*Overview of UW FTI Inertial-Electrostatic Confinement (IEC) and Other Research**

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Engineering Physics Department

UW Plasma Seminar
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THE UNIVERSITY of WISCONSIN MADISON

Mission of the Fusion Technology Institute

- **Develop Clean, Safe, and Economical Fusion Energy Sources for Use in the 21st Century**

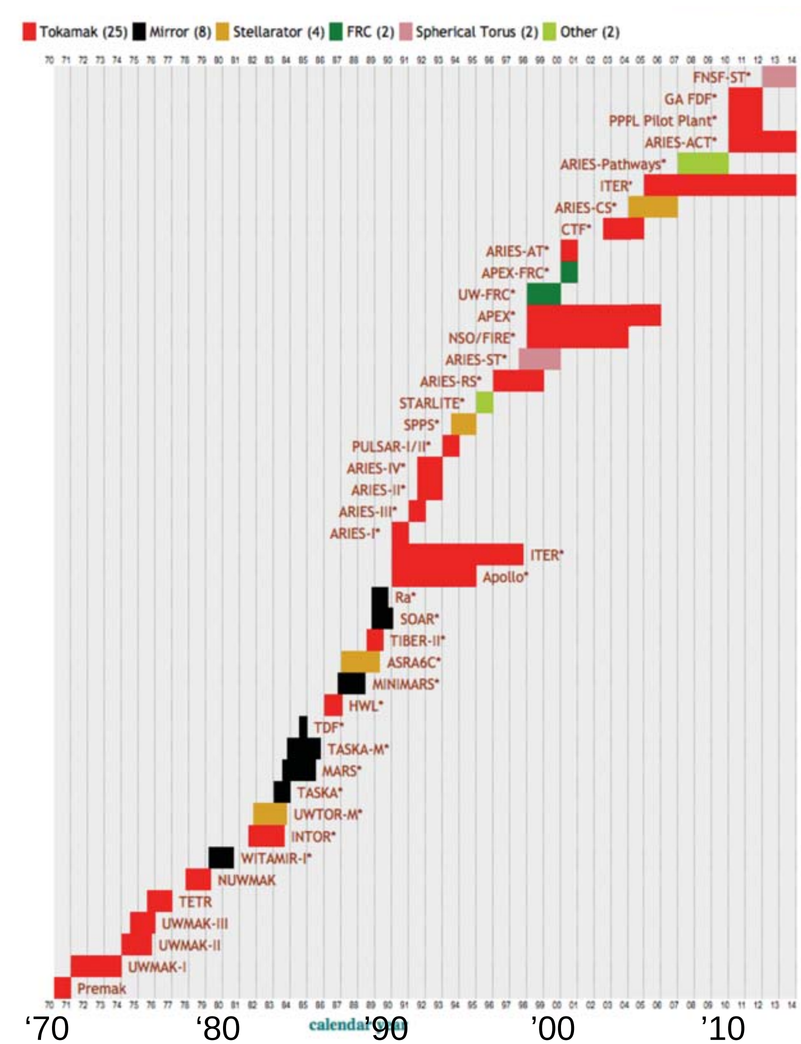
- **Create Near-Term Commercial Products that Use Fusion Energy to Enhance the Quality of Life**

- **Educate Students in the Science and Technology of Fusion Energy**

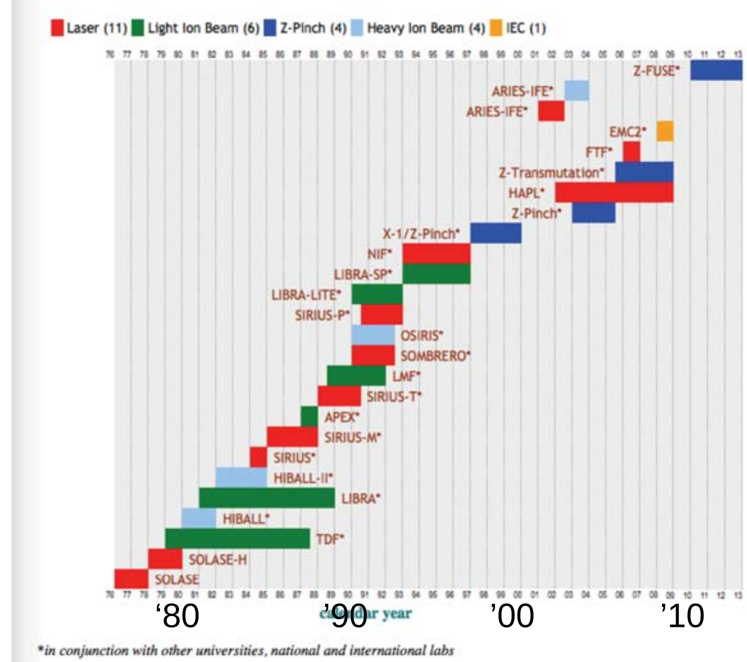
http://fti.neep.wisc.edu/

Fusion Technology Institute Personnel Have Participated In 69 Reactor and Test Facility Studies

MFE



IFE



<u>Conceptual Designs</u>

43 MFE

25 IFE

1 IEC

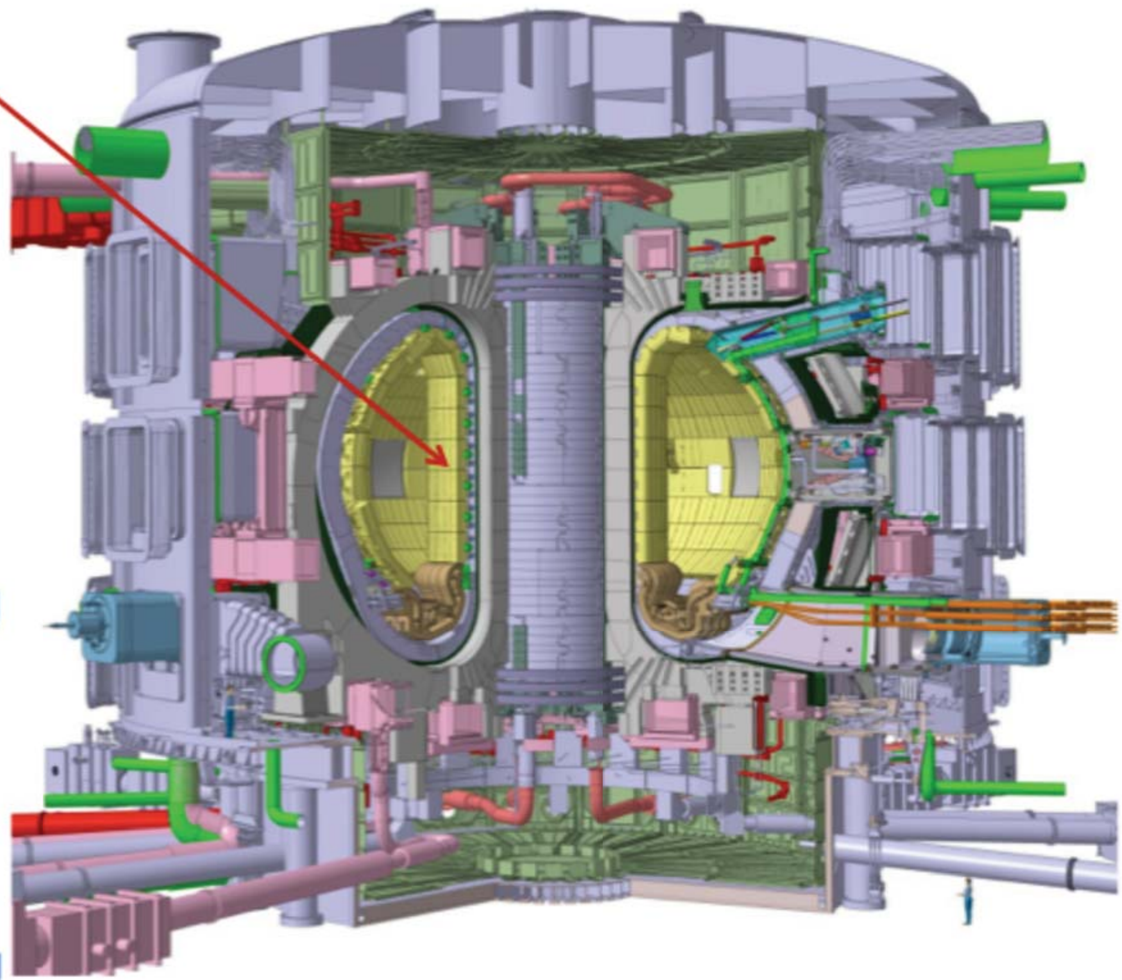
Ongoing & Recently Completed FTI Research Activities

- ITER Neutronics US Lead - DOE
- LIFE Laser ICF Reactor - LLNL
- ^{99}Mo Production - SHINE & PNL
- IEC n Source Detection of HEU & Explosives - Private
- 3D CAD / Neutronics Coupling - DOE
- ICF Rad Hydro - LLE & Univ Chi
- IEC Production of PET Radioisotopes - Private
- Detection of Defects in Artillery Shells - PNL
- Advanced Fusion Reactor Design - DOE
- Shock Waves on Liquid Surfaces - DOE, LANL, LLNL
- IEC Atomic & Molecular Physics - DOE & Greatbatch
- Material Surface Damage by He Ions - Private
- Fusion Materials Recycling & Clearance
- Z-pinch Reactor - SNL
- IEC Adv Fuel Physics - Grainger & Greatbatch
- Adv Fuel Fusion Physics & Power Plant - EMC2
- Liquid Metal Safety - DOE
- Magnetized-Target Fusion (MTF) - DOE
- Lunar ^{3}He & Fusion Space Applications - Greatbatch

FTI Researchers Investigate Most Features of Fusion Reactor Design

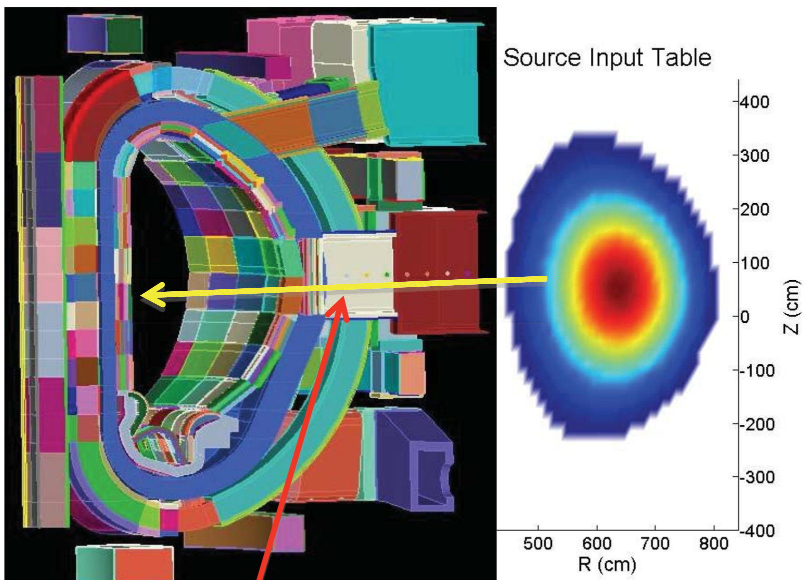
Main functions of a first wall and blanket in a DT Tokamak fusion reactor

- Collects the majority of the plasma power.
- Breeds the tritium in DT systems
- Contributes in providing neutron shielding to superconducting coils.
- Provide limiting surfaces that define the plasma boundary during startup and shutdown.

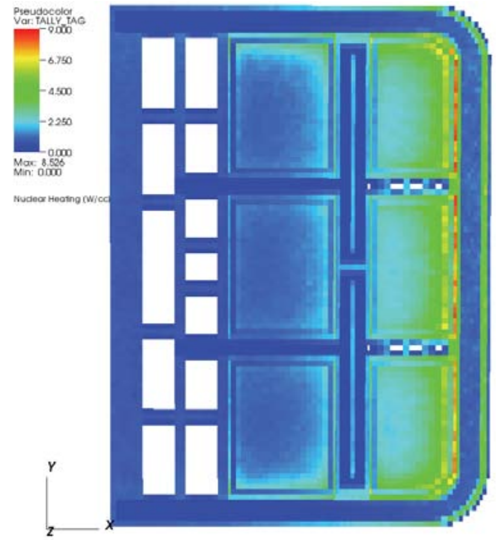


Slide from G. Kulcinski

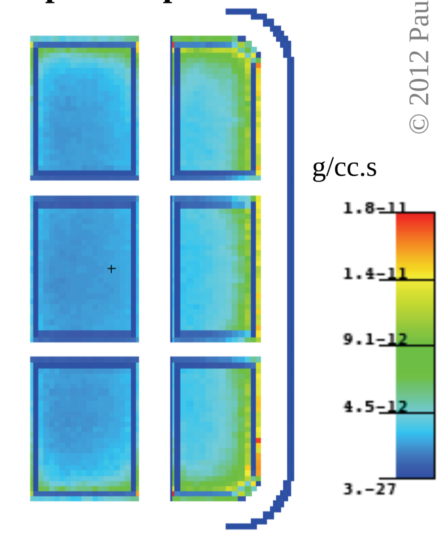
Capability for Coupled CAD & Neutronics Greatly Facilitates Detailed 3-D Analysis

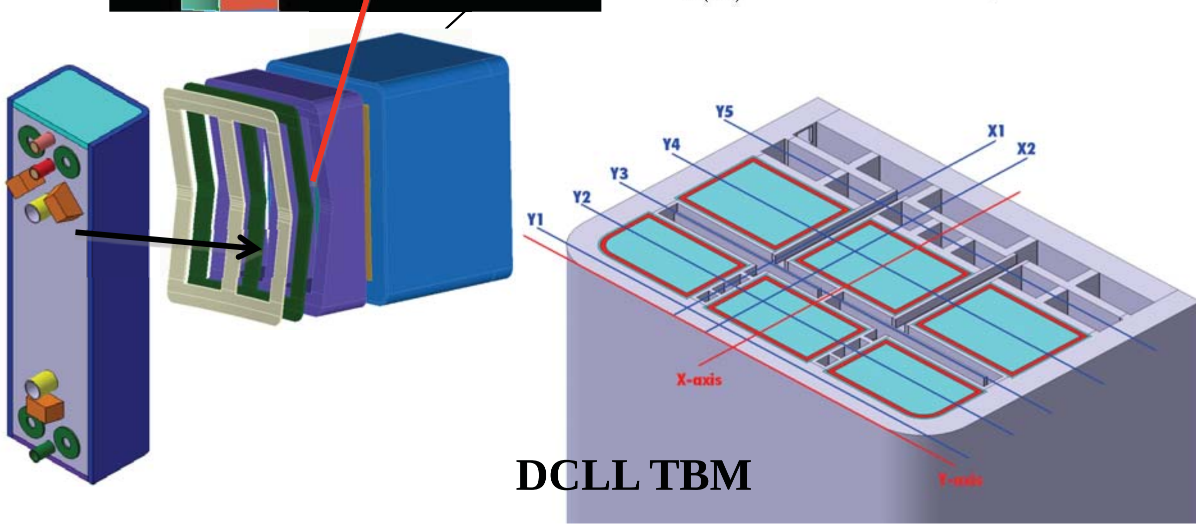


Mid-plane nuclear heating



Mid-plane T production





DCLL TBM

Steel damage at section X2

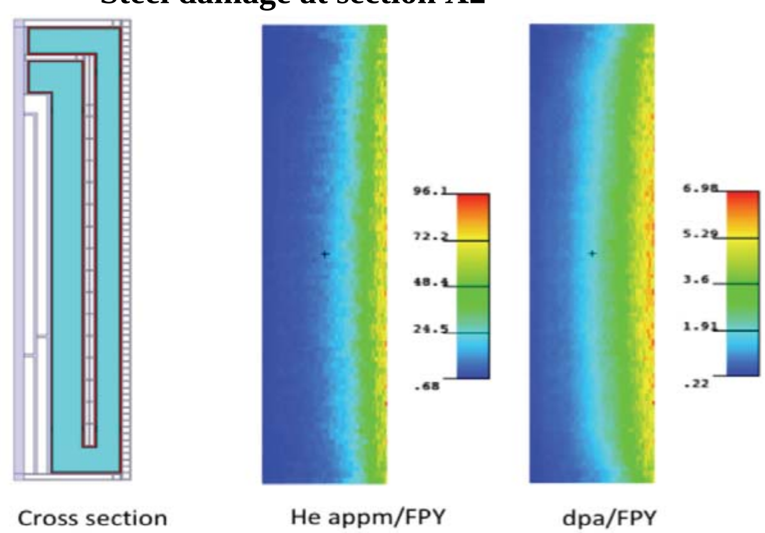
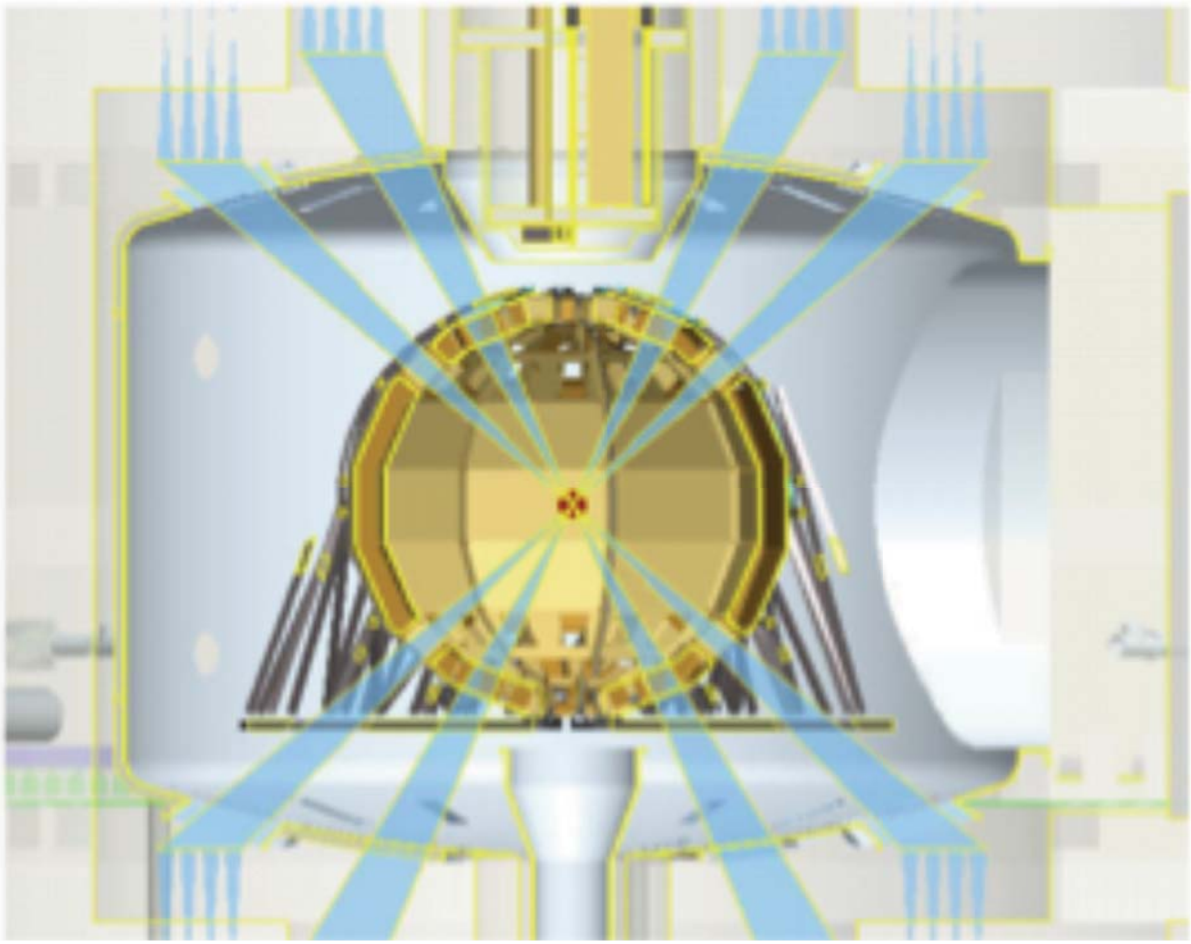


Illustration of Laser Inertial Fusion Energy (LIFE) Reactor Design

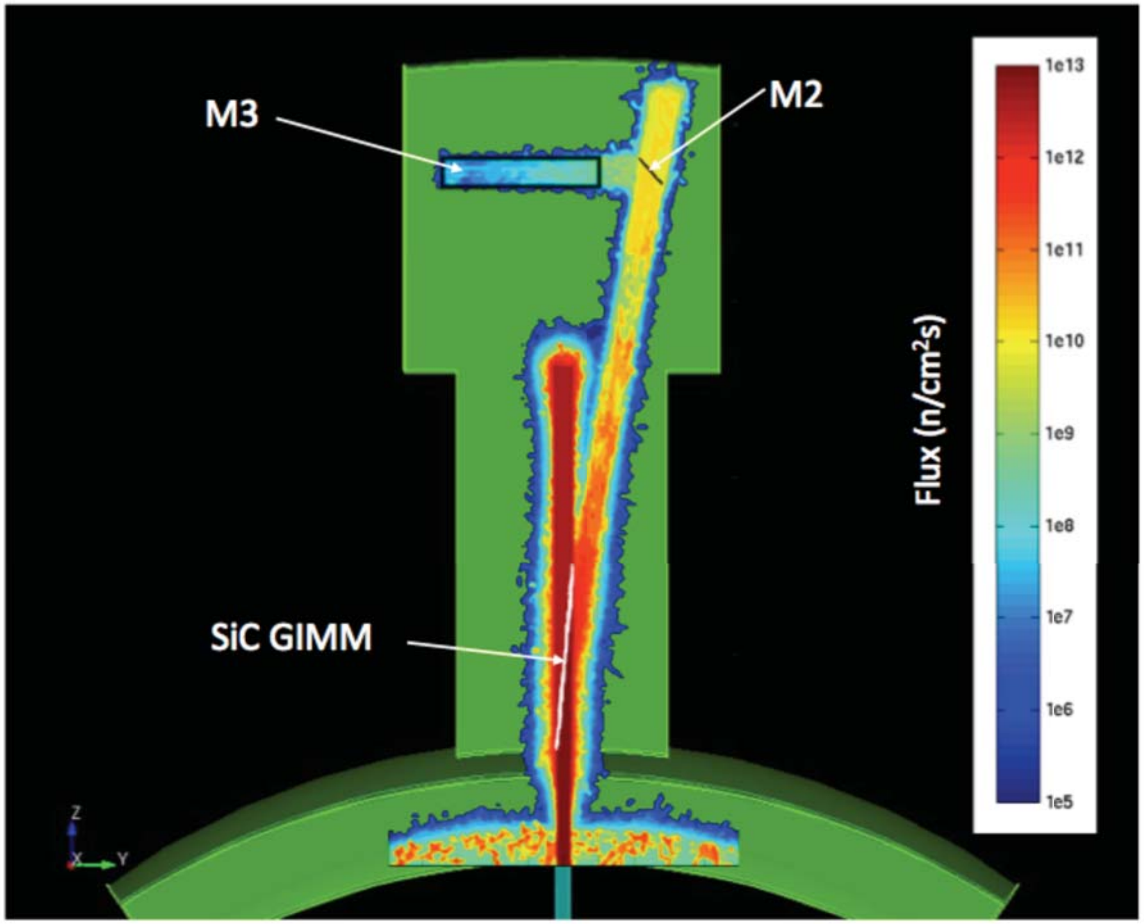
LIFE



Inside NIF target chamber

HAPL Final Optics Shielding Challenges Neutronics Analysis

Fast Neutron Flux Distribution in Final Optics of HAPL



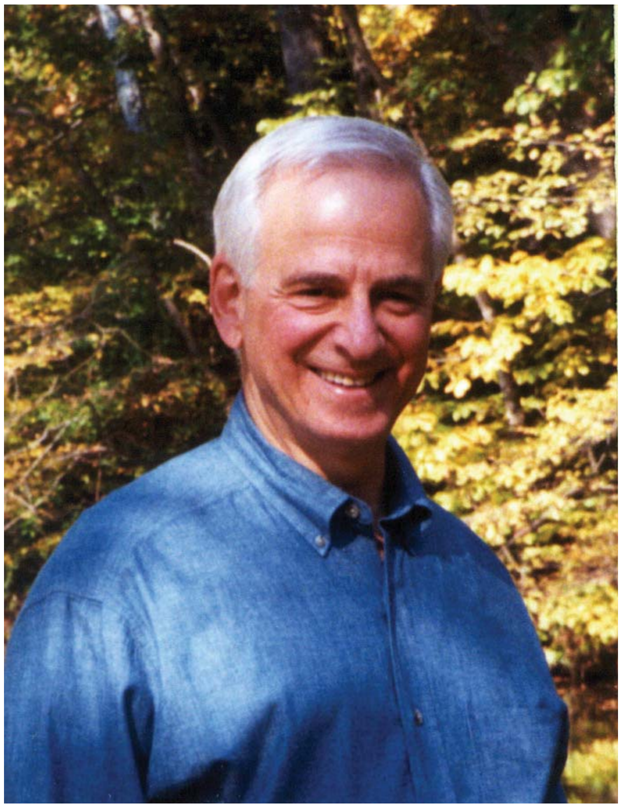
Inertial Electrostatic Confinement Devices First Introduced by Lavrentyev and Farnsworth in the Late 1950s

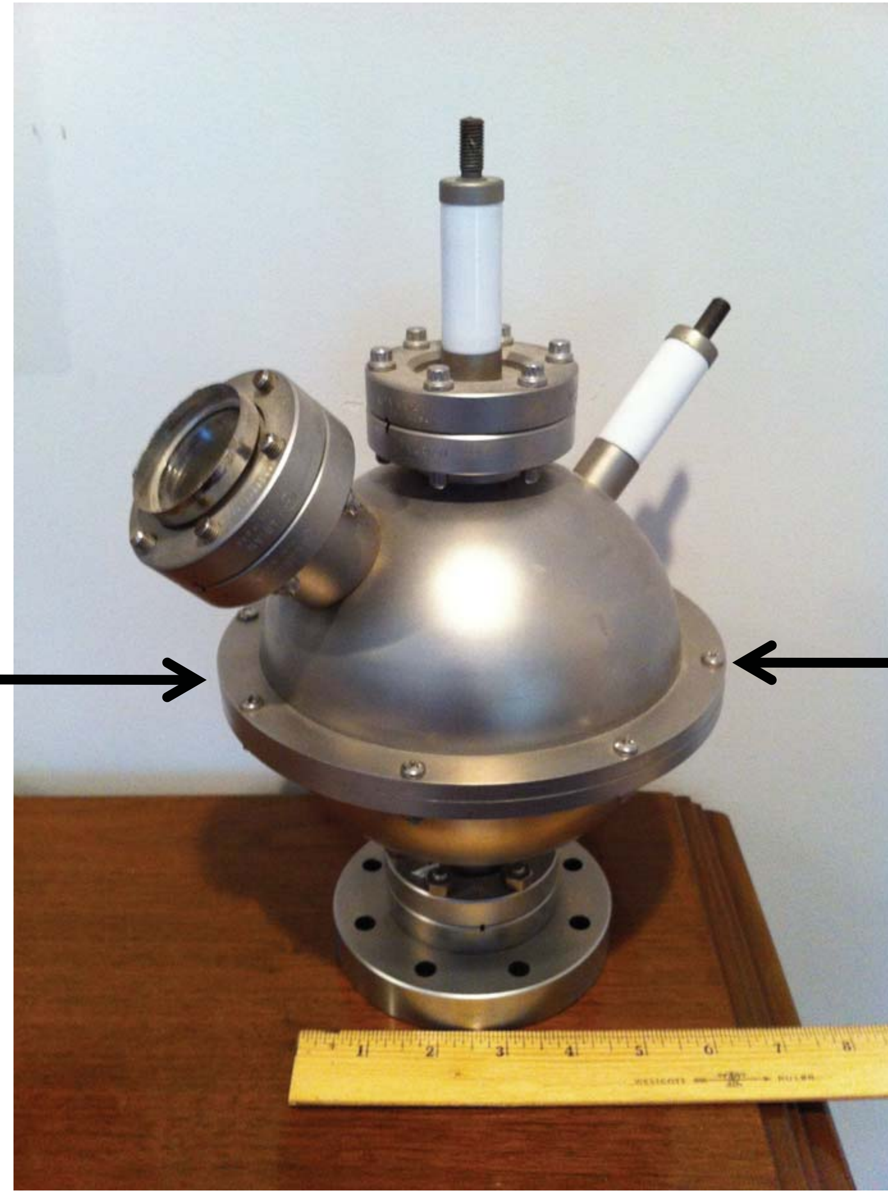
Lavrentyev

Farnsworth

After T. Dolan

Robert Hirsch Reported High Neutron Production Rates in the First Ion IEC Device in 1968 at ITT-Farnsworth in Indianapolis, IN





20 cm

Convergence, electrostatic potential, and density measurements in a spherically convergent ion focus

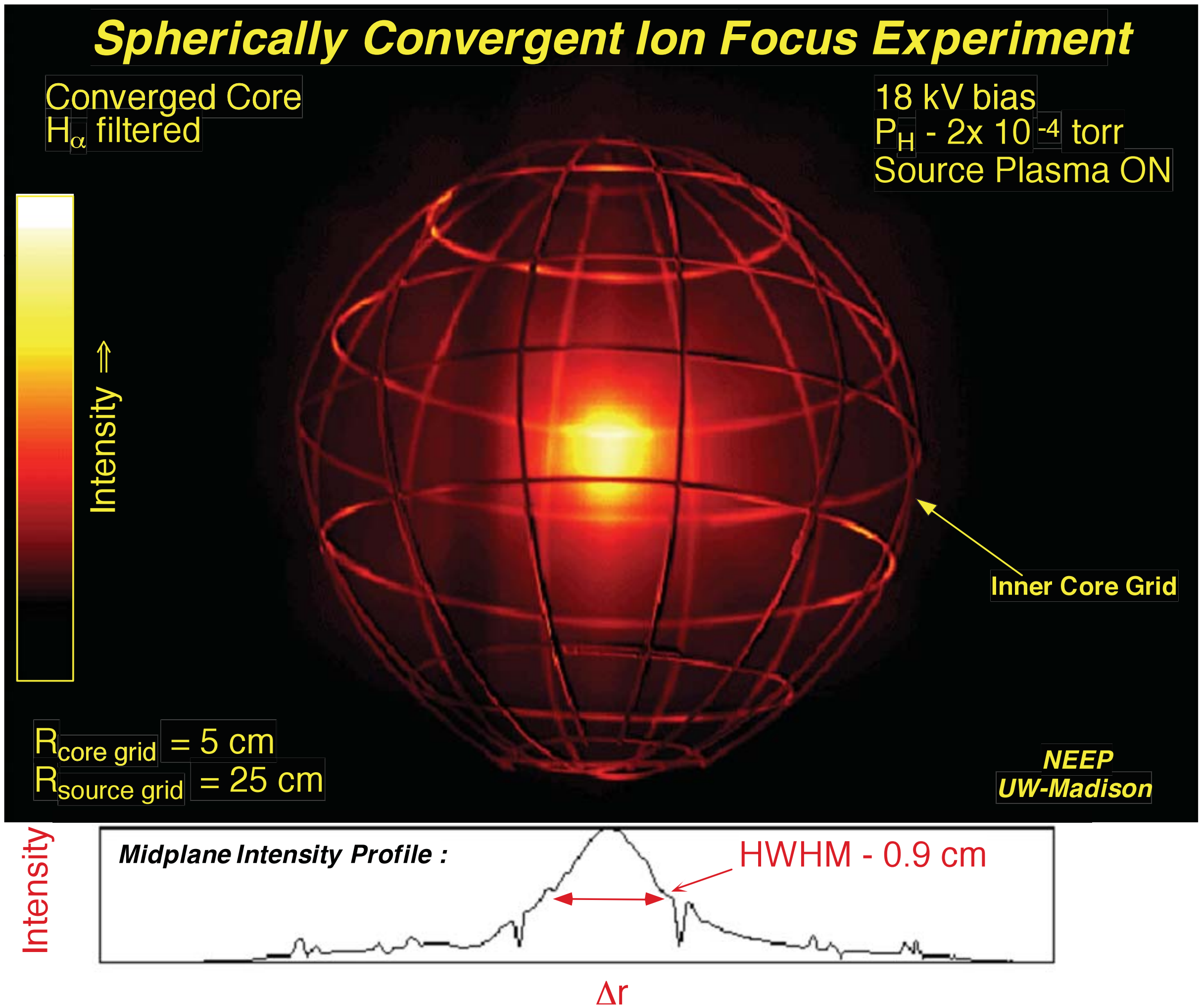
T. A. Thorson,[a] R. D. Durst, R. J. Fonck, and L. P. Wainwright
University of Wisconsin—Madison, 1500 Engineering Drive, Madison, Wisconsin 53706

Phys. Plasmas **4** (1), January 1997

FUSION REACTIVITY CHARACTERIZATION OF A SPHERICALLY CONVERGENT ION FOCUS

T.A. THORSON, R.D. DURST, R.J. FONCK, A.C. SONTAG
University of Wisconsin-Madison,

NUCLEAR FUSION, Vol. 38, No. 4 (1998)



ION FLOW AND FUSION REACTIVITY CHARACTERIZATION OF A SPHERICALLY CONVERGENT ION FOCUS

by

Timothy A. Thorson

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

(Nuclear Engineering and Engineering Physics)

at the

UNIVERSITY OF WISCONSIN - MADISON

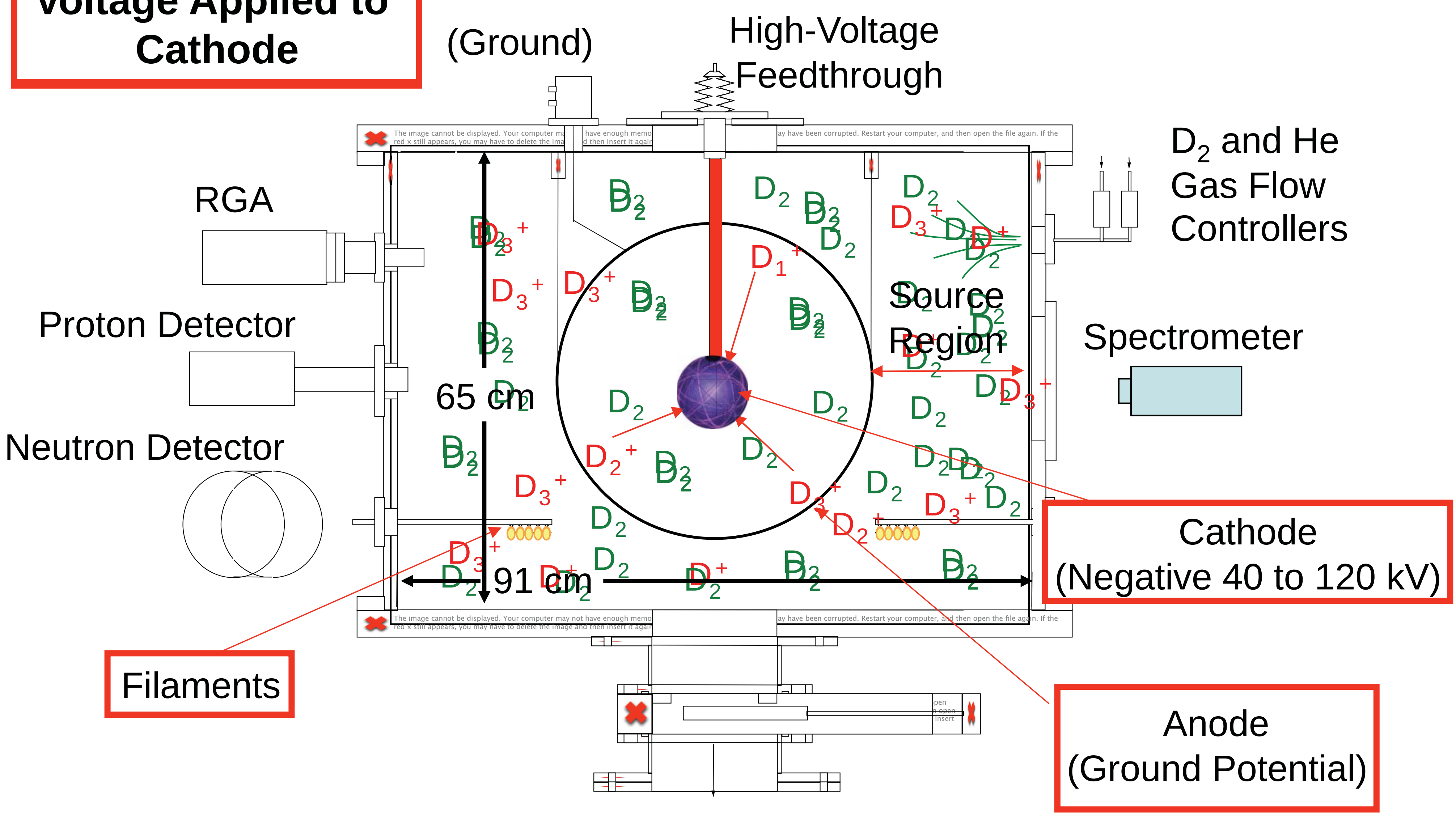
1996

University of Wisconsin IEC Team

New students 2012

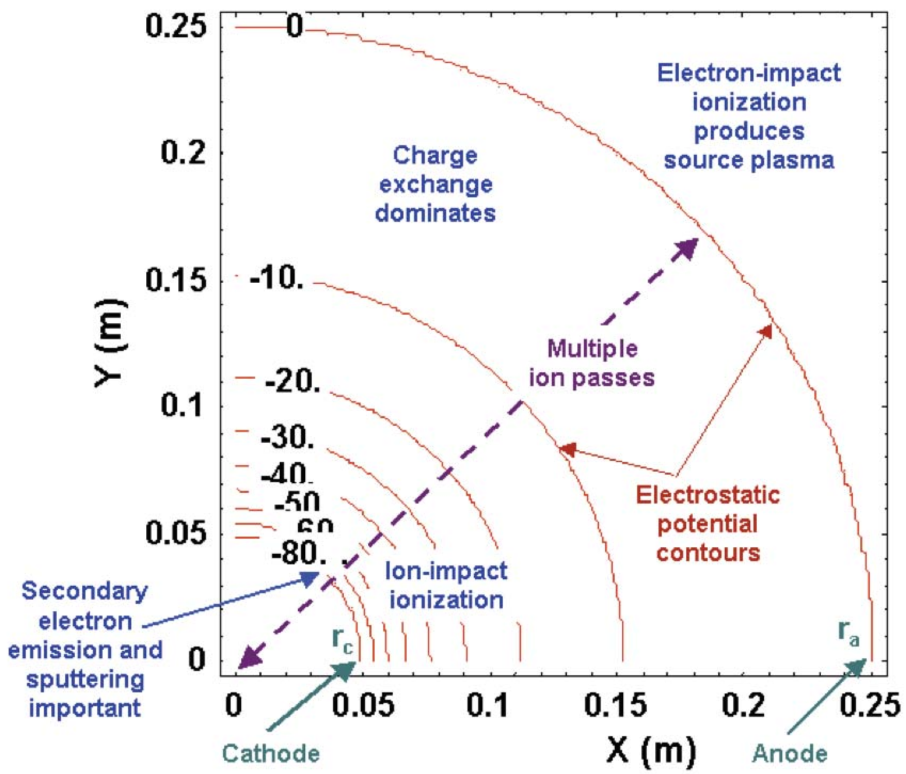
Operation of Inertial-Electrostatic Confinement Fusion Device HOMER

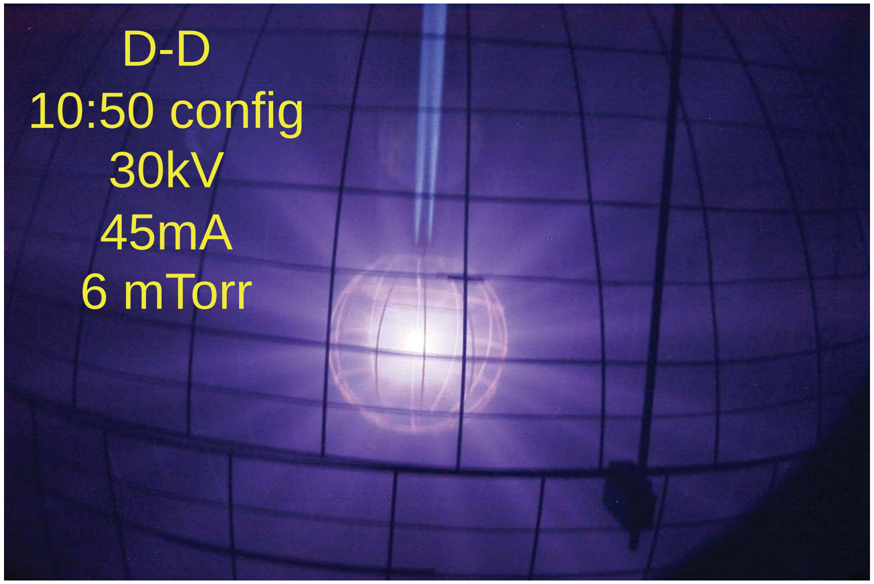
Voltage Applied to Cathode



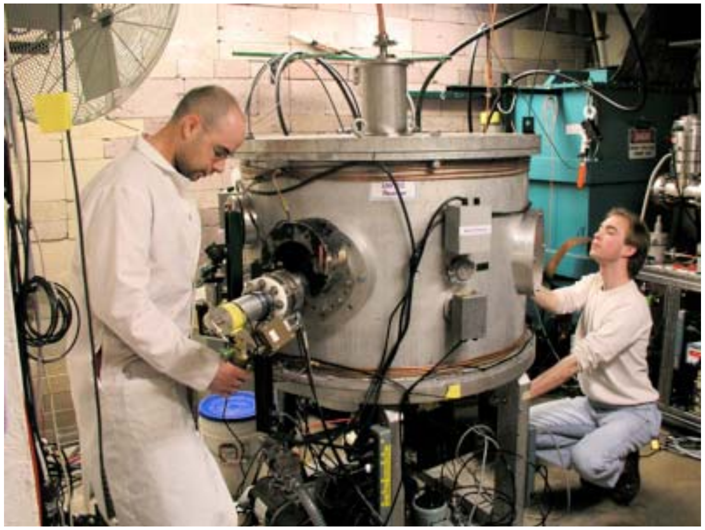
Gridded IEC Concept: a Large Voltage Difference between Nearly Transparent Grids Accelerates Ions through a Background Gas

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

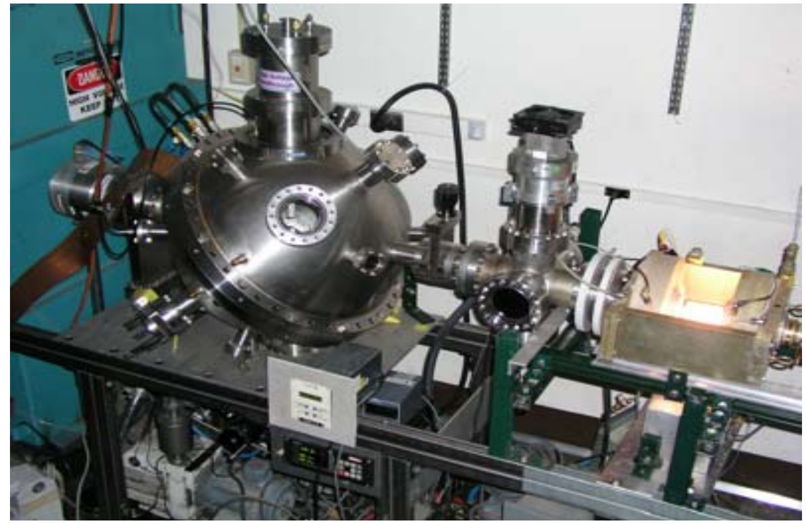




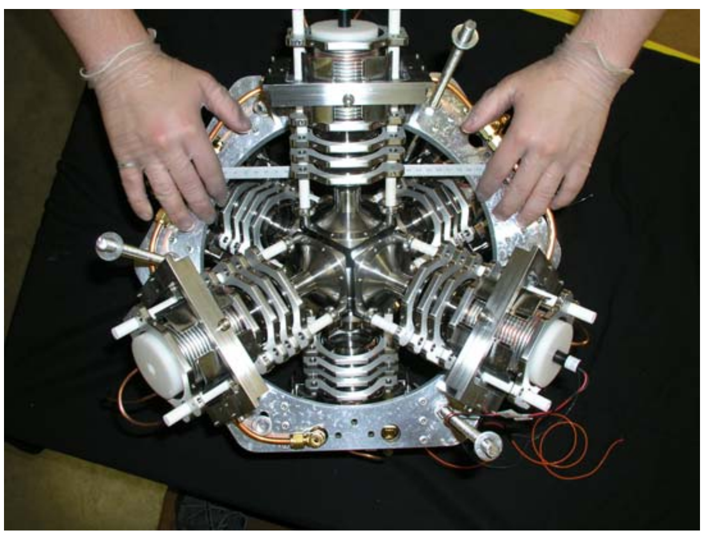
Four IEC Chambers Presently Operate at UW



HOMER



HELIOS & helicon ion source



SIGFE

MITE-E (ion gun irradiation facility)

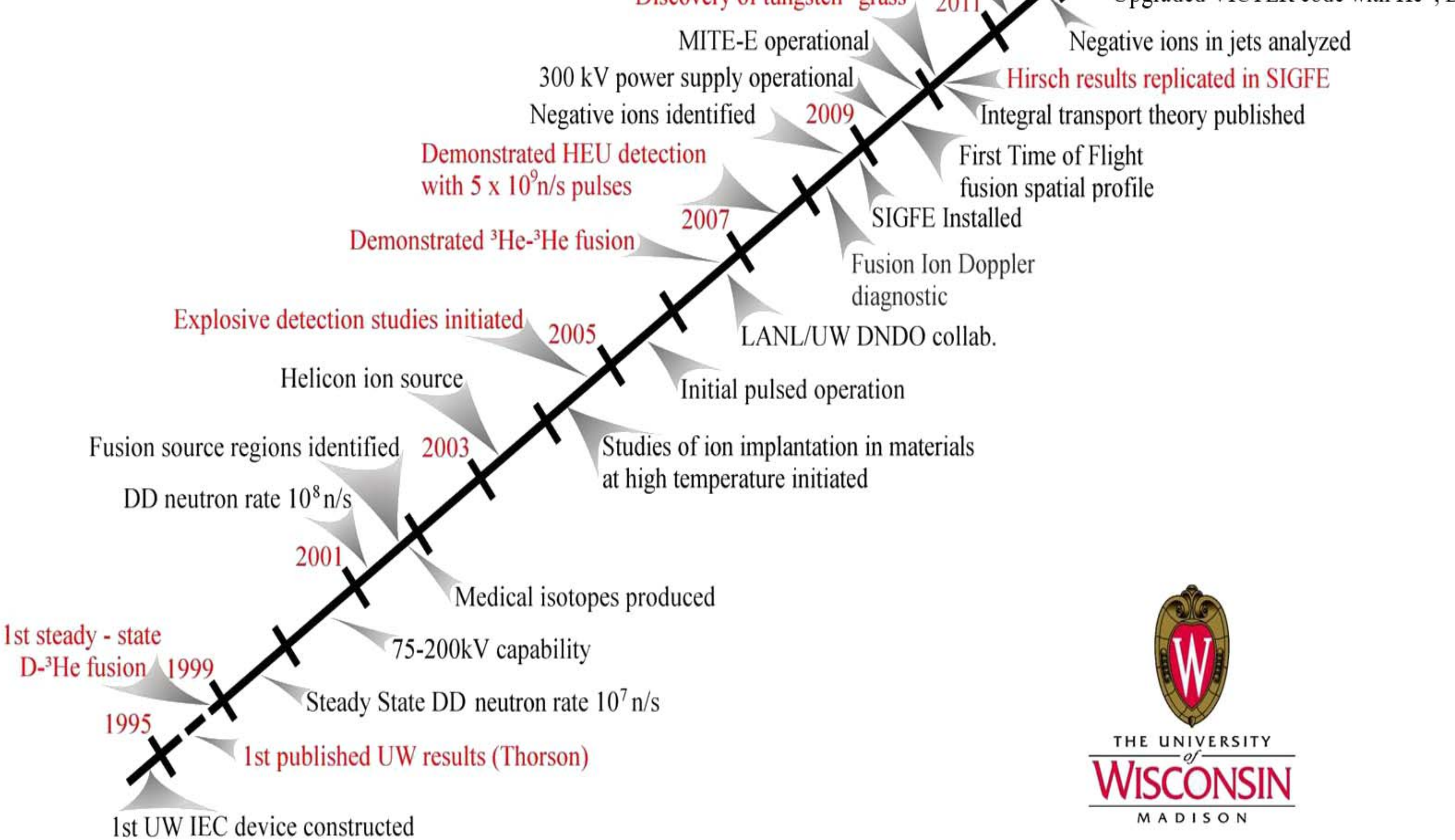
Objectives of UW IEC Research

1. Optimize fusion reaction rates in an IEC device:
   a. 2.45 MeV neutrons from D-D
   b. 14.7 MeV protons from D-^{3}He
2. Use fusion-product neutrons and protons for applications, such as:
   a. detecting clandestine materials, and
   b. creating radioisotopes for nuclear medicine.
3. Understand and optimize gridded IEC device physics and engineering.

Summary of UW IEC Capabilities

- Operate four IEC chambers with various geometries and operating conditions.
  - 300 kV, 200 mA power supply
  - D_2, H_2, ^3He, and/or ^4He
  - Pulsed or steady-state
- Build high-voltage stalks and feed-throughs.
- Measure neutrons, protons, neutral gas, material temperatures, and fusion reaction locations.
- Possess low-noise, fast (MHz) diagnostics.
- Theoretically model IEC experiments with reasonable accuracy.

The University of Wisconsin IEC program is 18 years Old



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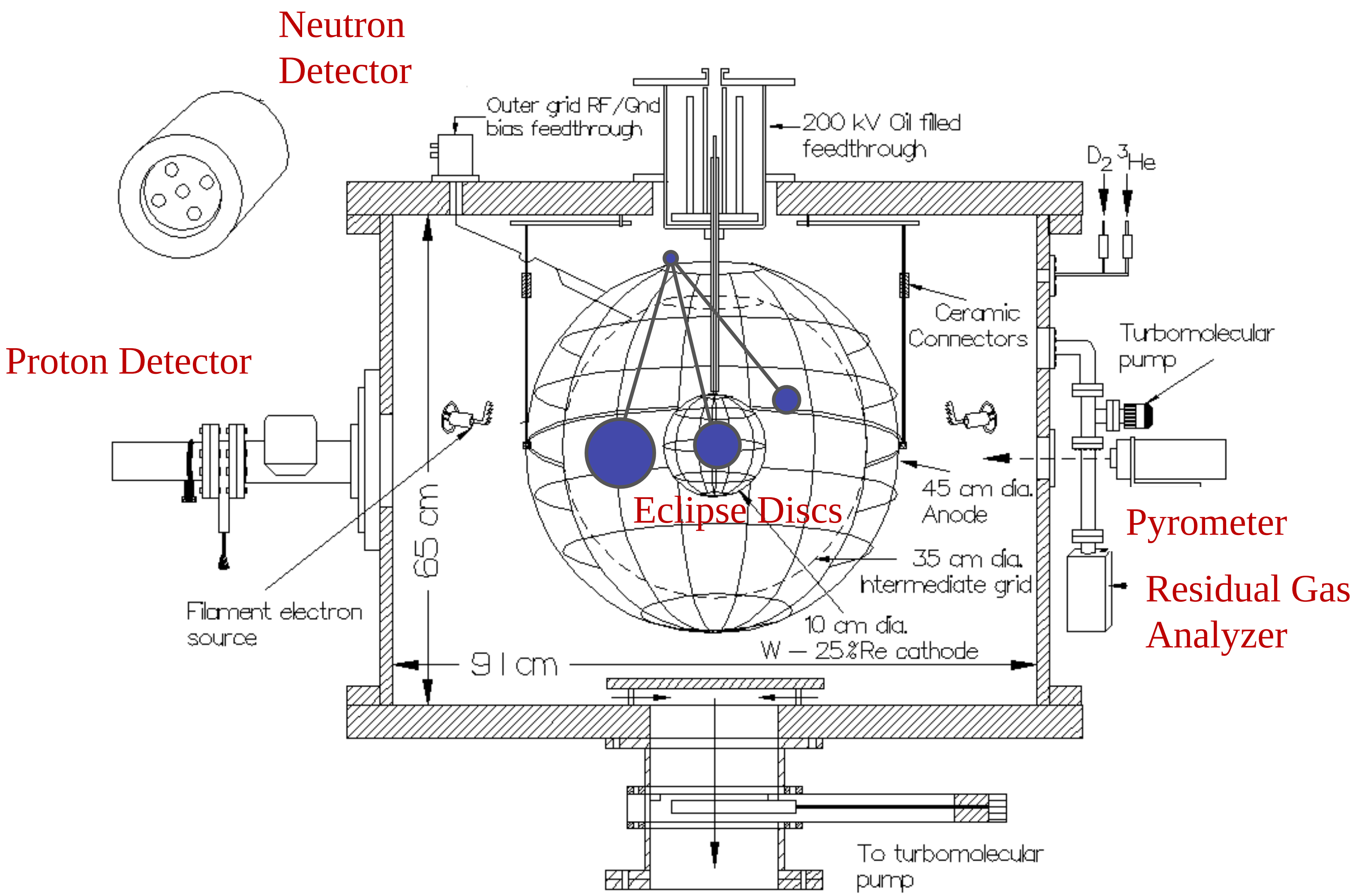
Diagnostics Measure Neutron and Proton Production, Gas Properties, and Material Temperatures

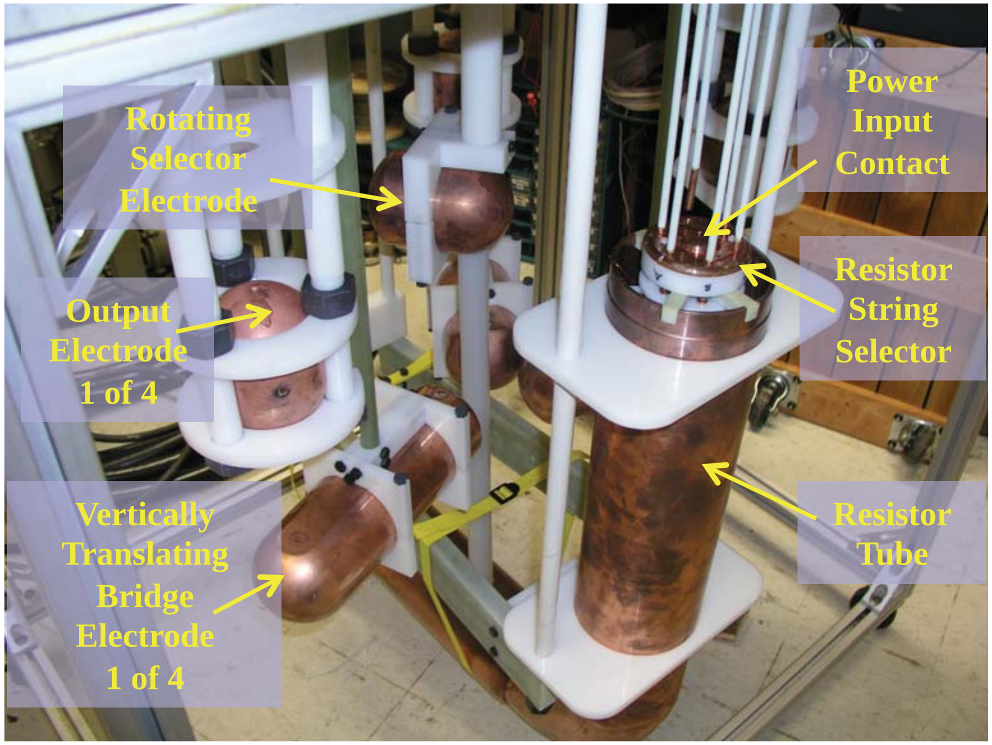


UW's New Power Supply Will Increase Fusion Product Production Rates and Expand IEC Parameter Regimes

PHOENIX NUCLEAR LABS
PROVIDING NUCLEAR TECHNOLOGY FOR THE BETTERMENT OF HUMANITY
info@phoenixnuclearlabs.com 608-210-3060

UW PhD Greg Piefer and his Phoenix Nuclear Labs LLC designed and built this power supply that provides 300 kV at 200 mA with sophisticated arc protection control.

Rich Bonomo and the IEC students designed and constructed a high-voltage switch for changing connections between power supply and IEC devices quickly.



System of power supply, switch, and IEC devices being connected and tested for operation in 2013

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

Key Fusion Fuels

1st 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}

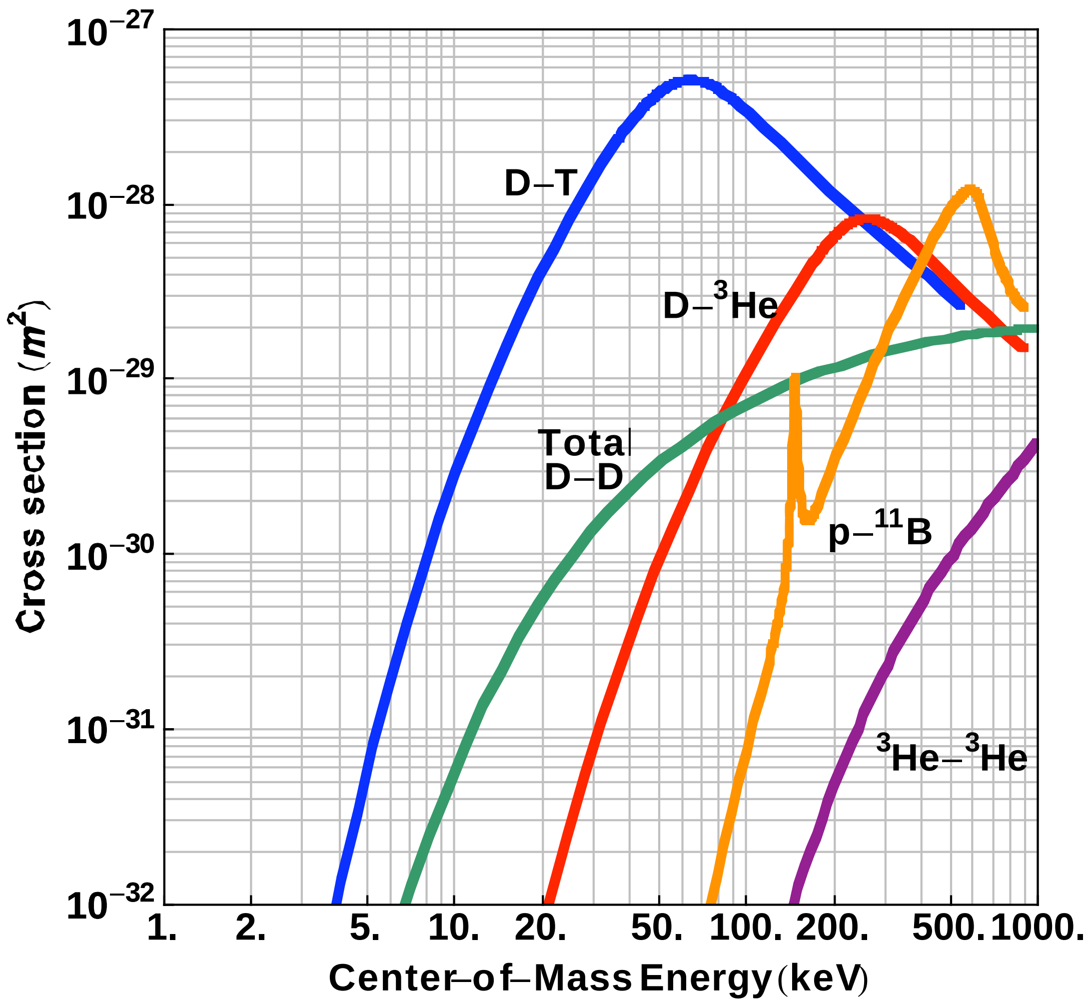
2nd Generation

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

3rd Generation

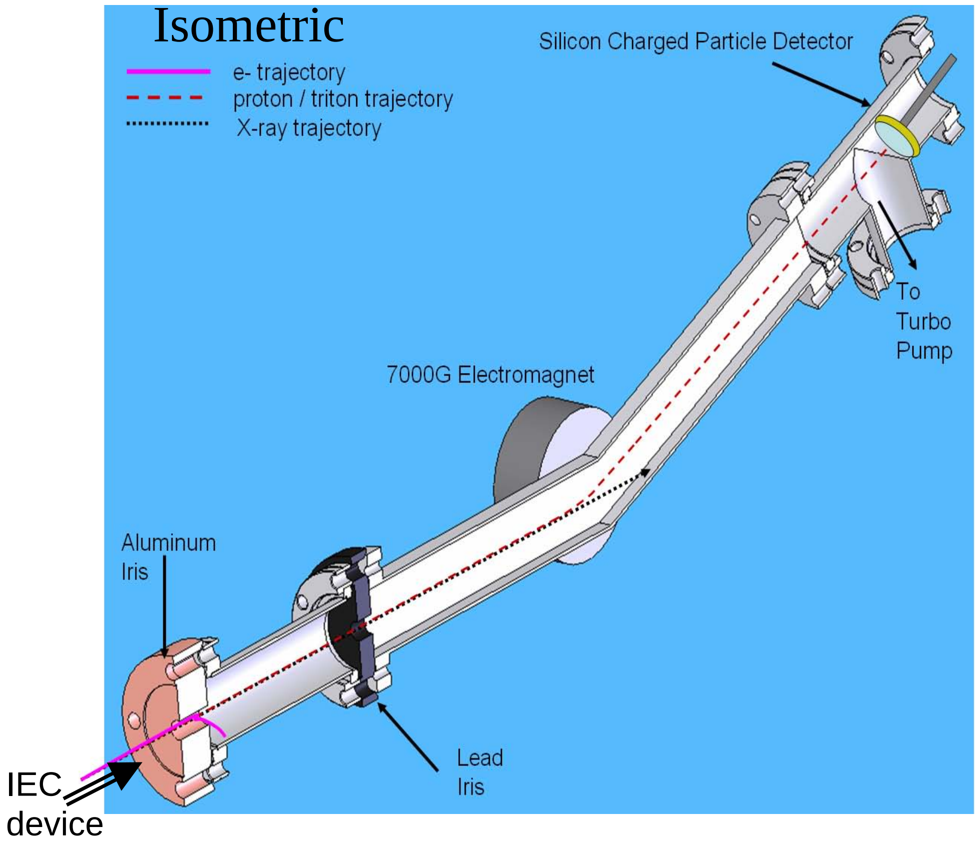
p + ^{11}B → 3 ^{4}He (8.68 MeV)

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

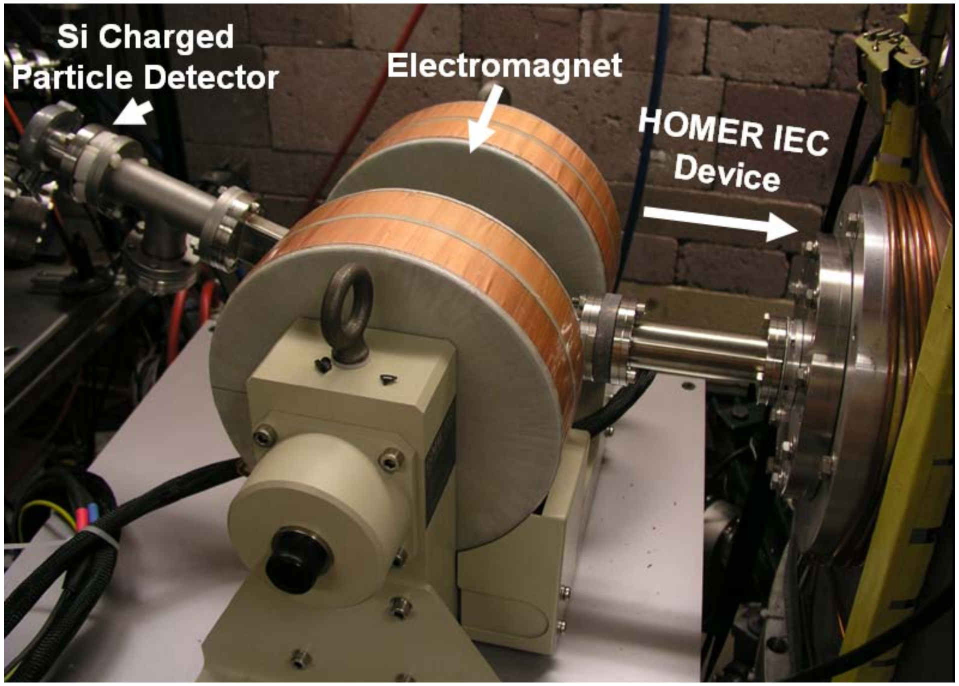


UW PhD Student Dave Boris Led the Development of the FIDO Charged-Particle Detection System

FIDO diagnostic schematic

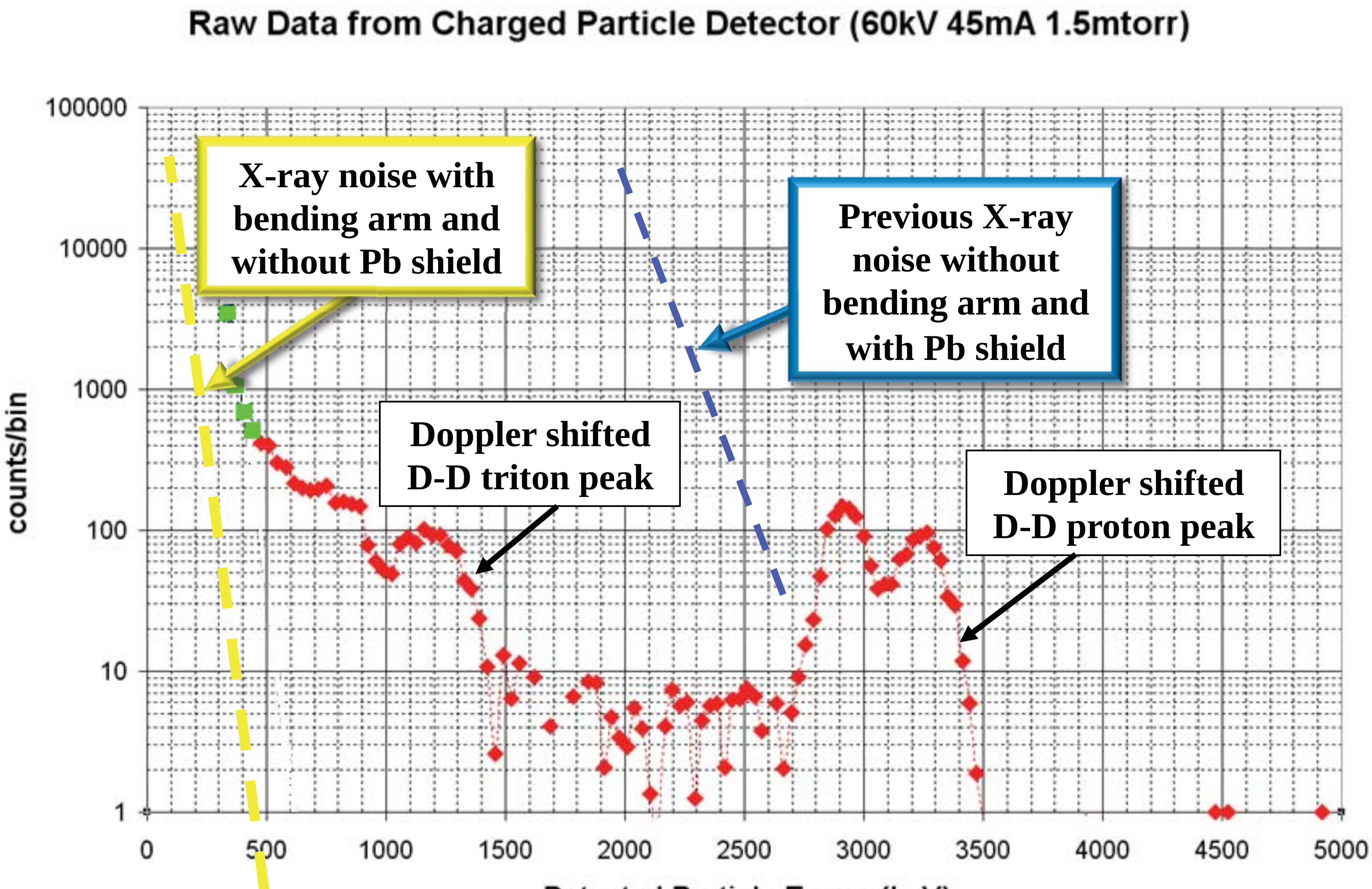


- Fusion Ion Doppler shift diagnostic (FIDO) bends charged particles into a Si proton detector.
- Greatly reduces bremsstrahlung x-ray noise.
- Works for fusion products and positive or negative ions.

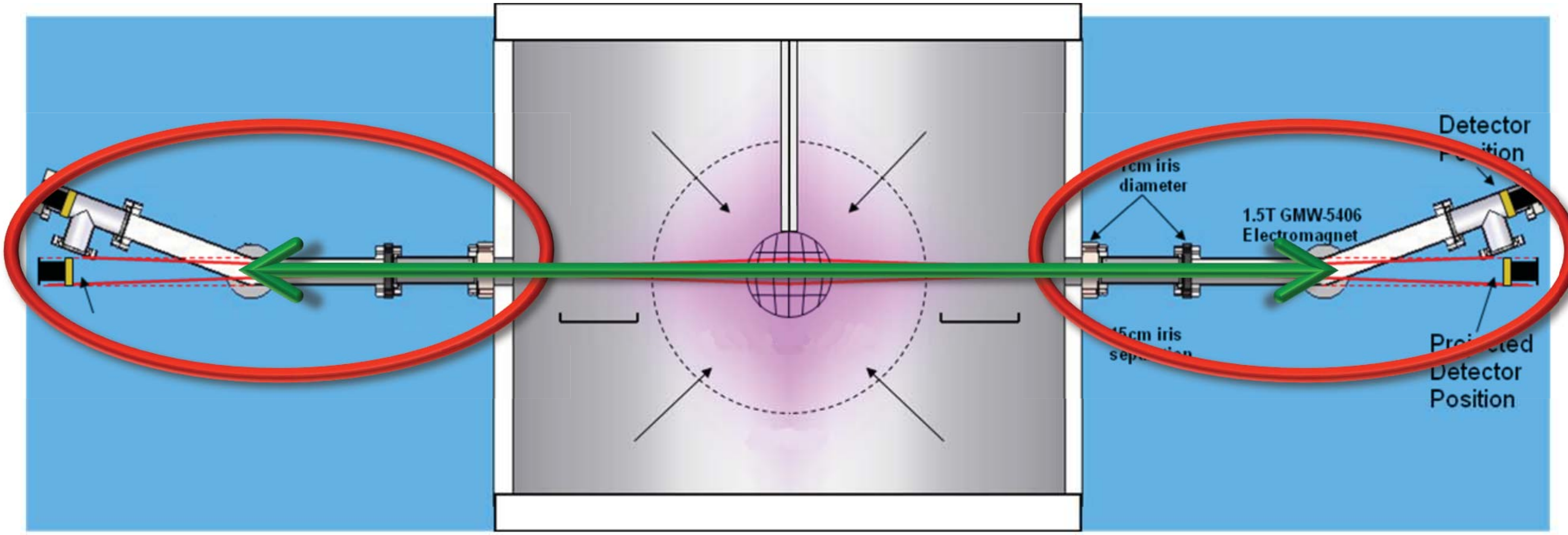


- D.R. Boris, G.L. Kulcinski, J.F. Santarius, D.C. Donovan, and G.R. Piefer, "Measuring D(d,p)T Fusion Reactant Energy Spectra with Doppler Shifted Fusion Products," *Journal of Applied Physics* **107**, 123305 (2010).

FIDO Bending Arm Allows both Protons and Tritons to be Detected

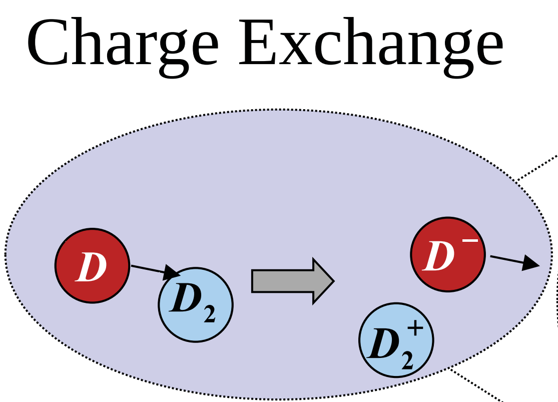


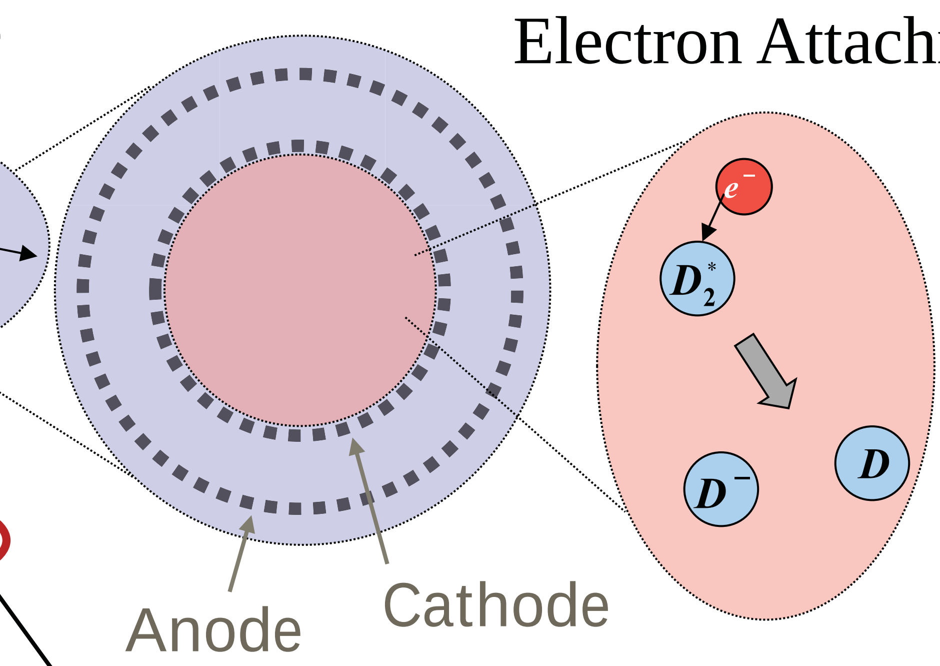
Time Of Flight (TOF) Diagnostic Uses Two FIDO Arms



- 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.
- D-D fusion creates a 3.02 MeV proton and 1.01 MeV triton, moving in opposite directions, that can be detected by coincidence counting.

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





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

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

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

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

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

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

Red denotes fast species

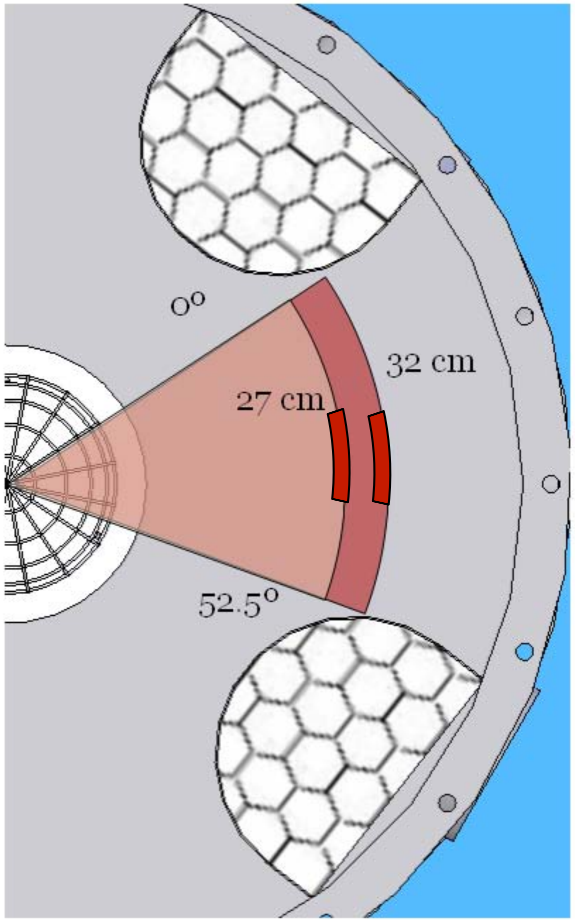
Most significant reaction

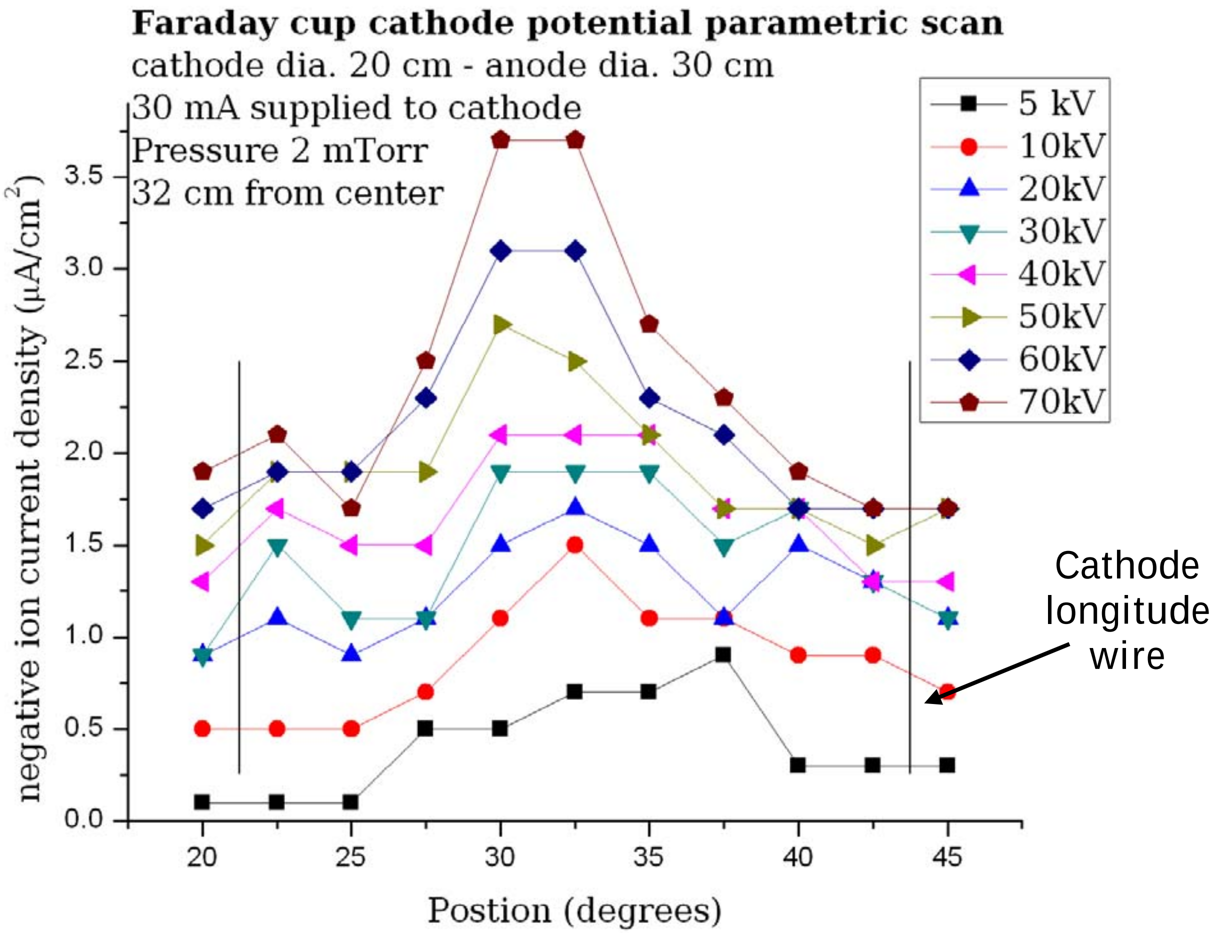
$$D_{2,(\nu)} + e^- \rightarrow D_2^- \rightarrow D^- + D$$

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

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).

Faraday Cup Measurements of Negative Ion Azimuthal Profiles Show Peaking at Jet Locations





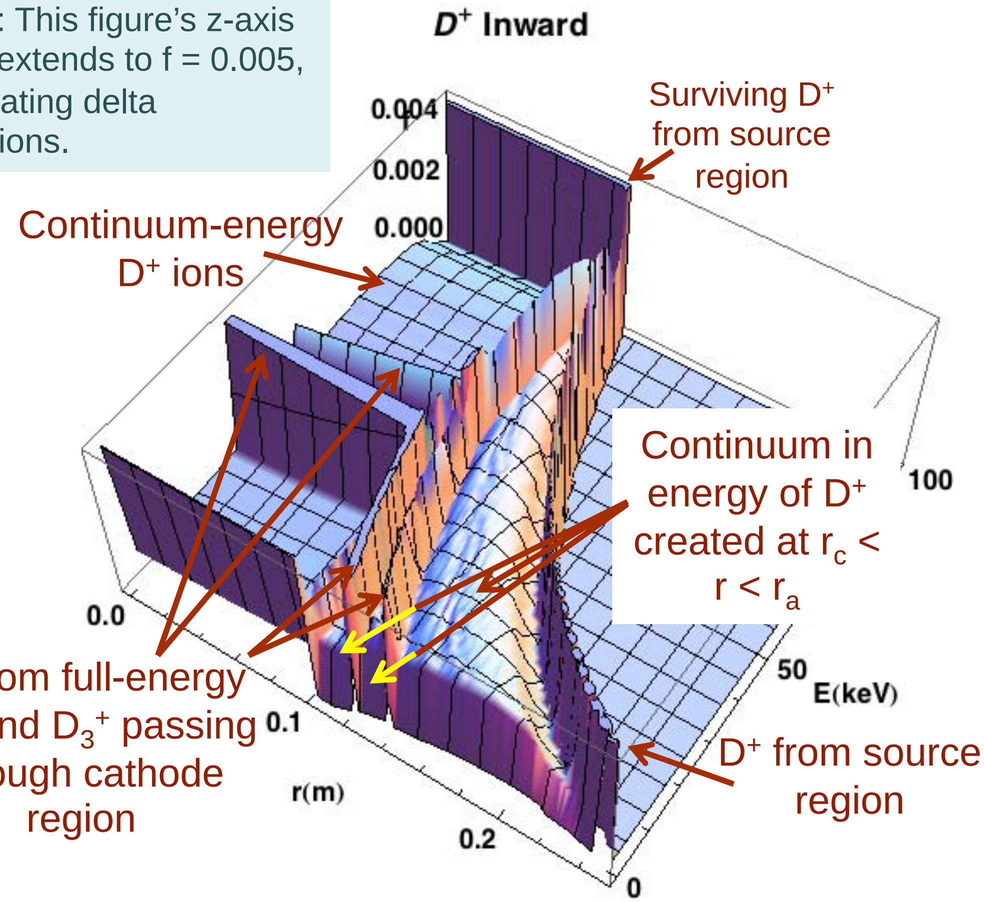
From Eric Alderson, *Experimental and Theoretical Characterization of Negative Deuterium Ion Distributions in a Gridded Inertial-Electrostatic Confinement Device*, UW PhD Thesis (2012).

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

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

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

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

Key Equations of VICTER and Comparison to Experiment

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

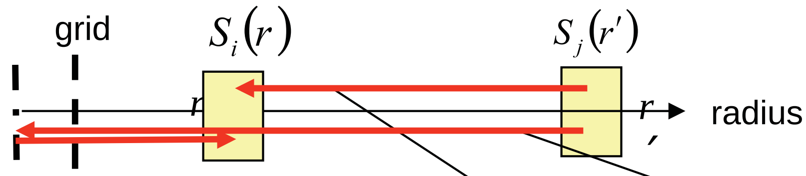
$$g(r,r') = \exp\left\{-\int_{r}^{r'} n_g \sigma_{cx}\left[E(r'')\right] dr''\right\}$$

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 $S(r)$:

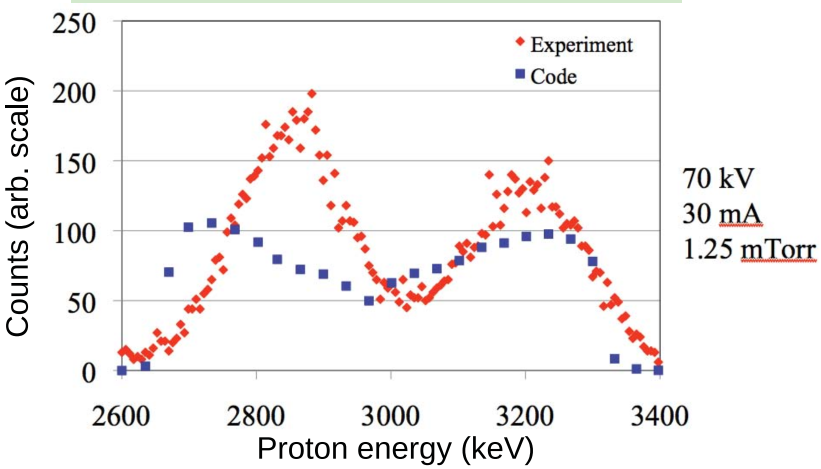


Slow Source contribution:

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

Gas density; Cross-section for producing *i* from *j*; Cathode transparency; Complete pass probability; Sum over passes

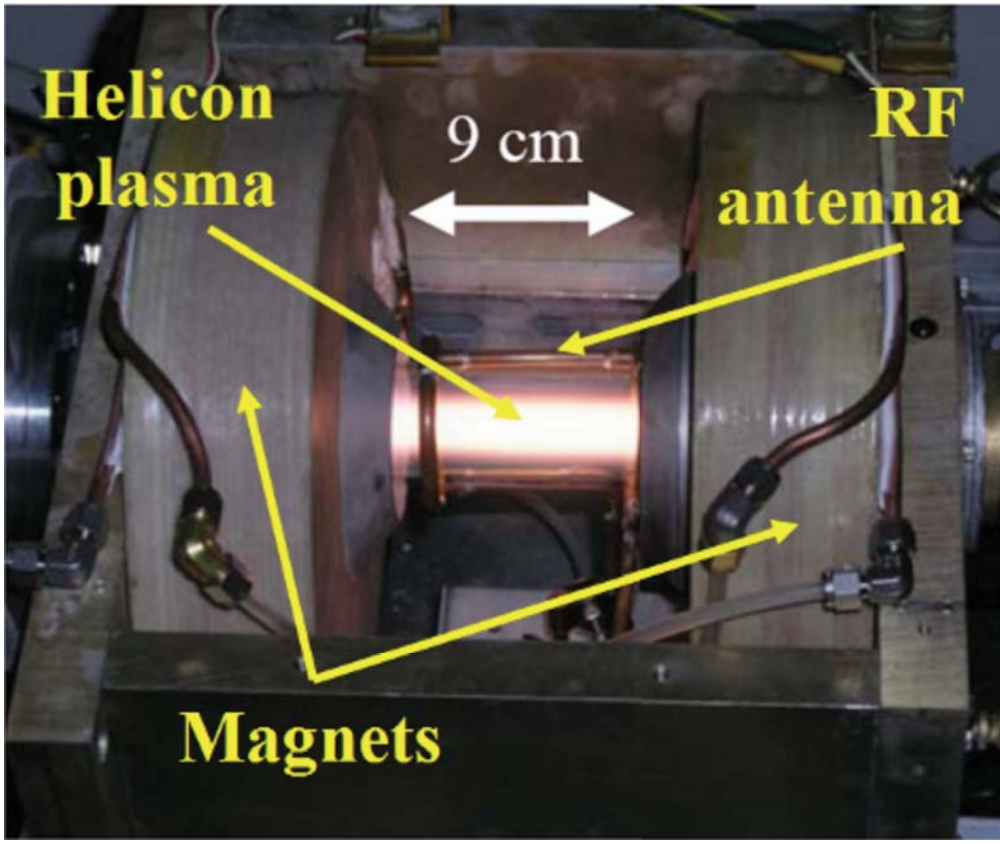
Comparison of theory and experiment

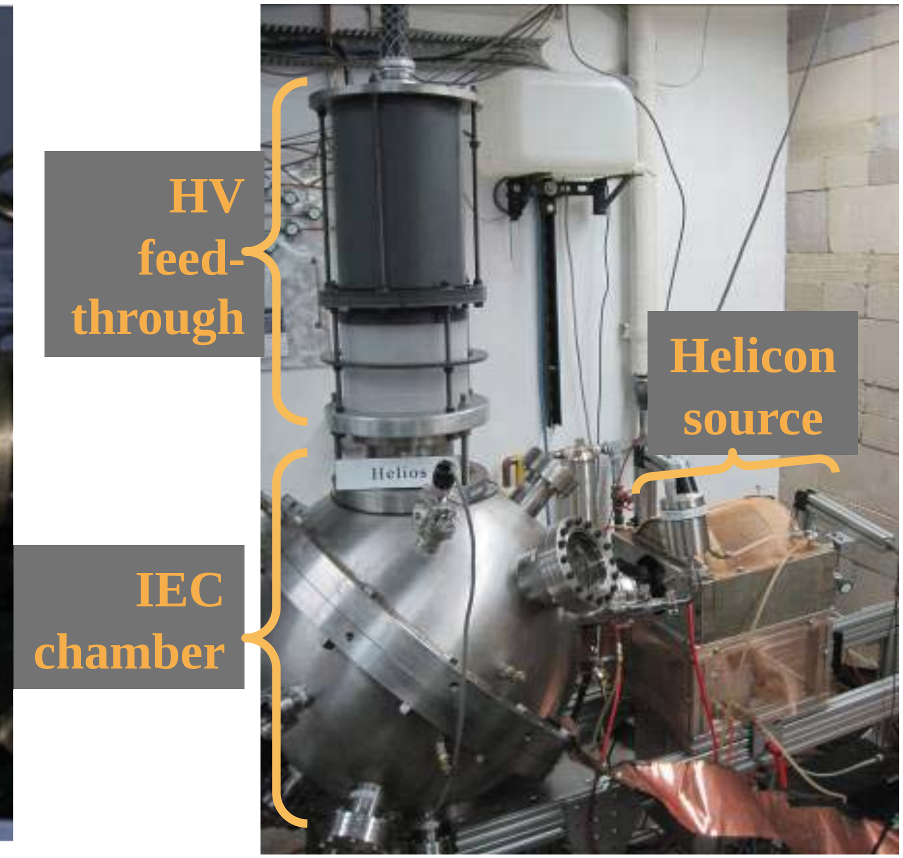


- Refs: G.A. Emmert and J.F. Santarius, “Atomic and Molecular Effects on Spherically Convergent Ion Flow I: Single Atomic Species” & “II: Multiple Molecular Species,” *Physics of Plasmas* **17**, 013502 & 013503 (2010).

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

Helicon Ion Source Operating with UW's Spherical IEC Chamber

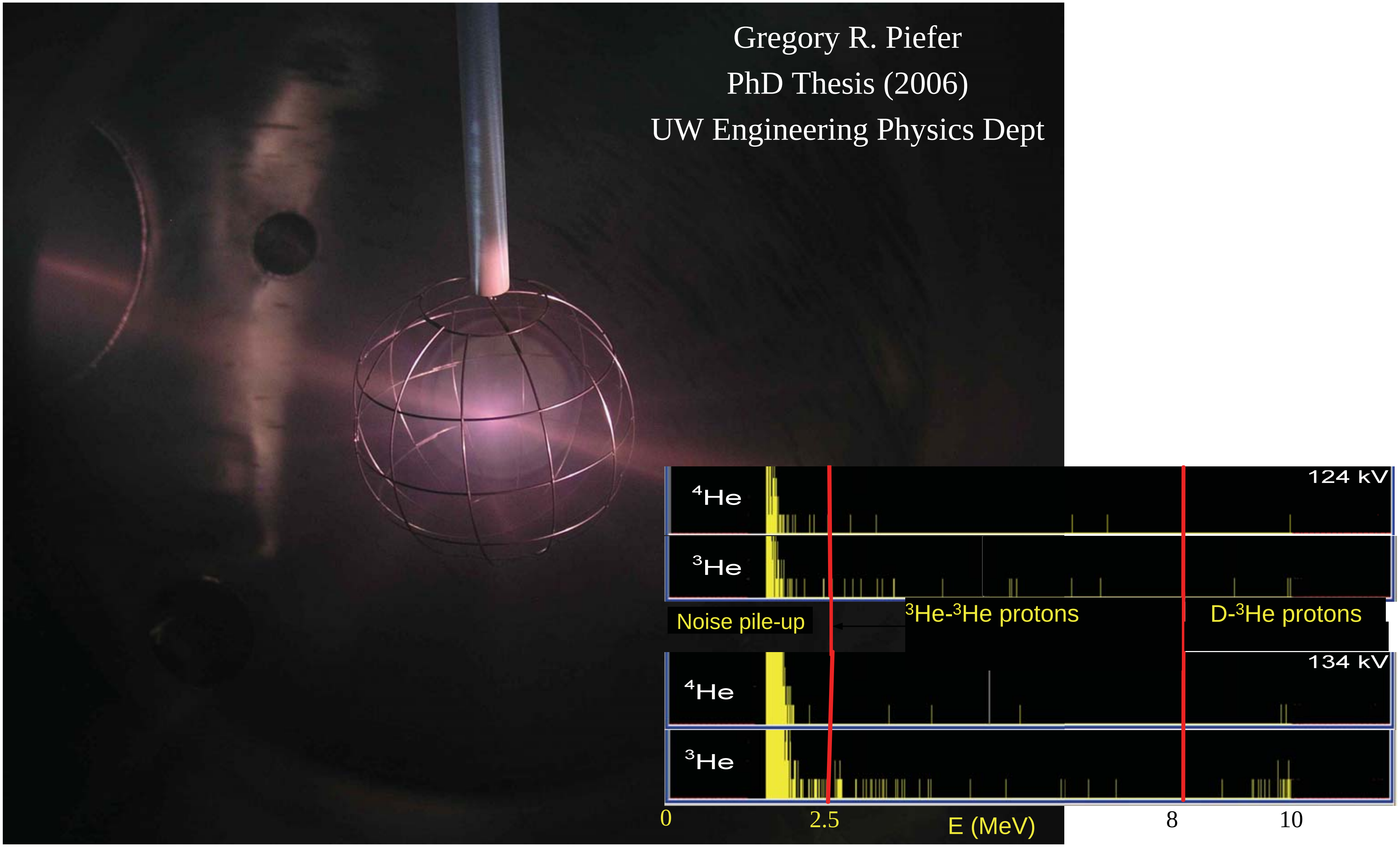




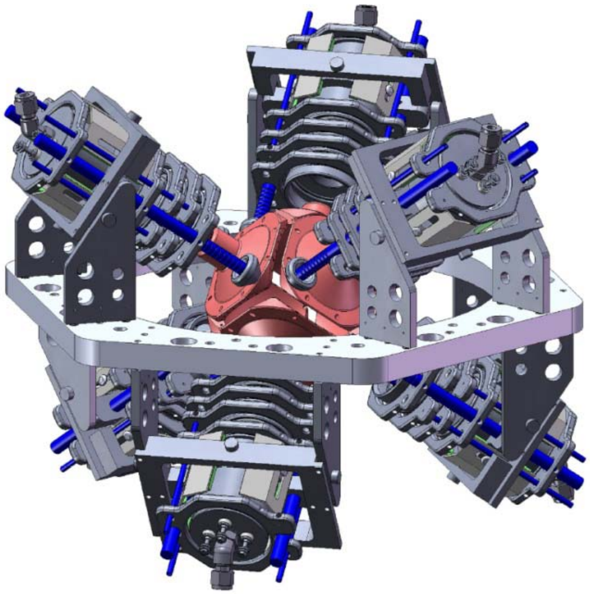
Figures courtesy of Gabriel Becerra.

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

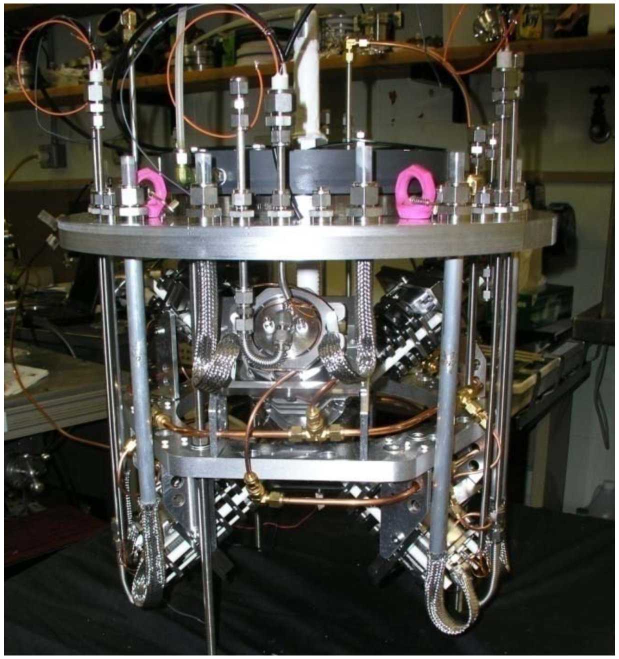
Gregory R. Piefer
PhD Thesis (2006)
UW Engineering Physics Dept



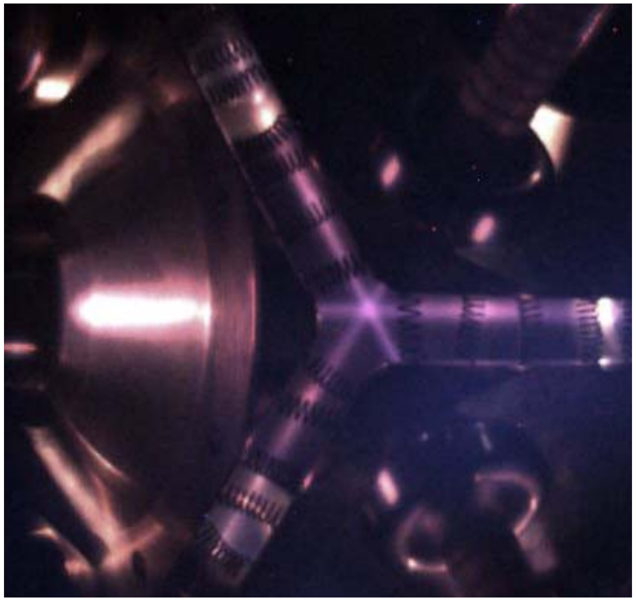
<u>S</u>ix <u>I</u>on <u>G</u>un <u>F</u>usion <u>E</u>xperiment (SIGFE)



December 2007



December 2008



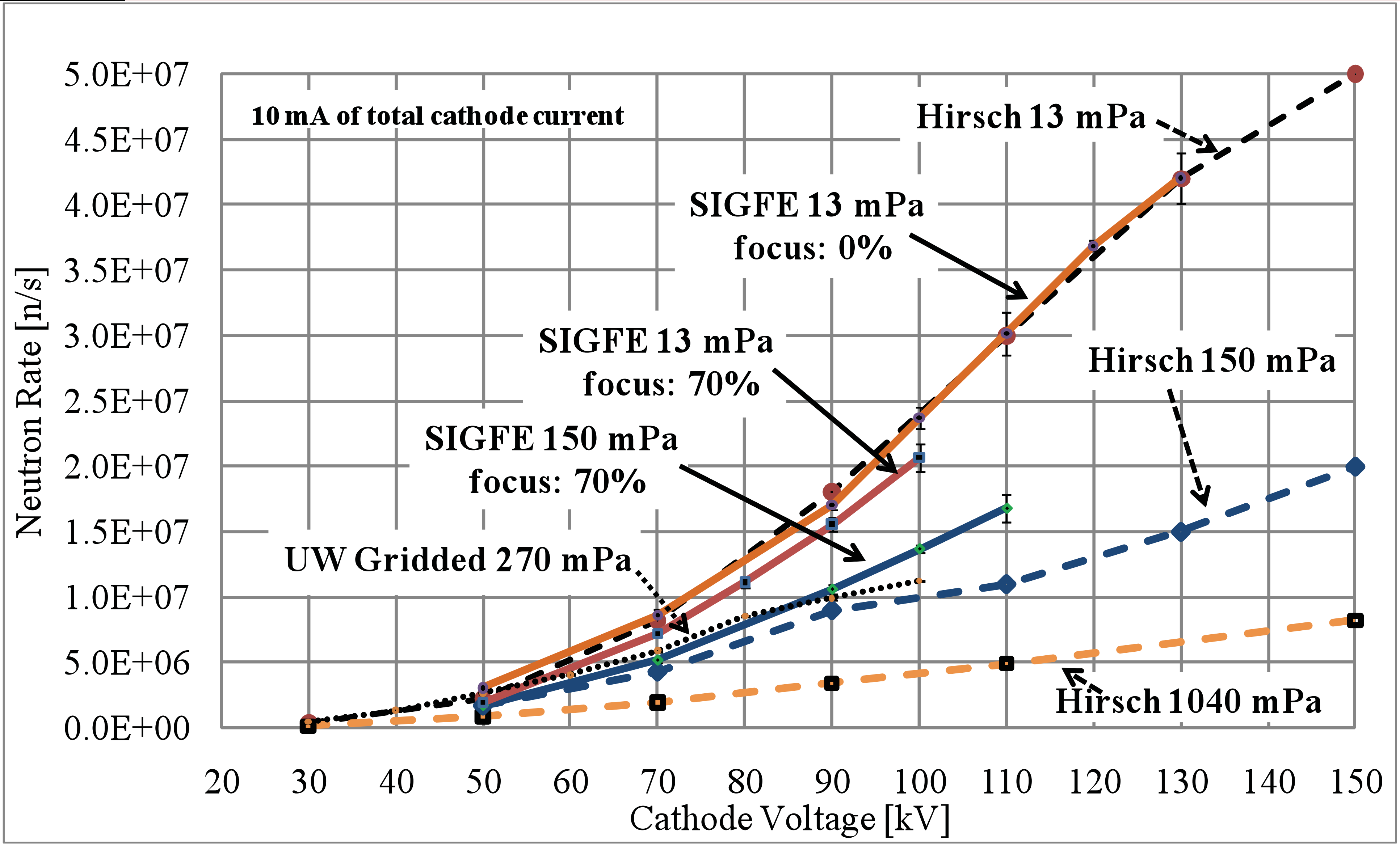
September 2009

<u>Project Goals:</u>

1) Increase D-D and D-^{3}He fusion rates for near term applications
2) Validate and extend the seminal 1967 experiments in Inertial Electrostatic Confinement (IEC)
3) Explore the plasma physics of converging ions

Slide from B. Egle

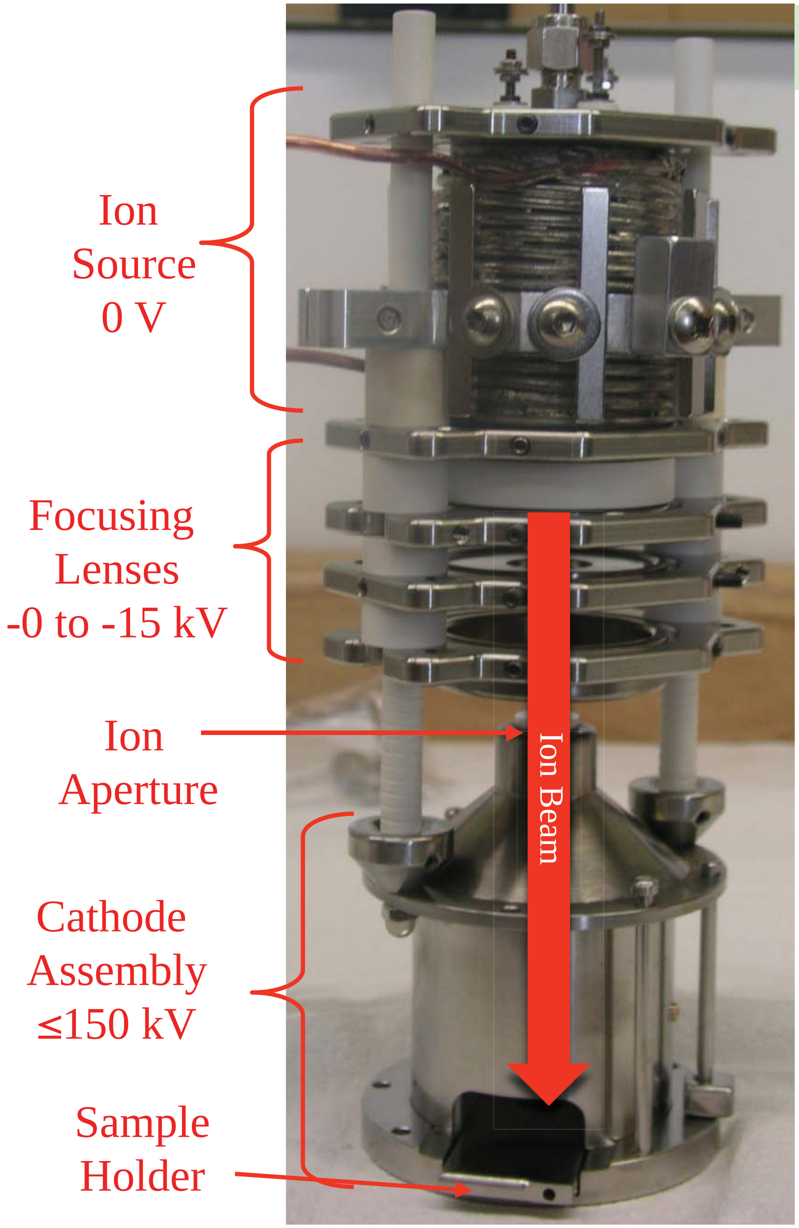
Defocused SIGFE matches Hirsch D-D neutron rates

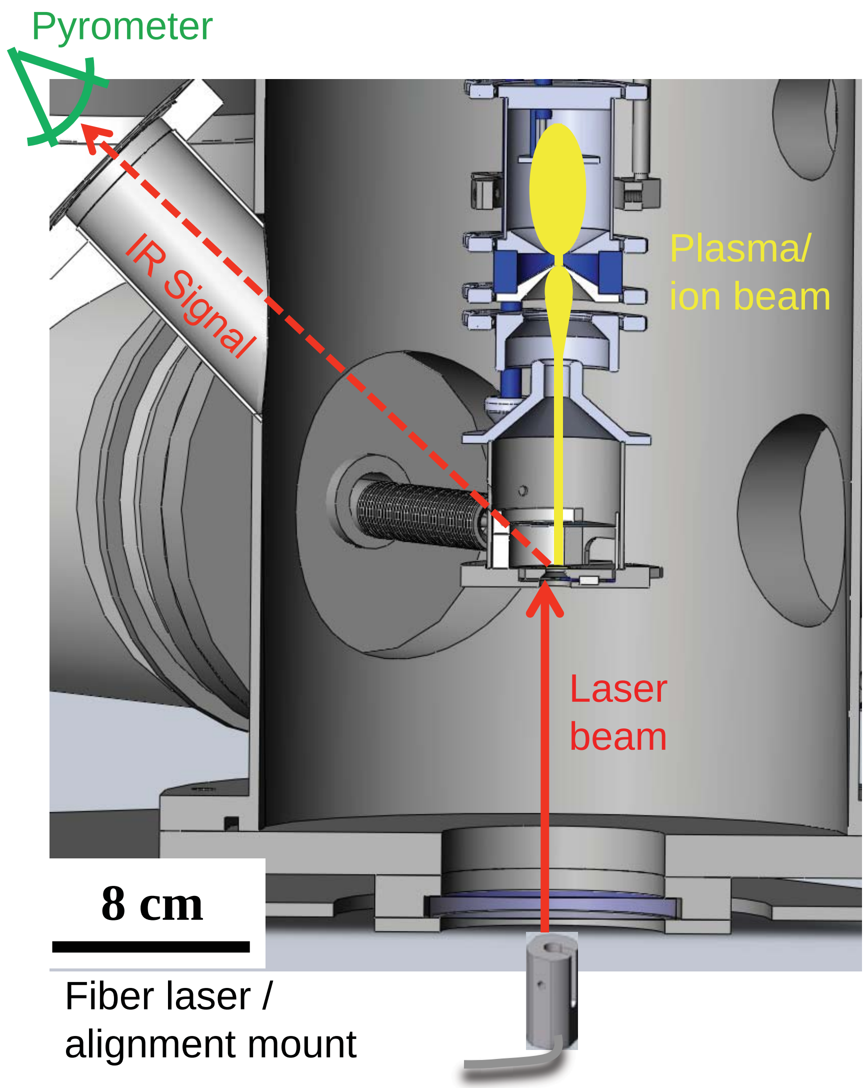


Slide from B. Egle

Materials Irradiation Test Facility
MITE-E

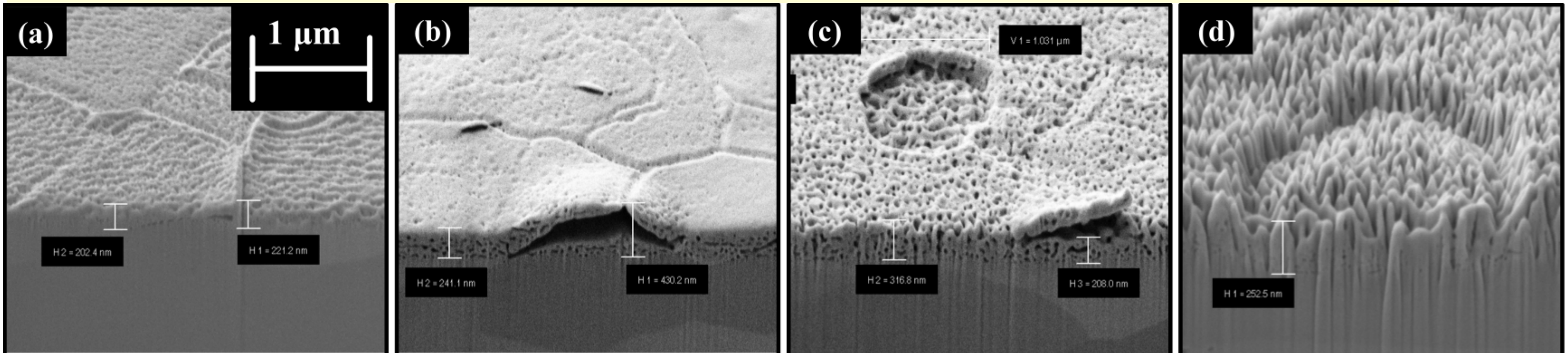
← Uses Brian Egle SIGFE prototype ion gun.





Fast He Ions Can Produce Significant Damage in Hot Materials

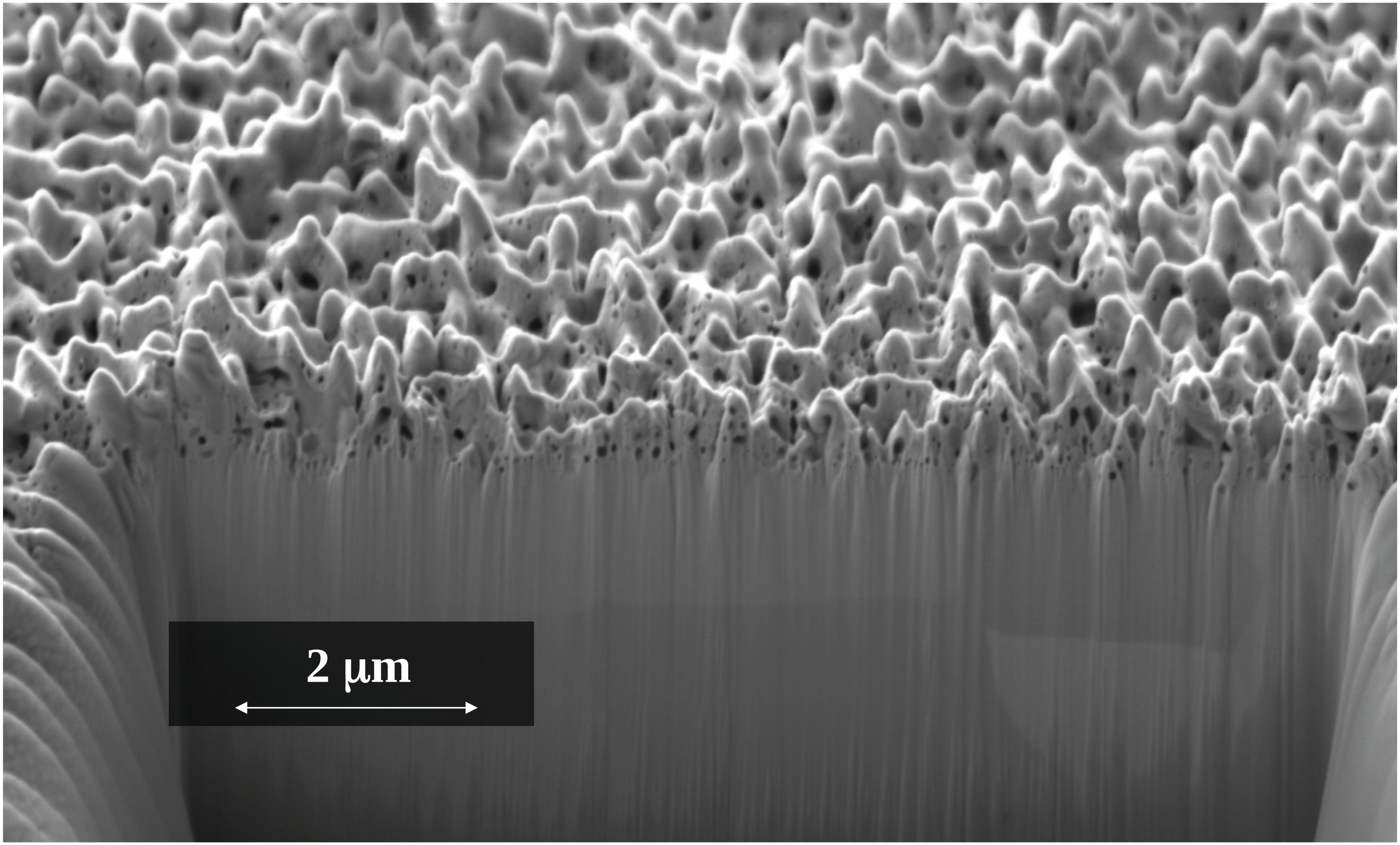
- Concerns exist for MFE divertor plates plus MFE and IFE first walls.



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.

Example of Pulsed He Ion Damage in W at ≈1,150 °C ($10^{19}/cm^2$)



30 keV He^+ irradiation of polycrystalline W (PCW) ⇨ multitude of structures

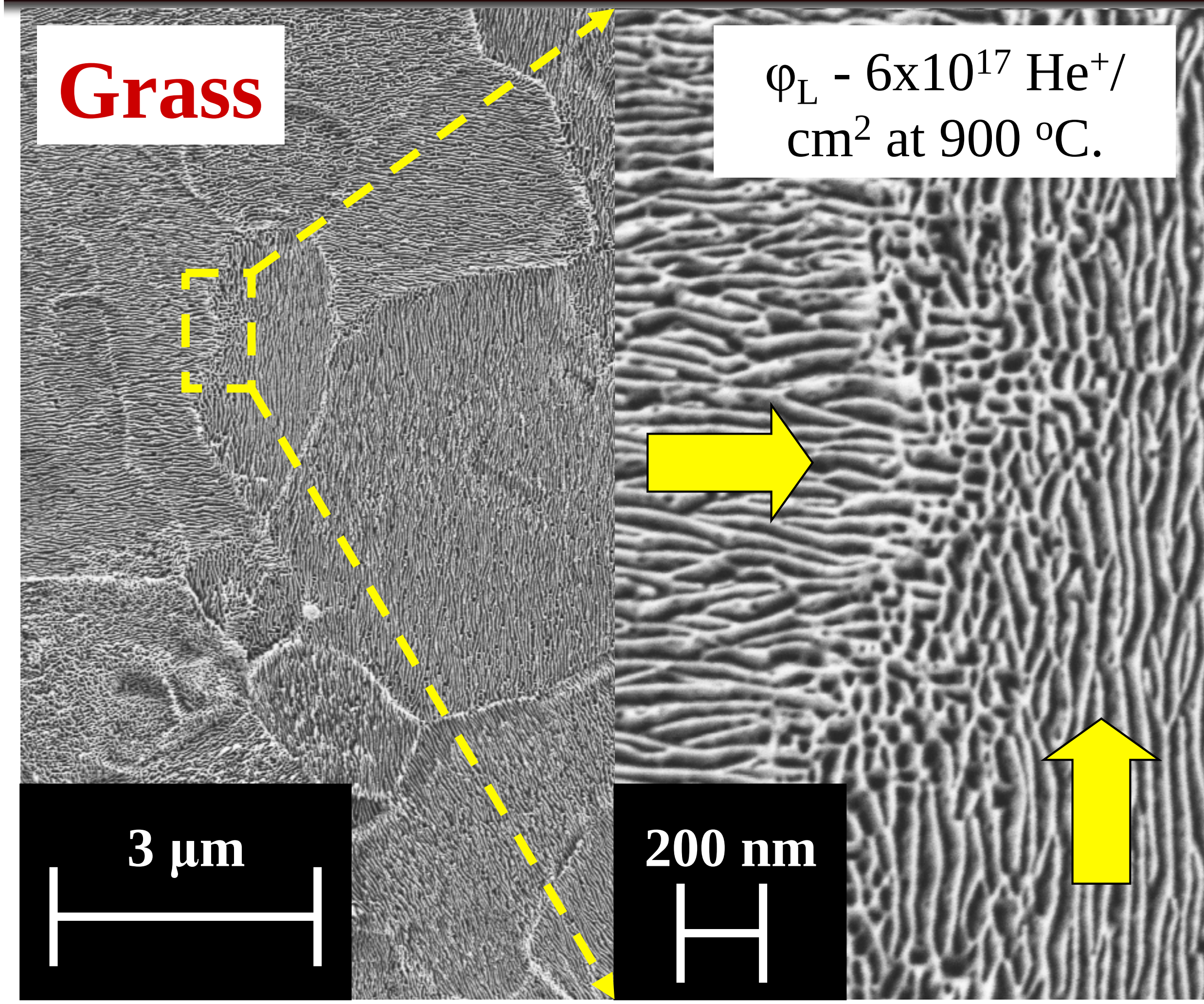
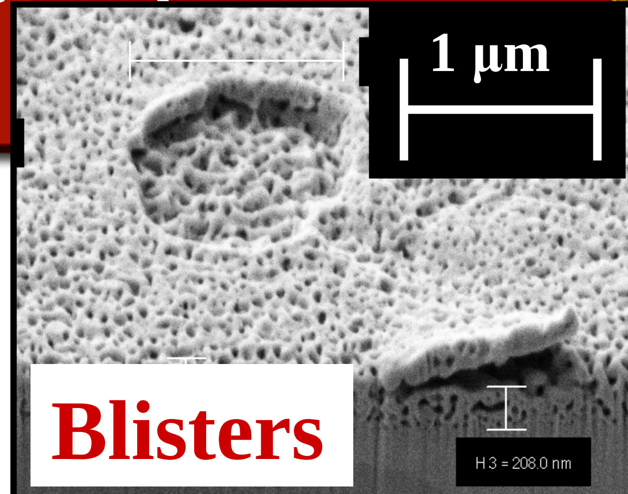
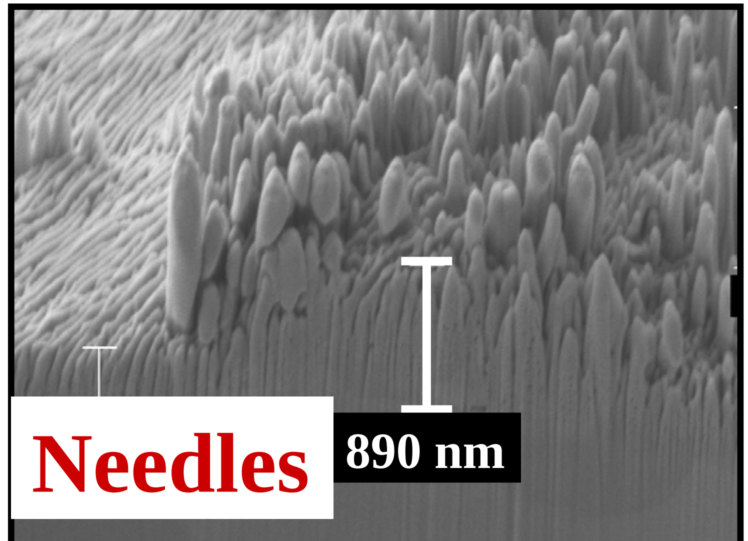


Fig. 9, 13, 4. S. J. Zenobia, L. M. Garrison, G. L. Kulcinski. "The response of polycrystalline tungsten to 30 keV helium ion implantation at normal incidence and high temperatures." *Journal of Nuclear Materials*, **425**, 1–3 (2012) 83–92.



φ_L – 1.8x10^{18} He^+/cm^2, T – 900°C



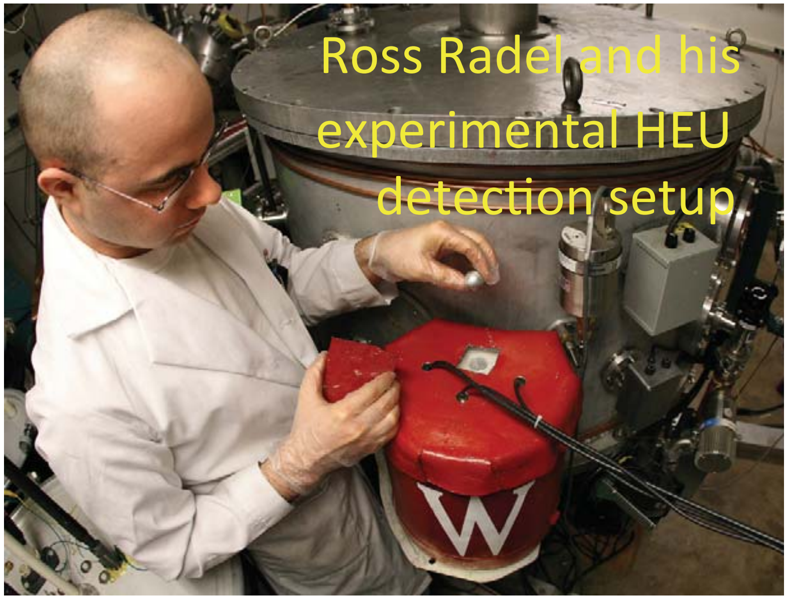
P27: φ_L – 3.6x10^{19} He^+/cm^2, T – 900°C, t – 6558 sec

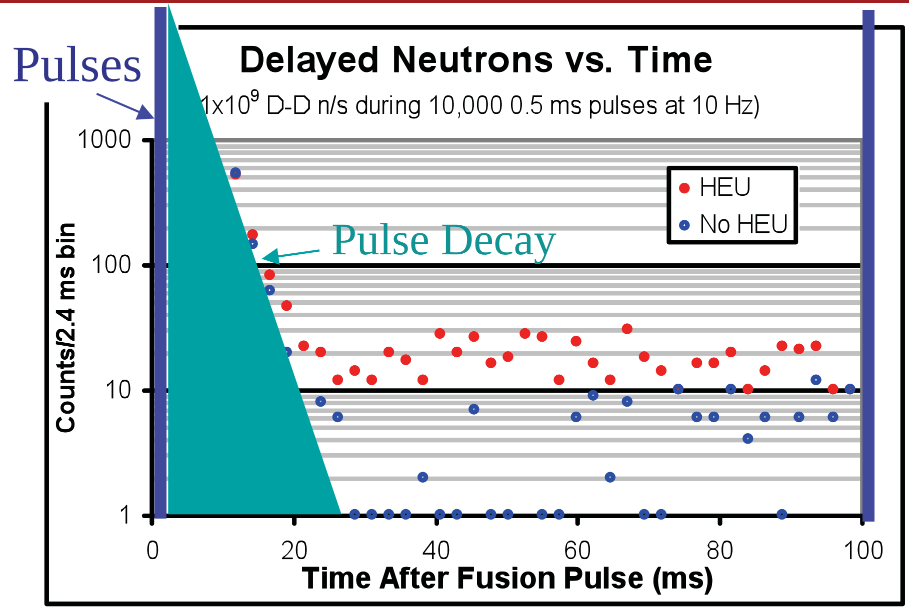
Extrapolating the Mass Loss from (110) Single-Crystal W to Fusion Reactors

High Average Power Laser (HAPL)	ITER
IFE reactor	MFE test reactor
Flux: $5\text{x}10^{13}$ $He^{+}/cm^{2}s$ Assume constant during full power day	Flux: $1.1\text{x}10^{14}$ $He^{+}/cm^{2}s$ 400 s pulse 54 pulses/day
First wall area: 1385 m^2	Divertor area: 400 m^2
18 kg eroded per Full Power Day	2.9 kg eroded per Full Power Day

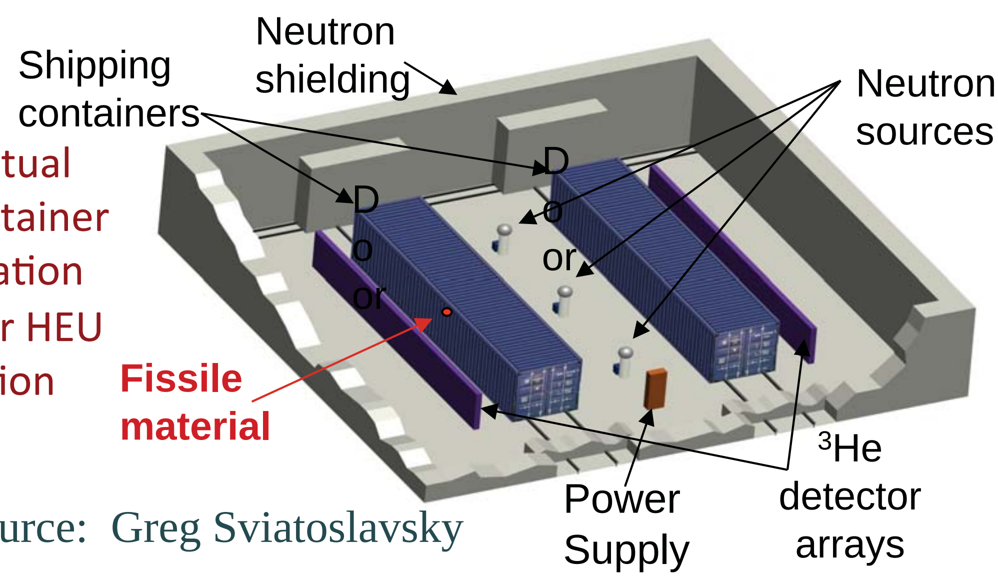
Slide from L. Garrison

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



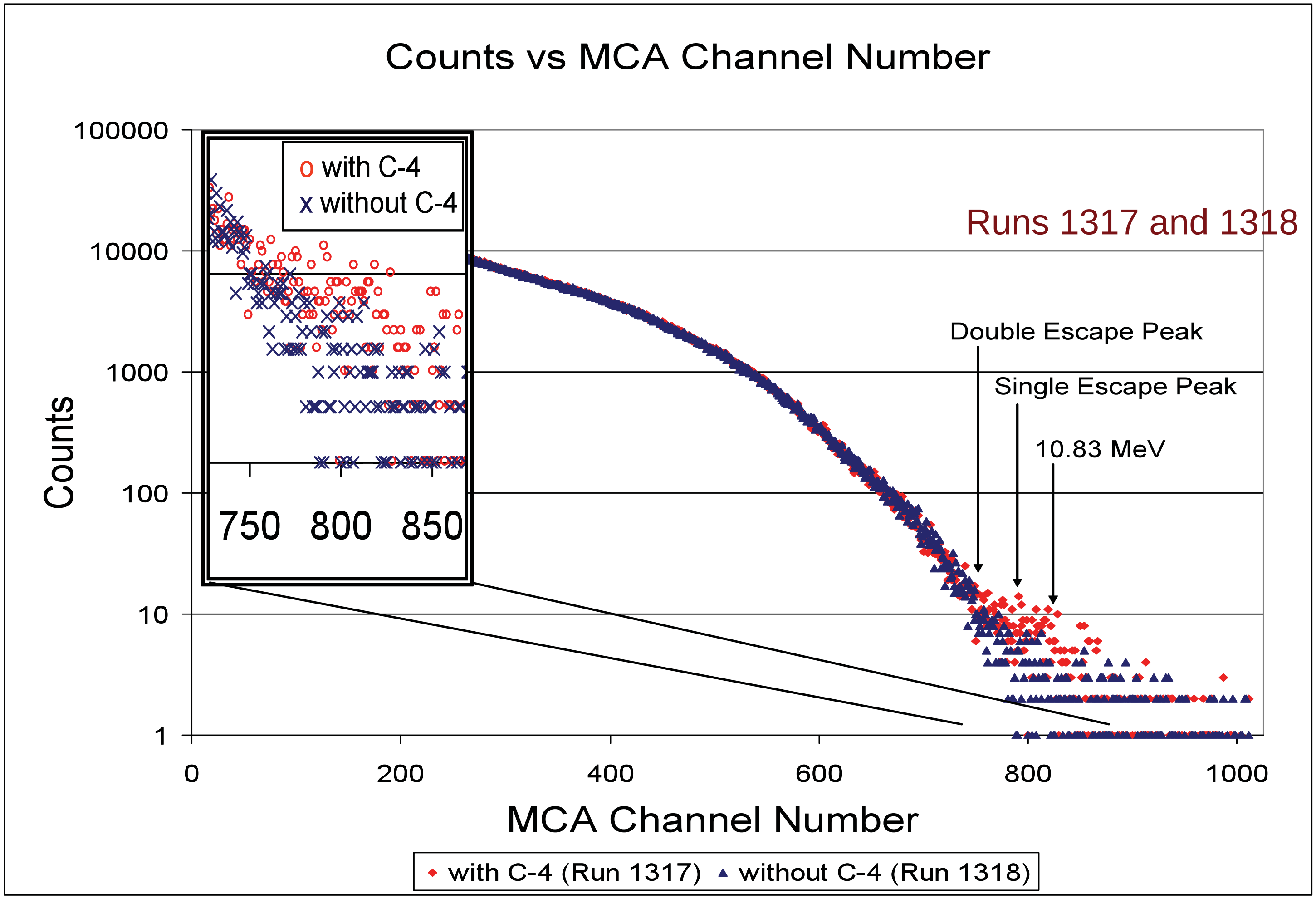


Ross Radel, *Detection of Highly Enriched Uranium and Tungsten Surface Damage Studies Using a Pulsed Inertial Electrostatic Confinement Fusion Device*, UW PhD thesis (2007).



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)

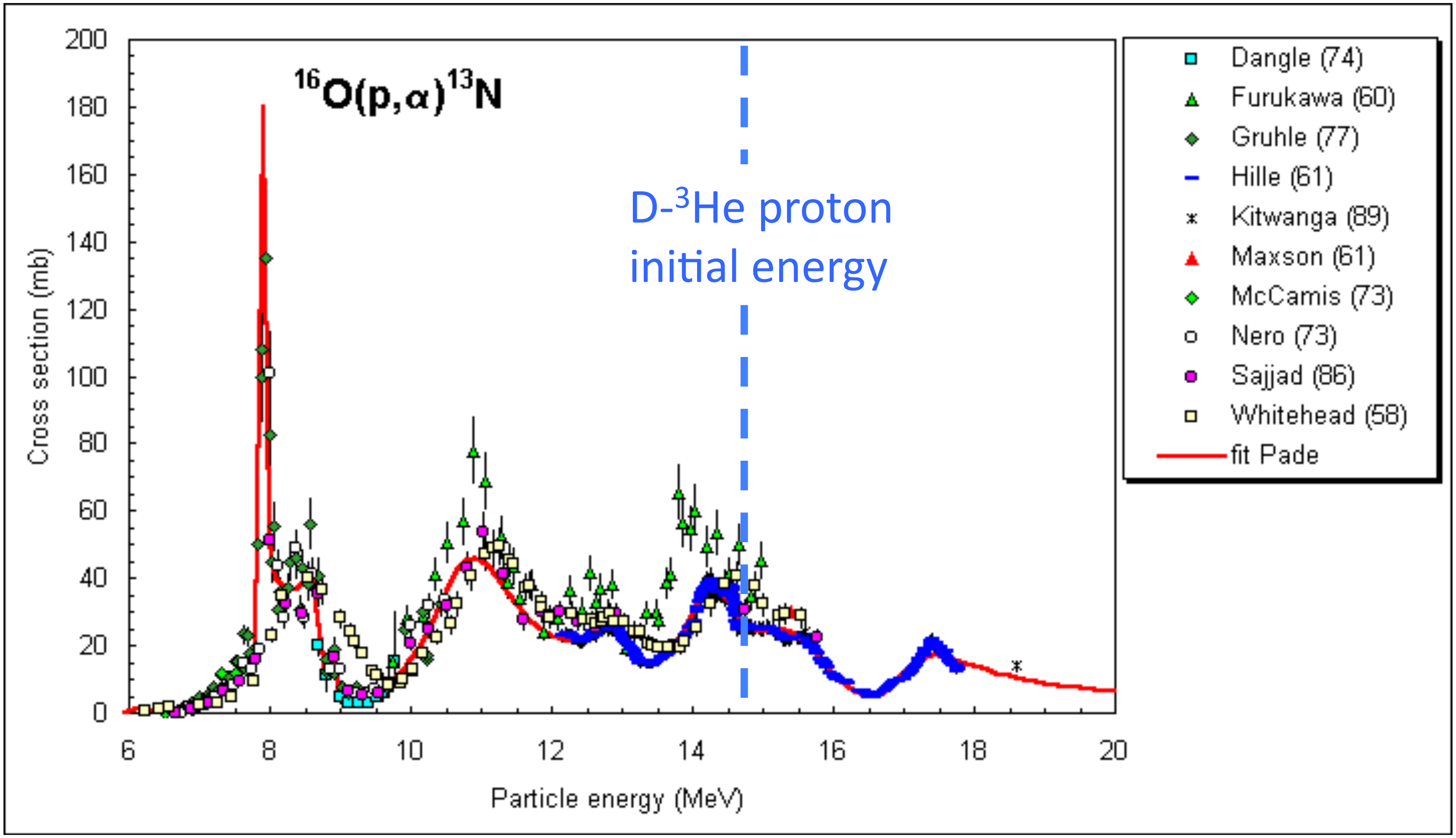
D-^{3}He Fusion Protons (14.7 MeV) Can Produce Short Half-Life, Positron-Emitting Radioisotopes

- 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

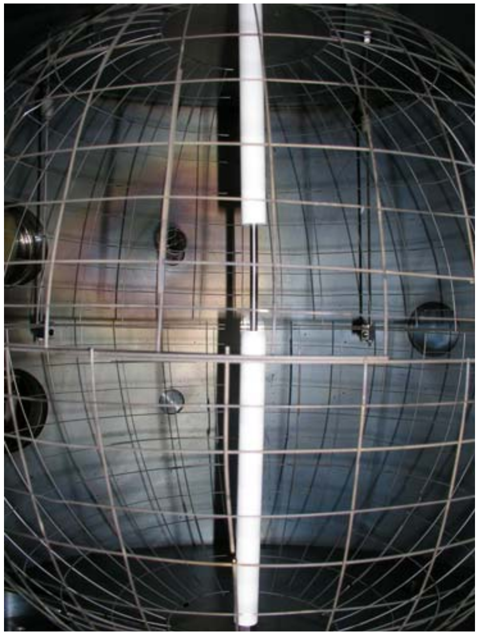
- D-D neutrons and D-^{3}He protons could also produce other radioisotopes or strategically important stable isotopes.

Oxygen $^{16}O(p,\alpha)^{13}N$ Cross Section Matches Proton Energy Well



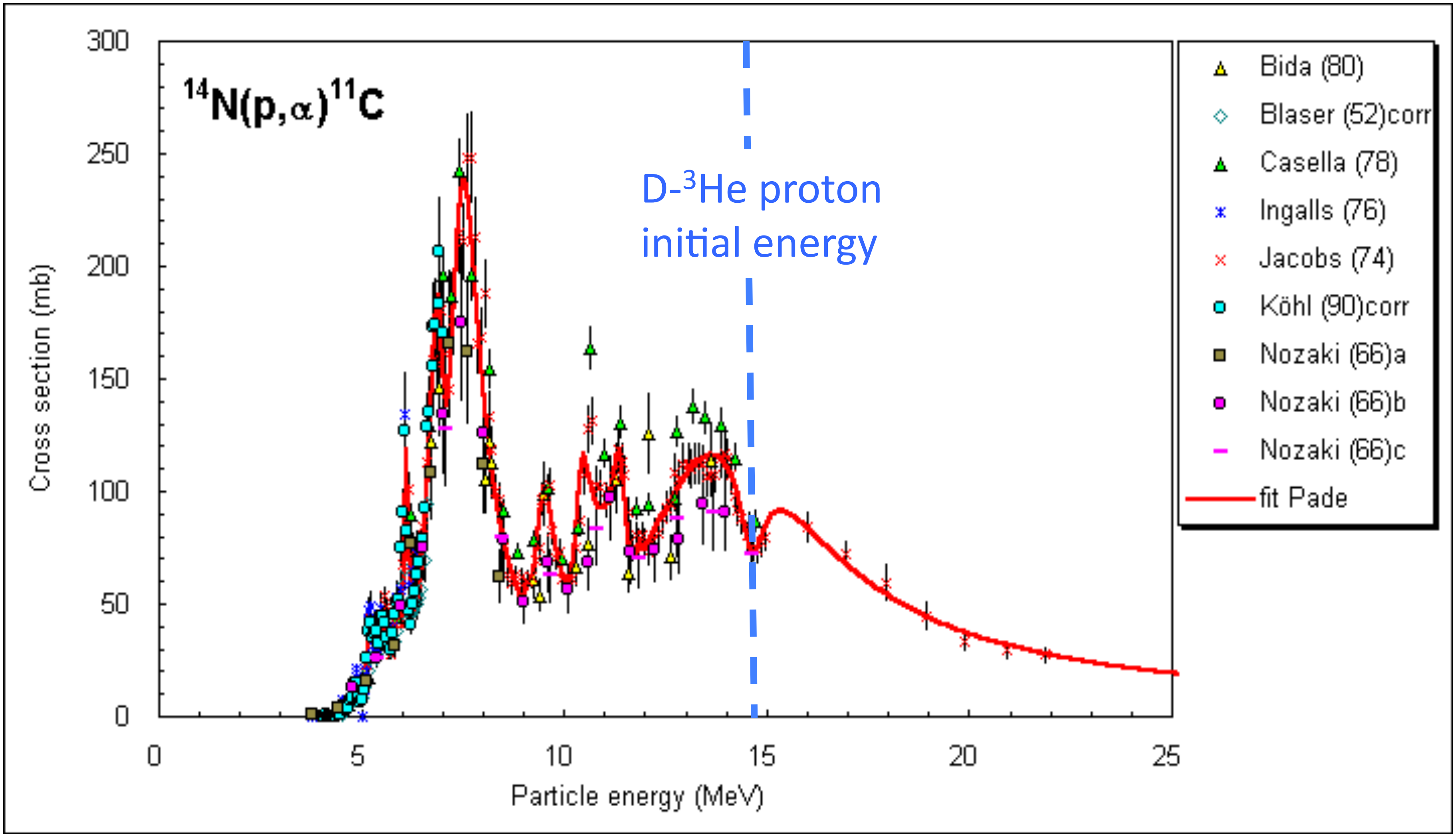
PET Isotopes Have Been Created in a UW IEC Device

- The positron emission tomography (PET) isotope ^{13}N was made by John Weidner in an IEC device by bombarding water in thin stainless steel tubes with D-^{3}He protons born in the central cathode region.
  - J. Weidner, et al., *FS&T* **44**, 539 (2003).

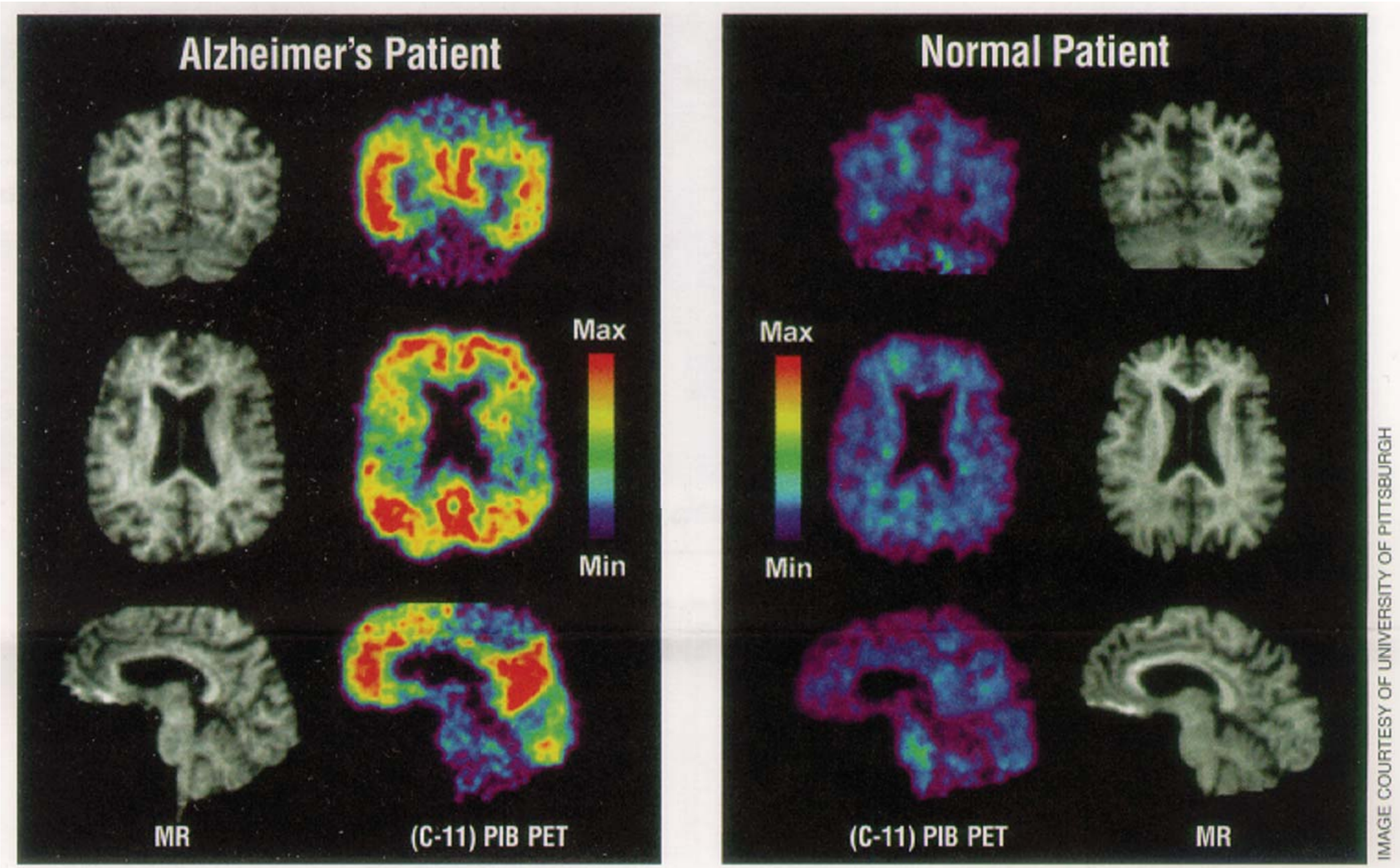


- The PET isotope ^{13}N was made by Ben Cipiti in an IEC device by bombarding water in a thin SS tube (acting as a cathode) with D-^{3}He protons born in the cathode.

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



A Critical Radioisotope is ^{99}Mo, Which Produces ^{99m}Tc

Why is ^{99}Mo ($t_{1/2}$=66 hr) Important?

- Its daughter, ^{99m}Tc, has a half life of 6.04 hr and is used in over 20,000,000 clinically administered procedures in the U.S. annually (80% of all radioisotope procedures).

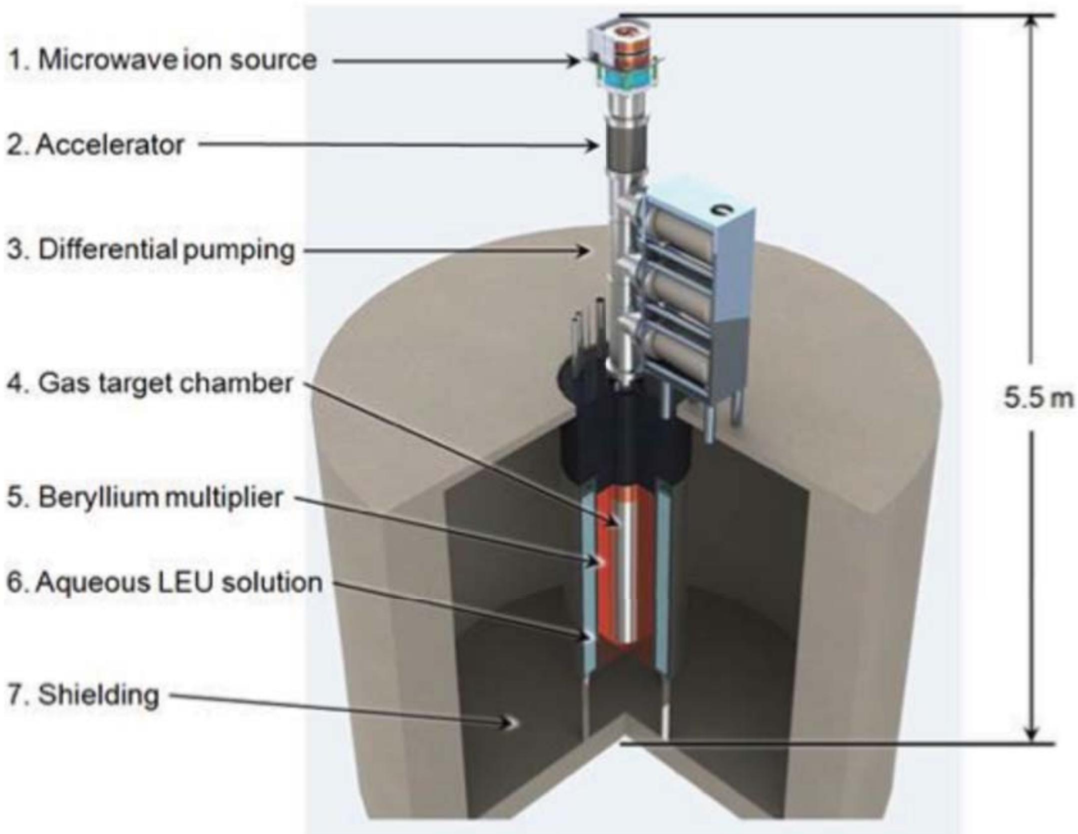
- ^{99m}Tc is used for:

bone scans	biliary scans	thyroid scans
lung scans	gastrointestinal scans	brain scans
heart scans	Meckel's (stomach) scans	white blood cell scans
liver/spleen scans	renal (kidney) scans	

- Roughly 40% of hospitalized patients in the U.S. have at least 1 nuclear medicine study during their stay.

Slide from G. Kulcinski

SHINE—Subcritical Hybrid Intense Neutron Emitter for Producing Medical Isotopes



- D-T source in center
- Be multiplier
- Annular Geometry
- LEU Solution
- Externally moderated
- No active control elements
- Uranium inventory: < 5 kg of 19.5% U per device
- Fission power: ~ 75 kW per device
- ^{99}Mo production rate: 500 units of 6-day Ci / wk

Greg Piefer, Ross Radel

UW PhDs, IEC group, 2006 & 2007

Slide from G. Kulcinski

SHINE Medical Technologies and Its Partners Are Poised to Produce Half of the US ^{99}Mo Supply in 2016

Greg Piefer, UW PhD (2006)

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.