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Assessing the effect of *in-situ* plasma cleaning on electrode plasma formation in a 650-kA MITL

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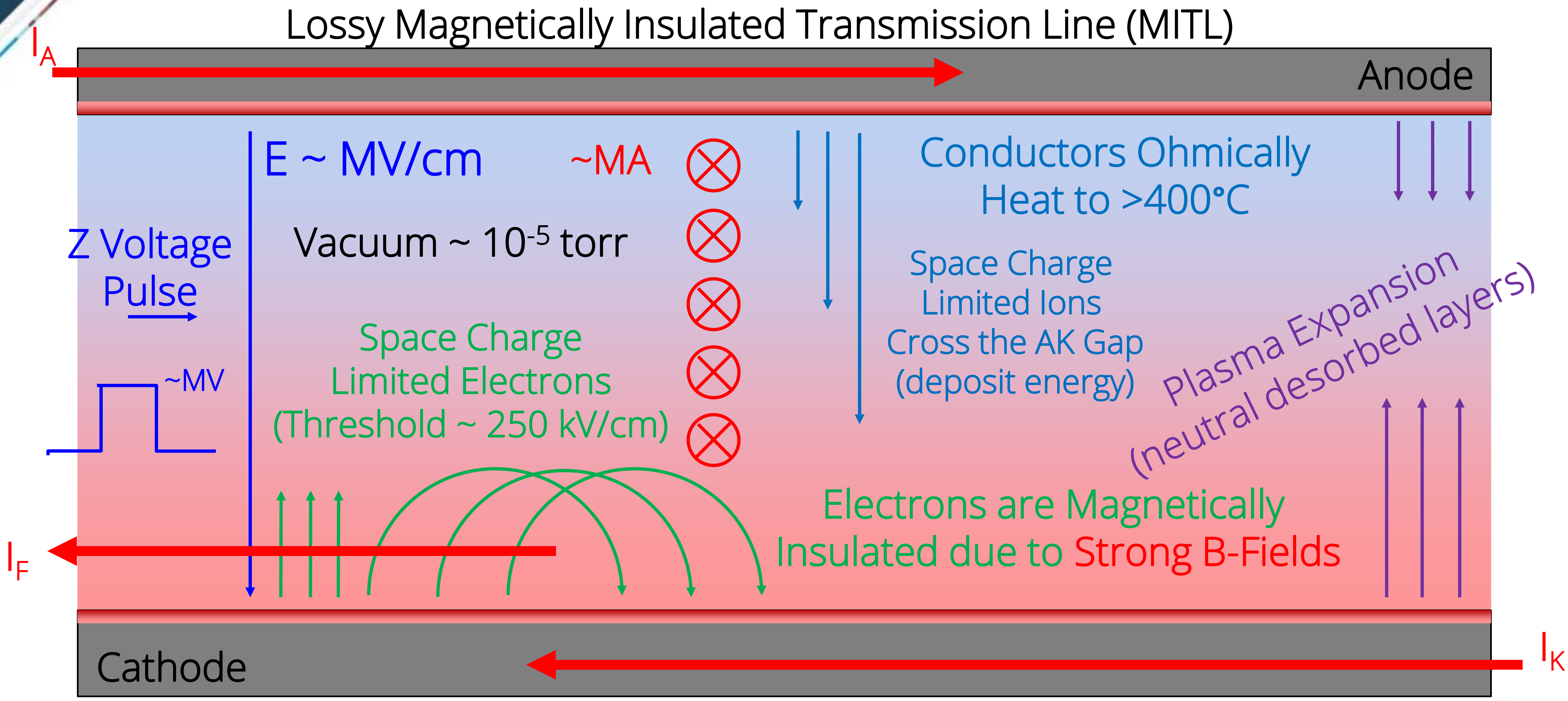
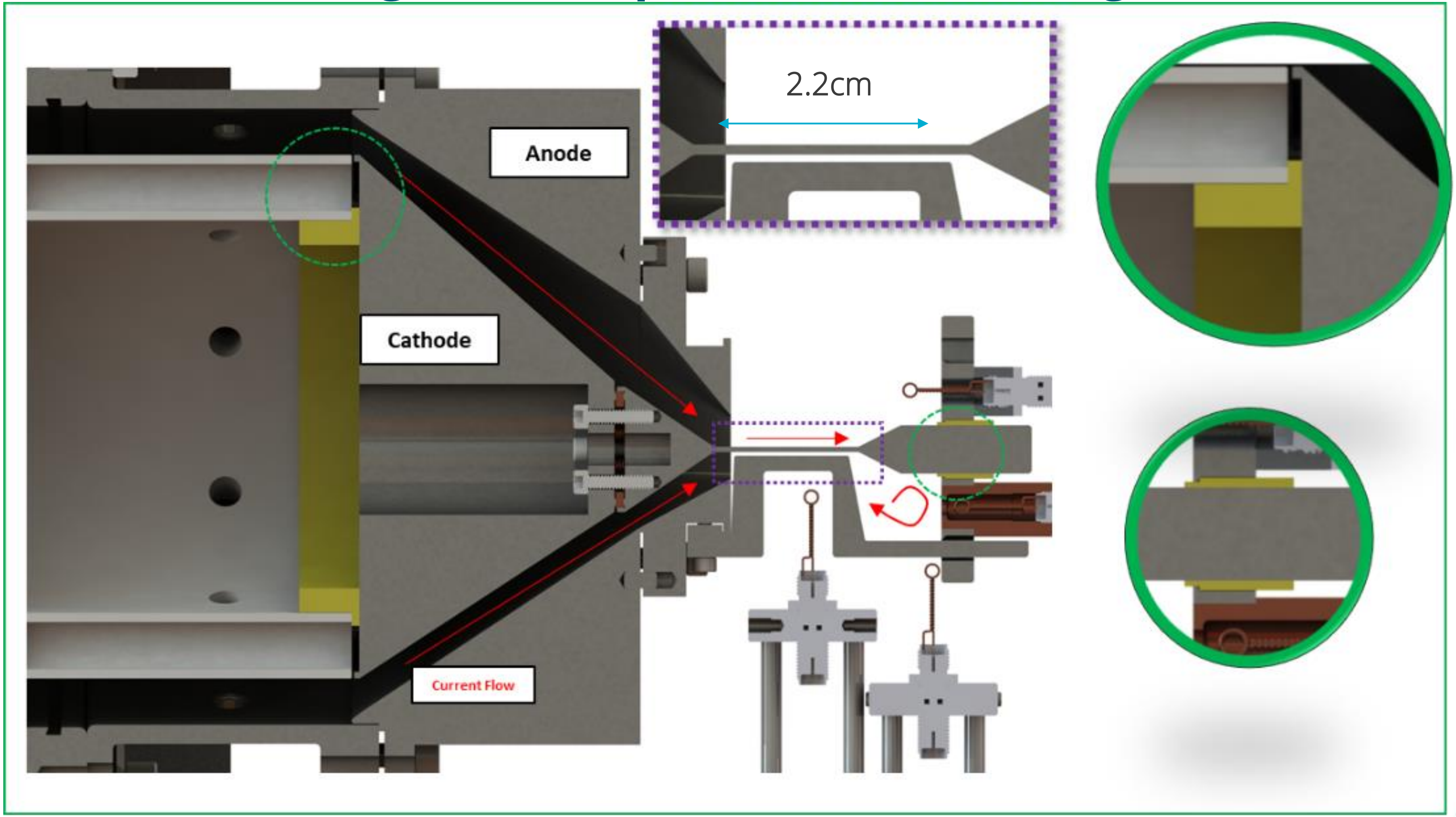
Light ion species desorbed from electrode surface contribute to Z Machine current loss



New accelerator load allows spectroscopic and imaging access to high-field experimental MITL region



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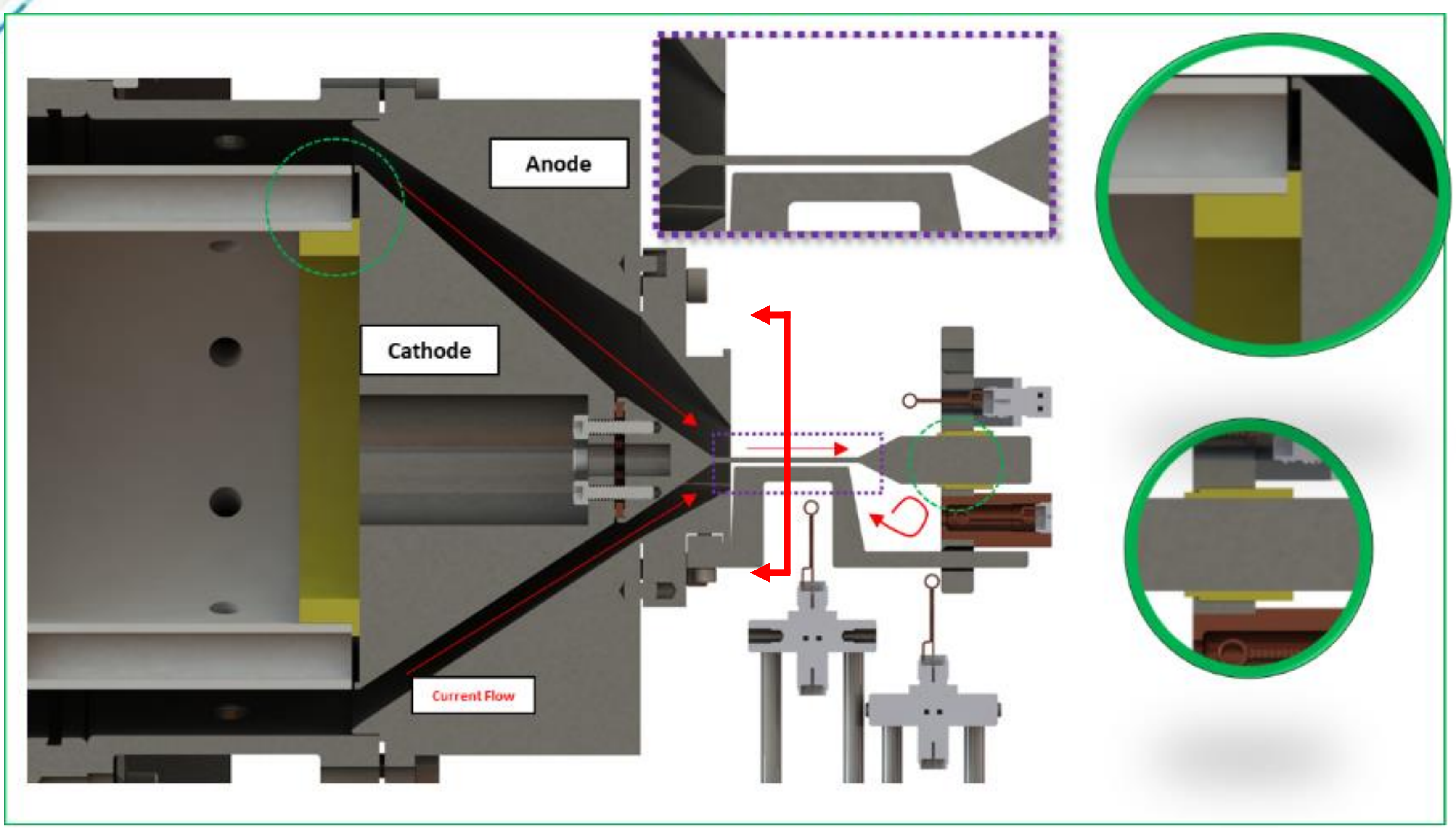
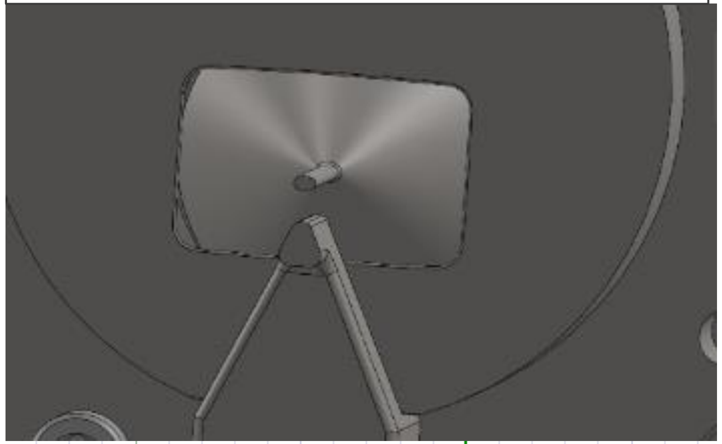
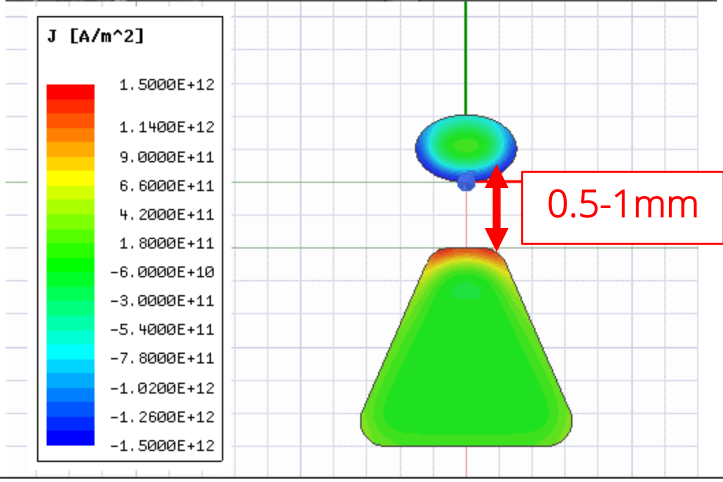


Adapting hardware modifies low-J axisymmetric current delivery into diagnosable parallel plate, high-field-stress experimental MITL region

Elliptical cathode cross-section enforces more uniform current distribution





Lineal current densities ~ 2 MA/cm, $\Delta T > 400°C$ in ~40ns

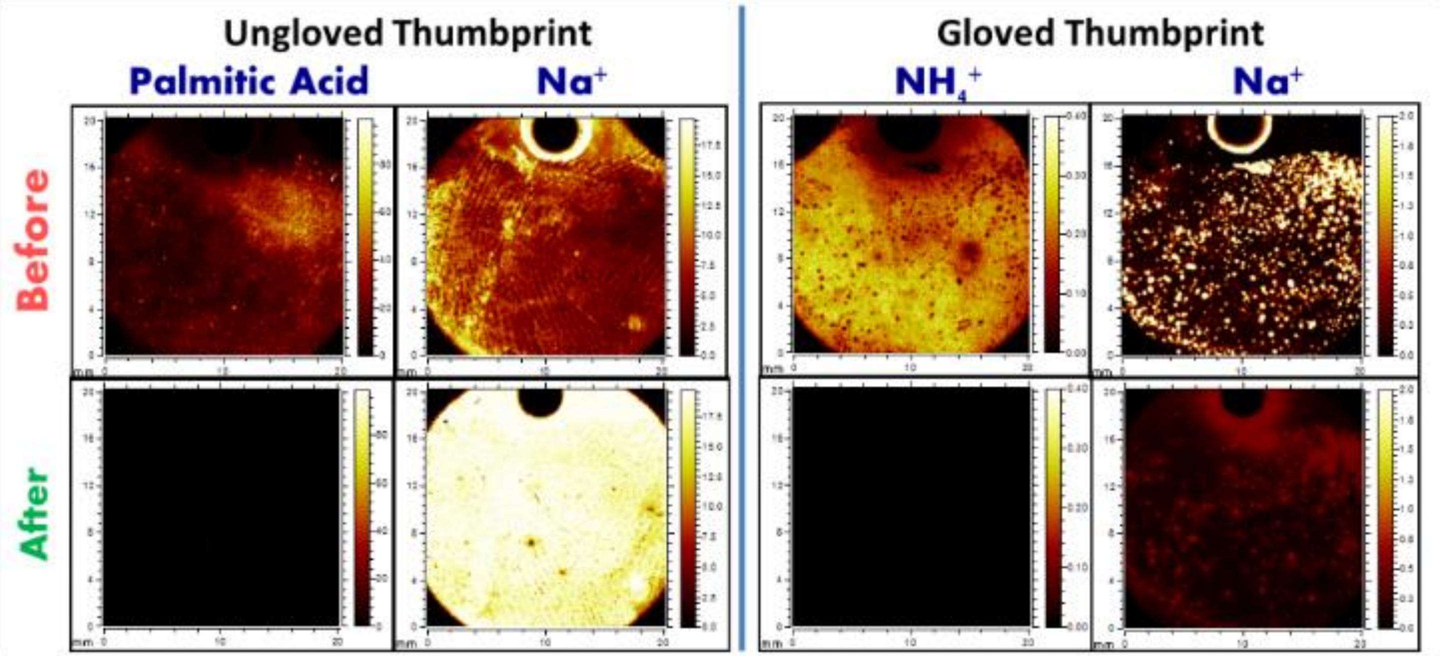
We are using an *in-situ* plasma glow discharge to remove contamination from electrode surfaces

An 80% Argon, 20% oxygen process gas is used.

- Argon ions sputter lightly-bound contaminants into the gap (H_20, H_2, C_xH_y, etc.)
- Oxygen ions chemically react with sputtered contaminants and are pumped out

We have developed an audio-frequency square wave (ASW) excitation on the accelerator electrodes themselves to ignite glow discharge

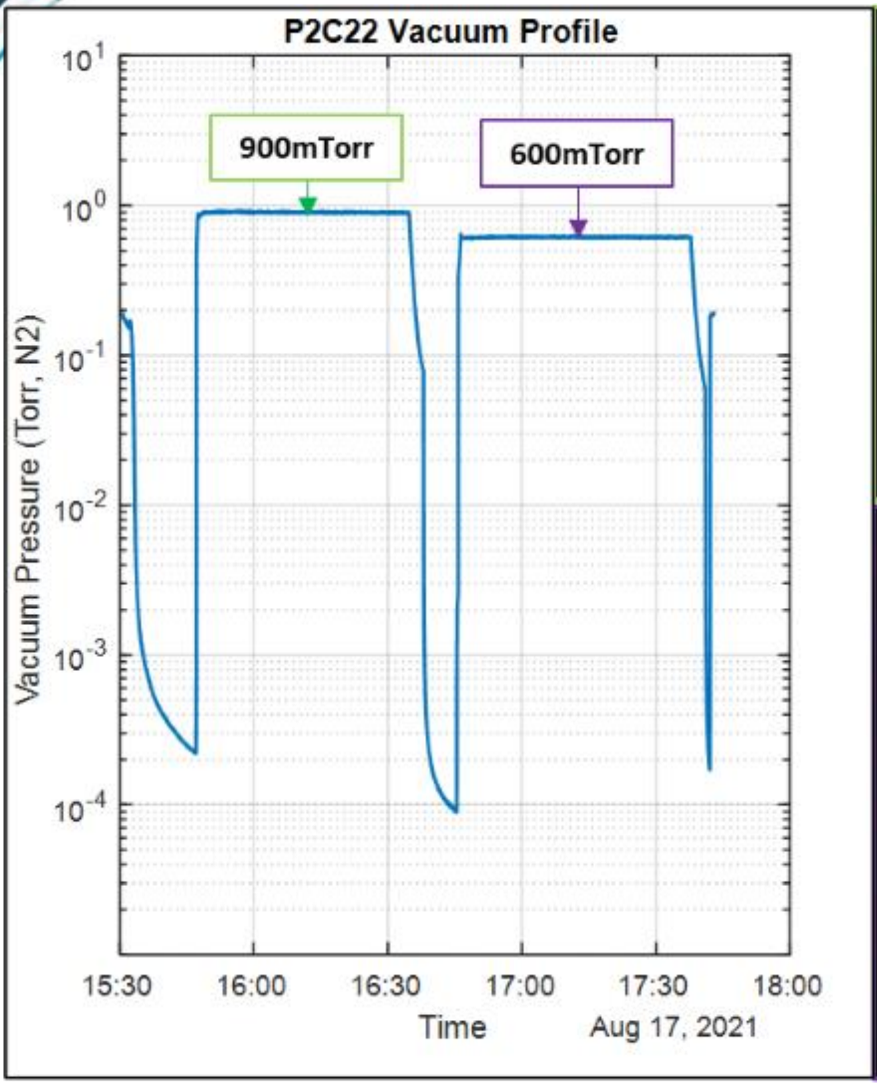
- Switching frequency ~ 10-25 kHz
- Background gas pressures ~ 0.1 – 1 Torr
- Effective AK gap cleaning ~ 0.1 - 1 cm
- +/- 1kV, up to 600W switch potential of MITL cathode
- Electrical insulators are used to localize cleaning plasma in the MITL regions with highest power density
  - Only clean the surfaces where losses occur

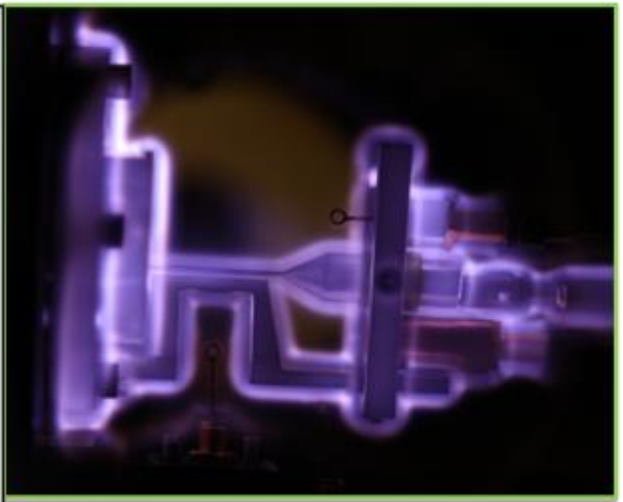


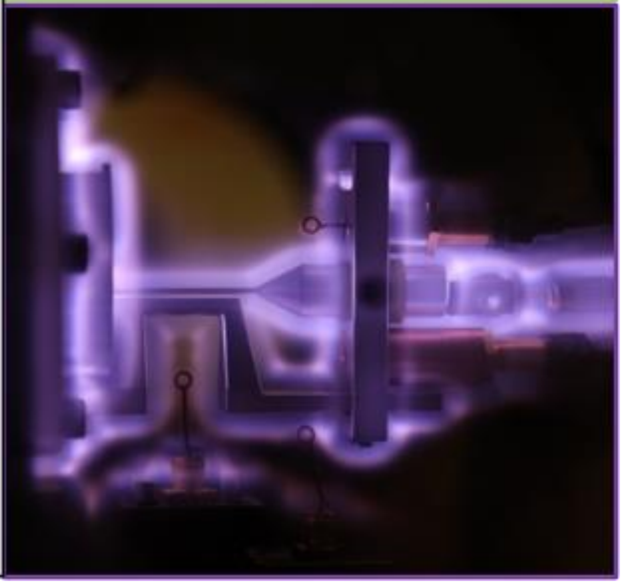
Ten minutes of argon-oxygen plasma cleaning process removes light molecules, exposes metal ions to surface-sensitive TOF-SIMS measurement technique.

Thanks to R. Tang, T. Ohlhausen, R. Sorensen, and many others at Sandia for work developing ASW and characterizing its effectiveness

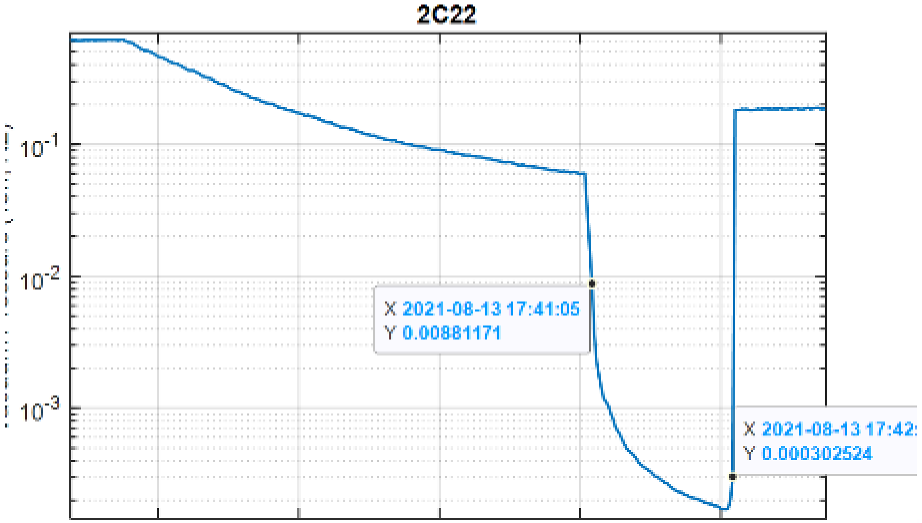
The *in-situ* cleaning process is performed under vacuum before the accelerator downline shot







- Chamber pumped to 1e-04 Torr
- 80/20 Ar/O_2 introduced to backfill to 900mTorr
- 75mA (25W) discharge for 45 min
- Pumped out.
- Refilled to 600mTorr.
- 75mA (25W) discharge for 45 min
- Stop gas flow, open gate valve, charge, fire



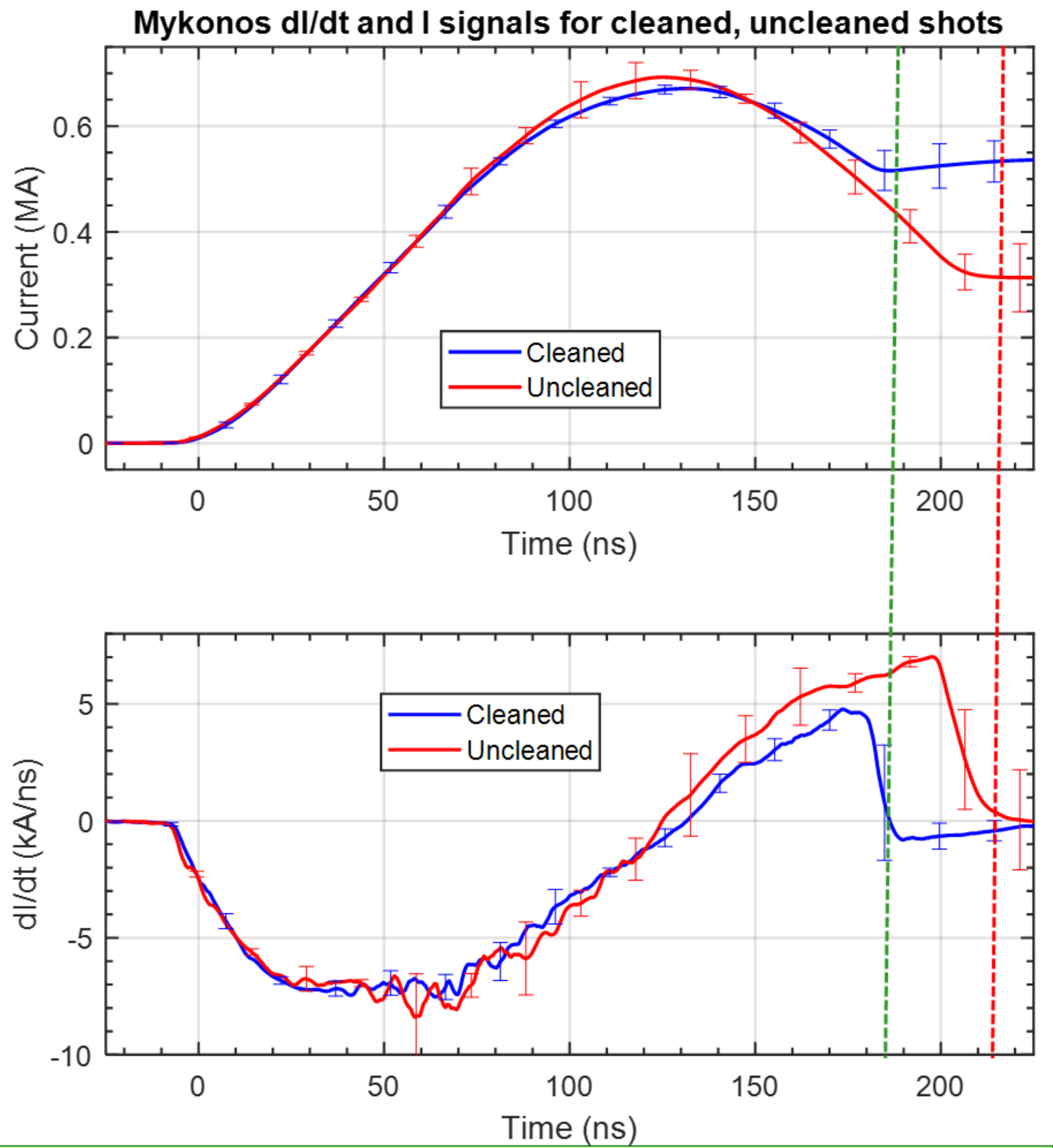
Machine is typically fired within 60 seconds of extinguishing plasma

Electrical diagnostics infer reduced electrode plasma accumulation in load region for cleaned experiments

We assert that *in-situ* cleaning delays electrode plasma turn-on and reduces accumulation of plasma densities sufficient to affect impedance

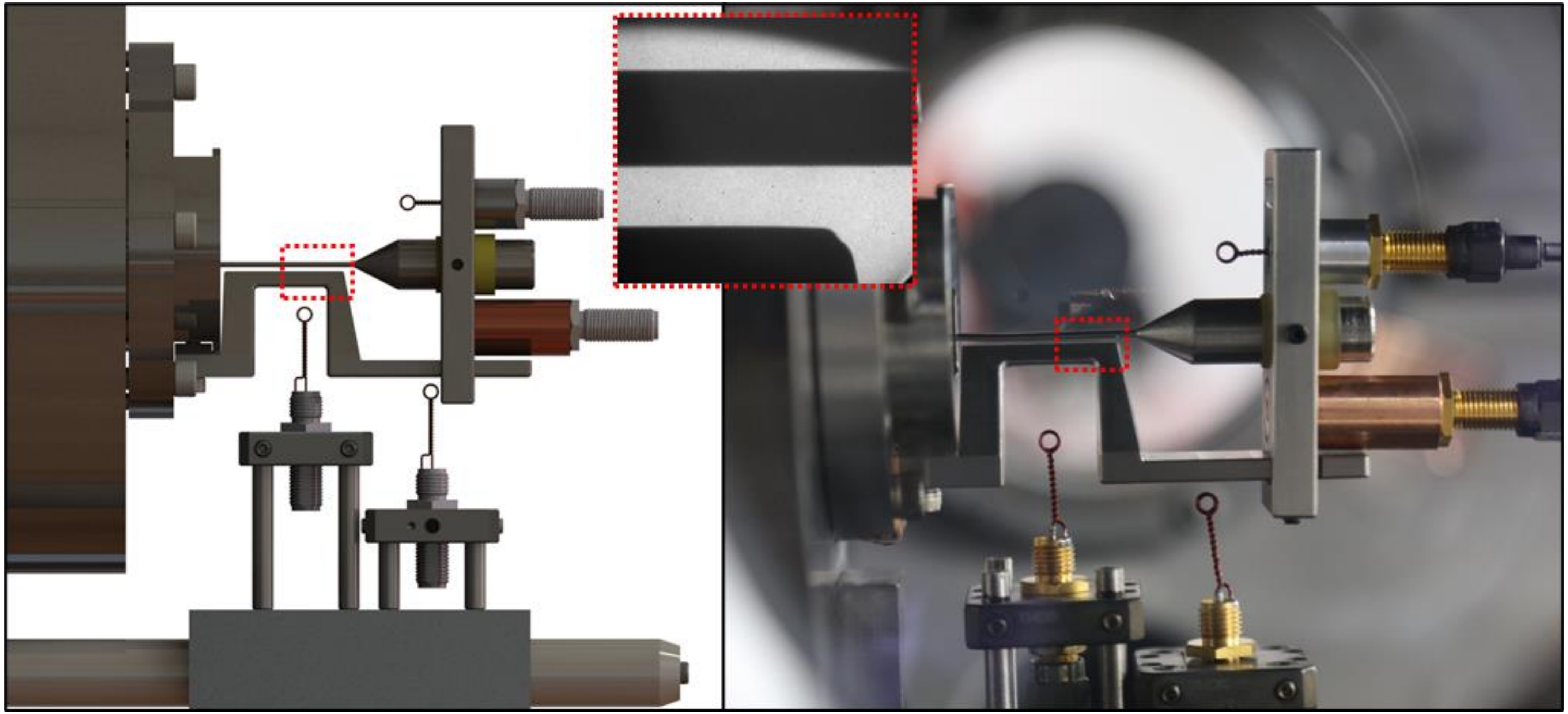
- Delayed expansion of dense electrode plasma maintains vacuum MITL impedance longer into the pulse
- Accelerator voltage reverses "on time" if the load impedance is not collapsing from this plasma effect
- Upstream water-vacuum insulator flashes over with voltage reversal, gives characteristic drop in dI/dt

We report that voltage reversal occurs ~25 ns earlier on cleaned experiments with MITL AK spacing ~ 0.75mm.



Subset of Mykonos experiments with AK spacing of 0.67-0.81mm shows ~27 ns delay from in voltage reversal "crowbarring" of load region

Parallel plate MITL enables gated imaging system to observe self-emission from electrode plasma

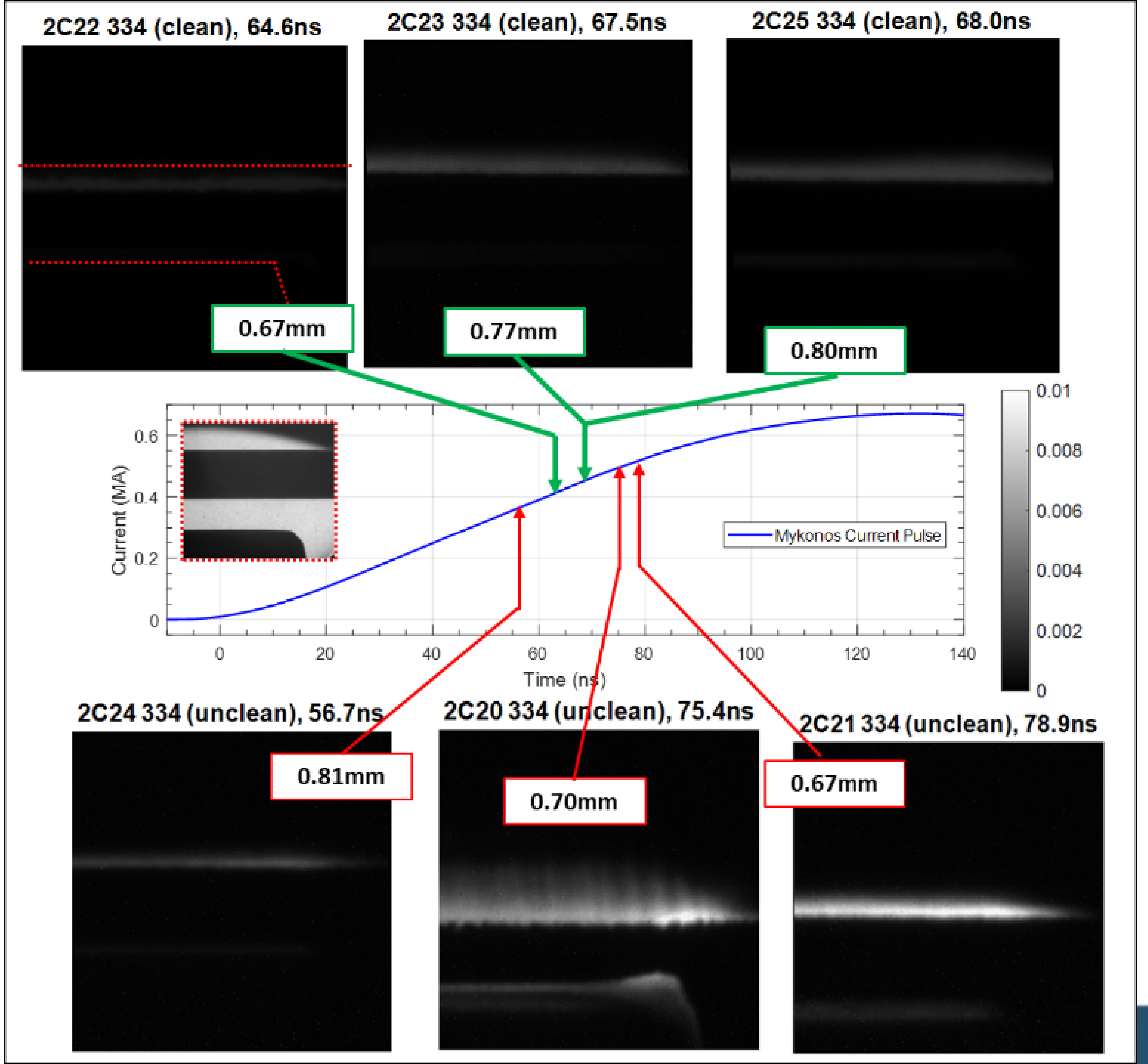


Side-view of an 0.5mm AK spacing, 2.1 MA/cm experiment. **Inset is the backlit magnfication-4 field of view**, for one ICCD; the cathode and the bend of the anode knee are visible. Power flows to the right in all images.

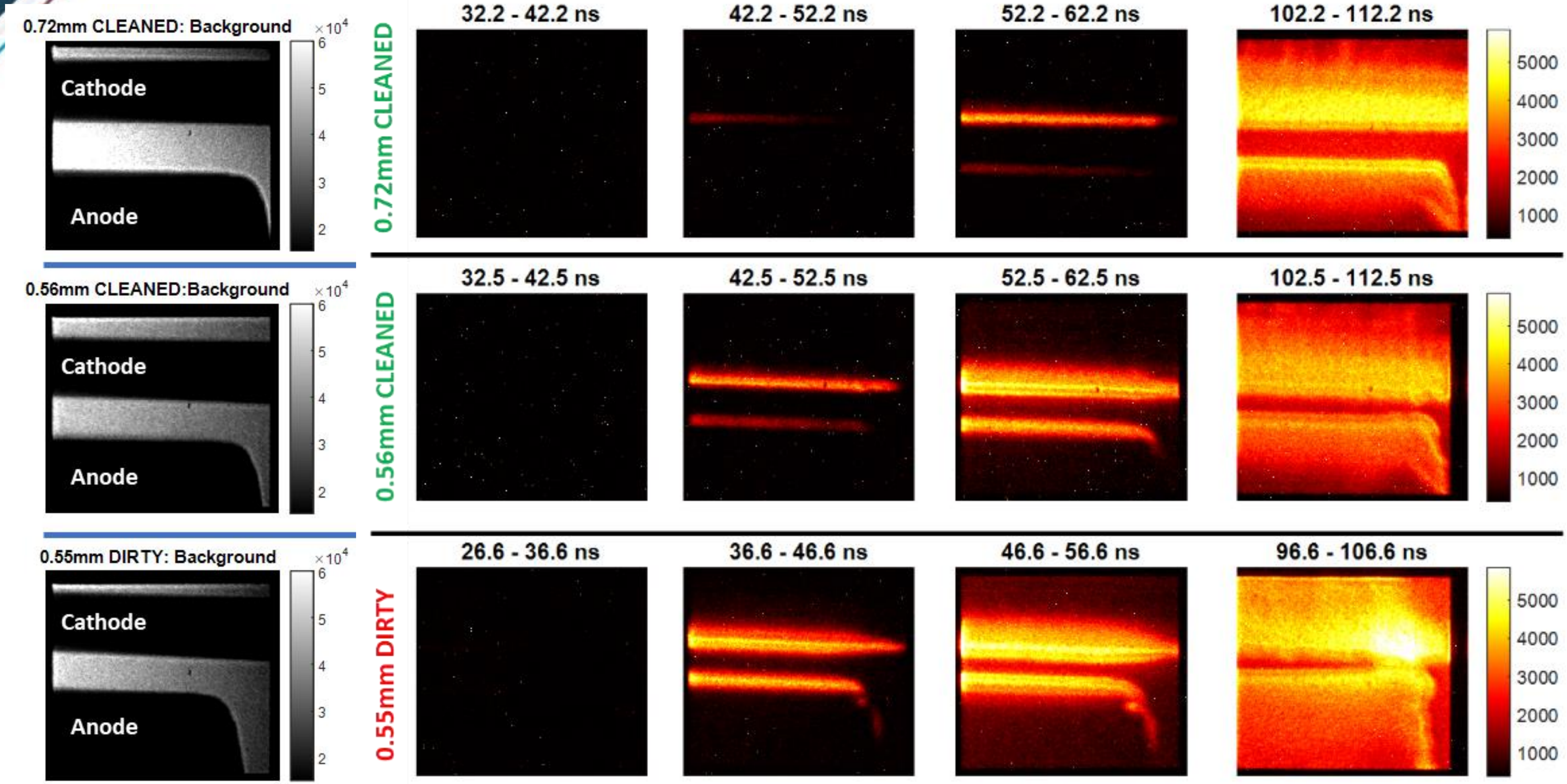
Gated images show cleaning delays electrode plasma self emission

Shots with *in-situ* cleaning observe <u>3-5X reduction</u> in intensity compared to uncleaned shots

- Data shown on same intensity colorbar
- Machine jitter prevented closely time-aligned comparisons between shots
- Images shown are for AK spacing ~0.7-0.8mm
- We observe strong variation in plasma formation and instability growth rates with changes in AK gap spacing

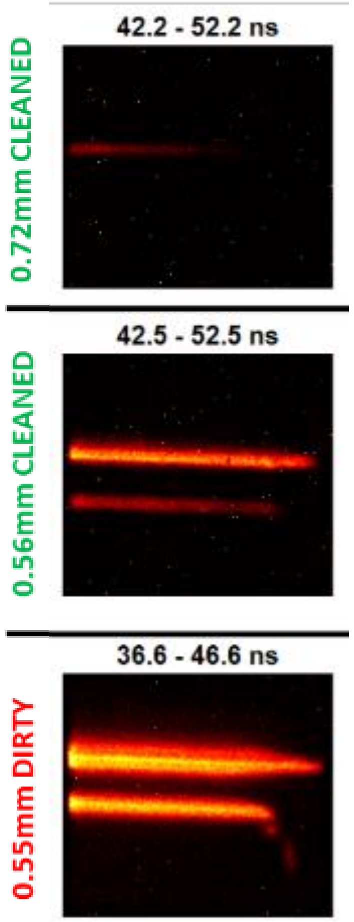


Fast framing camera data shows *in-situ* plasma cleaning delays self emission and apparent gap closure of 0.55mm MITL AK gap

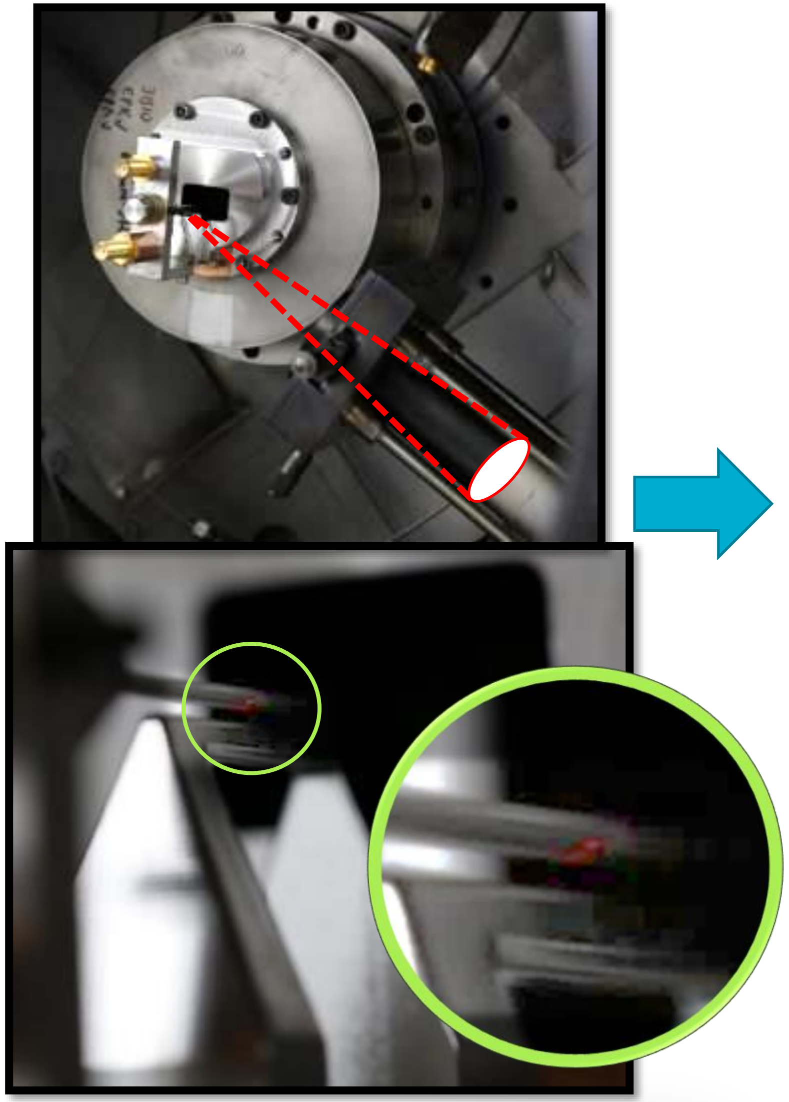


12 frames, 10-ns exposure, zero interframe delay – 120ns total record length

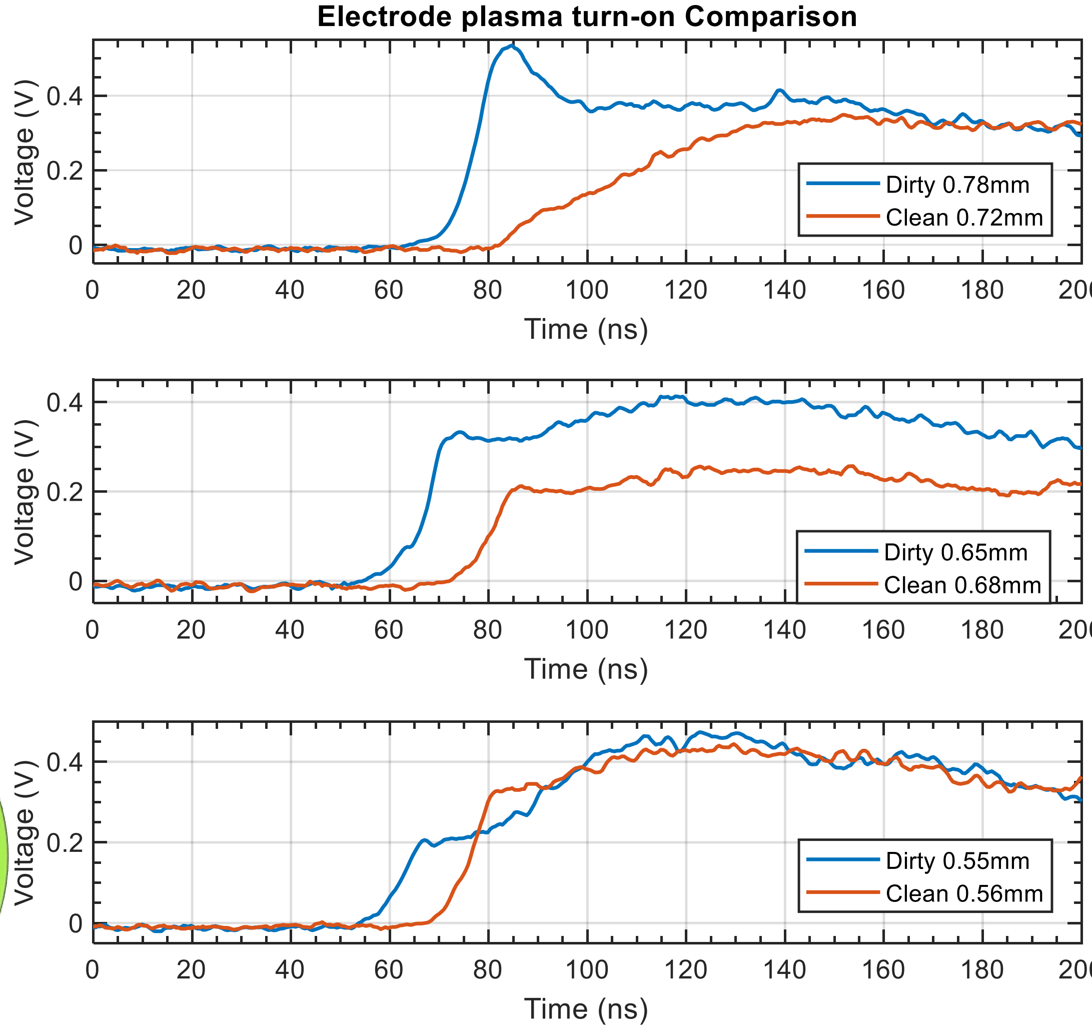
Filtered avalanche photodiodes observe 12-15ns delay in electrode plasma emission on cleaned experiments.



10-ns exposures result in ambiguous estimates of turn-on time …

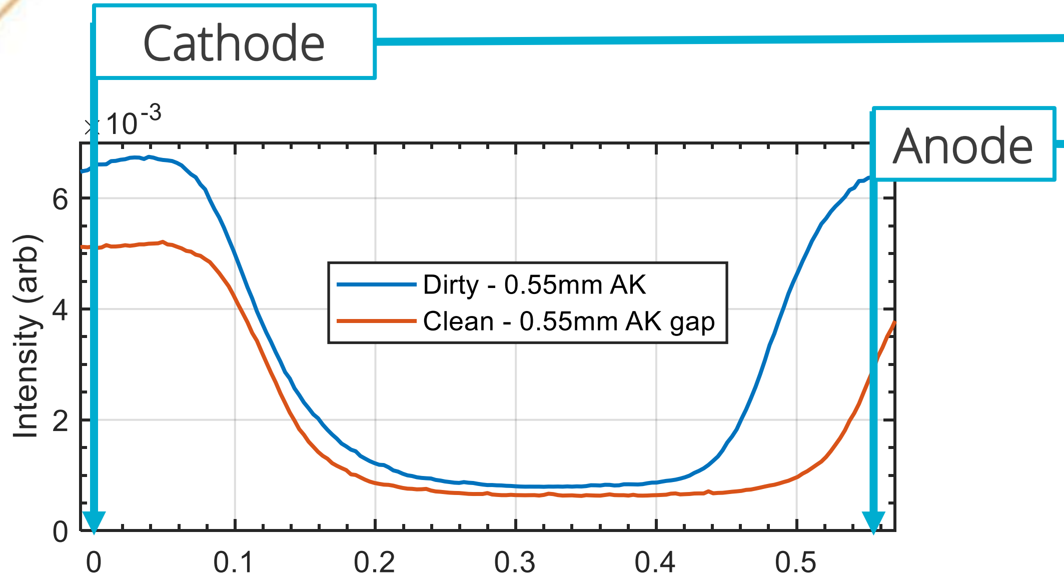


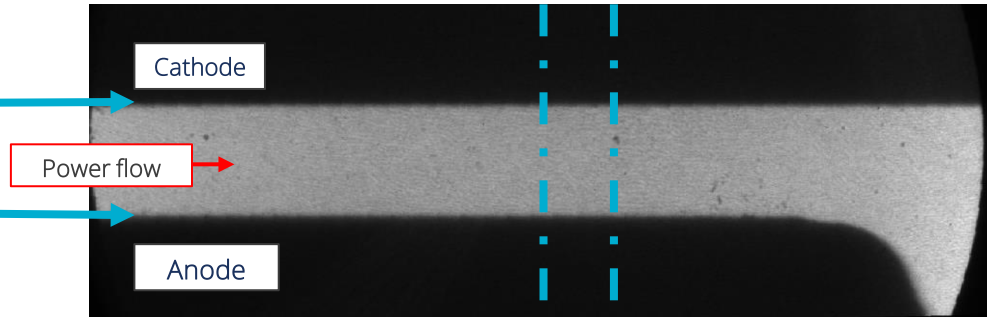
Focused optical path interrogates ~1mm diameter spot size on cathode

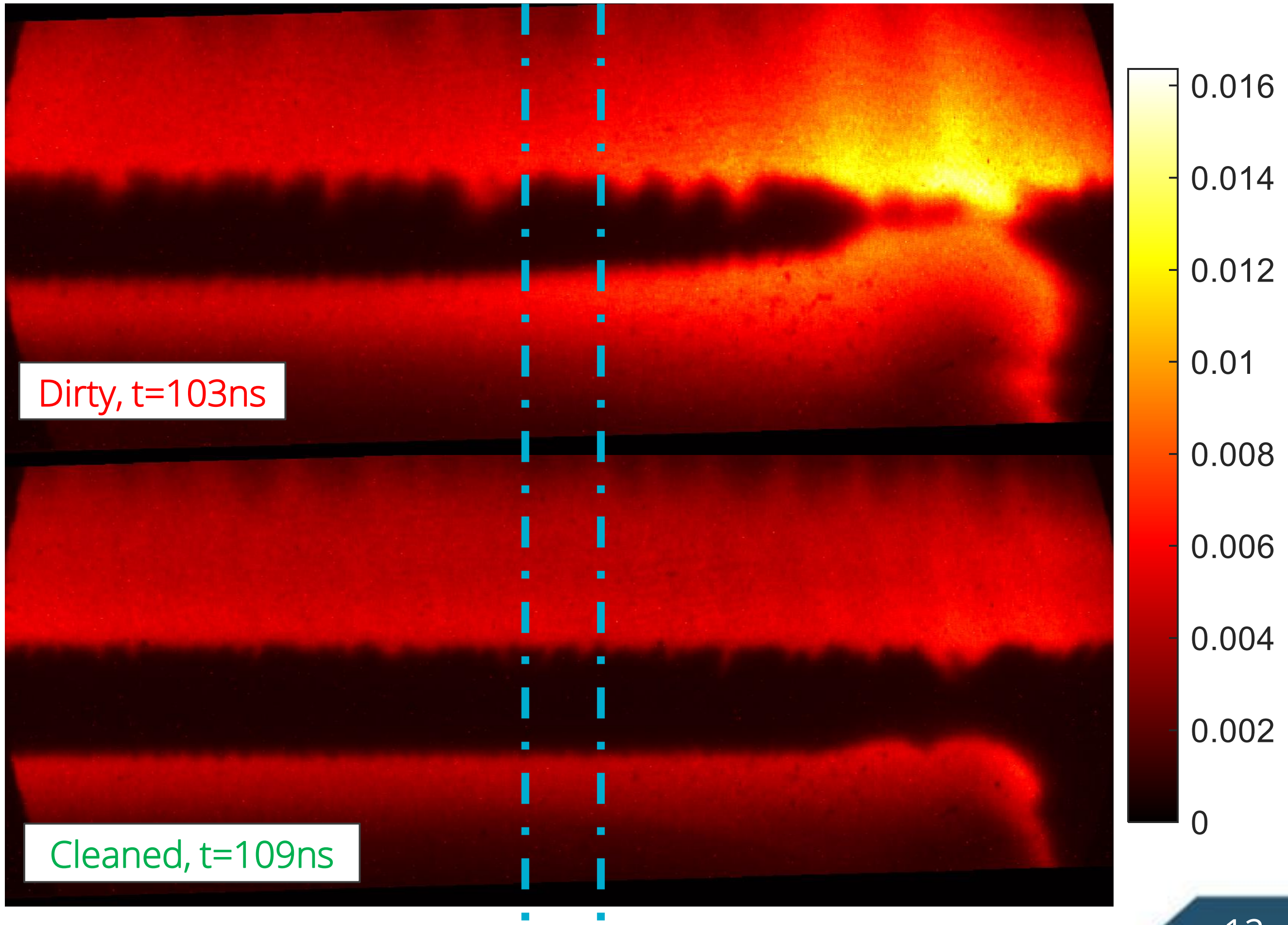


Cleaned shots observe 12-15 ns delay in electrode plasma turn-on (observable self emission within 640 +/-5nm) compared to dirty shots. AK gap spacing matters.

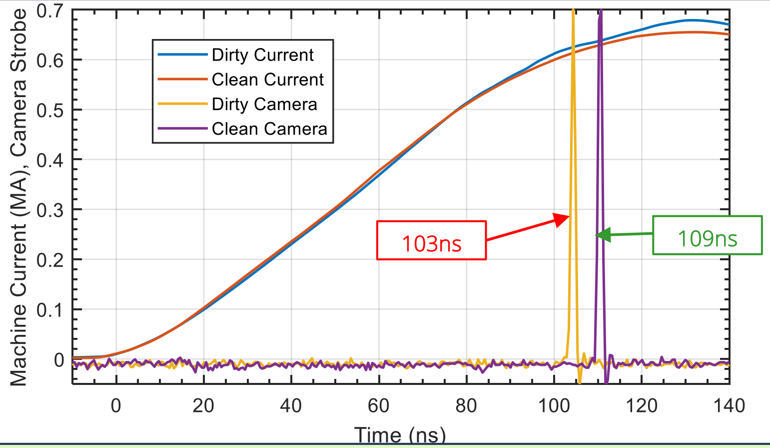
Anode plasma expansion is delayed by plasma cleaning process







Higher intensity self emission appears earlier, further into gap on uncleaned versus cleaned shot

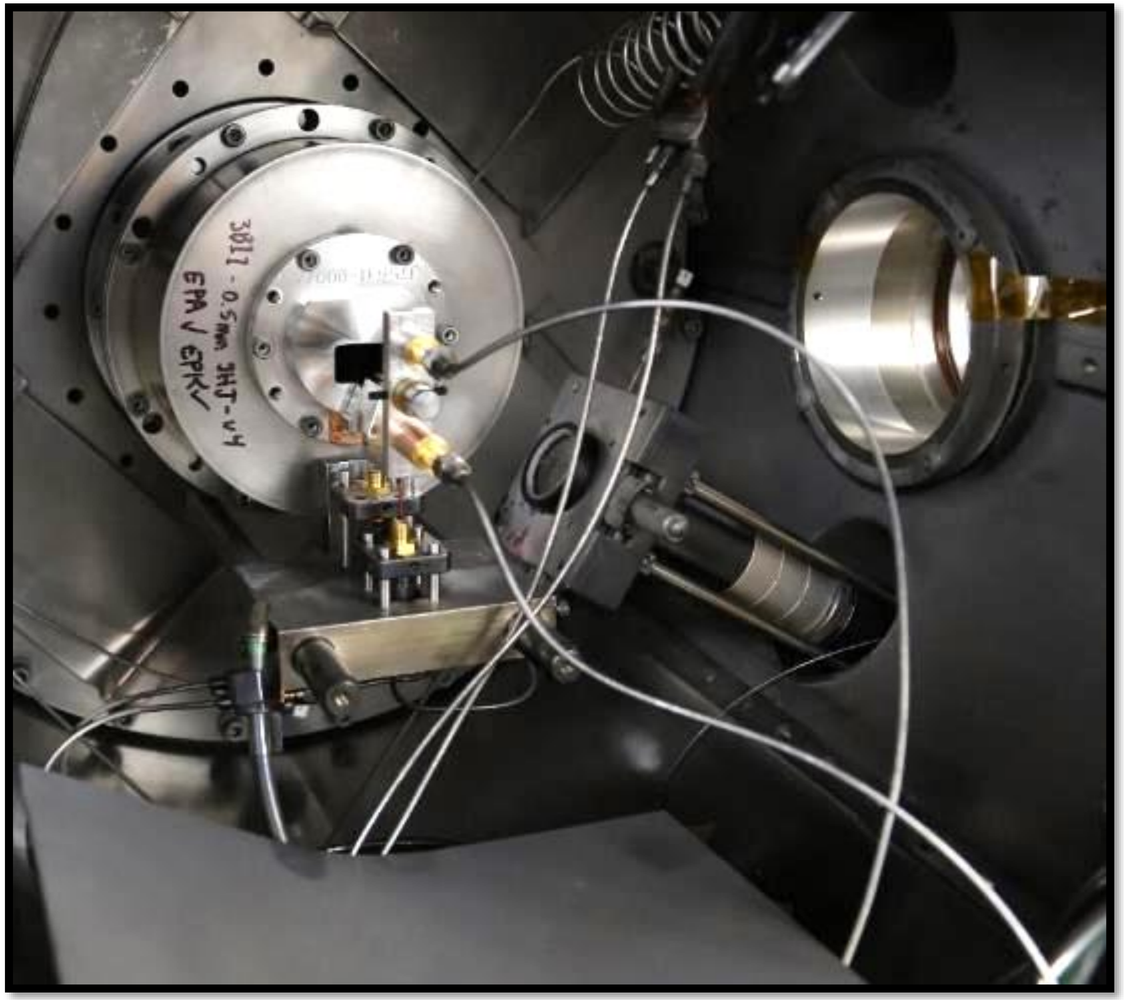


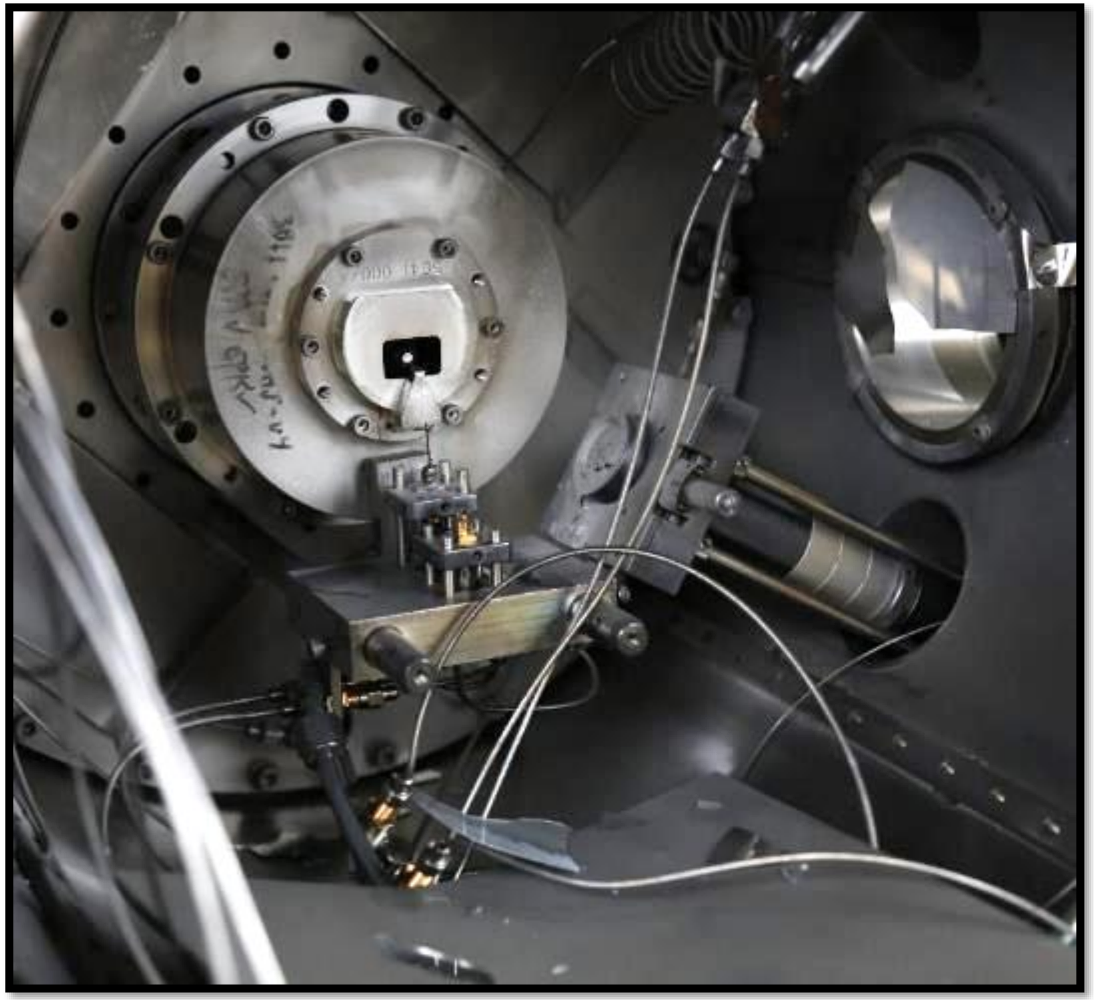
High-resolution, 5-ns single-frame exposures near peak current for 0.55mm AK gaps

Summary and Next Steps

- **We are seeing a significant impact from *in-situ* plasma cleaning in delaying electrode plasma formation, reducing total density.**
  - Gated imaging shows 3-5X reduction in observed emission intensity
  - Time-resolved APDs report 12-15 ns delay in electrode turn-on (640 +/- 5nm)
  - Cleaned experimental hardware displays characteristics of delayed impedance collapse within the load region.
  - **To our knowledge, this data is the first of its kind**
- **We have much work to do with this experimental platform**
  - Quantify delays in electrode turn on, load dynamic impedance, apparent closure velocities
  - Utilize spectrally resolved diagnostics to quantify plasma densities and constituent species
- **We have much work to do with the plasma discharge cleaning protocol**
  - Quantify, optimize contaminant removal rates as a function of canonical AK gap
  - Develop a protocol (varying backfill pressures, species, excitation power) that optimally cleans the Z Machine load hardware

Questions?





Like the Z Machine, Mykonos experimental hardware has a lifetime of one shot.

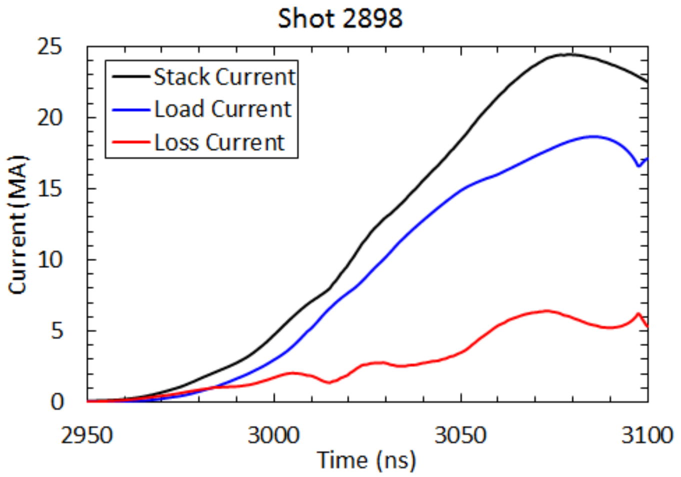
Backup

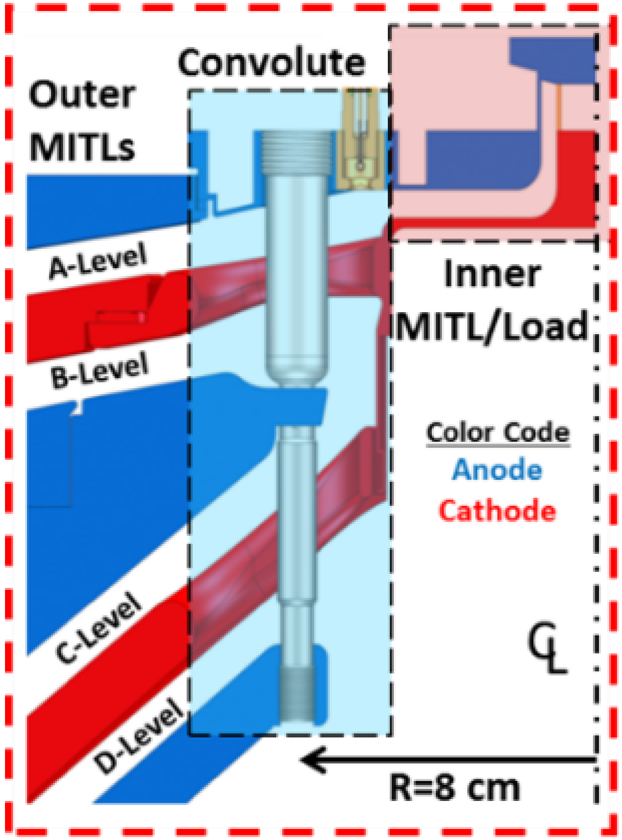
Z delivers up to 27MA to well-matched HEDP targets, but some loads can lose 5-6 MA

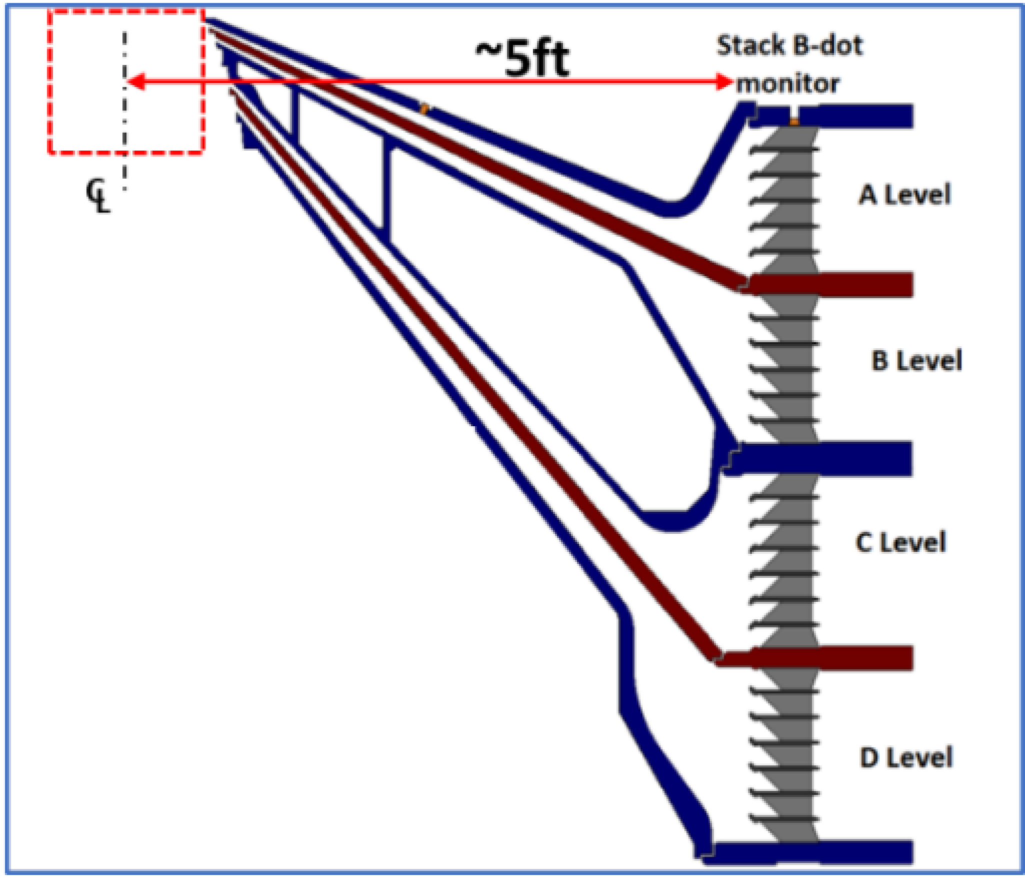
Current loss negatively impacts all Z experiments

- Reliable, achievable pressure profiles in dynamic material properties
- Radiated power for radiation sources
- Fuel compression for inertial confinement fusion

Current loss occurs in double post-hole convolute, inner MITL







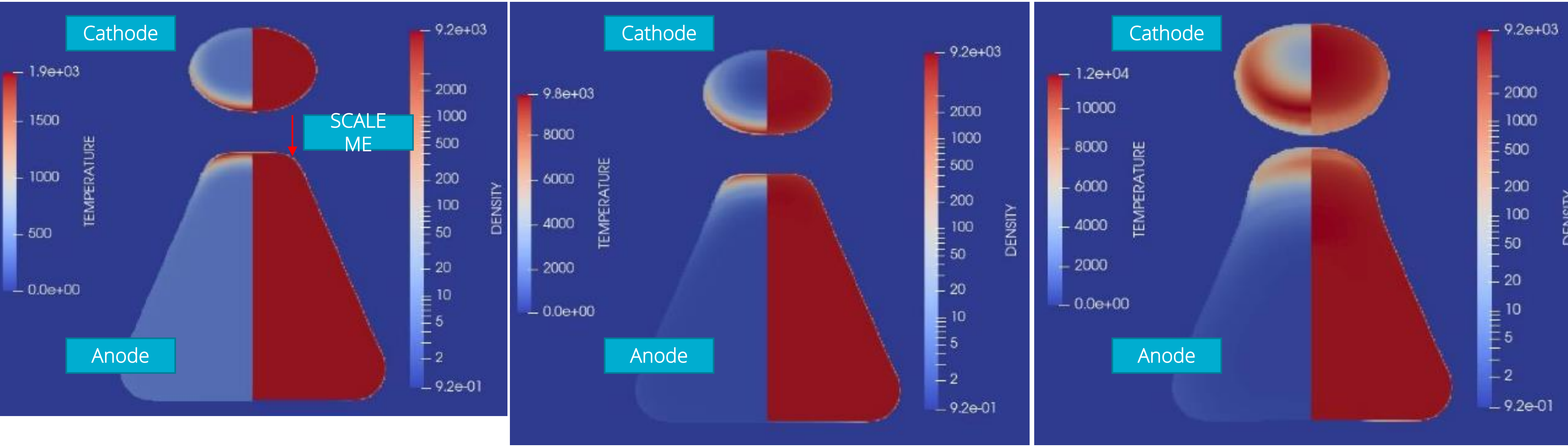
The Z Dual Post-Hole Convolute (above, left) is used to combine current from four parallel MITLs (above, right) into a single inner MITL that feeds the target. Depending on the load impedance, significant current can be lost before it arrives at the load (left).

MHD simulation of geometry shows rapid heating of electrodes, bulk material nearly 1eV at time of machine peak current

Where are we in the Z fee
Add slice plane on represen
geometry to show where

Mykonos accelerator current ~650 kA in 120 ns

t=50ns t=100ns t=200ns



- Desorption temperature (>$\Delta 400°C$) met within 40ns on each electrode
- Heavy electrode material does not contribute to apparent AK gap closure during current pulse
- Bulk electrode material gets hot - nearly 1eV – providing a backlight for any contaminant plasma
- A cleaned Mykonos experiment should asymptotically approach this condition.

|B|~250 T in 0.5mm AK gap experiment at 100ns

Particle in Cell calculations in Chicago show plasma dynamics sensitive to AK gap spacing, in general agreement with experiment