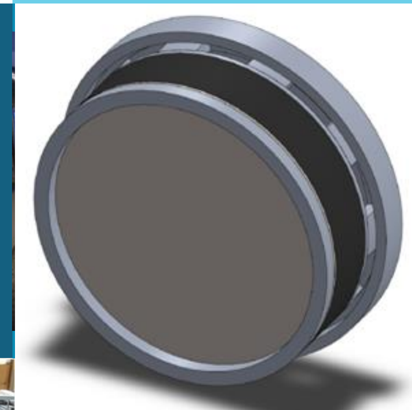
SAND2022-14738C

Sandia National Laboratories

Characterization and Optimization of Bremsstrahlung X-ray Diodes



M.D. Johnston[1], D.V. Rose[2], D.R. Welch[2], T.C. Grabowski[1]

[1]Sandia National Laboratories, Albuquerque, NM 87185, USA

[2]Voss Scientific, LLC, Albuquerque, NM 87108, USA

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Abstract

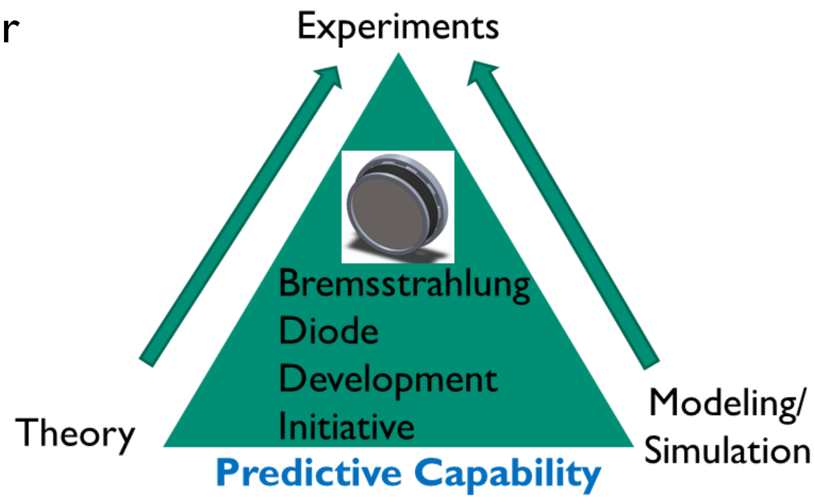
Investigations are underway at Sandia National Laboratories looking into characterization and optimization of bremsstrahlung x-ray diodes operating in the >10 MeV regime using the CHICAGO™ particle-in-cell code. These diodes typically use a hollowed-cathode geometry to form a circular beam on a high Z metal target. This paper will discuss driver target impedance matching, look at beam uniformity on target, estimate anode surface temperatures, and examine near and far-field dose predictions. Other cathode geometries such as a solid hemispherical ball will be considered as well. All geometries are designed to keep the anode surface temperature below 400° C to prevent ion formation and beam pinching to the axis. Anode target geometry will be discussed including the advantages and disadvantages of specific materials such as titanium and tantalum. Comparisons will be made to previous HERMES III and RITS-6 experimental bremsstrahlung diodes data.

Outline

- Overview
- HERMES III hollow-cathode diode geometry at 20MeV
  - Comparison of new PIC simulations to historical data for model verification
- Scaled, lower voltage, hollow-cathode geometry PIC simulations at 13MeV
  - New machine parameters
- Solid, semi-hemispherical cathode geometry PIC simulations at 13MeV
  - Reduction of high-current density on axis
- RITS-6 experimental data using semi-hemispherical shaped cathode at 10MeV
- Summary and Future Work

Objectives

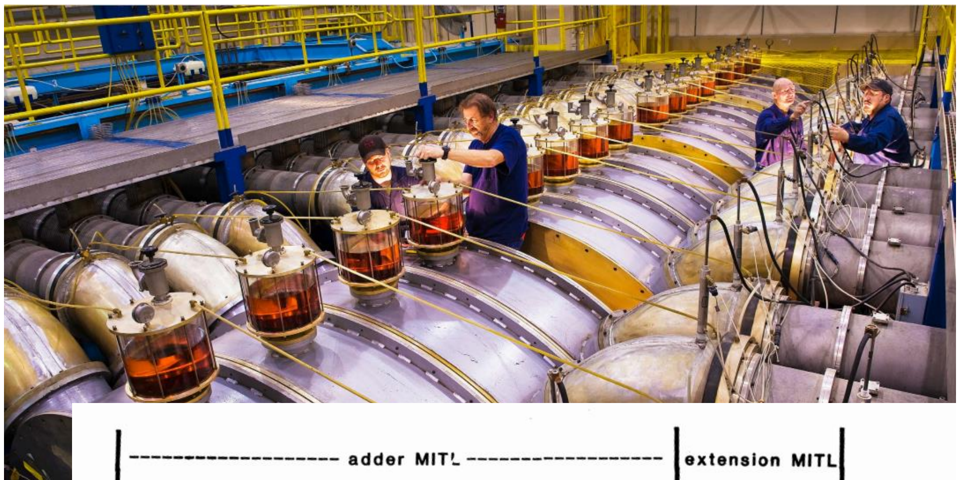
- Design a new e-beam bremsstrahlung diode for operations at endpoint energies >10 MeV.
- Optimize on target beam uniformity and total x-ray dose output.
- Allow multiple shots without breaking vacuum by maintaining a minimal (< 400°C) surface temperature rise.
- Design diode to fit within a small (≤ 1ft. diameter) spatial region, to enable ease of coupling to various experimental facilities.

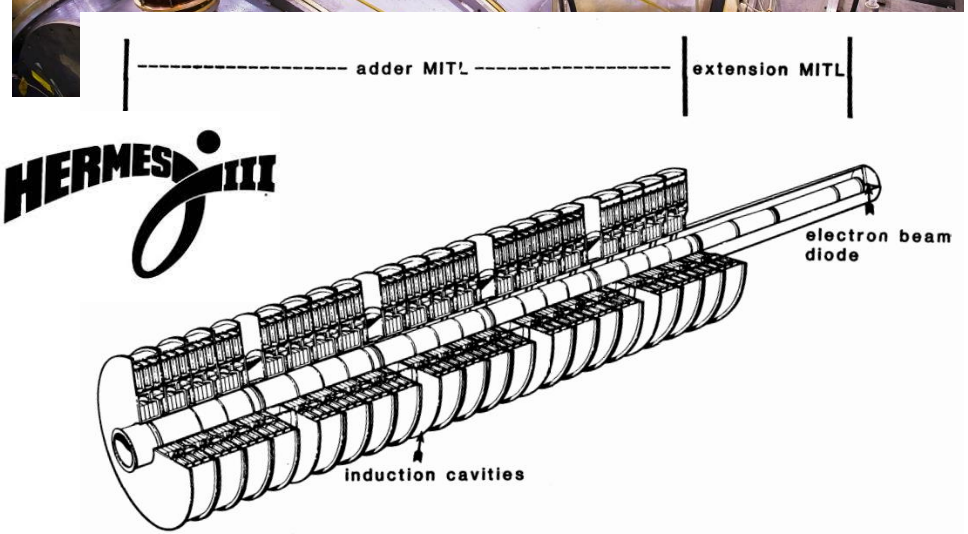


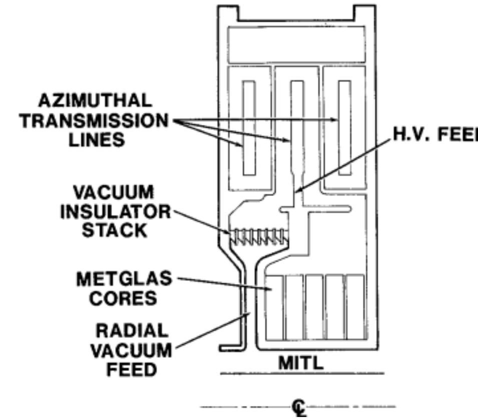
- Develop a predicative modeling capability, using PIC (ex. CHICAGO™ and EMPIRE) and radiation transport codes (ITS, CYLTRAN), to tailor diode geometries to accelerator drive parameters.
- Expand theoretical interpretation of e-beam diode physics to explain phenomena such as current filamentation, electron bunching, and instabilities.

HERMES III Pulsed-Power Accelerator at Sandia National Laboratories

HERMES (High-Energy Radiation Megavolt Electron Source) III is a 20 MeV, 700kA, 25ns Marx driven twenty-stage Inductive Voltage Adder (IVA)[1]



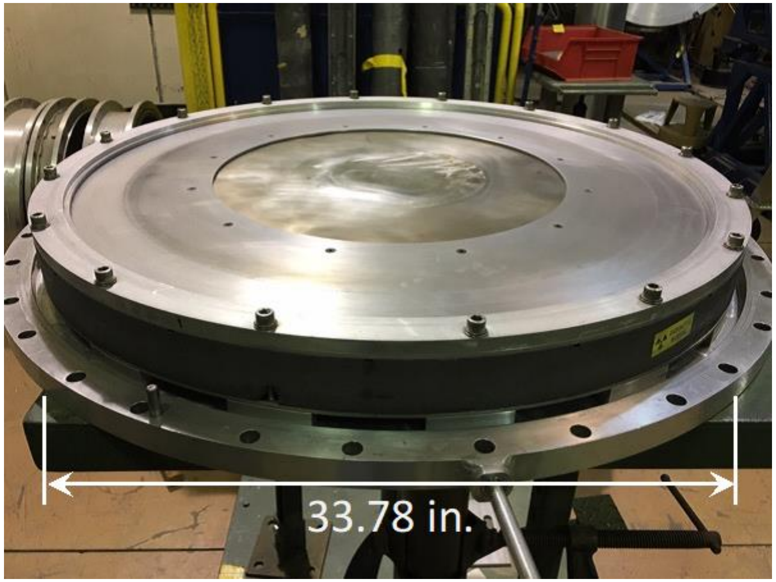




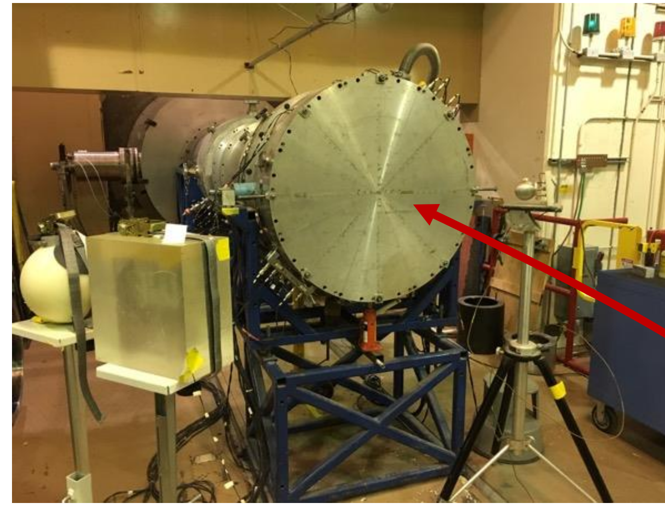
HERMES III Induction Cavity

[1] J.J. Ramirez, Proc. Particle Accel. Conf., Chicago, IEEE Cat. No. 89CH2669-0, p. 1446 (1989).

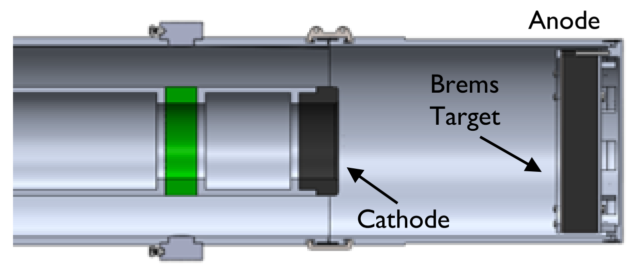
HERMES III Bremsstrahlung Diode

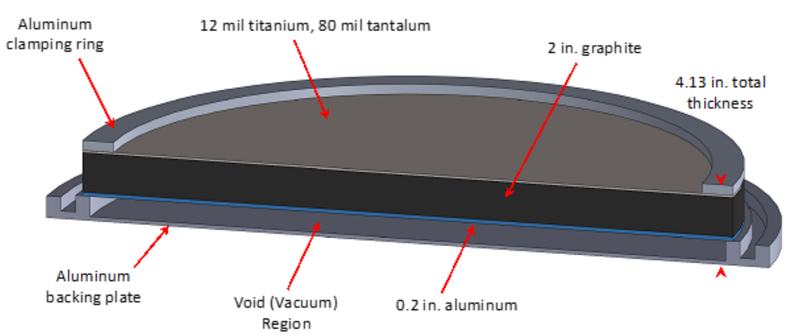


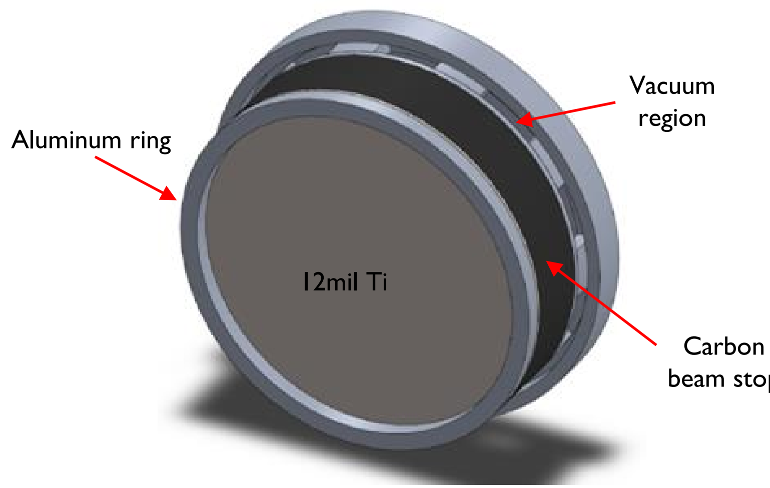
HERMES Bremsstrahlung Converter



End-on view of HERMES III Backplate





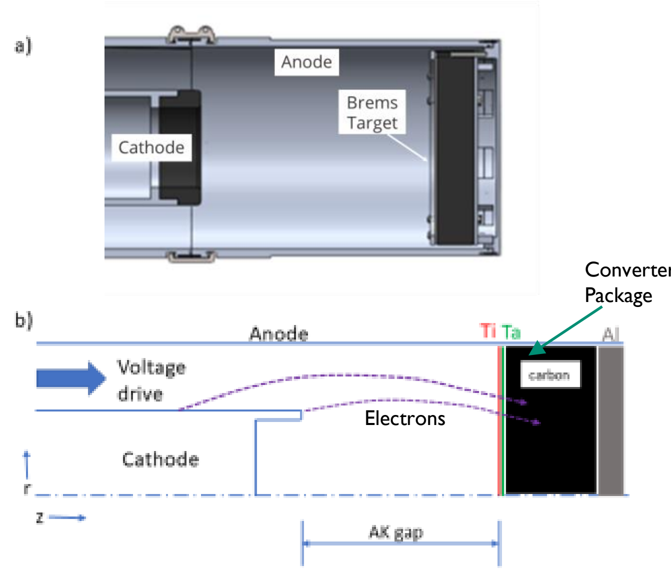


HERMES Converter Package

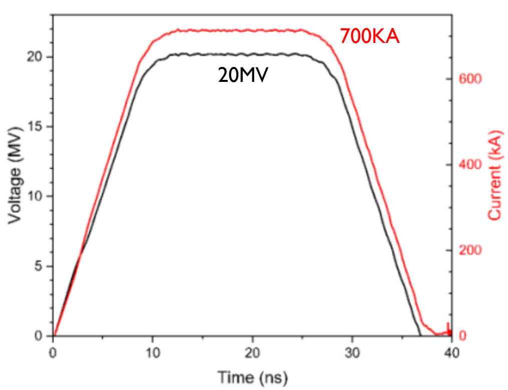
CHICAGO™ Simulation model[2,3]

- Typical diode configuration on HERMES III
  - Cathode diameter ~14.5 in. (36.8cm)
  - Anode (target) diameter ~33.75 in. (85.7cm)
  - AK gap 53 ~ 63 cm

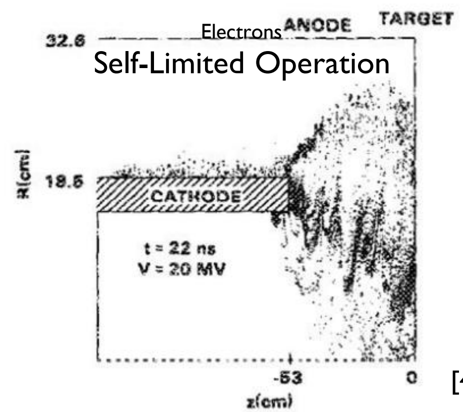
Converter Package
- 12-mil (0.3mm) Titanium
- 80-mil (2.0mm) Tantalum
- 50cm Carbon
- 2.2cm Aluminum



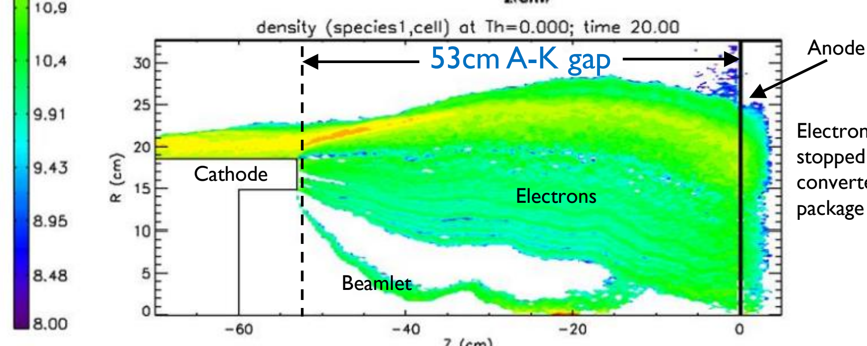
2D (r,z) axisymmetric simulation setup



Idealized voltage and current waveforms used in HERMES III simulations



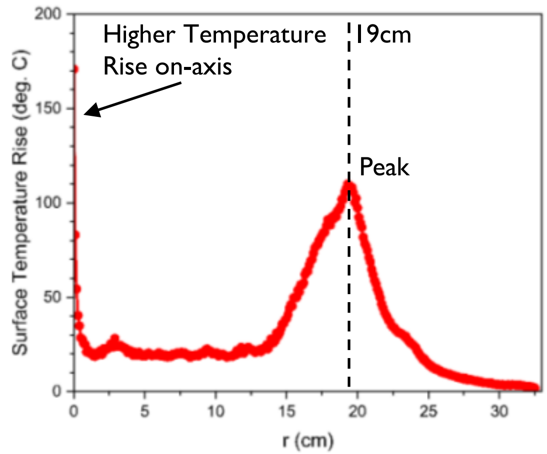
[4] Sanford: 1988



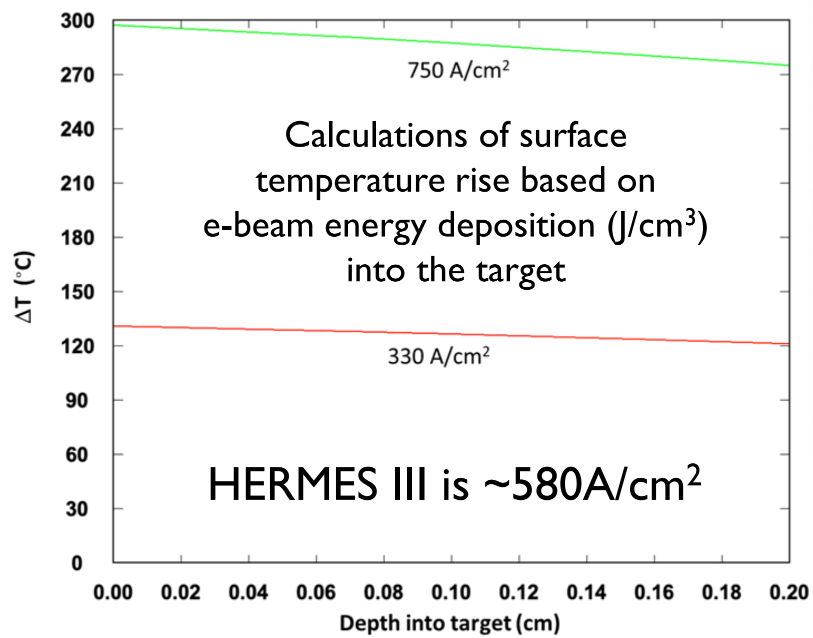
D.V. Rose: 2022

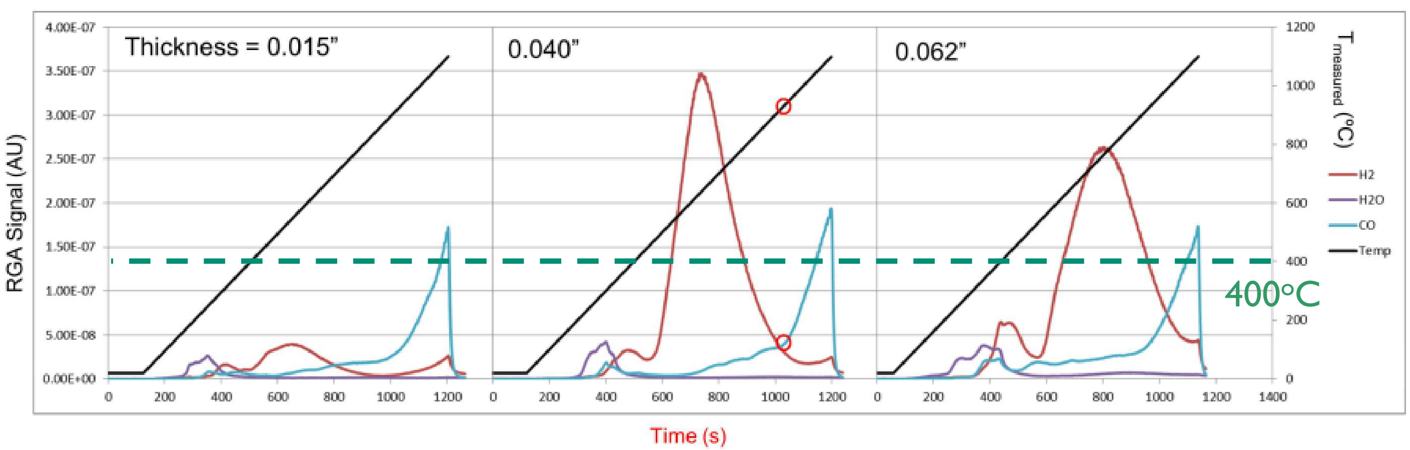
[2] C. Thoma, *et al.*, Phys. Plasmas, 24, 062707 (2017)
[3] D.R. Welch, *et al.*, Phys. Rev. Accel. Beams 23, 110401 (2020)
[4] T.W. L. Sanford, *et al.*, Nucl. Instrum. Meth. Phys. Res. B34, 347 (1988)

Anode Foil: Surface Temperature Measurements and Calculations



Calculated Ti foil surface temperature rise as a function of radius





Want to keep ΔT < 400°C to suppress ion formation

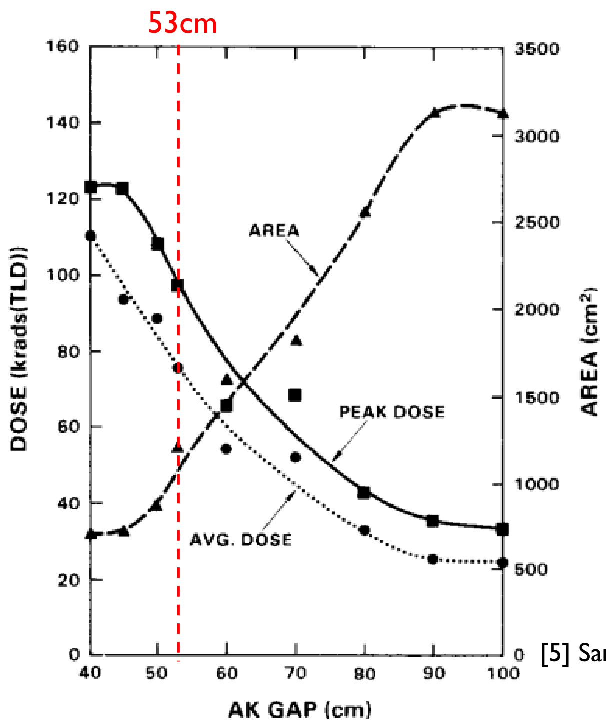
H_2 peak at T= 548 °C
H/Ta = 0.067
~.00119 mols of H

H_2 peak at T= 640 °C
H/Ta = 0.147
~.00696 mols of H

H_2 peak at T= 764 °C
H/Ta = 0.093
~.00683 mols of H

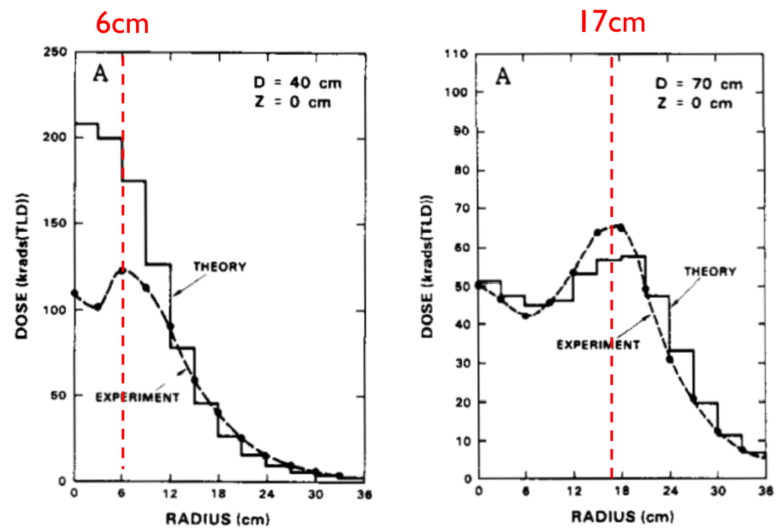
Experimental temperature programed desorption (TPD) of 1" diameter Ta foils

HERMES III Peak and Average Dose Measurements



[5] Sanford: 1989

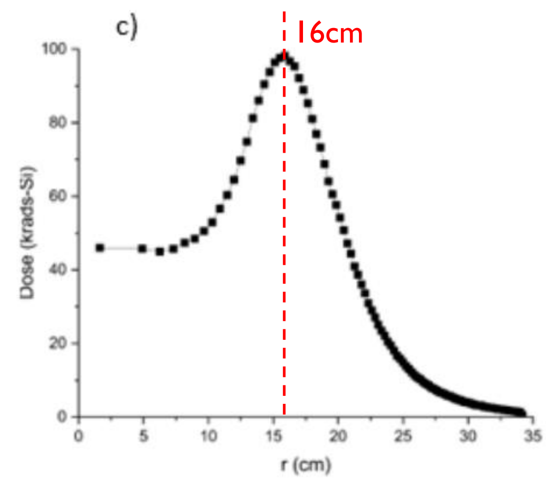
Experimental peak and average dose as a function of A-K gap spacing



[5] Sanford: 1989

Experimental radial dose profiles at 40cm and 70cm A-K gaps

Simulated peak and average dose of 98kRad and 76kRad, respectively.

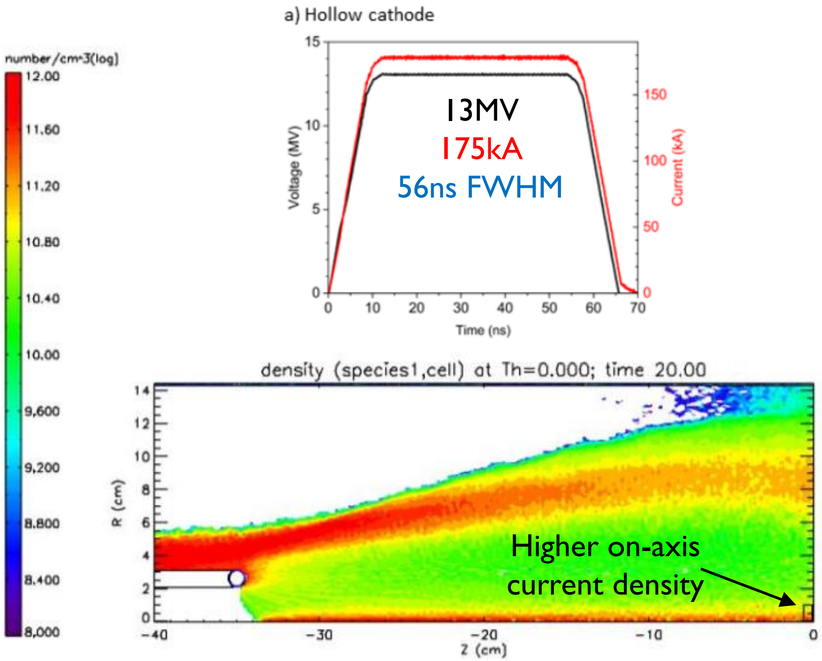


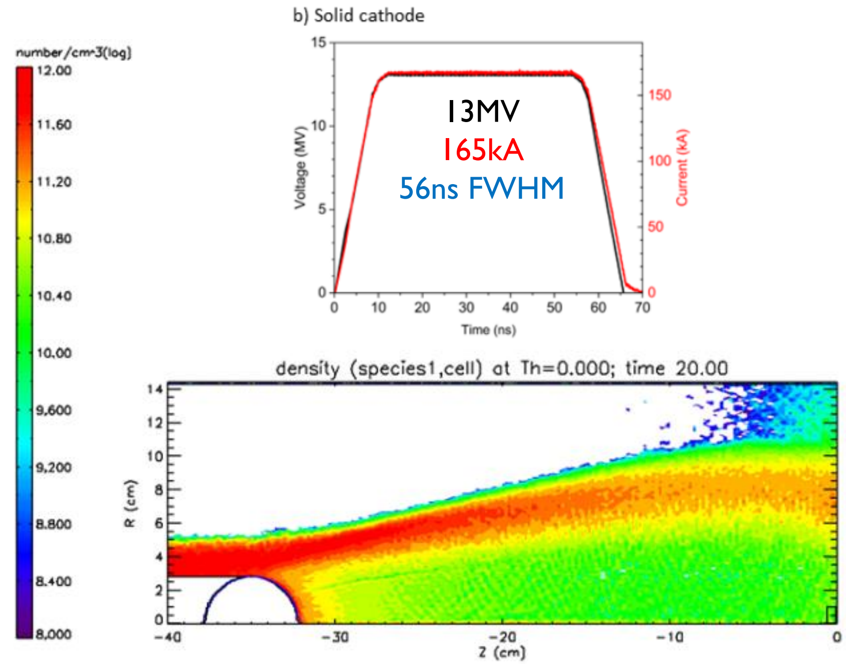
D.V. Rose: 2022

Simulated radial dose profile at 53cm A-K gap

[5] T.W. L. Sanford, *et al.*, IEEE Trans. Nucl. Sci., 36, 1391 (1988)

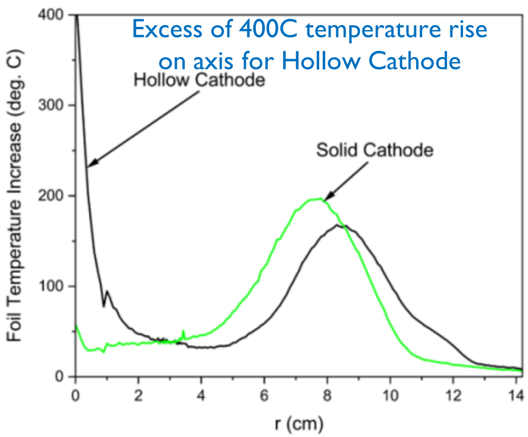
13MV Simulation Results (New Machine Parameters)

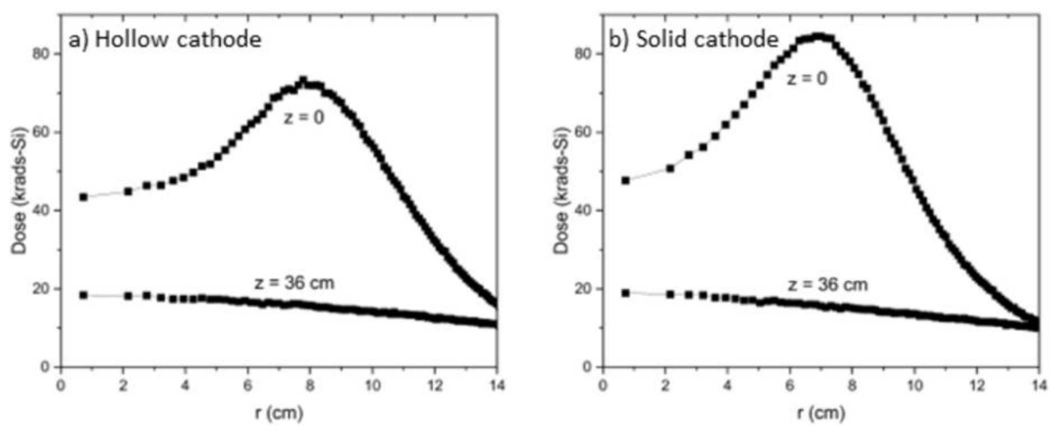




Cathode diameter: 6.2cm
Anode diameter: 28.6cm
A-K gap: 35cm

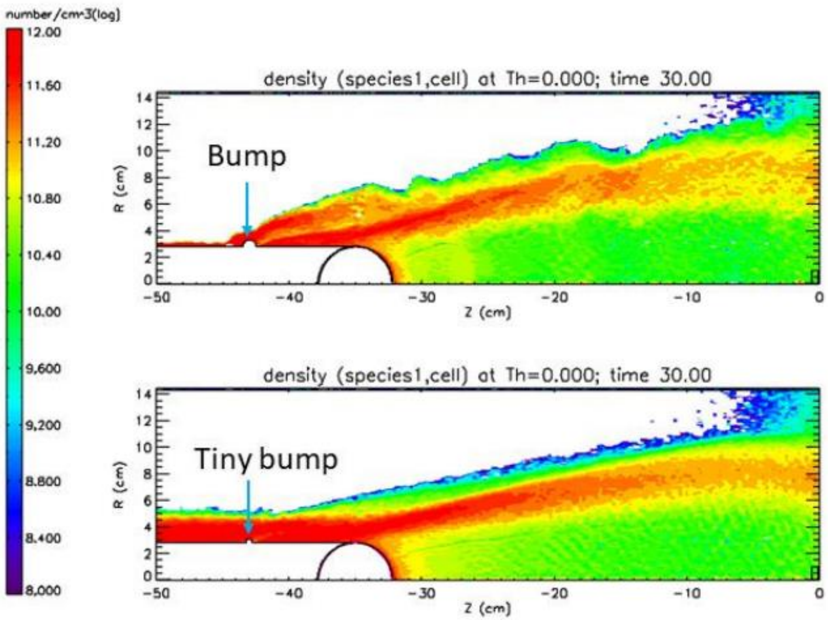
Cathode diameter: 5.6cm
Anode diameter: 28.6cm
A-K gap: 35cm



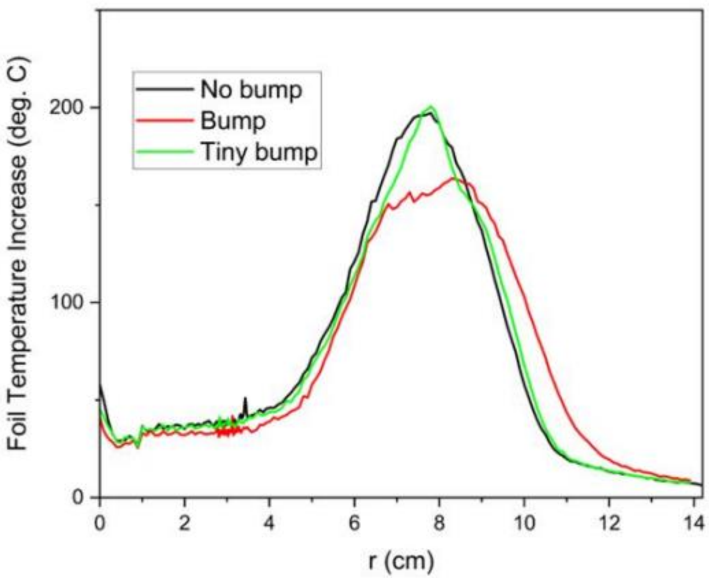


Dose as a function of radius at different axial locations

Affecting MITL Flow Current for Improved Beam-Target Uniformity



Small protrusions ("bumps") added to the surface of the cathode to divert/disrupt the MITL flow.

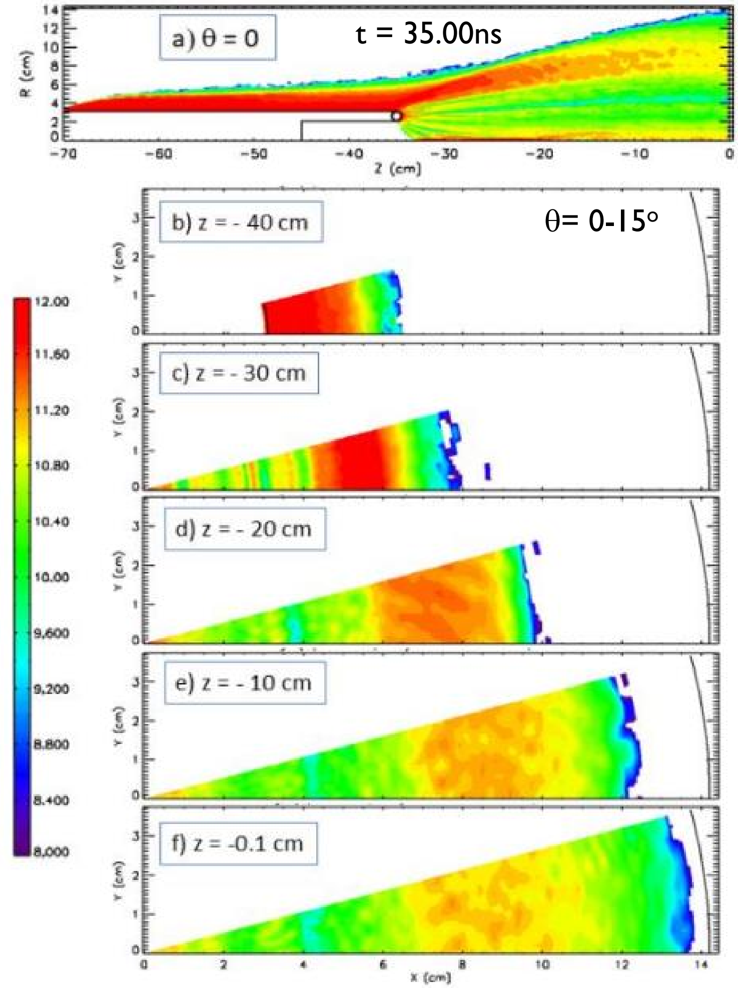


Foil anode temperature rise as a function of radius

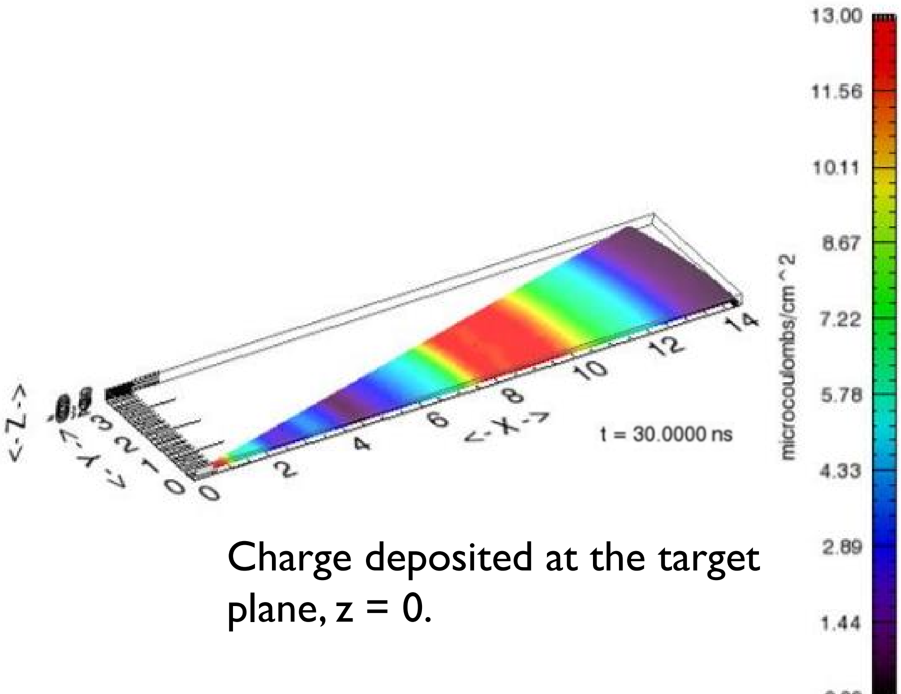
The larger, 5mm cathode bump gave an ~15% decrease in peak foil temperature, but caused a retrapping wave upstream, altering the MITL flow at the cathode.

Future CHICAGO™ Modeling Work

- 3D simulations to investigate beam stability
- Perform x-ray dose calculations using CYLTRAN code[6]
- Validate against new experiments on HERMES III



3D simulation of 13MV Diode

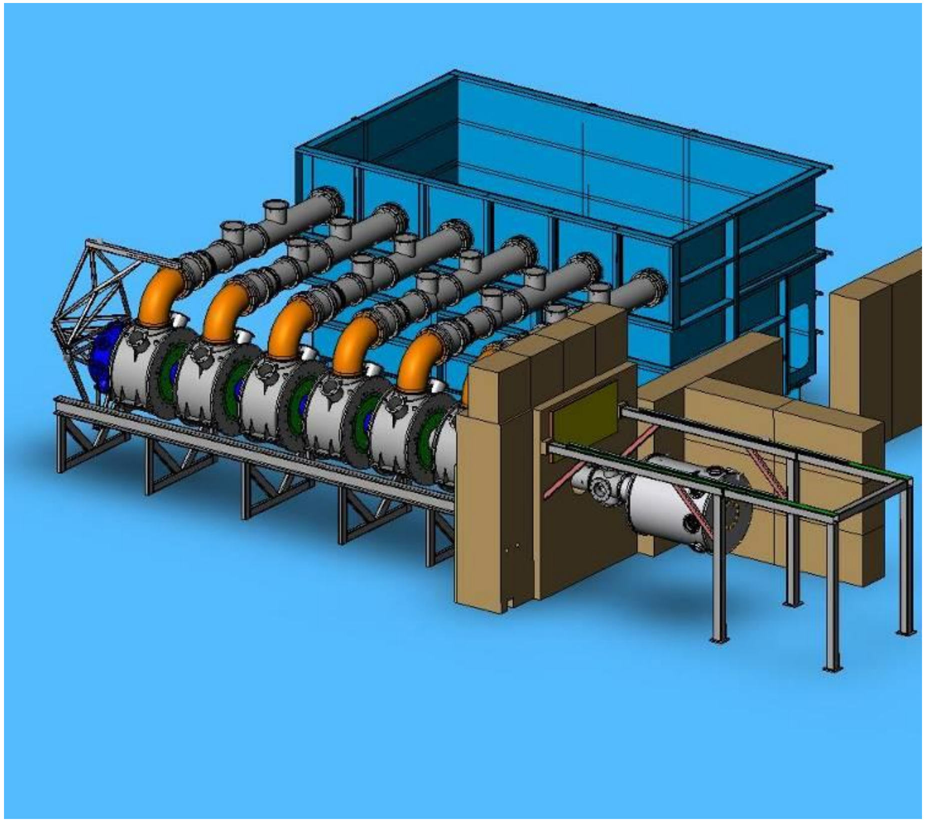


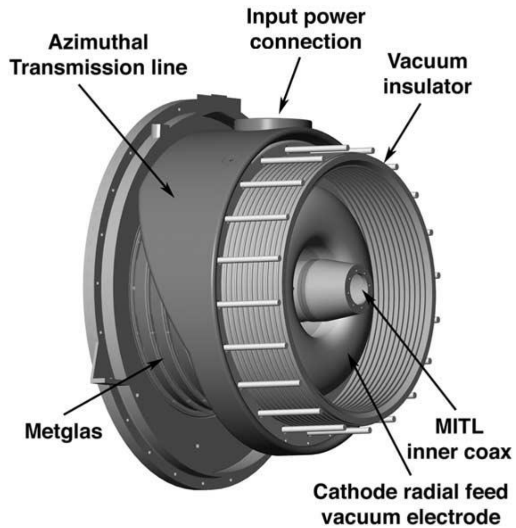
Charge deposited at the target plane, z = 0.

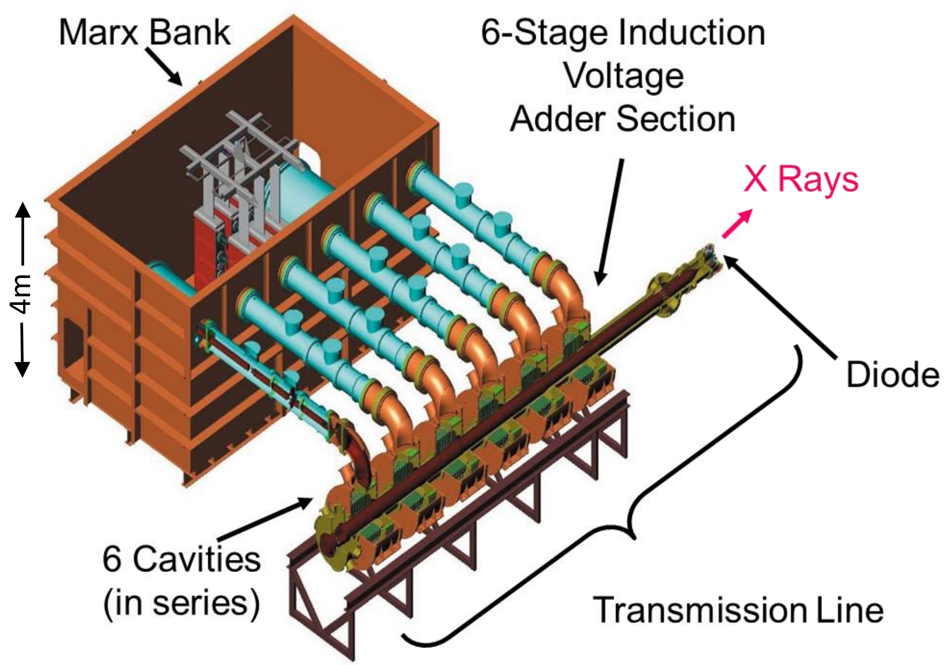
[6] **J.A. Halbleib, *et. al.*, Nucl. Sci. Eng. 92, 338 (1986).**

RITS-6 Pulsed-Power Accelerator at Sandia National Laboratories

RITS-6 is a 8-11 MeV Marx driven six-stage Inductive Voltage Adder (IVA) capable of driving a variety of electron beam diodes.[7]



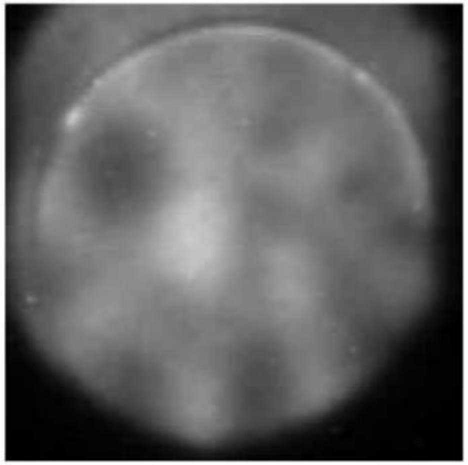




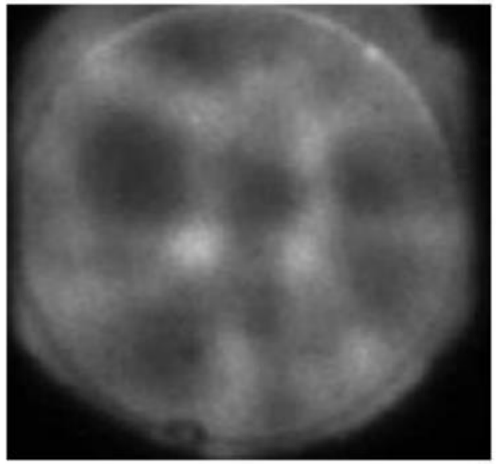
[7] D. Johnson, et al., *Proc. 15th IEEE Int. Pulsed Power Conf.* (IEEE, Jun. 13-17, 2005) p. 314–317.

RITS 6: Solid Hemispherical Cathode Results Showing Beam Non-Uniformities

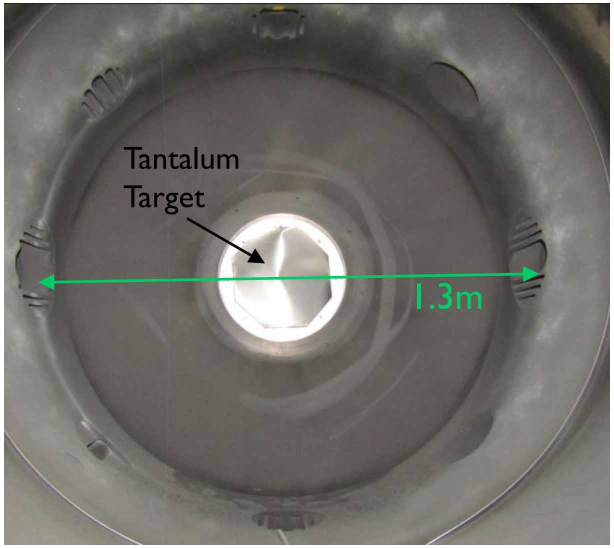
End on Cherenkov light emission at anode location



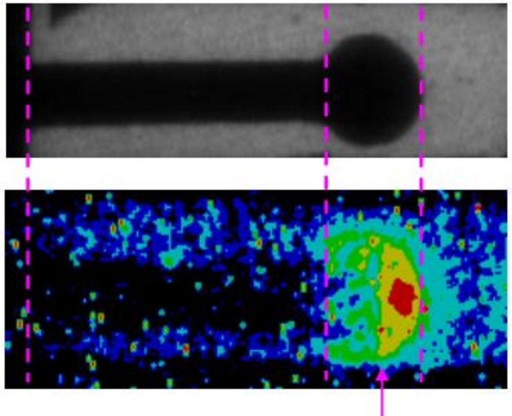
Early-time camera gate



Late-time camera gate



Tantalum Foil target on RITS



Side-viewing gated ICCD optical cathode light emission

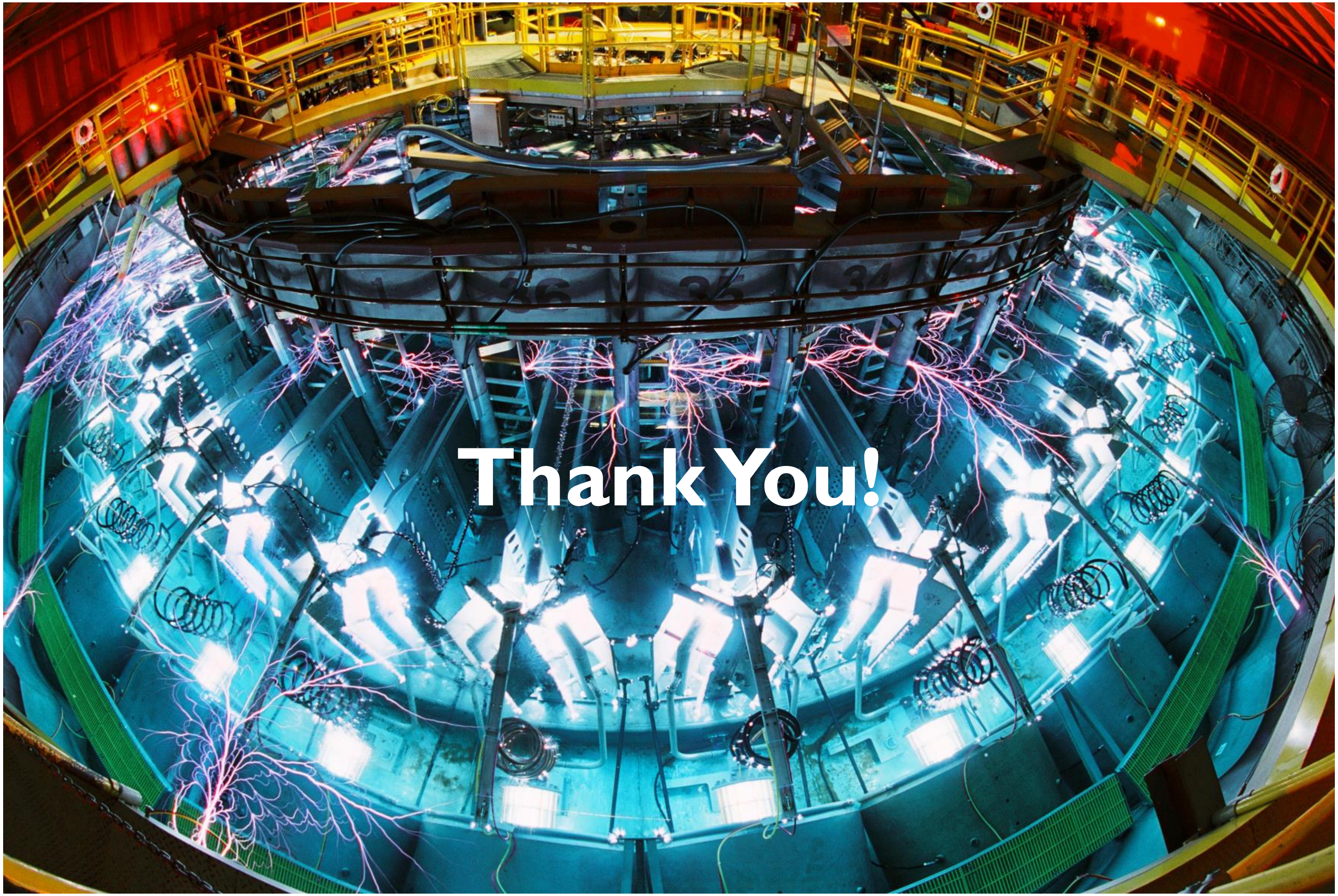
Emission extends beyond the tip of the cathode. Images show structure on the cathode, and end-on Cherenkov images suggests inhomogeneous current density at the anode.

[8] T.J. Webb, *et. al.*, IEEE Trans. Plasma Sci., 38, 923 (2010).

Future Work

- Continue investigations of cathode geometry modifications (ex. hemispherical cathode)
- Minimize current density and surface heating rates on target (beam uniformity)
- Determine surface heating limits (A/cm^2) for ion formation and beam pinching for various relevant materials
- Optimize multilayer targets, materials, and thicknesses for highest dose production
- Explore advanced concepts such as heating and/or cleaning of diode surfaces[9,10]
- Explore beam-angle effects on total dose production[11]
- Explore the effects of vacuum and surface contamination on ion formation
- Conduct new experiments on suitable pulsed-power drivers, including HERMES III, at multiple voltages and currents to test various diode configurations for PIC model validation
- Calculate and measure near and far-field dose profiles for various diode geometries
- Measure x-ray output energy spectrum

[9] B.V. Weber, *et. al.*, IEEE Trans. Plasma Sci., 30, 1806 (2002).
[10] T.J. Renk, *et. al.*, Phys. Plasmas 29, 023105 (2022).
[11] T.J. Renk, *et. al.*, Phys. Plasmas 29, 023106 (2022).


Thank You!