FIRST RESULTS FROM WHAM AND THE REALTA FUSION TANDEM MIRROR DEVELOPMENT PATH

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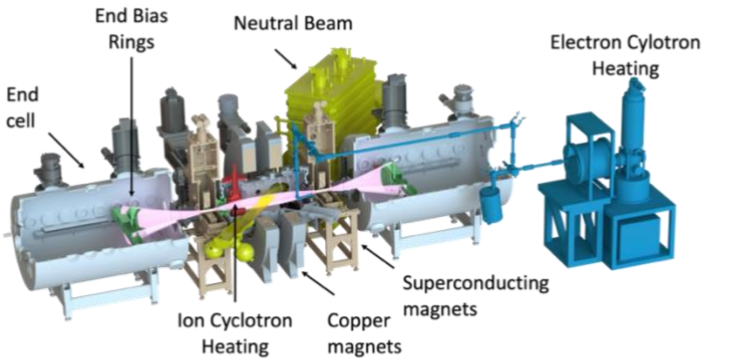

Figure 1 The Wisconsin HTS Axisymmetric Mirror (WHAM)

The construction of **WHAM** [1] (see Fig. 1), originally funded by ARPA-E, is now complete and the device is providing physics model validation risk reduction for the mirror development path [2]. Realta Fusion is an early-stage startup that now jointly operates WHAM as an equal partner in the UW-Realta experimental team. WHAM is the first machine to harness the high-field capabilities of REBCO superconductors for fusion, enabling confinement with steady-state electromagnets applying 17 T on the plasma column. WHAM is a unique facility (both in the US and in the world) pursuing fusion energy via the high-field, compact magnetic mirror. Its four advanced MW-class plasma heating systems (110 GHz ECH, 30 MHz HHFW, 18-25 keV NBI, and a 3 kA-2 kV active biasing for rotation drive) are now providing unprecedented experimental results. The near-term research program is focused on stabilizing the interchange instability through a combination of finite Larmor radius stabilization from well-confined fast ions and by controlling the azimuthal flow shear.

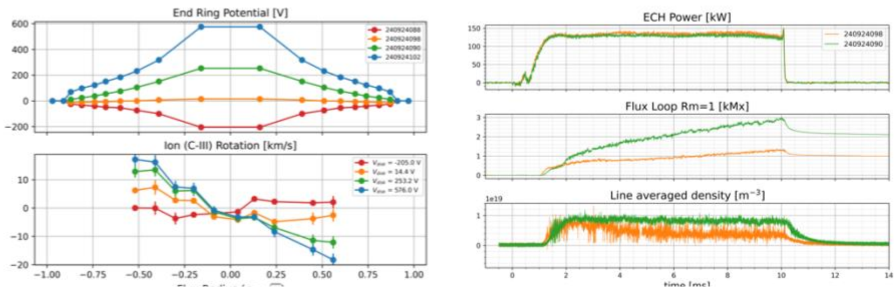

Figure 2 (Left) The potential measured on 10 concentric end rings, and the velocity profile measured by ion spectroscopy (Right) Time evolution for ECH power, diamagnetic pressure measured by a flux loop and line averaged density measured at z=0.

In the first experimental campaign (July-October 2024) the two CFS supplied HTS magnets maintained full field for 78 days and landed safely for a set of planned upgrades. The base-line diagnostic set included a 1 mm wave interferometer for density, diamagnetic flux loops for stored energy, visible and X-ray spectroscopy, UV tomography, an array of NBI shine-through detectors to infer density profiles, bolometry, end-loss analyzers, and fusion product measurements.

Research conducted on WHAM has already achieved significant milestones during its initial experimental campaigns. First, successful electron cyclotron resonance breakdown was demonstrated using a high-field-side X-mode launch, facilitated by a split waveguide antenna which prevents RF breakdown by sweeping electrons liberated within a single RF cycle by use of (~2 kV) DC bias. The application of up to 400 kW of ECH demonstrated robust target plasma formation achieving line averaged densities up to ~ 10^{20} m^{-3}, with very clear evidence of both a warm high-density plasma and a low density but very energetic hot electron plasma (with hard x-rays of energy >100 keV observed for multiple seconds, 100× longer than the pulse length). Second, the anticipated MHD instabilities, including high-*m* flute modes and the low-*m* rigid shift (*m*=1) mode were clearly observed, as expected, on fast cameras and other plasma measurements. Third, the plasma rotation can be controlled through limiter and end-ring biasing; spectroscopic measurements show flows of up to 20 km/sec (see Fig. 2); and the biasing has shown significant influence on MHD activity, improving performance in the initial experiments. Fourth, WHAM has accessed a high-density plasma regime by utilizing neutral beam injection for fueling.

During the first campaign, neutral beam injection was successfully used to fuel the plasma by injecting into ECH target plasmas but was incapable of sustaining the plasma without ECH due to poor fast ion confinement due to charge exchange. During the first maintenance/upgrade period an extensive wall conditioning program, including vacuum vessel baking to >100 C, lead to NBI sustained discharges during the second campaign and substantially improved plasma stored energy when combined with optimized plasma biasing, thus justifying further planned efforts to reduce recycling [6].

Realta Fusion is now in the middle of a two-year design phase of a next step compact mirror called **Anvil** (a breakeven class simple mirror [3]) to follow WHAM that would be a single next step to a modular end plug of a tandem mirror fusion energy system **Hammir** [2]. A key risk-reduction strategy for Realta is to assemble and further develop a state-of-the-art suite of codes that can be validated against WHAM data and can be used to predict the performance of Anvil. Presently, this model includes an anisotropic equilibrium solver Pleiades coupled to the CQL3D-m bounce-averaged Fokker Planck code and realistic plasma heating and fuelling sources for long time scale transport simulations. The transport time scale simulation of the equilibrium evolution has also been self-consistently mapped into the kinetic particle-in-cell code VPIC to assess kinetic and MHD stability on growth rate time scales [5].

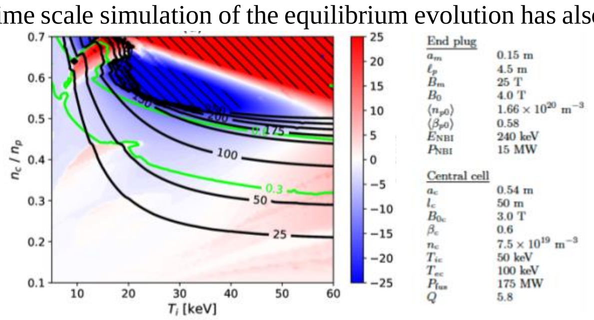

Figure 3: A POPCON for the central cell of the tandem mirror. Fusion power is shown in black contours, beta is shown on green contours, red and blue contours show the required RF power applied to reach a given operating point. Negative values (blue) of RF power indicate a thermally unstable ignited operating point.

The Hammir design point for a fusion pilot plant [2] used these integrated end plug simulation models including heating, equilibrium, and transport like that used in [3] coupled to a 0D classical tandem mirror confinement model that self-consistently includes alpha particle heating that gives an ignited central cell plasma [as illustrated in tandem mirror central cell plasma operation contours (POPCONs) in Fig. 3]. Using this model, it is shown that an end plug utilizing high temperature superconducting magnets and modern neutral beams enables a classical tandem mirror pilot plant producing 175 MW of DT fusion power with fusion gain Q > 5.

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