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

*This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with DOE Public Access Plan (*http://energy.gov/downloads/doe-public-access-plan*)*

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 Overview of the Vacuum Pumping Systems for the SPARC Tokamak**, ***Matt Fillion,*** *A. Kuang, O. Mulvany, J. Fountas, P. Winn,* Commonwealth Fusion Systems

Commonwealth Fusion Systems (CFS) is a spin-off from the Massachusetts Institute of Technology aiming to bring fusion energy to the grid. CFS is currently building the SPARC tokamak—a superconducting, high-field, deuterium-tritium fueled tokamak that is designed to reach Q>1. SPARC is a crucial step to develop the technologies and refine the physics necessary for ARC, a commercial fusion power plant capable of delivering net energy to the grid.

The Vacuum Pumping System of SPARC consists of three primary subsystems. The cryostat pumping system generates and maintains vacuum insulation of the cryostat to support the superconducting magnets. The leak detection system provides vacuum guarding for the many tritium secondary interspaces and double seals throughout SPARC. Lastly, the torus pumping system is responsible for four main functions: the containment of tritium, reaching and maintaining the primary vacuum vessel base pressure, the recovery of the inter-pulse pressure, and providing particle control during the plasma discharge by pumping from the divertor regions.

Each of the three vacuum pumping subsystems has an independent set of two dry screw pumps to provide rough vacuum and fore line pumping, mag-lev turbomolecular pumps for achieving ultrahigh vacuum, and a residual gas analyzer for leak detection and analysis of the plasma exhaust composition. In addition, the cryostat and torus pumping systems each contain custom tritium compatible closed loop refrigerator cooled cryogenic pumps to provide temporary enhanced pumping speeds. The cryostat and torus pumping systems also feature piping up to DN540, which calls for the development of a custom CF-style knife-edge flange.

The magnetic field strength and neutronic flux can damage or heat components near the tokamak, including the cryogenic pumps, sensors, turbomolecular pumps, and cables. This provides a narrow design window for equipment, and in some cases requires local shielding to protect sensitive components. Boron carbide (B4C) neutronic shielding will be used to prevent a large flux of neutrons from the plasma through the vacuum ducting. The vacuum conductance was analyzed in the molecular and transitional flow regimes to optimize the size, shape, and position of the B4C.

This talk will provide a general overview of the SPARC vacuum pumping systems and associated challenges, with a focus on the torus pumping system and the design of custom tritium compatible pumps required by this system.

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 ^4He 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 ^4He 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.

Author Index

Bold page numbers indicate presenter