtenstein

Leak testing is a common task in the daily laboratory routine. There are simple but lengthy procedures available to test for leaks, for example the rate-of-rise method. To check if a gas such as water or oxygen is below a certain concentration is often done just by waiting for a time that has been determined by experience. More powerful methods are also available such as mass spectrometers, in particular residual gas analyzers, or dedicated leak detectors. However, they tend to be expensive, are often not very easy to operate, and operate at low pressures. Alternative methods exist such as optical emission spectrometer. They tend to be bulky and extracting robust information is not that easy and below a certain pressure there is not enough light available to analyze.

We have now developed a compact optical plasma gauge to address the questions and shortcomings mentioned above. It combines a gas type monitoring optical plasma sensor with a total pressure sensor. Its design is optimized to allow a gas detection measurement in the range between 10^{-7} and 5 hPa. The gauge allows for the detection of gases such as oxygen, nitrogen, hydrogen or argon in–situ or in a rate of rise leak testing. Above 20 hPa the plasma generation is switched off in order to prevent plasma damage in the sensor. The total pressure sensor operates from 10^{-5} Pa to atmosphere. Discharge pressure is known to play a substantial role in the various competing collisional excitation and de-excitation processes that occur in the plasma. The measured optical spectrum is convoluted with the independent total pressure data to provide higher accuracy. The intelligence implemented directly on the gauge automatically configures the optimal measurement setting in order to ensure easy integration and optimized signal-to-noise ratio. Impurities > 10 ppm can be detected.

2:15pm **VT2-MoA-4 Design and Construction of a Fixed Length Optical Cavity (FLOC) Pressure Calibration Standard for Calibration of Military and Commercial Aircraft***, **Jacob Ricker**, K. Douglass, J. Hendricks, T. Bui,* NIST

NIST has constructed several Fixed Length Optical Cavity (FLOC) pressure standards based on gas refractivity and shown that they are effective at measuring absolute pressure [1]. The US Air Force has recently funded development of these standards for the support of their Air Data Calibration Systems. These Air Data Systems provide calibration for altimeters and air speed indicators and traceability of these sensors is crucial for all operational military and commercial aircraft. The current US airspace requirements dictate every aircraft be calibrated at least every 2 years with a device that has an accuracy of pressure reading around 0.03% at pressures around 1/10th of atmosphere.

The air force maintains hundreds of portable standards, working standards, and secondary standards worldwide to achieve that goal. Additionally, the Air Force also maintains other high-pressure standards to meet the operational requirements to provide calibration of pressures up to 10,000 kPa. The air force desires a high accuracy, portable standard that operates over the full pressure range using direct traceability via gas refractivity. A portable standard that is based on fundamental constants rather than frequent recalibration can be forward deployed and will save significant time and money for all civilian and military aircraft operators. With a redesigned FLOC, NIST believes it can meet all the requirements with one portable unit. This presentation will describe the design and construction of a new lower cost/robust/portable calibration system capable of calibrating gas pressure sensors over the entire range of 1 Pa to 10 MPa.

References:

[1] https://doi.org/10.1016/j.measen.2021.100286.

2:30pm **VT2-MoA-5 Analysis and Adaptability of the ITER Diagnostic Residual Gas Analyzer Vacuum System***, **Brendan Quinlan**, C. Marcus, J. Perry, C. Smith III, C. Klepper, T. Biewer,* Oak Ridge National Laboratory **INVITED**

The composition of exhaust gases in the divertor region is a critical measurement for long pulse devices like ITER. This measurement will provide important information for areas such as fuel-cycle processing and plasma heating [1]. The ITER Diagnostic Residual Gas Analyzer (DRGA) is well suited to make these measurements because it is a multi-sensor diagnostic system capable of resolving isotopic compositions of hydrogen and helium as well as other heavier elements and compounds [1]. The DRGA will sample a slip stream of gas from the cryogenic pump duct via a sampling pipe that is approximately 7 meters in length and 70-100 millimeters in diameter. At the sampling pipe entrance, an orifice is present which creates molecular flow conditions in the entire length of the sample pipe. The sampling pipe has recently been updated to reflect necessary changes in the ITER port cell area. To provide measurements on timescales that are relevant, the DRGA vacuum system conductance must be revisited from [2] to ensure the appropriate response time and pressure can still be achieved. In this work, Molflow+, which is a Test Particle Monte Carlo (TPMC) simulation code, is used to simulate the conductance and assess the impact of the revised pipe routing. In addition to the new pipe routing, a new pumping scheme has been proposed in previous work and will provide the ability for variable pump speed [3, 4], while overcoming limitations of using an inter-stage port for the optical gas analysis [5]. In the event the orifice is restricted over time, the variable pump speed provides the added benefit of adaptability to ensure the appropriate conductance can be maintained. The restricted orifice is simulated using Molflow+ and compared to test data collected from an in-lab prototype. This study provides important guidance for the design of the ITER DRGA and confirm key operational parameters.

[1] C.C. Klepper et al., 2022 *IEEETPS*, 50 (12) 4970-4979

[2] C.C. Klepper et al., 2021 *Fusion Science and Technology*, DOI 10.1080/15361055.2021.1898867

[3] C. Marcus et al., 2024 SVC TechCon, Pending

[4] B.R. Quinlan et al., 2024 *IEEETPS*, DOI 10.1109/TPS.2024.3387443

[5] C.C. Klepper et al., 2017 JINST 12 C10012

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

3:00pm **VT2-MoA-7 Effect of Thermal Transpiration on Calibration of Sapphire-Based Capacitance Manometer***, **Kimihiro Sato**,* Azbil Corporation, Japan

In semiconductor manufacturing, capacitance manometers are generally used for measuring the pressure during deposition or etching. These process gases are highly reactive and often corrosive and the manometers are often heated to 100 to 300 °C to prevent byproduct depositions inside them. Therefore, they are required to have high corrosion resistance and operate at these high temperatures. In order to meet these requirements, we have developed capacitance manometers equipped with a MEMS (Micro-Electro-Mechanical Systems) sensor chip based on sapphire, which has the excellent chemical corrosion resistance and thermostability [1].

Since manometers are often used at high temperatures, they must be calibrated at similar temperature at production. These products are heated to various temperatures depending on the target process, while the reference gauge is kept at a constant temperature (near room temperature) for the production efficiency. In this case, the pressure may be different between the product side and the reference side by thermal transpiration. It occurs when two vessels with different temperatures are connected by a narrow tube and the gas flow is in molecular or intermediate flow regime. Therefore, the difference must be compensated in the calibration process and we correct it based on the formula [2,3].

Conventionally, the instrumental error between the product and the reference gauge had been a typical specification (accuracy) that indicates the performance. In addition, the ISO standard [3] requires that the uncertainty be considered. It improves reliability of measurements and brings benefits to the users. In order to comply the standard, it is essential to consider thermal transpiration which is one of the uncertainty factors.

Since the uncertainty of the formula [2,3] is unknown, we studied the effect in the productional facility by comparing experimental and simulated results. In the experiment, the pressure difference between the product side and the reference gauge side was measured. In the simulation, the temperature distribution of each part in the environment was obtained by thermal analysis, and the pressure distribution was obtained by Monte Carlo direct simulation (DSMC-Direct Simulation Monte Carlo). We show the results and consideration of the two efforts.

[1] T. Ishihara, Upgrading a sapphire-based capacitance manometer for reduced size and enhanced anti-deposition characteristics, azbil Technical Review, April 2023.

[2] T. Takaisi and Y. Sensui: Trans. Faraday Soc., 59 (1963) 2503.

[3] ISO 20146:2019, Vacuum technology — Vacuum gauges — Specifications, calibration and measurement uncertainties for capacitance diaphragm gauges.

3:15pm **VT2-MoA-8 Measurements of Electrode Temperatures in the Standardized Ion Reference Gauge***, **Janez Setina**,* Institute of Metals and Technology, Slovenia

A consortium of European National metrology institutes and industrial partners has recently developed a new type of reference ionization vacuum gauge. It is distinguished by its well-known sensitivity and excellent temporal stability, which is the result of straight electron trajectories. Electrons flying through the ionization volume have practically the same path lengths, so the probability of ionization of gas molecules is almost the same for all electrons [1]. The novel Ion Reference Gauge is on its way to standardization of electrode system configuration in ISO TS 6737.

The source of electrons in the gauge is the thermionic cathode, which heats the surrounding surfaces with thermal radiation. Therefore, the ionization cell has a higher temperature than the temperature of the vacuum system in which we want to accurately measure the gas pressure. In non-isothermal systems at low pressures (in the molecular regime), due to the so-called phenomenon of thermal transpiration, the pressure in parts with different temperatures is not the same.

In our research, we measured the temperatures of individual electrodes in the vicinity of the thermionic cathode with the aim of evaluating the influence of the phenomenon of thermal transpiration on the sensitivity of the gauge. In this talk, we will present the experimental setup and the obtained results.

[1] Jousten K, et all, Electrons on a straight path: A novel ionisation vacuum gauge suitable as reference standard, Vacuum 189, (2021), 110239

3:30pm **VT2-MoA-9 Calibrations of Spinning Rotor Gauges Towards International Comparison of Vacuum Standards***, **Yoshinori Takei**, H. Yoshida,* AIST, Japan

With the advancement of the semiconductor industry and the transition to a hydrogen energy society, the demand for vacuum measurement has surged. In such circumstances, the spinning rotor gauges (SRG) has garnered attention as one of the most accurate vacuum gauges capable of measuring the vacuum pressure range from 0.1 mPa to 1 Pa. In metrology field, the SRGs have been used as a reference standard for many years.

In national metrology institutes around the world, several vacuum standards such as static expansion system, optical pressure standard and orifice-flow method system are managed for the calibration of vacuum gauges like SRGs, diaphragm gauges, and ion gauges. These standards are based on physical principles, and their uncertainties are evaluated in each metrology institute. For instance, the static expansion system in Japan calibrates SRGs with a relative expansion uncertainty of 0.28% (k=2) [1]. Furthermore, this uncertainty is expected to improve further by combining static expansion system with the optical pressure standard [2]. To verify the consistency of uncertainty, national metrology institutes compare their vacuum standards. Since transporting the vacuum standards themselves for direct comparison is challenging, the same vacuum gauge (SRG) is transported. The calibration results for the same gauge with the vacuum standard of each country are compared. However, the reproducibility of SRG poses a challenge in this process. While SRGs are excellent vacuum gauges, their values may change by about 1 % during transportation, limiting the comparison accuracy of vacuum standards. Therefore, for enhancing the accuracy of international comparison of vacuum standards in the future, careful selection of superior SRGs and in-depth understanding of calibration conditions are essential.

Until recently, only one manufacturer produced SRGs. However, another company has recently entered the market, manufacturing and selling SRGs. There are some differences in the specifications of these SRGs. In this study, we experimentally confirmed the differences when using the SRGs for metrological purposes. Additionally, with the recent publication of ISO 24477 concerning the calibration of SRGs, which describes two calibration methods, we experimentally confirmed the differences. We also conducted calibrations by varying conditions such as the rotation frequency of the rotor, the rotor itself, and the mounting angle of the flange. These experimental results are shown in this presentation.

[1] Yoshinori Takei et.al., Vacuum, 187, 110034, (2021).

[2] Yoshinori Takei et.al., Measurement: Sensors, 22, 100371, (2022).

4:00pm **VT2-MoA-11 Vacrysim - Modeling Noise from Residual Gas for Cryogenic Interferometry***, **Henk Jan Bulten**,* Nikhef, Netherlands*; V. Erends,* High Voltage Engineering Europa, Netherlands*; B. Munneke,* Nikhef, Netherlands **INVITED**

Since 2015, gravitational waves (small ripples in the fabric of spacetime) that arose from the mergers of black holes and/or neutron stars have been measured with the large, ultra-precise interferometers of LIGO and Virgo. Einstein Telescope (Fig. 1) is a plan for a next-generation gravitational-wave observatory with a strain sensitivity of 10^{-25}, allowing for precision tests of general relativity, cosmology and astrophysics. In order to reduce thermal noise, Einstein Telescope will operate with mirrors at cryogenic temperatures. This poses new stringent criteria on the vacuum system. Residual gas introduces noise via optical path length changes in the arms, Brownian motion of the mirrors, and ice build-up on the mirror coatings. Einstein Telescope requires residual gas pressures of below 10^{-10} hPa in the (10-km long) arms, and better around the cryogenic mirrors.

The design of the Einstein telescope requires accurate modeling of migration of molecules through the vacuum system, which contains complicated metal support structures and thermal shields, electronic devices with polymer cable mantles, silicon mirrors, etc. We want to model the outgassing and incident particle rate of all components as a function of time. This outgassing is strongly dependent on the history and on the applied temperatures.

Generally, heat flow and molecular flow predictions in finite-element based toolkits like Molflow or Comsol are calculated for steady-state;:adsorption/desorption from the surfaces is taken as constant. However, to numerically calculate the time evolution of the system and see where the molecules deposit/evaporate one needs millions of time steps in which the coupled equations are solved. We developed a simulation toolkit, vacrysim, that is capable of this feat thanks to separating the time-independent tracking information from the time-dependent material properties information. Vacrysim can track thermal radiation and molecular paths and subsequently solve for conductive and radiative heat flow, and adsorption/desorption. Using vacrysim one can model the performance of cryogenic designs in terms of cool-down times, ice build-up and pump-down times. For instance one can predict the ice build-up on the mirror, and the time-dependence of the water distribution in a kapton-coated cable, after venting and evacuating a part of the vacuum system.

In this presentation we will address vacuum requirements for cryogenic interferometry and discuss the vacrysim toolkit.

Vacuum Technology
Room 121 - Session VT3-MoA

Leaks, Flows, and Material Outgassing

Moderators: Marcy Stutzman, Jefferson Lab, **Alan Van Drie**, TAE Technologies

4:30pm **VT3-MoA-13 Practical Considerations When Using Low Carbon Steel for Extreme High Vacuum Applications***, **Aiman Al-Allaq,*** Old Dominion University*; M. Mamun, M. Poelker,* Thomas Jefferson National Accelerator Facility*; A. Elmustafa,* Old Dominion University

The very low outgassing rate of low-carbon steel – of the order 1000 times smaller than degassed stainless steel - suggests this material could provide the means to routinely achieve significantly better vacuum, well into the extreme high vacuum range. At Jefferson Lab, low carbon steel will be used for the construction of a new spin-polarized electron source. The improved vacuum we expect to achieve will ensure reliable and long-lasting beam delivery at milliampere beam currents, which is roughly one hundred times more current than today's state-of-the-art spin-polarized electron sources provide. However, reaping the full benefit of low-carbon steel depends on practical matters, namely, limiting the surface area of all non-low-carbon steel materials required to build a functional photogun. For example, the pressure reduction expected in a photogun with a surface area composed of just 10% stainless steel (e.g., the surface area contribution from an all-metal gate valve leading to the accelerator beamline) would be just a factor of ten, and not the factor of 1000 suggested by the ratio of outgassing rates. This submission describes outgassing rate measurements of chambers built using low-carbon steel and stainless steel and the ultimate pressures achieved for vacuum systems composed of low-carbon steel and stainless steel and pumped using a non-evaporable getter and ion pump. A factor of ten pressure reduction was observed in the system with a surface area dominated by low-carbon steel, consistent with MolFLow+ predictions based on measured outgassing rates. Lower pressures are expected when more thoughtful steps are taken to limit the amount of surface area of non-low carbon steel material.

4:45pm **VT3-MoA-14 Systematic Approach for Ultra-Clean Vacuum***, **Freek Molkenboer,*** TNO Science and Industry, the Netherlands

The demand for smaller, faster, higher accuracy and lower noise levels continues in the scientific field and applications i.e. microchip manufacturing. Contamination concerns that use to be not a concern now suddenly are. This also applies for the vacuum environment. To ensure the desired cleanliness a systematic approach is advised.

During the definition phase of a system, it is important to clearly define the needs of the system. A common methodology within systems engineering is using the v-model. After defining the needs of the system, the design and realisation phase of the system starts. The v-model ends with the validation that the needs are satisfied.

With the increasing cleanliness demands adding cleanliness needs or requirements during the definition phase will increase the successful outcome and will save overall cost.

In my presentation I will show the increase of complexity of a product when cleanliness is key for performance. For this I will use the design of a reflectometer that will be used to measure EUV reflection as a real life example.

5:00pm **VT3-MoA-15 Optimal Load Lock Pressure Measurement Technology?***, **Tim Swinney**, G. Brucker,* MKS Instruments, Inc., Pressure and Vacuum Measurement Group **INVITED**

Transferring silicon wafers from ambient atmosphere into a semiconductor manufacturing cluster tool is a critical step that must be carefully sequenced and controlled. Every wafer must be (1) individually loaded into a load lock chamber through a loading port, (2) sealed against ambient pressure, (3) pumped down to a target pressure level and (4) transferred into a buffer chamber through a transfer port. Once at vacuum, the wafer can then be cycled across multiple process chambers. The same Load Lock chamber is then accessed, operated in a venting sequence, to return the wafer to ambient pressure conditions.

Careful control of differential pressures-i.e. ambient-to-load lock and load lock-to-buffer chamber, during pump-down and venting processes is critical to assure not only the compatibility of pressure levels between chambers and also to minimize the lifting and transport of damaging particles into the tool. Load lock pressure gauges, specifically designed to monitor and control both pump down and vent operations, are preferred pressure sensors for the Semiconductor industry. Load lock pressure gauges provide both differential and absolute pressure readings with accuracy levels required to ensure particles are not disturbed during wafer-load, -pump down, -transfer and -venting processes. Particle control has become critical as feature dimensions continue to drop.

MKS Instruments, Inc. offers multiple pressure measurement instruments that can assist Load Lock operation; however, its exclusive line of compact gauges delivering simultaneous absolute and differential pressure monitoring capabilities has rapidly become a new industry standard. With MEMS technology, two-sensor combination-Differential Piezo resistive diaphragm (PRD) plus Pirani sensor- and proprietary pressure calculation algorithms these sensors can provide accurate differential measurements between ambient and load lock chambers unmatched by any other multi-sensor combination in the market. Their ability to track ambient as well as chamber pressures allows particle-safe pump-downs and vents even after sudden changes in ambient pressure. The pressure measurement technologies in these device as well as planned future enhancements will be discussed. Interface options, calibration routines and control algorithms built into the load-lock sensors will also be described in detail.

Vacuum Technology
Room 121 - Session VT1-TuM

Vacuum Technology for Semiconductor
Moderators: Sol Omolayo, Lawrence Berkeley National Laboratory, **Jacob Ricker**, NIST

8:00am **VT1-TuM-1 New Advanced Home-Built Reactor for in-Situ Studies of ALD and ALE**, ***Cristian van Helvoirt**, C. van Bommel, M. Merkx, J. Zeebregts, F. van Uittert, E. Kessels, A. Mackus,* Eindhoven University of Technology, Netherlands

In the field of nanotechnology atomic scale processing is getting more and more advanced and requires in-depth understanding of the reaction mechanisms of deposition and etching processes. In-situ diagnostics are essential for accomplishing this. Within our group a reactor is designed and installed capable for in-depth study of atomic layer deposition (ALD) and atomic layer etching (ALE) surface reactions, with the focus on infrared spectroscopy (IR) at sub-monolayer sensitivity.

In-situ IR spectroscopy has proven itself to be a powerful tool to study the mechanism of ALD and ALE. [1,2]. To improve sensitivity into the sub-monolayer regime, the technique becomes dependent on the substrate material. Solutions can be found using pressed powder, ATR (attenuated total reflection) for dielectrics or grazing incidence RAIRS (Reflection Absorption Infra-Red Spectroscopy) for metals. The wish to be able to perform this type of diagnostics in one tool made us design a new reactor with the capability for in-situ transmission and reflection IR spectroscopy. For this versatility the back flange is designed to be able to load samples vertically (for transmission) and horizontally (for reflection).

Based on the experiences within our group and the field, the system has a hot wall reactor that is equipped with a loadlock, has the capability to bias the substrate for ion energy control and has a cabinet to mount up to eight different precursor/inhibitor bubblers. The system is pumped down using a turbo-molecular pump backed with roughening pump, to be able to reach high vacuum levels. As an extra feature the setup has the option to install up to four plasma, light or particle sources at a 45-degree angle which is to expand the research in the field of surface science and plasma physics. These ports also give the capability for extra in-situ diagnostics, e.g. optical emission spectroscopy (OES), quadrupole mass spectroscopy (QMS), quartz crystal microbalance (QCM). This contribution will outline the background, design, and capabilities of this next generation home-built reactor.

[1] Goldstein *et al., J. Phys. Chem. C* **112**, 19530 (2008)

[2] Mameli *et al., ACS Appl. Mater. Interfaces* **10**, 38588 (2018)

8:15am **VT1-TuM-2 Plasma Delayering for Non-Selective Precision Etching**, ***Leonid Miroshnik**, J. Iannello III,* University of New Mexico; *T. Stevens, J. Duree, R. Shul, C. Nakakura, S. Han,* Sandia National Laboratories

Non-selective, high-precision, plasma-assisted delayering provides a robust means for failure analysis of heterogeneously integrated devices. While chemical mechanical planarization (CMP) is often used to planarize different layers, dishing and erosion reduce the use of CMP for high-precision delayering as CMP damages the processed layer of interest. In this work, we are developing a non-selective, material-independent plasma delayering technique that is uniform over large areas, requiring only a single dry etching tool. Argon (Ar) and carbon tetrafluoride (CF4), commonly used in high-volume microchip fabrication, were selected as the etchants of dielectric and metallic surfaces. The addition of methyl acetate (MeOAc) can halt the etching process completely during etching. The relative MeOAc mass flow rate provides fine-tuned control of the precision etching with a well-defined planarization process window. In this talk, we will share our initial understanding of the mechanisms by which the acetate precursors suppress the etching process. Our goal is to scale up the dry etching process for industrial applications.

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government

8:30am **VT1-TuM-3 Improved Thermal Uniformity in Pedestal Heaters Through the Integration of Thermal Pyrolytic Graphite (TPG®)**, ***Matt Gallaugher**, I. Nas, A. Murugaiah, J. Troha, D. Sabens,* Momentive Technologies

Thermal uniformity is a critical metric for pedestal heaters used in semiconductor thin film processing, particularly in chemical vapor deposition (CVD) and atomic layer deposition (ALD). Heaters made of aluminum alloys have a reasonable inherent thermal conductivity (~150 W/mK), but thermal conductivities of stainless-steels and nickel alloys used in higher temperature applications are much poorer (~10-20 W/mK). As a result, stainless steel and nickel alloy heaters have poorer thermal uniformity, unless complex engineering solutions such as multiple heating zones are implemented. A simple alternative is possible: embedding a high thermal conductivity material, such as Thermal Pyrolytic Graphite (TPG®), inside a billet of stainless-steel to passively improve the thermal uniformity of the heater. The unique properties of the TPG® (~1700 W/mK in-plane, ~10 W/mK out of plane thermal conductivity) serve to distribute the heat across the surface of the heater for greater temperature uniformity. The advantage of this “thermally conductive billet” approach is that it can be flexibly integrated into different heater designs, enabling machining on both its bottom surface (heating coils and/or cooling loops) and its top surface (mesas, backside gas, etc.). A simplified schematic of this design is shown in Figure 1. To demonstrate the concept, a stainless-steel billet with embedded TPG® was made into a single zone, 8” heater to reveal the thermal uniformity improvement. Greater than 2x improvement in uniformity was realized, as shown by the variation (standard deviation / average) measured via a thermal camera (Figure 2). In addition, local azimuthal variations were eliminated, leading to a more symmetric profile. These real-world results were used to create a thermal-mechanical model, which was scaled up to conceptual 12" stainless-steel heater designs with both one and two heating zones. The models demonstrated improved thermal uniformity changes in all cases: >2x improvement. Although this work sought to optimize the heater temperature uniformity, the thermally conductive billet and/or the heating pattern could be designed to optimize the wafer thermal uniformity as well, including using two zone temperature control with superior intra-zone thermal uniformity.The integration of TPG® is a key technological path for passively improving the thermal uniformity of pedestal heaters used in more demanding applications.

Vacuum Technology
Room 121 - Session VT2-TuM

Sustainable Energy Production
Moderators: Sol Omolayo, Lawrence Berkeley National Laboratory, **Jacob Ricker**, NIST

8:45am **VT2-TuM-4 Photochemistry and Photocatalysis of Alcohols – Vacuum Technology for Sustainable Chemistry**, ***Moritz Eder**,* TU Wien, Austria; *P. Petzoldt, C. Aletsee, M. Tschurl,* Technical University of Munich, Germany; *J. Pavelec, G. Parkinson,* TU Wien, Austria; *U. Heiz,* Technical University of Munich, Germany **INVITED**

In photocatalysis, light is harvested by semiconductors to utilize its energy for chemical reactions. Despite being highly promising for sustainable chemistry driven by (sun)-light, large-scale applications are still nonexistent due to the low efficiency of these photocatalysts. Screening for more efficient photocatalysts by mixing different powder materials has so far not led to the desired breakthrough.

With a more recent approach based on vacuum technology, photocatalysts can be optimized by observing the chemical and physical processes at the atomic level. To this end, single-crystalline semiconductors with atomically defined surfaces are investigated with different analytical techniques in ultra-high vacuum (UHV) during illumination with light. Since this is a comparably young topic in vacuum technology as well as physical chemistry, I will show the different approaches to the problem as well as the technological requirements and developments which go along with them.

While the investigation of a broad range of semiconductor materials for the bigger picture is still lacking, titania (TiO_2) has been investigated thoroughly as a photocatalyst in the last years. Among other substrates, alcohols have often been used as reactants with very unexpected results. While structurally more complex than common model substrates such as CO or water, alcohols provide a very versatile chemistry. Furthermore, molecular hydrogen can be produced selectively and efficiently by alcohol photocatalysis.

Using alcohols on the $TiO_2(110)$ surface as an example, I will present the tools which have been developed and utilized in UHV to elucidate the photocatalytic processes. I will show the learning process of how photocatalysis on titania works at the atomic level over the last decade. Finally, I will discuss the most recent developments, which aim at designing devices for (near) ambient pressure photocatalysis. The goal is to close the so-called pressure gap between model systems and applied catalysts. This way, one can utilize vacuum technology for the rational design of photocatalytic materials and pave the way for sustainable, light-driven chemistry.

Vacuum Technology
Room 121 - Session VT3-TuM
Novel Vacuum Instrumentation

Moderators: Sol Omolayo, Lawrence Berkeley National Laboratory, **Jacob Ricker**, NIST

9:15am **VT3-TuM-6 Enabling Vacuum Process Monitoring with Time-of-Flight Spectroscopy***, **Marco John**, K. Bergner, S. Hüttl, K. Kirsch, A. Trützschler,* VACOM Vakuum Komponenten & Messtechnik GmbH, Germany

As the complexity of industrial vacuum processes increases, detailed knowledge of the vacuum itself becomes even more important. A crucial aspect to manage this challenge is the importance of fast in-situ monitoring and control of process parameters such as pressure and residual gas composition. Improving process control in this way minimizes production errors, avoids damage to process equipment and ensures longer operating times. The capabilities of hot cathodes and quadrupole mass spectrometers are limited for this complex task, as they can only measure either the total pressure or the gas composition. One answer to this challenge is our novel ion source NOVION®, which combines the well-known technology of time-of-flight spectroscopy with our patented ion trap to an industrially available gas analyzing application.

In this talk we present the fundamental physical principles of the novel ion source and explain the compact combination of time-of-flight spectroscopy with our own patented ion trap. On the one hand we demonstrate the capability of precise total pressure measurements over a wide pressure range. On the other hand, we show the available possibilities to use the novel ion source in partial pressure measurement mode, leak detection and detection of air leaks.

We discuss the advantages and limits in different applications as well as best practices in the field and show the capability to push the principle to its limits at high pressures without compromising the performance or lifetime of the filaments. In addition, we demonstrate a special signal enhancement method to improve the resolution in the near signal-to-noise range.

Vacuum Technology
Room 121 - Session VT4-TuM
Accelerators and Large Vacuum Systems

Moderators: Sol Omolayo, Lawrence Berkeley National Laboratory, **Jacob Ricker**, NIST

11:00am **VT4-TuM-13 Vacuum System for the High Magnetic Field Beamline at Cornell High Energy Synchrotron Sources***, **Yulin Li**,* Cornell University

After a very successful CHESS-U upgrade in 2019, a special new X-ray beamline is currently under development at CLASSE. The new beamline, the High Magnetic Field (HMF) beamline, enables users to study samples under up to 20-Tesla magnetic field, with 4X larger optic access, a factor of 10e4 in the photon flux at photon energy >20 keV. The design and fabrication of vacuum components for the HMF beamline is presented in this talk, including the storage ring modification, the front ends, and a very large end station vacuum system.

11:15am **VT4-TuM-14 Leveraging SLAC Facilities and Expertise to Optimize Vacuum Beamline for LCLS-II Accelerator***, **Giulia Lanza**,* SLAC National Accelerator Laboratory

The success of the Linac Coherent Light Source II (LCLS-II) accelerator critically hinges on the efficient operation of its vacuum beamline, demanding the presence of technical facilities and skilled personnel. This presentation showcases the resources available at SLAC National Accelerator Laboratory (SLAC) tailored to support the vacuum beamline of the LCLS-II accelerator.

The plating shop provides vital support for the cleanliness of components. The brazing and welding expertise at SLAC allows the construction and repair of vacuum beamline infrastructure, fostering resilience and longevity in the face of demanding operational conditions. Multiple bake stations facilitate processing of different components in parallel, ensuring optimal vacuum conditions. Moreover, SLAC's array of cleanrooms tailored to diverse particle-free requirements guarantees the integrity and purity of vacuum components, essential for maintaining operational efficiency and minimizing contamination risks. Rounding out SLAC's capabilities are systems specific for outgassing tests and residual gas analysis, providing the possibilities to test non-standard material and composites.

This presentation illuminates how the integration of SLAC's facilities and skilled workforce supports the vacuum beamline of the LCLS-II accelerator, underpinning its mission to push the boundaries of scientific exploration.

11:30am **VT4-TuM-15 Factors Affecting XHV Polarized Electron Source Lifetime***, **Marcy Stutzman**,* Jefferson Lab*; J. Yoskowitz,* Jefferson Lab, Los Alamos National Lab

The Jefferson Lab polarized electron source utilizes a combination of ion pumps, NEG pumps, and NEG coating to achieve pressures as low as 2x10^-12 Torr. Operational lifetime is primarily limited by residual gas in the system being ionized by the electron beam and accelerating into the photocathode, which is susceptible to ion implantation damage. Recent upgrades to the injector vacuum system include additional pumping in the first 15 meters downstream of the electron gun. Additionally, the anode in the gun has been biased to reduce ion impingement from gas ionized downstream of the anode. We will present a study of the effect of these upgrades, and our efforts to distinguish improvements due to the biased anode from those due to the improved beamline vacuum, including comparison of beamline vacuum modeling and ion implantation simulations.

11:45am **VT4-TuM-16 Vacuum Technology Developments at Daresbury Laboratory for Modern Accelerators***, **Keith J. Middleman**, C. Benjamin, J. Conlon, R. Luff, O. Malyshev, E. Marshall, O. Poynton, D. Seal, L. Smith, R. Valizadeh, S. Wilde,* STFC Daresbury Laboratory, UK

The Vacuum Solutions group at the STFC Daresbury Laboratory has a unique position in that it has the capability to operate and design the vacuum systems for new accelerators whilst maintaining a very active research laboratory looking at many new facets of vacuum design for accelerators.This gives the group the opportunity to develop ideas in the laboratory before implementing them on the accelerator.This paper will present some of the latest accelerator ideas and machines at Daresbury and provide an insight into how some of our laboratory developments are helping improve the vacuum design.

A range of topics will be covered such as:

1. Machine developments – CLARA, FEBE and the vacuum challenge of plasma-wakefield experiments
2. NEG coatings – our latest research
3. Thin films – SRF coating developments
4. Photocathode research – metal and semiconductor cathode developments
5. New cleaning solutions for UHV and XHV
6. In-Kind contributions to major projects, ESS, Hi-Lumi LHC and PIP-II

Vacuum Technology
Room 121 - Session VT1-TuA
Aerospace Research and Applications

Moderators: Giulia Lanza, SLAC National Accelerator Laboratory, **Julia Scherschligt**, National Institute of Standards and Technology

2:15pm **VT1-TuA-1 Gas Analysis and Vacuum Characterization for Space and Lunar Exploration***, Andres Diaz,* INFICON **INVITED**

Mankind is always curious and looking for the next frontier. In recent years there has been a sharp increase in all sorts of space activities, from numerous rocket launches to new space vehicles and landers trying to reach orbit, Moon, Mars, and beyond.National government agencies in charge of space activities like NASA, ESA, ISRO, JAXA, DLR, ASI, ROSCOSMOS, CNSA, etc, and commercial entities like Blue Origin, Space X, ULA, Rocket Lab, Sierra Space, Astra Bigelow, CASC, Astrobotics, Intuitive Machines, etc, are speeding efforts to build rockets, spacecraft, probes, space stations, satellites, telescopes, landers, rovers and even drones, to explore space and planets in a rate never seen before.

This new wave is targeting the Moon as a stepping stone for human exploration. Many missions have been launched or are targeted to be launched in the coming years and this brings a need for sensors and instruments that can measure and characterize either the vacuum surrounding the spacecraft while approaching a planet or moon, or the quality of air inside the cabin when transporting humans, or else deployed onboard a lander or a rover to characterize the lunar atmosphere, its surface and subsurface looking for water and volatiles for in situ resource utilization (ISRU) activities.

There have been many unique successful gas analysis instruments that have been flown into space or landed on planets, such as mass spectrometers (MS) and optical emission spectrometers, providing extremely useful gas composition data and vacuum characterization conditions of the exploration target. Nevertheless, in the same way rockets are now being manufactured with orders of magnitude lower cost by commercial rocket companies, this new wave of exploration requires commercial instruments developed by companies, not government agencies, that can provide time and time again, ready-to-use, space-qualified, cost-effective systems to be carried in any space exploration vehicle when vacuum and gas analysis are necessary.

This presentation provides an overview of the different instruments used in gas analysis and vacuum measurements in space exploration over the years, especially targeting planetary and moon exploration.It also includes the most recent developments of commercial-off-the-shelf (COTS) space-ready mass spectrometer planned to be used in different lander missions through the Commercial Lunar Payload Services (CLPS) initiative as part of NASA ARTEMIS going back to the Moon program, as an example of this new approach to do commercial instrumentation for space applications.

Vacuum Technology
Room 121 - Session VT2-TuA
Vacuum Technology for Fusion Energy

Moderators: Giulia Lanza, SLAC National Accelerator Laboratory, **Julia Scherschligt**, National Institute of Standards and Technology

3:00pm **VT2-TuA-4 ITER Service Vacuum System Client Connections***, C. Smith III,* ***Jared Tippens,*** Oak Ridge National Laboratory

The ITER project has the goal to demonstrate the feasibility of fusion and to advance the scientific and engineering understanding of fusion for future commercial reactors. Nearly five thousand volumes, commonly called “clients”, throughout the ITER facility require vacuum service during operations. This vacuum is provided by seventy-seven distribution boxes around the complex, where “client connections” in the form of stainless-steel tubing bridge the gap between distribution boxes and individual clients.

There is an estimated total of 42 kilometers of 6 mm outer diameter tubing, 2 kilometers of 12 mm outer diameter tubing, and 1 kilometer of 38 mm outer diameter tubing. The size of the tubing is correlated to the volume of the clients needing vacuum service. Most clients throughout the facility are below 50 liters, often taking the form of interspaces of double-contained pipes, valves, and flanges. Many of these client connections have the possibility of containing tritium, a radioactive isotope of hydrogen. This creates the need for the tubing to be capable of handling combinations of pressure, thermal, and seismic loads and for the analysis to validate this.

In addition to the structural qualification of the client connections and their associated supports, several practical challenges exist. The first challenge is routing space constraints, as the majority of areas where the tubing is routed are congested and often require complicated routings to avoid clashes. The bigger challenge is installation, as the tubes are routed with a high packing density and the installers will have limited space to compress fittings or weld tubes together.

A solution has been proposed by US ITER and design is approaching completion for this client connection system. A packaging solution is being implemented for bundles of tubing, and mitigation strategy for thermal loads is underway. An installation plan for the tubing is in progress that will allow the routing of nearly five thousand tubes in a congested environment.

An overview of the Client Connections System and the associated qualification effort will be given. These design details are applicable to other fusion facilities where tritium will be present, particularly for large power plants where vacuum is required on many supporting systems.

3:15pm **VT2-TuA-5 All-Metal Mechanical Pumping Solution Replacing the ITER Cryogenic Regeneration Roughing Pump System***,* ***Jonathan Perry,*** Oak Ridge National Laboratory*; S. Hughes,* ITER Organization, France*; C. Smith,* Oak Ridge National Laboratory

This paper gives an overview of replacing the ITER[1] Cryogenic regeneration roughing pump system with a newly developed all-metal mechanical pumping solution.

The United States Domestic Agency of ITER is responsible for the final design, procurement, and acceptance testing of the ITER roughing pump system (RPS). The current Torus cryopump (TCP) and Neutral Beam cryopump (NBCP) regeneration roughing pump systems are based around Cryogenic Viscous Compressor (CVC) which requires substantial cryogenic infrastructure to be provided, operated, and maintained within the RPS. However, due to advancements in mechanical all-metal vacuum pumps, opportunities from partnerships with various experts in the fusion and tritium communities, in addition to refinement of ITER operational principles, the use of all-metal mechanical pumps to move tritiated gas, is now a potential design solution.

This paper will present an overview of the current configuration, as well as the design history evolution. The paper will then review the main performance requirements for the Cryogenic regeneration roughing system and present results of analytical modeling of the performance of the system using an all-mechanical pump configuration. The paper will also discuss the advantages in progressing the all-mechanical pump option, while outlining remaining testing for this solution and ultimately replacing the current cryogenic configuration.

[1] Nuclear Facility INB-174

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4:00pm **VT2-TuA-8 Exploring Vacuum Technology in Nuclear Fusion: Challenges and Opportunities within STEP Fuel Cycle***,* ***Sophie Davies,*** United Kingdom Atomic Energy Authority, UK*; A. Tarazona,* United Kingdom Atomic Energy Authority (UKAEA), UK **INVITED**

Generating energy through fusion has garnered significant attention from research institutions, government programs, commercial entities, and investors due to its potential to provide virtually unlimited low-carbon and renewable energy supplies. Deuterium and Tritium stand out as the primary fuels for fusion devices, from inertia to magnetic confinement systems, owing to the net fusion energy released in their reaction, despite facing various fundamental and engineering challenges. Vacuum pumping, a critical aspect among these challenges, plays a pivotal role in preventing plasma contamination, minimizing losses through particle collisions with residual gas molecules, and ensuring the overall efficiency of the fusion reaction. This paper provides an overview of the most relevant nuclear fusion devices where vacuum technology plays a crucial role, focusing on the vacuum requirements for experimental Tokamaks. Furthermore, it delves into the challenges associated with vacuum pumping, highlighting its significance for successfully operating fusion power plants. As a case study, the discussion extends to the STEP (Spherical Tokamak for Energy Production) program, elucidating its vacuum challenges and some strategies to address them. This work aims to contribute to understanding the intricate interplay between vacuum technology and nuclear fusion, shedding light on advancements and challenges in this ground-breaking field.

4:45pm **VT2-TuA-11 An Enhanced, High-Vacuum System and Related Testing of Plasma Cell Prototypes for the ITER-DRGA Project***, **Chris Marcus,** T. Biewer,* ORNL*; J. Brindley,* Gencoa, UK*; A. Jugan,* North Carolina State University*; C. Klepper,* ORNL*; P. McCarthy,* Gencoa, UK*; B. Quinlan,* ORNL

The ITER Diagnostic Residual Gas Analyzer (DRGA) performs fusion neutral gas analyses. The ROI comprises low-amu species (1 thru 6), and includes the isotopic profiles of hydrogen and helium [1]. There are challenges in obtaining accurate measurements. First, the method sensitivity must suffice to resolve trace amounts accurately (≤1%). Second, the gas signal must be free of bias caused by the latent presence of these gases to acquire accurate measurements. For the lightest gases, backstreaming a fraction of the pumped gas load can be a source of such latency effects. This phenomena is attributed to modest inertia due to their lowest weight and smallest size. As a result, collisional effects create a reverse flow into the analysis region, which can contaminate the real-time measurement. To fully eliminate this adverse effect, a conductance-limiting device – or orifice – has been installed in the high-vacuum pumping system of the present DRGA prototype. It is intended to eliminate backstreaming by increasing the back pressure within the inter-pump volume (IPV).

An added benefit of the orifice-restricted pumping concept is that the upstream pressure increase is beneficial to the DRGA plasma cell used optical gas analysis. These sensors are attached to the IPV in the present DRGA design. The glow discharges will typically have a brighter light emission with increasing plasma cell pressure. For the DRGA, one of the glow discharge sources being evaluated for this system is a prototype made by Gencoa Limited (UK), which has been designed to exhibit satisfactory immunity to fringing fields, simulated for the tokamak environment. Also, the unique circuitry control for the input power control of the cell, when coupled with the specialized magnetic confinement of the plasma, have optimized the profile shapes of line emissions of interest for these isotopes, of which some emission lines are difficult to deconvolute.

Described herein are two ITER-DRGA related concepts: Vacuum system testing to validate elimination of light gas backstreaming and test results from using the prototype light source and a modified, Penning cathode.

This work was supported by the U.S. D.O.E. contract DE-AC05-00OR22725.

[1] C.C. Klepper et al., 2022 IEEE-TPS 50 (12) 4970

5:00pm **VT2-TuA-12 Design and Development of an Optical Gas Sensor for Fusion Applications***, **Joe Brindley**, P. McCarthy,* Gencoa, UK*; C. Marcus, C. Klepper, B. Quinlan,* ORNL

Fast and accurate neutral gas measurement systems will be critical for the realisation of future deuterium-tritium (D-T) fusion reactors. This is required for the closed loop fuelling cycle of the reactor, where quantities of exhaust fuel gases, consisting primarily of isotopes of hydrogen (H) and helium (He), are monitored in real time.

Typically, quadrupole mass spectrometry (QMS) is employed to measure gas partial pressures, however the very similar mass-to-charge ratios of fusion gas species makes this measurement using QMS extremely challenging. For example, the masses of D_2 and ^{4}He are separated by 0.02 amu. Techniques such as threshold ionisation mass spectrometry can be utilised to separate closely spaced masses, however this method has difficulty resolving low concentrations with adequate speed.

An alternative route, using remote optical emission spectroscopy (ROES), was demonstrated by Klepper et al[1] and this is seen as a promising method for overcoming the inherent mass measurement problem encountered by QMS. ROES involves the generation of a small, remote plasma which is used to excite gaseous species into emitting light, which can then be measured by an optical spectrometer and the gases identified and quantified by their light emission.

Whilst ROES is an extremely promising technique it is not without its challenges for use in fusion applications. Whilst D and ^{4}He light emissions are separated by > 10 nm, the isotopic emissions of He and H are very closely spaced, requiring high resolution optical spectroscopy. Furthermore, the sensor will be required to operate in reactor fringing fields of more than 0.2T whilst maintaining a stable plasma within the sensor. A further complication is the inherent presence of ionising radiation produced by the fusion reactor.

In this paper we present the development and design of a ROES sensor for fusion applications. The sensor is qualified in its ability to detect small (<0.1%) concentrations of H and He gas isotopes with a speed of response of less than 1 second. This surpasses the requirement for the future fusion reactor, ITER. Optimisation of the sensor's plasma for resolving closely spaced emissions will be presented. Finally, the stability of the sensor's operation in a representative fusion environment is discussed. Experimental results of sensor operation during exposure to magnetic fringing fields and gamma radiation (up to 0.5 T and 500 kGy respectively) will be presented.

1. C. C. Klepper et al., "Developments and Challenges in the Design of the ITER DRGA," in IEEE Transactions on Plasma Science, vol. 50, no. 12, pp. 4970-4979, Dec. 2022

5:15pm **VT2-TuA-13 Development of the SPARC Tokamak Exhaust Purification System***, **Eric Dombrowski,*** Commonwealth Fusion Systems

The SPARC device is a high-field, compact, D-T burning tokomak with the goal of demonstrating net energy gain (Q>2). Burning plasmas on SPARC are anticipated to require less than 1g of tritium fueling. During a fusion pulse, the unspent D-T mixture and helium ash are pumped through the divertor via eight cryosorption pumps which are subsequently regenerated and exhausted through the torus vacuum pumping system. During tritium operations this exhaust gas is directed to the first stage of the tritium fuel cycle, the torus exhaust purification (TEP) system. The impurities are separated from the hydrogenic species and sent to the trace tritium recovery system for further processing. The hydrogen is sent to isotope separation where a new D-T mixture is prepared.

TEP has three main operations. The torus exhaust gas is passed through a high conductance, liquid nitrogen cooled, zeolite based cryosorption pump. All species except for helium and neon are adsorbed onto the zeolite media. The helium is extracted through the back end of the cryosorption pump by an all-metal scroll pump and exhausted to the Trace Tritium Recovery System. The cryosorption pumps' regeneration gasses are passed through a Pd/Ag permeator to generate a pure stream of hydrogenic species for isotope separation. Periodically, a full regeneration of the cryosorption pump to 350 °C is carried out at the end of a day's campaign to liberate chemically bound tritium from the zeolite packing material. This effluent is reacted over a nickel catalyst and passed through a second Pd/Ag permeator onto isotope separation.

A full-scale experimental test loop has been assembled and validated with hydrogen and deuterium isotopes at CFS' SPARC location in Devens, Massachusetts. These components are now in final design for manufacturing in collaboration with Torion Plasma Corporation where they will be integrated into the tritium compatible processing assembly to be completed in Q2 of 2025.

Vacuum Technology
Room Central Exhibit Hall - Session VT-ThP
Vacuum Technology Poster Session

VT-ThP-1 Surface Characterization and Vacuum Performance of AISI 1020 Low-Carbon Steel for High-Performance Vacuum Systems*, **Aiman Al-Allaq,*** Old Dominion University*; M. Mamun, M. Poelker,* Thomas Jefferson National Accelerator Facility*; A. Elmustafa,* Old Dominion University

The Cosmic Explorer, a next-generation gravitational wave observatory, will be very large with evacuated interferometer arms ten times longer than Advanced LIGO operating today, 40 km each. Consideration is being given to building this extremely large vacuum system using comparatively inexpensive low-carbon steel, commonly used today for natural gas delivery. But besides reduced cost, low-carbon steel offers a vacuum advantage, too. Low-carbon steel has a much lower hydrogen outgassing rate compared to stainless steel. In addition, studies performed worldwide within the gravitational wave observatory community suggest low carbon steel – particularly with a magnetite surface coating – may provide a more rapid pump down, possibly reaching acceptable vacuum conditions with only an 80 °C heat treatment. At Jefferson Lab, we plan to construct a new spin-polarized electron source using low-carbon steel, which we hope operates at a much lower pressure than our photoguns built using stainless steel. In support of this objective, we are performing studies related to water outgassing, pump down times, and ultimate pressure achieved using low-carbon steel. Some of these studies seek to understand if material surface transformations occur following different heating protocols. Small coupons made of AISI 1020 low-carbon steel were characterized using SEM, AFM, XRD, and EDS after various heat treatments. The results showed minimal oxidation up to 150 ˚C, with layered magnetite and hematite developing at higher temperatures. A steam-treated sample exhibited vertical grain orientation, while thermal oxidation favored lateral oxide colony formation. Tests on magnetite-coated and bare low-carbon steel chambers demonstrated that the magnetite-coated chamber consistently achieved lower pump down pressure and lower throughput water outgassing rates, supporting the idea that magnetite coating can improve the vacuum performance of low-carbon steel. Ongoing research at Jefferson Lab focuses on characterizing bare and magnetite-coated low-carbon steel chambers to explore their feasibility in next-generation vacuum systems, such as those required for the Cosmic Explorer project, and for spin-polarized electron guns where improved vacuum will help sustain reliable beam delivery.

VT-ThP-2 Fabrication and Characterization of a Standard Leak Element Based on Capillary Tubings*, **Han Wook Song,*** KRISS, Republic of Korea*; M. Salazar,* ITDI, Philippines*; J. Kim, M. Seo, S. Cho, S. Woo,* KRISS, Republic of Korea

Leak artefacts made of different materials with well-defined geometry are in constant development to improve the knowledge of gas dynamics in narrow channels. In this study, a unique, low-cost material of micro-scale capillary tubing was used to develop a standard leak element (SLE) that will be practical and easily duplicated for industrial use. Two designs of the SLE were fabricated, both designs were developed with variable lengths and throughput were measured through the pressure-rise method. A leak artifact assembly was fabricated with variable lengths and diameters, and throughput rates were measured using the pressure rise method. Throughput rates of up to 10^{-11} Pa m^3 s^{-1} were observed with a relative expanded uncertainty (*k = 2*) of 12%. An established model involving the viscous flow in long pipes was used to verify the results of the actual measurements. This study utilized the ideal gases such as Helium and Nitrogen. Behaviour of the results of actual measurements of throughputs of the first design contradicts the theoretical predictions of the conventional theory while that of the second design is in agreement with the classical theory which indicates that the structure may be an excellent choice for a standard leak artifact that fits the aforementioned purpose and applications.

VT-ThP-3 Commissioning of the New NIST High-vacuum Calibration Standard*, E. Newsome, **Daniel Barker,** J. Fedchak, J. Scherschligt,* National Institute of Standards & Technology

We report our efforts toward commissioning NIST’s new ionization gauge calibration system (IGCS). Ionization gauges are critical to applications operating in the high-vacuum and ultra-high vacuum ranges. These gauges determine pressure in a vacuum chamber by first ionizing gas molecules in the vacuum via collisions with electrons emitted from a cathode, then collecting the ions on a wire, and measuring the subsequently generated current. Because the conversion of ion current to pressure depends on gauge geometry, collection efficiency, electrode potential, and other factors, individual gauge sensitivity will vary and, in general, requires calibration to achieve the best measurement accuracy. In the range of 0.1 Pa to 10^{-7} Pa, the IGCS calibrates ion gauges by comparing the gauge reading to a known pressure step using the dynamic expansion technique. We describe the design of the IGCS, focusing on improvements over NIST’s previous high-vacuum standard. We also present initial tests of the IGCS and calibration results for NIST gauges.

VT-ThP-4 Developing an Extreme Environment Vacuum System for ITER's Ion Cyclotron Heating Antenna*, **John Michael Clark,*** Oak Ridge National Laboratory

The ITER project is designed with the goal of demonstrating the feasibility of fusion energy, and to advance the technological understanding of fusion for future commercial reactors.In order to achieve a “burning plasma”, various heating methods, such as Neutral Beam, Electron Cyclotron Heating, and Ion Cyclotron Heating (ICH) are employed in the ITER fusion device. Each of these technologies require high vacuum environments to ensure safe and efficient operation; however,ICH, in particular, poses unique issues in developing a vacuum system.

The proximity of the ICH antenna, and associated vacuum pumping system of the ICH Removable Vacuum Transmission Line (RVTL) Rear Windows,to the ITER Tokamak necessitates a vacuum system that is able to withstand dynamic magnetic fields in excess of 500 mT and activation of up to 10^4Gy. Vacuum technology and hardware layouts that have become common across ITER vacuum systems are not operablein this extreme environment. To develop a functional vacuum system for the ITER ICH antenna’s RVTL Rear Windows, it must be designed with hardware and an arrangement that tolerates the environment and meets pressure requirements without significant increase inevacuation time.

VT-ThP-5 Secondary Electron Yield Measurements of Vacuum Insulators*, **Minh Pham,** R. Goeke,* Sandia National Laboratories

Ceramics are commonly used for high voltage insulation in vacuum systems. The vulnerability of its high voltage standoff is a flashover of the insulator surface. The principal mechanism for this breakdown is a secondary electron emission (SEE) avalanche. In this process, some electrons striking the insulator surface produce more electrons which strike the surface again producing additional electrons. This process continues until a flashover of the insulator surface occurs and the high voltage standoff is lost. We have developed a test stand to measure SEE yields as function of incident electron energy using very small doses of electrons to minimize surface charging of the insulators. This system utilizes a Hemispherical Grid Retarding Field Analyzer to capture all the secondary and backscatter electrons in an Ultra High Vacuum environment, ensuring an accurate measurement of SEE yield. By firing quick small pulses of electrons enables us to analyze insulating samples before the surface becomes charged which will alter the electron emission process. Results from our measurements on ceramic insulators will be

presented.

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— B —
Barker, D.: QS1+VT-MoM-1, 1; VT-ThP-3, **9**
Beck, K.: QS1+VT-MoM-6, **1**
Benjamin, C.: VT4-TuM-16, 6
Bergner, K.: QS1+VT-MoM-2, **1**; VT3-TuM-6, 6
Biewer, T.: VT2-MoA-5, 2; VT2-TuA-11, 8
Brindley, J.: VT2-TuA-11, 8; VT2-TuA-12, **8**
Brucker, G.: VT3-MoA-15, 4
Bui, T.: VT2-MoA-4, 2
Bulten, H.: VT2-MoA-11, **3**
— C —
Cho, S.: VT-ThP-2, 9
Clark, J.: VT-ThP-4, **9**
Conlon, J.: VT4-TuM-16, 6
— D —
Davies, S.: VT2-TuA-8, **7**
Diaz, A.: VT1-TuA-1, **7**
Dombrowski, E.: VT2-TuA-13, **8**
Douglass, K.: VT2-MoA-4, 2
Duree, J.: VT1-TuM-2, 5
— E —
Eckel, S.: QS1+VT-MoM-1, **1**
Eder, M.: VT2-TuM-4, **5**
Elmustafa, A.: VT3-MoA-13, 4; VT-ThP-1, 9
Elsen, M.: QS1+VT-MoM-2, 1
Erends, V.: VT2-MoA-11, 3
— F —
Fedchak, J.: QS1+VT-MoM-1, 1; VT-ThP-3, 9
— G —
Gallaugher, M.: VT1-TuM-3, **5**
Gerlach, L.: QS1+VT-MoM-2, 1
Goeke, R.: VT-ThP-5, 9
Goldstein, B.: QS1+VT-MoM-5, 1
Grosse, J.: QS1+VT-MoM-2, 1
Gruber, C.: QS1+VT-MoM-2, 1
— H —
Han, S.: VT1-TuM-2, 5
Heiz, U.: VT2-TuM-4, 5
Hendricks, J.: QS1+VT-MoM-5, **1**; VT2-MoA-4, 2
Hertel, J.: QS1+VT-MoM-2, 1
Hughes, S.: VT2-TuA-5, 7
Hüttl, S.: QS1+VT-MoM-2, 1; VT3-TuM-6, 6
— I —
Iannello III, J.: VT1-TuM-2, 5
— J —
John, M.: VT3-TuM-6, **6**
Jugan, A.: VT2-TuA-11, 8
— K —
Kaiser, S.: VT2-MoA-3, 2
Kanzenbach, L.: QS1+VT-MoM-2, 1
Kato, A.: QS1+VT-MoM-3, **1**
Kessels, E.: VT1-TuM-1, 5
Kim, J.: VT-ThP-2, 9
Kirsch, K.: VT3-TuM-6, 6
Klepper, C.: VT2-MoA-5, 2; VT2-TuA-11, 8; VT2-TuA-12, 8
— L —
Lanza, G.: VT4-TuM-14, **6**
Lesker IV, K.: VT1-MoA-1, **2**
Li, Y.: VT4-TuM-13, **6**
Löwinger, F.: QS1+VT-MoM-2, 1
Luff, R.: VT4-TuM-16, 6
— M —
Mackus, A.: VT1-TuM-1, 5
Malyshev, O.: VT4-TuM-16, 6
Mamun, M.: VT3-MoA-13, 4; VT-ThP-1, 9
Marcus, C.: VT2-MoA-5, 2; VT2-TuA-11, **8**; VT2-TuA-12, 8
Marshall, E.: VT4-TuM-16, 6
McCarthy, P.: VT2-TuA-11, 8; VT2-TuA-12, 8
Merkx, M.: VT1-TuM-1, 5
Middleman, K.: VT4-TuM-16, **6**
Miroshnik, L.: VT1-TuM-2, **5**
Molkenboer, F.: VT3-MoA-14, **4**
Munneke, B.: VT2-MoA-11, 3
Murugaiah, A.: VT1-TuM-3, 5
— N —
Nakakura, C.: VT1-TuM-2, 5
Nas, I.: VT1-TuM-3, 5
Newsome, E.: VT-ThP-3, 9
— P —
Parkinson, G.: VT2-TuM-4, 5
Pavelec, J.: VT2-TuM-4, 5
Perry, J.: VT2-MoA-5, 2; VT2-TuA-5, **7**
Petzoldt, P.: VT2-TuM-4, 5
Pham, M.: VT-ThP-5, **9**
Poelker, M.: VT3-MoA-13, 4; VT-ThP-1, 9
Poynton, O.: VT4-TuM-16, 6
— Q —
Quinlan, B.: VT2-MoA-5, **2**; VT2-TuA-11, 8; VT2-TuA-12, 8
— R —
Richter, D.: QS1+VT-MoM-2, 1
Ricker, J.: VT2-MoA-4, **2**
— S —
Sabens, D.: VT1-TuM-3, 5
Salazar, M.: VT-ThP-2, 9
Sato, K.: VT2-MoA-7, **2**
Scherschligt, J.: QS1+VT-MoM-1, 1; VT-ThP-3, 9
Schmidt, T.: QS1+VT-MoM-2, 1
Schneider, J.: QS1+VT-MoM-2, 1
Seal, D.: VT4-TuM-16, 6
Seo, M.: VT-ThP-2, 9
Setina, J.: VT2-MoA-8, **3**
Shul, R.: VT1-TuM-2, 5
Smith III, C.: VT2-MoA-5, 2; VT2-TuA-4, 7
Smith, C.: VT2-TuA-5, 7
Smith, L.: VT4-TuM-16, 6
Song, H.: VT-ThP-2, **9**
Stevens, T.: VT1-TuM-2, 5
Stutzman, M.: VT4-TuM-15, **6**
Swinney, T.: VT3-MoA-15, **4**
— T —
Takei, Y.: VT2-MoA-9, **3**
Tarazona, A.: VT2-TuA-8, 7
Tippens, J.: VT2-TuA-4, **7**
Troha, J.: VT1-TuM-3, 5
Trützschler, A.: QS1+VT-MoM-2, 1; VT3-TuM-6, 6
Tschurl, M.: VT2-TuM-4, 5
— V —
Valizadeh, R.: VT4-TuM-16, 6
van Bommel, C.: VT1-TuM-1, 5
van Helvoirt, C.: VT1-TuM-1, **5**
van Uittert, F.: VT1-TuM-1, 5
Vergason, G.: VT1-MoA-1, 2
— W —
Warner, M.: QS1+VT-MoM-2, 1
Wieland, S.: QS1+VT-MoM-2, 1
Wilde, S.: VT4-TuM-16, 6
Woo, S.: VT-ThP-2, 9
Wüest, M.: VT2-MoA-3, **2**
— Y —
Yoshida, H.: VT2-MoA-9, 3
Yoskowitz, J.: VT4-TuM-15, 6
— Z —
Zeebregts, J.: VT1-TuM-1, 5