Notes from the UW-Madison Fusion Experiment Workshop on Neutrals and Impurities
May 28th, 2025

These notes are a rough transcription of the questions taken by Doug Endrizzi. As I am not a professional typist, I can guarantee that this is NOT an accurate transcription. Please use it only qualitatively.

Morning Session: Neutrals
WHAM Neutrals, Kunal Sanwalka
HSX Neutrals (A), Thomas Gallenberger
HSX Neutrals (B), Benedikt Geiger
Pegasus Neutrals, Sophie Redd
MST, Patrick Tracy

Afternoon Session: Impurities
WHAM Impurities, Mason Yu
MST Impurities, Joe Flahavan
HSX Impurities, Alexis Wolfmeister
Pegasus Impurities, Temo Rodriguez Sanchez

Participant List:
Doug Endrizzi (WHAM/Realta)
Levi Grantz (WHAM)
Dmitry Yakovlev (WHAM)
Dev Ashish Khaitan (WHAM/Realta)
Josh Reusch (Pegasus)
Molly Aslin (Pegasus)
Mason Yu (WHAM)
Sophie Redd (Pegasus)
Corben Browne (Pegasus)
Patrick Tracy (MST)
Elliot Claveau (WHAM/Realta)
Kunal Sanwalka (WHAM)
Temo Rodriguez (Pegasus)
Wayne Goodman (HSX/Xantho)
Ethan Pevlow (HSX)
Alex Thornton (HSX)
Thomas Gallenberger (HSX)
Chris Seyfert (HSX)
Mark Nornberg (HSX, Pegasus-III)
Isaac Rudey (MST)
Noah Hurst (MST)
Ed Marriot (WHAM/Realta)
Ishita Kemeny (WHAM/Realta)
Joe Flahavan (MST)
Tyler Walters (Pegasus)
Tony Qian (WHAM)
Alexis Wolfmeister (HSX)
Sam Farrar (MST)
Ben Rujak-Ford (Pegasus-III)
Jay Anderson (WHAM!)
Cary Forest (WHAM, MST)
Steve Oliva (WHAM, MST, Phaedrus)
Daniel Den Hartog (MST)
Alex Squitieri (MST)

WHAM Neutrals, Kunal Sanwalka

Mark Nornberg: was the goal to get as good vacuum conditions as possible? Or did you have a target in mind given charge-exchange cross sections.
KS: No, we really didn't have a model of the neutral profile, or the wall recycling coefficient.
Cary Forest: We did have estimates of FI confinement given neutral pressure in the edge, and it could vary from microseconds to ms, depending on how low the neutral pressure got. If nothing else, this was a 'let's turn this knob and see what happens'.

CF: Were you able to strike a discharge end to end?
KS: With field present, yes. I didn't do it during this glow discharge process.

Wayne goodman: Do you have a measure of the species ratio, H/He, in those plasmas?
KS: We don't have that for those shots.

Tony Qian: Are there other things that could be different about those two shots? (Reference slide 27).
KS: Yes, unfortunately. Gas injection setup, gas pressures, valve timings, opening amounts. But I tried to find self-similar. One important difference, the gate valve was in the plasma during the first campaign.
Doug Endrizzi: Can you explain the magnetized gate valve story?
KS: Yes, over time the gate valves between the center and end cells magnetized and clipped out plasma. The viton oring and SS body was fully exposed to the plasma.
Cary Forest: One of the crazy things about working with a magnetic field at 17 T, is there are all these things you have to think about, including how do you glow-discharge?

Tony Qian: How do you distinguish between outgassing from the beam-dump and ingassing from the NBI source?
KS: good question, you can run the NBI system without turning on the accelerating grid. In those cases, the neutral pressure in the CC doesn't move at all. The two large cryo-panel pumps do a very good job of keeping neutrals out of the central cell.

Benedikt Geiger: Why titanium and not lithium or tantalum?
CF: Lithium in principle is better at absorbing fast neutrals and not letting them come back.

Mark Nornberg: On the sandblasted aluminum beam dump, was there specifications about surface roughness?
KS: No, the roughness was to increase surface area and also to let the titanium adhere. From the literature, it could be a 5x increase in surface area.

CF: 5x increase in pumping speed?
Dmitry Yakovlev: Not quite, there are shadowed regions.

BG: Have you considered glow discharge in other gases, like Neon?
KS: We were worried about the tungsten embrittlement.
Jay Anderson: We were overly concerned about the tungsten.
BG: Heavy ions are VERY good at sputtering.

HSX Neutrals (A), Thomas Gallenberger
Tony Qian: Whats the clearance between the plasma and wall?
TG: About 3 cm.
Alexis Wolfmeister: Exactly 3 cm, 12 cm minor radius average.

Jay Anderson: Have you studied the effects of baking at different temperatures?
TG: We have not. We're concerned about stresses on weldments, or pieces on the vessel that aren't modeled. Rule of thumb from Kurt Lesker, every 10 degC doubles the outgassing rate.

KS: Is the baking closed loop controlled?
TG: Yes, we set to 60 degC and it's a controlled system. We bake for 2-14 days, we turn the bake on an then walk away.

CF: Do you operate hot?
TG: Not normally.

Mark Nornberg: What's important to note about this Boric acid failure mechanism is that is a subtle failure, where the sensitivity decreases. You think that the vacuum is better than it is. That's why it's important to have multiple gauges, with different mechanisms.

JA: Slide 13, the 2hr glow didn't do much to water?
AT: We'll bake for 2 weeks and then glow for like a day, then we'll get the inverted triangle, like Wayne Goodman pointed out in the RGA traces.

HSX Neutrals (B), Benedikt Geiger
Cary Forest: What's the larmor orbit size? How many gyro radii?
BG: We are at 1.25 T, so it was ~1 cm larmor radius.
CF: And the poloidal larmor radius is small and unimportant?
BG: It should be fine. Predictions are that the ripple in HSX is bad, and so this will be tested. Having an ion heating system would be beneficial for us.

Tony Qian: Can you comment on W7X baking habits? Do they glow discharge?
BG: They glow discharge and boronize, beforehand, not between shots. At asdex-U, they would boronize once a month. They used diborane, the whole building was closed. It was great for the first two experiments, and then it would degrade.

CF: Carbon limiters at HSX?
BG: We have no limiters. The strike points are SS, most likely coated. In the past, HSX was boronized and carbonized. We cleaned the vessel. We ran an argon discharge which provided a layer everywhere, also on our windows. This is how we know it.
Kunal Sanwalka: Can you explain?
BG: Argon is heavy, it sputters well. Those sputtered layers of carbon, oxygen, steel, get redeposited elsewhere. Wayne found some literature on Neon as perhaps a lower sputtering option.

Pegasus Neutrals, Sophie Redd
Jay Anderson: What are the bright spots?
SR: Those are high field gas injection. The bright spots on the edge are probably PMI.

Doug Endrizzi: You don't have many viton orings?
SR: That's correct. Only a few around the helicity injectors, and some windows.
Josh Reusch: We force flux through the vacuum vessel. This is an old vessel, with a lot of history. The 18" flanges were taco'd by the people who installed them, 'cause they didn't know what they were doing. We don't bake because we're so nervous about these welds.

Josh Reusch: The numbers on slide 4 are flipped. Its 100 hr of hydrogen, 20 of helium. The 20 hrs is to remove the hydrogen. That was only for that first glow after the first wall install. Our subsequent glows are helium glows. The hydrogen glow was for all the new stainless steel.

Mason Yu: How did you increase the PV10 flow rate?
JR: We increased the voltage and the throttle.

Cary Forest: Can you say a little more about the protection of the windows?
SR: We have shutters on 3 total windows. We only gettering from the top side of the tank, so we put awnings, shades, hatbrims. The LHI systems have insulators on them, and they're exposed to the gettering, but they're in the plasma so its not the biggest problem.
CF: Does it flake off?
SR: We have had flakes. We have removed many many grams of titanium from the vessel. We haven't had any flammability problems. As soon as some water comes in, it takes care of that problem.

CF: Do you see any titanium signatures in the plasma?
Temo: I'll show slides later. It depends on the discharges. The radiative power could be high. Maybe 200 kW/m^3. Close to order unity radiated power fraction.

Benedikt Geiger: The titanium coating system...
SR: We have two stalks, sublimating titanium from those into the tank.
BG: Since only 80% is coated, have you considered doing this in combination with a glow discharge?
Chris Seyfert(?): In phase 2, we settled down and stopped glowing, unless we put in some kind of new material.

Jay Anderson: Have you studied the effect of the titanium coverage percent?
SR: We don't necessarily have control over that.
JA: Can you shut off one of the heaters?
SR: We have broken one of the heaters before, and we didn't notice.
JA: The reason I ask is that at WHAM we're designing a system, and we're trying to design fully coverage.
CS(?): I'll add, in phase 2 we used 4 stalks, compared to 2 now. There was no appreciable difference.

Derek Sutherland: Back on your particle inventory slide with the 1% ionization fraction, how do you quantify in this context what's good enough?
SR: So that's a great question. I thought this was low because it was 2 orders lower than the electron density. Our temperatures tend to be around 50 eV, we tend to be radiation dominated. We have hollow temperature profiles, perhaps because we're heating from outboard injection. Measured via TS.
DS: Your Te profiles are hollow because of the helicity injection and relaxation in the edge, is that right?
SR: Yes, and we're radiation dominated in the core.
DS: What's the dominant radiation in the core.
Temo Rodriguez: We'll talk about this in the afternoon session.

MST, Patrick Tracy

Jay Anderson: Do you know what ceramic was used to protect the oring between the halves?
Steve Oliva: Lava (alumina silicate).

Cary Forest: Can you explain the triple joint?
PT: There's a special joint called the pink baby, I'll show pictures of this.
CF: To be clear about the triple joint, this is a very non-trivial seal.

Tony Qian: Base pressure?
PT: Not listed here, but mid to high 10^-7. We're a bit lower than we've been since I started, now we're at 4-5e-7.

Benedikt Geiger: 80 F or C?
PT: 80 F, of course.

Tony Qian: I'm under the impression that MST vents rarely.
PT: Very rarely.
CF: Its not a small point, that since MST mostly operates as a tokamak, and the field has been increased up to about a Tesla, that's pretty impressive given that it's a single turn.

DY: How do you enter the vessel?
PT: There are photos of people inside the vessel?
CF: Only done with lid lifts.
Noah Hurst: Comment on that, there was talk about drilling a manhole for this purpose, but the ports introduce field errors.
PT: We do get lots of field errors. This was part of the motivation for the many small holes in the pumping duct.
CF: Just to crow a little bit, this was done very well, it’s the brainchild of Don Kernst, who is the father of UW Madison plasma physics. It’s a very cool machine.

WHAM Impurities, Mason Yu

Mark Nornberg: What collisional processes are you taking into account?
MY: Electron impact, and also charge exchange.

Benedikt Geiger: Does the location of heating affect the interchange?
MY: Certainly, off access ECH heating leads to huge impurity injection

BG: My other point is about UFOs. On HSX, we think it is dust that we mobilized.
MY: Turns out the USB webcam is the best, better than the fast camera.
DE: Might be because of the timescales, since the macro particles are moving much slower, through the afterglow plasma, and not through the well digitized timescale.

Doug Endrizzi: What about the correlation between the UFOs and the hot electron kinetic instability?
MY: We've seen cases where we don't see any UFOs, but still see this weird fast electron interchange. Of course its possible that they just weren’t in the field of view of the camera, but it seems they are unrelated.

MST Impurities, Joe Flahavan

Benedikt Geiger: Wavelength of C V is around 227 nm? Just confirming, this isn't fully ionized, even in the core.
JF: Yes, that's correct.

Cary Forest: Re PDC, what's the voltage? What's the input power? How much is deposited on the wall? 3 ms, 100 V? 10 V?
Steve Oliva: 10-15 kW average draw on the power supply.
CF: The speculation is that these are extremely effective UV sources?
JF: This is largely UV.
CF: So the UV is knocking the crap out of the water in the walls.

Derek Sutherland: Plasma impedance?
JF: Yeah, sorry I don't have this off the top of my head.
Benedikt Geiger: Plasma parameters during PDC?
JF: Actually, I don't know a lot of this because it runs automated, and we haven't collected data on this.

CF: With the new bolometers, it would be really interested to know the radiated power fraction to the walls via UV or to the limiter via contact.
JF: Yes, we'll take data on this PDC soon.

Kunal Sanwalka: Slide 17, where are the fringe skips?
JF: Unclear in this shot, but they are there.

Jay Anderson: The boron-carbide technique, did it work as well as this gaseous method?
JF: It had spots of inconsistency, depending on how much was released from the target. From what I've seen, in the radiated it performed as well. Ultimately, the retractable probe was a pain in the butt.
JA: The solid target boronization seems like a good idea.

CF: The O-carborane isn't dangerous, like the diborane?
JF: No, we didn't have to worry about contamination of the air.
CF: And none of these have been applied to MST tokamak performance? Do we think it will have a big impact?

Kunal Sanwalka: Why did ASDEX use the diborane instead of O-carborane?
Alex Thornton: Diborane just works. It's a little bit harder to get carborane to stick.

BG: B_2H_6, no carbon inside. They didn't want to get carbon inside of the machine.
Steve Oliva: We used TMB, trimethyl borane, on the Phaedrus. It was much less toxic.

HSX Impurities, Alexis Wolfmeister

Cary Forest: The 0.5 T is 2nd harmonic, you're able to break down?

AW: IT works great, even with that lower density performance, its pretty good. And a recent upgrade makes it a 15 minute swap to go between polarizations.

CF: 0.5 T O-mode?

BG: We can't start in O2.

Alex Thornton: We can try tomorrow.

Tony Qian: I wanna follow up, your name is Alex Thornton?

Alex Thornton: Actually my name is Thomas Gallenberger... [whole room laughs]

Jay Anderson: I this slide 10 color scale, do you have the peak to the minimum value?

AW: I do not.

CF: This is DEGAS?

AW: Yes, Degas 1, not DEGAS 2. Now that we have EMC-EIRENE capabilities, we're moving that way instead. For constraining neutral measurements, DEGAS has benefits.

Tony Qian: Your shot is 50 ms, what sets the t=0?

AW: Copper coils, ramp up slowly. The 50 ms is set by the ECH heating.

CF: Maybe a topic for a different day: I would've thought O-mode absorption should have no effect unless the plasma is already hot.

AW: Yes, we do have fast electrons, a seed population from the magnet turn on and the dBdt and induced Electric field. We had a flapper probe that we'd use to remove the fast electrons, and then pull it out just before the ECH turned on.

CF: Are you getting the runaway density because of fast electrons hitting the wall? I'm surprised it worked at all.

AT: We just didn't ask questions and it worked.

Tony Qian: Can you comment on the radiated power?

AW: These are not true bolometers, these were AXUV photodiodes that were looking through pinholes.

Jay Anderson: Any difference in CX losses now?

AW: We haven't done a quantitative assessment.

TQ: How many years was the boronization good for, before it deteriorated?

AW: About 8 years.

Alex Thornton: Until April 24th, 2017 [whole room laughs].

CF: Slide 34, is that consistent with TEM?
AW: Possibly, might change collisionality and then the ion behavior.

Pegasus Impurities, Temo Rodriguez Sanchez

Cary Forest: This SPRED detector is all in vacuum?
TR: Yes, the intensified phosphor screen is under vacuum, and the visible light passes out to the camera.

Tony Qian: Are you using Astro-py? Astronomers have nice automated packages to identify lines.
TR: Thank you, that will help.

Mason Yu: Can you elaborate about the absolute calibration of the branching ratio technique?
TR: When you know the emission coeffcient ratio between two lines?
MY: I see you cross calibrate between visible and invisible.
TR: They need to have the same line of sight. We have target lines people have used in the past. The best thing to do is to take it to a synchrotron.
Mark Nornberg: Somebody got rid of ours… [referring to SRC? Room laughs]

CF: Earlier, you said the radiated power fraction was big. You think that can be controlling the central eelectron temperature?
TR: When we look at the reconstructions, the typical current profile of LHI is very hollow. If ohmic heating is our only source, then we have very low core heating, and limits the core impurity/heating. We have to be very clean in order to not limit.
CF: But your thermal conductivity to the core might be high, and so you'll need to have a sink of energy.

Tony Qian: Slide 10, the erosion at the base, is this parallel transport?
TR: One mechanism is that the plasma is here, but also there's some backstreaming towards the plate.
TQ: So if you're backstreaming, you do have to cross field lines to get back.
Josh Reusch: yes, that ring structure around it is all floating, and they interrupt the electric field, but there is still a potential, so if it drifts off then it will backstream.,

Benedikt Geiger: You said you're launching a lot of electrons, the arc density is 10^21. Is the plasma Maxwellian? Or dominated by the electron beam? Can you assume for the Zeff inference that its Maxwellian?
JS: We think the beam density is quite low, 10^17. The beam goes around one or two times around the machine. The bulk plasma is separated from the beam by this reconnection

process. With the Thomson, we have caught the beam a couple times, and we can catch the shift of the beam. It's a very narrow shift, and the bulk plasma seems Maxwellian.