SAND2012-6404C

Negative Ion-Based Associated Particle Imaging Neutron Generator

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CAARI 2012
SSCD03 Radiation Sources for Interrogation Systems
Wednesday, August 8

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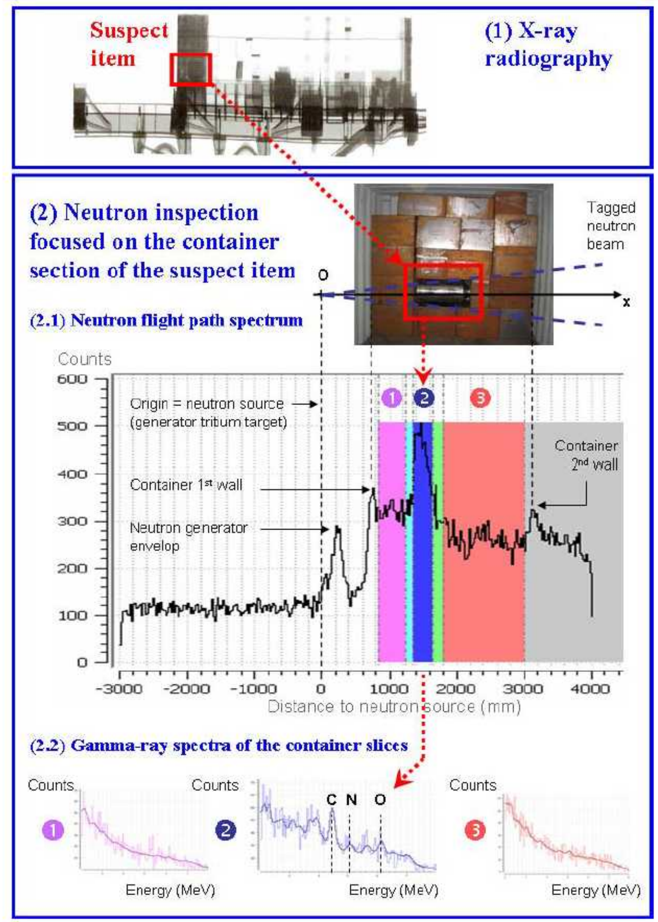
Motivation

- **Neutron imaging (via associated particle, induced fission, or radiography) with a time-tagged point neutron source provides high fidelity material characterization and improved signal-to-noise.**
- **We are developing an Imaging Neutron Generator that utilizes a negative ion source to enable 1 mm pixel resolution.**

Associated Particle Imaging for Cargo Inspection



From Bertrand Pérot *et al.*, "Applications of the Associated Particle Technique", Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA), 2009.

Need for Better NG

- Current Associated Particle-Type NGs use Penning ion sources
  - Low power, low pressure operation
  - Sealed operation, robust, simple design, portable

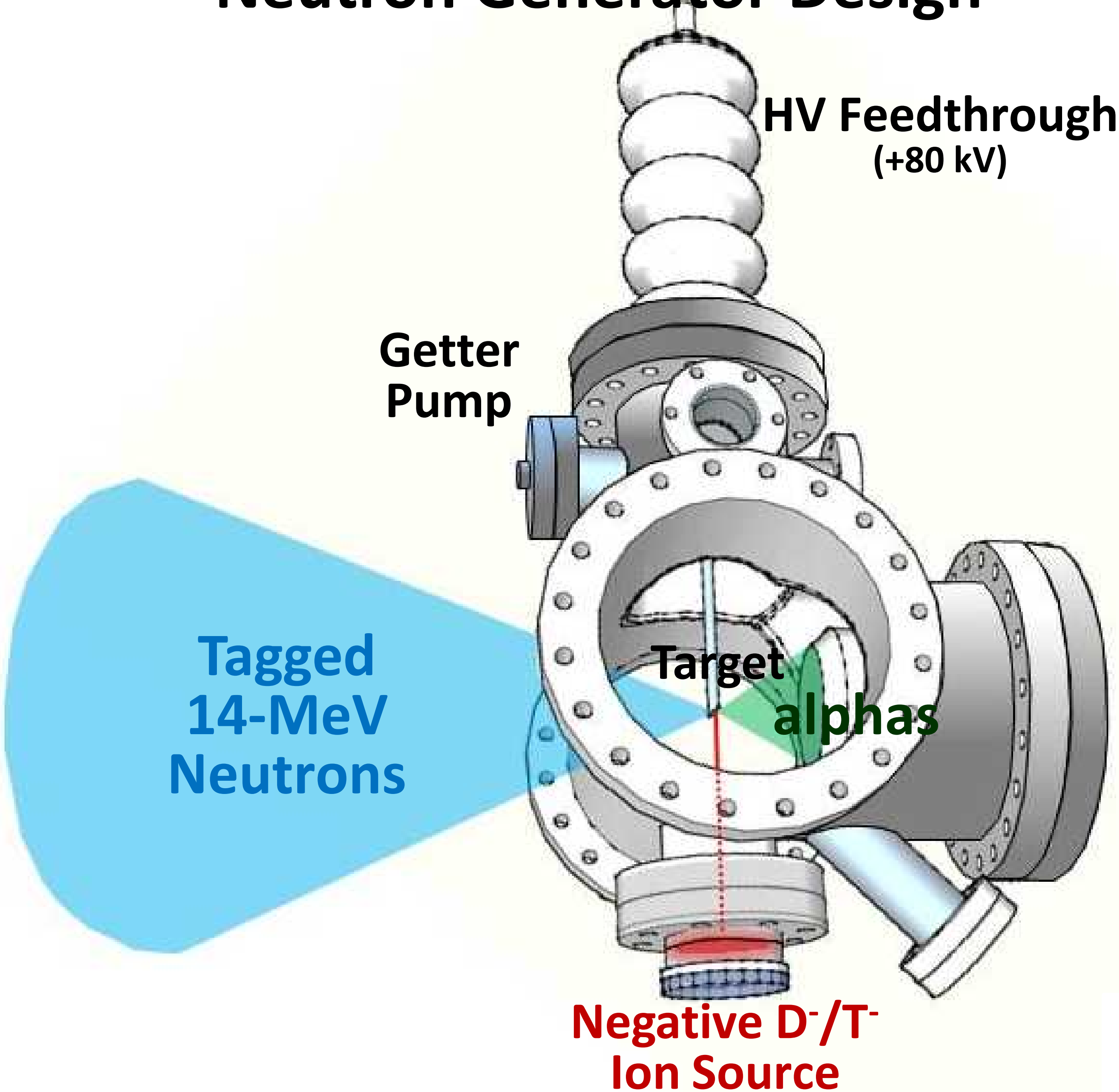
  but,
  - Very low atomic ion fraction (<15%)
  - Limited lifetime due to sputtering of extraction cathode and target
- API requires a small beam spot for imaging. The "inherent" spot size in current API NGs is the full size of the target (~12 mm) and the generator produces an output of ~10^8 neutrons per second.
- The size of the target can be reduced with a Cu mask that doesn't load, but intensity is reduced. For imaging, the generator is operated with ~3 mm target spot size, producing about 10^7 neutrons per second total intensity.
- The lifetime is reported to be >1000 hrs when operated at 10^7 n/s, although operational lifetimes of only a few hundred hours are common.

Negative Ion Source NG

- ✓ **Low pressure operation**
  - prevents voltage breakdown
- ✓ **100% atomic D^-/T^- beam extraction**
  - reduces beam current (increases neutron output)
  - reduces sputtering (longer lifetime, better resolution, and less coating of insulators)
  - minimizes contamination of target from implanted impurities
- ✓ **Positive HV target**
  - eliminates field emission of electrons
  - prevents sparking/arcing
  - simplifies ion optics
  - prevents back-streaming of secondary electrons that cause higher current load, x-rays, and possible damage to components

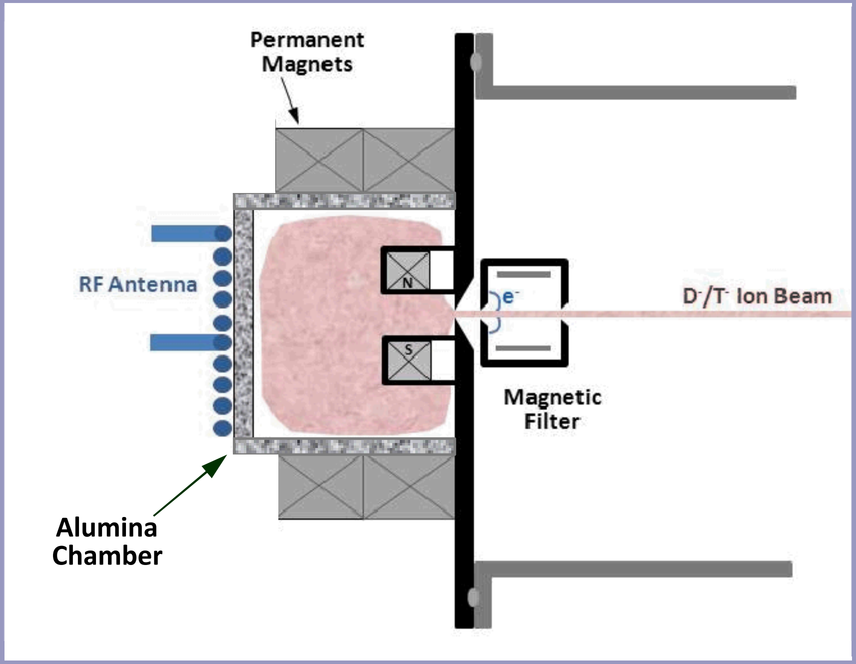
Negative ion source enables better resolution, higher reliability, and longer source life.

Neutron Generator Design



RF-Driven Ion Source

- Small 8cm diameter x 4cm long alumina chamber surrounded by columns of permanent magnets.
- The plasma is produced by 13.5 MHz RF induction discharge.
- Alumina provides excellent RF coupling to the plasma, can be robustly sealed to the stainless steel flange of the generator, and is an excellent tritium barrier material.



- Only atomic D^- and T^- ions are produced (no molecular ions) → minimizes target sputtering and maximizes neutron production.
- Negative ion beam extracted through small aperture gives ~1 mm^2 beam spot on target; achieve 30-40 μA negative ion current without cesium injection
- As the negative ions exit the electron filter, they will be further accelerated towards the target electrode which is biased at +80 kV.

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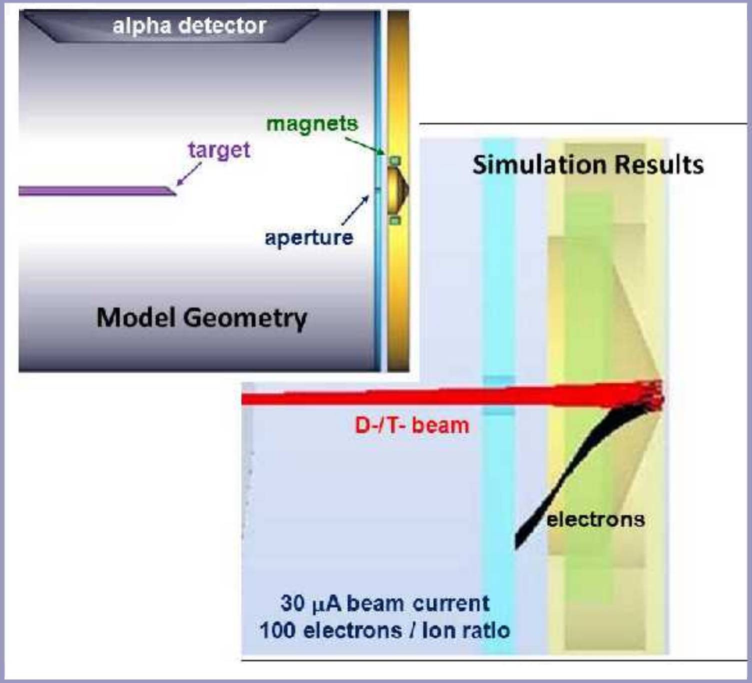
Electron Filter

- The negative ion beam is extracted by applying a low voltage (~4 kV) on the extraction electrode.

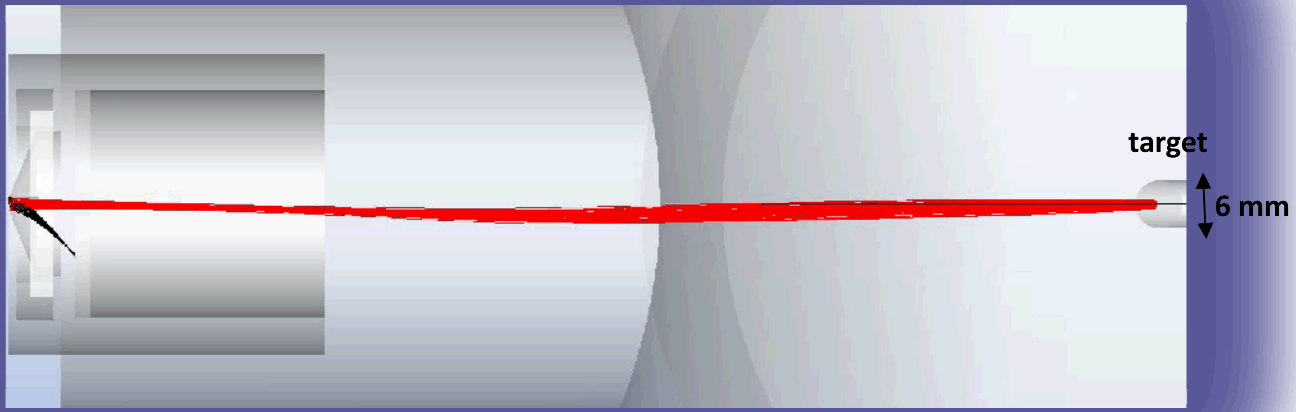
- The extracted beam also contains copious amounts of electrons which need to be filtered out before they are accelerated to high energy.

- A small permanent-magnet electron filter is incorporated with the extraction electrode.



- Electrons will be deflected and captured on the side-walls of the filter; the higher mass D^-/T^- ions will pass through with very little deflection and accelerate towards the target.

Neutron Production Target



- The beam-loaded titanium target is biased at positive high voltage to accelerate the D^-/T^- beam and eliminate field emission current.
- A beam-loaded target enables longer lifetime than a chemically preloaded-target.
- The titanium target is mounted to a copper rod which serves both as the HV terminal and heat sink.
- Fusion occurs on the target surface producing D-T, D-D and T-T neutrons; only the D-T reaction produces a 14 MeV neutron and associated 3.5 MeV alpha particle.
- Ion optics compute an elliptically shaped beam spot (0.8mm x 1.1mm).

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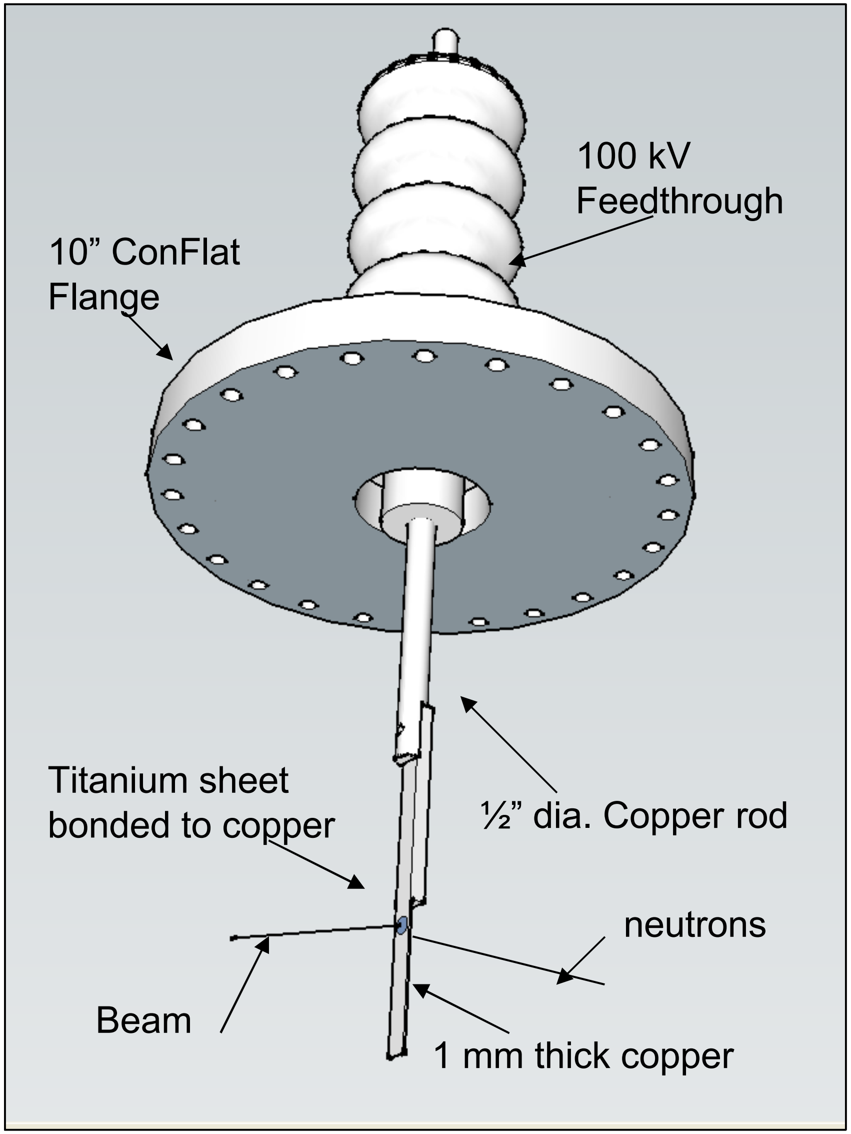
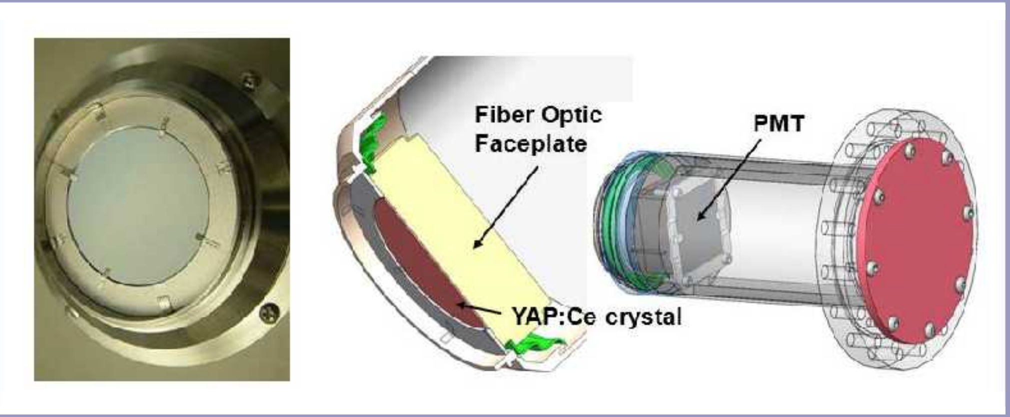
Target Assembly

- HV feed-through rated for 100 kV (actual voltage = +80 kV)
- ½ inch diameter copper rod provides thermal conductivity to minimize target heating and loss of tritium
- 1 mm thick copper at target area to minimize neutron scattering
- Thin titanium sheet mechanically bonded to 1 mm thick copper
- Target geometry designed for optimum beam focus
- Temperature rise at target from 4 W beam heating estimate to be less than 100 degrees C.



Alpha Particle Detector

- Pixellated 50 mm ϕ x 100 μm thick YAP:Ce crystal with a 1 μm aluminum coating on the target side to stop scattered beam and target fluorescence, decrease charge buildup, and reduce background (by slowing down or stopping scattered beam).



- YAP:Ce crystal is mechanically coupled to Schott 75C fiber optic faceplate; faceplate is coupled to SS flange via glass-to-metal (frit) flange

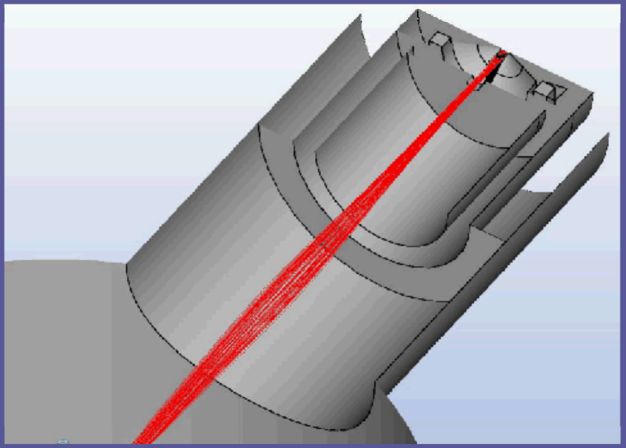
- Target-to-detector distance of 60 mm gives wide field-of view (~45°); the re-entrant chamber port can accommodate a larger diameter detector to further increase the field-of-view (60° possible).

Current detector has been successfully used in commercial API NGs.

Operational Considerations

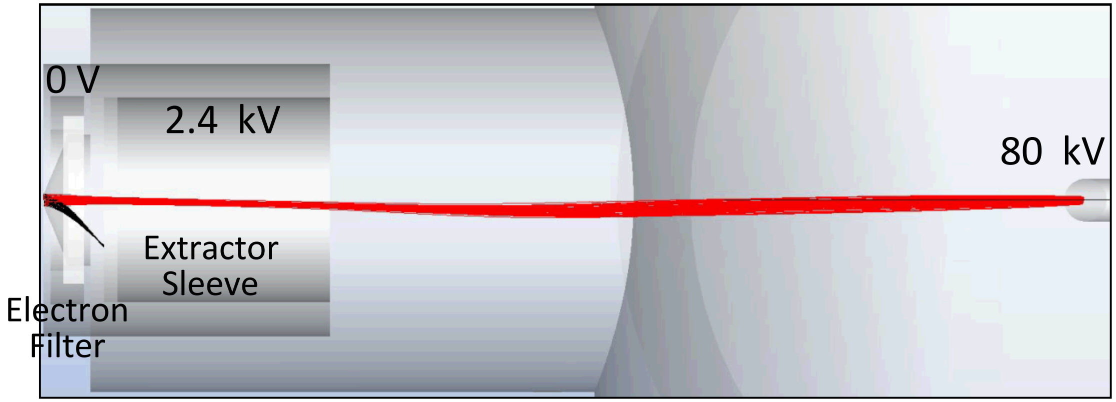
Extensive modeling and analysis performed to quantify[1]

- **extraction aperture size**
- **electron filtering**
- **beam spot size on target**
- **power density on target**
- **target geometry**
- **target sputtering**
- **alpha particle and neutron scattering**
- **alpha particle field deflection**
- **D-T kinematic deflection**

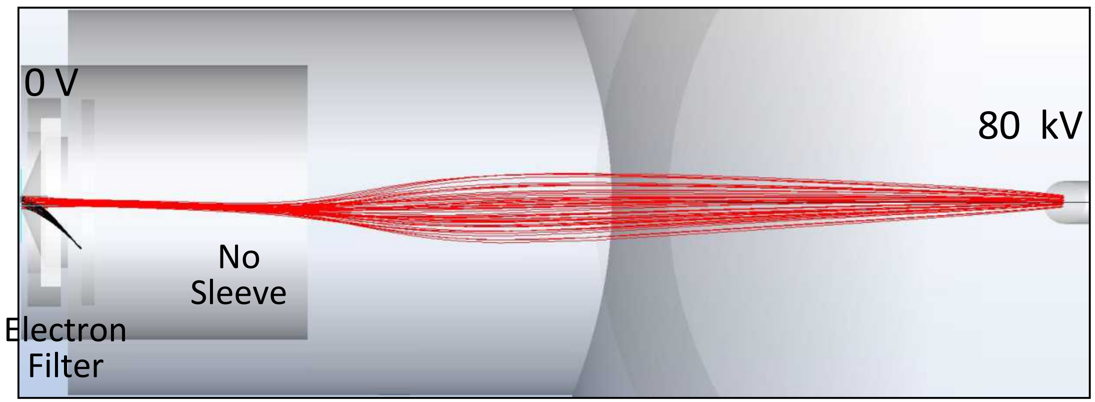


[1]Lorentz (www.integratedsoft.com) 3D ion optics calculations performed by Dr. S.K. Hahto, Charged Particle and electromagnetic Technologies LLC, Nashua, NH.

Beam Profile



With extractor sleeve → 1 mm beam spot size on target; beam spot can be made smaller by tuning the extractor voltage and sleeve geometry



Without extractor sleeve, beam blows up much more after exiting the extractor resulting in large beam spot size on target

Modeling Parameters:

2 mm extraction aperture
40 μA D^-/T^-
100:1 e:ion ratio

Beam Spot on Target:

With sleeve: 0.8 mm x 1.1 mm
Without sleeve: 1.5 mm x 1.5 mm

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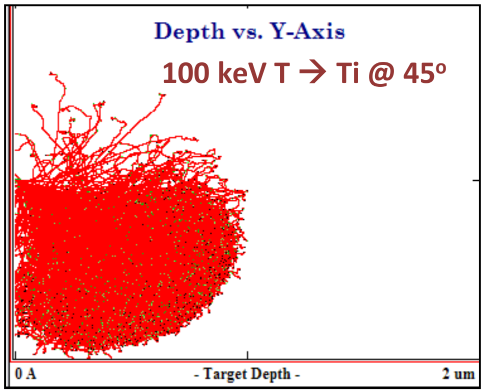
Target Sputtering

- TRIM full cascade model
- 10^5 histories D → Ti and 10^4 histories T → Ti



100 keV D → Ti		100 keV T → Ti	
Angle	*Sputter Yield*	*Angle*	*Sputter Yield*
0	0.00028	0	0.0022
30	0.00077	30	---
45	0.00116	45	0.0042

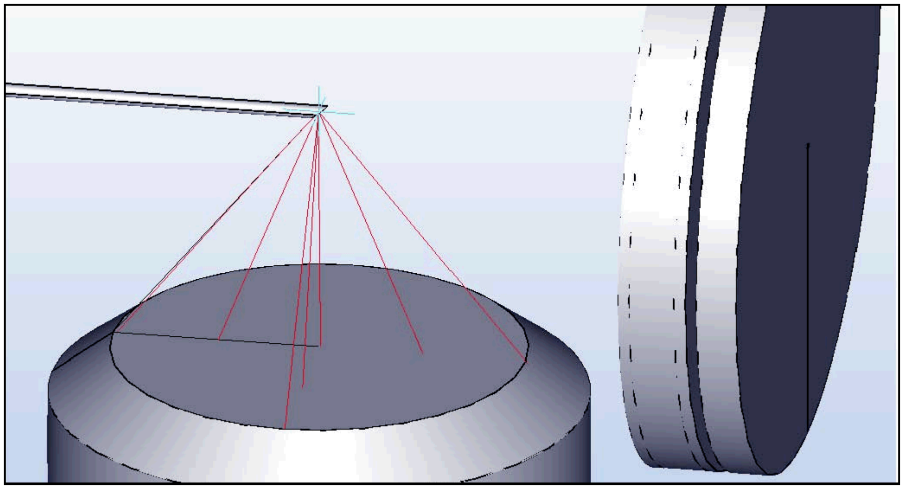
Example:
1000 hr at 20 μA D current and 45° incidence gives
(1000)(3600)(20)(6.24e12)(.00116) = 5.2E17 Ti atoms sputtered

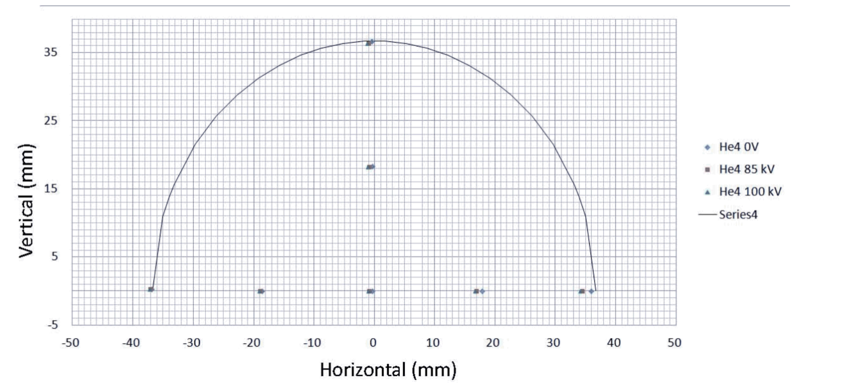
A beam spot area of 1 mm^2 corresponds to 5.2E19 Ti atoms/cm^2

The sputtered crater from 20 μA, 100 keV D → Ti at 45° would attain a depth of 9 microns in 1000 hr (33 microns for T → Ti)

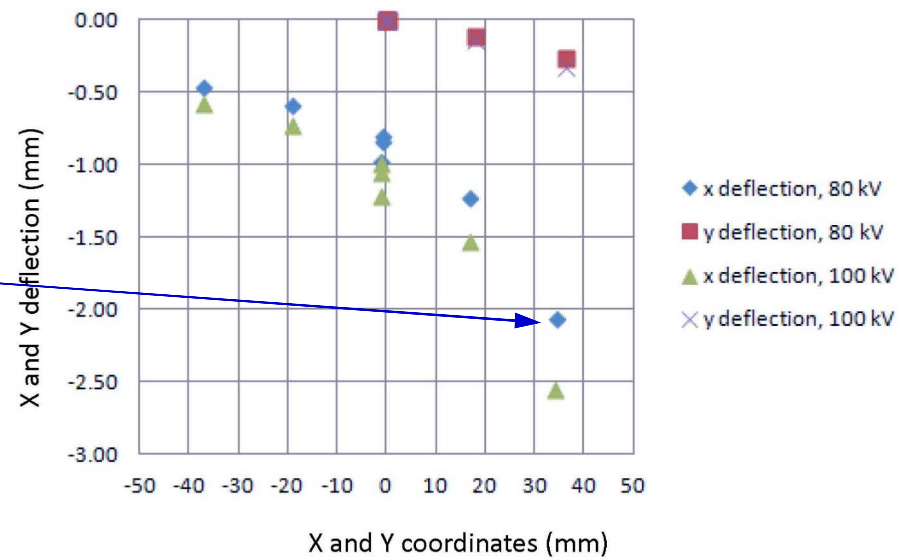
The sputtered crater depth from 20 μA, 100 keV D → Ti at normal incidence is 2 microns in 1000 hr (17 microns for T→ Ti)

Alpha Particle Deflection Due to Field





3.5 MeV alpha particle deflection



At 80 kV, the largest deflection is 2.1 mm

If the field is known, the alpha particle deflection will cause a predictable (i.e., correctable) distortion in the image.

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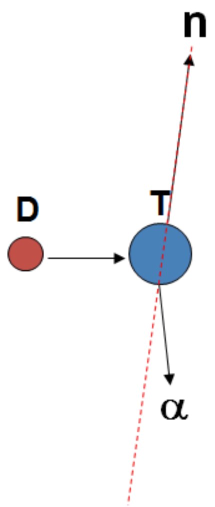
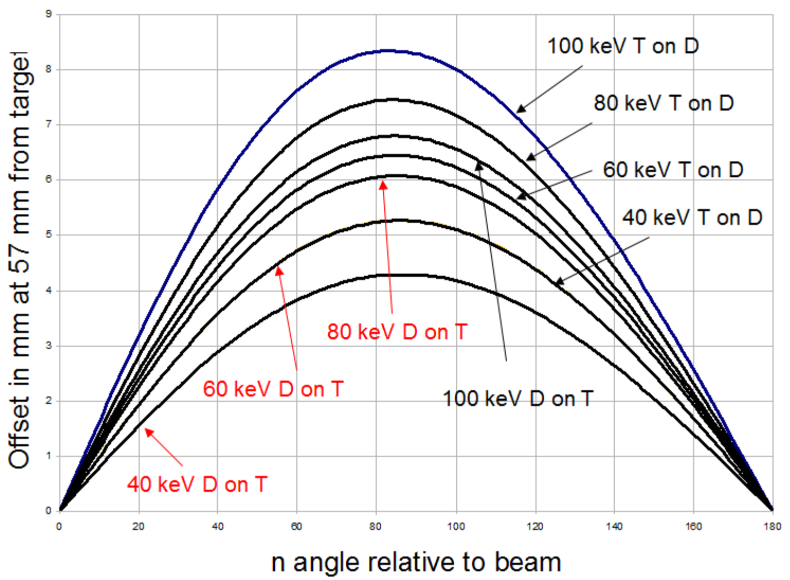
Kinematic Offset



Neutron and alpha are 180 degrees apart in center-of-mass frame, not in the lab frame.



- Alphas are deflected from their "true" position by ~5mm on the detector at 90^{o} as the D energy increases from 40 keV to 80 keV.
- The 2 mm spread in offsets is equivalent to the effect of a 2 mm beam spot. The range is more for 100 keV and much more if T reaction is included.
- The offset decreases at other detector angles.

The offset due to detector position will cause a predictable (i.e., correctable) distortion in the image.

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Operational Characteristics

Negative Ion-Based API-Type NG

Ion Source	RF D^-/T^-
Power	~200 W
Beam Current	30-40 μA
Beam Energy	80 kV
Beam Spot	<1 mm
Monatomic Fraction	100%
Max Neutron Yield	10^8 n/s
Lifetime @ Max Yield	>1000 hrs

Acknowledgements

Thanks to the DOE/NA-22 Office of Nonproliferation Research and Development for funding this project.

Thank you for your attention

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