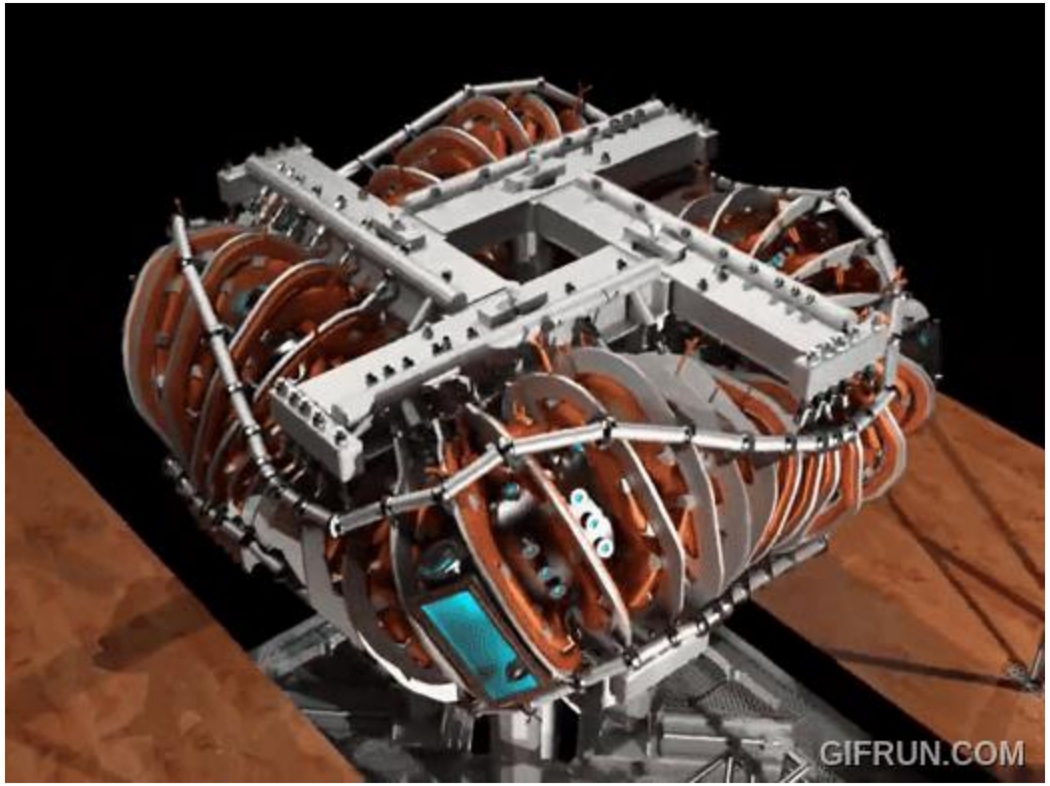
Just Install A Bake System Already

A historic overview of HSX's relationship with wall conditioning



A. Wolfmeister and the HSX team

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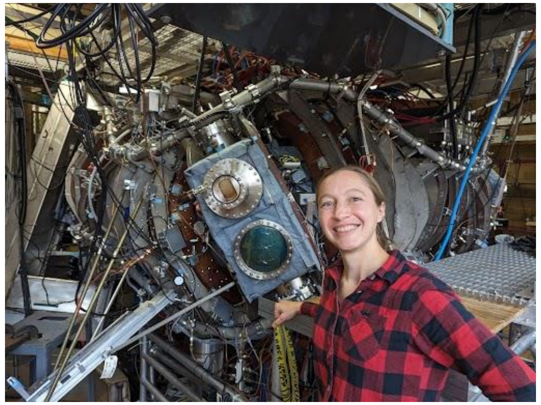
College of Engineering
UNIVERSITY OF WISCONSIN–MADISON

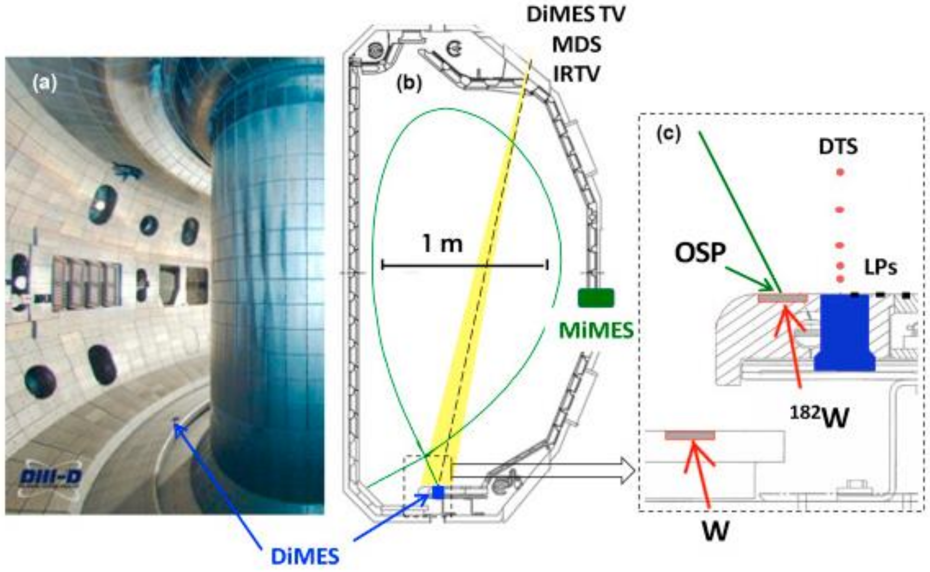
Overview

- Who I am and why you might want to listen to me
- Very brief introduction to HSX
- HSX's wall conditioning journey
  - **Bare steel walls**, successful lower confinement operations (B=0.5 Tesla) 2000-2006
    - Higher confinement (B=1 Tesla) caused density control issues 2006
  - **Carbonization** provided transient density control 2006-2009
  - **Boronization** is better, but lead to slag buildup 2009-2022
  - **Manual wall reset** + **BAKING SYSTEM** (2022) allows robust density control in both high and low confinement regime with only helium glowing
    - Currently operation with no *ization
- An overview of spectroscopic diagnostics on HSX
- Physics motivations for impurity control in HSX
  - Ion composition impacts turbulence and electron temperature

Alexis Wolfmeister, Previously Briesemeister

- 2005 to 2013 Graduate student at HSX
  - Implemented the CHERS system
  - Studied impurities (1 m spectrometer)
- 2013 to 2017 Post-Doc=> Researcher for ORNL at DIII-D
  - Ran the MDSpectrometer which looks at the divertor including the DiMES head
  - Ran the filterscopes
- 2017 to 2023 Hiatus
- 2023 to Now: 0.5 Scientist II at HSX
  - Implemented the Multiple Impurity Monitoring System (MIMS)

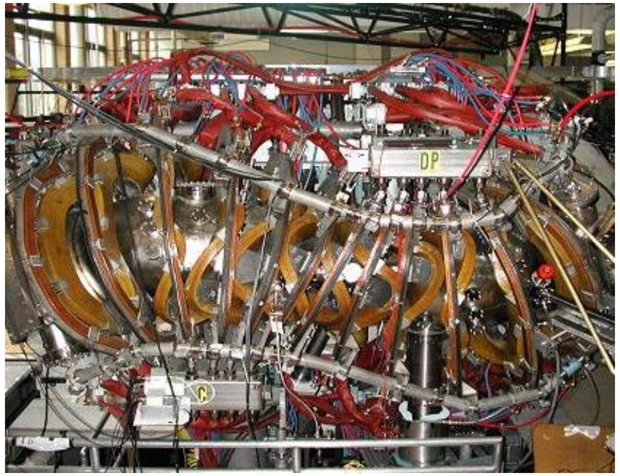




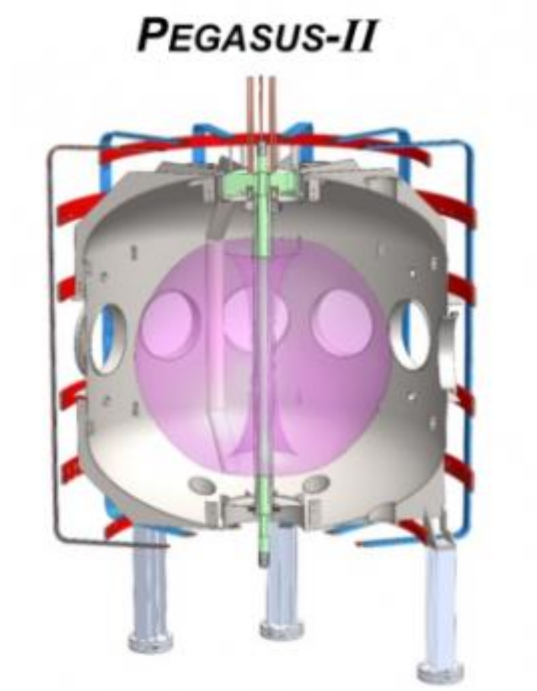
A very brief introduction to the HSX stellarator

HSX is a toroidal device with no direct current drive. poloidal and toroidal fields are generated by external coils

HSX



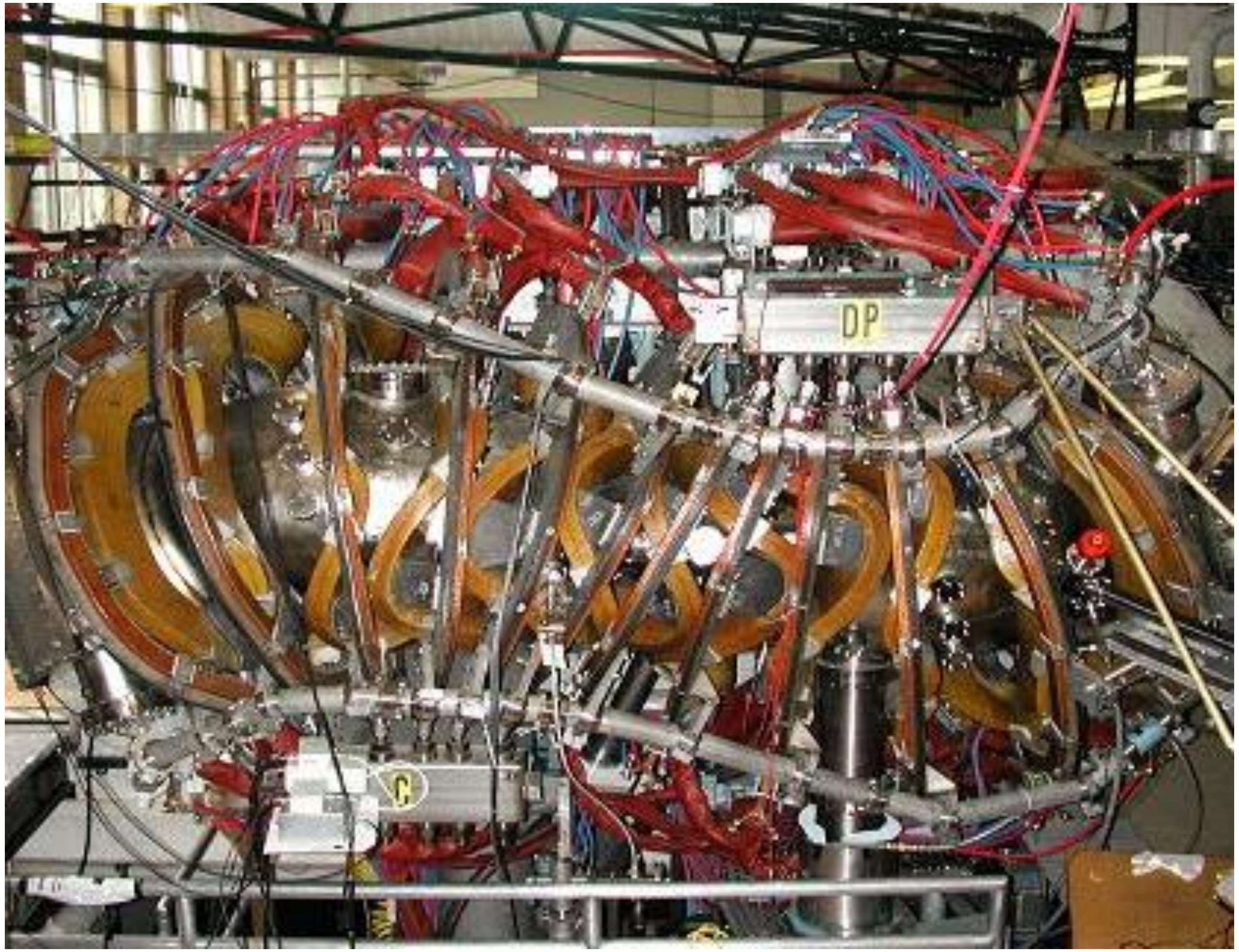
- Plasma currents do arise in HSX, but they are small
- I_p~150 A in HSX



I_p~150 kA in Pegasus-II *

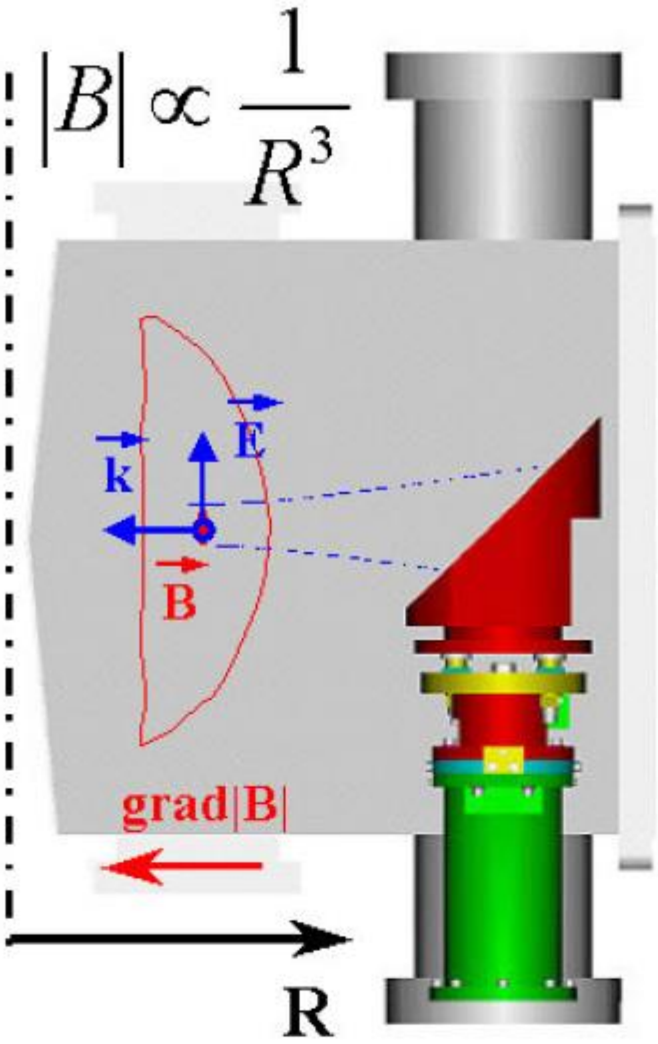
*K.E. Thome APS-DPP 2010 Poster https://pegasus.ep.wisc.edu/wp-content/uploads/sites/1310/2020/01/KET_APS10.pdf

HSX is a moderate size stellarator



- Effective Major Radius=1.2m
- Effective Minor Radius=0.12m
- ENTIRELY **ECRH** Heated
- Magnetic fields 0.5 Tesla or 1 Tesla for on-axis heating

ECRH Cutoff Sets HSX's Density Limit

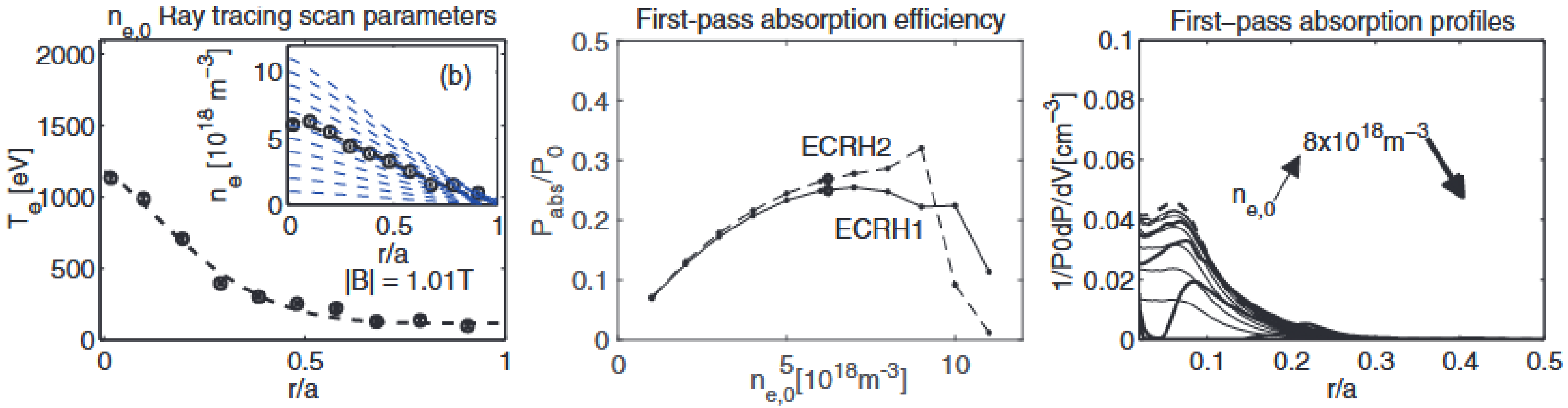


- Existing System 28 GHz System
  - B_T=0.5 Tesla,
    - X-Mode Heating
    - Density Limit ~ 4.9 x 10^{18} m^{-3}
  - B_T=1 Tesla,
    - O-Mode Heating
    - Density Limit ~ 1 x 10^{19} m^{-3}

Coming Soon 70 GHz System!!!

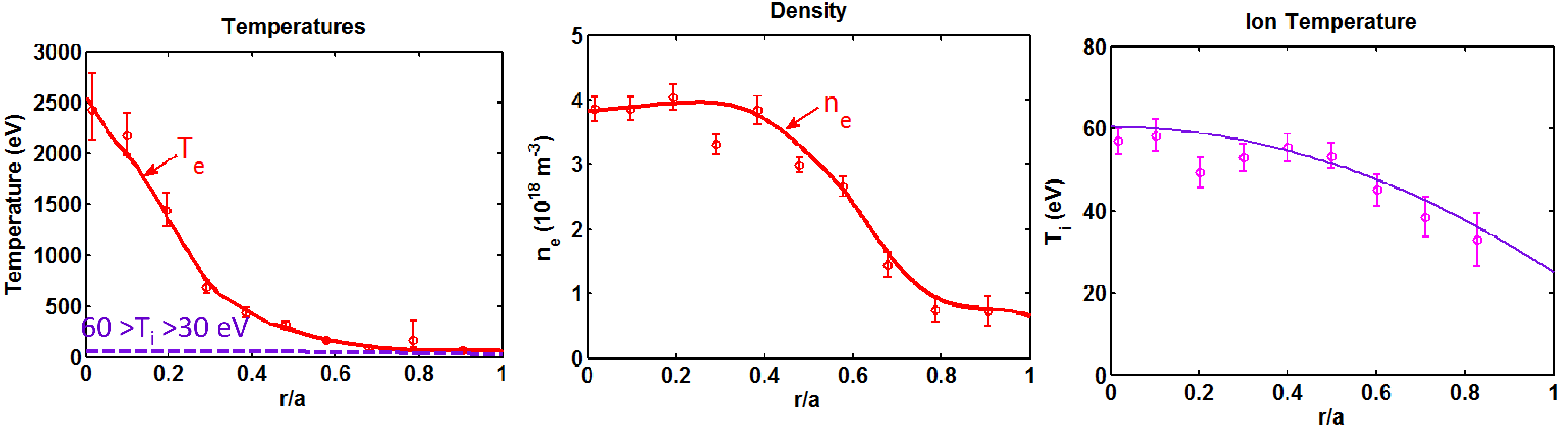
- B_T=1.25 Tesla,
  - X-Mode, Density Limit=3 x 10^{19} m^{-3}

Absorbed ECRH power, calculated from TRAVIS ray tracing, depends on density profile



- Cut-off density approximately describes where the absorbed power will fall off
- G.M. Weir et. al Nucl. Fusion 55 (2015) 113011 (7pp) doi:10.1088/0029-5515/55/11/113011

When All Goes Well 2.5 keV electrons are achieved with 100 kW launched ECRH and 1 T field



- 100 kW launched electron cyclotron resonance heating (ECRH) was used
- Strongly peaked electron temperature profiles
- No direct ion heating, charge exchange limits ion temperatures

Neutral Penetration Into the Core of HSX

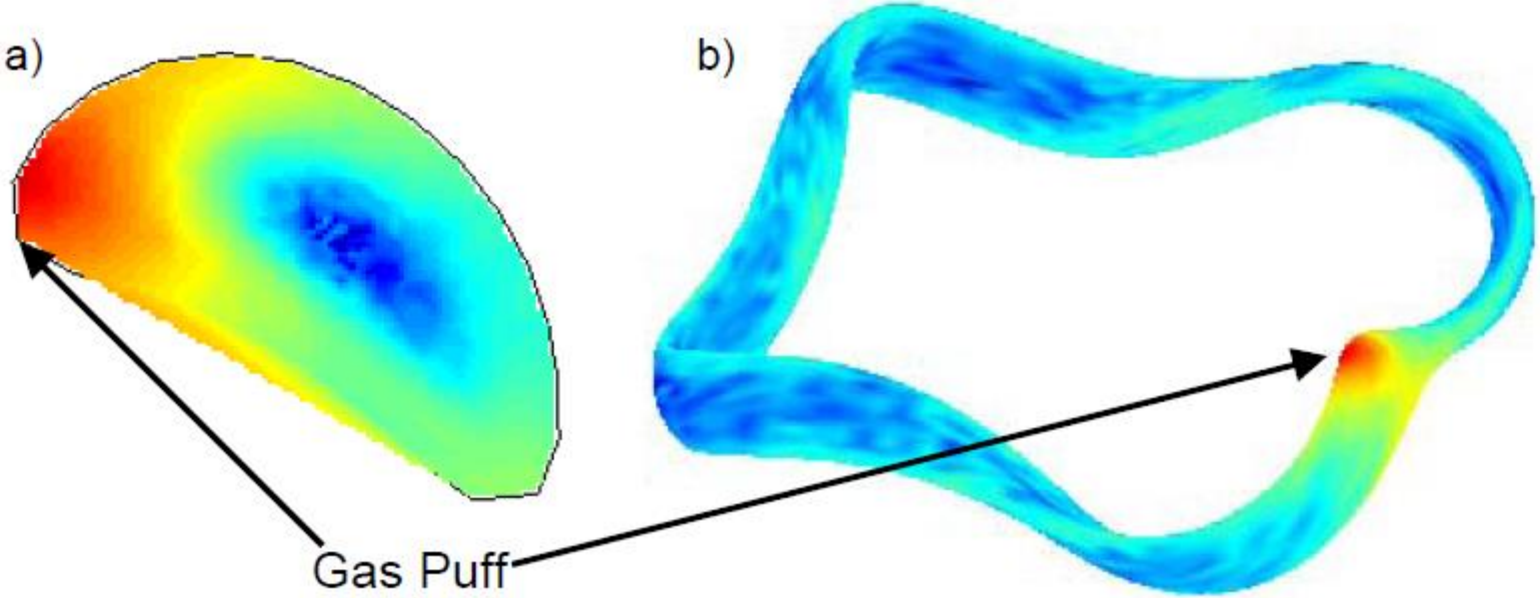


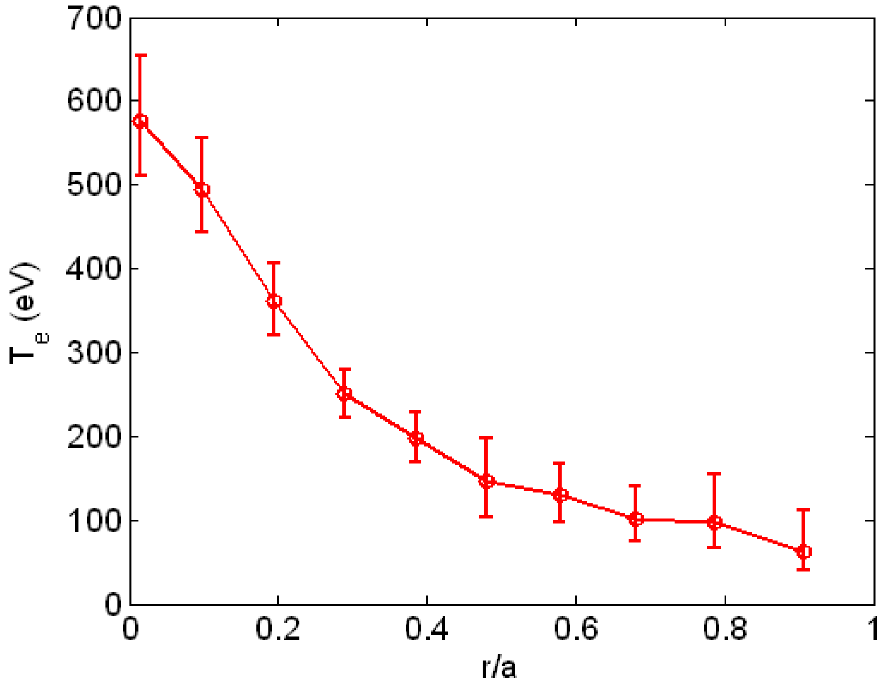
Figure 4.5: Colors indicate the density of molecular hydrogen (in arbitrary units) at a) a cross section of the vacuum vessel located near the gas valve and b) a view of the full torus

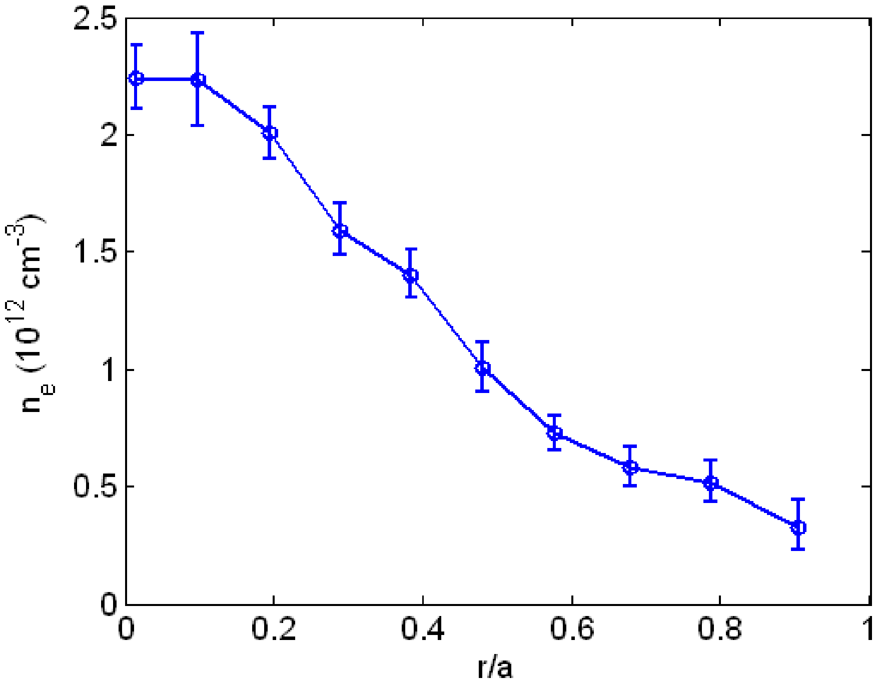
Now for the history lesson

HSX Operated at 0.5 Tesla, X-mode 28 GHz from August 2000 to 2006

- Plasma facing surface of 304 Stainless Steel vessel was electro-polished
- Helium glow discharge cleaning used to remove water and residual hydrogen (as determined by RGA)
- Typical base pressures 2×10^{-8} Torr
- Original glow system 2 anodes in box ports, Current system 4 retractable anodes

HSX 0.5 Tesla Operation, Density Limit ~ 4.9 x 10^{18} m^{-3}

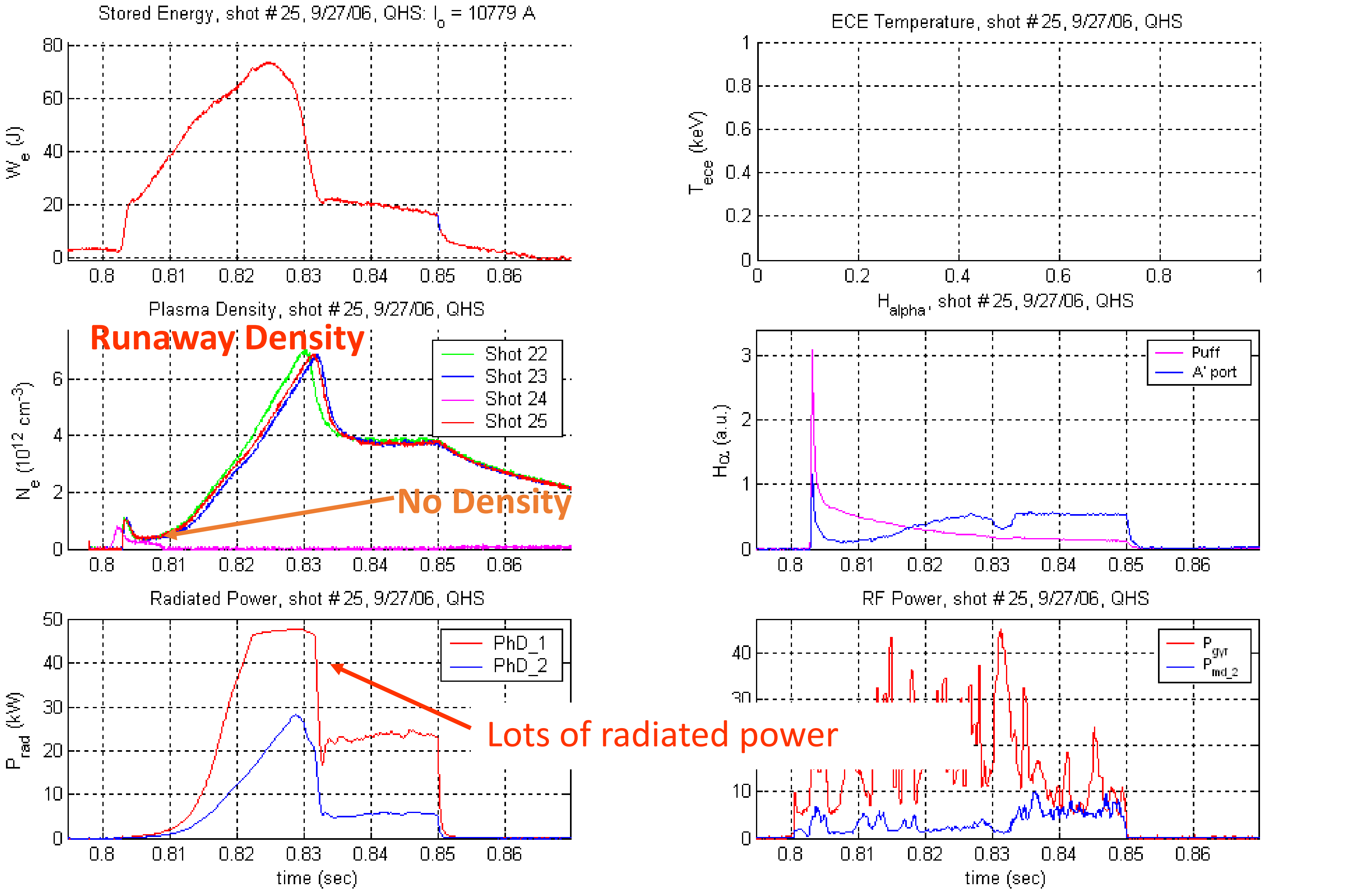




- Canik 2005 ISHW

- With no wall conditioning reasonable density control was achieved
- 50 kW Heating, Ran this way for about 6 years

In 2006 initial attempts to run 1 Tesla, O-Mode



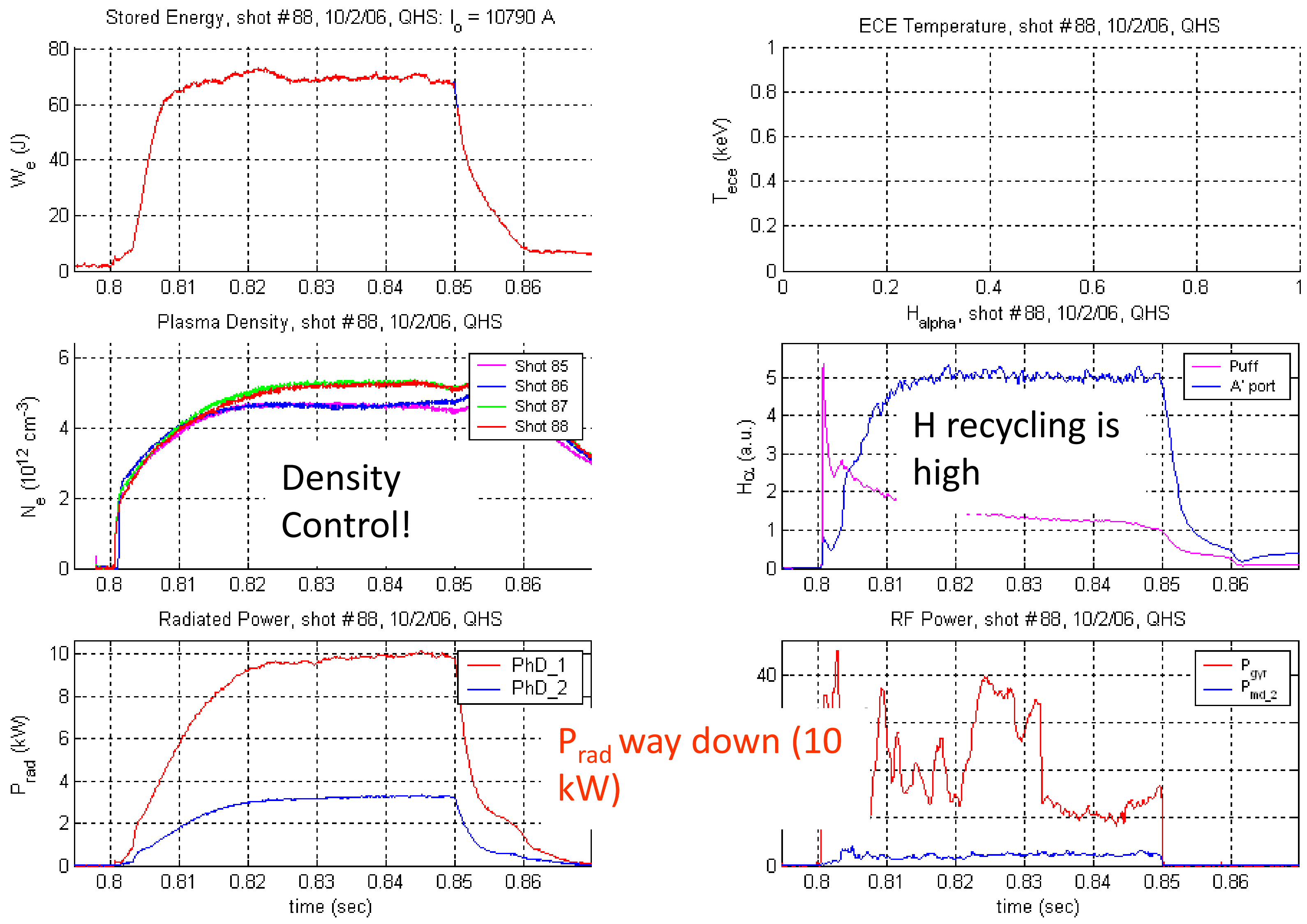
How we tried to fix it

- We didn't know what's causing it
  - Not hydrogen recycling
  - Candidates are Oxygen, Iron, or Helium (TJ-II had He problems from the glow)

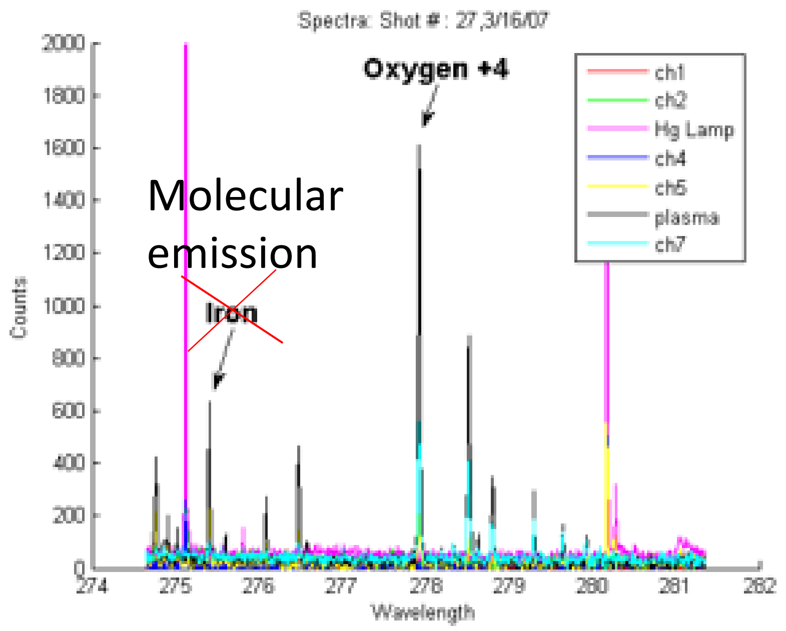
- Things we tried (that failed)
  - Argon glow to get rid of He – did nothing
  - H2 glow to get rid of wall oxides – did nothing

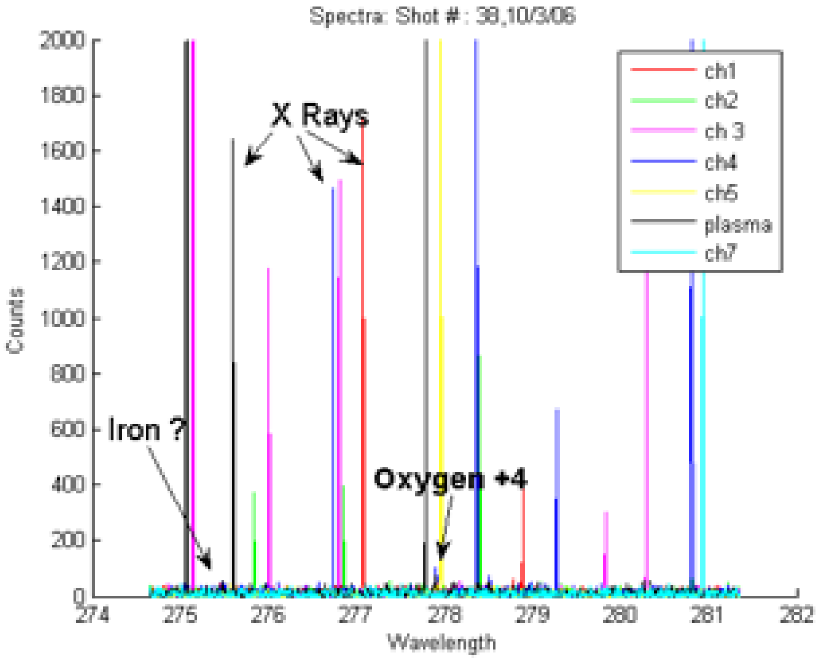
- How we fixed it: Carbonization!
  - Methane was used in the glow discharge cleaning system to intentionally coat the walls in carbon
  - Helium glow discharge cleaning was used to remove hydrogen

Carbonization Worked! October 2006



Carbonization probably trapped impurities, including oxygen





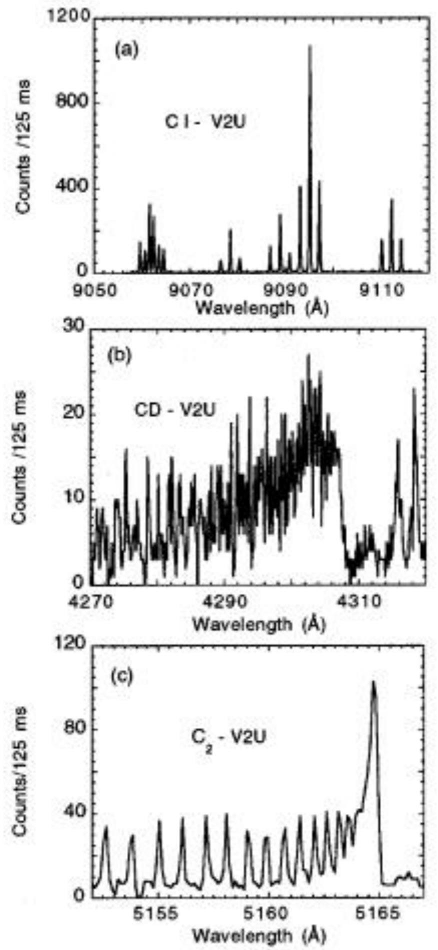


FIG. 2. CI, C_2, and CD signals from unconditioned tiles for 9 MW NBI, USN [V2U, Fig. 1(a)].

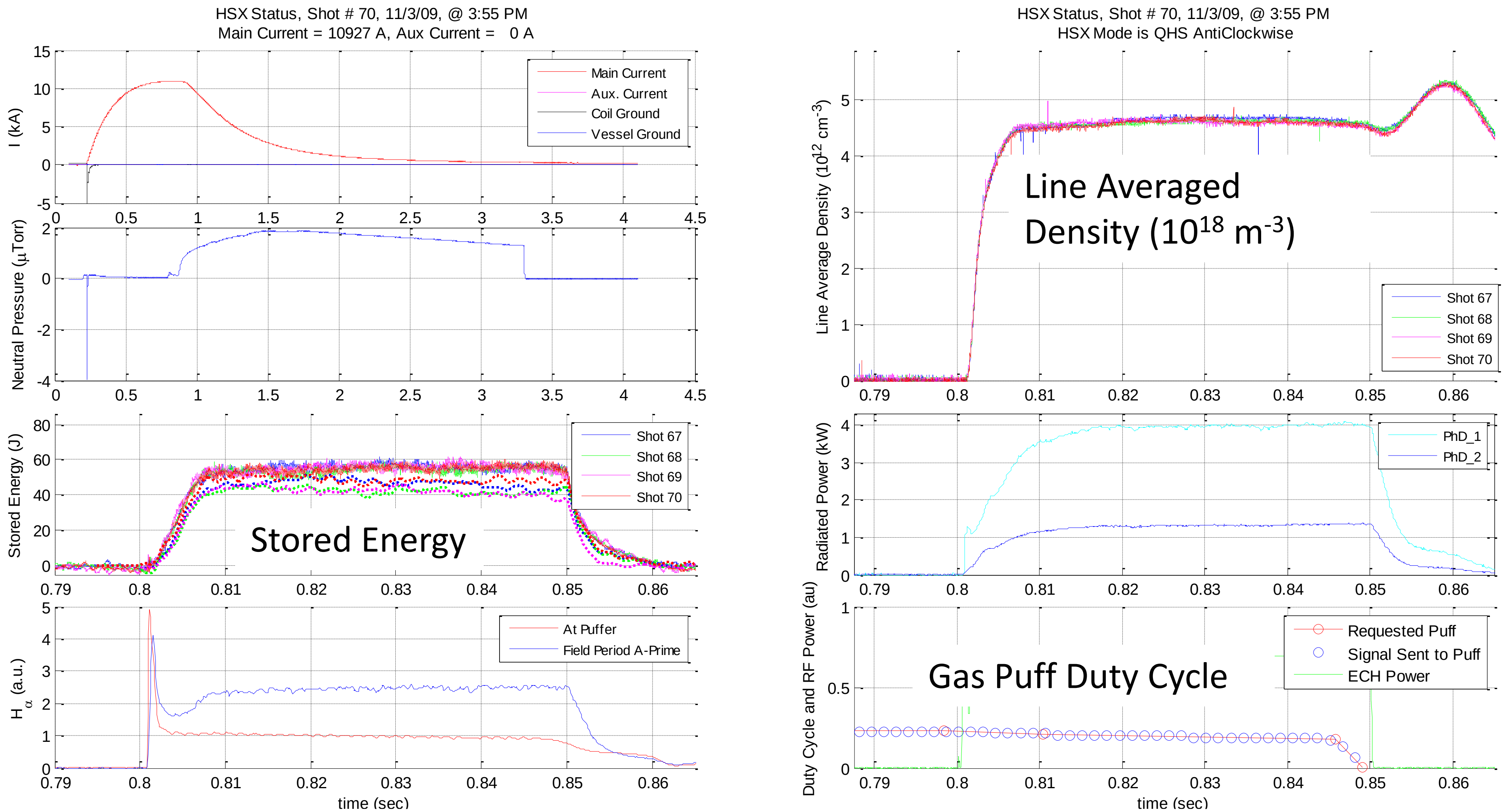
R. C. Isler et al. PoP 2001

- Oxygen is not fully stripped in the core of HSX
- Spectroscopy showed a zoo of lines, in hind-sight these were probably molecular emission

Behavior with Carbonization

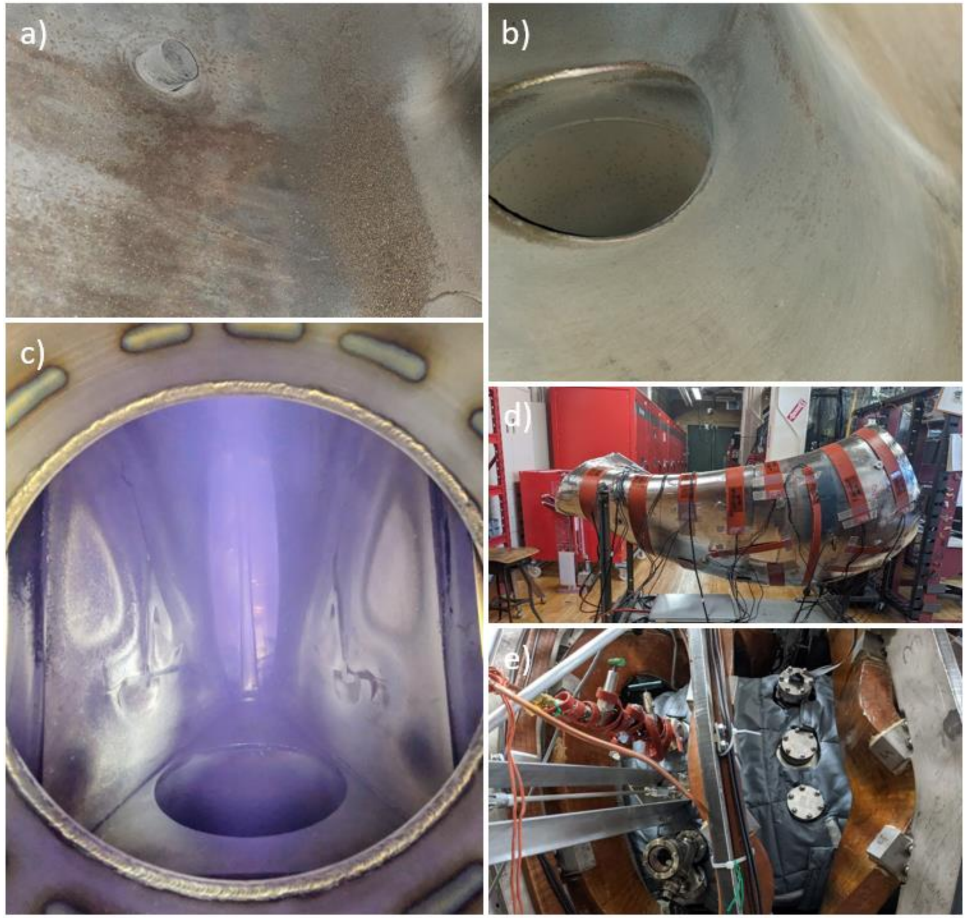
- He after each run day
- The beginning of the day, density control is easy
  - Need lots of gas puff throughout the shot (carbon layer absorbs hydrogen)
- It gets worse later in the day (40 shots?)
  - Less puff, eventually density ramps (no control, carbon layer saturates)
- Another He glow seems to help this
- This is sort of what other machines see
  - Need to He glow to knock H_2 off the walls

Boronization Was Even Better! November 2009



- Could run all day with no mid-day glow

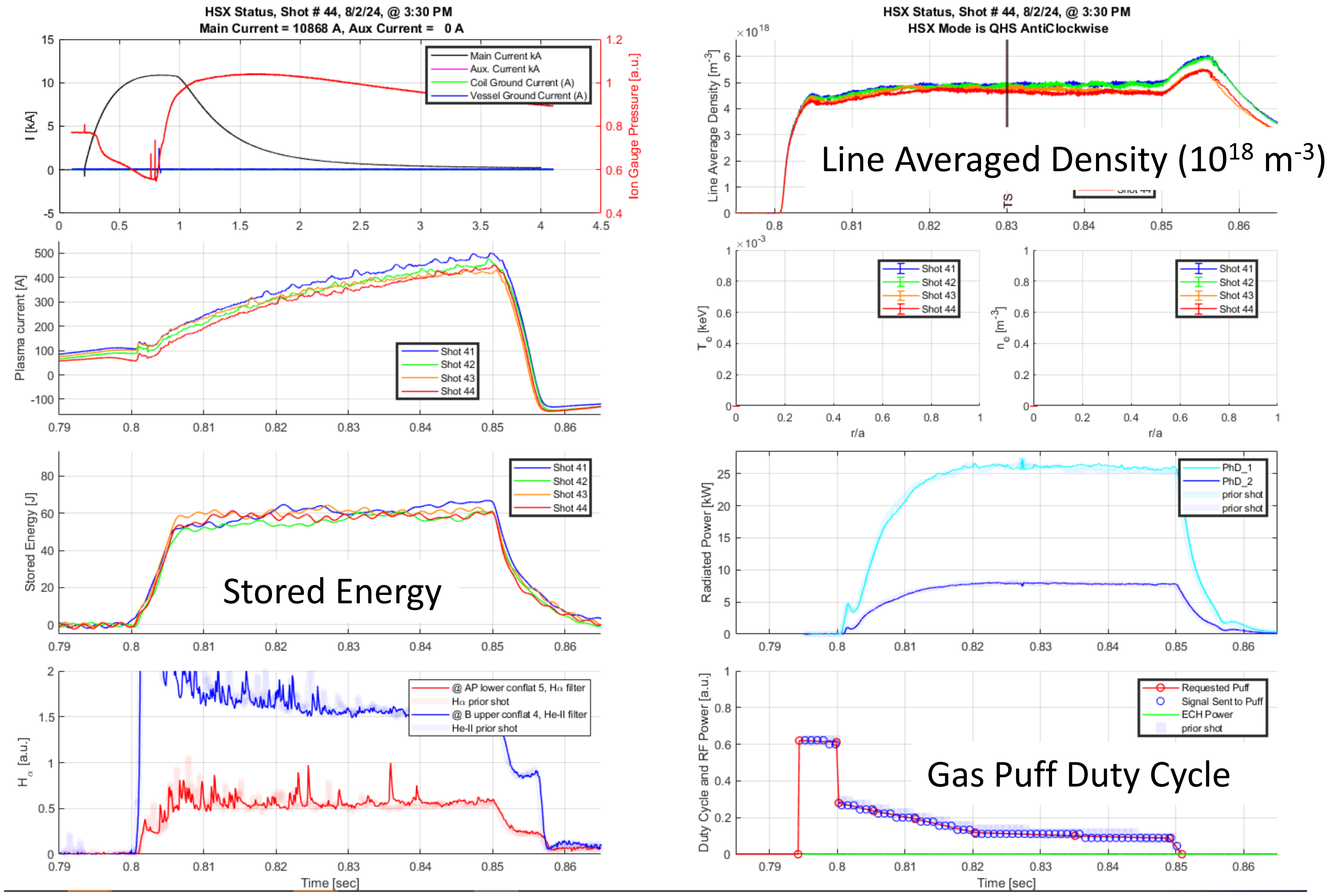
Until it wasn't.



- Years of wall conditioning lead to significant amounts of dust and scale on plasma facing surface
  - Dust entering the plasma prevented stable operation
- First wall re-set was performed
- Baking system was installed
- Currently operating with an un-conditioned steel wall

Wall cleaning lead by D. Damaskopoulos

Now we're back to great plasma operations! And we aren't boronizing!

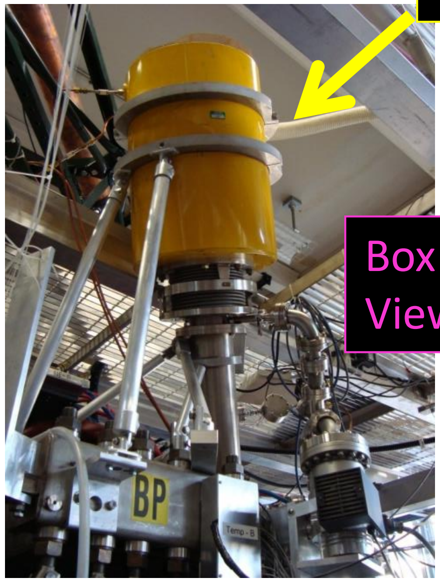


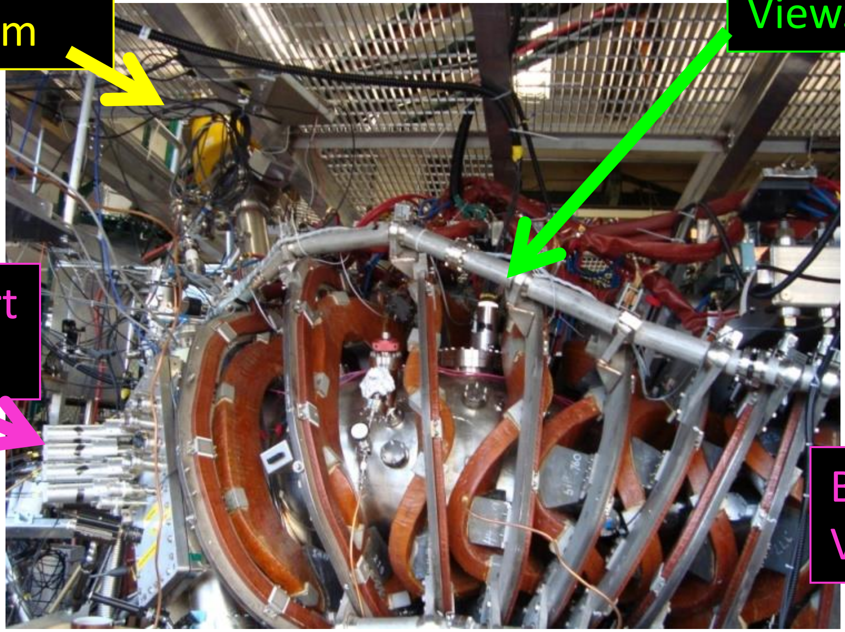
Take aways from our journey

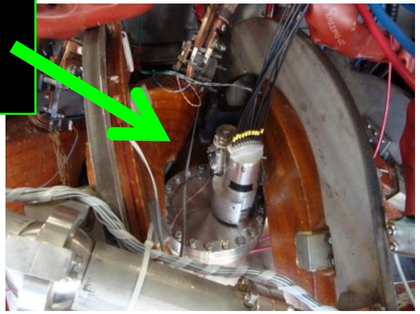
- After venting: density control issues are seen when walls aren't re-conditioned
  - (~1 week +) baking at modest temperatures (~50^{o} Celsius~ 122^{o} F) along
  - Helium Glowing (~4 hours)
  - Plasma operations (1-2 run-days)
- So far we haven't needed to return to boronization
- Higher performance (1.25 T, 70 GHz heating) may change this

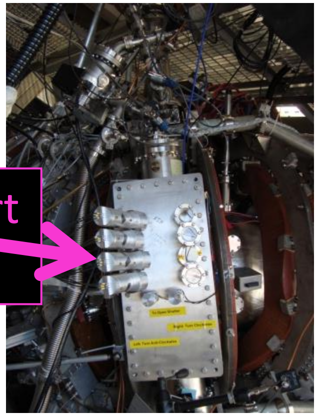
Current Spectral Diagnostics At HSX

CHERS Charge Exchange Recombination Spectrscopy System









- Typically used with the 529 nm emission line
- Attempts currently being made to use the 468 He line
- Provides spatially localized impurity density measurements

Photodiodes used to measure H-alpha, He I and He II emission

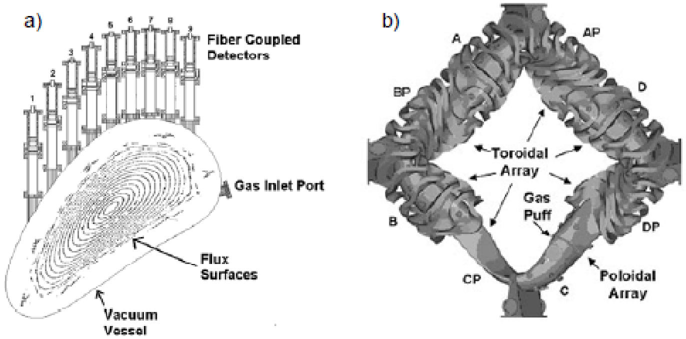


Figure 4.7 a) poloidal and b) toroidal arrays of H_α detectors, from ref [7]

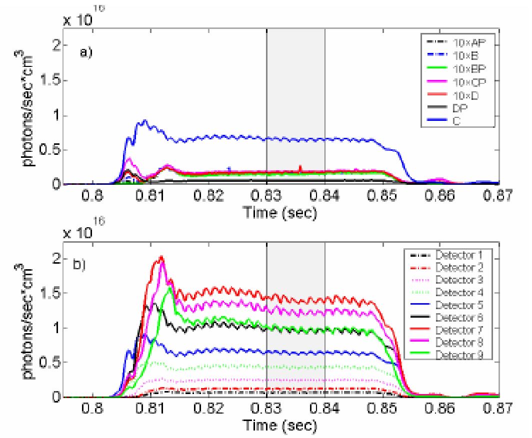
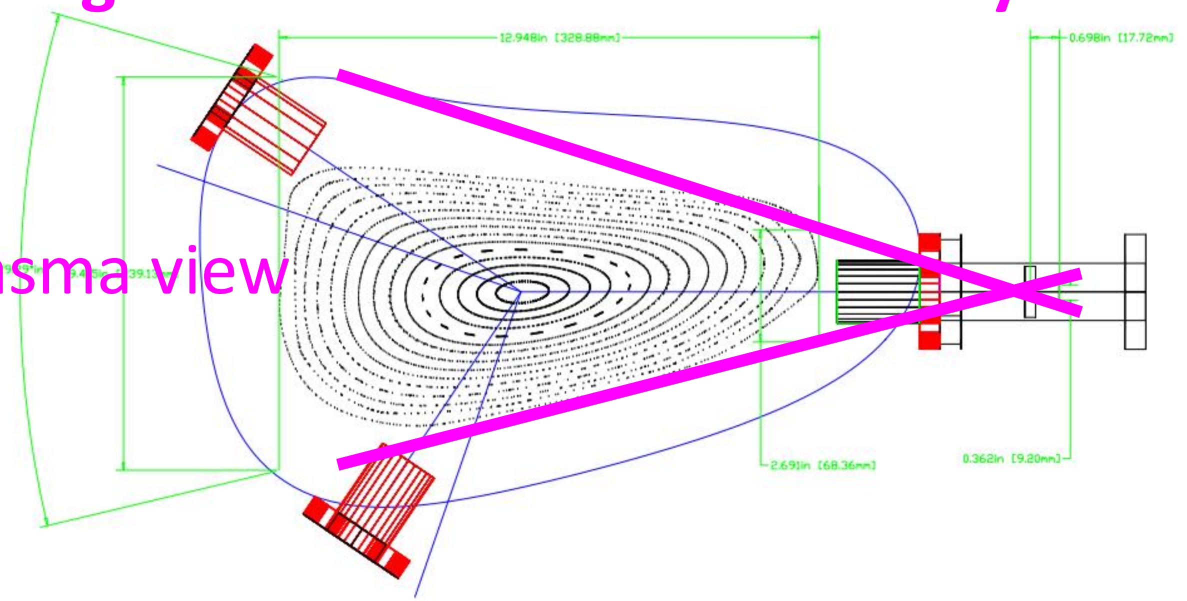


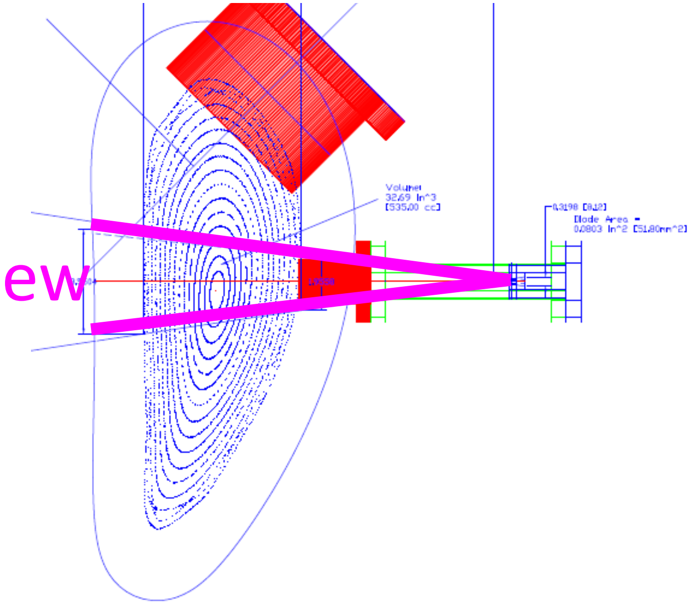
Figure 4.8 Typical H_α signals for the a) toroidal and b) poloidal arrays, from ref [7]

- Optically filtered emission coupled to photodiodes
  - 10 kHz (0.1 ms period) sampling, but could be faster
- DEGAS has been historically used for neutral emissions calculations
- EMC3-Eirene simulations now available

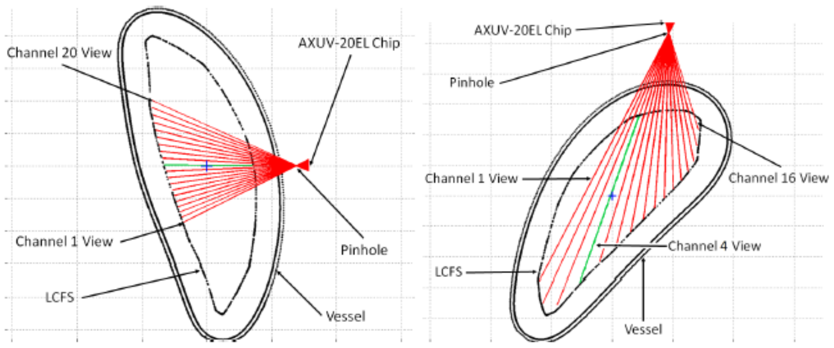
AXUV Photodiodes used to approximate bolometers

2 Single Detectors Used Historically





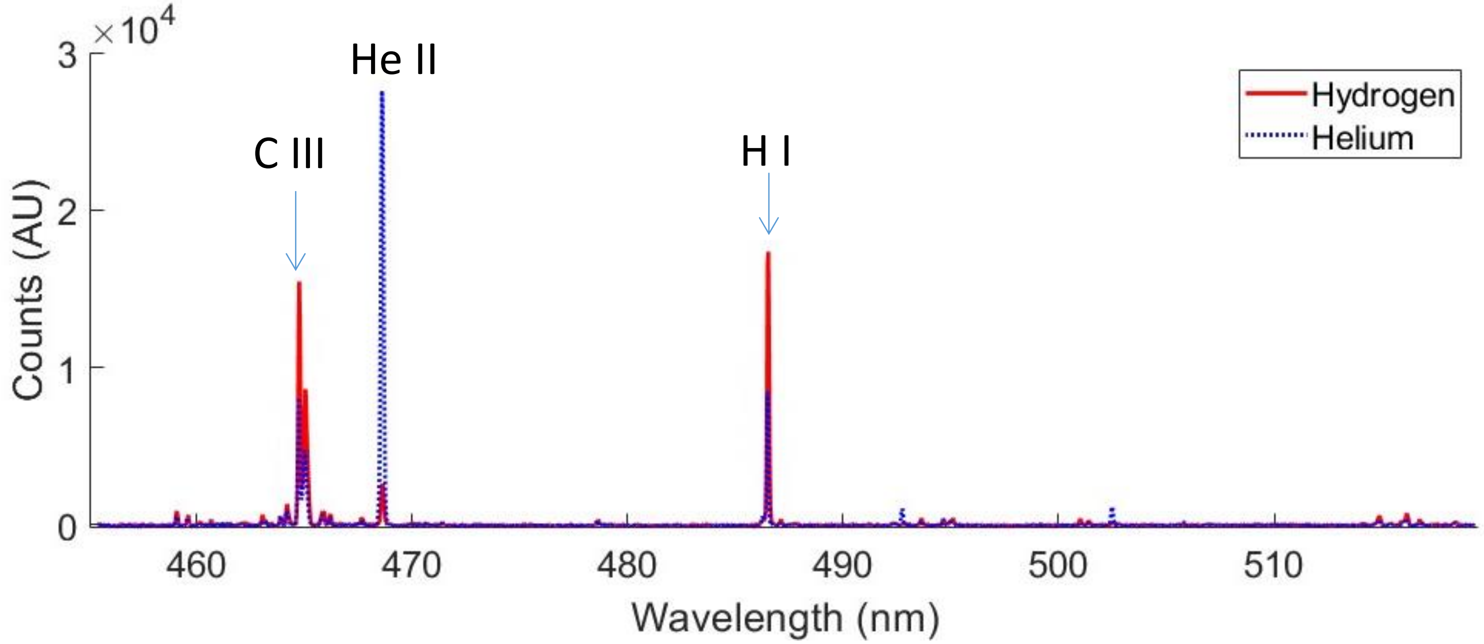
AXUV arrays deployed for Laser Blow Off Measurements also available

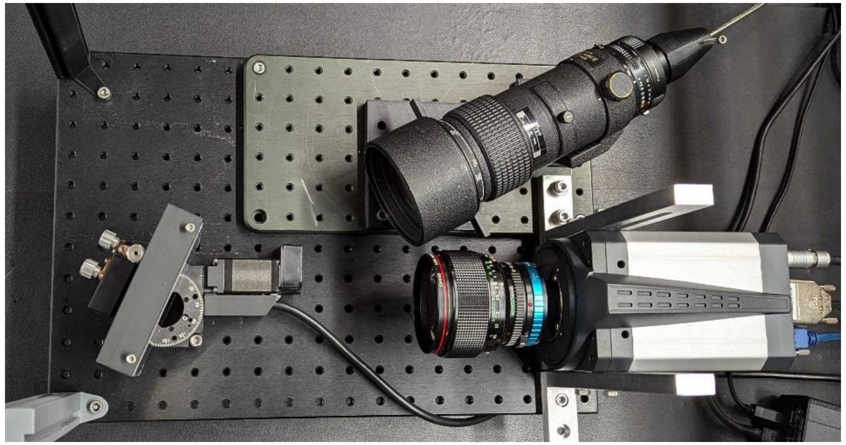


(a) Lines-of-Sight for Array A12M (b) Lines-of-Sight for Array A34

F. Castillo Thesis

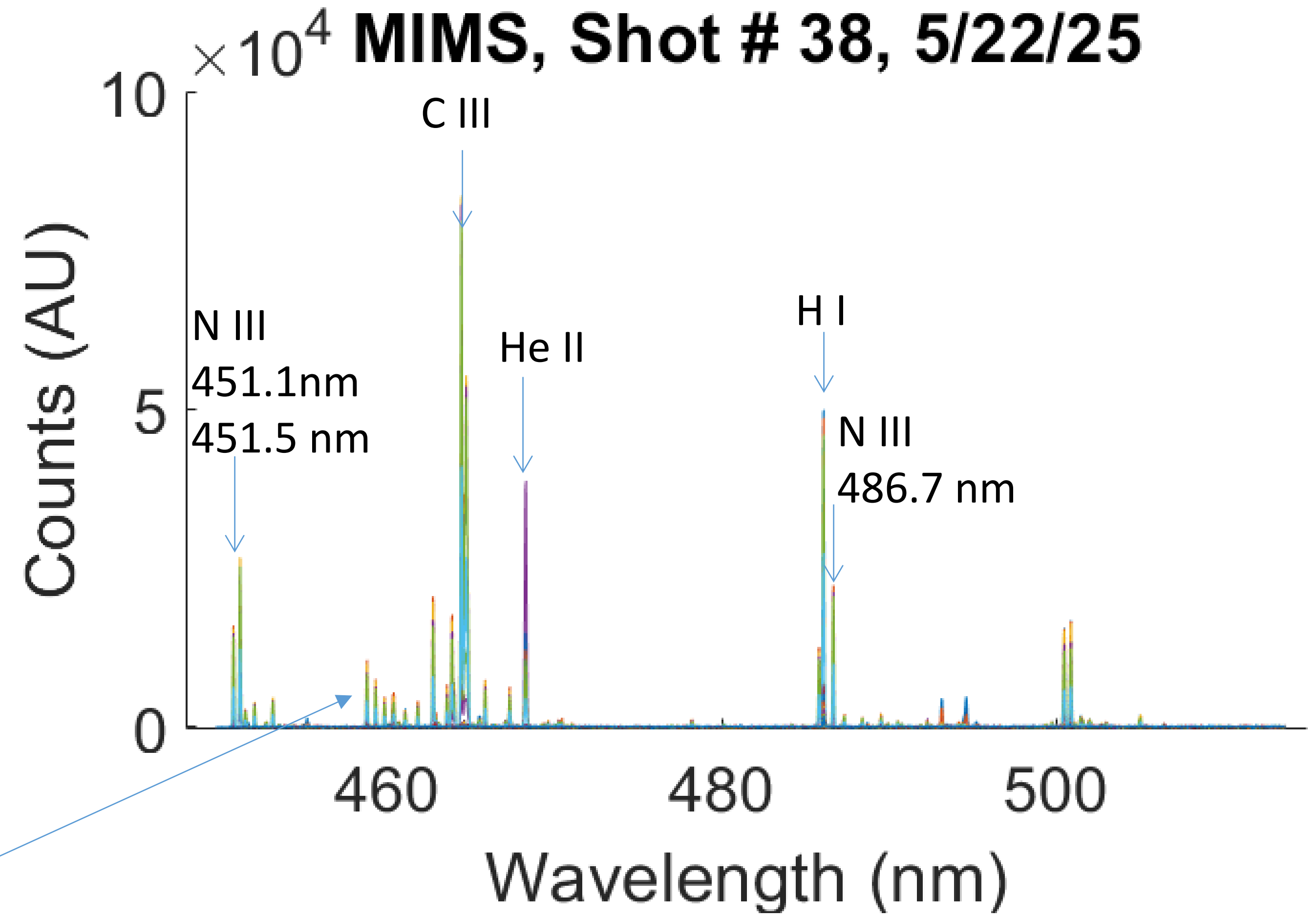
Multiple Impurity Monitoring System (MIMS)





- Spectrometer developed in-house by B. Geiger, C. Swee et. al
- 65 nm wide spectrum, tunable within the visible range
- Andor Sona sCMOS camera

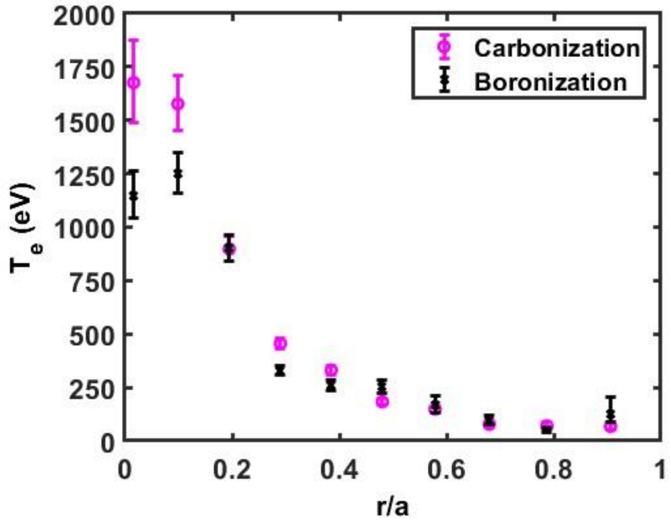
MIMS shows evidence of nitrogen emission after a long up to air

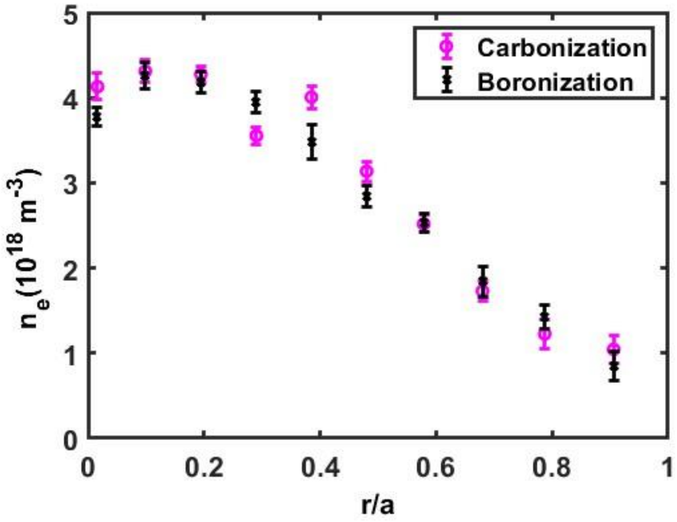


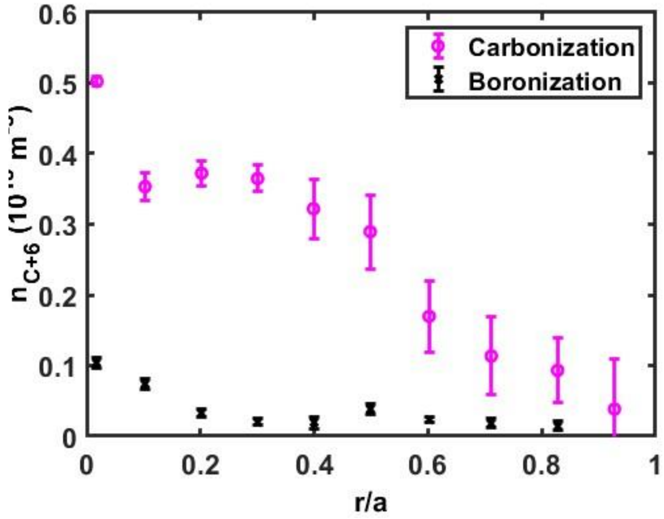
- Molecular emission also present

Science reasons we care about neutrals and impurities

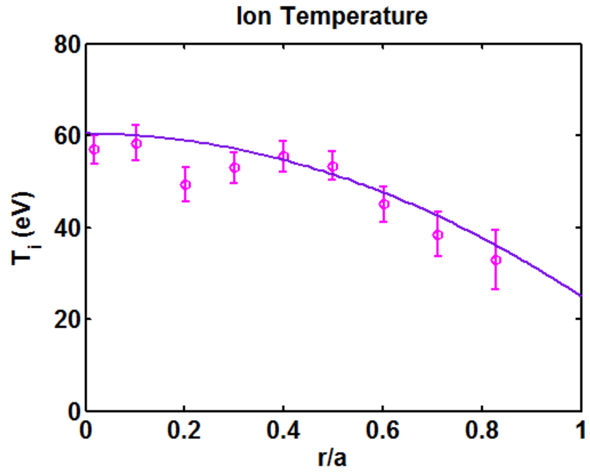
Impurity content effects the ion and electron temperature

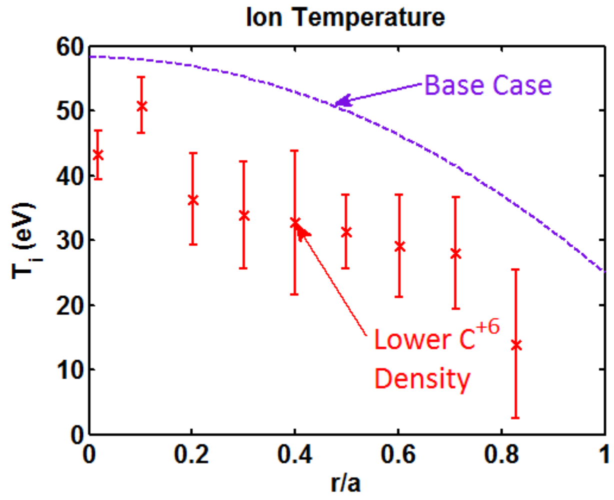






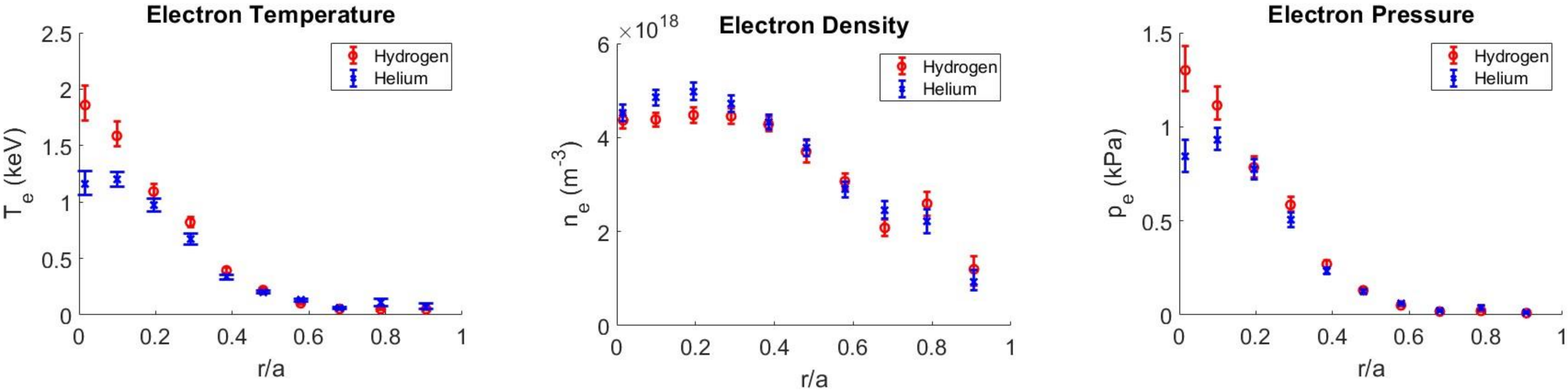
- Using a full METHANE puff with boronized walls introduced less carbon than operating on Carbonized walls
- Higher electron and ion temperatures were seen with higher carbon content





Briesemeister Thesis

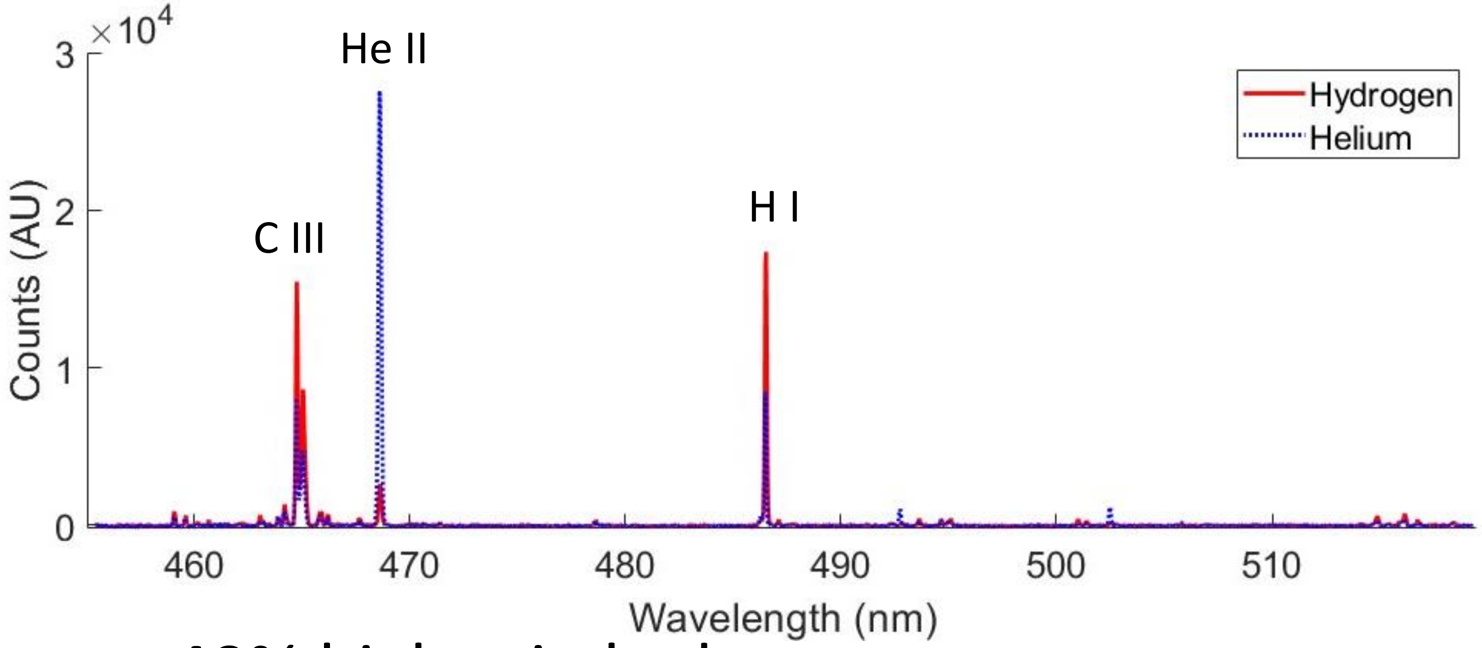
Operating in helium leads to lower core electron temperatures



- The electron temperature is measurably higher for the inner third of the plasma in hydrogen plasmas
  - $\Delta T_{e\ Axis}$~600 eV
- Difference cannot be explained by the slightly higher electron density

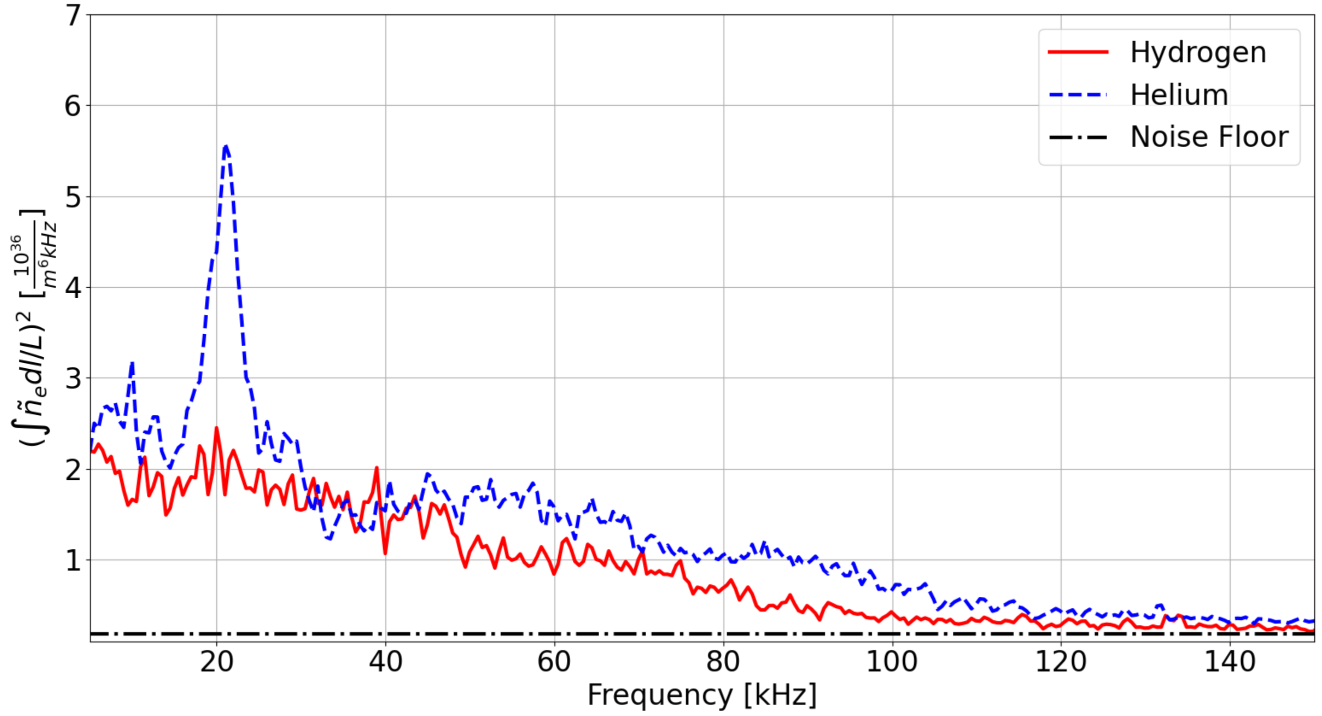
Thomson Scattering data by W. R. Goodman

Hydrogen plasmas showed higher radiated power and higher carbon content



- Radiated Power 40% higher in hydrogen
  - Increase C III radiation seen in hydrogen fueled discharges
  - Carbon content has previously been correlated with higher core T_e
  - The role of carbon is under investigation
- Both ionization power loss and changes in electron ion heat exchange are too small to explain the changes in T_e

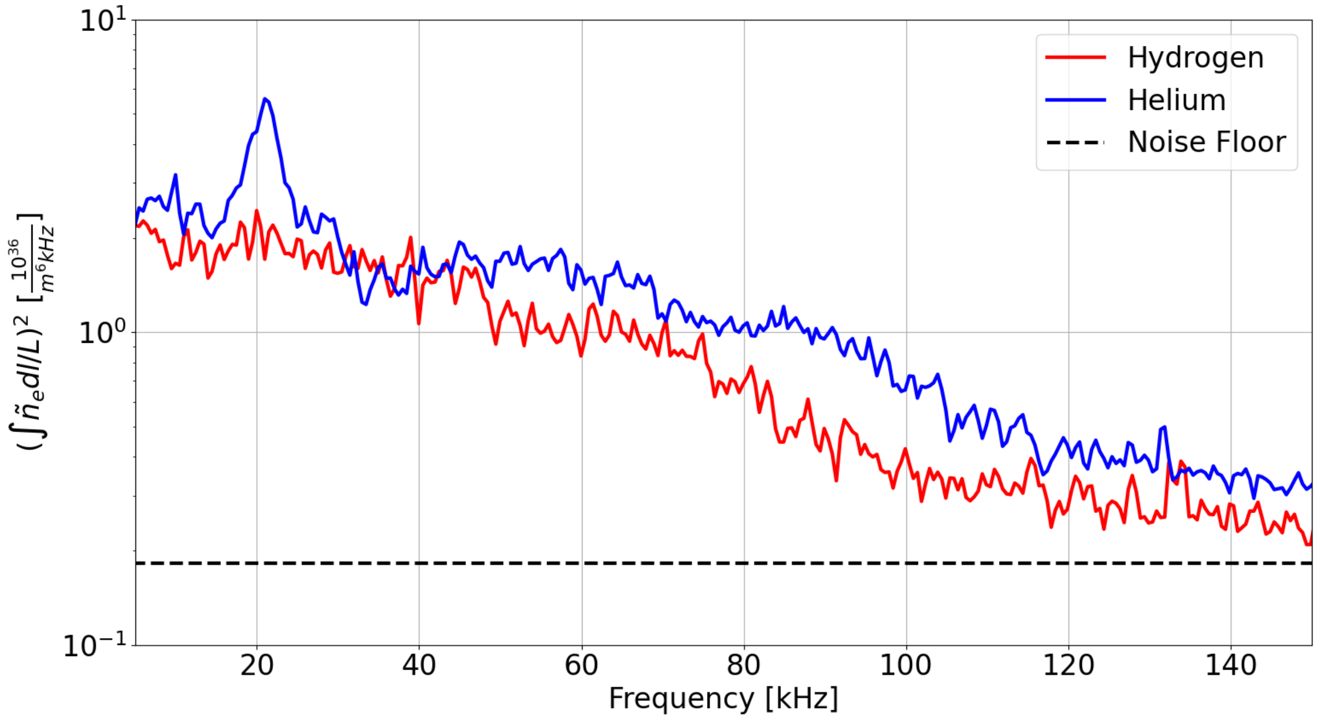
Density fluctuations measured interferometry



- Coherent mode is seen near 20kHz in helium plasmas
  - Only seen in much higher density hydrogen discharges
- 20kHz mode also observed on magnetic pickup coils
  - Indicates electromagnetic mode

Analysis and Plots by H. O. M. Hillebrecht; Interferometer data by W. R. Goodman

Log plot of the measured density fluctuations shows higher broadband fluctuations in helium



- Broadband fluctuations in HSX are generally a result of TEM turbulence
- Higher energy confinement time measured in hydrogen

$\tau_{E\ Hydrogen}$=5.3 ms $\tau_{E\ Helium}$=3.8 ms

Analysis and Plots by H. O. M. Hillebrecht; Interferometer data by W. R. Goodman

Conclusion

- Impurities have a negative impact on density control
- Baking systems work!
- Impurities can sometimes increase electron an ion temperatures, despite also increasing radiated power
  - Evidence of reductions in density fluctuations seen

Future Work

- Build up a more comprehensive, experimentally based emission data base, particularly molecular emission
- A comprehensive study of the effects of ion content on turbulent transport

HSX is heated using Electron Cyclotron Resonance Heating (ECRH)

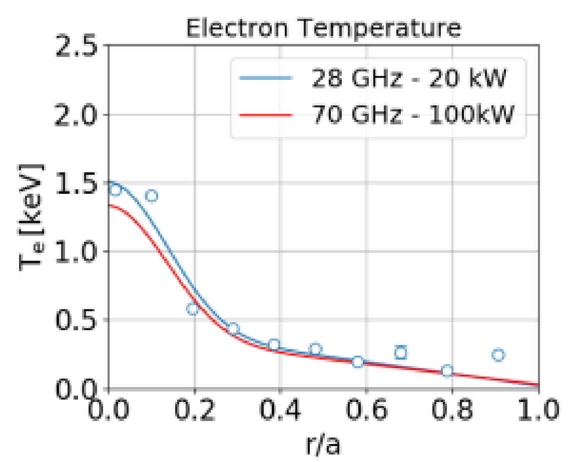
- Heating frequency must resonate with electron cyclotron frequency
  - Scales with magnetic field strength
  - Confinement field determines heating location
- Current heating system: 28 GHz
  - For on-axis heating B_T=0.5 Tesla or 1 Tesla
  - ECRH cutoff our density to <1x10^{19} m^{-3}
- Upgraded system: 70 GHz,
  - For on-axis heating $B_{T=}$1.25 Tesla
  - Higher density limit (<3x10^{19} m^{-3}), higher absorption

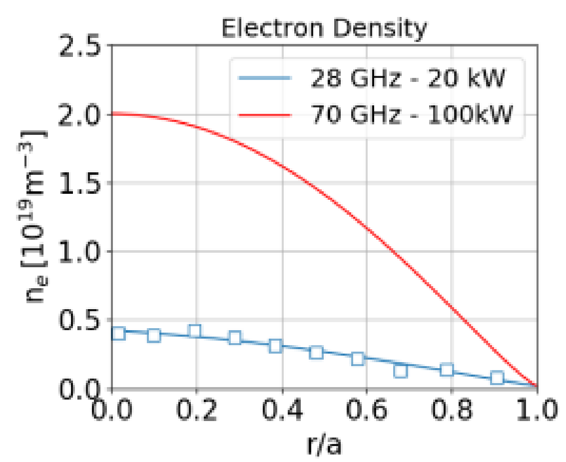
ECHR upgrade led by A.L.F. Thorton

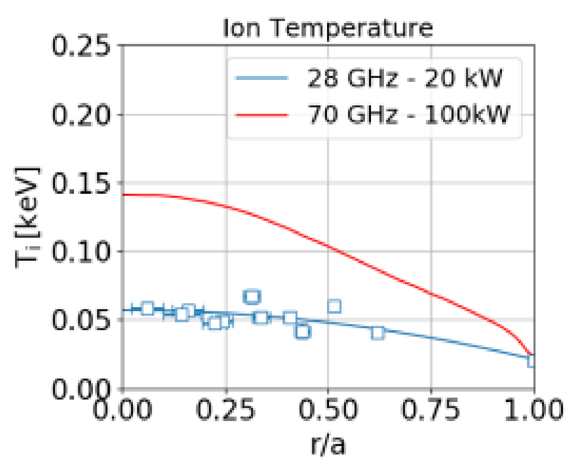
HSX has an extensive suite of diagnostics

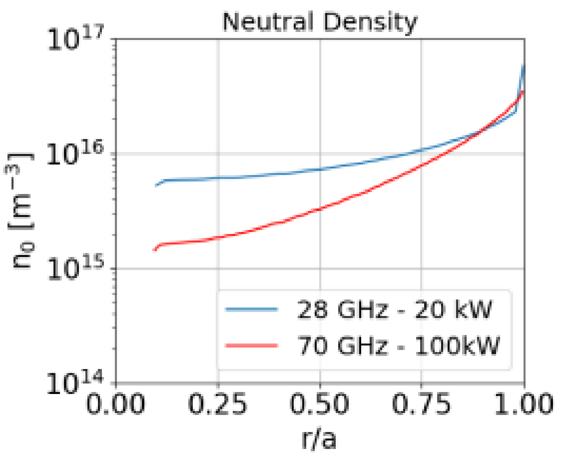
- **Thomson Scattering**
- **Interferometry**
- Spectroscopy
  - **Charge Exchange Recombination Spectroscopy**, Visible Spectrum Filtered Photodiodes, AXUV Photodiodes**, Multiple Impurity Monitoring Spectroscopy**
- Correlation Electron Cyclotron Emission
- Reflectometry
- “Julich” Probe
- Magnetics
  - Rogowski Coils, Flux Loop, Mirnov coils

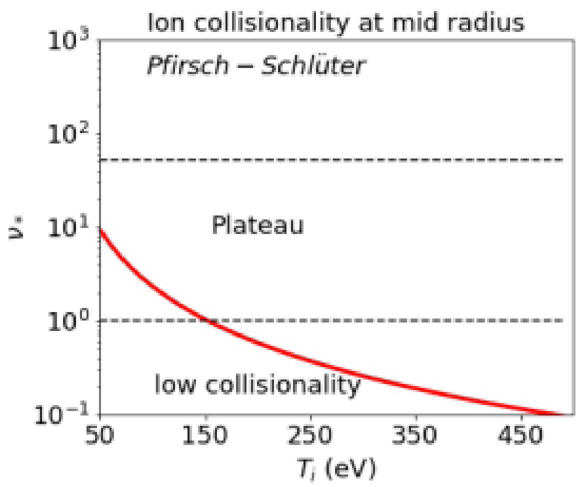
Calculations show that the heating system upgrade will significantly reduce ion collisionality





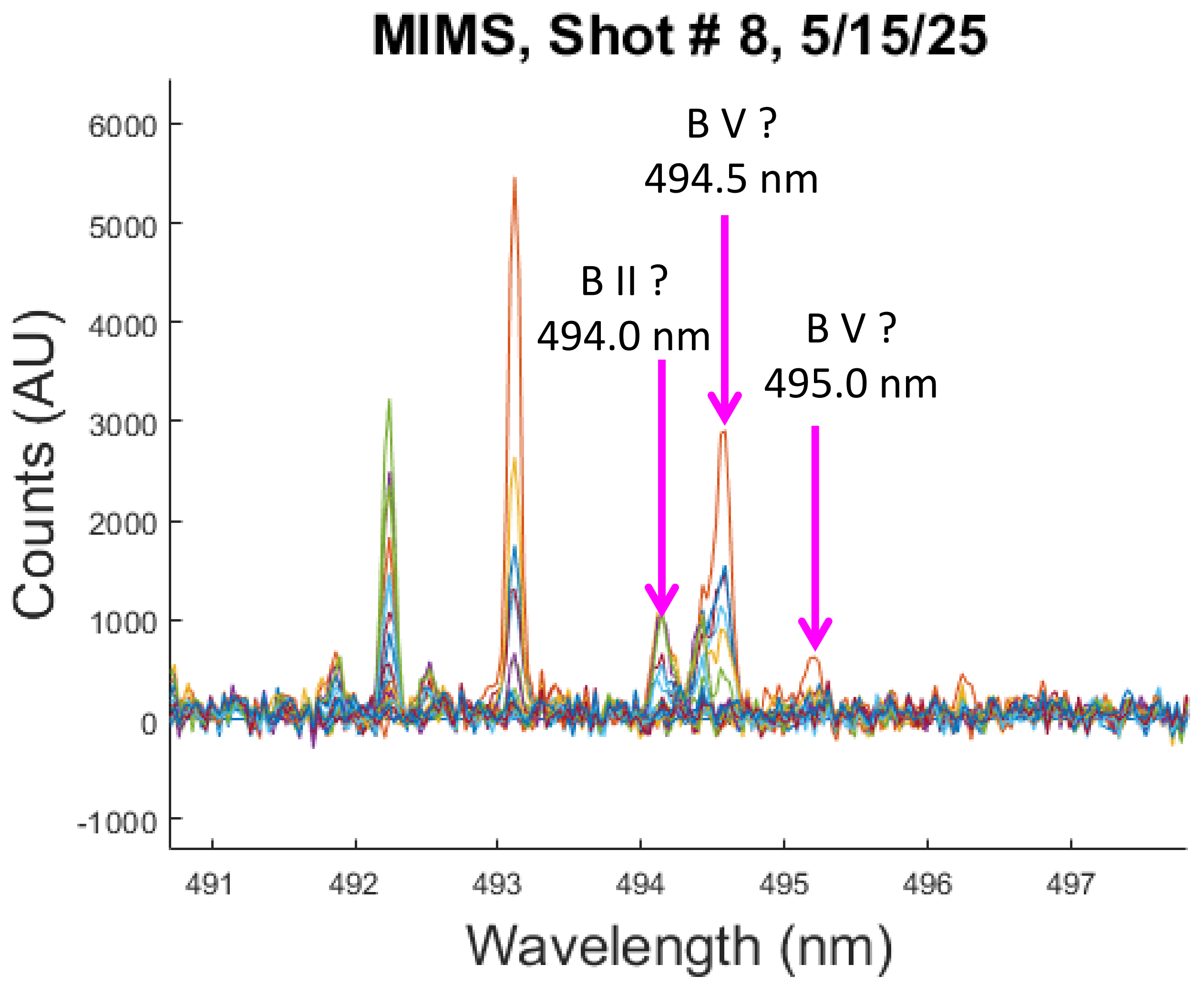






- Ion temperatures in HSX are limited by charge exchange losses
- Higher electron densities will reduce neutral densities in the plasmas

- S. Kumar APS-DPP 2022 https://event.ipp-hgw.mpg.de/event/159/sessions/43/attachments/117/195/HSX_ISHW2022A0PosterV1.pdf


MIMS, Shot # 8, 5/15/25
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5000
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492
493
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495
496
497
Wavelength (nm)
B V ?
494.5 nm
B II ?
494.0 nm
B V ?
495.0 nm

the Fulcher- band system is expected to be strong in the wavelength region from 4500Y6500 8

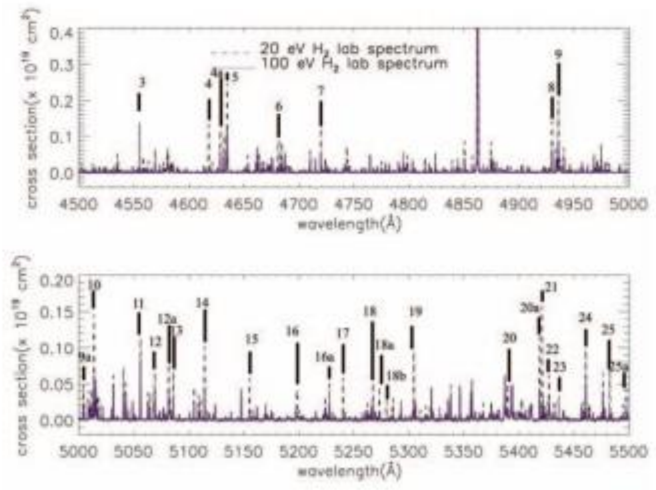


Fig. 7.—Electron impact–induced fluorescence spectrum of H_2 at 20 and 100 eV from 4500 to 5500 Å. The strongest triplet series rotational lines are labeled 1–25a and are identified by the rotational branch, vibrational quantum numbers, and electronic band system in Table 3.

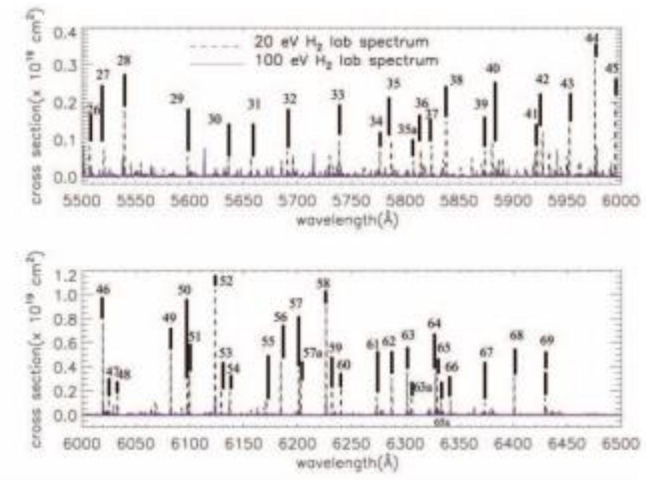


Fig. 8.—Electron impact–induced fluorescence spectrum of H_2 at 20 and 100 eV from 5500 to 6500 Å. The strongest triplet series rotational lines are labeled 26–69 and are identified by the rotational branch, vibrational quantum numbers, and electronic band system in Table 3.

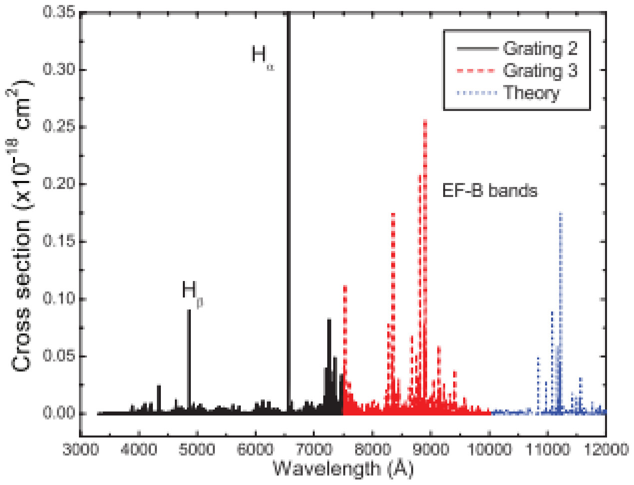
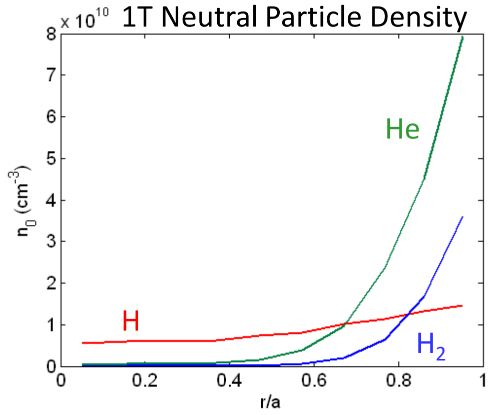


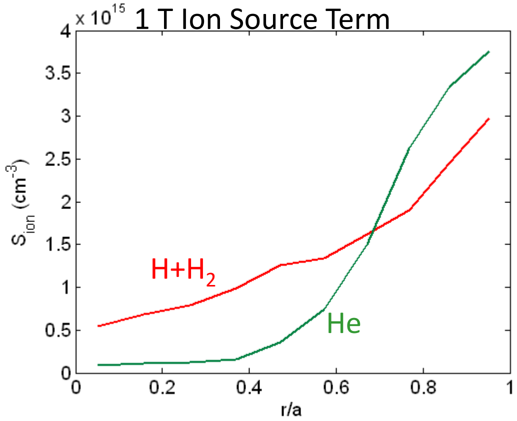
Fig. 6.—Cross sections in cm^2 for the electron impact–induced fluorescence spectrum from 3300–12000 Å of H_2 at 100 eV in three wavelength regions: (1) grating 2 (3300–7500 Å) in black, grating 3 (7500–10000 Å) in red and theory (10000–12000 Å) in blue. The H_α feature is off scale.

- THE ELECTRON-EXCITED MID-ULTRAVIOLET TO NEAR-INFRARED SPECTRUM OF H2: CROSS SECTIONS AND TRANSITION PROBABILITIES Alejandro Aguilar,1 Joseph M. Ajello, Rao S. Mangina, and Geoffrey K. James
- The Astrophysical Journal Supplement Series, 177:388Y407, 2008 July # 2008. The American Astronomical Society. All rights reserved. Printed in U.S.A

DEGAS Calculations for He and H

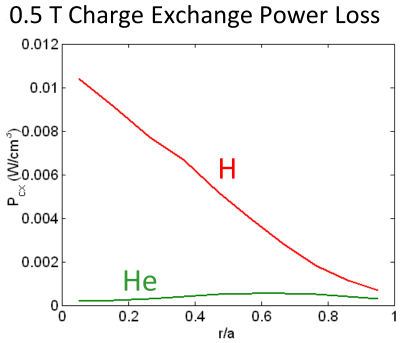
The following DEGAS calculations were performed by J. Canik

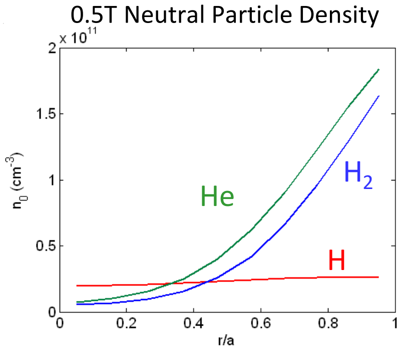


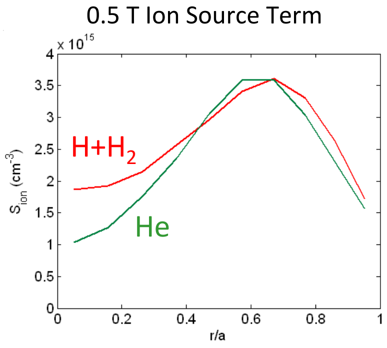


Total neutral density will be lower in the core for helium plasmas

Ion source rates are lower in the core for helium plasmas



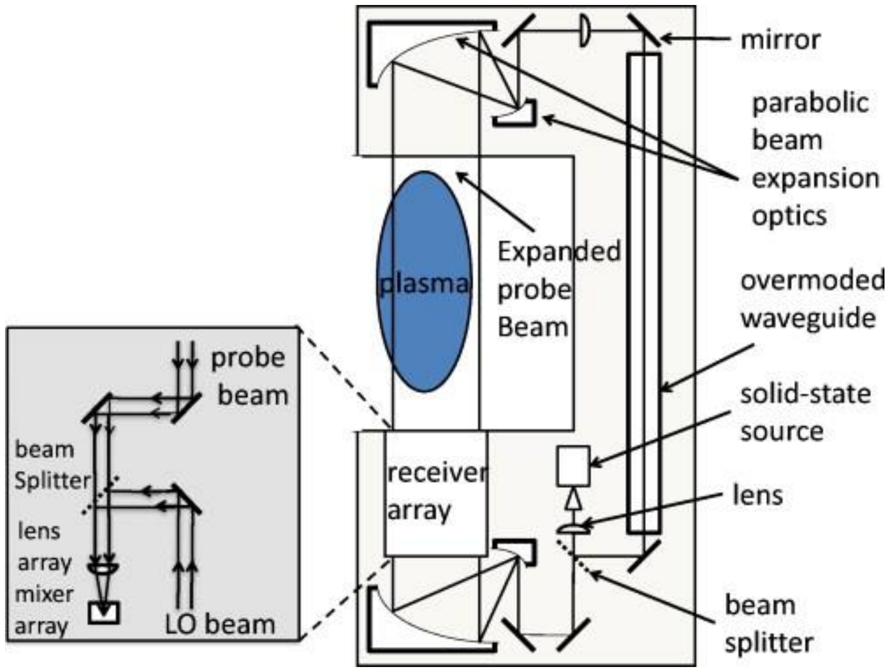




Power lost through charge exchange is reduced through the entire plasma even when the total neutral densities are comparable because the charge exchange cross section is much smaller for helium than for hydrogen

Interferometer used to make high speed line integrated electron density measurements

- The line integrated density of the plasma causes a phase shift in the microwaves sent through the plasma
- Interferometer is used to measure the phase shift relative to the reference signal
- 7 view chords are available
  - Inversion can be used to measure the density profiles
  - Fluctuations up to 300 kHz can be measured



C. B. Deng RSI 2010

Current operation and upgrades by W. R. Goodman