Comparison of Uncoated and Tungsten-Coated Electrode Performance on CTIX

Robert D. Horton, David Q. Hwang,
Ruth Klauser, Russell W. Evans
UC Davis Compact Torus Injection Experiment

Dean A. Buchenauer, Bernice Mills
Sandia National Laboratory, Livermore, CA

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P2.030

Abstract

The Compact Toroid Injection Experiment (CTIX) is currently being used to demonstrate efficient production of CT plasmas of high atomic mass, using accretion of noble gas puffed in the acceleration region. An important application of such high-Z CTs is the suppression, by a combination of collisional and bremsstrahlung effects, of highly-relativistic electrons produced by disruptions in large tokamaks. In order to produce CTs with number density and energy density relevant to this application, high power densities are required on electrode surfaces, which may result in surface damage. By coating the inner electrodes with vacuum-sprayed tungsten, such damage may be minimized. Two new inner electrodes have been constructed for CTIX, one of stainless steel and one of tungsten-coated Inconel.

Abstract, cont'd

Experiments are underway comparing the performance of the two electrodes, using the usual magnetic and density diagnostics, combined with fast imaging of the axially-viewed plasma, and surface measurements of the electrodes after operation. Initial results indicate significantly reduced inner electrode damage (melting) with tungsten coating. Also, axial imaging measurements indicate that high performance, indicated by large axial magnetic field in the acceleration region, is associated with high azimuthal uniformity of CT visible emission. By maximizing uniformity of light emission by altering operating conditions such as voltage and gas timing, it may be possible to obtain higher-performance and more reproducible CTs for future applications.

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

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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=57cm, z=142 cm (z=91cm unavailable)
- Added amplified, Hα-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 μs

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

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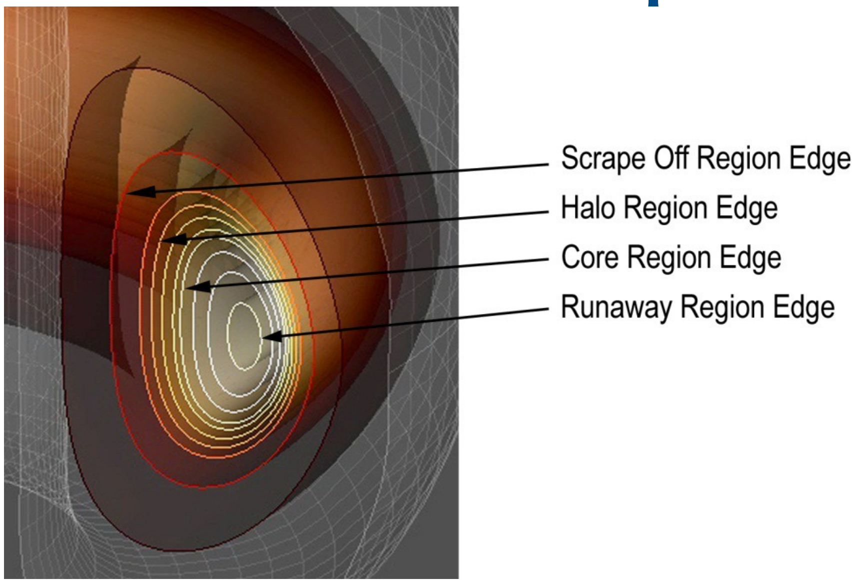
Application of accelerated CT for disruption mitigation



Normal Operation

VDE Simulation*

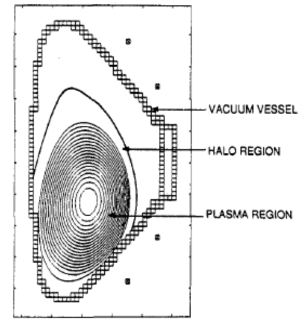


FIG. 1. Schematic representation of TSC plasma and halo regions. The halo region is bounded by the poloidally continuous vacuum vessel and by a specified increment in poloidal flux.

RE Simulation**

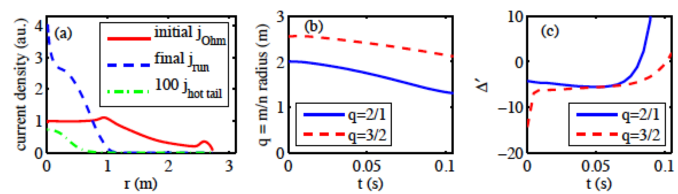


Figure 1. A runaway current simulation for a 15 MA inductive ITER scenario disruption. (a) The pre- and postdisruption current density profiles and the hot tail runaway seed. The latter is multiplied by 100 for better visibility. (b) Position of the resonant surfaces $q = 3/2$ and $2/1$. (c) The evolution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

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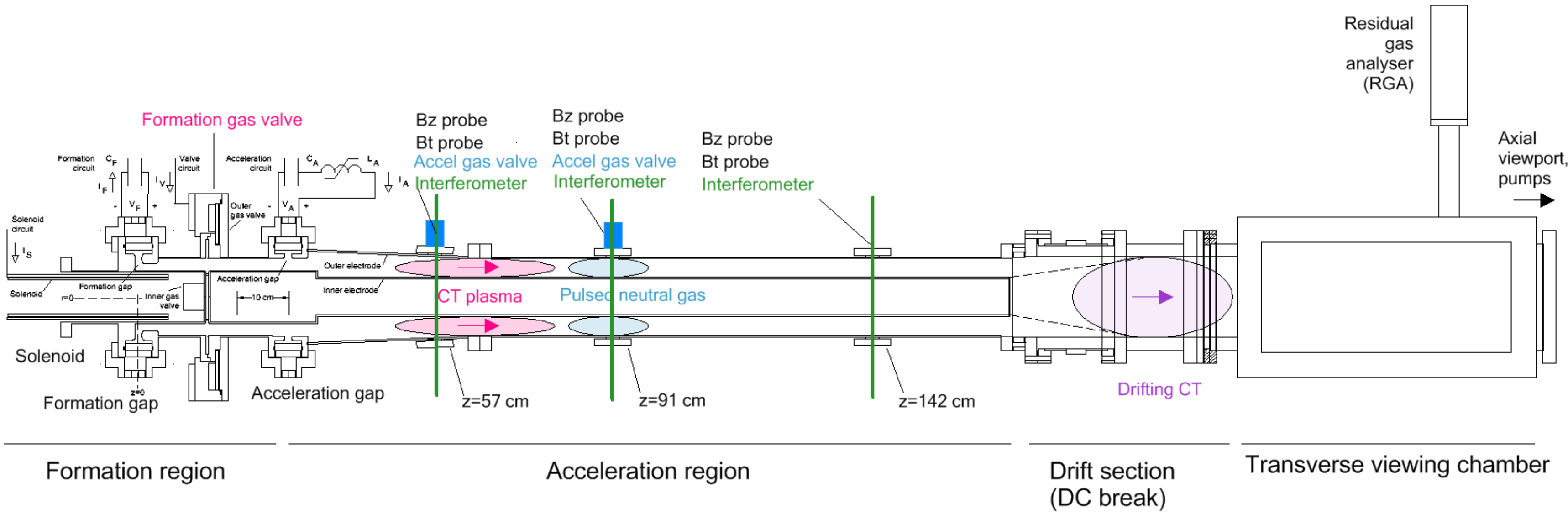
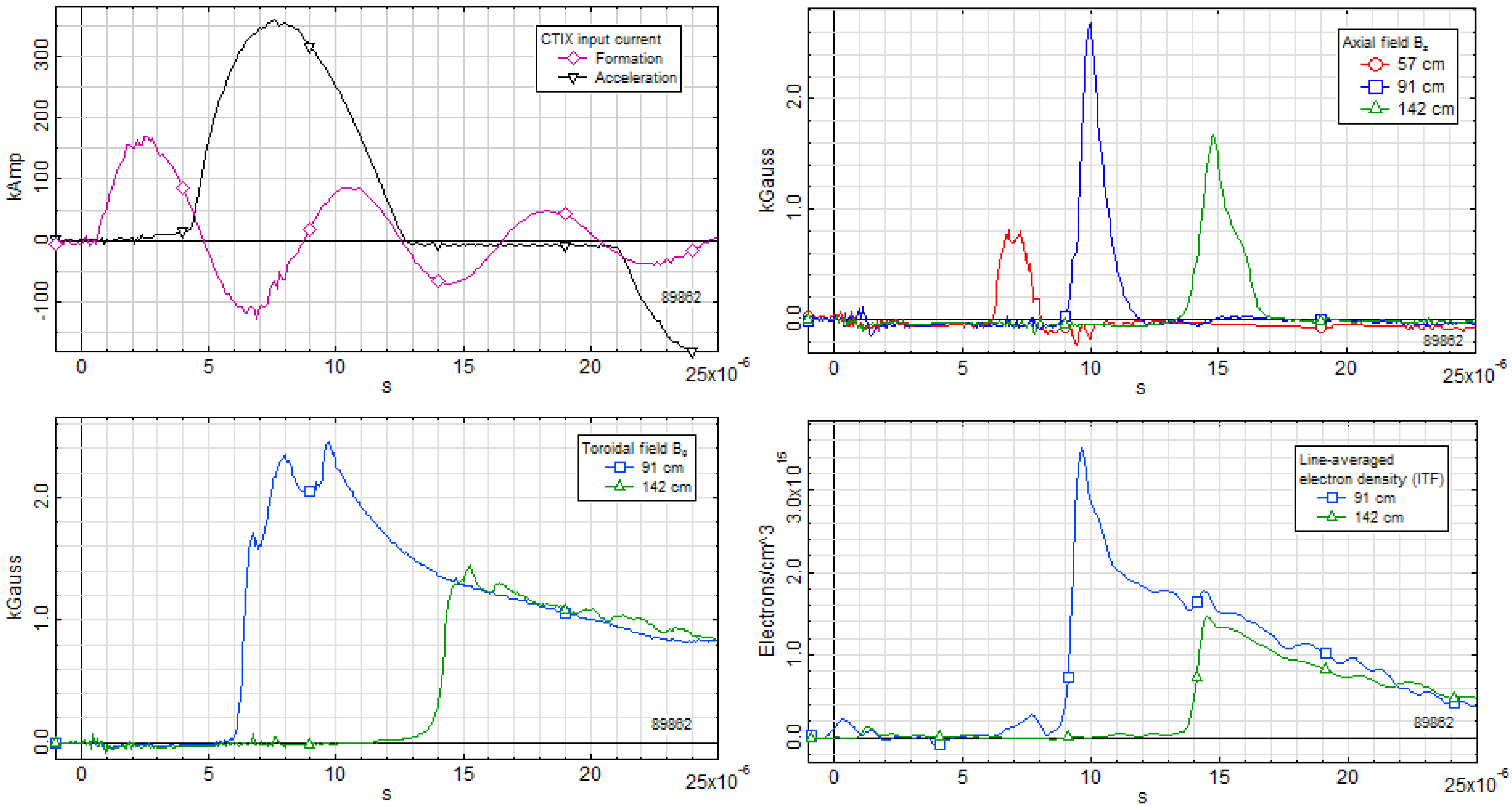
* Syer, R.O. et al. Nuclear Fusion v33 #7 (1993)
** Smith, H.M. et al. Plasma Phys & Control Fusion 51(2009) 124008

Experimental setup on CTIX



Hydrogen gas puffed shot – standard



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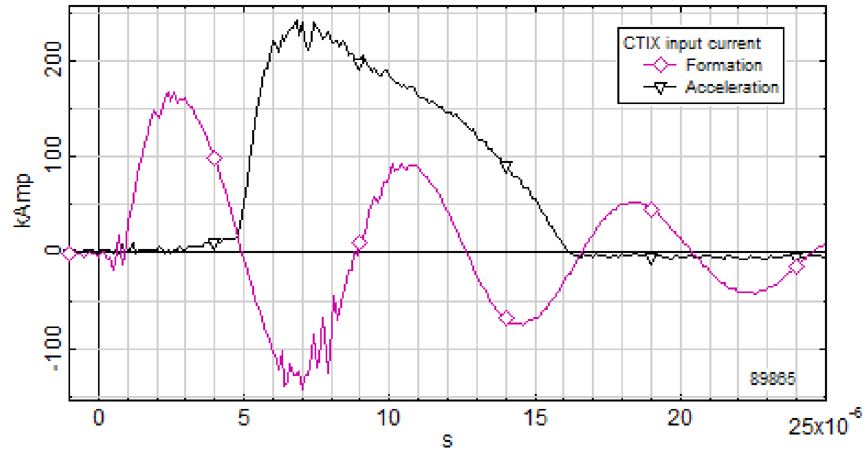
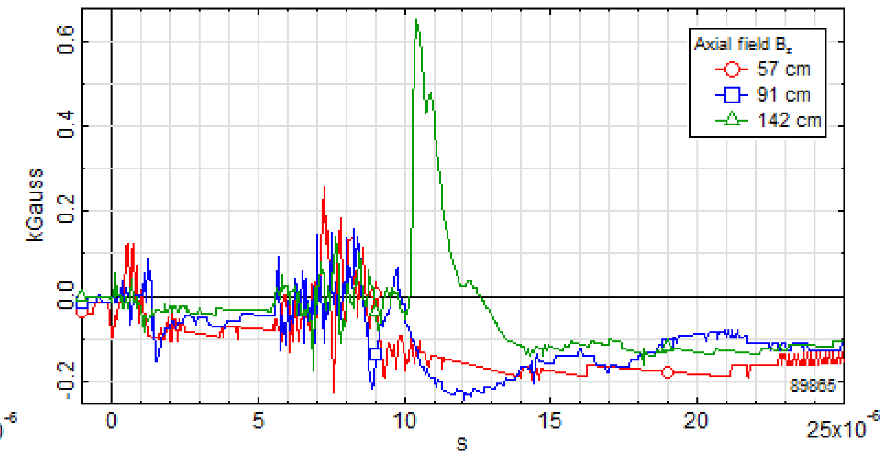
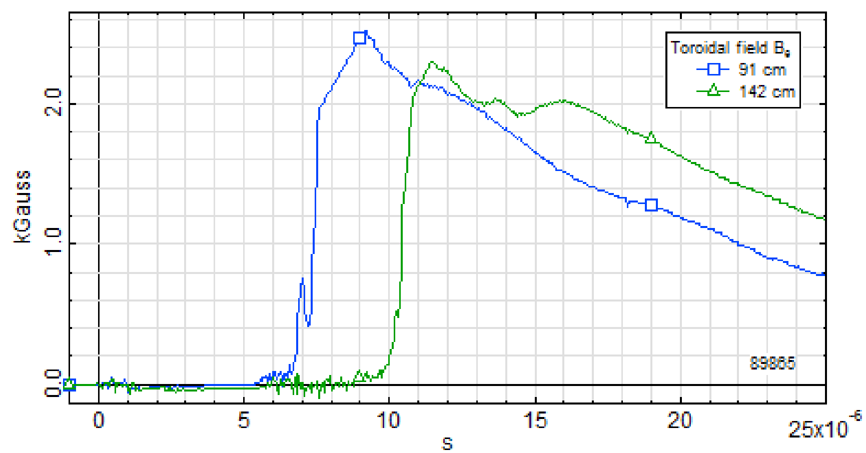
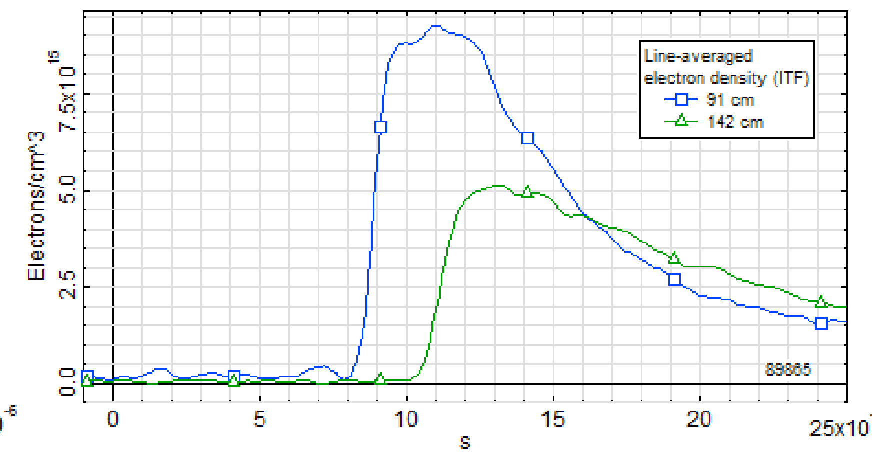
Hydrogen gas puffed shot – high-performance

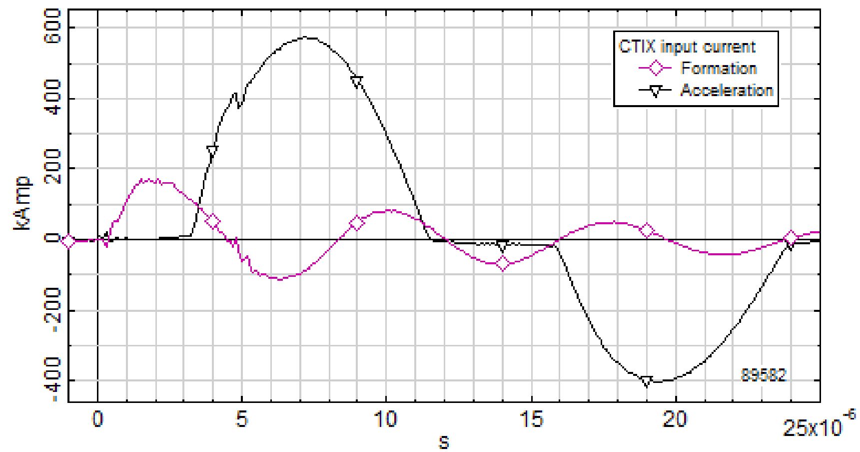


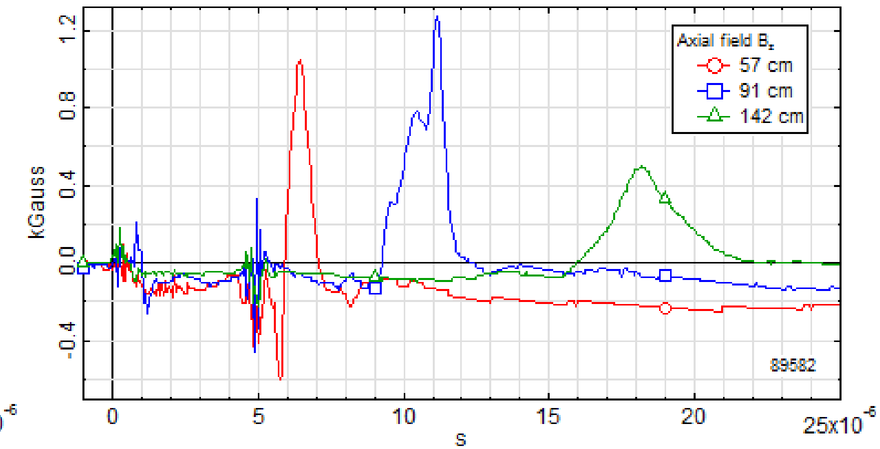


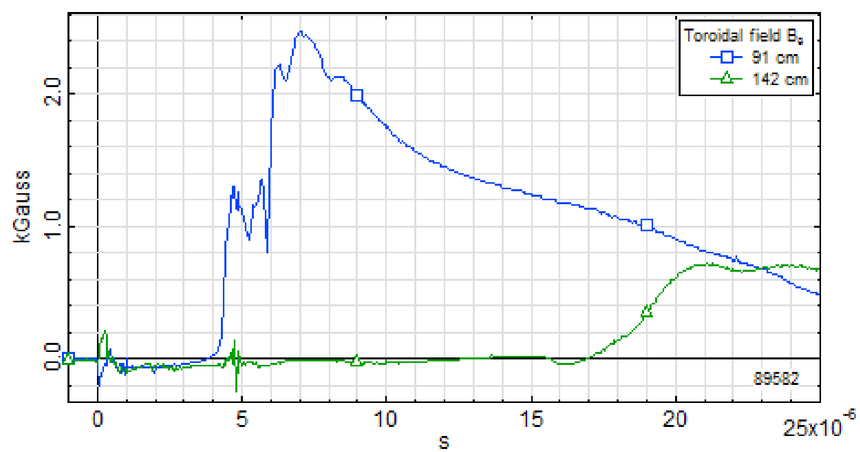


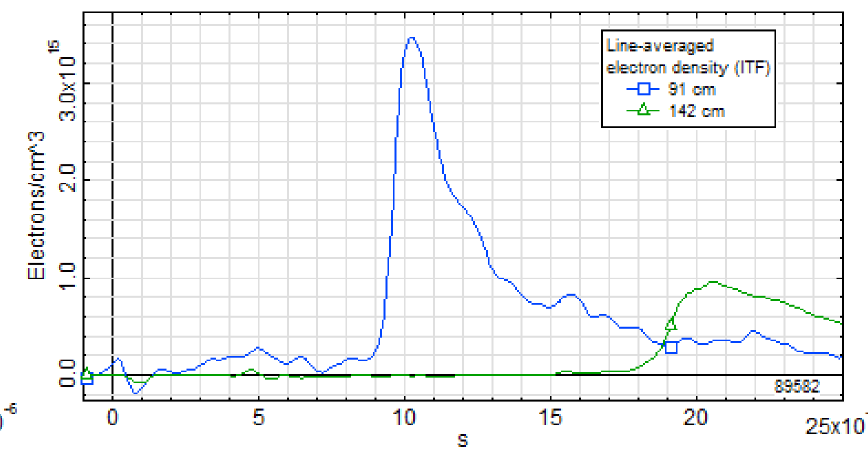


Helium gas puffed shot – standard









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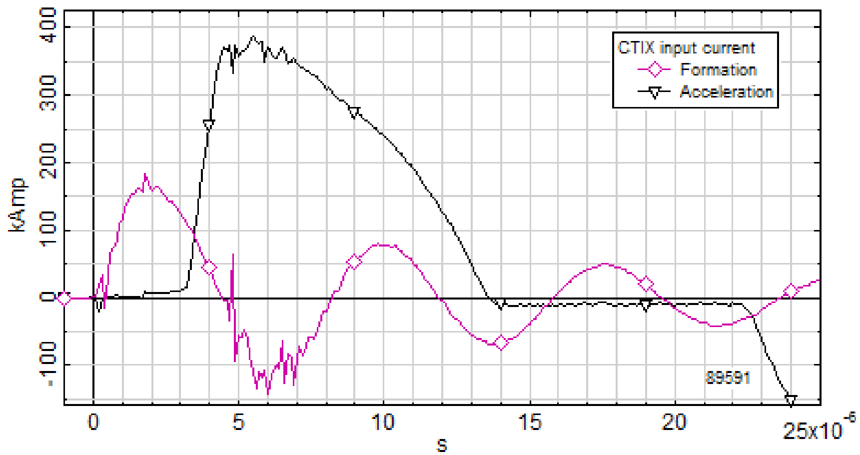
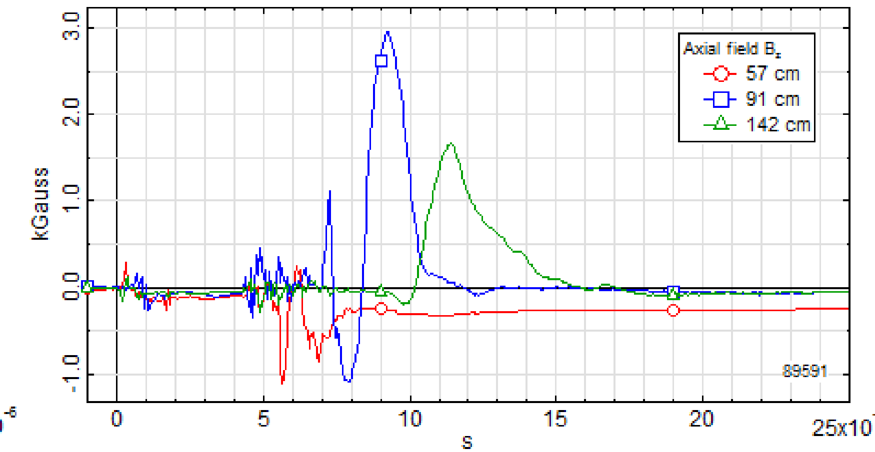
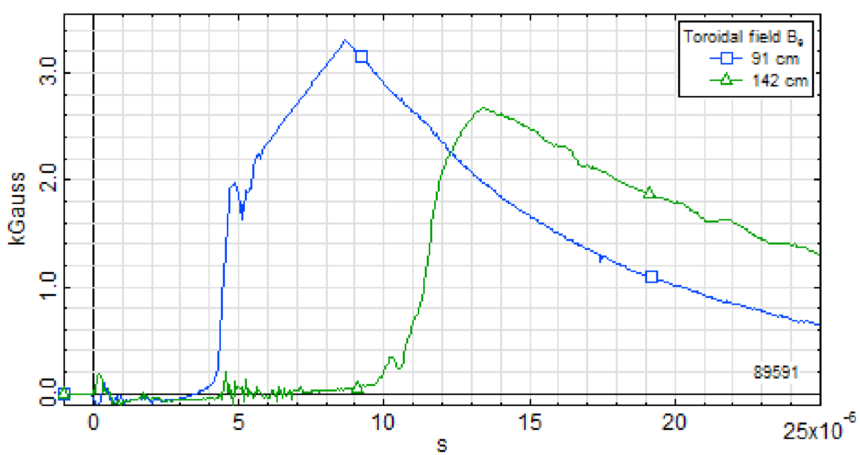
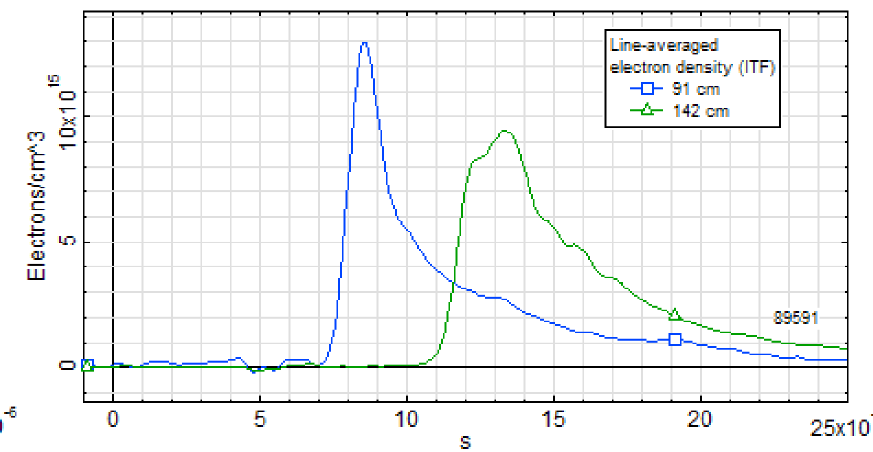
Helium gas puffed shot – high-performance









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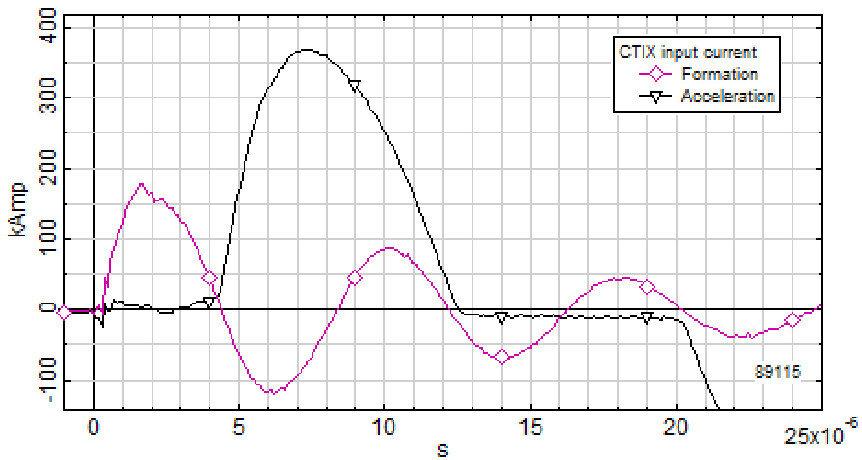
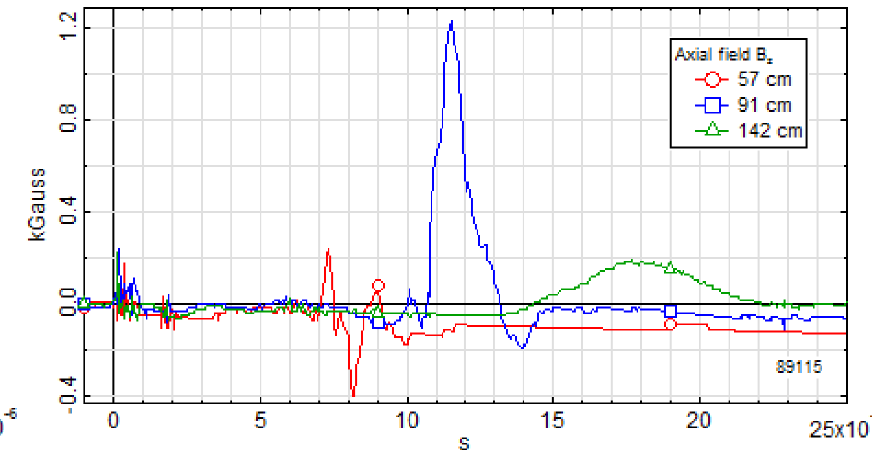
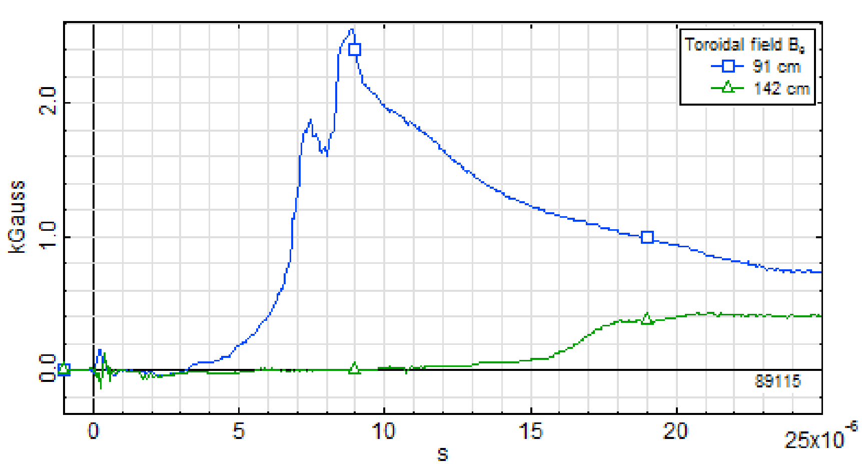
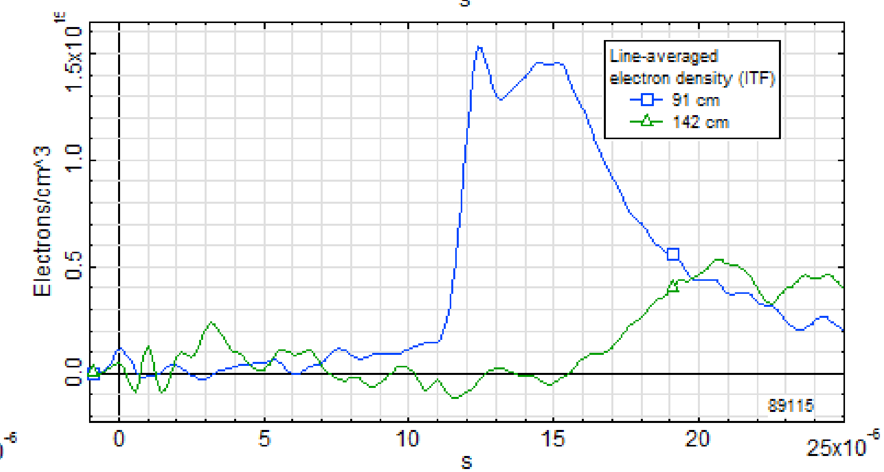
Neon gas puffed shot – standard









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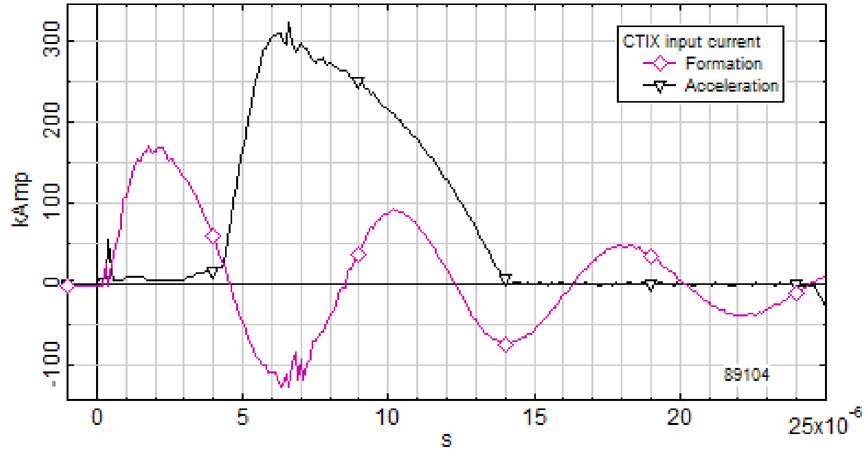
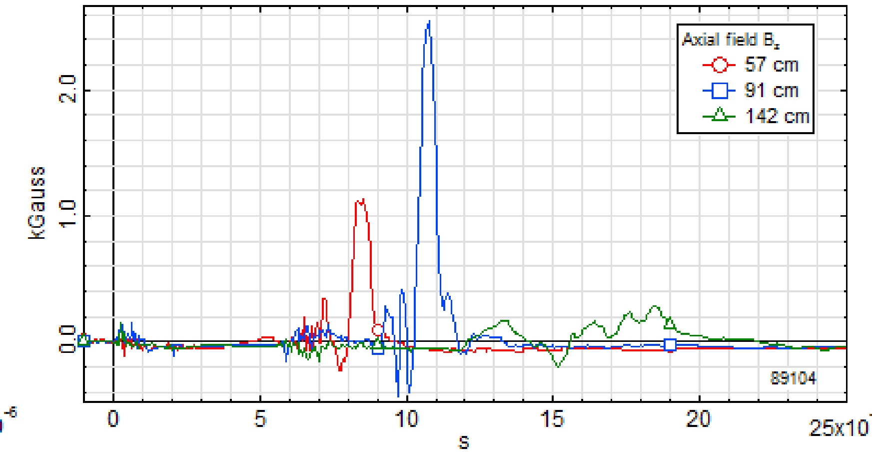
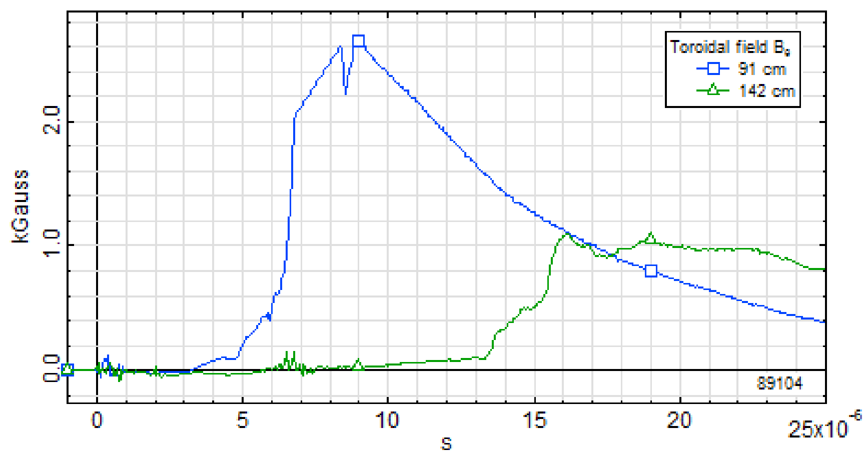
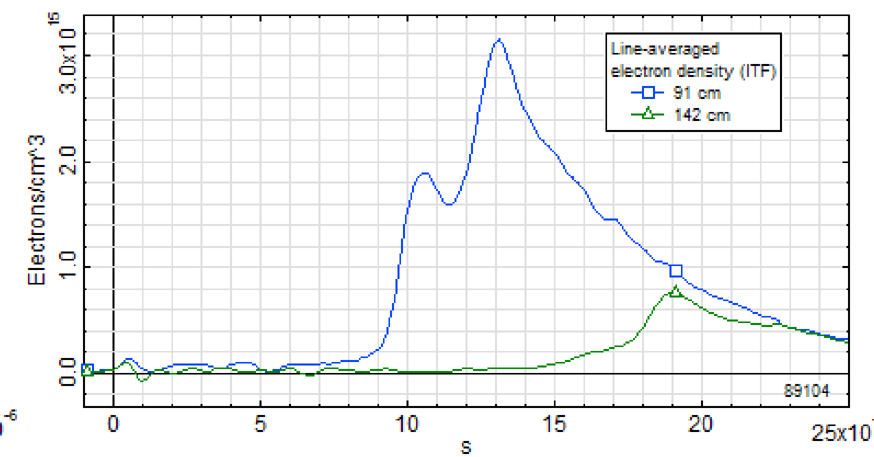
Neon gas puffed shot – high-performance









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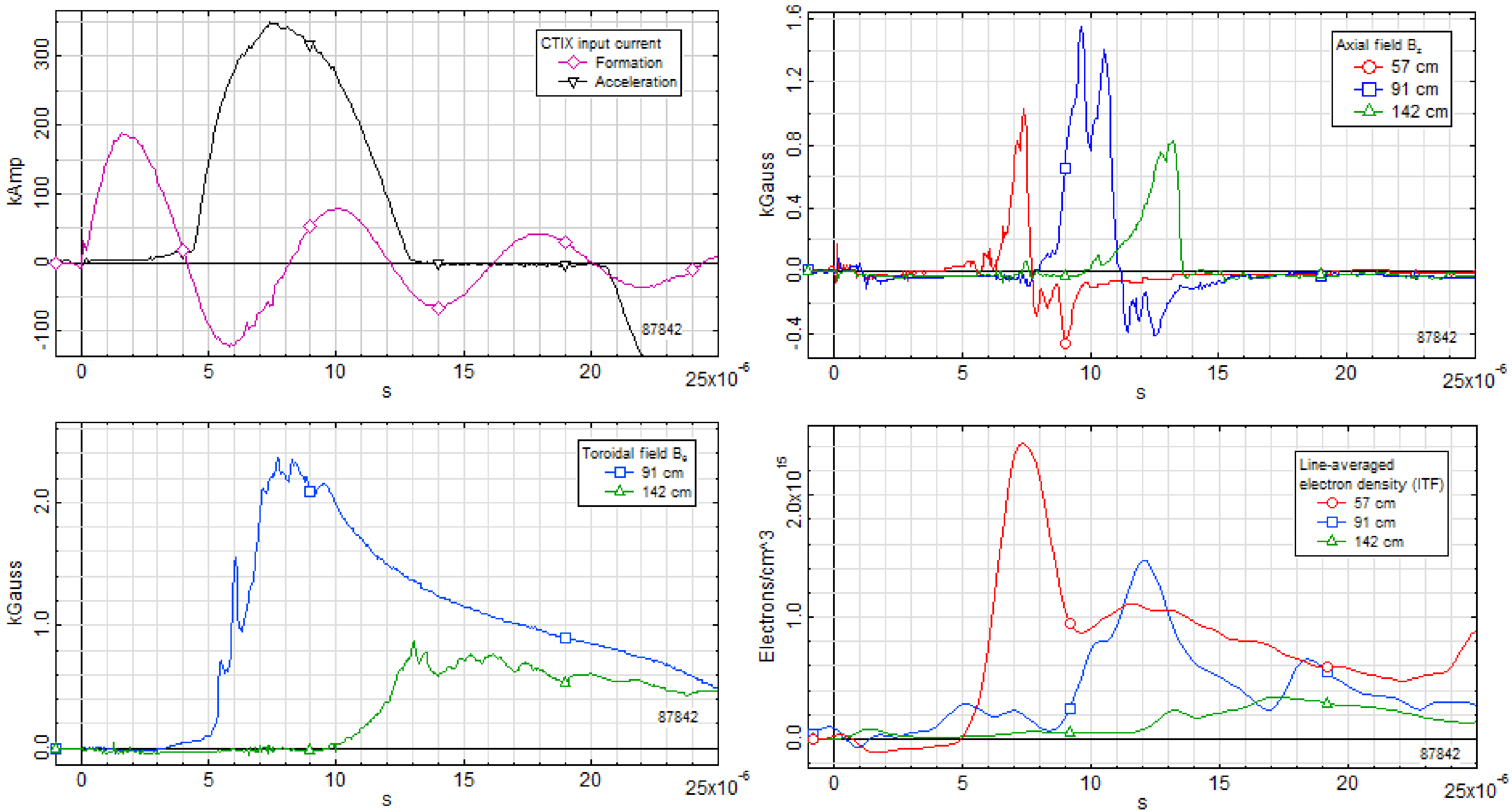
Argon gas puffed shot – standard



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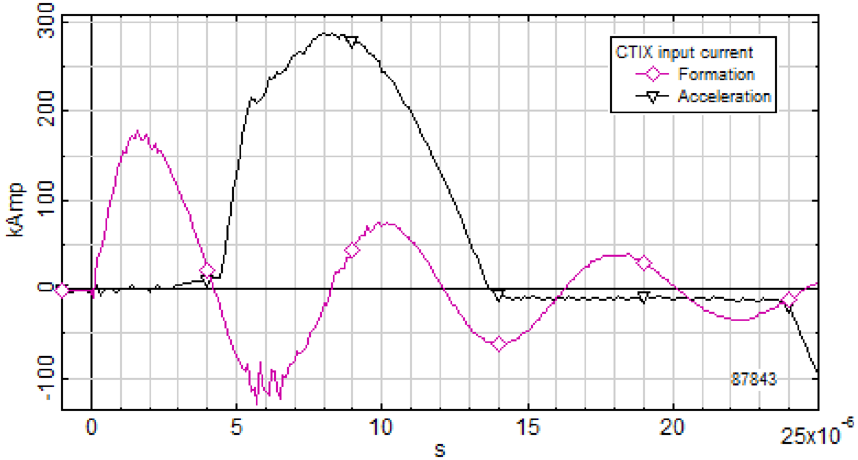
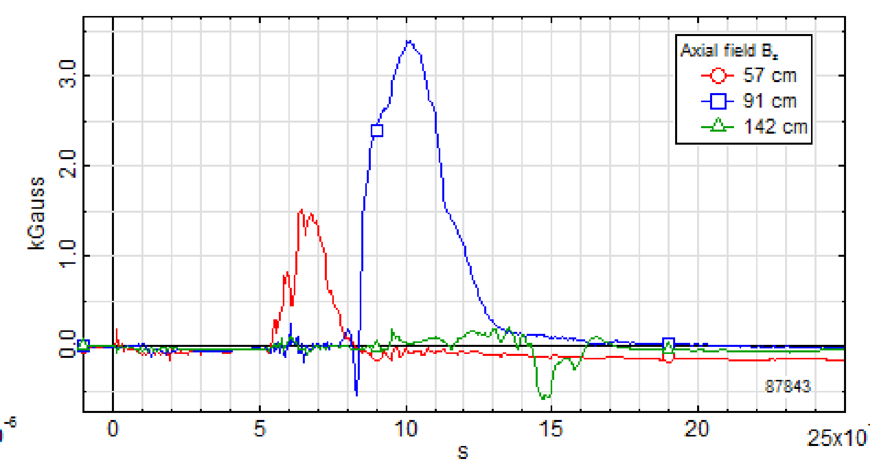
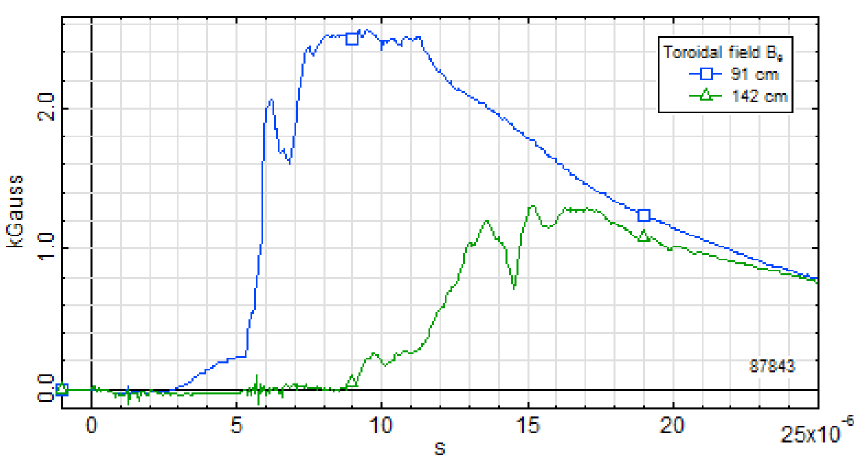
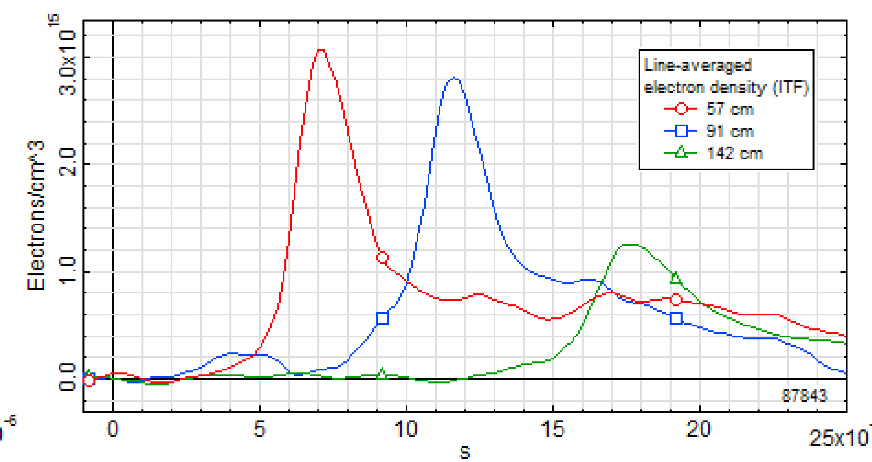
Argon gas puffed shot – high-performance









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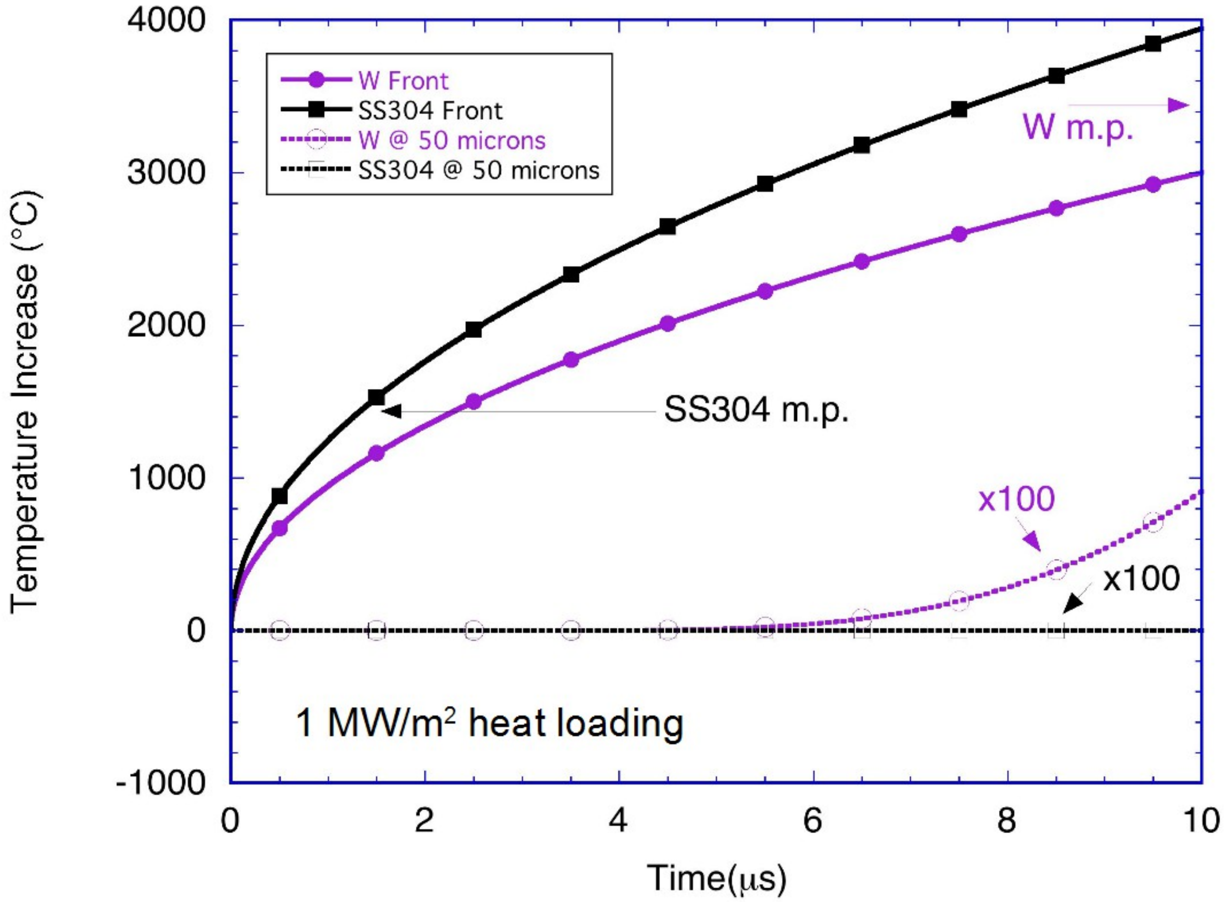
1D model shows greatly reduced electrode surface temperature change with W coating



Buchenauer et al 2013 EPR

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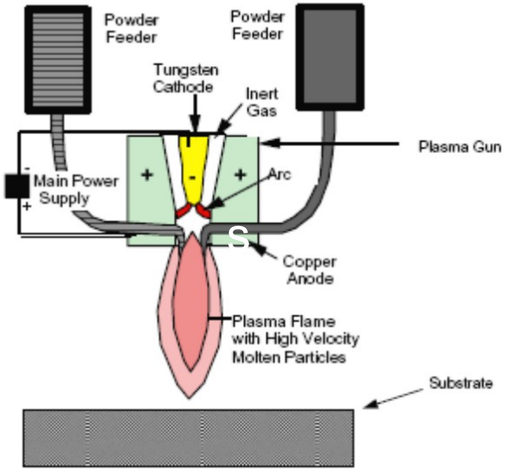
Next inner electrode has been fabricated, using vacuum deposition of tungsten



Plasma Processes Inc, Huntsville AL

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Summary of experimental results-1

- 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)

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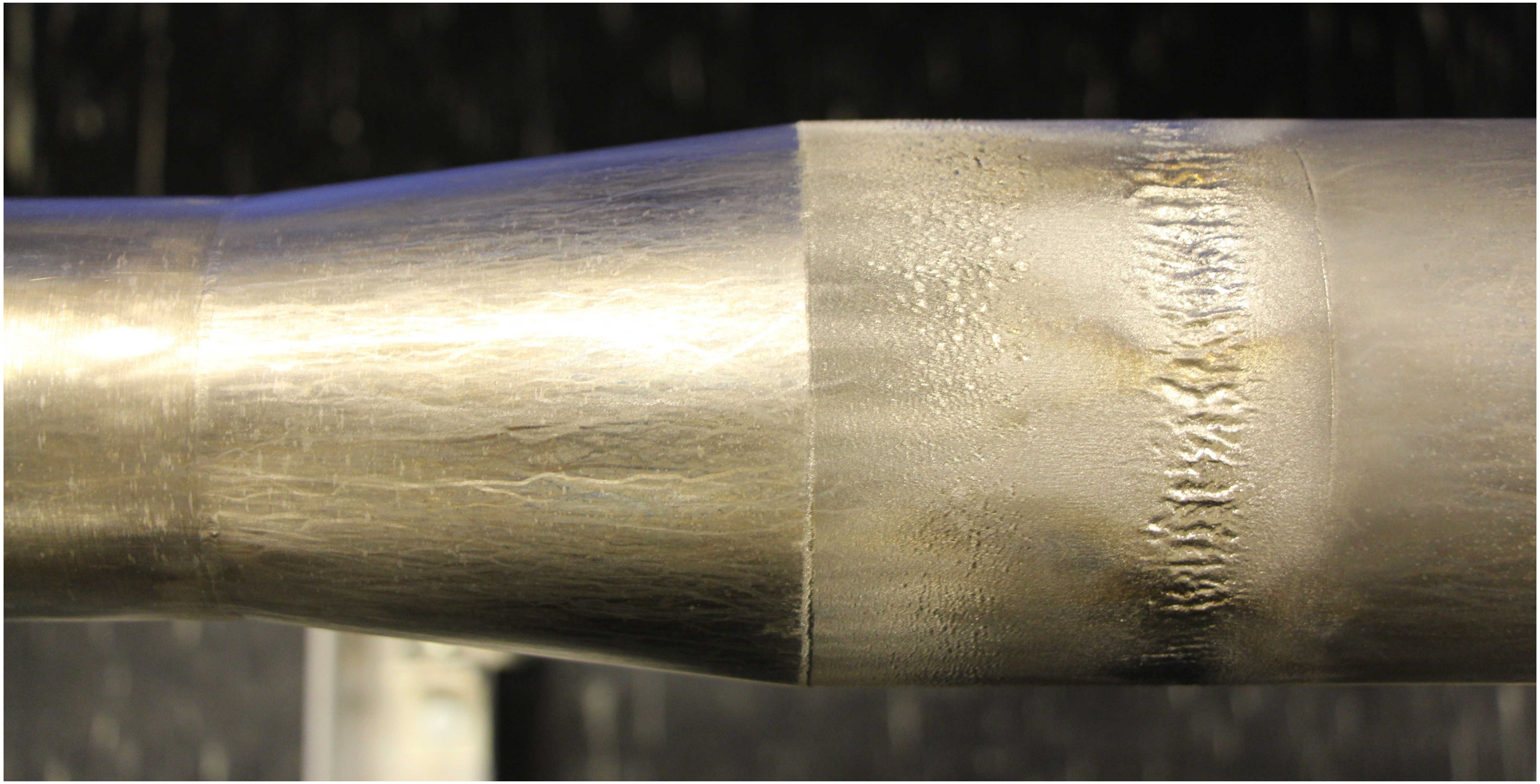
Summary of experimental results-2

- 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

Summary of experimental results-3

- Before initial W-electrode operation, β-backscattering measurements show ~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 fluoresence (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

Fe electrode after first 5000 shots



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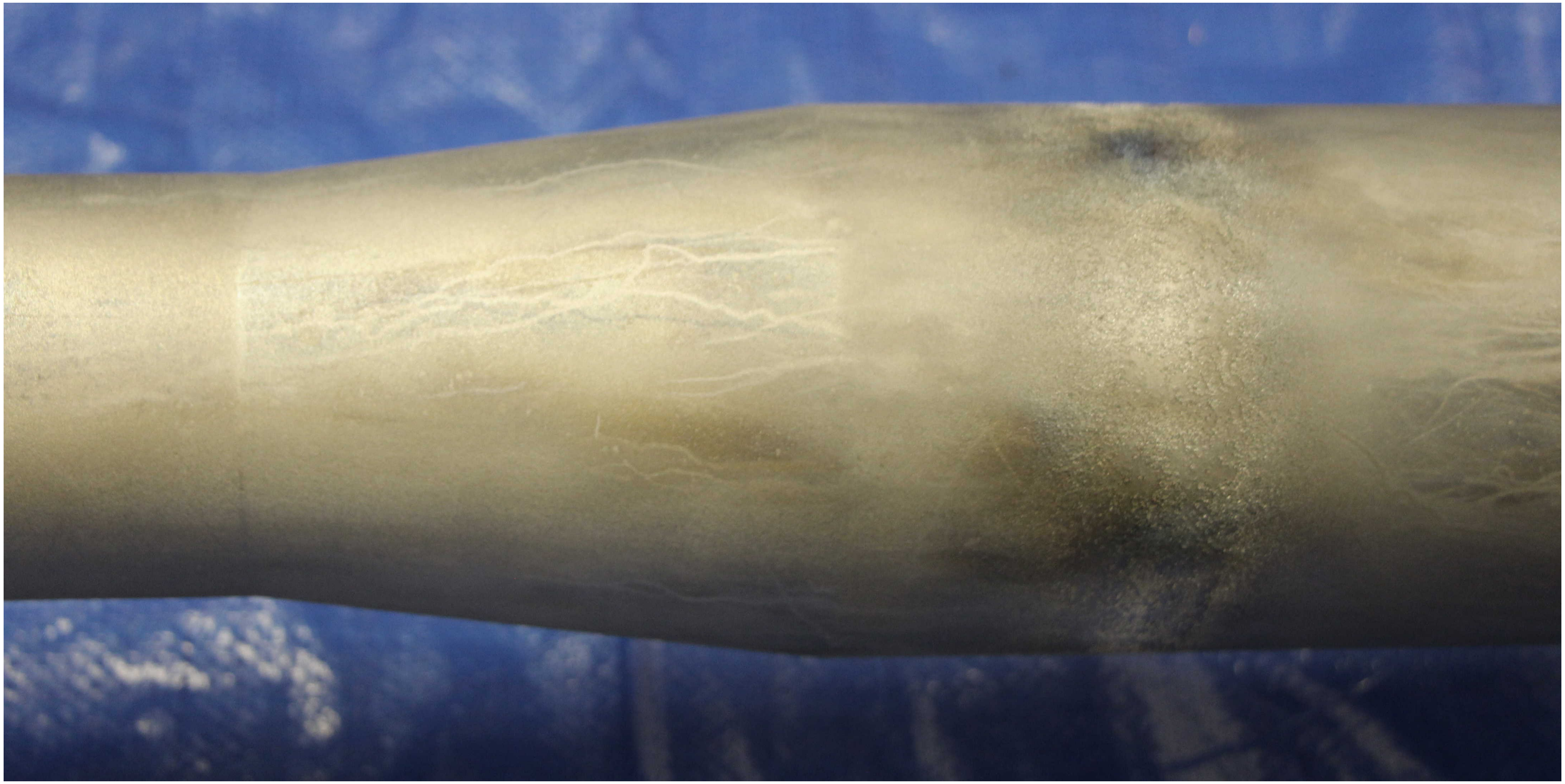
W electrode after first 5000 shots



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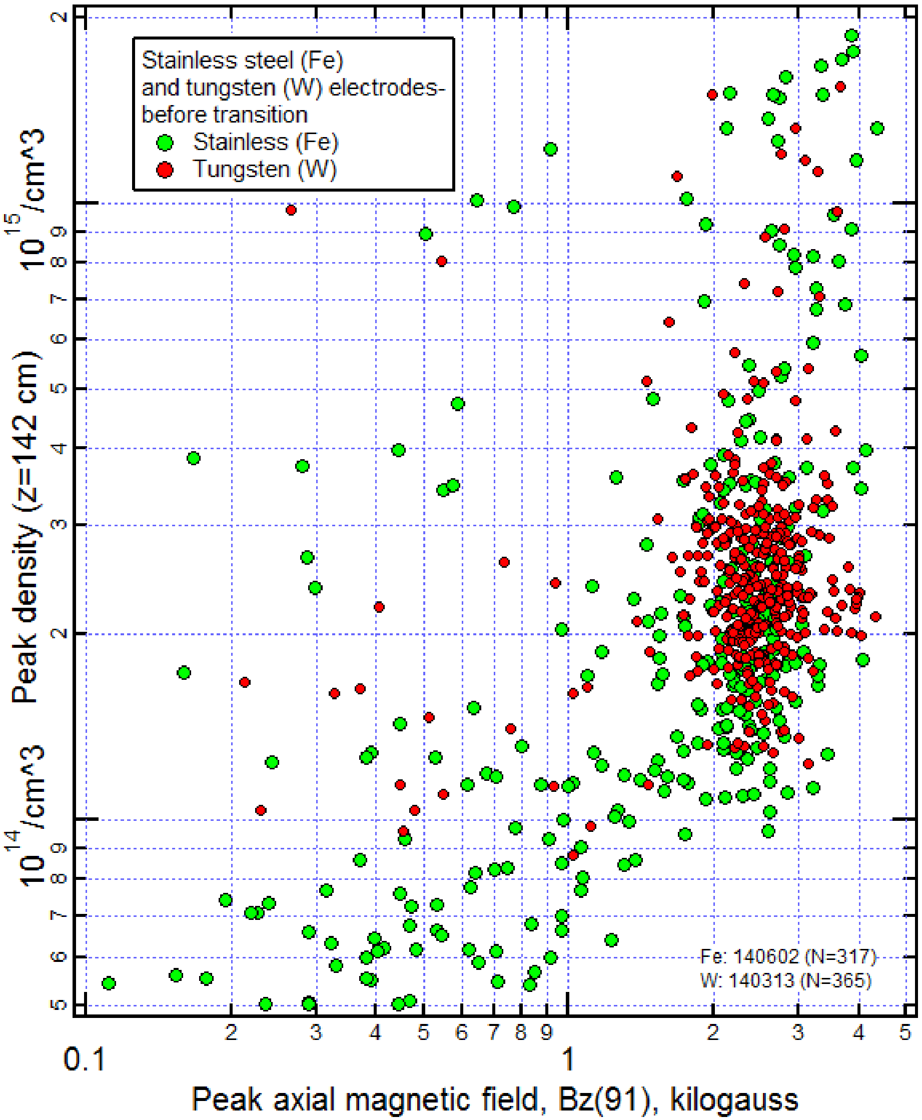
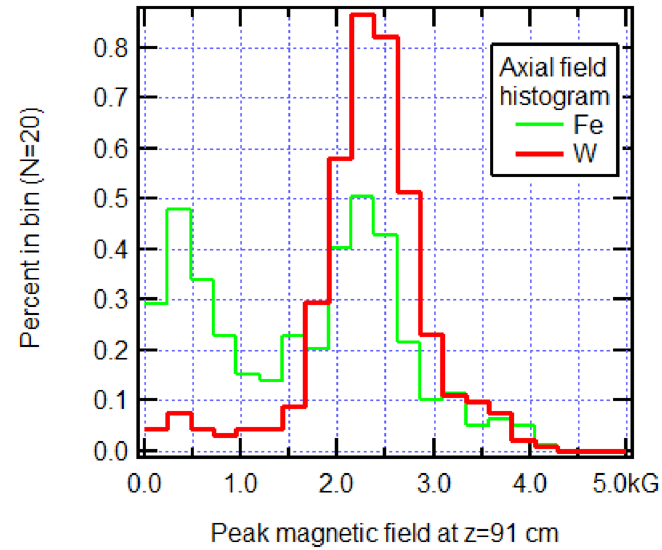
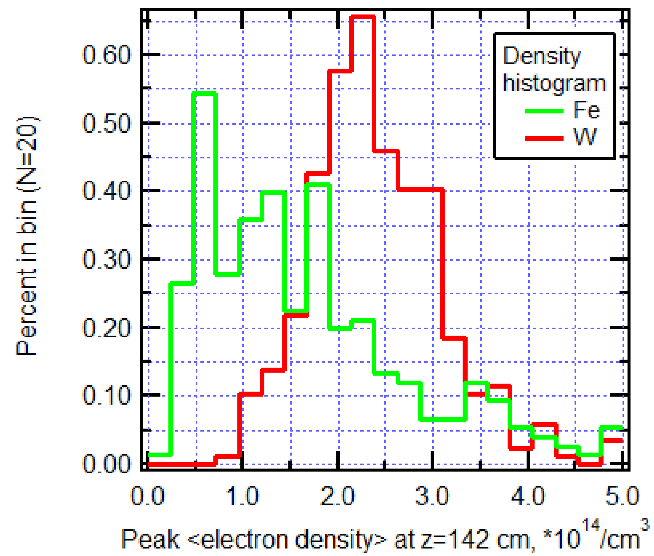
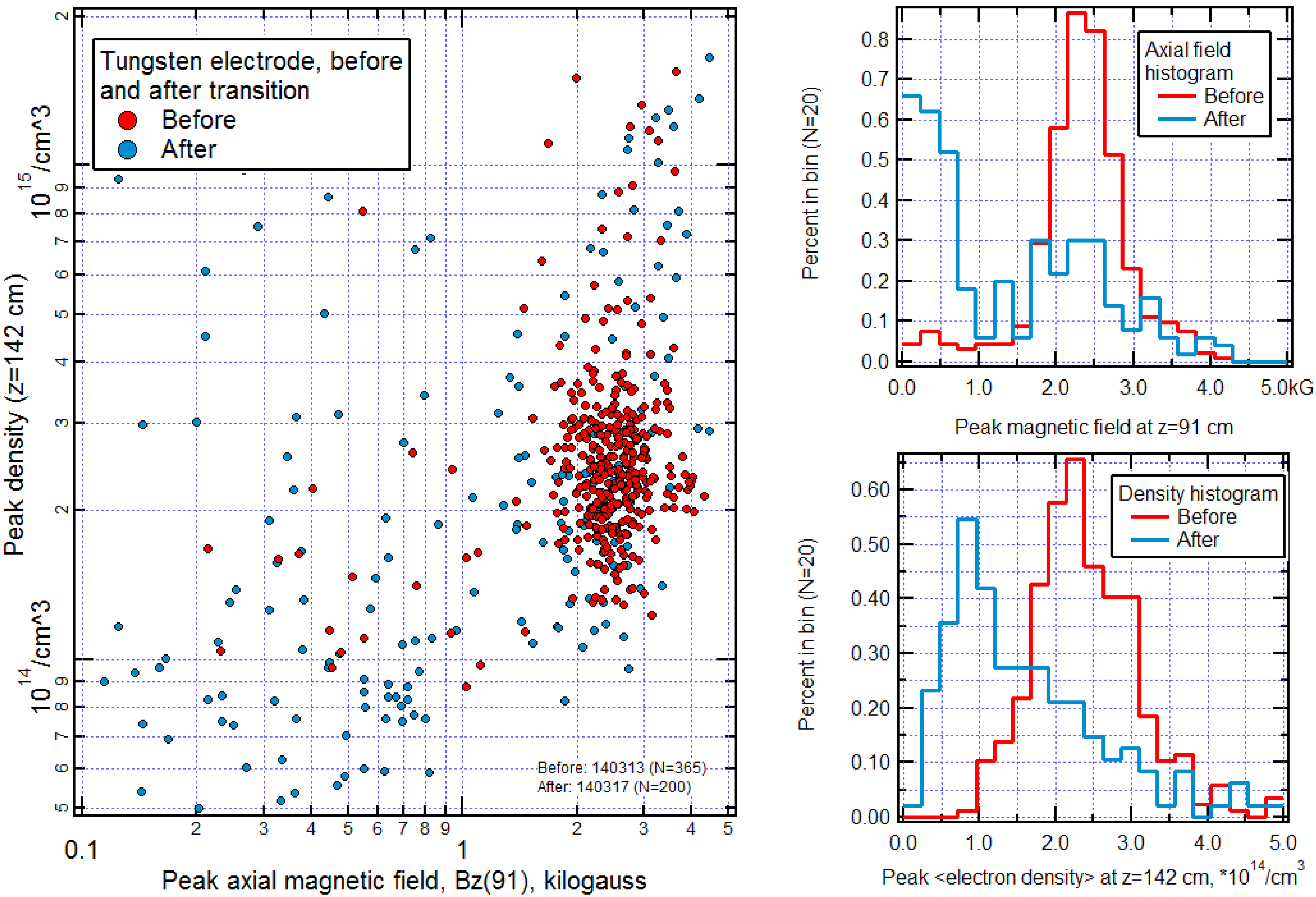
Fe-electrode vs initial W-electrode



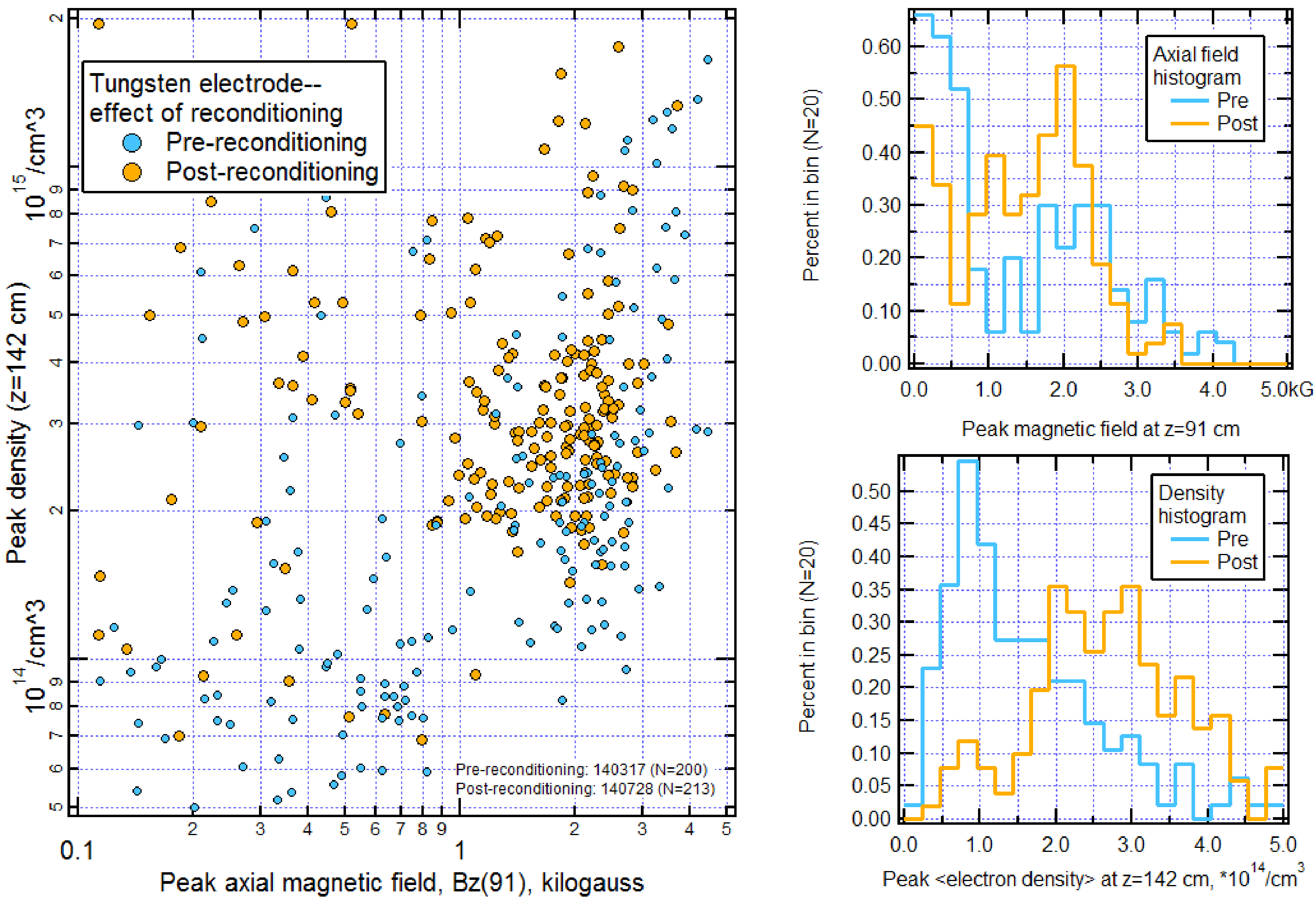




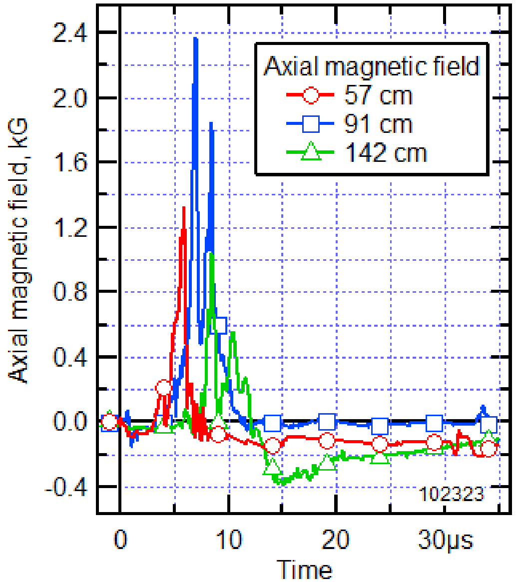
W-electrode transition

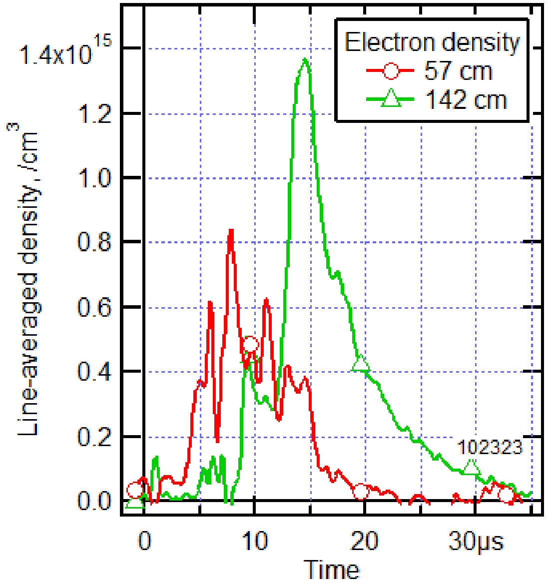


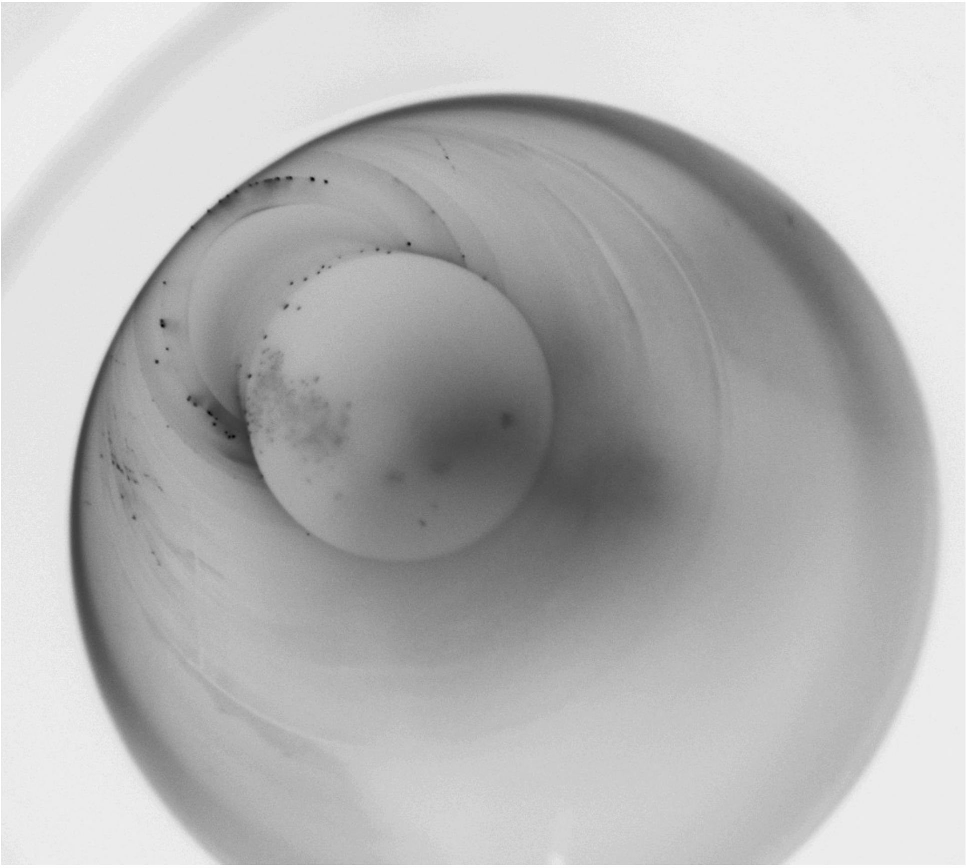
W-electrode reconditioning after transition



Good (Bz,ne) shots have dim, symmetric image

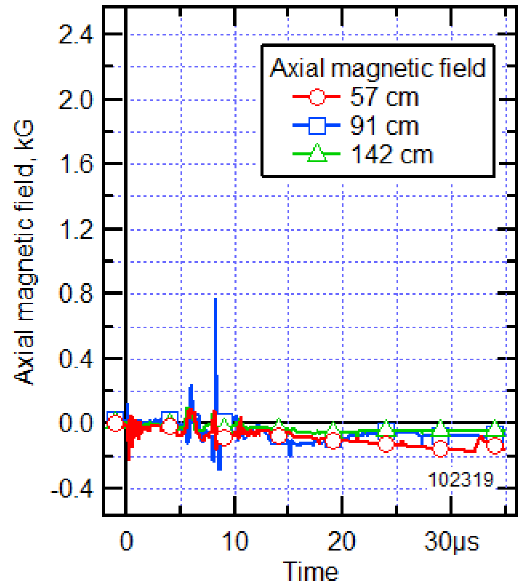


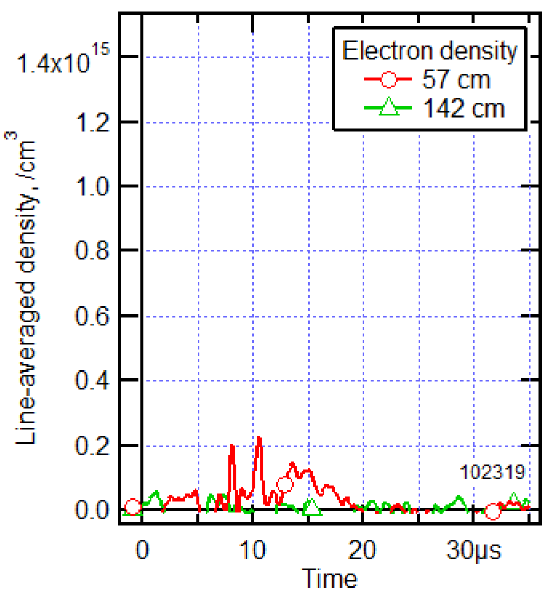




-9/9 kV form/accel, 2psig H2, no puff, Fe electrode
Inverted Cooke axial image 20140708_153102
0-20 usec

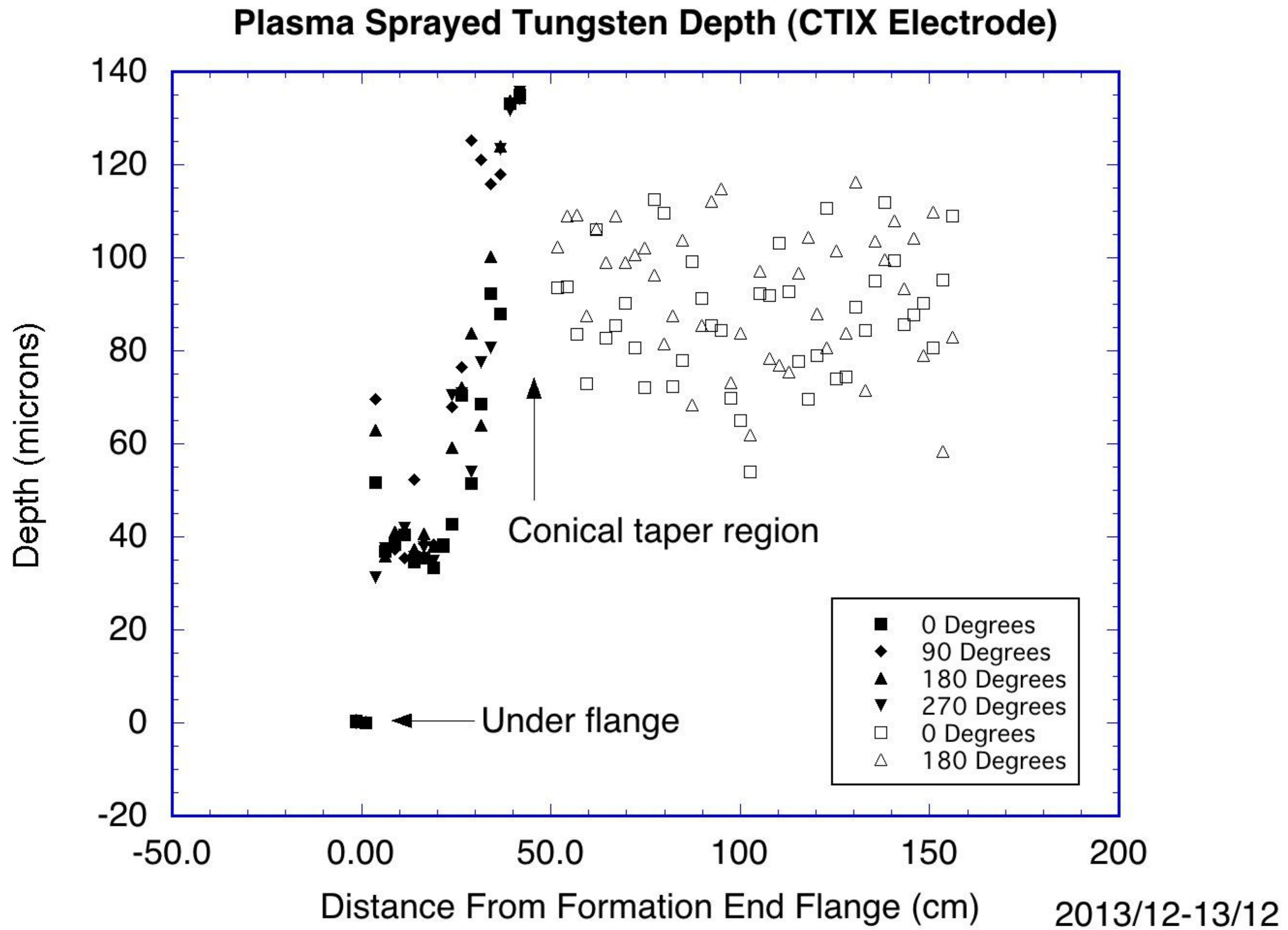
Bad (Bz,ne) shots have bright, asymmetric image





-9/9 kV form/accel, 2psig H2, no puff, Fe electrode
Inverted Cooke axial image 20140708_153102
0-20 usec

Beta Backscattering Used to Determine Tungsten Coating Thickness (Nominal value was 100 microns)



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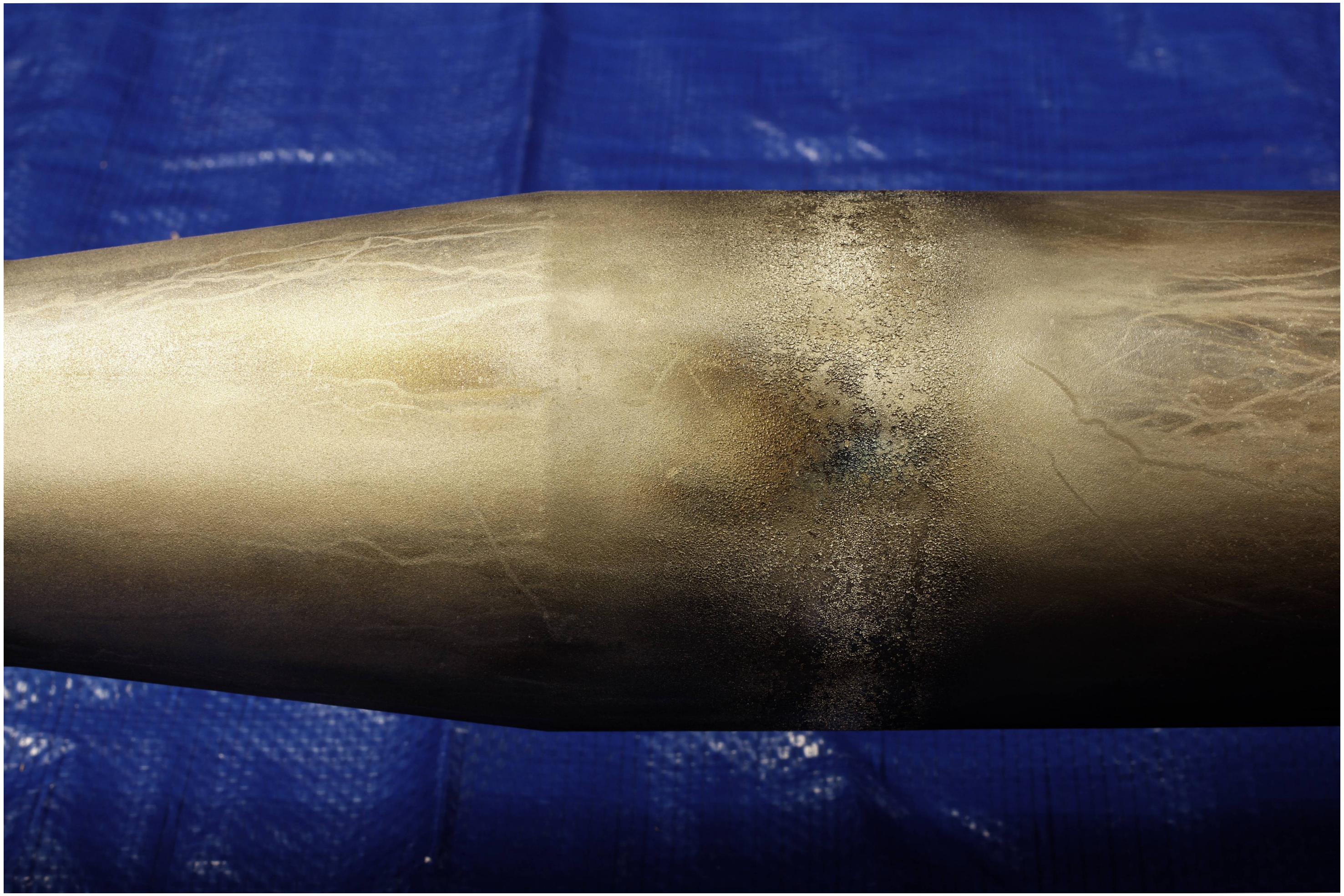
Spallation of Tungsten Coating Evident Opposite Accelerator Gap (on Outer Electrode)



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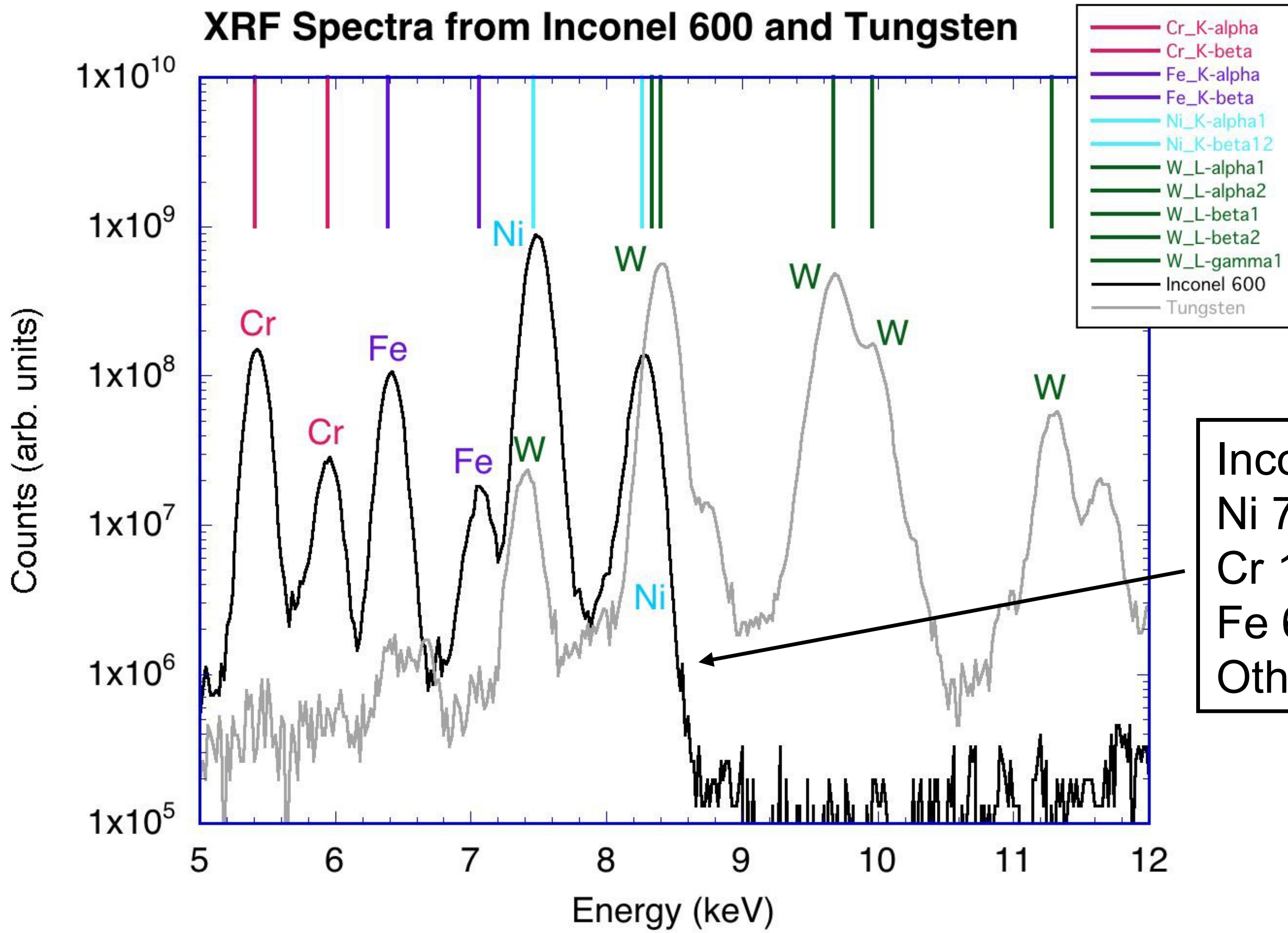
X-Ray Fluorescence Spectroscopy Used to Investigate Spallation of and Coating on the Tungsten



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

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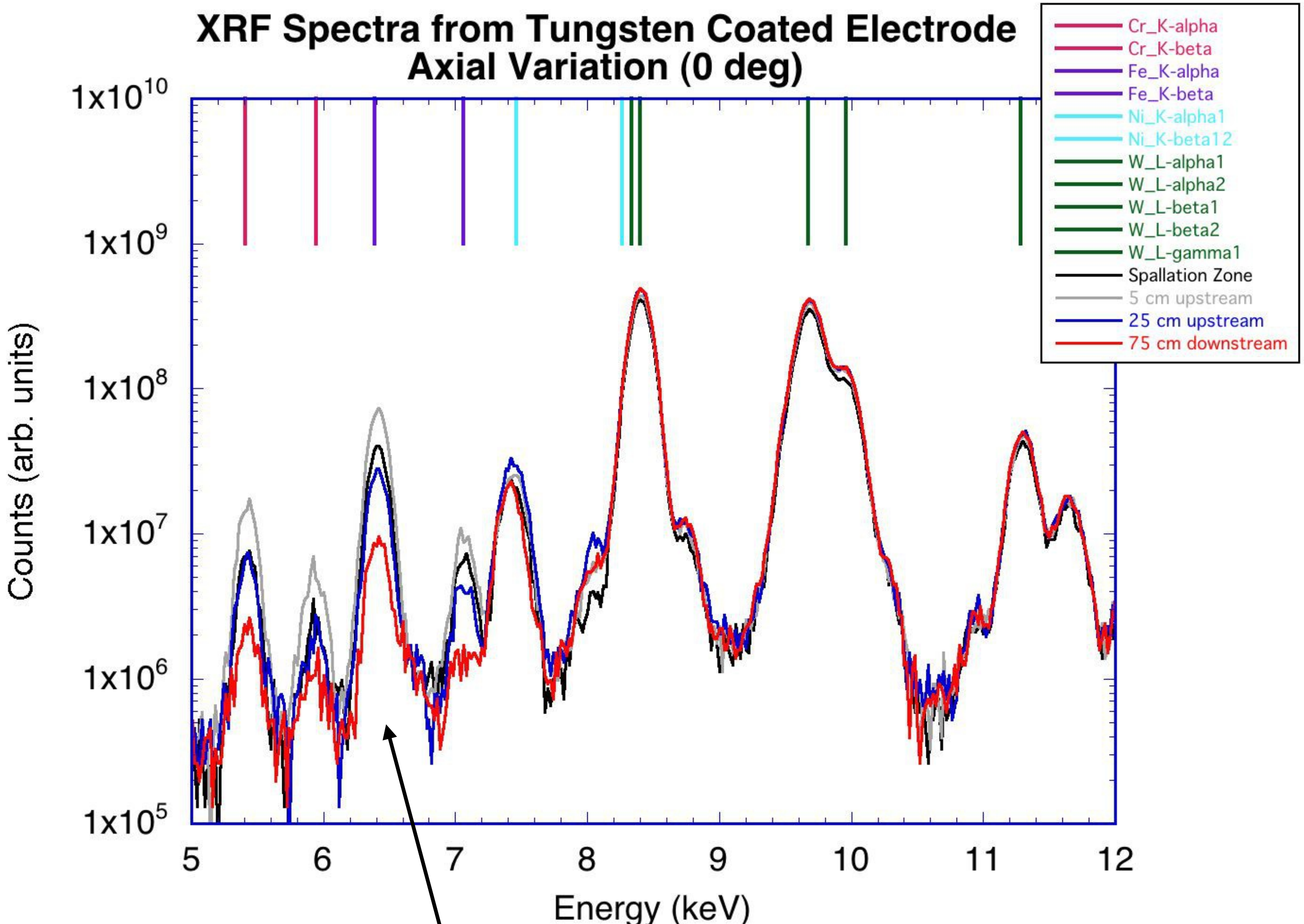
X-Rays should not penetrate beyond the tungsten coating

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

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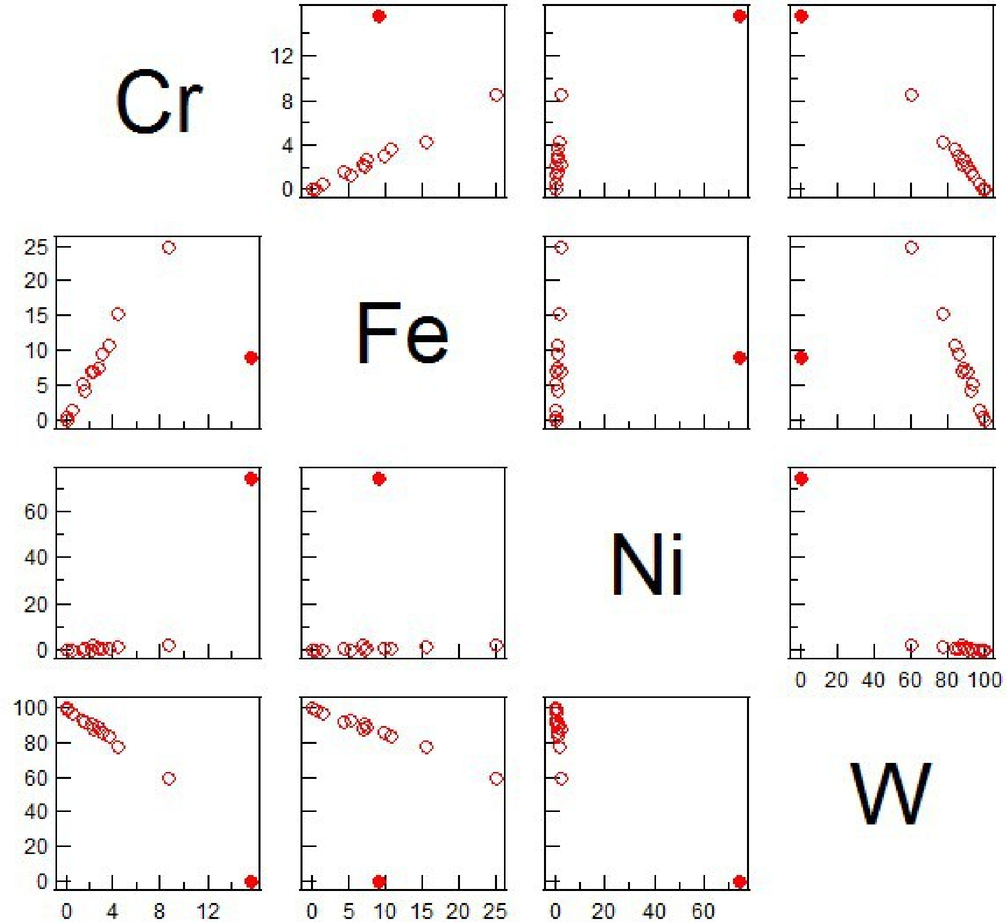
Correlation of XRF Peaks Not Consistent with Inconel 600: More Typical of Stainless Steel (Outer Electrode Material)

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

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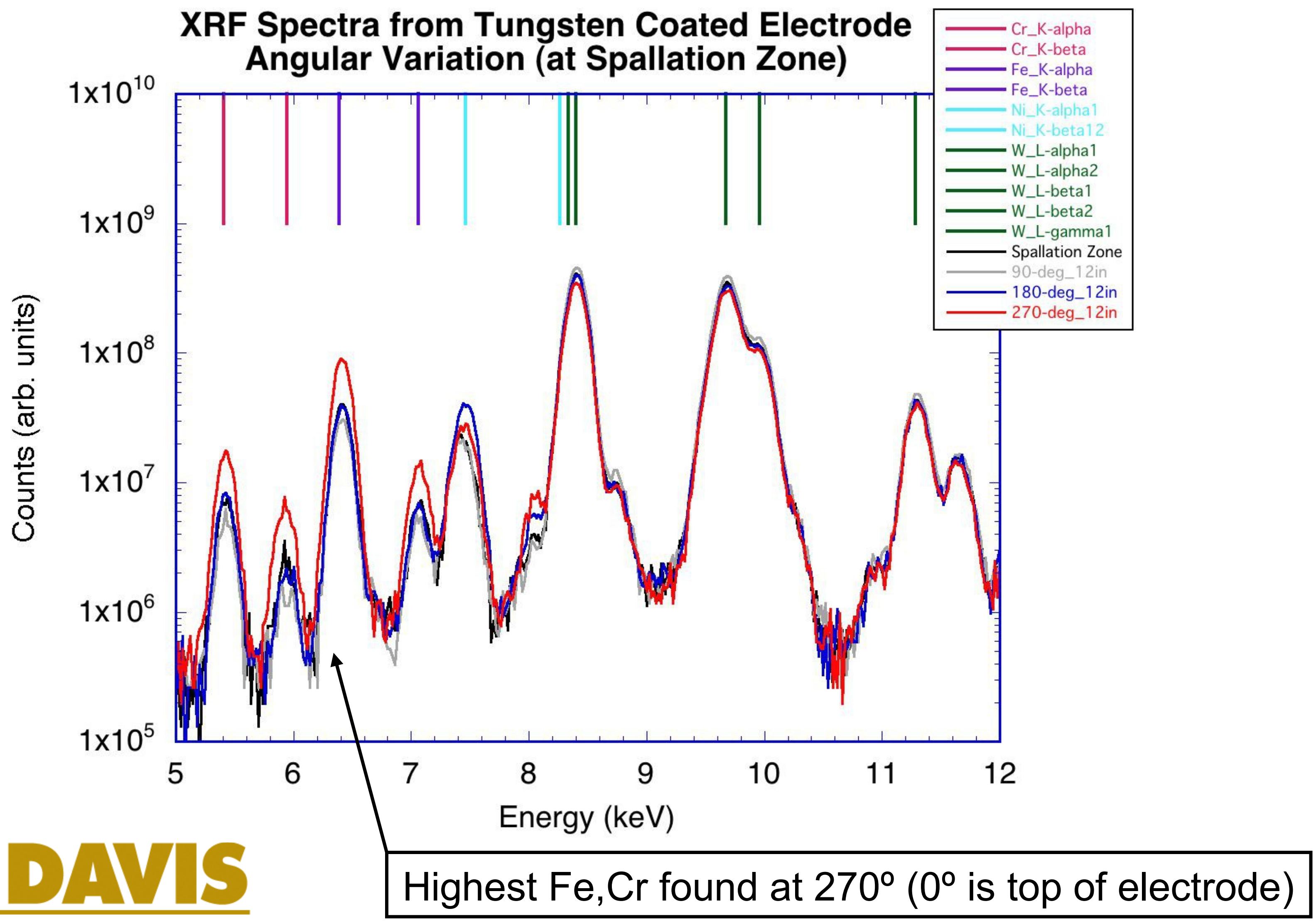
Some Angular Variation is Also Evident in XRF Measurements



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Future work

- 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
- Using improved power-handling capability of W-electrode, increase operating voltages to create CTs of higher number and kinetic energy density
- 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 chemical reconditioning of inner electrode
- Consider methods to prevent outer-electrode stainless-steel overcoating – modified outer electrode (localized W); elimination of acceleration gap by dual-capacitor drive; optimized operating conditions.

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