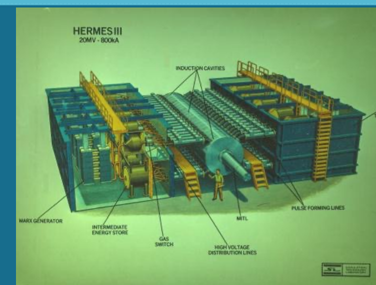
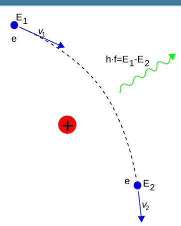
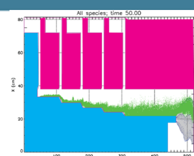
Pulsed Power Experiments on HERMES III in support of Sandia's National Security Mission







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Arms Control and Internal and Domestic Security Series (ACDIS)

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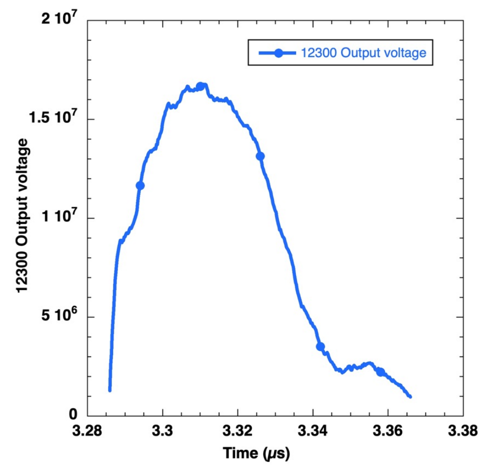
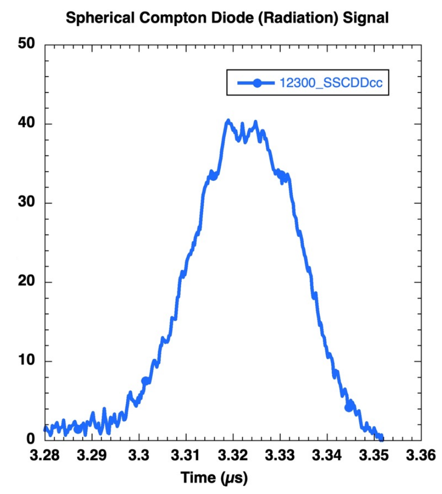
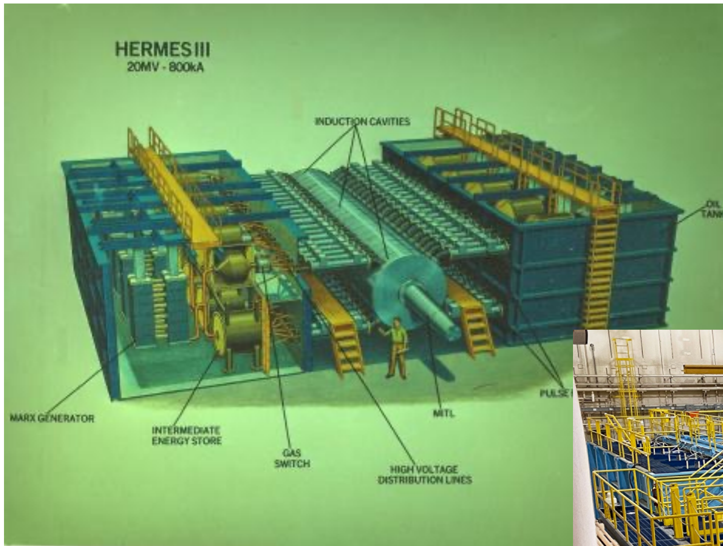
First Question: What does 'Pulsed Power' mean?

- Wikipedia: *Pulsed power* is the science and technology of storing energy over a relatively long period of time and releasing it instantly, thus increasing the instantaneous power.
- Slow part: a Marx generator (set of capacitors) is charged over ~ 90 seconds, producing an output pulse ~ few *μ*s long.
- Several stages of *pulse compression* result in a voltage pulse at the *diode* ~ 40 ns long (RIGHT).
- In the diode, an *electron beam* is formed, leading to a *radiation pulse* (FAR RIGHT) of similar FWHM.
- The goal of pulsed power as operated on HERMES is to produce a large volume of photons for the intended application.
- More on this point later.





Second Question: What is HERMES? a high-power pulsed x-ray source



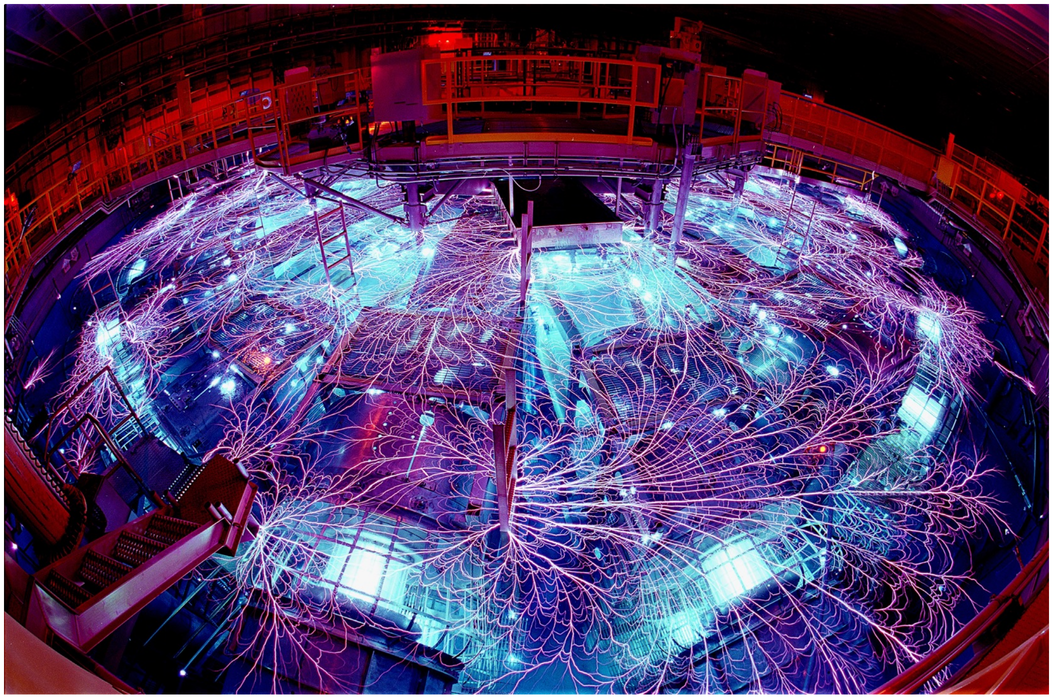
Photon Source: a
Bremsstrahlung Diode

- **(LEFT) Conceptual drawing (c. 1985) of HERMES-III, an Inductive Voltage Adder (IVA) with 2 banks of Marxes and 20 induction cavities. Protruding MITL has inner (negative) conductor 37 cm diameter, outer (positive) 65 cm.**
- **(MIDDLE) photograph of HERMES taken from the upper indoor gallery.**
- **(RIGHT) Photograph, outdoor ‘courtyard’ with Test Object. End of the HERMES MITL is seen just inside the double doors.**

More images of HERMES-III

- **(LEFT) Photo of HERMES-III courtyard outfitted with neutron-producing target. Double-doors are covered with concrete blocks except for small aperture. Diagnostic trailers visible in the background.**
- **(RIGHT) Photograph of Author standing next to a Bradley Fighting Vehicle.**

HERMES-III is next door to the Z Facility

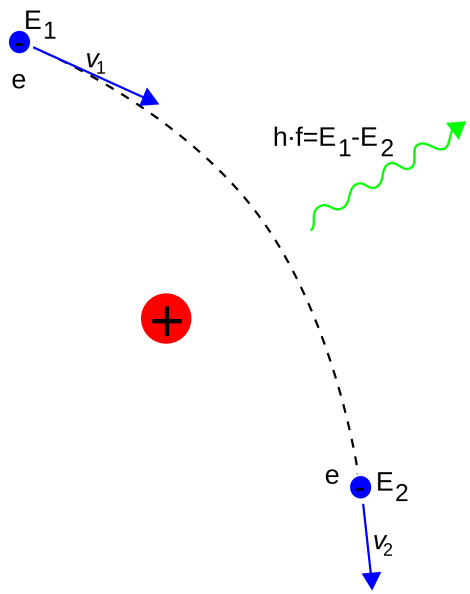


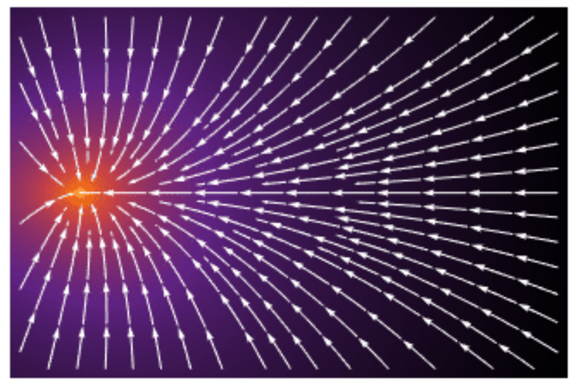
- Open-shutter photograph of the Z machine taken during a shot.
- Unlike HERMES, Z is arranged in a circular geometry, with 36 Marx generators surrounding a load at the center.

How does a pulsed power accelerator like HERMES differ from a *particle accelerator*? (Tevatron, LHC)

- In a particle accelerator, a small batch of particles (electrons, charged ions) is accelerated to high energy by traversing many acceleration gaps, and guided by imposed self-fields such as those created by quadrupole magnets.
- In order for the imposed guide fields to control beam quality (*emittance*), the amount of beam current must be kept very small. Therefore, high voltage, very small current.
- Applications of particle accelerators consist of mostly small controlled experiments where the beam interacts with some kind of sample material.
- In an accelerator like HERMES, high currents are desired (like 650 kA). Power is then delivered to a *single-stage* diode. Since both ions and electrons may be present, such mixed-species beams will not survive multi-stage acceleration.
- While diode geometries have become more refined, the emphasis here is on beam *Quantity*, not beam *Quality*.

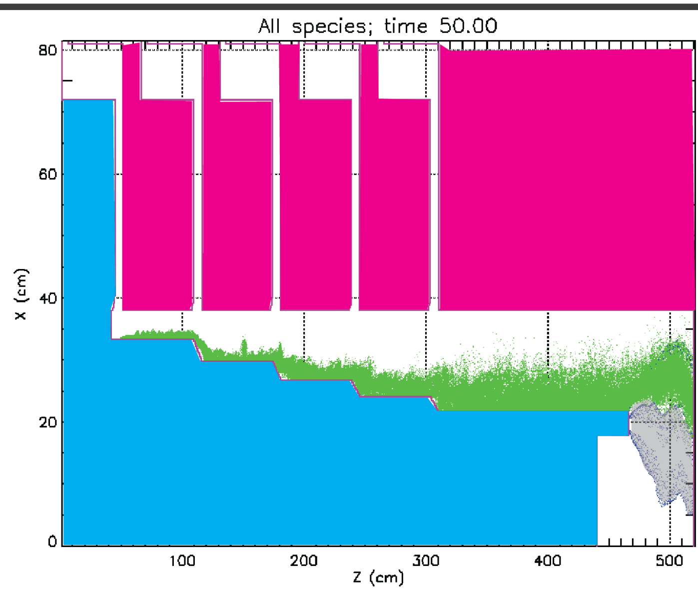
What is Bremsstrahlung? 'Braking radiation' caused when moving electrons slow down in matter





- **(LEFT) Electron E1 passes by atomic nucleus ('+'), and orbit bends from velocity V_1 to V_2, and energy changes from E_1 to E_2. Result is photon emission proportional to amount of energy lost.**
- **(RIGHT) Conceptual plot (from Wikipedia), illustrating how field lines of electron produce plain wave (radiating energy) after electron is decelerated.**
- **The bigger the deceleration, the more energy is radiated (more photons produced). And the higher the beam energy, the more *forward-biased* is the bremsstrahlung radiation.**
- **Mechanism for photon production: accelerate electrons in beam form, and let them impinge on *Hi-Z metal*, i.e. metal with heavy nuclei. Preferred metal: tantalum sheet (Z = 73).**

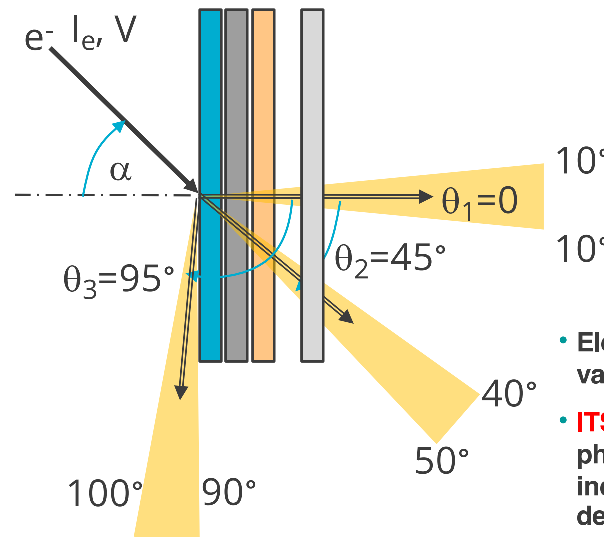
Schematic view of power flow towards the anode 'converter package'



- (Outer) anode side, 20 acceleration stages, each adds ~ 1 MeV energy.
- (Inner) cathode side. GREEN shows electron flow outside the cathode stalk
- Inner and anode conductors constitute a *Magnetically Insulated Transmission line (MITL)*.
- Right Side – *electron beam diode*. Electrons emitted from outer tip (BLUE dots) join with GREEN flow to strike the anode. Ratio of electron flow to MITL flow depends upon the *MITL impedance*.
- Since electron impact is spread out, there is little or no damage to the anode, and machine can be operated with many shots before opening vacuum.

Anode 'converter package':

Titanium cover sheet, 0.33 mm (13 mil) thick
Tantalum converter, 2.03 mm (80 mil)
Carbon beam stop, 50.8 mm (2")
Space, 31.8 mm (1.25")
Aluminum final beam stop, 12.7 mm (0.5")

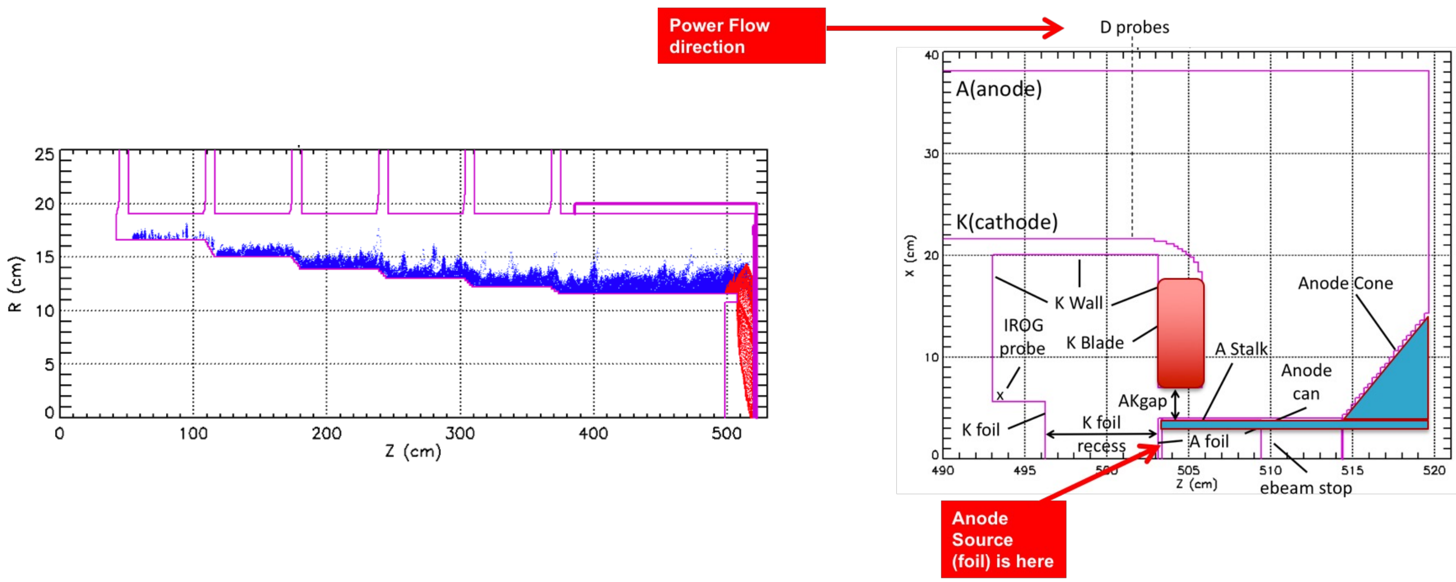


- Electrons strike converter package at various angles.
- ITS *photon generation code* predicts photon flux for near- and far-fields, including angle(s) shown where detectors are located
- Experimenters place test objects in the region to right of converter package.

How does making lots of photons impact National Security? Let’s talk about MAD.

- In the Cold War, both the US and USSR kept nuclear assets on hair-trigger standby basis, ready to use.
- Either side might be tempted to strike first, wiping out their opponent. This makes for an unstable situation.
- BUT, if both sides know that the other could survive a first-strike and return fire with devastating results, this discourages either side from initiating a first-strike. This concept is known as *Mutually Assured Destruction* (MAD). It has resulted in no further use of nuclear weapons (other then testing) since 1945.
- To enhance the ability of weapons components to survive a first strike, such components are subject to a simulated flux of photons and/or neutrons to test whether they can survive. This is know as ‘radiation or *rad* hardening’.
- The photon flux produced by HERMES is judged to be a credible simulation of a nuclear blast. Candidate components are then placed in front of HERMES and exposed to photon fluxes to test for survivability.

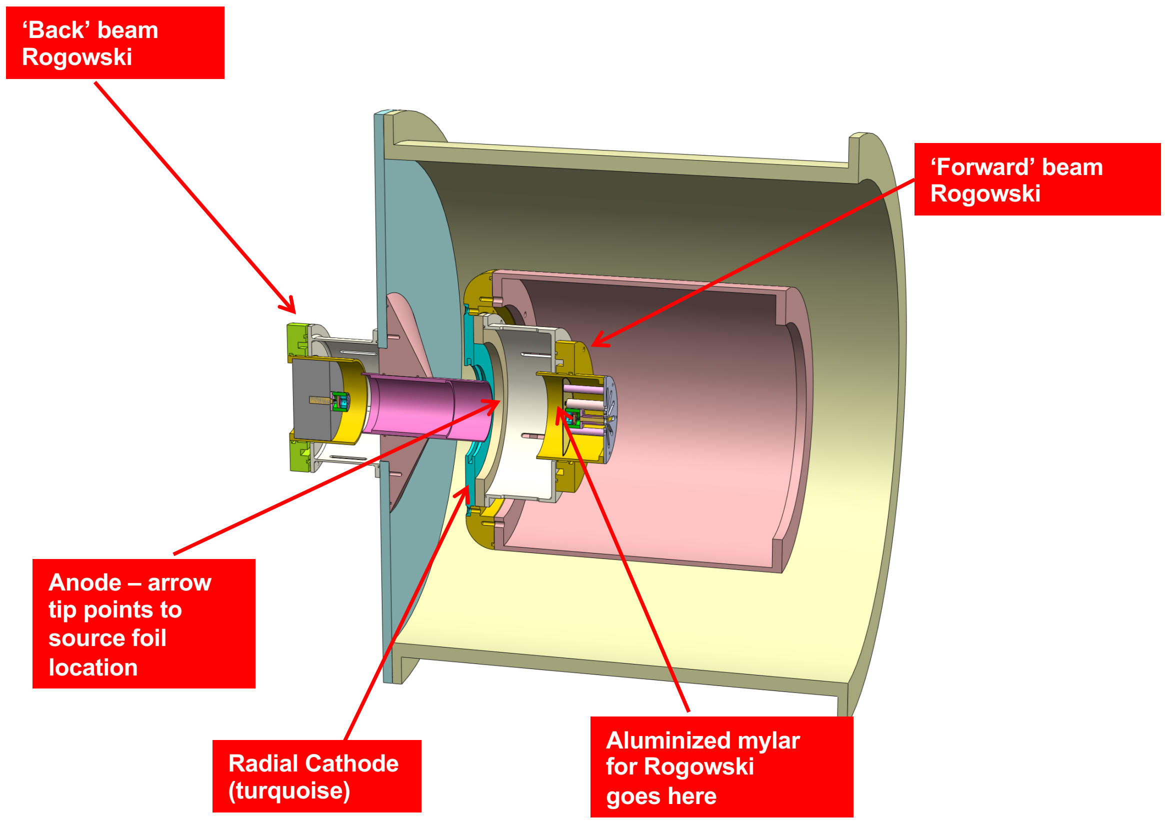
HERMES has also been used to make neutrons (Renk, LDRD, 2017-19).



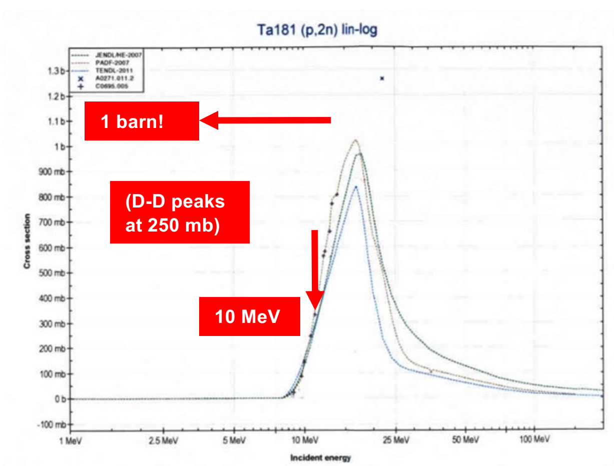
- **(LEFT) Simplified drawing of HERMES MITL power flow in negative polarity operation**
  - **MITL flow electrons (BLUE) flow to right and are joined by diode electrons (RED).**
  - **A-K gap is AXIAL and ~ 53-63 cm: output is 17-18 MV, 600-650 kA, 40 ns pulse.**

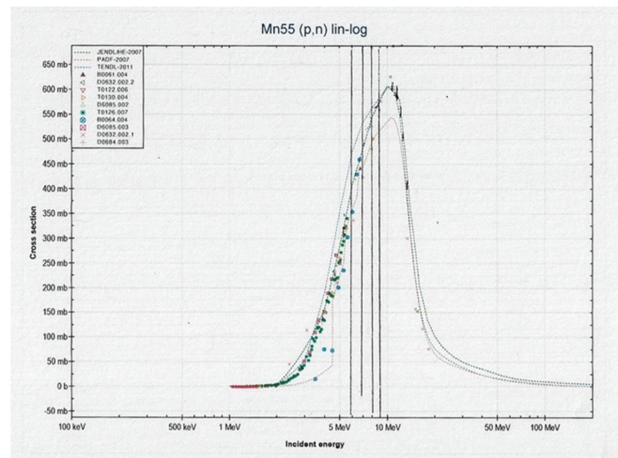
- **(RIGHT) Schematic drawing, RADIAL ion diode, Cathode (RED) and Anode tube (BLUE). A-K gap = 4 cm (radial)**
  - **Electron flow initially strikes anode can, then after self-insulation occurs, flows across and 'turns on' the plastic on anode end that acts as the ion source. Resultant ion beam propagates into the machine.**
  - **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. NOTE: orientation opposite that of previous slide.



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

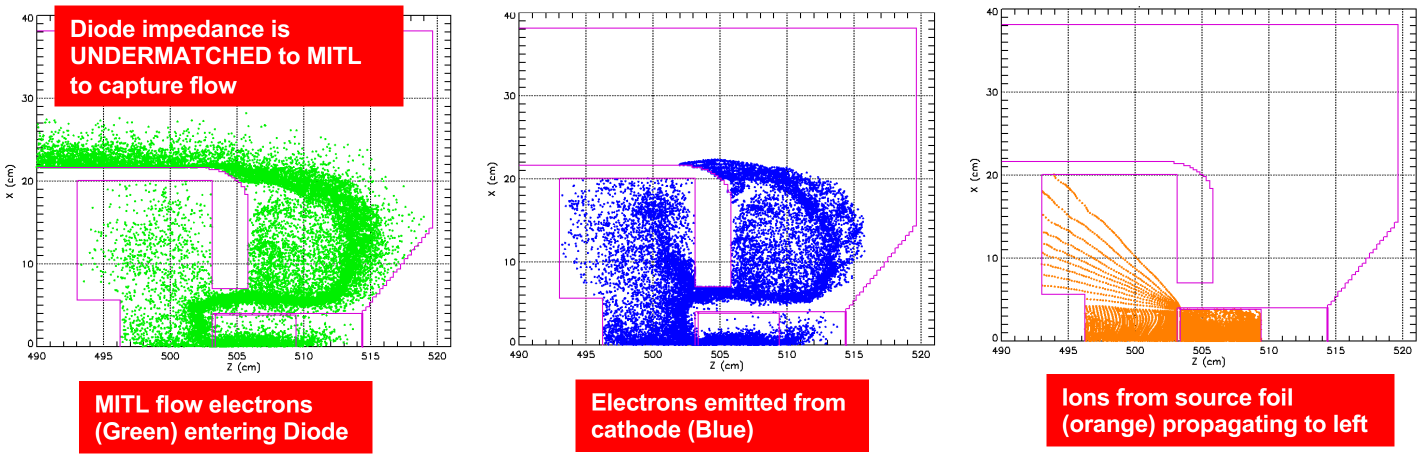




Example: 0.2 mm Ta foil + 0.3 mm Mn

- **(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.**
- **What about activation? We want to minimize that.**
  - **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.



- **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.**

Clarification of the term 'National Laboratory'

- There are many US labs called 'national laboratories'. Example: Argonne, Brookhaven, Lawrence Berkeley.
- The distinction between the three laboratories known as 'national labs' is that
    - The three labs: Sandia, Los Alamos, and Livermore – are involved in various aspects of nuclear weapons production. All are administered by the National Nuclear Security Administration (NNSA) of DOE.
    - Much of the work is thus Classified, and stringent classification rules apply.
- **Livermore and Los Alamos work focus on the 'physics package' – the heart of a nuclear device. Sandia is responsible for weapon 'packaging' – work on firesets, triggering mechanisms. Sandia grew out of the Z Division of Los Alamos (1948), starting with the Manhattan Project, as the group responsible for assembling nuclear devices.**
- **Sandia has also taken on much work sponsored by the Department of Defense (DoD). Example: hypersonic weapons.**
- **But Sandia is also involved in many research diverse aspects that are not as well known as the weapons work.**
- **The next slide gives some example of this non-weapons work.**

Examples of Sandia research in various non-weapon areas

- **Cleanroom**: a Sandia invention (1963).
- **Energy** generation:
  - Novel ***Twistact*** electrical contact eliminates need for rare-earth materials in wind turbines. SNL exploring partnering with private industry to make Twistact a commercial reality.
  - Re-inventing **offshore wind turbines**: replace tall towers with floating generators with blades pulled taut by guide wires.
- **Environmental** Impacts:
  - SNL researchers are studying the use of clay and other nano-materials to capture CO_2 directly from the air.
  - SNL researchers are working on filtration and other methods to remove PFAS chemicals from the environment.
  - Nanocomposite materials made from layers of carbon black and silica form protective layers for many applications.
  - Sandia researchers are finding new clues as to why the Arctic is warming up faster than any other region on Earth.
- **Medical** Impacts:
  - A polymer-based detector that can detect misplaced doses to protect healthy tissues from damage in radiation treatments.
  - A micro-needle array extracts more interstitial body fluids, making possible sooner and more comprehensive disease detection.
- **Materials Science** Impacts:
  - A molecule added to polymers increases its durability and better matches thermal properties to metal interfaces.
  - Under certain conditions, nano-scale cracks in metals have been observed to heal themselves, as predicted by a Texas A&M professor. If this can be generalized, could lead to a whole generation of self-healing metals which could help mitigate fatigue cracking.

Intern Institute Programs

Intern institutes provide interns challenging work experience in multiple disciplines critical to Sandia's mission. Within the institutes, interns perform leading-edge research under the guidance of a Sandia mentor. Interns work on an array of projects during their internship.

- Computer Science Research Institute (CSRI)
- Future of Research for Climate, Earth, and Energy (FORCEE)
- Interdisciplinary Design, Engineering, and Assurance Students (IDEAS)
- Interns for Security, Arms Control, and Force Protection Engineering (iSAFE)
- Mission Services Talent Acquisition Team (MSTAT)
- Monitoring Systems and Technology Intern Center (MSTIC)
- Nonlinear Mechanics and Dynamics (NOMAD)
- ND Mission Technologies (MissionTech)
  - Component Science, Engineering, & Production (CSEP)
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- Student Intern Group for Microelectronic Advancement (SIGMA)
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- TITANS:
  - AutonomyNM
  - Cybersecurity
  - Math and Analytics
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Intern Institute Website

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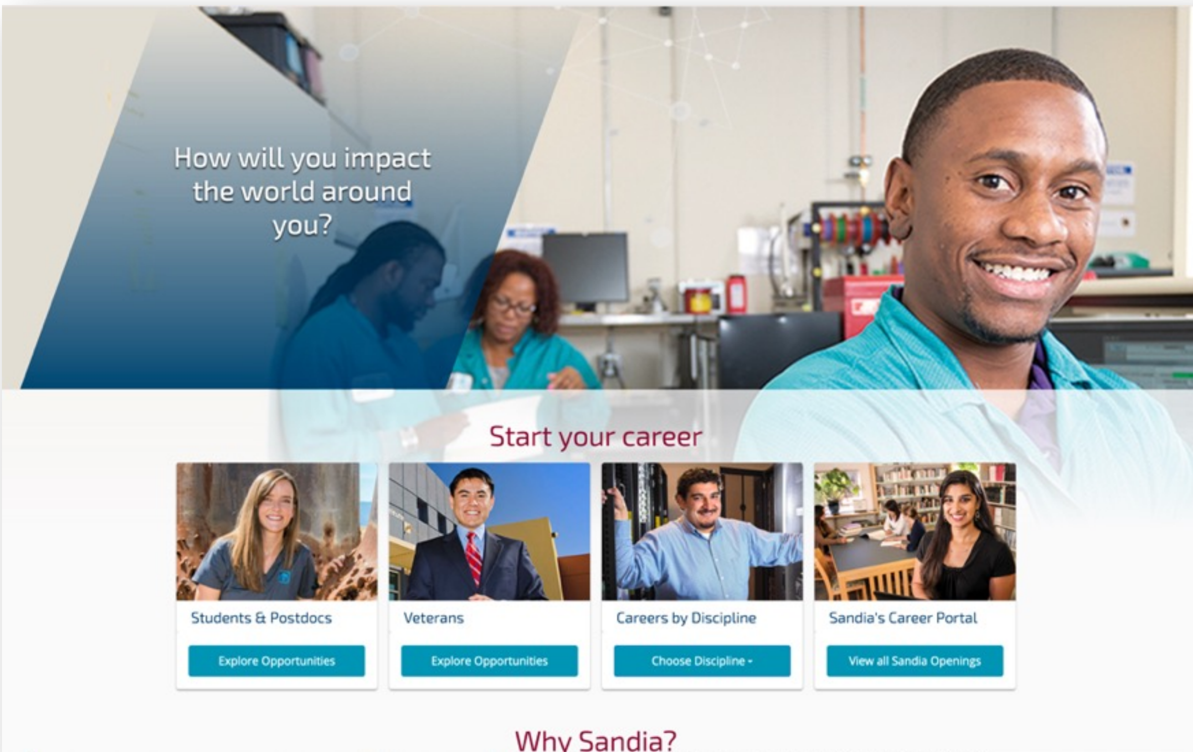

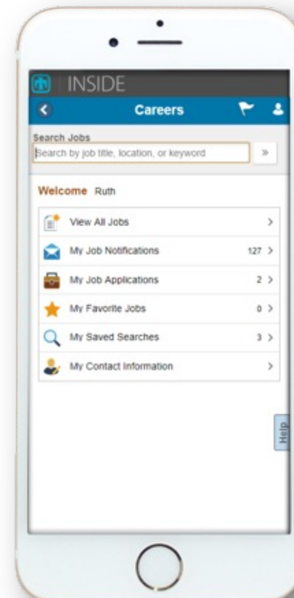

THANK YOU

Questions?