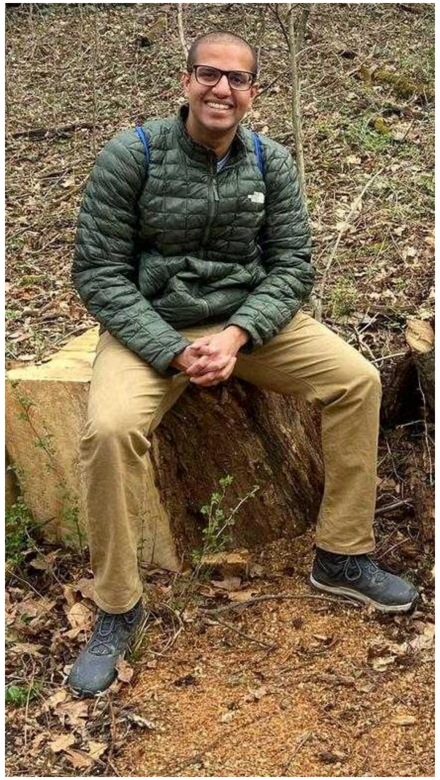
Vessel conditioning made me lose my hair!

Before tackling vessel conditioning

After

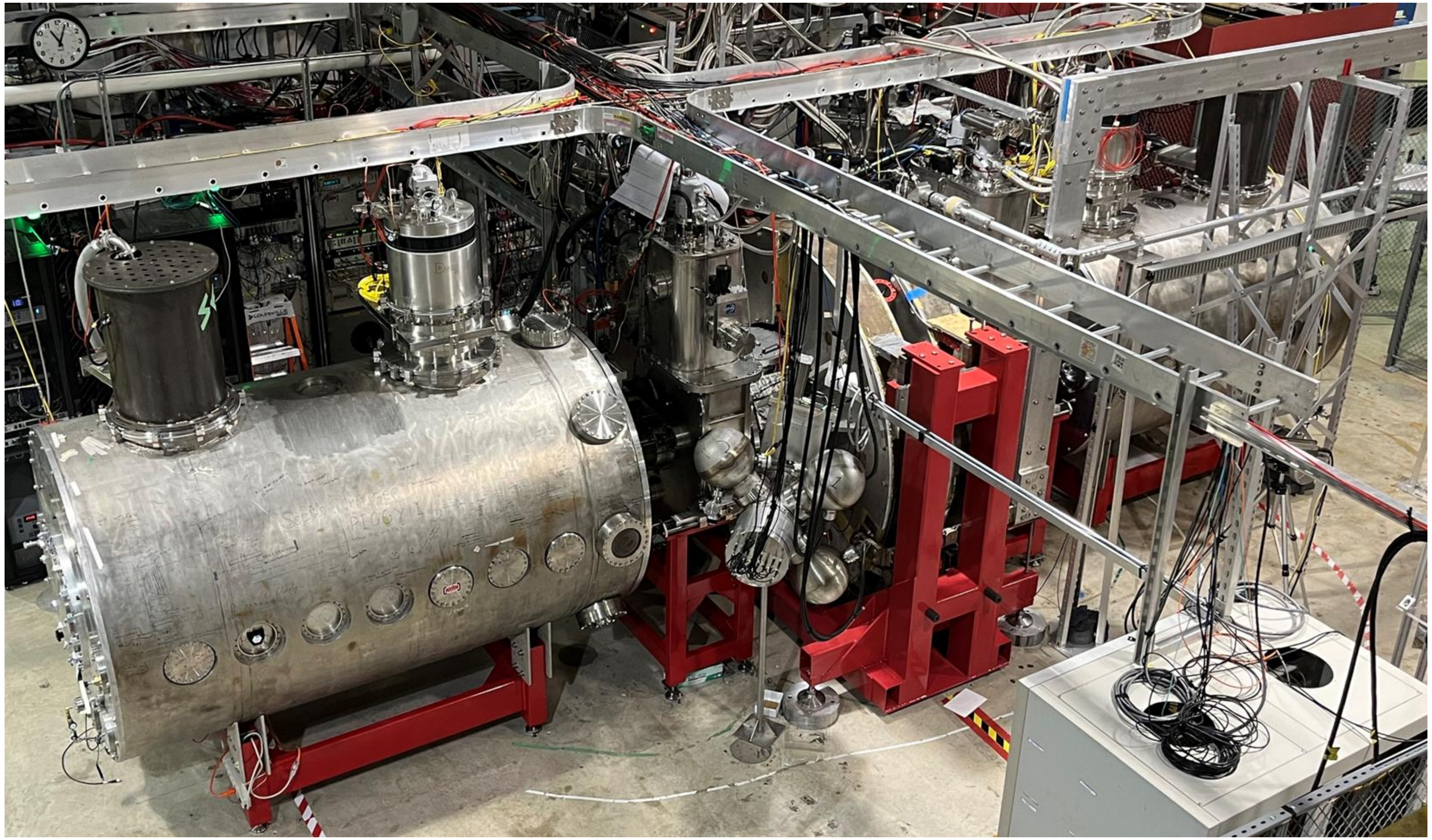


Hard fought lessons learned about vessel conditioning

Kunal Sanwalka on behalf of the WHAM team

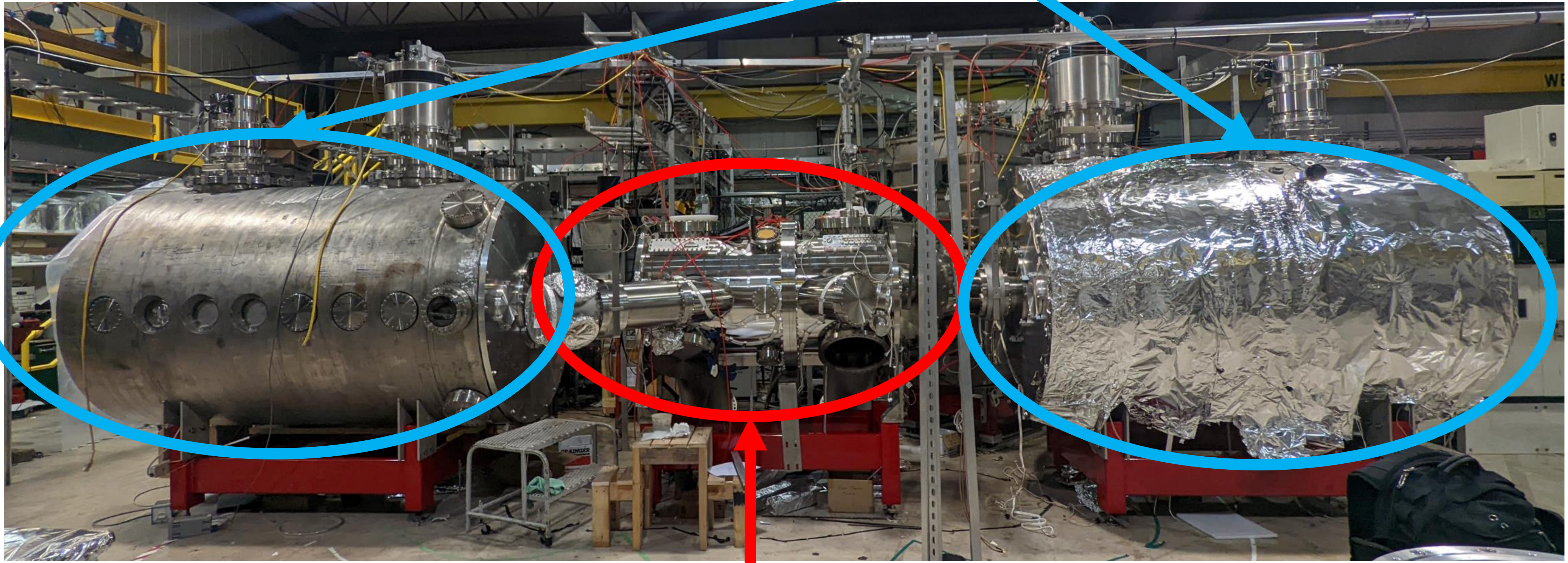
Introduction to WHAM

WHAM is a magnetic mirror machine



WHAM has 3 main vacuum vessels

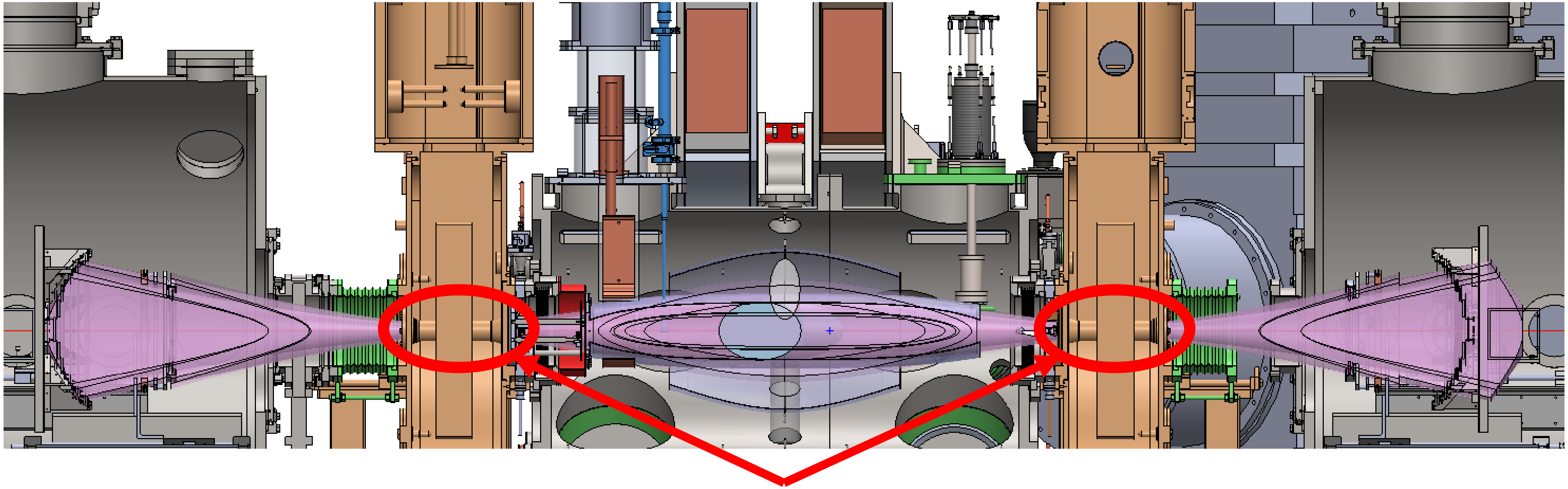
North and South end cells (NEC and SEC)



Central cell (CC)

Vessels are connected by a small magnet bore

South North

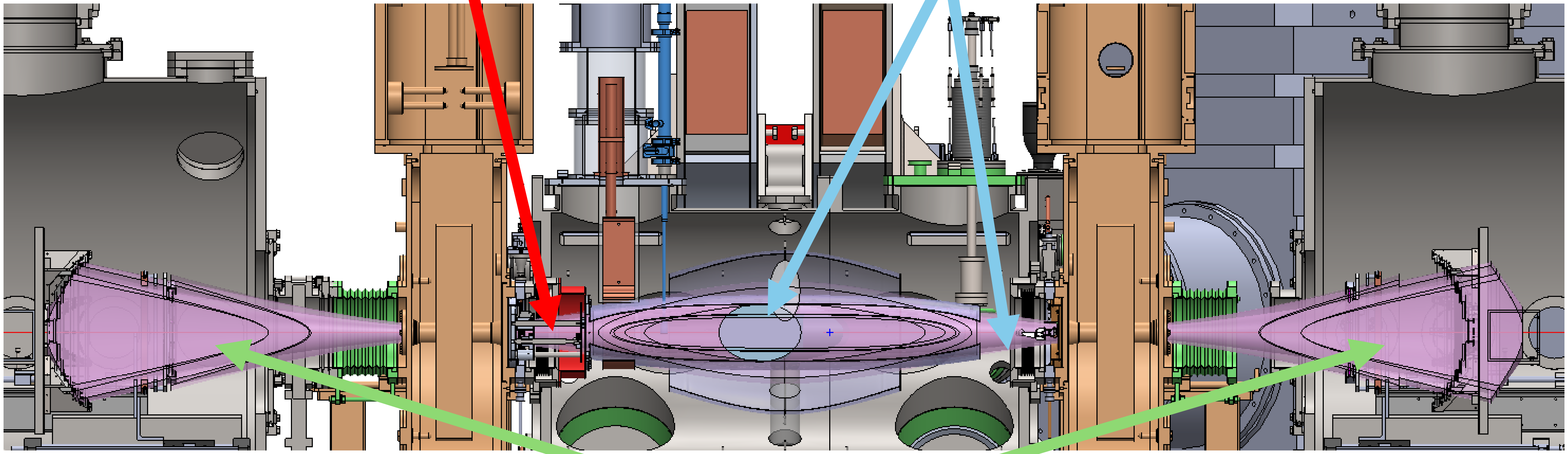


Magnet warm bore-
Diameter = 5.5cm
Length = 30cm

Plasma is produced and heated in the central cell

Gas injection

1MW NBI + 0.5MW ECH



Plasma exhausts into the end cells

Neutrals control is needed for MHD stability

MHD stability on WHAM is partly provided via FLR effects

- WHAM aims to be the 1st plasma device to have a collisionless, axisymmetric, MHD stable plasma.
- MHD instability manifests itself as interchange.
- m>1 interchange is expected to be stabilized by finite larmor radius (FLR) effects.

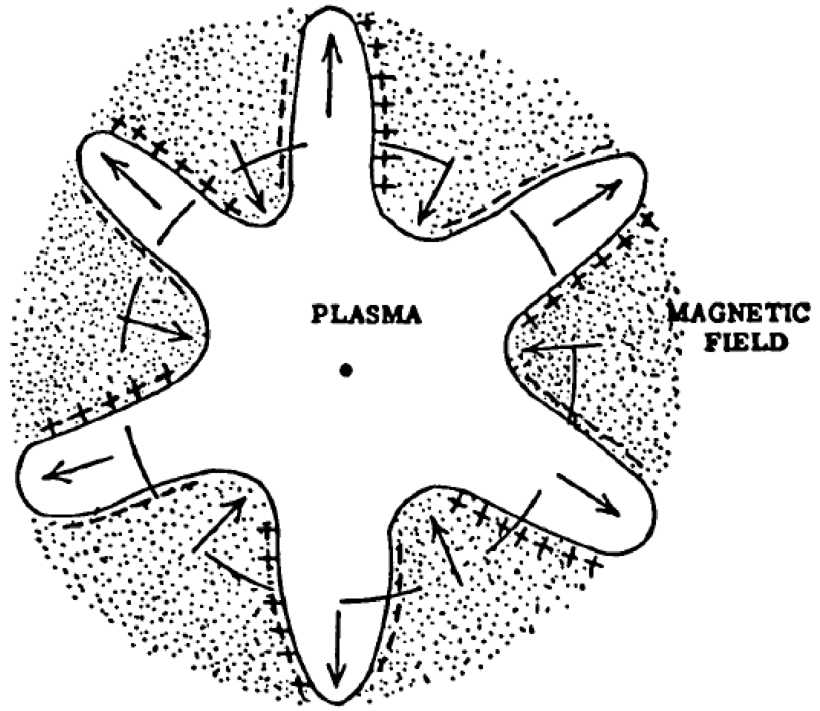
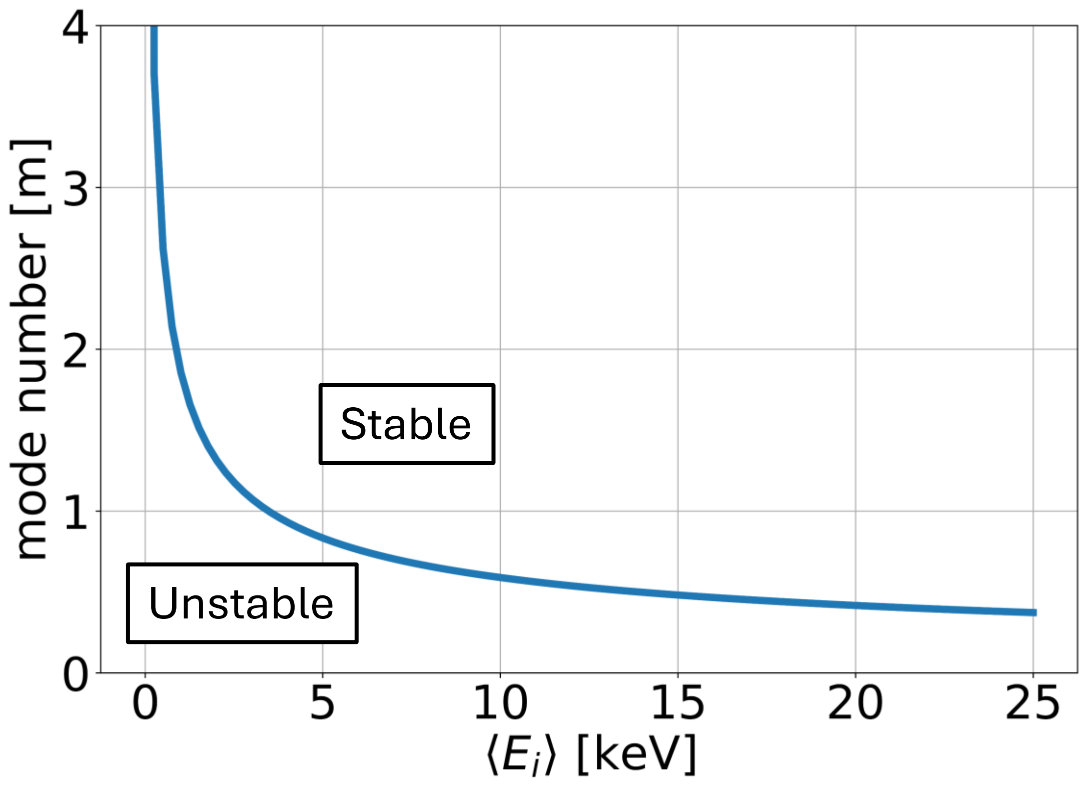


FIG. 30. Schematic illustration of the high-m flute instability in a simple mirror field, showing polarization fields and directions of unstable motion.

Figure from- R.F. Post Nucl. Fusion 27, 10 (1987)

FLR stabilization requires hot ions

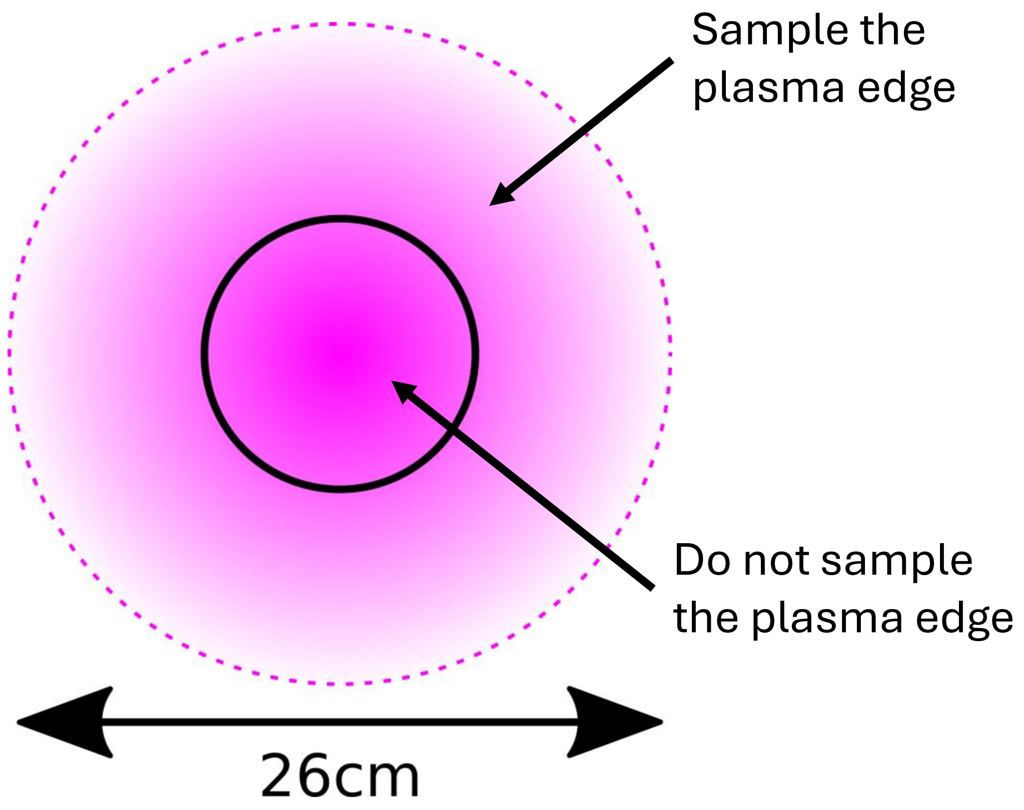
- Stability is given by the condition[1]- $m > 2\frac{a^2}{L\rho_i} = 2\frac{a/\rho_i}{L/a}$
  - m = mode number
  - a = plasma radius
  - L = plasma length
  - ρ_i = ion gyroradius
- Letting $\rho_i = \frac{\sqrt{2m\langle E_i\rangle}}{qB}$, we can write the stability condition as-
  - $m > 2\frac{a^2 qB}{L\sqrt{2m\langle E_i\rangle}}$



1. Ryutov et. al. Phys. Plasmas 18, 092301 (2011)

Hot ions require low edge neutral density

- Most WHAM fast ions sample the plasma edge
- Plasma parameters-
  - Plasma radius = 13cm
  - B_0 = 0.3T
  - Fast ion larmor radius (D) = 7.6cm
- Fast ions that sample the plasma-vacuum boundary can CX with edge neutrals.



Cartoon of plasma radius at the midplane. All fast ions from NBI with a gyrocenter outside the black circle will sample the plasma-vacuum boundary. Gyrocenters further out will spend more time past the plasma-vacuum boundary.

MHD stability via FLR

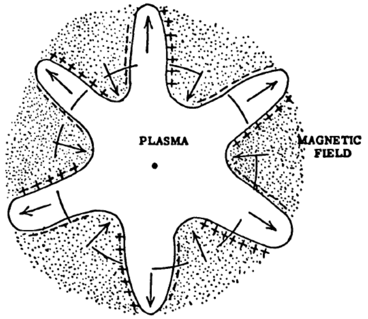
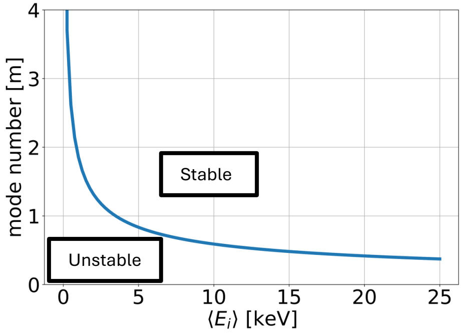
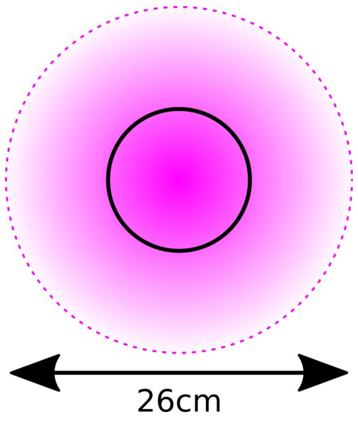


FIG. 30. Schematic illustration of the high-m flute instability in a simple mirror field, showing polarization fields and directions of unstable motion.

High $\langle E_i \rangle$



Lower edge CX rate

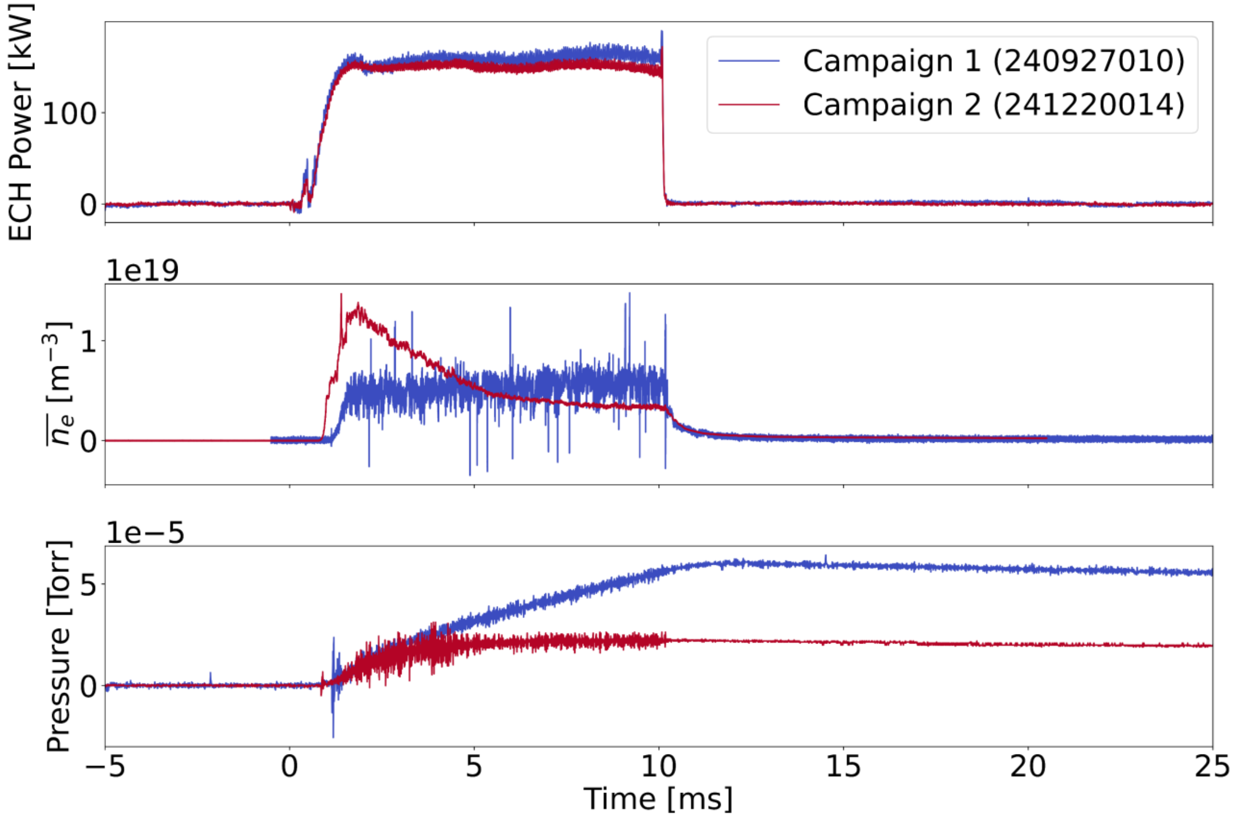


Neutrals control
(this talk)

Initial WHAM plasmas had poor performance

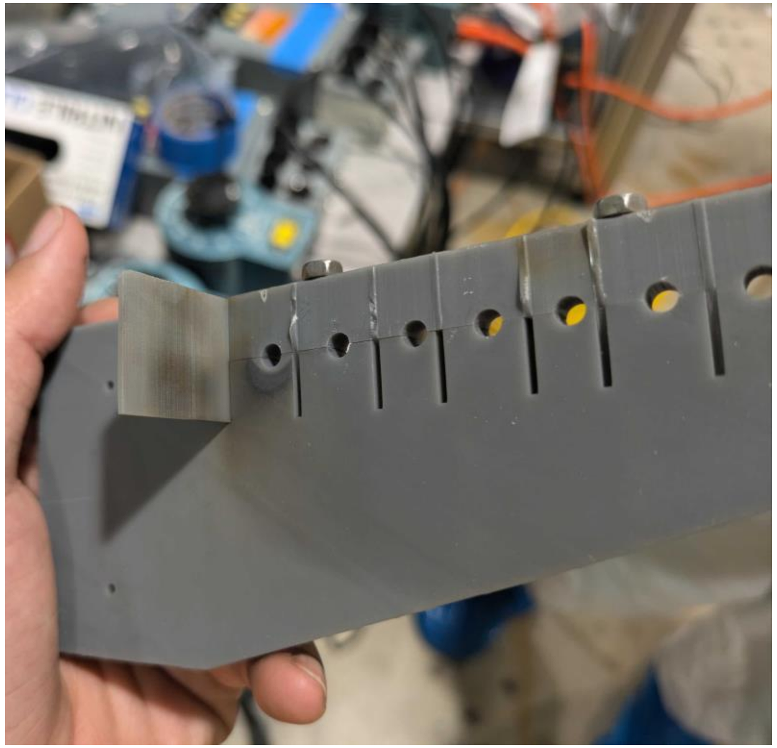
Initial WHAM plasmas had poor performance

- Symptoms-
  - No plasma sustainment with NBI
  - Plasma density clamped with large oscillations
  - Higher neutral pressure with plasma than without
- Causes-
  - Frequent vents
  - 3D printed parts in the vessel
  - No vessel conditioning performed before first plasma



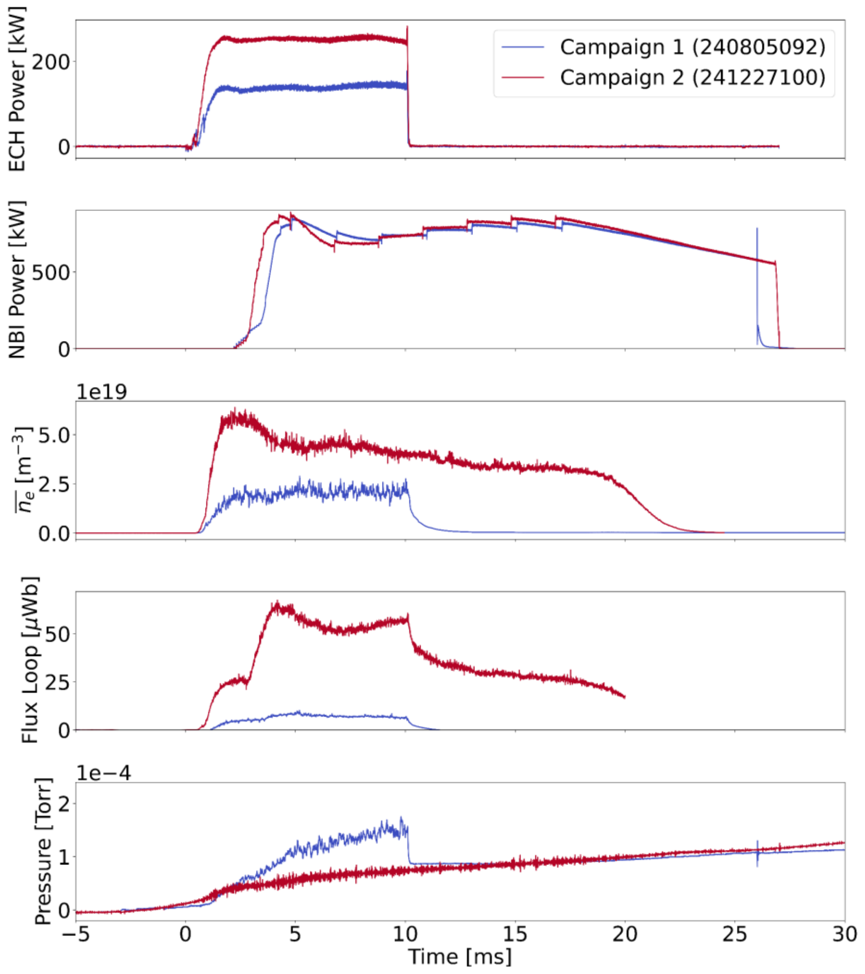
DO NOT PUT PLASTIC PARTS IN VACUUM!

- Plastic is a long polymer which consists of C, F, H etc.
- Since it is a solid body, it is a near infinite source of impurities.
- Cannot 'bake-out' plastic. It will keep sourcing impurities until it is fully ablated.
- Certain plastics are all too happy to desorb when exposed to UV light emitted from a plasma discharge.



Plasma not sustained with NBI

- WHAM has a 25keV, 40A NBI system.
- Once breakdown has been initiated, the NBI is expected to fuel and heat the plasma itself.
- This was not seen in WHAM Campaign 1.
- Hypothesis- Fast ions are lost too rapidly due to CX at the edge.



WHAM used 3 tools to control neutrals

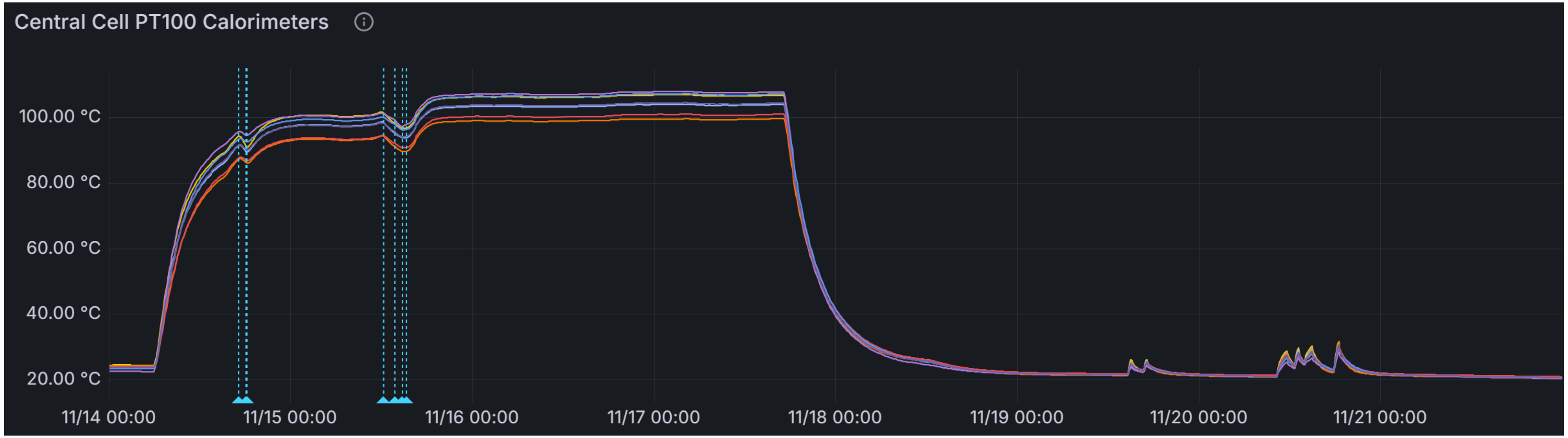
WHAM used 3 tools to control neutrals

1. Baking
2. Glow Discharge Cleaning (GDC)
3. Additional pumping with Titanium gettering pumps

Additionally, WHAM used spectroscopy of the plasma to identify impurity species to narrow down sources.

WHAM was baked at 100°C for 3 days

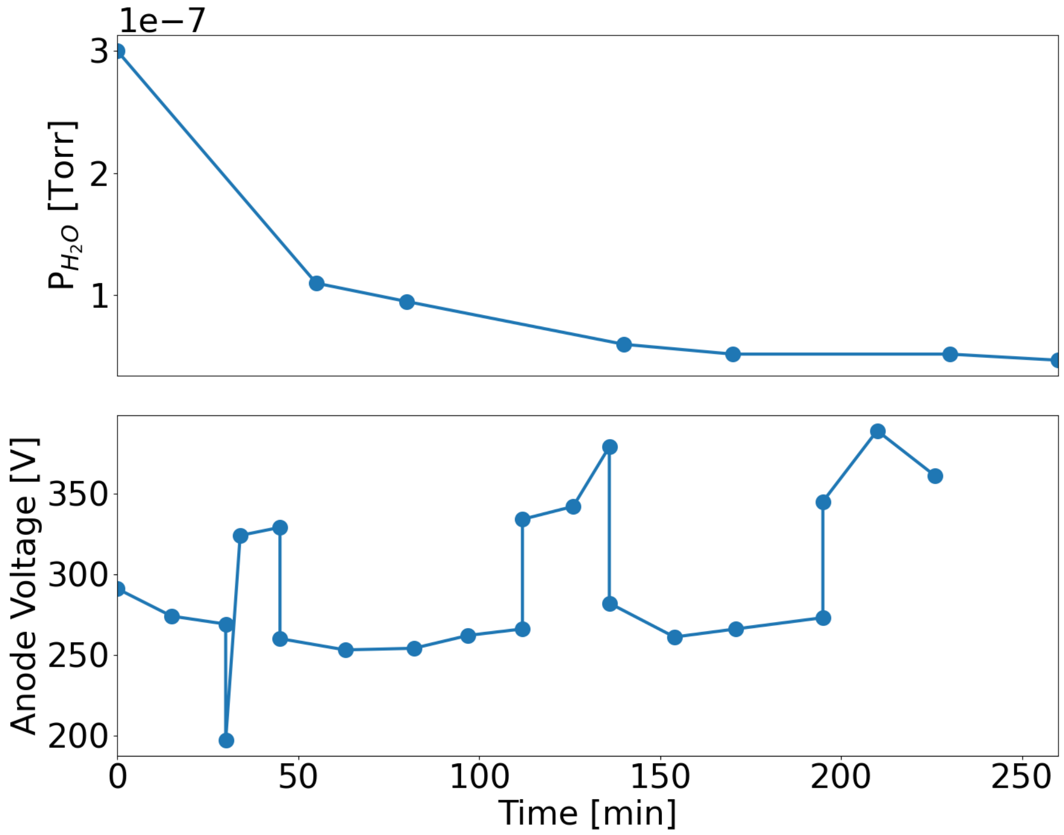
- Baking temperature limited by Viton o-ring seals
- Baking time limited by patience of scientists (24hr monitoring is brutal)
  - Target was P_{H2}/P_{H2O} >= 5 (WEST baking criteria[1])
  - Baking stopped when $P_{H2}/P_{H2O} = 1.2$
- P_{H2O} went from 2.2×10^{-6} Torr to 2.8×10^{-7} Torr due to the bake.



1. A. Gallo et al. Nucl. Materials and Energy 24, 101741 (2024)

GDC recipe called for alternating H_2 and He

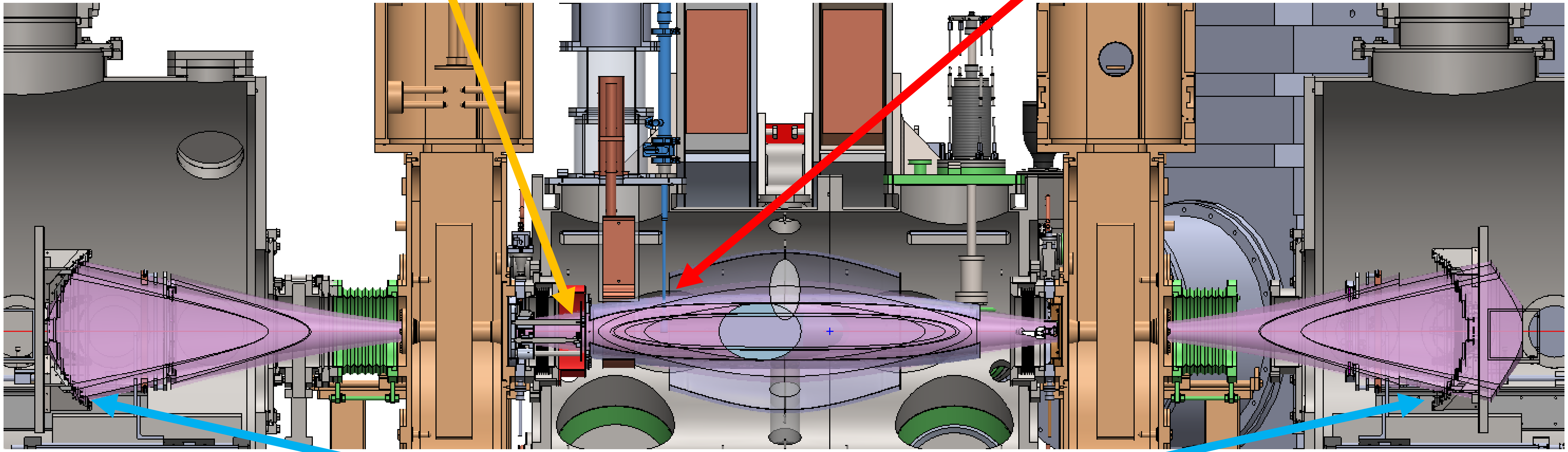
- WHAM has a tungsten limiter
- Worried about embrittlement of the limiter if He GDC was run for too long
- H_2 GDC helps clean surface trapped H_2
- He GDC helps remove H_2 trapped from H_2 GDC
- Finish with He GDC
- Further drop in P_{H2O} by 6x to 4.7×10^{-8} Torr



GDC done with 4 anodes

Limiter (gas box + magnet bore)

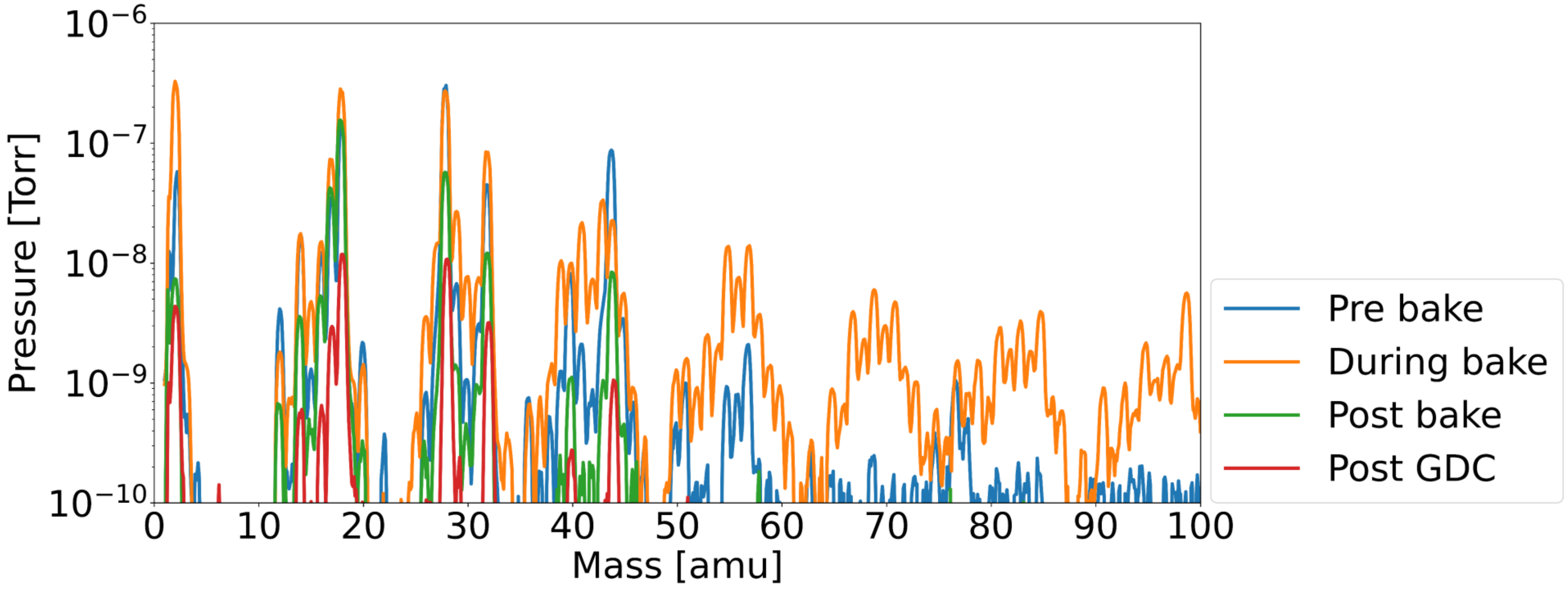
Glow discharge anode (can reach machine r=0)



End ring anodes (end cell + magnet bore)

Conditioning improved RGA trace

- Dramatic reduction in high amu impurities (hydrocarbons)
- Reduction in P_{H2} and P_{H2O}. Indicating an improvement in vessel surface conditions



Conditioning improved RGA trace

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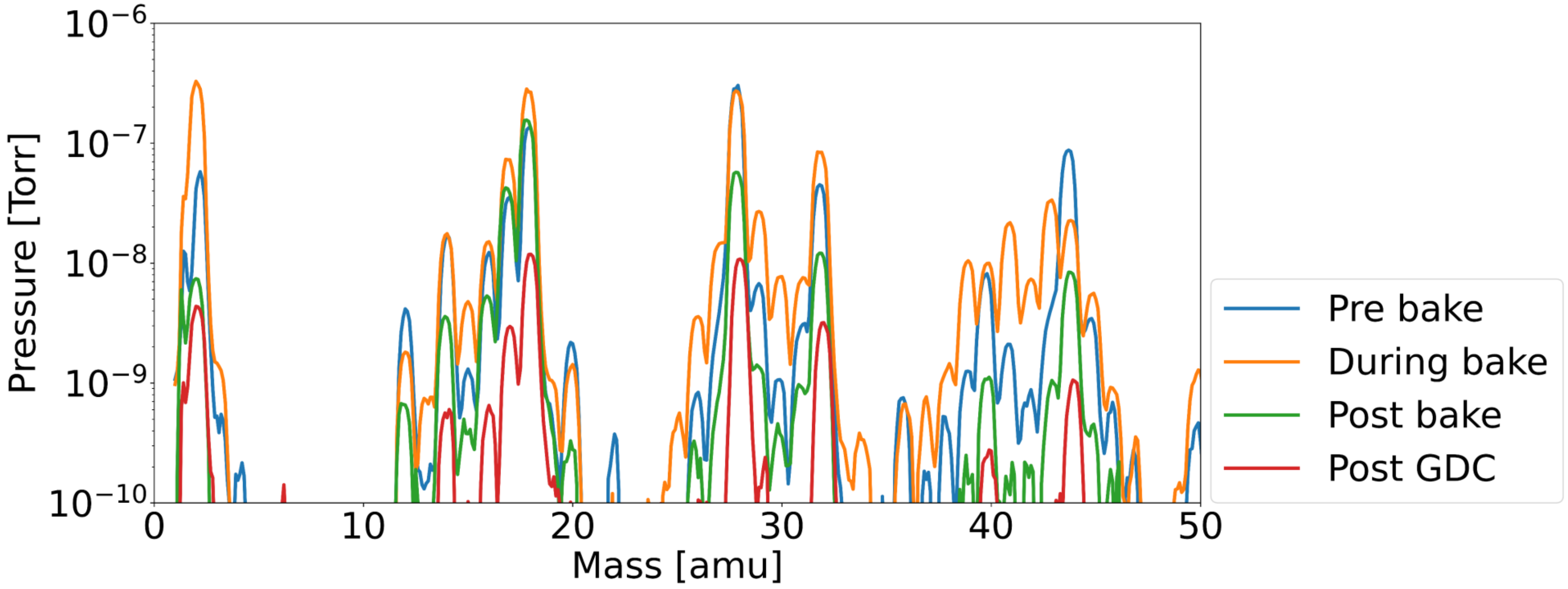
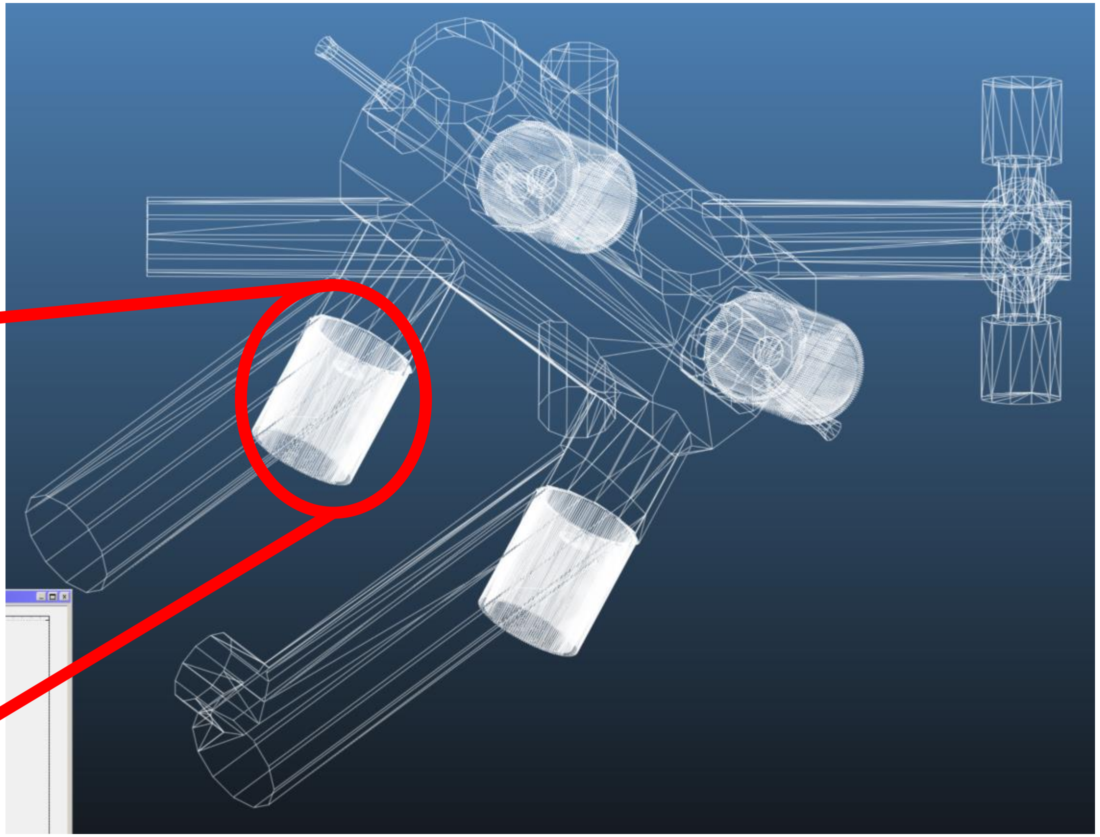


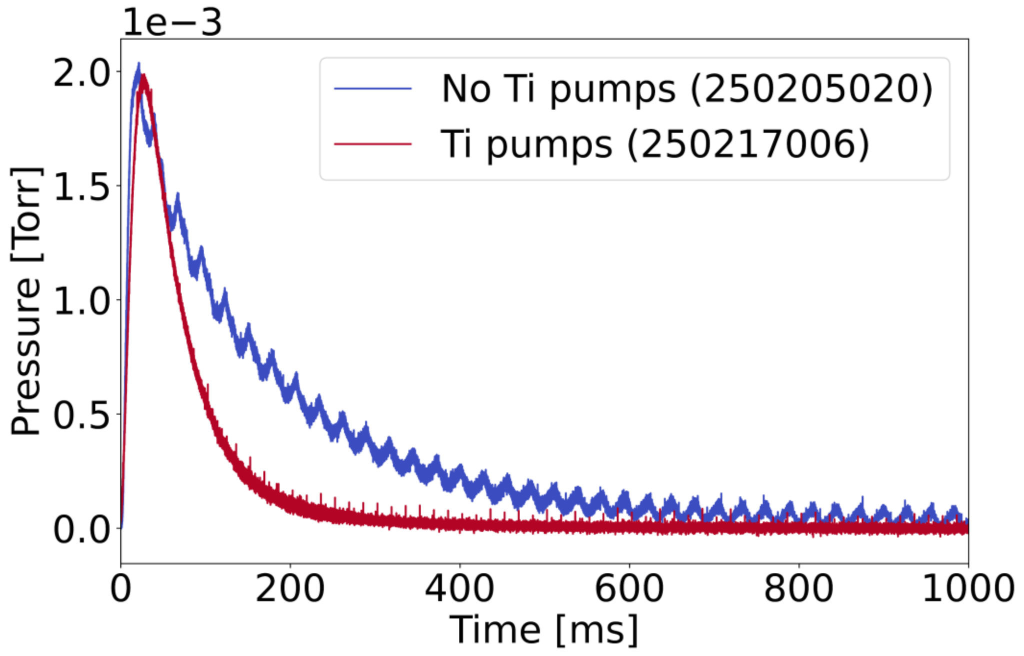
4 large Ti pumps installed on WHAM

- Project lead- Dmitry Yakovlev
- Corrugated and sandblasted to increase the pump surface area



Ti pumps increased pumping speed by 7x

- e-folding decreased from 180ms to 25ms
- Ti pumps improved performance as they were conditioning with Ti coatings over 10’s of hours.
- Takeaway- Large Ti gettered surfaces need multi-day conditioning to be fully effective.

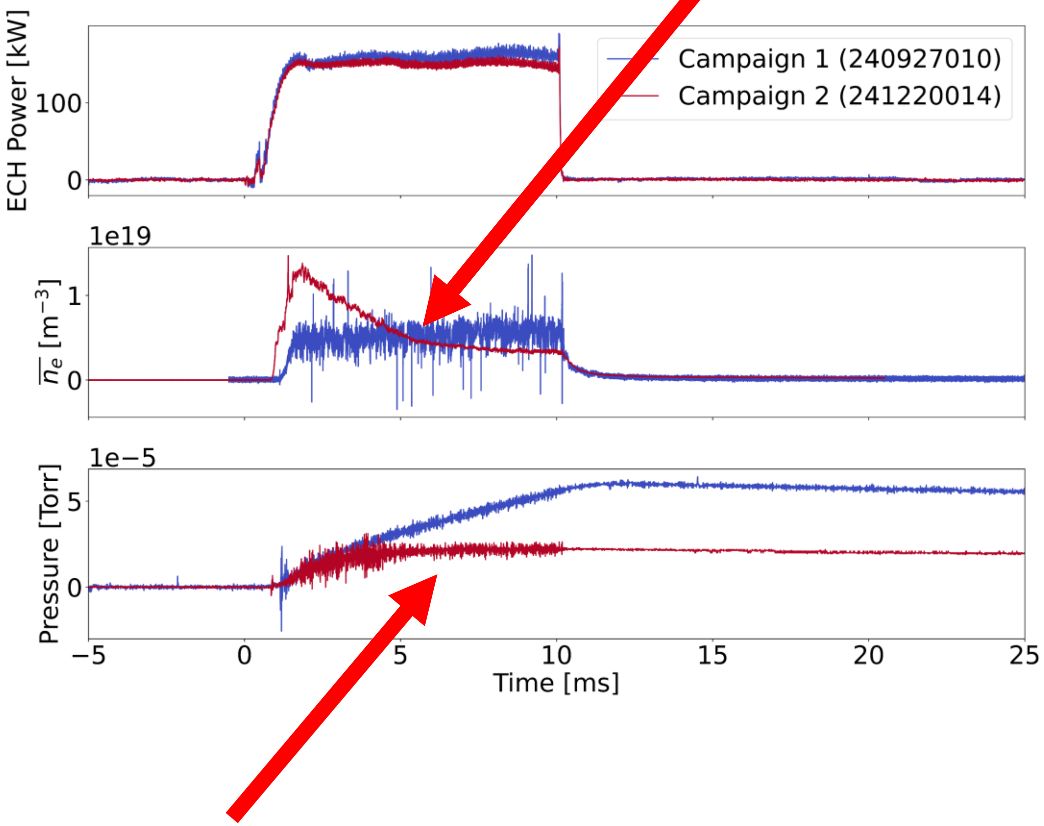


Vessel conditioning improved plasma performance

Density pump-out consistent with mirror confinement

- Particles in a mirror are de-confined when the scatter into the loss cone-
- $\frac{dn_p}{dt} = -\frac{1}{\tau_s} n_p$
- Effect seen right after a bakeout + GDC. i.e. walls with less sorbed gasses.

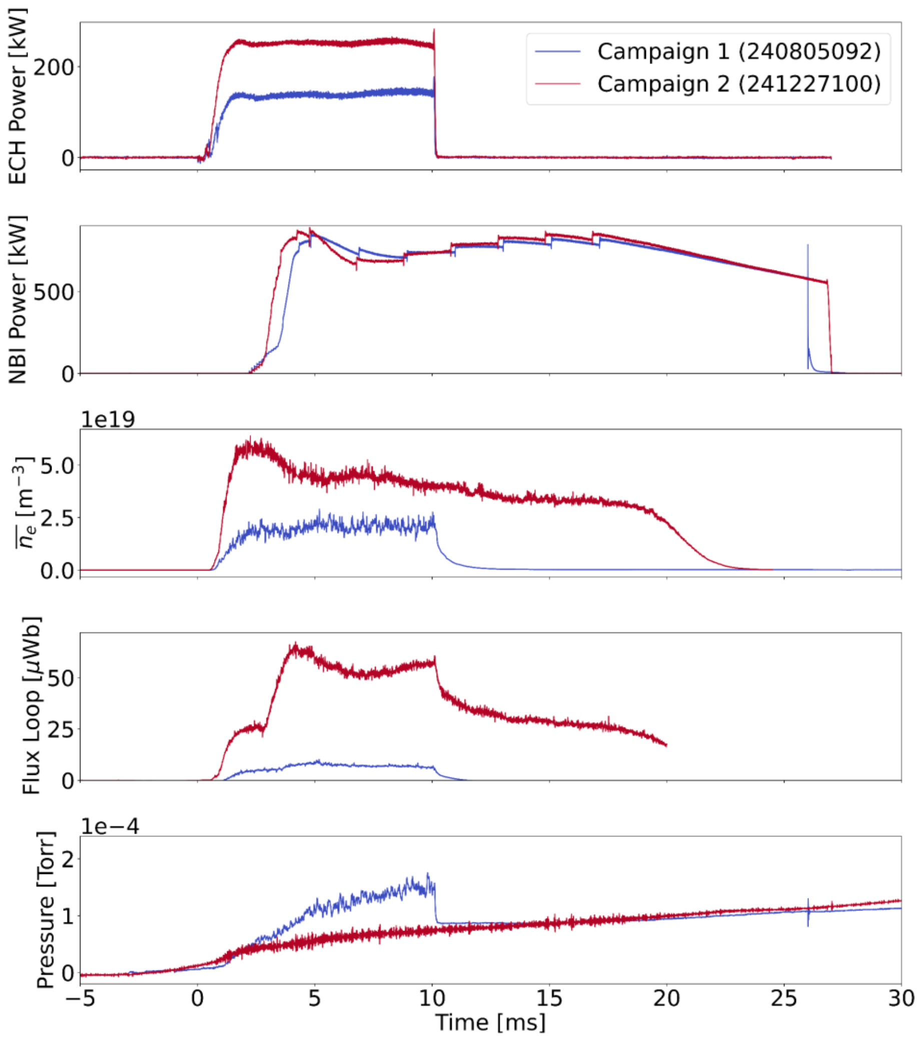
Exponential decay of central cell plasma density



Reduction in background pressure during a shot

Plasma sustained with NBI

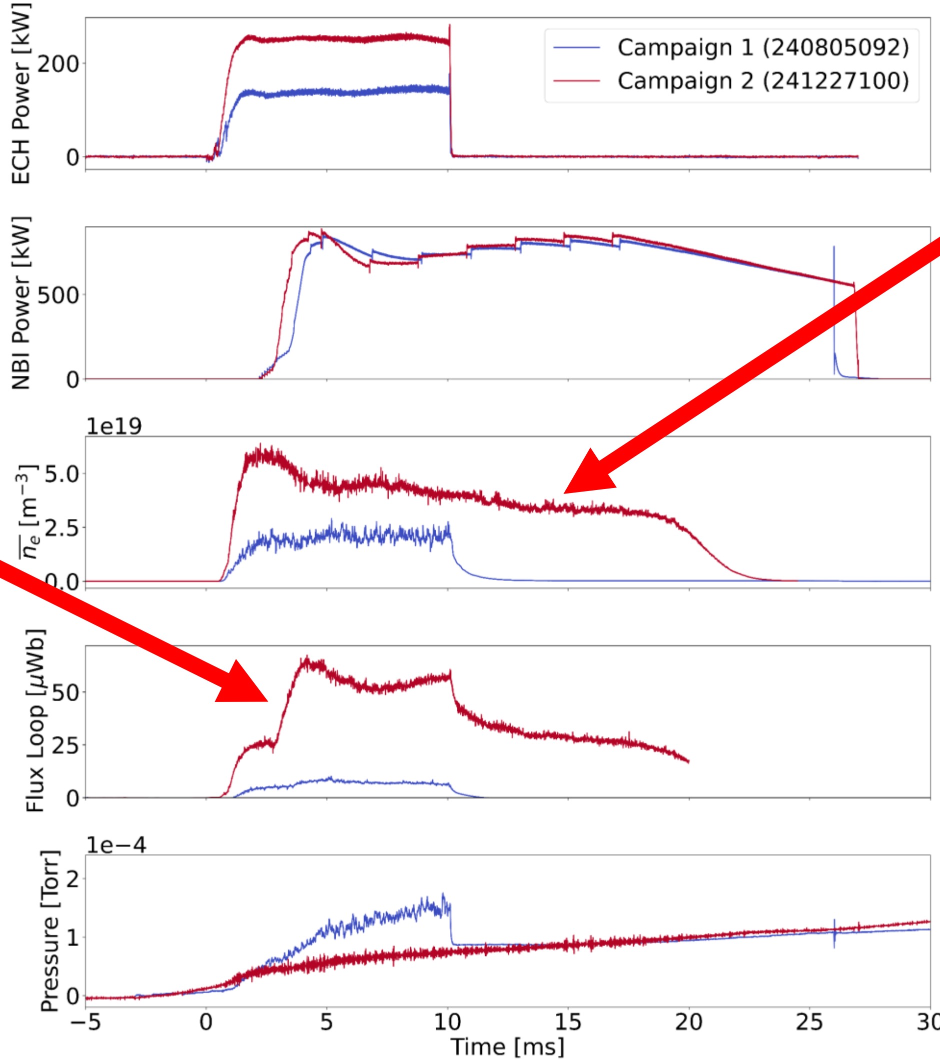
- Plasma sustains past ECH turnoff.
- Increase in plasma flux due to NBI is a sign of fast ion confinement.



Plasma sustained with NBI

Plasma persists past ECH turnoff

Bump in flux due to NBI. Evidence of fast ion confinement

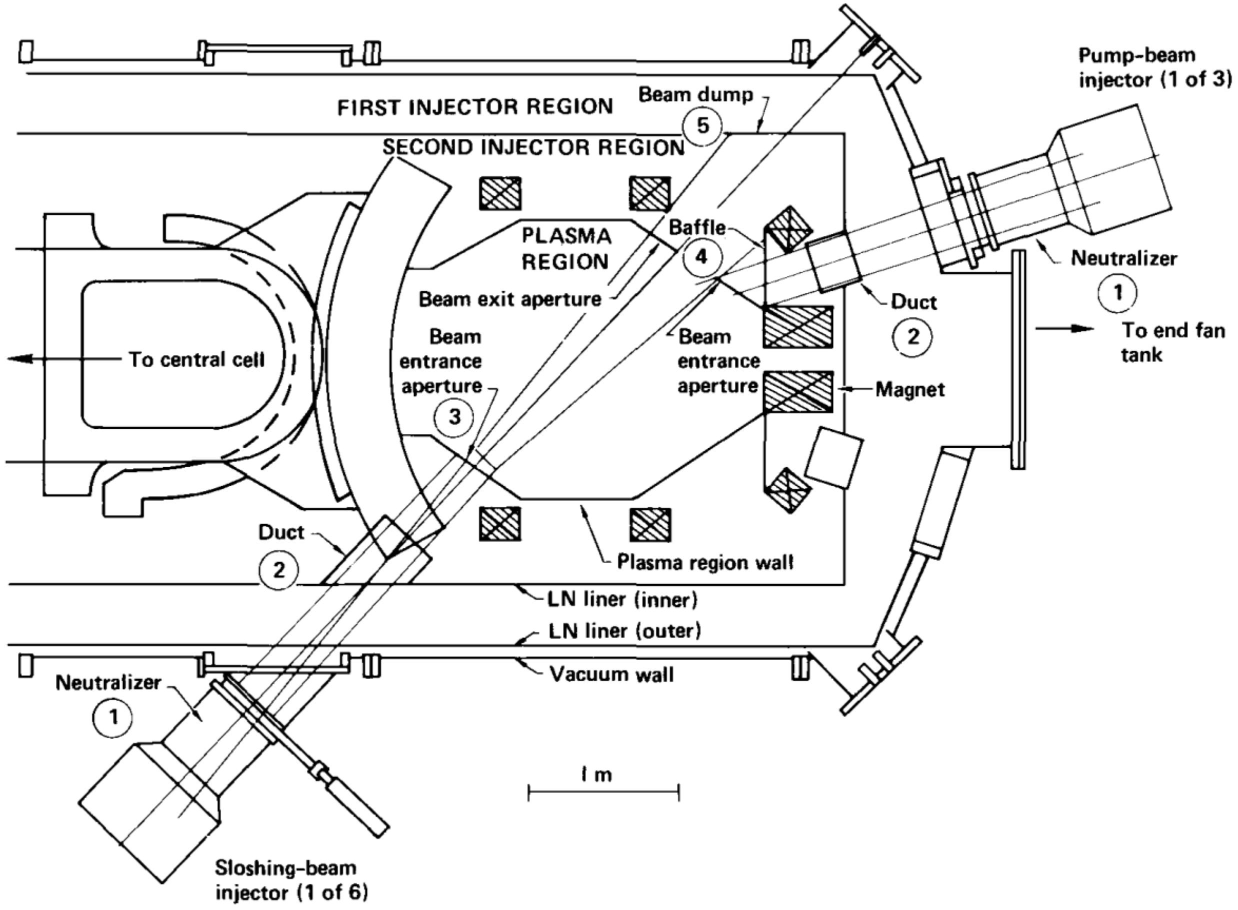


How do other mirrors handle neutrals control?

TMX-U

- Base pressure- 2×10^{-8} Torr
- Pumping speed- 10^{6} L/s
- Plasma density- 2×10^{18} m^{-3}
- 3 nested Ti gettered walls
- LN_2 cooled Ti gettered walls

G.D. Porter, TMX-U Final Report, UCID-20981, 1988



TARA

- Plasma density- $2 \times 10^{18}\ m^{-3}$
- Ti gettered first wall
- LN_2 cooled Ti gettered beam dumps
- Beam dump as big as neutralizer tank

R.S. Post et al., *J. Nucl. Mat.*, 145-147 (1987)

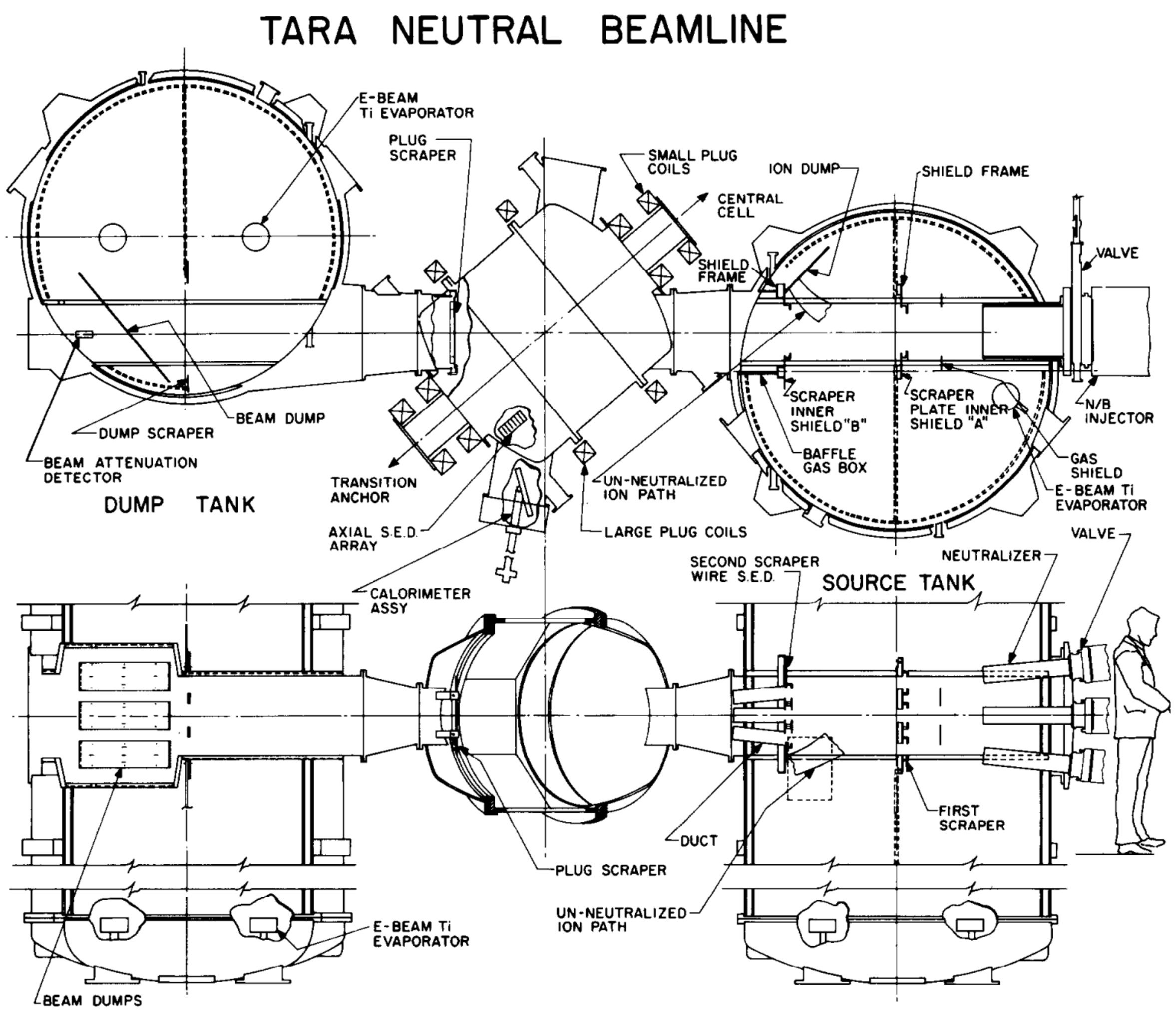
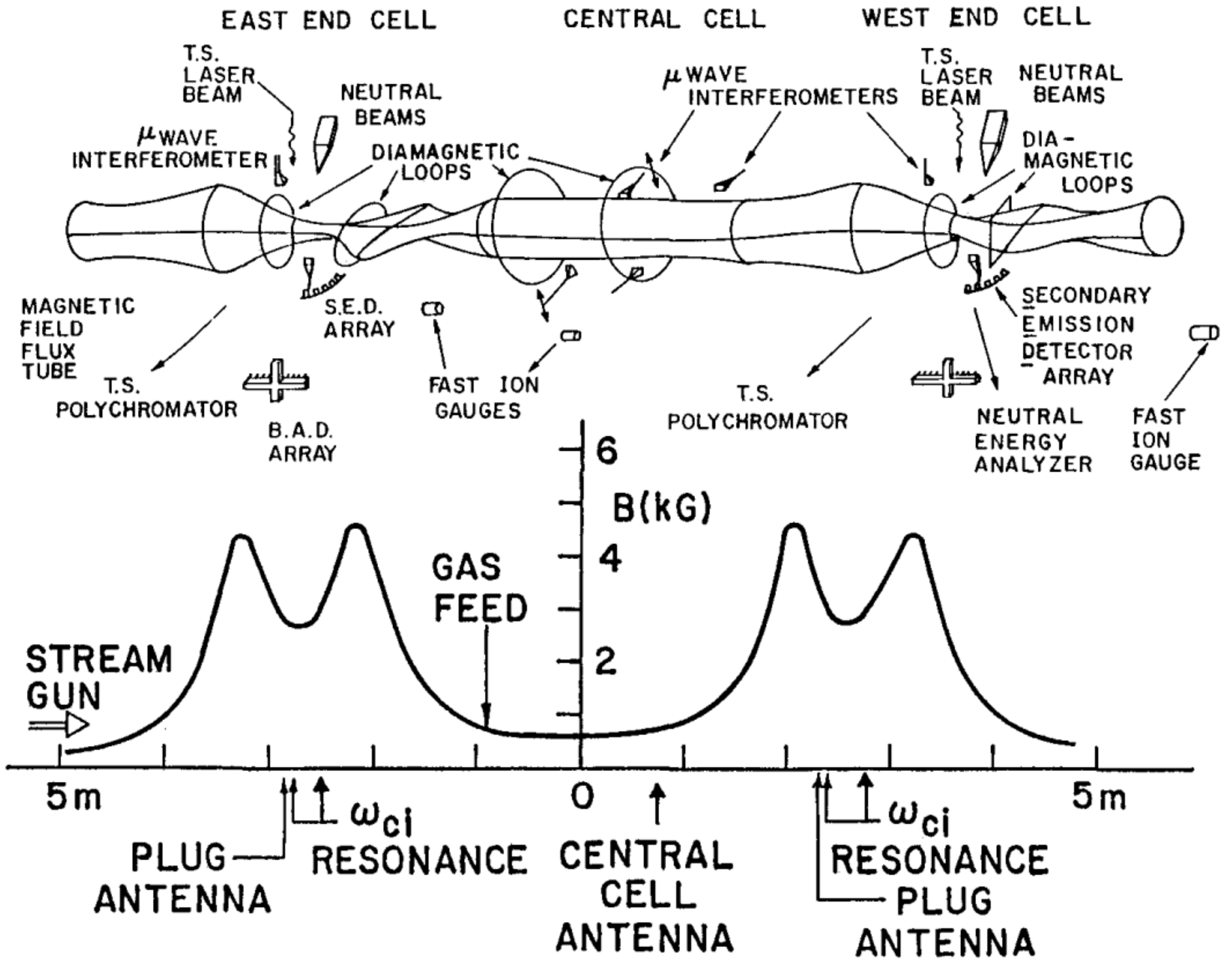


Fig. 4. A top and side view of the neutral beam line, dump and the plug chamber. The chambers act as differential pumps to limit the gas flow into the plug to 0.15 Torr l/s out of the 100 Torr l/s used in the sources.

Phaedrus

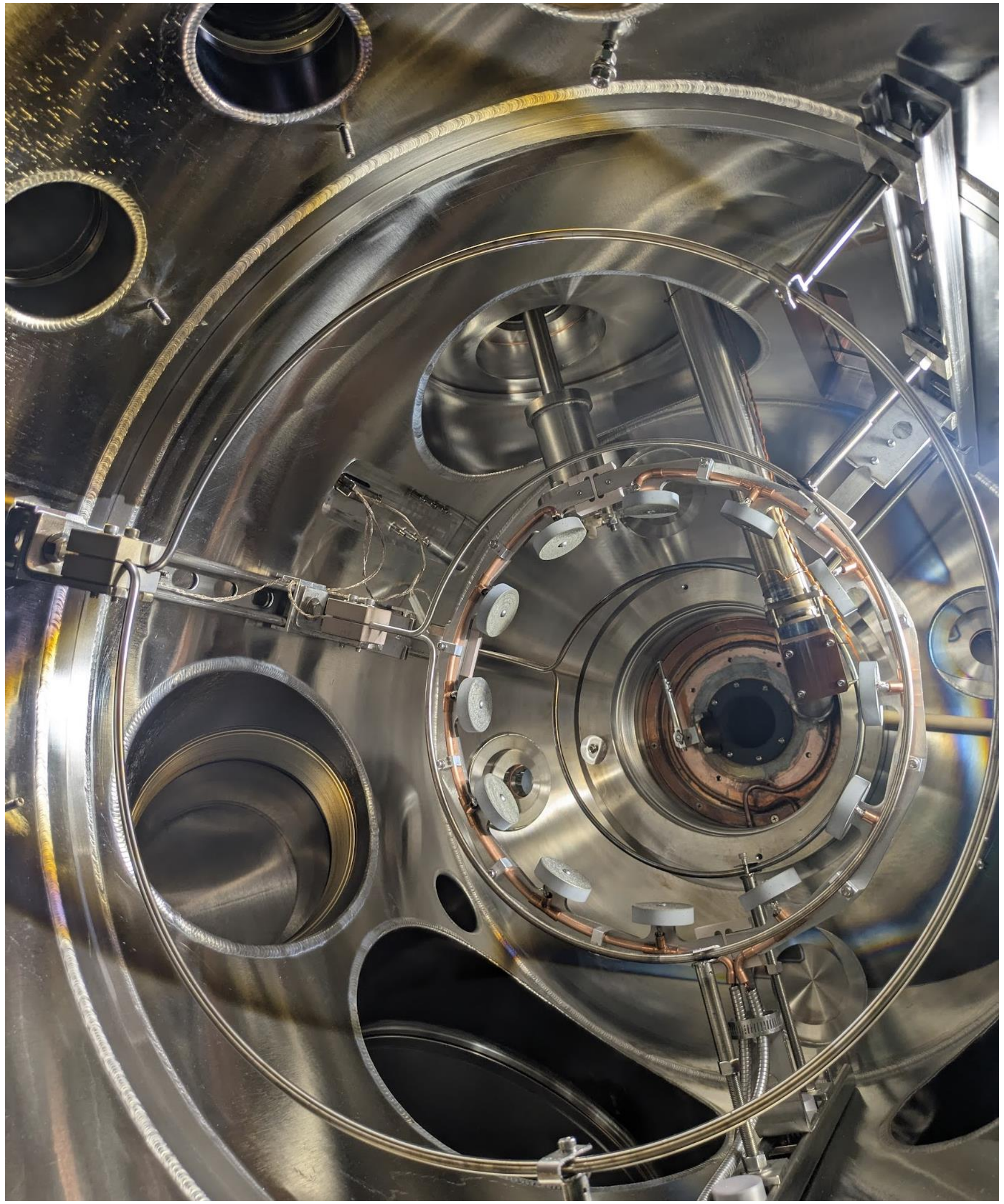
- Base pressure- 5×10^{-8} Torr
- Ti gettered first wall
- 120A injected beam current

R. A. Breun et al., *J. Vac. Sci. Technol. A* 5, 265–272 (1987)



WHAM

- Base pressure- 7.5×10^{-8} Torr
- Pumping speed- $\sim 10^4$ L/s
- Plasma density- 5×10^{19} m^{-3}
- Ti pumps
- Stainless steel first wall



All high performance mirrors share common characteristics

	TMX-U	TARA	Phaedrus	WHAM
Base Pressure (10^{-8} Torr)	2		5	7.5
Pumping Speed (L/s)	10^6			$\sim 10^4$
Density (10^{18} m^{-3})	2	2	5	50
Features	• LN2 cooled, Ti coated walls • Sandblasted Al substrate for Ti coating	• LN2 cooled, Ti coated beam dump • Beam dump as big as NBI neutralizer tank	• 10hr of Ti coating everyday • 120A injected beam current	• 316SS first wall • Ti pumps with corrugated, sandblasted Al substrate

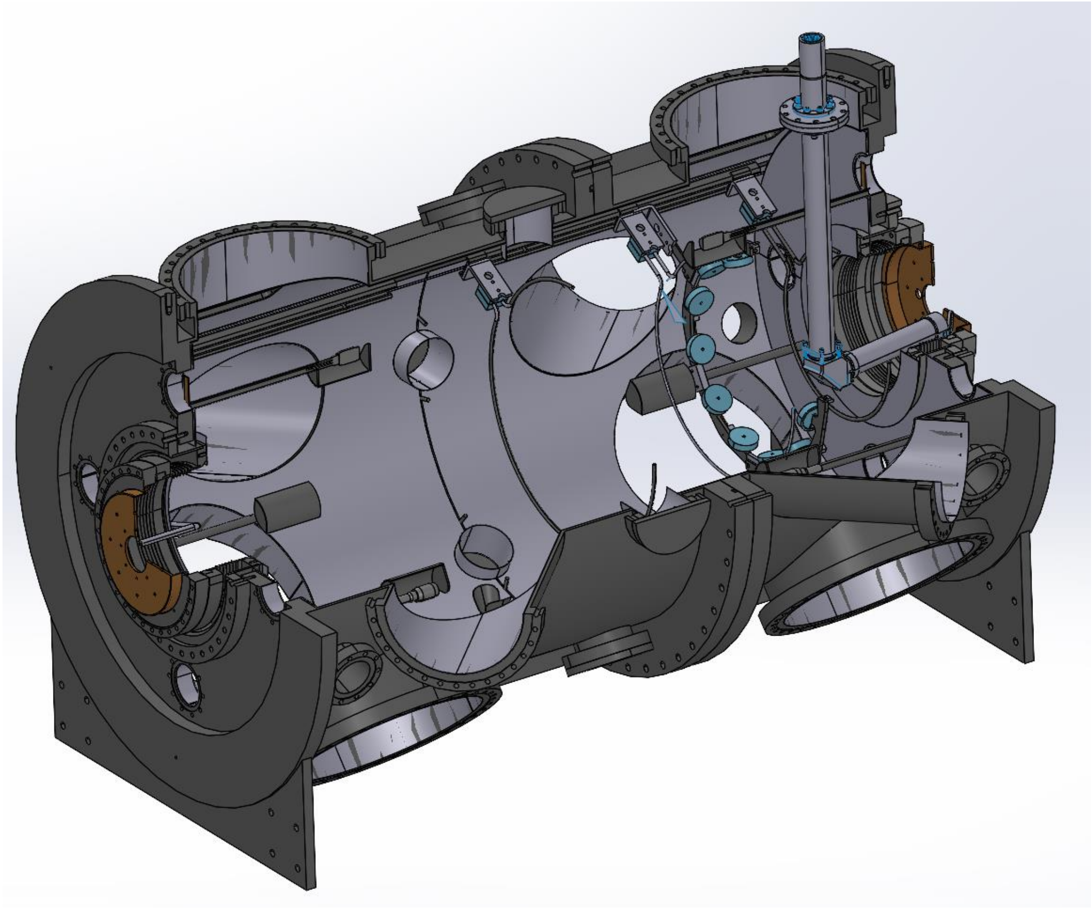
All high performance mirrors share common characteristics

- Ti gettered first wall
- Long duration Ti coating before each run day or Ti coating before every shot
- Base pressure <= $5x10^{-8}$ Torr
- Long (>20h) bakeouts and glow discharge cleaning (>10h) after vents

WHAM will adopt similar strategies for its first wall

WHAM will add a Ti gettered first wall

- Project lead- Dmitry Yakovlev
- Ti gettered first wall on a sandblasted Al liner
- Al liner allows-
  - Sandblasting to increase surface area
  - Replaceable if Ti wall needs to be removed
- Ti slugs can be run at a ‘black heat’ to bake the vessel walls from the inside



WHAM is installing a more reliable and efficient bakeout system

- First WHAM bakeout required lots of hands-on attention
  - Round the clock monitoring
  - Frequent loss of variacs
  - Frequent Menards trips to purchase more insulation
- Better vessel insulation designed and installed (Jon Pizzo)
- More reliable power supplies for the heater tapes

Beam dump is a source of neutrals

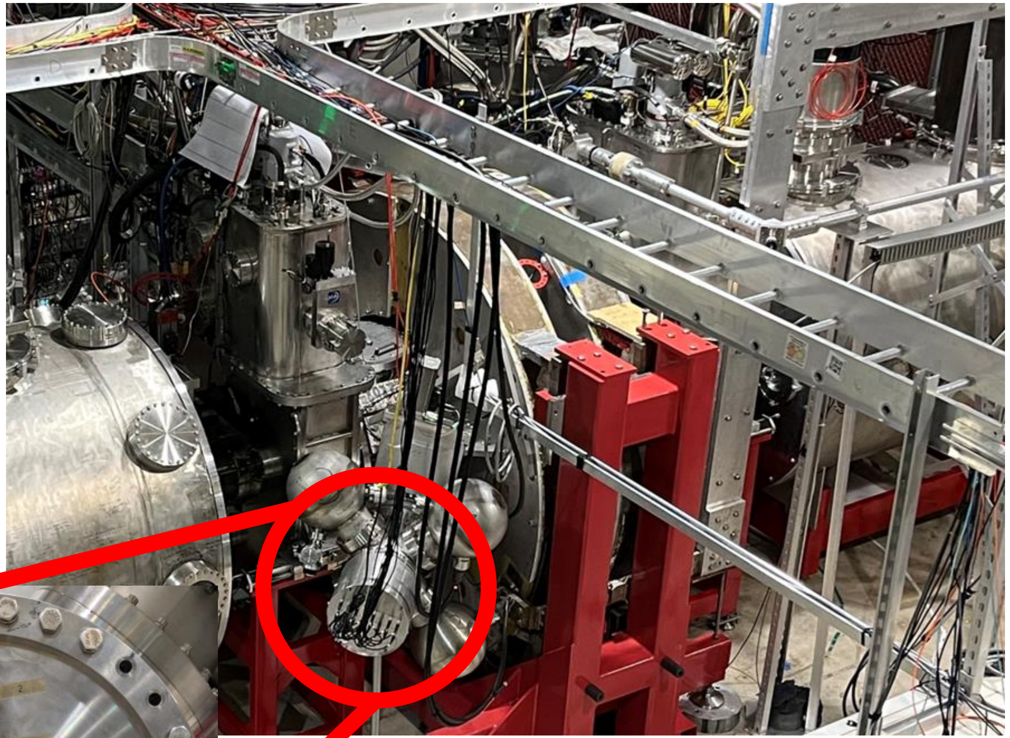
40A NBI for 25ms injects 6.2×10^{18} particles into the vessel

- Injected particles-
  - 40A NBI for 25ms
  - 6.2×10^{18} particles
- WHAM plasma parameters-
  - Density = 5×10^{20} m-3
  - Volume = 50L
  - Plasma ions = 25×10^{18}
- Total injected neutral particles is comparable to total plasma ions in WHAM

Current beam dump setup is insufficient

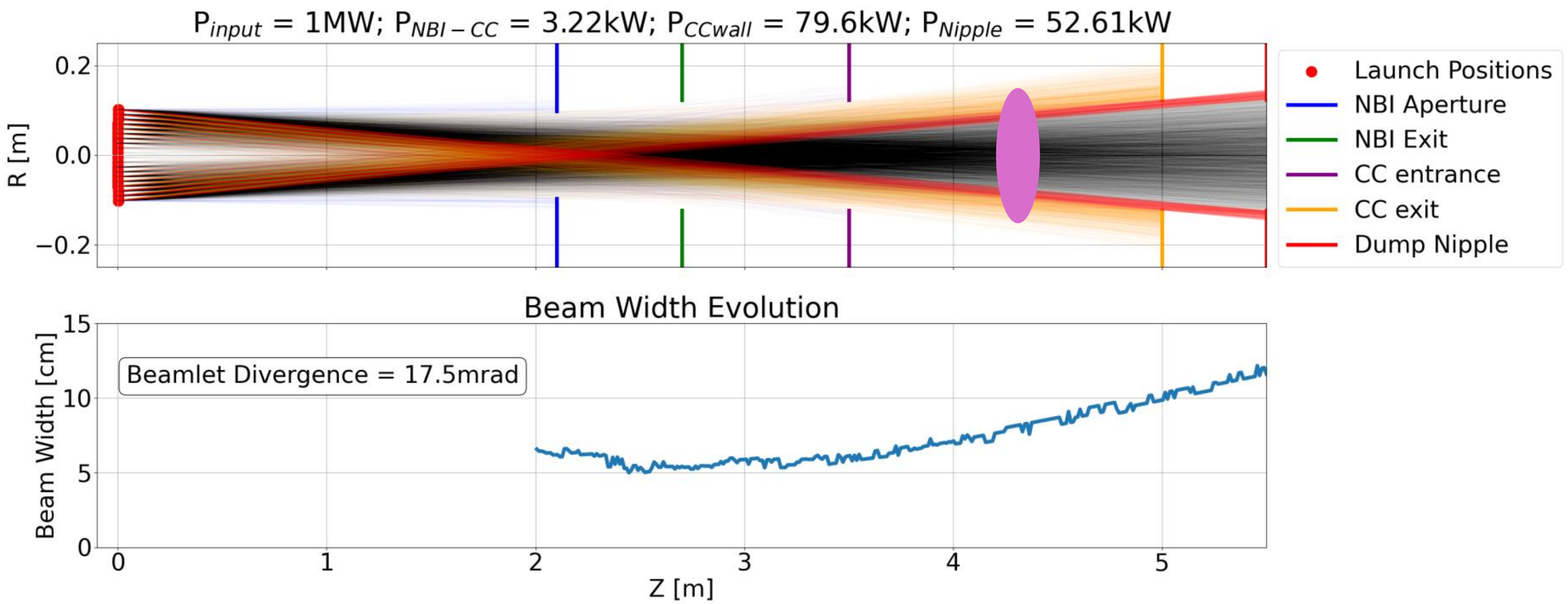
- Outgassing from the beam dump is sufficient to make plasma with $\overline{n_e} = 3\times10^{18}\ \mathrm{m}^{-3}$
- Beam dump consists of a sandblasted Al cone that can be coated with Ti.

Inside vacuum



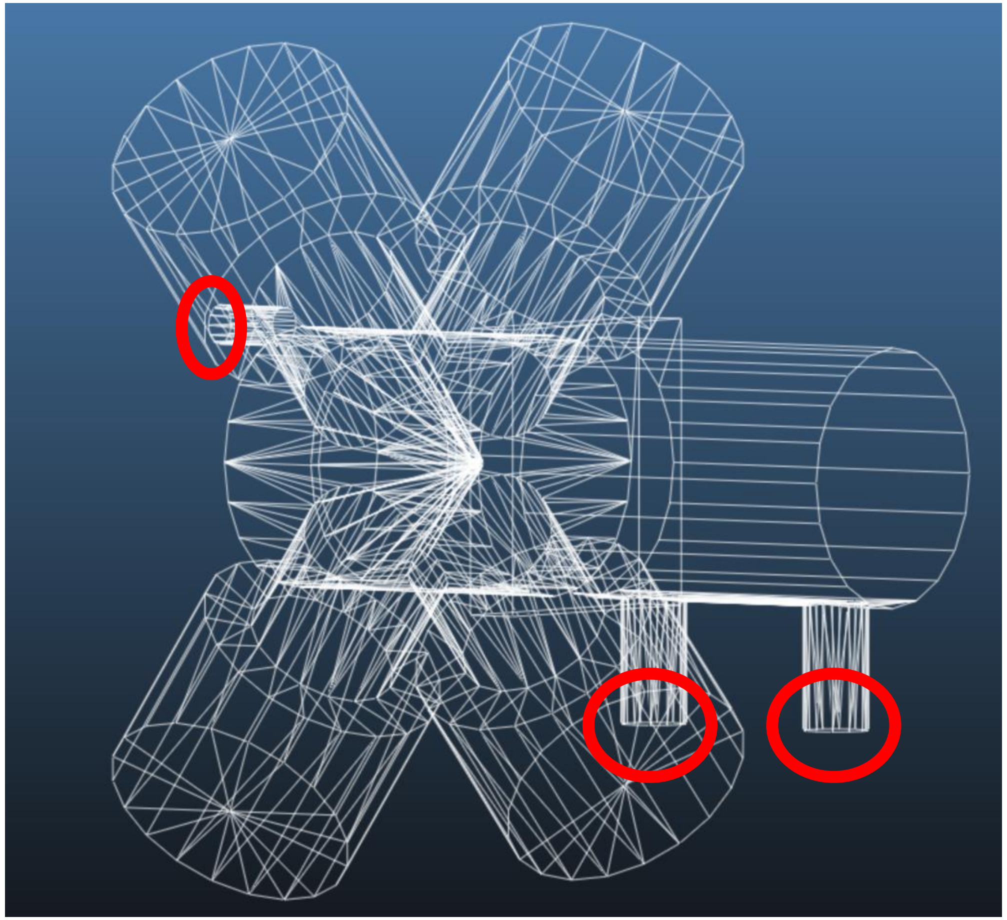
Experiment setup to study outgassing from beam dump

- Outgassing could be coming from-
  - NBI scraping on inner wall of the CC
  - Scraping on the flight tube to the beam dump
  - The beam dump



Outgassing experiment will inform design of v2 beam dump

- C2 with TAE technologies, TARA and Gamma-10 are linear machines with have beam dumps as big as the beam neutralizer tank.
- Bigger volume provides inertial pumping. Helpful in short pulse experiments.
- Data + molflow simulation will inform us of the outgassing location.



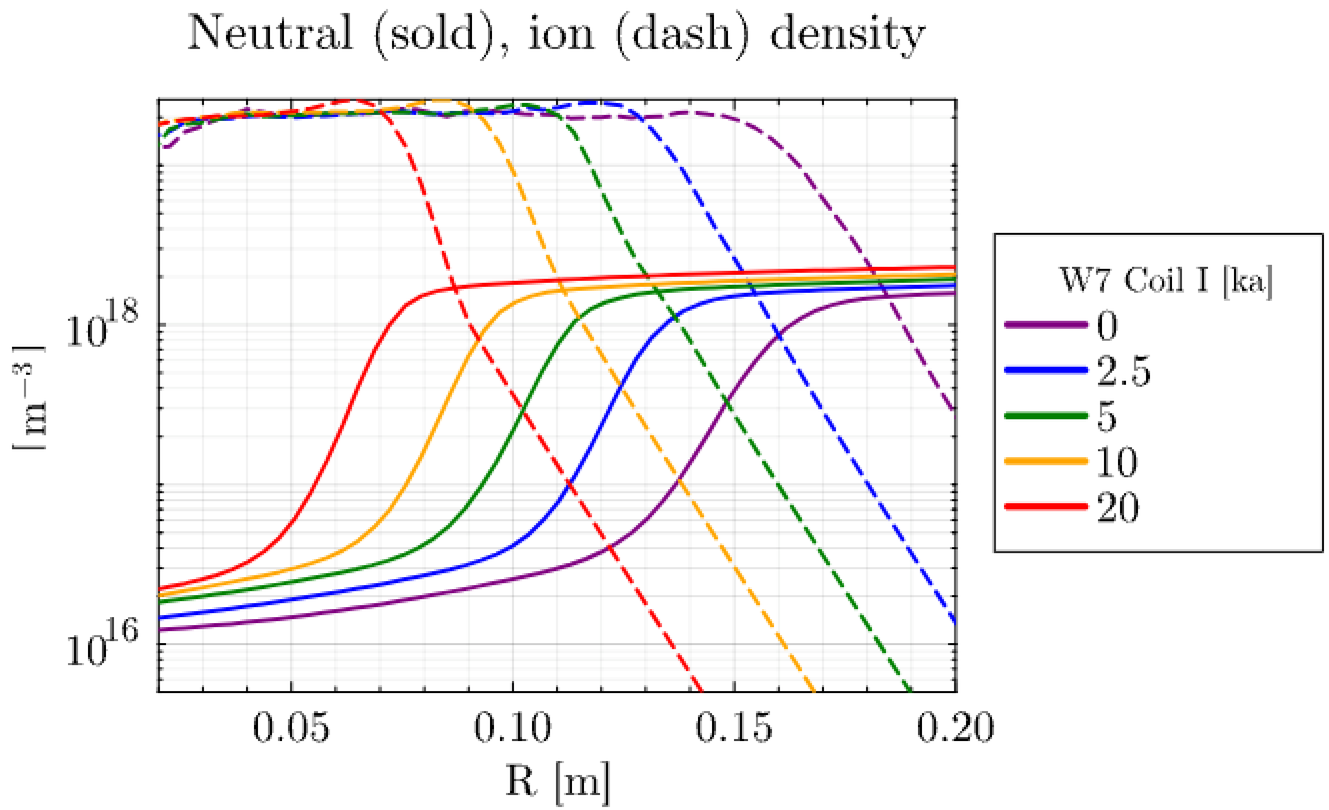
Simulation setup in Molfow. Gauge locations circled in red.

Conclusions

- WHAM needs edge neutrals control for MHD stability
- Baking and GDC conditioned the walls which led to improved plasma performance
- WHAM was able to sustain plasmas with NBI only after conditioning improvements
- WHAM needs further improvement via a Ti gettered first wall and reliable baking
- Beam dump upgrade campaign underway
- More pressure gauges being designed and constructed to measure gas flows through the machine

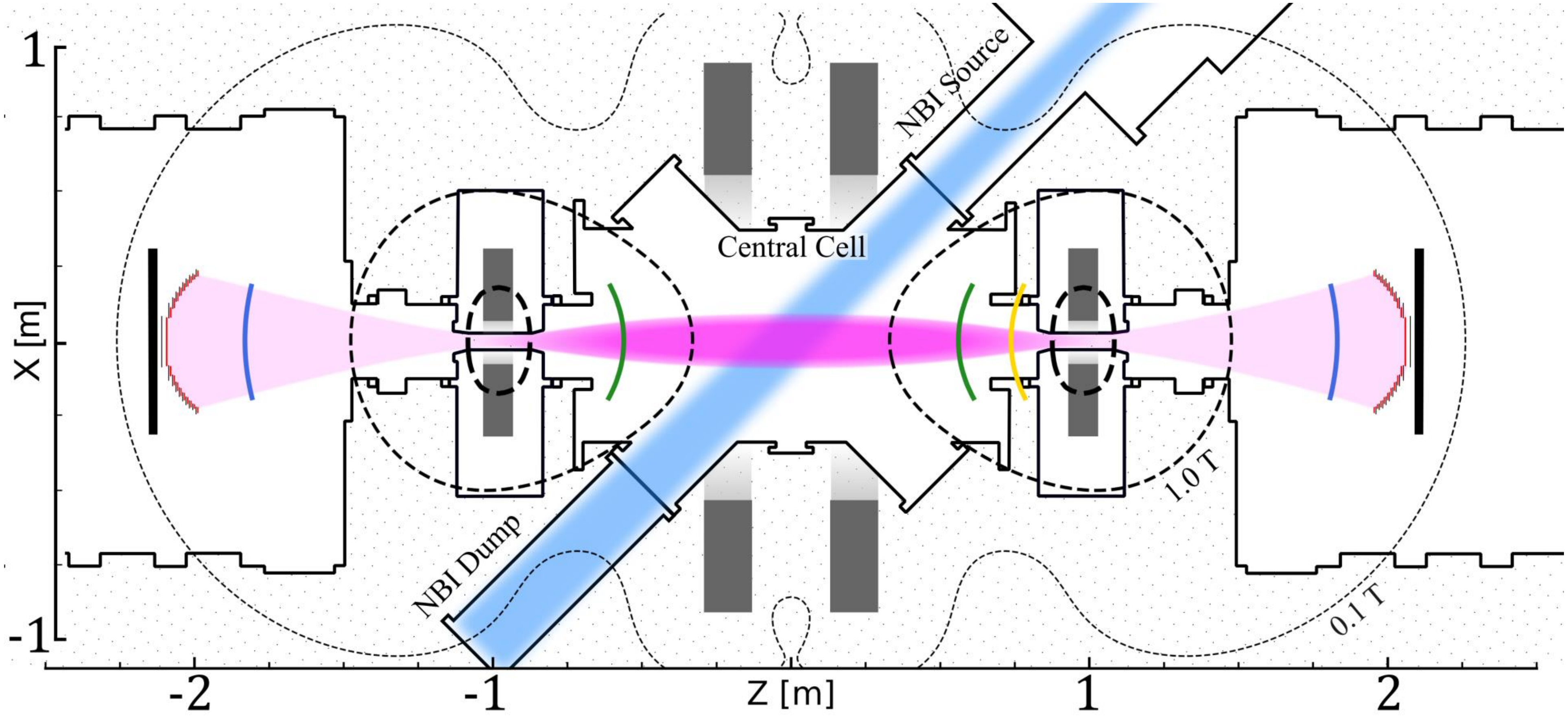
Extra stuff

Neutral screening due to plasma



Simulation of radial ion and neutral density profiles in WHAM for different magnetic fields. Figure credit- Bodhi Biswas

Top-down view



Data during bakeout looks like W7-X data

- Spacing between peaks seems to be 13 amu. Same as spacing in WHAM RGA data. CH^+ ions?
- A Goriaev *et al* 2020 *Phys. Scr.* **2020** 014063

W7-X

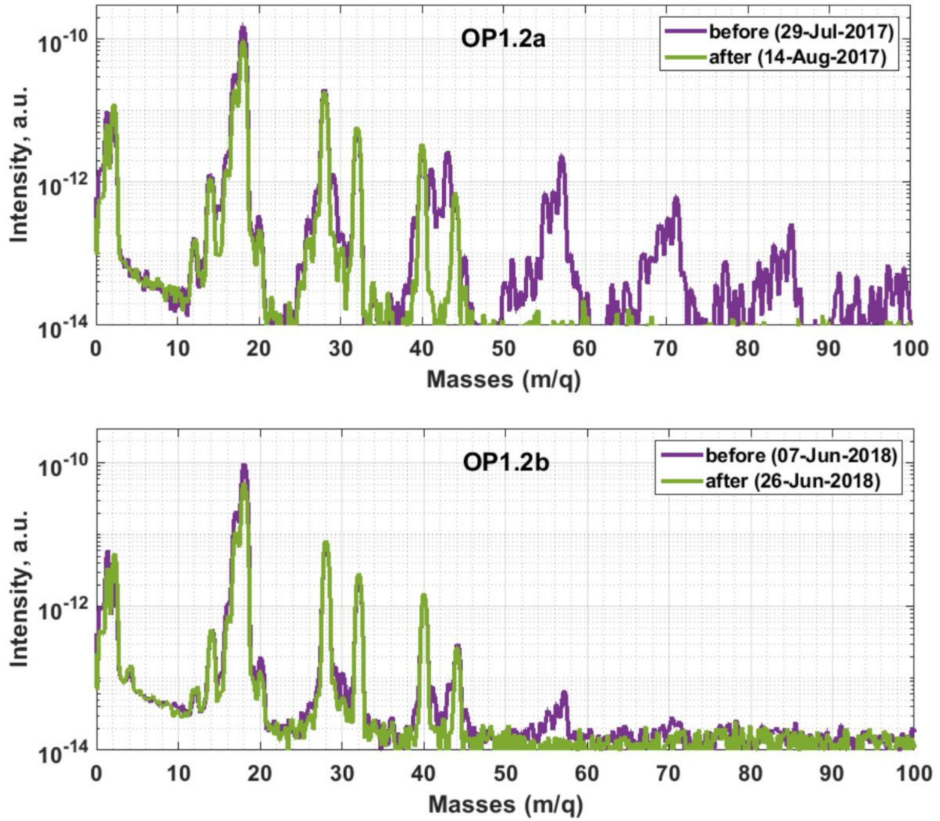
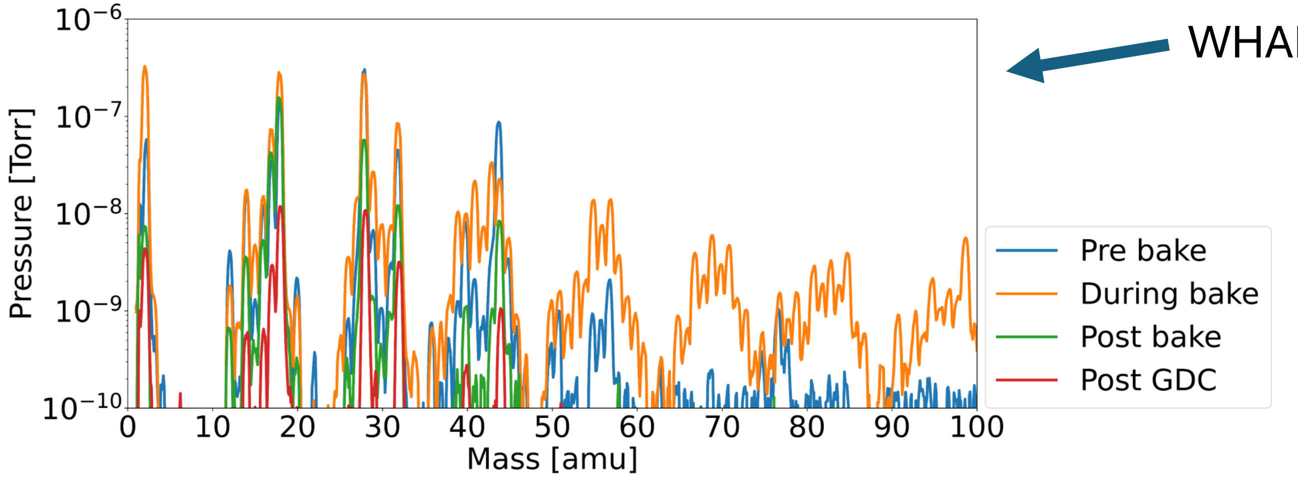


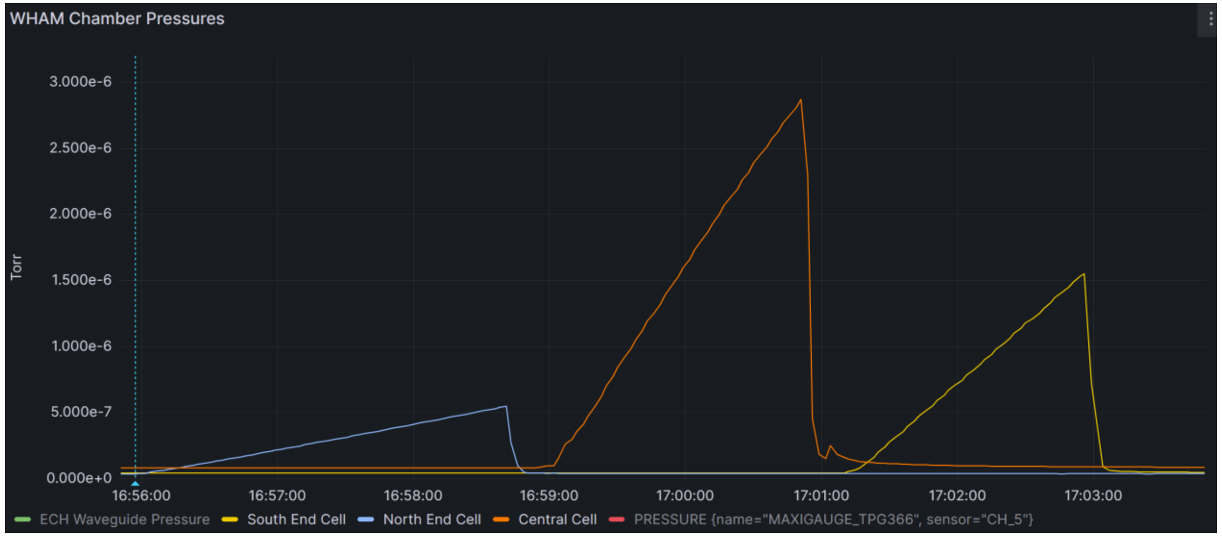
Fig. 1 Residual gas content before (magenta line) and after (green line) baking: top – OP1.2a (01-Aug-2017 – 12-Aug-2017), bottom – OP1.2b (11-Jul-2018 – 23-Jul-2018).

WHAM



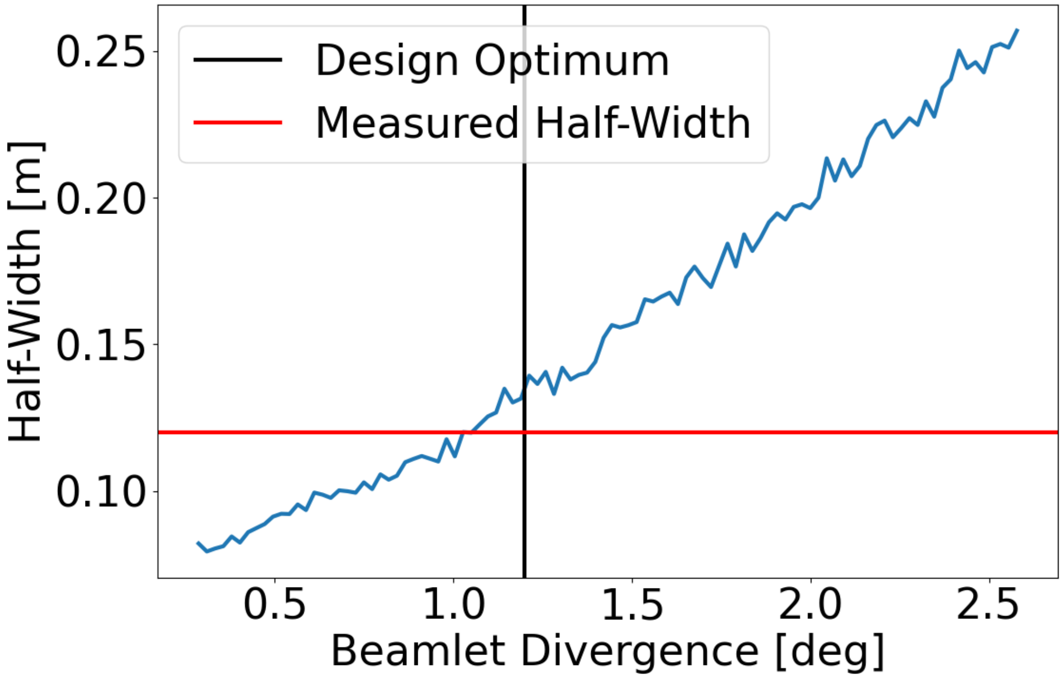
Vessel rate-of-rise tests

- Leak rates for each vessel (3rd December, 2024)-
  - CC – 2.12×10^{-5} Torr L/s
  - NEC – 1.2×10^{-5} Torr L/s
  - SEC – 6.4×10^{-5} Torr L/s

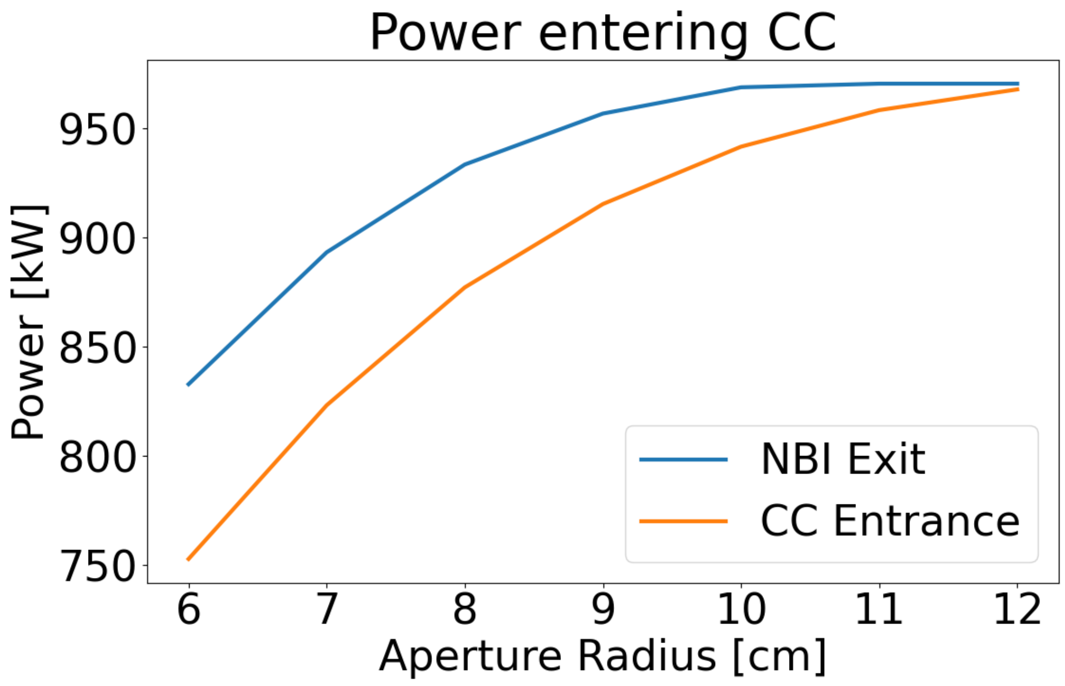


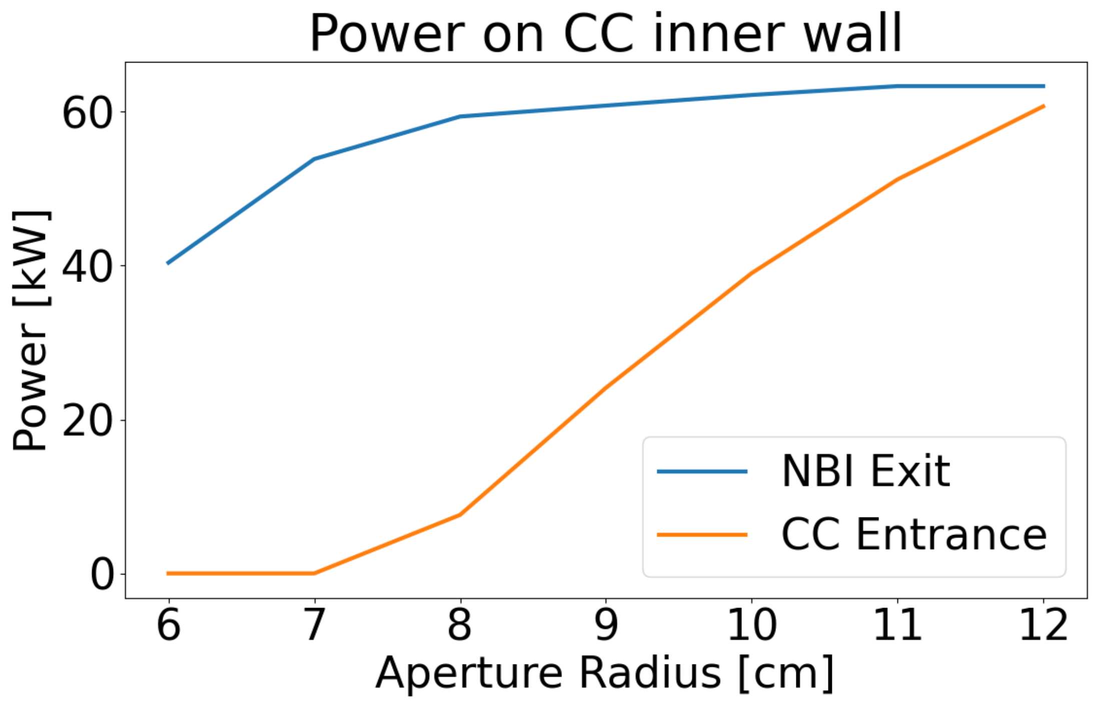
Sanity check of beam data

- A. Sorokin paper mentions the beamlet angular divergence is measured to be 1.2^o (shown in black).
- Measured half-width with the SEE array at the 18kV optimum is 12cm (shown in red).
- Good agreement between 2 sets of data means that everything 'checks out'.
- Use 1.2^o beamlet divergence for all analysis shown in these slides.



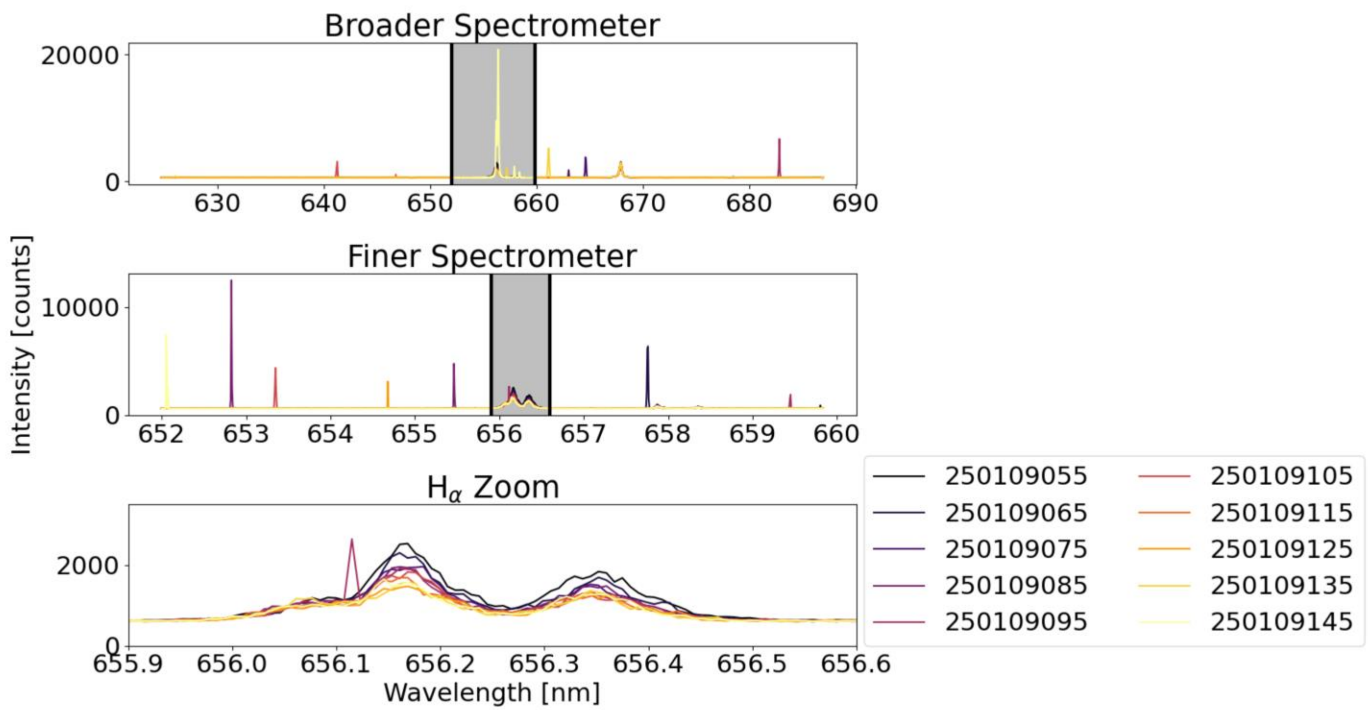
Apertures are best located close to the entrance of the CC (1000kW input power)



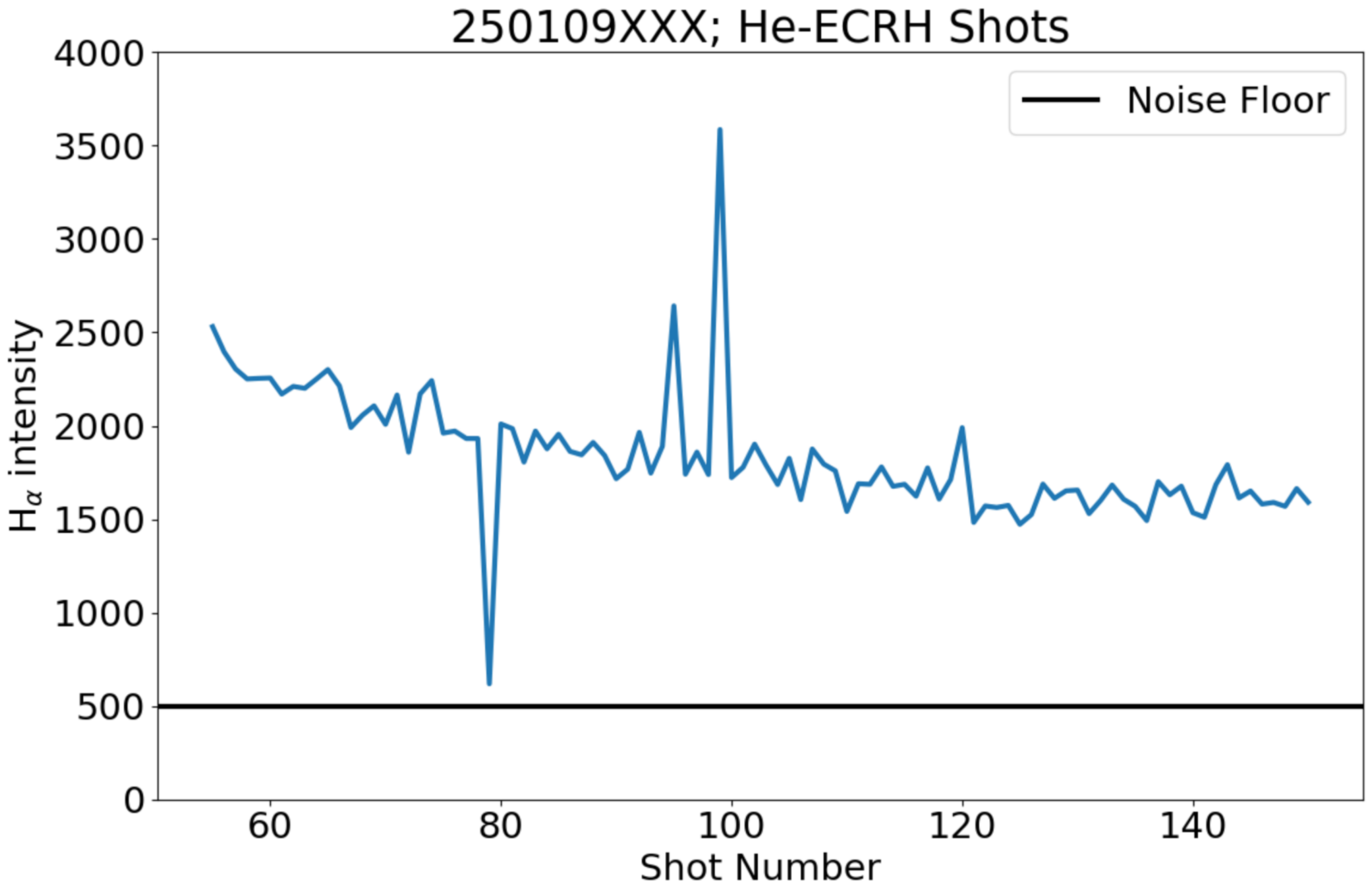


ORNL spectrometers used for analysis

- CC RGA- Broken
- Oscar Guage- Broken
- H_a/D_a intensity is used as a proxy for conditioning status
- Spectrum taken 9ms into a 10ms ECH pulse
- Coarse and fine spectrum centered around 656nm.

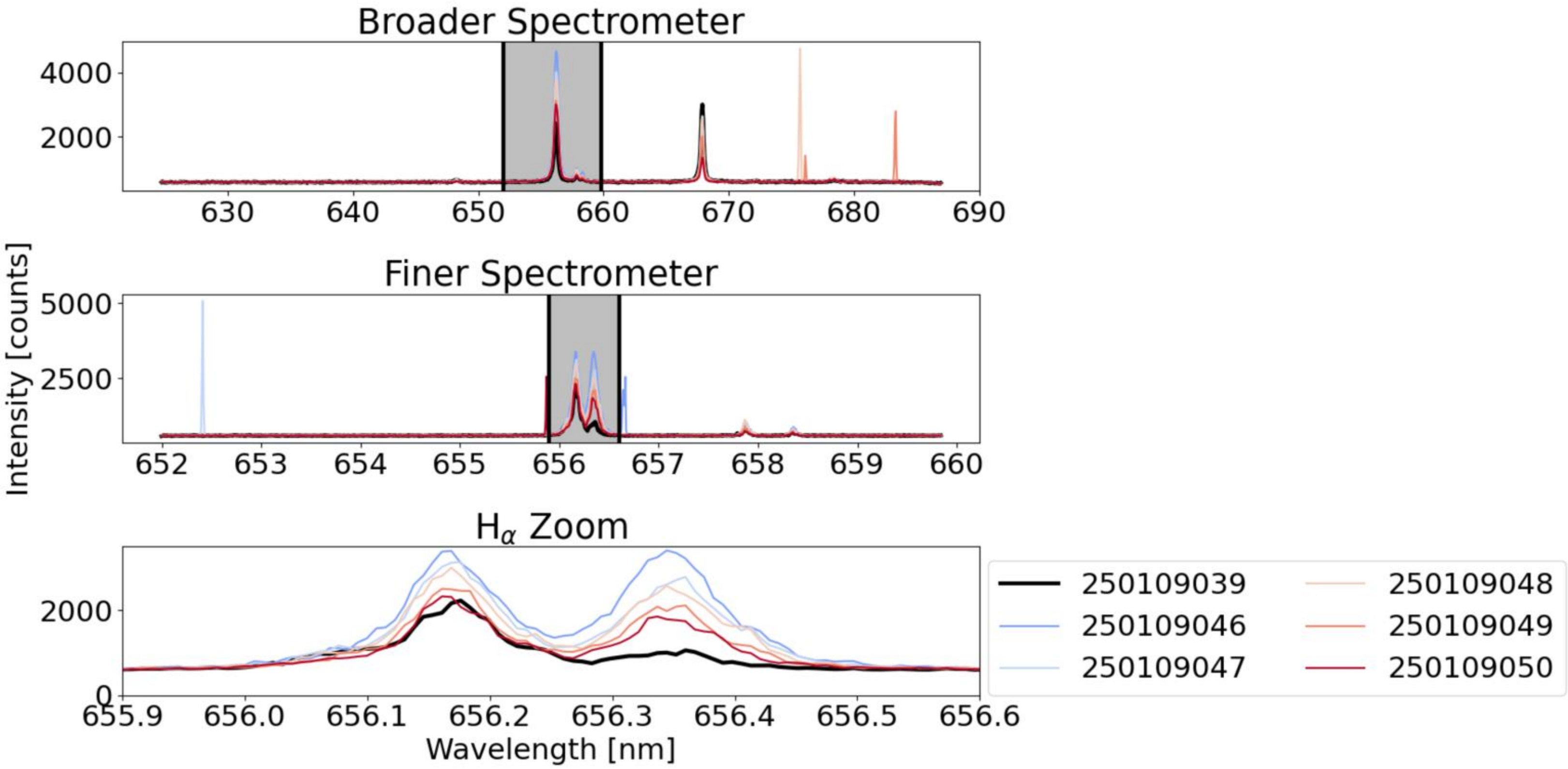


~100 shot He-ECRH discharges reduced H_a intensity by 40%

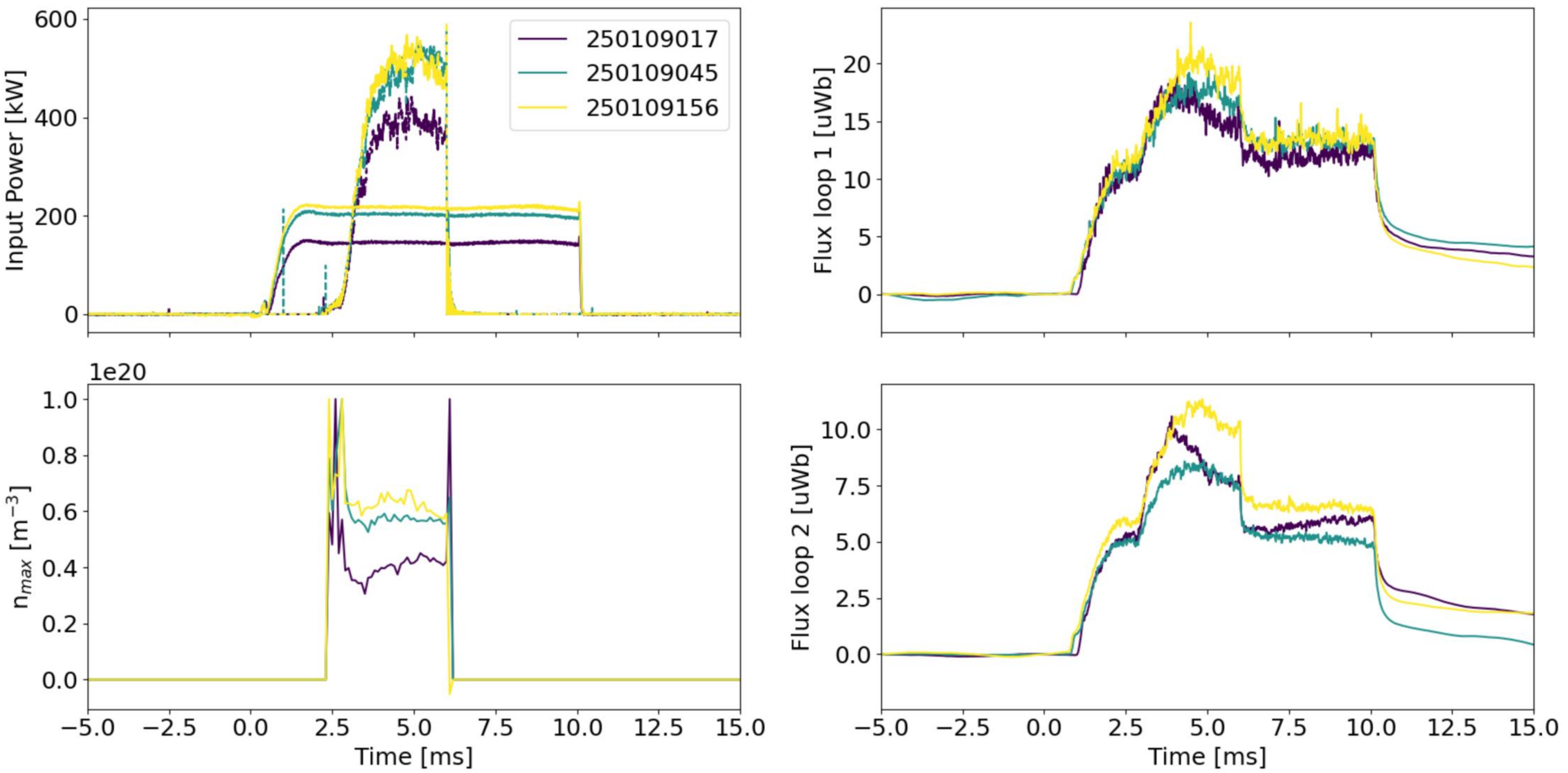


Big bump in H_a light right after some H_2 plasma shots

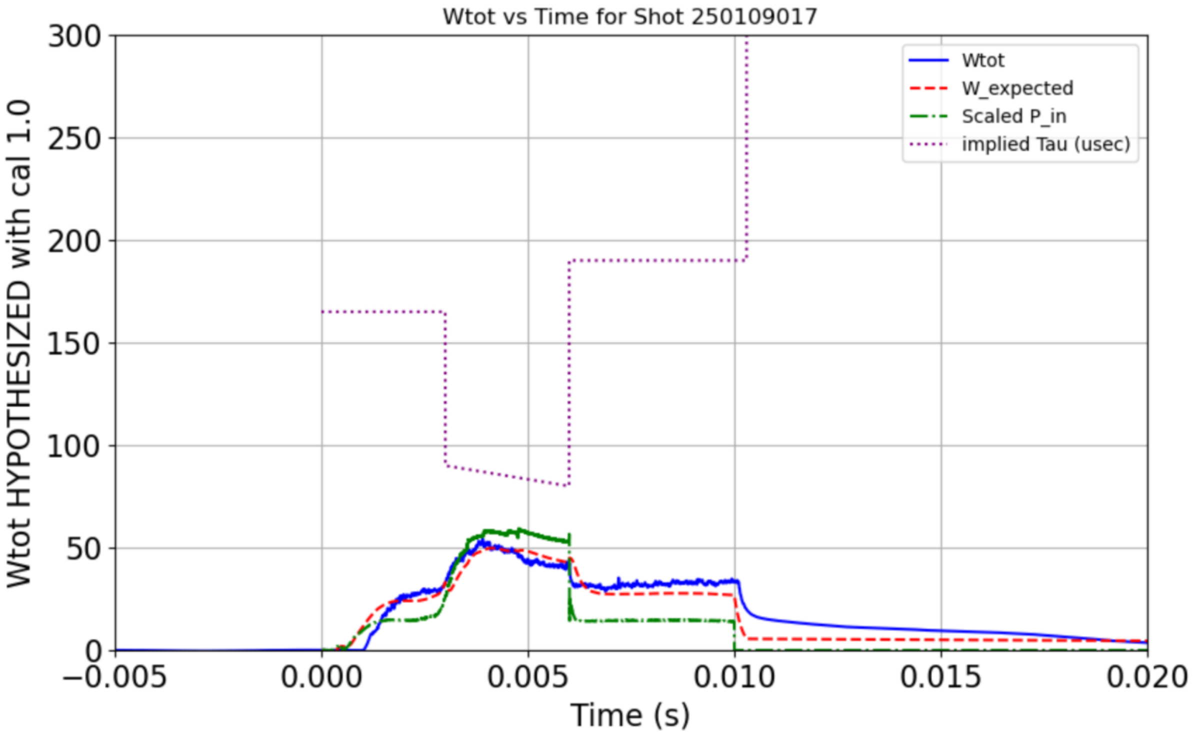
- 39- 20th He-ECRH shot
- 40-35- H_2 plasmas
- 46-50- He-ECRH shots
- Right after a series of H_2 shots, we see a bump in H_a intensity.

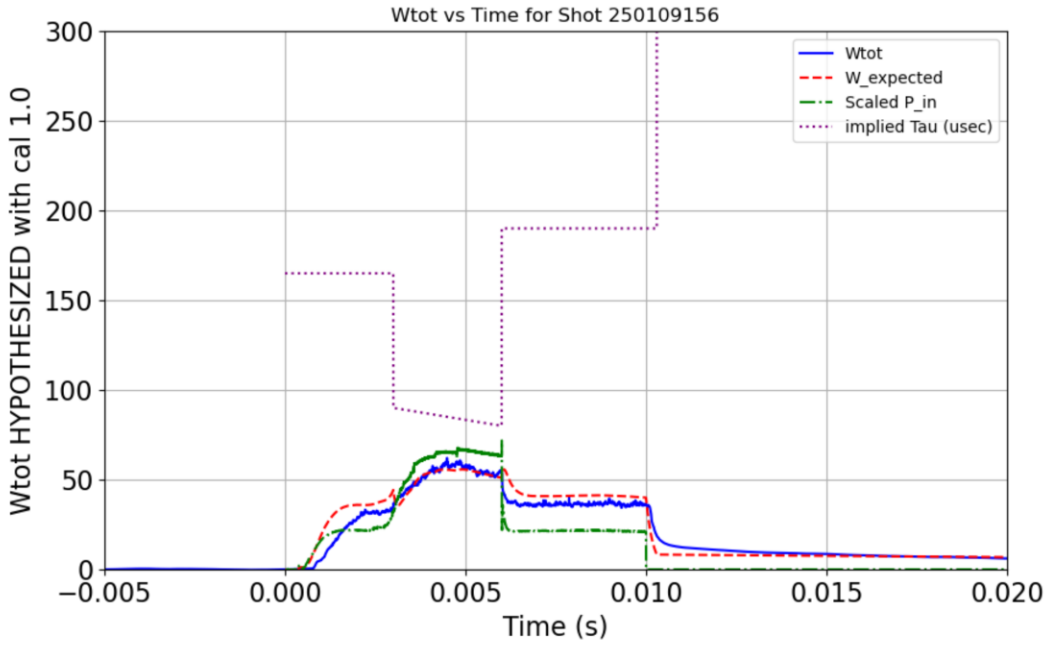


Pre and post He-ECRH shots

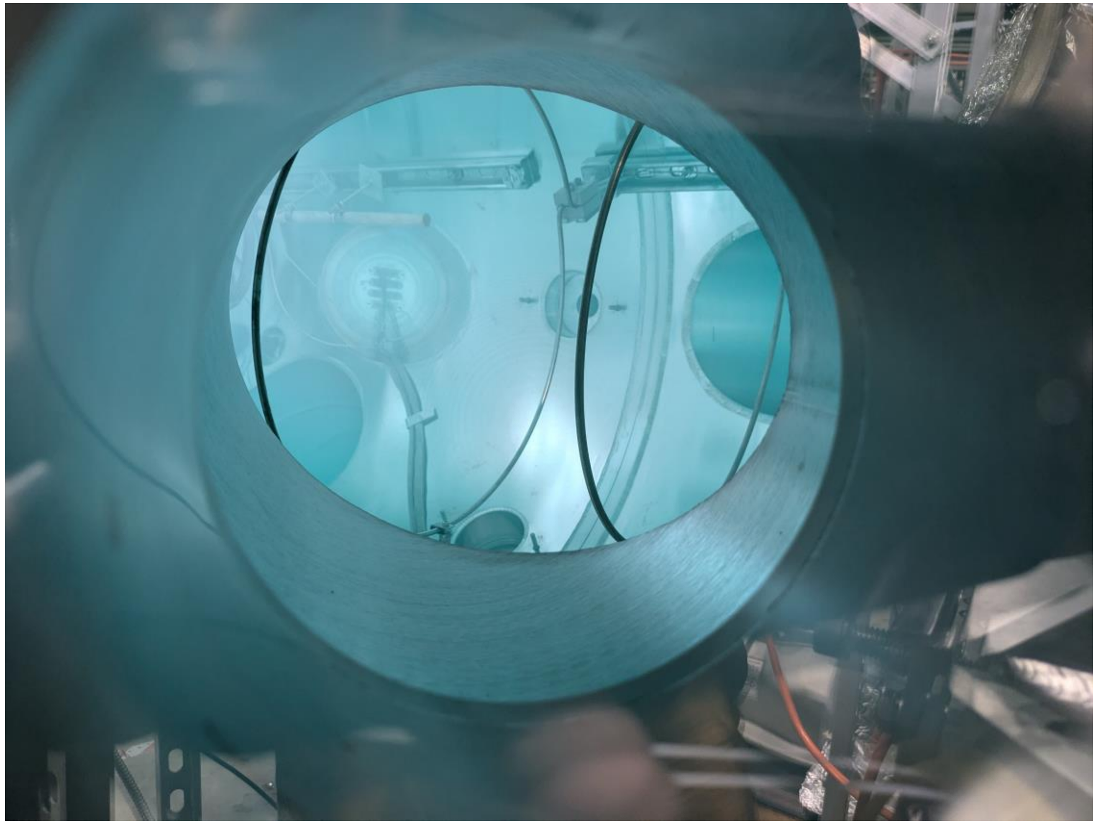


No change in confinement time model pre and post He-ECRH

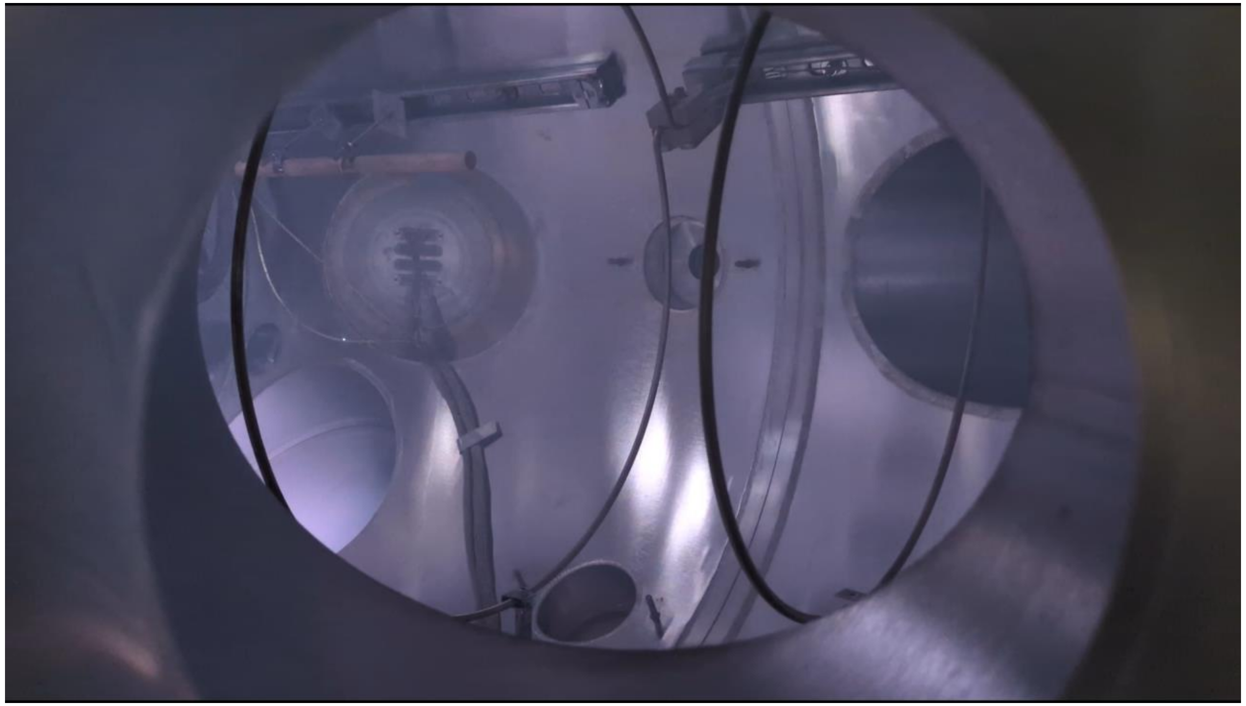




We have a plasma!

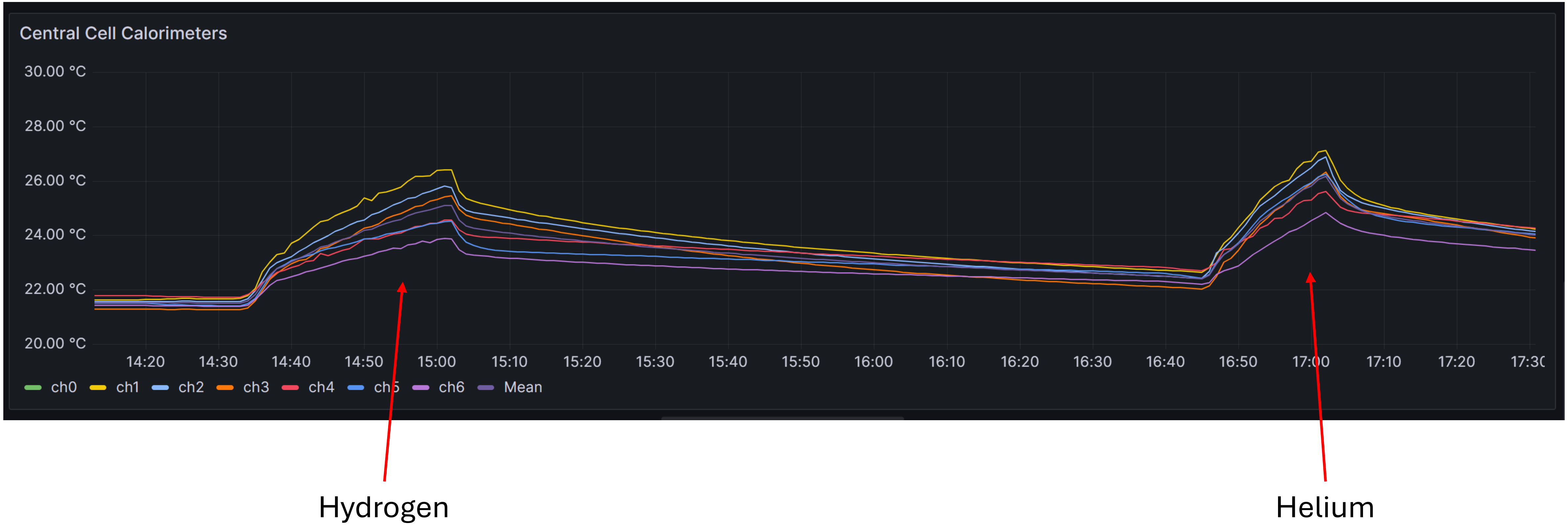


Helium



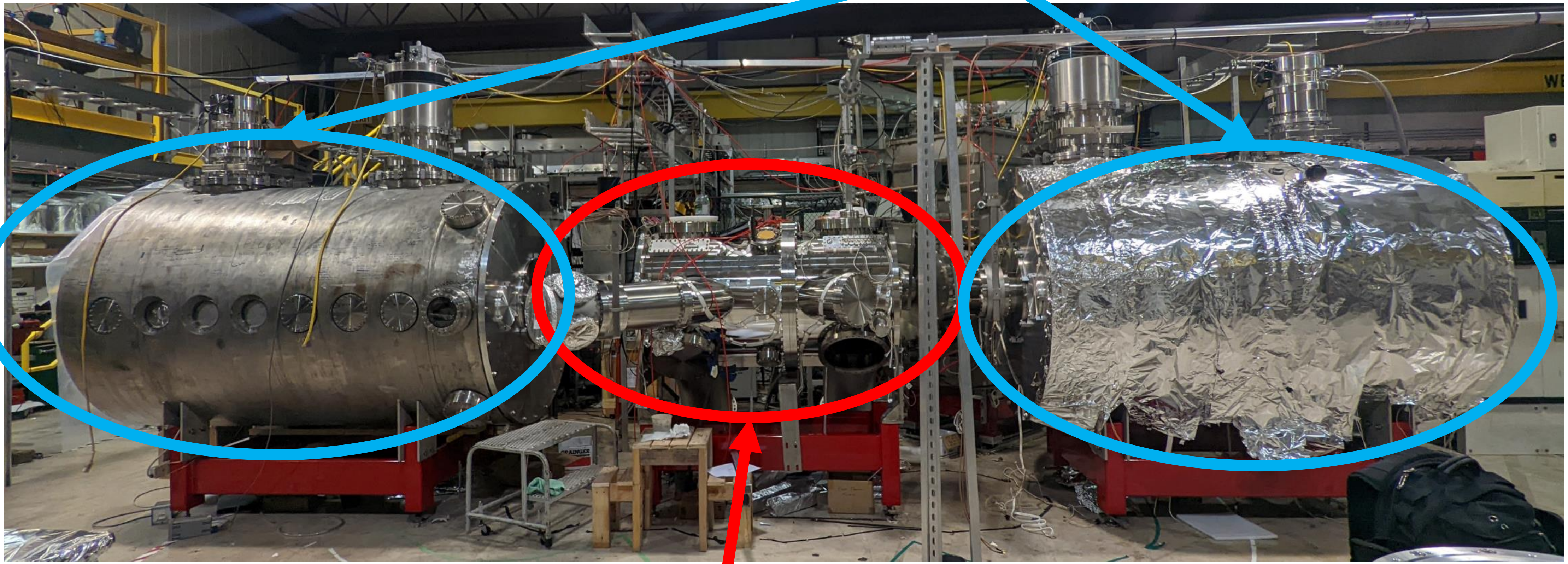
Hydrogen

Cu Bolometers suggest the GDC is ~even across the vessel



WHAM heater tape layout (37.5kW)

Heater tape on end cells being installed (12.5kW each)



Heater tape on CC and pump ducts installed (12.5kW)