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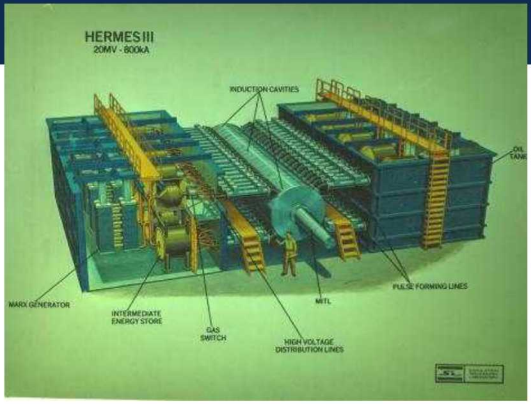

Pulsed Neutron Fluxes produced by 15 MeV-Level Intense Ion Beams on HERMES III at Sandia National Laboratories*

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2019 Pacific Symposium on Pulsed Power and Applications

Koloa (Kauai), Hawaii USA. August 6-9, 2019

***This work sponsored by the SNL Laboratory Directed Research &Development (LDRD) Program**

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Talk Outline

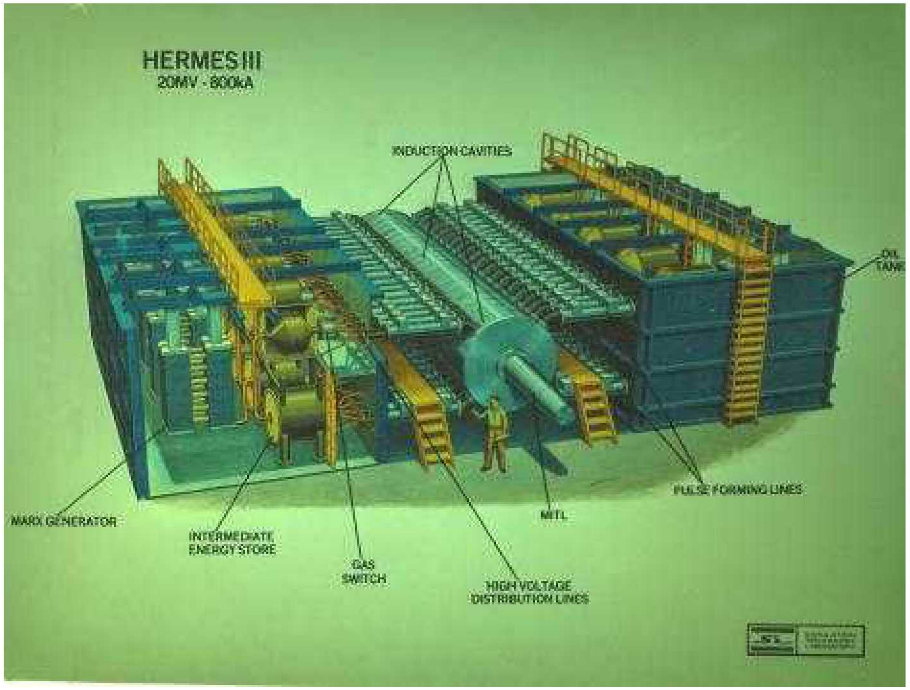
- **GOAL: Generate an intense proton beam with energies > 10 MeV for neutron generation**

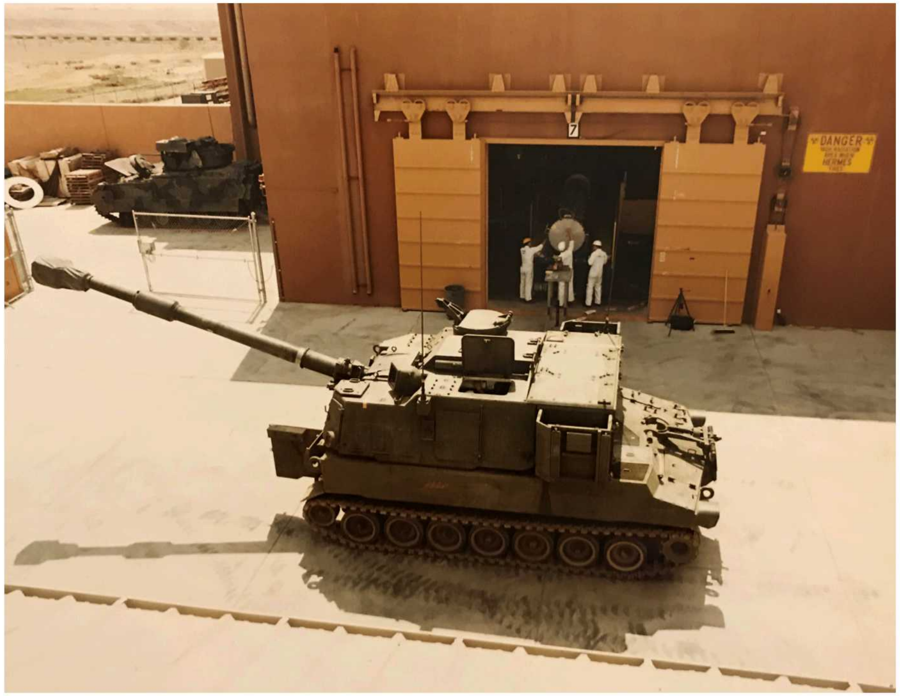
- **Method: Beam-target: Protons impinging on select metal targets (ex. Ta) access (p,n) reactions with high cross-section peaking in the ~ 10+ MeV energy range. No D or T.**

- **Requirements:**
  - **Ion Diode operated at 15+ ohms in Negative Polarity (dominant mode of HERMES-III operation), at the end of the HERMES Inductive Voltage Adder (IVA), where (@ 34 ohm vacuum impedance) 2/3 of the total current is in MITL flow.**

- **This Talk divided into**
  - **Ion Diode Design: physics of operating a diode load at the end of an 34 ohm IVA**
    - **High impedance drives self-field Radial Diode Design**
  - **MCNP simulations of neutron output: Bremsstrahlung vs ion beam neutron targets**
  - **Some Results from recent June 2019 experiments**

HERMES-III ion beam production must co-exist with dominant machine mode: high-power e-beam-pulsed x-ray source





- **(LEFT) Conceptual drawing, HERMES-III, an Inductive Voltage Adder (IVA) with 2 banks of Marxes and 20 cavities. Protruding MITL has inner (negative) conductor 37 cm diameter, outer (positive) 65 cm.**
- **(RIGHT) Photograph, outdoor 'courtyard' with Test Object. Crew stands next to the tantalum converter location in the 'outdoor' configuration.**

Negative polarity maximizes forward-going power.
Ion diode reverses power flow and features radial A-K gap.

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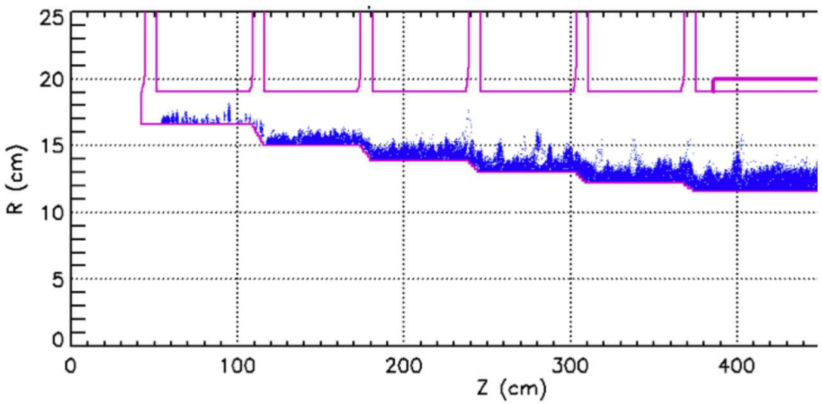
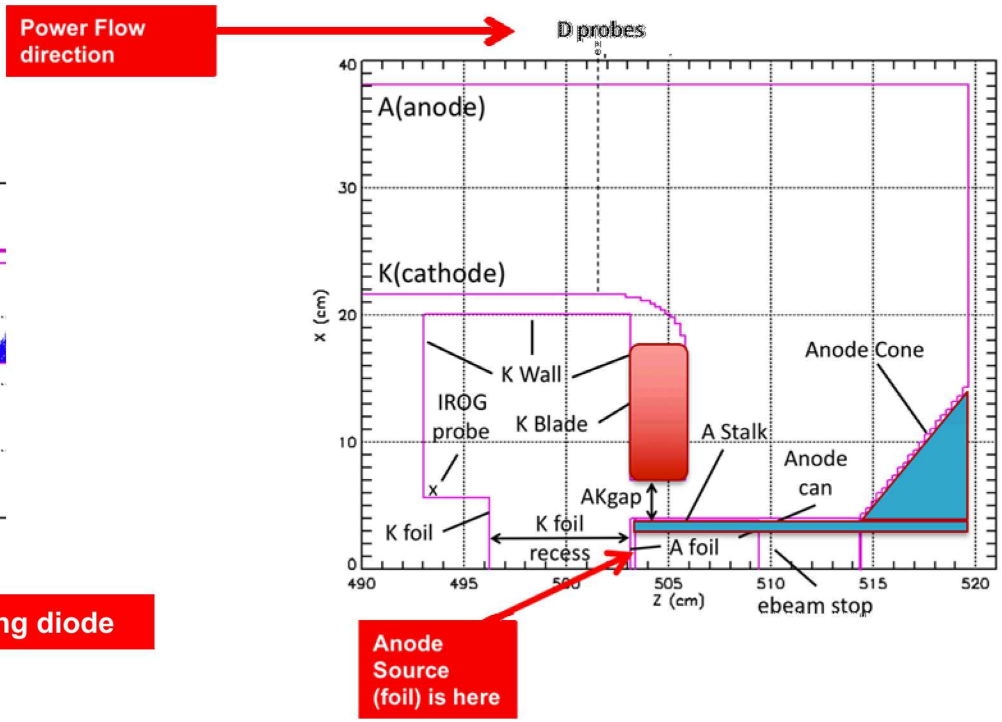
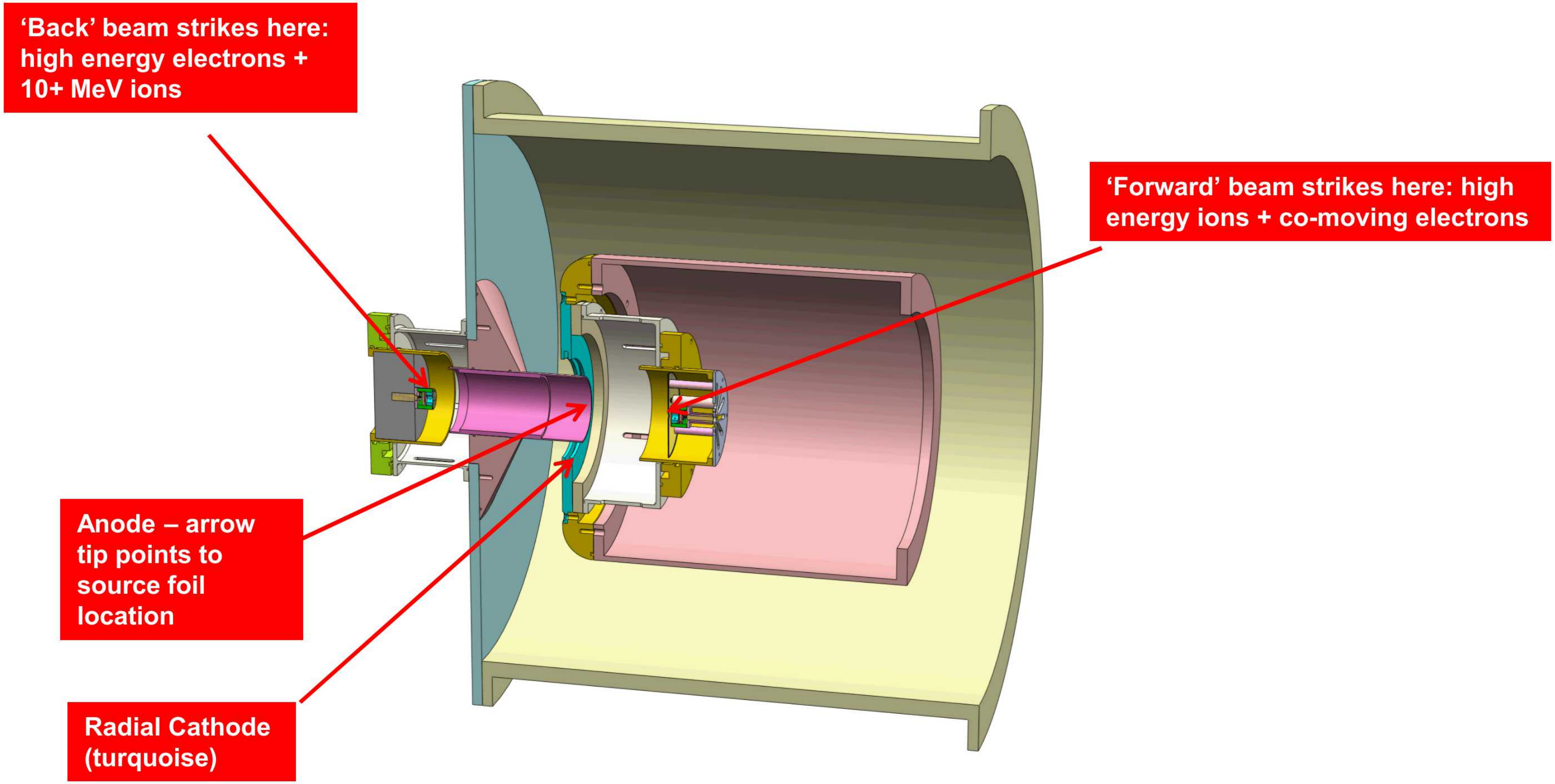


Schematic of power flow with standard Bremsstrahlung diode



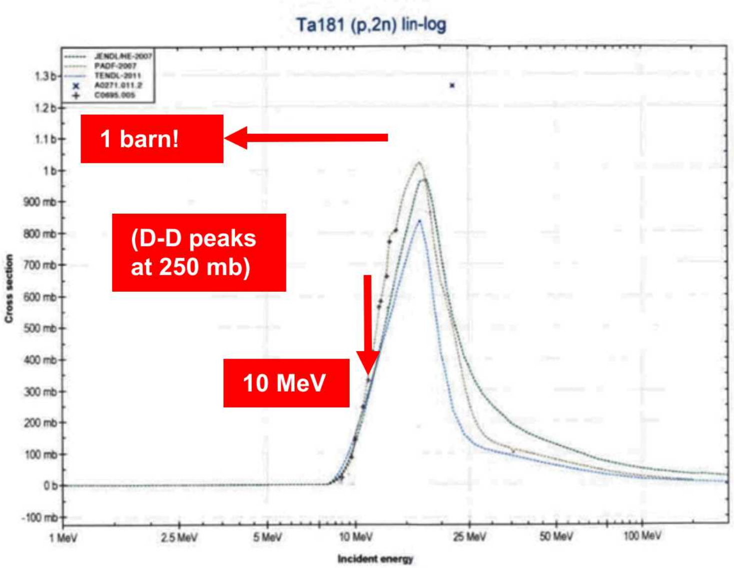
- **(LEFT) Simplified drawing of HERMES MITL power flow in negative polarity operation**
  - **MITL flow electrons (BLUE) flow to right and are joined by diode electrons (RED).**
  - **A-K gap is AXIAL and ~ 53-63 cm: self-limited impedance for 18 MV, 650 kA, 40 ns pulse.**
- **(RIGHT) Schematic drawing, RADIAL ion diode, Cathode (RED) and Anode tube (BLUE). A-K gap = 4 cm**
  - **Electron flow initially strikes anode can, then after self-insulation occurs, flows across and 'turns on' plastic flow across anode end. Resultant ion beam propagates into the machine.**
  - **A-K gap kept low enough to undermatch load impedance (~ 17 ohms) to MITL flow impedance (27 ohms) in order to capture all of flow (2/3 or total current) into diode. Diode ion efficiency estimated at ~ 20%.**
  - **Some fraction of high-energy electrons penetrate the ion source foil and flow to the RIGHT, dragging ions with them. Thus there are TWO ion beams, one FORWARD (left) and one BACKWARD (right)**

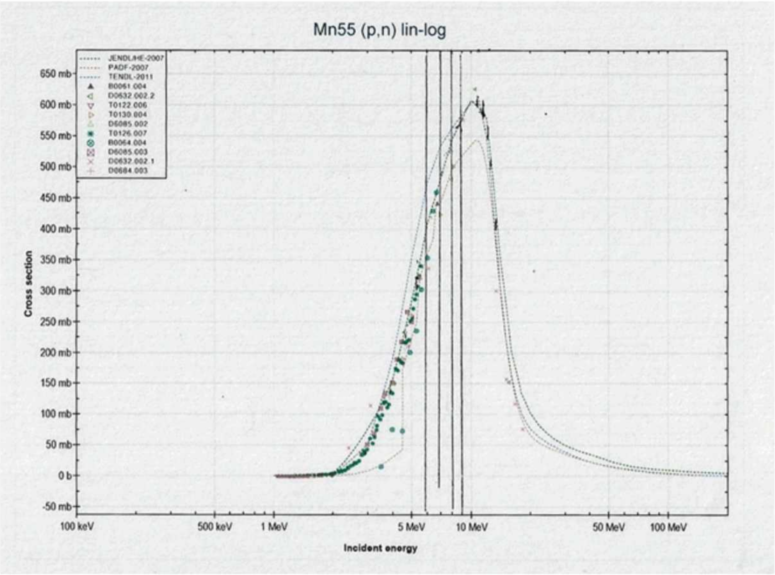
Exploded view of front-end region, showing hardware for measuring ion beam properties (Rogowskis, Fcups, etc)



- For investigating neutron production, both 'front' and 'back' ion beam diagnostic assemblies are replaced by neutron foil targets followed by test fixtures (upright cylinders with samples)

How is ion diode used to make neutrons? multiple sub-range high (p,n) cross-section targets. Here is an example.





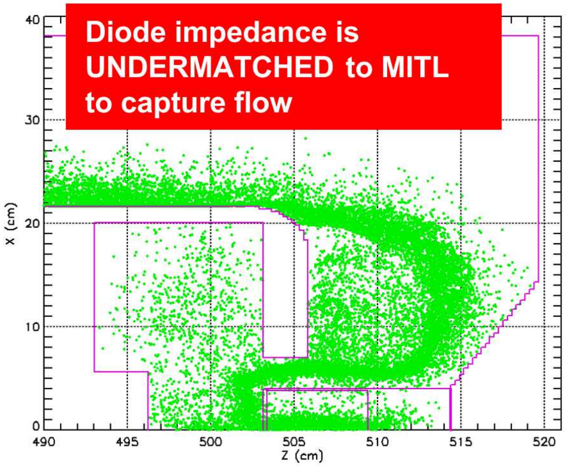
Example: 0.2 mm Ta foil + 0.3 mm Mn

- **(LEFT) Cross section, Ta181(p,2n)W180. Peaks at 1 barn (!)* at ~ 17 MeV. But threshold is at ~ 7-8 MeV. So the last 7-8 MeV of a thick-target would yield no neutrons. So combine with**

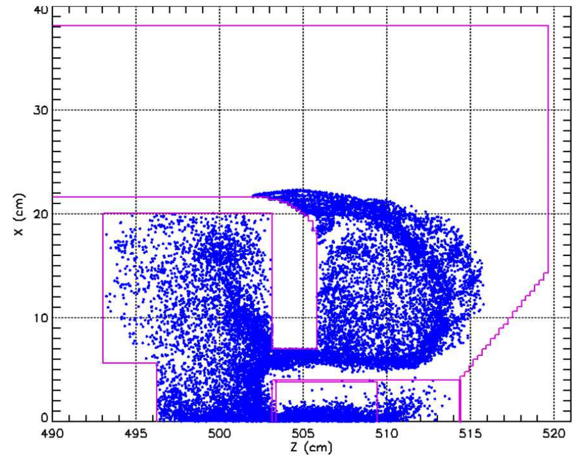
- **(RIGHT) Cross section, Mn55(p,n)Fe55. Peaks at 600 mb 11 MeV, threshold at 2 MeV. TWO sub-range targets extract maximum neutron yield.**
  - **MCNP calculations using this composite target yield 4.5e13 neutrons/4pi per pulse.**

- **What about activation? Must be minimized to facilitate shot turn-around.**
  - **Ta181(p,2n)W180: W180 has half-life of 1.8e18 years.**
  - **Ta181(p,n)W181: W181 has half-life of 121.2 days, but peak cross-section is only ~ 100 mb.**
  - **Mn55(p,n)Fe55 : Fe55 has half-life of 2.7 years.**

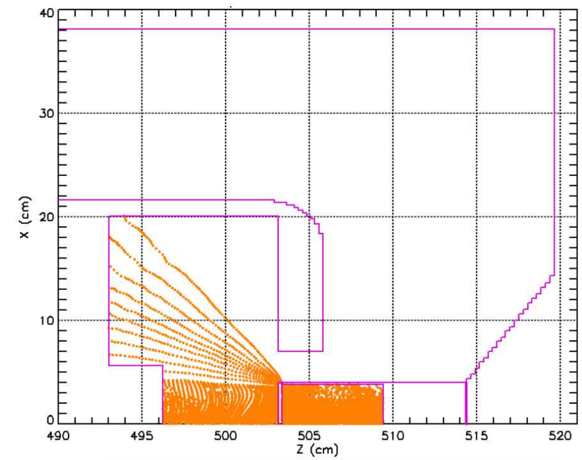
LSP simulations predict complete incorporation of MITL flow into diode.
MCNP simulations (neutron generation) predict benign neutron environment.



MITL flow electrons (Green) entering Diode



Electrons emitted from cathode (Blue)

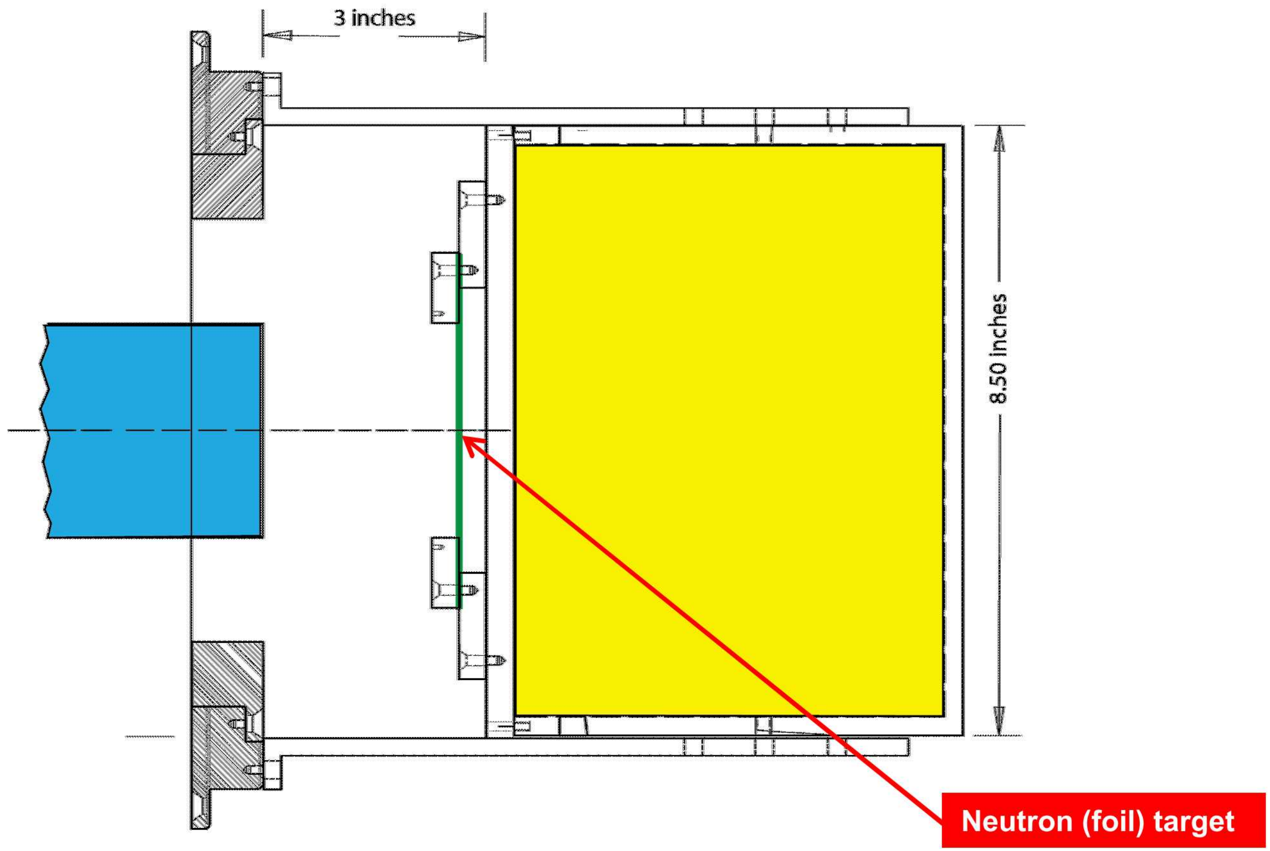


Ions from source foil (orange) propagating to left

- **Prediction of (LEFT) MITL flow into diode, (MIDDLE) emitted electrons from cathode, and (RIGHT) ions in the forward direction. Estimated load voltage is 13-15 MV, due to impedance undermatch).**
  - **Simulation indicates ALL of MITL flow (GREEN - 2/3 of total current) becomes part of diode current. This has major implications for theory of IVA-diode coupling.**
  - **Ion beam (ORANGE) propagates to left WITHOUT FOCUSING. Electrons also propagate to RIGHT (Back Beam) and drag ions with them. Represents another source of neutrons.**
  - **Particle snapshots are taken at PEAK power.**

- **MCNP modeling of neutron generation yields important results:**
  - **This ‘neutron diode’ generates less total neutrons than the standard e-beam bremsstrahlung shots at higher voltage, but many more high-energy (> 1 MeV) neutrons.**

Due to excessive ion beam damage on diagnostic package, we switched to measuring neutrons instead of ions



- The hatched flange mounts to the HERMES INNER MITL. The outer MITL is at larger radius top and bottom and out of sight. To the right is HERMES, left is the end flange. The vertical GREEN line is the 2-layer foil neutron target. The yellow volume is the test fixture interior.
- A similar but smaller box is mounted in the 'rear' beam direction (to the left of the parts pictured)
- Activation foils fielded inside text fixtures to attempt to measure neutron spectrum

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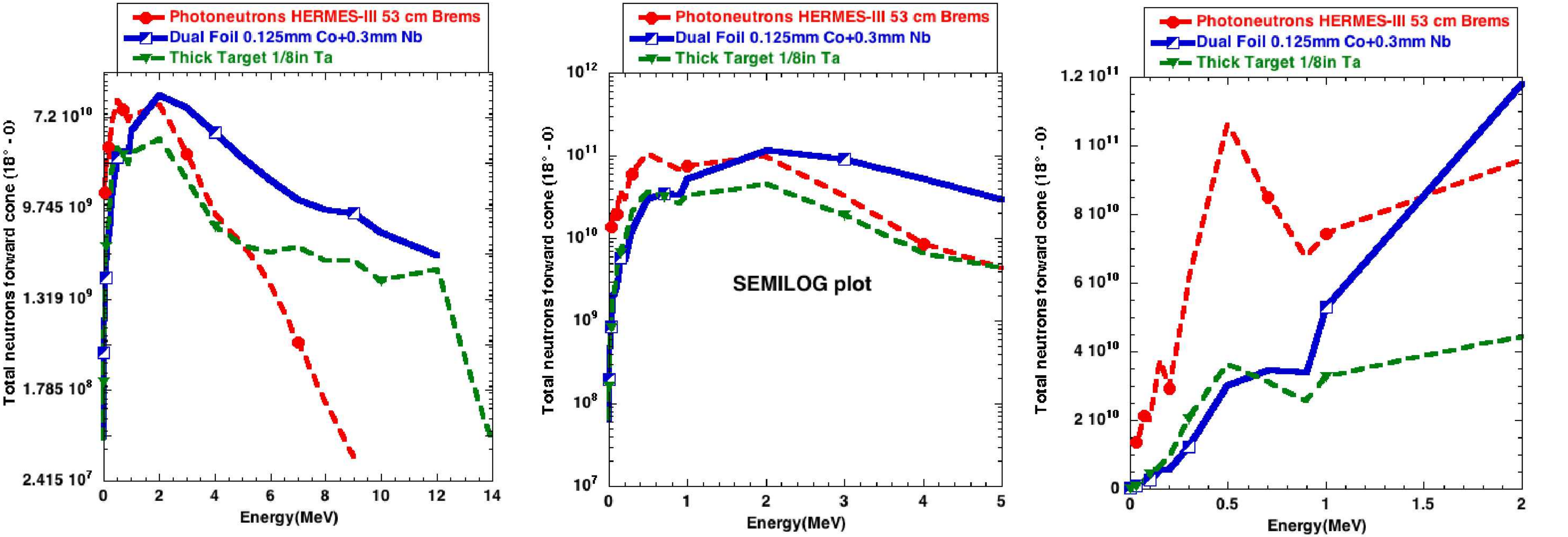
3. Comparison of Neutron output: Photoneutrons (HERMES Brems) and Ion Diode

- **The following slide compares predicted neutron output and spectrum (MCNP) for three cases:**
  - **HERMES-II 'Standard Mode' 53 cm A-K gap, photoneutron output**
  - **Ion Diode, thick-target Tantalum (1/8 inch thick)**
  - **Ion Diode, Dual-Foil configuration: 0.125 mm Cobalt + 0.3 mm Niobium**
- **The neutron output from ion diode assumes 100 kA proton beam in 'forward' direction + 50 kA in 'backward direction at peak energy ~ 13.5 MeV.**
- **This slide addresses the question: 'if the HERMES Brems configuration can generate neutrons, why don't we just use that instead of the ion diode?**

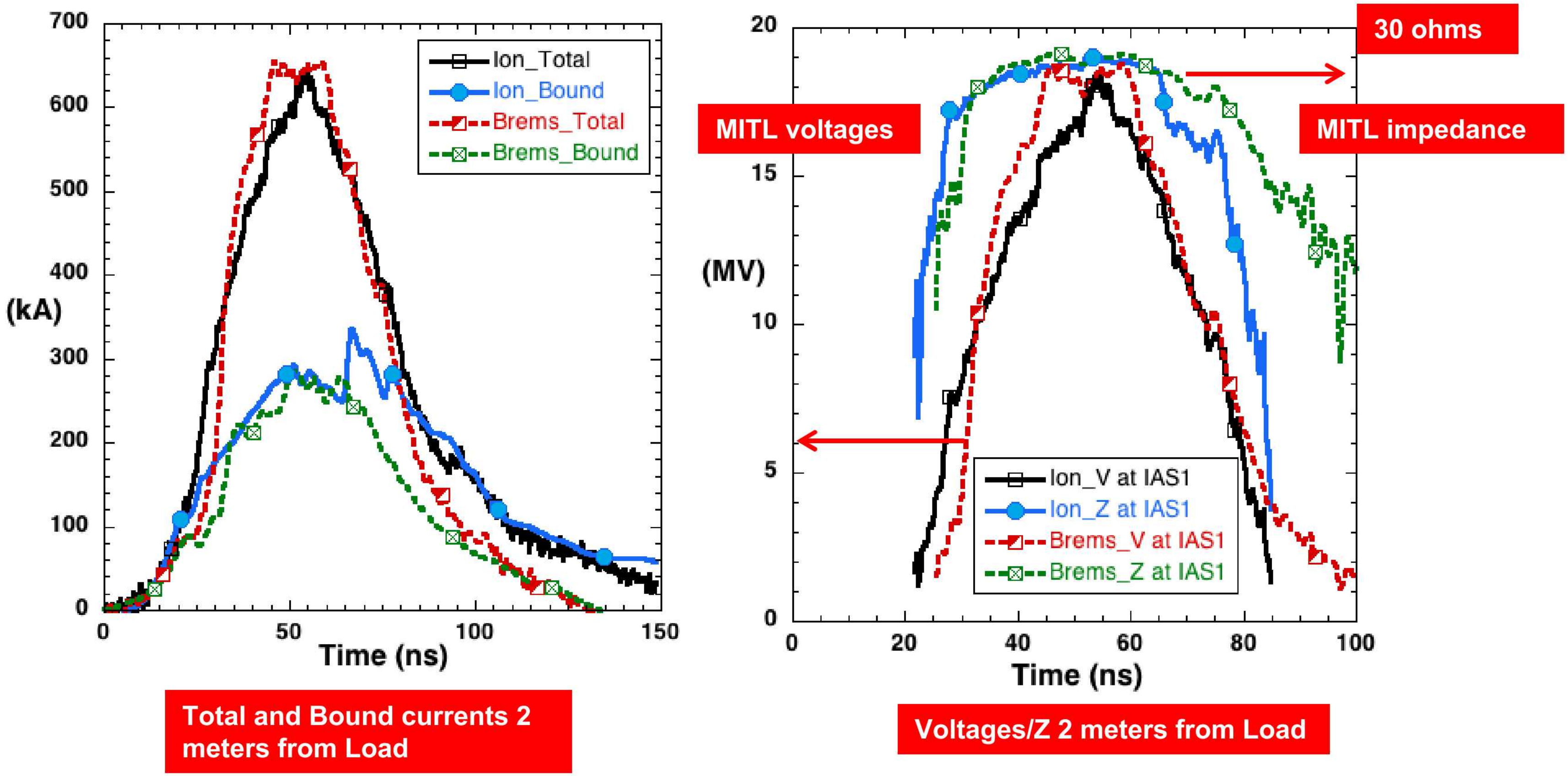
Forward-directed (18 – 0 degrees) neutron spectrum for the 3 cases



All Plots: neutron output into Forward Cone (18 – 0 degrees)

- **(LEFT) Total neutron output into forward cone (18° - 0) as function of neutron energy. Linear plot to 14 MeV max. Note how photoneutron output tails off above ~ 5 MeV.**
- **(MIDDLE) Total neutron output into forward cone (18-0) as function of neutron energy. SEMILOG plot to 5 MeV maximum. Double Foil exceeds photoneutron output above 2 MeV.**
- **(RIGHT) Total neutron output into forward cone (18-0) as function of neutron energy. Linear plot to 2 MeV max (emphasizes lower energies). Below 1 MeV, photoneutron output dominates.**

June 2019: currents similar to a Brems shot until retrapping wave hits



- **(LEFT) Total and bound currents, Ion Diode shot (11105 - SOLID) vs a previous Bremsstrahlung shot (10433, dotted). Ion bound current (BLUE) comparable to Brems until retrapping wave arrives. Location in MITL is 2 meters from Load. Ion diode waveforms slower to fall. All this indicates coupling to lower impedance load in ion diode case.**
- **(RIGHT) Voltages in MITL (calculated from Mendel formula) on LEFT, MITL impedance on RIGHT. Ion diode voltage rises slower, and drops when retrapping wave from load arrives. Ion diode MITL impedance follows Brems (~ 28 ohms) until retrapping wave arrives.**

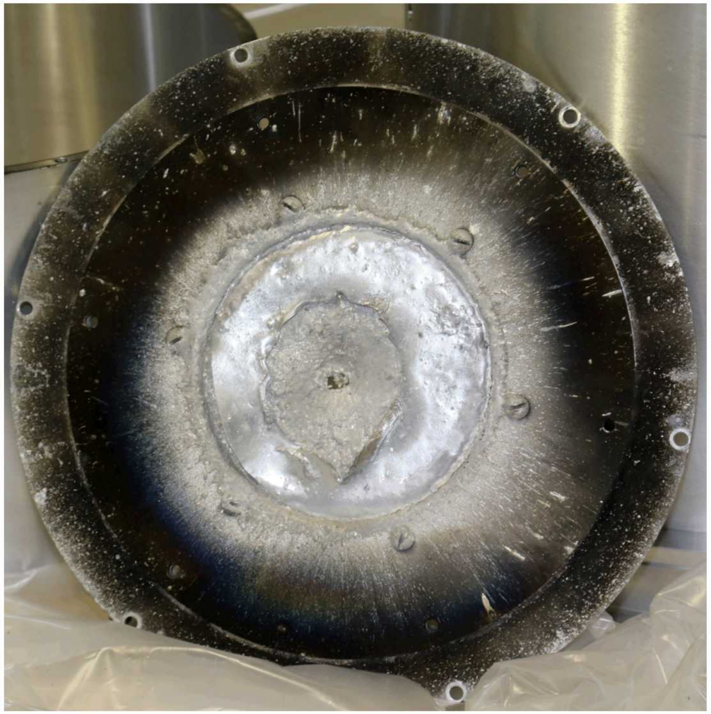
Good News from June 2019 testing: improved diode survivability

June 2019: (dark) outer sleeve is 1/4 - inch thick 1026 Cold-Rolled Steel

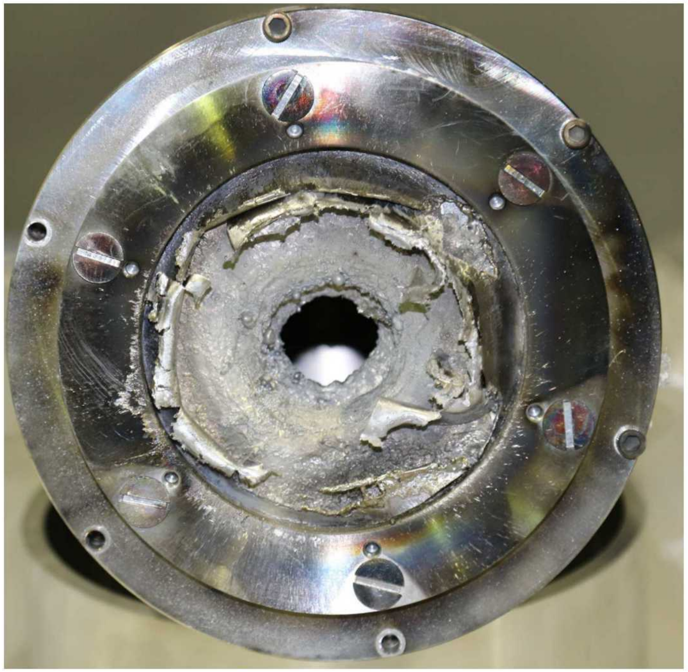
April 2017: (remaining) outer sleeve is 1/8-inch thick aluminum 6061

- **(LEFT) Closeup of 3 inch- diameter 1/4-inch wall cold-rolled steel anode after a recent full-power shot. It, like the cathode, is UNDAMAGED and can be used again. (Speckled spots are blown-back melted aluminum from test fixture.)**
- **(RIGHT) Anode tube made of 1/8-inch aluminum 6061 (April 2017), surrounded by anode cone, after a single shot.**

Bad News from June 2019: the test fixture covers were heavily damaged



FRONT test fixture cover



REAR test fixture cover

- (LEFT) FRONT test fixture cover. Two plates were behind the neutron foils (shiny annulus is foil remnant). Ion beam penetrated first 1/8-inch plate, but not the second 3/8-inch plate. On the FIRST shot, only the 1/8-inch thick plate was installed, and beam penetrated and exposed the test samples.
- (RIGHT) REAR test fixture cover. Image shows remnants of neutron foils (shredded) and a ~ 1 inch hole cut through TWO 3/8-inch aluminum plates. Samples inside were recoverable, but for future shots, this fixture will be eliminated and replaced with a robust beam stop.

Summary and Path Forward

- We have designed and operated a Radial Ion Diode as a load for HERMES-III that a) maximizes power flow in negative polarity, and b) incorporates all the MITL flow current into the diode region for maximum ion generation. Estimates for load voltage are 13-16 MV. This is lower than the standard bremsstrahlung diode voltage of ~ 18 MV, due to the use of undermatching the load impedance so as to draw in the MITL flow.

- The diode is an operational success at this 'full'-power level: Routine one shot/day, no excessive activation with previous targets, slightly more with most recent target (cobalt).

- Listing the requirements for successful experiment outcome:
  - 1 Shot/day e.g. no activation issues — can switch to other foils
  - Current, Voltage, Impedance adequate ✓
  - Debris limited ✓
  - 'Adequate' neutron generation — No data back from shot series

- TWO more series scheduled for FY19: August and September 2019
  - FRONT test fixture cover replaced with tantalum plate
  - REAR test fixture replaced by Robust beam stop
  - Experiment with different neutron foil combinations

Acknowledgement

- The authors greatly appreciate the hard work of the HERMES crew in contributing to the success of these experiments:
  - Ben Hughes
  - Gary Tilley
  - Keith Tunell
  - Moe Archuleta