Design Specifications & Restriction

- high radiation area
- tight environment
- non-serviceable area
- passive components
- optics only, no active electronics
- transmit image through flexible fiber bundle
Optical Layout

Spherical mirror

laser illumination

image collection

Ø6” Secondary Containment

cm scale

test target

Works OK in this tight environment
Experimental Setup

Optical Components
- 50/50 beam splitter: Edmund, 0.5 cm cube
- Spherical mirror: Edmund, f=3-in, D=3in< Au coated
- Small prism mirror: Edmund, 1x1x1.4 cm, Au coated
- Large prism mirror: Edmund, 2.5x2.5x3.54 cm. Au coated
- Imaging fiber Edmund: ⅛-in diameter, 12-µm core, 0.55 NA
- Illumination fiber: ThorLabs, 0.22 NA, SMA-905 840 -µm core
- Imaging lens: Sunex, f=0.38-cm, f/# 2.6, diagonal FOV 54°, φ1.4-cm x 2.0 cm
Cameras & Glass Imaging Fiber

**SMD 64KIM camera**
- CCD size: 13.4 x 13.4 mm
- Pixels: 960x960
- Single frame: 240x240 pixels
- Frame rate: 16 frames up to 1 µs/frame
- Reduced pixel size: 56 x 56 um

**FastVision**
- CCD size: 15.4 x 12.3 mm
- Pixels: 1280x1024
- Single frame: FPGA programable
- Frame rate: 500/s @ full resolution
- 500k/s @ 1x1280

**CERN Olympus Encore PCI 8000S**
- 4 kHz recording rate, 25 us electronic shutter

**glass imaging fiber bundle**
- Core size: 12 µm, diameter: 1/8”
- Total fiber counts ~50,000 in 3.17 mm diameter
- Imaging ~243 x 243 fibers on 960 x 960 CCD array
- ~1 imaging fiber on ~4x4 pixels on full frame
- ~1 imaging fiber on ~1 pixel on a single frame
Laser Sources

Laser diode, SLI 15-W, Class IV
Power = 15 Watts
\[ I_{th} = 4.5 \text{ Amp} \]
\[ \lambda = 808 \text{ nm} \]

JDS Uniphase Laser diode, SDL-2300-L2
Power = 1 Watts
\[ I_{th} = 0.3 \text{ Amp} \]
\[ \lambda = 850 \text{ nm} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>25</td>
<td>°C</td>
</tr>
<tr>
<td>Rated power</td>
<td>20</td>
<td>W</td>
</tr>
<tr>
<td>Current at rated power</td>
<td>35.38</td>
<td>A</td>
</tr>
<tr>
<td>Maximum current</td>
<td>41.63</td>
<td>A</td>
</tr>
<tr>
<td>Threshold current</td>
<td>6.2</td>
<td>A</td>
</tr>
<tr>
<td>Center wavelength</td>
<td>808.6</td>
<td>nm</td>
</tr>
<tr>
<td>Linewidth FWHM</td>
<td>2.64</td>
<td>nm</td>
</tr>
</tbody>
</table>
Stationary images of NIR laser illumination

target shifted 1.5 cm upstream
field of view
NIR illumination
0.01 ms frame rate
target shifted 1.5 cm downstream
Chopper Image In Motion
@ 4 kHz

Linear Velocity @ ~40 m/s

Stationary image

100 µs/frame

10 µs/frame

1 µs/frame
Optical Diagnostics System Design
In Secondary Containment

One set of optics per viewport

Conceptual design completed
Irradiation Studies of Optical Components - I

CERN, ~ April 15-24, 2005
Irradiation Condition:
1.4 GeV proton beam
4 x 10^{15} proton
Irradiation dose: equivalent to 40 pulses of 24 GeV proton beam
28 TP/pulse
total of 1.2 x 10^{15} proton
Received radiation dose:
3231 Gy, ~ 323 krad

Schott glass imaging fiber is not good
CERN, ~ Oct. 24, 2005
Irradiation Condition:
1.4 GeV proton beam
5 x 10^{15} proton
Irradiation dose: equivalent to
40 pulses of 24 GeV proton beam
total of 5 x 10^{15} proton

<table>
<thead>
<tr>
<th>28-Dec-2005</th>
<th>Results of optical components irradiated at CERN on Oct. 24, 2005</th>
<th></th>
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<tbody>
<tr>
<td>proton beam energy: 1.4 GeV</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>no. of protons: 5x10^{15}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>transmittance measurements at 650 &amp; 850 nm wavelengths</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>item # components</th>
<th>wavelength @ 650 nm</th>
<th>wavelength @ 850 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 0.5-inch thick Lexan window</td>
<td>0.940</td>
<td>0.840</td>
</tr>
<tr>
<td>9 5-meter singlemode fiber</td>
<td>0.600</td>
<td>0.022</td>
</tr>
<tr>
<td>10 5-meter multimode low-OH fiber</td>
<td>0.830</td>
<td>0.850</td>
</tr>
<tr>
<td>11 30-cm long Sumitomo imaging fiber</td>
<td>0.850</td>
<td>0.640</td>
</tr>
</tbody>
</table>

overall radiation activity ~ 3 times above background on Dec 16, 2005

Sumitomo fused silica imaging fiber is good
# Product Lineup

<table>
<thead>
<tr>
<th>Set</th>
<th>IG-02/03</th>
<th>IG-02/06</th>
<th>IG-03/06</th>
<th>IG-03/10</th>
<th>IG-05/10</th>
<th>IG-08-300</th>
<th>IG-15/30</th>
<th>IG-20/50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of picture elements</td>
<td>3,000</td>
<td>6,000</td>
<td>6,000</td>
<td>10,000</td>
<td>10,000</td>
<td>30,000</td>
<td>30,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Jacketing diameter (um)</td>
<td>260</td>
<td>280</td>
<td>350</td>
<td>370</td>
<td>500</td>
<td>800</td>
<td>1,500</td>
<td>2,000</td>
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<tr>
<td>Picture elements area diameter (um)</td>
<td>180</td>
<td>252</td>
<td>315</td>
<td>333</td>
<td>450</td>
<td>720</td>
<td>1,350</td>
<td>1,800</td>
</tr>
<tr>
<td>Coating diameter (Primary) (um)</td>
<td>250</td>
<td>340</td>
<td>420</td>
<td>450</td>
<td>590</td>
<td>960</td>
<td>1,900</td>
<td>2,400</td>
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<tr>
<td>Coating diameter (Secondary) (um)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>2,500</td>
<td>3,000</td>
</tr>
<tr>
<td>Circularity</td>
<td>&gt;= 0.93</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Core material</td>
<td>GeO2 Containing Silica</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cladding material</td>
<td>F Containing Silica</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coating material</td>
<td>Silicone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coating material</td>
<td>Silicone + PFA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lattice defect (%)</td>
<td>&lt;= 0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowable bending radius (mm)</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>40</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Allowable max temp (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
</tr>
</tbody>
</table>

## Cost Details

- **Cost per foot**
  - IG-02/03: $78
  - IG-02/06: $158
  - IG-03/06: $305

- **Cost in 10 meter**
  - IG-02/03: $2574
  - IG-02/06: $5214
  - IG-03/06: $10065

- **Total cost for 4 fibers (40 meter)**
  - IG-02/03: $10.3k
  - IG-02/06: $20.8k
  - IG-03/06: $40.3k

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- **IGN-08/30 sample**
  - 0.3-meter
  - 30,000 pixels

- **Continuous 10-20 meter available**

- **Continuous 10 meter maybe available**

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*Sumitomo Imaging Fibers*
Fujikura Imaging Fibers

ULTRATHIN IMAGEFIBER SPECIFICATIONS
(FIGH series N-Type 50k-100k)

<table>
<thead>
<tr>
<th>Item</th>
<th>FIGH-30-850N</th>
<th>FIGH-50-1130N</th>
<th>FIGH-70-1300N</th>
<th>FIGH-100-1500N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of picture elements (nominal)</td>
<td>30,000</td>
<td>50,000</td>
<td>70,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Image circle diameter (μm)</td>
<td>790 ± 50</td>
<td>1,025 ± 80</td>
<td>1,200 ± 100</td>
<td>1,400 ± 120</td>
</tr>
<tr>
<td>Fiber diameter (μm)</td>
<td>850 ± 50</td>
<td>1,100 ± 80</td>
<td>1,300 ± 100</td>
<td>1,500 ± 120</td>
</tr>
<tr>
<td>Coating diameter (μm)</td>
<td>950 ± 50</td>
<td>1,200 ± 100</td>
<td>1,450 ± 100</td>
<td>1,700 ± 150</td>
</tr>
<tr>
<td>Minimum bending radius (mm)</td>
<td>90°1 ± 50°2</td>
<td>110°1 ± 80°2</td>
<td>150°1 ± 100°2</td>
<td>200°1 ± 130°2</td>
</tr>
<tr>
<td>Coating material</td>
<td>Silicone resin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lattice defect (%)</td>
<td>&lt; 0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncircularity (%)</td>
<td>&lt; 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length/pc</td>
<td>Maximum length of 1pc: 10ft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cut and rough polish are available.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cut length of 1pc: Customer order</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Cost per foot                       | $85          | $250         | $540         |
| Cost in 10 meter                    | $2805        | $8250        | $17.8k       |
| Total cost for 4 fibers (40 meter)  | $11.2k       | $33k         | $71.8k       |

| Cost/foot                           | $210         | $371.4       |
| Cost in 10 meter                    | $6,935.65    | $12,256.7    |
| Cost in 20 meter                    | $15,607.9    | $49,026.8    |
| Total cost for 4 fibers (40 meter)  | $27,742.6    | $49,026.8    |
Uniformity of Imaging Fibers

30,000 picture elements

Sumitomo IGN-08/30

Fujikura FIGH-30-850N

50x

800x

NO significant difference in the uniformity of imaging fibers
camera SMD illumination
NIR pulse, 10 us/frame

NO significant difference in image quality
Should go with Sumitomo fibers
(20 meters have been ordered)
The implementation of the new setup depends on the irradiation test.
Image Capture in All-In-One Optical Layout Setup

0.1 ms NIR pulse

0.01 ms NIR pulse

Sumitomo IGN-08/30

Fujikura FIGH-30-850N
Example: Tapered Nozzle with Straight (atm. condition)

Velocity = Distance × FPS

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Rate (fps)</td>
<td>2500</td>
</tr>
<tr>
<td>Exposure Time (µs)</td>
<td>200</td>
</tr>
<tr>
<td>Resolution</td>
<td>1280 × 200</td>
</tr>
</tbody>
</table>
Experimental Parameters
Investigation For Water Jet

\[
\text{Re} = \frac{\rho_0 V_0 D}{\mu_0}, \quad Ec = \frac{V_0^2}{c_{p_0} (T_w - T_0)}
\]

\[
\text{Pr} = \frac{\mu_0 c_{p_0}}{k_0}, \quad C = \frac{P_a - P_0}{\rho_0 V_0^2}
\]

\[
Fr = \frac{V_0^2}{g D}, \quad We = \frac{\rho_0 V_0^2 D}{\Gamma}
\]

\(\rho\) : density
\(V\) : velocity
\(D\) : diameter
\(\mu\) : viscosity
\(C_p\) : specific heat
\(P\) : pressure
\(\Gamma\) : surface tension
\(k\) : thermal conductivity

**Nondimensionalized Basic Equations**

\[
\frac{\partial \rho^*}{\partial t^*} + \nabla \cdot \rho^* V^* = 0
\]

\[
\frac{DV^*}{Dt^*} = - \nabla P^* + \frac{Gr}{Re^2} \beta^* T^* g^* + \frac{1}{Re} \nabla \cdot \tau_{ij}^*
\]

\[
\rho^* c_p^* \frac{DT^*}{Dt^*} = Ec \frac{Dp^*}{Dt^*} + \frac{1}{Re \text{Pr}} \nabla \cdot (k^* \nabla T^*) + \frac{Ec}{Re} \Phi^*
\]

\[
\Phi = \tau_{ij} \frac{\partial u_i}{\partial x_j}
\]

\[
\beta = - \frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p
\]

**Boundary Condition (Free Surface)**

\[
w^* = \frac{D \eta^*}{Dt^*}
\]

\[
P^* = C + \frac{1}{Fr} \eta^* - \frac{1}{We} (R_x^{*-1} + R_y^{*-1})
\]

Later, Magnetic field effect should be considered for MHD experiment and the deformation of jet is going be investigated experimentally based on the parameters.
Other Issues

1. Laser power increase to ~40 W/pulse (instead of 10 Watt/pulse)
2. Viewports: sapphire window
3. Number of viewports: 4
4. Location of the viewports: 6-inches apart
5. How many fast CCD camera? 1 fast (1 µs) camera, ~3 slower (250 µs) camera?
6. Potential to illuminate all viewports with one laser system
7. Make mockup with 1 viewports based on all-in-one optical layout fitting inside 6” diameter secondary containment and optical feasibility test in terms of image quality