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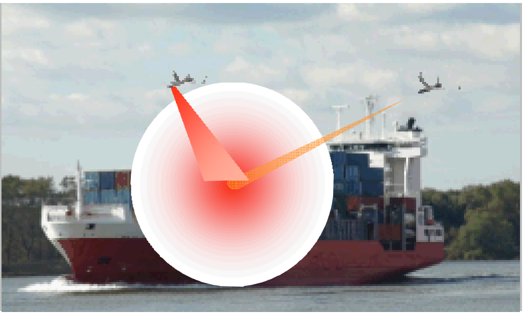

A Brief Overview of Research Into Radiation Source Development and Radiation Sensors in the Microfabrication Program at Sandia National Laboratories

Sandia National Laboratories

Exceptional service in the national interest

Presented by Mark Derzon,
Sandia National Laboratories, 10/1/2012

U.S. DEPARTMENT OF ENERGY

NNSA

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NSTec: E.C. Hagen

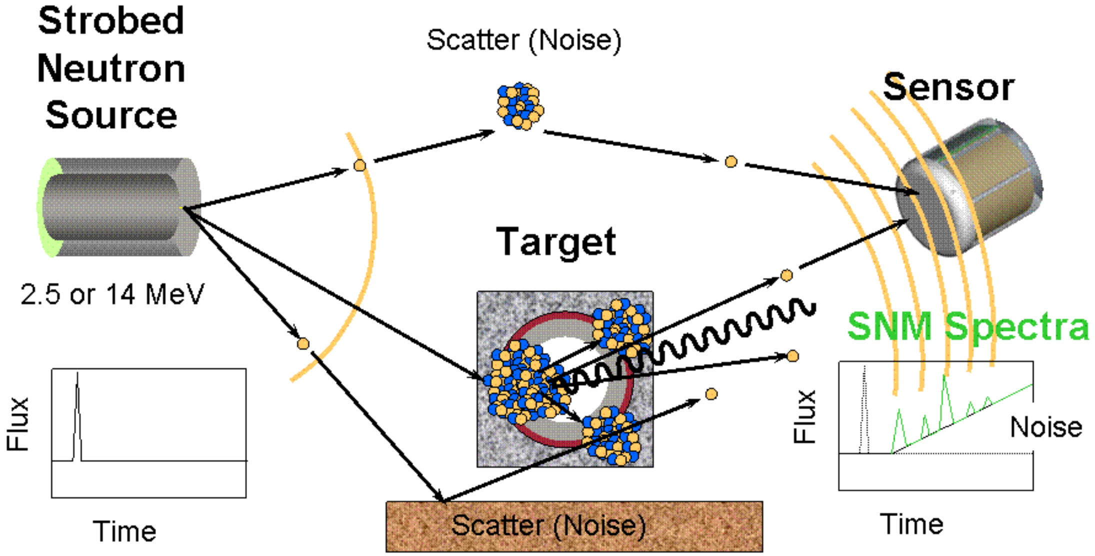
DTRA: A. Stevenson and J. Bevins

Agenda

- **Prompt Emission as a Method for Detecting Materials**
- **The MicroPinch Neutron and X Ray Source**
- **Microfabrication Efforts in Radiation Sensor Development**

Summary of Prompt Emission Method

- *This method:*
  - ***Uses a single short pulse for neutron TOF***
  - ***Uses Prompt neutron signal.***
  - ***Primary signatures' attained within 100 microseconds***
- Challenge:
  - ***Bright source weak signal***
  - ***Background***
- Benefits:
  - ***Less dose (Safer!)***
  - ***Immediate results***
  - ***2m to ~100m?***



What Makes This Approach Different from Others

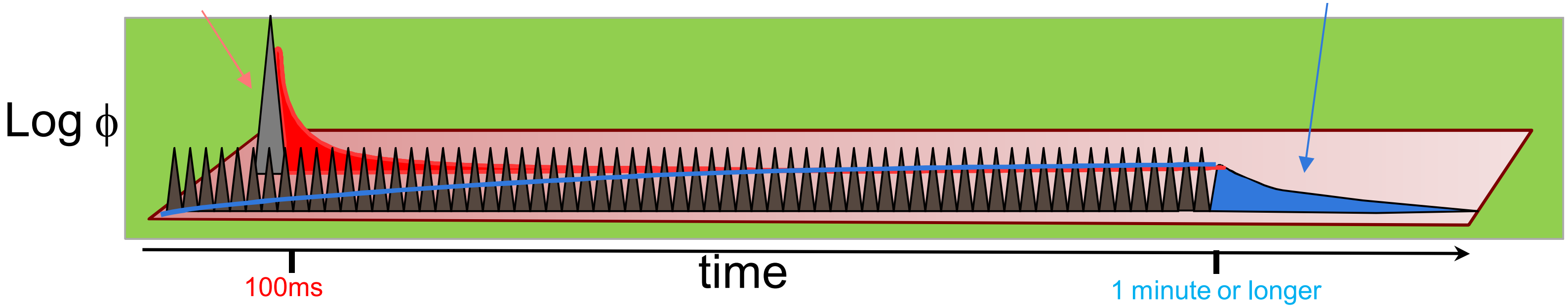
- *Uses a single short pulse for neutron time-of -flight*
- *Uses prompt fission emission which is 99% of total emission*

Short Pulse (<100ns)

- **Our Approach** (Boeing, SNL)
- **IPAD** (DTRA, NRL)

One Short Pulse w/ Prompt Signatures makes Bigger Signal with Less Total Dose

Delayed Signature (1%) after emitter signal dissipates



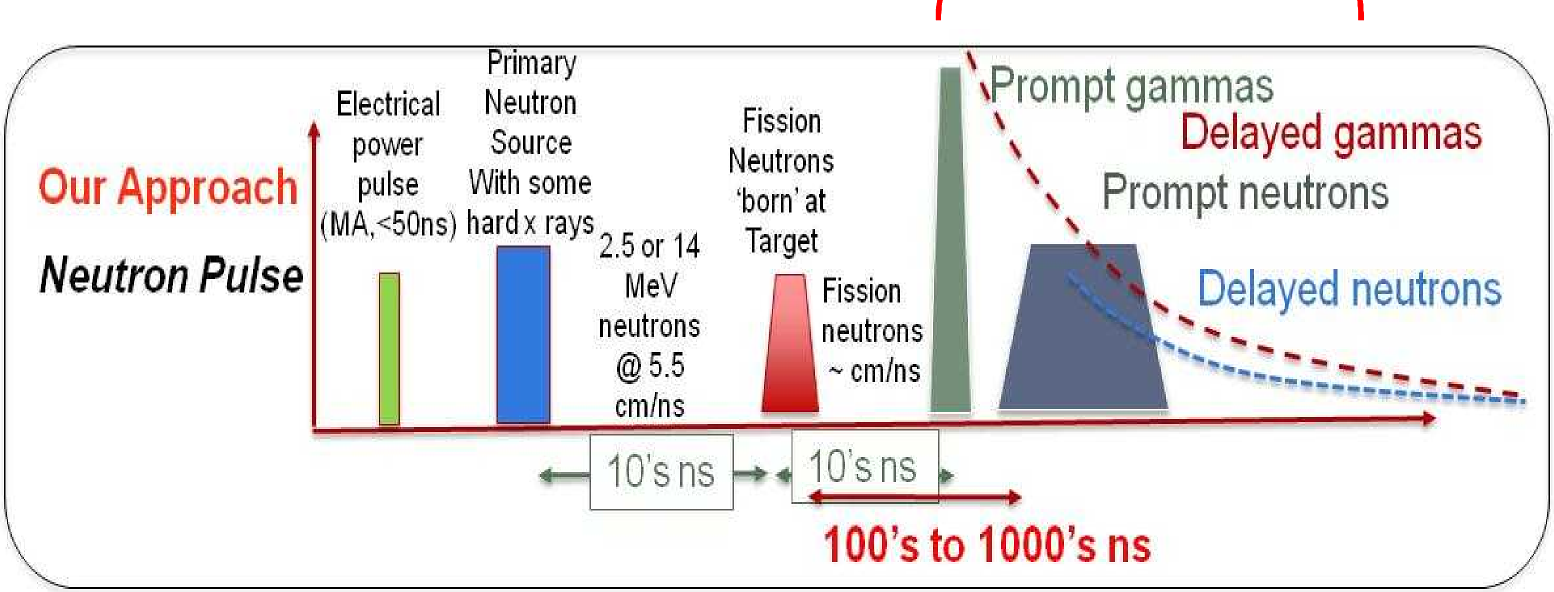
What Makes This Approach Different from IPAD

More Information per Quanta (Much Less Dose)

Prompt Neutrons

- Key Information within 100 μs
- Prompt fission emission (99% of total)
- Smaller radiation source (DPF)
- Vastly reduces background for both neutron and gamma signatures

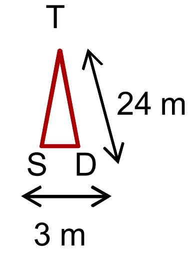
Neutron TOF and Gamma counting, spectroscopy and imaging



Challenge – Bright Source Weak Signal

- Challenge can be overcome

Background with Collimated Source

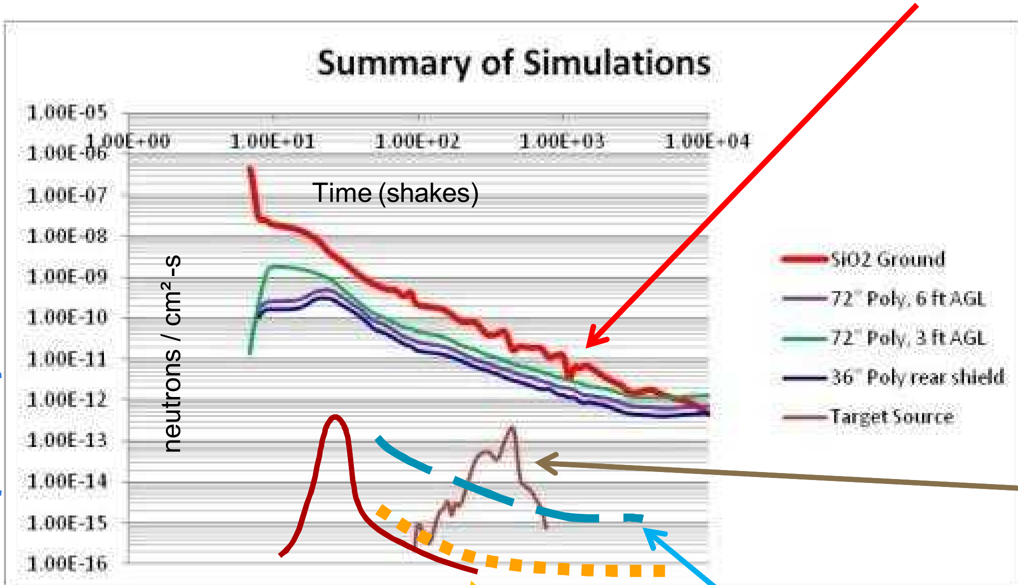


Test Configuration

Target obscured by background

Target Signal now visible

Enhanced Detection*



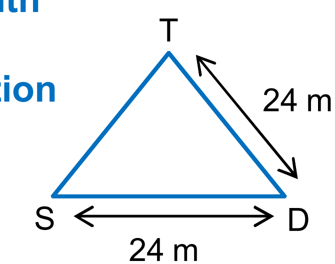
Neutron Target Signal

*Test data taken at 2 m showed a signal-to-noise ratio of 16 dB

Gamma Signal (idealized)

Add Directional Detector

Background with 24 m Detector, Source Separation

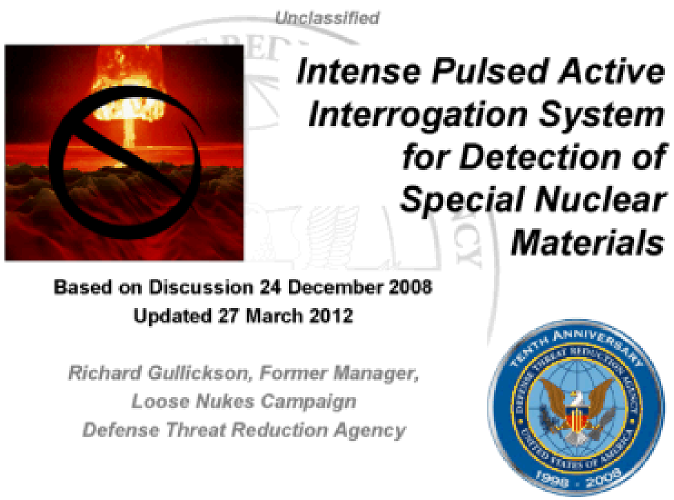


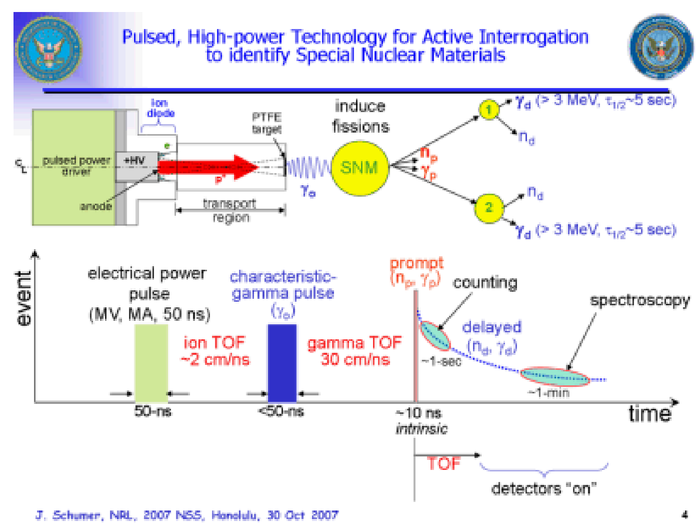
Test Configuration

T=Target
S=Source
D=Detector

Related Work

- PFNA, Gozani, et al, Pulse Train, Activation, die away, etc., long time
- ISIS … expensive, complex, large, high dose, long pulses/trains
- HERMES, high voltage gammas, single pulse, physics sound
- Gullickson, a little different – still looks at delayed, also uses pulsed power technology as the source
- V. Gribkov, M. Chernyshova, M. Scholz, R. Prokopovicz,, K. Tomaszewski, K. D., U. Wiacek, B. Gabanska, D. Dworak, K. Pytele & Zawadkae, a. A. A single-shot nanosecond neutron pulsed technique for the detection of fissile materials. *Journal of Instrumentation*, doi:10.1088/1748-0221/7/07/C07005 (2012).





Specific to this Method

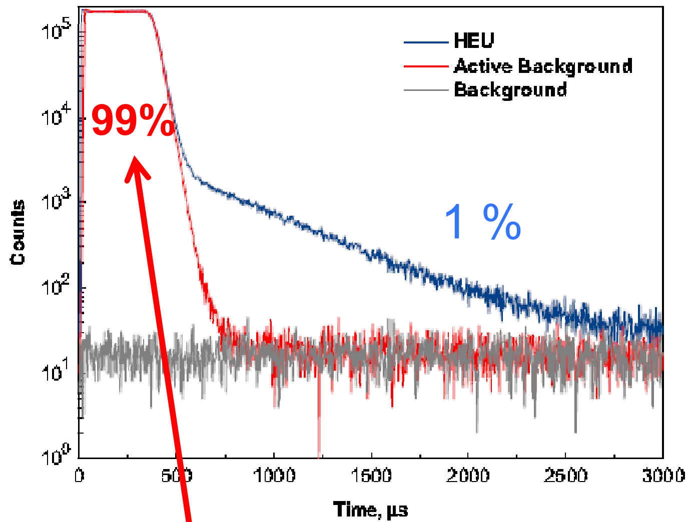
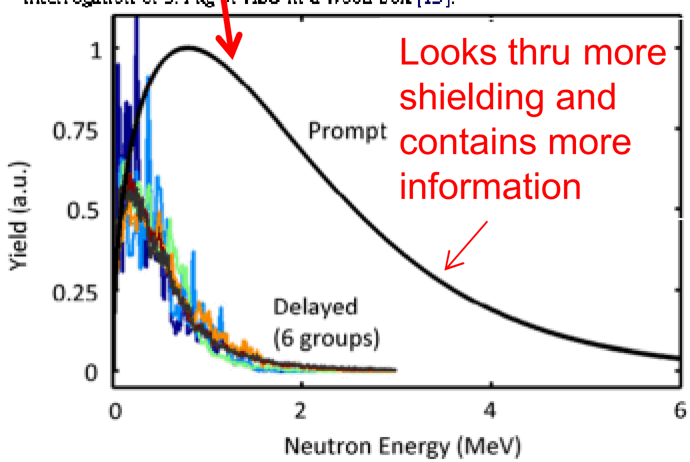


Fig. 6. Demonstration of the inter-pulse, die-away neutron signature following interrogation of 9.4 kg of HEU in a wood box [13].



This method:

- ***Uses 99% of prompt fission emission***
- ***Uses a short pulse for TOF***
- ***Uses a directional, gamma insensitive fast neutron detectors***
- ***Uses imaging gamma spectroscopy***
- ***Existing Source Technology***

- Previous methods are documented in the review article of Runkle. Most use delayed fission gammas and neutrons. This means they use 1% of emissions. Associated particle method is the only other that uses prompt emission.
- There is an implicit assumption in the active detection community that sensors cannot operate when the source is on. This is not true for our method. Historically this is what has driven people to use the 1%.
- This method uses Fast Neutrons as Interrogators and Prompt Fission Emission as signatures. It is different: short single neutron pulses with TOF detection. This is **not** considered in the Runkle review.

-Cooperstein, et al, have however, discussed short pulse (unpublished). IPAD program is somewhat related – they use gammas and we suggest neutrons.

*From Runkle, Chichester, et al, 2012.

Compare SNL Results with Recent Russian/Polish Safeguards Experiment

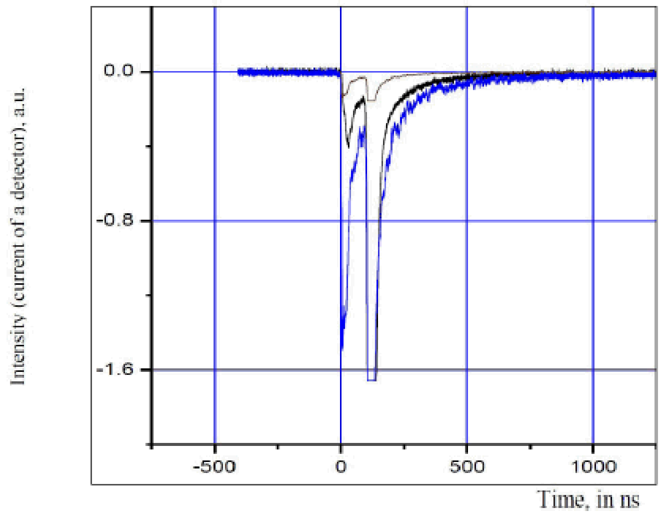


Figure 19. Two oscilloscope traces overlapping one another: one is taken without fuel element (the black one, smooth) and another one is taken with fuel element (the blue one with multiple peaks); the red one is the same as the blue one taken with much lower sensitivity of the oscilloscope channel. *

* From Gribkov, JIINST, 2012

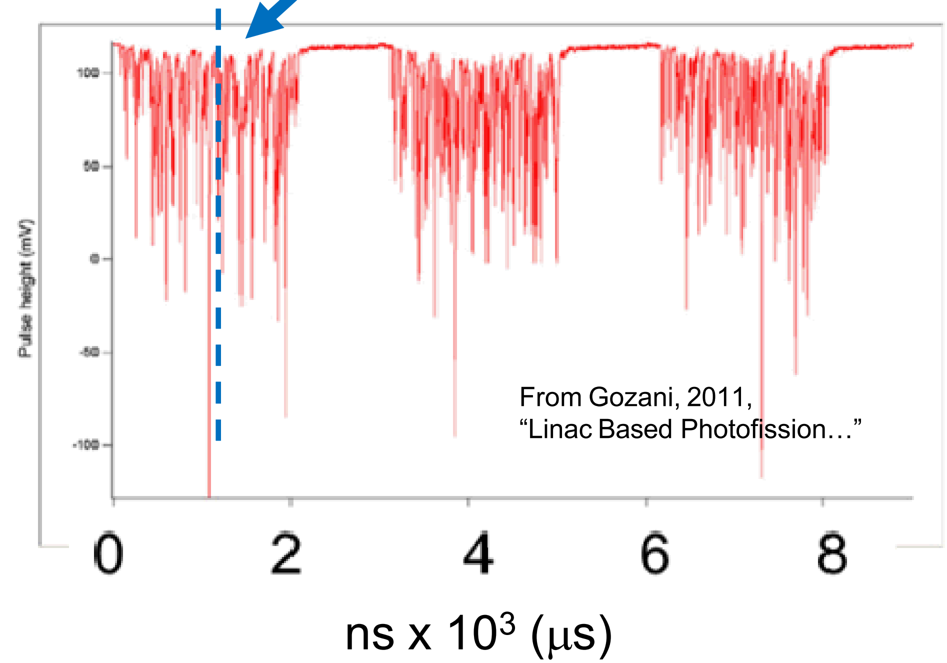
Experiment	Target	Source to target Distance (m)	Target to Detector Distance (m)	Brightness (neutrons/pulse)	Neutron energy (MeV)
SNL/NSTec	2 kg DU	2	2	2e11	2.5
Gribkov, et al.	16 nuclear fuel rods 50 cm long	0.1	6	2e8	2.5 and 14

Why Focus on Single Nano-Second Pulse?

- Active Detection with nano-second pulses
  - Source of neutrons separated from signal. Background reduction is key!
  - Allows you to utilize the greatest portion of neutrons. – the “prompt” neutrons.
  - Time-of-flight reveals location.
  - Use is limited by available Neutron Sources.

TOF Signal Return.
Can not use PFNA (Gozani’s) ns pulses.
>10^8 noise.

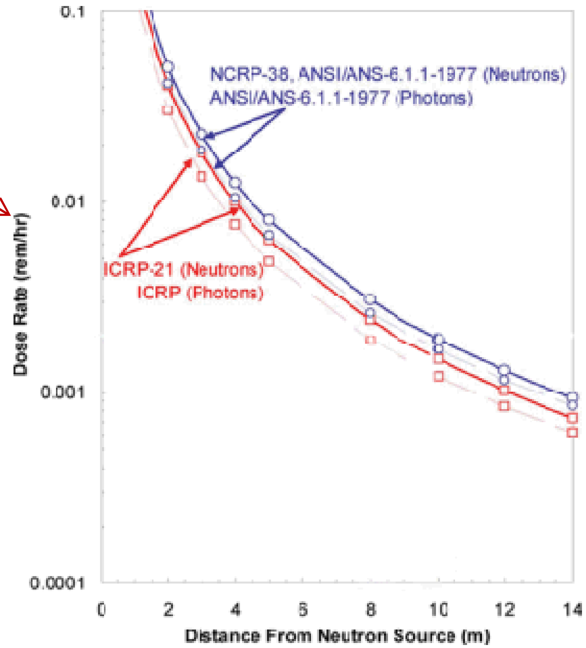
“Much shorter (<50 ns) duration neutron pulses have been proposed for use in active interrogation …”. Runkle et al. (2012)



At 30m what you want most is at 2 μs

Method requires Less Dose - Safer!

Note units



Comparison of dose rate versus distance estimated using the NCRP (circles) and ICRP (squares) conversion factors for a 1×10^8 n/s DT neutron source 1 m above a concrete pad without scattering (dashed lines, calculated using $1/r^2$ scaling) and with scattering (solid lines, calculated using MCNP 5).*

*IEEE TRANS. ON NUC. SCI., VOL. 55, NO. 1, (2008)
Radiation Fields in the Vicinity of Compact Accelerator Neutron Generators
David L. Chichester, Brandon W. Blackburn, *et al.*

- **Neutron Dose**
  - **$1\text{-}10^{10}$ pulse at 1m gives ~3 mrem;**
    or 4×10^{11}~100mr at 1m); 100 mrem is rad-worker-limit/yr at SNL
  - **4×10^{11} pulse at 3 m gives ~20 mrem to a human in a container. [compare 1 hr@10^8/s]. Could get away with a much smaller pulse if short.**
  - **Simple analytical estimate suggests**
    6 μrad at target may be enough to find SNM in a moving vehicle w/ encapsulating detector. [comparing dose; CONOPs]

It is very hard to make a pulsed neutron source a strong radiation hazard with a single pulse.

For short pulse detection – need a source and sensors

Now - lets talk sources – in particular lets talk microsources, where the diode is made small.

Components of a Pulsed Power System

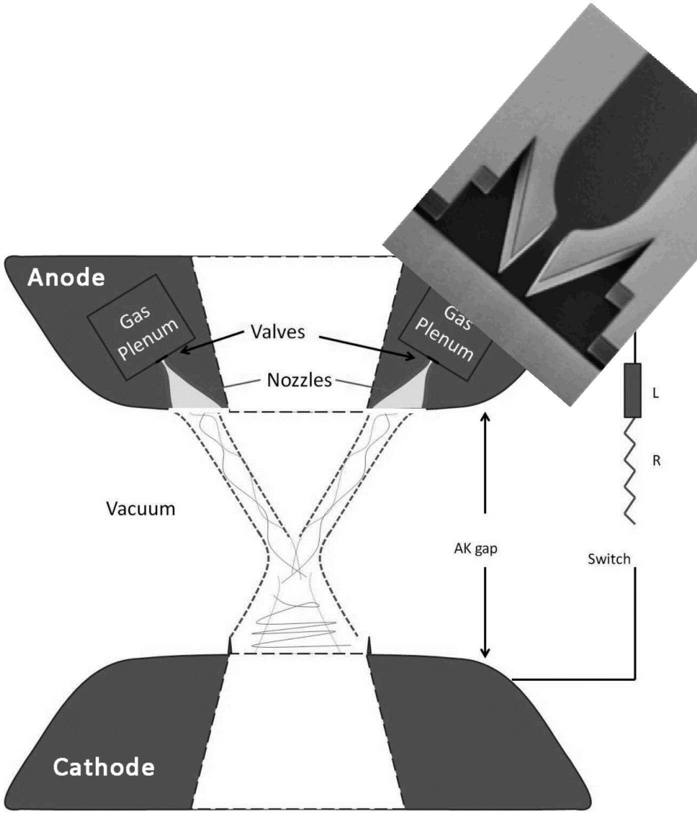
Schematic of a simple pulsed power system with a load – in this case - the x pinch diode.

New Load - Microscale Quasispherical Implosions (Z Pinch or X Pinch)

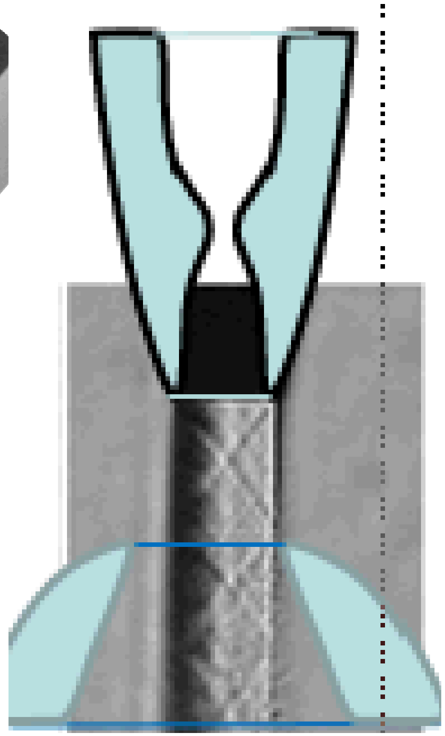
- Micro X Pinch Scales slightly better than z pinch because the aspect ratio of the pinch gives low mass in the target and high energy per particle

- High tolerancing for alignment, rate, pressure, nozzle

- Many diodes/wafer



X Pinch

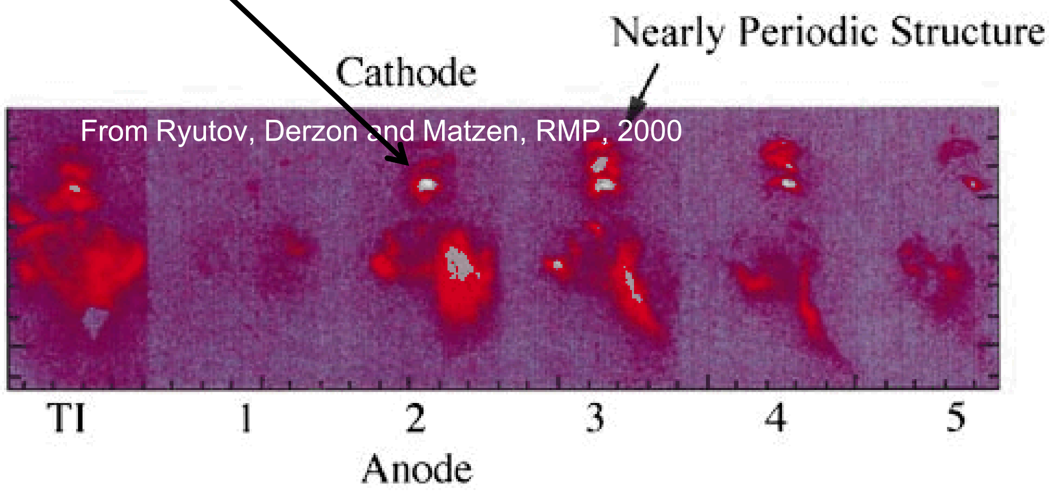


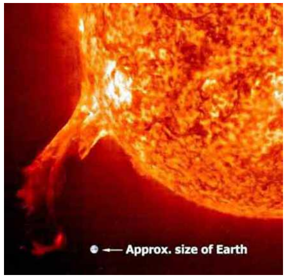
Z Pinch

Hopefully a cool ‘source’ for basic science experiments – a sort of ‘micropinch’

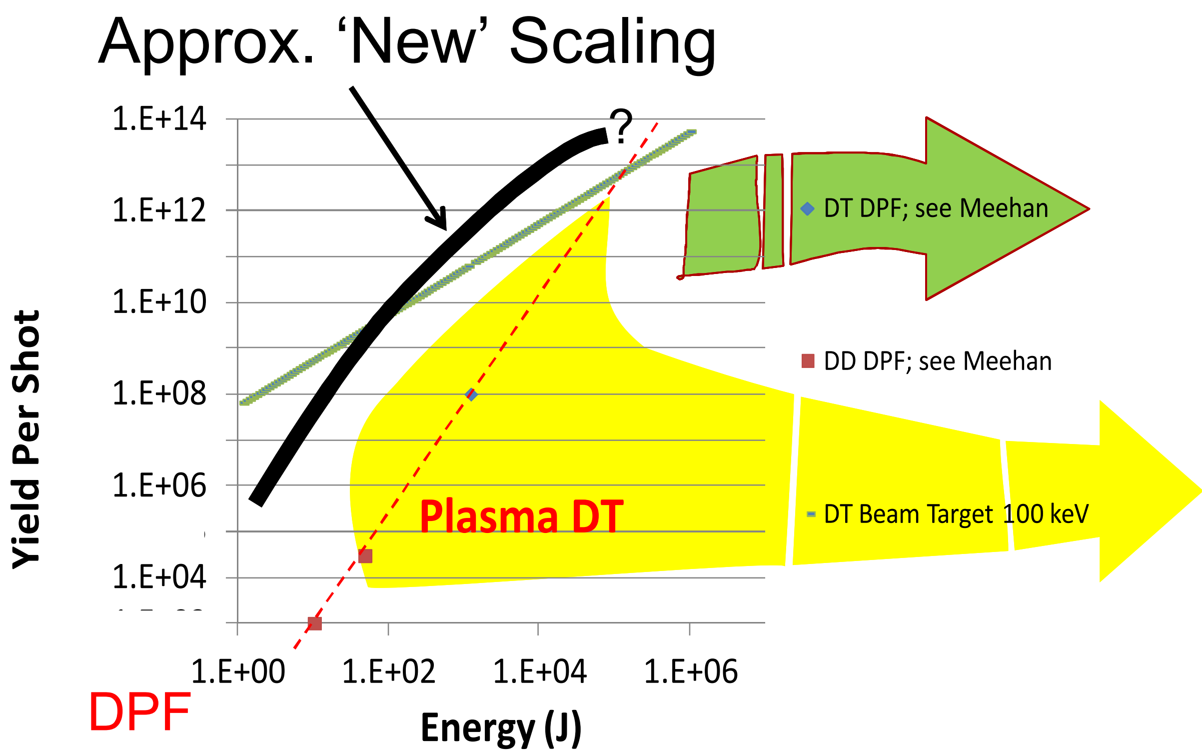
- X-Pinch
  - Plasma Experiments on a Chip!
  - X-Ray source
- M-Tesla magnetic fields
- Diagnostics Development and Non-thermal x ray production
- Neutrons?

M=0 mode in a plasma instability





Neutron Generators are Based on Either Beam-Target or Thermonuclear Mechanisms and They Scale Differently



X Pinch Performance based on Thermonuclear (hot plasma) Mechanism. Historically, Rough I^4 scaling presides. ***The micro pinch is off the traditional scaling***

Both beam-target and plasma neutron generation have advantages in terms of scalability of neutron flux, pulse tailorability, reliability and size/energy.

Both methods have advantages are a result of the microfabricated nature of the devices.

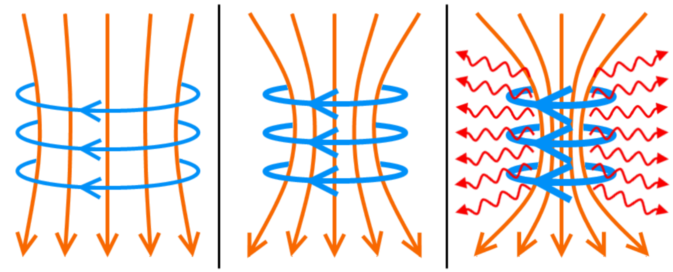
What is the key physics?

Temperature is related to the Mass that is heated

Kinetic energy is supplied by the driver; it is a function of the current supplied and the voltage. The whole length of the pinch sees the same current (except the central node). The whole pinch then heats. **The shorter the pinch the more efficient the heating** per unit supplied energy of the ion in the central feature.

The central feature is much like an m=0 unstable mode. The convergence dominates the final compression and determines the pinch timing and ultimately the yield.

Density and Temperature Together Make Neutrons

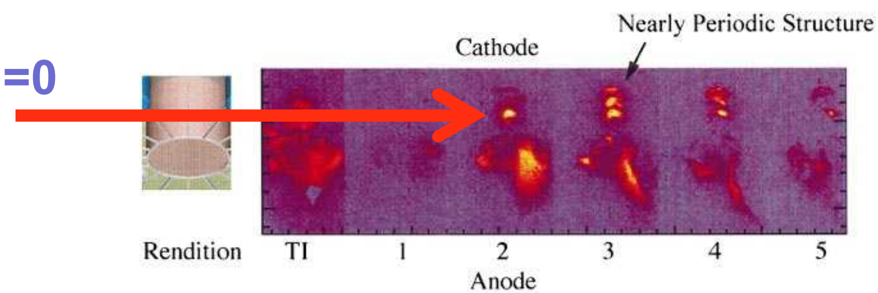


Current is Constant Along The Height

$$T(eV) \sim \frac{2}{3}(W_{kin}/M) = \frac{2}{3}\left(\frac{\mu I^2 t^* \ln(C)}{4\pi}\right)/M = \left(\frac{\mu t^* \ln(C)}{6\pi}\right)\frac{I^2_{max}}{M}$$

Key physics

m=0

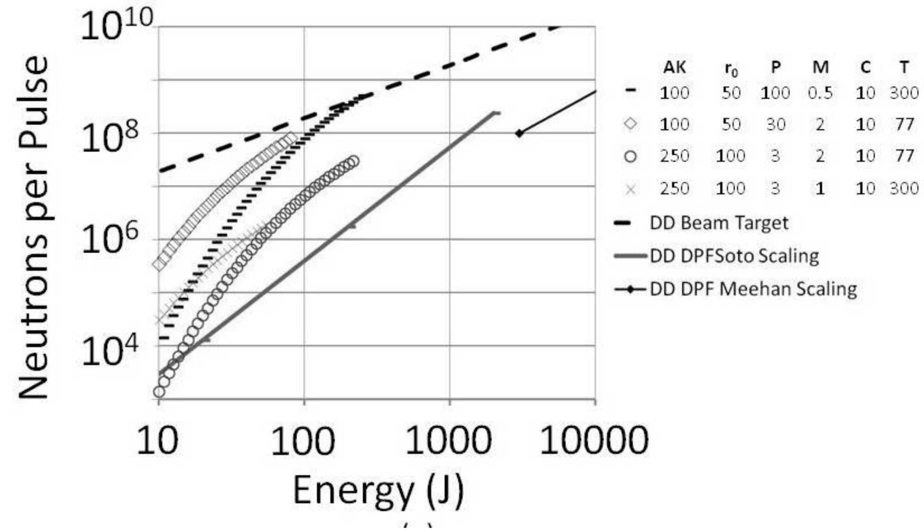


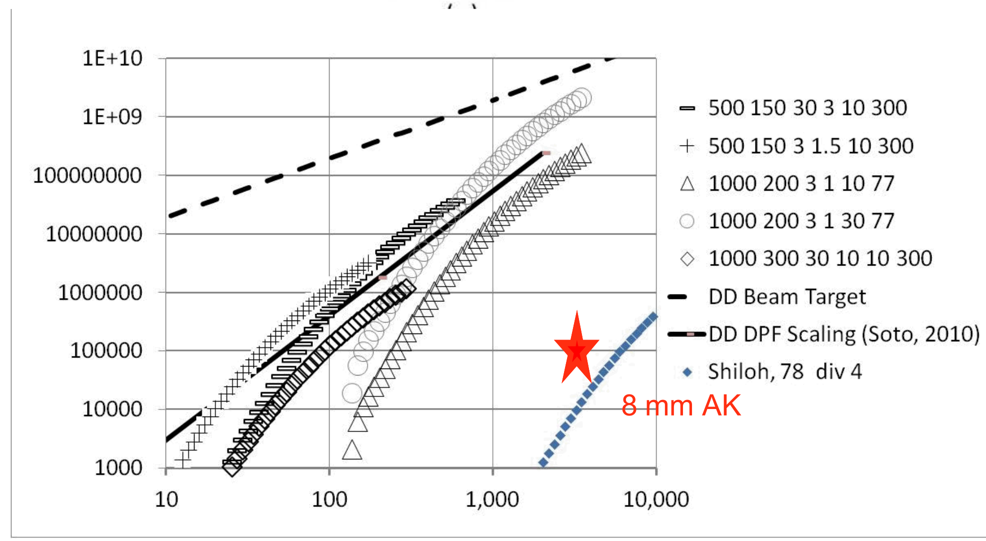
Available Pulsed Power Source offers an Estimate of Performance

Estimated Single Pulse DD yields. a) Estimated x pinch yields for AK gaps of 100 and 250 micron compared to estimated beam target yields and measured DPF performance. b) Estimated x pinch yields for AK gaps of 500 and 1000 micron compared to estimated beam target yields and measured DPF performance. The traces show single pulse yields. The legend lists AK gap (mm), nozzle radius (mm) gas, plenum pressure (atm), Mach number, compression ratio, plenum temperature (K).

AK gap	Peak Field	Predicted Outcome
1 mm	1.5 MV/cm	Formation of Pinch
0.1 mm (100 μm)	15 MV/cm	Uncontrolled Breakdown

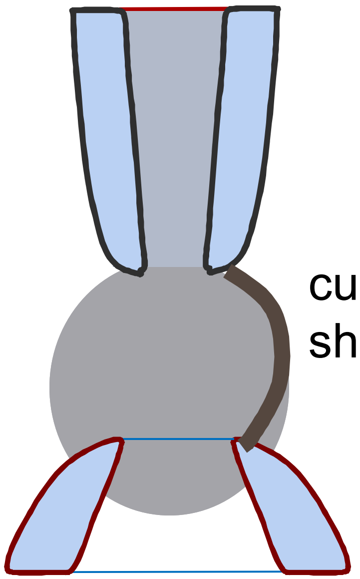
Predict ~10⁶/pulse within an order of magnitude of Shiloh result for DD gas

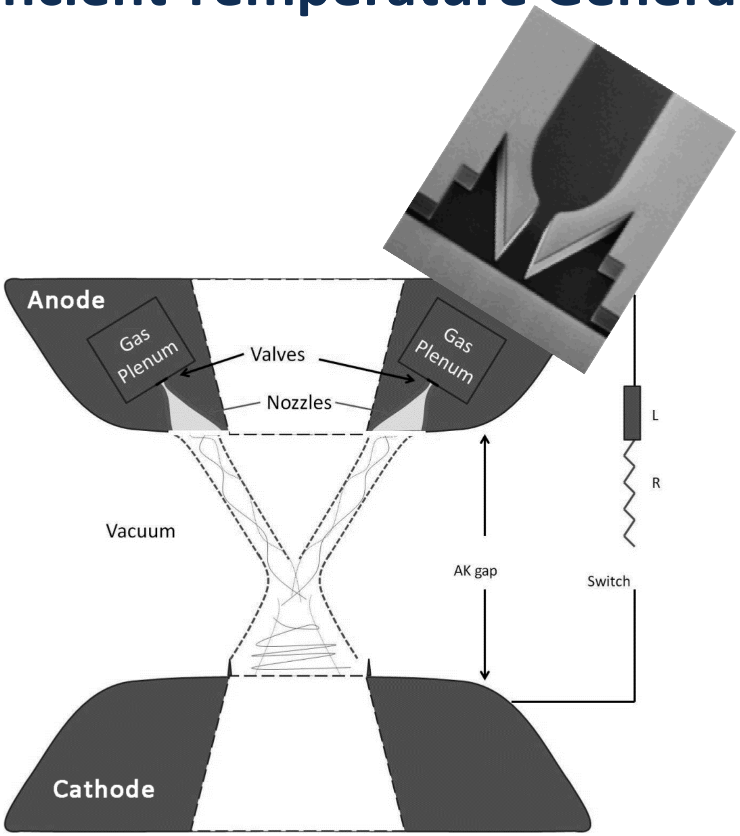


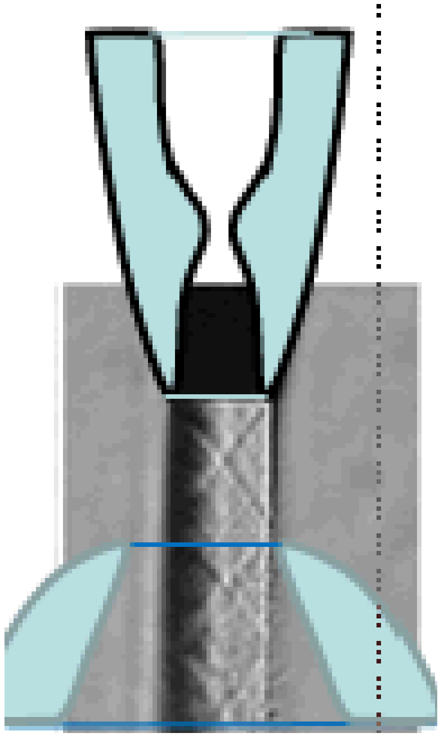


Shiloh, 1978, Gas Puff Z Pinch

Microscale Quasispherical Implosions (Z Pinch or X Pinch) as Neutron Source and Efficient Temperature Generators





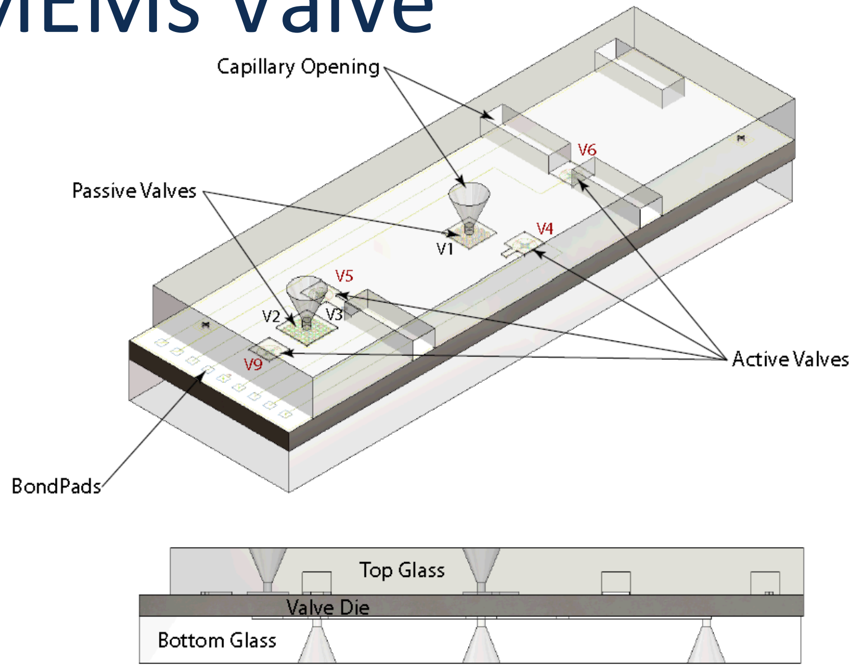


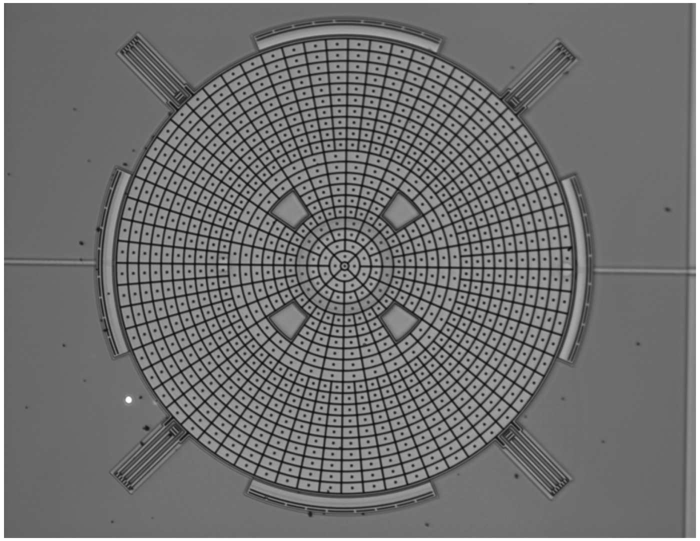
Low Mach Number
Gas Puff QuasiSpherical
M=0.5

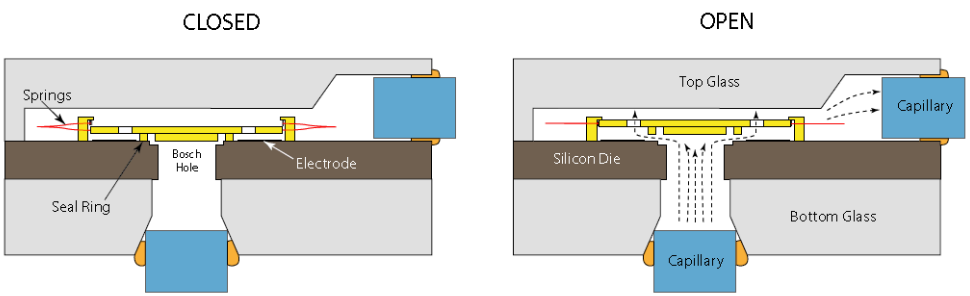
X Pinch

Z Pinch

MEMs Valve







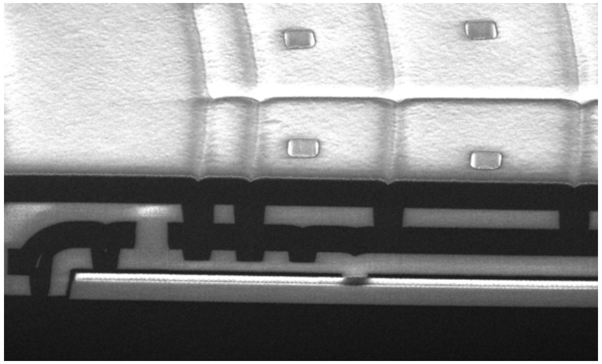


Figure 2: Valve chip layout with top and bottom glass (transparent). Passive valves (black) V1 and V2 are valve arrays containing 16 valves and bosch holes. Valve 3 is a single passive valve. Active valves (red) V4-V6 are shown. V9 – single active valve for venting the PC if necessary.

Current Initiation is A Concern

Option 1) Puff In a ‘slug’ of Gas – shape the electrode to have electric field multiplication to seed the initial pinch configuration.

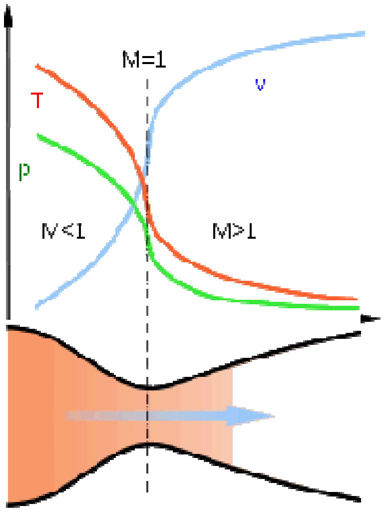
- Historically this works – start with a z pinch.
- Severely underexpanded compressible flow nozzles offer the potential for well defined jets under needed conditions. We have options to high Mach nozzles in MEMs at the right pressures.
- The downside will be valve timing control; upside they don’t have to fully open.

Option 2) Gas Puff with Chilled High Mach Number Nozzle

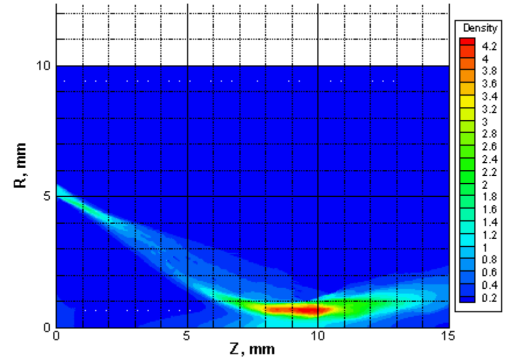
- Provides control at low complexity

Option 3) Laser Initiated in Conjunction with either of the above

- Greater control than either of the above



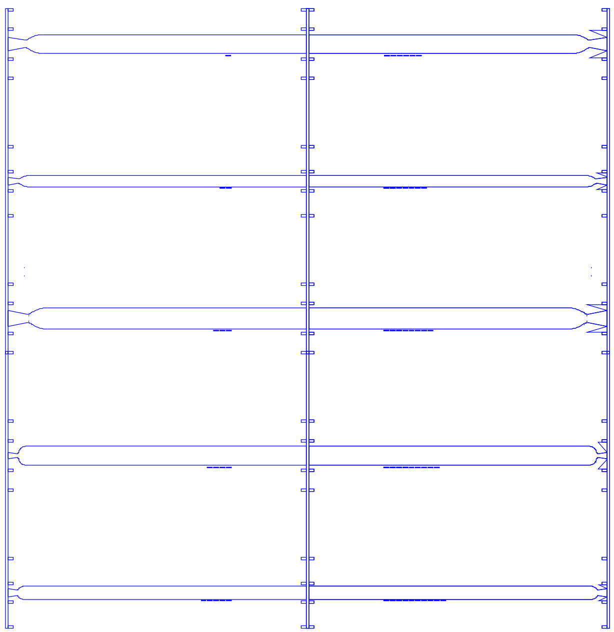
http://www.dhcae.com/images/freejet03.gif

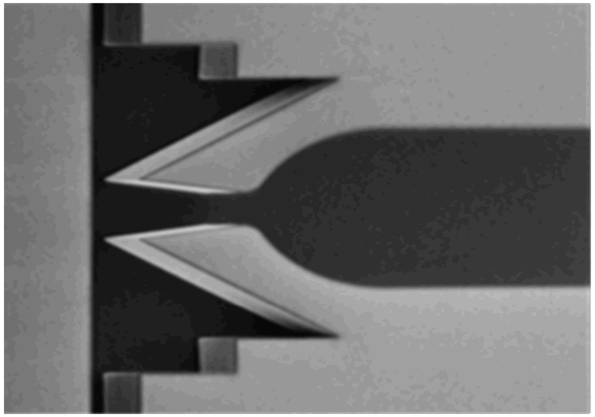


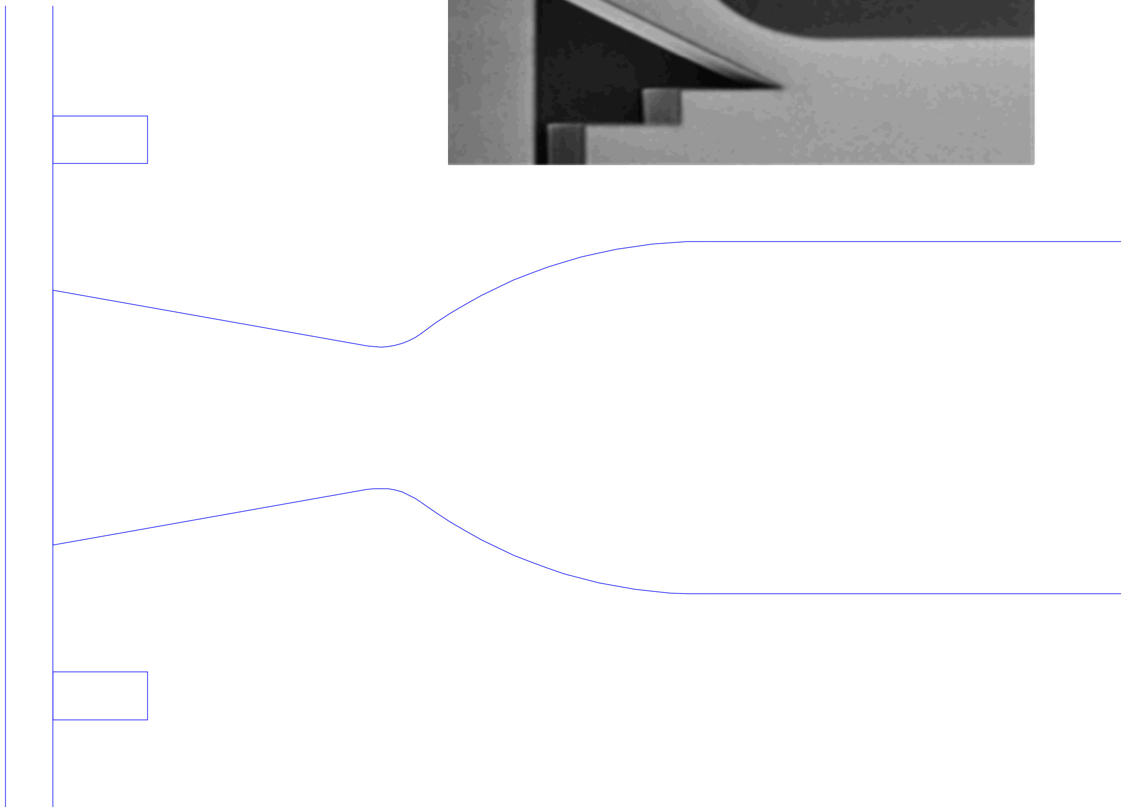
Boldarev, 2007

Gas Puff Dynamics – proven in experiment and modeling

Many Nozzle Devices are Made on a Single Wafer







Device 1 and 6; device 6 same as 1 except with boat tail.

Electrode-Plasma Interaction

Peterson, et al, 1999; MS Derzon, was PI on the effort and experimental lead

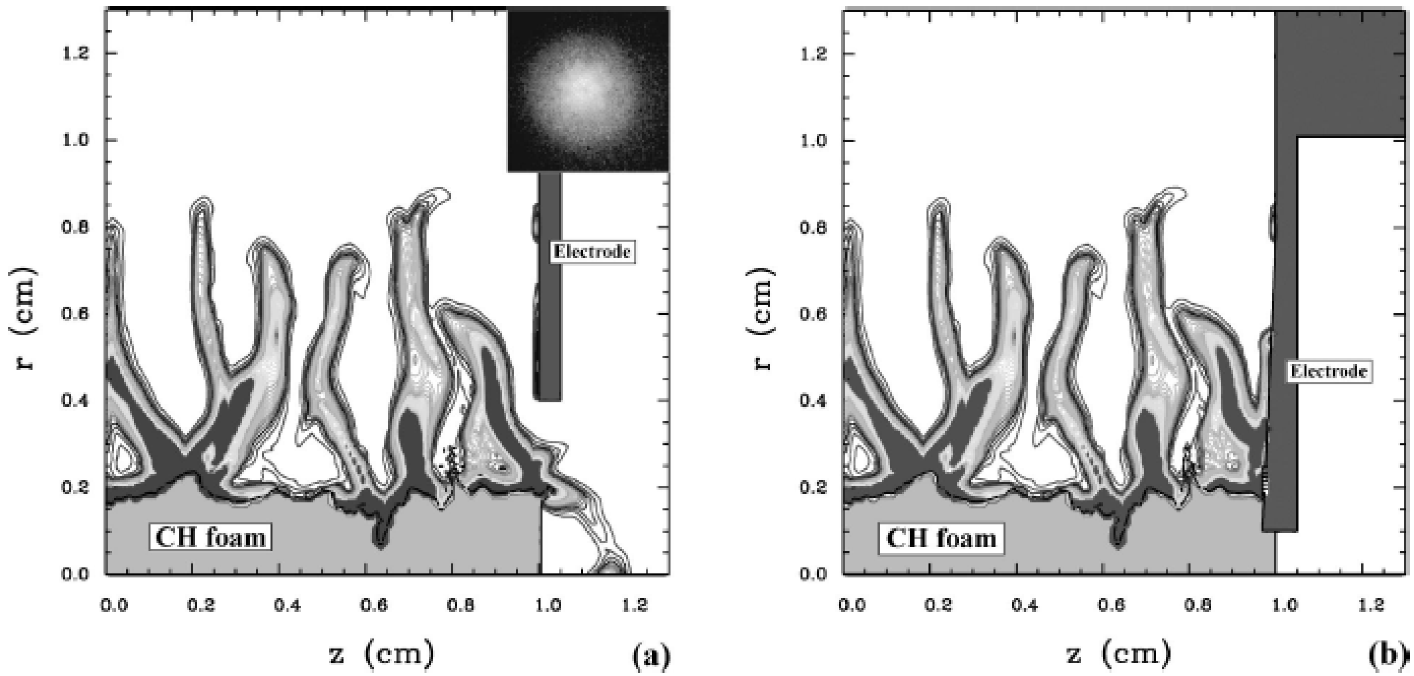


FIG. 10. Isodensity contours of tungsten impacting on the foam target for the (a) Z-113 configuration and with the redesigned electrode and aperture (b) used in later experiments. The large aperture and straight electrode allow tungsten to collapse on axis to the right of the foam interfering with the diagnostic view of the dynamic hohlraum. A sample of the pinhole photographs showing an early bright spot on-axis is shown inset in the upper right of (a).

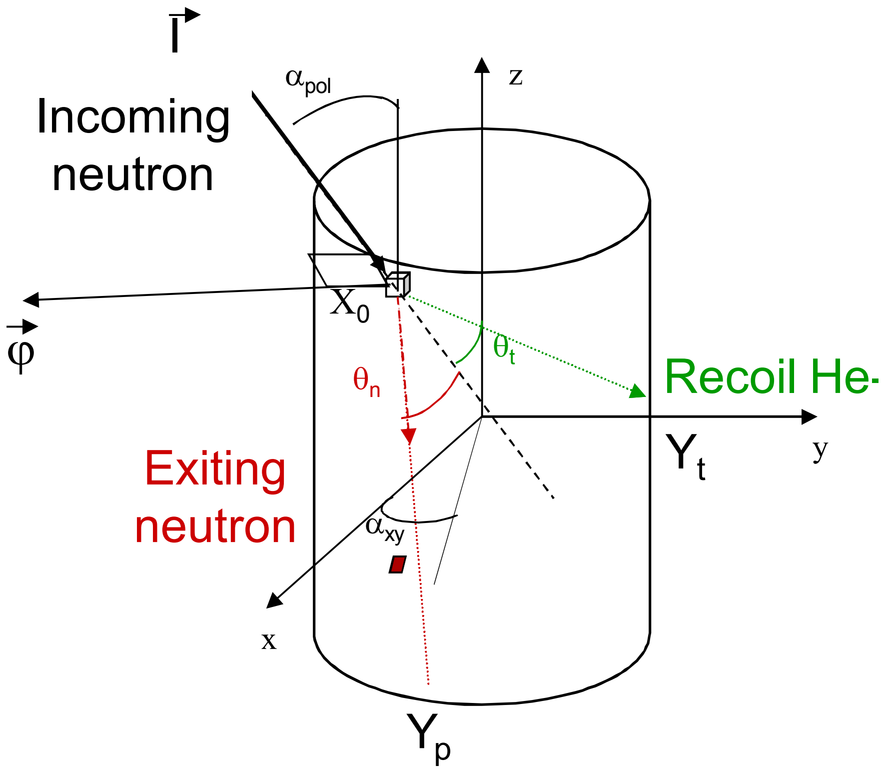
Electrode Plasma Effects on a 2 cm radius Z pinch can be limited to <200 μm

Conclude: the electrode effects can be negligible for a <1 mm dia. pinch .

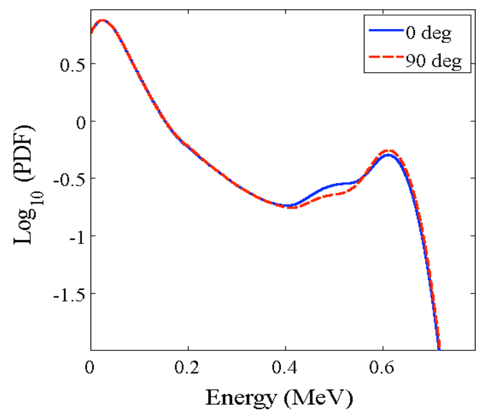
Agenda

- Prompt Emission as a Method for Detecting Materials
- The MicroPinch Neutron and X Ray Source
- **Microfabrication Efforts in Radiation Sensor Development**

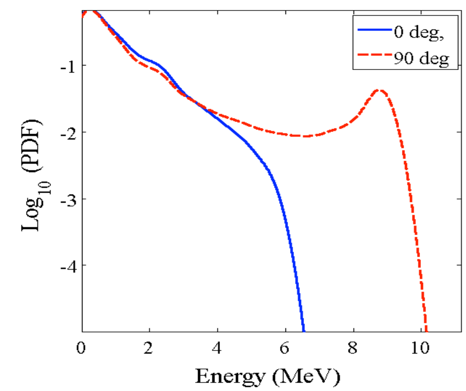
The Directional Detector is a Recoil He-4 Ionization Chamber.

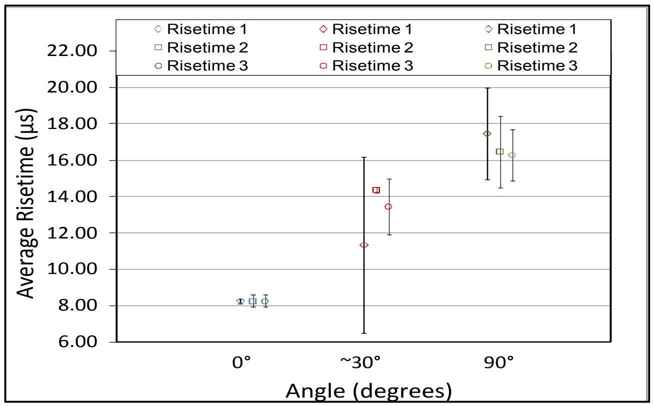


1 MeV Neutrons



14 MeV Neutrons





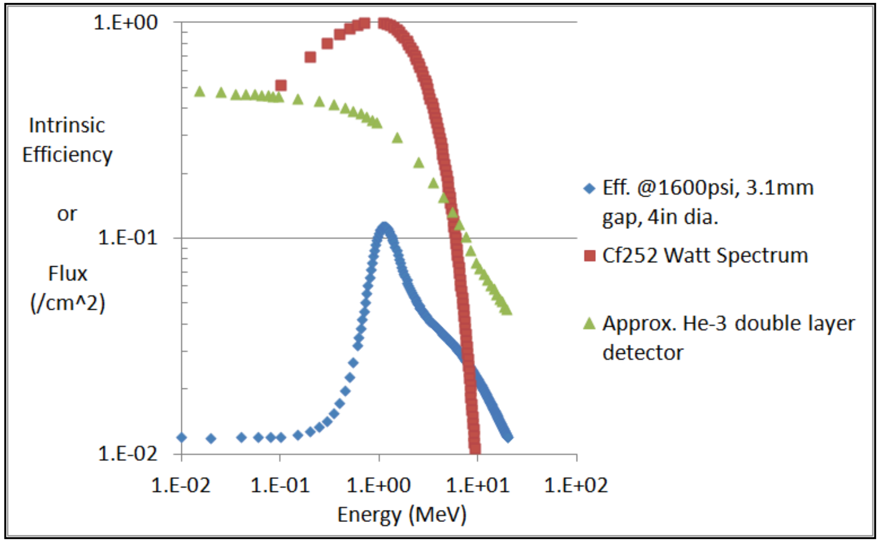
Both risetime and energy deposited are functions of incident angle.

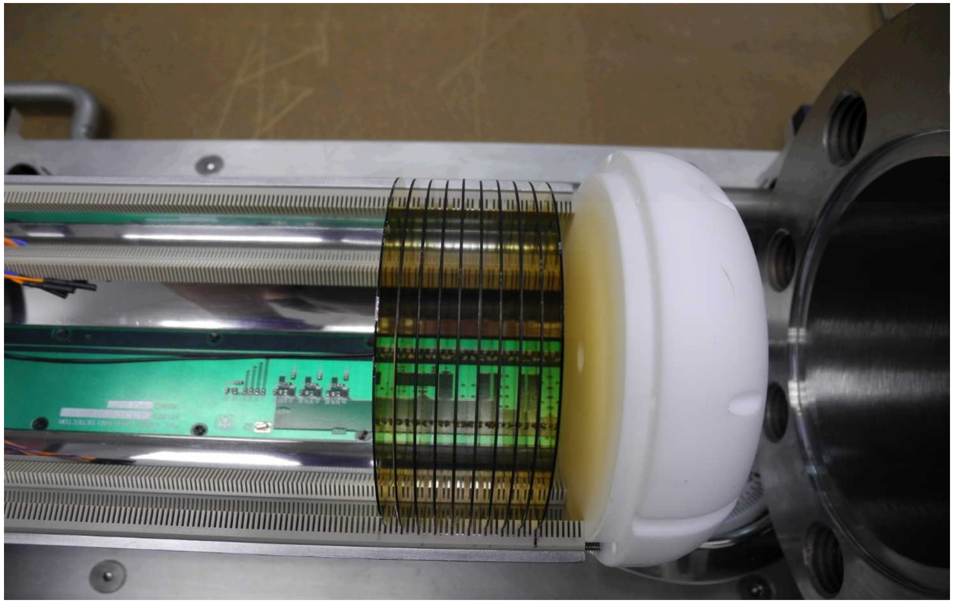
To Make this Work the Range must be greater than 1-, or 2- of the device dimensions.

Prototype Design Fielded on HERMES

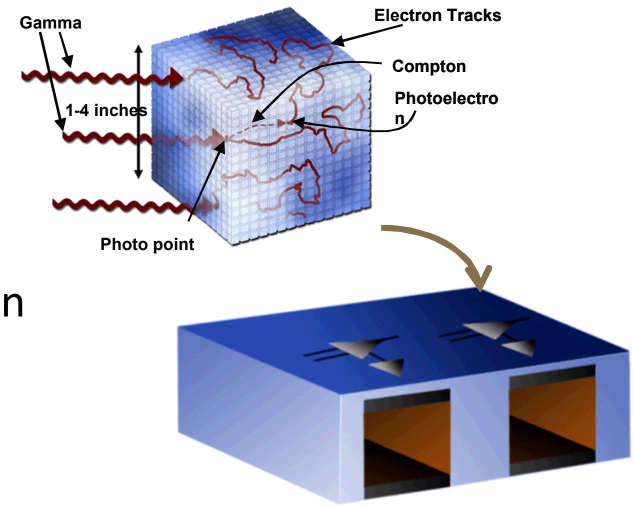
10 cm diameter wafers
23 cm active length possible
(5 cm fielded on HERMES)
3 mm spacing
1600 psi
Moles=6.9
Volume=1.4L

230 cm^2@ 10% Average Intrinsic Efficiency Per Canister





Problem - 3D Tracking and Monolithic Fabrication

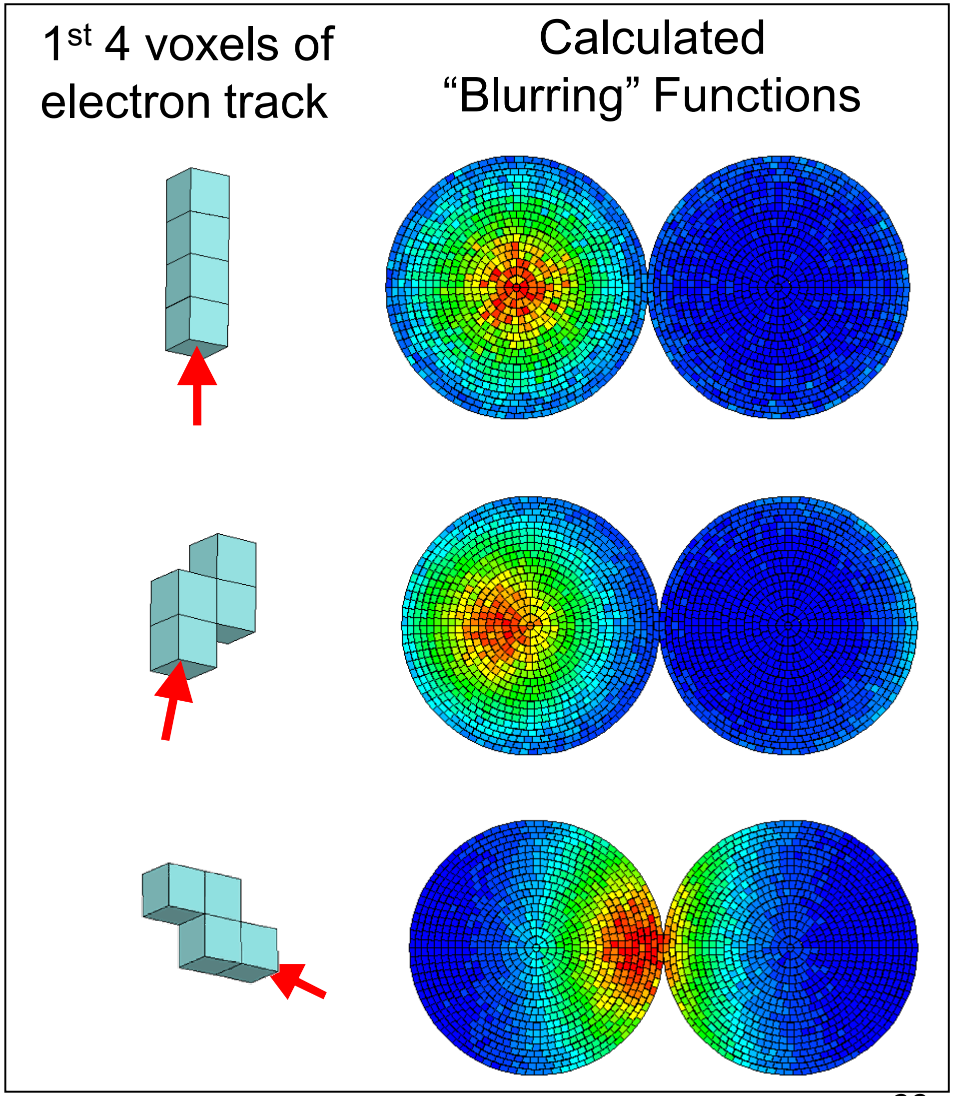


- Identifying photoelectron, Compton and Pair Production in monolithic sensor at microscale –
- Fully 3D devices - Special Niche for SNLs MESA
- Segmenting to pull more information out of an incident radiation field than bulk; numerous groups are pursuing this
- Enables new semiconductors to be used as gamma sensors

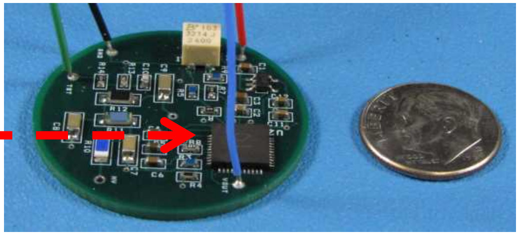
- Societal Implications
  - lower US/World medical radiation dose
  - Better SNM, proliferation detection

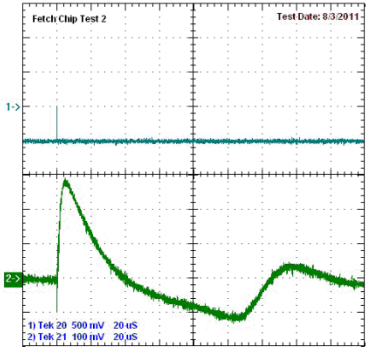
Photoelectron and Compton Scattering can Contribute to Directionality

- **Due to the large amount of electron scattering, a pixellated track only determines a probability distribution of the electron initial directions**
- **Such distributions can be calculated by ITS (modified), an electron/photon Monte Carlo radiation transport code**
- **Examples shown for 400 keV electrons in liquid Xe for 100-micron-edge voxels. (Note lower two only differ by a rotation)**

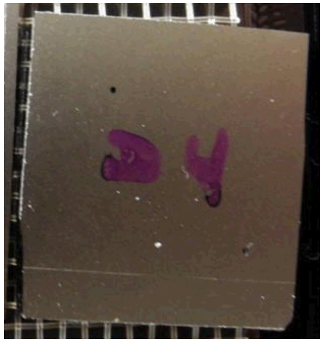


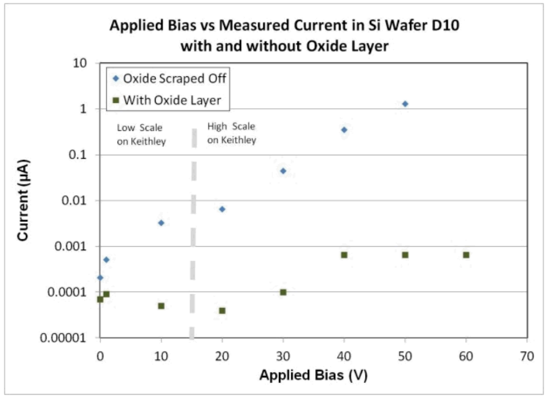
Progress

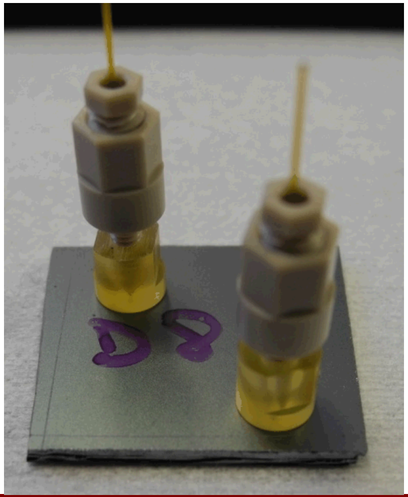


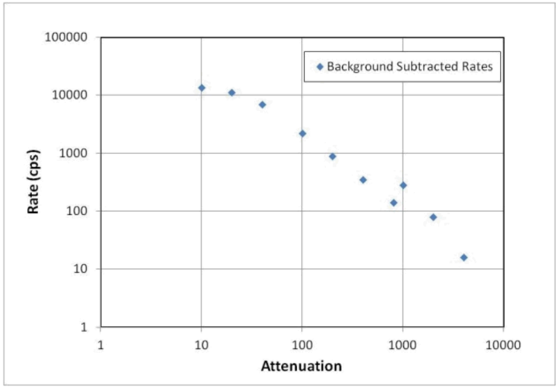


- ‘Fetch’ Chip custom ASIC
- Pressurized to 3000 psi
- Devices packaged and tested separately
- Gamma, Neutron and both. Concepts tested.
- Risetime reflects position of event









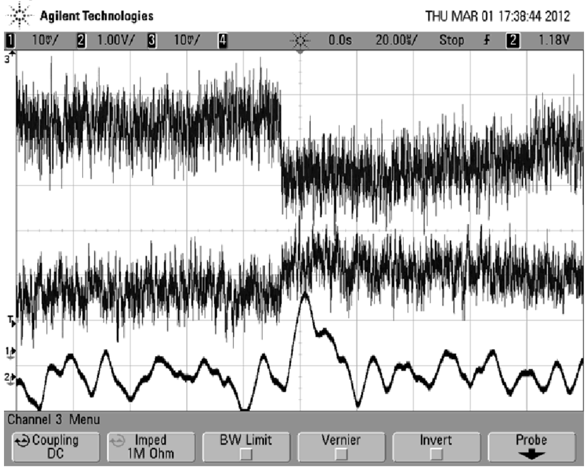
Early and preliminary result:

Neutron - Gamma Discrimination

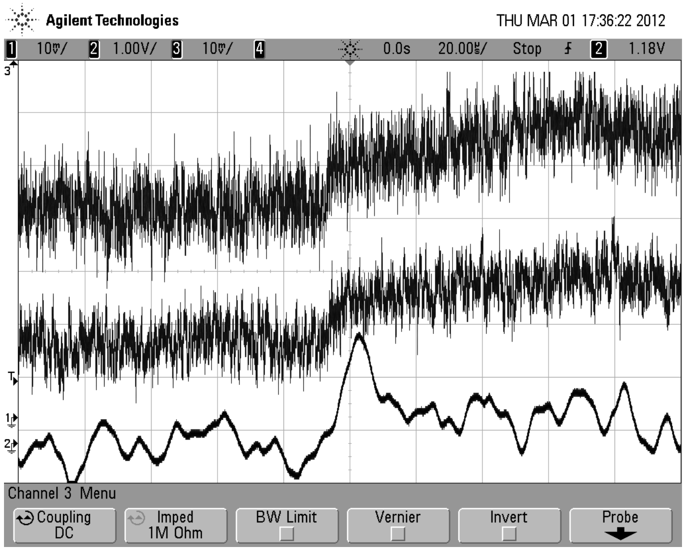
Spatially based neutron/gamma discrimination has been shown in the lab. This can result in separate neutron and gamma spectra.
Or at least removal of gammas form the neutron spectra.

This is the first we know of this being done. If you know of any other work on this please let us know.

Neutron



Gamma



Summary

- We have an active interest in detecting materials (nitrogen, actinides, etc.) using the prompt fission and gamma emission from materials with short bursts of neutrons
- It may be possible to make a more energy efficient neutron and x ray source
- We have been experimenting with methods to get more information out of a radiation field

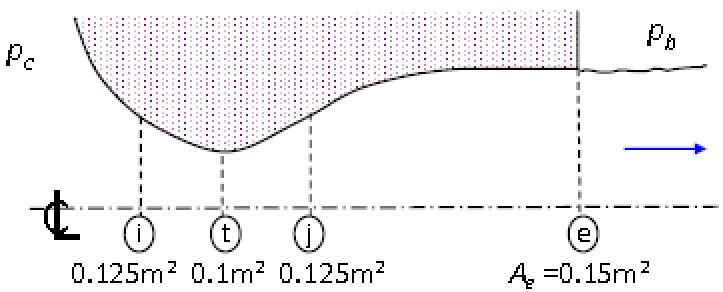
Additional Information

Backup Slides

where λ

The Following Issues Came Up During the

Example- Converging-Diverging Nozzle



Compute M, p at (i) (j) (t) (e)

(a) For entirely subsonic flow with p_b/p_c =0.9

(b) For p_b/p_c just low enough to choke flow

(c) At design

$$\mathrm{Re} = \left[\frac{DV\rho}{\mu}\right]$$

$$K_n = \frac{\lambda}{L} \prec 1$$

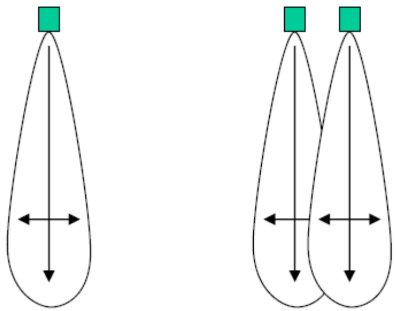
Continuum assumption is good in the nozzle

$$Kn = \frac{k_B T}{\sqrt{2}\pi\sigma^2 p L}$$

$$Kn = \frac{Ma}{Re}\sqrt{\frac{\gamma\pi}{2}}.$$

Molecular mean free path to spatial length

Single orifice nozzle   Multiple orifice nozzle



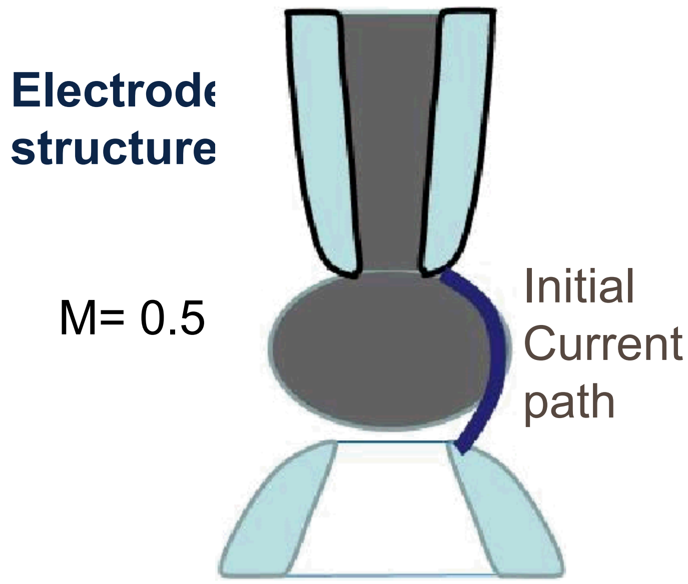
For particle dynamics in the atmosphere, and assuming standard temperature and pressure, i.e. 25 °C and 1 atm, we have $\approx 8 \times 10^{-8}$

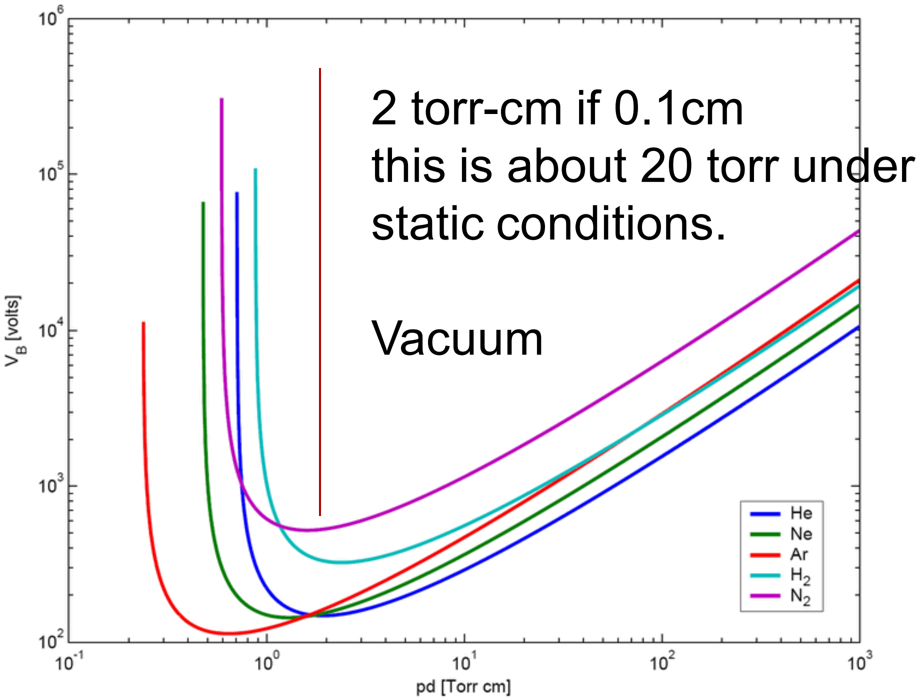
http://en.wikipedia.org/wiki/Knudsen_number

1) Low Mach Number Option May be Best

Gas << slower than the power pulse
Initiate Pinch as Gas Crosses Gap. Initiate Breakdown. Will Breakdown Generate Current Sheath Surrounding trapped gas? And if so will trapped gas get Compressed?

Why? Low Mach Number will give Highest Density and Potentially Highest Compression





Paschen Curve , Wikipedia, accessed 7/2012

Breakdown Should not be an Issue

-150 kV with a 300 micron gap – reasonable, 5 MV/cm.
Scale to literature mult or div 2. Z, PBFA, Saturn, Speed, etc.

- Z Pinch w/ neutron Been done at this scale; Shiloh, 1978

A modified version of the vacuum spark experiment, in which a jet of argon is injected from the anode, is described. Experiments on a **1.26-kJ** system *[150kA, added]* have shown a strong pinching of the plasma with good reproducibility. The pinched plasma (-20 ns lifetime) is submillimeter in size with estimated temperature of **6—9 keV** and density' 10'8e/cm. Advantages of such a device for the study of high-density plasmas and scaling up are discussed. Results are compared to vacuum spark and exploding wire experiments performed on the same system.
Shiloh, 1978

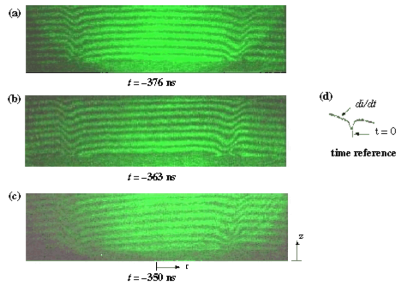


Figure 4. The interferograms taken at times well before the final pinch phase. The actual size of each interferogram in this paper is 22 mm × 12 mm. The anode is at the top and the cathode (nozzle end) at the bottom.

- Interferometry, recent Chinese work; Zou, 2005
-- hollow profile suggests initiation model for low mach # puffs should be good!

-Interferometry, density profiles bear out the 'physics via electron density. , Qi, 2004

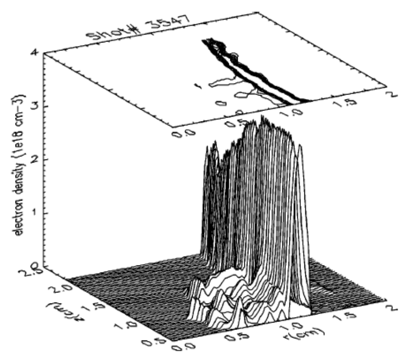


FIG. 3. Derived electron-density profile for shot No. 3547.

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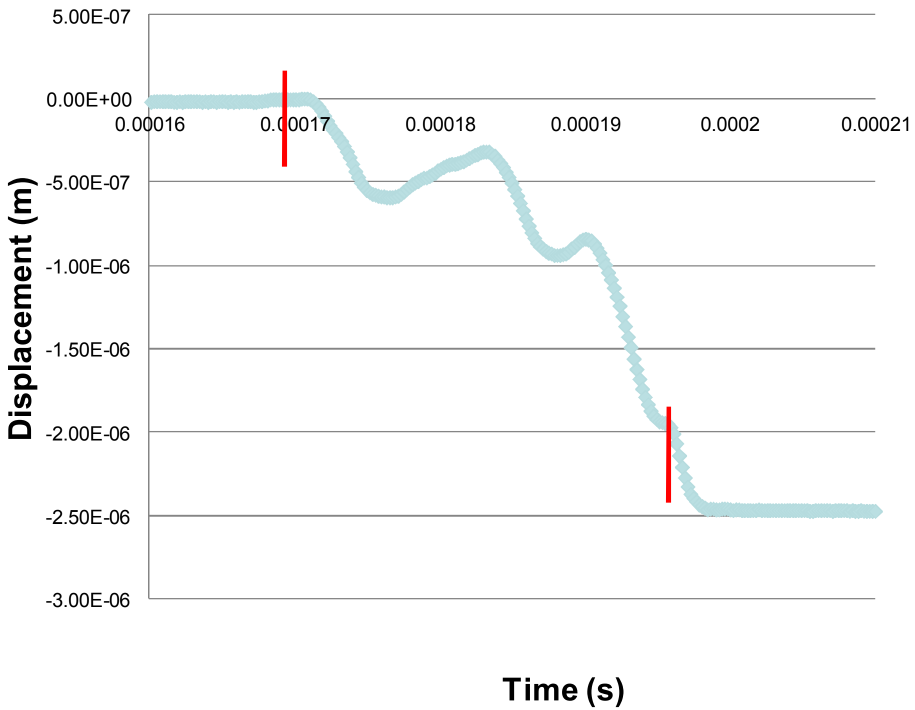
100 V, 2 psi closing time (4 tests total)

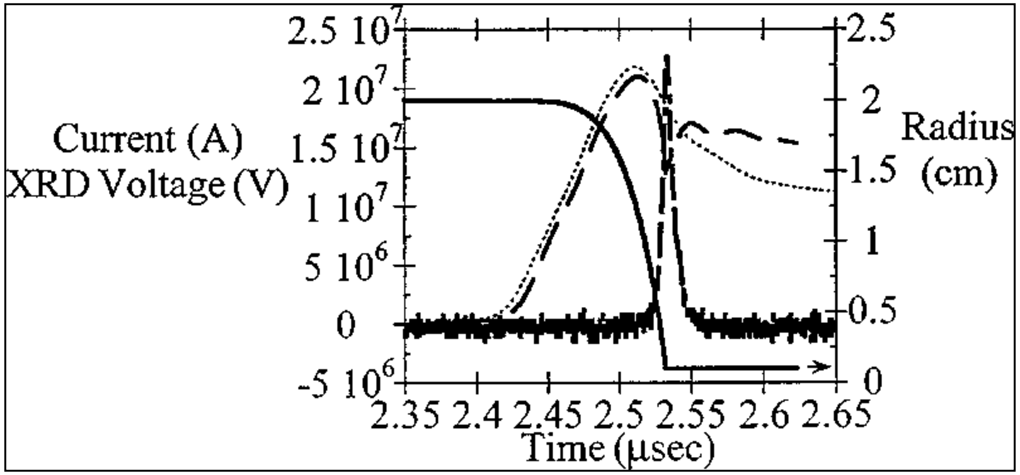


Average closing time ~ 25 us
Displacement ~ -2.75 um

A Key Feature is that a Partial Opening is all that is Required

The Role of Instabilities and Implosion Time

From Ryutov, Derzon and Matzen, RMP, 2000



The risetime desired has a lot to do with the model of energy storage in the pinch.

Energy stored integrates – if there is radial inward motion of the pinch prior to on-axis implosion a longer pulse is good. It means lower voltage and lower current for a longer time.

In x pinch wire array experiments might as well have a fast pulse, because there isn't much inward motion. For instance, in Hammer, et al, (1990), a 40ns driver was used.

Scaled from Boldarev; Puff is Good!

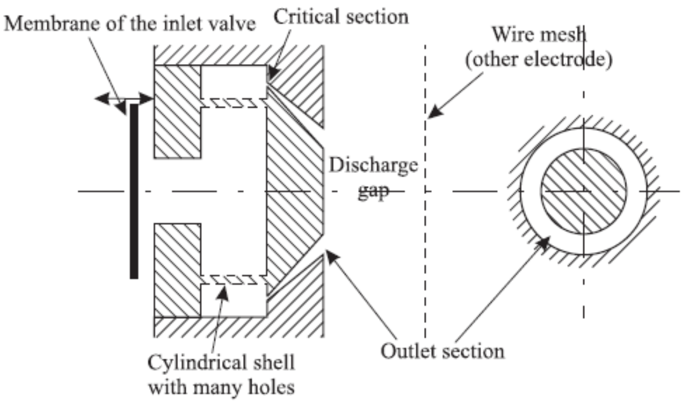
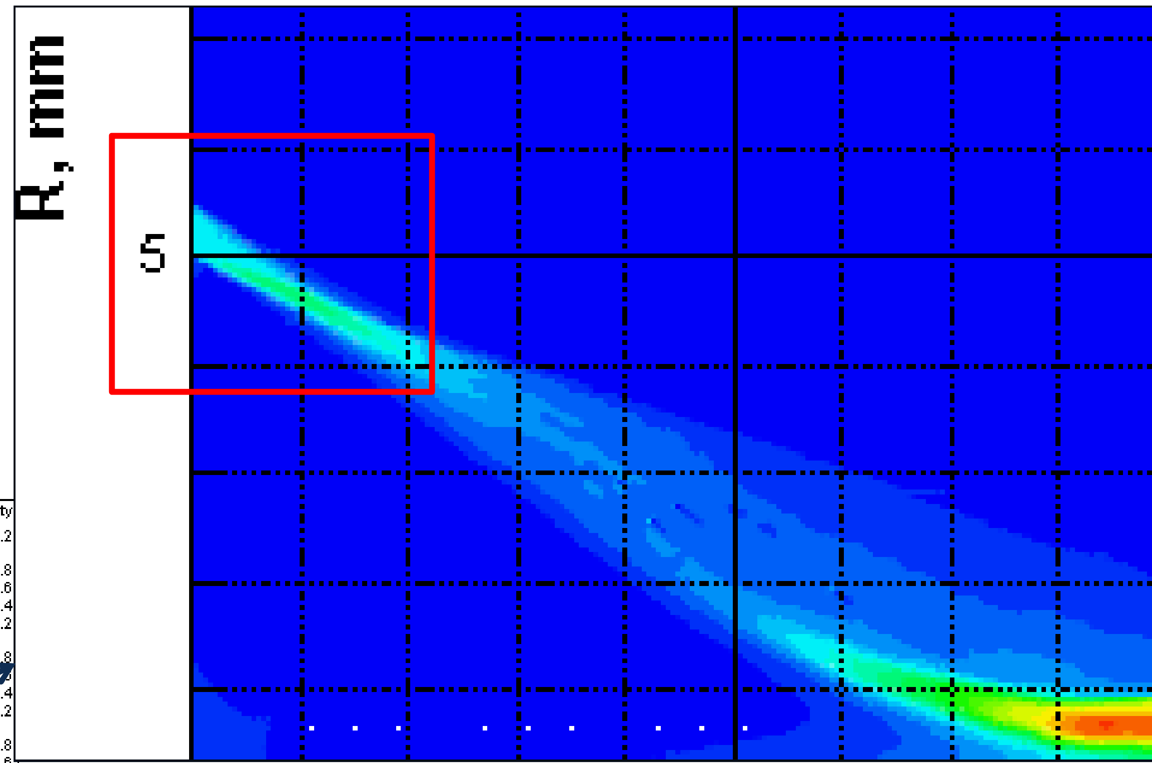
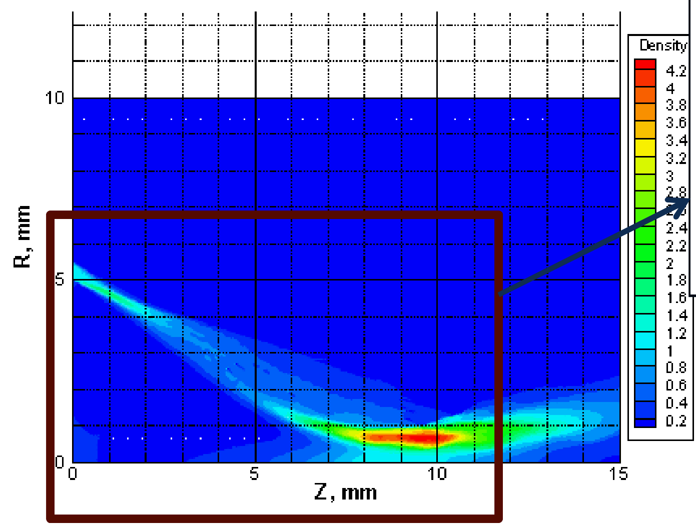


Figure 5. A ring-shaped nozzle and the discharge gap

1 mm is the width of the slit
Black grid is 1 mm





Key: 1) D2 or DT vs Ar
2) Our largest would be ~1 mm gap
3) We could do this dimension at M=10; with chilled D2

Dynamics Stages in Gas Puff an X Pinch