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Advances on the Six Ion Gun Fusion Experiment

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11th US-Japan IEC Workshop

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Six Ion Gun Fusion Experiment (SIGFE)

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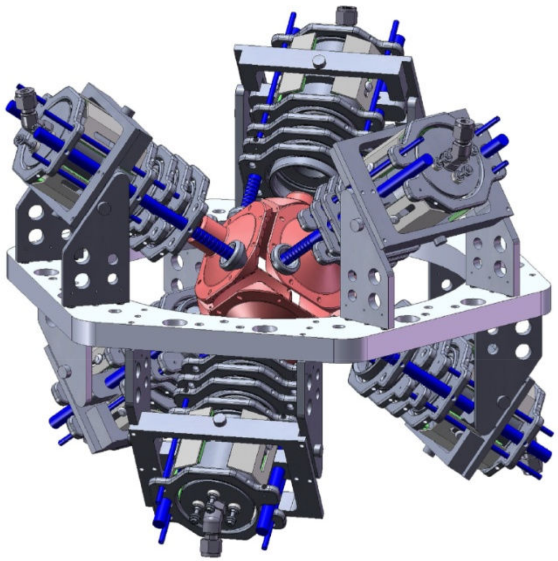
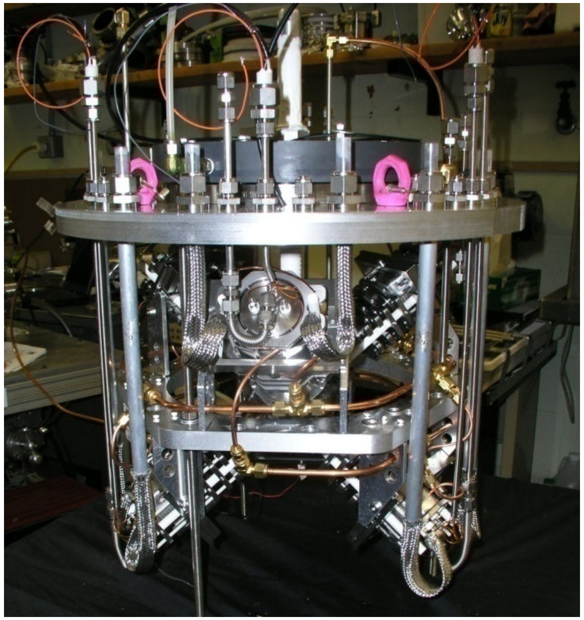


December 2007



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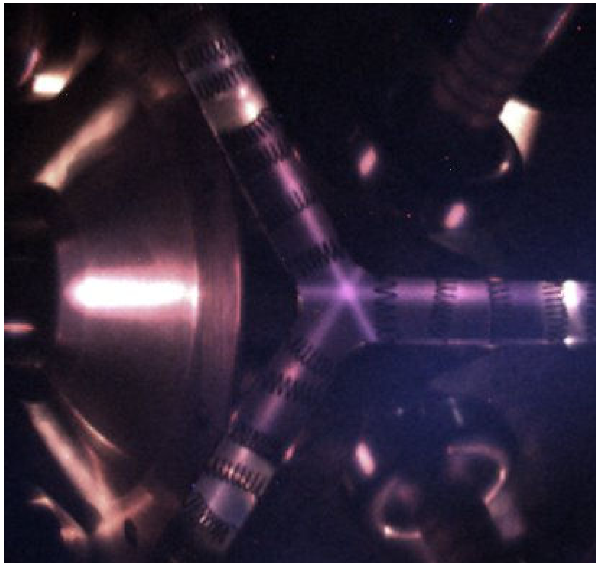


September 2009

Project Goals:

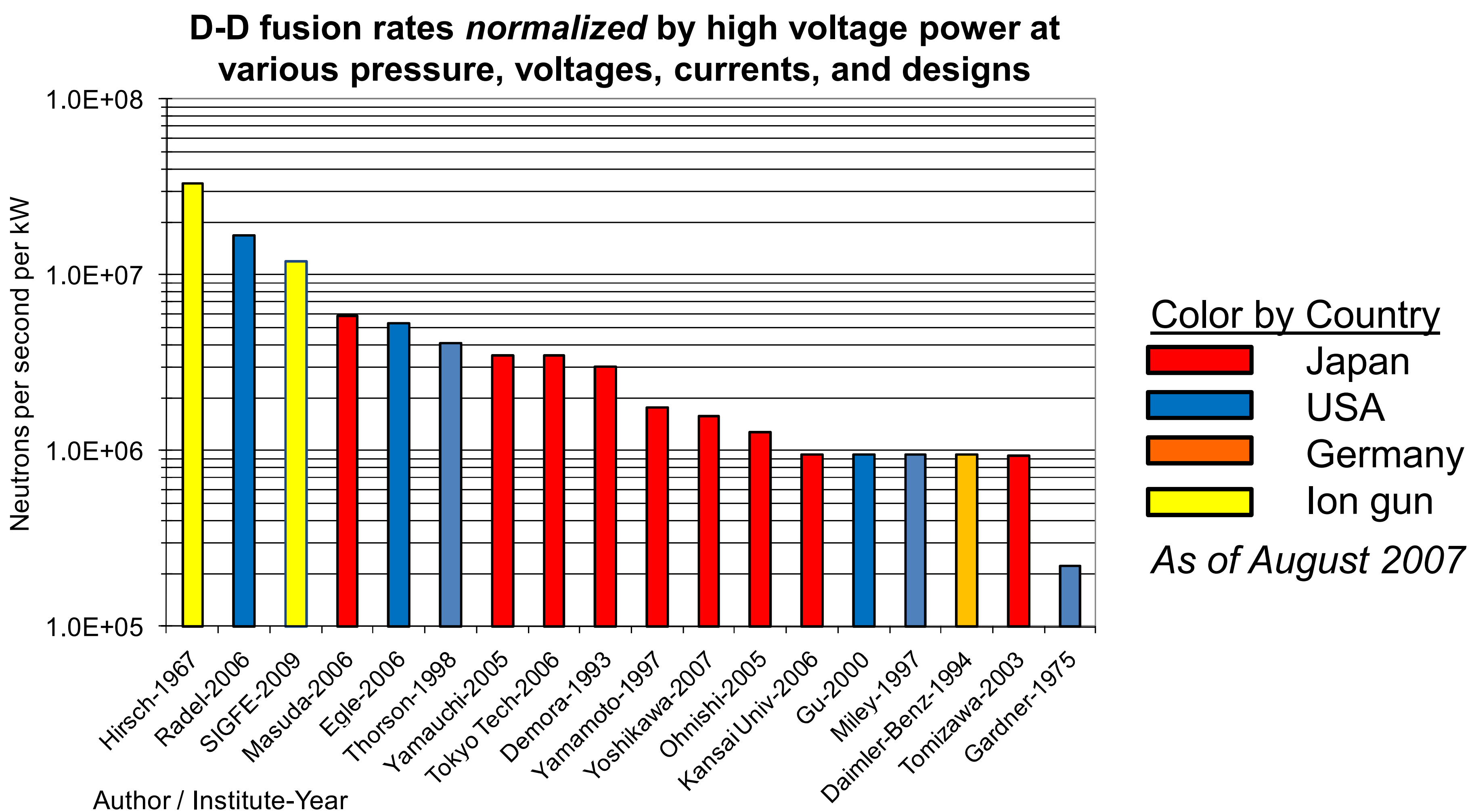
1) Increase D-D and D-^{3}He fusion rates for near term applications
2) Validate and extend the seminal 1967 experiments in Inertial Electrostatic Confinement (IEC)
3) Explore the plasma physics of converging ions

Outline of Presentation

- Motivating results and main points from Hirsch-1967 experiment and previous theory literature
- Brief description of SIGFE device
- Results from SIGFE:
  - *SIGFE neutron rate is approximately a factor of 2 lower than Hirsch-1967*
  - *Ion beam focus and alignment each change neutron rate by a factor of approximately 2*

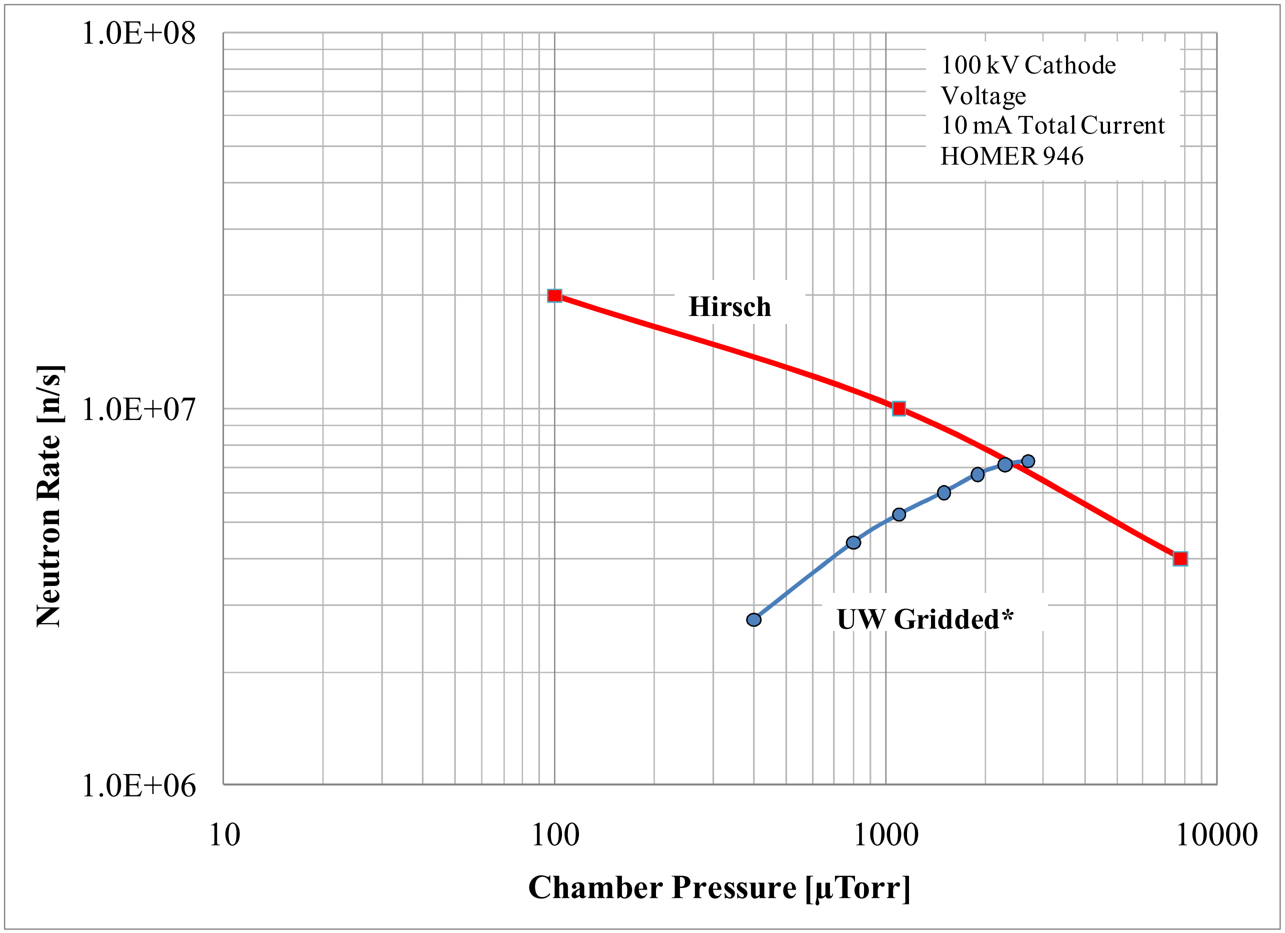
Comparison of D-D Fusion Rates

Hirsch-1967 still the highest



The original IEC experiment by Hirsch (1967) had the highest <u>neutron rate per kilowatt</u>

Pressure Sensitivity of D-D Fusion Experiments



Vastly different response to pressure

UW gridded results are consistent with beam-background mode

Conclusion: Hirsch was likely not in the beam-background mode

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

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Experimental Results of Hirsch Showed Tri-modal Distribution

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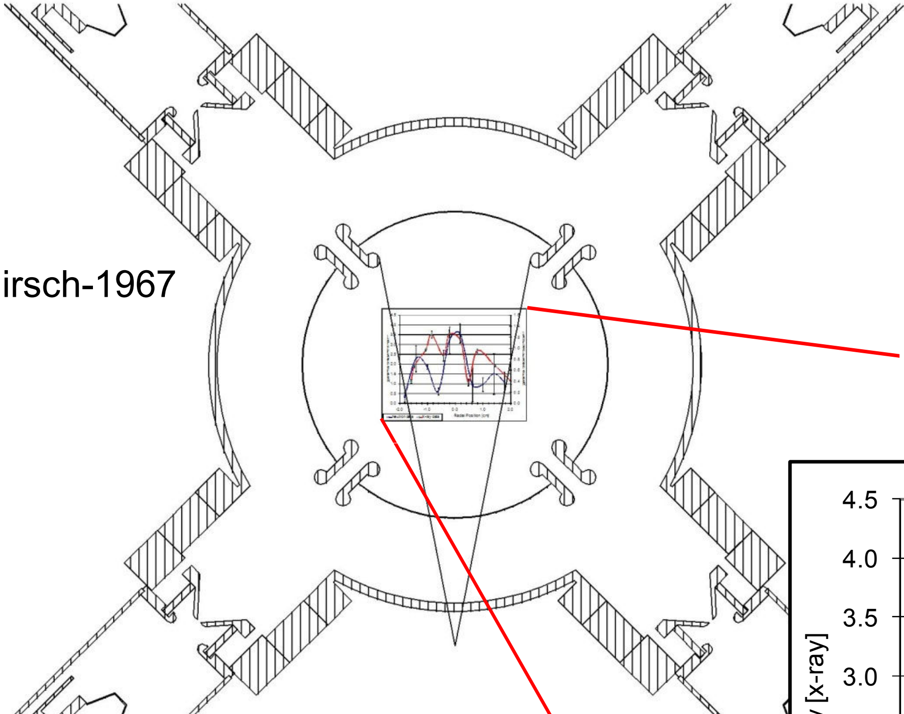
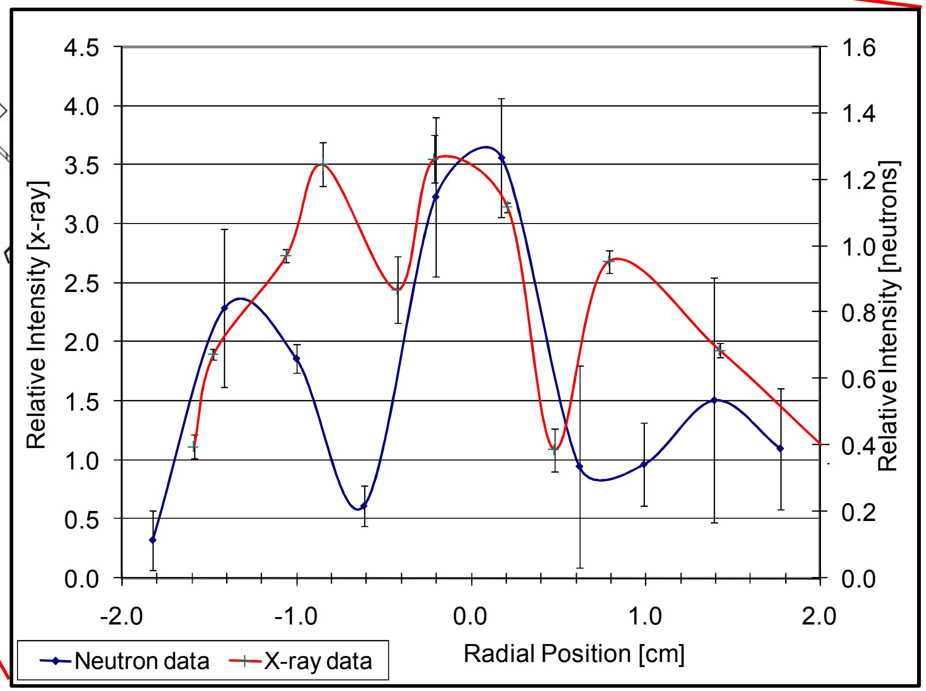
Hirsch-1967



- **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**

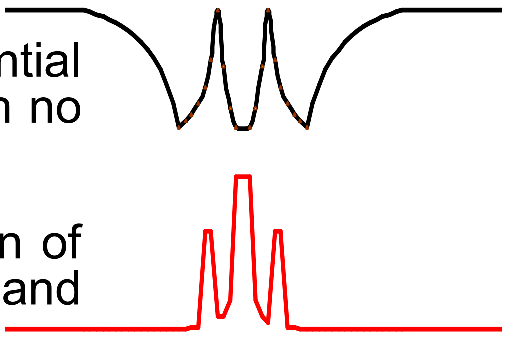


Data taken at pressures between 0.3 to 1 Pa (2 to 8 mTorr)

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

Virtual Electrode Physics

- **Development of virtual electrode theory**
  - Hirsch (1967) calculated an infinite number of potential wells could form by assuming mono-energetic ions with no transverse momentum
  - Dolan et. al. (1972) included a large square distribution of both radial energy spreading and angular momentum and predicted no potential well formation
  - Black et. al. (1974) extended Dolan's solution by restricting the distributions to much smaller values and predicted the formation of a finite number of potential wells
  - Ohnishi et. al. (1997) used a 2D PIC code to predict a ion current threshold that is a determined by the angular momentum and radial energy spread of the incoming ions



- **Main points from theory literature:**

Virtual electrode formation requires:

- well aligned and well focused ions
- low transverse component of ion velocity
- low radial ion energy spreading

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SIGFE is Based on the Original 1967 Hirsch Paper

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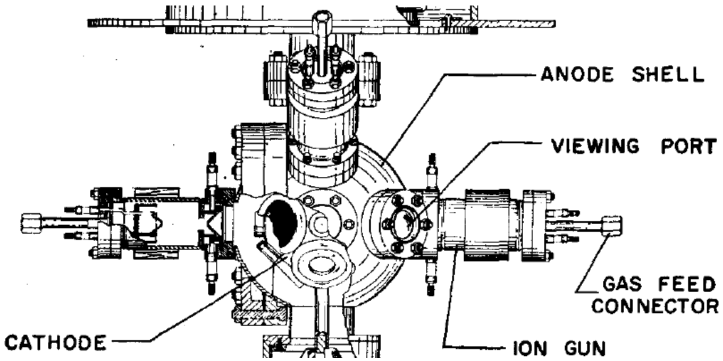
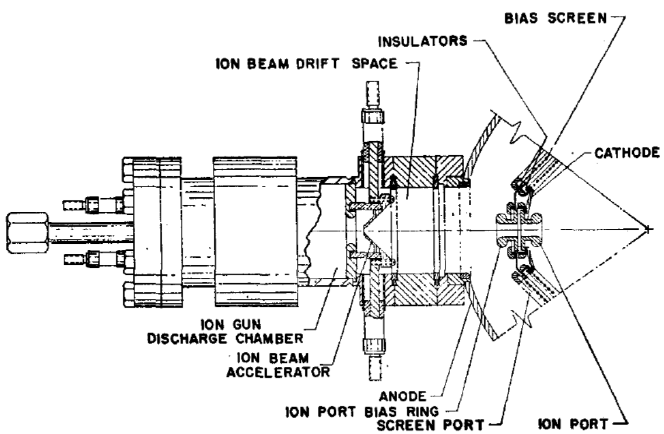
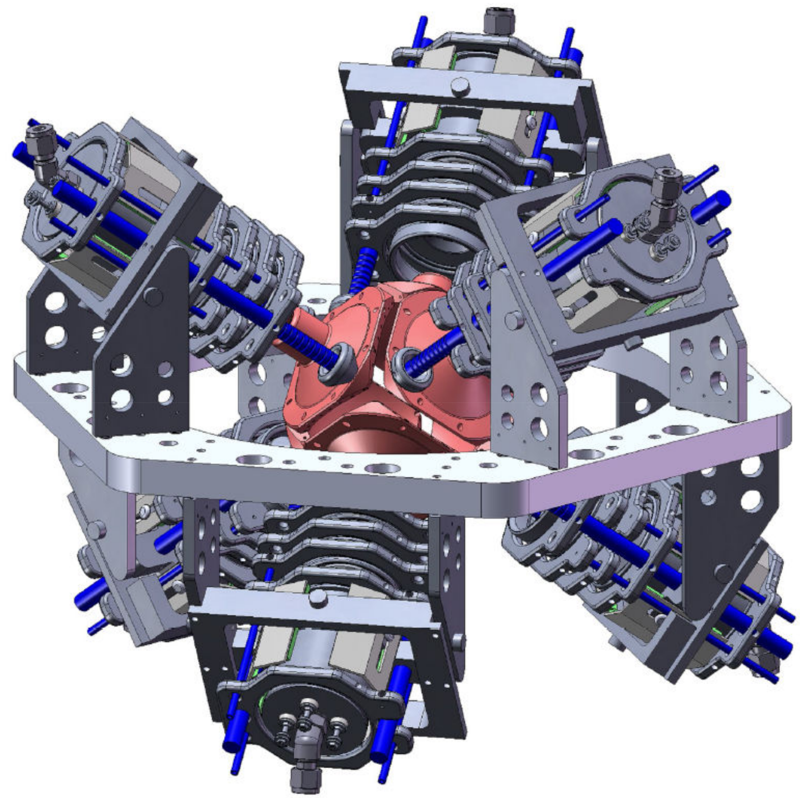




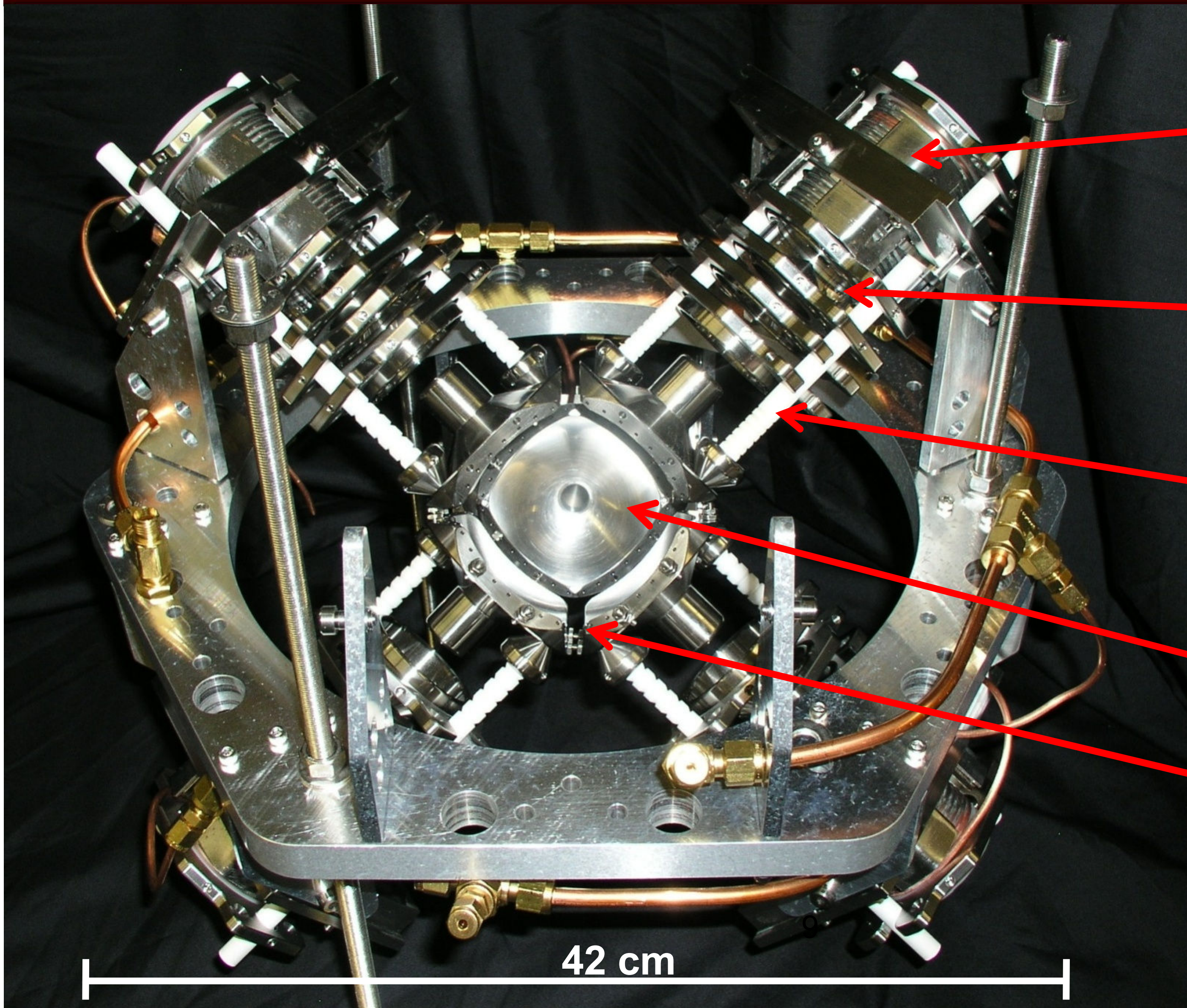
Started with drawings in the original publications



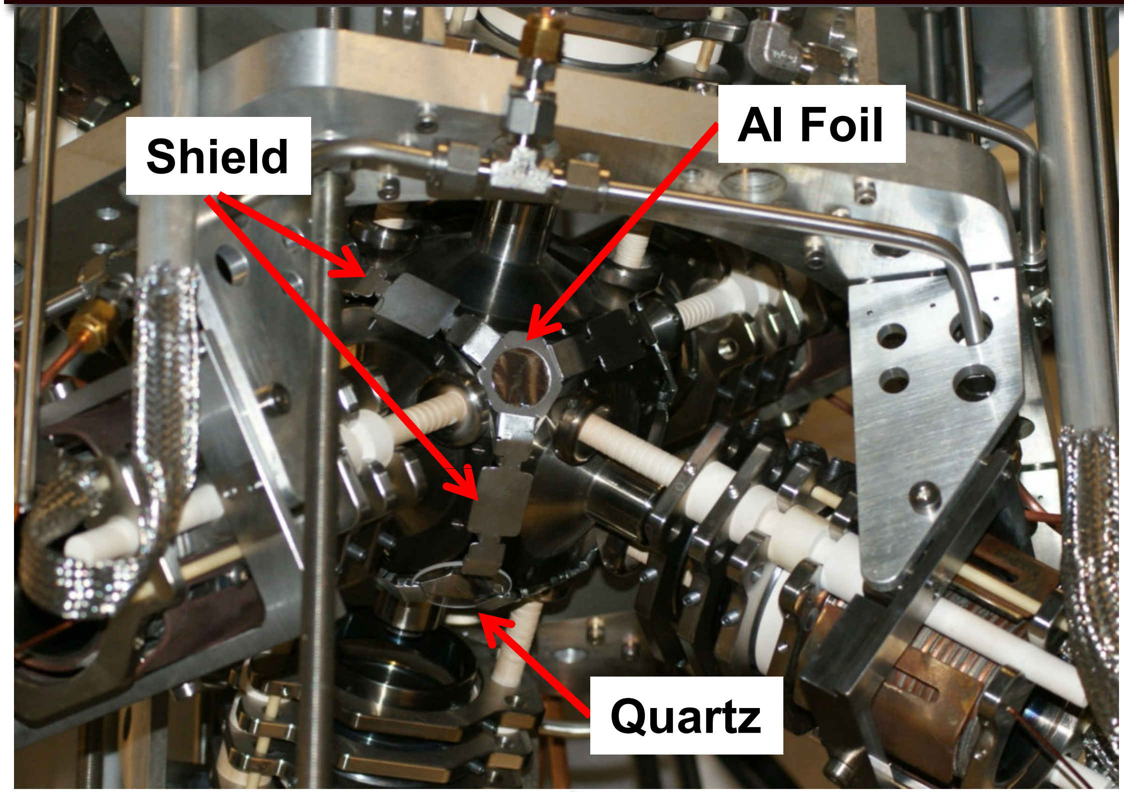
The Six Ion Gun Fusion Experiment (SIGFE) replicates and extends Hirsch's design with improvements in lens alignment and ion focusing

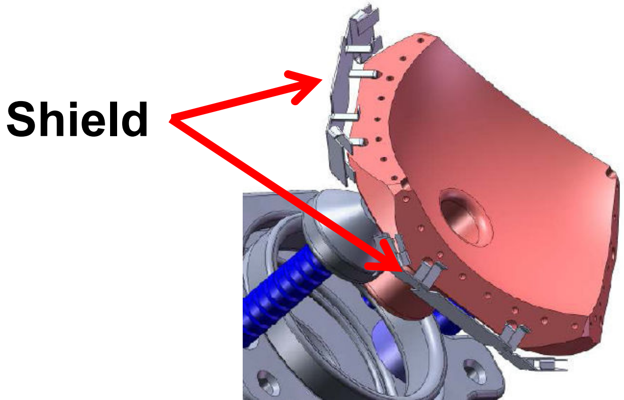
Source: Hirsch, R.L. (1967). Inertial-electrostatic confinement of ionized fusion gases. *Journal of Applied Physics, 38*(11), 4522-4534

Spherical Cathode Formed by Ion Guns (one gun removed)



Electron Shields at Seams in Cathode





- Electron shields span the gaps between the cathode lenses
- Gap between shield and lens allow neutral gas pumping
- Electrons are prevented from escaping due to limited line of sight out of cathode
- 8 μm Al foil at corners for proton diagnostics
- Quartz window at bottom corner for visible light camera

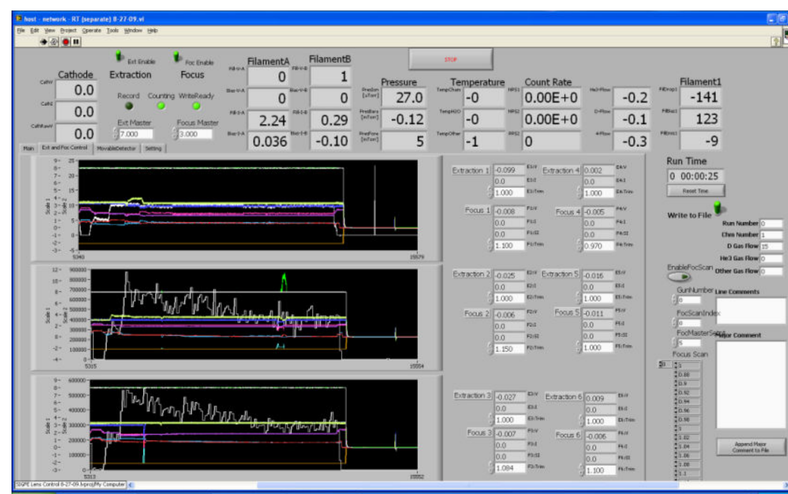
Diagnostics, Computer Control and Data Logging

Extraction Supplies
-15 kV, 5 mA

Focus Supplies
-15 kV, +/- 2.5 mA

LabView enabled, high speed control and data acquisition device

- Majority (~90%) of operating parameters displayed in real time and logged to a text file, including neutron and proton data
- Two independent ^{3}He tube neutron detectors
- Independent focus and extraction supplies controlled by custom LabView application



SIGFE Operation to Date October 7, 2009

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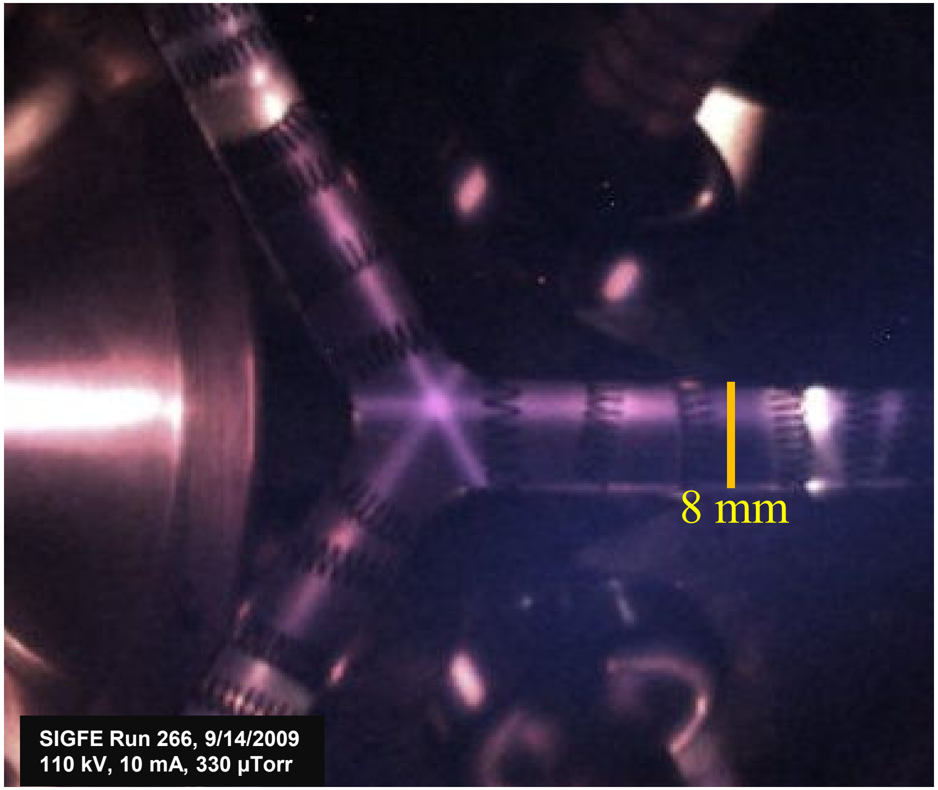

- Stable 150 kV operation obtained
- 40 to 300 μTorr operation at 10 mA
- 1 mm ion beam width at cathode center
- 20 mA of total cathode current obtained, capable of 60 mA
  - Limited by temperature
  - Melted stainless extraction lens
  - Replaced with Molybdenum alloy
  - Boron Nitride HP limited to 1150ºC
  - High temperature causes misalignment

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D-D Neutron Rate and Cathode Voltage

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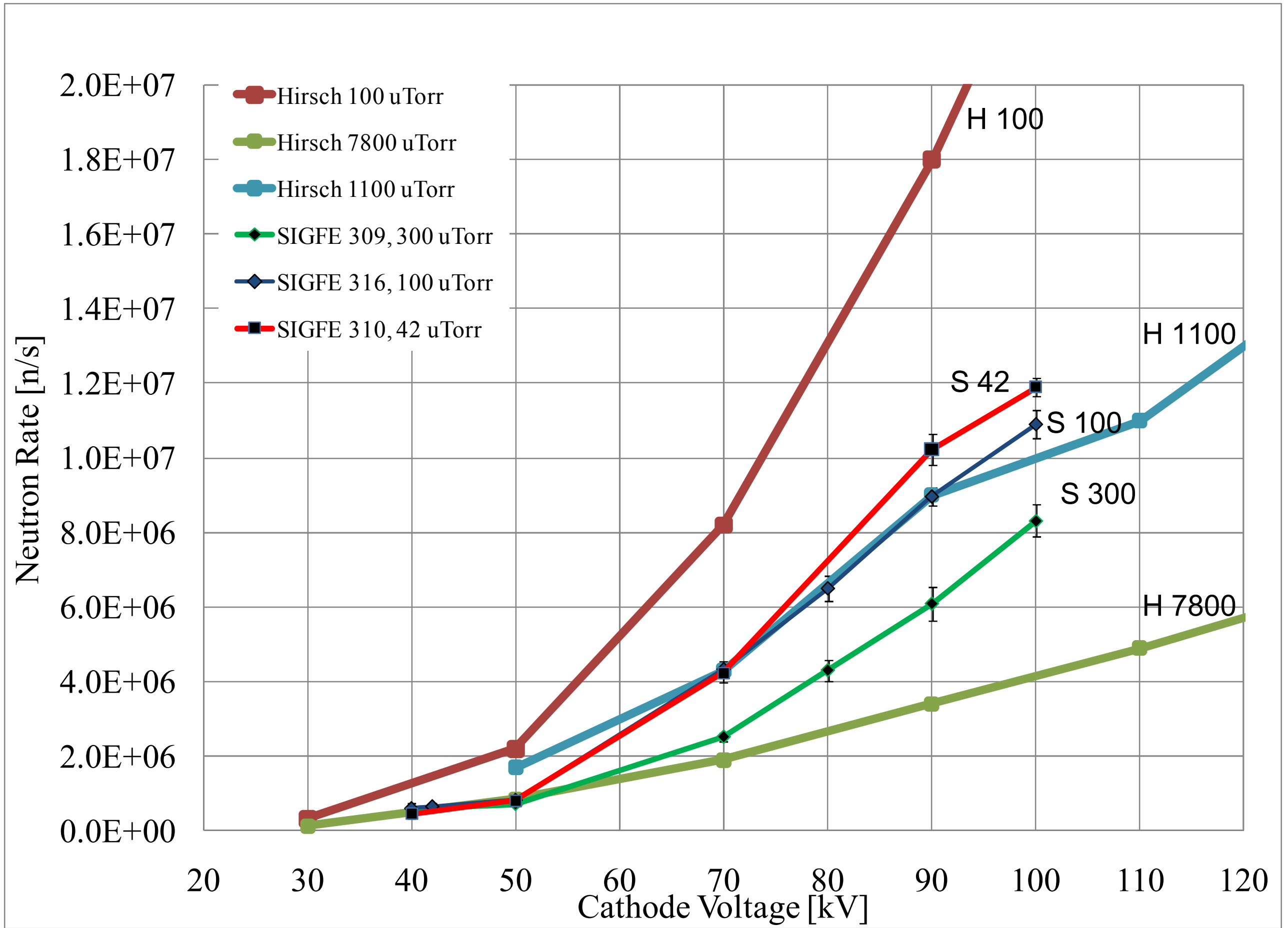
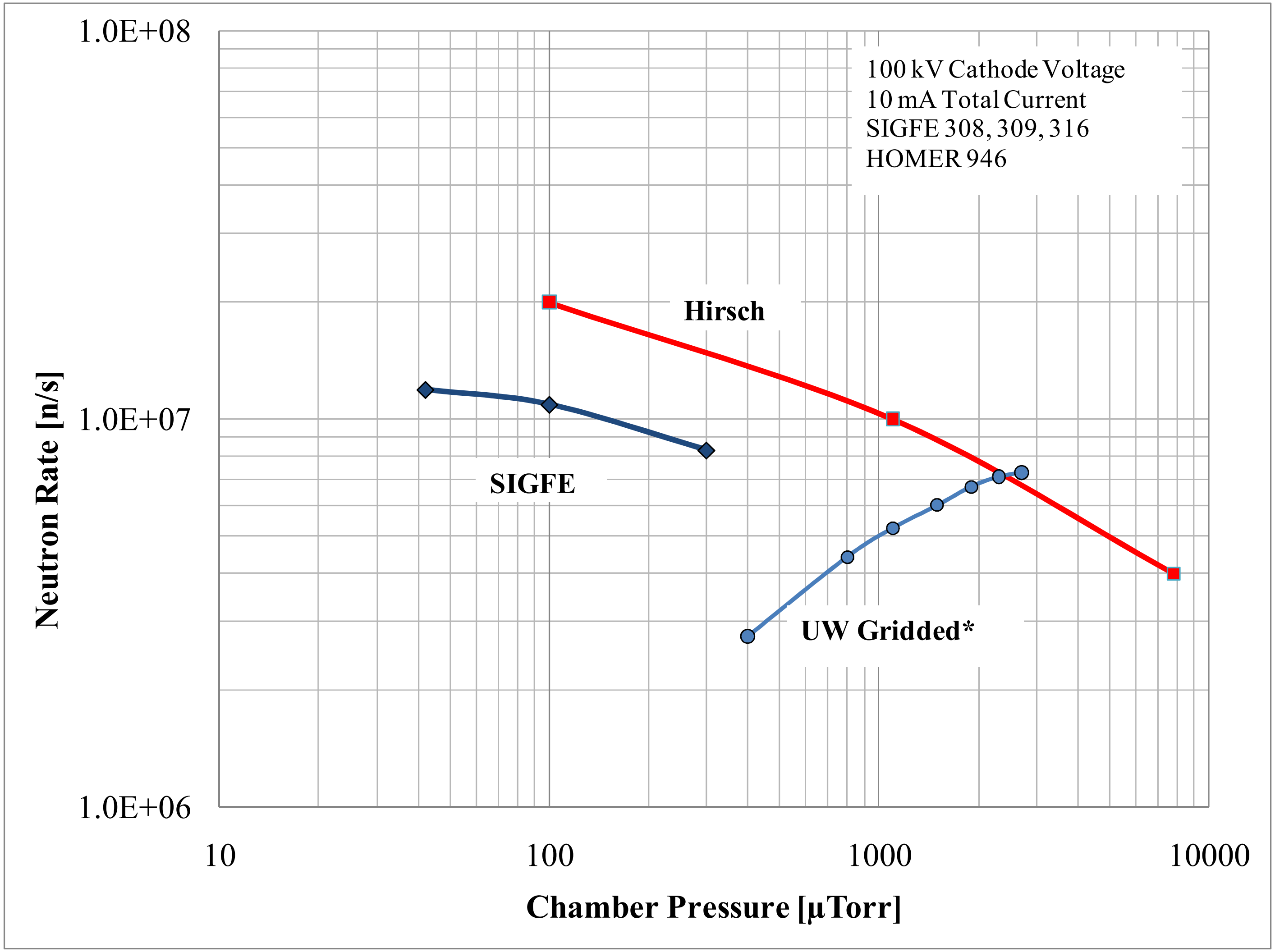


- 1.2×10^7 n/s best SIGFE
- Increasing neutron rate with decrease pressure
- At 90 kV:

1.8×10^7 Hirsch 100 μTorr
1.0×10^7 SIGFE 42 μTorr
0.6×10^7 SIGFE 300 μTorr

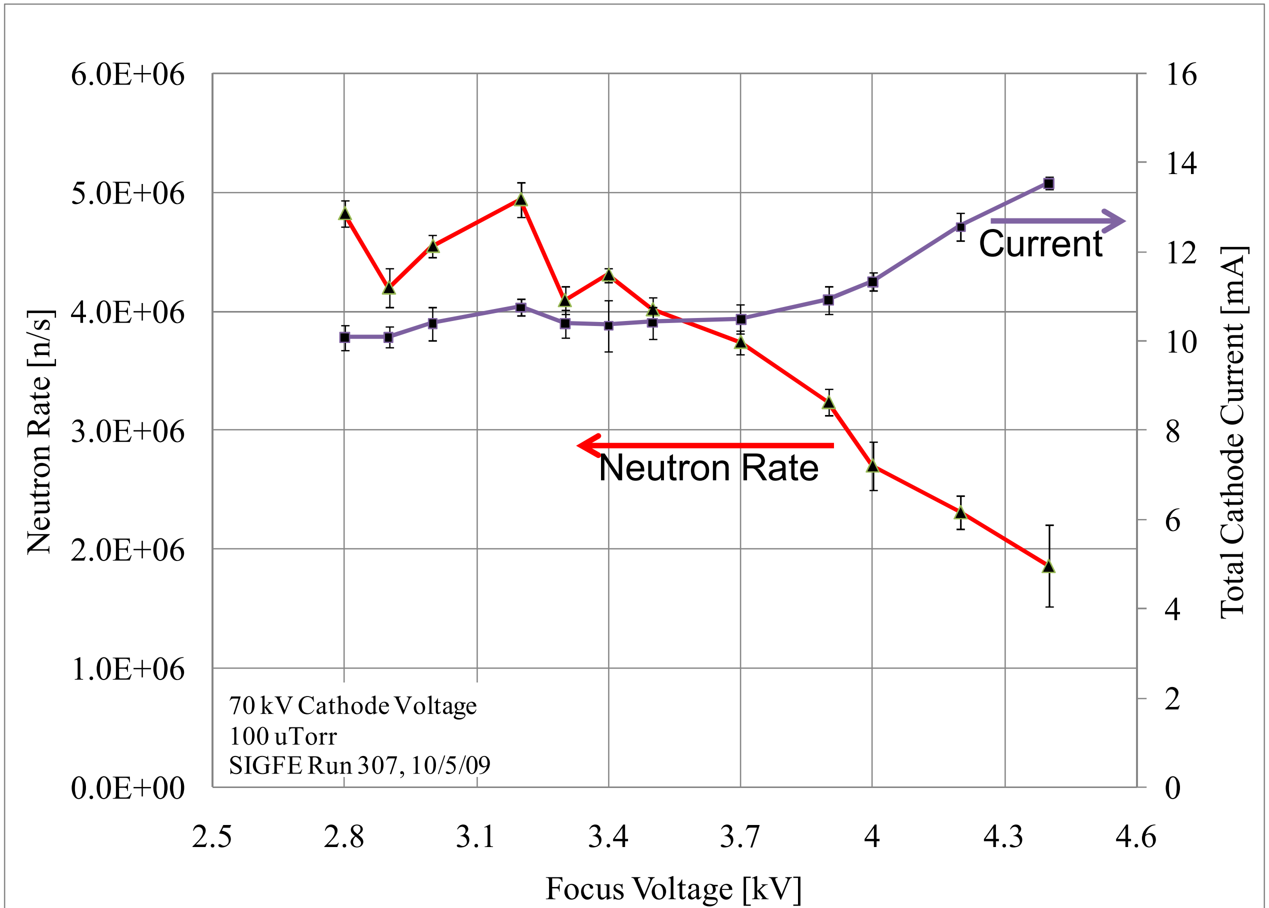
- All data at 10 mA of total (meter) cathode current, electron shields installed, and well aligned lenses

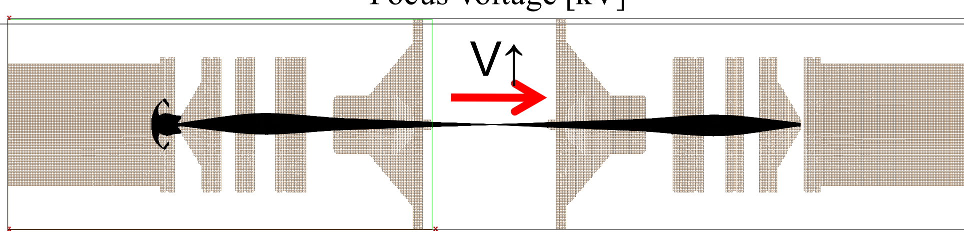
Neutron Rate Increases with Decreasing Pressure



*UW Gridded data corrected from 30 mA

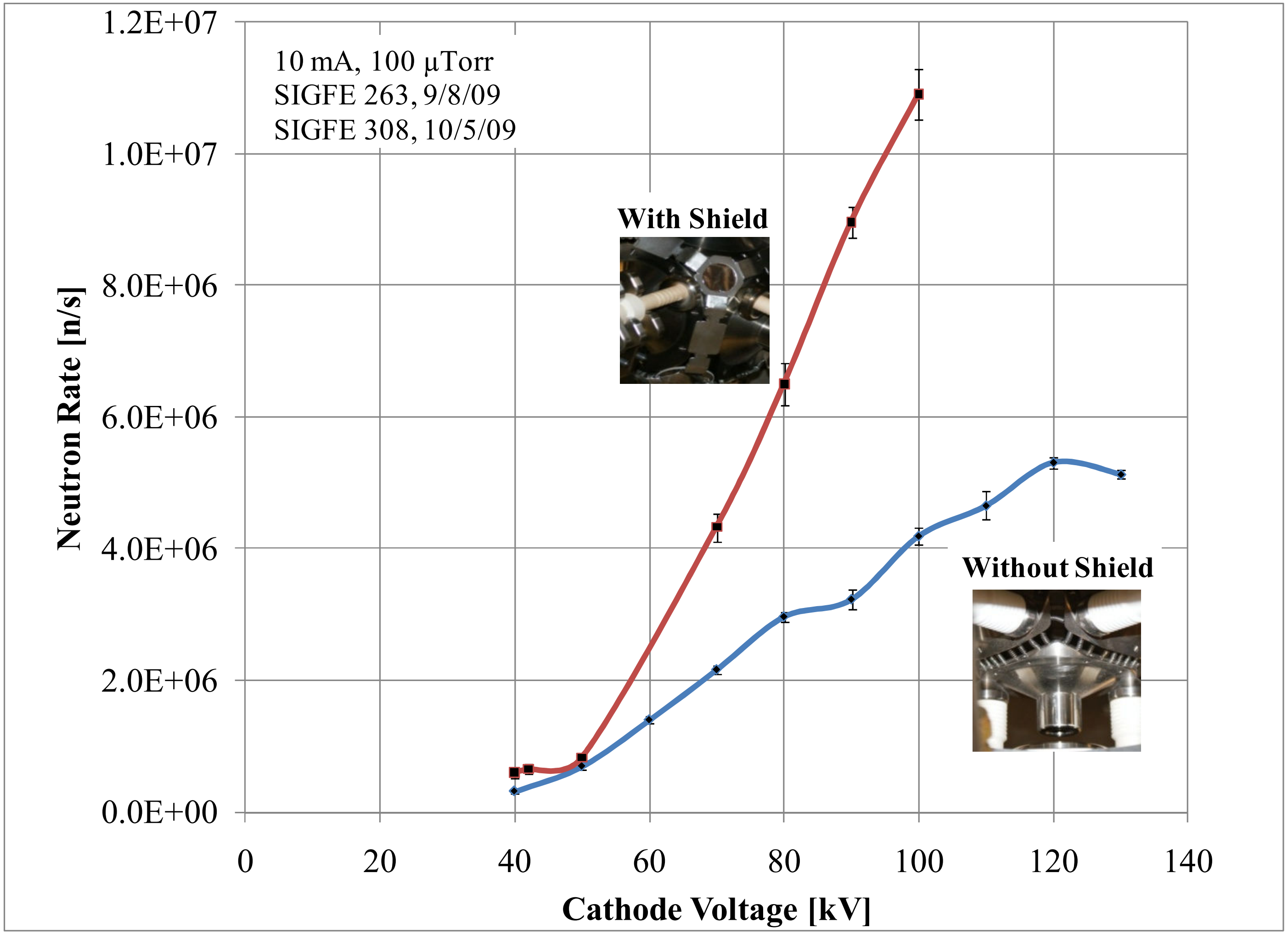
Factor of 2-3 Neutron Rate Change with Focus Voltage





- Factor of 2 to 3 is typical neutron rate change with focus lens voltage
- Increase in current suggests increase in electron current as ion strike outside of cathode lens
- As cathode voltage increases focus voltage of max neutron rate and current threshold increases (not shown)

Electron Shields Increased Neutron Rate



- Electron shields improved neutron rates by factor of 2.6 at 100 kV
- Presumably, less secondary electrons escape cathode with shields
- Rate increase is possibly due to increased faction of ion current in measured total cathode current

Well Aligned Lenses Increased Performance

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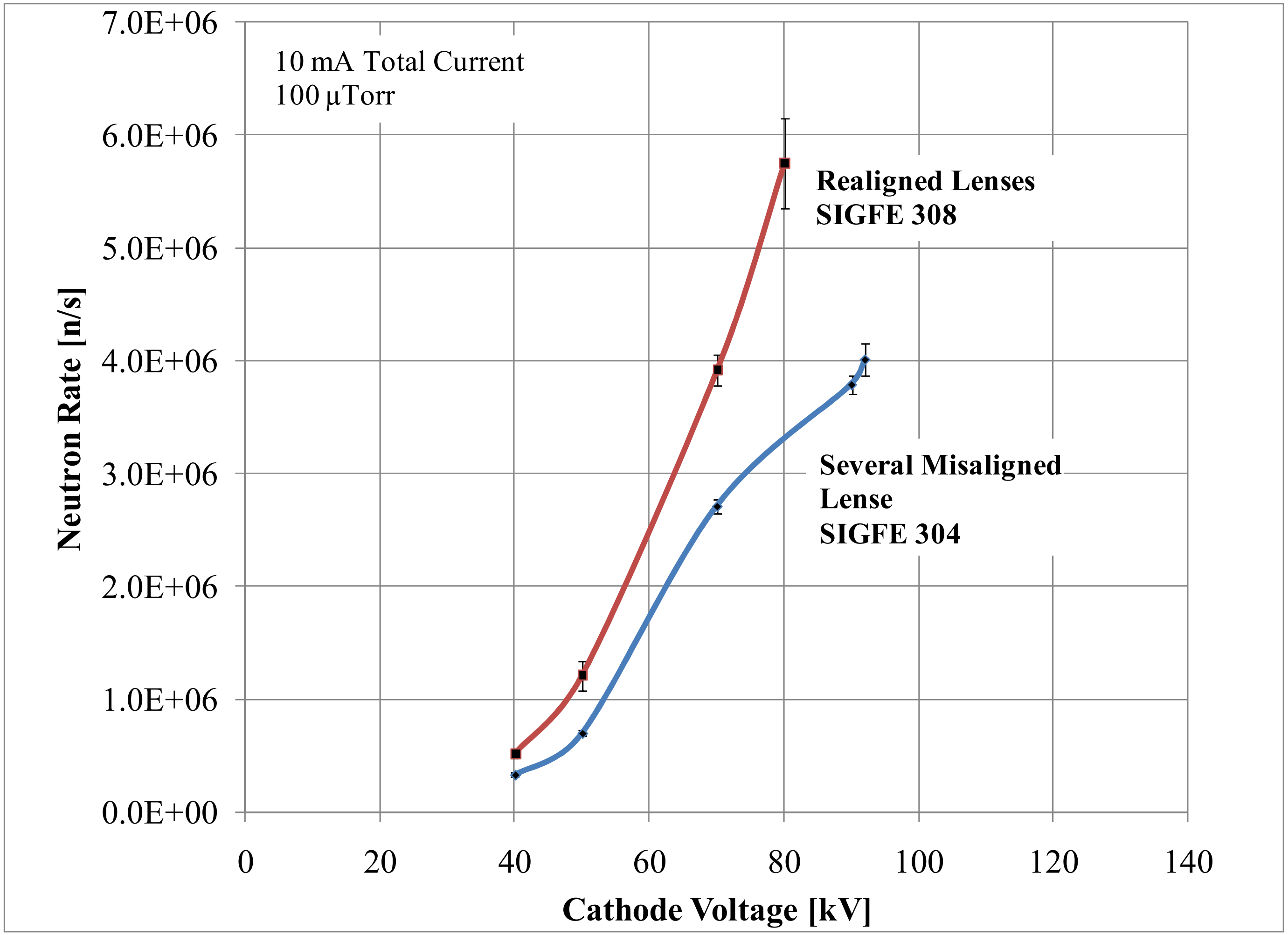

- Lenses were realigned after SIGFE 304
- Three extraction lenses found out of place due to heat effects
- Results of 308 are similar to results of 297. 297 was a recently aligned system

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Future Directions

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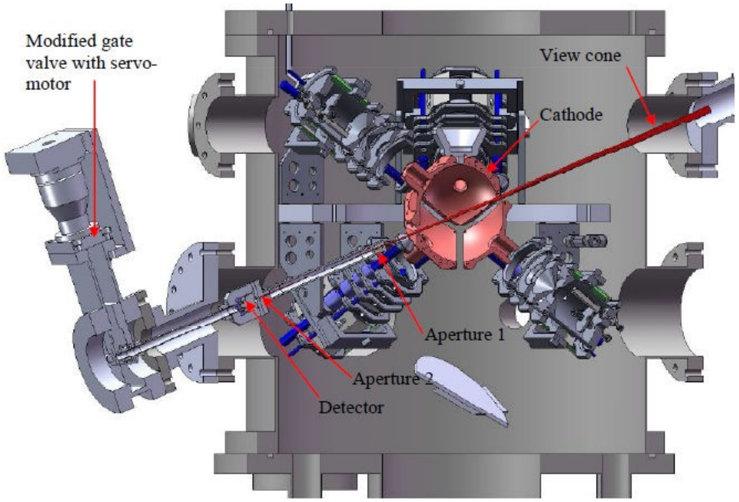
Planned Measurements and Diagnostics

- Detailed measurements of D-D proton and neutron rates versus pressure at various focus voltages
- High resolution (0.3 mm) spatial distribution of D-D and D-^{3}He fusion protons
- Doppler shift measurements of D-D fusion protons to measure energy spectrum
- D-^{3}He fusion rate scaling with cathode voltage, pressure, and beam focus



Summary and Conclusions

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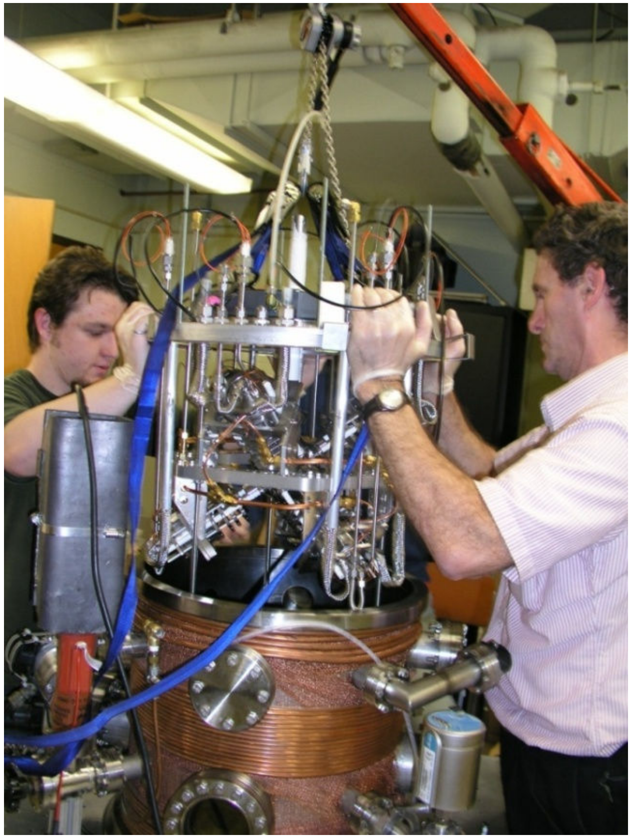
- Produced 1.2 x 10^7 n/s at 100 kV, 10 mA, 43 μTorr
- D-D neutron rate increased with decreased pressure
- Performance is extremely sensitive to lens alignment, ion beam focus, and secondary electron emission
- Current SIGFE neutron rates within a factor of two of Hirsch-1967 results at 100 kV

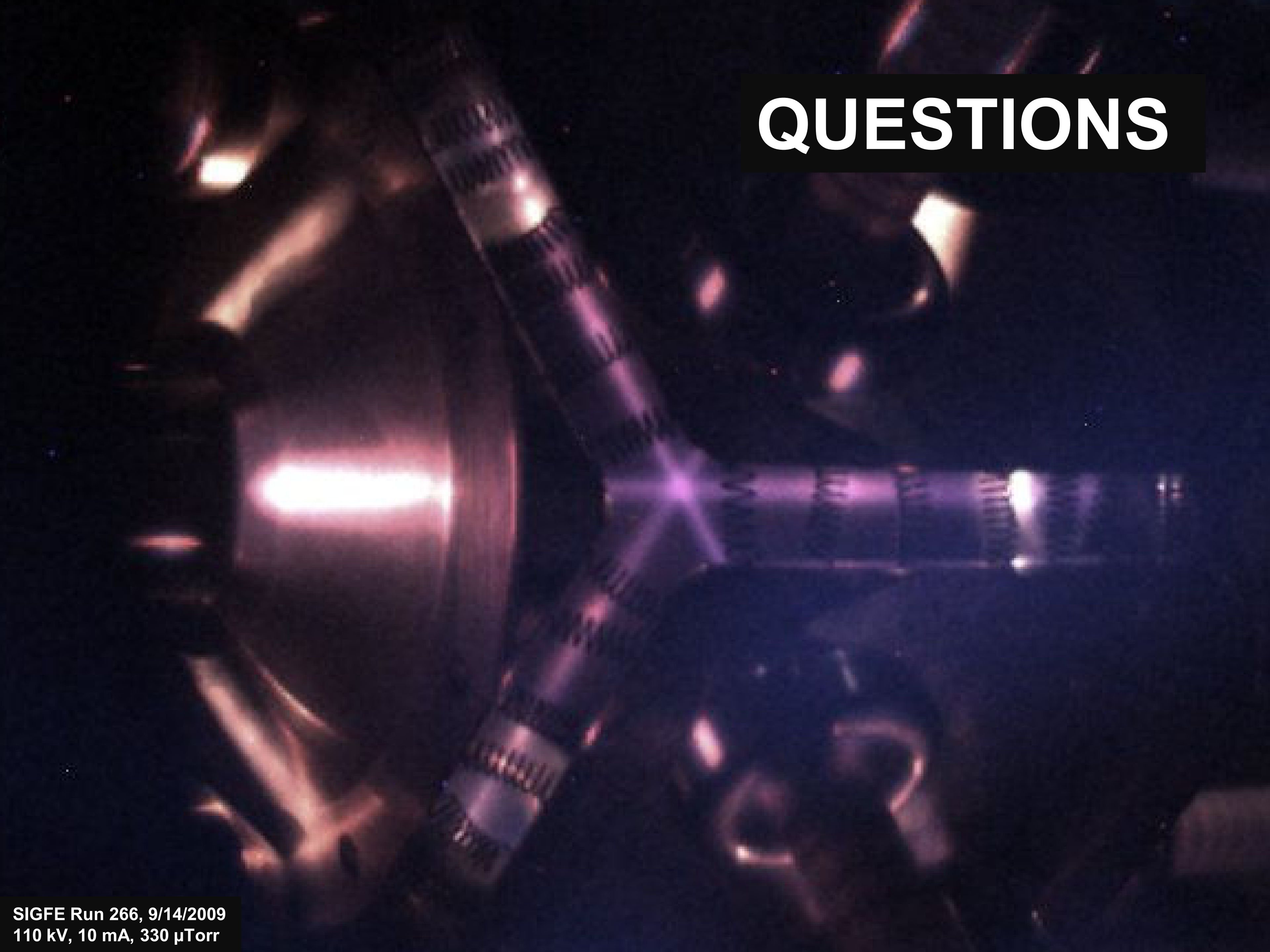
The Team



<u>Great thanks to the whole UW-IEC team</u>,

Sam Zenobia, Craig Schuff, Matt Michalak, Lauren Garrison, David Donavan, Logan Campbell, Dr. Dave Boris, Rich Bonomo, Gabriel Becerra, Eric Alderson, John Santarius, Gerald Kulcinski

QUESTIONS



SIGFE Run 266, 9/14/2009
110 kV, 10 mA, 330 µTorr