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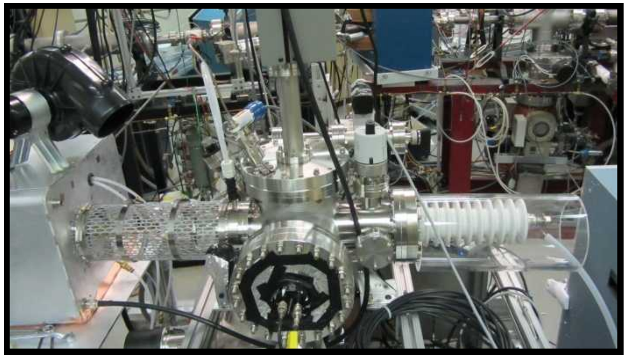

Charged Particle Source Technologies for Homeland Security and Defense

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Technologies for HS&D

- **Radiological Source Replacement**
    - ✓ **Pyroelectric Crystal-Powered Gamma Source**
- **Screening Cargo Containers and Conveyances**
    - ✓ **Associated Particle Imaging Neutron Generator**
    - ✓ **High Flux Neutron Generator**
- **Nuclear Forensics and Attribution**
    - ✓ **Associated Particle Imaging Neutron Generator**

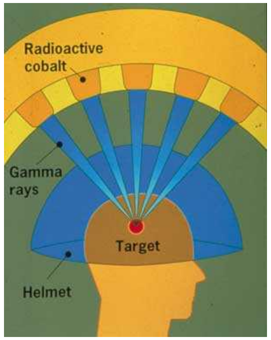
Pyroelectric Crystal-Powered Gamma Source

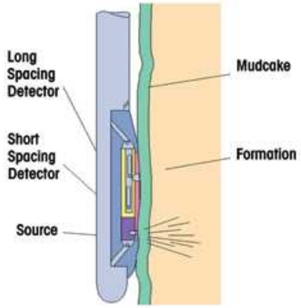
for

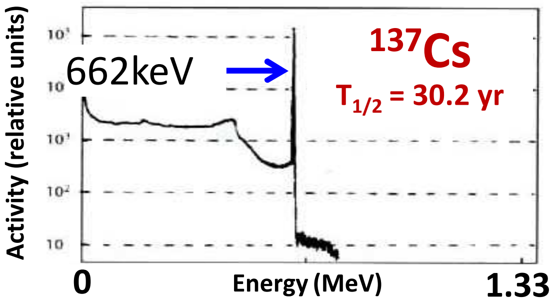
Radiological Source Replacement

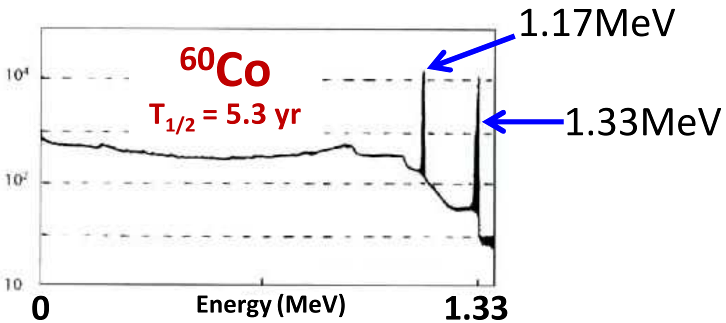
Gamma Source

- High activity radiological sources are used in many industrial and medical applications
- The most common radioisotopes are Am-Be (neutron) and Co-60, Cs-137, and Ir-192 (gamma)
- Approximately 55000 high activity radiation sources are licensed for use in the United States today.









Problem: High-activity radiological sources pose a risk to national security and the environment.

Gamma Source

- **Neutron generators have been developed to replace Am-Be radiological sources in some applications.**

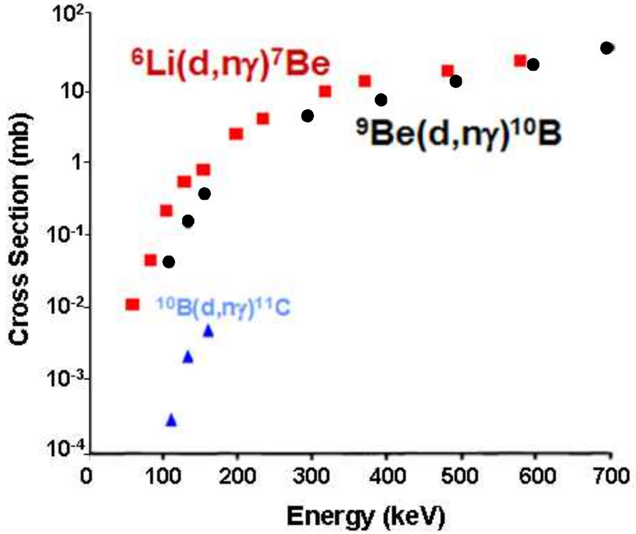
- **Similarly, electron linear accelerators (linacs) have been explored for replacing gamma radiological sources, but they do not produce mono-energetic gammas & are large, heavy, and produce unwanted dose to surroundings due to low-energy photons.**

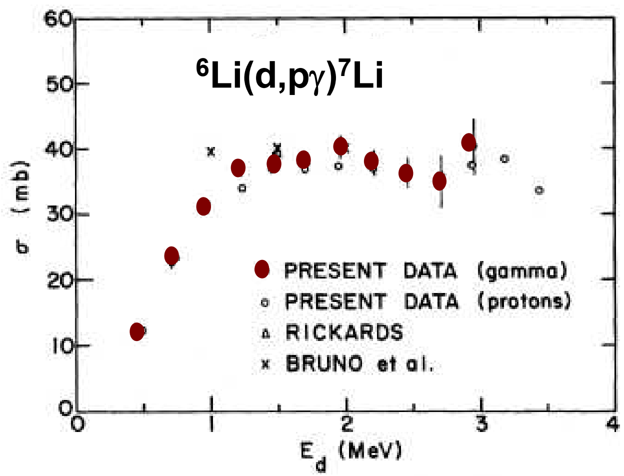
Sandia is developing compact gamma sources based on nuclear reactions that produce mono-energetic gammas to replace Cs-137, Ir-192, and Co-60.

Gamma Source

Sandia National Laboratories

Nuclear reactions that produce ~1 MeV gamma rays





Nuclear Reactions

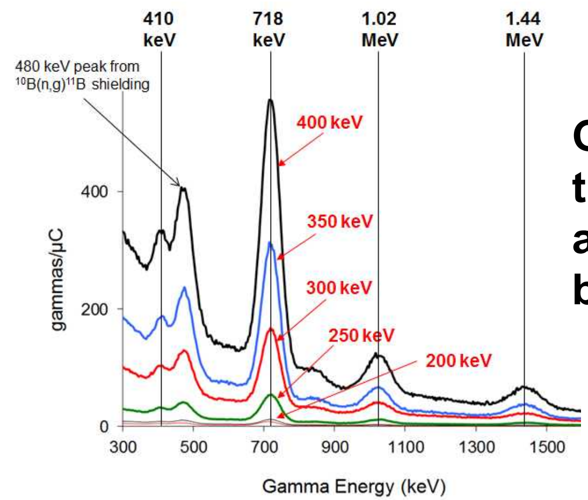
^{9}Be(d,nγ)^{10}B → 480 keV γ's

^{6}Li(d,pγ)^{7}Li → 478 keV γ's
^{6}Li(d,nγ)^{7}Be → 720 keV,1.03 MeV γ's

Both reactions also produce neutrons, but a reaction such as

$$n + {}^{10}B \rightarrow \gamma + {}^{7}Li + {}^{4}He$$

can be used to convert the neutrons to 480 keV gammas.



Gamma spectra of the D-^{9}Be reaction at various deuteron beam energies.

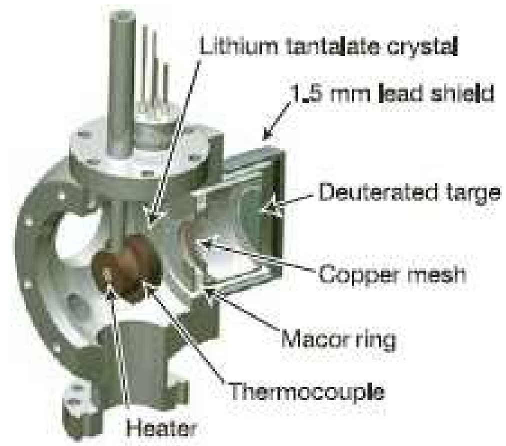
From F.E. Cecil, R.F. Fahlsing and R.A. Nelson, *Nuclear Physics* A376 (1982) 379-388.

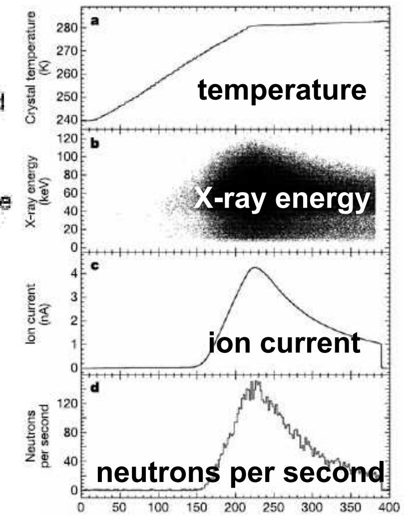
Gamma Source

Recently, X ray and neutron production have been demonstrated with small pyroelectric crystals.

Commercial Pyroelectric Crystal Powered X-ray Source

http://www.amptek.com/coolx.html





B. Naranjo, J.K. Gimzewski, and S. Putterman, Nature 434 (April 2005) 1115

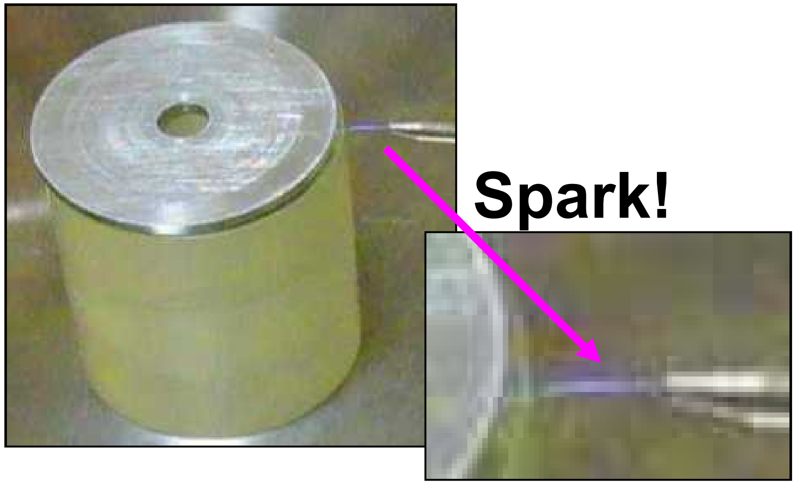
Requirements

x rays	→	~10’s keV electrons, few nA
neutrons	→	~100 keV D ions, 10 nA
γ rays	→	>300 keV D ions, ~mA

Gamma Source

- Pyroelectric crystals can provide the HV acceleration potential without requiring a large external power supply.
- A single 1” x 1” $LiTaO_3$ pyroelectric crystal was demonstrated to achieve voltages up to 300 kV when heated or cooled in vacuum.[1]

Sandia is exploring pyroelectric crystal powering systems for compact gamma sources.



Spontaneous polarization occurs when a pyroelectric crystal is heated or cooled.

The charge on the crystal surface is given by $Q = \gamma A \Delta T$

Pyroelectric coefficient (γ) = 0.19 nC/cm^2/^{o}K for $LiTaO_3$

Example: 3 cm-ϕ crystal, $\Delta T = 100^o$
Predict Q ~ 0.1 μA
Best measured[2] to date,
Q ~ 10 nA

[1]W. Tornow et al., Jour. Applied Phys. 107, 063302 2010
[2]V. Tang *et al.*, Rev. Sci. Instr. **78**, 123504 2007

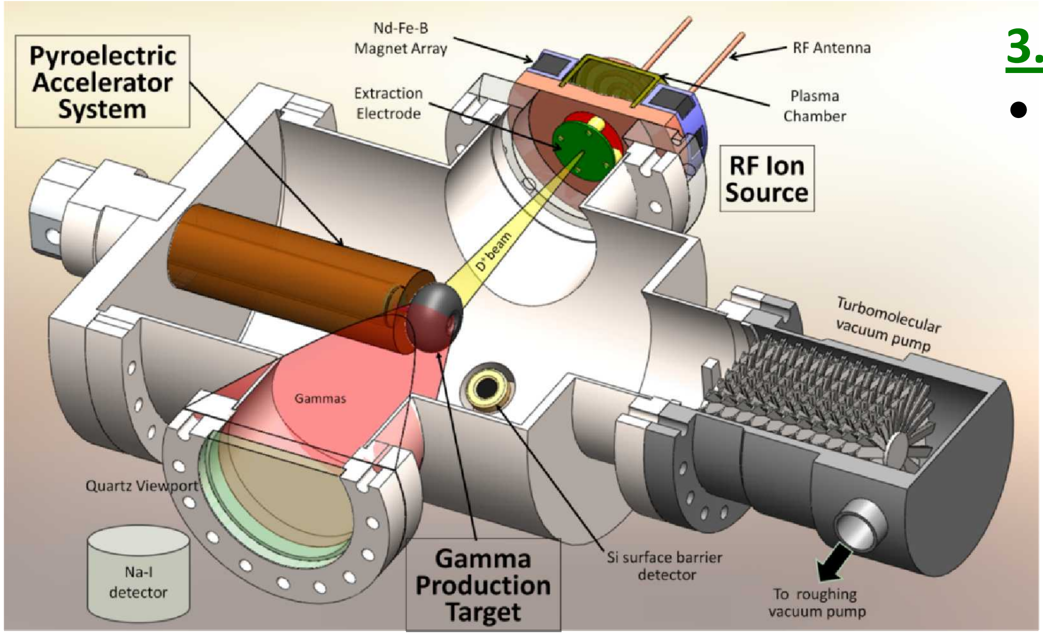
Gamma Source

1. Deuterium Ion Source

- Provides the D^+ (D^-) ions for the reaction
- independent control of the ion current

2. Pyroelectric Powering System

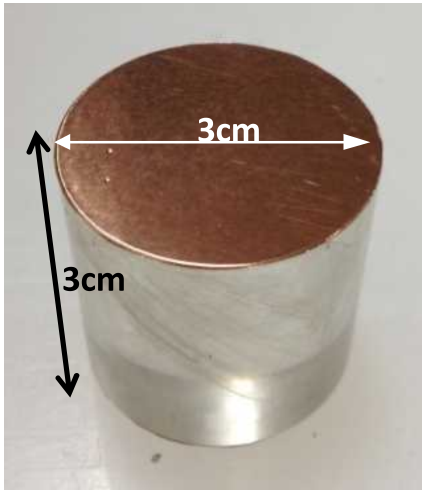
- Generate high voltage using pyroelectric crystals without conventional power supply
- Need >300 kV for significant gamma production
- Amenable for developing compact pulsed source

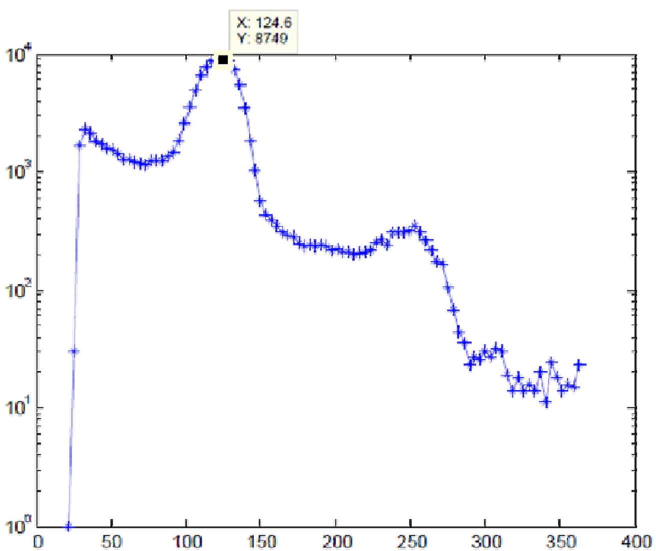


3. Gamma Production Target

- Use low-energy nuclear reaction between deuterium and beryllium to generate high-energy gamma rays

Gamma Source



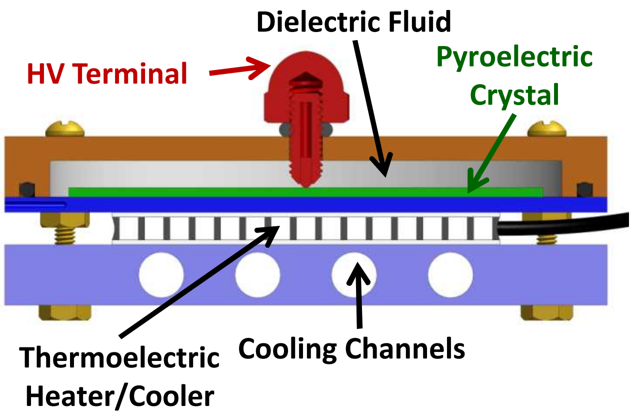


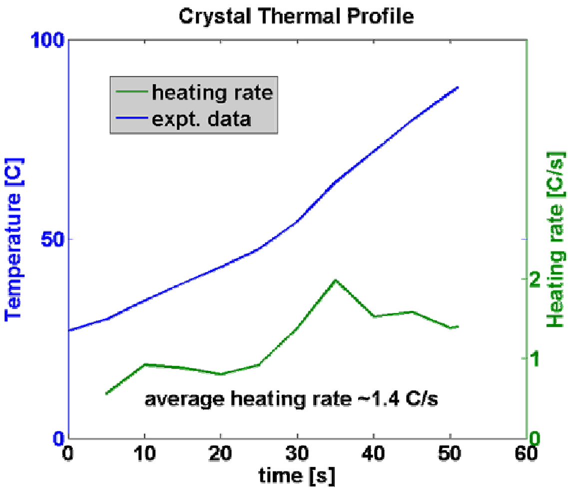
- A large crystal (3 cm ϕ x 3 cm long) was heated in vacuum using a thermoelectric device and achieved 125 kV.
- Maximum voltage appears to be limited by arc tracking along the crystal surface.
- Temperature needs to be kept uniform across the crystal to prevent cracking (~0.03°C/s).

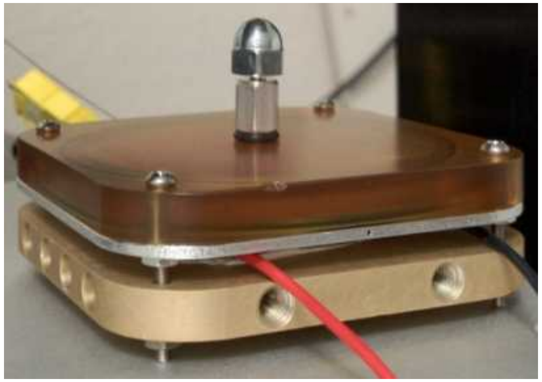
Thinner crystals can be heated and cooled faster while keeping the temperature uniform.

Gamma Source

Thin Pyroelectric Crystal Accelerator







Maximum measured E-field generated in different length crystals

Length (mm)	E-field (kV/mm)	Average ΔT (K)	Energy (kJ/m^3)
1	22	62	123
10	7.5	15.7	11.2
30	4.2	8.8	3.5

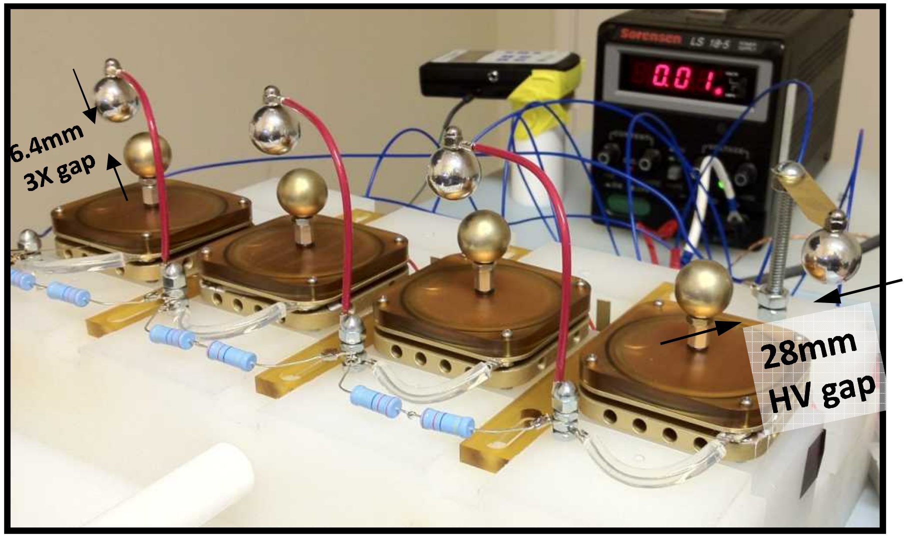
- 5cm ϕ x 0.1cm long crystal is used
- To mitigate the arcing issue, the crystal is immersed in a dielectric bath.
- An voltage of ~22 kV was demonstrated which is also the maximum limit due to coercive field of $LiTaO_3$

Electric field generated in thin crystals is 3-5X greater than the long crystals.

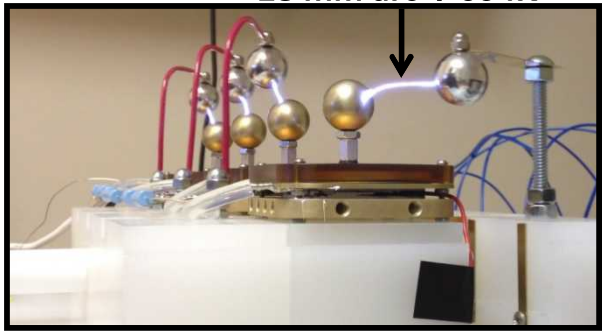
Gamma Source

Pulsed Pyroelectric System

- **Thin crystals generate less voltage for the same electric field.**
- **A stacked thin crystal modular configuration increases the net voltage in a pulse.**
- **A 4-module system using 5cm ϕ x 1mm long crystals were heated to generate >15 kV per crystal.**
- **Demonstrated final "stacked" voltage of >60 kV.**



28 mm arc → 60 kV

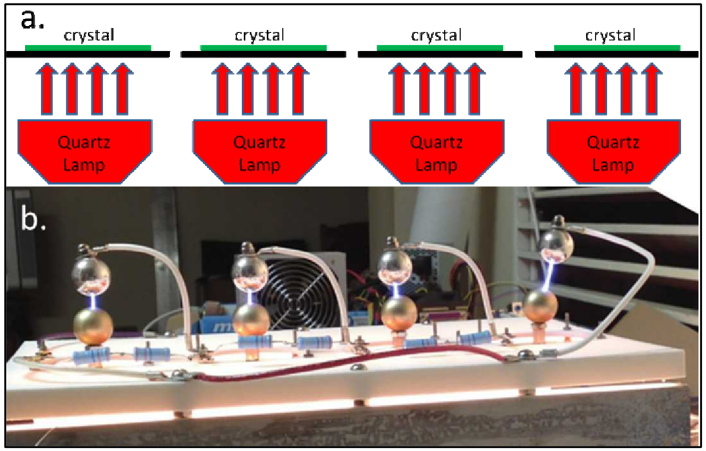


A 20-module stacked system can generate a pulsed output voltage of >300kV, meeting the requirement for the D-^{9}Be based gamma source.

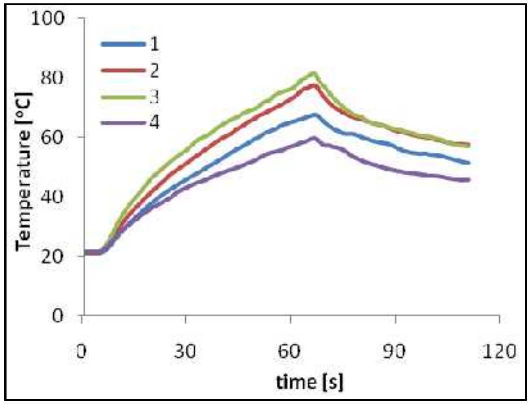
Gamma Source

Recent Results

- **HV radiatively heated pyroelectric crystal pulser**



~75 kV pulse discharge for ΔT = 75º



Temperature at the base of each crystal as a function of time

Next Steps

- **Develop HV radiatively heated pyroelectric crystal accelerator**

Associated Particle Imaging Neutron Generator (API NG)

for
Screening Cargo Containers and Conveyances
and
Nuclear Forensics and Attribution

API NG

- **No single detection technology <u>alone</u> has sufficient performance to assure successful detection and interdiction**
- **Active interrogation can provide an effective means for detection of shielded materials**
- **Response concept of operations (ConOps) is critical (detection, interdiction, and alarm resolution)**
- **Training, exercise and assessment programs are necessary**

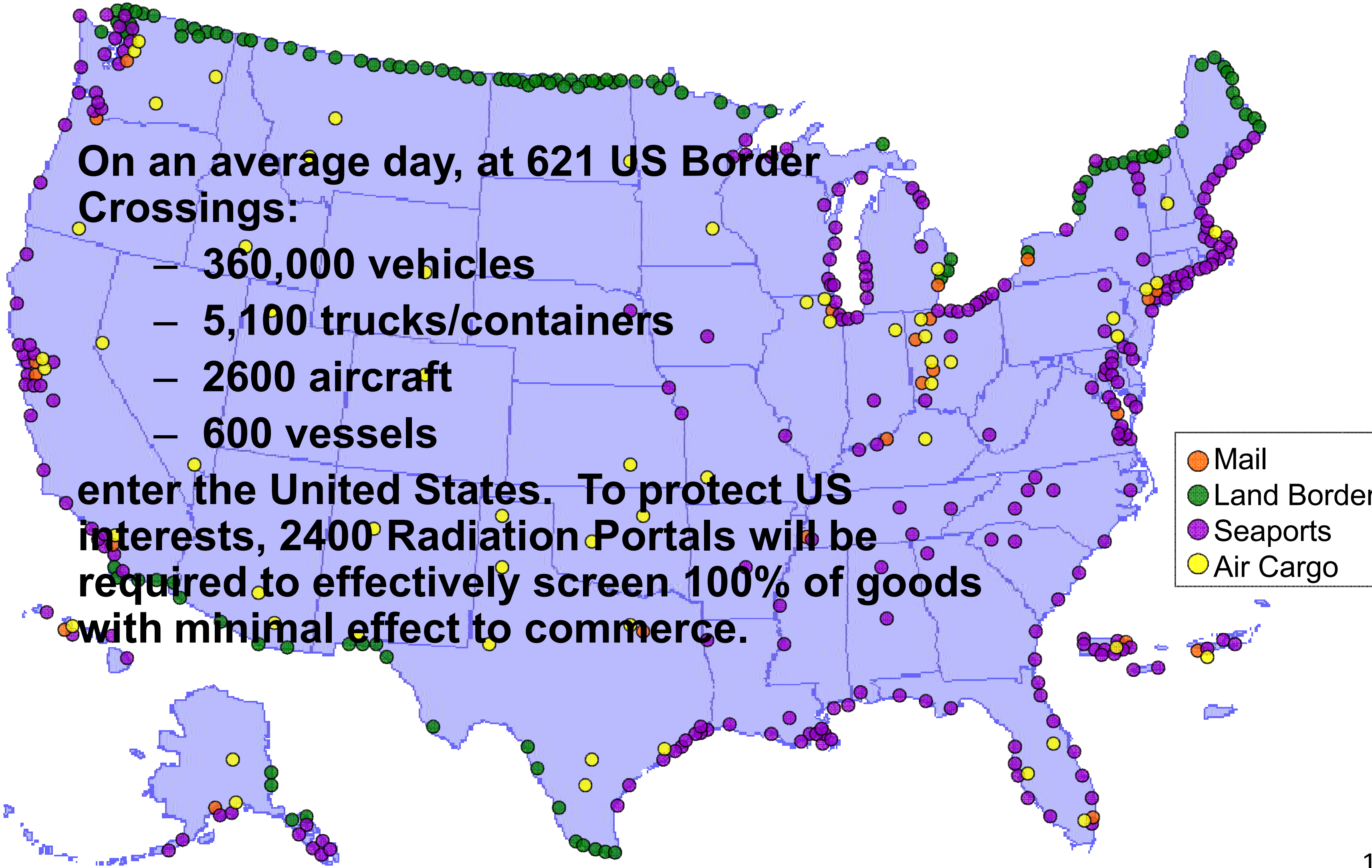
API NG

A broad range of delivery vectors must be considered

API NG

Sandia National Laboratories

The magnitude of the border screening effort is enormous



On an average day, at 621 US Border Crossings:

- **360,000 vehicles**
- **5,100 trucks/containers**
- **2600 aircraft**
- **600 vessels**

enter the United States. To protect US interests, 2400 Radiation Portals will be required to effectively screen 100% of goods with minimal effect to commerce.

API NG

Goal

Develop Charged Particle Sources (CPS) and Detector Technologies (DT) for detecting contraband materials at Ports-of-Entry and other locations.

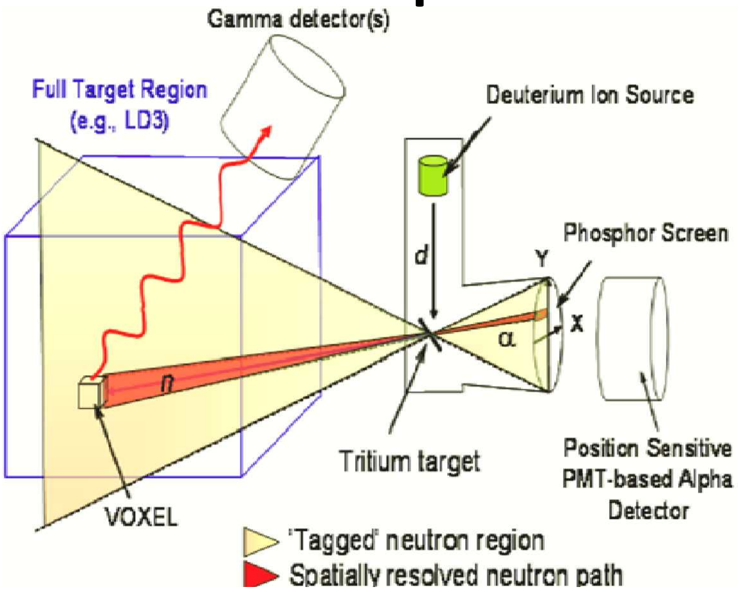
Technology Development

- **Detection of shielded materials ← CPS ← API NG**
- **Long range detection ← CPS**
- **Detection in transit ← DT**
- **Cost-effective, highly sensitive detectors and systems ← DT (handheld, portal, etc.)**
- **Robust active inspection technologies for cargo ← CPS ← API NG (automated, faster, less intrusive, more definitive)**

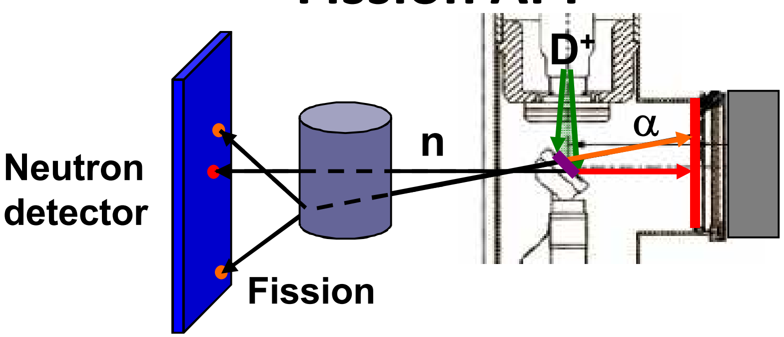
API NG

What is Associated Particle Imaging?

Chemical Composition API



Fission API



- 14 MeV neutrons from D-T neutron generator interrogate object and cause (n,γ) or (n,f) reactions
- *Time and direction* of interrogating neutrons are known from the associated 3.5 MeV alpha particle in the D + T → α + n reaction
- The neutron trajectory, time-of-creation and detector time stamps are used to determine the 3D location where the reaction originated
- Direction resolution determined by beam spot size on target and alpha particle resolution

API NG

Need for Better API NG

Thermo Physics API-120

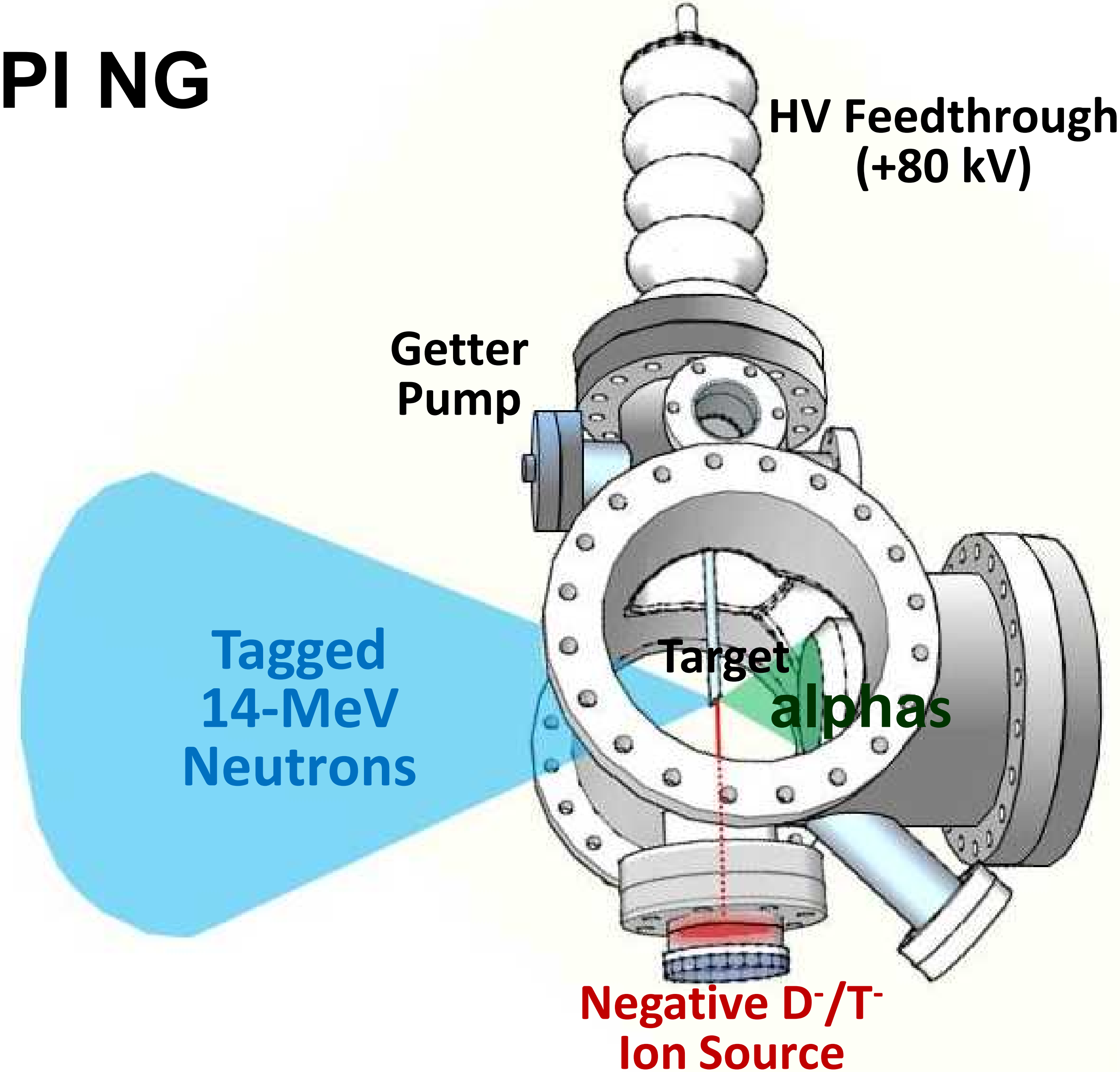
- **Current commercial systems use HV Penning ion source with target/chamber at ground**

  When injecting beam, HV positive ions bombard and scatter from last electrode → no focusing effect at target → beam spot less defined

- **Higher beam current needed to compensate low atomic fraction (<10%) from Penning ion source**
- **Limited operational lifetimes due to sputtering of extraction cathode and target**

Sandia is developing a new type of API NG based on a negative ion source

API NG


HV Feedthrough
(+80 kV)
Getter
Pump
Tagged
14-MeV
Neutrons
Target
alphas
Negative D⁻/T⁻
Ion Source

API NG

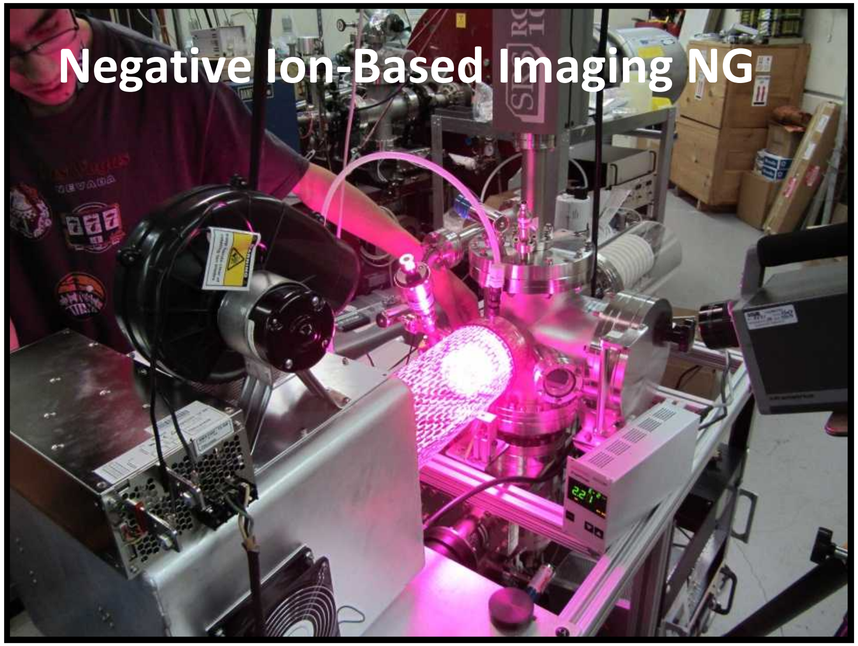
Sandia's API NG Technology

- **Employs *negative* ion source**
  - ✓ **100% atomic ions → increases neutron output**
  - ✓ **Lower beam current → reduces power requirement**
  - ✓ **Minimizes target sputtering → longer lifetime, better resolution, and less coating of insulators**

- **Employs positive HV target**
  - ✓ **Eliminates field emission of electrons at target → no damage to integrated alpha detector**

Imaging NG enables better resolution, higher operational reliability, and longer lifetime

API NG



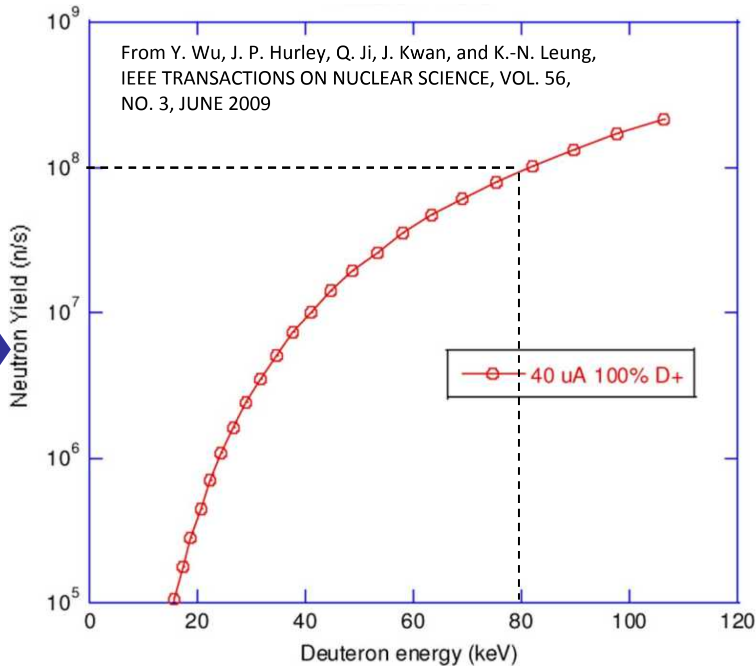
Imaging NG Characteristics

Ion Source	RF D^-/T^-
Power	Few hundred watts
Beam Current	40-80 μA
Beam Energy	80 kV
Beam Spot	~1 mm
Atomic Fraction	100%
Neutron Output	10^8 n/s
Lifetime	>1000 hrs
Field of View	>45°
Operation	Reliable

API NG

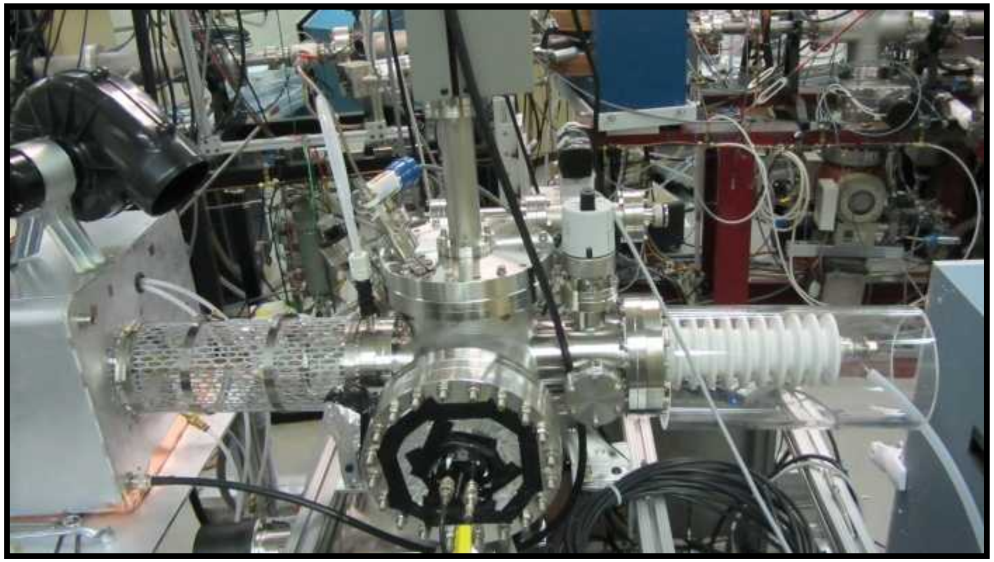
Requirements

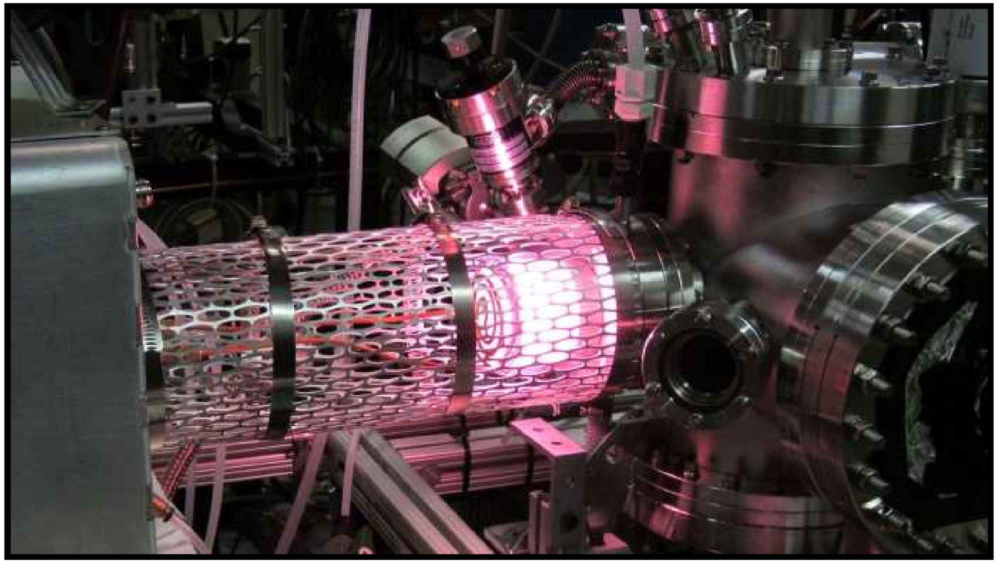
- **Neutron yield is determined by the ion beam current density, energy, and atomic ion fraction**
- **10^8 D-T n/s source intensity with 40 μA deuterium ion current @ 80 keV**
- **With 2 mm extraction aperture, the negative ion current density needed is $J^- \sim 5\ mA/cm^2$**
  - **This current density is achievable with a few hundred watts of RF power and without the need for cesium injection**
  - **An RF-driven cesiated H^- ion source has been operated successfully in large accelerator systems (e.g., SNS at Oak Ridge and the neutral beam injection system for ITER in France)**



Maximum neutron yield for 40 μA deuterium ion beam
(Assumes 100% monatomic ions impinging upon a fully loaded tritium metal target)

API NG





Recent Results

- Demonstrated neutron production
  - ~10^5 D-D n/s
  - Goal is 10^6 D-D n/s
- Measured 1.0 - 1.5 mm beam spot size on target
  - Hi Res Infrared Camera
  - Goal is 1.0 mm
- Stably operated for >120 minutes at HV (+90 kV)
  - Goal is 1000 hr lifetime

Next Steps

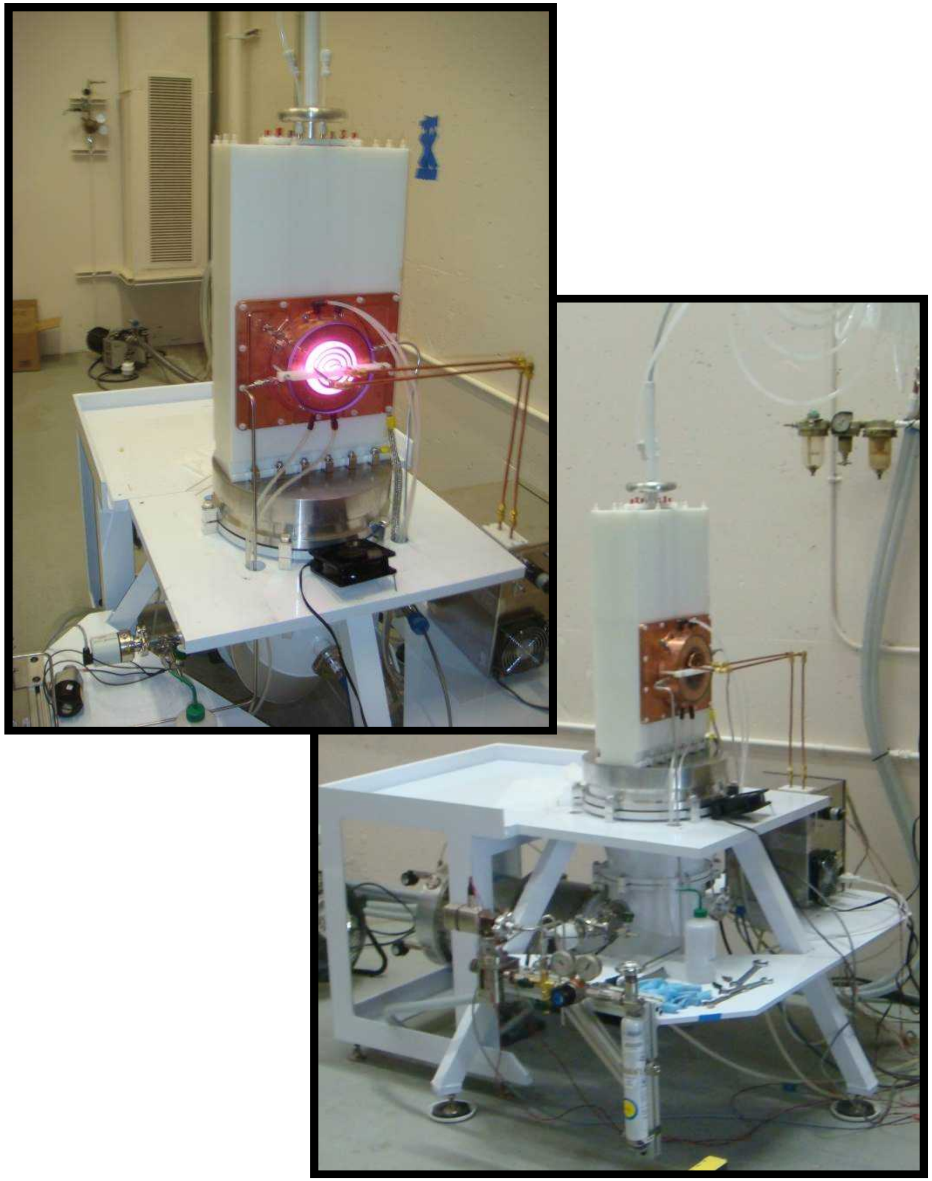
- Optimize D-D NG to achieve neutron flux goals
- Design and test tritium compatible system

High Flux Neutron Generator (HFNG)

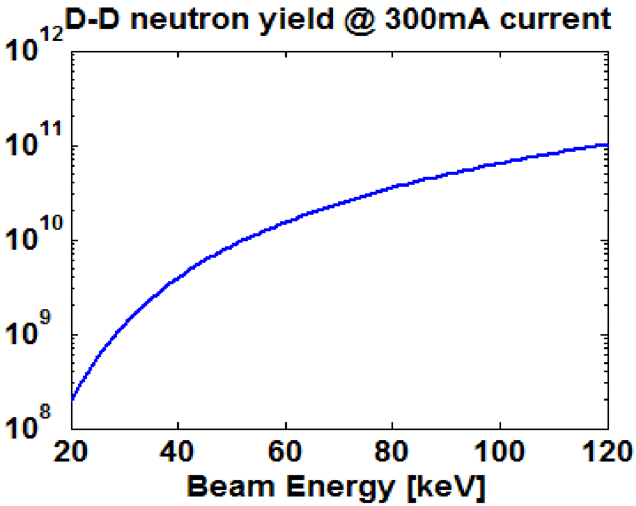
for

Screening Cargo Containers and Conveyances

HFNG



- Designed for up to 10^{11} D-D n/s at 100 keV and 320 mA
- Similar design to UC-Berkeley system for geochronology applications
- Initial application is thermal neutron imaging



Computed maximum neutron yield as a function of target voltage.

HFNG

Recent Results

- Demonstrated ~10^9 D-D n/s at 70 keV and 80 mA (neutron output measured by gold foil activation)

Next Steps

- Demonstrate high power operation (SNL has HV power supply capable of 120 kV and 320 mA)
- Test thermal and fast neutron imaging
- Modify and test High Flux D-T NG