

Wall Conditioning and Impurity Content in TCS-Upgrade

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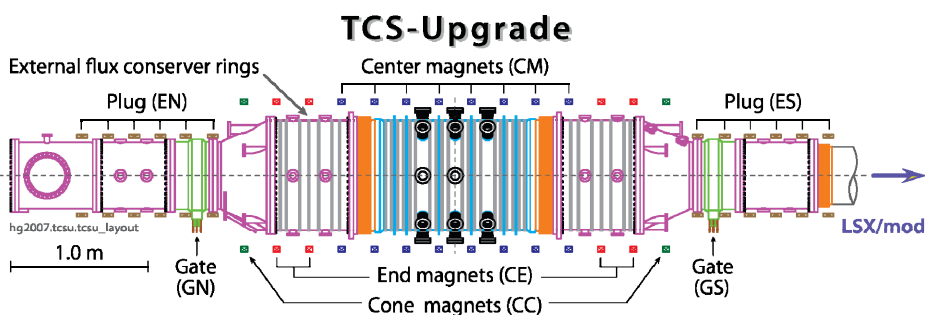
Abstract

The new Translation, Confinement, and Sustainment Upgrade (TCSU) [1] device has been built with impurity reduction, overall recycling reduction, and vacuum hygiene as top priorities. It was built with a bakable, ultra-high vacuum chamber, and wall conditioning systems such as glow discharge cleaning (GDC), siliconization, and titanium gettering. The plasma temperature of the previous TCS device was limited by high impurity content and radiation barriers to 10s of eV. Within the first few weeks of operation TCSU achieved sustained total temperatures ($T_e + T_i$) of 200 eV. In the diamagnetic FRCs these higher temperatures produced about double the TCS magnetic fields and toroidal currents. The TCSU results were so improved that the plasma temperature was actually limited by the electron rotation rate approaching the RMF frequency, at which point RMF current drive ceases.

The first wall conditioning technique used in TCSU was helium GDC. This was seen to reduce overall recycling and impurity influx. To help determine the effectiveness of our wall conditioning techniques on impurity content a campaign of dedicated impurity doping experiments with Silane, CO_2 , CD_4 , and O_2 was run to determine the content of the major radiating impurities oxygen, carbon, and silicon. All three impurities were found to be present in very small amounts, much lower than in TCS. With this as a baseline, further wall conditioning techniques including siliconization and titanium gettering will be carried out. Preliminary results from siliconization will be reported.

[1] K.E. Miller, J.A. Grossnickle *et al.*, Fusion Science and Tech., 54:4, (2008)

The TCS-Upgrade Device: A Clean Vacuum System and Advanced Wall Conditioning to Tackle the Impurity Problem



- Great care was taken to insure all parts on the machine were properly cleaned for UHV before installation.
- Minimizing the leak rate, permeation, and outgassing was a design priority.
- All chambers are stainless steel with copper wire seals except the quartz main chamber and source chamber.
- All o-ring seals, on quartz to metal transitions, are differentially pumped.
- Heating blankets cover the entire machine and allow heating up to 200 °C, although typical operating temperature is 120 °C.
- Versatile magnetic coil system to allow for control of axial magnetic field profile, with additional external flux conserving rings.

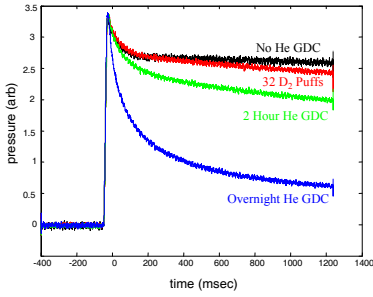
Additional Improvements and New Diagnostics

- Glow discharge cleaning is an integral part of TCSU and has been in use since operation began.
- Provisions for Ti gettering and siliconization wall conditioning have been included in the design.
- Surface analysis tools have been added to TCSU, in a collaboration with Prof. Fumio Ohuchi, Dept. Materials Sciences, to monitor the conditions of the walls. See poster by A. Tankut.
- Multi-point Thomson scattering will be added in the near future.
- A 2D internal magnetic probe has just been added.

TCSU Vacuum System Achievements

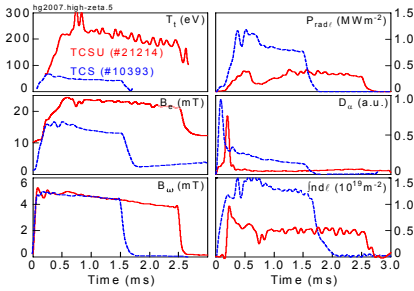
- Achieved a base pressure of low 10^{-10} Torr at 27 °C, and low 10^{-9} Torr at 120 °C.
- Leak rate of 6×10^{-8} Torr-liter/sec for nitrogen (our design goal was 1×10^{-7} Torr-liter/sec).
 - This introduces $\sim 2 \times 10^{17}$ particles/day
 - A TCSU plasma has $\sim 10^{19}$ particles
 - In 1 day the total number of particles entering the vacuum system is less than 2% of a single TCSU plasma
 - Typically a plasma is made every 5-10 minutes during operation
 - This implies $\sim 0.015\%$ leakage into fill gas between plasmas.
- Hydrogen is the dominant species present in the residual gas. Water base pressure is 10^{-10} Torr.

He Glow Discharge Cleaning Greatly Increased Wall Pumping of Deuterium



- Wall pumping rates were measured by puffing deuterium into the system with all pump valves closed and then measuring the drop in pressure as a function of time with a fast ion gauge.
- Results clearly show an increase in deuterium wall pumping rates after helium glow discharge cleaning, as seen by the much more rapid drop in chamber pressure as deuterium was adsorbed on to the walls.
- The glow does, however, leave a coating of elements from stainless steel on the quartz surfaces. This coating is being studied in collaboration with the UW Materials Science Department (see poster by A. Tankut)

TCSU Shows a Significant Plasma Performance Improvement Over TCS

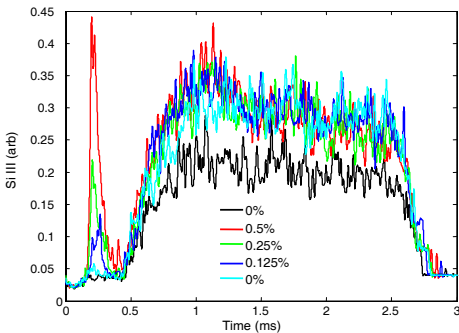


- Higher T_1 resulted in nearly double the B_c and higher toroidal currents at the same RMF B_w .
- Both radiation and H recycling are reduced in TCSU allowing for low n_e and high T_1 operation.
- On TCS vibrations limited the accuracy of the interferometer on shots longer than 1.5 ms. That has been improved on TCSU.

Impurity Studies on TCSU

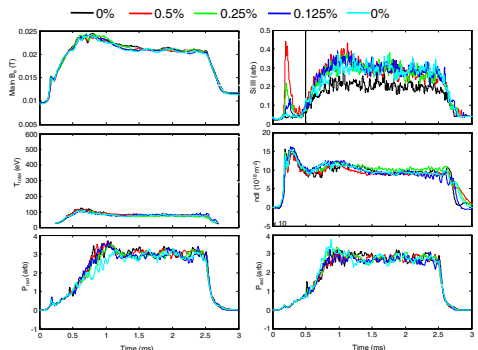
- During the steady state period of TCSU operation the plasma is dominated by recycling from the wall.
- The purpose of the impurity studies was to determine the concentration of carbon, oxygen, and silicon during this steady state period.
- To determine the concentration of carbon, oxygen, and silicon we ran a set of experiments where our usual operating gas, deuterium, was doped with small percentages of impurity gas.
- The experiments were performed using a standard operating condition (in 100% D_2 fill gas).
- The gasses used for doping were CD_4 , CO_2 , SiH_4 , N_2O , and N_2 .
- The seeded atomic impurity concentration ranged from ~0.25% to upwards of 4% for most fill gasses.
- SiH_4 was limited to a range of ~0.125% to ~0.5% due to the danger of high concentrations of Silane in our vacuum system.
- During the experiments we had 3 monochromators set to monitor C III, O III, and Si III. We were also able to monitor a N III line that was very near the Si III line.
- In addition, we were able to use a multi-channel ICCD spectrometer to get some axial resolution as well as to monitor other impurities and confirm our monochromator measurements.

Silane doped series



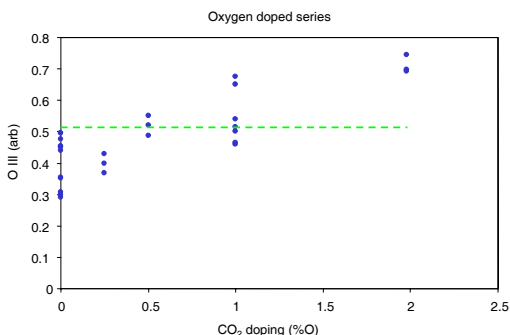
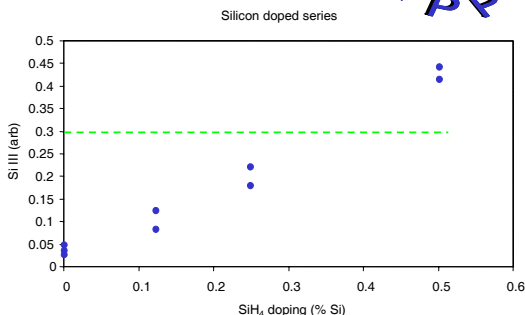
- The first two pulses showed a lower level of steady state radiation, however, doping with 0.5% silicon (the 3rd pulse in the Silane set) caused the steady state level to increase for the remainder of the Silane doped pulses.

Silane doped series



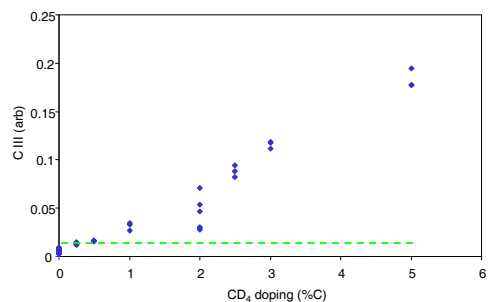
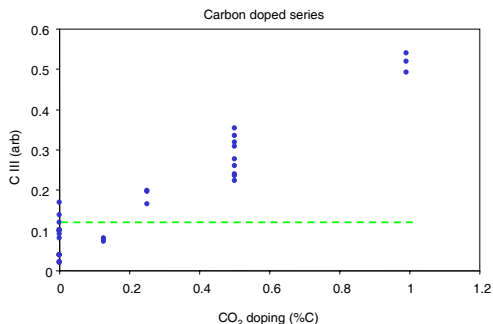
- The plasma conditions for all the shots in the silane series are very similar.
- This was typical of shots for low concentrations of doping for other gasses as well.

- During the steady state period the concentration of silicon is approximately 0.35%.
- The steady state level of Si III, measured by the monochromator, is shown in green and is constant throughout the set of pulses.
- The blue points represent the peak level of Si III radiation measured during the initial formation period when virtually all of the silicon present is due to the doped gas puff. Assuming the radiation rates are the same for these two periods, we can determine the silicon concentration.



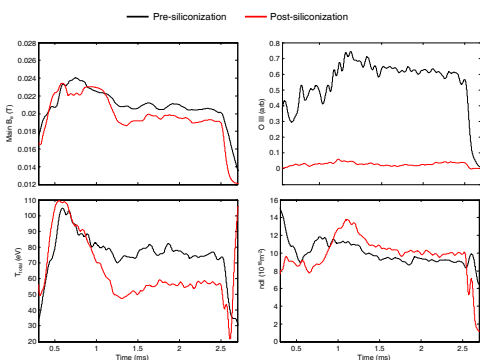
- During the steady state period the concentration of oxygen is approximately 3%.
- The steady state level of O III, measured by the monochromator, is shown in green and is relatively constant throughout the set of pulses.
- The blue points represent the peak level of O III radiation measured during the initial formation period when virtually all of the oxygen present is due to the doped gas puff. Assuming the radiation rates are the same for these two periods, we can determine the oxygen concentration.
- The N₂O doping experiments did not yield useful results due to drastic performance degradation with introduction of more than 0.1% atomic nitrogen (confirmed by N₂ doping).

- During the steady state period the concentration of carbon is approximately 0.45% from the CD₄ doping and 0.4% from the CO₂ doping.
- The steady state level of C III, measured by the monochromator, is shown in green and is relatively constant throughout the set of pulses.
- The blue points represent the peak level of C III radiation measured during the initial formation period when virtually all of the carbon present is due to the doped gas puff. Assuming the radiation rates are the same for these two periods, we can determine the carbon concentration.



Siliconization

- Siliconization was done with a 90:10 He:SiH₄ glow discharge for ~30 minutes with ~100°C wall.
- The OIII signal was reduced by siliconization (at similar plasma conditions to pre-siliconization), however, plasma performance did not seem to be improved.
- However, there was approximately an order of magnitude increase in our SiIII signal after initial silicon deposition. It has subsequently returned approximately to its pre-siliconization level after about 1000 shots.
- Consequently, siliconization did not yield any improvement in plasma performance.



Future Plans

- A Titanium gettering system has been developed and should be ready for deployment in the next few months.
- The coating deposited by the glow discharge will be removed from the quartz main chamber and some doping experiments will be repeated, after internal flux rings are installed.

Conclusions

- TCSU was built with a very clean vacuum system and advanced wall conditioning to tackle the impurity problem.
- TCSU plasma performance was significantly better than that of TCS within weeks of starting operation.
- Baking and glow discharge cleaning, primarily in He, have proved to be crucial to improved plasma performance.
- Doping experiments using CD₄, CO₂, SiH₄, N₂O, and N₂ were carried out to determine the concentration of impurities coming off the wall during the steady state phase of operation.
- During the steady state period the concentration of silicon is approximately 0.35%, oxygen is approximately 3%, and carbon is approximately 0.45%.
- At these concentrations and our plasma conditions we estimate these impurities to radiate about 300kW. Absorbed RMF power is about 1.8MW
- Siliconization reduced OIII but did not increase plasma performance.
- A titanium gettering system will be deployed soon.