Progress in the Development of a $^3$He Ion Source for IEC Fusion


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Outline

- $^3\text{He}-^3\text{He}$ Fusion
  - Rationale for experiments
  - Reaction physics
  - IEC beam-background reaction rate estimate
  - Detectability

- Ion source development
  - Status as of the last meeting
  - Progress since the last meeting
  - Summary
Purpose of $^3\text{He}-^3\text{He}$ Fusion in an IEC

- **Benefits of $^3\text{He}-^3\text{He}$ Fusion**
  - No Radioactive fuels or products
  - Possibility of direct energy conversion
  - Minimal or no activation of reactor vessel

The $^3\text{He}-^3\text{He}$ fusion reaction

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2\text{Proton} \]

12.9 MeV Total
Purpose of $^3\text{He}-^3\text{He}$ Fusion in an IEC

- IEC offers some advantages over other research experiments
  - Higher energy capability than MFE or ICF devices
  - Higher current capability than accelerators
  - Allows for study of cross sections where counting statistics are currently poor

The $^3\text{He}-^3\text{He}$ fusion reaction

- Proton
- $^{12.9}\text{MeV}$
- $^4\text{He}$
- Total
Purpose of $^3$He-$^3$He Fusion in an IEC

- $^3$He-$^3$He fusion has some significant disadvantages
  - Very small cross section at low voltages
  - Relatively difficult to obtain fuel in large quantities

![Diagram of the $^3$He-$^3$He fusion reaction](image)
$^3$He-$^3$He Fusion Cross Section is Substantially Lower than D-D
The 3-body $^3\text{He}$-$^3\text{He}$ reaction (~90% of reactions at 190keV CM energy)

- The three body reaction gives a relatively flat continuum of proton energies, which will be difficult to separate from noise.

The two 2-body $^3\text{He}$-$^3\text{He}$ reaction (~10% of reactions at 190keV CM energy)

- The 2-body reaction however, gives discrete proton energies, which will appear as a peak on top of the continuum at 9.3 MeV.
Reactivity in IEC will be Modeled as a Monoenergetic Beam-Background Source

- Beam currents low enough so that converged-core reactions are assumed to be insignificant
- Background gas pressure kept low enough such that ion charge exchange time is long compared to ion lifetime
- Model assumes proton detector observes reactions only inside of the cathode
Setup for $^3$He-$^3$He Experiments

- 450 l/s Turbopump
- -200 kV (maximum)
- 1.9 cm Boron Nitride High Voltage Insulator
- 61 cm Diameter
- 20 cm Gate Valve
- Tungsten Cathode Solid State Proton Detector
- To Ion Source
- Water-cooled Stainless Steel Chamber
- RGA
- Mounting Table
Setup for $^3$He-$^3$He Experiments
Assumptions for Rate Calculation

- Cathode current \( \sim 10 \text{ mA} \)
- Cathode voltage = 200 kV
  - \(^3\text{He}\) singly ionized \(\rightarrow\) Center of mass energy = 200 keV
- Cathode Transparency = 99%
- Average secondary emission coefficient = 2
- Background gas pressure = 0.2 mtorr (27 mPa)
- Cathode/anode radius ratio sufficiently small such that full ion current can be drawn
Fusion Rate can be Calculated from Assumed Parameters

- The fusion rate for a beam-background mono-energetic system can be calculated by the following equation:

\[ F = n_b \times \frac{I_{cath} \times 2R_{cath}}{e(1 - \gamma)(1 + \sigma_{se})} \times \sigma(E) \]

- \( n_b \) is the background gas density, \( I_{cath} \) is the measured cathode current, \( R_{cath} \) is the cathode radius, \( \sigma(E) \) is the fusion cross section, \( e \) is electron charge, \( \gamma \) is the grid transparency, and \( \sigma_{se} \) is the average secondary emission coefficient.
Fusion Rate can be Calculated from Assumed Parameters

- The fusion rate for a beam-background mono-energetic system can be calculated by the following equation:

\[ F = n_b \times \frac{I_{\text{cath}} \times 2R_{\text{cath}}}{e(1 - \gamma)(1 + \sigma_{se})} \times \sigma(E) \]

- Using existing data for $^3\text{He} - ^3\text{He}$ cross sections, this gives a fusion rate of $2 \times 10^5$ fusions/second
Detection Rate Should be Observable

- Detector is ~ 50 cm from center of device
- Detector area = 1200 mm$^2$
- The number of detected counts can be expressed as:

$$D = \frac{F}{4\pi R_{det}^2} A_{det}$$

- Detection rate ~ 76 counts/sec
- If 10% of these are 2-body reactions, the 9.3 MeV peak will have 7.6 counts/sec
Ion Source Status as of Last Workshop—October 2003, Tokyo, Japan

- Helicon source on-line with $^4\text{He}$
- 2 mA cathode current observed in main system at modest voltage (~35 kV)
- Extraction system not yet constructed
- Ion current difficult to control
- Helicon fringing fields affected extracted beam
Ion Extraction Region Completed and Operational

- New electrode designed to minimize erosion
- Beam collection plate diagnostic added
Extraction System Tested in $^4$He with Collection Plate
Ion Extraction Current Versus Extraction Voltage Shows Good Current Capability

Ion Current Versus Extraction Voltage (RF Power=60 W)

Extraction Voltage (V)

Current (mA)

Helicon Field = 1.5 kG

Helicon Field = 1.2 kG
Stray Fields from Helicon Source Appear to Cause Beam Deflection
New Helicon Magnets are Installed and Now Being Tested
Fringing Fields Shunted Through Magnetic Circuit

35 cm
IEC Operation with Ion Source is Improving

- Operation at voltages up to 130 kV
- Operation at cathode currents up to 10 mA
- Operation at pressures as low as 50 μtorr, and as high as 0.5 mtorr
Some Instability in High Voltage Discharges
Conclusions

- IEC experiments looking for $^3\text{He} - ^3\text{He}$ fusion reactions are underway
- Good results so far with $^4\text{He}$, and some with $^3\text{He}$
- Ion source and IEC operation with source have improved markedly
  - Extraction region online
  - Helicon fringe fields reduced
  - IEC operating voltage up to 130 kV
- Still some problems to overcome
  - HV breakdown at high cathode voltages
  - He beam deflection
Questions?