Relationship Between Cathode Spot Formation and Injector Properties During Local Helicity Injection on the Pegasus-III Experiment

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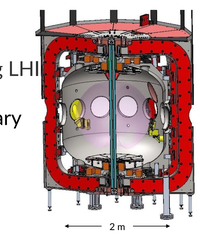
Pegasus-III Experiment

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The Pegasus-III Spherical Tokamak

- Pegasus-III is an ultra-low aspect ratio tokamak in which plasma startup 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.
- Local Helicity Injection (LHI) is the primary method of plasma startup.
  - Specialized electron injectors ionize background deuterium gas and inject helicity.

Figure 1: Pegasus-III



- 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
- 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}
- Consistently observed in vacuum discharges, yet mechanism is poorly understood.

Figure 2: Bright cathode spot visible on tip of Pegasus-III injectors

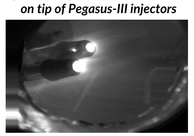


Figure 3: Cathode spots lead to sharp reduction in injection voltage

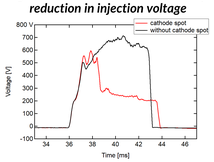
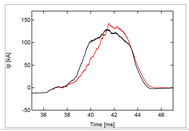


Figure 4: Profile of plasma current versus time (with and without cathode spots)



Cathode Spots Independent of Externally Imposed Physical 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:

$$\vec{F}_{net} = -\nabla P_e - |e| n_e \overrightarrow{E_r} \qquad (1)$$

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

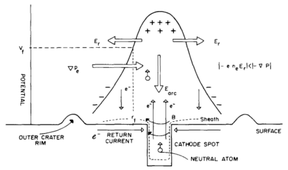


Figure 5: Summary of neutral particle desorption, electron emission, recombination, and radial electric field & pressure gradient expansion processes in unipolar arcing [1]

SEM & EDS Reveal Surface Properties and Composition

- Scanning electron microscopy (SEM) produces images by shooting electron beam onto a sample
  - Secondary electron/"in-lens" detector produces most images presented in this work.

Figure 6: Samples are placed on sample holder and mounted onto SEM stage (pictured)

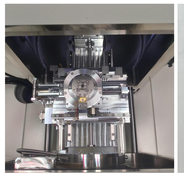
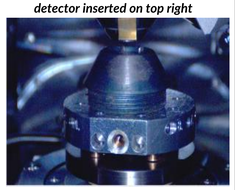


Figure 7: Molybdenum frustum shield (L), frustum (R), and ring (bottom)



Figure 8: SEM electron beam focused on upper part of frustum with EDS detector inserted on top right

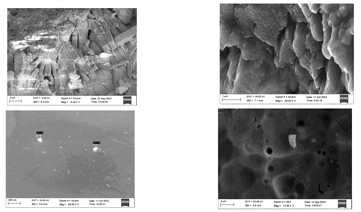


- Microcracks, voids, impurities, and other features of the crystalline structure are studied.
- Energy dispersive x-ray spectroscopy (EDS) used for elemental and structural analysis of the sample.

SEM Images Uncover Damage and Impurities

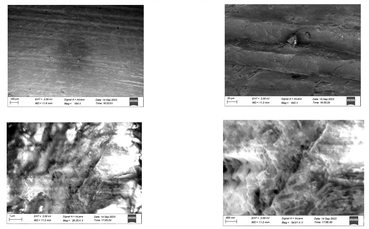
- Mo frustum, frustum shield, and rings are materials of interest

Figures 9-12 (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, and unused 57.6mm ring showing bubbles and swelling



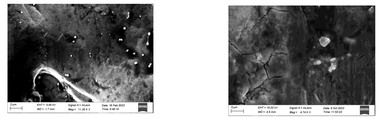
- Pristine frustum shield examined for comparison

Figures 13-16 (Top Left to Bottom Right): New Mo frustum shield imaged at 164x – 54.91kx magnification. Images are clean relative to used parts and show circumferential tracks from manufacturing. Microcracking visible at the highest magnification

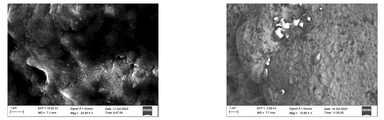


- Non-conductive particles observed on new, used, and used W frustum shield
  - **The origin of these particles is of interest**

Figures 17 – 18: Oxide particles and cracking seen on used stainless steel (L) & molybdenum (R) frustum pieces



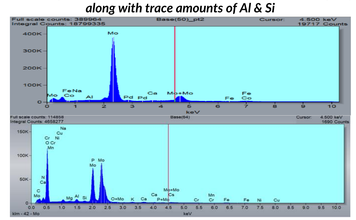
Figures 19 - 20: Used molybdenum (L) and tungsten (R) frustum shield pieces. Both exhibit oxide formation, but tungsten shows less severe cracking, roughness, and surface irregularities.



EDS Spectra Quantify Effects of Chemical Composition

- EDS confirms the presence of Mo and reveals impurities
- Al & Fe seen in EDS spectra from different samples
- Some Na & Ca present due to contamination
- Non-conductive particles suspected to be oxides
  - Presence of oxygen and carbon confirmed by EDS
  - Higher particle density on previously installed pieces compared to pristine pieces

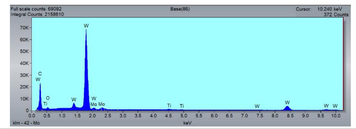
Figures 21-22: EDS spectrum of unused 59.3mm ring (top) shows mostly Mo with trace amounts of Fe, Al, Na, , and Ca. Spectrum of used Mo frustum shows high oxygen & carbon count on surface, along with trace amounts of Al & Si



- The effect of manufacturing processes on these oxides and material lifetime will be considered

- Ti seen on used W frustum shield due to titanium gettering process performed on Pegasus-III

Figure 23: Tungsten frustum shield shows presence of carbon, oxygen, and titanium (0.78%wt) at the surface.



Findings from SEM Data Warrant Further Investigation & Verification

- Cathode spots damage injector hardware & limit plasma performance
- Unipolar arcing is proposed as a mechanism for type 2 spot formation
- Damage to injector materials is quantified using experimental techniques
  - SEM reveals extensive oxidation that may be the result of, and further exacerbate, cathode spot formation.
  - XPS and profilometry to be used to reveal other characteristics of interest

Reprints available at https://pegasus.ep.wisc.edu/technical-reports.

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

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