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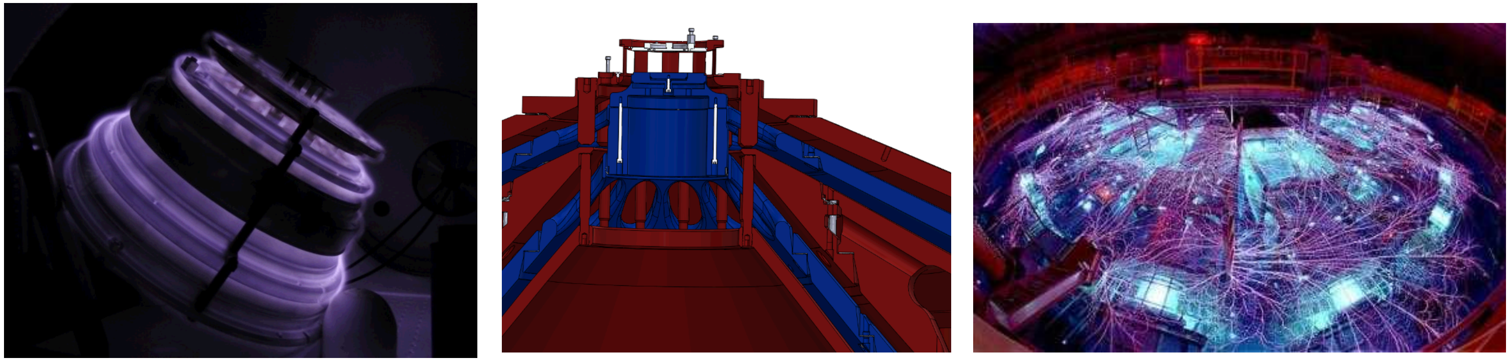

Development of a Plasma Cleaning System for Z

897 – R. Tang, P. A. Miller, E. V. Barnat, M. Hopkins
Stinger – D. Coleman, G. Denison, et al.
SITF – D. Lamppa, G. Shipley, et al.
Other Efforts – B. Clark, R. Sorensen, et al.

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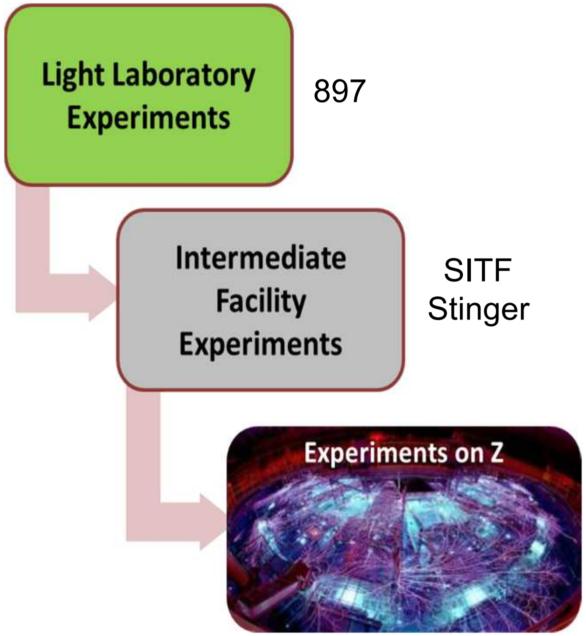
Approach for plasma cleaning on Z



Light Laboratory Experiments

897

Intermediate Facility Experiments

SITF
Stinger

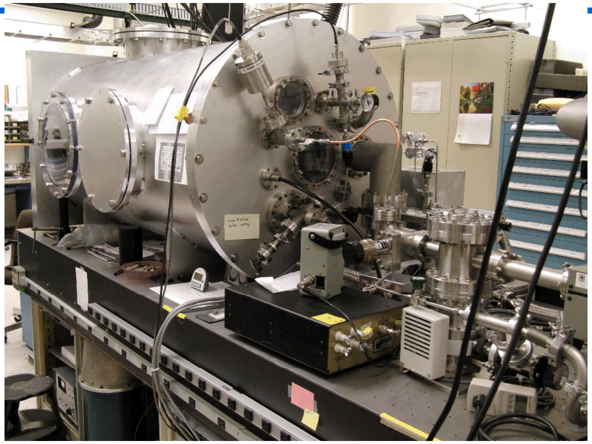
Experiments on Z

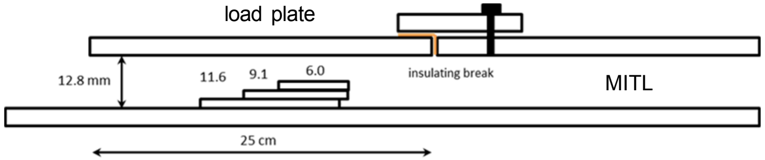
- **Based on past experience[1,2], plasma cleaning of convolute surfaces immediately prior to a shot is expected to reduce current losses on Z.**
  - **"Cleaning" means removing many monolayers of surface contaminants.**
  - **Effect of cleaning drops as time increases between plasma extinction and shot (0.5 min good, 10 min bad).**
- **In early CY2015 we are conducting a plasma-cleaning test on pulsed-diode Stinger experiment.**
  - **Stinger conditions do not replicate Z-convolute conditions.**
  - **However, gas absorption and plasma removal of surface contaminants are likely to be similar.**
  - **The CONOPS for the Stinger test will be practice for Z.**
- **Important parameters for plasma cleaning necessitate intermediate testing at SITF:**
  - **Delay between end of plasma cleaning and the shot.**
  - **Cleaning duration, gas pressure, and plasma power.**
  - **Plasma localization by insulating breaks in the MITLs.**

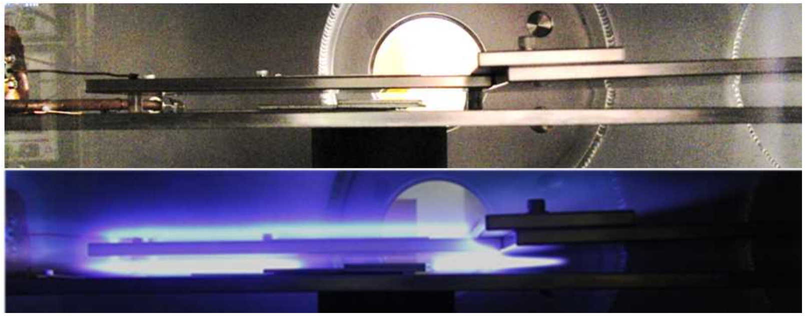
1. M. E. Cuneo – The Effect of Electrode Contamination, Cleaning and Conditiong on High-Energy Pulsed-Power Device Performance.
2. M. E. Cuneo, P. R. Menge, D. L. Hanson, W. E. Fowler, M. A. Bernard, G. R. Ziska *et al* – Results of Vacuum Cleaning Techniques on the Performance of LiF Field-Threshold Ion Sources on Extraction Applied-B Ion Diodes at 1-10 TW.

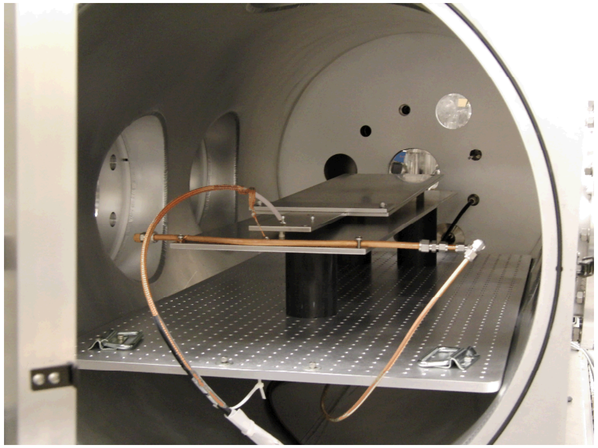
“10%” plasma test bed

- **700 liter cylindrical vacuum chamber.**
  - **Turbo pump, flowing Ar/O_2 mixture.**
- **Parallel-plate assembly to simulate MITLs and convolute (load) region.**
  - **4”x10” load plates ~10% of full scale load.**
  - **Insulating break to localize discharge.**
  - **Variable gaps.**
  - **Power via 60-foot coax cable; typically 50 W.**



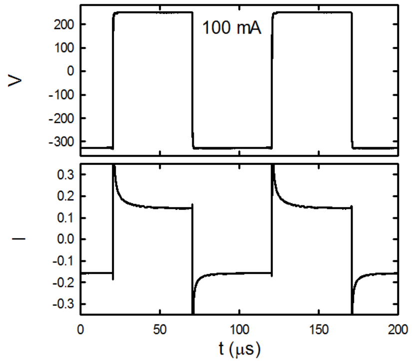


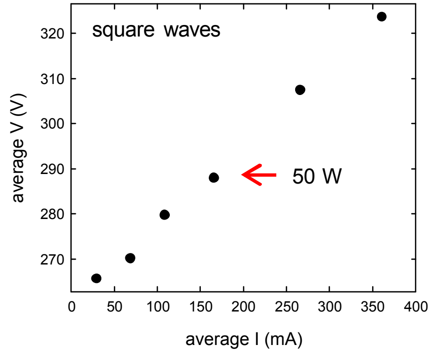




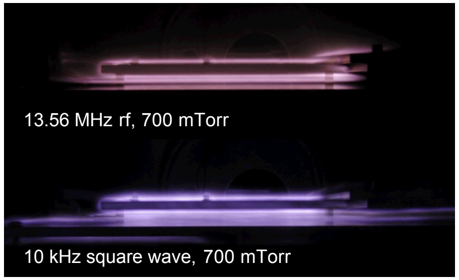
Discovery: plasma generation by audio square waves

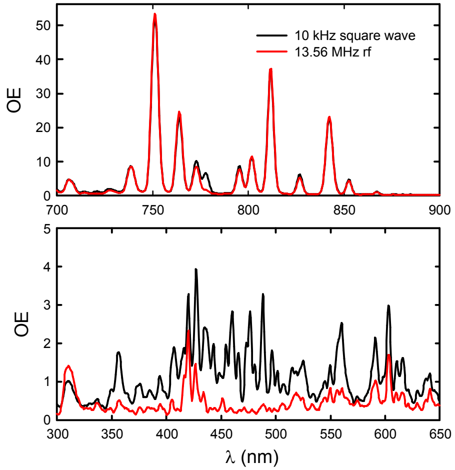
- **We discovered that we can generate plasma effectively using audio-frequency bi-polar square waves (“ASW”) with fast rise and fall.**
  - **Somewhat faster removal of hydrocarbons than 13.56-MHz rf.**
  - **Higher voltage than rf → more sputtering.**
  - **Insulating breaks should be more effective at keeping plasma out of MITLs.**
    - **Capacitance has higher impedance at lower frequencies.**
  - **OES indicates higher ion density with ASW than with rf at similar powers.**
  - **Don’t need impedance matching network with ASW.**





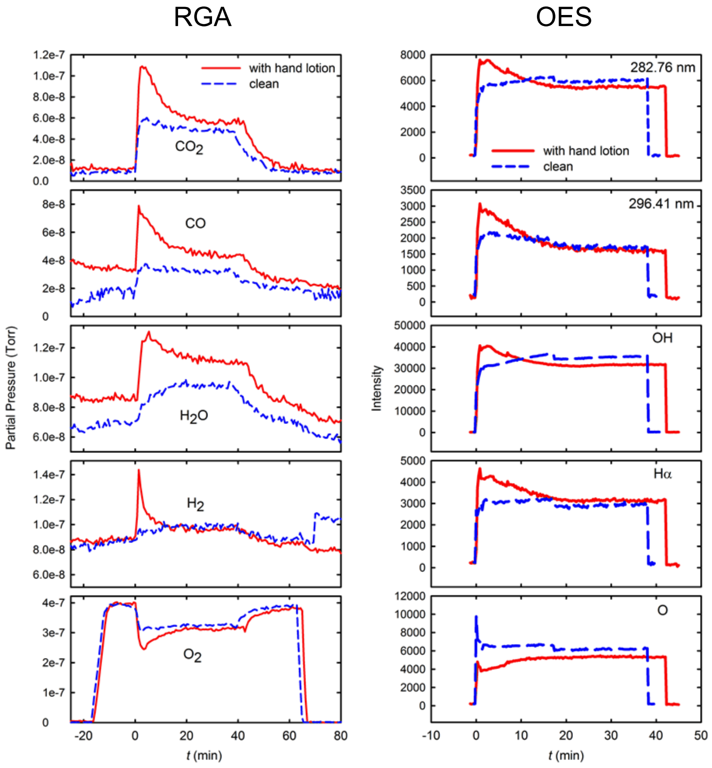
50 W @ 13.56 MHz → ~ 50 V peak





Plasma removed thick layers of contaminants

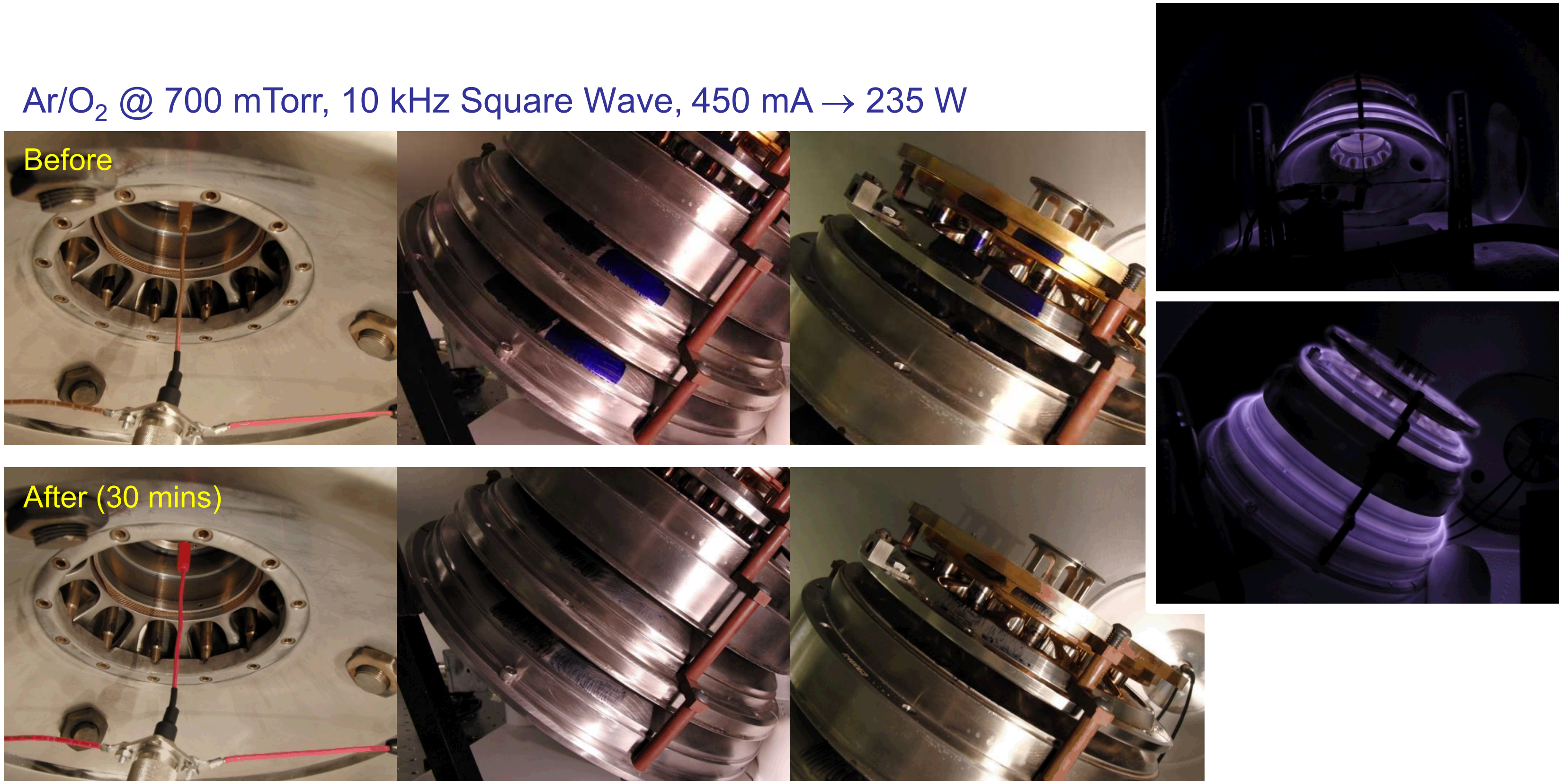
- **Plasma cleaning techniques were developed in light-lab.**
  - **Grease, Aerodag, and ink coatings ("contaminants") were applied by hand to test objects.**
  - **Contaminants were removed in 15 to 30 minutes by plasma generated in argon/20% oxygen gas mixture, 700 mTorr, ~50W power.**
    - **Removal diagnosed by RGA signals, OES, weight change measurements, and visual observation.**
  - **Contaminant removal is due to chemical etching and sputtering.**



Example: Thick ink layers on 4"-square aluminum plates were treated by plasma.

Old convolutes have been exposed to plasma to qualitatively explore removal of sharpie markers

Ar/O_2 @ 700 mTorr, 10 kHz Square Wave, 450 mA → 235 W



We quantified removal rates of several materials

- **Removal of surface coatings was measured by weight change.**
- **Plasma removes carbon and oil effectively (e.g. 10 nm/min).**
- **Plasma has little effect on NaCl and on glass.**

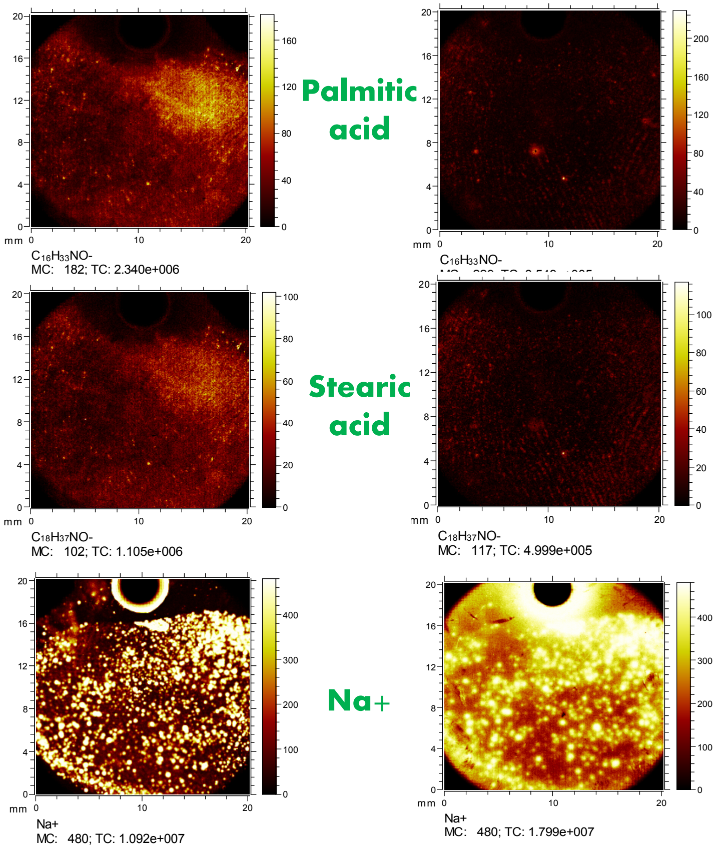
coupon			processing conditions									results		
ID	coating	init amt (µg/cm2)	test date	time (min)	gen pwr (W)	freq (MHz)	bias	p (mTorr)	flow (sccm)	gap (mm)	comments	loss rate (µg/cm2/min)	etch rate nm/min if ρ=3	amt removed %
S01	Aerodag	90	3/20/14	5	150	13.56	0	400	100	13	uniform electrode gap	3.64	12.1	20.1
S02	Aerodag	116	3/20/14	10	150	13.56	0	400	100	13		3.83	12.8	33.1
S03	Aerodag	122	4/10/14	15	150	13.56	0	800	50	12	tapered electrode gap; low-loss coax	2.71	9.0	33.3
S04	Aerodag	121	4/10/14	15	150	13.56	0	800	50	7		2.82	9.4	35.1
S05	Aerodag	120	4/11/14	15	150	13.56	0	400	50	12	over etched: little 'dag remaining	5.54	18.5	69.2
S06	Aerodag	125	4/11/14	15	150	13.56	0	400	50	7		1.00	3.3	12.0
S07	NaCl	69	4/25/14	15	150	13.56	0	400	50	11		0.06	0.2	1.3
S08	NaCl	89	4/25/14	15	150	13.56	200Vp	400	50	11	60 Hz bias	-0.01	-0.03	-0.2
S09	Z oil	7	4/28/14	5	150	13.56	0	400	50	11		0.88	2.9	64.4
S10	Z oil	4	4/28/14	5	150	27.12	0	400	50	11		0.39	1.3	52.2
S11	Aerodag	186	5/28/14	60	50	10 kHz	0	700	50	9	square wave	2.33	7.8	75.1
S12	Aerodag	186												
S13	Aerodag	189	5/28/14	60	36	13.56	0	700	50	9		0.62	2.1	19.7
S14	Aerodag	181												
S15	NaCl	52	5/28/14	60	50	10 kHz	0	700	50	9	square wave	0.03	0.1	3.3
S16	NaCl	46	5/28/14	60	36	13.56	0	700	50	9		0.01	0.04	1.7
S17	NaCl	49	7/10/14	270	50	10 kHz	0	700	50	9		nil		
S18	NaCl	58	7/9/14	270	50	13.56	0	700	50	9		nil		
S19	Z oil	8	5/28/14	60	50	10 kHz	0	700	50	9	square wave	0.11	0.4	88.9
S20	Z oil	28	5/28/14	60	36	13.56	0	700	50	9		0.43	1.4	93.1
S21	Z oil	17												
S22	Z oil	8												
-	glass	-	7/7/14	182	50	10 kHz	0	700	50	9	square wave	nil		

We measured environmental contamination in Z highbay and in Lab 101 and plasma-cleaned them

- **Coupons were fielded and analyzed to determine surface contamination species and deposition rates.**
  - **Coupons located around 983 and cycled through vacuum system.**
  - **Initial exposure in 983 for 2 weeks.**
  - **Analyze surfaces, starting with TOF-SIMS, and SEMs.**

- **Coupons were plasma-cleaned and surfaces were reanalyzed.**
  - **700 mTorr for 10 mins at ~50 W power.**

Before **After**

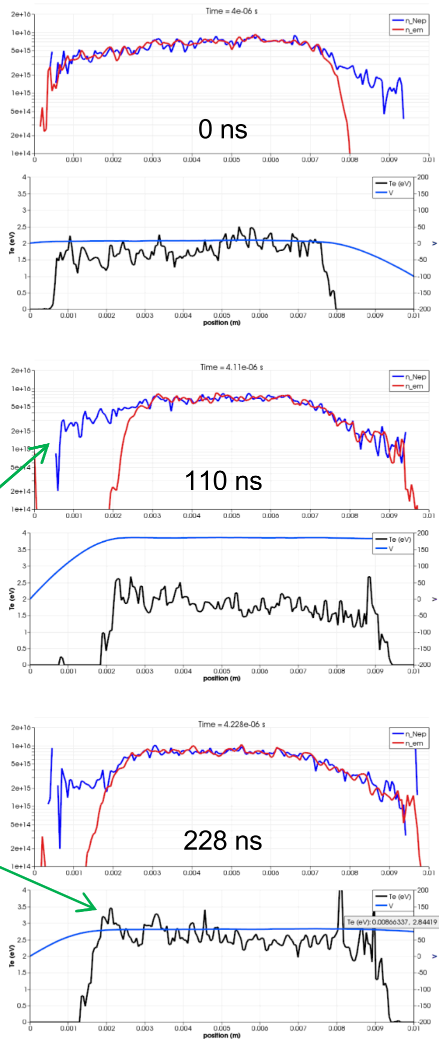


Preliminary modeling of square waves suggests possible mechanisms contributing to its effectiveness

- **The polarity switch in a low frequency square wave causes a much more abrupt potential variation to support interesting transport phenomena.**
  - **Generation of a “wave” of higher temperature electrons leading to more ionization leading to higher cleaning efficiency.**
  - **“Sheath capture” of a higher density bolus of ions that are accelerated to the wall when the polarity switches.**

- **Three snapshots of the plasma state at the beginning of a polarity switch.**
  - **Deep sheath structure at the left boundary at 110 ns → a population of ions have been “captured” and will be accelerated into the wall.**
  - **Increased electron temperature at 228 ns.**

100-ns Polarity Switch



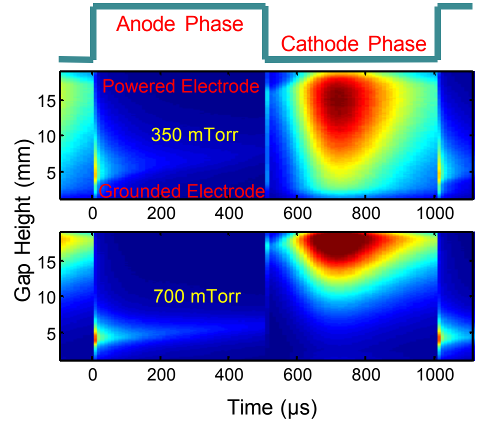
Small-scaled experiments provide insights for plasma cleaning

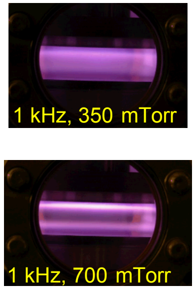
Objectives:

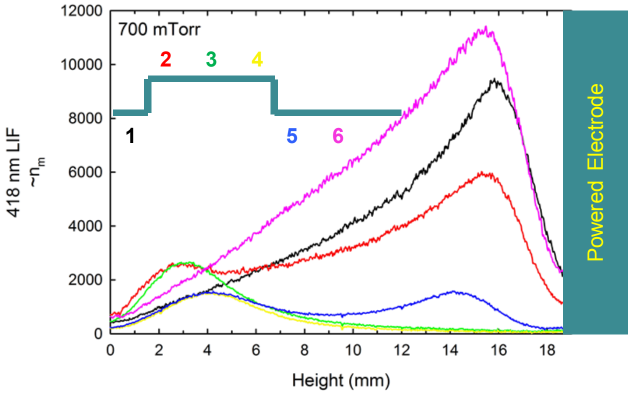
- **Investigate temporal-spatial dynamics of square-wave plasma.**
  - **Coupon studies revealed its effectiveness. What drives the mechanism?**
  - **How does the plasma evolve?**
  - **When is energy being deposited?**

Plasma Generation

- **ICCD camera captures plasma formation during pulses.**
  - **Streak-like images revealed pressure-dependent dynamics and asymmetry in plasma generation.**
- **Plasma induced emission (PIE) shows strong plasma generation during cathode phase.**
  - **Energy deposition into powered electrode is straight-forward.**
- **During anode phase, plasma persists for short duration.**
  - **Planar LIF show significant Ar $1S_5$ metastable density decay during anode phase (3 & 4), and subsequent generation with transition to cathode phase (5→6).**

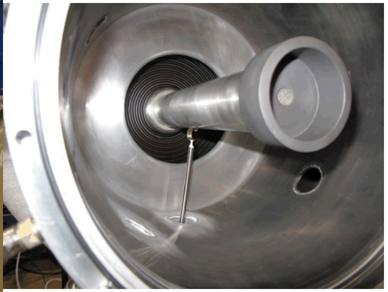


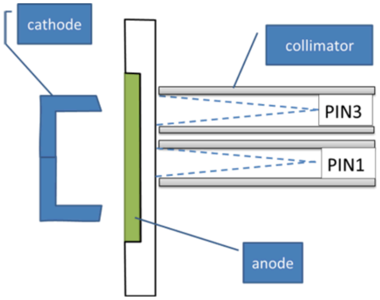


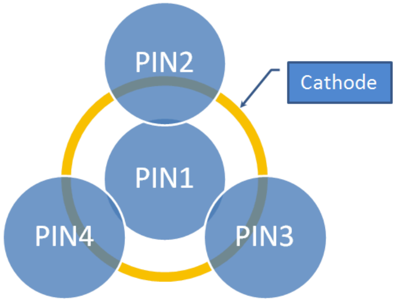


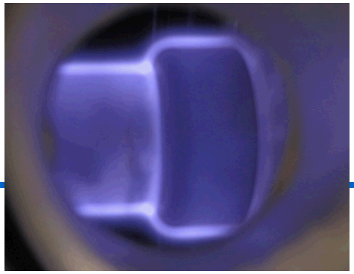
Intermediate facility – plasma cleaning on SMP diode Stinger

- **E-beam pinch formation speed is directly tied to anode coatings and anode plasma generation.**
  - **Thermal desorption of adsorbed gases off anode is function of specific heat of and electron stopping power of coating.**
  - **Resulting anode plasma leads to strong pinch.**
- **Goal for plasma cleaning on Stinger is to determine whether we can delay pinch formation.**
  - **If plasma cleaning is effective → delay anode plasma formation → delay pinch.**
  - **Pinch detected by time-resolved x-ray signals from pin diodes.**



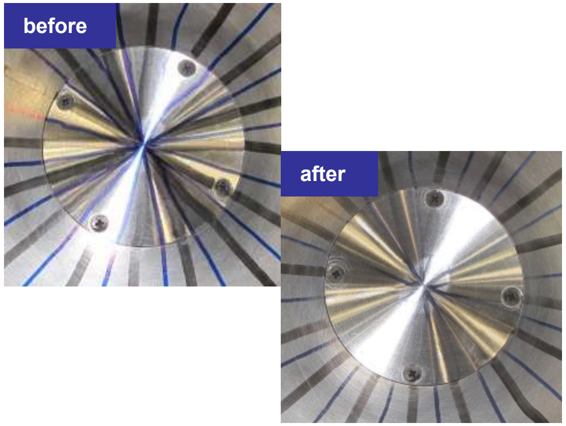




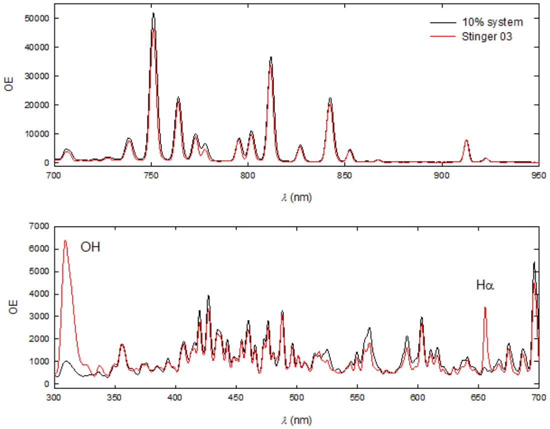


Tests show cleaning of Stinger anode

- **Marker Test**
  - Qualitative, but great indicators of surface cleaning.
  - Provides indication of whether plasma is present in locations that are otherwise difficult to see visually or with diagnostics.
  - Provides first-line evidence of whether the chosen conditions (power levels, gas pressure, cleaning duration) are sufficient in removing surface contaminants.

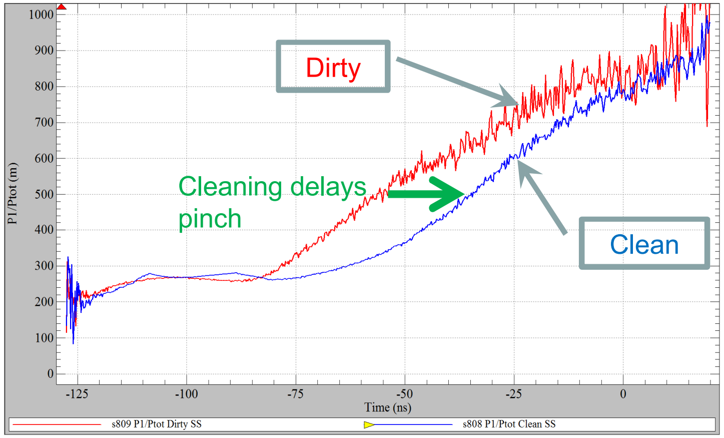


- **OES spectral comparison with the plasma in our light lab suggests that plasma emission is essentially identical.**
  - Provides a consistent diagnostics for our cleaning plasma across different systems.



Plasma cleaning shows delay in pinch

- **Typical conditions: 80/20% Ar/O2; P = 0.5 Torr; Flow rate = 94 cm^3/min; 200 mA power supply setting**
- **Cleaning leads to 10-20 ns delay in pinch onset for stainless steel anode.**
- **Cleaning effects persistent after cleaning stops.**

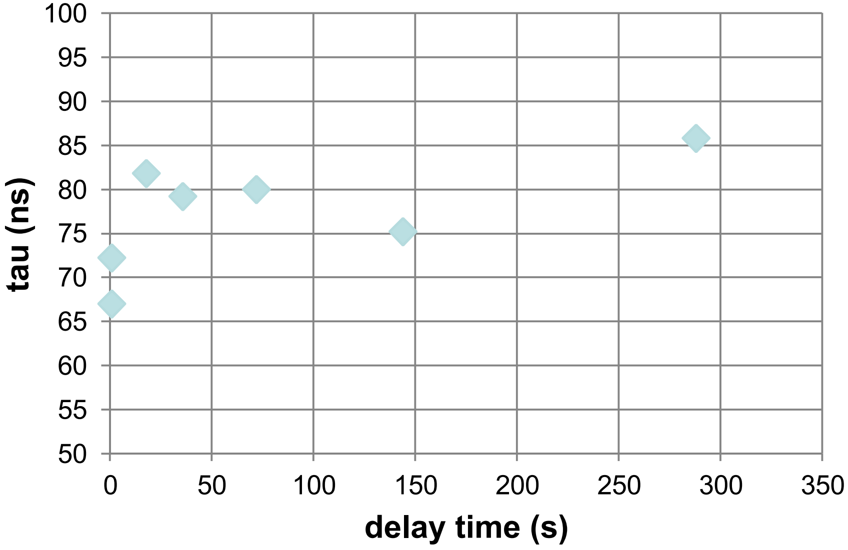


Dirty

Cleaning delays pinch

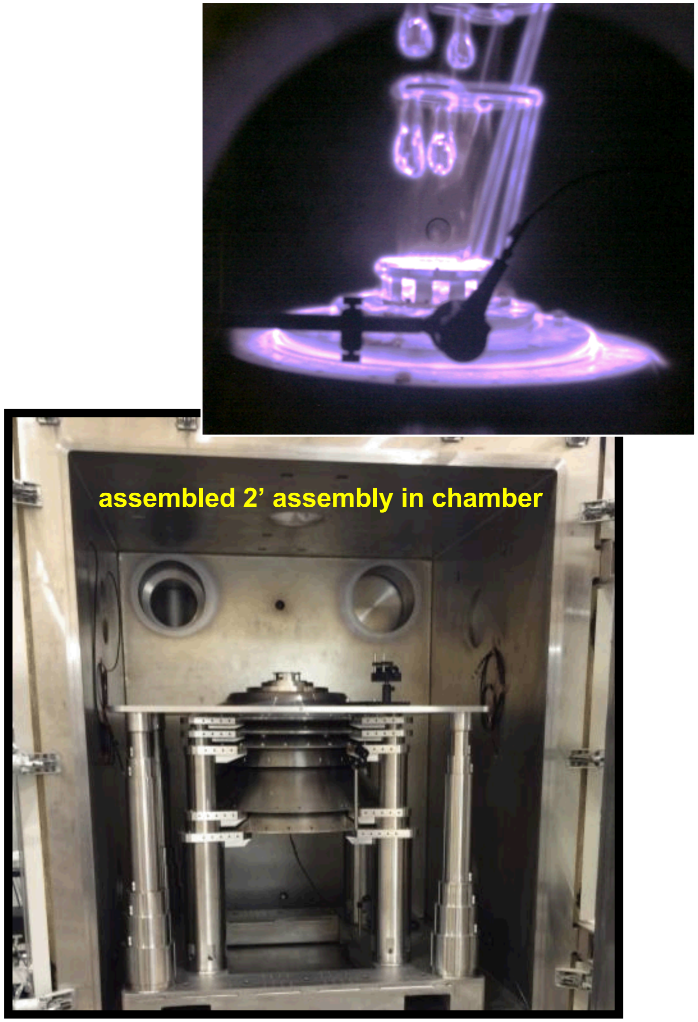
Clean

time to pinch (P1/Ptot=0.5)



Stinger with a 40-min clean time followed by varying delay time.

SITF Surrogate Diode Deployment (S2D2) to perform plasma cleaning on shot hardware, convolutes, 2’ and 4’ MITLs

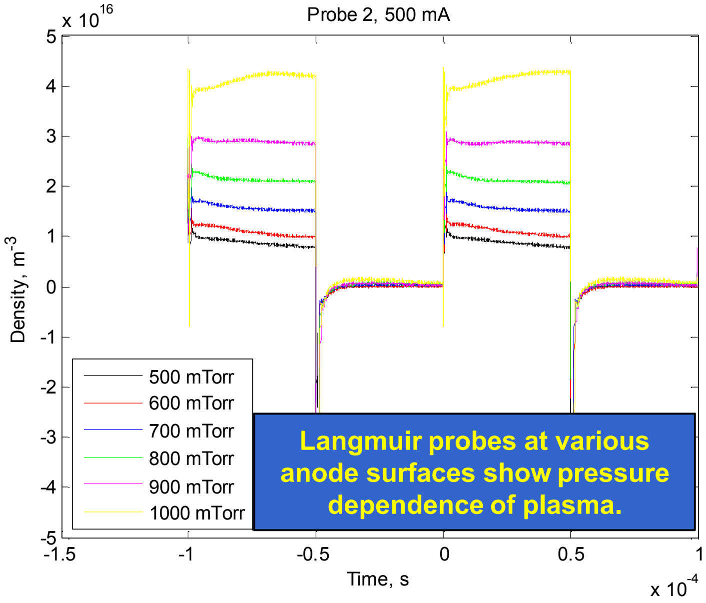


- **We have been assigned time on Z.**
  - **Nested 70mm SS wire array is well-characterized.**
  - **Preparing hardware for commissioning and downline shots.**
- **S2D2 explores Z-relevant plasma cleaning technical challenges.**
  - **Insulating breaks in MITL hardware, load region.**
  - **Diagnostic development to evaluate plasma localization.**
  - **Cleaning rates and material removal experiments.**
  - **Pressure dependence of plasma localization and cleaning efficiency.**
  - **Vacuum CONOPS and plasma behavior during pumpdown, cross-over.**
  - **Testbed for inductive heating?**

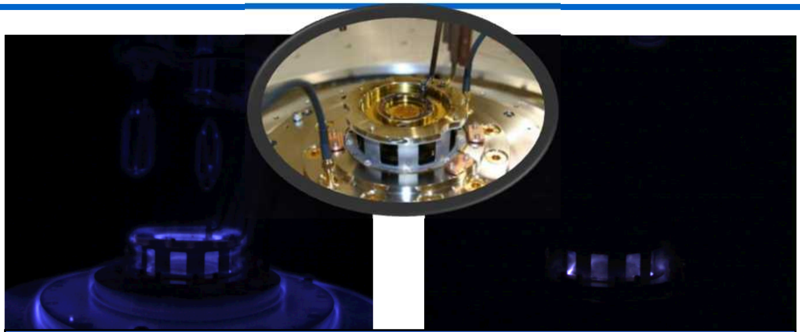
Sharpie marks show cleaning on lower anode, before (left) and after (right).

We are developing an efficient cleaning protocol that will be used on Z

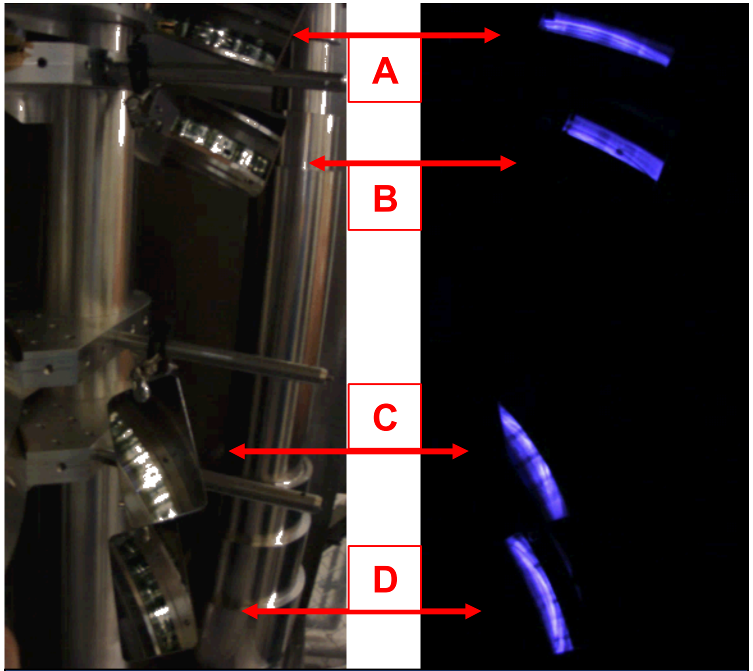
- **Define a cleaning protocol for Z**
  - **Impact on shot timeline is paramount.**
  - **The 1’ region has varied gap spacing.**
- **Explore plasma distribution using Z convolute and wire array.**
  - **Planar Langmuir probe to collect ion current.**
  - **OES to look at plasma emission.**
  - **Direct LOS imaging of the MITL levels.**



Langmuir probes at various anode surfaces show pressure dependence of plasma.



Load region plasma sensitive to backfill pressure.
Left: 700mTorr. Right: 800mTorr.



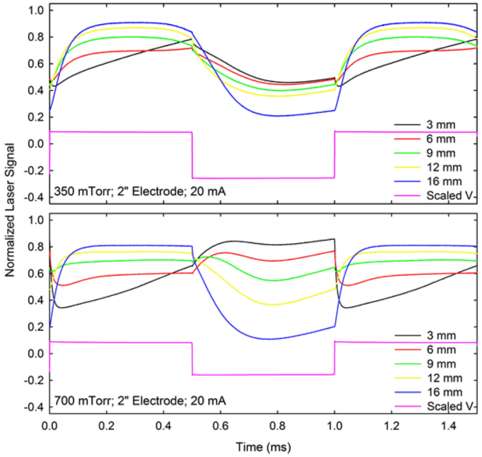
Direct LOS imaging of Z’s four MITL levels (A-D) shows anode posts and localized plasma distribution.

Backup

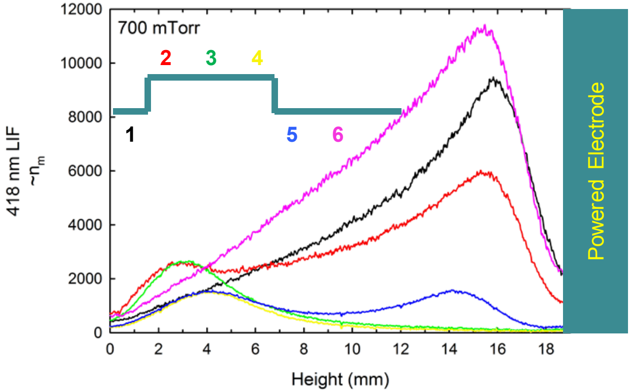
Evolution of Ar metastable reveals plasma dynamics

- **Track dynamics by measuring Ar $1S_5$ metastable concentration.**
    - **Diode laser absorption: probe 811.5-nm Ar $1s_5 \rightarrow 2p_9$ transition.**
    - **Planar LIF: excite Ar from $1s_5$ to $3p_2$ state, monitor 418.2-nm $3p_2 \rightarrow 1s_3$ transition.**

- **Laser absorption shows evolution of Ar metastable at various electrode gap height.**
    - **Strong pressure dependence in dynamics, especially at cathode-to-anode transition.**
    - **Asymmetry in metastable generation correlated with plasma generation.**
    - **Plasma persists for short, initial duration of anode phase → "useful" work.**



- **Planar LIF measures Ar metastable at discrete time-points.**
    - **Transition of main plasma region from powered to grounded electrode as pulse moves from cathode to anode phase.**
    - **Drastically reduced metastable density at end of anode phase (3 & 4).**
    - **Onset of metastable generation in anode-to-cathode transition (4→5).**



Plasma induced emission captures plasma formation and dynamics during pulse.

700 mTorr