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Update on the VICTER Code for Modeling Gridded, Spherically Symmetric IEC Devices*

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US-Japan Workshop
Sydney, Australia
Dec. 7-8, 2011

*Research supported by the US Dept. of Energy
under grant DE-FG02-04ER54745
and the Grainger Foundation

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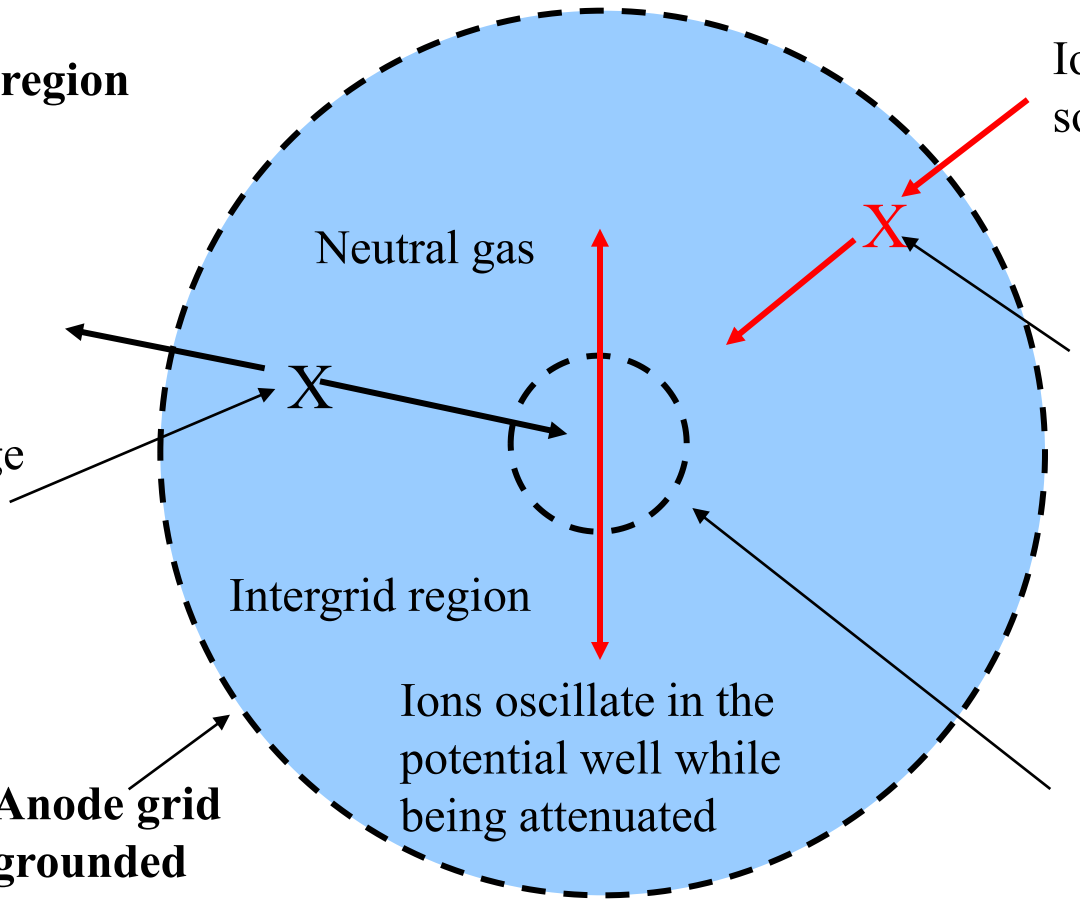
VICTER* Model



Source region

Ions enter from the source region

Neutral gas

Ions formed in the intergrid and cathode regions by ionization, charge exchange, and dissociative processes

Fast neutrals formed by charge exchange and dissociative processes

Intergrid region

Ions oscillate in the potential well while being attenuated

Anode grid grounded

Cathode grid at potential –V_0

*** Volterra Integral Code for Transport in Electrostatic Reactors**

Basic Assumptions in VICTER

- Background D_2 gas
- Spherical symmetry – ignore stalk, defocusing, and jets
- Prescribed electrostatic potential profile
    - Child-Langmuir or vacuum potential in intergrid region
    - Flat in the cathode region
- Deuterium (D^+, D_2^+, and D_3^+) ions enter from the source region
- D^+, D_2^+ ions created in the intergrid and cathode regions by impact ionization, charge exchange, and dissociation of fast ions colliding with the background D_2 gas
- D^- ions created by charge exchange processes
- Interactions occur without momentum transfer between nuclei; daughter products travel at the same speed as parent
- Collisionless ion motion between interactions

Atomic and Molecular Processes Included

$D^+ + D_2 \rightarrow D + D_2^+$	charge exchange of D^+
$D^+ + D_2 \rightarrow D^+ + \ldots$	stationary D^+ production
$D^+ + D_2 \rightarrow D_2^+ + \ldots$	stationary D_2^+ production
$D_2^+ + D_2 \rightarrow$ various products	destruction of D_2^+
$D_2^+ + D_2 \rightarrow D^+ + \ldots$	fast D^+ production
$D_2^+ + D_2 \rightarrow D^+ + \ldots$	stationary D^+ production
$D_2^+ + D_2 \rightarrow D_2 + D_2^+$	charge exchange of D_2^+
$D_3^+ + D_2 \rightarrow$ various products	destruction of D_3^+
$D_3^+ + D_2 \rightarrow D^+ + \ldots$	fast D^+ production
$D_3^+ + D_2 \rightarrow D_2^+ + \ldots$	fast D_2^+ production
$D_3^+ + D_2 \rightarrow D^+ + \ldots$	stationary D^+ production
$D_3^+ + D_2 \rightarrow D_2^+ + \ldots$	stationary D_2^+ production

Some of these processes are sums over various reaction channels.

Two Coupled Volterra Integral Equations Determine the Source Functions, $S_i(r)$

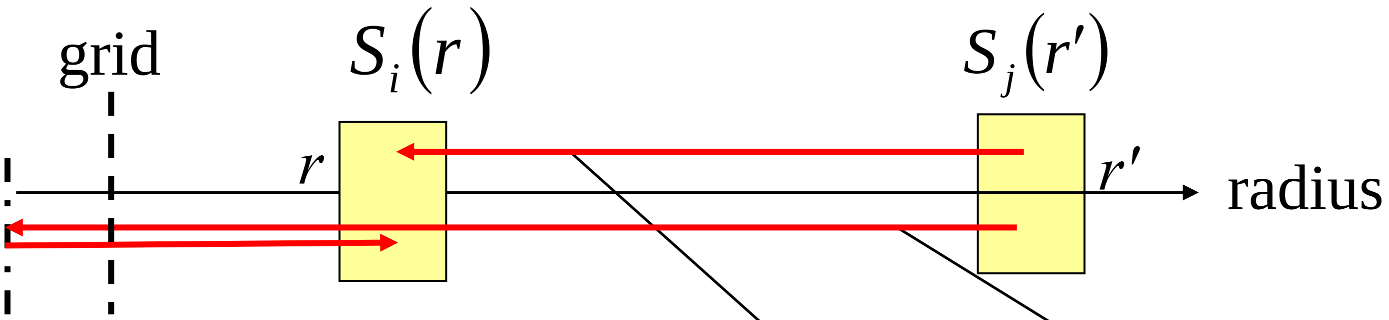
Sum over all generations of daughter ions and all ion passes for D^+ ($i = 1$) and D_2^+ ($i = 2$)

$$S_i(r) = A_i(r) + \sum_{j=1}^{2} \int_r^{\text{anode}} K_{ij}(r, r') S_j(r') dr', \quad i = 1,2$$

$S_i(r)$ = number of ions born per unit volume per sec at radius r.

$A_i(r)$ = slow ion source due to ions from source region

Kernel relates the Source at one Radius to the Source at another Radius



Slow Source contribution:

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

gas density

cross-section for producing *i* from *j*

cathode transparency

sum over passes

complete pass probability

The Ion Energy Spectra are Obtained from the Source Functions

Inward traveling ions:

$$F_s^{\,in}(r,E)=4\pi e r'^2\,\frac{S_s(r')}{\left|\dfrac{\partial e\varphi}{\partial r'}\right|}\left(\frac{g_s(r,r')}{1-T_c^{\,2}g_{cps}(r')}\right)+4\pi e b^2 h_s\Gamma f_s(r)\,\delta\big(E-e\varphi(r)\big)$$

Outward traveling ions:

$$F_s^{\,out}(r,E)=\frac{4\pi e r'^2}{g_s(r,r')}\,\frac{S_s(r')}{\left|\dfrac{\partial e\varphi}{\partial r'}\right|}\left(\frac{T_c^{\,2}g_{cps}(r')}{1-T_c^{\,2}g_{cps}(r')}\right)+4\pi e b^2 h_s\Gamma\,\frac{T_c^{\,2}f_{cps}}{f_s(r')}\,\delta\big(E-e\varphi(r)\big)$$

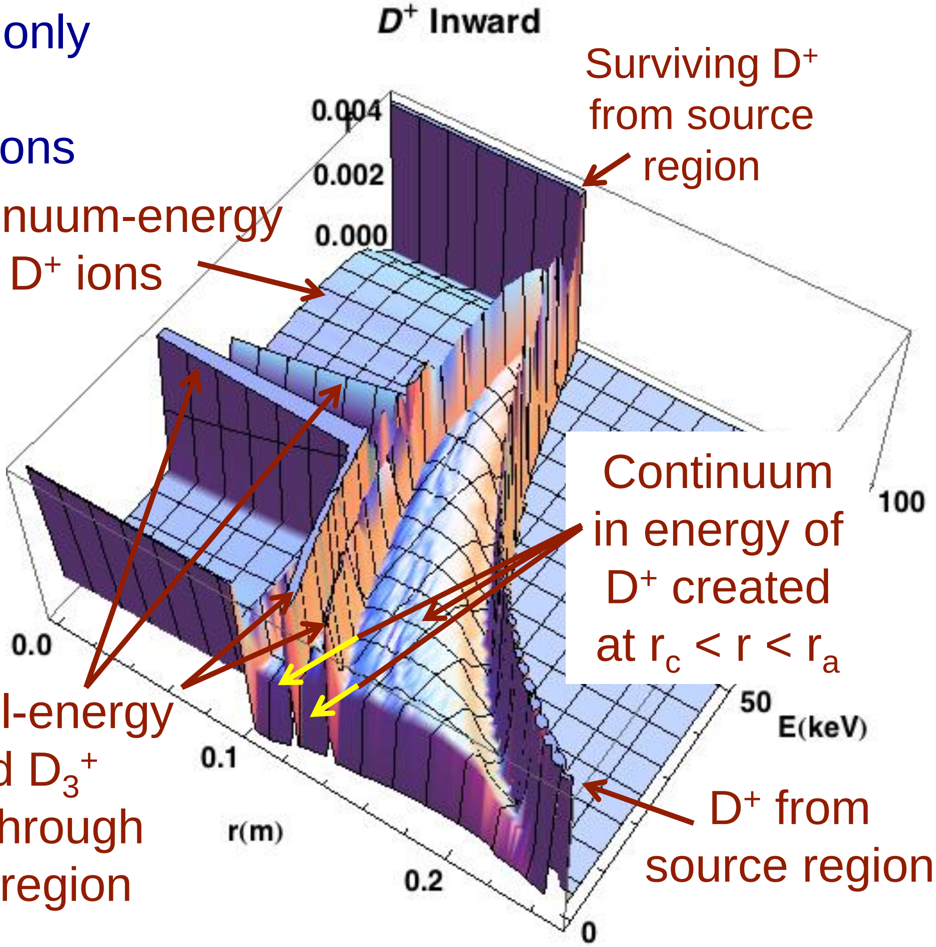
where $E=e\big(\varphi(r')-\varphi(r)\big)$

and *s* denotes the species ($s = 1$ (D^+), $s = 2$ (D_2^+), and $s = 3$ (D_3^+))

Example Energy Spectra of D^+ Ions Traveling Inward

Note: This figure's z-axis is only to f = 0.005

(The tops of the delta functions are cut off.)



Surviving D^+ from source region

Continuum-energy D^+ ions

Continuum in energy of D^+ created at $r_c < r < r_a$

D^+ from full-energy D_2^+ and D_3^+ passing through cathode region

D^+ from source region

100 kV, 100 mA, P=2 mTorr, r_c=0.1 m, r_a=0.25 m, source D^+:D_2^+:D_3^+=0.06:0.23:0.71

The Ions Produce Fast Atoms and Molecules by Charge Exchange and Dissociative Processes

Define a fast neutral atom source function:

$$S_a^{in,out}\left(r,E\right)dE = \sum_{s=1}^{3} F_s^{in,out}\left(r,E'\right) n_g \sigma_{sfa}\left(E'\right)dE'$$

Fast Atom and Molecule Energy Spectra is gotten from solving:

$$\frac{\partial}{\partial r} F_{a,m}^{in,out}\left(r,E\right) = S_{a,m}^{in,out}\left(r,E\right)$$

Formation of Fast Neutral Atoms and Molecules Included

$D^+ + D_2 \rightarrow \text{fast } D + \ldots$

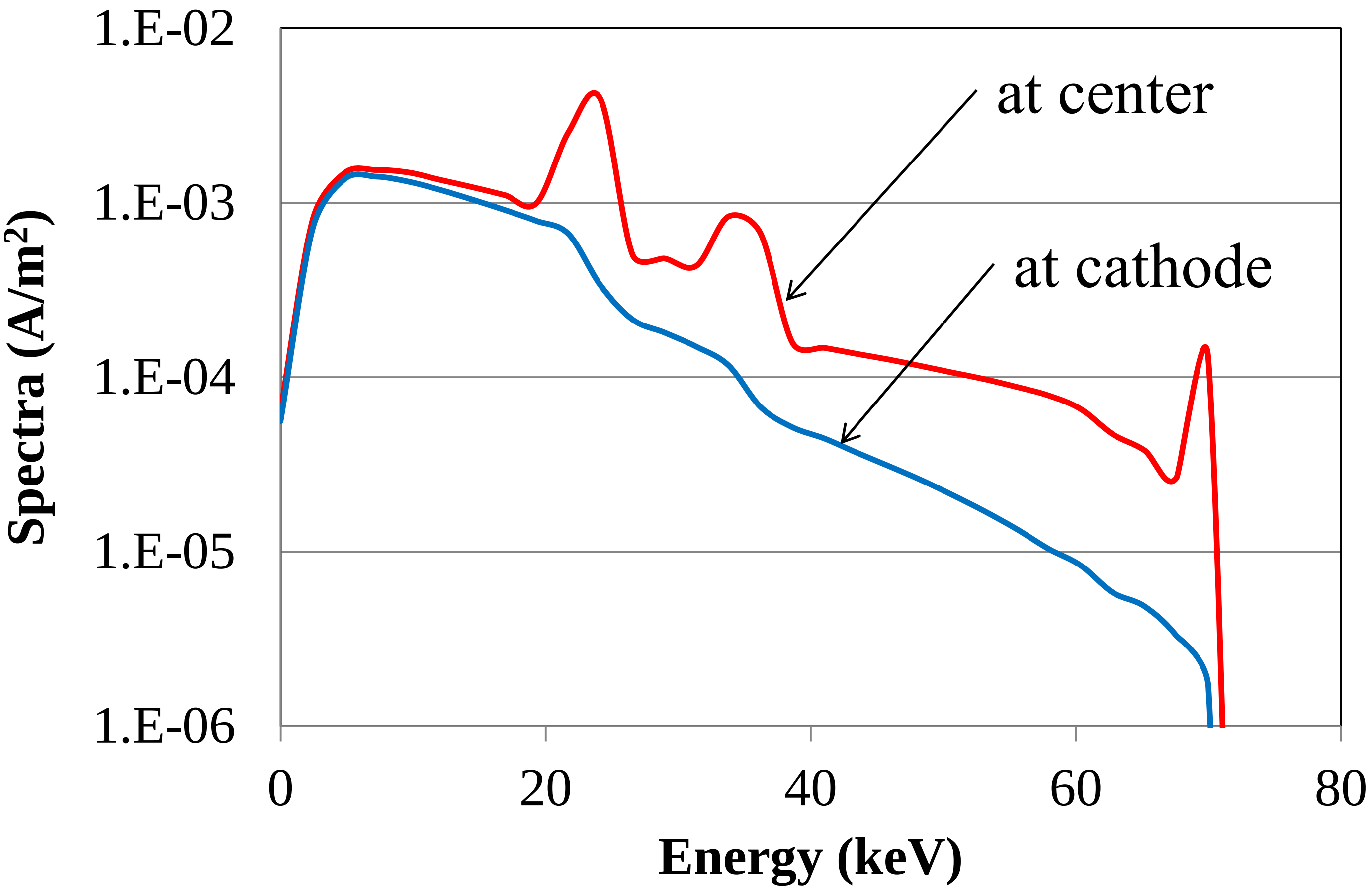
$D_2^+ + D_2 \rightarrow \text{fast } D + \ldots$

$D_2^+ + D_2 \rightarrow \text{fast } D_2 + \ldots$

$D_3^+ + D_2 \rightarrow \text{fast } D + \ldots$

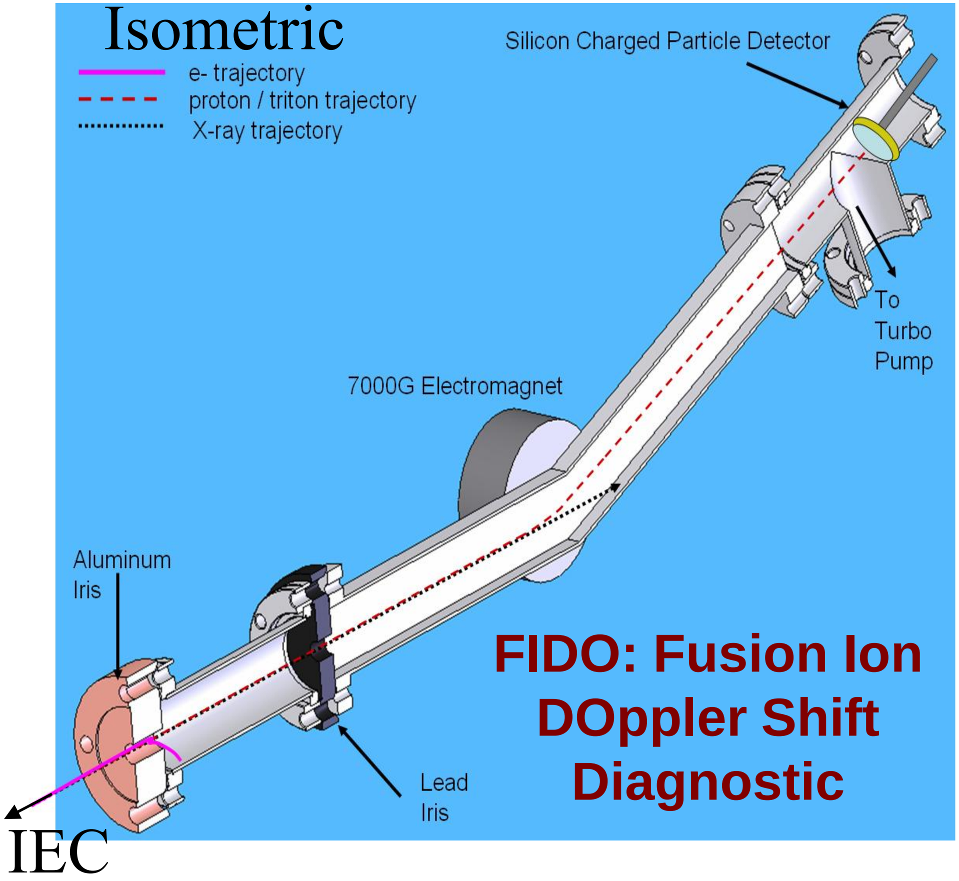
$D_3^+ + D_2 \rightarrow \text{fast } D_2 + \ldots$

Typical D Atom Energy Spectra

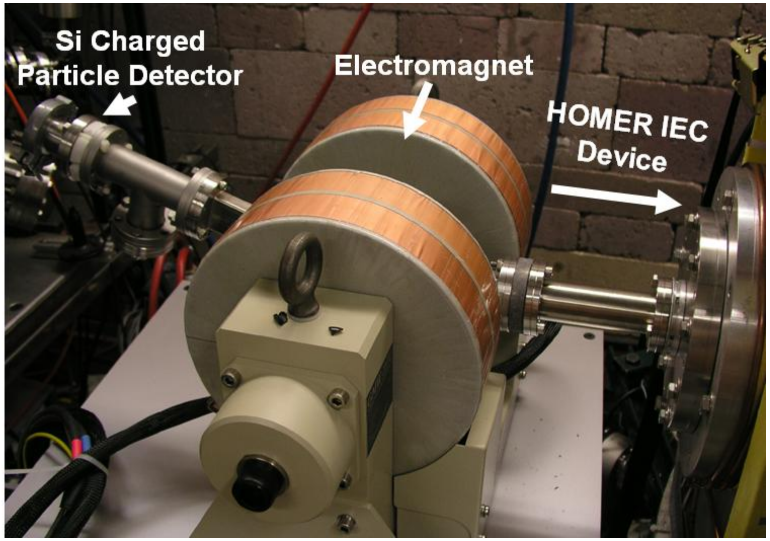


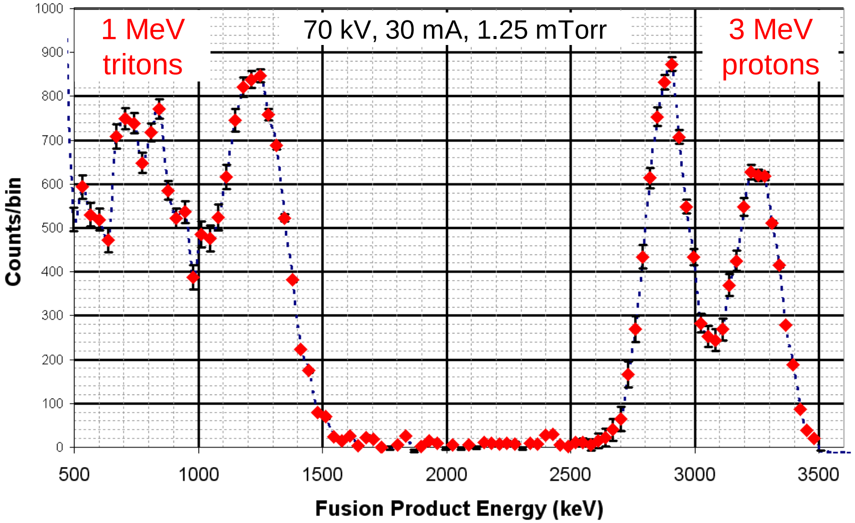
70 kV, 30 mA, 1.25 mTorr

Dave Boris and David Donovan Developed a Low-Noise, Charged-Particle Detection System



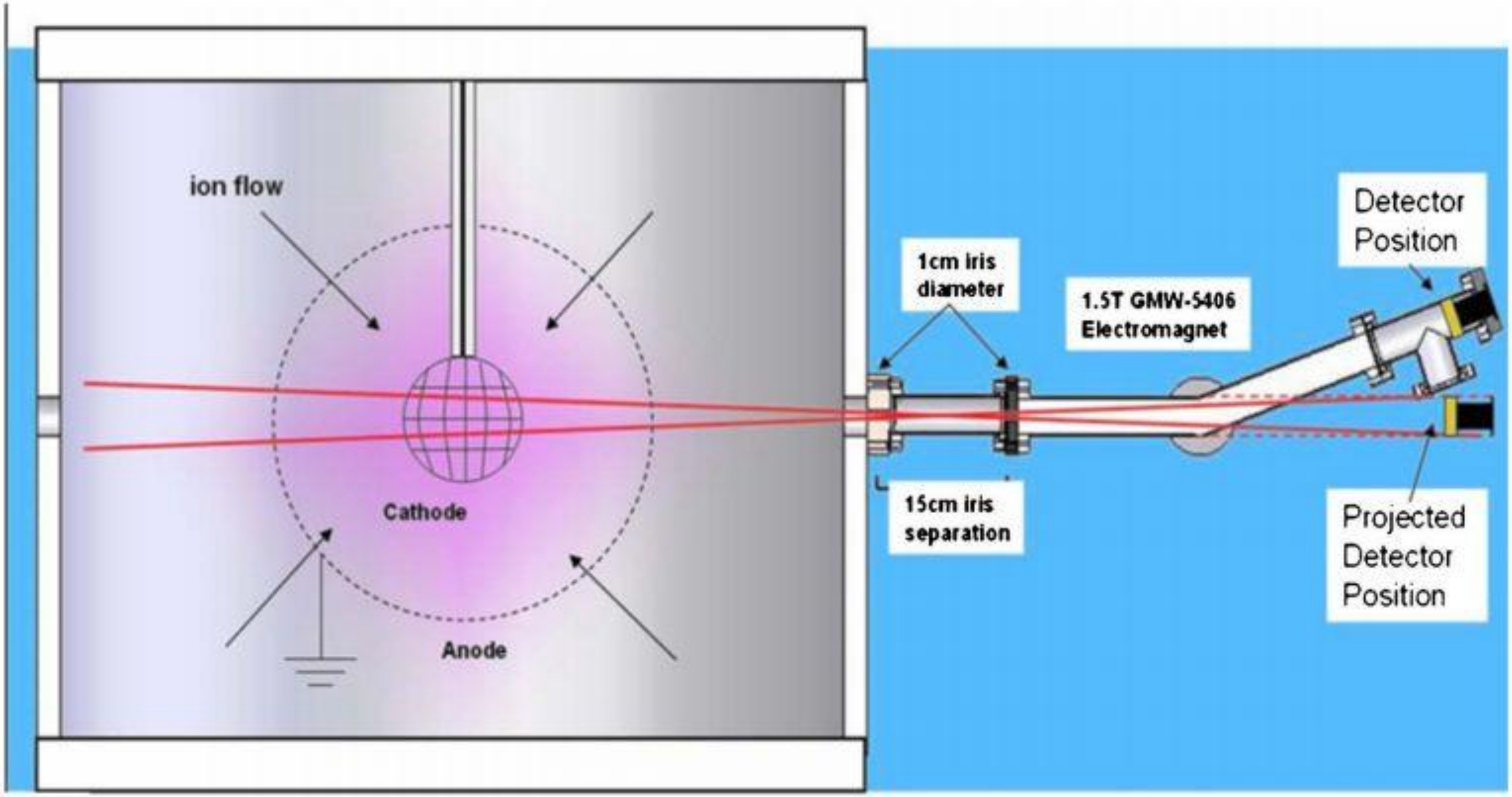
FIDO: Fusion Ion DOppler Shift Diagnostic





- Examining either side of the double-peaked spectra can yield center-of-mass energy of the deuterium reactants

FIDO diagnostic



Using VICTER to Simulate FIDO

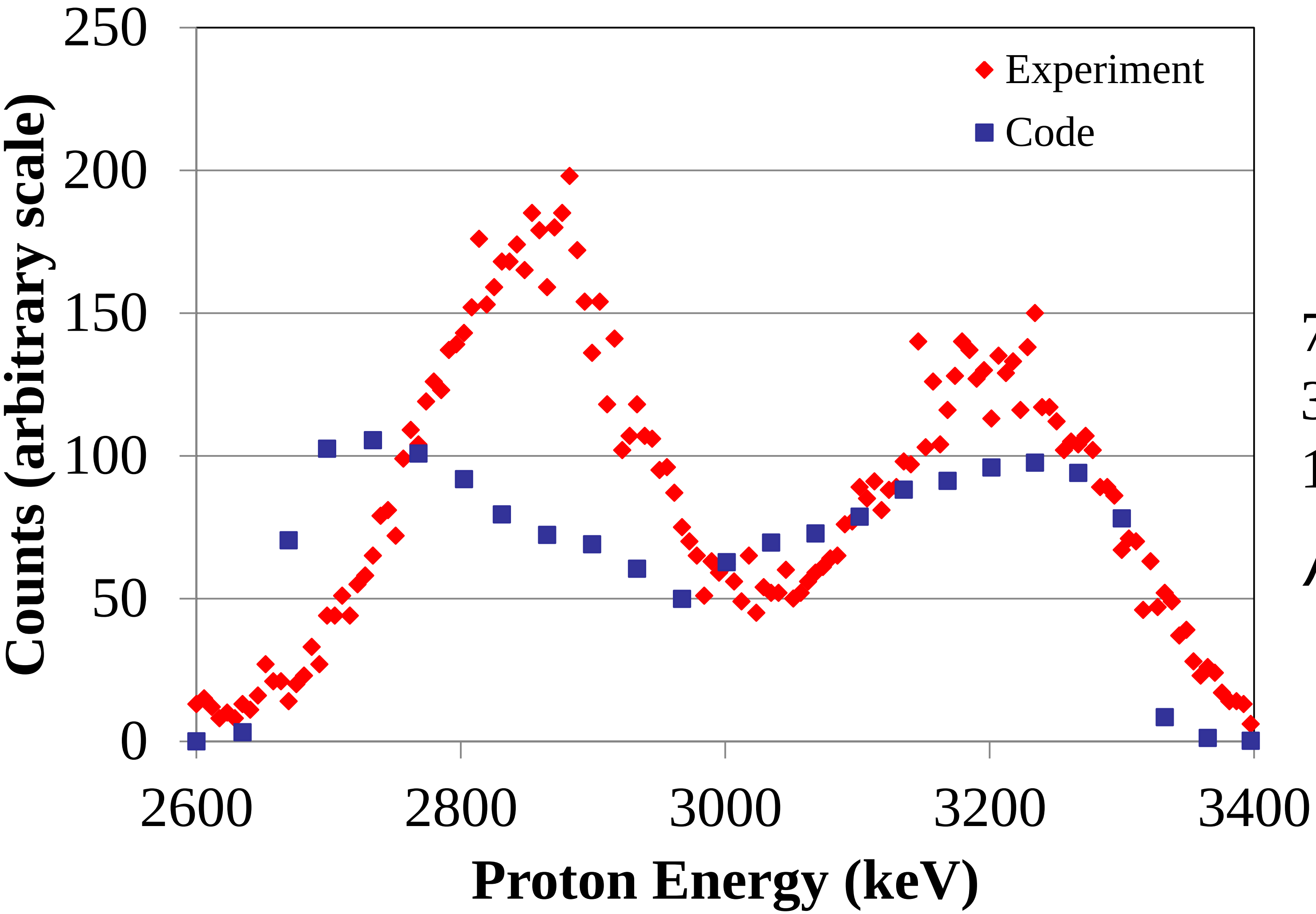
Integrating over the detection cone and the solid angle for protons to reach the detector gives

$$S_{fido}\left(E_p\right)dE_p = \frac{1}{4\pi} n_g \sigma_f\left(E_{CM}\right)\times$$

$$\int_0^c dr \int \sin\theta d\theta \left\{ F_i\left(r,E\right)\frac{V_{Li}^2}{V_p^2\cos\alpha_i} + F_o\left(r,E\right)\frac{V_{Lo}^2}{V_p^2\cos\alpha_o} \right\} \Delta\Omega_{lab} dE$$

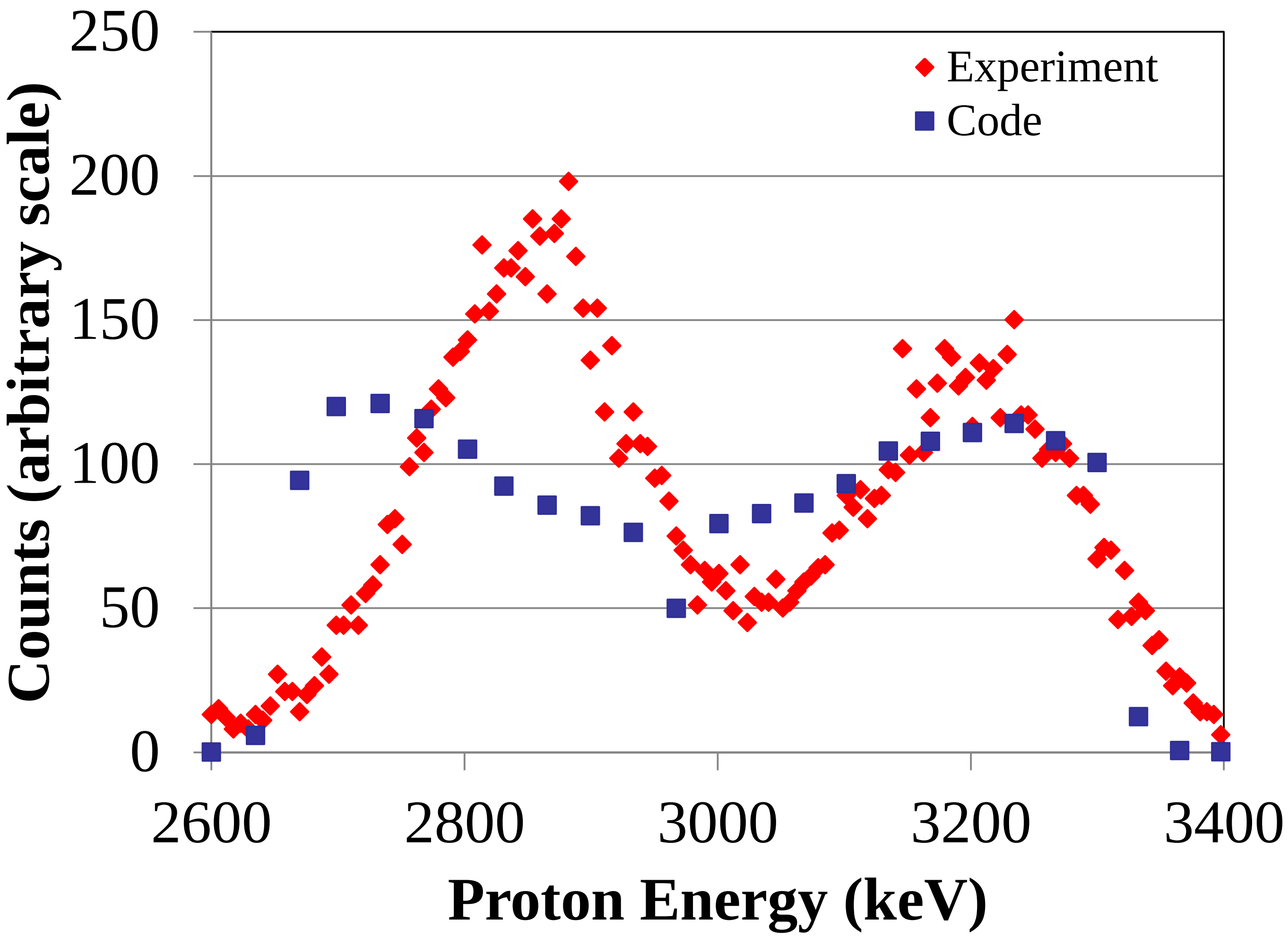
$S_{fido}(E_p)$ = number of protons detected at energy E_p per unit energy per unit time.

Simulating the Proton Energy Spectra



70 kV
30 mA
1.25 mTorr
$\beta = 3.8°$

Simulating the Proton Energy Spectra

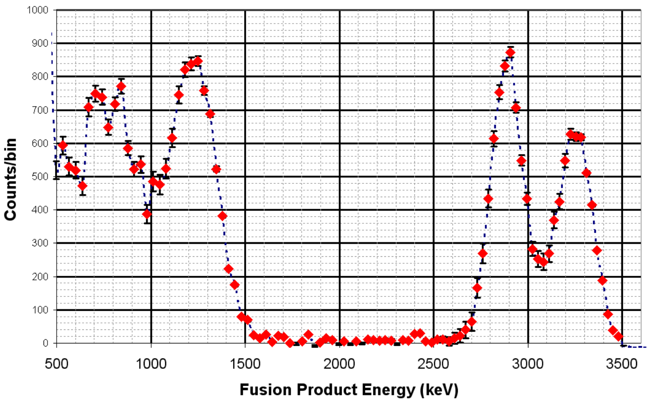


70 kV
30 mA
1.25 mTorr
$\beta = 1°$

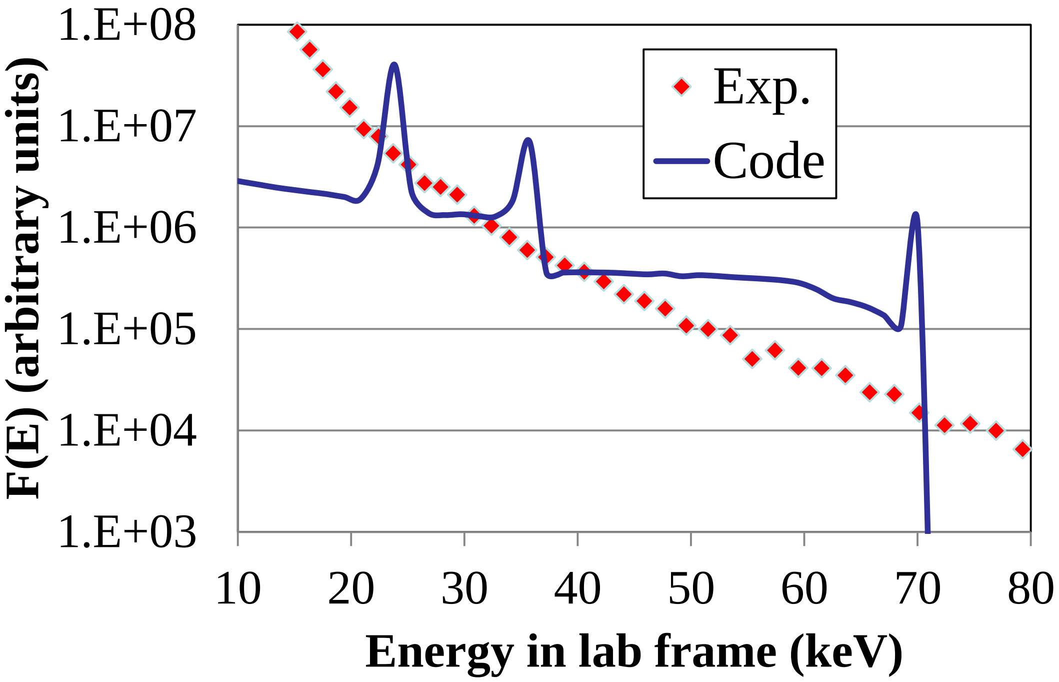
“Line – Averaged” Deuteron Energy Spectra

To infer the “line – averaged” F(E) from the experimental proton energy spectra, have to assume parallel or antiparallel fusion events

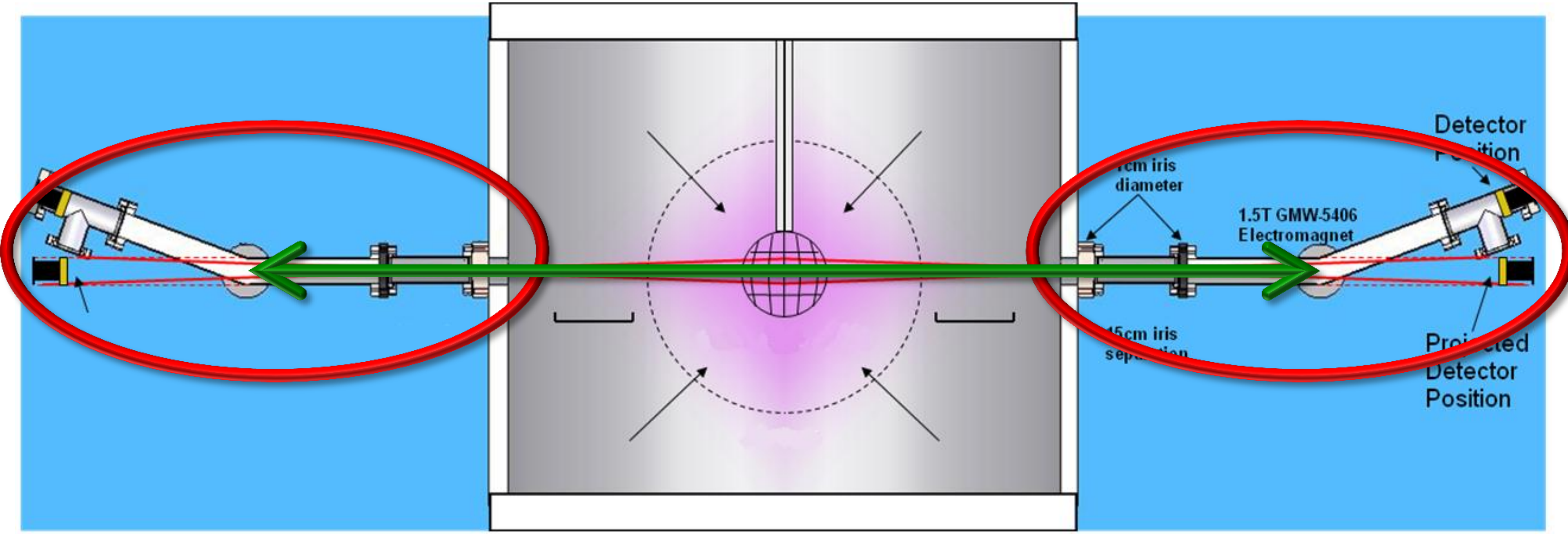
$$V_{lab}^{p} = V_{CM}^{p} \pm V_{CM}$$



70 kV, 30 mA,1.25 mTorr

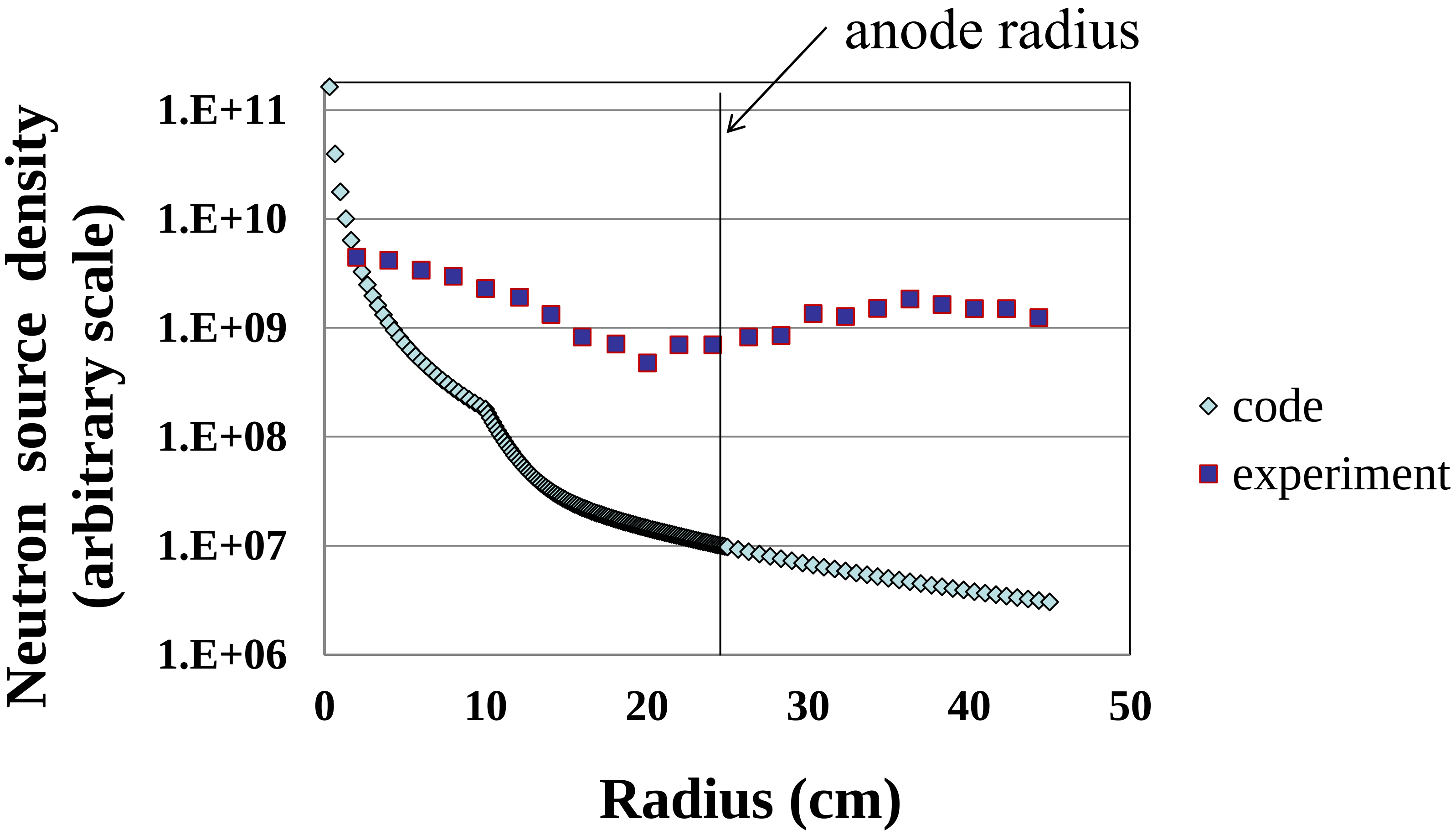


Time Of Flight (TOF) Diagnostic is an Advancement on the FIDO concept



- Initiated by Boris and developed by Donovan
- 2 identical FIDO setups on opposite sides of HOMER
- Direct line of sight created through both arms and center of chamber

Donovan's Time of Flight Diagnostic - Comparison of Neutron Production Profile



60 kV, 30 mA, 2 mTorr

Negative Ions are a Recent Addition to VICTER

Negative Ion Processes included:

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

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

$D_3^+ + D_2 \rightarrow D^- + 2D_2^+$

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

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

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

$D^- + D_2 \rightarrow D + D_2 + e^-$ (stripping)

Modeling Negative Ions

Negative ion source function

$$S_N^{in,out}\left(r,E\right)dE = \sum_{species} n_g \sigma F_{species}^{in,out}\left(r,T'\right)dT'$$

total energy of a negative ion

Energy spectra of positive ions and neutrals

Cross section for producing negative ions

The negative ion energy spectra is then:

$$F_N^{in,out}\left(r,E\right) = \int S_N\left(r',E\right)p\left(r,r',E\right)dr'$$

Survival probability

Survival Probability

Probability of a negative ion born at *r'* with total energy E and reaching *r* is

$$p(r, r', E) = \exp\left[-\int n_g \sigma_{strip}(r'')\, dr''\right]$$

The integral is along the path of the negative ion from the birth point *r'* to *r*. There are three kinds of paths:

1. Purely outward motion
2. Inward, pass through the center to become outward
3. Inward, reflect at the turning point to become outward

See Alderson's talk for details and experimental comparison

Summary and Conclusions

- The VICTER code can calculate the detailed energy spectra of the various ion and neutral particle species as a function of radius.
- Negative ions have added to the code.
- Comparison with experimental results:
  - Numerical energy spectra are in approximate agreement with experimental results, except
  - Experimental energy spectra does not show the predicted discrete spectra.
  - Calculated neutron production profile is more peaked than seen experimentally.

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Thank you for your attention.

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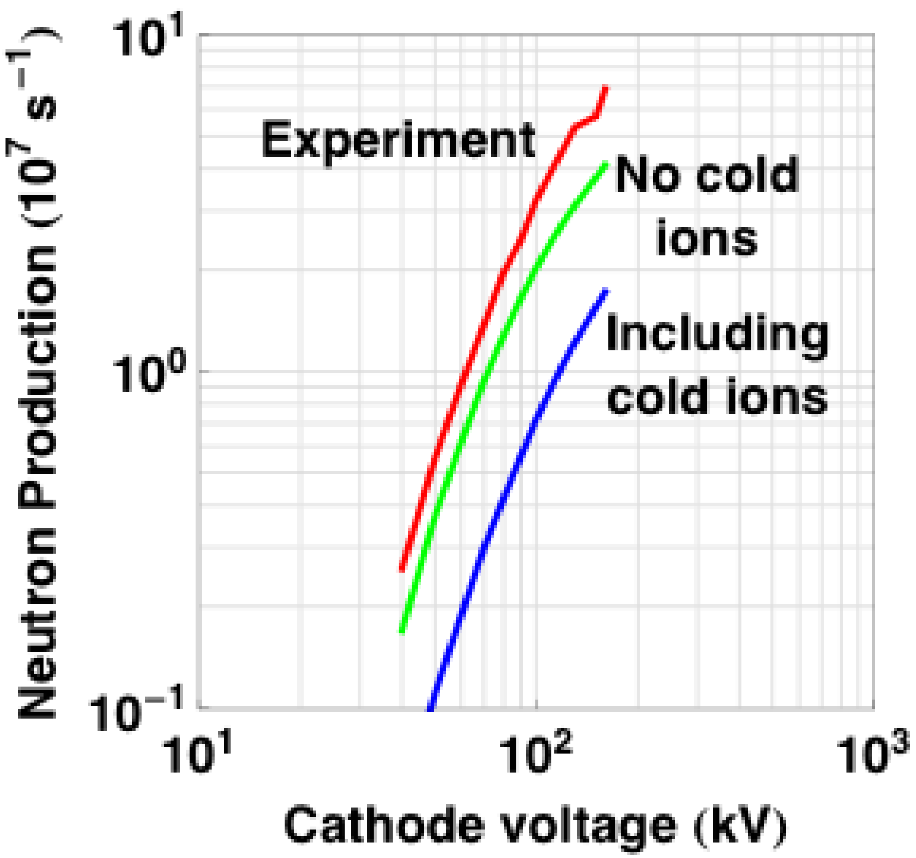
Theoretical Neutron Production Rate is in Reasonable Agreement with Experimental Results

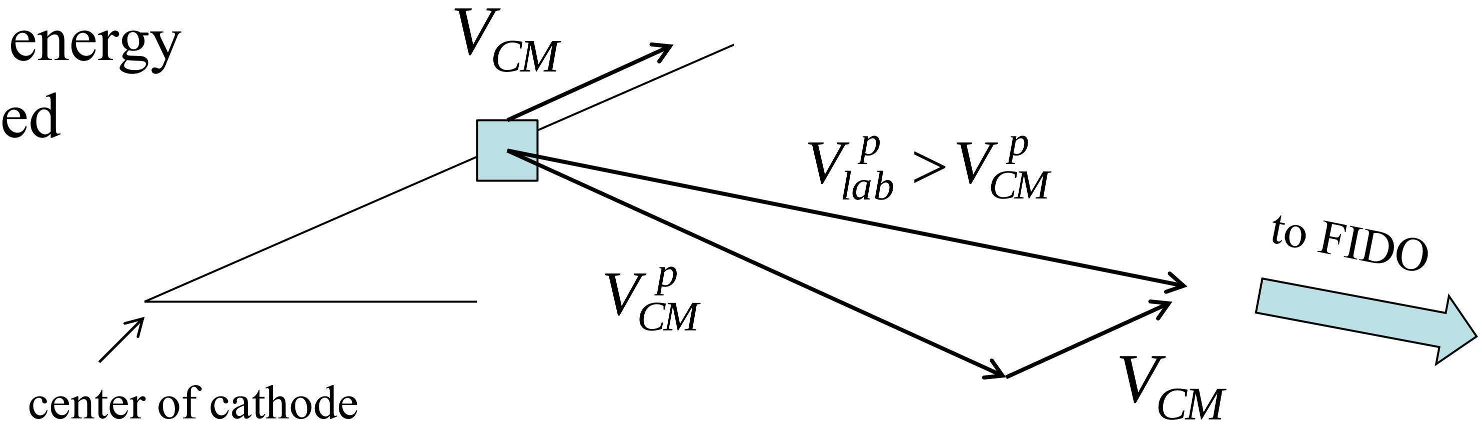
70 kV, 30 mA,1.25 mTorr, r_c=0.1 m, r_a=0.2 m
source D^+:D_2^+:D_3^+=0.06:0.23:0.71

- NB: need to include cold ion recombination with cold electrons to make agreement “reasonable”



Proton Energy in CM and Lab Frames

Proton energy upshifted



V_{CM}

$V_{lab}^{p} > V_{CM}^{p}$

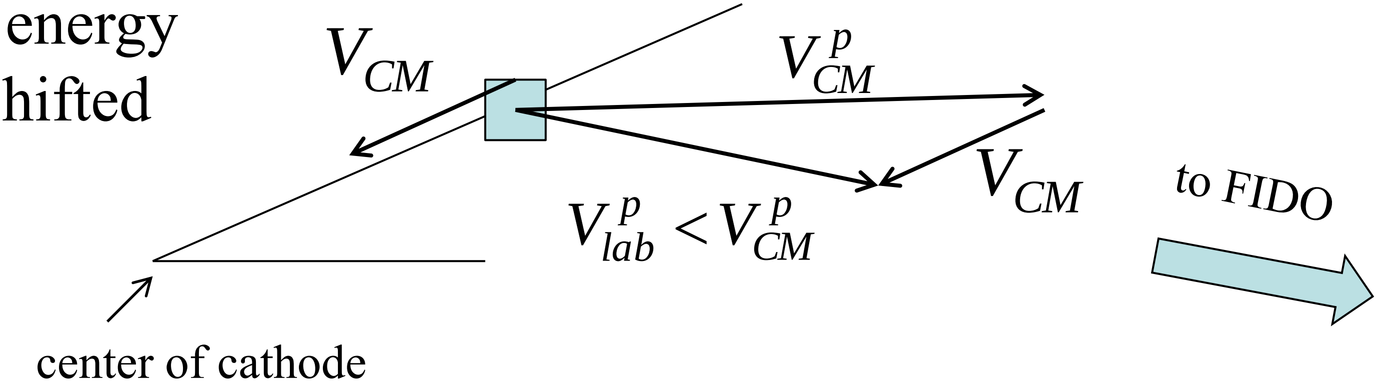
to FIDO

V_{CM}^{p}

V_{CM}

center of cathode

Proton energy downshifted



V_{CM}

V_{CM}^{p}

V_{CM}

to FIDO

$V_{lab}^{p} < V_{CM}^{p}$

center of cathode

Molecular Ions are Attenuated by Dissociation and Charge Exchange with D_2 Gas