PLAN

MATERIAL STUDIES FOR PULSED HIGH-INTENSITY PROTON BEAM TARGETS

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CHALLENGES FOR THE INTEGRATED TARGET SYSTEMS
AS WE GET TO 1+ MW SYSTEM

• Heat generation and removal from the target system

• Target thermo-mechanical response from energetic, high intensity protons

• Irradiation and corrosion effects on materials

• Beam window survivability

SOLUTION:
Look for new materials that are continuously being developed for other applications but seem to fit the bill as targets

There is a catch!
These materials have not been tested for their resilience to radiation exposure
The collaboration has been looking into these materials for some time

Candidate materials studied for applications as targets windows are:

• Inconel-718
• Aluminum-3000
• Havar
• Ti-6Al-6V
• Graphite (ATJ)
• Carbon-Carbon
• SuperInvar
PHASE I: Graphite & Carbon-Carbon Targets
E951 Results: ATJ Graphite vs. Carbon-Carbon Composite
The results demonstrate the superiority of CC in responding to Beam SHOCK.
The question is: Will it maintain this key feature under irradiation ???
We will find out in the course of this irradiation phase
Irradiation Studies to Assess how Super-Invar responds to radiation.

Its key feature (low CTE up to 150 °C) needed to be scrutinized.

Specimens and dilatometer in hot cell
BNL Irradiation Studies

Super Invar & Inconel-718
Super-Invar Irradiation Study – CTE assessment

![Graph showing thermal expansion (dL) versus temperature for non-irradiated and irradiated samples](image1)

![Graph showing Coefficient of Thermal Expansion (10^-6/K) versus displacements per atom for different planes](image2)
Inconel-718 CTE assessment

Inconel Dilatometer Measurements

Coef. Thermal Expansion, 10^-6/K vs. Displacements per Atom

Dilatometer Measurements

- Plane 1
- Plane 4
- Base
Super-Invar Irradiation Study - Effects of Irradiation on stress-strain behavior

WHY STUDY super Invar?
• High-Z with low CTE (0-150 °C)
• How is CTE affected by radiation?
• What happens to other important properties?

While the dpa received were as high as .25, they were enough to capture the tendency of the material to change. Similar effects at such low dpa can be seen in Incinel (Figure below).
Super-Invar Irradiation Study - Irradiation vs. Yield Strength

Effect of irradiation on yield strength of SuperInvar

Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A
Super-Invar Irradiation Study – Temperature Effects

Effect of Heat Treatment in non-Irradiated Invar Samples

Load (N) vs. Extension (mm) for different heat treatments:
- non treated Invar
- Temp (300 C)
- Temp (500 C)
Super-Invar Irradiation Study
Stress-strain (load-displacement) in stainless steel samples to test system stability

Verification of System Stability on Stainless Steel Samples

Graph showing load (N) vs. displacement (mm) for stainless steel samples.
PHASE-II TARGET MATERIAL STUDY

WHAT’S NEXT? Repeat irradiation/mechanical property changes experiment for baseline materials

**Carbon-Carbon composite**
This low-Z composite gives the indication that it can minimize the thermal shock and survive high intensity pulses. Because of its premise it is the baseline target material for the BNL neutrino superbeam initiative. The way its key properties (such as CTE or strength) degrade with radiation is unknown.

**Titanium Ti-6Al-4V alloy**
The evaluation of the fracture toughness changes due to irradiation is of interest regarding this alloy that combines good tensile strength and relatively low CTE

**Toyota “Gum Metal”**
This alloy with the ultra-low elastic modulus, high strength, super-elastic like nature and near-zero linear expansion coefficient for the temperature range -200 °C to +250 °C to be assessed for irradiation effects on these properties.

**VASCOMAX**
This very high strength alloy that can serve as high-Z target to be evaluated for effects of irradiation on CTE, fracture toughness and ductility loss

**AlBeMet**
A low-Z composite that combines good properties of Be and Al. Effects of irradiation on CTE and mechanical properties need to be assessed

**TG-43 Graphite**
PHASE-II TARGET MATERIAL STUDY

WHAT’S DIFFERENT FROM PHASE-I?

~ 100 MeV of Proton Beam (200 to 100 MeV)

Challenge of inducing UNIFORM Beam degradation

MORE Material to go in (optimization of dE/dx for range 200 MeV-100 MeV)

OPEN Issue: Study of Fracture Toughness for some materials?
Carbon-Carbon Composite Target

<table>
<thead>
<tr>
<th>Temp.</th>
<th>% elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 ° C</td>
<td>0%</td>
</tr>
<tr>
<td>200 ° C</td>
<td>-0.023%</td>
</tr>
<tr>
<td>400° C</td>
<td>-0.028%</td>
</tr>
<tr>
<td>600° C</td>
<td>-0.020%</td>
</tr>
<tr>
<td>800° C</td>
<td>0%</td>
</tr>
<tr>
<td>1000° C</td>
<td>0.040%</td>
</tr>
<tr>
<td>1200° C</td>
<td>0.084%</td>
</tr>
<tr>
<td>1600° C</td>
<td>0.190%</td>
</tr>
<tr>
<td>2000° C</td>
<td>0.310%</td>
</tr>
<tr>
<td>2300° C</td>
<td>0.405%</td>
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</table>
Gum Metal (Toyota Ti alloy)
**AlBeMet®**

**AM162**
- By weight, contains 62% commercially pure beryllium and 38% commercially pure aluminum.
- By Metallurgical definition, AlBeMet® is an alloy but can be considered a composite.
- AlBeMet® sheet, plate and bar are powder metallurgy products.
  - The powder is produced by a gas atomization process which yields spherical powder with a fine beryllium structure.
  - The powder is densified by three consolidation processes, each resulting in different mechanical properties, while maintaining AlBeMet's unique physical properties.

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**AlBeMet® Property Comparison**

<table>
<thead>
<tr>
<th>Property</th>
<th>Beryllium</th>
<th>AlBeMet® AM162</th>
<th>AlBeMet® AM16H</th>
<th>E-Material E-40</th>
<th>Magnesium AZ31B-T6</th>
<th>Aluminum 6061-T6</th>
<th>Stainless Steel 316</th>
<th>Copper HD4</th>
<th>Titanium Grade 4</th>
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<tbody>
<tr>
<td>Density</td>
<td>0.067 (1.66)</td>
<td>0.070 (2.10)</td>
<td>0.091 (2.21)</td>
<td>0.066 (1.60)</td>
<td>0.028 (0.70)</td>
<td>0.29 (8.0)</td>
<td>0.39 (11.0)</td>
<td>0.12 (3.7)</td>
<td>0.163 (4.6)</td>
</tr>
<tr>
<td>Modulus GPa</td>
<td>44 (303)</td>
<td>26 (193)</td>
<td>40 (275)</td>
<td>6.6 (45)</td>
<td>10 (80)</td>
<td>30 (200)</td>
<td>16.7 (116)</td>
<td>16.2 (106)</td>
<td>16.2 (106)</td>
</tr>
<tr>
<td>Ultimate Tensile</td>
<td>47 (324)</td>
<td>36 (262)</td>
<td>38.3 (273)</td>
<td>41 (280)</td>
<td>46 (310)</td>
<td>76 (515)</td>
<td>46 (310)</td>
<td>96.7 (660)</td>
<td>96.7 (660)</td>
</tr>
<tr>
<td>YS KSI</td>
<td>36 (241)</td>
<td>26 (193)</td>
<td>N/A</td>
<td>36 (260)</td>
<td>40 (278)</td>
<td>30 (200)</td>
<td>40 (278)</td>
<td>86.0 (190)</td>
<td>86.0 (190)</td>
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<tr>
<td>Elongation %</td>
<td>2</td>
<td>2</td>
<td>&lt; .05</td>
<td>6</td>
<td>12</td>
<td>40</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Fatigue Strength KSI</td>
<td>37.9 (261)</td>
<td>14 (97)</td>
<td>N/A</td>
<td>14.6 (100)</td>
<td>14 (96)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>128 (216)</td>
<td>121 (210)</td>
<td>121 (210)</td>
<td>44 (74)</td>
<td>104 (186)</td>
<td>9.4 (16)</td>
<td>225 (391)</td>
<td>9.75 (16.9)</td>
<td>9.75 (16.9)</td>
</tr>
<tr>
<td>Calorific Value</td>
<td>46 (1.98)</td>
<td>.373 (1.56)</td>
<td>.310 (1.26)</td>
<td>.261 (1.06)</td>
<td>.214 (0.89)</td>
<td>.12 (4.8)</td>
<td>.092 (3.85)</td>
<td>.129 (5.4)</td>
<td>.129 (5.4)</td>
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<tr>
<td>Thermal Expansion</td>
<td>6.3 (11.3)</td>
<td>7.7 (13.9)</td>
<td>3.4 (6.1)</td>
<td>14.4 (28)</td>
<td>13 (24)</td>
<td>3.6 (17.3)</td>
<td>9.4 (17)</td>
<td>4.8 (8.5)</td>
<td>4.8 (8.5)</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>4.2 E-06</td>
<td>3.5 E-06</td>
<td>N/A</td>
<td>14.6 E-06</td>
<td>4 E-06</td>
<td>72 E-06</td>
<td>1.71 E-06</td>
<td>69 E-06</td>
<td>69 E-06</td>
</tr>
</tbody>
</table>
VASCOMAX® C-200

**Physical Properties**

- **Average Coefficient of Thermal Expansion (°F/ft)**: 5.5 x 10^-6/°F
- **Modulus of Elasticity**: 30.3 x 10^7 psi
- **Density**: 2.85 lbs/ft³
- **Thermal Conductivity at 68°F**: 0.11 Btu/(hr·ft·°F)
- **Melting Point**: 2050°F

**Nominal Annealed Properties**

- **Hardness**: 35 Rockwell C
- **Yield Strength**: 100 ksi
- **Ultimate Strength**: 165 ksi
- **Brazability**: 85%
- **Reduction of Area**: 72%

**Nominal Room Temperature Properties after Aging**

<table>
<thead>
<tr>
<th>Size</th>
<th>Direction</th>
<th>Hardness</th>
<th>Rockwell C</th>
<th>Tensile Strength</th>
<th>0.2% Yield Strength</th>
<th>Elongation</th>
<th>Reduction of Area</th>
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<tbody>
<tr>
<td>5/8” Round</td>
<td>Longitudinal</td>
<td>41.0</td>
<td>361.0</td>
<td>307.0</td>
<td>12.0</td>
<td>60.0%</td>
<td>60.0%</td>
</tr>
<tr>
<td>1/4” Round</td>
<td>Longitudinal</td>
<td>41.0</td>
<td>361.0</td>
<td>307.0</td>
<td>12.0</td>
<td>60.0%</td>
<td>60.0%</td>
</tr>
<tr>
<td>3/16” Round</td>
<td>Longitudinal</td>
<td>41.0</td>
<td>361.0</td>
<td>307.0</td>
<td>12.0</td>
<td>60.0%</td>
<td>60.0%</td>
</tr>
<tr>
<td>1/8” Square</td>
<td>Longitudinal</td>
<td>41.0</td>
<td>361.0</td>
<td>307.0</td>
<td>12.0</td>
<td>60.0%</td>
<td>60.0%</td>
</tr>
<tr>
<td>Transverse</td>
<td>Transverse</td>
<td>41.0</td>
<td>361.0</td>
<td>307.0</td>
<td>12.0</td>
<td>60.0%</td>
<td>60.0%</td>
</tr>
<tr>
<td>5/32” Sheet</td>
<td>Transverse</td>
<td>41.0</td>
<td>361.0</td>
<td>307.0</td>
<td>12.0</td>
<td>60.0%</td>
<td>60.0%</td>
</tr>
</tbody>
</table>

**Effect of Test Temperature on Charpy V Notch Impact Strength**

- Charpy V-notch impact strength decreases with increasing test temperature.

**Effect of Aging Time on Tensile Properties**

- Tensile strength and yield strength increase with increasing aging time.

**R.R. Moore Rotating Beams Fatigue Tests**

- Fatigue strength decreases with increasing cycles.

All specimens solution treated for one hour at 1550°F, air cooled and aged at 900°F for three hours.
### Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, Brinell</td>
<td></td>
<td>334</td>
<td></td>
</tr>
<tr>
<td>Hardness, Knoop</td>
<td></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Hardness, Rockwell C</td>
<td></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Hardness, Vickers</td>
<td></td>
<td>349</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength, Ultimate</td>
<td></td>
<td>950 MPa</td>
<td>135000 psi</td>
</tr>
<tr>
<td>Tensile Strength, Yield</td>
<td></td>
<td>890 MPa</td>
<td>120000 psi</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td></td>
<td>14 %</td>
<td></td>
</tr>
<tr>
<td>Reduction of Area</td>
<td></td>
<td>36 %</td>
<td></td>
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<tr>
<td>Modulus of Elasticity</td>
<td></td>
<td>113.6 GPa</td>
<td>16500 ksi</td>
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<tr>
<td>Compressive Yield Strength</td>
<td></td>
<td>970 MPa</td>
<td>141000 psi</td>
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<tr>
<td>Notched Tensile Strength</td>
<td></td>
<td>1450 MPa</td>
<td>210000 psi</td>
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<tr>
<td>Ultimate Bearing Strength</td>
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<td>1080 MPa</td>
<td>155000 psi</td>
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<tr>
<td>Bearing Yield Strength</td>
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<td>1430 MPa</td>
<td>215000 psi</td>
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<tr>
<td>Poisson's Ratio</td>
<td></td>
<td>0.342</td>
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<tr>
<td>Charpy Impact</td>
<td></td>
<td>17 J</td>
<td>12.5 ft-lb</td>
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<tr>
<td>Fatigue Strength</td>
<td></td>
<td>240 MPa</td>
<td>34800 psi</td>
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<tr>
<td>Fatigue Strength</td>
<td></td>
<td>510 MPa</td>
<td>74000 psi</td>
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<tr>
<td>Fracture Toughness</td>
<td></td>
<td>75 MPa-mm²</td>
<td>88.1 ksi-in²</td>
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<tr>
<td>Shear Modulus</td>
<td></td>
<td>44 GPa</td>
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<tr>
<td>Shear Strength</td>
<td></td>
<td>550 MPa</td>
<td>78000 psi</td>
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#### Electrical Properties

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<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>Electrical Resistivity</td>
<td></td>
<td>0.000178 ohm-cm</td>
<td>0.000178 ohm-cm</td>
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<tr>
<td>Magnetic Permeability</td>
<td></td>
<td>1.00005</td>
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<tr>
<td>Magnetic Susceptibility</td>
<td></td>
<td>3.30e-06</td>
<td>3.30e-06</td>
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#### Thermal Properties

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<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>CTE, Linear 20°C</td>
<td>8.0 μin/in °C</td>
<td>4.78 μin/in °F</td>
</tr>
<tr>
<td>CTE, Linear 250°C</td>
<td>3.2 μin/in °C</td>
<td>1.8 μin/in °F</td>
</tr>
<tr>
<td>CTE, Linear 500°C</td>
<td>3.6 μin/in °C</td>
<td>2.0 μin/in °F</td>
</tr>
<tr>
<td>Heat Capacity</td>
<td>0.5268 Btu/°F-h-ft²°F</td>
<td>0.126 Btu/°F</td>
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<tr>
<td>Thermal Conductivity</td>
<td>6.7 W/m·°C</td>
<td>40.5 Btu/in²·°F·°F</td>
</tr>
<tr>
<td>Melting Point</td>
<td>Average over the range 20-160°C</td>
<td>1894 - 1660 °C</td>
</tr>
<tr>
<td>Solidus</td>
<td></td>
<td>1664 °C, 2920 °F</td>
</tr>
<tr>
<td>Liquidus</td>
<td></td>
<td>1860 °C, 3320 °F</td>
</tr>
<tr>
<td>Beta Transus</td>
<td></td>
<td>Average over the range 20-850°C</td>
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</tbody>
</table>
Tensile & CTE Specimen Design for Upcoming Irradiation Study

TENSILE specimen design for:

- Ti-6Al-4V alloy (39 specimens)
- Gum Metal (60 specimens)
- AlBeMet (39 specimens)

Total Length = 29 mm
Tensile & CTE Specimen Design for Upcoming Irradiation Study
Vascomax-350 specimen variation due to its high strength

**VASCOMAX-350 TENSILE Specimen**
- Thickness ~ 1.6mm
- Neck-Down width = 1.5mm
- Tensile Strength ~ 350 Ksi (2400 MPa)

**CTE Specimen for Vascomax-350**
- Number of specimens needed = 13

Alignment 1mm diam.
THRU hole

Dimensions:
- 1mm
- 1.5mm
- 3mm
- 42mm
- 6mm
- 9.5mm
- 2mm
- 6mm
- 4.5mm
- 29mm
Tensile & CTE Specimen Design for Carbon-Carbon and TG-43 Graphite

**CARBON CARBON Tensile Specimen**
- Total Length = 42 mm
- Neck-down width = 2.5 mm
- Thickness = 2 mm

CTE Specimen MATCHING the Tensile Specimens designed with a 2.5mm neck width
LAYOUT OF Specimen Assembly

VIEW LOOKING DOWN ON THE BOX

Top Plate with spacers

Front View

Beam
Tentative Sample Identification Scheme

SPECIMEN SHOWN is at position:

- **Layer-5 (4 chamfers)**
- **Back specimen in triplet**
- **Two (2) positions to the right from specimen at centerline**

**Alignment hole (1mm diam.)** in all specimens and at both sides

- 0.5mm blind hole(s) indicating the column of the specimen
  - 0 = dead center
  - 1 = 1st to right (hole at position 1)
  - 2 = 2nd to right (holes at 1 & 2)
  - 3 = 3rd to right (holes at 1, 2 & 3)
- For RHS (going into BOX) holes on same face as LAYER indication.
- For LHS on opposite face.

**Chamfer denotes LAYER in Box** (layer consists of 3 specimen in depth)

- NO Chamfer = 1st layer into box
- 1 chamfer = layer 2
- 2 chamfers = layer 3
- 3 chamfers = layer 4
- 4 chamfers = layer 5

**CTE specimen marking for Vastco-Ti-Gem**

- **LAYER - 1**
- **#3 RHS**

**Alignment Thru-Hole (1.5mm-diam.)** present at both sides and ALL CTE specimens

- 0.5mm diam. blind hole indicating Right or Lefthole
- Hole in figure is RHS

**CHAMFER indicating LAYER** (Base with Vastus, Ti, Gem bars 5 layers, CC and Graphite bars 3 layers)

- NO chamfer = 1st layer
- 1 chamfer = 2nd layer
- 2 chamfers = 3rd layer
- 3 chamfers = 4th layer
- 4 chamfers = 5th layer