Vacuum Technology Division
Room On Demand - Session VT-Contributed On Demand
Vacuum Technology Contributed On Demand Session

VT-Contributed On Demand-1 Study on Copper Thermal Spray Coating to Mitigate Electron Cloud Effect in SuperKEKB*, Mulee Yao,* SOKENDAI, Taiwan*; Y. Suetsugu, K. Shibata, H. Hisamatsu, T. Ishibashi, S. Terui,* KEK, Japan

To investigate the effect of the copper thermal spray coating on reducing the secondary electron yield (SEY) and verify its feasibility for accelerators as a countermeasure against the electron cloud effect (ECE), we coated the aluminum substrates (A6063) with copper powder by thermal spraying and measured their SEY, roughness, surface composition and outgassing rate. To establish the best coating parameters for the beam pipes of the SuperKEKB positron ring, we tested different spray conditions, such as particle size of copper powder, substrate surface treatment, spray angle and temperature, and exposure of the coating to electrons. Now we have produced a straight aluminum beam pipe with copper thermal spray coating that can be installed in the SuperKEKB, in order to observe the effect on reducing the ECE in the near future. In the study of the relationship between SEY and roughness, we found that the SEY was inversely proportional to the Sdr (developed interfacial area ratio) or Sa√Spd in the simulation, where Sa is arithmetical mean height and Spd is density of peaks. But the experimental results from the thermal spray sample were not consistent with it. The most probable reason is the limitation of the roughness measuring instrument on the fine and complex surface like thermal spray coating.

VT-Contributed On Demand-4 NIST on a Chip: Photonic and Quantum-Based Sensors for Metrology and Beyond*, Jay Hendricks,* NIST

This talk will briefly outline the NIST on a Chip (NOAC) Program.The unifying theme of the program is aimed at the development of standards and sensors that are small, deployable, that don't require calibration back at NIST.The core the idea of NOAC is that quantum-based measurements, or measurements based on fundamental physics, when employed in sensors and standards, are invariant.In the NIST on a Chip embodiment, the standards lab, or in this case "NIST", is "on a chip"and is powerful to industry and society as it means that large networks sensors (or sensors "integrated" into a product or device) can be deployed and trusted to provide accurate measurements without costly re-calibration. The overall strategy of the program is to first identify working prototype of laboratory scale devices and standards and then, overtime, build prototypes that can be further miniaturized to the chip scale. The successful program means that measurement technology enables high quality measurements to be done "outside the National Metrology Institute" but owed to base properties of nature and are therefore directly tracible to the international system of units known as the SI. Nested within this idea is the development of quantum-based standards for SI traceability. Given time example of lab scale and early prototypes of miniaturized versions will be presented.

VT-Contributed On Demand-7 Improving Temperature Uniformity of Stainless-Steel Components in Thin Film Processing Equipment*, Sudarshan Natarajan, D. Sabens, A. Murugaiah,* Momentive Technologies

This presentation outlines the characteristics, potential applications, and benefits of the Momentive Technologies stainless-steel encapsulated thermal leveler. Target applications include temperature uniformity improvement in wafer carriers or pedestals and other internals in chemical vapor deposition (CVD) or atomic layer deposition (ALD) equipment.

Momentive Technologies offers highly crystalline graphite known as thermal pyrolytic graphite (TPG), which exhibits 4X thermal conductivity than copper. Pedestals or wafer carriers or other internals of high temperature and corrosive thin film processing equipment can be manufactured by stainless steel alloys. But the temperature uniformity of these parts are severely limited by the poor thermal conductivity of the alloys. Momentive technologies recently developed stainless alloy encapsulated TPG leveler addresses this issue of temperature non-uniformity. Results of the temperature uniformity improvement and thermal cycle stability of the newly developed leveler are presented.

VT-Contributed On Demand-10 Particle Tracing the ISO Gauge*, Martin Wüest, F. Scuderi,* INFICON Ltd., Liechtenstein*; B. Jenninger, A. Stöltzel, P. Kucharski,* CERN, Switzerland*; O. Teodoro, R. Silva, N. Bundaleski,* Nova School of Sciences and Technology, CEFITEC, Portugal*; C. Illgen,* Physikalisch-Technische Bundesanstalt, Germany*; J. Šetina,* Institute of Metals and Technology, Slovenia*; K. Jousten, M. Bernien,* Physikalisch-Technische Bundesanstalt, Germany*; F. Boineau,* Laboratoire national de métrologie et d'essais, France*; M. Vičar,* Czech Metrology Institute, Czechia

In the framework of the EURAMET project 16NRM05 a novel ionization gauge was developed. The goal was to develop a more stable ionization gauge that could be suitable for standardization. The gauge design was completely developed by computer simulations. To increase the reliability of the simulation results, three different software packages were used in parallel (COMSOL, OPERA, SIMION). With these codes the gauge design was refined and experimental features explained. Despite different treatment and methods used in the ionization module of the simulation codes, the results agree very well with the experimental results.

Acknowledgement:

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VT-Contributed On Demand-13 Three-Dimensional Analysis and Design Assessment of the Mast-U Double Beamline Cryogenic Pumping System*, Xueli Luo, S. Hanke,* Karlsruhe Institute of Technology, Institute for Technical Physics, 76021 Karlsruhe, Germany*; A. Shepherd,* Culham Centre for Fusion Energy, Abingdon, Oxfordshire, OX14 3DB, United Kingdom*; C. Day,* Karlsruhe Institute of Technology, Institute for Technical Physics, 76021 Karlsruhe, Germany

The MAST upgrade program (MAST-U) is an ongoing nuclear fusion project in Culham Centre for Fusion Energy (UK), aiming to resolve important plasma physics questions and develop advanced divertor designs. In addition, as part of the MAST-U Enhancements project, MAST-U will be used to test steady state operation with current driven by a novel double beamline neutral beam injection (NBI) system. With one axial beamline and one off-axial beamline at 10.6 degrees, this unique design could have greater possibilities and flexibilities in the plasma heating, control and diagnostics.

Fig. 1. Sketch of the MAST-U double beamline NBI system design.

However, as shown in Figure 1 (Please see the supplemental file Figure_1.pdf), this novel NBI system is very complex with many sub-systems. The focus of this paper is the analysis and design assessment of its cryogenic pumping system. Two aspects were systematically studied by simulations with the test Monte Carlo simulation code ProVac3D developed in KIT. First, the dependency of the density profiles along the double beamlines to the in-vessel cryopump was obtained by changing the capture coefficient of the cryopump as a whole in the simulation. Combined with simulation results using the MCNP code, we can estimate the total pumping speed needed to fulfil the requirement of the density profiles. Secondly, different configurations of the cryopump were simulated and a conceptual design, which could deliver the right total pumping speed, was proposed. In order to simulate such a complex system and have high precision for so many simulations in reasonable computation time, all simulations were carried out in supercomputer Marconi-Fusion by using 2560 cores in parallel to simulate 10^{11} test molecules. Obviously, the simulation results obtained in this study will be extremely useful to the success of the challenging tasks of MAST-U.

ACKNOWLEDGEMENTS

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VT-Contributed On Demand-16 Cost Description and Characterisation of Gases used in immiscible gas Enhanced Oil Recovery processes (IGEOR), ***Ofasa Abunumah****, P. Ogunlude, E. Gobina,* The Robert Gordon University, UK

The cost implication of gases used in the oil industry has been characterised through data mining and experimentally. About 70% of oil is trapped in reservoir pores globally due to the limitation of primary oil recovery processes. Consequently, certain gases are injected into reservoir pores to displace the trapped oil in a process calledImmiscible GasEnhanced Oil Recovery (IGEOR). Common gases injected are CH_4, N_2, Air & CO_2. The flow mechanisms, such as surface energy, permeability and momentum have been extensively studied by investigators. However, only a few studies have implicated or coupled injected gas cost. No experimental investigation that simultaneously studies the 4 commonly used gases. Nevertheless, the injectant cost is a major part of the operating expense (OPEX) cost centre.It is expected that the gas cost competitiveness of the gases would aid reservoir screening and gas selection in IGEOR applications. Therefore a study is needed to bridge this knowledge gap. From the literature review, it was indicated that the displaced oil is proportional to injected gas volume. It is therefore expected that competition could be tied to gas dynamics in pore surfaces for the respective gases. e

Methodology and Materials

Materials: 5 analogous reservoir porous core samples with different structural parameters, such as micro and macro surface area. 4 IGEOR gases (CH_4, N_2, Air, CO_2) were selected.

***Operating Condition*:** Temperature range 293-673K andPressure range 20-300KPa.

Procedure: Gas was injected into the core samples at a set pressure and temperature. Permeate flow rates, temperature and pressure collected as steady state.

Data ming : 353

Experimental Data: 1,097 runs and 8,777 data.

***Gas Cost Types*:** Market, Field and experimental gas cost

Result

Analyses of the field and experimental data show thatIGEOR gases can be characterised. All three cost types were found to be strongly correlated to the 6 gas thermophysical properties (R^2).It was found that **$CO_2$is** the least expensive gas for all 3 gas cost categories, and thus the most competitive. The **Air** EOR process is the most sensitive to cumulative injectant cost.The slope of the graph between gas cost and properties indicated that 9 of the relationship are inversely correlated with the gas properties, while 8 are positively correlated.

Market cost CO_2 > Air> N_2 > CH_4.

Field project gas cost:CO_2 > Air> N_2 > CH_4.

Experimental project gas cost: CO_2 > N_2 > Air > CH_4..

Contribution to Practice: Engineers can apply this knowledge to select the best IGEOR gas for a given reservoir or porous surface. The discovered competitiveness of CO_2 would further incentivise the Carbon Capture and Sequestration (CCS) programmes to reduce greenhouse gases.

VT-Contributed On Demand-19 Vacuum level Sensing Using Optical Refractive Index, ***Kevin Douglass****, J. Ricker,* NIST

Towards the goal of quantum-based traceability of the Pascal, NIST has developed an optical pressure measurement system where traceability is achieved through accurate quantum mechanical calculations of the refractivity virial coefficients of . To bridge the gap in quantum standards between the NIST Fixed Length Optical Cavity (FLOC) and the Cold Atom Vacuum Standard (CAVS) we are pushing the limits in low pressure sensing. We will discuss recent results and ultimate low-pressure limit.

VT-Contributed On Demand-22 Simulation of the Operation of an Ion Pump, ***Tiziano Isoardi****, P. Manassero, L. Bonmassar,* Agilent Technologies, Italy

An ion pump is a system that is capable to produce the ultra-high vacuum. The basic element of this pump is the Penning trap which confines free charged particles in a cylindrical space. This can be done using a combination of an electrostatic-multipolar and a magnetic-dipolar field which allows to trap electrons and to accelerate ions towards one of the two cathodes. The ultra-high vacuum is reached because the ion-cathode collisions generate sputtering phenomena of chemically active Titanium film on anode to which gas molecules from the trap are attached. The process is fed by electrons generated by secondary emissions due to the ion-cathode collisions. These electrons have an elevated total energy (equal to the potential of the cathode) with respect to the ionization potential that allows them to ionize gas molecules more than once until they lose all their energy forming a non-neutral plasma. This mechanism should lead to an exponential increase of the current until the complete emptying of gas molecules, but actually the current stabilizes almost immediately (tens of milliseconds). This means that there is some phenomena that prevent the current exponential growth. In order to investigate the current behavior, we studied all phenomena that occur inside the pump through repeated Monte Carlo simulations of single electrons inside the trap, by studying all the single charge interactions. It is known that in a non-neutral plasma there is a maximum charge density that can be achieved which depends on the magnetic field magnitude and on the single charge mass. This is called Brillouin limit and can be easily calculated. So we built simulations at the Brillouin limit approximating the plasma as an electrically charged cylinder (taking into account the influence of plasma on the electric field) considering steady-states at different pressures of a single gas (N2 or H2). After that we built a parameterization to calculate the ionization frequency for a single electron that we used to obtain the current at the cathodes. The current values resulting from simulations closely match the experimental data (see attached Fig.1-3). According to the results of the simulation the plasma absorbs a large fraction of the energy of the free electrons generated at the cathode until they can not ionize the gas molecules. This means that the energy loss in the plasma is responsible for the saturation of the current. When the Brillouin limit is reached the current is stabilized to a value that depends essentially only from the density of the gas and decreases together with the residual pressure of the gas in the trap.

VT-Contributed On Demand-25 Experimental Characterization of a NEG Pump of Novel Size - A Step to its Application in the DEMO Neutral Beam Injectors, ***Stefan Hanke****, C. Day, T. Giegerich, X. Luo,* Karlsruhe Institute of Technology (KIT), Germany*; F. Siviero, M. Mura, A. Ferrara, E. Maccallini, P. Manini,* SAES Getters, Italy*; E. Sartori, M. Siragusa, P. Sonato,* Consorzio RFX, Italy

A fusion reactor requires powerful heating systems among which the neutral beam injectors (NBI) are the most powerful ones. Operation of NBI systems requires very high pumping speeds in the order of several 1000 m^3/s at relatively moderate pressures of 0.02 Pa to manage the high gas flux in the neutralizer part of the NBI. In the past large customized cryopumps were used. A very promising concept for future NBI applications is based on high capacity getter materials. The material candidate is ZAO® developed by SAES Getters, Italy, providing a performance for the pumping of hydrogen approximately two orders of magnitude higher compared to conventional getter materials.

In a systematic technology development over 6 years, the concept of a NEG pump for NBI was developed within the European Fusion Programme to develop a demonstration fusion power plant (DEMO). It started with the comprehensive characterisation of the material and its properties, in particular at pressures which were significantly higher than in previous UHV applications of getter materials. With the time the knowledge was expanded not only regarding pumping and regeneration characteristics of ZAO® itself but also concerning the heating, thermal management, assembly to larger units for scalability and control of these units during operation. The recent step was the design, manufacturing and operation of a NEG pump which is of relevant size to answer all the DEMO NBI relevant questions, to demonstrate the use of ZAO® in a large pump and to confirm the scalability of the chosen design.

The resulting NEG pump of novel size contains 16 kg of getter material, it was tested in the dedicated test facility TIMO at KIT. The paper describes the design of the pump and presents the experimental results, in particular a systematic investigation of sorption characteristics (depending on pressure, gas flux, getter temperature, loading of the getter with gas) and the regeneration behaviour.

VT-Contributed On Demand-28 Shenzhen Synchrotron Radiation Facility Project, ***Dongbai Sun****, G. Liu, R. Si, Y. Cui, B. Yang, Z. Zhou,* Institute of Advanced Science Facilities, Shenzhen, China

A new synchrotron radiation facility is currently in the planning stage and will be constructed in Shenzhen, China, by the Institute of Advanced Science Facilities, Shenzhen（IASF）. The proposed synchrotron light source consists of a 0.2 GeV linac, a full energy booster ring, and a 3 GeV fourth-generation diffraction-limited storage ring which is based on a seven-bend achromat (7BA) to achieve a low emittance of <100 pm·rad. It delivers X-ray synchrotron radiation with a broad range of energies and a brightness in the order of 10^{21} phs/sec/mm^2/mrad^2/0.1BW. Besides, 27 beamlines of various methods covering scattering/diffraction, spectroscopy, and imaging have been proposed for the primary phase. The new synchrotron light source is believed to be one of the most essential large-scale science and research facilities in Shenzhen and provides a fundamental platform to serve researchers around the world, and to contribute to industrial development in China's Greater Bay Area.

VT-Contributed On Demand-34 Progress Towards Comparison of Quantum and Classical Vacuum Standards*, **Daniel Barker**, N. Klimov, E. Tiesinga, J. Fedchak, J. Scherschligt, S. Eckel,* National Institute of Standards and Technology (NIST)

We present our progress towards a comparison of NIST's cold atom primary vacuum standard and a dynamic expansion vacuum standard. The cold atom vacuum standard (CAVS) converts the loss rate of atoms from a magnetic trap to a vacuum pressure using *ab initio* calculations of the quantum atom-molecule collision cross-section. To validate the CAVS, we have constructed a new flowmeter and dynamic expansion system that can produce low-uncertainty pressures in the ultra-high-vacuum range that is required for atom trapping. We present initial studies of systematics in both the CAVS and flowmeter. We will also discuss prospects for comparisons of both the CAVS and flowmeter to deployable quantum vacuum sensors.

VT-Contributed On Demand-37 NIST's New Flowmeter for the Extremely-High Vacuum*, **Stephen Eckel**, D. Barker, J. Fedchak, E. Newsome, J. Scherschligt, R. Vest,* NIST

At NIST, we have been developing a new, fully-automated, low-outgassing, constant-pressure flowmeter capable of measuring flows to better than 0.5% over the range from 10^{-13} mol/s to 10^{-9} mol/s. While based on the design of the constant-pressure flowmeter used at NIST to calibrate leaks and high vacuum and ultra-high vacuum pressure gauges, our design incorporates several novel features. To achieve measurement of such low flows, our design uses both small variable volumes (<15 mL each) and ultra-small displacements (0.25 mL max). By constructing our variable volumes from low outgassing materials like titanium and designing the flowmeter to be fully bakeable, we achieve <10^{-15} mol/s outgassing rates. The leak that generates the flow is a stainless steel sintered standard leak element. We measure its stability and its conductance (approximately 26 nL/s for N_2) over 4 decades of pressure. We present comparisons to our current flowmeter over the overlapping operating range of about 10^{-11} to 10^{-9} mol/s. When coupled to an orifice flow standard with a 40 L/s conductance for N2 and a 99/1 flow splitter, the combined system can generate partial pressures as low as 10^{-11} Pa, extending NIST's measurement capability into the extremely-high vacuum (XHV) regime. The first application of the flowmeter will be to measure loss rate coefficients of the newly developed cold-atom vacuum standard (CAVS).

VT-Contributed On Demand-40 Jefferson Lab Injector Beamline Upgrade*, **Marcy Stutzman**,* Thomas Jefferson National Accelerator Facility

Jefferson Lab is in the midst of an upgrade of the injector beamline. The upgrade has several goals, all of which support upcoming high profile parity violation experiments such as SOLID and Moeller. First, we are developing several paths toward a higher voltage electron source. With highly polarized beam at 200 keV out of the electron gun rather than the current 130 keV operational voltage, the Coulomb repulsion effects in the beam will be minimized, and photocathode damage due to ionization within the cathode/anode gap can be mitigated. Secondly, the only warm RF accelerator cavity at CEBAF, the Capture, and the first SRF accelerator cavity, called the quarter cryo module, will both be replaced by a graded SRF booster module. The booster has two graded cavities to accelerate non-relativistic electrons from the polarized source to energies up to 10 MeV. However, the higher gun voltage of 200 keV is required for this booster to work well. Finally, in support of these upgrades, the entire injector beamline has been redesigned, and the vacuum upgrades for this system and their impact on the performance of the electron source will be discussed.

VT-Contributed On Demand-43 Gas Transmission Rate of Elastomer Seal With a Divided Back-Up Ring Seal*, **Masaharu Miki**, Y. Miki,* EM Technical Lab Inc., Japan

It was presented in the last AVS (VT-TuP4) that the elastomer seal with the back-up ring seal has very low Helium gas transmission rate, which is about less than 10% of the case without the back-up ring seal. Then divided back-up ring seal which is made of some parts was studied. That is because it is less manufacturing cost than non-divided back-up ring seal, especially, in case that the shape of elastomer seal is not a circle but a complicated shape like a horseshoe.

Air gas transmission rate of an elastomer seal with a divided back-up ring seal was evaluated from the ultimate pressure measured. It was found that the divided back-up ring seal has the same performance as a non-divided back-up ring seal. And when a divided back-up ring seal has some space between the parts, it gets worse performance according to the amount of the space. It means that when it has little space between the parts, it gets about 100% performance of a non-divided back-up ring seal, and when it has 10% space of all, it gets about 90% performance of a non-divided one.

Performance of divided back-up ring seals which have some space between the parts were measured and a model to explain the performance of the back-up ring seals has been constructed.

Furthermore, performance of some divided back-up ring seals which are made of some different materials are evaluated.

VT-Contributed On Demand-46 Thermal Evaluation of a Fixed Length Optical Cavity Pressure Standard*, **Jacob Ricker**, J. Hendricks, K. Douglass,* NIST

Over the past few years, NIST has constructed and tested several Fixed Length Optical Cavity (FLOC) Pressure Standards for measuring gas pressure using refractometry. This refractometry technique has been shown to have similar uncertainty to the current NIST primary standards. However, to achieve this performance they must have uncertainties of temperature measurements on the order of 1 mK. This is easy in a static environment; however, pressure standards need to be able to measure more than one pressure, so pressurization/compression/flow of gas molecules is required. The NIST Fixed Length Optical Cavity (FLOC) pressure standard was designed to accommodate pressure changes while being able to accurately determine the temperature of the gas molecules and glass cavity by using a Platinum Resistance Thermometer (PRT).

From the ideal gas law and thermodynamics, we can estimate the temperature rise due to pressurization of the gas molecules to increase the temperature by 120 K when going from vacuum to atmospheric pressure. However, due to the small heat capacity of gas this quickly dissipates into the surrounding environment.This results in a small, but measurable temperature rise that is significantly larger than our uncertainty.Physical measurements and computer modelling were used to predict the temperature of the FLOC and allow placement of a PRT to provide accurate measurements of the gas temperature to within an uncertainty of 0.5 mK.

VT-Contributed On Demand-49 Stability of Bakeable Capacitance Diaphragm Gauges*, **Julia Scherschligt**, D. Barker, S. Eckel, J. Fedchak, E. Newsome,* NIST

Capacitance diaphragm gauges (CDGs) are workhorse transfer standards for NIST and other metrology labs around the world. Here, we present a stability study of bakeable CDGs, which are useful in vacuum systems with low outgassing or base pressure requirements. In our studies, a set of three bakeable CDGs was baked in a vacuum furnace at 450 C for about 20 days to reduce hydrogen outgassing. After assembly into a NIST transfer standard, the CDGs were baked again at 110 C to reduce water outgassing. After the initial 450 C bakeout, we found that the calibrations of the CDGs shifted by about 15%. However, after the first 110 C bakeout, the CDGs calibrations remained extremely stable, with <0.2% (k=2) change after each subsequent bake. We performed additional tests, which included dropping a 10 kg weight from a height of 30 cm nearby the gauges, venting the system, completely disassembling, sonicating with acetone and ethanol, and reassembling the system. With this expanded regimen, the gauges drifted further, but no more than 0.6% (k=2). These bakeable CDGs are thus remarkably stable, provided they are temperature stabilized when being used. They now form the transfer pressure standard for our new extremely-high vacuum (XHV) flowmeter, being developed as part of our new cold atom vacuum standard (CAVS) program.

VT-Contributed On Demand-52 Outgassing of A36 Carbon Steel Vacuum Chambers*, **James Fedchak**, J. Scherschligt,* NIST-Gaithersburg

A36 steel is a low-carbon (mild) steel commonly used as a structural steel in the US. Secondary refining processes reduce the hydrogen content in mild steel, making these steels excellent candidates as materials for ultra-high vacuum chambers because of their potential to be low-outgassing.Previously we measured and compared the H_2 and water outgassing rates for 7 identical vacuum chambers constructed of common vacuum materials and heat treatments: 304L, 316L, 316LN-ESR (electroslag re-melt), titanium, aluminum vacuum-fired 316L, and vacuum-fired 316LN-ESR. These chambers are of identical geometry and are from the same manufacturer. In the present study, we measure the hydrogen and water outgassing rate of an A36 chamber with similar geometry to these 7 chambers.We show that the A36 chamber produces one of the lowest outgassing rates compared to any of these vacuum materials.Thus, A36 may be an excellent choice for ultra-high or extreme-high vacuum applications.Compared to stainless-steel such as 304L or 316L, mild steels are more corrosive and magnetic, but the are inexpensive, have excellent properties for welding and machining, and, as we will show, have excellent outgassing properties.This makes them a good candidate for large vacuum systems such as future gravity wave detectors. In this presentation, we will present outgassing results for the A36 chamber and compare these results to the seven other chambers mentioned above.

VT-Contributed On Demand-55 An in-Situ and in-Vivo Characterization Facility for Ion-Gas-Neutral Interactions With Surfaces (IGNIS-2) Under Fusion-Relevant Vacuum Conditions*, **Ethan Kunz**, C. Jaramillo, H. Schamis, M. Parsons, S. Kolecki, M. Fredd, C. Smith, M. Nieto, J. Allain,* Pennsylvania State University

The study of plasma-facing materials (PFMs) in the field of fusion plasma material interaction research involves testing new materials hypothesized to sustain the intense neutron radiation, particle flux, and heat flux of future plasma-burning thermonuclear fusion reactors. Studies involving long-term evaluation of tokamak first wall materials encounter issues with contamination when vacuum is broken on the system and the samples are transported for ex-situ analysis. Therefore, there is a need for facilities capable of simulating key aspects of the fusion environment and analyzing the surface morphology and chemistry of the sample without the necessity of exposure to the ambient environment. However, relevant vacuum conditions that mimic fusion devices are critical to enable interpretation in ex-vessel facilities designed to test and qualify candidate PFMs including background ambient pressure (partial H2O), working gas pressure (D2 at mTorr ranges), wall conditioning (e.g. B, Li) and radiative gas shielding (e.g. N, Ne).

In this work, we present the design of the Ion-Gas-Neutral Interactions with Surfaces (IGNIS-2) facility, currently being built at the Pennsylvania State University. IGNIS-2 is the fourth generation of a series of advanced experimental surface science facilities developed by Allain et al. [1]. Surface modification and ion beam irradiation with ion energies ranging from 50 to 5000 eV and current densities up to 7 mA cm-2 will be performed in this facility. IGNIS-2 will use in-situ characterization to accurately study the surface evolution under exposure to simulated fusion conditions. Characterization techniques include high-pressure X-Ray Photoelectron Spectroscopy (XPS) using a monochromated X-Ray Source, Ion Scattering Spectroscopy (under forward and backward scattering configurations), UV-Vis-NIR reflectance spectroscopy, Multi-Beam Optical Stress Sensor (MOSS), mass spectrometry, and in-situ erosion measurements.

IGNIS-2 will be composed of multiple vacuum stages which will be interconnected via a subway system that will allow sample transfer within stations in-vacuo, retaining the characteristics of the modified surfaces without exposure to air and contamination. The system will also be integrated with a glovebox with in-vacuo capabilities for the preparation of samples for air sensitive processes. Additional stations in the system will host capabilities for thin film deposition and liquid metal application, including a lithium dropper and contact angle measuring station designed in conjunction with the NSTX-U Liquid Metal research being conducted at Penn State.

[1]Allain, J.P., Nieto, M., Hendricks, M.R., Plotkin, P., Harilal, S.S., Hassanein, A. (2007): Review of Scientific Instruments, 78, 11, 113105.

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VT-Invited On Demand-1 Small Diameter NEG Coated Vacuum Chambers by Copper Electroforming*, **Lucia Lain Amador**,* CERN, Switzerland **INVITED**

Non-evaporable getter (TiZrV) thin film coatings provide ultra-high vacuum conditions in particle accelerators. They are deposited on the internal walls of the vacuum chambers, transforming them from a gas source into a chemical pump. The trend in electron accelerators design consists in approaching the poles of the steering magnets close to the electron beam. This implies reducing the magnet aperture and using very small diameter vacuum pipes [1]. The application of physical vapor deposition (PVD) in such small diameter chambers becomes then very difficult. The aim of this work is to develop a novel procedure of coating/assembly, using a sacrificial aluminium mandrel as substrate of the thin film together with the creation of a surrounding copper chamber by electroforming [2]. As low as 3 mm diameter coated vacuum chambers were successfully produced using this method. After process optimization, TiZrV getter coating showed a good H_2 pumping performance with slightly delayed activation temperature compared to reference NEG coating values.

[1] C. Steier et al., Proceedings of IPAC, Richmond, USA p. 1840 (2015)

[2] L. Lain Amador, P. Chiggiato, L. M.A Ferreira, V. Nistor, A. T. Perez Fontenla, M. Taborelli, W. Vollenberg, M-L Doche, J-Y Hihn, J. Vac. Sci. Technol. A, 36, 021601 (2018)

VT-Invited On Demand-7 Vacuum Technology for Fusion Research*, **Christian Day**,* Karlsruhe Institute of Technology (KIT), Germany **INVITED**

Vacuum technology is of paramount importance for the design and operation of nuclear fusion devices. Since the start of the first tokamak and stellarator machines in the 60s, vacuum requirements in the harsh fusion environment turned out be design driving. One has to know that, contrary to the accelerator community, where there is a quest for lowest pressures, the pressure requirements in fusion (during the plasma pulse) are relatively moderate (1 Pa range). The pumping speed challenge in fusion, in particular for the larger devices, is not driven by low pressures but comes from the high throughput needed to compensate for the low burn-up of the injected deuterium-tritium fuel.

The first lab-scale machines triggered the development of high throughput turbomolecular pumps. With increasing size, pumping speed requirements became larger and larger. Nowadays, most medium-size fusion devices are equipped with cryogenic pumps. A highlight of this technology is ITER, where the use of tritium poses additional requirements on the vacuum system design.

The next step after ITER, then producing its own tritium and providing electricity to the grid, will be a demonstration fusion power plant (DEMO), the pre-conceptual design of which is under elaboration in different places on the world. On DEMO scale, accumulation pumps would build up excessive tritium inventories which imply regulatory issues. This is why a R&D programme has been launched in Europe to develop alternative pump technology.

The paper will introduce in how the requirements and challenges have evolved over the last five decades of nuclear fusion vacuum technology. Examples will be given for turbomolecular and cryogenic pumps. The DEMO development programme which looks into tritium-compatible mercury driven diffusion and liquid ring pumps as well as high capacity getter pumps will be reviewed and recent highlights be presented.

VT-Invited On Demand-13 Innovations in Gauges and Gas Analysis*, U. Bergner,* VACOM, Vakuum Komponenten & Messtechnik GmbH, Germany*; **Klaus Bergner**,* VACOM Vakuum Komponenten & Messtechnik GmbH, Germany **INVITED**

Due to the rapidly advancing digitalization, many B2B and B2C products are experiencing increasing miniaturization to make them more robust, more powerful and require less energy. At the same time, these products are expected to have increased functionality and flexibility. Typical examples are computer chips, OLEDs or smartphones. These products are manufactured by complex equipment. Key function is in first step to make grown complexity visible and in second step to become proficient with it. This is the only way to reach high yield and first time right rates as well as high reproducibility. Hereby many components, which are usually out of focus, are very important; vacuum measurement sensors. In our contribution we describe the current development of partial- and total pressure measurement technology including innovative solutions.

VT-Invited On Demand-19 Quality and Regulatory Issues for Vacuum Technology in Nuclear Power Plants*, **Charles Smith**,* US ITER / ORNL*; A. Buckley,* US ITER **INVITED**

The ITER Project is a collaboration between China, the European Union, India, Japan, Korea, Russia, and the United States to build the world's largest tokamak, a magnetic fusion device that will prove the feasibility of fusion energy on a large scale. The device incorporates a large, multi-function vacuum system as part of its primary systems. This will be the first such vacuum system which must be designed to meet the requirements of a nuclear regulatory body. US ITER Project Office (USIPO), which is managed by UT-Battelle on behalf of Oak Ridge National Laboratory for the US Department of Energy, is responsible for the design, fabrication, and delivery of major subsystems, including the Roughing Pump System (RPS) and the Vacuum Auxiliary System (VAS) to the ITER site in Cadarache, France.

Quality and regulatory compliance are of paramount importance to ensure the safe and reliable operation of ITER. As such, the vacuum system is subjected to the requirements of ASME B31.3 and must also undergo review in accordance with the European Pressure Equipment Directive (PED). All fabrication of bespoke components must undergo enhanced surveillance and monitoring to ensure it will perform as required in this challenging regulatory environment. As US ITER supplies equipment to the ITER Project construction site in Cadarache, France for integration, contracts are awarded across the globe. Ensuring compliance is an added challenge when working with a variety of 'equivalent' codes which vary based on the version year cited, differing ways to define qualified personnel, use of different unit systems, and adapting commercially available vacuum technology to meet the rigorous regulatory requirements for an operating nuclear power plant.

This presentation will discuss the quality assurance and regulatory challenges associated with a first of its kind system, the challenge of ensuring the implementation of an ITER approved quality program using a variety of standards and codes, and methods by which the USIPO has adapted its on-site surveillance program to ensure the production of quality hardware during the Covid-19 pandemic.

VT-Invited On Demand-25 Progress in the Construction of the ITER Vacuum System and Advancement in Vacuum Technologies for Fusion*, **Robert J.H. Pearce**, I. Banerjee,* ITER Organization, France*; J. Benet,* Fusion for Energy, Spain*; B. Boussier, J. Buckerfield,* ITER Organization, France*; F. Canadell,* Fusion for Energy, Spain*; F. Chitu, A. Cobalt, M. Dremel, S. Giors, G. Godia, S. Hughes, E. Quinn,* ITER Organization, France*; C. Smith,* US ITER Project*; A. Teissier,* Fusion for Energy, Spain*; D. Williamson,* US ITER Project*; L. Worth,* ITER Organization, France **INVITED**

ITER is under construction in the south of France in order to demonstrate the feasibility of fusion as a clean power source. It is one of the world's largest scientific and engineering collaborations. The civil structures have progressed, allowing the start of installation of very large vacuum vessels, in-vacuum components and vacuum piping networks.

The ITER vacuum system will consist of a number of large volume vessel systems including: the Cryostat (~ 8500 m3), the Torus (~1330 m3), the Neutral Beam injectors (~180 m3 each) and a large number of lower volume systems. The Vacuum System forms an integral part of the Fusion Fuel Cycle, streaming all gas originating or injected into the tokamak, through the Roughing Pumping System, to the other Tritium Plant processing systems.

The technology of the Vacuum Systems is particularly driven by ITER's fusion power operational phases, where gas streams dominated by hydrogen isotopes will be pumped in a magnetic and ionizing radiation environment. More than 90% of the vacuum system will however be installed and operational for the First Plasma phase.

An overview of the ITER construction is given with details of the challenges and solutions for assembling the UHV systems whilst completing civil works.

New technological developments, to facilitate the demanding vacuum and pumping duties coupled with safe confinement of radioactive/tritium inventories, are highlighted with results from the qualification programs for: in-vacuum nuclear dust filtration, large demountable rectangular UHV metallic sealing, tritium compatible mechanical vacuum pumps, cryogenic pumps, vacuum/cryogenic valves, vacuum instrumentation and vacuum leak localization techniques.

The paper will show spectacular progress in the construction of ITER and in the advancement of vacuum fusion technologies. Confidence in the vacuum system design and operability for both the ITER first plasma and fusion power phases will be demonstrated.

VT-Invited On Demand-31 Overview of the Outgassing Behavior of Metals, Polymers and Ceramics*, **Katharina Battes**, C. Day, V. Hauer,* Karlsruhe Institute of Technology (KIT), Germany **INVITED**

For every vacuum system the outgassing behavior of the applied materials has an impact on the pump down time and the minimum achievable pressure. Especially, at large systems or if low pressures are required, outgassing rates play a major role.

To systematically study their outgassing rates, different metals, polymers and ceramics were investigated at the Outgassing Measurement Apparatus (OMA) at KIT. OMA uses the so-called difference method, a modified throughput method, to determine specific outgassing rates related to the geometrical surface area of the sample. The advantage of the difference method is that a second vacuum chamber, which is identical to the sample chamber, is used as a reference in order to directly subtract the background outgassing rate of the chamber.

The investigated materials include stainless steel 316L, tungsten and copper alloys, Viton® and Vespel® as well as alumina, titanium nitride and silicon carbide, for example.

This paper compares the results of the performed outgassing rate measurements of the different materials as a function of time and temperature, ranging from 10^{-2} to 10^{-9} $Pa \cdot m^3/(s \cdot m^2)$. Information about the outgassing species are furthermore determined with a quadrupole mass spectrometer. Finally, the influence of manufacturing and pre-treatments of the samples will be discussed and a recommendation regarding the use of the material in vacuum is given.

VT-Invited On Demand-37 SynRad and MolFlow for Vacuum Analysis of CERN*, **Marton Ady**, R. Kersevan, P. Baehr,* CERN, Switzerland **INVITED**

SynRad+ and MolFlow+ are Monte Carlo simulators for synchrotron radiation (SR) and ultra-high vacuum (UHV), currently developed at CERN.

SynRad+ allows to trace photons - emitted by common magnetic accelerator elements - in a geometry describing the vacuum chamber by polygons. The calculated SR flux can be converted to dynamic gas load, and imported to MolFlow+ for an independent UHV simulation, predicting the pressure profile.

This talk presents recent developments, such as the transition to open-source and cross-platform, the support for geometry editing within the graphical user interface, and an external tool to convert large accelerator sequences to optics and geometry files readable by the codes.

The future development roadmap is outlined, including scripting and iterative simulations. Of particluar importance, the effort to run the codes on latest-generation Nvidia GPUs is presented, with early results showing 300x speedup on entry-level consumer cards. Finally, the feasibility of running the codes on high-performance clusters is discussed.

VT-Invited On Demand-43 Next Generation Synchrotron Light Source: Vacuum System of the 3 GeV Electron Storage Ring at MAX IV Laboratory*, **Marek Grabski**,* Max IV Laboratory, Sweden **INVITED**

The 3 GeV electron storage ring at MAX IV laboratory is the first synchrotron light source that implemented compact multi-bend achromat (MBA) magnet lattice to lower the beam emittance, and fully coated with non-evaporable getter (NEG) vacuum system to ensure low gas density. The storage ring started commissioning in August 2015 and currently delivers photon beams from insertion devices to several beamlines that are in user operation or commissioning.

Several technological challenges had to be tackled in order to achieve ultra-low emittance of the stored electron beam. One of the challenges was the vacuum system, which had to cope with severe space constraints, imposed by the compact MBA lattice, and intense synchrotron radiation from the circulating electron beam. To ensure compact, reliable and cost effective solution the vacuum chambers were constructed out of water cooled, extruded copper pipes. The inner surface of the vacuum system was NEG coated all along the storage ring circumference.

After over 5 years since the start of commissioning, the NEG coated vacuum system proved to be reliable and conditioning well. Average dynamic pressure measured around the storage ring is below 1 picobar and is reducing with the accumulated beam dose. The beam lifetime related to residual gas density is greater than 39 Ah. The total beam lifetime is above the design value of 5 Ah - thus is not limited by the vacuum level. Several successful interventions to install new vacuum components were performed on a few achromats in the storage ring during shutdowns. This was done utilizing venting of the system with purified neon gas, thus avoiding the need of re-activation of the NEG coating and saving intervention time without compromising the storage ring performance.

Design principles, performance and operational issues of the 3 GeV storage ring vacuum system will be presented.

VT-Invited On Demand-49 Vacuum Technology of Hyperloop*, **Tom Kammermeier,*** Leybold GmbH, Germany*; D. Corcoran,* Leybold USA Inc.*; S. Rosenstraeter,* Leybold GmbH, Germany **INVITED**

The anticipated demand of vacuum technology for a large scale Hyperloop track of some hundreds of kilometers is enormous. Even though the requirements of evacuating a huge air-filled chamber and the maintaining of a low pressure environment seems simple at a first glance, the details might be much less trivial. Unlike every other vacuum chamber in the world, in this case, the pumping stations will be scattered over hundreds of kilometers. Pressure variations along the track are only permissible in a small range, otherwise there would be an impact on the pods' aerodynamics. The operation pressure must be a trade-off between aerodynamic friction, energy consumption of the pumping system and a low leak rate of the tube construction. Finally, a short pump down time after e.g. a maintenance interval is desirable but easily impacts the investment into vacuum pumps – and can result in an unnecessary abundance of pumping speed, which could mean a lot of idle machinery during standard operation.

Peak energy consumption for any hyperloop vacuum system will occur during end-to-end pump-down along the track. Pump down times of the order of 12–24 hours can be anticipated. Issues for pump systems can include overheating due to gas compression; overloading of the motors; or exceeding temperature limits due to low heat dissipation at low gas pressures. Total pumping speed requirement can easily add up to millions of m^3/h for a 1000 km track. In view of this, calculations of power requirements or energy consumption, respectively, have become as important as vacuum performance.

By using the Leybold-Simulation Software, we have calculated different scenarios. The software accounts for all relevant parameters like pumping speed curves, conductance effects of piping, energy consumption, variable rotation speeds depending on gas load etc. Results are discussed in particular with regard to energy efficiency.

VT-Invited On Demand-55 Latest Developments and Uses of Neg Technology in Fusion Energy Applications*, **Enrico Maccallini,** P. Manini, M. Urbano, F. Siviero, L. Caruso, A. Ferrara, M. Mura,* SAES Getters SpA, Italy*; M. Siragusa, E. Sartori, P. Sonato,* CONSORZIO RFX, Italy*; G. Motojima, T. Murase, S. Masuzaki, T. Morisaki,* NIFS, Japan*; C. Day, S. Hanke,* KIT, Germany **INVITED**

ZAO® is a new sintered getter material allowing the use of the Non-Evaporable Getter (NEG) technology in fusion energy applications where large fluxes of hydrogen and its isotopes have to be adsorbed/desorbed with unchanged pumping properties over multiple cycles. In this presentation, we report the experimental characterization of ZAO®sintered getters, in pressure regimes and sorption amounts relevant for fusion applications. Experimental results will be presented on the integration of ZAO®based pumping system in final applications such as NBI and divertor devices.

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