Fiber optic readout feasibility for NEXT 100 tracking plane D. Shuman 2/14/13

DRAFT, for review

This is a feasibility study of the idea to use optical fibers to bring EL light that is normally incident on the SiPMs, out of the vessel to exterior SiPMs. Plastic (PMMA) optical fibers of 0.25 to 1.0 mm are available that have high acceptance angle (numerical aperture, or NA) to be reasonably efficient at collecting the light that would normally be incident on the SiPMs. A total of ~2500 bare fibers (cladding only, no jacket), each 1.0 mm dia., can be bundled in a hex pattern, fitting within an 80 mm circle, and potted into a drilled stainless steel feedthrough flange. There is sufficient web area remaining to be fully pressure resistant. This allows as many channels as we have now in NEXT100. It is envisioned that the fibers from each feedthrough be bare and full length on the inside (~1m) , so as to reach small drilled holes in a PTFE reflector plate just behind the EL anode, as we have now with the DBs. Each fiber end would be coated with TPB so as to accept light uniformly (Lambertian), and to avoid having a narrow cone of vision which might disallow pixel weighting and averaging.

This has the following advantages:

1. SiPM's can be cooled to reduce dark noise, by two or more orders of magnitude
2. Radiopurity is much higher (assuming fiber cladding is radiopure, like PMMA generally is) .
3. No electronics inside the vessel
4. No problems with SiPM's being damaged from EL sparking

Potential problems:

1. Xe permeation, possibly leading to high attenuation or swelling
2. Fiber crosstalk from bare fibers (outside fiber sections will need light tight enclosure, maybe jacketing)
3. Leakage from swelling (Xe permeation?) or improper potting
4. Difficulty in handling and stringing of TP plane; fiber marking disallowed?
5. Difficulty in fixation of bare fibers, which is needed to avoid damage from high gas velocity under vent condition

Feasibility testing

1. measure attenuation loss, swelling under high Xe pressure - see below
2. design and build small fiber feedthrough for NEXT-DBDM TP (# of channels as space permits)
3. devise a crosstalk test
4. develop TPB coating method for fiber ends (Teflon AF matrix?)

Pulse spreading

Single electron transit time in EL (from A. Goldschmidt)

$$t_{el} := 1\mu s$$

Optical fiber (preferred) is an high N.A. PMMA step index with fluorinated cladding (Toray PJ series) :

$NA := 0.63 \quad l := 2m \qquad d := 1mm \qquad n_{core} := 1.49 \qquad \lambda := 430nm \qquad n_{ext} := 1 \quad a := 0.5d$

Acceptance angle: $\theta := 2\,\mathrm{asin}(NA) \qquad \theta = 78.1\,deg$

$NA := \sqrt{n_{core}^2 - n_{clad}^2} \qquad n_{clad} := \sqrt{n_{core}^2 - NA^2} \qquad n_{clad} = 1.35$

from: http://www.fiberoptics4sale.com/wordpress/basic-optics-for-optical-fiber/

Modal dispersion (this is main source of pulse spreading)

Calculate V number. For V>10 use ray optics, otherwise use wave optics (single mode for V<2.45)

$V := \frac{2\pi a}{\lambda}\cdot\sqrt{n_{core}^2 - n_{clad}^2}$ or, for :

$\Delta := \frac{n_{core} - n_{clad}}{n_{core}} \qquad \Delta = 0.094 \qquad \Delta := \frac{n_{core}^2 - n_{clad}^2}{2n_{core}^2}$

$V := \frac{2\pi a}{\lambda}\cdot n_{core}\cdot\sqrt{2\Delta}$

$V = 4.715\times 10^3$ use ray optics

$\Delta\tau := 1\cdot\frac{(n_{core} - n_{clad})}{c}\cdot\left(1 - \frac{\pi}{V}\right) \qquad \Delta\tau = 0.932\,ns$ compare --> $t_{el} = 1\,\mu s$ negligible

Coupling efficiency from Doric Lenses we find formulas for LED to fiber coupling.

$\eta = \left(\frac{P_{input}}{P_{source}}\right) = \eta_{geo}\times\eta_{Fresnel}\times\eta_{ang}$

where : η = Fiber coupling efficiency
P_{input} = Power couplet into the fiber
P_{source} = Power emitted by the source
η_{geo} = Geometrical losses factor for coupling efficiency
$\eta_{Fresnel}$ = Fresnel losses factor for coupling efficiency
η_{ang} = Angular losses factor for coupling efficiency

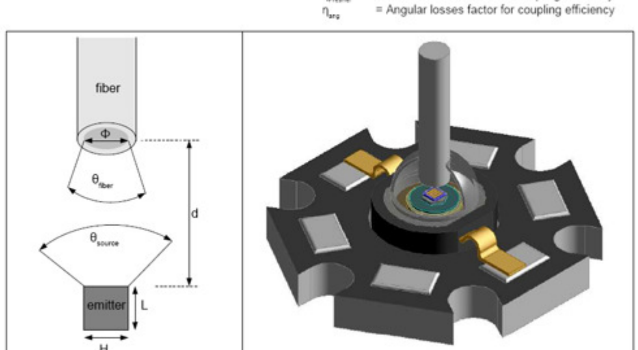

Fig 1. a) Schematic of butt coupling
Fig 1. b) Luxeon III pigtailed LED

8. REFERENCES

[1]. David K. Cheng, Field and Wave Electromagnetics (2nd edition), Prentice Hall (1989).
[2]. B. Saleh and M.C. Teich, Fundamental of photonics, Wiley-Interscience (1991).

This document has been written December 05st 2005 by Jean-Luc Néron, ing. jr for Doric Lenses Inc.

$\eta_{geo} := .7854$ assume end of fiber is source (TPB coating on fiber end)

$\eta_{fres} := 1$

$I(\theta) := I_0\cdot\cos(\theta)^m$ for lambertian radiator, m=1

$m := 1$

$NA = 0.63$

$\theta_{fiber} := \mathrm{asin}(NA) \qquad \theta_{fiber} = 39.05\,deg$

$$\eta_{ang} := 1 - \cos(\theta_{fiber})^{m+1} \qquad \eta_{ang} = 0.397$$

$$\eta_{tot} := \eta_{geo} \cdot \eta_{fres} \cdot \eta_{ang} \qquad \eta_{tot} = 0.312$$

Note: A fair comparison would be to assume there will be some inefficiency in light collection for the SiPM itself, as there are reflection, and some geometry losses associated with the window covering it; I would guesstimate actual light collection efficiency of a TPB coated SiPM to be ~ 80% .

Fiber attenuation test

This test consists of placing a spool of bare fiber inside the small 6" dia. pressure chamber we have, with both ends coming out through single fiber feedthroughs designed for 1mm bare fibers. An LED transmitter is fitted to one end and a photodetector reciever is fitted to the other end. These are all low cost components available from i-fiberoptics .com, except for the feedthroughs which are $175 ea. A price breakdown is shown below

Normal fiber attenuation:

$$\eta := 0.2 \frac{dB}{m} \qquad \text{@450 nm}$$

Choose fiber length:

$$L_f := 100m$$

Total attenuation at start of test:

$$N := \frac{-0.2}{m} \cdot L_f \qquad N = -20 \quad dB$$

Transmitter, LED , use IFE92A, 430nm emitting, in DC mode

$P_t := 25\mu W$ @ $I_f := 10mA$ V = 3.5V claimed as delivered into 1 mm POF

Power at end of fiber (assume negligible coupling losses)

$$P_{fe} := P_t \cdot 10^{0.1N} \qquad P_{fe} = 0.25\,\mu W$$

Receiver, use IFD-93, a high sensitivity photodarlington, in DC mode

Responsivity	Max collector current	Dark Current
$R := 200 \frac{\mu A}{\mu W}$	$I_{c\_max} := 50mA$	$I_{dc} := 100nA$

Minimum sense current to stay well above dark current:

$$I_{min} := 10 I_{dc} \qquad I_{min} = 1\,\mu A$$

$$P_{min} := \frac{I_{min}}{R} \qquad P_{min} = 5 \times 10^{-3}\,\mu W$$

Current range to measure

$$I_{max} := P_{fe} \cdot R \qquad I_{max} = 50\,\mu A$$

Dynamic range:

$$DR := \frac{P_{fe}}{P_{min}} \qquad DR = 50$$

in dB this is:

$N' := -10 \cdot \log(DR) \qquad N' = -17$ or

so we can essentially measure an attenuation change of:

$\eta' := \frac{N'}{L_f} \qquad \eta' = -0.17 \frac{1}{m} \quad \frac{dB}{m}$ which is a doubling of the normal unit attenuation

Test setup to measure xenon permeation and any resulting fiber attenuation.
Ideas:
1. Use long length of fiber to amplify small changes in attenuation (per unit length).
2. Use high initial attenuation to minimize relative effect of attenuation losses at couplings, as well as minimize small changes in transmitter and receiver response. This can be done by choosing a minimum length of fiber that gives >2 orders of magnitude more attenuation than estimated variance in attenuation.

Place spool of 100m POF inside pressure chamber, with both ends coming out through OZ feedthrough's.
Jacket exposed ends and install LED and receiver. Check for light leaks. Measure transmitted light, DC.
Read relative light though short section of POF.
Alternative, read light through a second spool of length Lf, above which is kept in air.
Fill with xenon to max pressure. Make periodic measurements

<u>Totals</u> <u>Items</u>

from Industrial Fiber Optics i-fiberoptics.com:

$65 100 m Eska CK-40 POF, 1mm dia, bare (note this is NA=0.5)
$10 (2) IF-D91 receivers
$10 (2) IF-D92 receivers
$15 (1) IF-E92A transmitter, 430 nm
$25 cutting tool
$10 polish puck, inexpensive

from OZ Optics www.ozoptics.com

from Ashby plumbing:

$150 (2) butyl type "M" gaskets (to reduce Xe permeation loss, will test with Ar first to see if necessary)

$350 (2) OZ feedthroughs for 1mm POF

$630

Number of fibers per feedthrough:

Assume a hexagonal packing pattern. packing factor is:.

$\eta_h := \frac{\pi}{6} \cdot \sqrt{3} \qquad \eta_h = 0.907$ http://mathworld.wolfram.com/CirclePacking.html

fiber spacing fiber hole diameter maximum feedthrough port dia (est)

$s_f := 1.5mm \qquad d_f := 1.1mm \qquad d_{ft} := 80mm$

$N \cdot a_f := a_{ft} \cdot \eta_h$

$$N_f := \frac{d_{ft}^2}{s_f^2} \cdot \eta_h \qquad N_f = 2580$$

fiber spacing for 1mm dia fibers could be as little as 1.25 mm, giving a possible 3750 fibers/feedthrough. alternatively, 1.5 mm dia. fibers could be used, if avail. in high NA, giving 27% additional (geometric) efficiency

Strength of feedthrough

Maximum stress of feedthrough will be shear stress at the periphery (assuming flange thickness is comparable to flange diameter), as perimeter increases linearly with radius, but area, and thus force, increases quadratically.

Given:

$$P := 15\text{atm} \qquad r := \frac{d_{ft}}{2} \qquad r = 4\,\text{cm}$$

for solid plug

$$\tau_s := \frac{F}{A_{perim}} \qquad \tau_s := \frac{P \cdot \pi \cdot r^2}{2\pi r \cdot t} \qquad \tau_s := \frac{P \cdot r}{2t}$$

web width, per "unit cell"

$$w := s_f - d_f$$

perimeter "packing" factor

$$f_p := \frac{w}{s_f} \qquad f_p = 0.267$$

assume hex packing so min web thickness spacing is same in any direction

flange thickness (z)

$$t_{fl} := 15\text{mm}$$

Maximum stress, per ASME PV code for 304 SS

$$\tau_p := \frac{P \cdot r}{2t_{fl} \cdot f_p} \qquad \tau_p = 1102\,\text{psi} \qquad S_{allow304} := 16700\text{psi}$$

Note: there will be some bending stress as well, but, as the flange is fairly thick it will be on the same order of magnitude as the shear stress. The flange should be designed for stiffness (low stress) to prevent flexure which might lead to leaks. The main challenge will be gun-drilling the holes accurately. Sinker EDM might be a good alternative method for producing the holes. Alternatively, a series of plates could be drilled, stacked and brazed together.