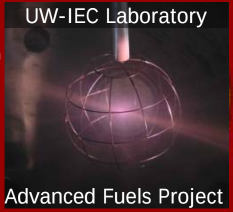
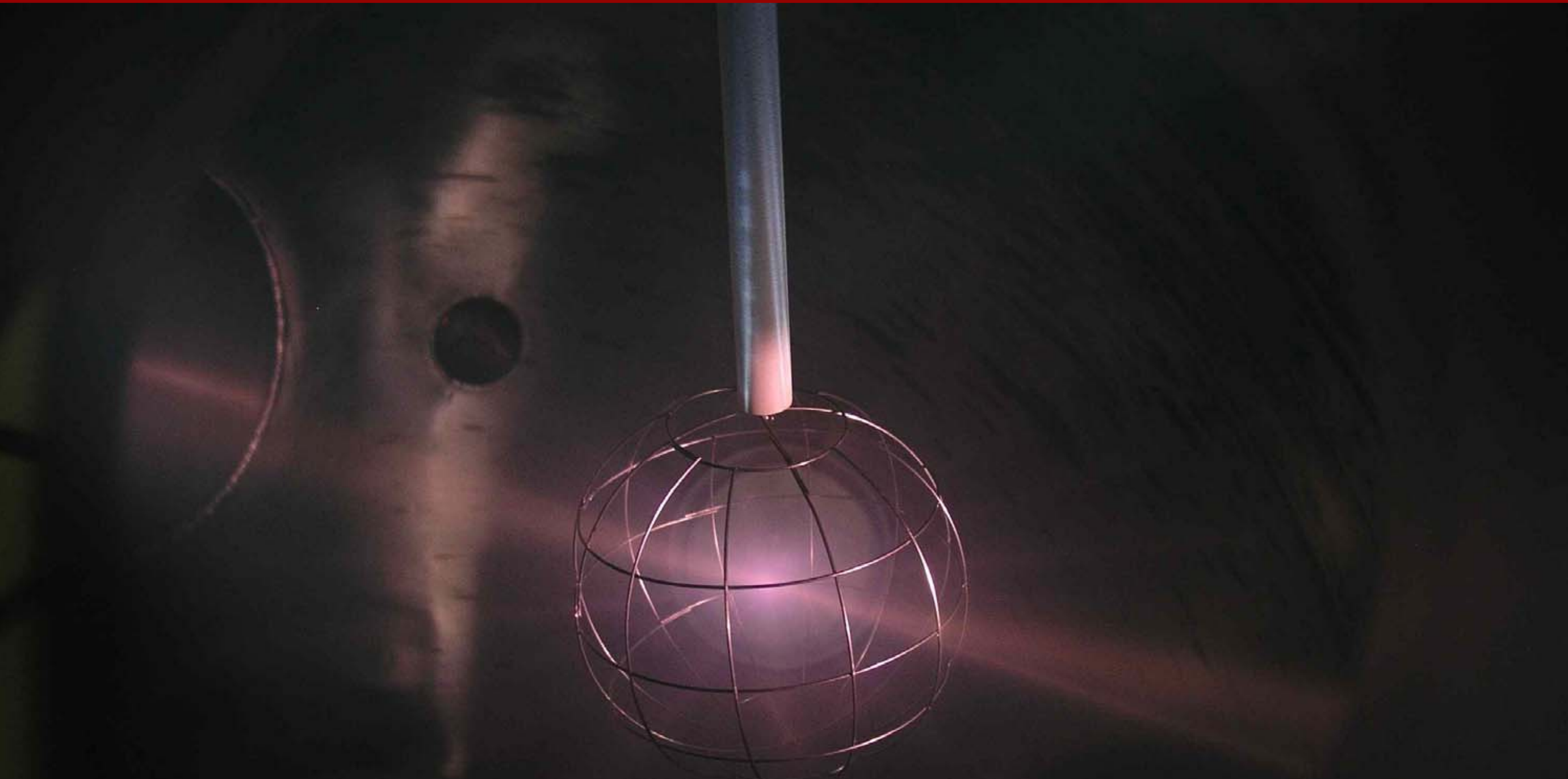
Development of an IEC Device for the Study of $^{3}He(^{3}He,2p)\,^{4}He$ Reactions





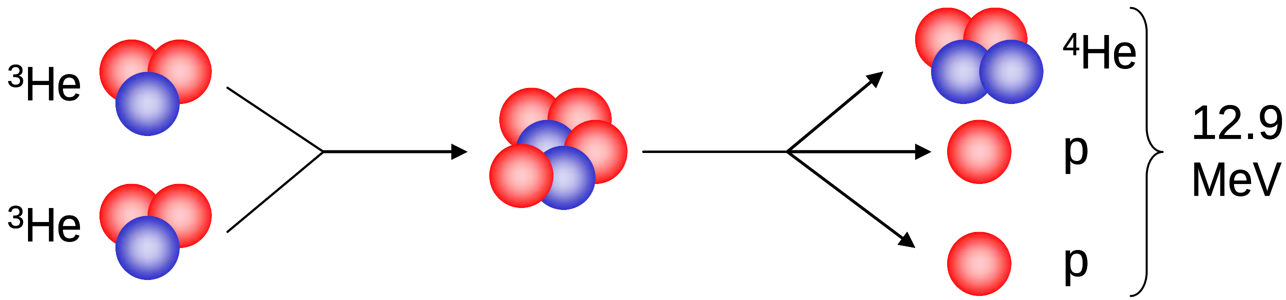
Gregory R. Piefer—grpiefer@wisc.edu
University of Wisconsin—Madison Fusion Technology Institute

US-Japan Workshop
Argonne National Lab

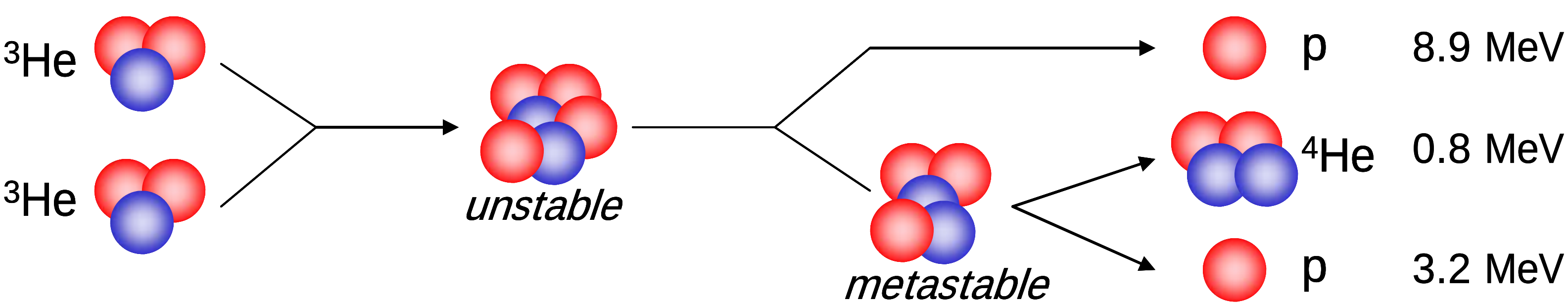
Presentation Overview

- ^{3}He-^{3}He reaction basics
- Benefits of IEC for ^{3}He-^{3}He studies
- Anticipated source regimes for ^{3}He-^{3}He reactions
- Experimental setup
  - IEC device
  - Ion source
  - Noise suppressing detection system
- Results
- Summary of research effort

$^{3}He(^{3}He,2p)^{4}He$ Reaction Overview



Most of the time, this reaction is a three body reaction, generating a continuum of particle energies



Roughly 10% of the time, a resonance occurs generating a pair of two-body decays, which gives the reaction products discrete energies

^3He-^3He Cross-Section at IEC Energies

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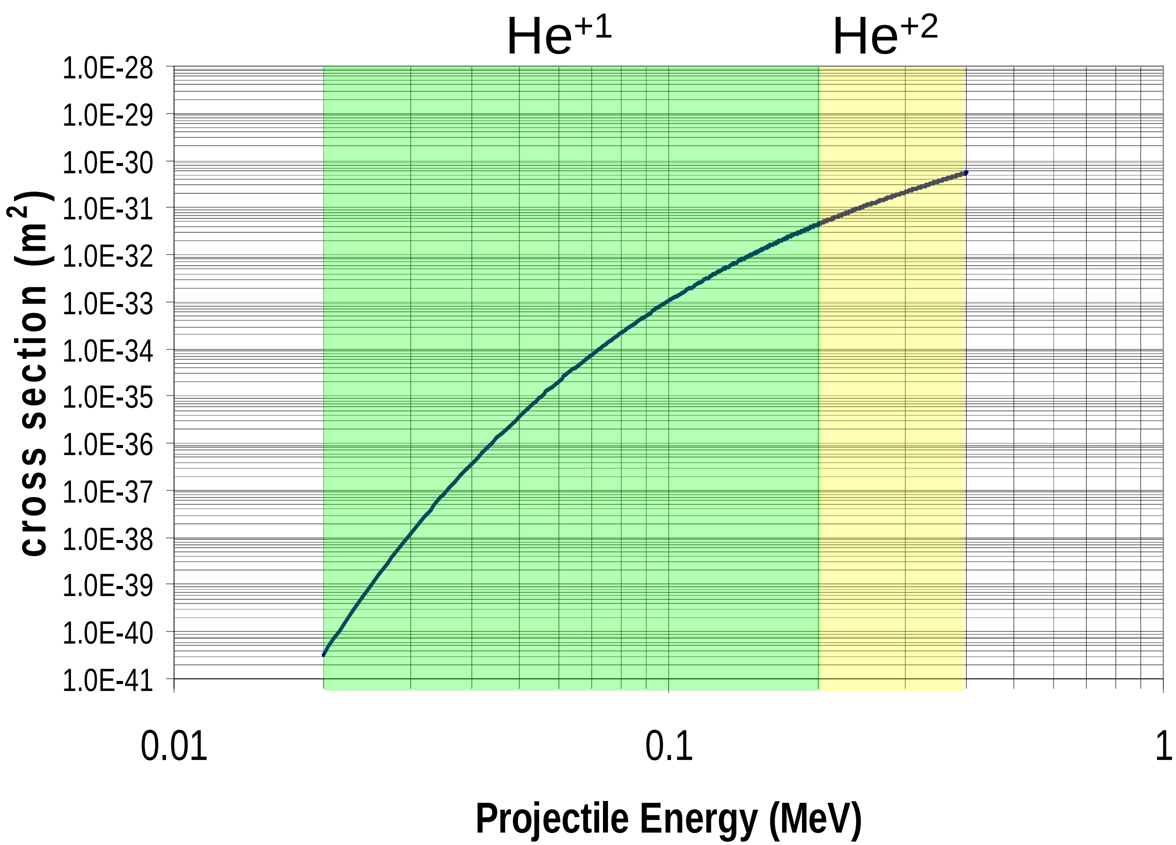


- Curve based on fit to data from "AEP Barnbook DATLIB" (1987)
- Cross section for projectiles on zero velocity targets
- Green range accessible to He^{+1}
- Yellow range accessible to He^{+2}

IEC Effective for Studying ^{3}He-^{3}He Reactions Below 1 MeV

- Accelerators very effective at measuring cross section at energies above 1 MeV
  - Good statistics become difficult as energy is decreased due to limited beam current (< 100 μA)
- IEC can provide relatively high ion current at lower energies
  - Recirculation allows for ion currents as high as 100 mA or more
  - Cathode voltages from -200 to 0 kV currently available

Reactions in IEC Devices Known to Come From Several Regimes

- Beam-background
  - Primary ions fuse with background neutral gas
- Beam-embedded
  - Primary or secondary ions collide with fuel embedded in grid
- Fast neutral-background
  - Primary or secondary ions that have charge-exchanged and become fast neutrals fuse with background gas
- Converged Core
  - Fast ions collide with other fast ions in device center

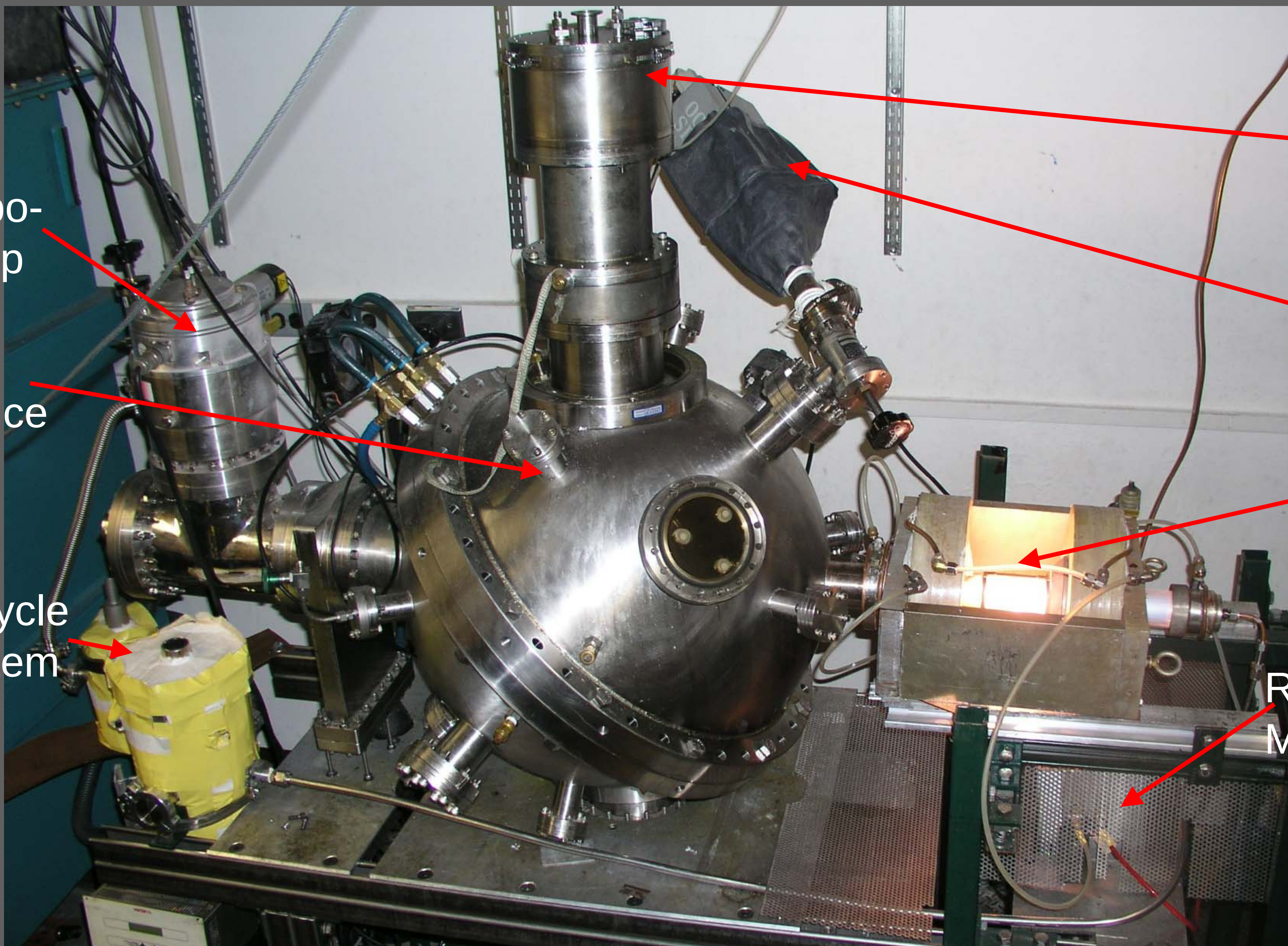
^{3}He-^{3}He Fusion Source Regimes Anticipated to be Similar those for D-^{3}He

Regime	D-D (Exp., 2 mtorr, 100 kV)	D-^{3}He (Exp., 2 mtorr, 100 kV)	^{3}He-^{3}He (Theory, 0.2 mtorr, 200 kV)
Beam-background (near cathode)	22%	5%	7%
Embedded	8%	95%	93%
Fast neutral-background + beam-background elsewhere	70%	0%	0%
Converged core	0%	0%	? But likely very small

IEC System Specifically Designed to Meet the Requirements to Observe ^{3}He-^{3}He Reactions

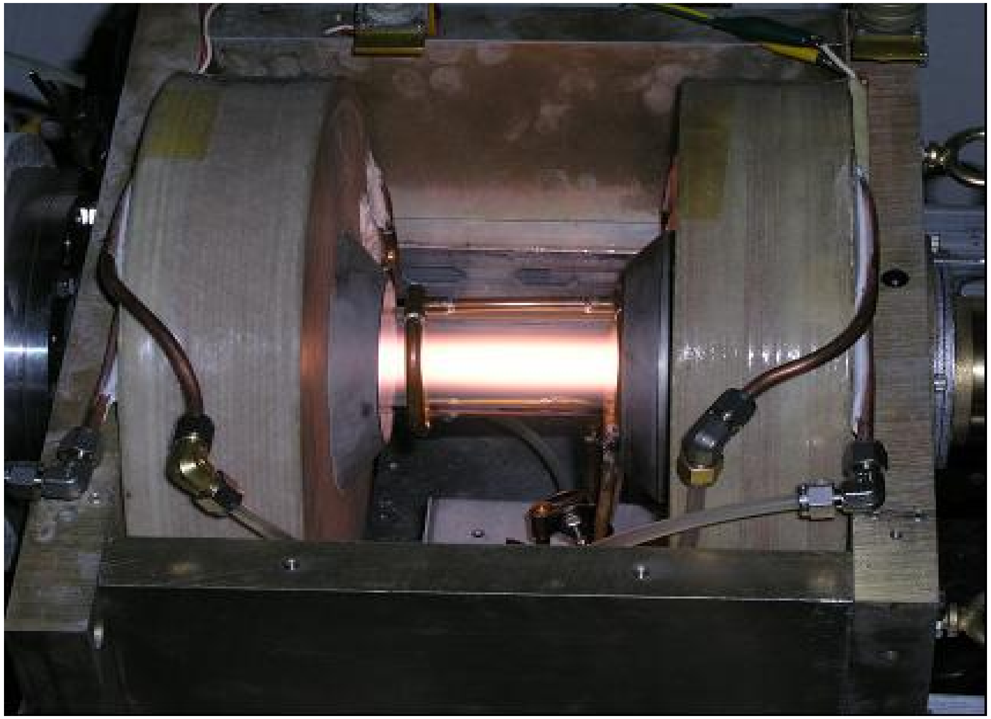
- New stainless steel, double walled vacuum chamber
  - Water cooled to allow for long runs
  - Free from D contamination
  - Equipped with various gas diagnostics (ion gauge, RGA, others)
- High voltage system
  - Current supply capable of 200 kV, 75 mA
  - Buffer circuit design stabilizes operation with plasma
  - Advanced insulator allows long lifetimes
- Helicon ion source
  - Allows for large ion current with minimal gas flow
  - Allows for direct measurement of <u>ion</u> current
- Gas recycle system
  - Uses liquid nitrogen to freeze out impurity gasses
  - Capable of operating for > 1 hour with only a few minutes of ^{3}He flow

^3He-^3He IEC System



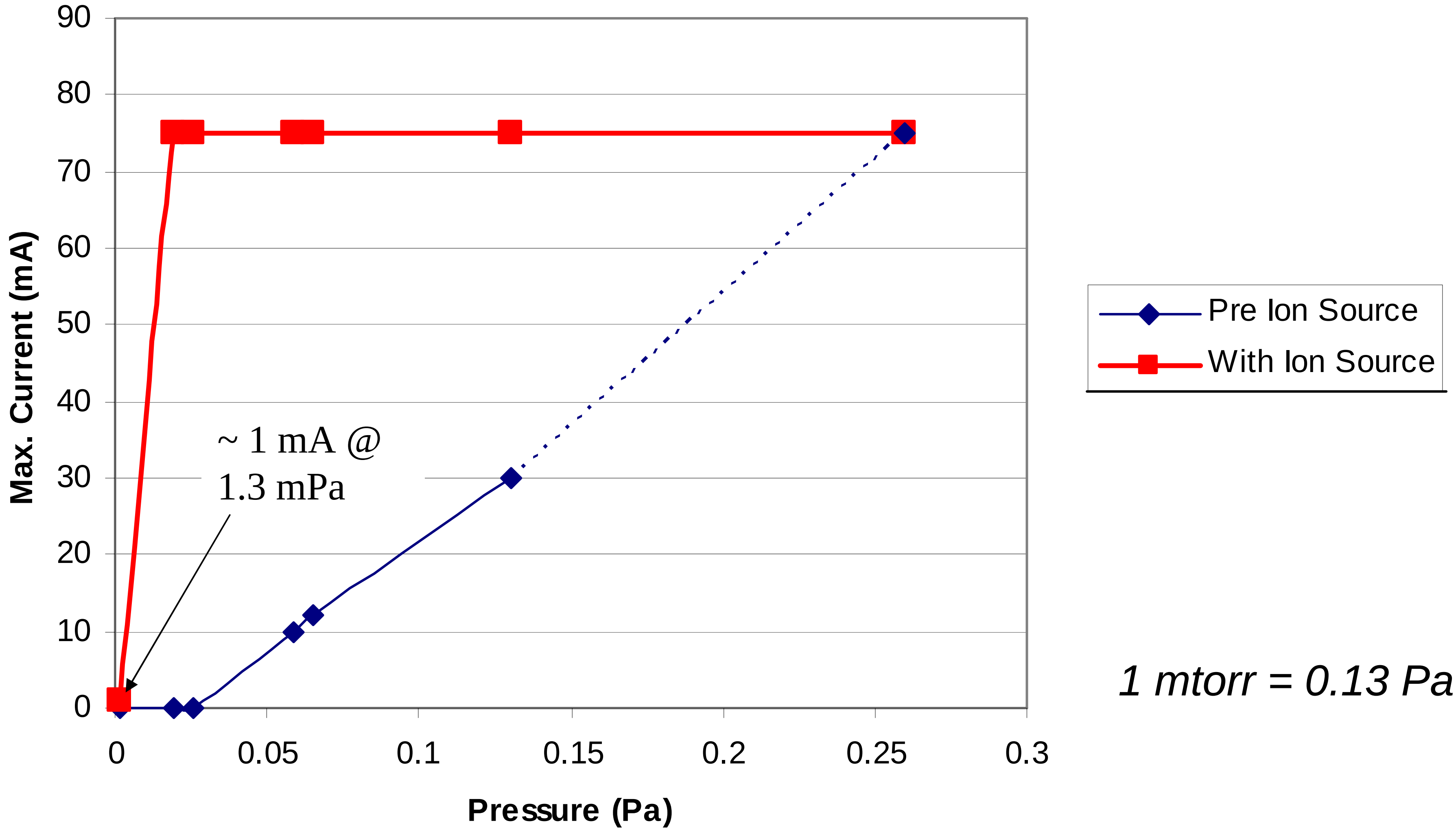
Helicon Ion Source Allows Operation in New Regimes

- Maximum ion current: 12 mA—independent of IEC conditions
- Minimum reaction chamber pressure at high current: 20 mPa
- Maximum run time: indefinite



- Other characteristics:
  - Max RF Power: 3kW
  - Max B field: 2 kG
  - Approx. Density: 10^{19} / m^3
  - Antenna type: Water cooled Nagoya III
  - Antenna coupling: inductive
  - Magnet type: water cooled solenoid

Helicon Source Allows High Currents at Low Pressures Compared to Previous Devices

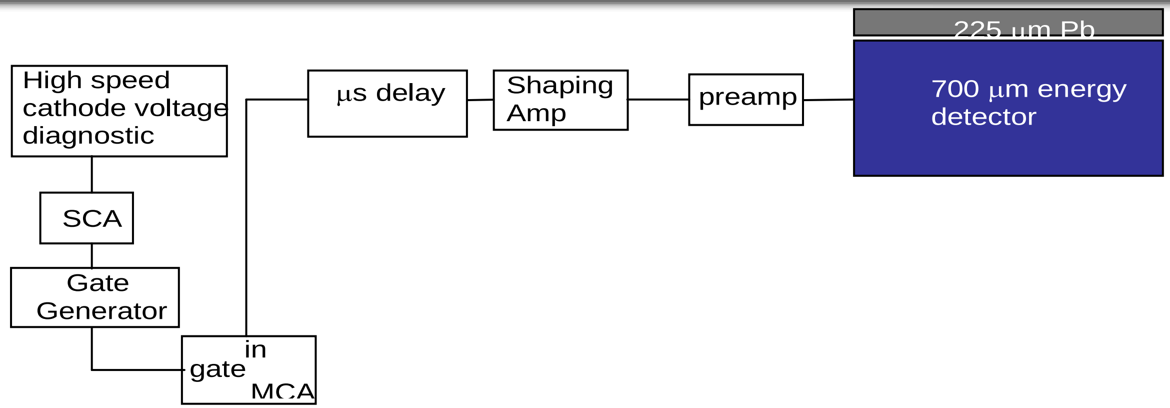


1 mtorr = 0.13 Pa

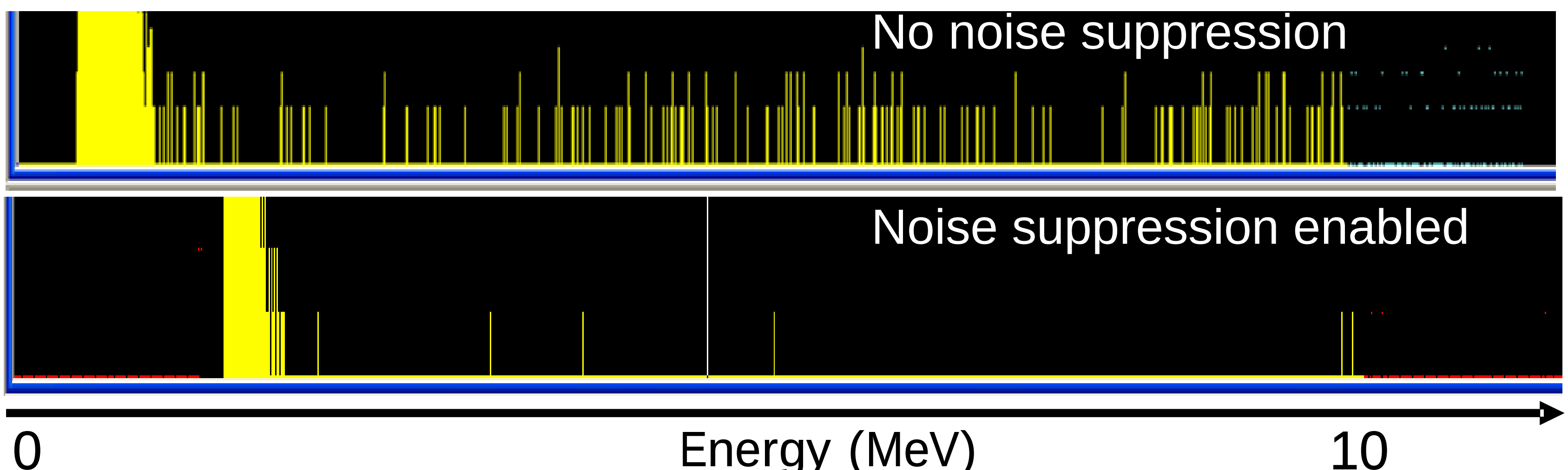
IEC Performance has Reached Voltages Necessary for Detection of ^{3}He-^{3}He Reactions

- Maximum voltage achieved: 170 kV
- Maximum sustained voltage (for 900 seconds): 150 kV
- Typical repeatable voltages: 120 kV – 140 kV
- About a dozen ^{3}He runs have been done at these conditions, and half of these with direct comparison between ^{3}He and ^{4}He fuel
- Typical current ~ 25 mA cathode (~ 7 mA ion current) at 0.03 Pa (200 μtorr) in He gasses

Noise Suppressing Detection System Required to Observe Low Reaction Rate

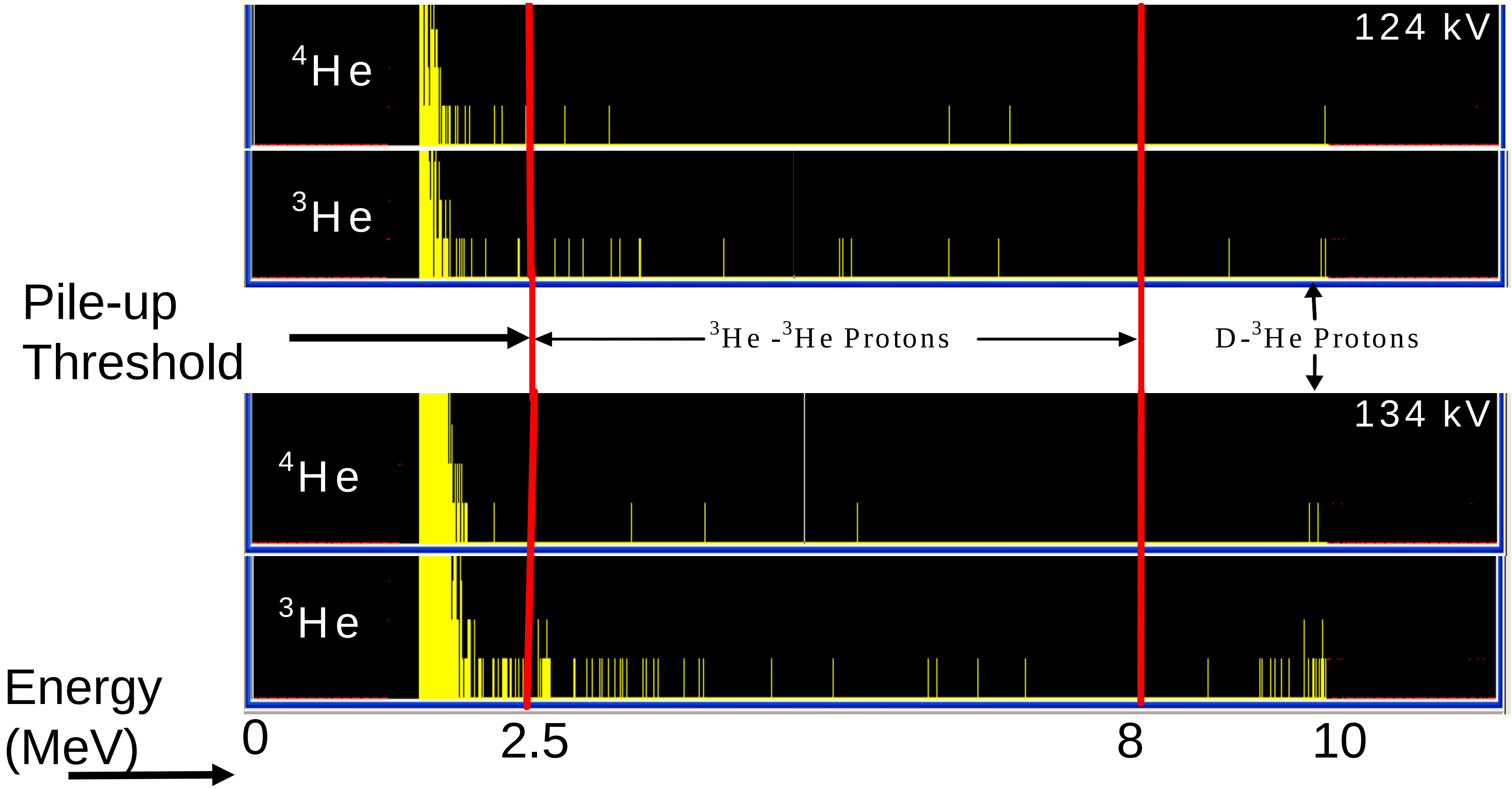


- System works by detecting instability, and disabling the MCA for a time before and after said instability occurs
- Result is a factor of 50-100 noise reduction



Completion of IEC and Detection Enhancements Allowed Observation of ^{3}He-^{3}He Reactions

- 900 second acquisition time; 25 mA cathode; 7 mA source current; runs back to back to ensure similar background data



Observed ^{3}He-^{3}He Reaction Rate is within 50% of Theoretical Estimate

- To improve statistics, all runs added together and averaged

Voltage	Theoretical Beam-Background Rate[1] (reactions / sec)	Theoretical Detectable Embedded Rate*[1] (reactions / sec)	Measured Rate (reactions / sec)
124 kV	16 ± 5	99 ± 15	144 ± 44
134 kV	31 ± 9	206 ± 30	400 ± 67

* Detectable rate is one half of actual embedded rate

[1] Cross section based on figure in slide 4, with error neglected

Summary of this Effort

- IEC device constructed that can run steady-state at high power levels
- High voltage components designed that allow operation in He at up to 170 kV, and sustained at 120-140 kV
- High voltage system reliability increased such that component failures have become rare
- Gas recycle system developed to allow for long term operation in ^{3}He gas with minimal gas use

Summary of This Effort (cont.)

- Ion source developed that allows for IEC operation at much lower pressure than previous devices without sacrificing ion current
- Ion source developed for independent control over source current, which allows for more accurate knowledge of ion current
- Proton detection system noise decreased by 50-100 times
- ^{3}He-^{3}He reactions detected in UW IEC device at an average rate of 400 $\pm$ 67 reactions / sec (maximum 600 / sec) at 134 kV

Summary of This Effort (cont.)

- Actual fusion rate is higher than detected rate since only half of embedded reactions are counted
- Using the theoretical prediction for the ratio of embedded to beam-background fusion gives an estimate of the true reaction rate

Voltage	Theoretical % of Reactions from Beam-Embedded Fusion	Measured Rate (reactions / sec)	Inferred Total Fusion Rate (reactions / sec)
124 kV (ave.)	86%	144 ± 44	268 ± 76
134 kV (ave.)	87%	400 ± 67	748 ± 117
134 kV (max.)	87%	600 ± 89	1122 ± 155

Questions?

Greg Piefer—grpiefer@wisc.edu

UW-Madison Fusion Technology Institute

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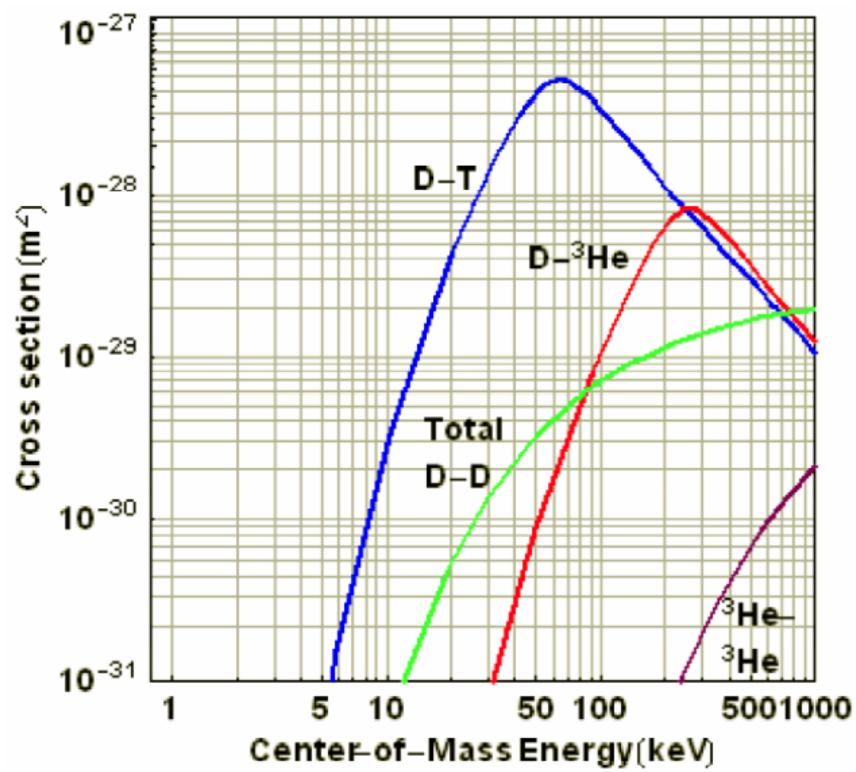
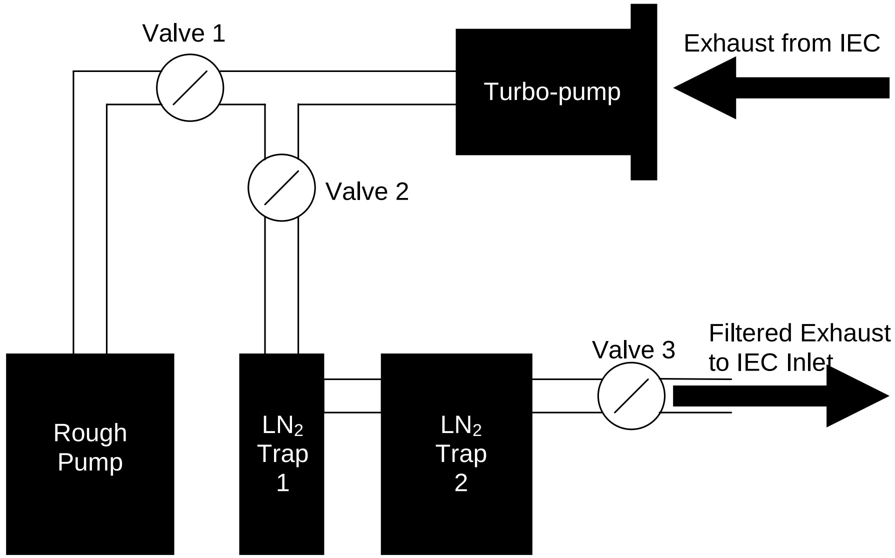
Fusion Cross Section Indicates High Energy Needed to Observe $^{3}He(^{3}He,2p)^{4}He$ Reactions



- *Operation at high cathode voltage and low background pressure required*

^{3}He Recycle System Objective Met

- Dual stage LN_2 condenser traps filter turbo-pump exhaust, which runs back into main system
- High compression turbo-pumps allow for operation of recycle system with no additional pumping stage



- Operation tested up to 1 hour with 2-3 minutes of ^{3}He flow

Motivation

- Overarching physics goal: study ^{3}He-^{3}He reactions in IEC device
  - Nuclear physics
    - Very few measurements of fusion reaction cross section
    - Measurements at energies < 1 MeV are statistically poor
  - Stellar physics
    - Observed number of neutrinos emitted by the sun did not match theoretical predictions, which led some to theorize that there was a low energy resonance in ^{3}He-^{3}He
    - Current models of stellar evolution indicate there should be a larger amount of ^{3}He in the universe than observed, which requires a mechansim for stars to burn ^{3}He more efficiently

Motivation (cont.)

- Overarching physics goal: study ^{3}He-^{3}He reactions in IEC device (cont.)
- ^{3}He-^{3}He nuclear energy (advantages)
  - All energy emitted in the form of charged particles
    - Minimal reactor activation
    - Possibility of direct conversion (non-thermal conversion)
  - No radioactivity associated with reactants or products
  - Tremendous resource believed to be available in lunar soil (1000 yrs)
- ^{3}He-^{3}He nuclear energy (disadvantage)
  - High temperatures required make $Q > 1$ reaction impossible in a thermal plasma

Helicon Source Allows High Currents at Low Pressures Compared to Previous Devices

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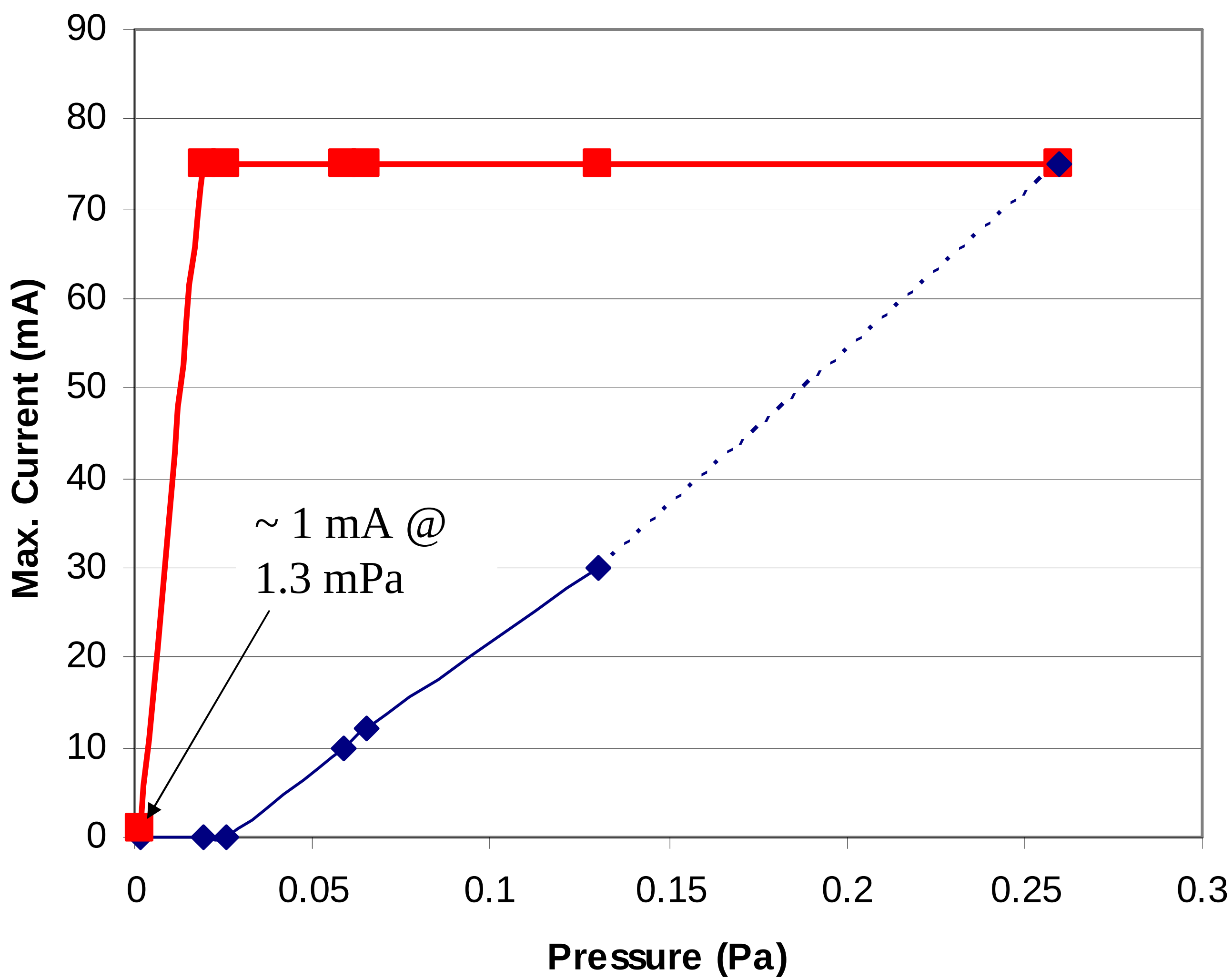
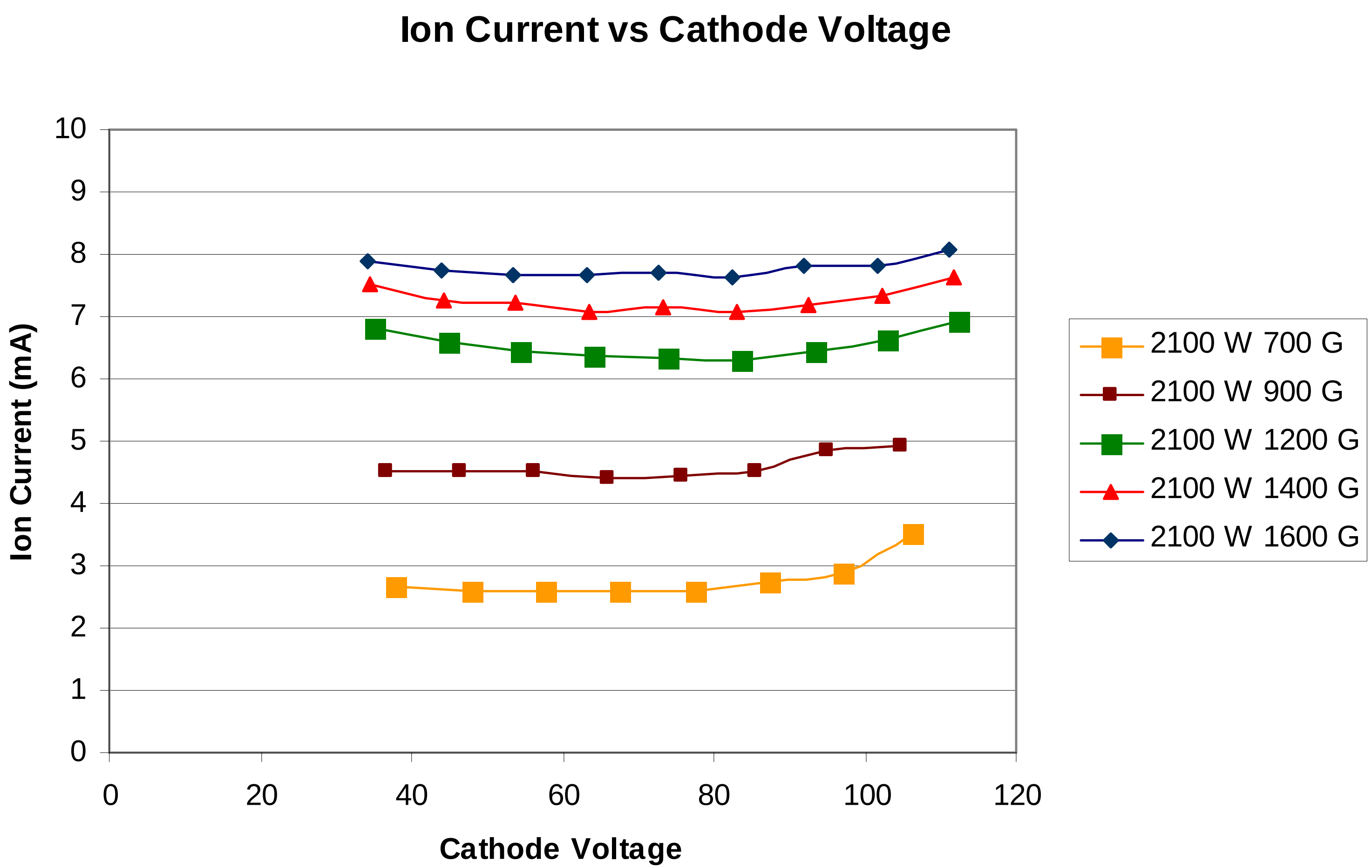
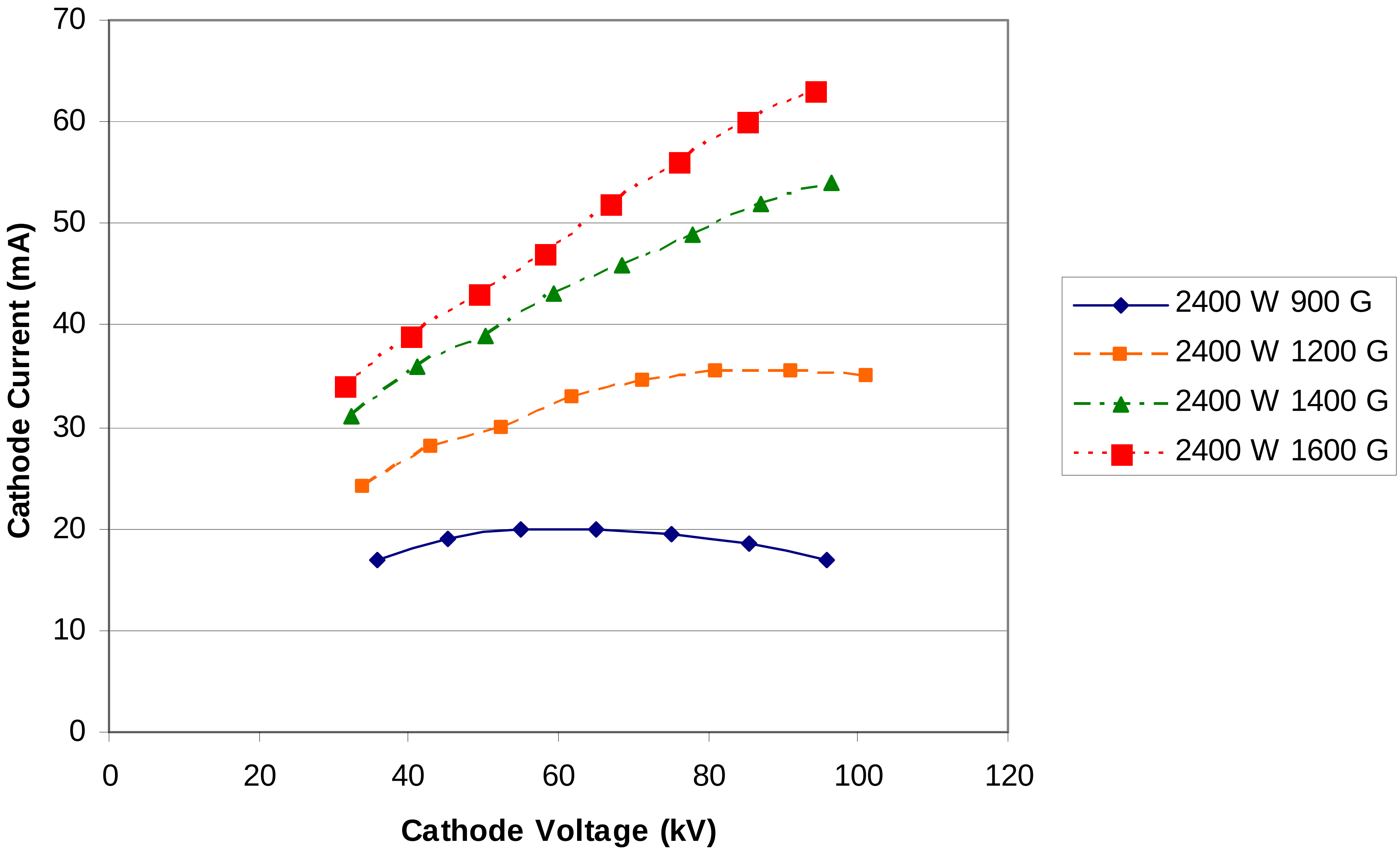


1 mtorr = 0.13 Pa

Ion Current Versus Cathode Voltage (weak dependance)



Cathode Current Versus Voltage



Grid Effective Secondary Emission Coefficient

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