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MITL ELECTRODE SURFACE PLASMA DENSITY MEASUREMENTS

at Sandia's 1 MA accelerator Mykonos

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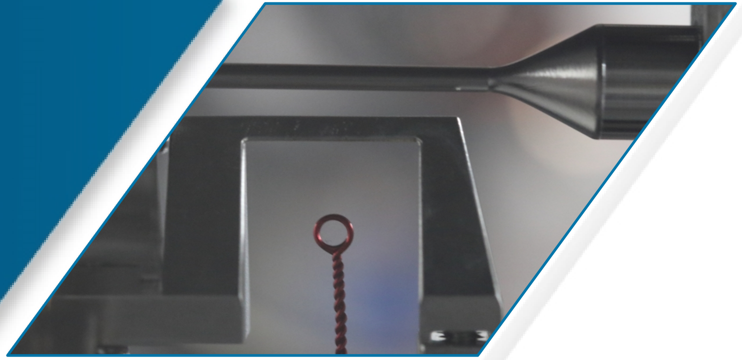

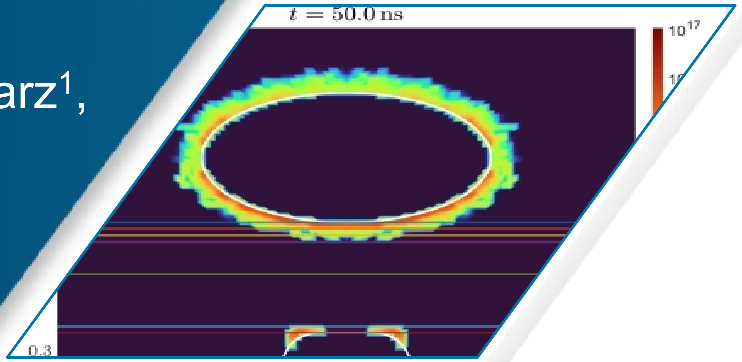

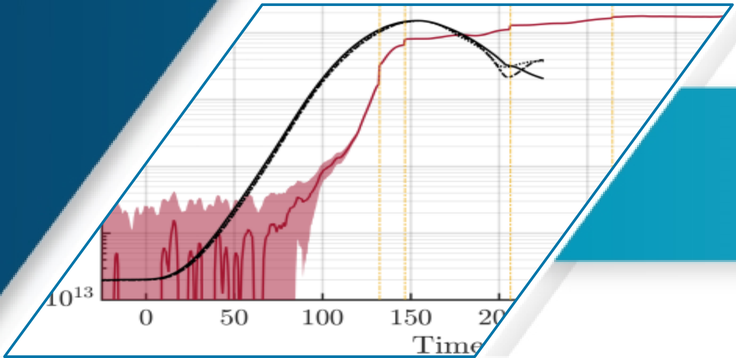

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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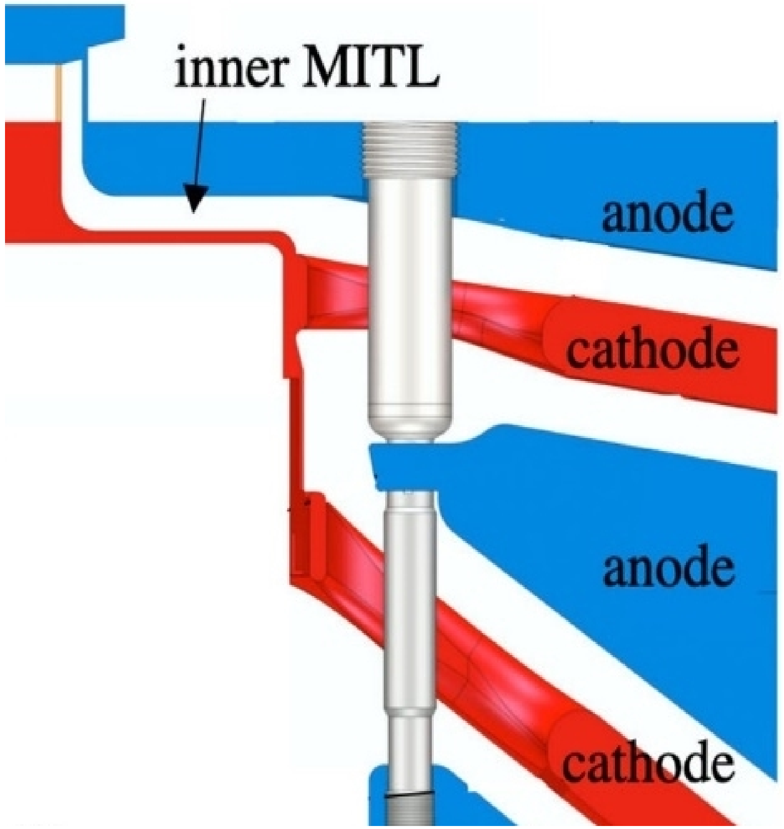
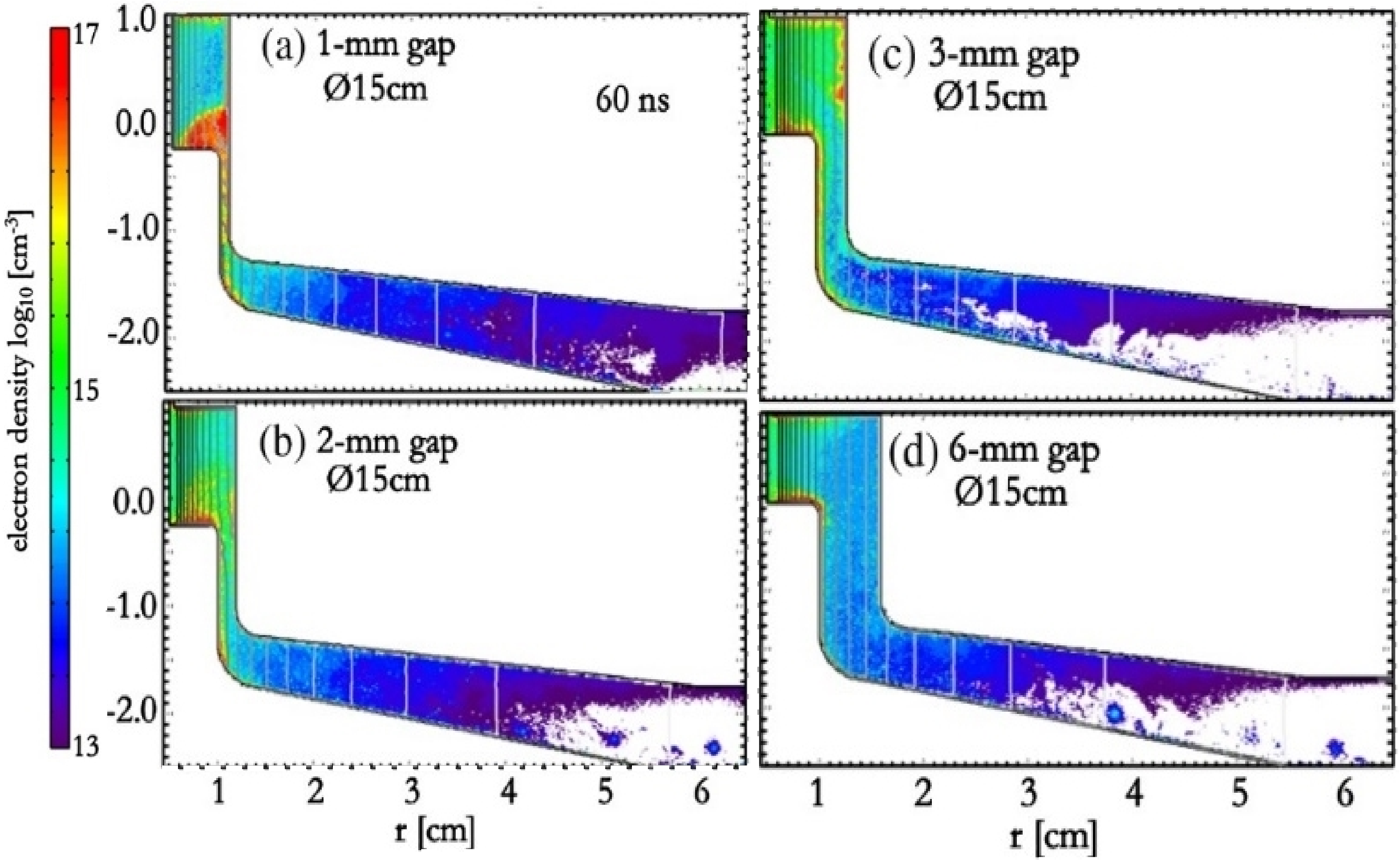
Z's inner MITL experiences current loss from charged particle cross-gap flow of expected e^- densities of 10^{13} - 10^{17} cm^{-3}

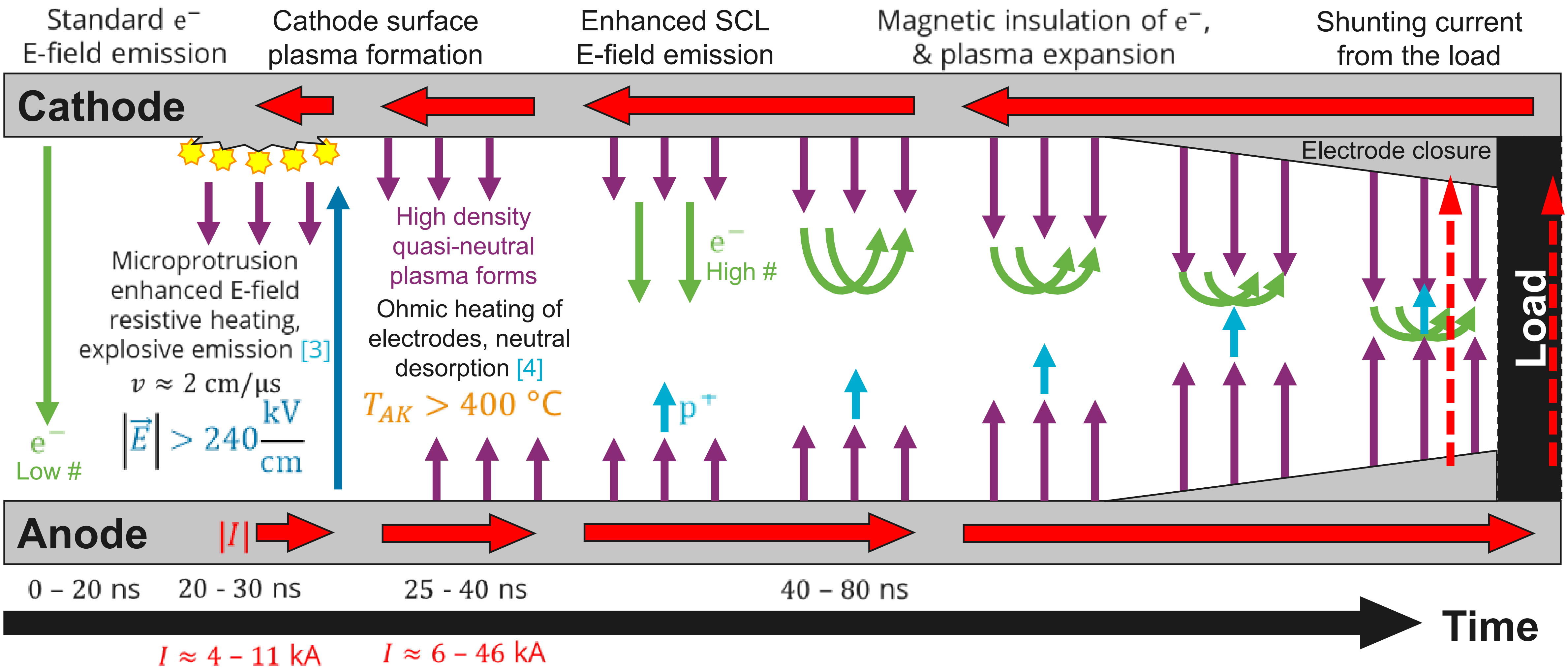




[1] W. A. Stygar et al., "55-TW magnetically insulated transmission-line system: Design, simulations, and performance," Phys. Rev. Accel. Beams, vol. 12, no. 12, p. 120401, 12/07/2009.

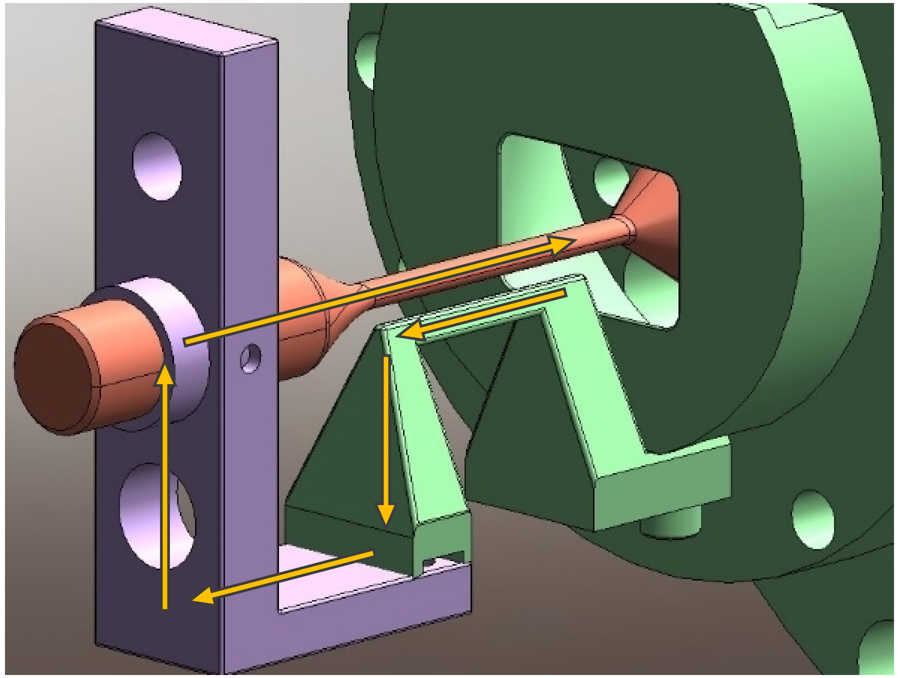
[2] N. Bennett, D. R. Welch, G. Laity, D. V. Rose, and M. E. Cuneo, "Magnetized particle transport in multi-MA accelerators," Physical Review Accelerators and Beams, vol. 24, no. 6, p. 060401, 06/23/2021.

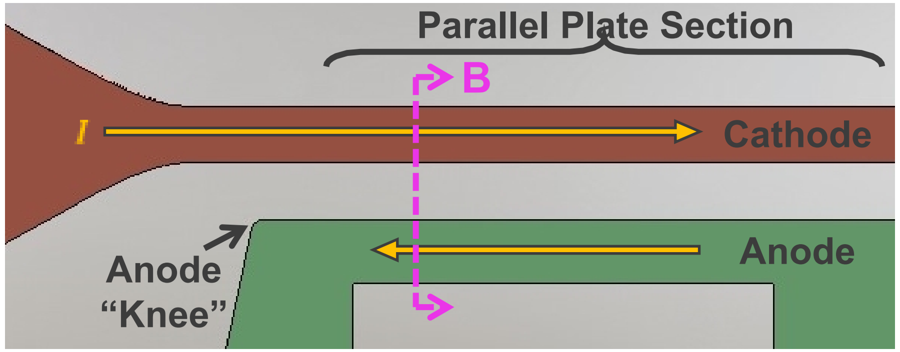
Power Flow Physics of a MITL (Specifically P^3 at Mykonos)

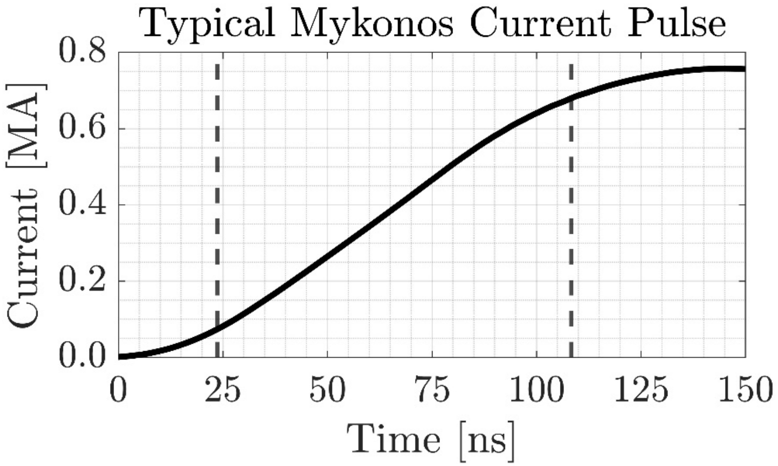


[3] S. P. Bugaev et al., Sov. Phys. Usp. 18 51 (1975)
[4] T. W. L. Sanford et al., J. Appl. Phys. 1 July (1989)

An existing platform on Mykonos provides diagnostically accessible A-K gap geometry scaled to match Z's inner MITL field strengths







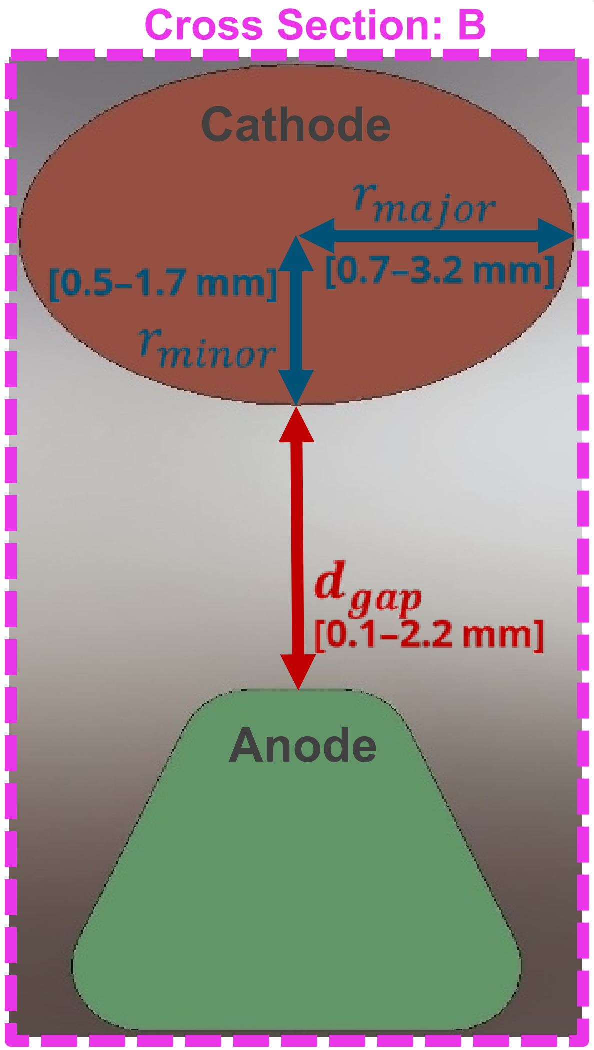
$t_{Rise} \approx 85$ ns

$1/d_{gap} \propto |\vec{E}|$ (electric field)

$|\vec{E}| \sim 0.5\text{-}5$ MV/cm

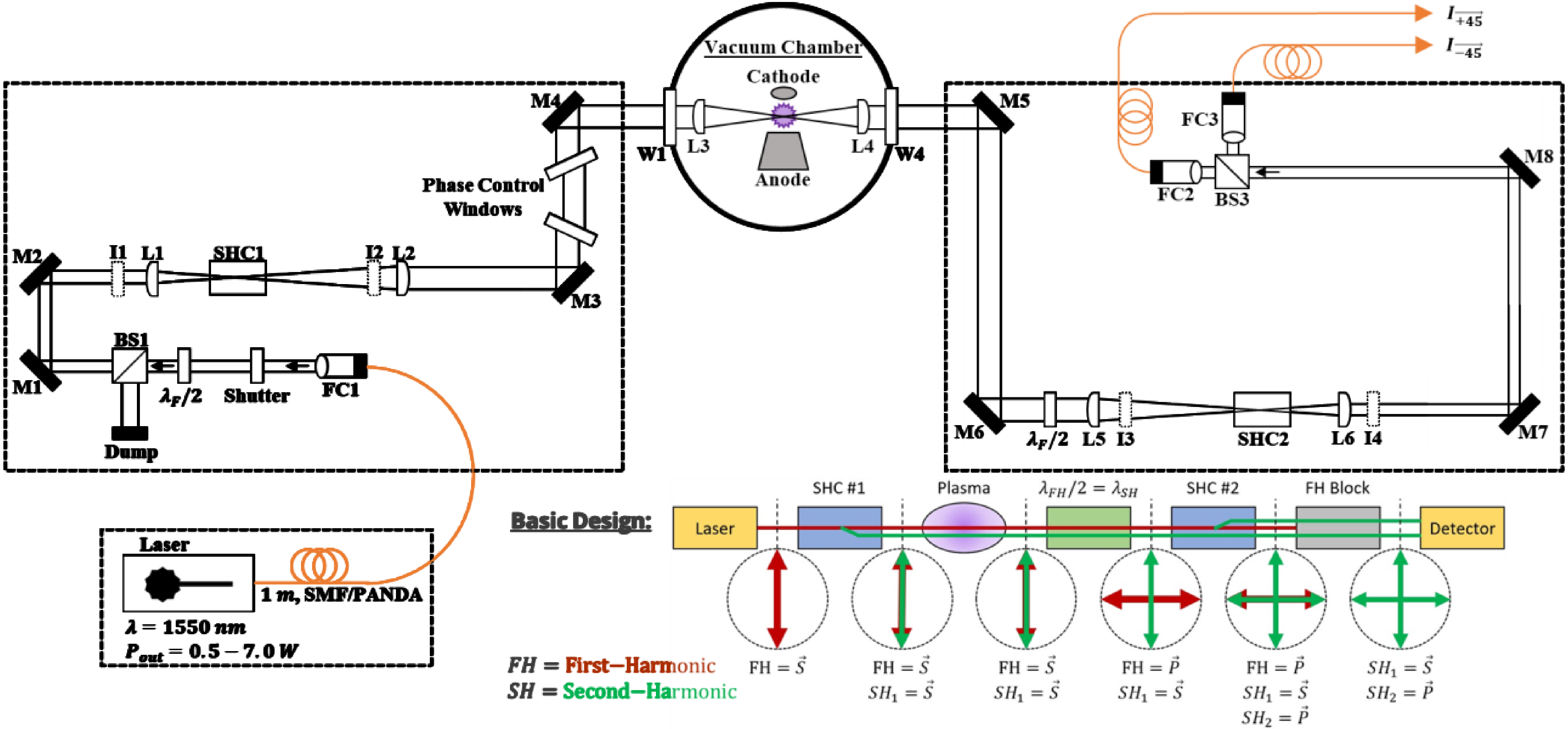
$1/r_{major}, 1/r_{minor} \propto |\vec{J}| \propto |\vec{B}|$

$|\vec{B}| \sim 50\text{-}500$ T



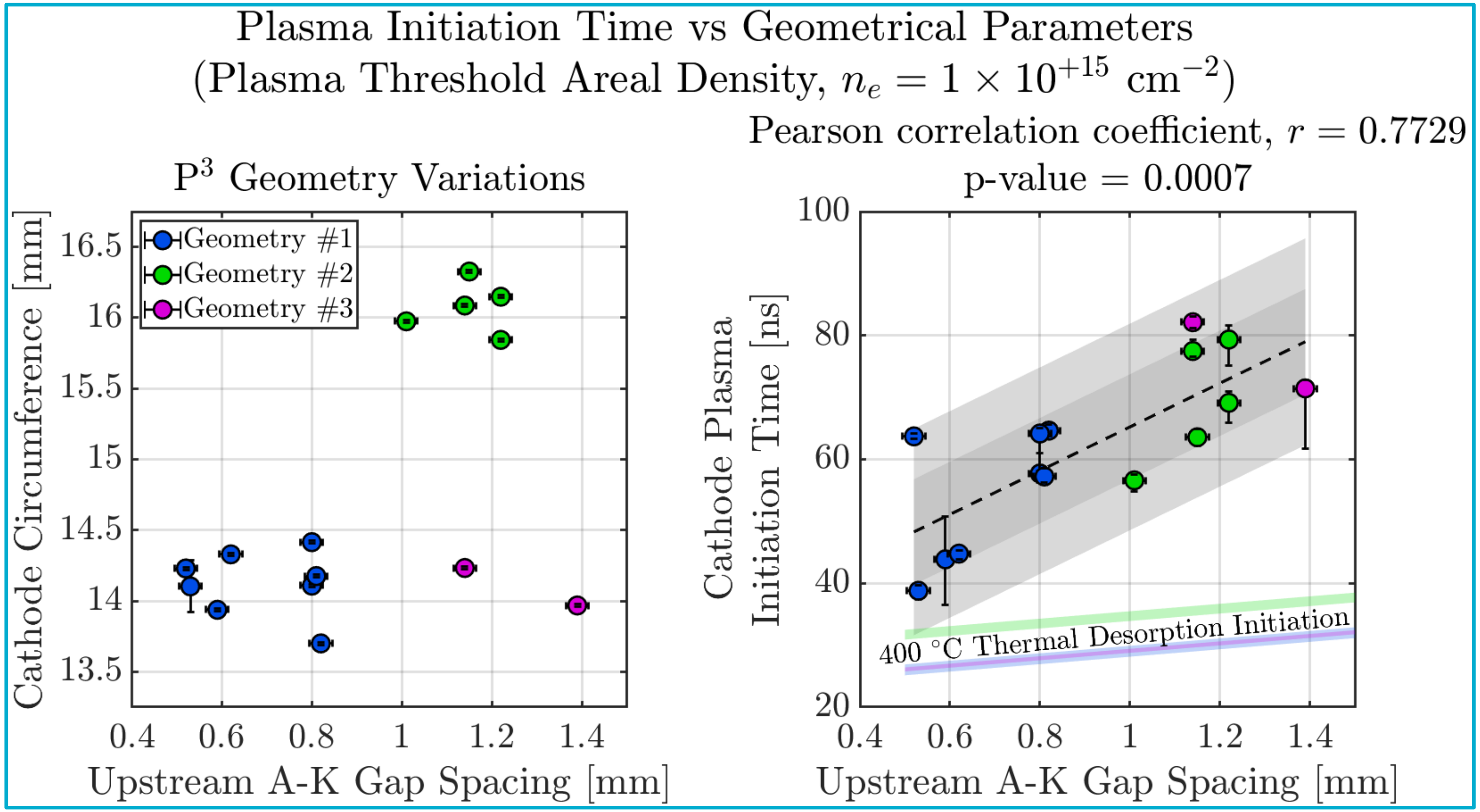
[5] D. Lamppa, S. Simpson, B. Hutsel, M. Cuneo, G. Laity, and D. Rose, "Assessment of Electrode Contamination Mitigation at 0.5 MA Scale," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2021.

Second-Harmonic Orthogonally Polarized Dispersion Interferometer (SHOP-DI) diagnostic design for Mykonos



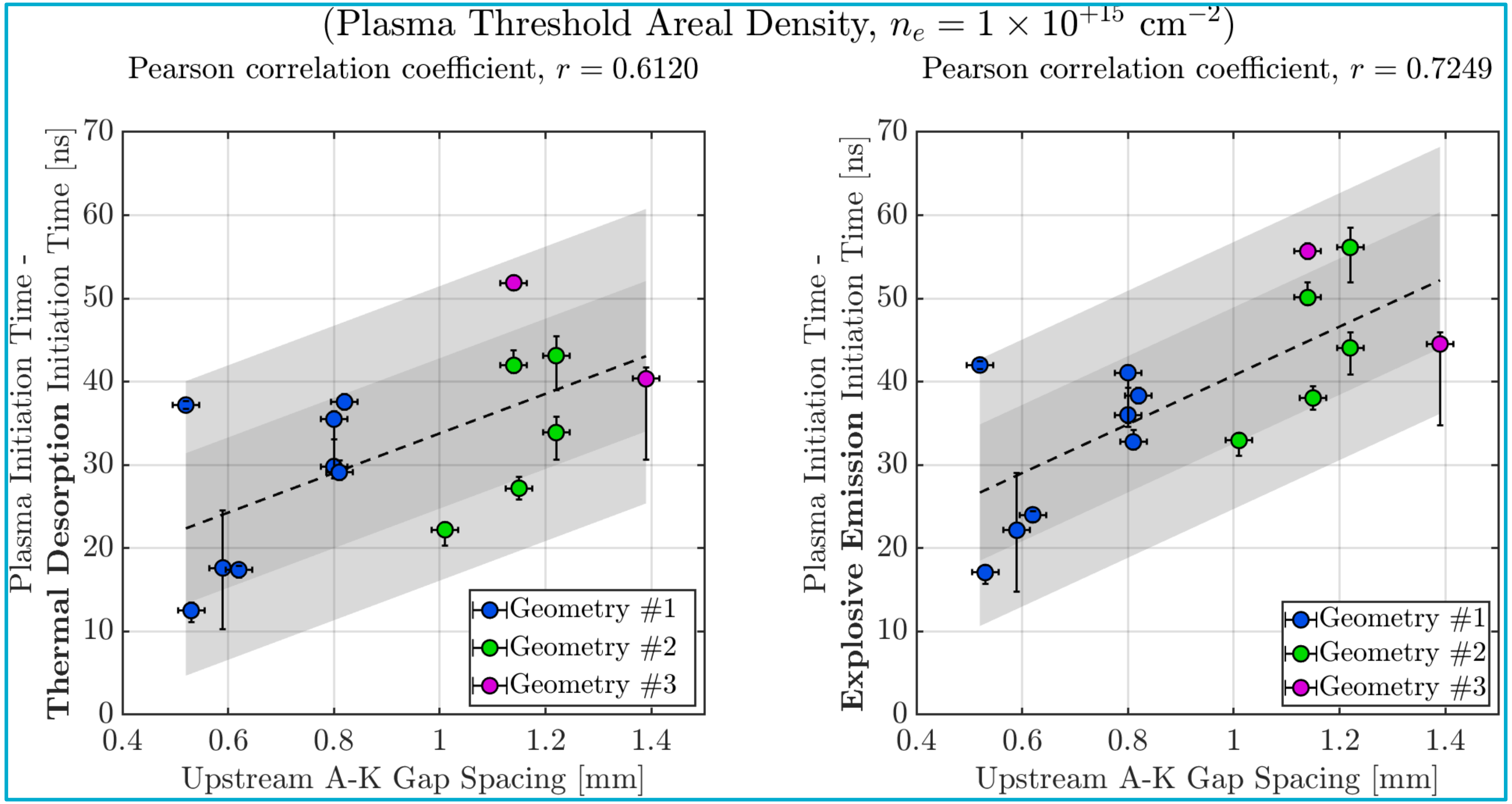
P^3 Hardware Geometric Effects on the Plasma Initiation Time

- Several P^3 geometries were utilized, varying the Cathode circumference and A-K gap spacing:
  - Larger Cathode circumferences reduce the current density and thus reduce Ohmic heating.
    - Leads to an expected variance in 400 °C thermal desorption initiation of 7 ns.
  - Larger A-K gap spacings reduce both the E-field and current density, thus delaying field emitted particles and reducing ohmic heating.
    - Leads to an expected variance in 400 °C thermal desorption initiation of 6 ns.
    - Leads to a variance in the 240 kV/cm field emission initiation of 7 ns.



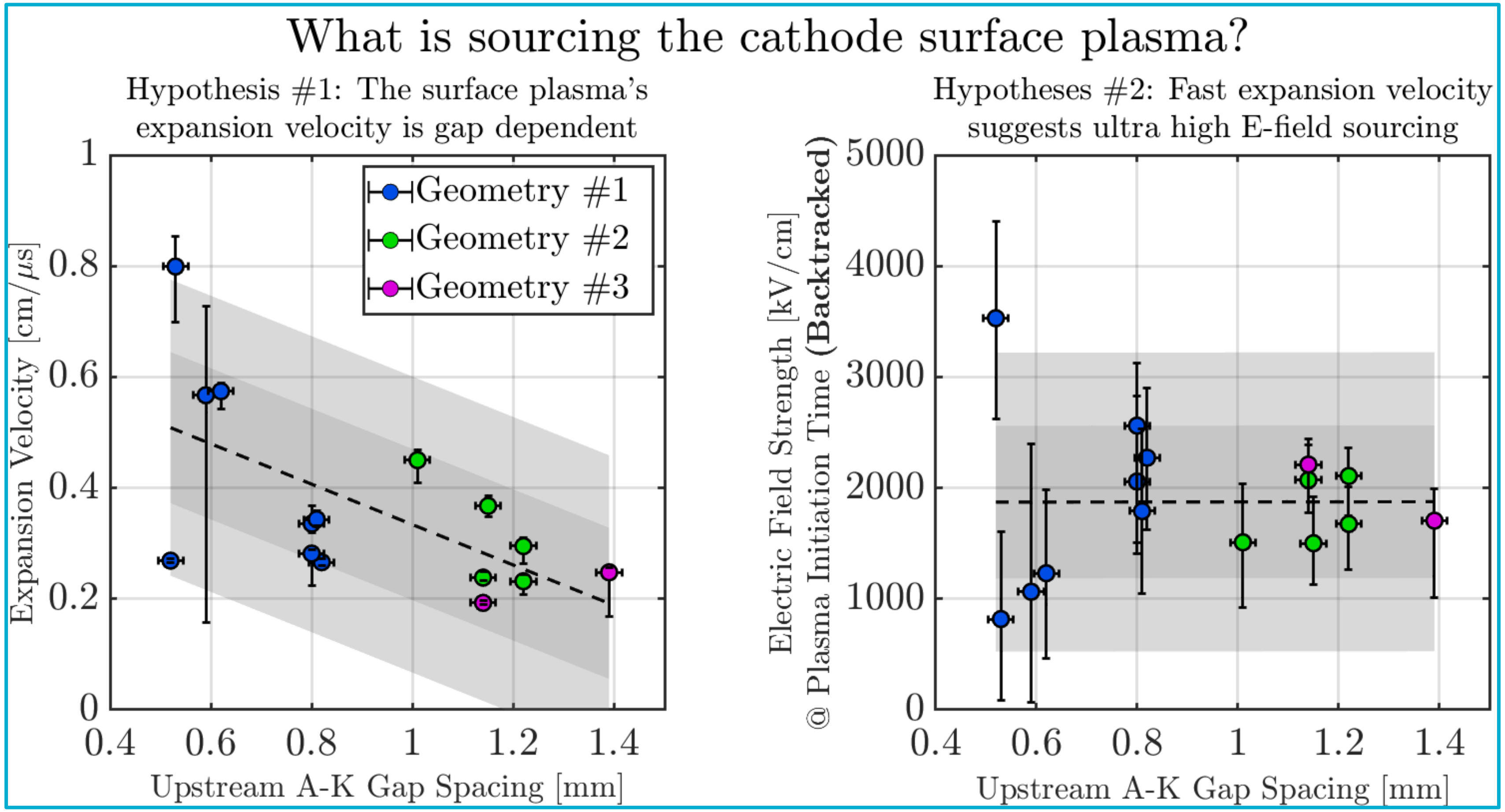
Standard (400 °C) Thermal Emission vs. Enhanced E-Field (240 kV/cm) Explosive Emission

- We can account for the variation in geometric effects by subtracting the expected thermal desorption initiation time.
  - A moderate correlation is shown between the 10^{15} cm^{-2} Cathode plasma detection time as a function of expected 400 °C thermal desorption initiation and the P[3] upstream A-K gap.
- However, the physics sourcing neutrals into the gap (that then ionize to source free electrons), may be dominated by field enhanced explosive emission.
  - A stronger correlation is made when factoring instead the earlier 240 kV/cm field enhanced explosive emission initiation.



Why is There an A-K Gap Dependent Delay Between Plasma Initiation and Plasma Detection?

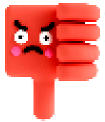
- Perhaps the plasma cross-gap expansion velocity is reduced as the Electric field strength is reduced.
  - A-K gaps expansion velocities would then vary between $0.1 < v_p < 0.5\ \mathrm{cm}/\mu\mathrm{s}$.
- Maybe ultra high E-field sources ions that bombard the Cathode, creating the cathode plasma that expands at faster velocities.
  - Backtrack formation time assuming a faster cathode plasma expansion velocity and known probing location.
  - Find that plasma initiation consistently potentially occurred at Electric fields of ~ $1.87 \pm 0.66\ \mathrm{MV/cm}$.
  - This matches the expected ultra high field strengths from [6]



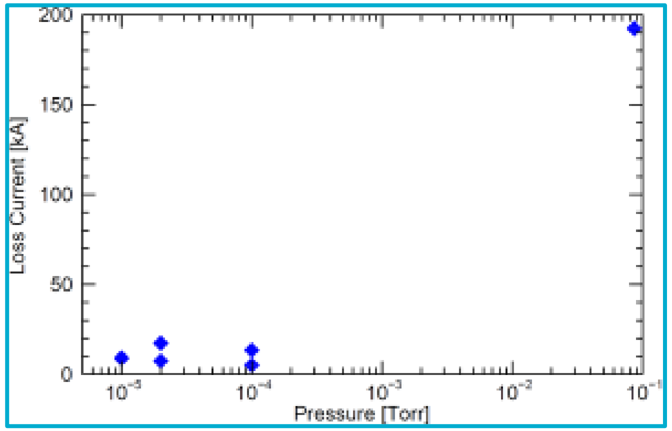
[6] D. J. Johnson et al., IEEE Transactions on Dielectrics and Electrical Insulation, vol. 13, no. 1, pp. 52-64, Feb. (2006)

The P^3 Vacuum Pressure Does Not Effect the Plasma Initiation

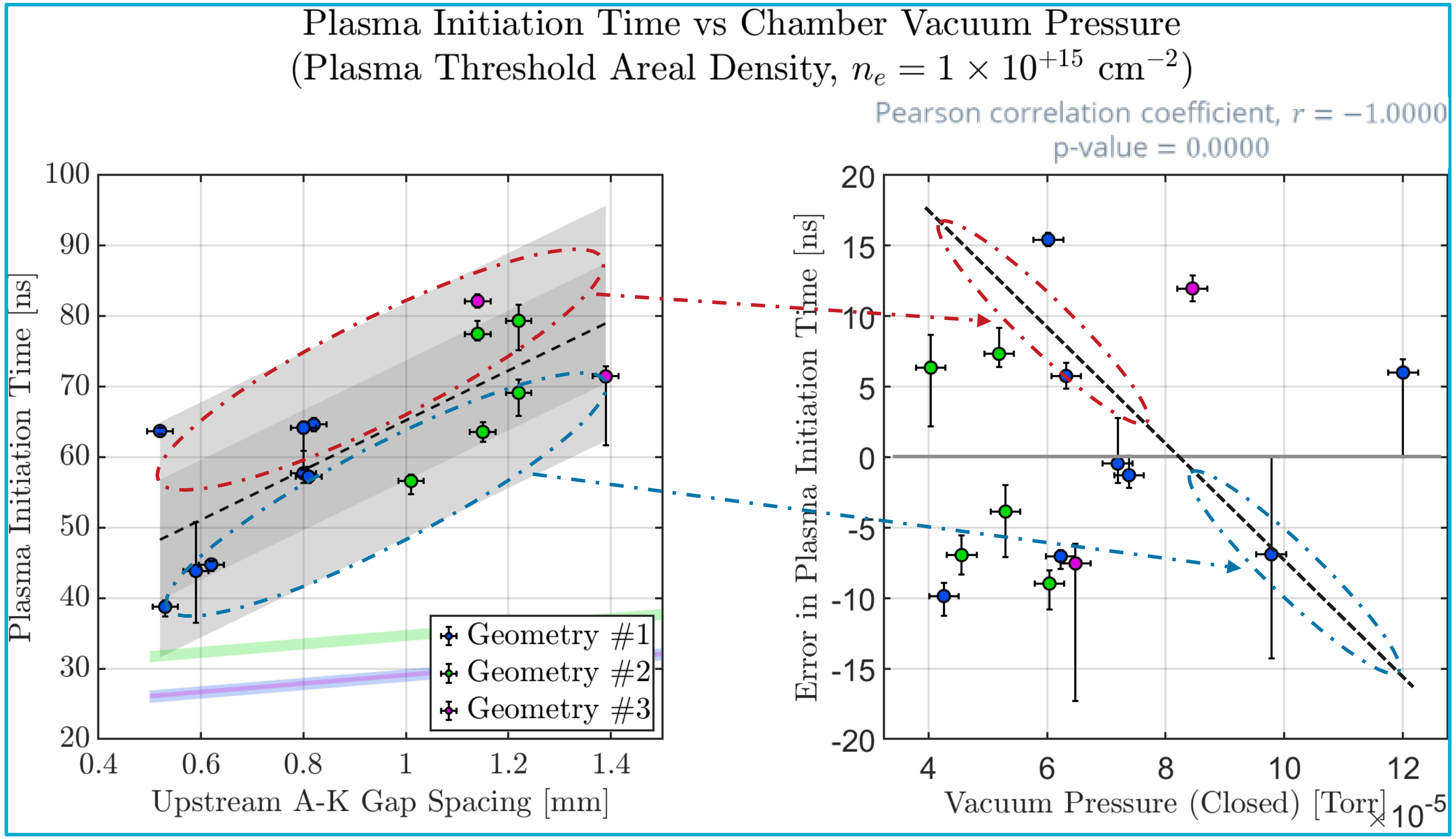
- Are the later than expected plasma formations caused due to less surface contaminates via a longer pump down duration (i.e. a lower downline vacuum pressure)?



- Within the mid– to high–10^{-5} Torr vacuum pressure region, there is no significant correlation to the plasma initiation times for these P^3 hardware sets.



- There is evidence of more extreme vacuum pressure differences effecting current loss.



[7] B. Hutsel et al., "Millimeter-Gap Magnetically Insulated Transmission Line Power Flow Experiments," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2014.

Conclusions

- There is a need to better understand Power Flow physics and Current Loss contributors.
- The SHOP-DI diagnostic at SNL can measure electrode plasma free electron effective areal densities that are expected to form in the inner MITL and convolute regions of TW-class accelerators like the Z machine.
  - $\langle n_e L \rangle_{\mathrm{min}} = 6.3 \times 10^{13}\ [\mathrm{cm}^{-2}]$ $(4.11\ [\mathrm{mrad}]$ sensitivity)
  - $\Delta \langle n_e L \rangle_{\mathrm{max}} = 4.8 \times 10^{16}\ [\mathrm{cm}^{-2}/\mathrm{ns}]$ $(2\ [\mathrm{GHz}]$ bandwidth)
- Preliminary experimental studies of Cathode plasma formation were conducted.
  - Variety of Ohmic heating rates and E-field strengths.
    - Perhaps the cathode plasma expansion velocity is lower than thought and is inversely related to A-K gap.
    - Or maybe plasma expansion velocity is higher and ultra high E-field cathode plasma initiation is occurring.
  - Mid- to high- 10^{-5} Torr vacuum pressure variances do not play a significant role.

SUPPLEMENTARY SLIDES

Conclusion

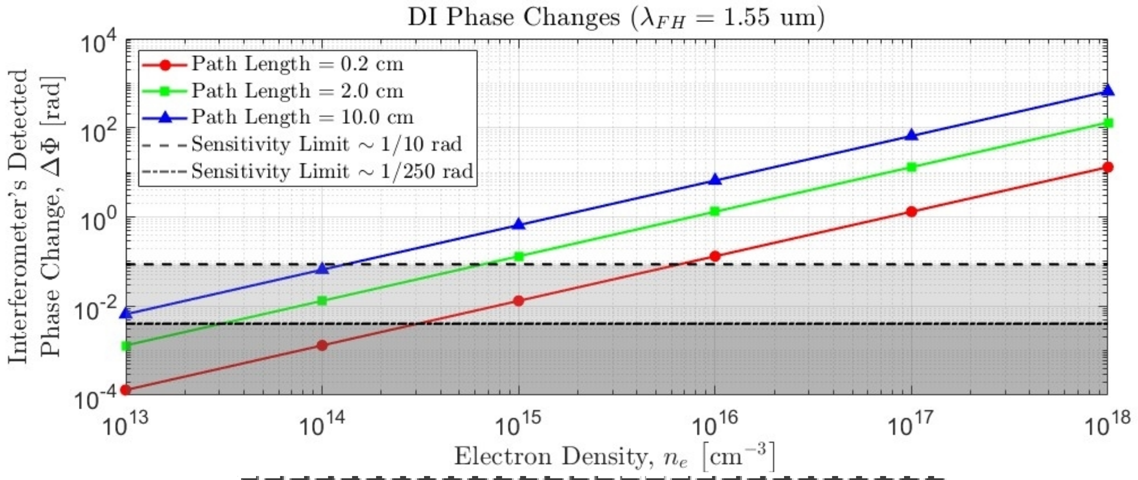
- The areal density is considered "free electron effective" since it's calculated assuming the plasma's **refractive index** is solely affected by free electrons.
  - There may in fact be substantial bound electrons that are affecting (positively) the detected phase change, thus affecting (negatively) the calculated electron areal density below reality. So, this is really a minimum free electron areal density measurement.

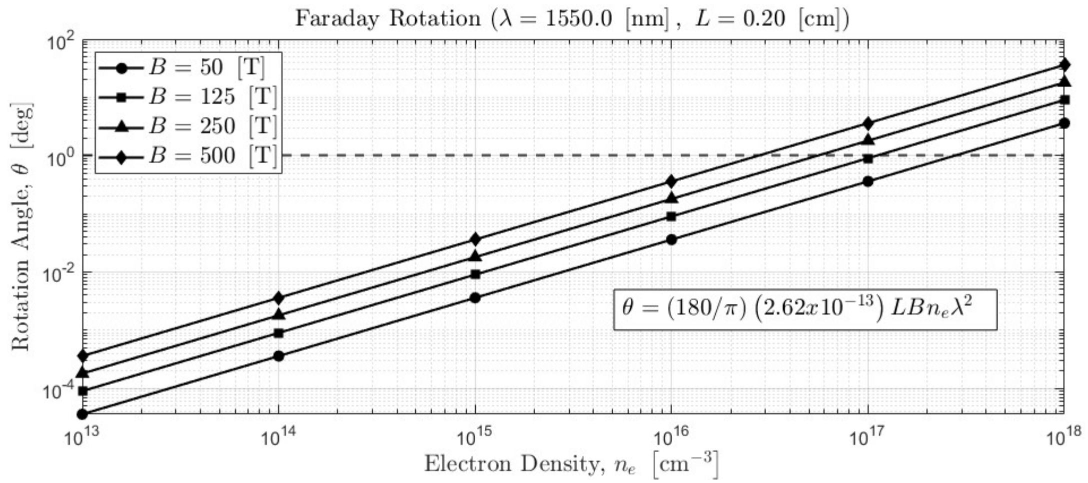
SUPPLEMENTARY PLOTS OF PARAMETER RELATIONSHIPS

R-L Wave: $\vec{k} \parallel \vec{B}$

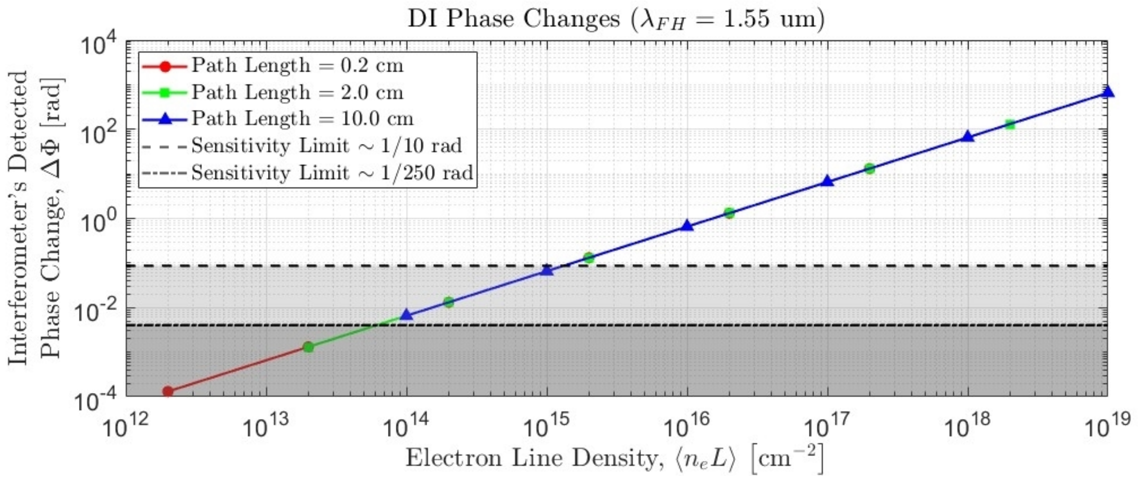
$$\tilde{n}^2 = 1 - \frac{\omega_p^2/\omega^2}{1-(\omega_c/\omega)} \quad \text{(R Wave)}$$

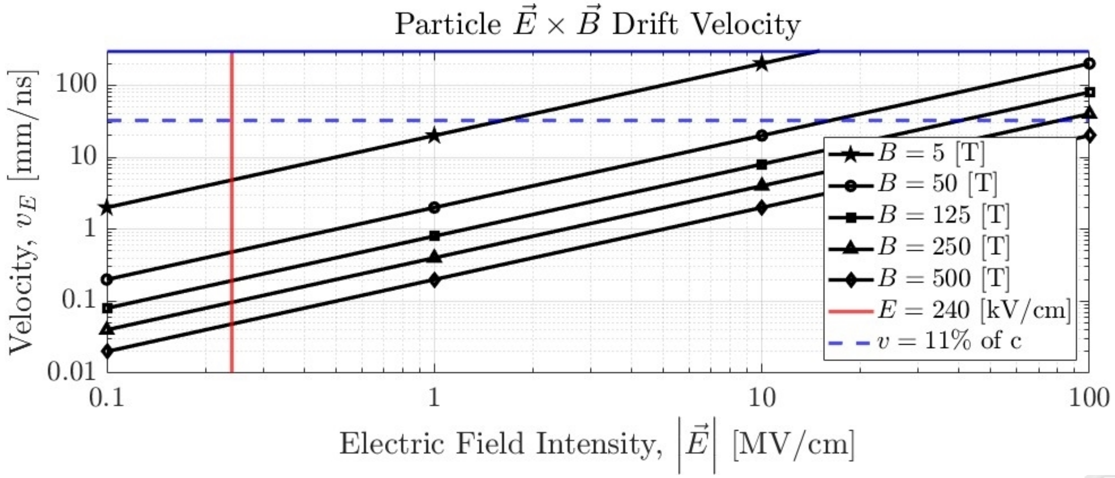
$$\tilde{n}^2 = 1 - \frac{\omega_p^2/\omega^2}{1+(\omega_c/\omega)} \quad \text{(L Wave)}$$



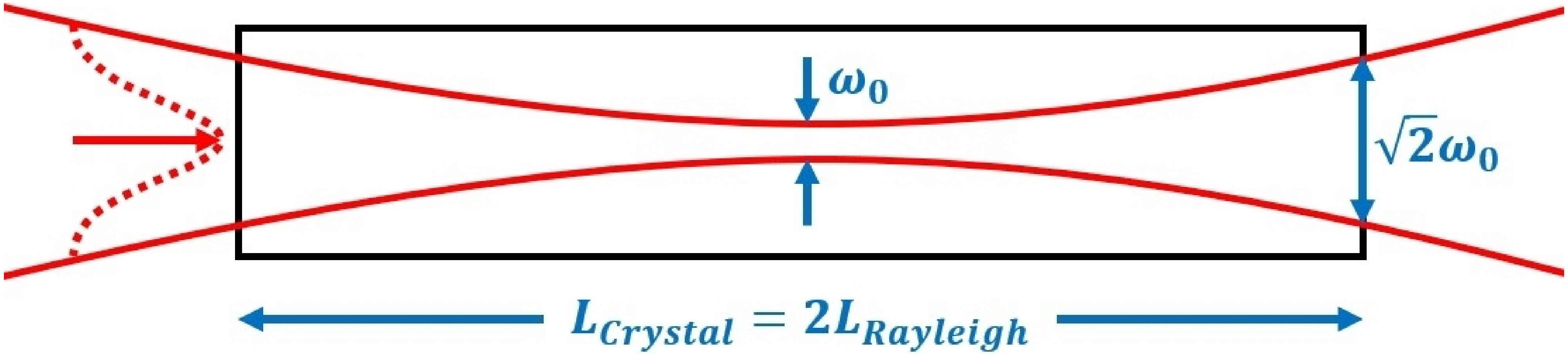


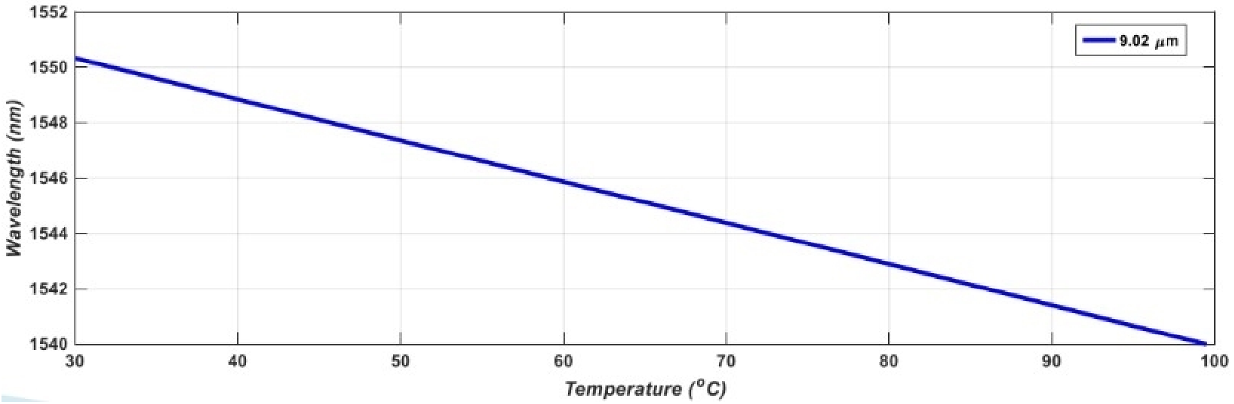
$$\langle n_e l \rangle\ [\mathrm{cm}^{-2}] = (-1.53 \times 10^{16})\,\Delta\Phi\ [\mathrm{rad}]$$

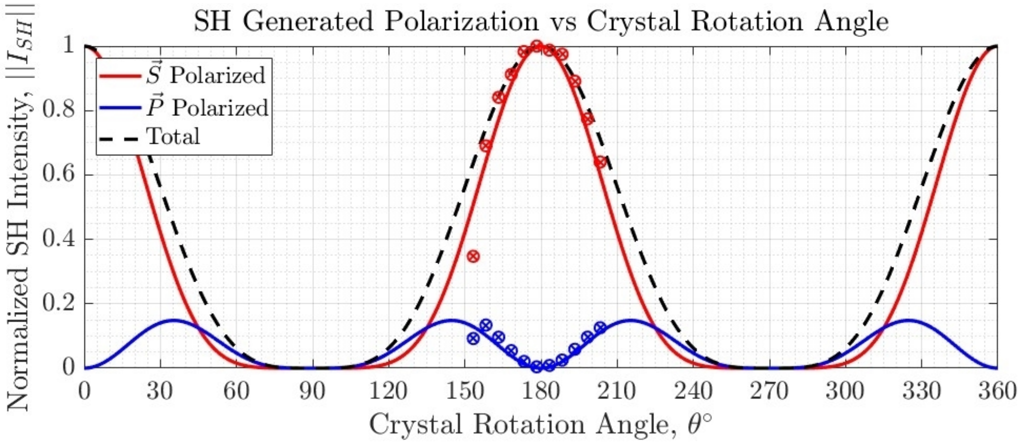




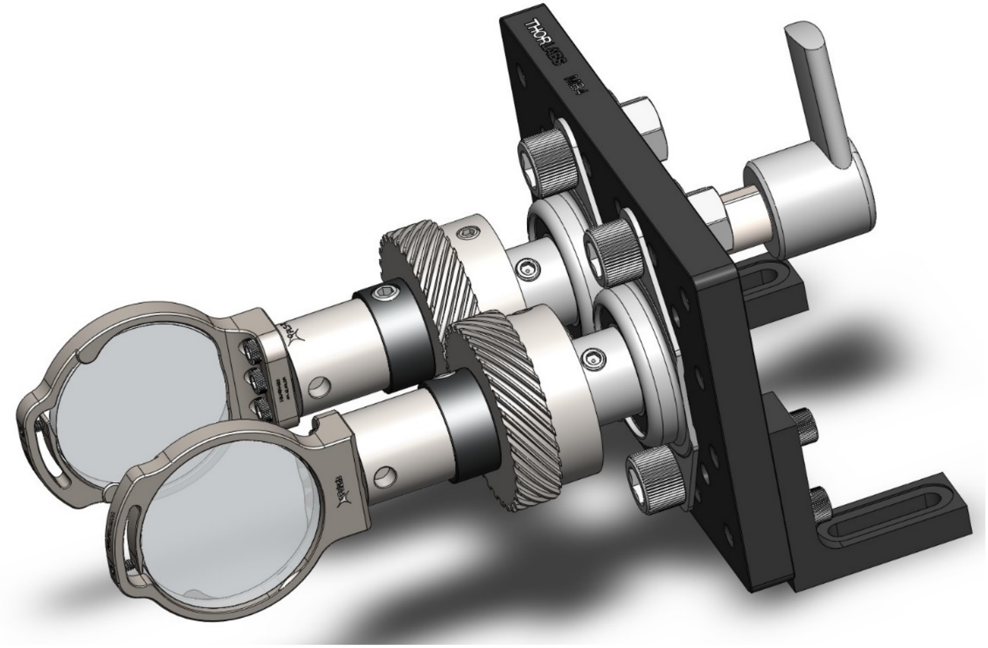
SECOND HARMONIC GENERATION EFFICIENCY IS FUNCTION OF TEMPERATURE, BEAM FOCUSING PARAMETERS, AND POLARIZATION

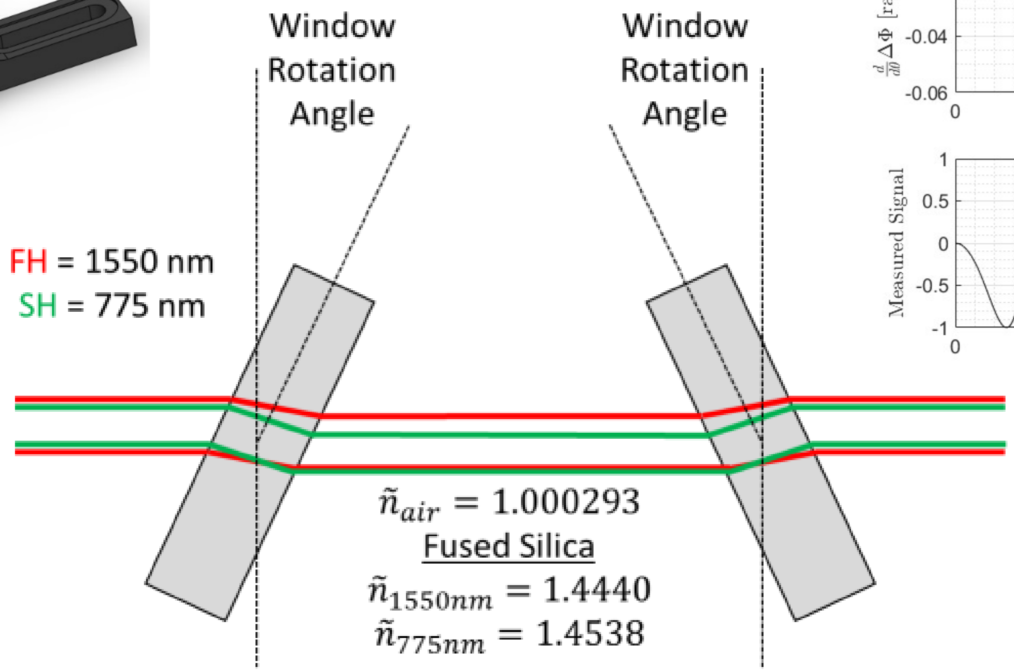


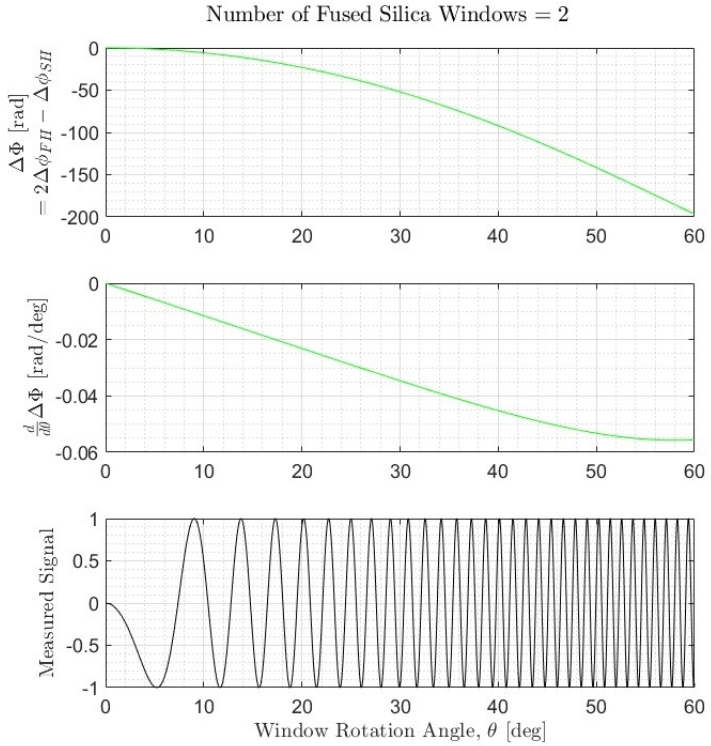




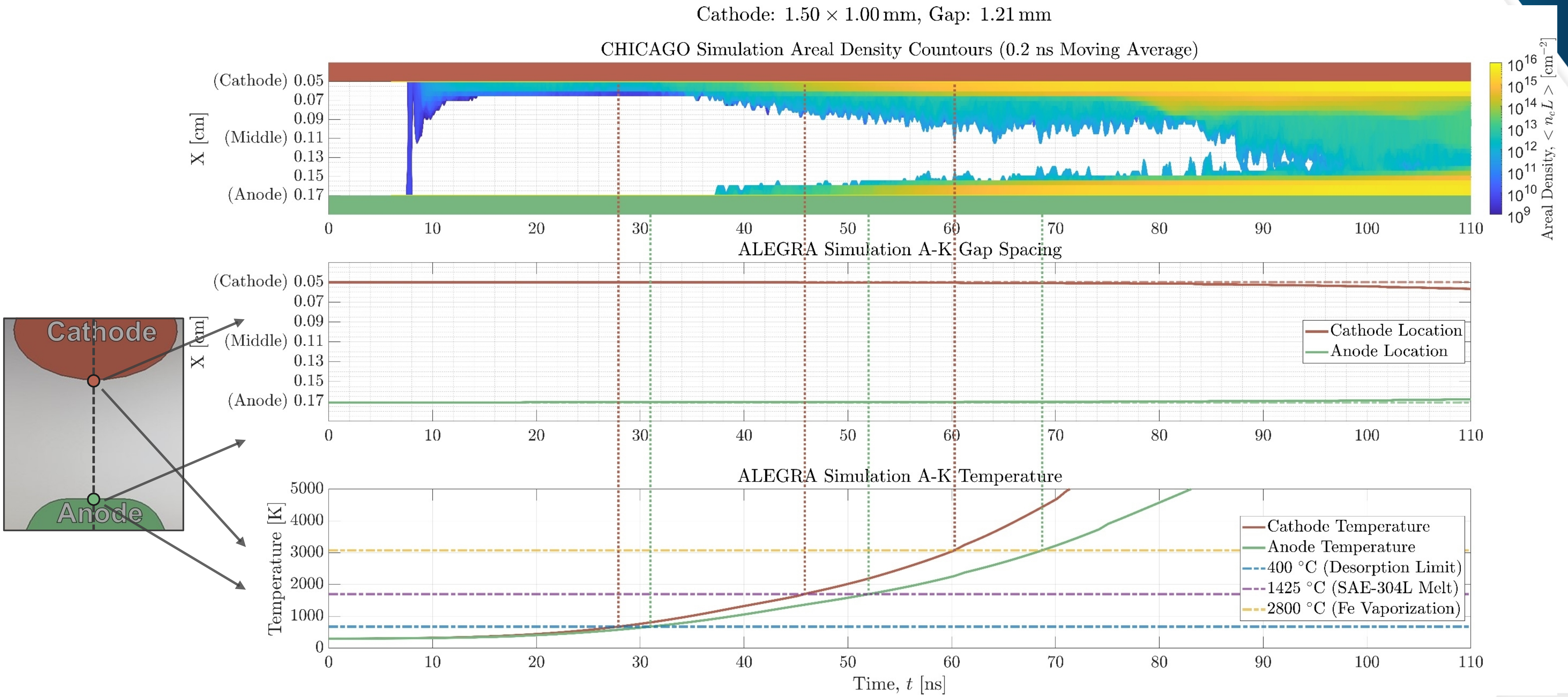
Phase Control Windows



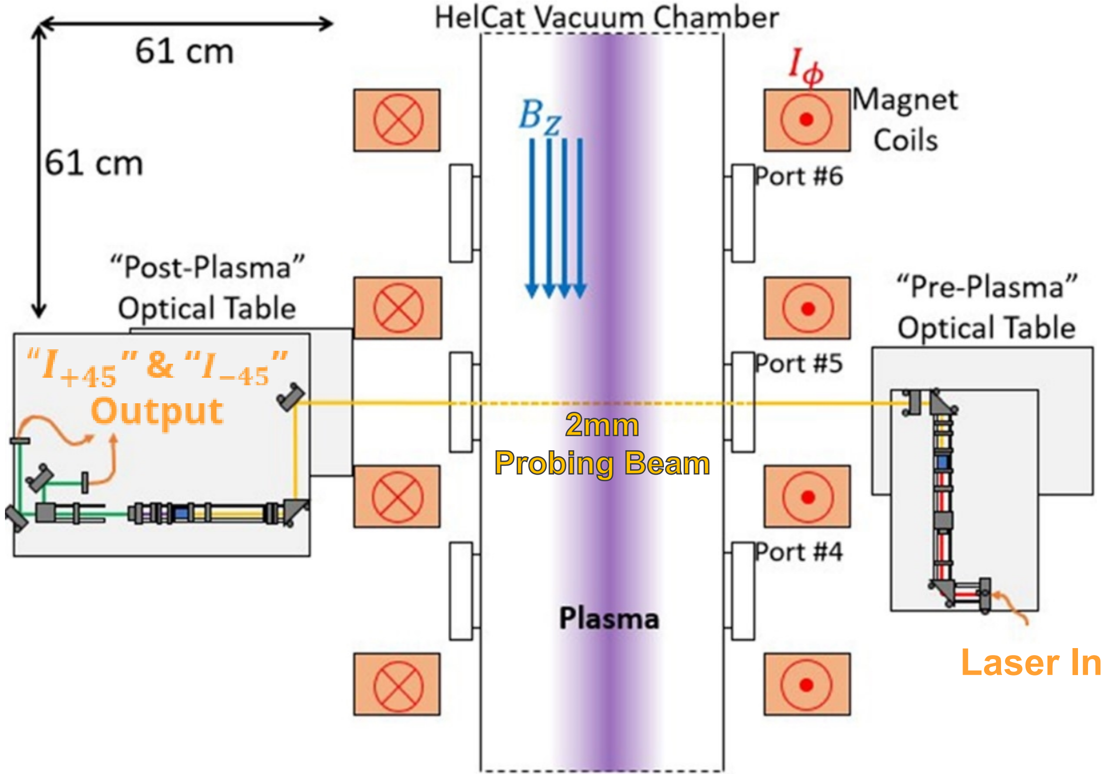


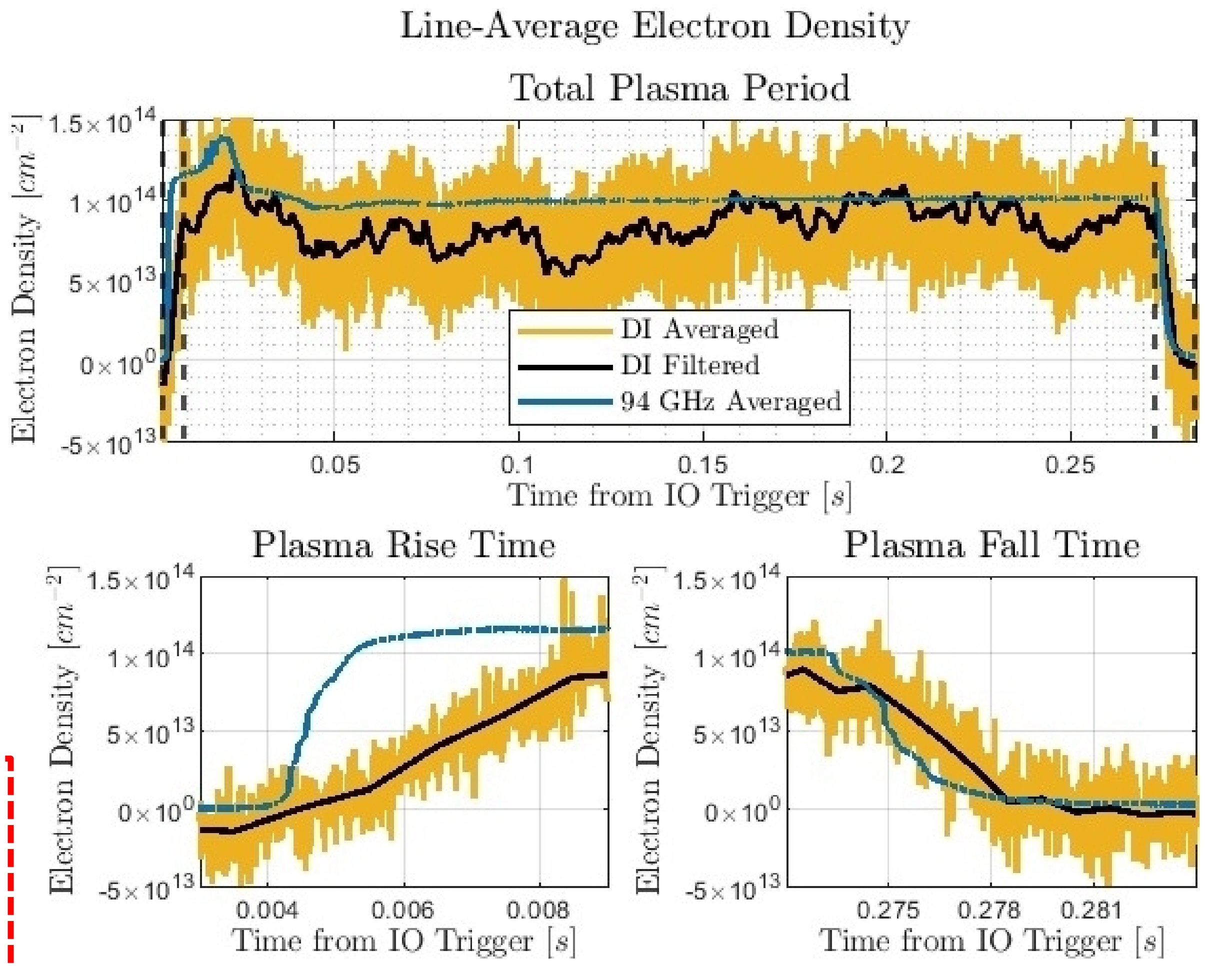


CHICAGO & ALEGRA simulations



SHOP Interferometer Install on the UNM HelCat Plasma Device Verified Functionality for Low Density Measurements





[5] N. R. Hines et al., "A fiber-coupled dispersion interferometer for density measurements of pulsed power transmission line electron sheaths on Sandia's Z machine," Review of Scientific Instruments, vol. 93, no. 11, p. 113505, November 2022.