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

glass imaging fibers

**SMD camera**
- **CCD size:** 13.4 x 13.4 mm
- **Pixels:** 960x960
- **Single frame:** 240x240 pixels
- **Reduced pixel size:** 56 x 56 µm

**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
Optical Diagnostics

retroreflected illumination

Spherical mirror

laser illumination

image collection

cm scale

test target

Works OK in this tight environment
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
Optical Diagnostics
Field of view – NIR laser illumination & imaging
Optical Diagnostics
optical design in secondary containment

One set of optics per viewport

Conceptual design completed
Optical Diagnostics

An optical chopper in motion @ 4 kHz

Stationary image

100 µs/frame

Velocity @ ~40 m/s

10 µs/frame

1 µs/frame
Optical Diagnostics

An optical chopper in motion @ 4 kHz cont'

- Velocity @ ~40 m/s
- 100 µs/frame with reflective mask
- Line Segment: 150.0 - 150,315
- Line Segment: 200.0 - 200,315

frame #12
Irradiation Studies of Optical Components

CERN, ~ April 15-24, 2005
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, ~ 3.2 x 10^5 rad
or
3.2 x 10^6 rem
(assume a quality factor of 10)
Optical components

Before irradiation April, 2005

After irradiation July 13, 2005
Irradiation summary – transmittance/reflectance measurements

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
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<tr>
<td>1</td>
<td>13-Jul-2005</td>
<td></td>
<td></td>
<td></td>
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<td>2</td>
<td>Results of optical components irradiated at CERN on April 15, 2005</td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>proton beam energy: 1.4 GeV</td>
<td></td>
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<td></td>
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<tr>
<td>4</td>
<td>no. of protons: 4x10^15</td>
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<td></td>
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<tr>
<td>5</td>
<td>transmittance and reflectance measured at the HeNe wavelength</td>
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<td>6</td>
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<tr>
<td>7</td>
<td>item #</td>
<td>components</td>
<td>before</td>
<td>after</td>
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<tr>
<td>8</td>
<td>2</td>
<td>Large gold mirror reflectance</td>
<td>0.910</td>
<td>0.920</td>
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<tr>
<td>9</td>
<td>3</td>
<td>Small gold mirror reflectance</td>
<td>0.930</td>
<td>0.940</td>
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<tr>
<td>10</td>
<td>4</td>
<td>50/50 beam splitter: transmittance</td>
<td>0.450</td>
<td>0.360</td>
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<tr>
<td>11</td>
<td>4</td>
<td>50/50 beam splitter: reflectance</td>
<td>0.530</td>
<td>0.423</td>
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<tr>
<td>12</td>
<td>5</td>
<td>imaging lens: transmittance</td>
<td>0.880</td>
<td>0.610</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>1-mm thick sapphire plate</td>
<td>0.863</td>
<td>0.867</td>
</tr>
<tr>
<td>14</td>
<td>7</td>
<td>1-mm thick fused silicia</td>
<td>0.914</td>
<td>0.859</td>
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<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>16</td>
<td>1</td>
<td>3-fleet long imaging fiber</td>
<td>0.394</td>
<td>0.000</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>18</td>
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</tr>
</tbody>
</table>

Activity right after irradiation: 4 mSv/h on contact
30 µSv/h at 50 cm away

Activity ~ 1 month later (5/23/05): 0.5 mSv/hr on contact (50 µrem/h)

Activity arrived at BNL ~ background level
3-feet long of Schott imaging fiber before and after irradiation

\[ I = I_0 e^{-\alpha t} \]

From fused silica results: \( \alpha = 0.62, \) for \( t = 0.1 \text{ cm} \)

Projected transmission for \( t=3\)-ft of the imaging fiber:

\[ e^{-0.62}(91 \text{ cm}) = 3 \times 10^{-25} \text{ for } \sim 40 \text{ proton pulses} \]

If \( \alpha \) is linearly prop. to # of proton pulses, transmission for 1 proton pulse = 0.244 for 1-meter

\[ = 4 \times 10^{-4} \text{ for 5-meter} \]
Fujikura imaging fibers

Table 3

<table>
<thead>
<tr>
<th>Item</th>
<th>FIGH-50-1100N</th>
<th>FIGH-70-1300N</th>
<th>FIGH-100-1500N</th>
</tr>
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<tbody>
<tr>
<td>Number of picture elements (nominal)</td>
<td>50,000 (Nominal)</td>
<td>70,000 (Nominal)</td>
<td>100,000 (Nominal)</td>
</tr>
<tr>
<td>Imagecircle diameter (µm)</td>
<td>1,025 +80/-80</td>
<td>1,200 +100/-100</td>
<td>1,400 +120/-120</td>
</tr>
<tr>
<td>Fiber diameter (µm)</td>
<td>1,100 +80/-80</td>
<td>1,300 +100/-100</td>
<td>1,500 +120/-120</td>
</tr>
<tr>
<td>Coating diameter (µm)</td>
<td>1,200 +100/-100</td>
<td>1,450 +100/-100</td>
<td>1,700 +150/-150</td>
</tr>
<tr>
<td>Minimum bending radius (mm)</td>
<td>110²(80²)</td>
<td>150°(100²)</td>
<td>200°(130²)</td>
</tr>
<tr>
<td>Coating material</td>
<td>Silicone resin</td>
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<td></td>
</tr>
<tr>
<td>Lattice defect (%)</td>
<td>&lt; 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncircularity (%)</td>
<td>&lt; 5</td>
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<td></td>
</tr>
</tbody>
</table>

*1: Minimum bending radius in storage
*2: Recommended bending radius in use (For your reference only, possibly to be happened breakage by static fatigue.)
Sumitomo imaging fibers

**Product Lineup**

<table>
<thead>
<tr>
<th></th>
<th>IGN-02/03</th>
<th>IGN-02/06</th>
<th>IGN-03/06</th>
<th>IGN-03/10</th>
<th>IGN-05/10</th>
<th>IGN-06/03</th>
<th>IGN-15/02</th>
<th>IGN-20/02</th>
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</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>
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<tr>
<td>Jacketing diameter (um)</td>
<td>200</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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<td>Picture elements area</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>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>
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<tr>
<td>Coating diameter (Primary)</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)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(um)</td>
<td></td>
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<td></td>
<td></td>
<td>2,500</td>
<td>3,000</td>
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<tr>
<td>Circularity</td>
<td>&gt;= 0.83</td>
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<td>Core material</td>
<td>GeO2 Containing Silica</td>
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<tr>
<td>Cladding material</td>
<td>F Containing Silica</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Coating material</td>
<td>Silicone</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Numerical aperture</td>
<td>0.35</td>
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<tr>
<td>Lattice defect (%)</td>
<td>&lt;= 0.1</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Allowable bending radius</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>
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<tr>
<td>Allowable max temp. (°C)</td>
<td>150</td>
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<td></td>
</tr>
</tbody>
</table>

All have small imaging area <2 mm diameter
Rad-hard?

IGN-08/20 - sample

>20 meter available
5 meter limit
1. Laser power increase to ~40 W/pulse (instead of 10 Watt/pulse)
2. Depth of focus → apparent image size variation
3. 3-in diameter spherical retroreflecting mirrors – on hand
4. Anti-reflection coated (@ 800 nm) viewports: lexan, sapphire, or fused silica
5. Number of viewports ? 4
6. Location of the viewports ? 6-inches apart
7. How many fast CCD camera ? 1 fast (1 μs), ~2 slower (250 μs), 1 video?
8. Switch from one viewport to the next with one (fast) laser/camera system ?
9. ~20-m long flexible rad-hard imaging fiber bundles
10. Radiation resistance of imaging fiber bundle and optics ? continue testing
11. …
BDL20-808-F6
s/n: 05091745

Output Power

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<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>9.2</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>

Input A: Current 20 A/div
Input B: Optical Power 4 W/div
Video camera capture of waterjet, August 19, 2005 @ Princeton
Camera: 30 frame/sec conventional video camera

nozzle: diameter ~? mm, length ?-inch
complete waterjet

640x480 pixels, 30 frame/sec, 20 frames
front view

close-up view of nozzle

angle view
Fast camera capture of waterjet
September 16, 2005 @ Princeton

Camera: FastVision 13 capability
1280x1024 pixels, 500 frames/sec, 0.5 sec video
or …

complete waterjet

waterjet in action: movie

close-up view of nozzle

nozzle: diameter ~8 mm, length 6-inch

1280x1000 pixels
50 frame/sec
20 frames of video
close-up view of waterjet

1st run @ 8:25 am

Frame rate: 500 frame/sec (2 ms per frame)
1280x1000 pixels, exposure time 0.5 ms
20 frames of video

waterjet velocity ~12-17 meter/sec
waterjet at varies pump speeds

6th, 7th, & 8th runs @ 9:14 to 9:24 am

Frame rate: 1000 frame/sec (1 ms per frame)
1280x500 pixels, exposure time 0.25 ms
20 frames of video

full speed

75% speed

50% speed

waterjet velocity
~10, 12, & 7 meter/sec, respectively

22 cm
Fast camera capture of garden hose spray

September 9, 2005

Camera: FastVision, 1280x500 pixels

1280x500 pixels
1000 frame/sec
20 frames of video
Velocity ~ 6.7 meter/s

22 cm

1280x500 pixels
1000 frame/sec
20 frames of video
Velocity ~ 20 meter/s