Relationship Between Cathode Spot Formation and Injector Properties on Pegasus-III

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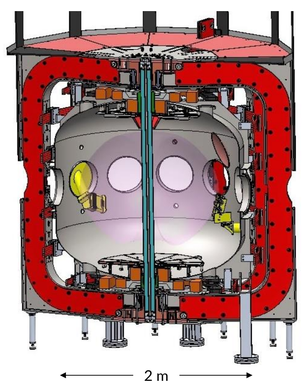
Pegasus-III Experiment

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The Pegasus-III Spherical Tokamak

- Pegasus-III is an ultra-low aspect ratio tokamak in which plasma initiation is achieved without a central solenoid.
  - Higher toroidal magnetic field and pulse length compared to Pegasus-II.
  - Will compare, contrast, and combine multiple startup techniques, including LHI, CHI, and RF.

Pegasus-III

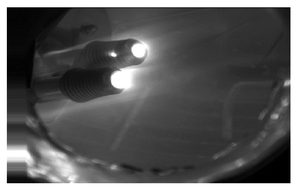


- Local Helicity Injection (LHI) is the primary method of plasma startup.
  - Specialized electron injectors ionize background deuterium gas and inject helicity.
- Cathode spots are commonly observed in the presence of a vacuum arc.
  - Visible on various LHI injector materials during plasma startup.
  - **Cathode spots have far-reaching implications on plasma current, injector hardware, and equipment lifetime, so they must be minimized.**

Cathode spots observed consistently during startup

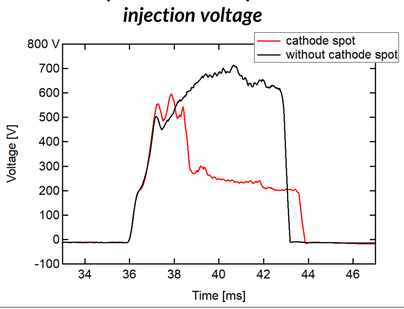
- LHI is achieved by creating an arc discharge within the injector
  - Injector biased with respect to vacuum vessel
  - Arc plasma acts as a virtual cathode for sourcing electrons

Bright cathode spot visible on tip of Pegasus-III injectors

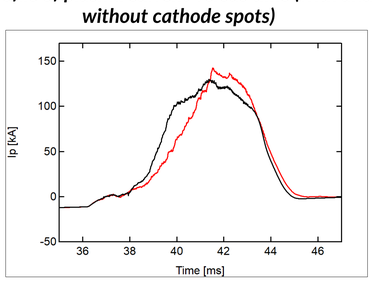


- During breakdown, metal surfaces of an electrode may act as current sources instead
  - Known as "cathode spots" or "arc spots."
  - Leads to sudden reduction of injection voltage V_{inj}
  - Sets upper limit on V_{inj}

Cathode spots lead to sharp reduction in injection voltage



Profile of plasma current versus time (with and without cathode spots)



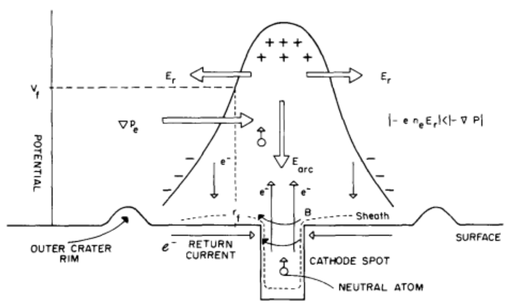
Cathode spots independent of external conditions

- Type 1 spots: fast moving (10-100 m/s) & short-lived (<10 μs).
  - Smaller, lower spot currents & material erosion rate
- Type 2 spots: slow moving (0.1-1 m/s) & long lived (100 μs).
  - **More damaging & observed during LHI discharges**
- **Weakly bound whisker material evaporates in type 1 spots, then transitions to type 2 by unipolar arcing**
  - "Unipolar": Both electrodes on the same metal surface
  - The plasma cloud created during spot formation is shielded from externally applied potentials:

$$\vec{F}_{net} = -\nabla P_e - |e| n_e \overrightarrow{E_r}$$

- **Radial pressure gradient and electric field provide the driving force for unipolar arcing.**

Figure 5: Summary of neutral particle desorption, electron emission, recombination, and radial electric field & pressure gradient expansion processes in unipolar arcing [1]



Microscopy reveals surface properties & composition

- Scanning electron microscopy (SEM) produces images by shooting an electron beam onto a sample.
  - Used to study microcracks, voids, and impurities
  - Energy dispersive x-ray spectroscopy (EDS) used for elemental analysis
- X-Ray Photoelectron Spectrometry (XPS) works via the photoelectric effect [2]:

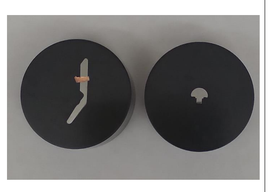
$$E_{binding} = E_{photon} - E_{kinetic} - \phi$$

  - Uses Ta2O5 ion source to etch sample for depth profile
  - Ar flood gun prevents charge buildup
- Optical Profilometry (Zygo9000) uses light to scan and obtain roughness information across a surface
  - Light reflected off test sample compared against reflection off an internal reference sample

Molybdenum frustum shield (L), frustum (R), and ring (bottom)



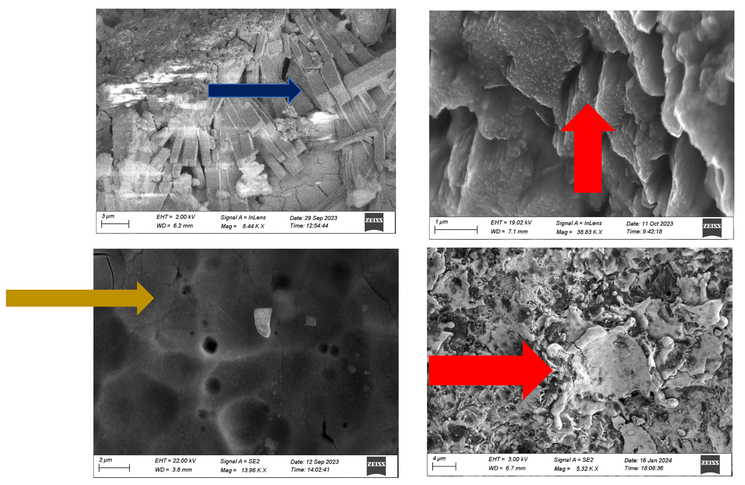
Cross-sections of frustum shield (L) and pristine 54.1mm ring (R) in conductive mount material



SEM images uncover damage and impurities

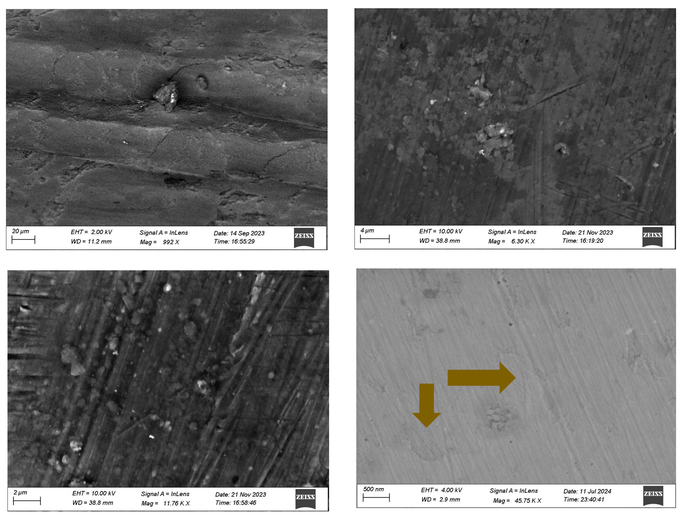
- Mo frustum, frustum shield, and rings are parts of interest

Top Left to Bottom Right: Used frustum with dendrite-like structures, used frustum with cracking on Ti-gettered side, used 70.6mm ring with impurities, like-new 57.6mm ring with swelling, and 54.1mm ring with large craters



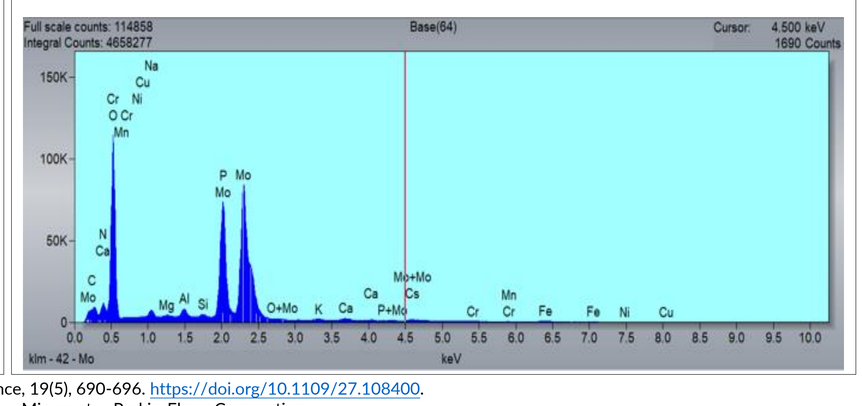
- Images reveal grain boundaries and properties consistent with type 2 spots
- Pristine frustum shield examined for comparison

Top Left to Bottom Right: New Mo frustum shield exterior imaged at 992x – 11.76kx magnification. Bottom right is cross-section of pristine ring at 45.75kx magnification. Images are clean relative to used counterparts. Last image appears to show grain boundaries.



- The origin of non-conductive particles observed is of interest
- EDS confirms the presence of Mo and reveals impurities
  - Presence of oxygen and carbon confirmed by EDS
  - Higher particle density on previously installed pieces compared to pristine pieces

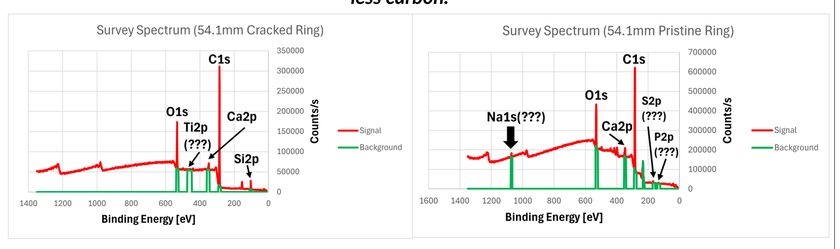
EDS spectrum of used Mo frustum shows high oxygen & carbon count on surface, along with trace amounts of Al & Si



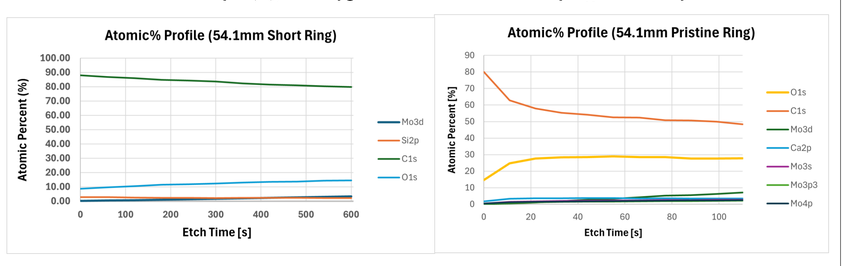
XPS and optical profilometry provide depth information

- XPS scans corroborate compositional measurements from EDS

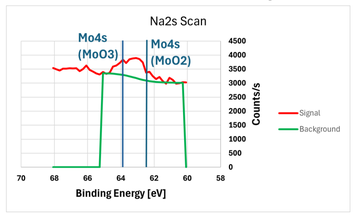
Survey spectrum of used 54.1mm ring (L) shows large amounts of oxygen and carbon (overlapping with the molybdenum peak). The new 54.1mm ring (R) also reveals oxygen but less carbon.



Atomic% depth profiles show that even after 11 levels of etching by Ta2O5, the used sample (L) retains more oxygen than molybdenum. Although surface impurity levels still remain high in the new sample (R), the oxygen and carbon levels drop off drastically

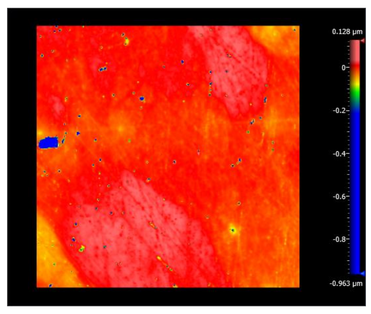


- Chemical state assessment reveals specific metal oxides

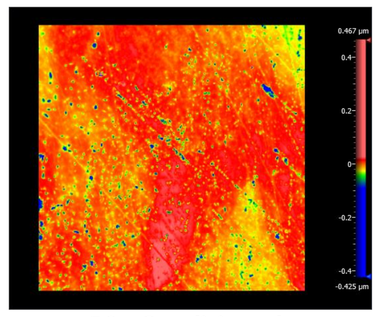


- Profilometer scans obtained to show surface roughness
  - Greater overall surface uniformity in pristine sample
  - 50x leads into analysis of frustum shield cross-section

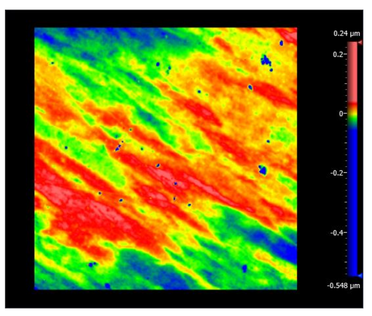
20x Pristine



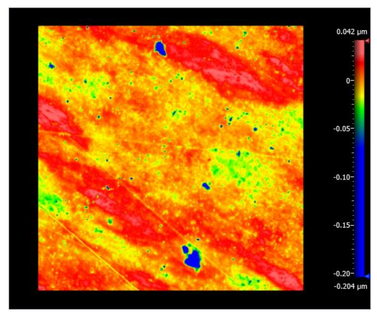
50x Pristine



20x Conditioned

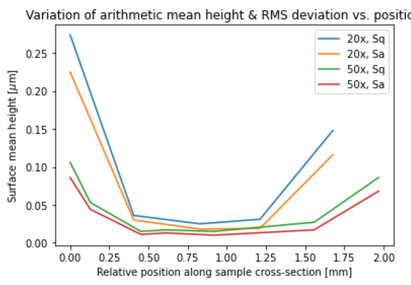


50x Conditioned

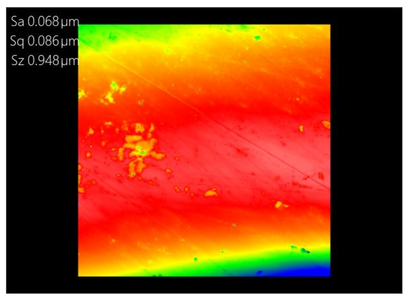


- Z-analysis parameters reveal height variation in used sample
  - Sa = Mean surface height
  - Sq = RMS surface height measured from "center line"
- Analysis is complicated by natural height variation arising from grinding & polishing process

Graph of average surface height and standard deviation versus position along cross-section of Mo frustum shield



Roughness color map positioned near sample edge (closest to polymer mount material)



Findings from experimental data warrant further investigation

- Cathode spots damage injector hardware & limit plasma performance
  - Damage to injector materials is quantified using experimental techniques
  - SEM & EDS reveal extensive oxidation that may result from (and worsen) cathode spot formation.
  - XPS supports EDS findings and specifies the oxides found on the surface
- Future work includes quantifying impurity depth & studying the impact of manufacturing on spot formation

References: [1] Schwirzke, F.R. (1991). Vacuum breakdown on metal surfaces. IEEE Transactions on Plasma Science, 19(5), 690-696. https://doi.org/10.1109/27.108400.
[2] Moulder, J.F.; Stickle, W.F.; Sobol, P.E..; Bomben, K.D. (1992). Handbook of X-Ray Photoelectron Spectroscopy. Minnesota; Perkin-Elmer Corporation.

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