The TCS Upgrade
Impurity Control

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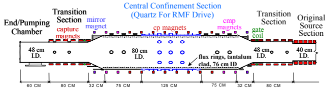
Outline

- The need for impurity control
- Key components/challenges of the upgrade
  - Design targets
  - Monitoring
  - Practical Implementation
  - Wall Conditioning
- Present status of the TCS upgrade

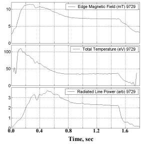
FRCs at RPPL



- FRC's have potential to make near ideal reactor - linear, high beta, ...
- Physics issues to address: stability, confinement, sustainment, flux levels, ... can form hot moderate flux w/o sustainment (LSX) or cold low flux steady state (RMF)
- **Present approach at RPPL:** Improve temperature and flux levels in steady state through impurity control. Low impurity levels should allow the impact of the RMF on the FRC's basic confinement to be addressed. (Get flux levels high enough to allow NBI)

Past Limit to TCS Operation: Impurity Radiation

- RMF drive physics imposes:
  $n_e \sim B_\omega / (\eta_\perp \omega_{RMF} r_s^2)^{0.5}$
  n_e independent of B_e and T
- Radial pressure balance:
  $B_e = (2\mu_0 n_e k T)^{0.5}$
- Result: if T is clamped, say by radiation, then B_e is also clamped
- Experimentally, bolometric measurements show that the majority of the RMF input power is lost as radiation.



Traces showing the correlation between the temperature and the radiated power, and the resultant fall in edge field B_e

RMF is Rotating Magnetic Field
ω_{RMF} is the RMF rotation frequency
B_e is the edge magnetic field
r_s is the FRC's separatrix radius
n_e is the plasma density
η is the plasma resistivity

UHV: How Clean is Clean Enough

- Two primary issues:

  How clean is the wall: Proper UHV Hygiene prior to assembly, Wall conditioning following assembly (Bake, Glow, Getter)

  How to keep the wall clean: The leak rate, the rate at which gas penetrates the vacuum envelope, must be kept sufficiently low.
  (Viton is 10^{-9} T-L/sec-cm at 20 °C and 10^{-7} at 100 °C)

- Some relevant numbers:
  - a leak of 3 x 10^{-6} T-L/sec introduces 1 x 10^{19} particles/day
  - 1 monolayer contains 1 x 10^{19} particles/m^2
  - at 1 x 10^{-9} Torr, a monolayer will form in 1 hour

- Putting these numbers into context:
  - TCS plasma contains 10^{19} particles, and is formed a few times per hour
  - A 1% impurity level will radiate 10% of the input power
  - Target leak rate < 10^{-7} T-L/sec, corresponds to 10^{-11} T pumping at 10^4 L/sec
  - Outgassing from the wall will likely keep the base pressure somewhat higher

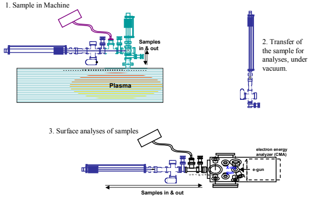
TCS Upgrade: Machine Improvements

- UHV system design: These keep the wall clean (keep leak rate low)
  - Replace o-rings with metal seals
  - Remove all elastomers to atmosphere
  - Differentially pump all elastomers/o-rings that can not be removed
- UHV hygiene and wall conditioning. These clean the wall

  Before/During assembly:
  - Remove most internal elastomers (limits outgassing)
  - Properly clean/prepare all vacuum surfaces
  - Use proper materials on plasma facing surfaces
  - Assemble system in a clean room (with monitor)

  After assembly:
  - Vacuum baking
  - Glow discharge cleaning
  - Wall Gettering

Monitoring the Wall: Sample Analysis
correlate plasma performance with wall condition



Surface Impurity Analysis Tools
Collaboration with Fumio Ohuchi, Dept. Materials Sciences

X-Ray Photoelectron Spectroscopy (XPS):
-X-rays (such as Al-K_α, Mg-K_α)hit the analyte surface; the energy of the emitted "photoelectrons" are characteristic to species, thus allow to determine surface composition.
-Elemental composition and charged states of surface atoms, high surface sensitivity (few nanometers).

Auger Electron Spectroscopy (AES):
-Electron beam hits the analyte surface; the energy of the emitted "photoelectrons" are characteristic to species, thus allow to determine surface composition.
-Elemental composition, high surface sensitivity (few nanometers), high spatial resolution.

Ion Sputtering:
-Ion beam (such as Ar, O) hits the analyte surface, resulting in the removal of the surface layer.
-Combined with XPS/AES, depth profile of the sample can be obtained.

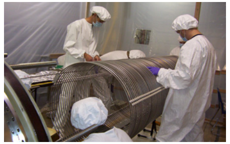
Scanning Electron Microscopy (SEM):
-Electron beam hits the surface, the intensity of the emitted secondary electrons are dependent on the depth and angle of the surface; hence the morphology/topology of the surface can be obtained.

Energy Dispersive X-Ray Spectroscopy (EDS):
-Electron beam hits the surface, leading to the characteristic x-ray emission from the surface/near surface atoms. The energy of the emitted x-rays can be used to determine surface composition.
-Versatile tool when coupled with imaging (such as SEM).
-Poor surface sensitivity (few 100 nm to microns)

Implementation

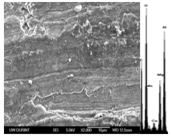
- Start by following 'standard' UHV guidelines, imitate larger labs
  - gloves, clean room, proper material selection, protocols...
- Unfortunately, there are many contradictions and inconsistencies
  - For example, around half the sources recommended electro polishing chambers, the other half indicated it was at best a waste of money, and at worst could seriously contaminate the pieces.
  - It was generally agreed that electro polishing chambers would reduce the effective chamber surface area by about a factor of 2.
- Vacuum baking of chambers is essential
  - particularly if electro polishing is done. At 450 °C overnight, all organics are driven off. This is typically done prior to assembly.
- UHV seems to be as much an art as a science

The Inner Flux Rings During Installation

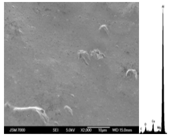


- The flux rings define a close flux boundary (as opposed to distant magnets), and keep the plasma off the walls and empirically, lead to more reproducible plasmas.
- The L/R field bleed through time of the flux rings was set at a few msec to allow for gradual ramp up or ramp down of the flux during operation
- The rings and plasma facing components were coated with 1 µm of Tantalum. Ta has a sputtering threshold of ~ 300 eV, vs 40 for Al, or 180 for W (brittle).

Aluminum Flux Ring Surface, Unclean and Clean



Uncleaned Aluminum, surface is mostly carbon and oxygen, 2000X.



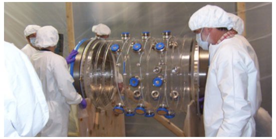
Cleaned, 1%HF-2.5%HNO_3-1.5%HCl for 16 min, then sonicated in DI for 2 hours.

- The Surface analysis tools were particularly helpful in establishing and verifying proper cleaning procedures.
- Stainless Steel components were sonicated in DI water and a Micro-90 solution (soap), followed by 2 to 3 DI rinses with sonication.

Cleaning the Al Flux Rings

Tanks of acid, followed by neutralization, rinsing, pressure washing, rinsing, ...

The Most Challenging Part of the Upgrade:
The Quartz to Metal Seals



- No commercial UHV seals available at such large diameters. Differential o-rings difficult due to out of roundness and unavailability of UHV grease.
- Solution: Differential RTV seal with custom Invar 36 bellows. Provides stress relief and CTE match. Never ever ever use RTV in UHV is sound advice.
- Permeability and outgassing rates are well within design limits at 20 °C, and just within limits at 200 °C.

Wall Conditioning - Baking and Glow

- Glow discharge:
  - system is fairly standard and copies existing design
  - will initiate glow at high pressure, then drop down to few mT level
  - 3 electrodes used due to quartz insulating breaks in vacuum system
  - 3 independent high voltage current limited power supplies, one per electrode, will provide glow current of ~ 0.1 A/m^2 of vacuum system wall.
- Vacuum baking
  - System designed to operate continuously at up to 200 °C, though for safety, initial operation will start at 120 °C
  - Minimum necessary temperature is 70 °C

Wall Conditioning - Gettering

- Even with glow and baking, gettering is still essential (TEXTOR, Winter)

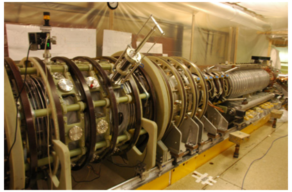
Ni	Cr	Mo	Fe	C	O	S	N	K	Cl	
49	18	2	5	3	13	5	4	1	1	%, Clean Surface, after 24 hour bake & glow
60	23	9	4	0	0	0	0	0	0	%, Nominal composition Inconel 625

- Initial Gettering candidates are Titanium or Silicon
  - **Titanium:** Have system, Application is line of site.
    Worked very well in tokamaks to the keV range (until NBI and non thermal tails)
  - **Silicon:** Works very well, Application is with glow.
    Coats all metal, long life, coating may be removable with He/H glow.
- Boron and Lithium may be tried later if needed, but Boronization is less effective than Siliconization, and has serious toxicity problems, while with Lithium, the coating lifetimes are short, and there is concern that it may not work well in non graphite coated machines.

Status of TCS Upgrade

- System is under vacuum.
  - N2 leak rate at design level of 1 x 10^{-7} T-L/sec
  - Base pressure low 10^{-9} T shortly after pump down, with no baking or wall conditioning. Desired 1 to 2 order magnitude drop should be realized in time with baking and wall conditioning. Water is the dominant species present.
  - As a point of comparison, PLT (Princeton Large Tokamak, 1978) had a water/methane partial pressure of ~ 3 x 10^{-7} T. After Ti gettering, the partial pressure of water fell to ~ 1 x 10^{-9} T, the partial pressure of methane was very low in the ohmic discharges, and the oxygen impurity was reduced to less than 0.1%.
- Work remaining:
  - Install RMF antenna, run cables to various magnets.
  - Complete gas fill system and control system wiring
  - Diagnostic installation
  - Operation should begin by the end of the year

Picture of TCS Upgrade, Near Completion



Summary

- The TCS Upgrade is nearly complete. A very clean vacuum system has been constructed, along with the necessary wall conditioning systems (baking, glow, getter).
- Once the impurity level in the plasma is reduced, significantly higher temperature and field operation should be possible. Such operation will hopefully allow us to address key issues such as plasma resistivity, thermal transport, and energy confinement, critical issues that have previously been obscured by the high radiation level.
- Operation will begin in December