Fusion Application Targets


Collaborators: FHG, GA
Inertial Confinement Fusion in the laboratory will lead to new scientific opportunities.

Complex target structures are necessary to take full advantage of the unique laboratory environment created by inertial confinement fusion experiments.

Fusion Application Targets

- DT ice
- Doped foam & DT ice
- Ablator

2 mm

<table>
<thead>
<tr>
<th>Astrophysics</th>
<th>Nuclear Physics</th>
</tr>
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<tbody>
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<td>Supernova 1994D</td>
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</table>
Fusion application targets

Fabrication of foam-lined indirect-drive fusion application targets is challenging!

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Direct drive targets for omega</th>
<th>Indirect drive fusion application targets for NIF</th>
</tr>
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<tbody>
<tr>
<td>Shell diameter [mm]</td>
<td>0.8-0.9</td>
<td>2</td>
</tr>
<tr>
<td>Thickness of the foam shell [µm]</td>
<td>50-120</td>
<td>15-30</td>
</tr>
<tr>
<td>Foam density [mg/cc]</td>
<td>50-250</td>
<td>&lt; 30</td>
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<tr>
<td>Foam composition</td>
<td>Mostly resorcinol-formaldehyde (RF) based</td>
<td>Ideally pure CH</td>
</tr>
<tr>
<td>Permeation barrier/ablator thickness [µm]</td>
<td>1-5</td>
<td>80-150</td>
</tr>
<tr>
<td>Permeation barrier/ablator material</td>
<td>Glow discharge polymer (GDP), polyvinylphenol (PVP)</td>
<td>GDP, Be, High-density Carbon (HDC)</td>
</tr>
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The combination of low-density, thin wall, large diameter and thick ablator is difficult to realize with the well-established emulsion technique.
Chemistry-in-a-capsule

Ablator shell

Outside-in chemistry-in-a-capsule

Sol

Use shell as beaker

Coating and Curing

Doping and drying
## Scientific challenges

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Effect/problem</th>
<th>Strategies</th>
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<tr>
<td>Development of mechanical robust and non-shrinking low-density CH aerogels</td>
<td>● Must survive shear during coating process</td>
<td>● Tune rheological properties of gel system</td>
</tr>
<tr>
<td></td>
<td>● Must survive DT-wetting</td>
<td>● Add high strength materials</td>
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<tr>
<td>Filling capsules with picoliter volumes of precursor solution</td>
<td>● Evaporation of solvent</td>
<td>● Pressure-differential filling</td>
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<td></td>
<td>● Surface tension</td>
<td>● Microfluidic filling</td>
</tr>
<tr>
<td>Coating the inside of hollow spheres with uniform gels films</td>
<td>● Overcome gravitation</td>
<td>● Deterministic rotation</td>
</tr>
<tr>
<td>Doping of aerogel coatings</td>
<td>● Doping through micron-sized fill hole</td>
<td>● Atomic-layer-deposition</td>
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<tr>
<td></td>
<td></td>
<td>● Add functionalized monomers</td>
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</tbody>
</table>
Chemistry-in-a-capsule challenges

- CH-based aerogel design
- Ablator shell filling
- Coating
- Doping
- Cryogenic test
Development of CH-based low-density aerogels

Non-shrinking low-density polymer aerogels

- **Dicyclopentadiene (DCPD)** cross-linked polymer network
- **DCPD** monomer
- **Ru** catalyst
- **Toluene**
- **TEM Image of a 30 mg/cc DCPD aerogel**

Carbon nanotube reinforced carbon aerogels

- Requires high temperature pyrolysis, but elastic behavior up to very large (~90%) strains

Worsley M.A. *et al.* 2009 *J. Mater. Chem.* 19, 3370
Worsley M.A. *et al.* 2008 *Langmuir* 24, 9763

We have developed mechanical robust, ultra-low density polymer and carbon aerogels
Development of new CH-based aerogels

Choice of catalyst and copolymerization allow us to explore novel polymer compositions and architectures

- Catalyst reactivity controls cross-linking
- Functional groups for doping and to control cross-linking, morphology and solubility

The properties of DCPD aerogels can be modified by catalyst reactivity and copolymerization with functional monomers

Gelation timescale can be adjusted by catalyst concentration
### Viscosity management
- Partially crosslinked network
  - Crosslinked
  - Linear

- Less crosslinked

- Highly crosslinked

### Doping
- Polymer modification
  - Electrophilic addition

- Functional monomers
  - Or

  - Or
    - On-going

### Solubility/Morphology
- Steric effect

- Electronic effect

- On-going
Example: Designing shear resistant gels

- **Cross-linker**
  - Very effective cross linking

- **DCPD**
  - Linear + some cross linking

- **Norbornene**
  - Only linear

**Increasingly cross-linked network**

- Delaying gelation by delaying cross-linking increases viscosity and thus shear resistance

**Graph**

- **Viscosity at gel point (Pa*s)**
  - X-axis: Norbornene (wt.%)
  - Y-axis: Viscosity

- **10-fold increase in viscosity and modulus**

- **Cross-linker**
  - High reactivity

- **DCPD**
  - Low reactivity
The higher viscosity of NB-modified gels enables coating of cylinders and spherical shells.

DCPD-based gel coatings formed in rotating shells

DCPD-based gel coatings formed in rotating vials

NB-addition increases the shear resistance of DCPD gels.

Less cross-linking
NB addition reduces the feature size in DCPD gels
Wetting of low-density DCPD aerogels with cryogenic hydrogen

Small angle x-ray scattering confirms that low-density (30 mg/cm³) DCPD aerogels are stable and can be wetted with liquid hydrogen
Chemistry-in-a-capsule challenges

- CH-based aerogel design
- Ablator shell filling
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- Cryogenic test
A pressure gradient method has been developed that allows filling of target shells with picoliter volumes of the aerogel precursor solution.
Chemistry-in-a-capsule challenges

- CH-based aerogel design
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Effect of film thickness and viscosity on film thickness uniformity

2D model: Rotating cylinder:

The Problem

Gelation occurs in solution layer flowing against gravitational acceleration. Completely overcoming the effect of gravitation would require prohibitively high rotational speeds of >1000 \( \text{rpm} \).

The thus unavoidable film thickness non-uniformity is given by:

\[
\frac{2gh^3}{3R \omega \nu} \approx h
\]

\( h = \) average film thickness
\( R = \) radius
\( \omega = \) rotational velocity
\( \nu = \) viscosity

For a 100 micron thick water film, a thickness homogeneity of better than 5% requires 640 \( \text{rpm} \).

The thickness uniformity of gel films formed in rotating cylinders improves with decreasing average film thickness and increasing viscosity near the gel point.
Simulating flow of gel precursors with Computational Fluid Dynamics (CFD)

2D simulation and experimental verification

- Too slow – liquid pools
- About right – near uniform
- Too fast – walls not wet; lumps

Once multi-axis rotation is included, we have a tool to identify the optimum rotational speed for various film thicknesses, and to the extract rate of shear in the precursor solution that affects gellation.
Deterministic Layer Formation

Two perpendicular and independently driven rotating frames in combination with computer controlled software provide a deterministic, continuous random change in orientation relative to the gravity vector thus simulating a true microgravity environment.

Projected track of a point on a sphere after 150 sec (10 and 14.14rpm)

2 mm diamond shell with an ~50-micron-thick layer of a DCPD polymer gel
Uniform and smooth foam coatings can be fabricated.

Capsule coated with a ~40 μm thick uniform DCPD/NB foam layer
(50 mg/cc DCPD with 10% Norbornene, iodine doped and super-critically dried)
Uniform and smooth foam coatings can be fabricated.

The non-concentricity (mode 1) is less than 3 micron, and the high mode surface roughness (> mode 10) is less than 10 nm.
Chemistry-in-a-capsule challenges

- CH-based aerogel design
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Doping via Atomic Layer Deposition (ALD)

ALD allows uniform doping of the foam layer inside the ablator shell

We have the alumina and titania ALD processes available:

\[ \text{Al(CH}_3\text{)}_3(g) + \frac{3}{2}\text{H}_2\text{O}(g) \rightarrow \frac{1}{2}\text{Al}_2\text{O}_3(s) + 3\text{CH}_4(g) \]

\[ \text{TiCl}_4(g) + 2\text{H}_2\text{O}(g) \rightarrow \text{TiO}_2 + 4\text{HCl}(g) \]

Other possible ALD process:

ZnO, W, Ru, Cu, Pt, Fe, ……

Other doping strategies include doping via chemical modification of the wet gel or dry foam, as well as the addition of functionalized polymer building blocks during polymerization.
Chemistry-in-a-capsule challenges

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Summary and Outlook

- We successfully fabricated foam lined target structures using the newly developed chemistry in-a-capsule approach.

- Future work will focus on improving the process (foam layer concentricity and the target yield) and on developing and testing new carbon-based low-density aerogels (graphene and CNT based systems).