Overview of Novel IEC Fusion Grids and Miniaturized Electron and Ion Sources at TU Dresden

J.-Ph. Wulfkühler, M. Tajmar, R. Bowden-Reid, J. Khachan

20th US-Japan Workshop on Fusion Neutron Sources for Nuclear Assay and Alternate Applications, Washington DC, October 16, 2018
1. Introduction of TU Dresden and Research at the Institute of Aerospace Engineering
2. Motivation of the Buckyball Geometry
3. Manufacturing of Electrodes
4. Experiments with Argon Glow Discharges
5. Comparison of Deuterium Fusion Rates of Buckyball shaped Grids with “Classic” Grid Geometries
6. Overview of Ion and Electron Sources
Technische Universität Dresden / Dresden University of Technology (TU Dresden)

- Founded in 1828, today 36,000 students (2nd largest technical school in Germany)
- German Elite-University, member of the leading technical schools (TU9)
- Budget of 550 M€, 536 (Full) Professors and 7800 Staff Members
- Dresden – #2 science city in Germany
Institute of Aerospace Engineering

Director: Prof. Dr. Martin Tajmar

Campus Johannstadt

- Structure
  - Two Chairs
  - WG Aerodynamics
  - Large-Scale Infrastructure (Wind Tunnel)

- Personal
  - 45 Staff
  - ca. 25 at Space Systems Chair

- External Funding
  - ca. 2 M€ (2016)

- Students
  - ca. 230 Majoring Aerospace Engineering (5.-10. Semester)
  - 50-60 Thesis / Year
Space as a Driver for High-Tech Products and Research

3 Research Groups / Core Topics

Small Satellites and Spin-Off Technologies

CubeSats
Gas Sensors (FIPERX)
Spin-Offs

Energy Systems for Space and Mobile Applications

Thermo-Electric Generators
Simulation and Testing
Energy-System Analysis

Space Propulsion and Advanced Concepts

Electric Propulsion (e.g. FEEP)
Student Rocket
Breakthrough Propulsion
Electric Propulsion

- MEMS Neutralizer/Thruster
- FEEP Thruster
- Low Power Hall Thruster and Cathode
- IEC Fusion

New Sensors

- Nano-Newton Thrust Balance
- Optical Accelerometers, Gyroscopes

Revolutionary Concepts

- Breakthrough Propulsion Physics

Formation Flying, Science, Enabling Technology, Small Satellites

Interstellar Propulsion
IECF with Buckyball-Shaped Grids
Abstract Design of Electrodes

- **Aim:** Design of grids with a more regular distribution of same shaped apertures compared with "classic" latitude/longitude structured wire grids
- **Final geometry:** Based on shape of truncated icosahedron and Buckminster fullerene

- **Left:** maximum theoretical transparency of grids with different numbers of circular apertures
  → “buckyball” shape with 32 circular apertures is a good compromise
  → 2 options for shape of apertures

A) 32 circular apertures

B) 32 polygon apertures
## Overview of Electrodes

### Manufacturing of Electrodes

- **Manufacturing technique of choice**: Selective Laser Melting (SLM)
- **SLM process**: determined sizes of the electrodes (max. Ø150 mm) and materials
- **Disk grids and wire grids**: with “classic” longitude/latitude structure for comparison

**Buckyball grids**

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Material</th>
<th>Density (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø40</td>
<td>stainless steel (304L)</td>
<td>80.5%</td>
</tr>
<tr>
<td>Ø80</td>
<td>bronze infused steel</td>
<td>74.1%</td>
</tr>
<tr>
<td>Ø150</td>
<td>SS (304L) 1/ Ti-6Al-4V 2</td>
<td>82.7%</td>
</tr>
</tbody>
</table>

**“Disk Grids” in all three sizes**

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Material</th>
<th>Density (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø150</td>
<td>stainless steel (1.4301)</td>
<td>82.5, 91.3, 95.3%</td>
</tr>
</tbody>
</table>

**“Wire Grid” Ø150 mm**

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Material</th>
<th>Density (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø150</td>
<td>stainless steel (1.4301)</td>
<td>Approx. 95%</td>
</tr>
</tbody>
</table>

Manufactured by:  
1. Leibniz Institute (IFW) Dresden, 2 Institute of Lightweight Engineering and Polymer Technology (ILK) Dresden, 3 Materialise NV, 4 Rapidobject GmbH
Comparison of Glow Discharge Characteristics

- Initial tests with argon discharges (-20 kV/ 6 mA)
- Buckyball grids with a more distinct star mode but also higher discharge voltages

Disk grids:

Ø80/150
Ø40/150

Buckyball grids:

Ø80/150
Ø40/150

Voltage pressure characteristics for 6 mA cathode current
Additional Experiments

- Tests at higher pressure levels with argon reveal jet mode $\rightarrow$ with increasing pressure the jet changes from a “tight” jet to a “spray” jet

- Multigrid tests with star mode (less pronounced than with two grids) and jet mode
Conducted by R. Bowden-Reid and J. Khachan at University of Sydney

- Cathode: -35 kV/-40 kV; 0.1 – 1 mA; Pressure steps: 1E-4, 5E-4, 1E-3, 5E-3 Torr
- Two 25x125 mm, 4 atm. He-3 tubes in high density polyethylene moderator
- Filament electron source for assisted glow discharge
- 5 test configurations:

<table>
<thead>
<tr>
<th></th>
<th>Buckyball Grid</th>
<th>Disk Grid</th>
<th>Wire Grid</th>
<th>Nested Buckyball</th>
<th>Nested Disk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>Ø150 mm Grid</td>
<td>Ø40 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td>Ø300 mm Chamber</td>
<td>Ø150 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fusion Experiments – Recorded Fusion Rates

- Fusion rate (2×NPR assuming 50:50 branching of DD reaction) increased nearly linearly in all configurations with current.
- Higher pressures increase fusion rate → Indicators for beam – target fusion.

Ø150 mm buckyball grid

DD Fusion Experiments

![Graph showing fusion rates vs. current for different pressures and voltages.]

- a) -35 kV
- b) -40 kV

- Indicators for beam – target fusion.
Fusion Experiments – Grid “Efficiency” per mAmp

- Fusion rate per mAmp for comparison of the grid performance
- Buckyball grids with higher fusion rate
- Nested grid designs with higher fusion rates

![Graph showing the fusion rate efficiency vs pressure for different grid designs](image-url)
Fusion rate $F$ consists of four parts:
1. Beam-beam fusion reaction
2. Beam-target fusion reactions:
   a) Neutral background gas
   b) Adsorbed
   c) Embedded fusion

\[ F = F_{\text{beam-beam}} + F_{\text{background gas}} + F_{\text{adsorbed}} + F_{\text{embedded}} \]

\[ \approx 0 \]
Fusion Experiments – Determination of Main Fusion Source (2)

- **Ø150 mm buckyball grid:**
  - Preconditioning with hydrogen discharge (1E-2 Torr) → surface is initially covered with hydrogen → slowly exchanged by deuterium
  - NPR increases slowly at constant pressure (1E-2 Torr) and drops slowly after sudden pressure decrease (1E-4 Torr) → indicator for fusion with deuterium adsorbed to surface

- **Ø150 mm disk grid:**
  - No preconditioning → surface becomes quickly covered with deuterium
  - NPR reacts instantaneously to pressure increase but decreases only slowly as pressure is decreased

→ **Strong indicators for fusion reactions with adsorbed deuterium as main contributor to the NPR**
Adsorption process is described by the **Langmuir isotherm**:

\[ F \approx \frac{I_c}{e} \sigma_F \cdot N_{ads}(p) = \frac{I_c}{e} \sigma_F \cdot N_0 \frac{\sqrt{K_{eq} p}}{1 + \sqrt{K_{eq} p}} \]

- \( I_c \) ... cathode current
- \( N_0 \) ... number of available adsorption sites
- \( K_{eq} \) ... constant

Pressure dependent fusion rate can be fitted to the **Langmuir isotherm**

- Embedded fusion does not seem to contribute significantly (no significant increase of NPR over time)

→ **Up to 80% of the fusion reactions originate from surface fusion on the cathode!**
Next Steps at TU Dresden

- Production of buckyball-shaped wire grid(s) with polygon apertures
- Probably tests with deuterium and new power supply (100 kV, 50 mA)
  → but at voltages below 40 kV

Final wax template in comparison with the silicone mold and the plastic template
Miniaturized Electron and Ion Sources
Miniaturized Electron and Ion Sources

Basic Principle of Field Emission Electric Propulsion (FEEP)

- High voltage potential between ion emitter and extractor electrode
- Liquid metal propellant pulled towards needle tip by capillary forces
- Our selection:
  - Needle: Porous Tungsten / Glass Capillary
  - Propellant: Gallium (low melting power – only \( \approx 50 \) mW)
- Reverse operation as electron source by change of polarity
- Features: Specific impulse: 1500 – 8000s; Thrust: 0-20 \( \mu \)N; Total Impulse: 7 – 24 Ns (56 – 200 Ns for larger version)

Principle of FEEP (needle type)
Miniaturized Electron and Ion Sources

Mission on UWE-4 (End of 2018)

- NanoFEEP (TU Dresden): 13 x 13 x 21 mm³

UWE CubeSat platform (University Wuerzburg)

Widest experience in CubeSat designing in Germany: 3 successfully launched CubeSats (UWE-1 to UWE-3)

In-Orbit demonstration of NanoFEEP on board of UWE (End of 2018)

Four thrusters integrated in CubeSat bars

4x Orbit control & 2-axes attitude control
**Cold CNT Neutralizer Chip**

- CNTs as cold electron emitters and neutralizers for FEEP thruster
- **Performance:**
  - 250 μA electron current from 8 x 8 mm² surface (max. 500 μA)
  - extractor voltage: 300 … 3000 V
- Over 500 h of continuous operation without degradation
- Test on onboard UWE cubesat (End of 2018)
C12A7 Electride Hollow Cathode

- C12A7 electride material has a very low work function material (0.6 – 2.1 eV)
- Heaterless hollow cathode designed and built at TU Dresden
  - successful ignition at room temperature (!)
  - total operating time of > 300 h (0.1 A @ 70 – 170 V keeper voltage)
- Large surface of buckyball geometry offers new opportunities for surface coatings
  → Thin film coating of C12A7 electride is possible
  → Thermionic electron emission from the inside cathode surface
  → Neutralization of ion space charge

BUT: chemical stability in deuterium vacuum atmosphere needs to be investigated
TUD-H1-S Hall-effect thruster

- Designed for a power range of 50-150 W (with Xenon)
- Ceramic-walled (boron nitride chamber walls)
- Solenoid with 500 windings for variable magnetic fields
- Gas flow through center stem for better dispersion
- Inner TC in order to monitor PEEK and solenoid temperature
- Channel dimensions: mean diameter 18 mm, width 5 mm, length 12 mm

Preliminary Characterization:
(with argon and wire cathode)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetic field</td>
<td>74 - 647 G</td>
</tr>
<tr>
<td>mass flow</td>
<td>0.13 – 0.28 mg/s</td>
</tr>
<tr>
<td>power</td>
<td>10 – 130 W</td>
</tr>
<tr>
<td>thrust</td>
<td>0.75 – 2 mN</td>
</tr>
<tr>
<td>$I_{sp}$</td>
<td>560 – 1300 s</td>
</tr>
</tbody>
</table>
Development of Compact ECR Microwave Ion Source

- Based on design by French company Polygon Physics
- Low power (~10W) 2.45 GHz microwave ECR ion source in early development phase
- 1 mA ion current at 40 kV; highly focused beams achievable (~Ø 0.1 mm)
- Applicable as H\(^+\), D\(^+\) ion source (need for Wien filter of molecular ions, e.g. D\(_2\)\(^+\), D\(_3\)\(^+\))

Ionization chamber (cavity)

Schematic with axial magnetic field (based on\(^1\))

---

\(^1\) P. Sortais, T. Lamy, J. Médard, J. Angot, L. Latrasse, and T. Thuillier, Rev. Sci. Instrum. 81, 02B314 (2010);
Conclusion

- Additive manufacturing of several electrode grids with 32 circular apertures based on the structure of the truncated icosahedron by means of selective laser melting → “buckyball” grids
- Successful argon glow discharge tests with different configurations:
  → Buckyball grids and long./lat. disk grids show a lot of common characteristics (star mode, jet mode)
  → Glow discharge tests with four-grid configurations
- Comparison of NPR from DD fusion between disk grids and buckyball shaped grids at University of Sydney:
  → At low voltages and pressures buckyball grids showed higher NPR
  → Strong indications found that in both grid types up to 80% of the fusion reactions are reactions between fast ions and deuterium adsorbed to the cathode surface
- Several ion and electron sources are currently under development and might contribute to future experiments
Two-Grid Setups

- Can be used for different grid types and diameters: Ø40mm or Ø80 mm at center, Ø150 mm as outer grid
- Tested with up to 20 kV
Multi-Grid Setups

- Use of PTFE and POM instead of ceramics for support structures
- Nested “matryoshka” design
- Plug-in system for easy assembling/dismantling
- Tested with up to 20 kV
Experimental Setups

Technical Equipment:

- Argon flux regulated via needle valves
- Max pressure with argon gas ~5e-3 mbar (3.75 mtorr)
- 20 kV feedthroughs
- LabVIEW program registered pressure, voltage and current at rate of 4 Hz

<table>
<thead>
<tr>
<th>Power-supply</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>FuG HCP 140-20000</td>
<td>-20 kV to +20 kV</td>
<td>6 mA</td>
</tr>
<tr>
<td>FuG HCP 35-20000</td>
<td>-20 kV to + 20 kV</td>
<td>1.5 mA</td>
</tr>
<tr>
<td>FuG HCP 35-35000</td>
<td>0 to -35 kV</td>
<td>1 mA</td>
</tr>
</tbody>
</table>
Buckyball Four-Grid Setup

- Star mode, but not as distinct as in two-grid setup
- Plasma influences potentials of grids → grids on floating potential
- Large current flow over vacuum chamber
- Voltages are higher than in two-grid setups

<table>
<thead>
<tr>
<th>Voltage, $10^3$ V</th>
<th>Pressure, $10^{-3}$ mbar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Grid 1 max</td>
<td>4</td>
</tr>
<tr>
<td>b) Grid 2 max</td>
<td>4</td>
</tr>
<tr>
<td>c) Grid 1, 2 max</td>
<td>4</td>
</tr>
</tbody>
</table>

Glow Discharge Experiments
Glow Discharge Experiments

Wiregrid Four-Grid Setup

- No star mode, only diffuse glowing ball at center
- Premature breakdown between grids due to sharp edges
- Lower discharge voltages compared to buckyball multi-grids

![Wiregrid Four-Grid Setup Image]

- Voltage, $10^3$ V
  - Grid 1 max
  - Grid 2 max
  - Grid 1, 2 max

![Graphs showing voltage-pressure relationship for different grids]
Buckyball Two-Grid Setup

- Bright star mode
- Glowing ball at center
- Discharge voltages are higher for 40 mm grid
- Current values spread more widely for 40 mm grid

Ø 40 mm

Ø 80 mm

![Graphs showing discharge experiments](image)

- Voltage, $10^3$ V
- Pressure, $10^{-3}$ mbar

- Lines for currents: 0.01 mA, 0.5 mA, 1 mA, 2 mA, 3 mA, 4 mA, 5 mA, 6 mA
Glow Discharge Experiments

Wiregrid Two-Grid Setup

- Rays of star mode visible only at “equatorial” apertures
- Glowing ball at center
- Interaction of Plasma with POM plate
- Lower discharge voltages and lower slope of curves
DD Fusion Experiments

Fusion Experiments – Pictures of Test Configurations

Ø150 Buckyball Grid
Ø150 Disk Grid
Ø150 Wire Grid

Ø40/150 Disk Grid
Ø40/150 Buckyball Grid
Fusion Experiments – Pictures of Glow Discharges