Effects of electrode coating on the CTIX injector performance during high-Z CT formation and acceleration

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UCDAVIS Compact Torus Injection Experiment

Abstract

One application of high velocity compact toroids (CTs) is the ability to deliver ions of various species to the magnetic axis of tokamak plasmas. The fast formation and acceleration of the CTs can react to rapidly changing events in a tokamak operation such as disruptions. As proposed in theoretical models [1], high-Z ions delivered to the magnetic axis of a reactor-grade tokamak have the benefit of cooling runaway electrons by the bremsstrahlung process and limiting the runaway electrons final energy and the potential damage to tokamak components. The Compact Toroid Injection Experiment (CTIX) is currently being used to demonstrate efficient production of high-Z CT plasmas using accretion of noble gases (He, Ne, Ar) puffed in the acceleration region. From previous observations of electrode damage due to repetitive operation of the CITX injector with hydrogen CTs, it was decided to coat the inner electrode surfaces with vacuum-sprayed tungsten. This was done to minimize the damage to the surfaces and increase the longevity of the injector under repetitive operation. The CT characteristics are measured using optical techniques, interferometry, and internal magnetic field probes. A detailed comparison of the CT behavior and parameters using the different electrodes, stainless steel and tungsten-coated Inconel, will be reported. In addition, analysis of the measured damage to the electrode surface will guide future improvements to the injector design that will yield the best high-Z CTs for the mitigation of runaway electrons.

[1] M. Bakhtiari, et al, Phys. Rev. Lett. **94**, 215003 June 2005.

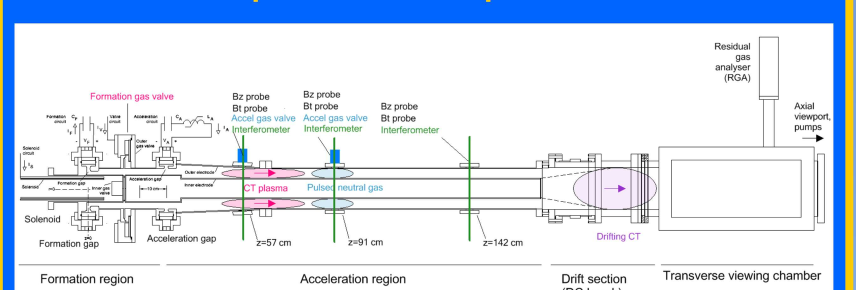
Overview

- Experiments on the Compact Torus Injection Device (CTIX) aim to produce high-velocity compact-toroid (CT) plasmas containing primarily ions of high atomic number (high-Z)
- The method of CT production is to form relatively low-mass, low-Z CTs followed by snowplow accretion of high-Z neutral gas puffed into the acceleration region, greatly raising CT mass
- The experimental rationale is development of high-Z CTs with kinetic energy density sufficient to penetrate tokamak interiors, for the purpose of disruption mitigation (see below)
- The immediate experimental goal is demonstration of high gas-utilization efficiency and energy efficiency on the relatively small CTIX device

Recent modifications to CTIX

- Replacement of uncoated stainless-steel (Fe) inner electrode with tungsten-coated (W) inner electrode of otherwise identical design
- Approximately 10,500 shots taken with new W-electrode
- Interferometers available at z=57 cm, z=142 cm (z=91 cm unavailable)
- Added amplified, H_α-filtered axial photodiode for continuous-time monitoring of all shots
- Added axially-viewing Oriel spectrometer for continuous-time monitoring of all shots at selected wavelength, 350-900 nm
- Added axially-viewing Cooke fast camera, for monochrome 1280x1024 imaging of any selected time slice of duration >= 0.5 ms

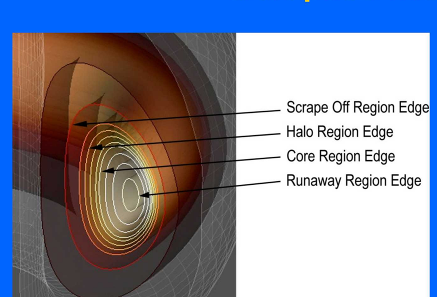
Experimental setup on CTIX



Mitigation and control of central runaway electrons

- Runaway electron (RE) current may be produced during current quench (CQ) phase of disruption mitigation
- Mitigation of RE current peak on axis thus requires fast and deep particle injection, preferably with high-Z species
- Collisions and bremsstrahlung both cause slowdown of RE
- Radiation can limit the RE energy
- From simulation studies, central injection of high-Z noble gases can terminate and control the CQ RE.
- CT injector may be able to deliver high-Z ions to tokamak center

Application of accelerated CT for disruption mitigation



Normal Operation

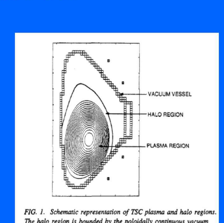


FIG. 1. Schematic representation of TSC plasma and halo regions. The halo region is bounded by the poloidally continuous vacuum vessel and by a specified increment in poloidal flux.

VDE Simulation*

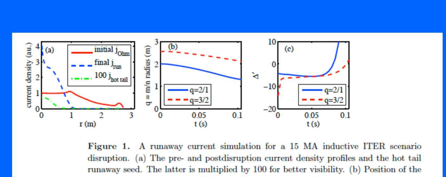
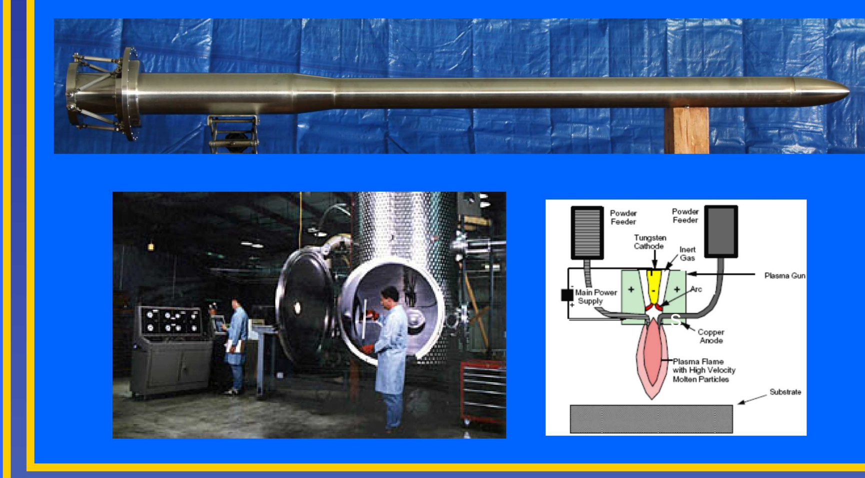


Figure 1. A runaway current simulation for a 15 MA inductive ITER scenario disruption. (a) The pre- and postdisruption current density profiles and the hot tail runaway seed. The latter is multiplied by 100 for better visibility. (b) Position of the resonant surfaces $q = 3/2$ and 2/1. (c) The evolution of Δ'.

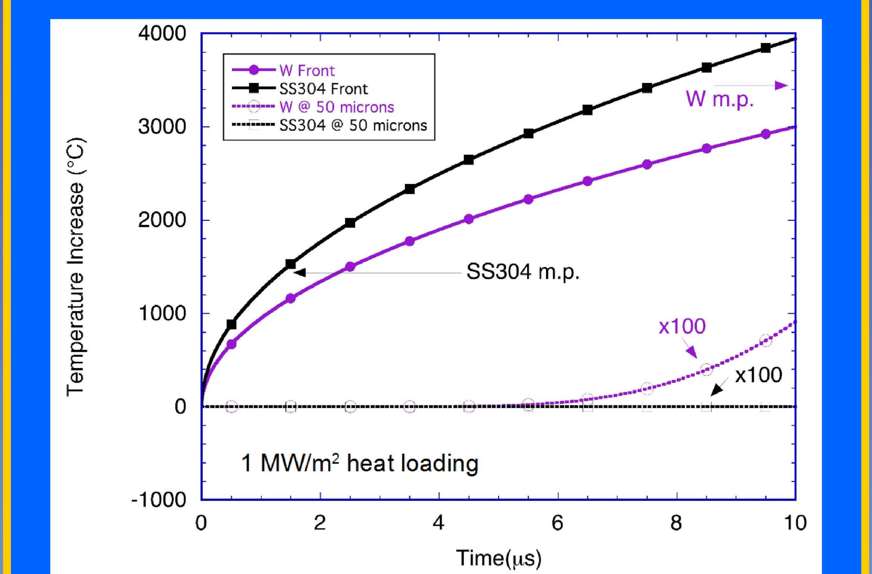
RE Simulation**

* Syer, R.O. et al. Nuclear Fusion v33 #7 (1993)
** Smith, H.M. et al. Plasma Phys & Control Fusion 51(2009) 124008

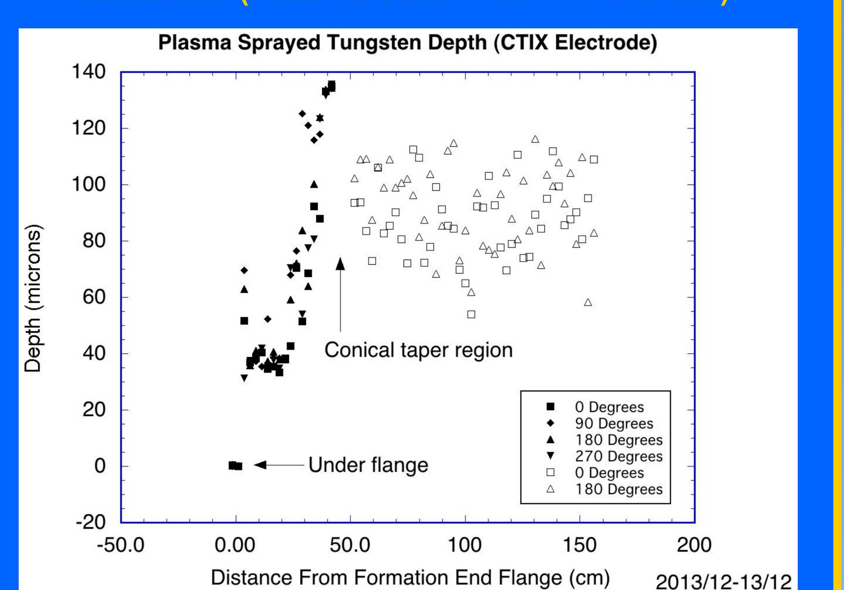
Next inner electrode has been fabricated, using vacuum plasma spray deposition of tungsten



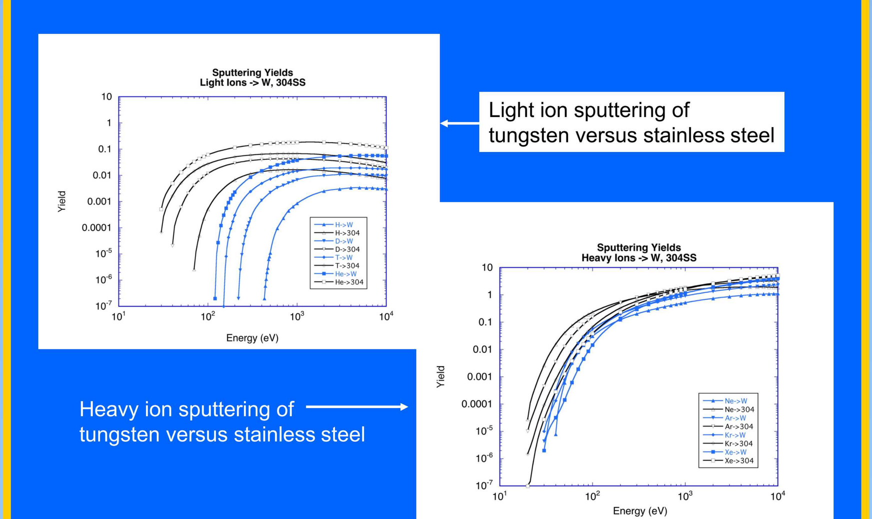
1-d thermal modeling shows improved resistance to melting with tungsten



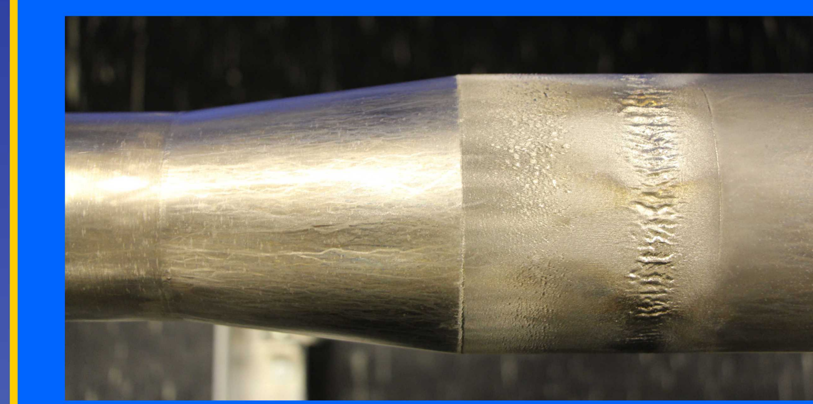
Beta backscattering used to determine tungsten coating thickness (nominal value was 100 microns)



Sputtering simulations show more improvement for light ion impacts

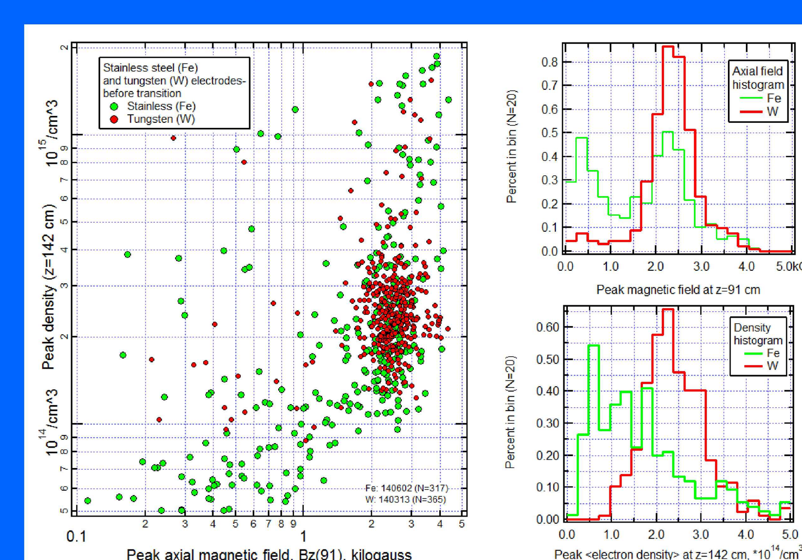


Fe-electrode after first 5000 shots

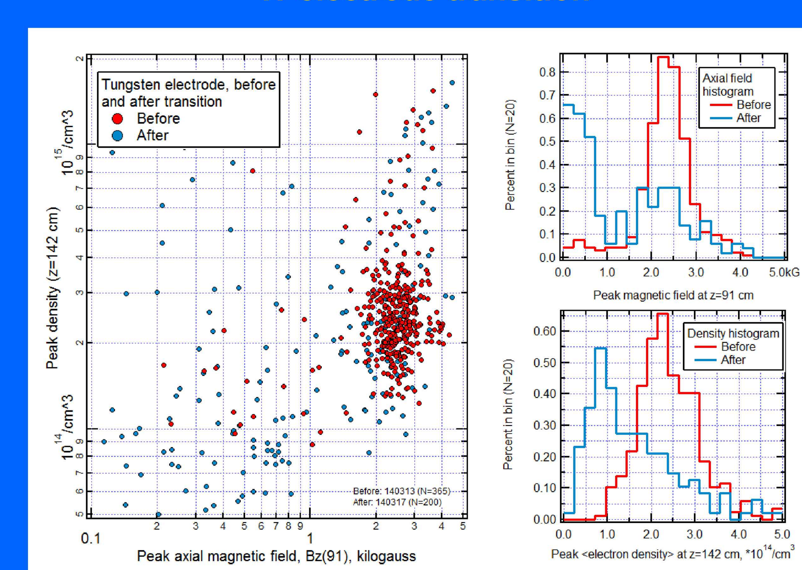


W-electrode after first 5000 shots

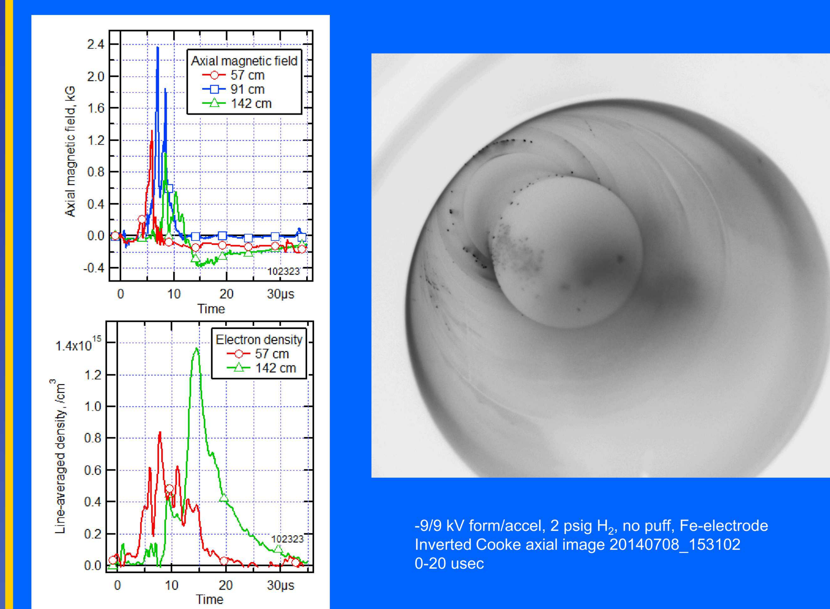
Fe-electrode vs. initial W-electrode



W-electrode transition

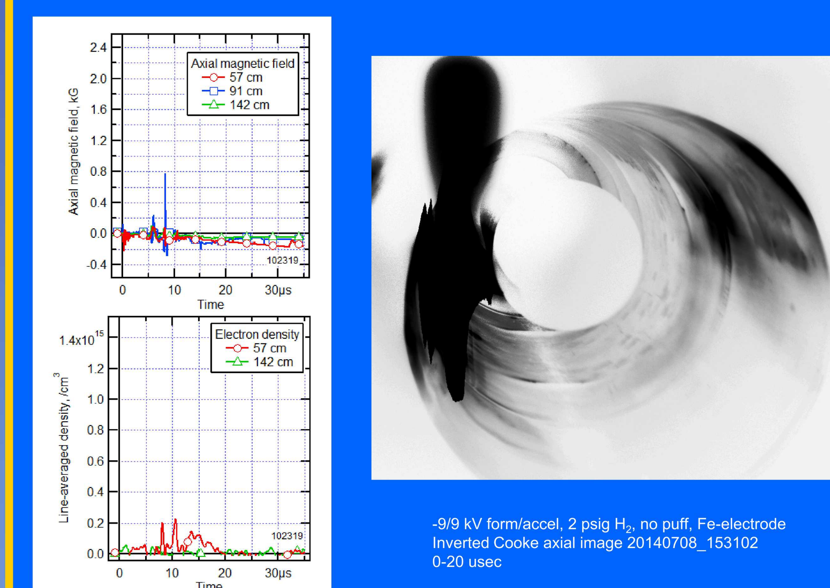


Good (B_z,n_e) shots have dim, symmetric image



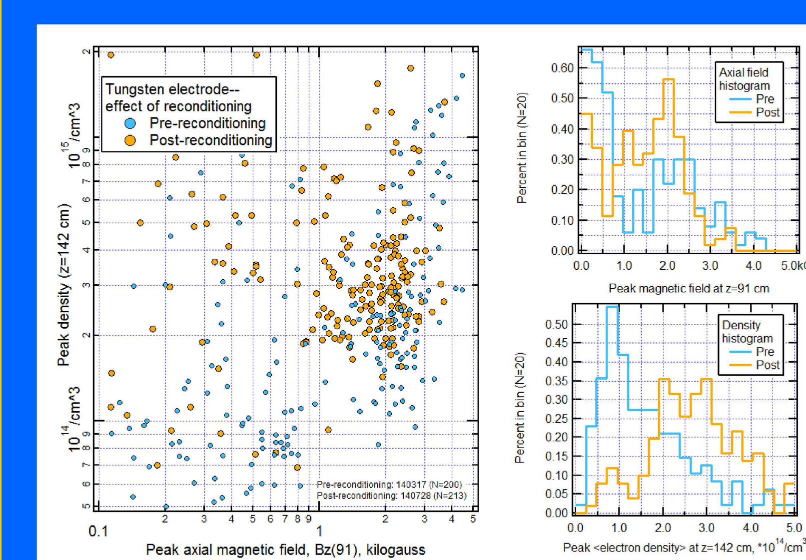
-9/9 kV form/accel, 2 psig H_2, no puff, Fe-electrode
Inverted Cooke axial image 20140708_153102
0-20 usec

Bad (B_z,n_e) shots have bright, asymmetric image

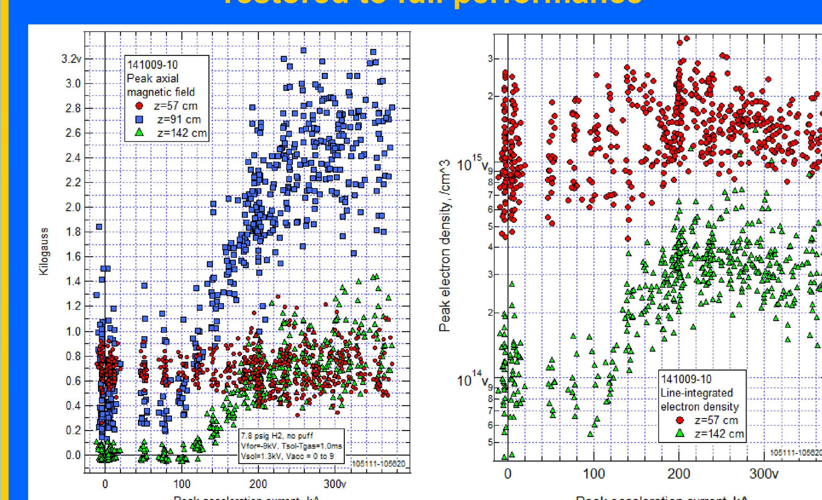


-9/9 kV form/accel, 2 psig H_2, no puff, Fe-electrode
Inverted Cooke axial image 20140708_153102
0-20 usec

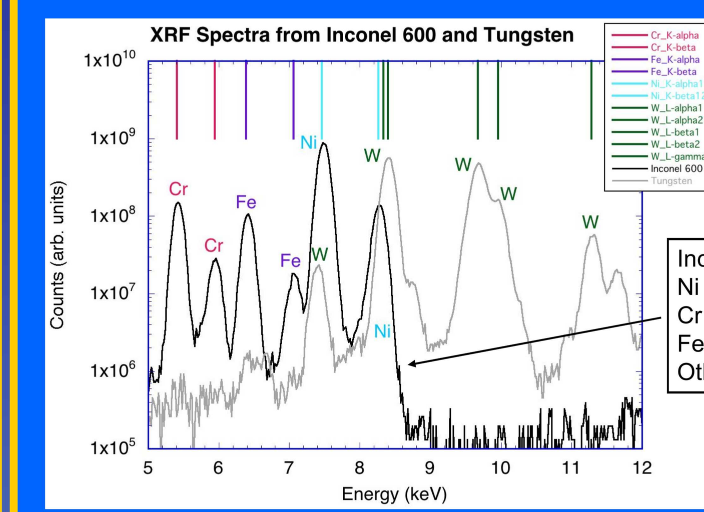
W-electrode reconditioning after transition



After conditioning, W-electrode is restored to full performance

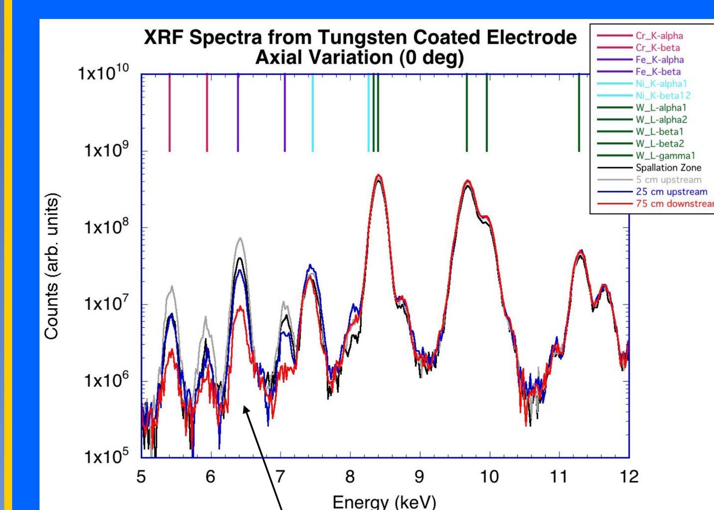


X-ray fluorescence spectroscopy used to investigate spallation of and coating on the tungsten



Incident x-rays should not penetrate beyond the tungsten coating

Axial variation of XRF spectra shows similar peaks in spallation and undamaged regions

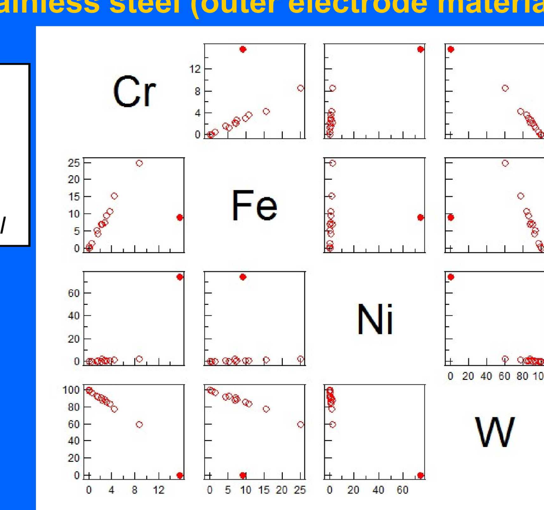


Highest Fe,Cr,Ni just upstream of spallation region and decreases dramatically downstream

Correlation of XRF peaks not consistent with Inconel More typical of stainless steel (outer electrode material)

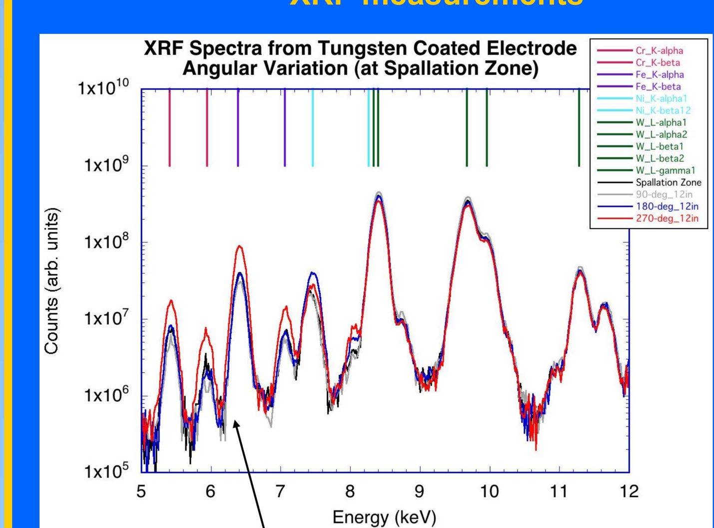
All XRF values used to examine % of elements versus one another:
Not consistent with high Ni alloy
Closer to Stainless Steel

Inconel 600:
Ni 72%
Cr 14-17%
Fe 6-10%
Others ≤ 1%



Open circles are measurements of electrode
Solid circles are Inconel 600

Some angular variation is also evident in XRF measurements



Highest Fe,Cr found at 270° (0° is top of electrode)

Summary of experimental results

- Density and magnetic field using W-electrode was similar to Fe-electrode in magnetic field and density measurements
- After replacement of uncoated inner electrode (Fe-electrode) with tungsten-coated inner electrode (W-electrode), good performance was obtained
- Density and magnetic field using W-electrode was similar to Fe-electrode in magnetic field and density measurements
- Percentage of "good" shots moderately higher with W-electrode vs Fe-electrode
- W-electrode was removed after initial ~5000 shots taken under standard conditions (-9/9 kV formation/acceleration, H_2 fill)
- Comparison of Fe-electrode and W-electrode after identical 5000-shot sequences shows much less melting of W-electrode in critical area (acceleration gap)

- After ~ 3000 shots of excellent initial performance, W-electrode made a sudden (< 50-shot) transition to lower performance
- After transition, "good" W-electrode shots were the same as before transition, but fraction of good shots was reduced from ~ 90% to ~ 30%. ("Good": normal density n_e and axial field B_z)
- Axial camera (Cooke) measurements tend to show bright, aziumuthally-nonuniform emission on low-performance shots
- Operation of W-electrode at higher H_2 operating pressure has a conditioning effect, increasing the fraction of good shots
- Effect of higher-pressure conditioning is persistent; good performance is currently obtained with W-electrode at original lower H_2 operating pressure

- Before initial W-electrode operation, beta-backscattering measurements showed ~ 40 micron W depth in formation region, rising to ~ 100 micron W depth in acceleration region
- After initial operation (~ 3000 shots at high-, ~ 2000 shots at low-performance) W-electrode was removed for examination. Visually, some tungsten loss from inner electrode and flakes on outer electrode floor near acceleration gap
- After ~ 5000 shots, X-ray fluorescence (XRF) measurements indicate W-electrode is overlaid with stainless steel (outer electrode material), with some azimuthal nonuniformity
- W-electrode was then reinstalled, and after reconditioning at higher H_2-pressure, performance was improved to near-original condition

Future work

- Current experiments are aimed toward implementation of active switching to improve uniform gas breakdown.
- Next: perform accelerator-region puffing with W-electrode with H_2, N_2 and noble gases He, Ne, Ar; compare results with Fe-electrode, and verify that tungsten coating continues to reduce inner electrode damage.
- Repeat X-ray and other surface-characterization methods on reconditioned inner electrode, to determine surface materials in formation and acceleration region, and their uniformity / nonuniformity.
- Consider methods to prevent outer-electrode stainless-steel overcoating – modified outer electrode (localized W); optimize operating conditions.
- Using improved power-handling capability of W-electrode, increase operating voltages to create CTs of higher number and kinetic energy density.

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