Exploring Non-Uniformities in Gun-to-Gun Performance on the Six Ion Gun Fusion Experiment (SIGFE)

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Presented at the
14th US-Japan IEC Workshop
14-16 October 2012 in College Park, MD

Research supported by the
Grainger Foundation and the
Greatbatch Foundation
Presentation outline

• Brief summary of experimental design and operation

• Key results from Dr. Brian Egle’s previous work on SIGFE

• Description of recent device recalibration

• Discovery of asymmetric gun behavior

• Discussion of reasons for asymmetry
SIGFE converges 6 focused ion beams into center of device

- SIGFE operates at a lower chamber pressure than many gridded IEC devices, as low as 10 mPa (75 µTorr)
- Variable beam focus

- Possible IEC operational modes
  - Beam-background
  - Beam-embedded
  - Converged core
  - Multiple virtual electrodes (Poissors)
SIGFE replicated and expanded the Hirsch experiment from 1967

• Original Hirsch device was most efficient IEC for neutron production per kW input power

![Graph showing comparison of neutron production per kW]  

- Six ion guns
- Gridded IEC devices

- SIGFE replicated some of the main mechanical and electrical features of Hirsch’s experiment
Schematic of two opposing guns

- Plasma tube and aperture – 0 V
- Focus lens – -3 to -5 kV
- Cathode lens – -50 to -150 kV
- Ground ring – 0 V
- Extraction lens – -10 kV
- Filament driven plasma

Same settings on this gun
SIGFE’s n rate vs. pressure is different than gridded IECs, for certain parameters

- 100% is ideal focus

- Neutron rates in an ideally focused SIGFE depend little on pressure

- Neutron rates in UW gridded devices and an over focused SIGFE are proportional to pressure

- SIGFE’s, as well as Hirsch’s experimental neutron rates scale inversely with pressure when under focused
SIGFE matched Hirsch’s neutron rates, evidence points to beam-embedded fusion

- SIGFE replicated the Hirsch device D-D fusion rates for the same parameters in the defocused state

- Results of defocused run suggest beam-embedded, inside cathode, as dominant mode of fusion in SIGFE
SIGFE used bending magnet to reduce X-ray noise while looking at cathode center

- A strong electromagnet (1.5 T max) was used to deflect particles out of line-of-sight X-rays to reduce noise
- Detector was looking as a small volume along the center of the cathode where the 6 beams intersected
Protons from beam intersection

Neutrons from whole device

- 100 kV Cathode voltage
- 5 mA total cathode current
- 80 mPa (600 µTorr)

D+D 50% → n+T
50% → p+³He

- The equal branching ratio of D-D fusion says one should have an equal number of protons and neutrons found in the system.
- When adjusted for detector view-factor, almost 1000 times more neutrons detected in whole device than protons from the center.
- Most fusions must be occurring elsewhere.
Lens alignment and electron confinement are important to performance

- The system measures total, not beam current
- 10 mA could be any combination of ion and electron currents

<table>
<thead>
<tr>
<th>Neutron Rate [n/s]</th>
<th>Cathode Voltage [kV]</th>
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<td>120</td>
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<tr>
<td>1.4E+07</td>
<td>140</td>
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</table>

- 2-3 times improvement in performance observed with good lens alignment and better electron confinement in the cathode
Mechanical and electrical system is very symmetrical gun-to-gun

- Lenses were machined to <0.05 mm
- Lens spacing <0.1 mm different gun-to-gun
- Guns aligned to <0.2 mm

- Focus and extraction lens voltages held within 40 V between guns (normal applied voltage is -4 and -10 kV, respectively)
Recent experiments verify SIGFE is performing the same as in 2009

- Before moving forward, experiments were conducted to verify SIGFE was operating the same as when earlier data was taken
- Top graph parameters: 300 μTorr, 10 mA meter cathode current
- Bottom graph parameters: 100 μTorr, 10 mA meter
Lens current data suggests differences in plasma and beam from gun-to-gun

- Total current on focus and extraction lenses is significantly different despite having an aligned system and consistent voltages on lenses
- This suggests significant differences in ion source plasma
- These differences lead to variation in beam focus
Single gun operation also suggests different plasma parameters gun-to-gun

- Filaments were turned on one-by-one
- Cathode current and neutron rates varied from gun-to-gun for same electrode voltages and chamber pressure parameters
Different filament resistances and source magnetic fields likely account for variation

- Filament resistances during operation vary from gun-to-gun by as much as factor of 2.5
- Filament resistance changes over operation time – amount not yet quantified
- Confining magnetic field differences would also contribute but are hard to measure accurately in current state
  - Permanent magnets set up dipole magnetic field to confine electrons in plasma source region
Adding Langmuir probes will help determine sources of non-uniformities

- Better beam diagnostics and knowing plasma parameters will help determine cause for differences between guns
- Langmuir probe in the plasma source region would be the simplest diagnostic to use in current system
Summary

- SIGFE replicated Hirsch’s neutron rates and efficiency
- Fusion rates in SIGFE are most likely due to beam-embedded fusion inside the cathode lenses
- Despite mechanical and electrical symmetry of the system, there is evidence of asymmetries in beams
- Differences in source plasmas between guns is probably the reason for asymmetries
Thank you for your attention – Questions?