Six Ion Gun Fusion Experiment (SIGFE) Findings and Future Work

Matt K. Michalak, Brian J. Egle*
Gerald L. Kulcinski, John F. Santarius

Presented at
13th US-Japan IEC Workshop
7-8 December 2011 in Sydney, NSW

*At ORNL

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Presentation outline

- Review of past information presented on the SIGFE
- Most recent results
- Diagnostics used
  - 2 Si proton detectors, 1 ^{3}He neutron detector
  - Fusion Ion DOppler shift (FIDO)
- Next steps

IEC fusion reaction modes

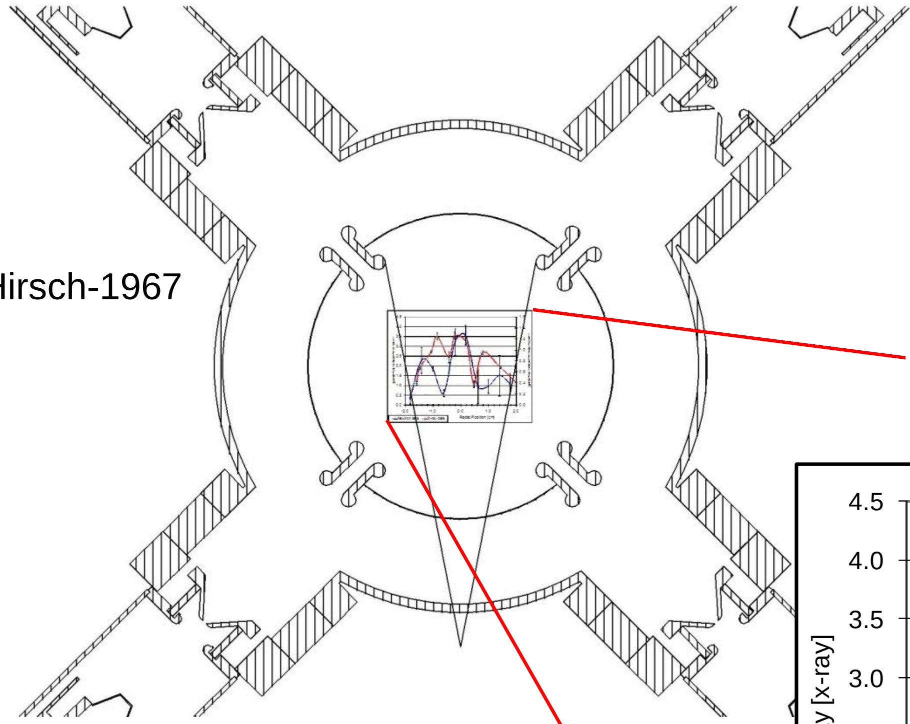
- Basic IEC operation modes
  - Beam-background
  - Beam-embedded
  - Converged core
  - Multiple virtual electrode formation (Poissors)

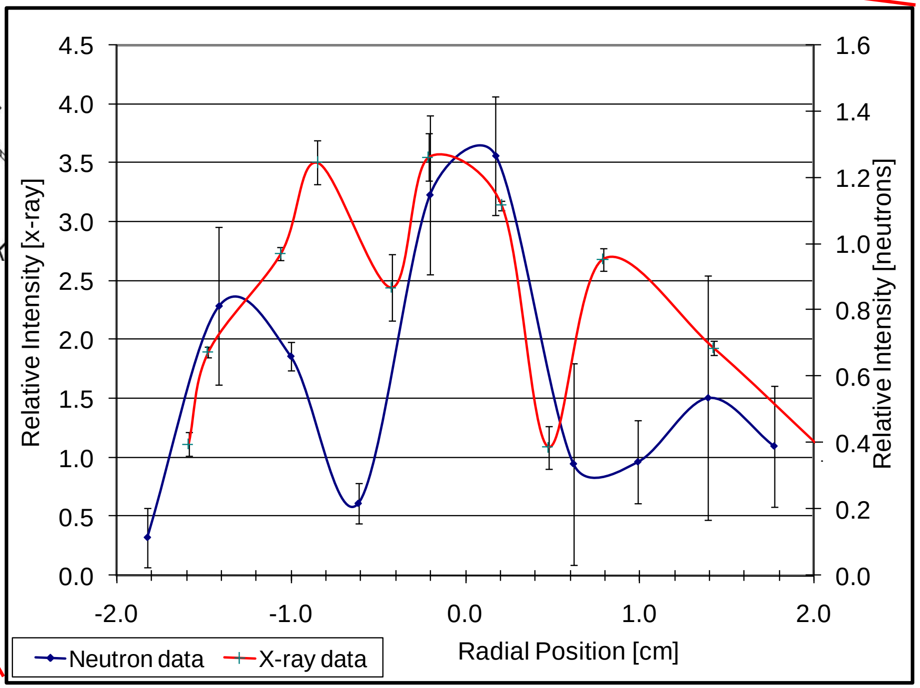
- Beam-background and beam-embedded shown to dominate in gridded systems with mid to high pressure (>0.3 Pa)

Experimental results of Hirsch showed tri-modal distribution

- **Hirsch-1967 reported a tri-modal spatial distribution of fusion neutrons and bremsstrahlung radiation inside the cathode**
- **Theory of virtual electrode formation (poissors) used to explain these results**

Hirsch-1967

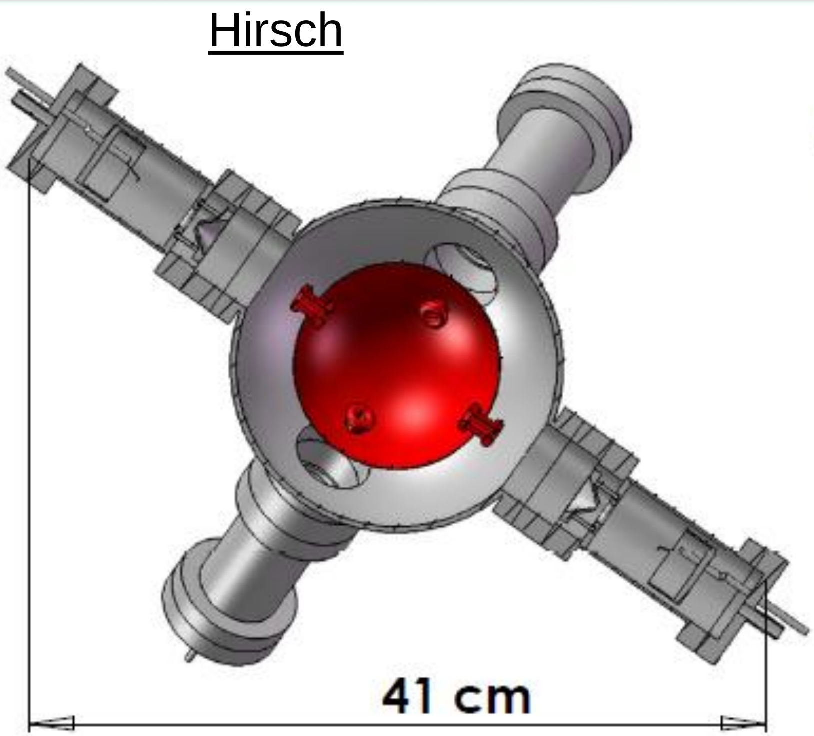


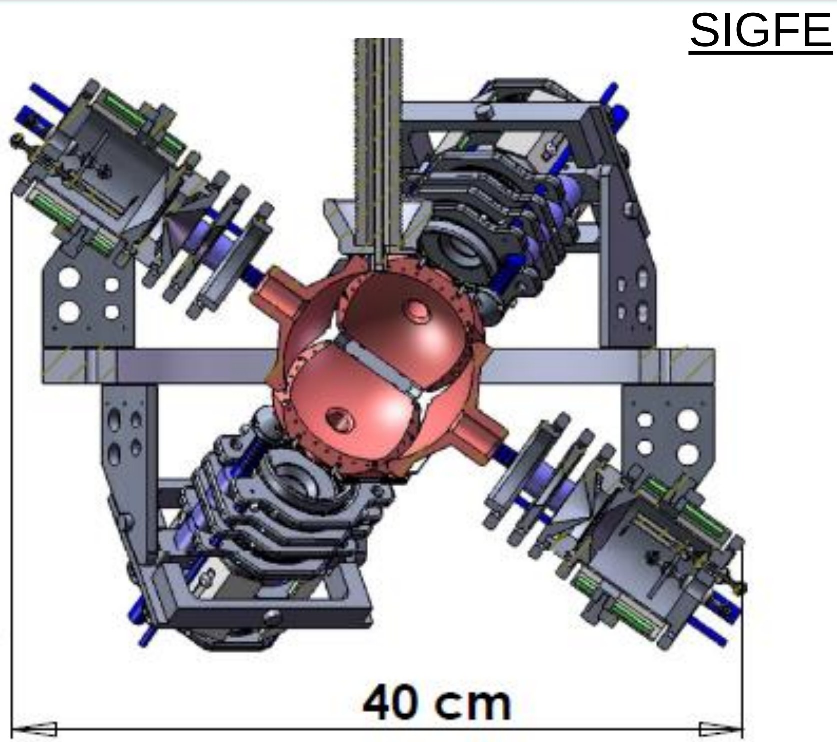


Data taken at pressures between 0.3 to 1 Pa (2 to 8 mTorr)

Source: Hirsch, R.L. (1967). Inertial-electrostatic confinement of ionized fusion gases. *Journal of Applied Physics, 38*(11), 4522-4534

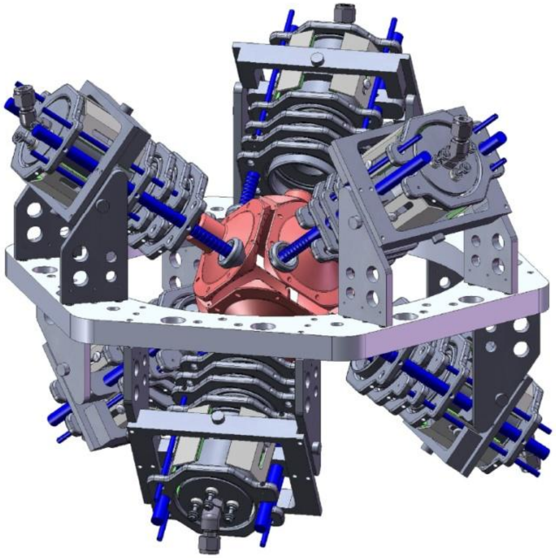
Comparison of the SIGFE to Hirsch geometry



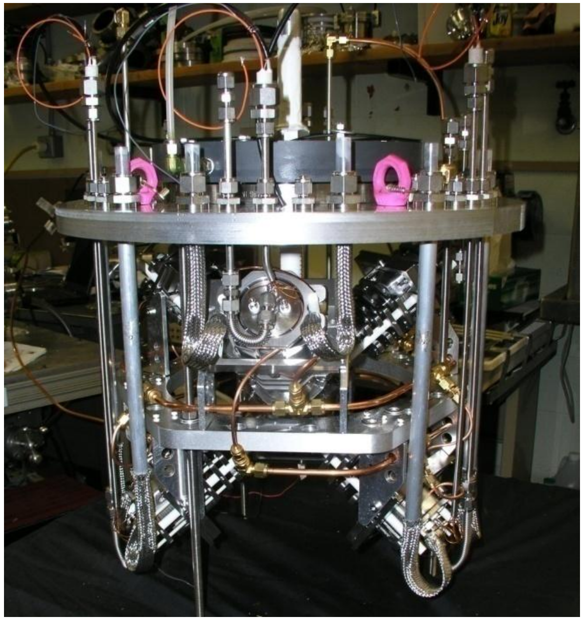


- SIGFE's design attempted to replicate the geometry of Hirsch-1967 as close as possible
- Major differences that may affect electric fields include:
  - Grounded ring in SIGFE replicates chamber wall as anode
  - Addition of focusing lens
  - Electron suppression on cathode

Design to reality



December 2007



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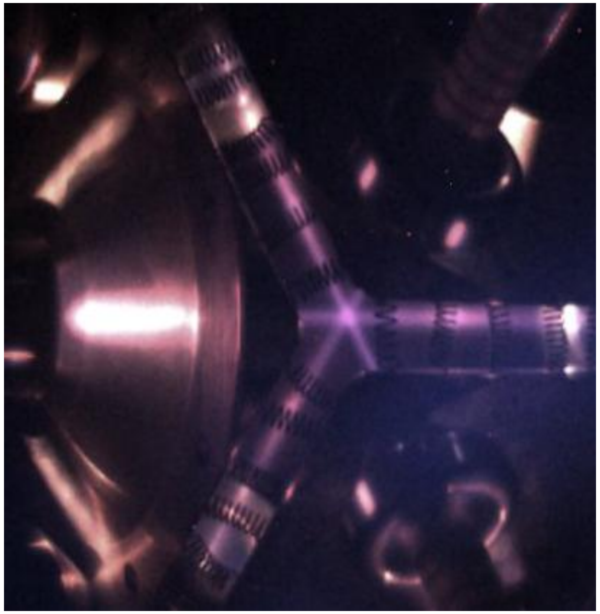

September 2009

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SIGFE can operate in a large parameter space

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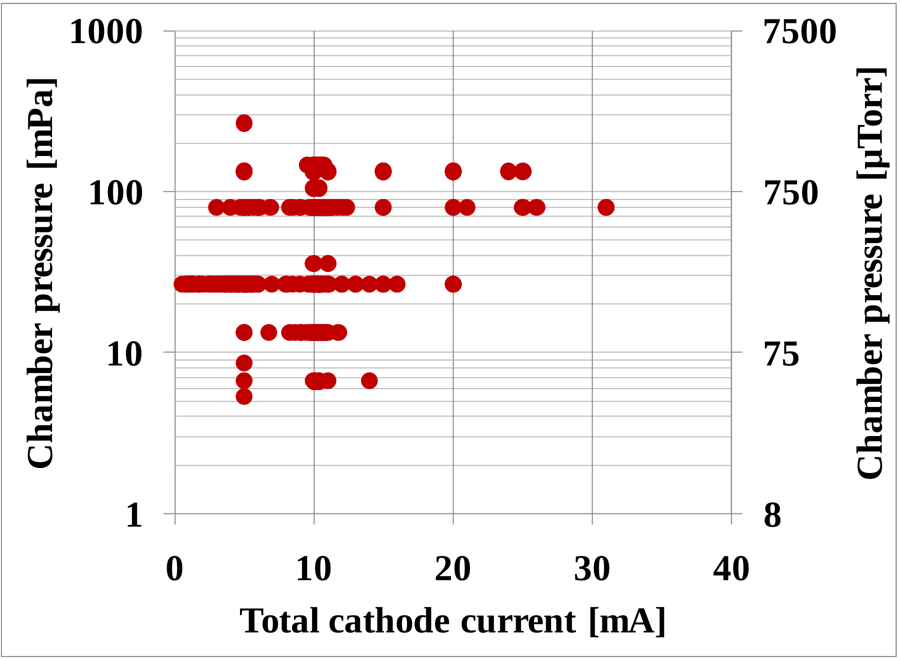
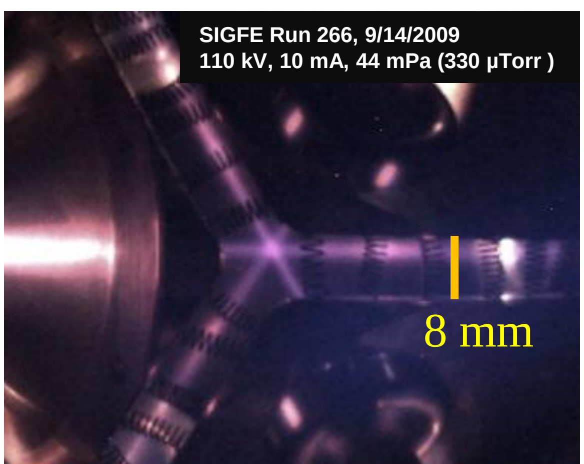
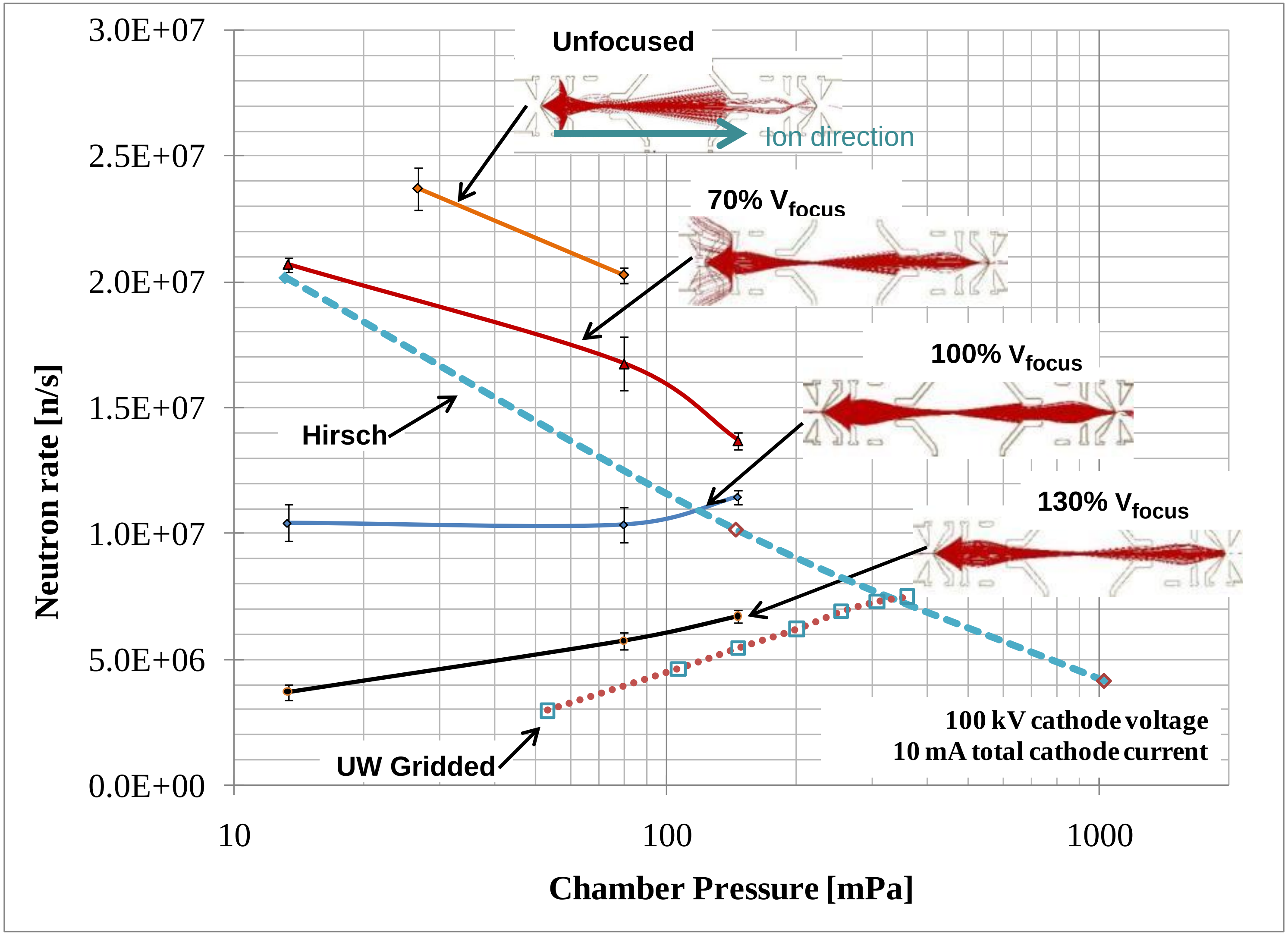




- Stable -150 kV operation achieved
- 2 mm ion beam width at cathode center at cathode voltages from -50 to -150 kV
- 2 to 31 mA total cathode current
- 5 to 270 mPa chamber pressure (deuterium)

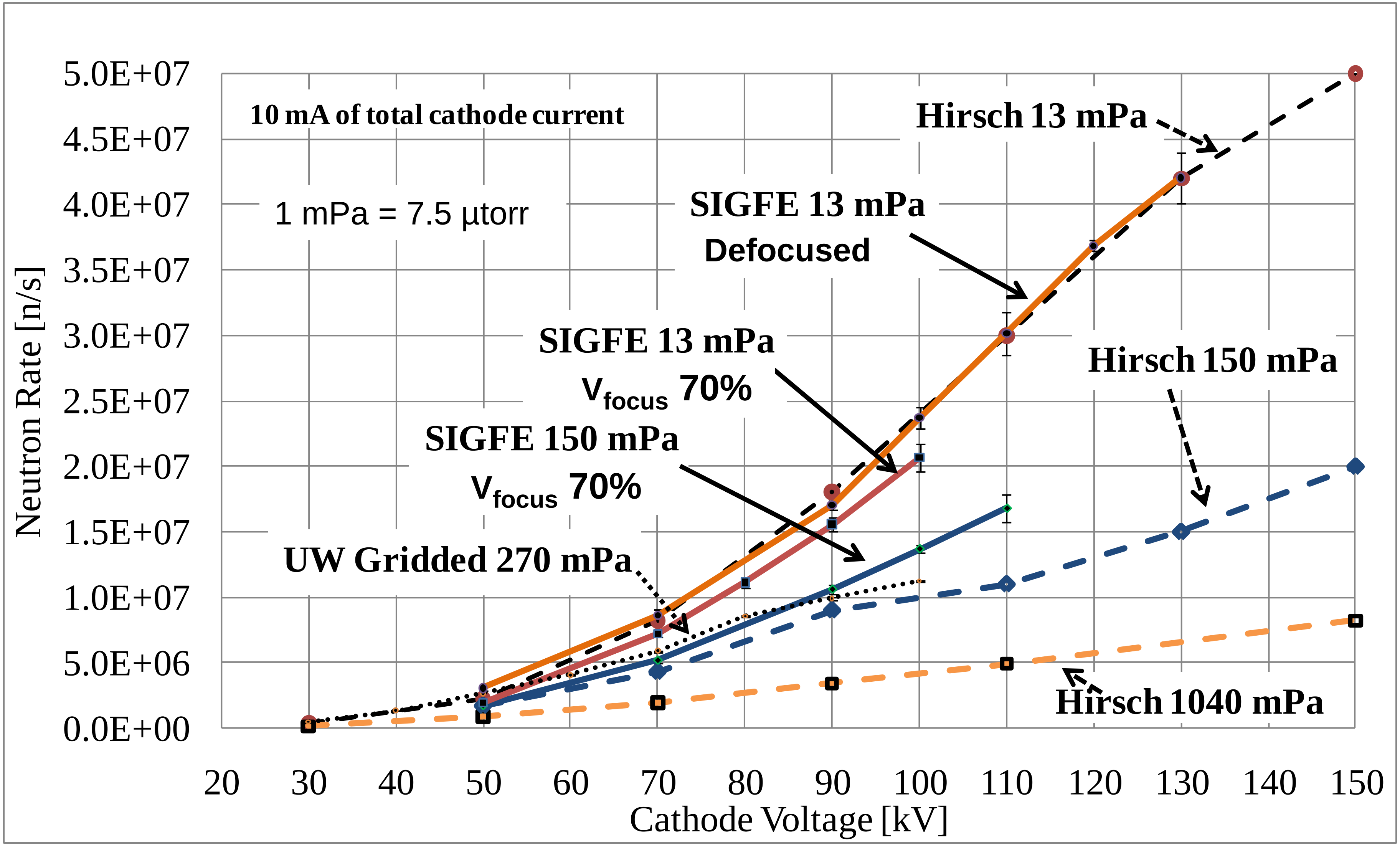
SIGFE neutron rate scaling with pressure is dependent on focus



- Well focused SIGFE n/s has weak pressure dependence
- Over focused SIGFE has direct n/s pressure dependence
- Under focused SIGFE has inverse n/s dependence
- Under focused SIGFE has similar scaling to Hirsch

1 mPa = 7.5 μtorr

Defocused SIGFE data matches Hirsch D-D neutron rates



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FIDO diagnostic measured <0.2% of total D-D fusion from cathode center

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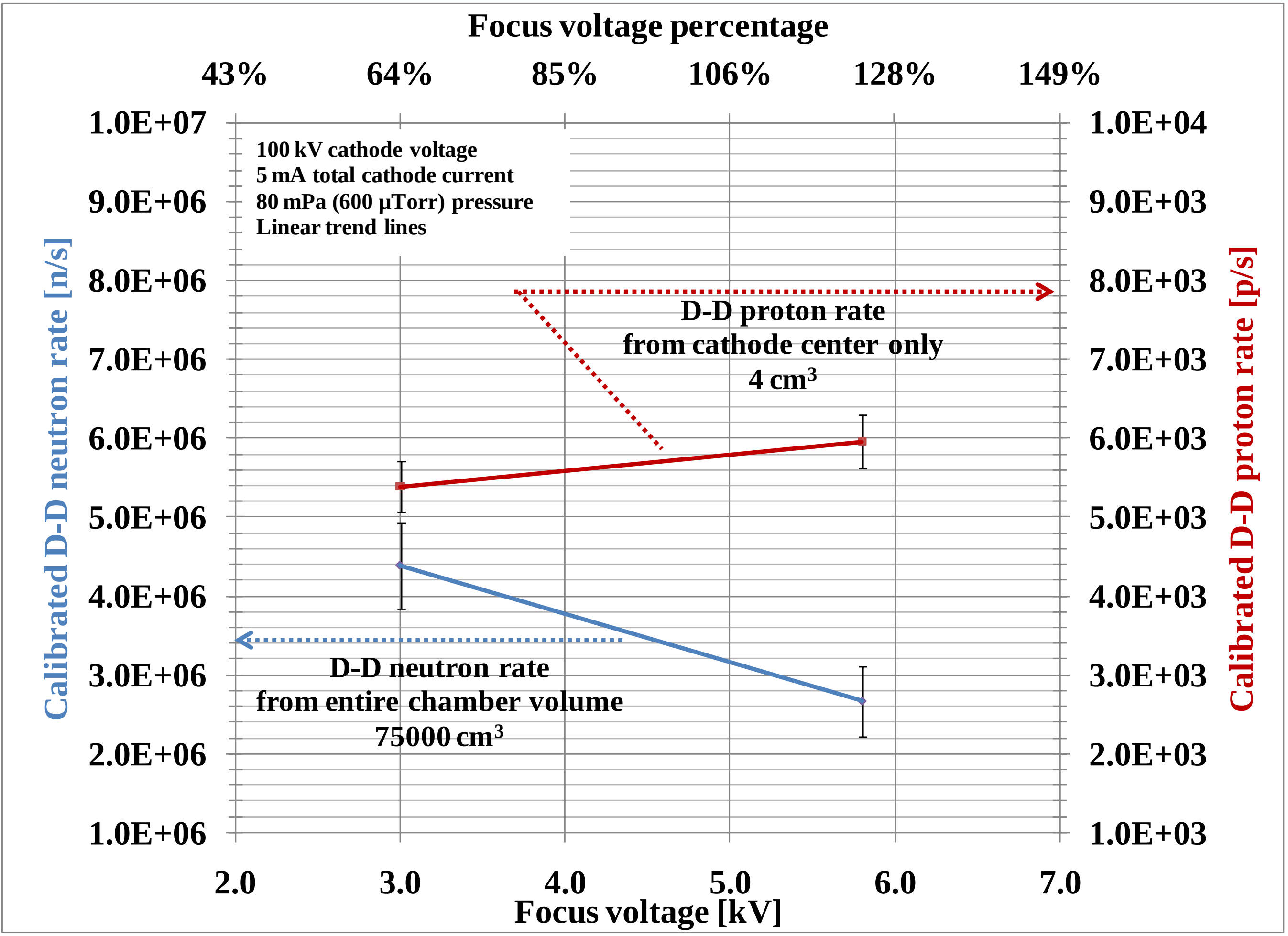

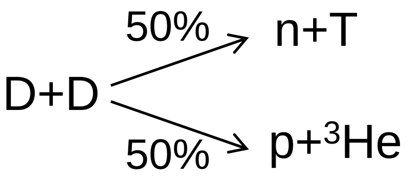

- Large difference in protons from center and neutrons from entire volume
- Virtual potential well formation is not a significant fusion mechanism within the SIGFE parameter space

Conclusions from SIGFE D-D experiments

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- D-D fusion rate scaled linearly with current at total cathode currents within the 2-31 mA operation space
- D-D neutron rate is highly dependent on the focusing of the ion beams
- Highest neutron rates in the SIGFE observed with defocused ion beams
    - *4.2 x 10^7 n/s*
    - *at -130 kV cathode voltage, 10 mA total cathode current, 13 mPa chamber pressure*

Evidence of virtual potential well formation not observed in SIGFE

Within the parameter space explored
(<31 mA total cathode current,-50 to -150 kV, 13 to 270 mPa)

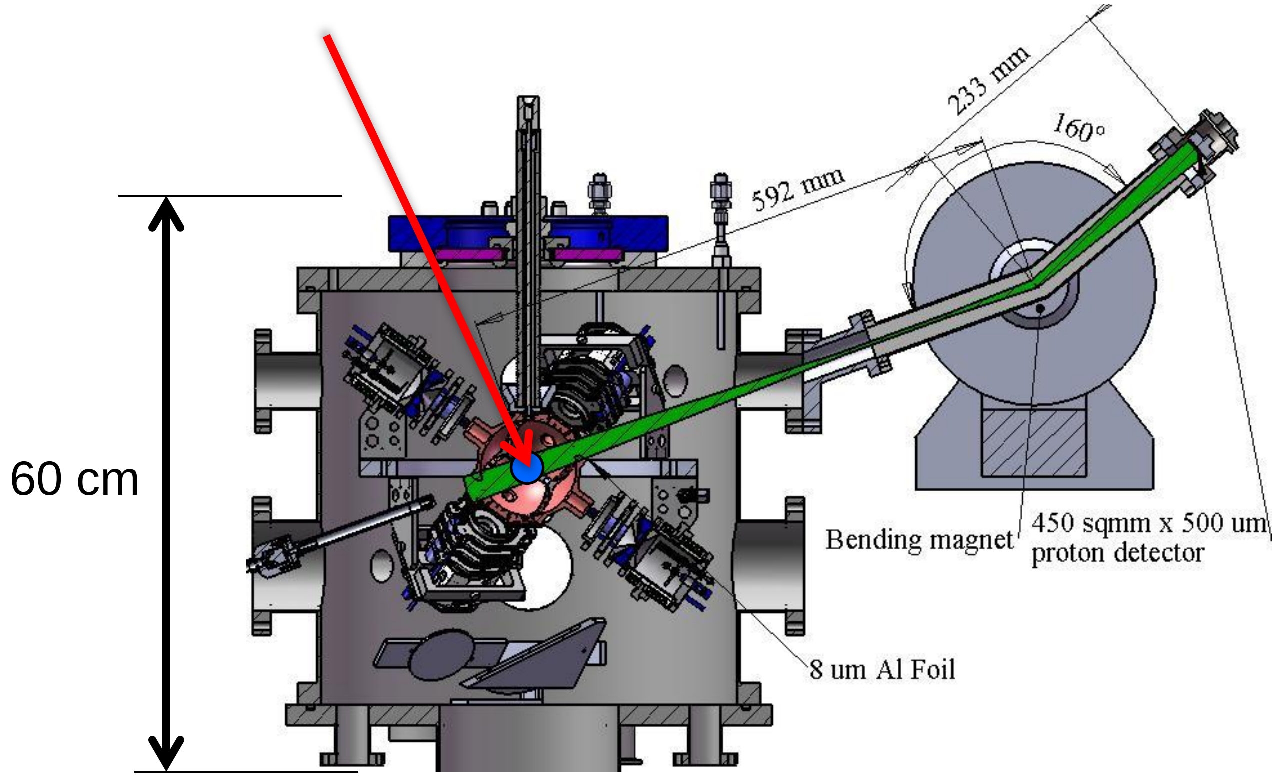
- Less than 0.2% of the D-D fusion reactions are from center of SIGFE device
- Virtual potential well structures and other space-charge related physics at the center of the SIGFE cathode are not a significant source of fusion
- D-D and D-^{3}He fusion protons observed from center are consistent with beam-background fusion
- The results of the SIGFE imply that beam-embedded fusion in the cathode lenses is the dominant D-D fusion mechanism in the SIGFE

Rational for SIGFE diagnostics

- Measure energy of reacting particles
- Determine location of fusion reactions within the cathode
- Identify the mechanism for high neutron production efficiency
  - Hirsch device was the most efficient IEC, until SIGFE, on a neutron production rate per kilowatt basis

Proton detector designed to only observe fusion from center

Proton detection volume
4 cm^3

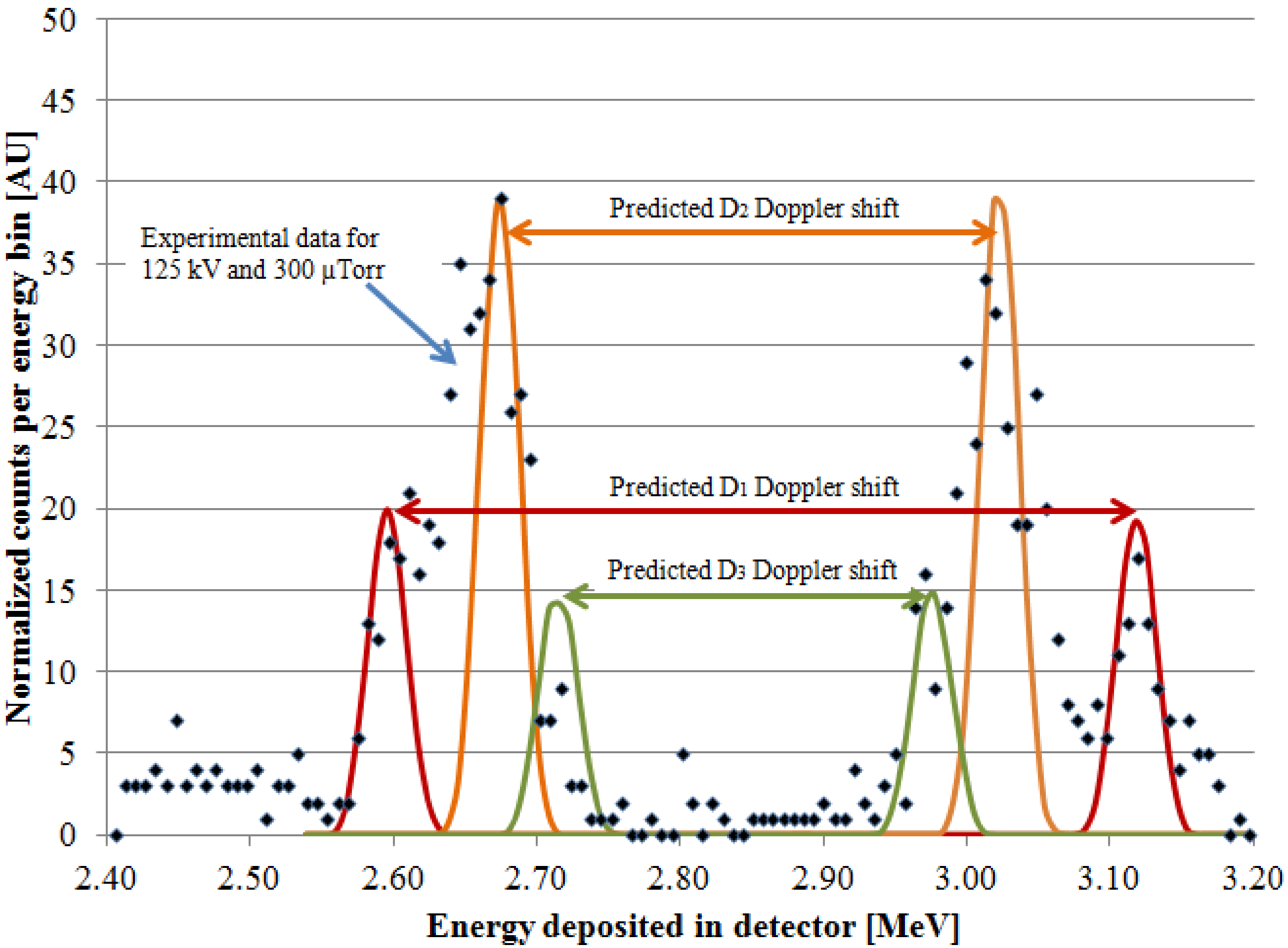


Fusion Ion Doppler Shift (FIDO) diagnostic[1]

- Energy of reactant particles determined from detected fusion proton spectrum
- x-ray noise reduced by bending protons out of line-of-sight of chamber
- 8 µm of Al foil at cathode edge
- Designed to detect protons from the center of cathode only
- Calibrated as a point source of protons at the center of the SIFGE

1. Developed by David Boris

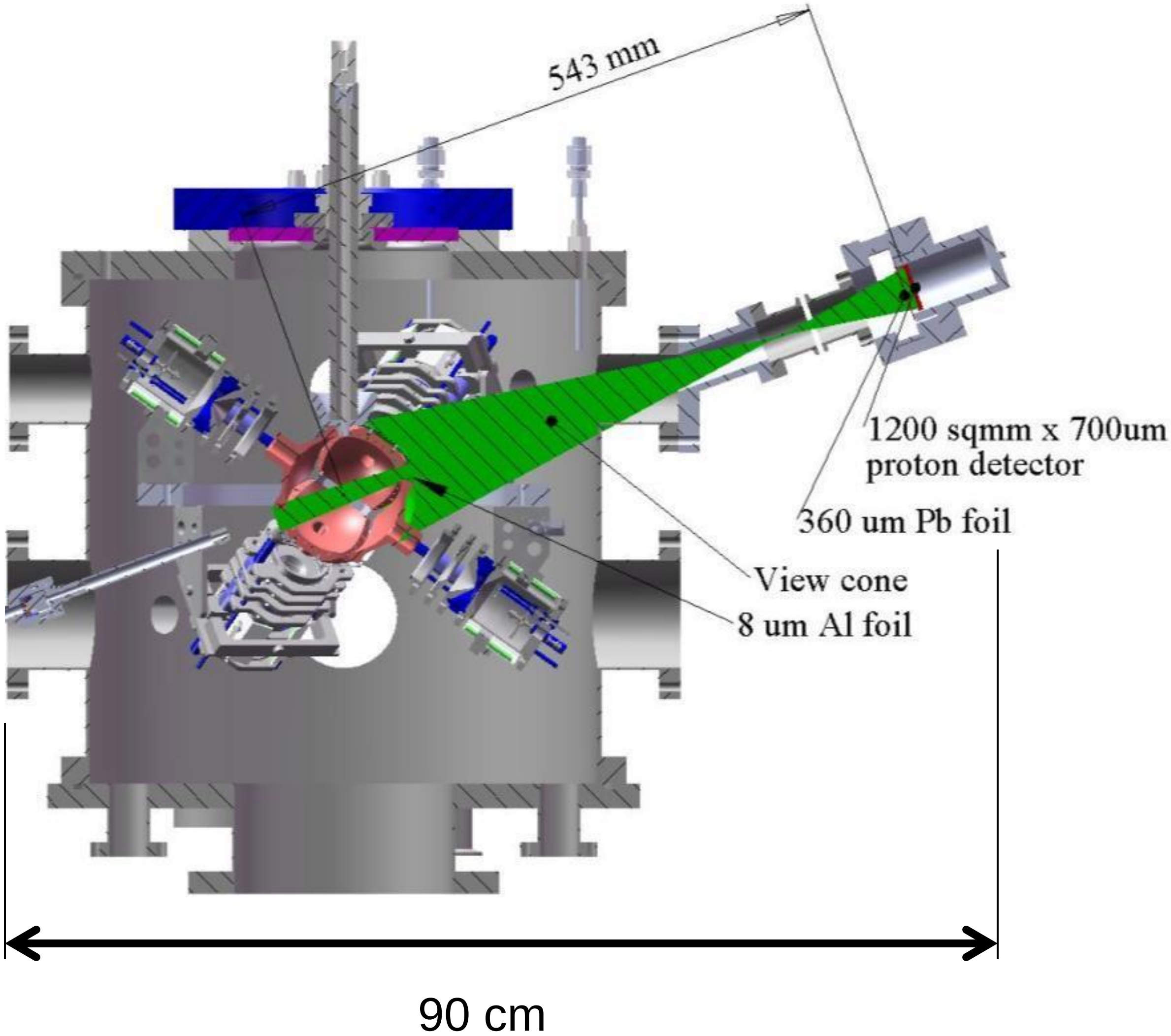
Protons from center consistent with beam-background fusion



- Doppler shift of D-D protons can be from D_1^+, D_2^+, and D_3^+ ion species
- Experimental proton spectrum consistent with near full cathode energy ions on stationary targets (beam-background)

Note: protons from 4 cm^3 volume at cathode center only

D-^{3}He proton detector

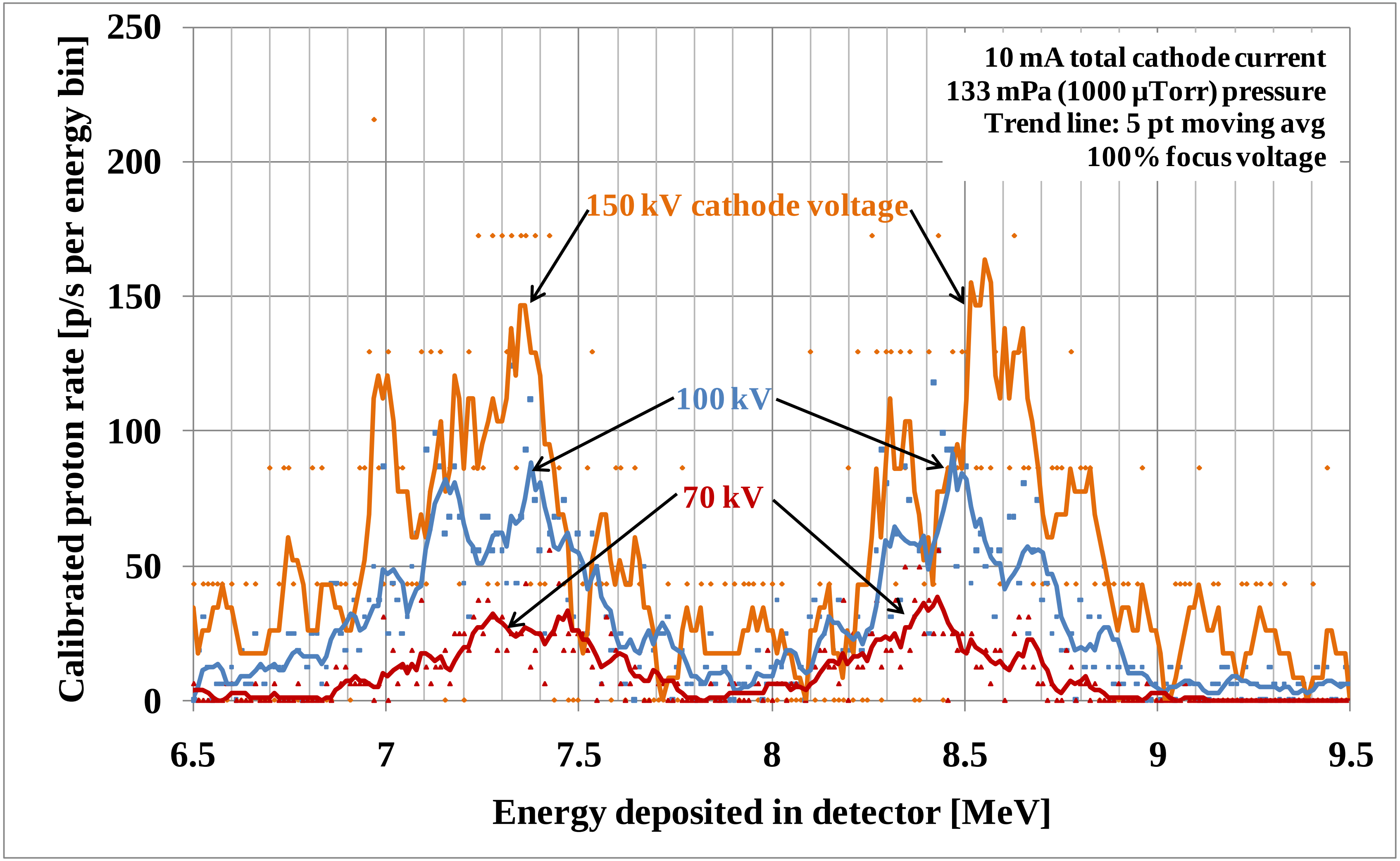


$D + {}^3He \longrightarrow p + {}^4He$

D-^{3}He proton detector

- Collimated to detect 14.7 MeV protons only from center of cathode
- Calibrated as a point source of protons at the center of the SIGFE
- 360 µm of Pb and 8 µm of Al foil between center and detector

Doppler shift is consistent with D-^{3}He beam-background fusion

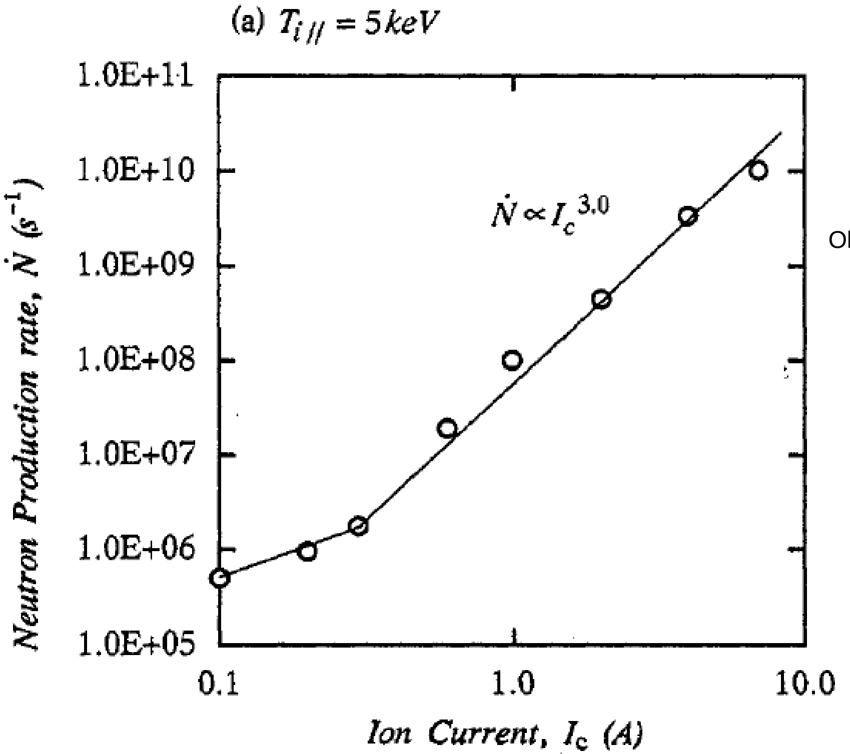


Summary

- SIGFE has been operated with different fuels and multiple diagnostics over a large parameter space
- Matched Hirsch results
  - Most likely operated in a beam-embedded mode

Next steps for the SIGFE

- Operate in a pulsed mode to achieve higher currents



Ohnishi, M., Sato, K. H., Yamamoto, Y., & Yoshikawa, K. (1997). Correlation between potential well structure and neutron production in inertial electrostatic confinement fusion. *Nuclear Fusion*, 37(5), 611-619.

- Explore new operating parameters

Questions?