Graphite/Carbon-Carbon Composite Target R&D

Neutrino Factory and Muon Collider Collaboration Targetry R&D Meeting
Dec. 15, 2000
Brookhaven National Laboratory
Tandem Library, Bldg 901A

John Haines
R&D Will Address Two Key Issues for Graphite Targets

• Thermal Shock
  – Results from August 2000 WNR tests
  – Instrumentation for AGS tests
  – Test plan

• Sublimation
  – Test chamber
  – Test plan
Thermal Shock Resistance of Graphites and C-C Composites Is Excellent

Figure of Merit (FOM) = \frac{\text{density} \times \text{specific heat} \times \text{strength}}{\text{thermal expansion coefficient} \times \text{Young's modulus}}

In this application carbon-based materials are even better since the heating/volume in carbon << heating/volume in W
# Comparison of Thermal Shock Conditions

<table>
<thead>
<tr>
<th></th>
<th>WNR Tests</th>
<th>Proposed AGS Tests</th>
<th>Proposed AGS Tests</th>
<th>Neutrino Factory 1 MW</th>
<th>Neutrino Factory 4 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton energy (GeV)</td>
<td>0.8</td>
<td>24</td>
<td>24</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Protons per pulse</td>
<td>2.8E+13</td>
<td>1.5E+13</td>
<td>1.5E+13</td>
<td>2.5E+13</td>
<td>1.0E+14</td>
</tr>
<tr>
<td>Gaussian Beam Sigma (mm)</td>
<td>10</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Peak energy density (MJ/m^3)</td>
<td>3.1</td>
<td>350</td>
<td>75</td>
<td>11</td>
<td>44</td>
</tr>
<tr>
<td>Peak microstrain</td>
<td>16</td>
<td>835</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Peak Stress (MPa)</td>
<td>0.13</td>
<td>7.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
ATJ Graphite Strains Were Measured for Single Pulse Tests at LANSCE/WNR

- WNR proton beam ($\sigma \sim 10$ mm radius) centered at $r = 4.9$ mm on 8.0 mm radius ATJ graphite rod
Optical strain sensor technique was validated on simple graphite rod test

- WNR proton beam ($\sigma \sim 10$ mm radius) centered at $r = 4.9$ mm on 8.0 mm radius ATJ graphite rod
- Deflection at 12 ms amplified by $10^4$
Optical Strain Gages Can Be Used in This Severe Environment

- Strain gauges based on miniaturized Fabry-Perot interferometer concept
  - Gauge length of a few millimeters
- Gauge is mounted on surface of interest
- Broadband light source centered at 860 nm wavelength reflects from two surfaces and two reflected signals analyzed by white light interferometry to produce two phase-related signals
- Interference fringes and calibration tracked by phase relationships of signals
Strain Measurement System

Proton Beam

Target

Strain Sensor

40-m FO Cable

8 VELoce Modules

Reset

VELOCE Analog Signals

VELOCE Processed Signals

DL716 Digital Scope

DL708E Digital Scope

PC Data Acquisition Sys.
Measured Strained Data Agrees With Predictions

Shot #: G1-03  Sensor: GR 01

Measured data

ATJ Graphite rod

Calculation

1st bending mode from 1D modal analysis = 348 Hz
Energy Deposition in ATJ Graphite Rod
1.5 \times 10^{13}, 25 \text{ GeV protons}, \sigma=1 \text{ mm}

Energy deposition vs. length along rod axis

Energy deposition vs. radius at Z=5.5 \text{ cm}
Axisymmetric Simulation of Graphite Rod Energy Deposited in 40 ns

- ATJ graphite rod axisymmetric model
- Isotropic properties used:
  - $E=9.6$ GPa, $\nu=0.13, \alpha=2.46\times10^{-6}/\degree C$, $\rho=1.73$ gm/cc
  - $C_v=690$ J/(kg*°C)
- Time step = 5 ns (Courant limit ~ 75 ns)

Max X +7.593e-07
at node 1043
Min X -2.575e-07
at node 2123
Max Y +5.760e-06
at node 101
Min Y -4.001e-06
at node 1

Typical deformed shape
this at $t=0.296$ ms
(dR*10^4, dZ*10^3)
Von Mises Stress at Element Near Location of Maximum Energy Deposition

Maximum stress < 10 MPa

MISES E: 25 IP: 1 ELSET ER0
XMIN 0.000E+00
XMAX 4.000E-03
YMIN 0.000E+00
YMAX 7.467E+06
Axial Displacement of 5 Equally Spaced Nodes Along Surface.

The longitudinal wave speed (uniform bar) is \( c = \sqrt{\frac{E}{\rho}} = 2356 \text{ m/s} \). The time for a wave to traverse the rod length is \( \frac{0.3073 \text{ m}}{2356 \text{ m/s}} = 130 \mu\text{s} \), or 7666 Hz. For the wave to reflect and traverse the length again, the frequency is 3833 Hz.
Thermal Shock Tests Should Be Conducted at Low Temperature

- Survival at room temperature ensures survival at high temperature
  - Strength and thermal shock resistance of graphite and C-C composites increases with temperature (very large increase in specific heat)
- Targets can be instrumented at low temperatures
  - Strains can be measured and models benchmarked
- High temperature tests are significantly more difficult
  - Vacuum chamber with heated samples in beam line
Graphite Becomes Stronger at Temperatures Up To ~ 2600 °C
Temperature Rise Is Much Smaller with Graphite at Operating Temperature
Thermal Shock Test Plans

• Conduct tests with a graphite rod and a carbon-carbon rod
  – Graphite: 15 mm diameter, 0.3 m long
  – Carbon-carbon composite: As close to graphite size as possible within cost and schedule constraints

• Install eight optical strain sensors on each rod
  – Two at the front (180° apart), two in the back (180° apart) and four in the middle (90° apart)
  – All sensors oriented axially (radius of curvature too small for circumferential mounting)

• Install rods inside a simple secondary container

• Use 40 m long fiber optic cables

• Will someone measure beam profile?
Sublimation Must Be Inhibited to Achieve Reasonable Lifetimes for Radiatively Cooled Carbon Target

Uniform axial heating distribution assumed

Sublimation rate in vacuum is excessive for beam powers > 1 MW
Use of He Atmosphere Is Proposed to Inhibit Carbon Sublimation

- Presence of helium reduces graphite sublimation
- Heat transport is still mainly by radiation
  - Conduction/convection heat transfer through helium is relatively insignificant
- Net erosion of graphite is limited by convection/diffusion of carbon from hot graphite to cooled vessel
- Tests required to validate approach and obtain quantitative data
## Carbon Sublimation Test Plan

- Modify existing chamber for tests Dec ‘00 - Jan 10 ‘01
- Fabricate heater/specimens Dec ‘00 - Jan 10 ‘01
- Perform tests Jan 10 - April 9 ‘01
- Issue report April 23 ‘01

<table>
<thead>
<tr>
<th>Material</th>
<th>Vacuum</th>
<th>1 atm He</th>
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</thead>
<tbody>
<tr>
<td>ATJ Graphite</td>
<td>2000 K</td>
<td>2000 K</td>
</tr>
<tr>
<td></td>
<td>2300 K</td>
<td>2300 K</td>
</tr>
<tr>
<td>C-C Composite</td>
<td>2000 K</td>
<td>2000 K</td>
</tr>
<tr>
<td></td>
<td>2300 K</td>
<td>2300 K</td>
</tr>
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Carbon Sublimation Test Chamber

- Gas Feed
- IR Camera
- Diagnostic Ports
- Substrate Holder
- Graphite Sample
- Graphite Heater
- Water cooled shroud
- Throughput Control Valve
- Turbomolecular Pump
- Water cooled shroud

SNS Experimental Facilities

Oak Ridge