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*Overview of University of Wisconsin Inertial-Electrostatic Confinement (IEC) Research**

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APS Division of Plasma Physics Meeting

Providence, Rhode Island

October 28–November 2, 2012

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* Research funded by DOE grant DE- FG02-04ER54751,
the Greatbatch Foundation, and the Grainger Foundation.

Present UW IEC Lab Topics of Investigation

Topic	Poster Pages
Basic IEC physics	5-8
IEC diagnostics	9-11
Negative ions	12-13
Integral equation IEC theory	14-15
Helicon ion source and ^{3}He-^{3}He fusion	16-17
Six ion gun beam convergence experiments	18-19
Hot materials irradiation experiments	20-21
Clandestine materials detection	22-23
Radioisotope production	24-26

University of Wisconsin IEC Team

Applications of IEC Device
Fusion-Product Neutrons and Protons

- Near Term (Q << 1)
  - Detection of highly enriched uranium (HEU) and special nuclear materials (SNM)
  - Detection of chemical explosives
    - Landmines
    - Improvised explosive devices (IEDs)
  - Detection of chemical wastes
- Mid Term (Q ~ 1)
  - Destruction of radioactive wastes
  - Destruction of fissile material

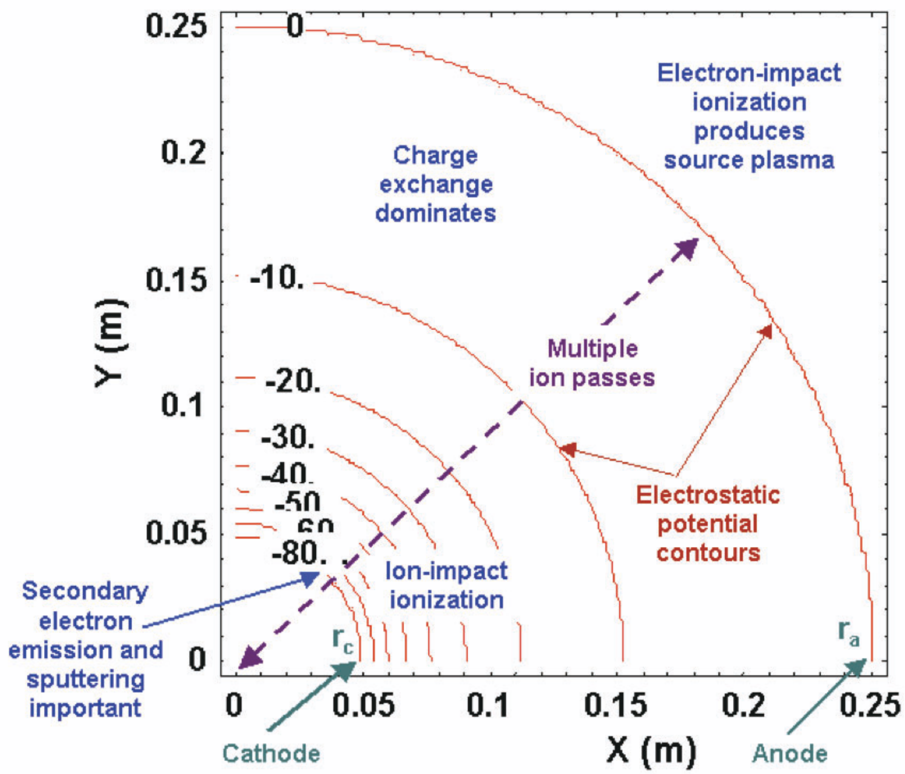
UW Gridded IEC Device

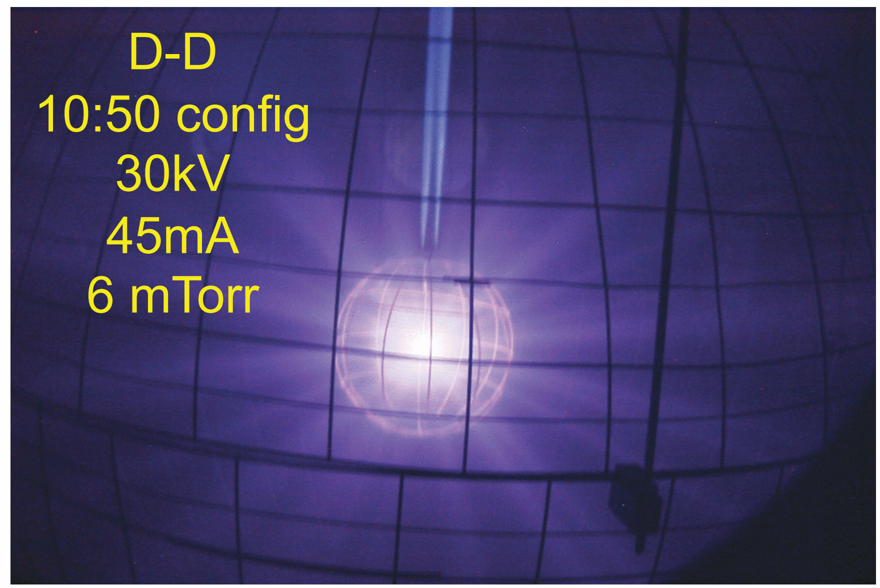
- Long Term (Q >> 1)
  - Small (~100 MWe) power plants
  - Quiet shipboard propulsion
  - Space power and propulsion
  - Base load electrical power plants
  - Hydrogen production
  - Synthetic fuel production

R.W. Bussard Polywell™
2006 International Astronautical Congress

Gridded IEC Concept: a Large Voltage Difference between Nearly Transparent Grids Accelerates Ions through a Background Gas

- At ~0.25 Pa (~2 mTorr) typical operation, most fusion reactions occur due to fast ions and neutrals interacting with cold background gas.





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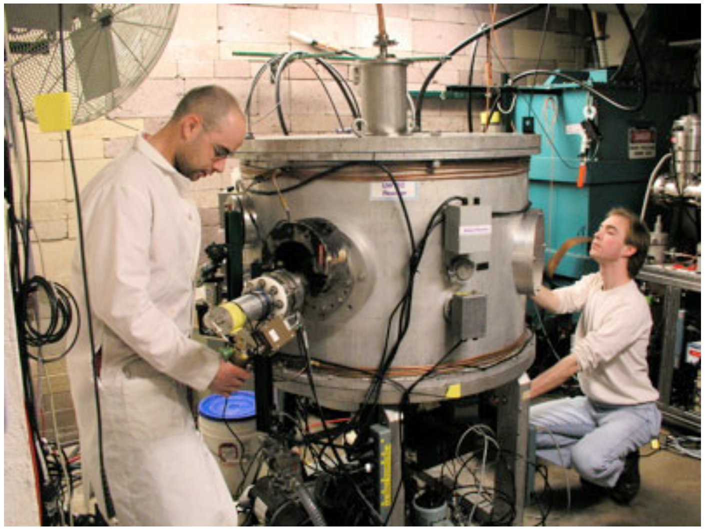
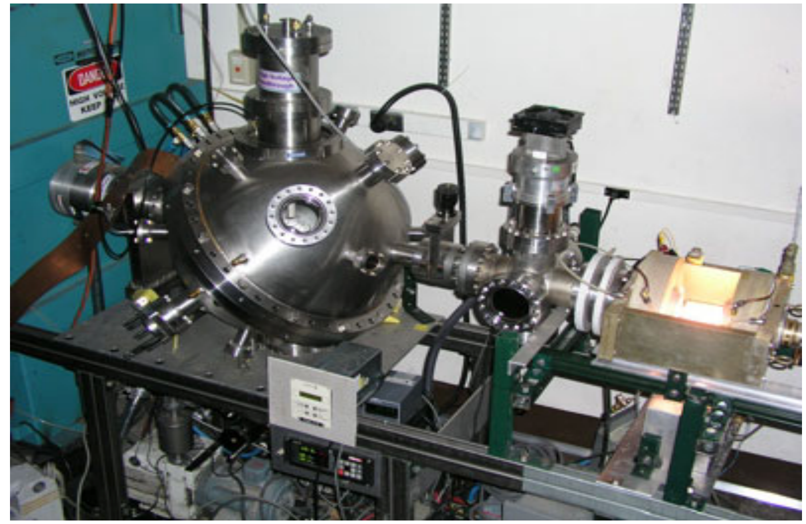
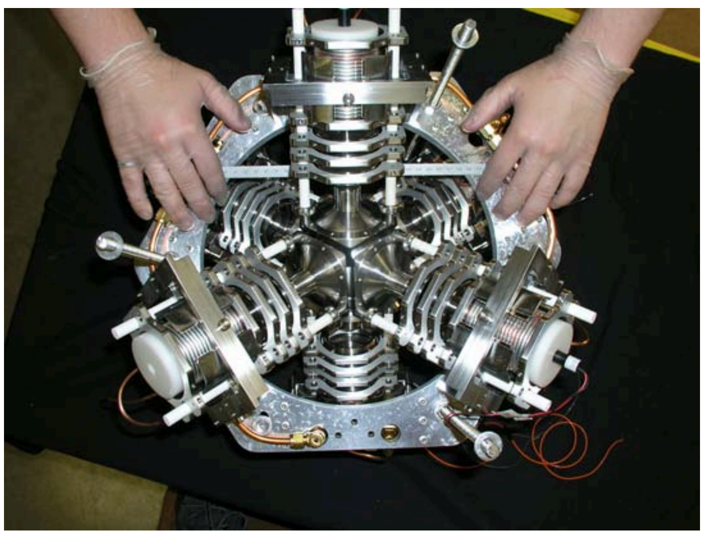
Four IEC Chambers Presently Operate at UW



HOMER



HELIOS & helicon ion source



SIGFE

MITE-E (ion gun irradiation facility)

UW's New Power Supply Will Increase Fusion Product Production Rates and Expand IEC Parameter Regimes

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PHOENIX NUCLEAR LABS
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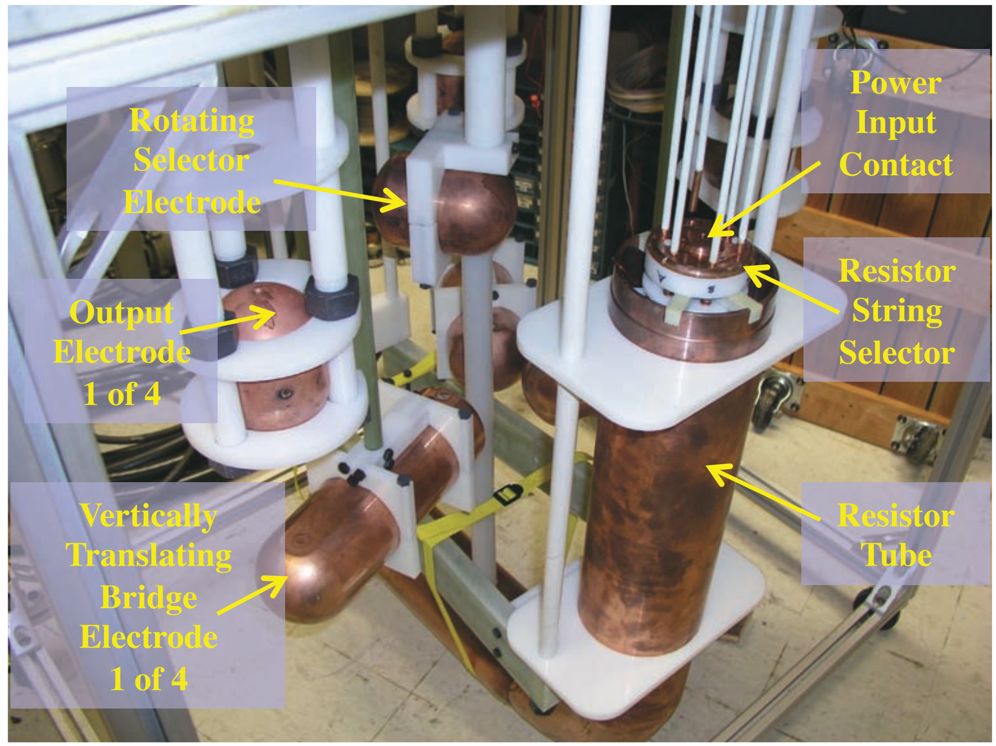
info@phoenixnuclearlabs.com 608-210-3060

UW designed and constructed high-voltage switch for changing connections between power supply and IEC devices quickly



This Phoenix Nuclear Labs power supply provides 300 kV at 200 mA with sophisticated arc protection control.

System of power supply, switch, and IEC devices being connected and tested for operation in 2012

IEC Devices Can Achieve High Voltages, Facilitating Use of Advanced Fusion Fuels

Key Fusion Fuels

1^{st} Generation

D + T → n (14.07 MeV) + ^{4}He (3.52 MeV)

D + D → n (2.45 MeV) + ^{3}He (0.82 MeV)

→ p (3.02 MeV) + T (1.01 MeV)

{50% each channel}

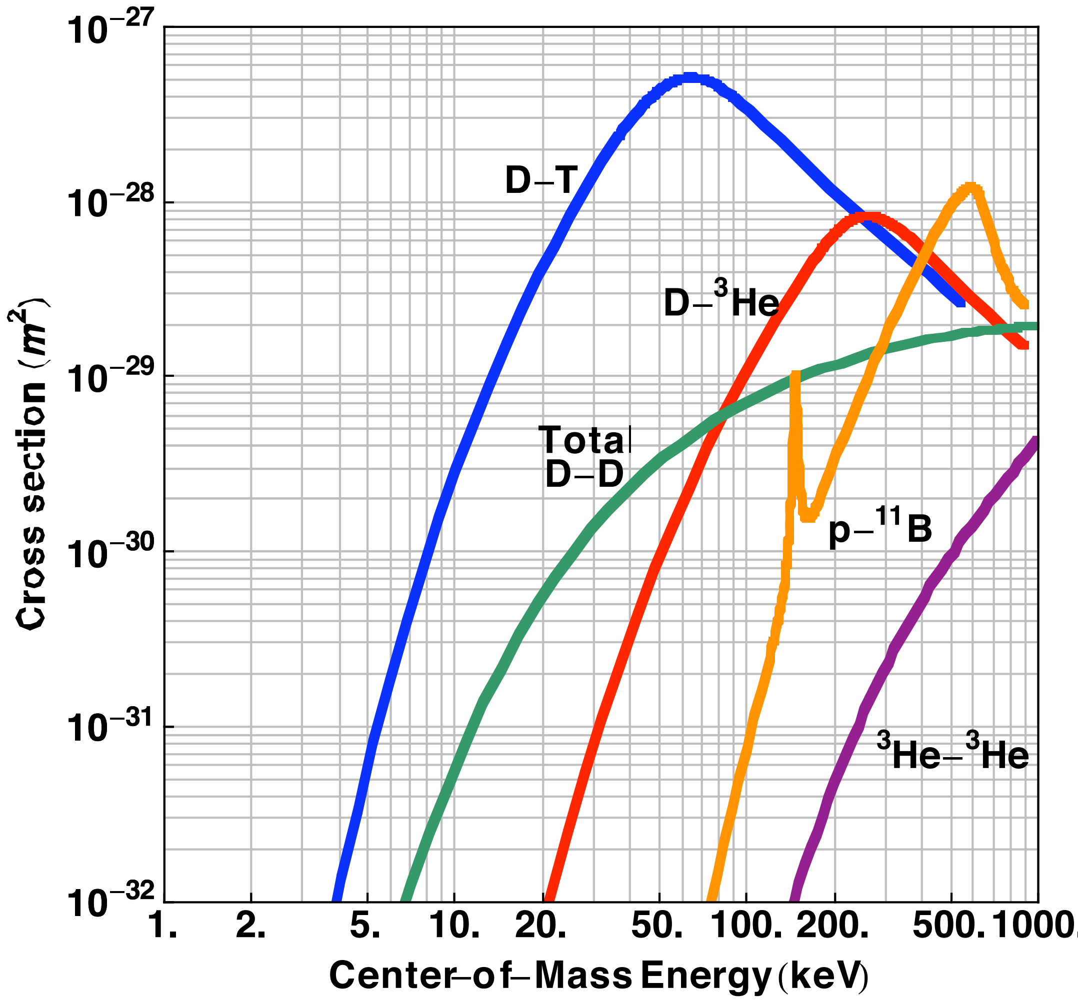
2^{nd} Generation

D + ^{3}He → p (14.68 MeV) + ^{4}He (3.67 MeV)

3^{rd} Generation

p + ^{11}B → 3 ^{4}He (8.68 MeV)

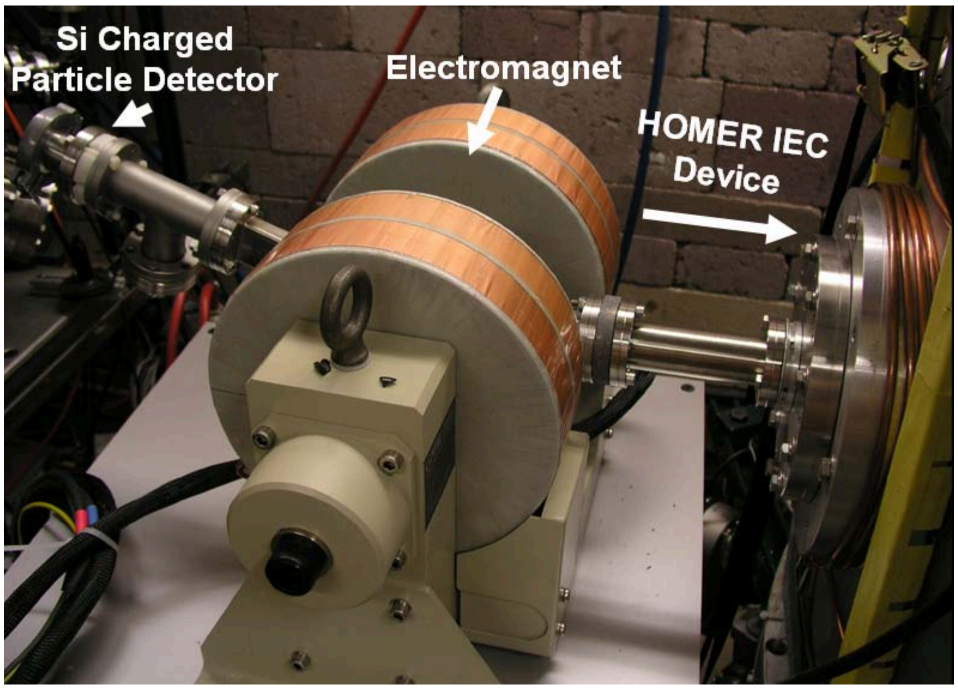
^{3}He + ^{3}He → 2 p + ^{4}He (12.86 MeV)

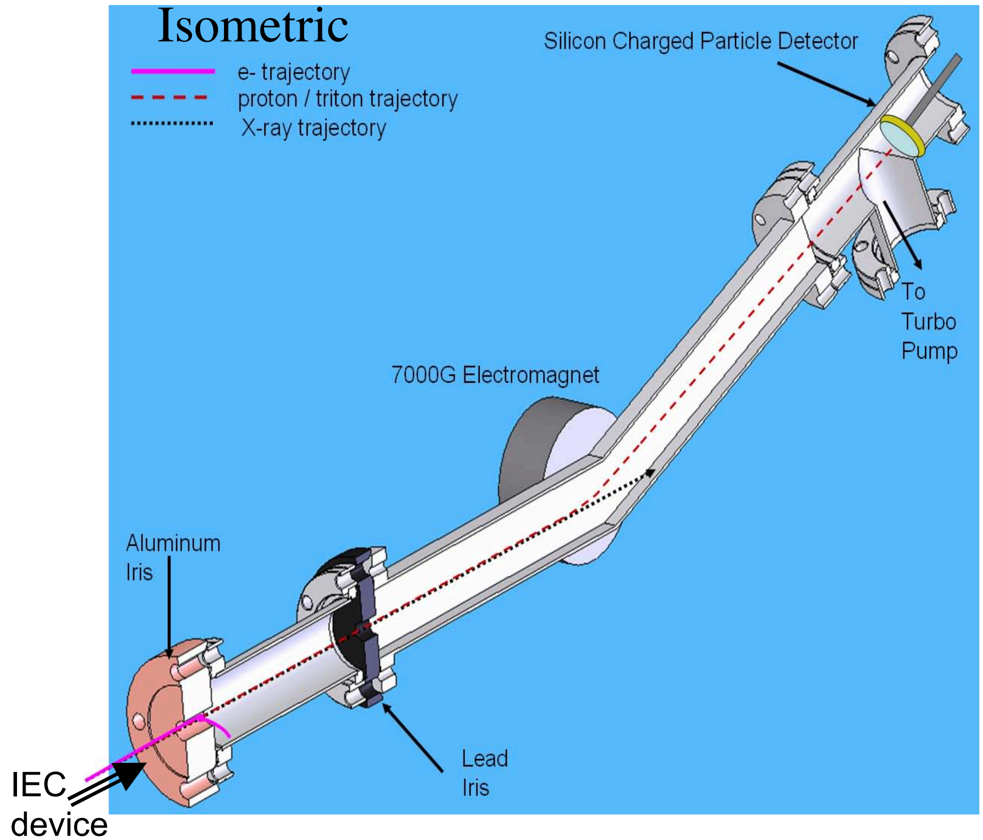


UW PhD Student Dave Boris Led the Development of the FIDO Charged-Particle Detection System

- Fusion Ion Doppler shift diagnostic (FIDO) bends charged particles into a Si proton detector.
- Greatly reduces bremsstrahlung x-ray noise.
- Works for fusion products and positive or negative ions.

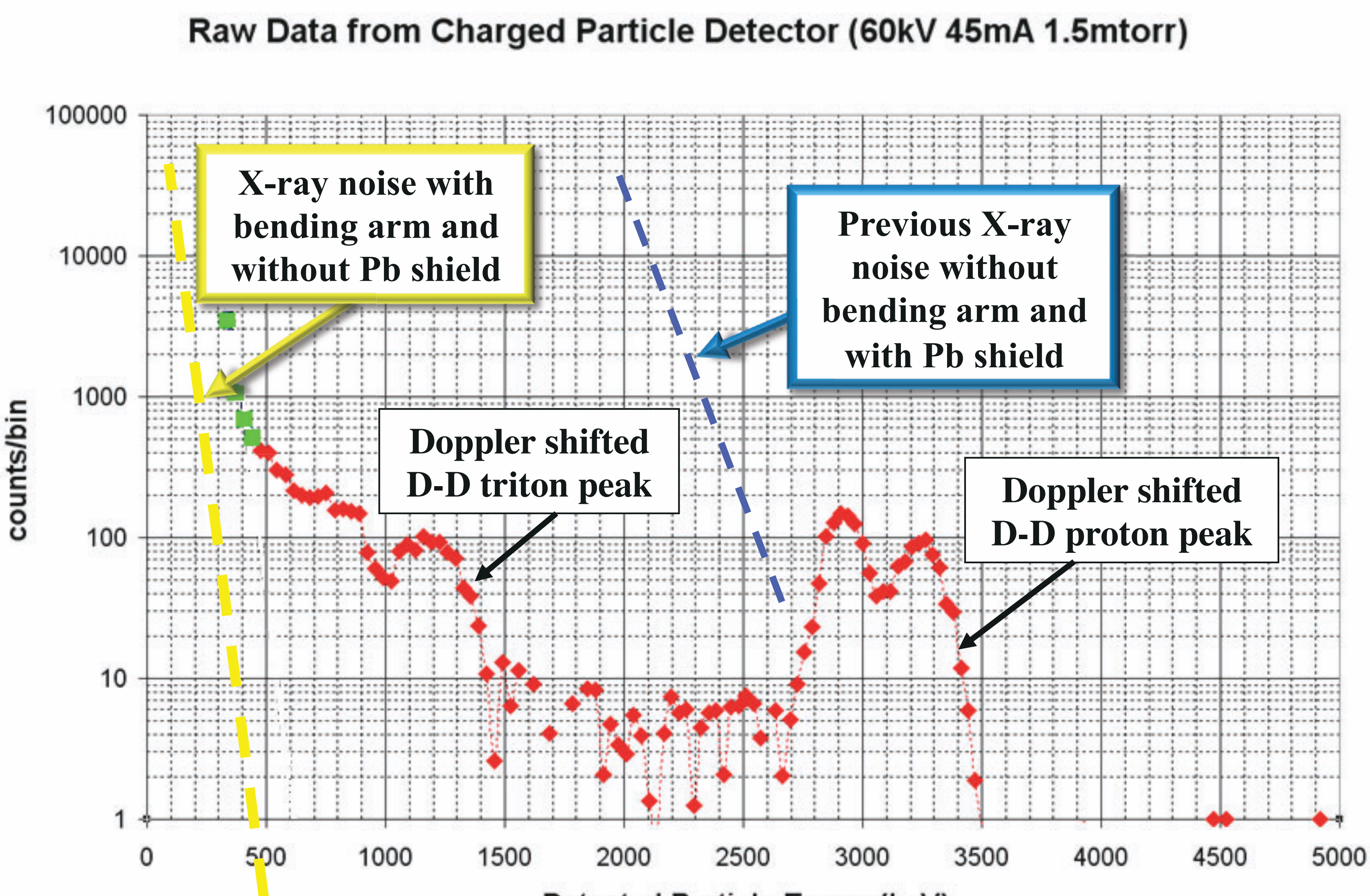
FIDO diagnostic schematic



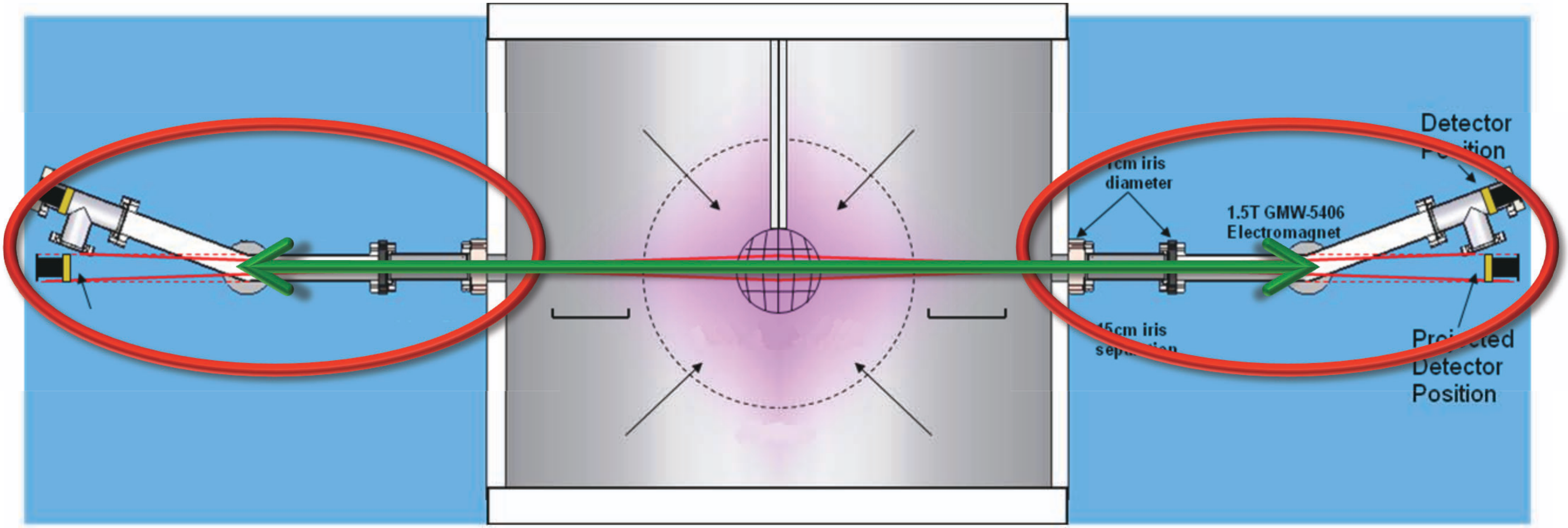


- D.R. Boris, G.L. Kulcinski, J.F. Santarius, D.C. Donovan, and G.R. Piefer, "Measuring D(d,p)T Fusion Reactant Energy Spectra with Doppler Shifted Fusion Products," *Journal of Applied Physics* **107**, 123305 (2010).

FIDO Bending Arm Allows both Protons and Tritons to be Detected



Time Of Flight (TOF) Diagnostic Uses Two FIDO Arms

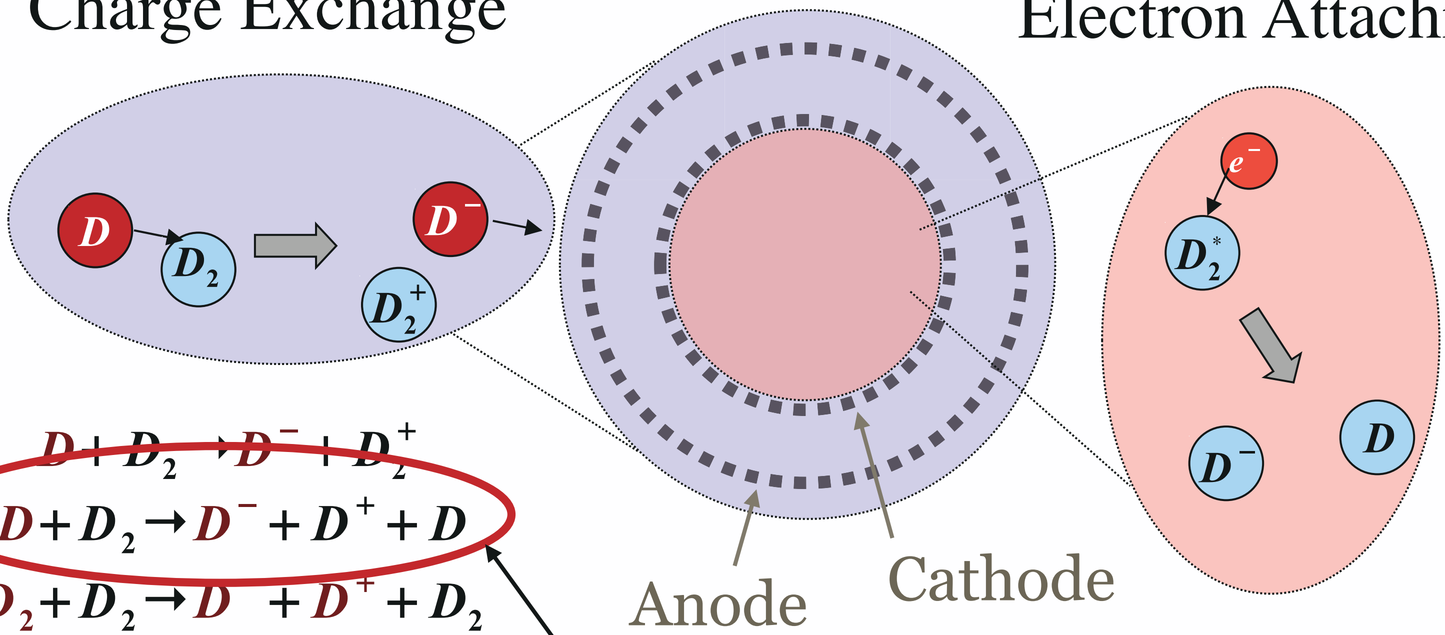


- TOF concept proposed by Greg Piefer and Dave Boris (2007)
- Implemented by Dave Boris and David Donovan (2008).
- Presently being refined by Aaron McEvoy.
- Allows identification of reacting ion location to ~2 cm.

Negative Ions Complicate the Problem, but Are Typically a Small Fraction of the Total Ions

Charge Exchange

Electron Attachment



$$D + D_2 \rightarrow D^- + D_2^+$$

$$D + D_2 \rightarrow D^- + D^+ + D$$

$$D_2 + D_2 \rightarrow D \;\; + D^+ + D_2$$

$$D^+ + D_2 \rightarrow D^- + 2\,D^+$$

$$D_2^+ + D_2 \rightarrow D^- + D^+ + D_2^+$$

$$D_3^+ + D_2 \rightarrow D^- + D_2^+ + D_2^+$$

Red denotes fast species

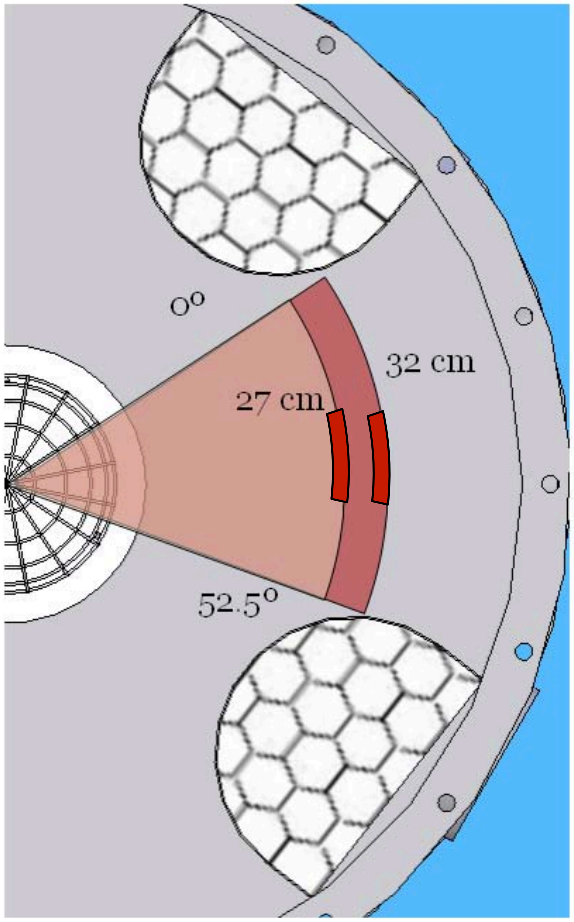
Most significant reaction

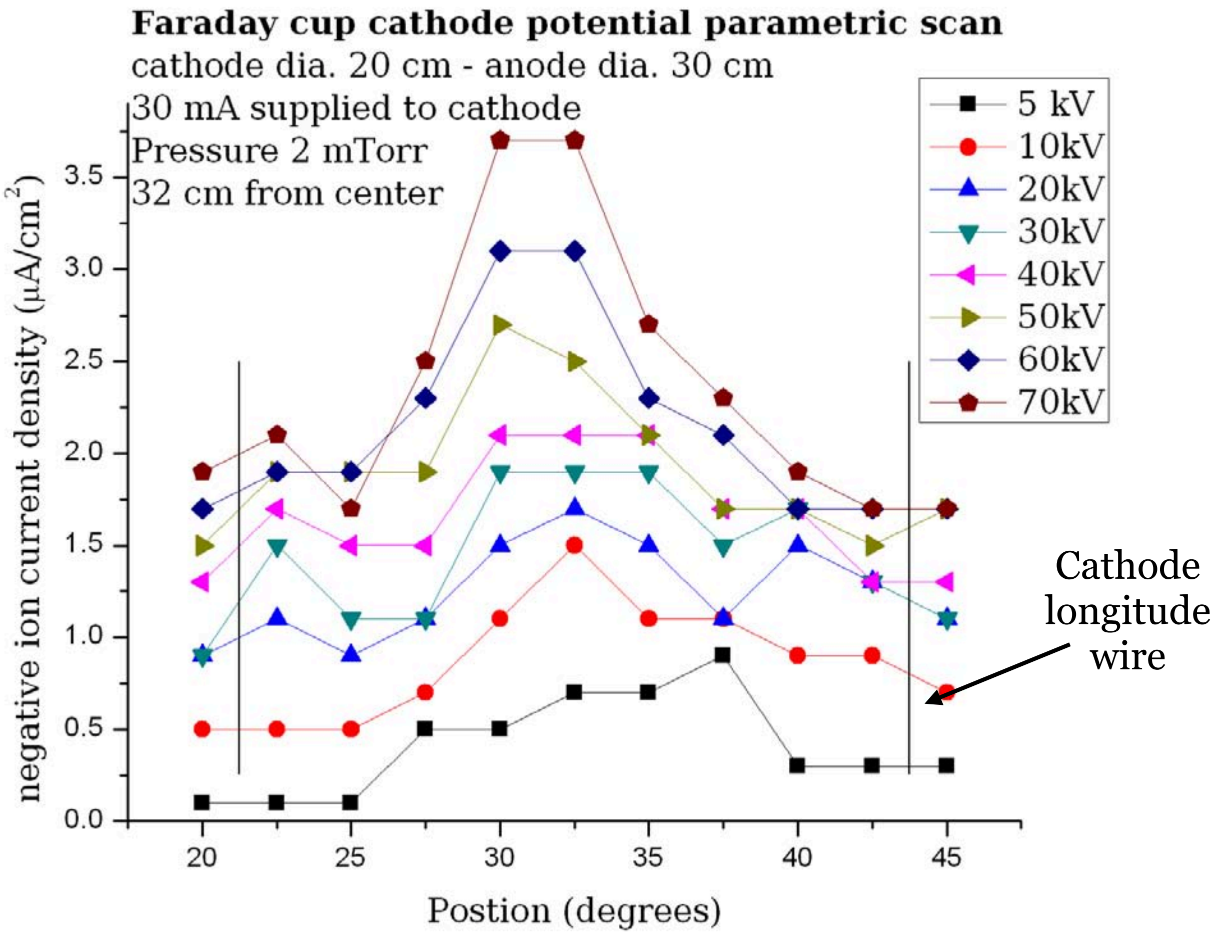
$$D_{2,(\nu)} + e^- \rightarrow D_2^- \rightarrow D^- + D$$

$$D_{2,(\nu,J)} + e^- \rightarrow (D_2^-)_m$$

Slide modified from Eric Alderson’s 2011 US-Japan IEC Workshop talk; see also D.R. Boris, E. Alderson, G. Becerra, et al., “Deuterium Anions in Inertial Electrostatic Confinement Devices,” Physical Review E 80, 036408 (2009).

Measurements of Negative Ion Azimuthal Profiles Show Peaking at Jet Locations





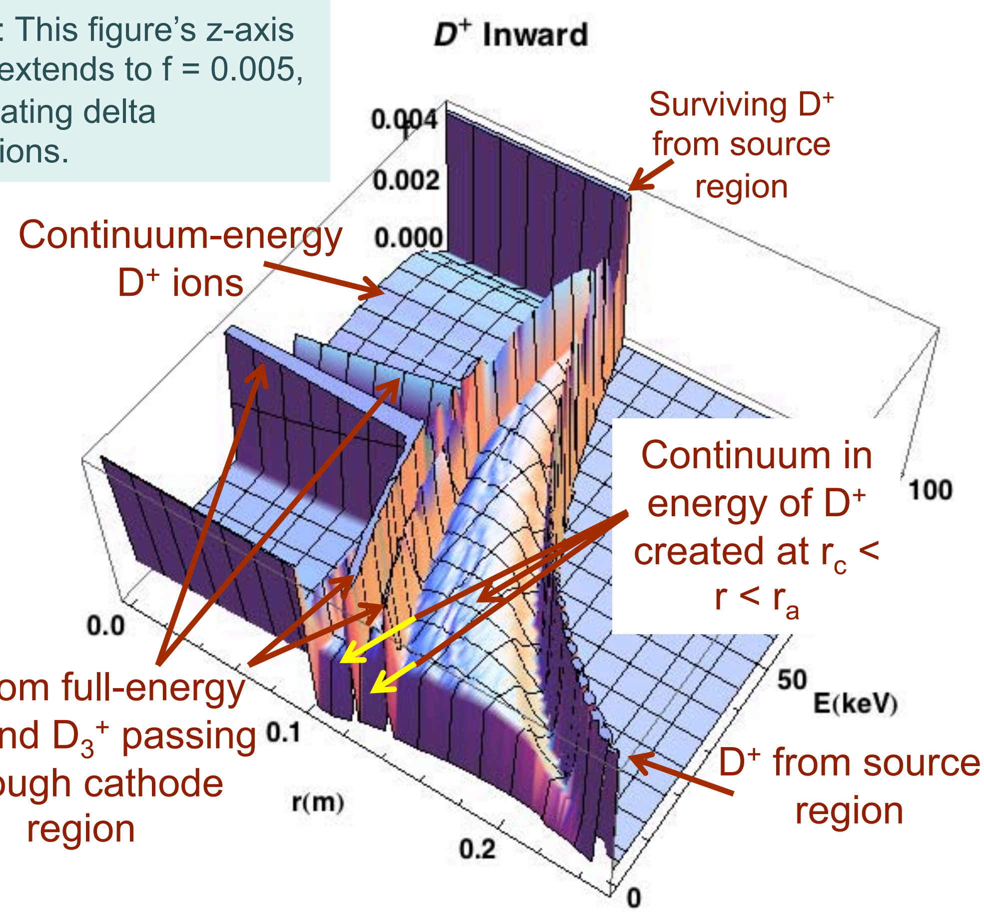
From Eric Alderson, *Experimental and Theoretical Characterization of Negative Deuterium Ion Distributions in a Gridded Inertial-Electrostatic Confinement Device*, UW PhD Thesis (2012).

UW's Volterra Integral Code for Transport in Electrostatic Reactors (VICTER) Models Multiple Ion & Neutral Species

Example: f(r,E) for D+ Ions Traveling Inward

Physics Modeled
VICTER-D code: D^+, D_2^+, D_3^+ D^-, D_2^0
VICTER-He code: He^0, He^+, He^{++}
The D and He version of VICTER will be merged.
Code assumptions: • 1D spherical, cylindrical, or planar symmetry • Prescribed Φ(r or x) • Ion source outside anode • Atomic & molecular physics reactions

Note: This figure's z-axis only extends to f = 0.005, truncating delta functions.



← IEC Device Model Parameters

- ΔV = 100 kV
- I_{meter} = 100 mA
- P_{gas} = 2 mTorr
- $r_{cathode}$ = 0.10 m
- r_{anode} = 0.25 m
- Ion source:
- D^+:D_2^+:D_3^+= 0.06:0.23:0.71

• See G.A. Emmert poster TP8 100, this session, for more information.

Key Equations of VICTER and Comparison to Experiment

- Coupled integral equations model multiple ion passes
  - Attenuation function = $g(r, r')$

$$g(r,r') = \exp\left\{-\int_r^{r'} n_g \sigma_{cx}\left[E(r'')\right]dr''\right\}$$

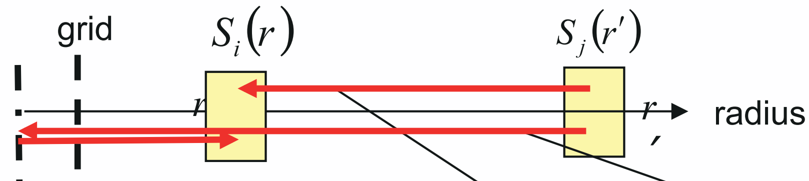
gas density

charge exchange cross-section

  - Cold ion source function = $S(r)$
  - Cold ions from source region=A(r)
  - Sum over all generations of cold ions and all ion passes:

$$S(r) = A(r) + \int_r^{\text{anode}} K(r,r')S(r')dr'$$

  - Kernel $K_{ij}(r, r')$ propagates ion source at r' to r: that is, $S(r')$ to $S(r)$:



Slow Source contribution:

$$K_{ij}(r,r') = n_g \sigma_{ij}\left(E(r,r')\right)\left(\frac{r'^2}{r^2}\right)\frac{\boxed{g_j(r,r')} + \boxed{T_c^2 \dfrac{g_{cpj}(r')}{g_j(r,r')}}}{\boxed{1 - T_c^2 g_{cpj}(r')}}$$

Gas density

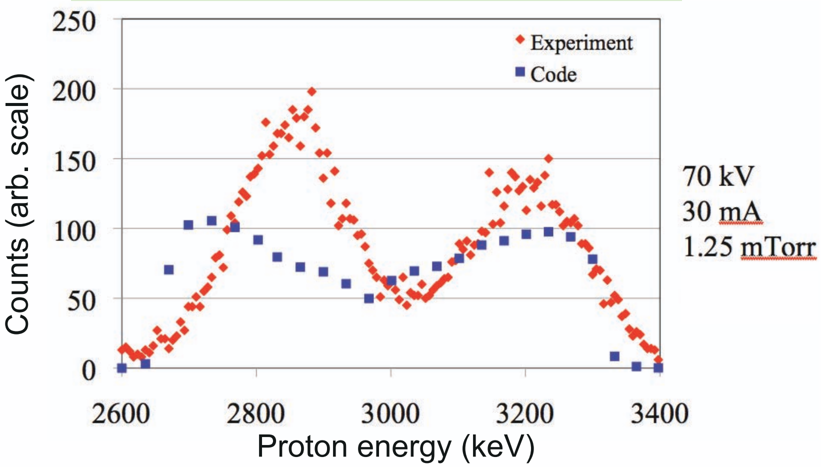
Cross-section for producing i from j

Cathode transparency

Complete pass probability

Sum over passes

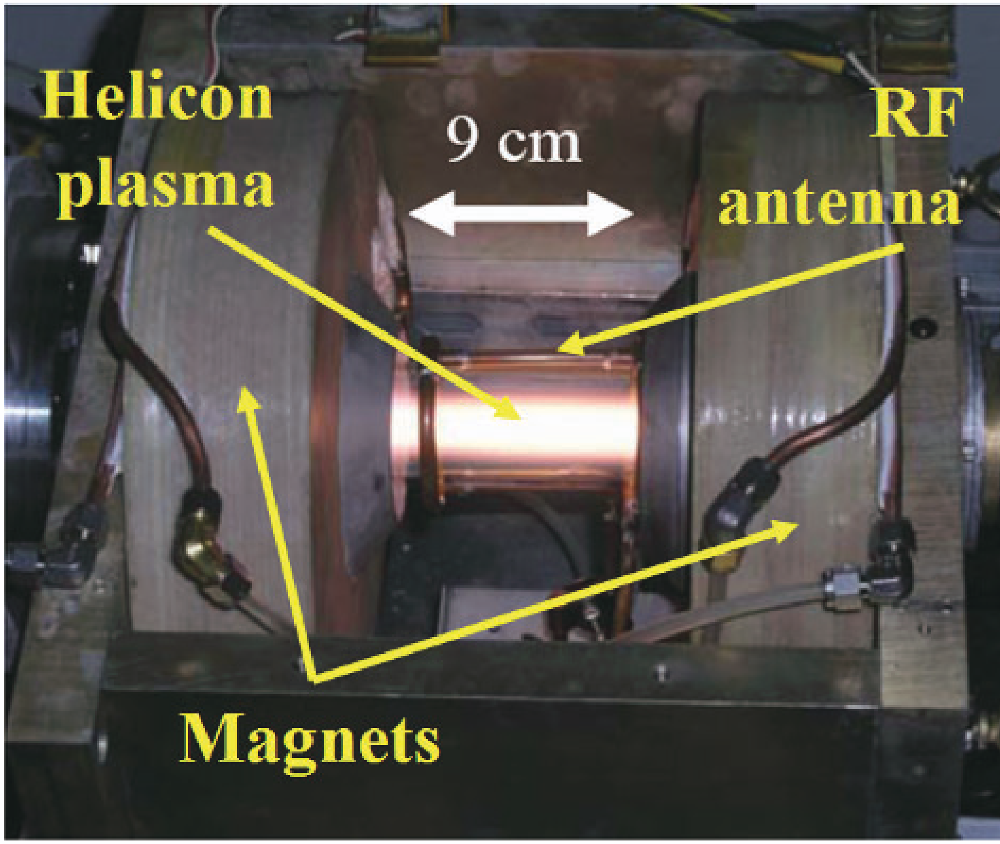
Comparison of theory and experiment

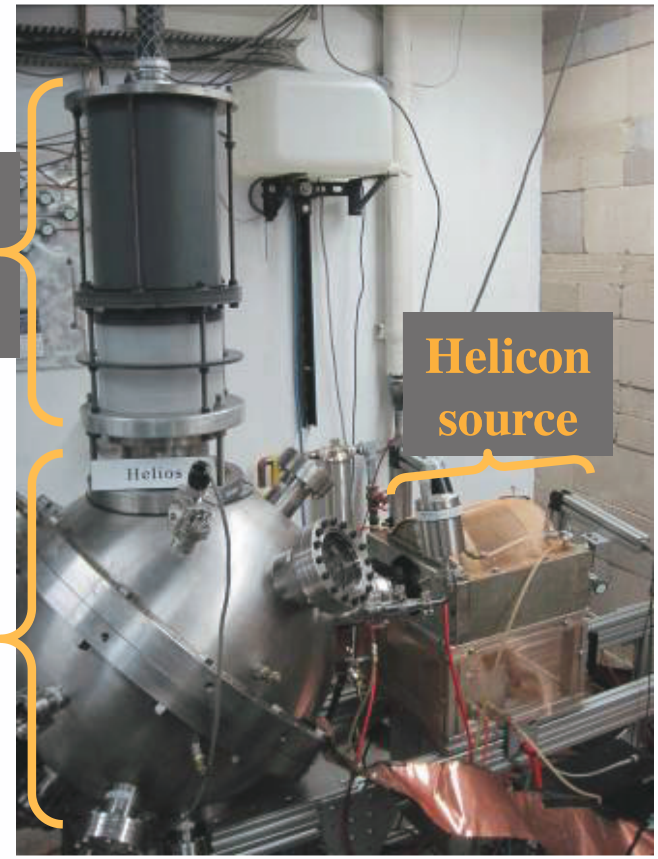


- Refs: G.A. Emmert and J.F. Santarius, "Atomic and Molecular Effects on Spherically Convergent Ion Flow I: Single Atomic Species" & "II: Multiple Molecular Species," *Physics of Plasmas* **17**, 013502 & 013503 (2010).

Maintaining High Helium Ion Energy Requires Operating at Low Pressures (< 0.1 mTorr)

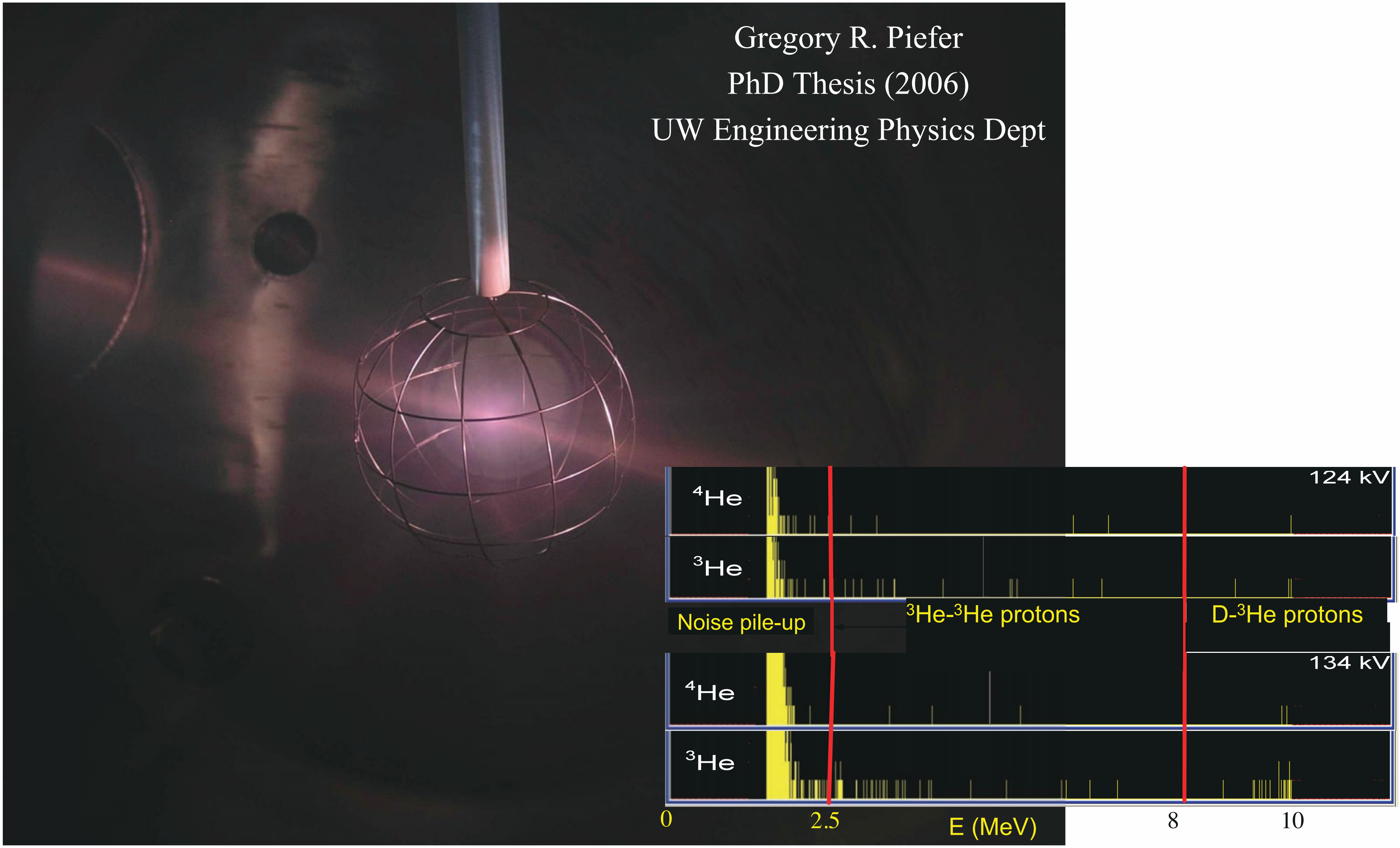
Helicon Ion Source Operating with UW's Spherical IEC Chamber





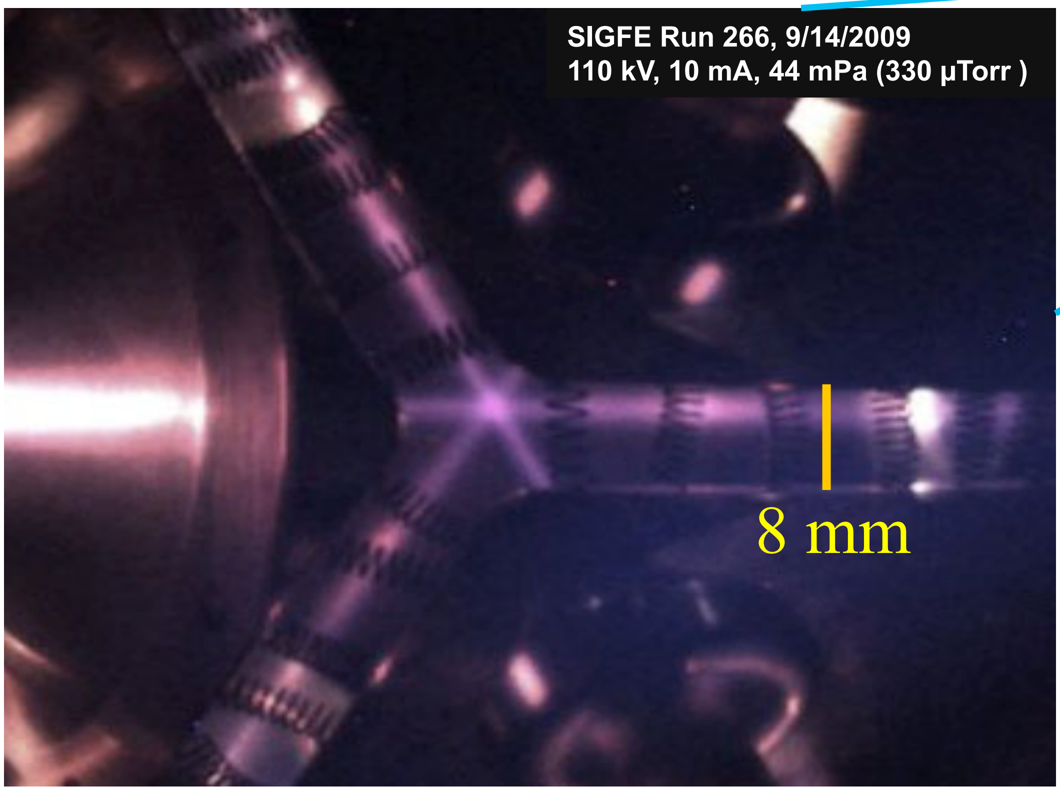
- Figures courtesy of Gabriel Becerra.
- See G.E. Becerra poster TP8 105, this session, for more information.

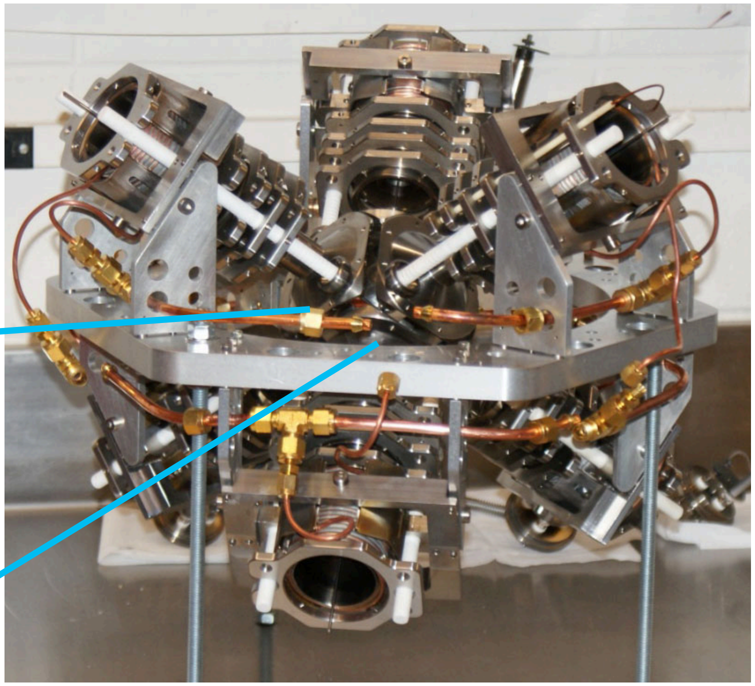
$^3He(^3He,2p)^4He$ Fusion Reactions Have Been Measured in a Fusion Device at UW-Madison



SIGFE Converges Six Focused Ion Beams into Center of Device

- SIGFE operates at a lower chamber pressure than many gridded IEC devices, as low as 10 mPa (75 μTorr)
- Variable beam focus

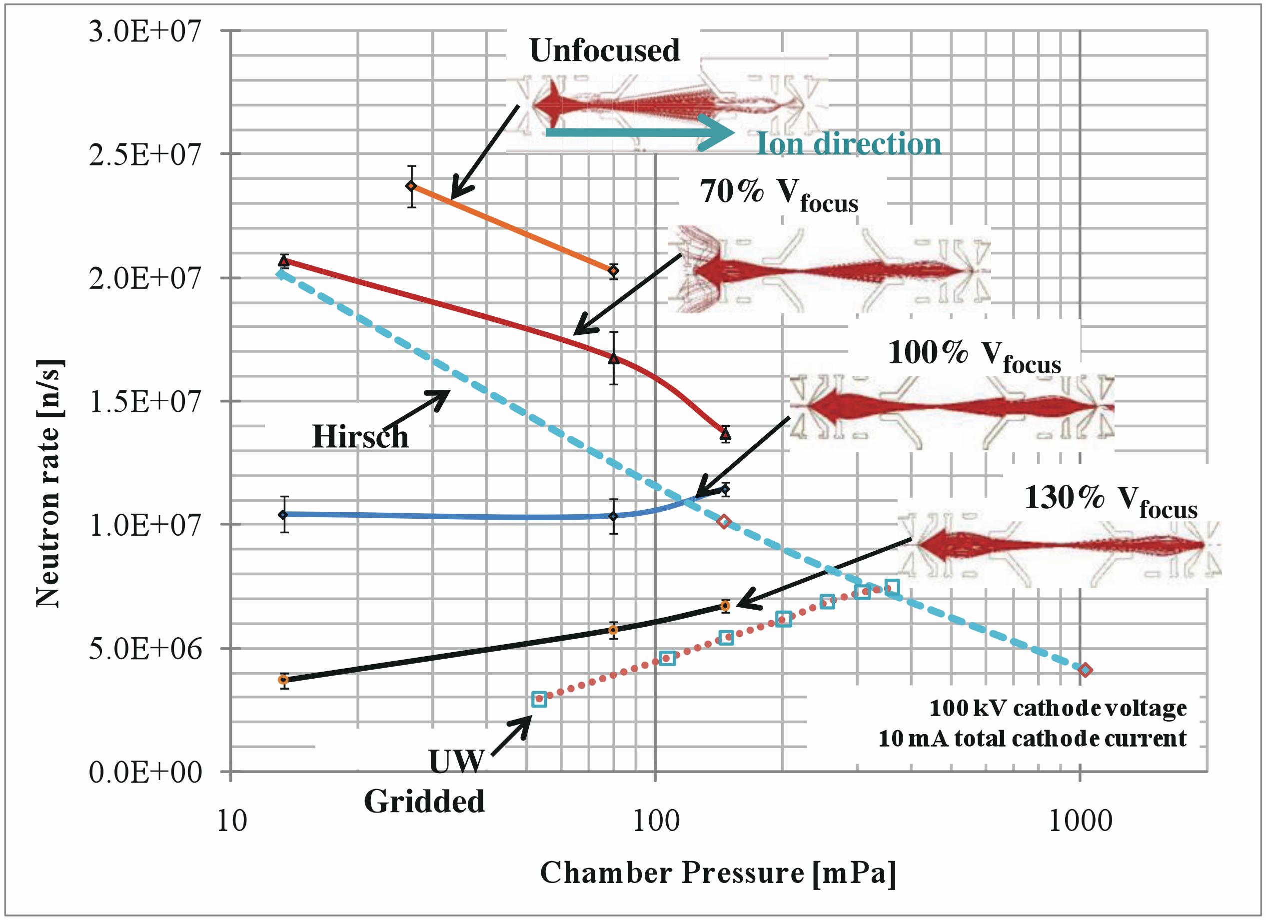




- Potential IEC operating modes
  - Beam-background
  - Beam-embedded
  - Converged core
  - Multiple virtual electrodes (Poissors)

SIGFE's Neutron Rate vs. Pressure Differs from Gridded IEC Devices for Some Parameter Regimes

- 100% is ideal focus;
  130% focuses at midplane.
- Neutron production rates in experiments on ideally focused SIGFE depend little on pressure.
- Neutron rates in UW gridded devices for an over-focused SIGFE are proportional to pressure.
- SIGFE's, as well as Hirsch's, experimental neutron rates scale inversely with pressure when under-focused



Materials Irradiation Test Facility MITE-E

← Uses Brian Egle SIGFE prototype ion gun.

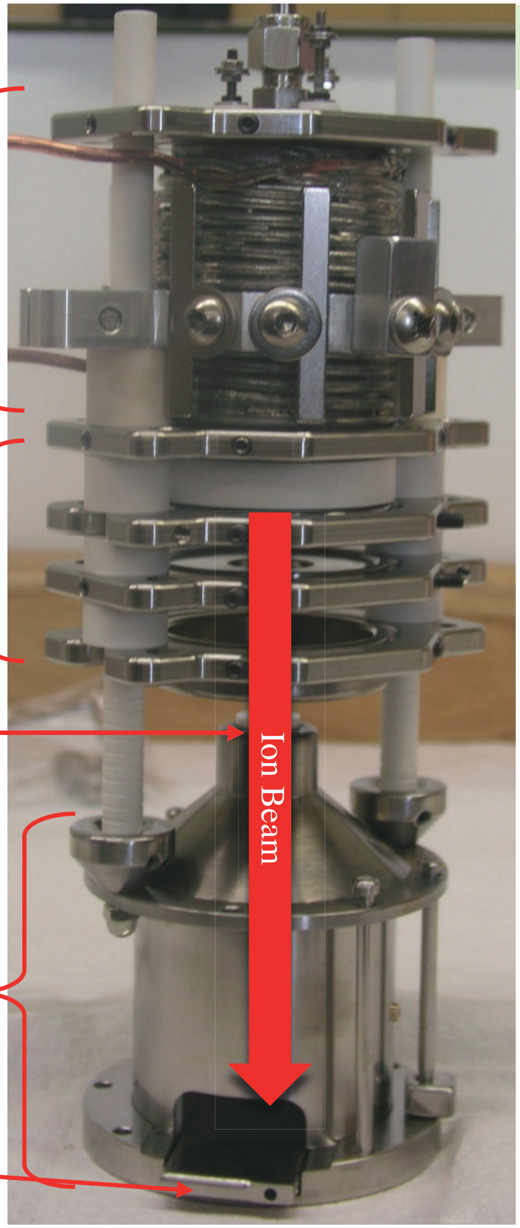
Ion Source 0 V

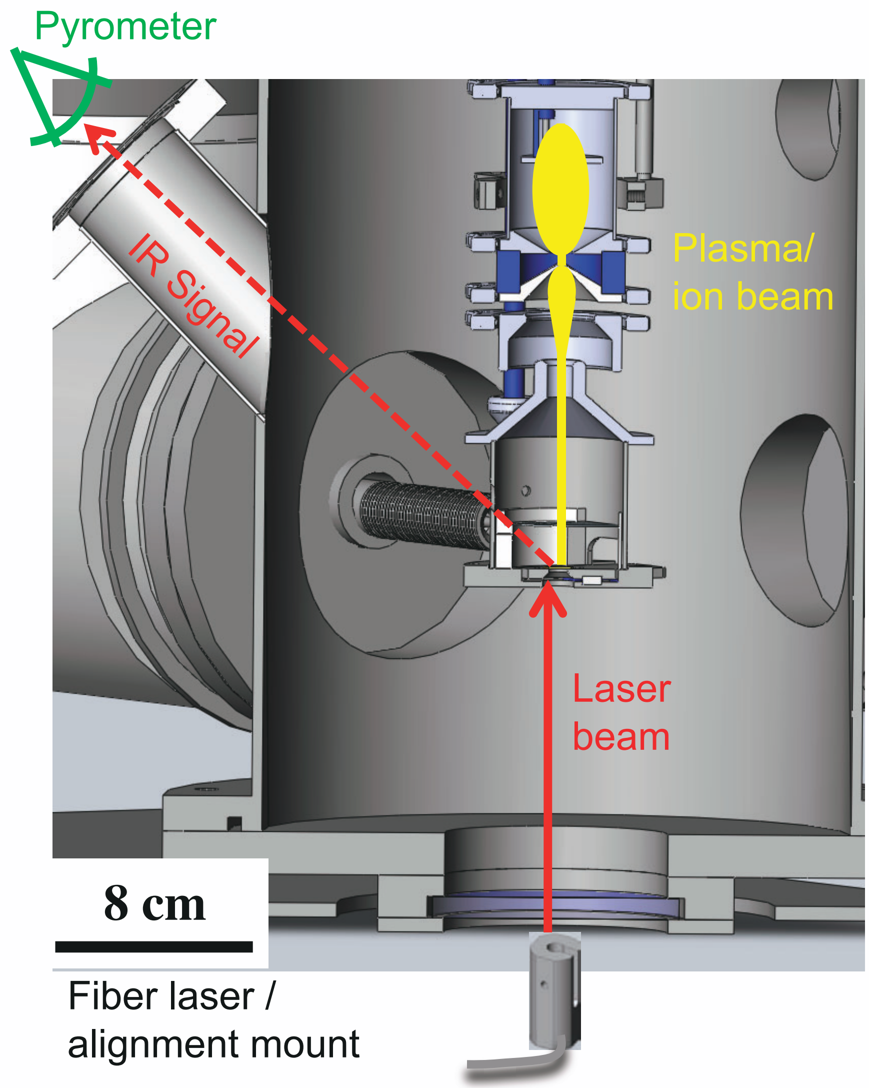
Focusing Lenses -0 to -15 kV

Ion Aperture

Cathode Assembly ≤150 kV

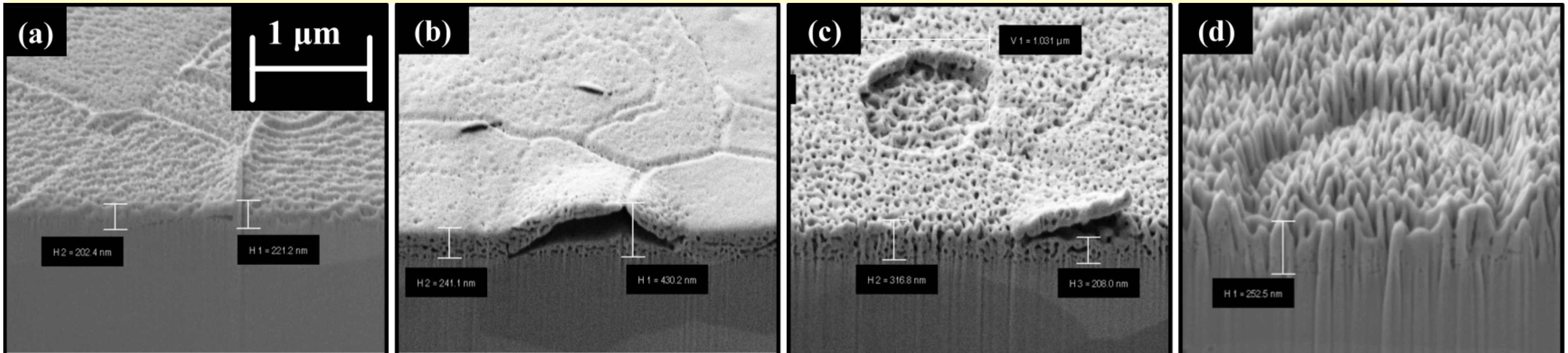
Sample Holder





Fast He Ions Can Produce Significant Damage in Hot Materials

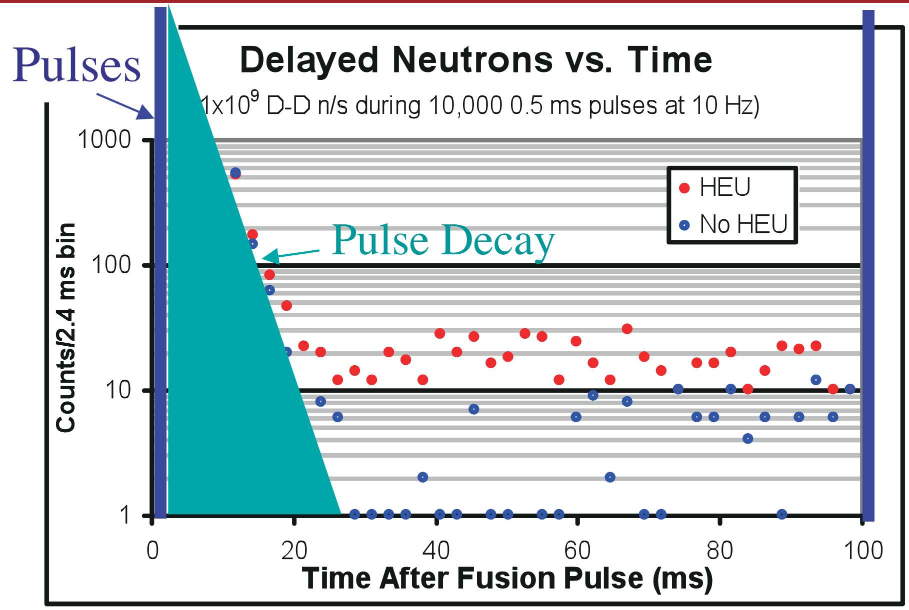
- Concerns exist for MFE divertor plates plus MFE and IFE first walls.



P27: φ_L – 6x10^{17} He$^+$/cm^2, T – 900°C	**P31:** φ_L – 1.3x10^{18} He$^+$/cm^2, T – 900°C	**P31:** φ_L – 1.8x10^{18} He$^+$/cm^2, T – 900°C	**P26:** φ_L – 1x10^{19} He$^+$/cm^2, T – 800°C

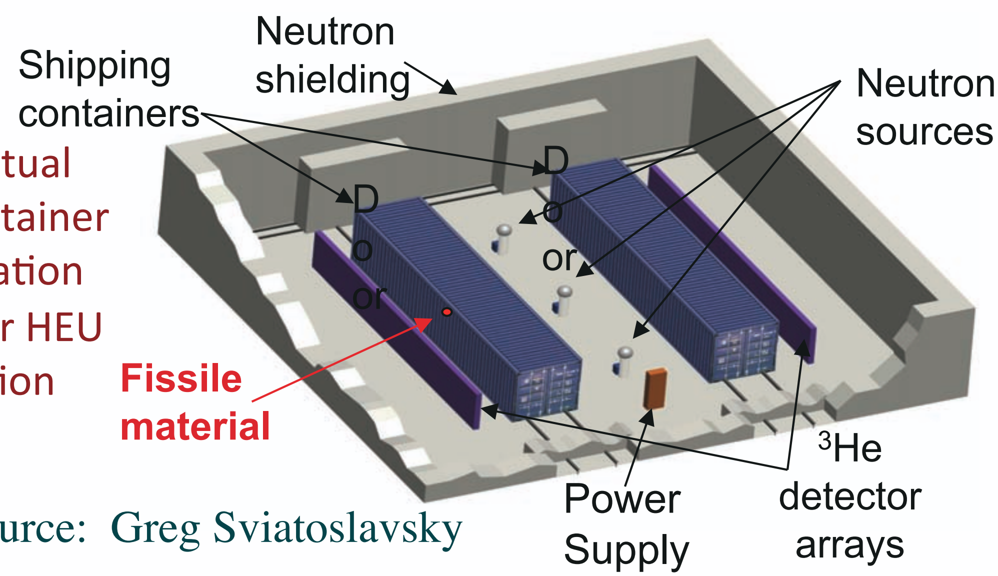
- Sam Zenobia, Lauren Garrison, and Gerald Kulcinski, “The Response of Polycrystalline Tungsten to 30 keV Helium Ion Implantation at High Temperatures and Its Dependence on the Angle of Incidence,” *Journal of Nuclear Materials* **425**, 83 (2012);
  Sam Zenobia, UW PhD thesis (2010).
- Present PhD students Lauren Garrison and Karla Hall are pursuing related research.

IEC Neutron Sources Facilitate Detection of Highly Enriched Uranium (HEU) and Special Nuclear Material (SNM)



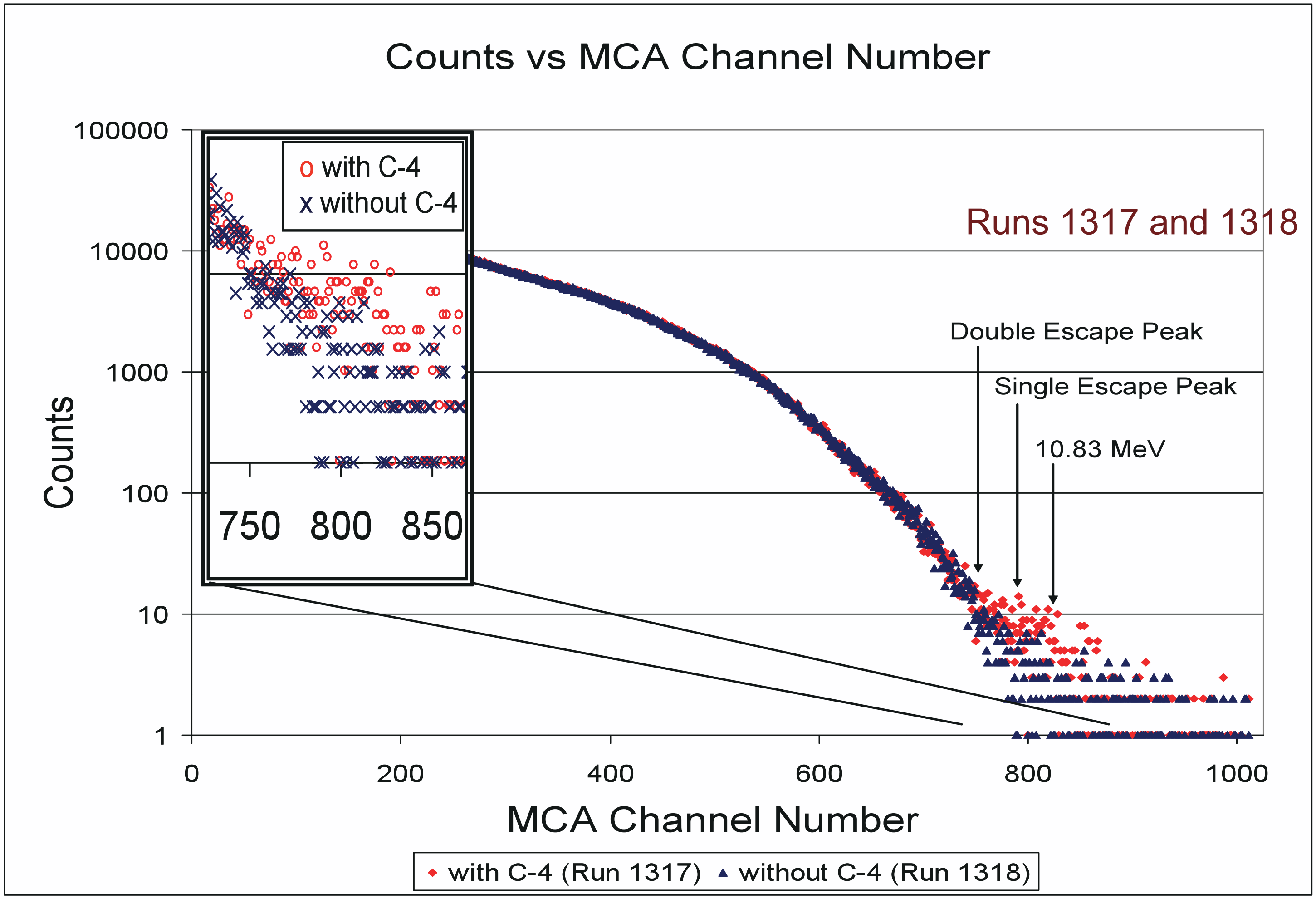
Ross Radel, *Detection of Highly Enriched Uranium and Tungsten Surface Damage Studies Using a Pulsed Inertial Electrostatic Confinement Fusion Device,* UW PhD thesis (2007).

Conceptual cargo-container interrogation system for HEU detection



Source: Greg Sviatoslavsky

IEC Neutron Sources Facilitate Detection of Chemical Explosives



Alex Wehmeyer, *The Detection of Explosives Using an Inertial Electrostatic Confinement D-D Fusion Device,* UW MS thesis (2005)

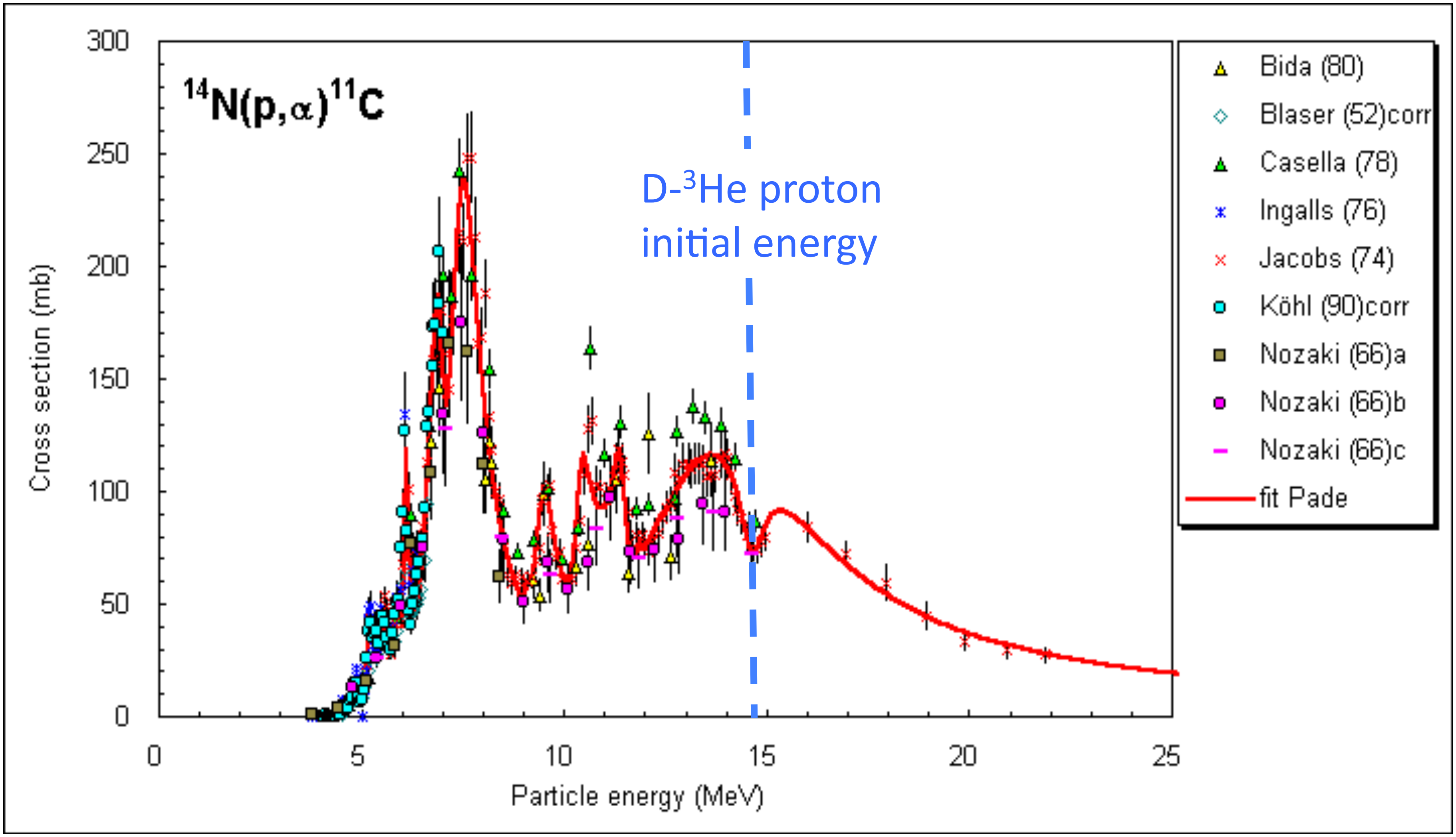
D-^{3}He Fusion Protons (14.7 MeV) Can Produce Short Half-Life, Positron-Emitting Radioisotopes

- Short half-lives reduce the radiation dose—particularly important for sensitive populations, such as children and pregnant women.
  - IEC radioisotope production would allow in-hospital or in-clinic production, thereby reducing distribution difficulties for radioisotopes that decay quickly.

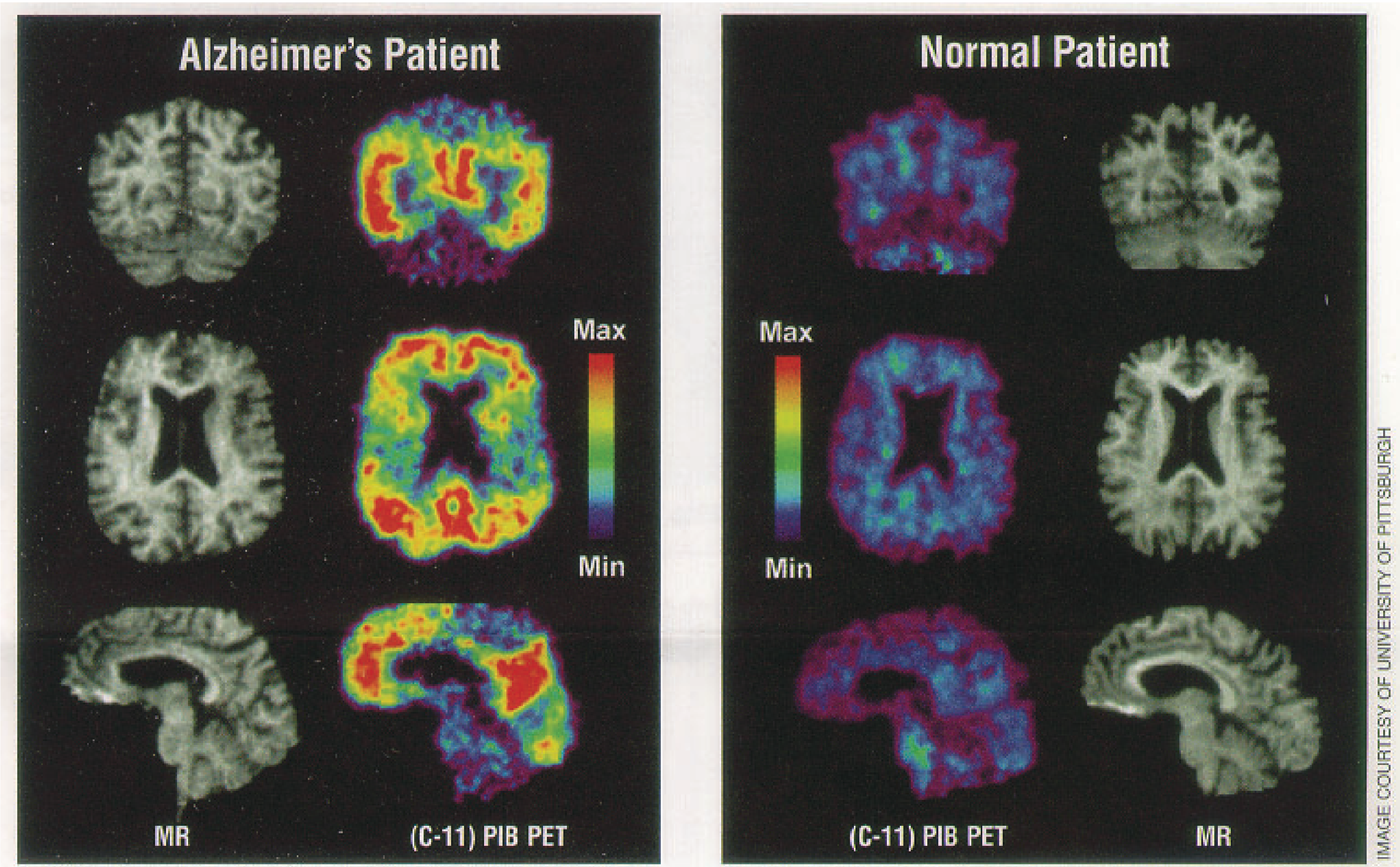
Parent Isotope	Production Reaction	PET Isotope	Half Life
^{18}O	(p, n)	^{18}F	110 min
^{14}N	(p, α)	^{11}C	20 min
^{16}O ^{13}C	(p, α) (p,n)	^{13}N	10 min
^{15}N	(p, n)	^{15}O	2 min

- D-D neutrons and D-^{3}He protons could also produce other radioisotopes or strategically important stable isotopes.

D-^{3}He Fusion Protons Slow Down through the Peak of the $^{14}N(p, \alpha)^{11}C$ Cross Section



^{11}C Tagged PIB Carrier Enables Early Detection of Alzheimer's Disease



Summary

- Inertial-electrostatic confinement (IEC) fusion devices:
  - Require relatively simple construction,
  - Necessitate high-voltage standoff,
  - Produce relevant neutron rates for detecting clandestine materials, and
  - Potentially can create radioisotopes for nuclear medicine.
- UW diagnostics and theory for gridded IEC devices have led to reasonably well understood physics in the moderate-pressure (~1 mTorr) regime.
- Ion guns and IEC devices can address plasma-material interaction issues for fusion reactor divertors and first walls.
- Fundamental ion-beam convergence and ^{3}He-^{3}He reactions are under investigation.