Title: Overview of WHAM Diagnostic Techniques and Realta Fusion Digital Validation Efforts

D.Endrizzi[1], C.B. Forest[1,2], J.K. Anderson[1,2], O. Anderson[2], D. Bindl[1] , B. Biswas[1] , E. Claveau[1], M. Clark[2], S. Frank[1], K. Furlong[1], R.W. Harvey[3], M. Ialovega[2], J. Kirch[2], A. Le[4], E. Penne[2], Y. Petrov[3], J. Pizzo[2], S. Oliva[2], T. Qian[2], K. Sanwalka[2], O. Schmitz[1,2], K. Shih[1], D.A.Sutherland[1], B. Terranova[2], Tran, A.[2], J. Viola[1], J. Wallace[2], D. Yakovlev[2], M. Yu[2]

1 Realta Fusion Inc, Madison, WI, USA
2 University of Wisconsin-Madison, Madison, WI, USA
3 CompxCo, San Diego, CA, USA
4 LANL, Los Alamos, NM, USA

Email: dendrizzi@realtafusion.com

The Wisconsin HTS Axisymmetric Mirror (WHAM) experiment and the University of Wisconsin-Madison commenced operation with its first plasma July 15th, 2024 [1, 2]. A large set of diagnostics, mostly constructed by the UW team, measure device performance. Machine data has been used by Realta Fusion for numerical validation of digital tools, particularly the RealTwin digital twin mirror model [3]. These tools have in turn provided great insight into the measured plasma behavior. Both the measurements and the validation efforts are essential first steps towards advanced stabilization techniques, like active feedback, that could enable the axisymmetric mirror concept to scale to a fusion energy system [4]. This presentation will cover the diagnostic suite and the four most productive examples of collaboration and numerical validation between the WHAM experiment and Realta Fusion: **neutral fueling**, **electron heating**, **fast fluctuation measurements**, and **equilibrium reconstruction**.

Neutral fueling in axisymmetric mirror simulations explains experimental data. Density profile measurements are made using a single chord mm-wave interferometer and a neutral beam shine-through array. High densities above 10^{20} m^{-3} are relatively easy to achieve, though inevitably lead to steep radial density gradients and increased refraction of the interferometer beam. An INFUSE project between Realta and ORNL brought a Thomson Laser system to WHAM to provide a third corroborating measurement of the density profile. As part of its model development, Realta has contracted with CompxCo to incorporate neutral fueling into CQL3D-mirror and RealTwin. Neutral fueling rates, referenced to base wall pressures, can be used to predict the radial profile.

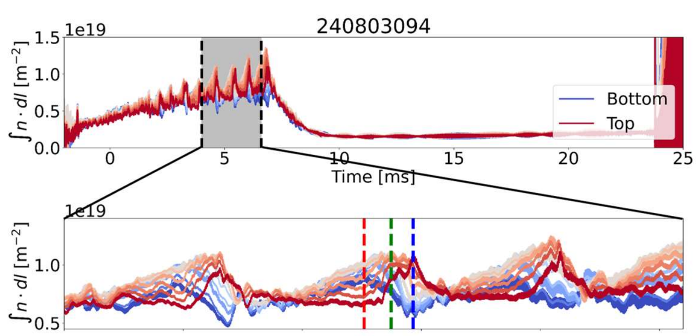

***Figure** 1: Measurements from an NBI shine-through diagnostic provide time resolved, line-integrated density measurements across the plasma. These agree very well with single-chord interferometry measurements and provide more information about the spatial fluctuations. In this particular shot, a gate valve magnetized by the high field was partially closed, leading to an unexpected oscillatory behavior.*

Energization of tail electrons via focused electron cyclotron heating is compared between digital model and experimental data. Spectral measurements of soft and hard X-rays produced by electron Bremsstrahlung have shown the strongly non Maxwellian distribution produced in high ECH power, low density discharges. These energetic electrons are well confined, emitting very high energy X-rays sometimes seconds after the electron cyclotron heating power has terminated. By either decreasing the input power or increasing the density, this energetic tail population can be reduced. Realta has attempted to describe this behavior using a version of CQL3D adapted for mirror geometry. Evidence of kinetic electron instability intermittently appears in the strongly non-Maxwellian afterglow plasma.

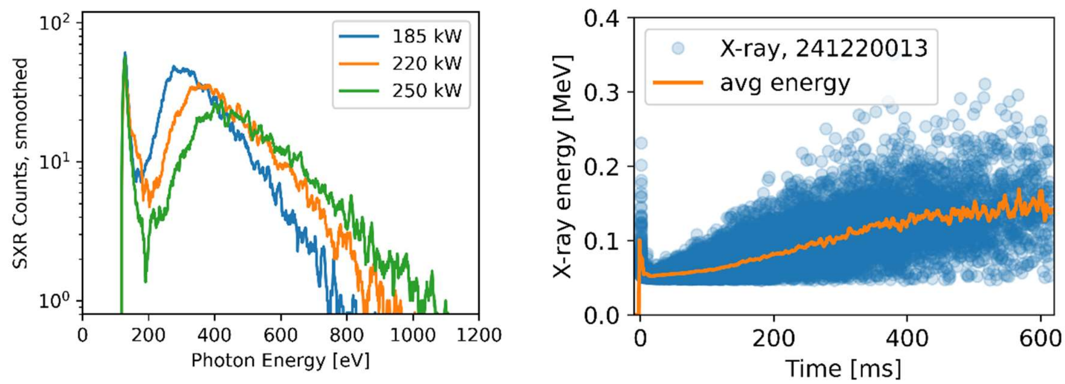

Figure 2: *Left: increased ECH power is reflected in the measured soft X-ray spectrum. Right: Hard X-ray measurements from a high power, low density ECH shot show signal long after the 20 ms of input power. In the afterglow, cold electrons scatter and deconfine more quickly, leading to 'evaporative heating'.*

Measured fluctuations in digital simulations and experiment compare plasma performance with and without end-ring biasing. Fluctuation measurements from an AXUV array (single position, 20 chord, filtered to admit 15-70 eV photons) reveal the effect of end-ring biasing on plasma stability and profile. An analysis code from Realta is used regularly by WHAM experiment personnel for shot-to-shot comparison of fluctuation amplitude. This same analysis code is used on synthetic hybrid-VPIC data. This work shows it is feasible to use plasma self-emission measurements for fast measurements of plasma position as part of an active feedback system for negative feedback on bad curvature driver radial displacement.

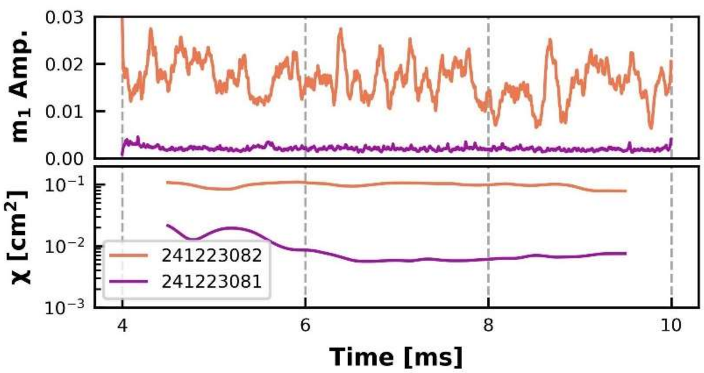

Figure 1: *Top, amplitude of m=1 plasma oscillations, as measured by a 20 chord AXUV diode array. Bottom, the y-axis parameter represents the phase space area of fluctuations in the centroid position and radius of the emission profile. The factor of 10x reduction in fluctuations is due to end-ring biasing applied in shot 241223081 and absent in 241223082.*

Equilibrium reconstructions can be used to measure relative pressures of fast ion, hot electron, and Maxwellian species. Axially resolved flux loop measurements, in a mirror geometry, provide crucial information about pressure anisotropy and pressure profiles. Three WHAM flux loops spaced 25 cm apart are sufficient to infer the pressure contribution from neutral beam fast ions injected at 45 degrees, from hot sloshing electrons resonating at the 4 T ECH surface, and from cold and collisional Maxwellian thermal populations. Realta has helped develop an equilibrium fitting routine for reconstruction of the plasma profile, estimating relative contributions from distinct plasma species.

1. Endrizzi D., et al. Physics basis for the Wisconsin HTS Axisymmetric Mirror (WHAM). *Journal of Plasma Physics*. 2023;89(5):975890501. doi:10.1017/S0022377823000806

2. Anderson, JK. (2024, Oct 7-11) *First physics results from the Wisconsin HTS Axisymmetric Mirror (WHAM)*. American Physical Society – Division of Plasma Physics 66th conference. Atlanta, GA.

3. Frank, S. J., et al. "Integrated modelling of equilibrium and transport in axisymmetric magnetic mirror fusion devices." *arXiv preprint arXiv:2411.06644* (2024).

4. Forest, C. B., et al. Prospects for a high-field, compact break-even axisymmetric mirror (BEAM) and applications. *Journal of Plasma Physics*, **90** (2024) 975900101.