

Recent results in the TCS-Upgrade device

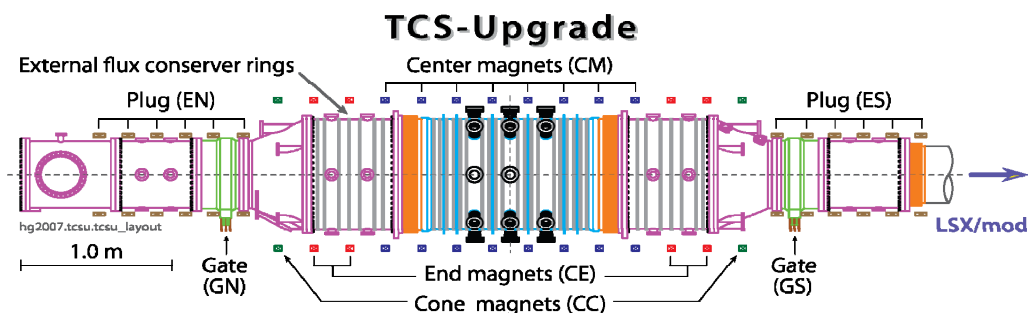
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Abstract

The original TCS experiment demonstrated the robust ability to form and sustain FRCs in steady-state using Rotating Magnetic Fields (RMF). However, temperatures were limited by impurity radiation to 10s of eV. A new device, TCSU [1], was built with a bakable ultra-high vacuum chamber in order to reduce impurities and overall recycling. Within the first few weeks of operation TCSU achieved sustained temperatures much higher than those in TCS. Impurity seeding experiments implied very low levels of oxygen, carbon, and silicon, using only glow discharge wall conditioning. This suggests very low radiated power, in agreement with bolometric measurements. To further lower impurity content, siliconization and Ti-gettering have also been used for wall conditioning. A 2-D internal magnetic probe has been installed that gives radial profiles of both toroidal and poloidal fields. Results from the wall conditioning and internal probe studies 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.

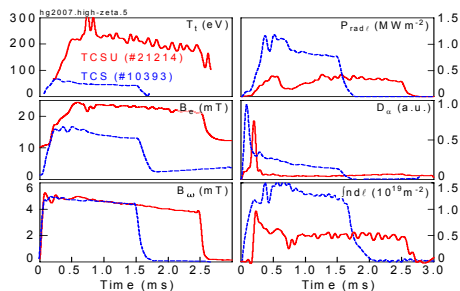
Additional Improvements and New Diagnostics

- 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 (Poster #GP6.00121)
- Multi-point Thomson scattering will be added in the near future.
- A 24 channel 2D internal magnetic probe has just been brought into operation.

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.

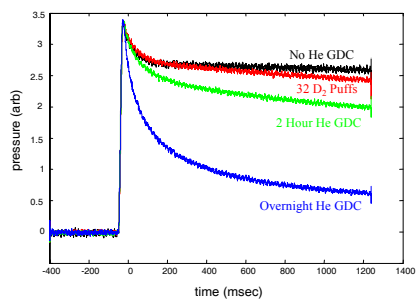
TCSU Shows a Significant Plasma Performance Improvement Over TCS



- Higher T_i resulted in nearly double the B_e 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_i operation.
- On TCS vibrations limited the accuracy of the interferometer on shots longer than 1.5 ms. That has been improved on TCSU.

Wall Conditioning

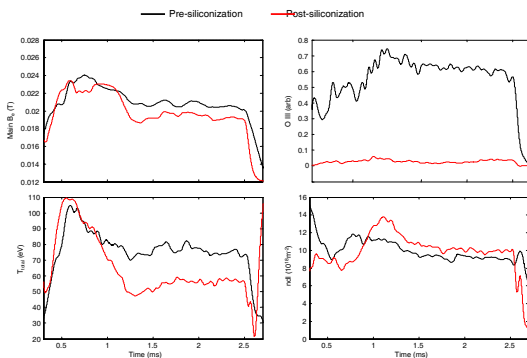
He Glow Discharge Cleaning Greatly Increased Wall Pumping of Deuterium



- 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)

Siliconization

- Siliconization was done with a 90:10 He:SiH₄ glow discharge for ~30 minutes with ~100°C wall.
- The OIII signal was reduced dramatically by siliconization (at similar plasma conditions to pre-siliconization), however, plasma performance did not seem to be improved.
- There was approximately a 150-fold increase in our Si III signal after initial silicon deposition. It has subsequently returned approximately to 20 times its pre-siliconization level today.
- Total radiation was decreased significantly.
- The fact that siliconization did not yield any improvement in plasma performance suggests TCSU energy losses are not predominantly radiative.

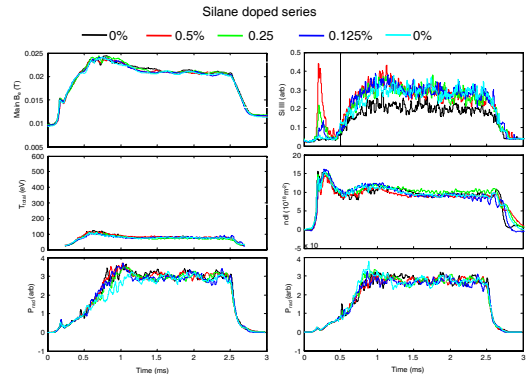
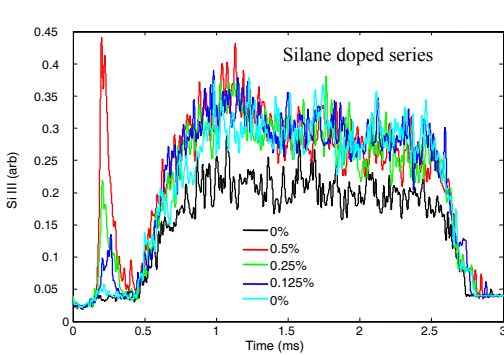


Titanium Gettering

- Titanium gettering balls were placed in each of the cone sections of TCSU.
- Specially designed baffles were placed on the Ti-ball so as to minimize coating of the quartz surface while still covering all of the metal chamber walls.
- Surface analysis shows that the applied layer of titanium did getter hydrogen and oxygen. RGA scans show a decrease in H₂, DH and D₂, and after each application the total vacuum system pressure dropped by a factor of 2.
- Interestingly, Ti gettering did not yield an appreciable decrease in oxygen radiation nor any improvement in plasma performance.
- It is probable that there are additional strike points on the ferromagnetic Invar bellows between the main quartz and stainless steel chambers. These bellows have no Ti coating and may be an appreciable source of impurity.
- Further tests will be done by moving the Ti gettering balls closer to the strike points of the scrape off layer plasma, to make sure this area gets a proper Ti coating.
- Properties of the Titanium film and the effect of plasma on it are being studied in collaboration with the UW Materials Science Department (see poster by A. Tankut).

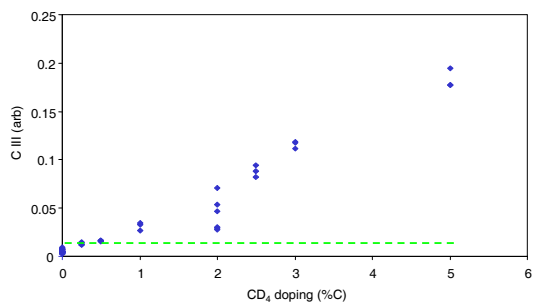
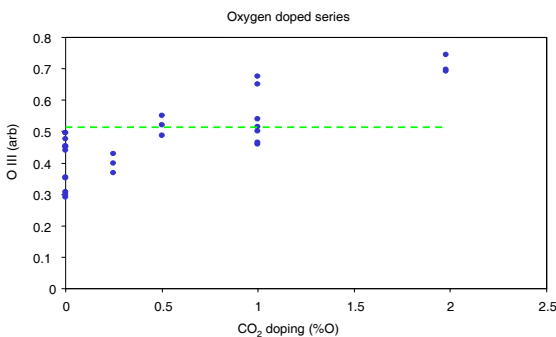
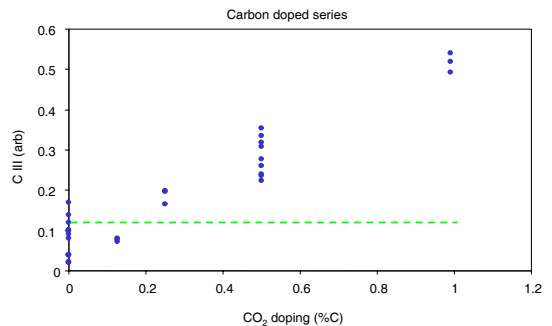
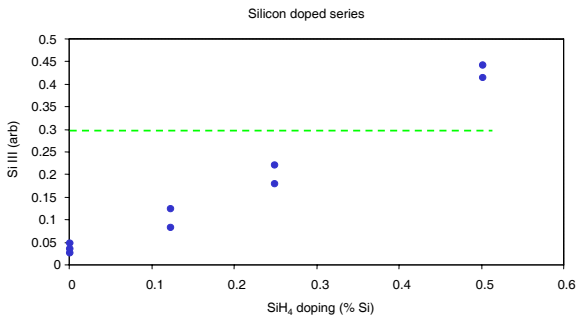
- During the steady state period of TCSU operation the plasma composition is dominated by recycling from the wall.
- The purpose of the impurity studies was to determine the concentration of carbon, oxygen, and silicon during this steady state period.
- To determine the concentration of carbon, oxygen, 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% D₂ fill gas).
- The gasses used for doping were CD₄, CO₂, SiH₄, N₂O, and N₂, with seeded atomic impurity concentration ranging from ~0.25% to upwards of 4% for most fill gasses.
- SiH₄ 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.

Results



- 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.

- 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.



- The steady state levels of Si III, O III, and C III measured by the monochromators, are shown in green and are constant throughout the set of pulses.

- The blue points represent the peak levels of Si III, O III, and C III radiation measured during the initial formation period when virtually all of the impurity present is due to the doped gas puff. Assuming the radiation rates are the same for these two periods, we can determine the impurity concentration.

- During the steady state period the concentration of carbon is approximately 0.45% from the CD₄ doping and 0.4% from the CO₂ doping.

- During the steady state period the concentration of silicon is approximately 0.35%.

- During the steady state period the concentration of oxygen is approximately 2%.

- 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).

2D Internal Magnetic Field Probe

- A fully 2 dimensional internal magnetic field probe has been installed and is in operation in TCSU.
- The probe consists of 24 magnetic pickup loops in each of the x and z directions spaced 2 cm apart.
- The probe is located in the midplane of the main quartz chamber and spans from -6 cm (6 cm past the centerline, $r=0$) to the wall ($r=40$ cm).
- The probe was designed and built not only to withstand a hot plasma (up to several hundred eV) and the noisy, high voltage RMF environment, but also to meet our exacting vacuum hygiene standards including baking to 200 °C.

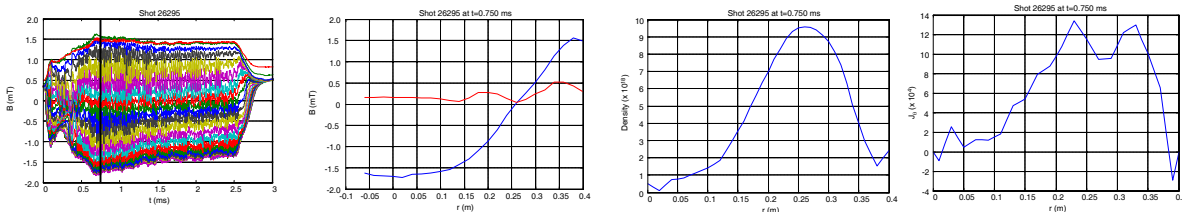
Design and Construction

- The probe is built on a Teflon form with the x and z components wound on top of each other.
- It sits on the air side of a 0.002" thick stainless steel tube which forms the vacuum boundary.
- It is electrically and electrostatically shielded by a gold plated Kapton tube between the stainless tube and the probe body.
- The stainless tube is electrically protected (to 22kV) from the plasma by a layer of Teflon heat shrink.
- The entire probe is then covered with a 0.205" OD Boron Nitride jacket.
- The entire system is in a bellows so that the tip can be inserted to any radius up to 10 cm past the centerline, and retracted during glow discharge cleaning and Ti gettering operation.

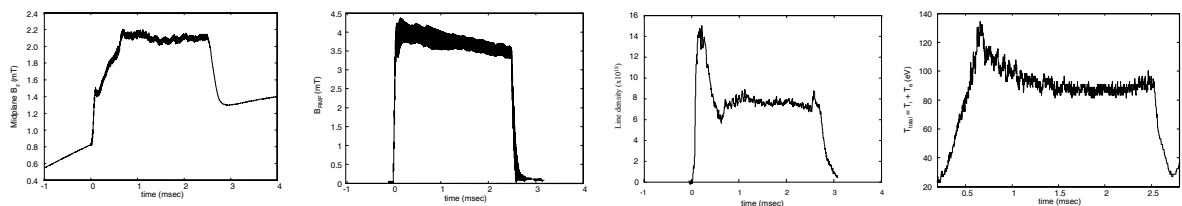
Calibration

- The probe was absolutely calibrated in a calibration box with a known magnetic field using Pearson probes and magnetic loops with a well known area.
- The probe was rotated through 210° in 15° increments during calibration to find the relative angle of each probe with respect to each other.
- After being installed on TCSU the probe was further rotated through a set of vacuum shots to find the optimum orientation of the probe with respect to B_z .
- With the angles known from calibration and the orientation in the machine, we can use a matrix inversion to separate B_x and B_z .

Probe Data



- Plotted above (left to right) are the 24 B_z channels vs. t, and the internal B_z and B_x profiles, the density profile and J_0 profile vs. r.
- The value of B_z shows slightly low for $r > 35$ cm due to an invar bellows which is ferromagnetic.



- Above are external diagnostics for the same shot. Shown are midplane B_z , $B_{z,RF}$, line density and $T_{total} = T_i + T_e$.

Conclusions and Future Plans

- 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 CD_4 , CO_2 , SiH_4 , N_2O , and N_2 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 2%, 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 presently about 1.0MW
- Siliconization reduced OIII radiation but did not increase plasma performance.
- A titanium gettering system has been deployed but also did not appear to increase plasma performance. This is consistent with impurity radiation no longer being our primary loss mechanism.
- The coating deposited by the glow discharge will be removed from the quartz main chamber and internal flux rings will be installed.