
Produced by University Communications

Integral Transport Modeling of Spherically Symmetric, Gridded IEC Devices*

G. A. Emmert and J.F. Santarius

Fusion Technology Institute

University of Wisconsin

12th US-Japan Workshop on

Inertial Electrostatic Confinement Fusion

Osaka, Japan,

October 20-21, 2010

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

THE UNIVERSITY of WISCONSIN MADISON

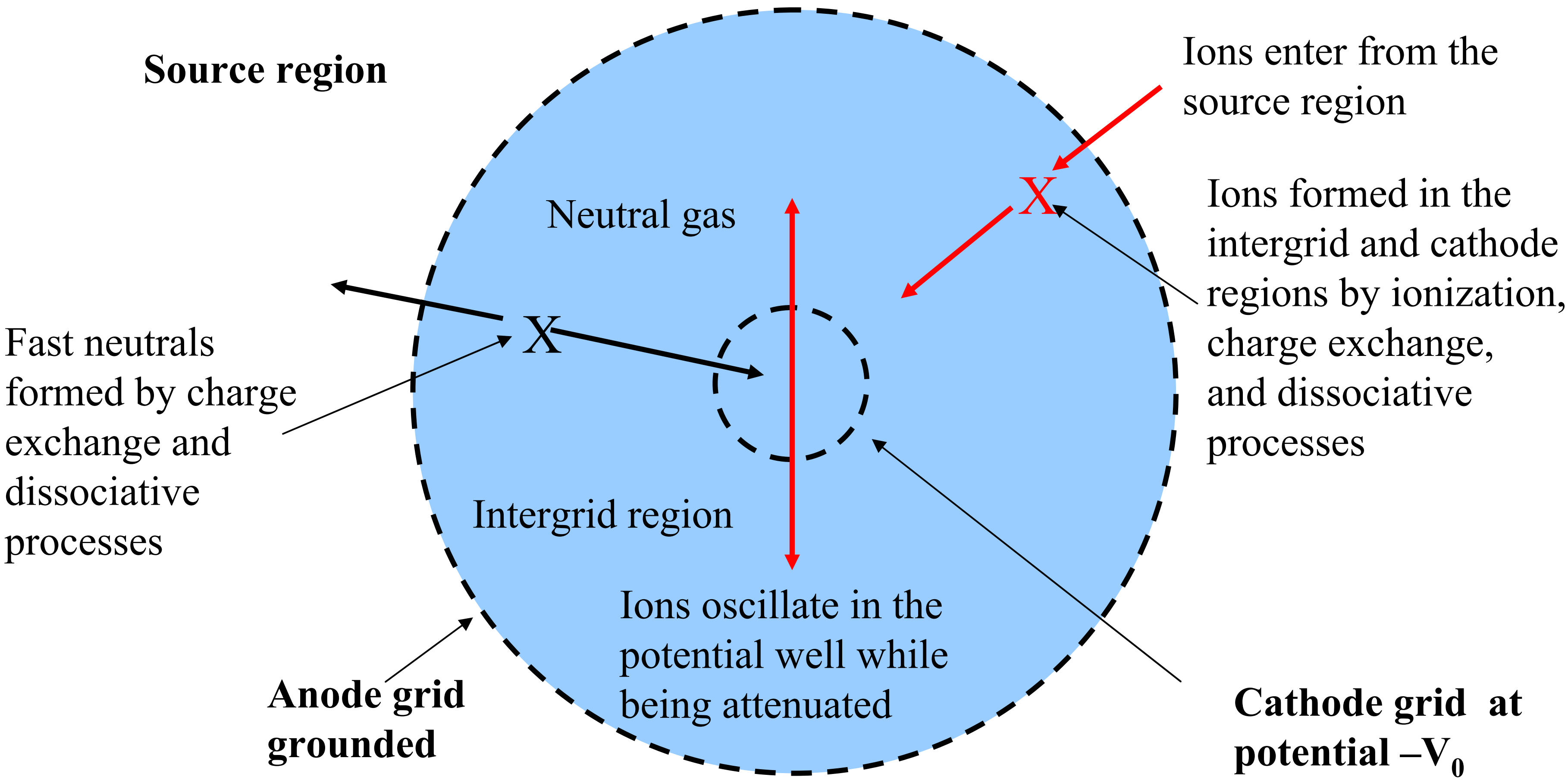
Outline

- Overview of the IEC integral equation approach
- Computer code predictions of the energy spectra of fast ions and neutrals
- Fusion ion Doppler shift (FIDO) diagnostic developed by Dave Boris
- Comparison of IEC computer code results with FIDO experimental results
- Summary and conclusions

Goal of this Research

- Understand the role of atomic and molecular processes in the flow of ions in gridded, spherical IEC devices
- Develop a computer model to predict the performance of these devices.
- The goal is a "first principles" model using experimental data for cross sections, and with no "adjustable parameters".

IEC Model

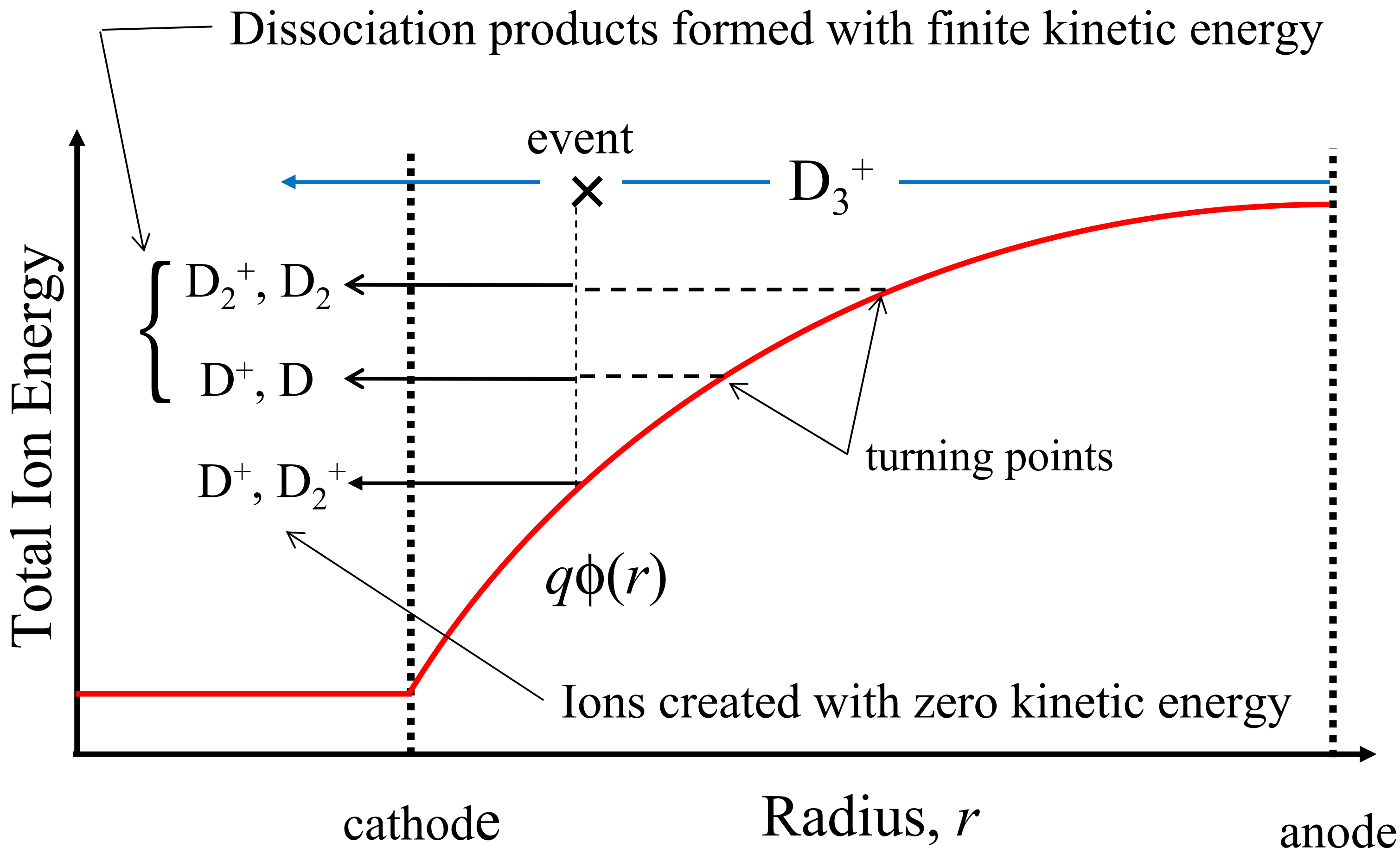


Source region
Ions enter from the source region
X
Ions formed in the intergrid and cathode regions by ionization, charge exchange, and dissociative processes
Neutral gas
X
Fast neutrals formed by charge exchange and dissociative processes
Intergrid region
Ions oscillate in the potential well while being attenuated
Anode grid grounded
Cathode grid at potential $-V_0$

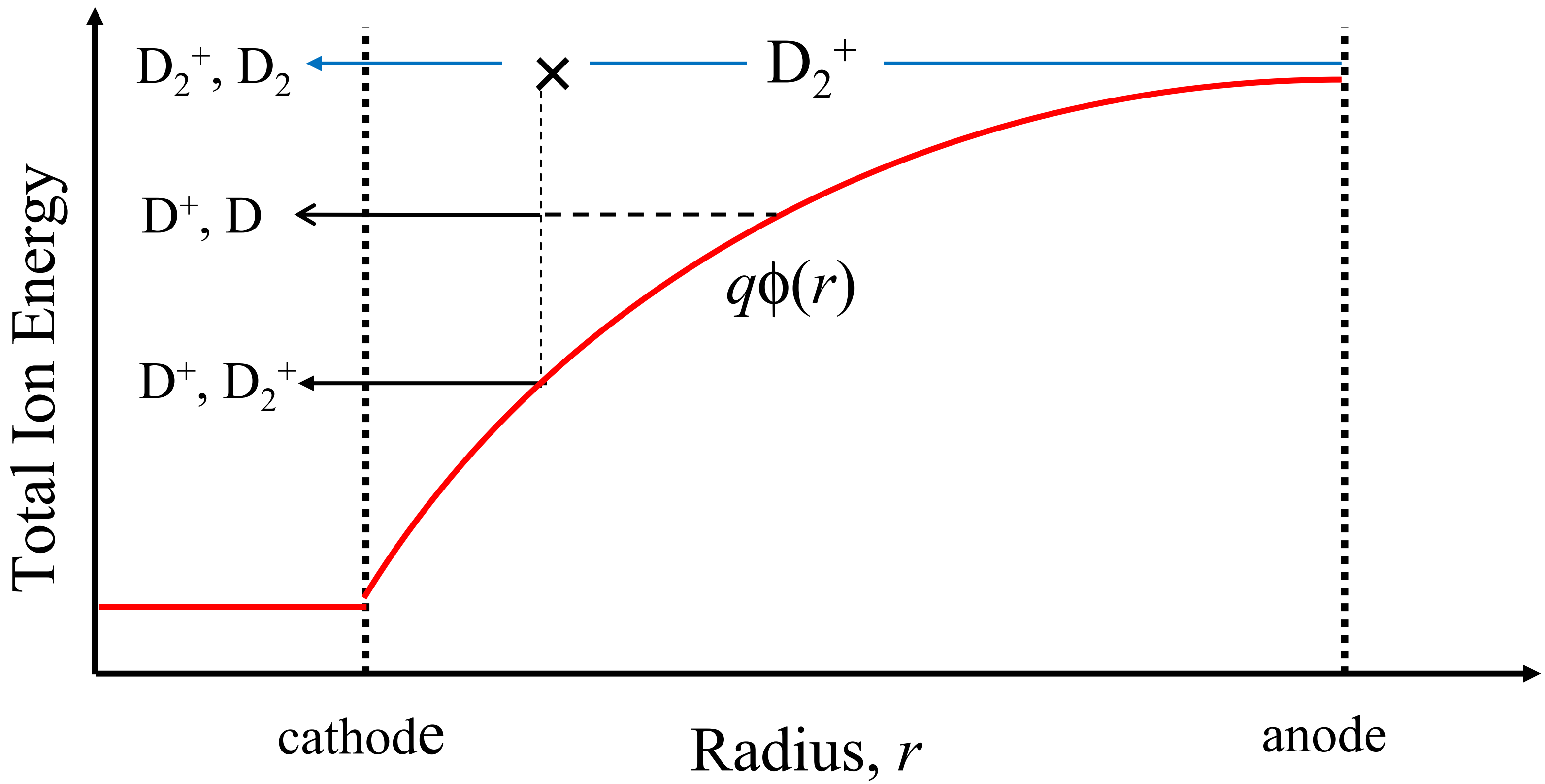
Basic Assumptions of the Model

- 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
- Interactions occur without momentum transfer between nuclei; daughter products travel at the same speed as parent
- Collisionless ion motion between interactions

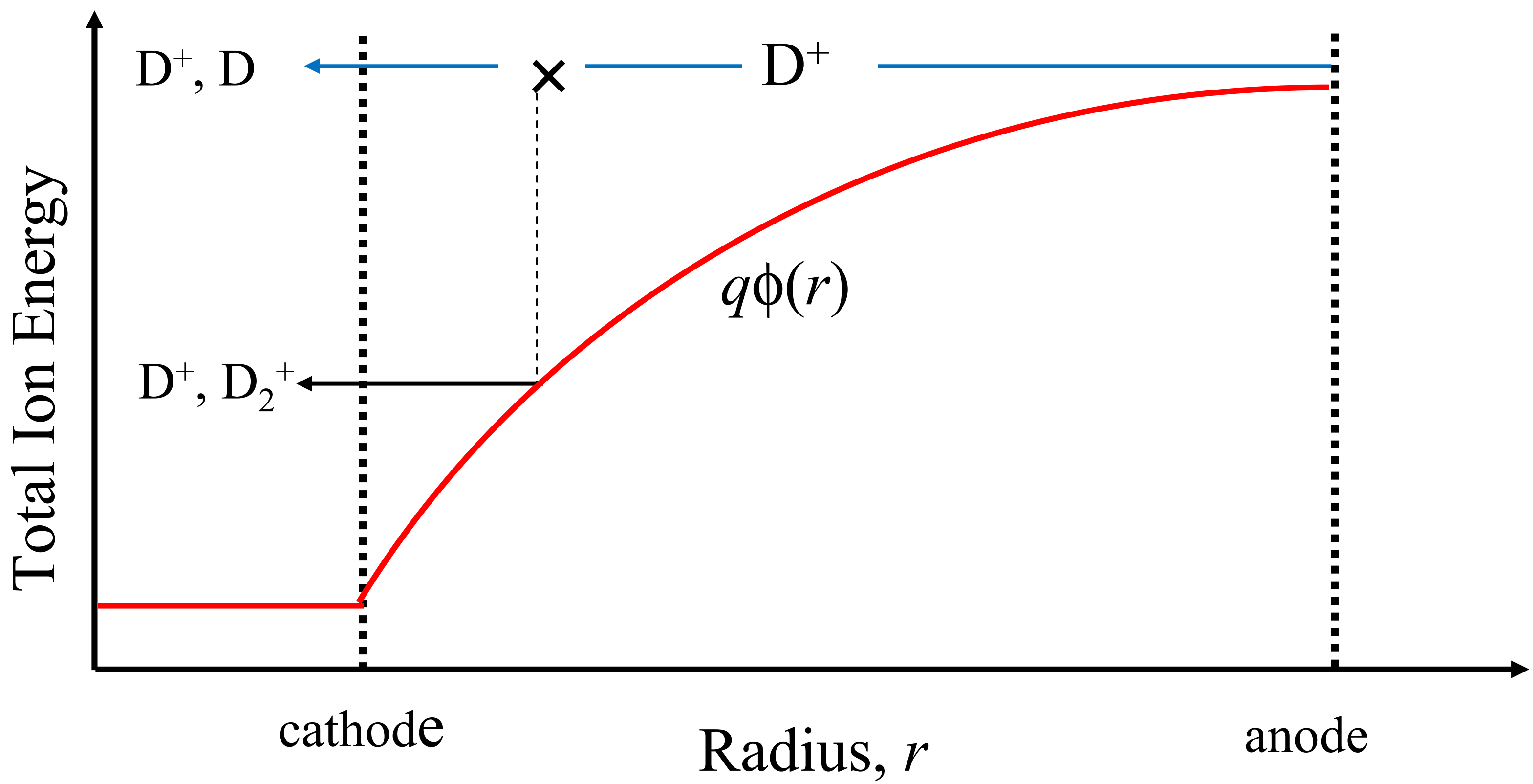
Molecular Ions are Attenuated by Dissociation and Charge Exchange with D_2 Gas



D_2^+ is Attenuated by Dissociation and Charge Exchange with D_2 Gas



D^+ is Attenuated by Charge Exchange with D_2 Gas



Formalism

$S_1(r)$ = slow D^+ source function

$S_2(r)$ = slow D_2^+ source function

S_1 and S_2 determined by ionization, charge exchange and dissociative processes involving the hot species interacting with the background D_2 gas.

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^+ ($i = 2$)

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

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

$K_{ij}(r, r')$ = kernel that relates the source function at one point to another point through molecular processes and acceleration by the electric field.

Given the Source Functions, $S_i(r)$, We Can Calculate:

- Energy spectrum, $f_i(r,E)$, of the current of each ion species
- Energy spectrum, $f_n(r,E)$, of the fast atom and molecule current
- Ion current collected by the cathode
- Neutron production rate
- etc

Example Calculation

Cathode radius = 10 cm

Anode radius = 25 cm

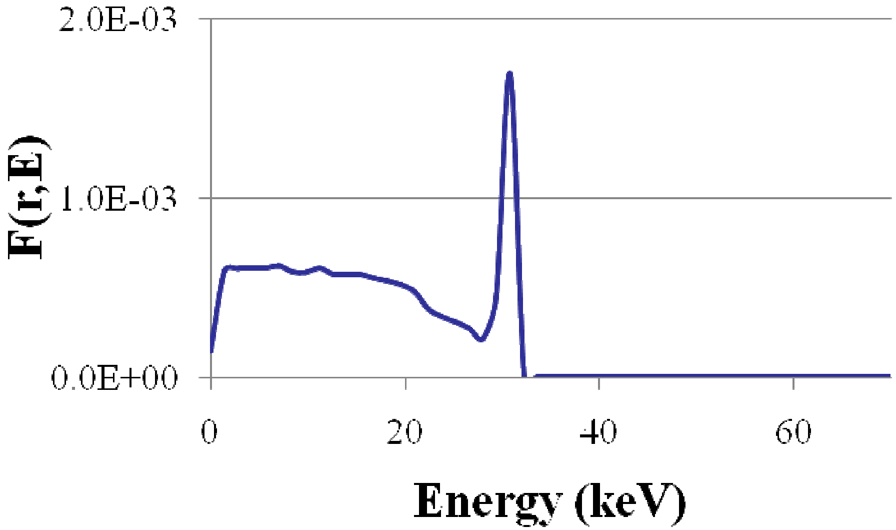
Cathode voltage = -70 kV

Cathode current = 30 mA

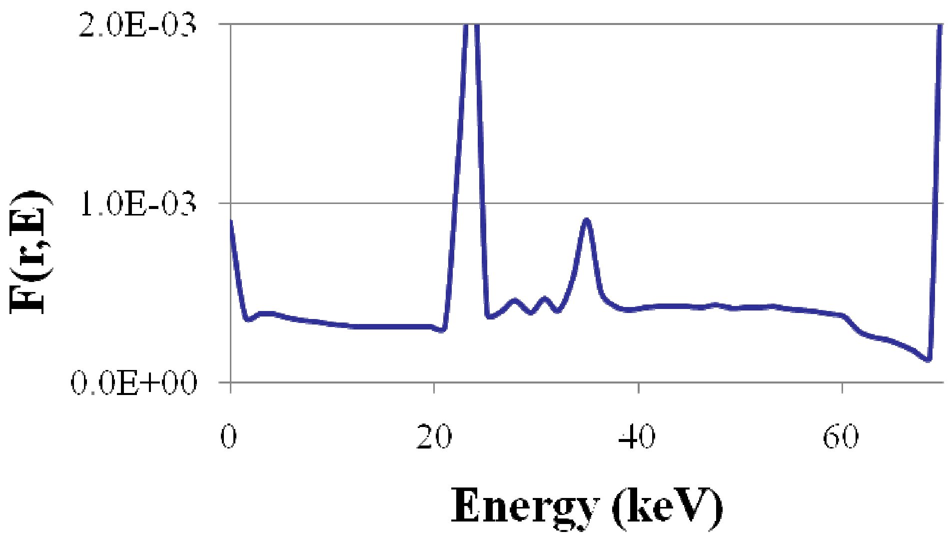
Gas pressure = 1.25 mTorr, D_2 gas

Source: D^+ (6%), D_2^+ (23%), D_3^+ (71%)

D^+ Energy Spectra, Inward Direction

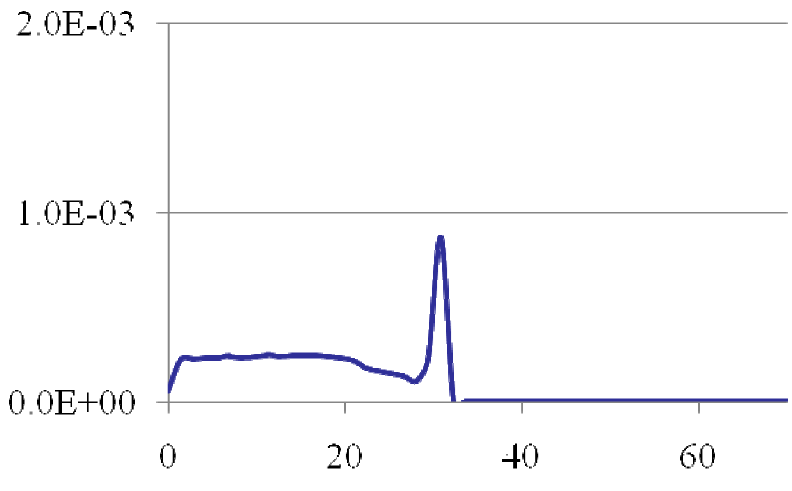


In the intergrid region
(r = 15 cm)

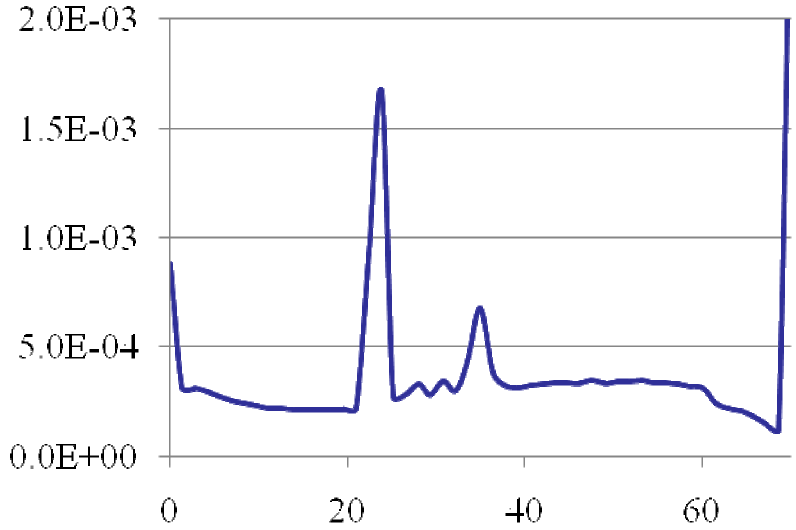


In the cathode region
(r = 5 cm)

D^+ Energy Spectra
- Outward Direction -

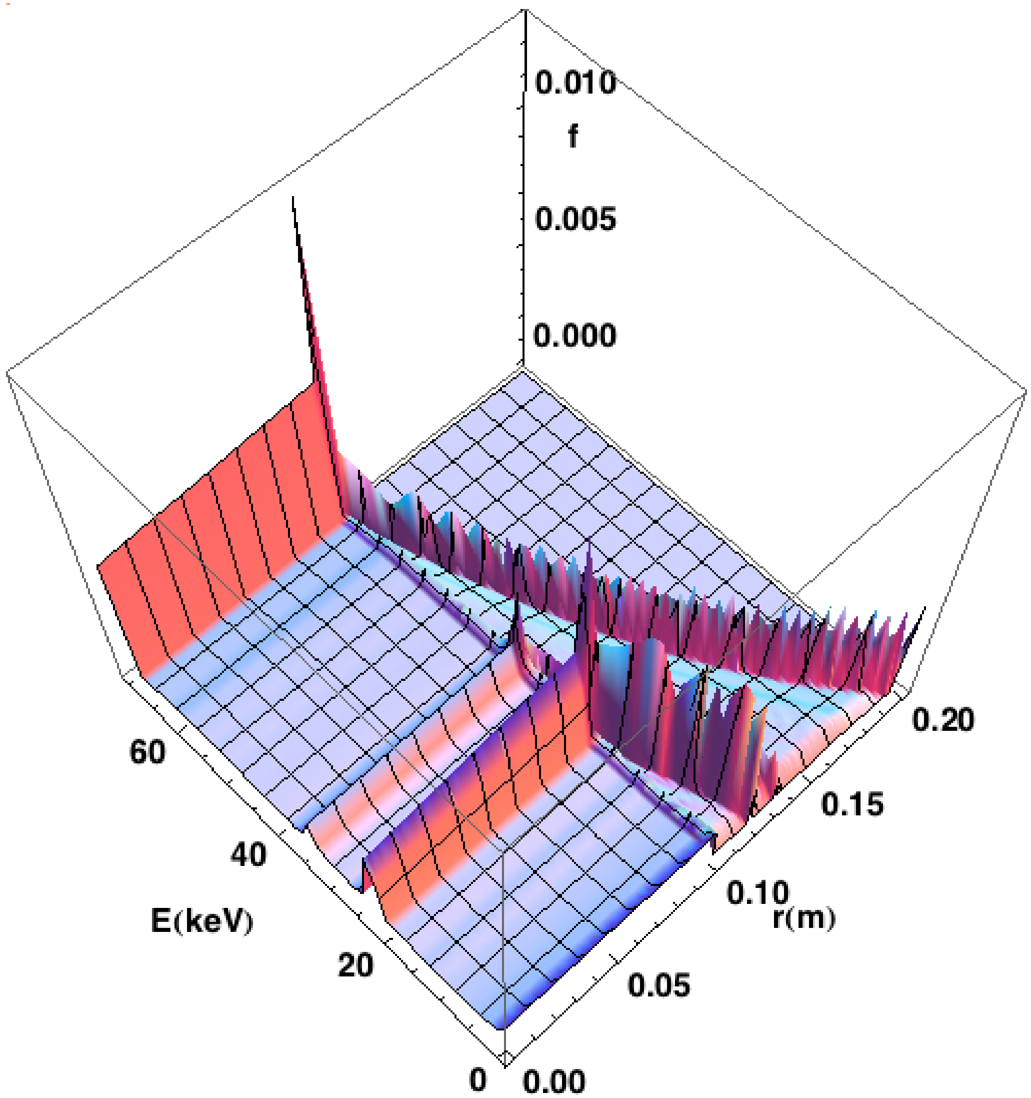


In the intergrid region
(r = 0.15 m)

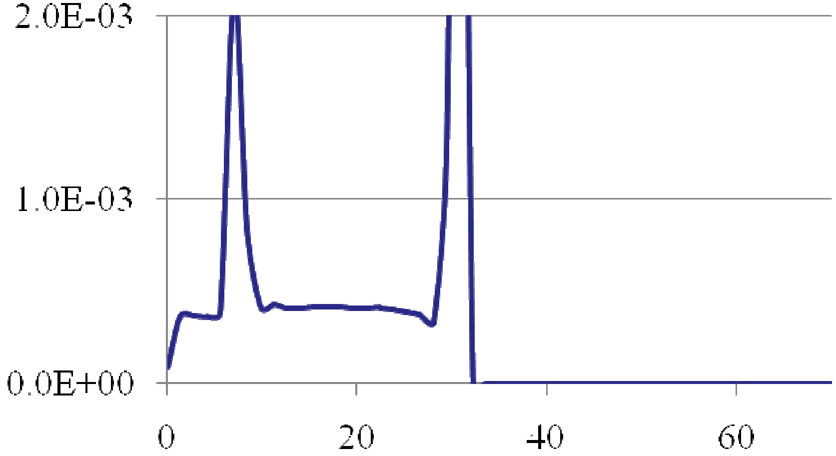


In the cathode region
(r = 0.05 m)

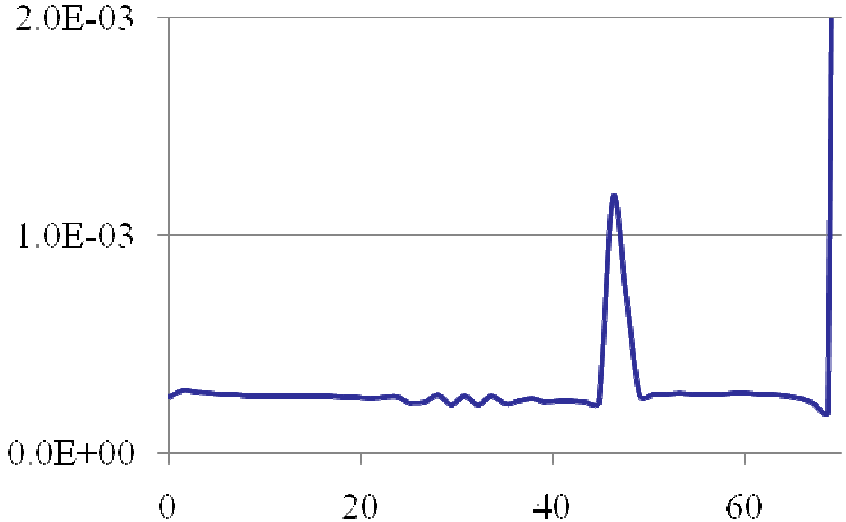
3-D View of Inward D^+ Energy Spectrum



D_2^+ Energy Spectra
- Inward -

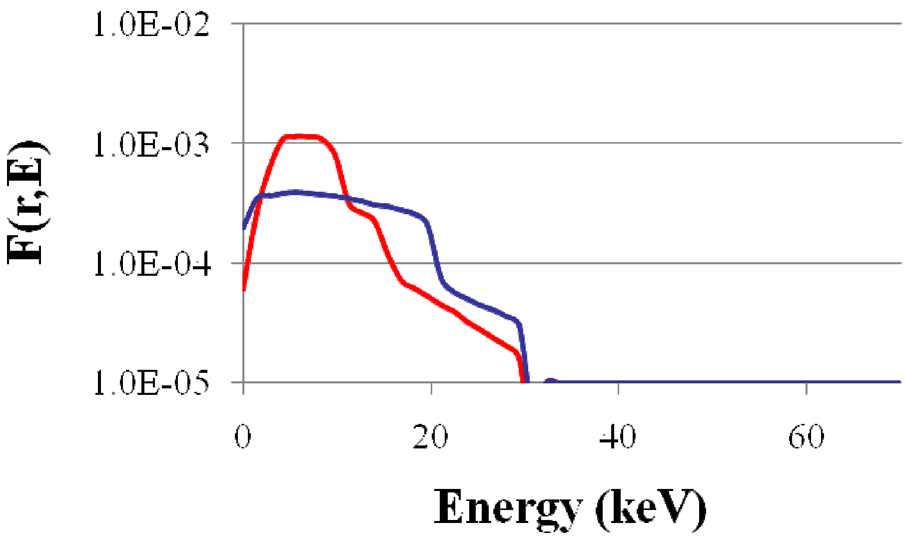


In the intergrid region
(r = 0.15 m)



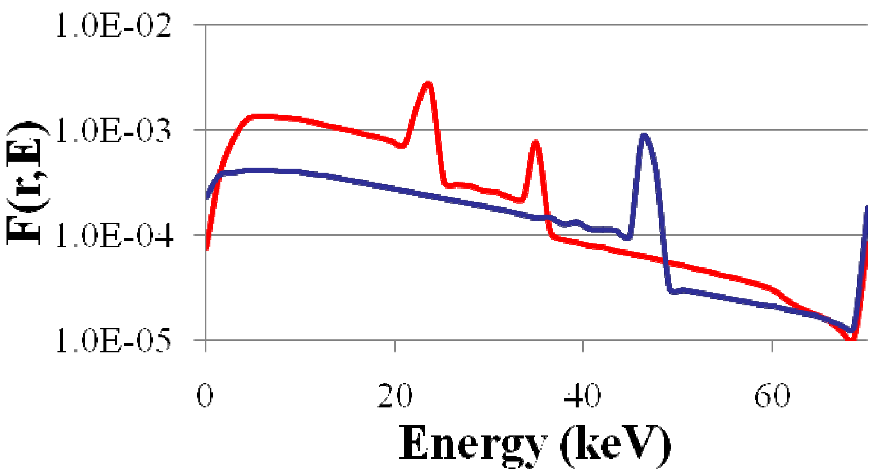
In the cathode region
(r = 0.05 m)

Energy Spectra of Atoms and Molecules
-Inward Direction-



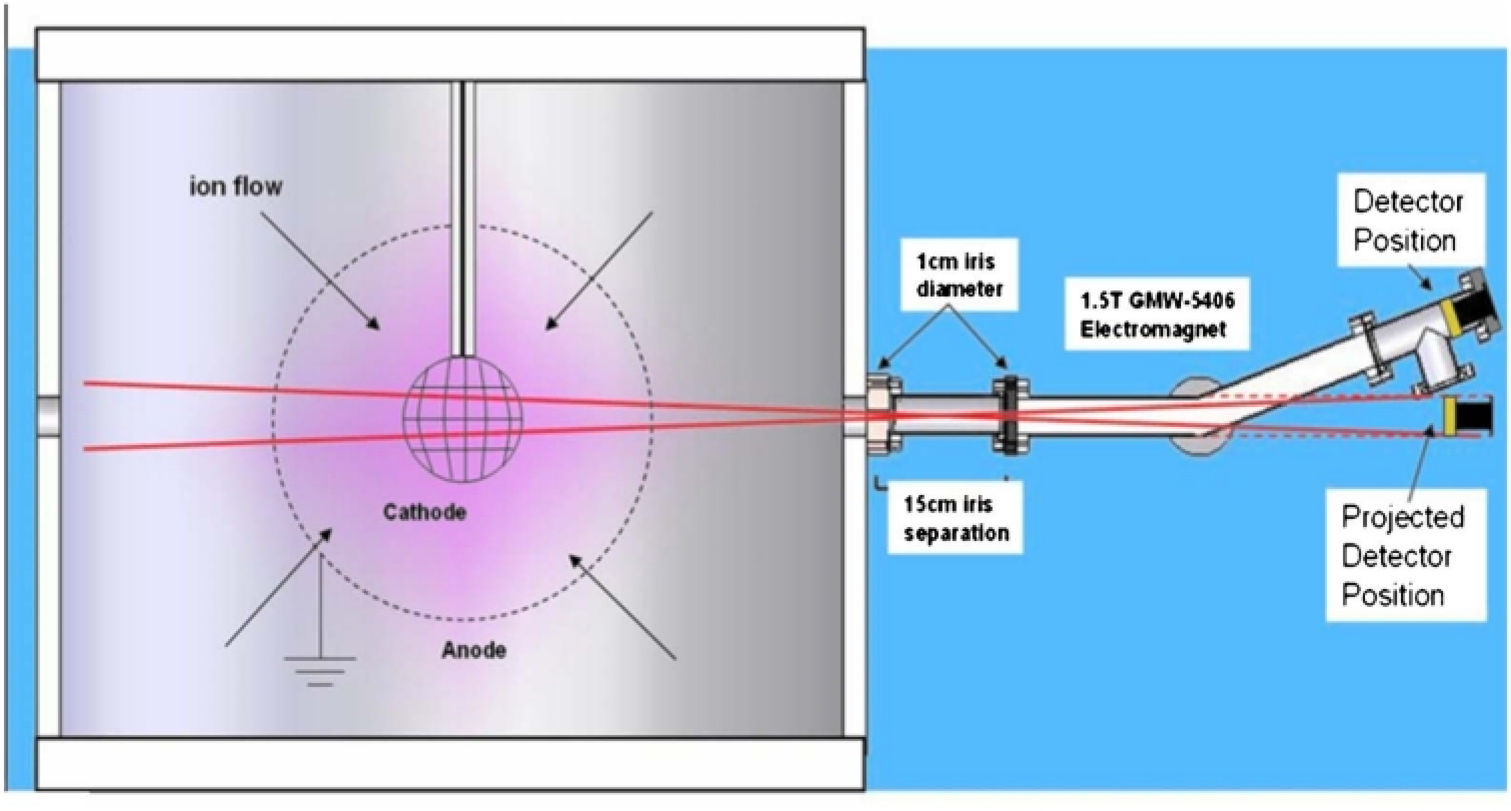
In the intergrid region
(r = 15 cm)

— D atoms
— D_2 molecules



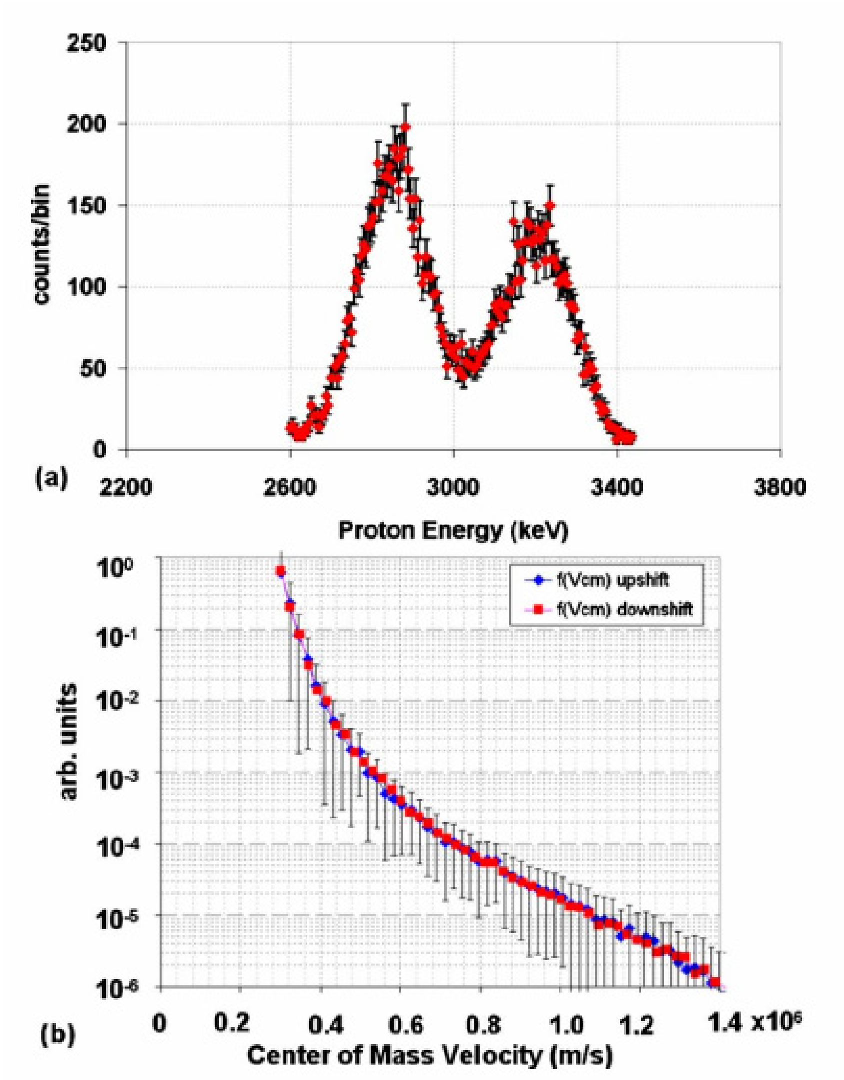
In the cathode region
(r = 5 cm)

Fusion Ion Doppler (FIDO) Diagnostic



Developed by Dave Boris, being extended by David Donovan

Analyzing FIDO data

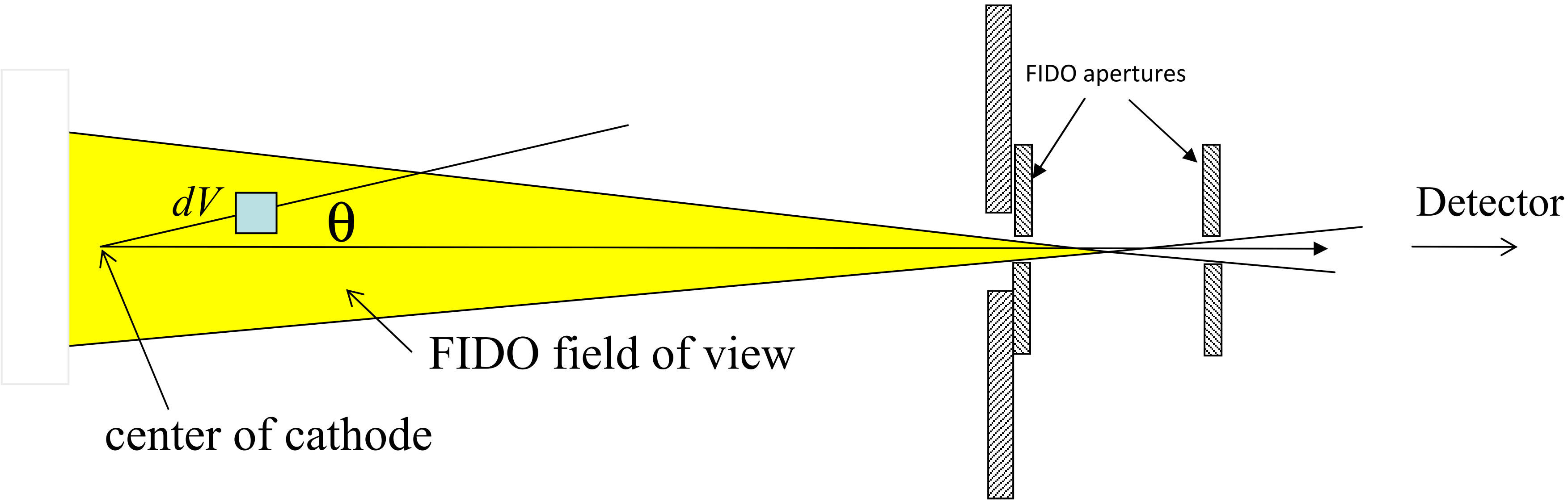


Boris assumed the FIDO diagnostic detected only protons emitted parallel (or anti-parallel) to the CM velocity of the reacting ions

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

$$\frac{m_p {V_{CM}^{p}}^2}{2} = \frac{3}{4}\left(Q + m_d {V_{CM}}^2\right)$$

FIDO Proton Energy Spectrum

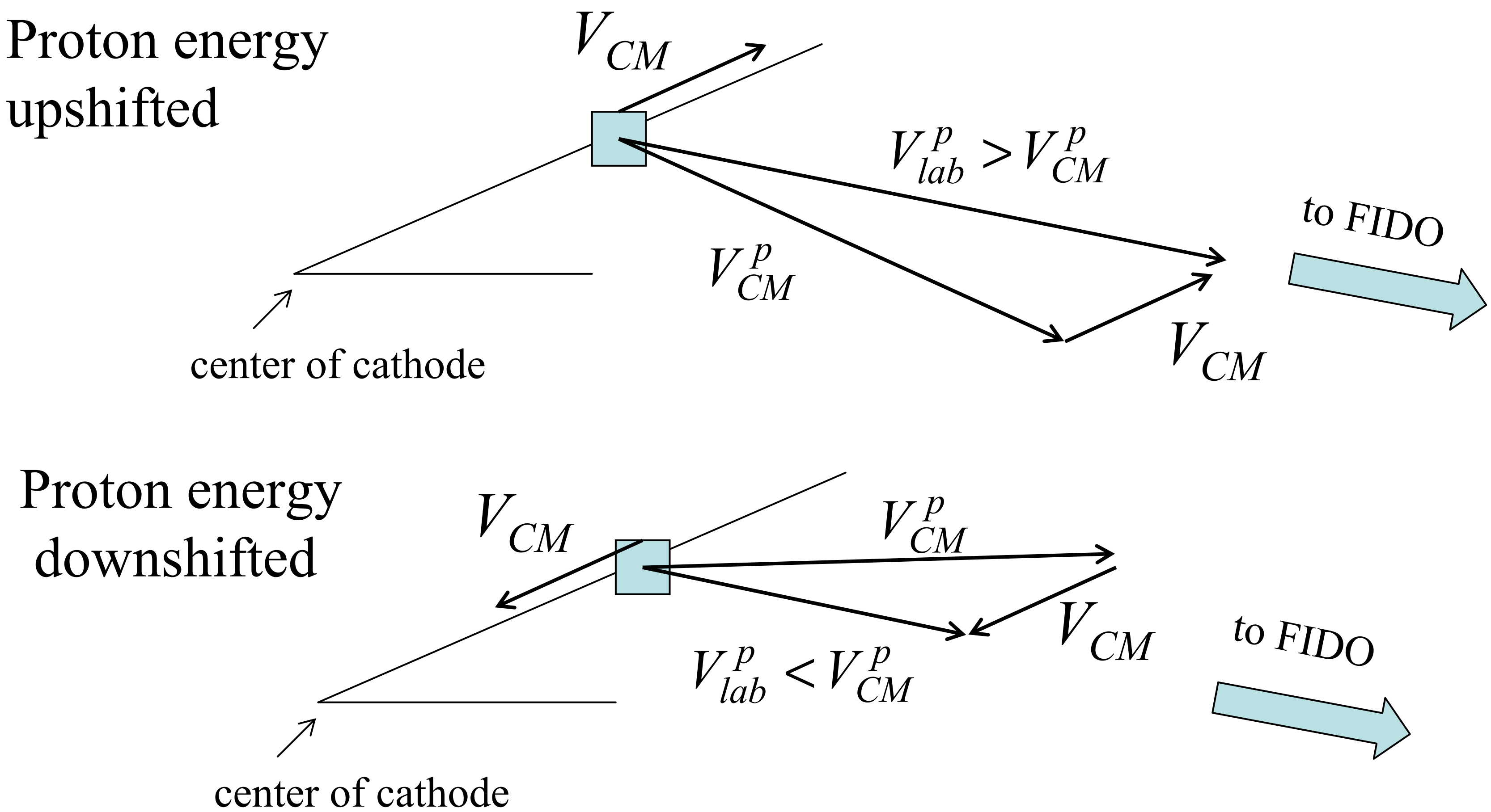


$$FIDO(E_p) = \sum_s \int dE \int dV \left\{ \left(\frac{1}{4\pi r^2} \right) F_s(r, E)(2n_g)\sigma_f(E_{CM}) \frac{\Delta\Omega(r,\theta)}{4\pi} \right\}$$

$\Delta\Omega$ = solid angle subtended by the FIDO apertures at point (r,θ)

s = inward, outward (radial direction of motion)

Proton Energy in CM and Lab Frames



FIDO is Sensitive to the Composite Energy Spectra

D^+, D_2^+, D_3^+ ions, D atoms, and D molecules all contribute to the FIDO signal. The relevant energy is the kinetic energy of the nucleus.

$$F_s(r,E) = \underbrace{F_{1s}(r,E)}_{D^+} + \underbrace{2F_{2s}(r,2E)}_{D_2^+} + \underbrace{3F_{3s}(r,3E)}_{D_3^+} + \underbrace{F_{as}(r,E)}_{\text{fast D atoms}} + \underbrace{2F_{ms}(r,2E)}_{\text{fast } D_2 \text{ molecules}}$$

Theoretical Analysis of FIDO

Integrating over volume, the upshifted part of the FIDO spectrum measures the energy spectrum averaged over radius, but with central weighting,

$$\int \left\{ G_R(r)\, F_o(r,E) + G_L(r) F_i(r,E) \right\} dr$$

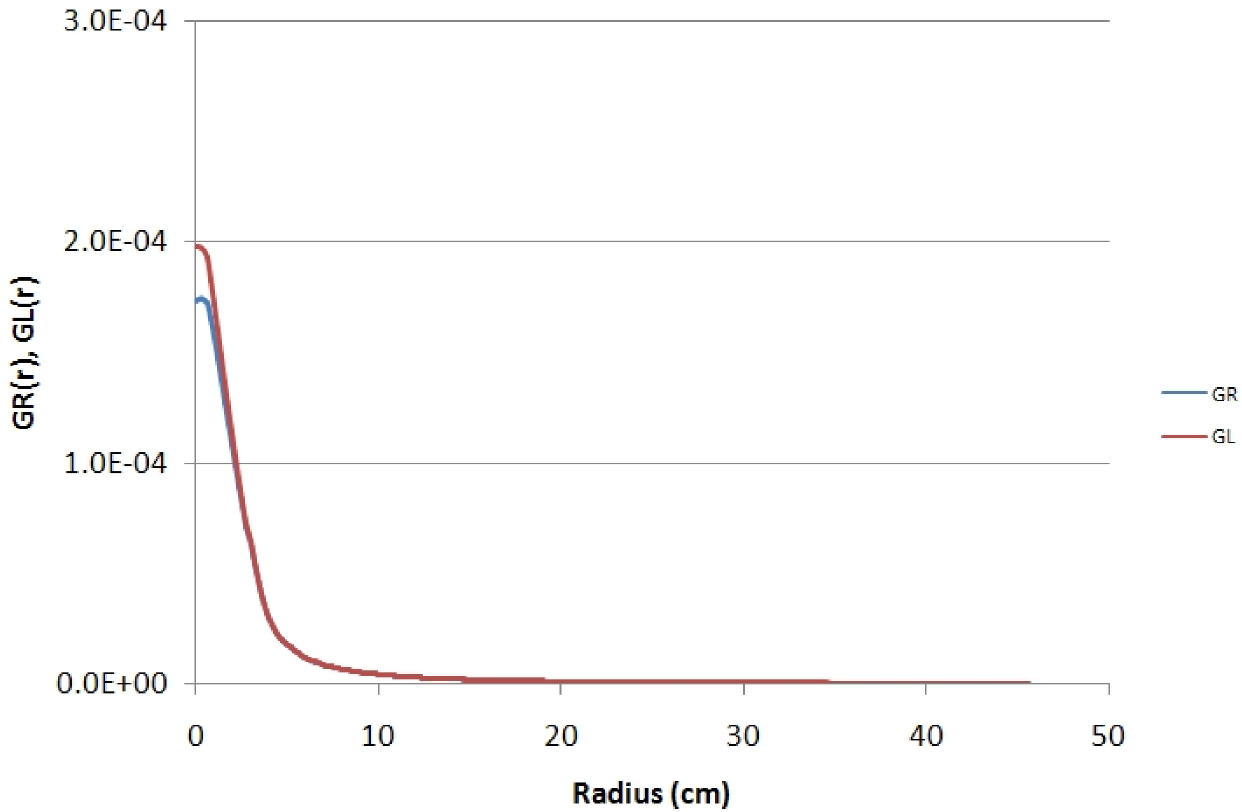
The downshifted part measures the energy spectrum averaged over radius, but with a different central weighting,

$$\int \left\{ G_R(r)\, F_i(r,E) + G_L(r) F_o(r,E) \right\} dr$$

where

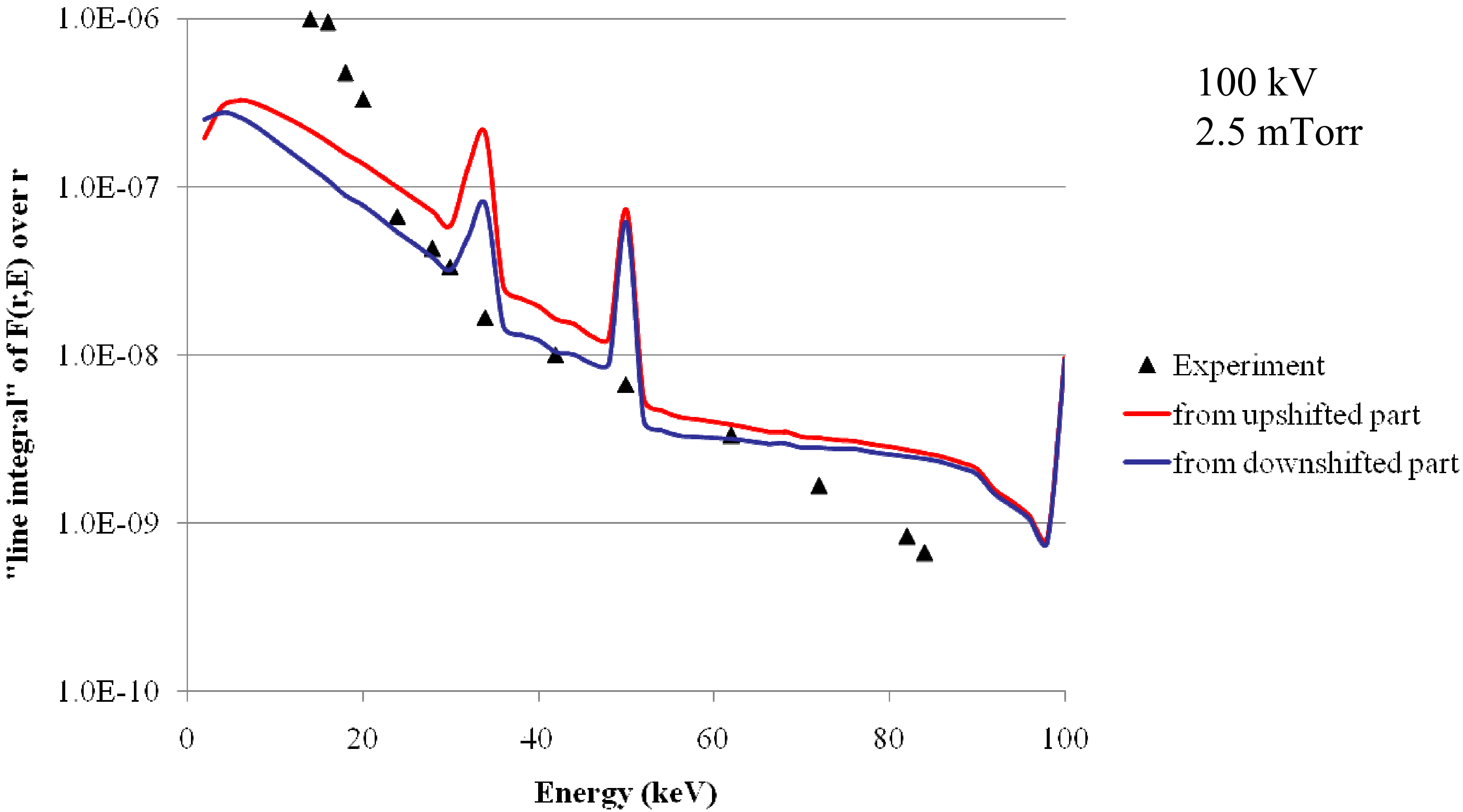
$$G_R(r) = \int_0^{\phi_1} \Delta\Omega(r,\theta) \sin\theta \, d\theta, \qquad G_L(r) = \int_{\phi_2}^{\pi} \Delta\Omega(r,\theta) \sin\theta \, d\theta$$

The origin dominates in the radial dependence of the G_R and G_L Functions



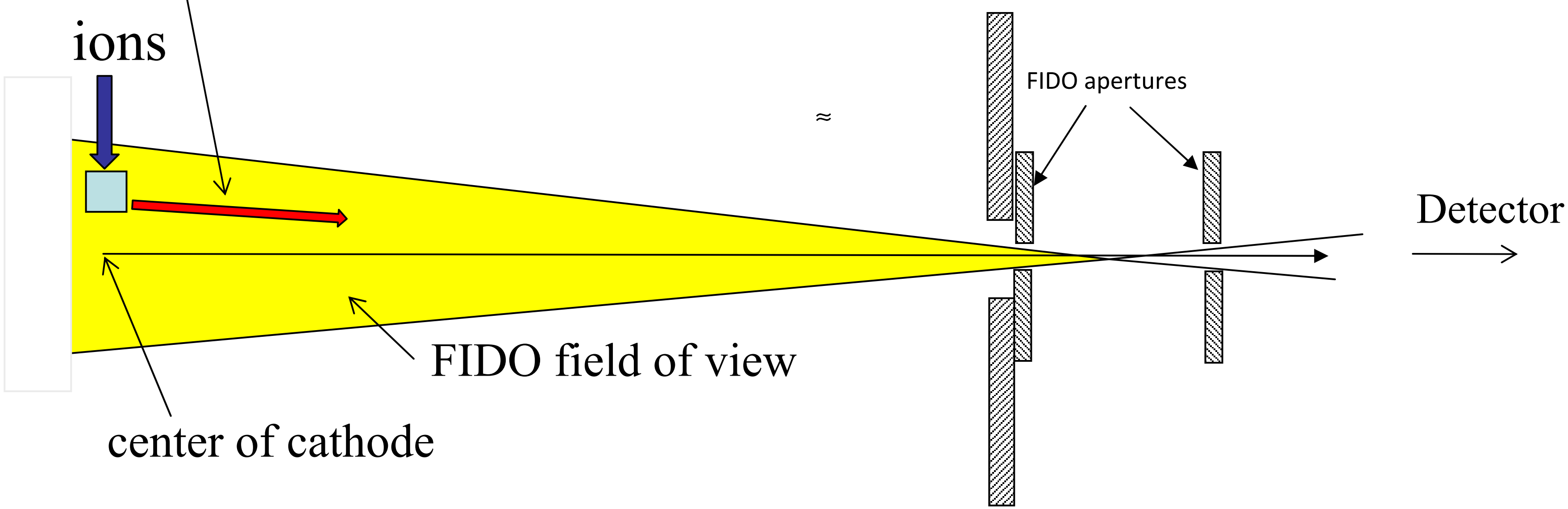
Caveat: the strong peak at r = 0 is due to our ideal model in which all ions are focused at the origin. Perturbations that break the symmetry and elastic scattering will defocus the ions and reduce the peak in the G functions.

Comparison of IEC Code with FIDO Experiment

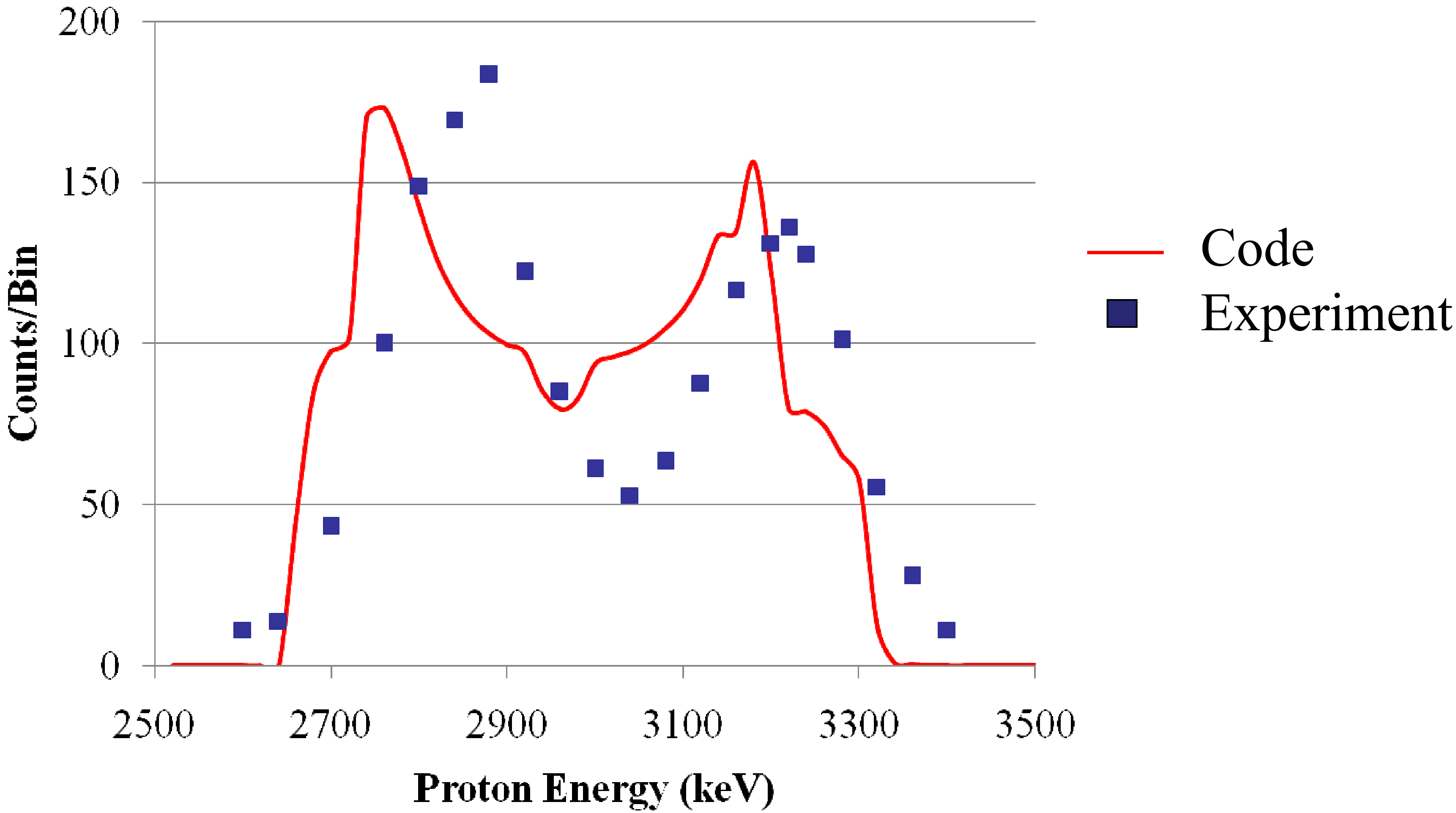


Parallel Velocity Assumption is Violated Near the Origin

For θ near 90° and r near zero, fusion protons emitted perpendicular to V_{CM} can reach the FIDO detector. These protons have little energy shift. The parallel velocity assumption treats them as having arisen from fusion reactions by low energy ions.

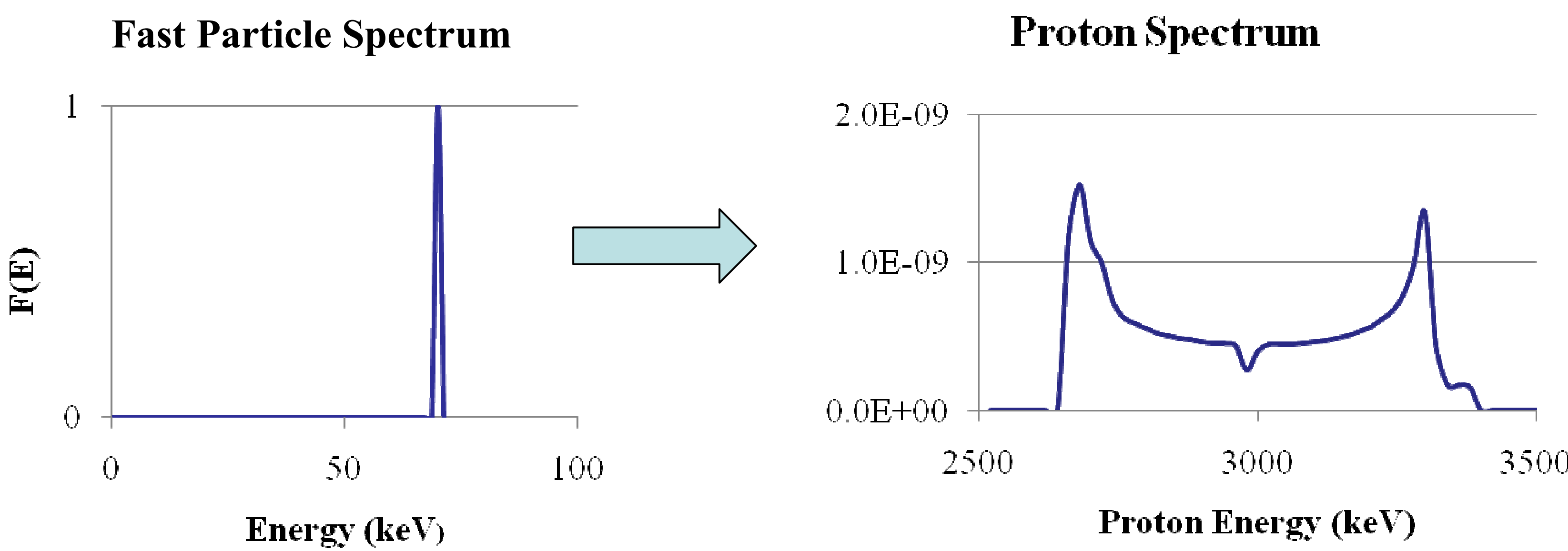


Comparison of Predicted Proton Energy Spectra with Measured Spectra



FIDO proton spectrum of a monoenergetic distribution

The proton energy spectrum arising from a mono-energetic fast particle distribution is not mono-energetic. Instead, it contains a broad spectrum of energies. The example below is for 70 keV neutral atoms traveling radially inward and outward.



Summary and Conclusions

- The IEC code can calculate the detailed energy spectra of the various ion and neutral particle species as a function of radius.
- The capability to simulate the FIDO diagnostic has been added to the code.
- Comparison with experimental results:
  - Numerical results are in approximate agreement with experimental results
  - Experiment does not show the predicted discrete spectra. This could be due to insufficient resolution in the experiment, or to incorrect assumptions in the model

Future Work

Areas where refinement of the IEC code will be pursued include:

- adding negative ions,
- simulation of the time-of-flight diagnostic,
- relaxing the assumption of flat potential in the cathode region.

Related Publications

- G.A. Emmert and J.F. Santarius, "Atomic and molecular effects on spherically convergent ion flow. I. Single atomic species", Physics of Plasmas **17**, 013502 (2010).
- G.A. Emmert and J.F. Santarius, "Atomic and molecular effects on spherically convergent ion flow. II. Multiple molecular species", Physics of Plasmas **17**, 013503 (2010).
- D.R. Boris, G.L. Kulcinski, J.F. Santarius, D.C. Donovan, and G.R. Piefer, "Measuring D(d,p)T reactant energy spectra with Doppler shifted fusion products", J. Appl. Physics **107**, 123305 (2010).

Produced by University Communications

Questions ?

THE UNIVERSITY of WISCONSIN MADISON