Distributed Temperature Sensing

Proof-of-Concept of Distributed Temperature Sensing Using Fiber Optics

GUG August 28-31, 2017

Agenda

- Existing Temperature Sensing Issues
- Machine Configuration and FO Installation
- Test and Results
- Next Steps

EXISTING TEMPERATURE SENSING ISSUES

Existing Temperature Sensing Issues

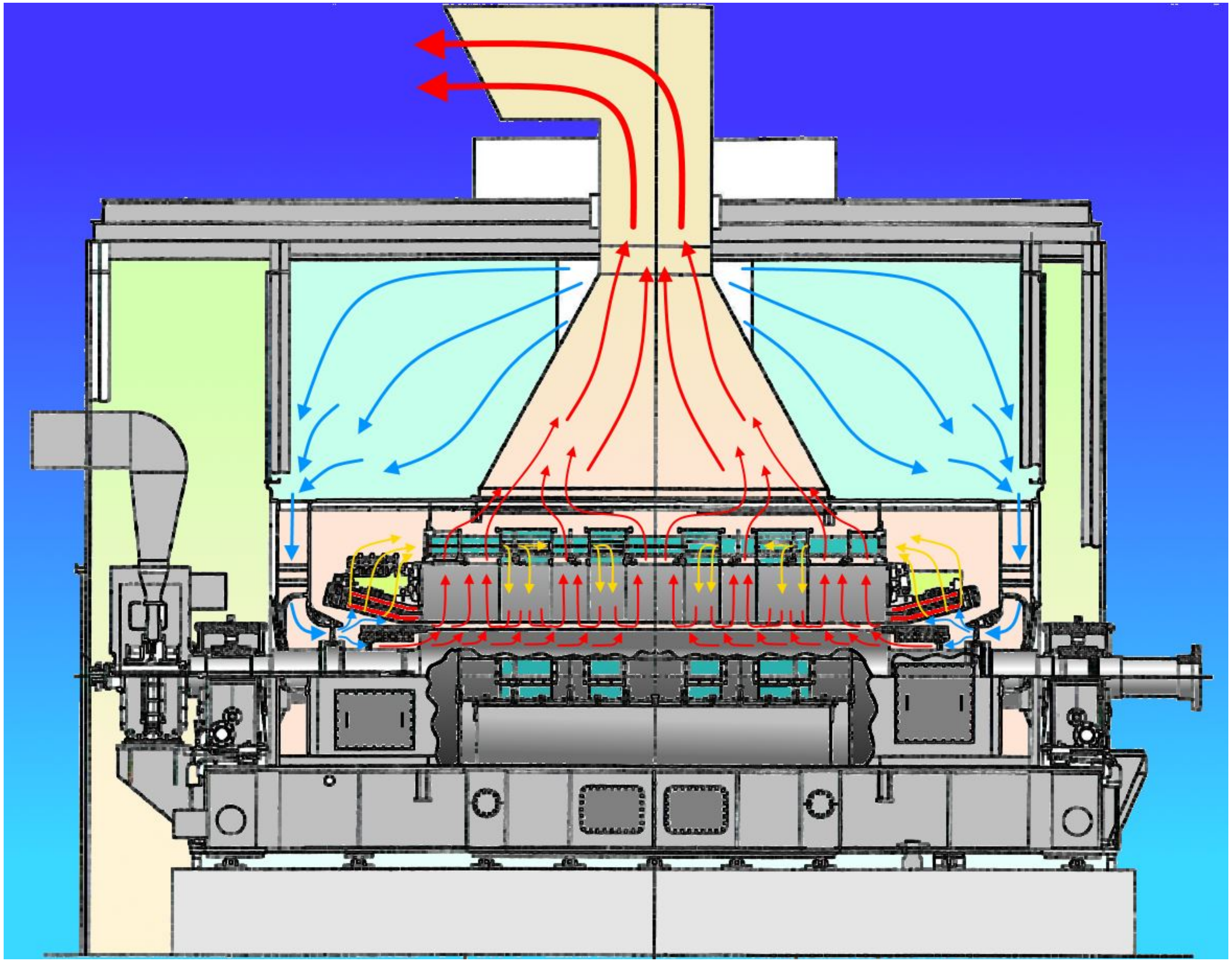
- RTDs are highly localized sensors
- RTDs subject to premature failure
- RTDs can be damaged during routine testing
- RTD monitoring doesn't provide adequate protection for stator cores
- Thermal cameras during loop/ring tests could be inaccurate
- Presently impossible to correlate offline core test findings to online core temperatures

MACHINE CONFIGURATION

and FO Installation

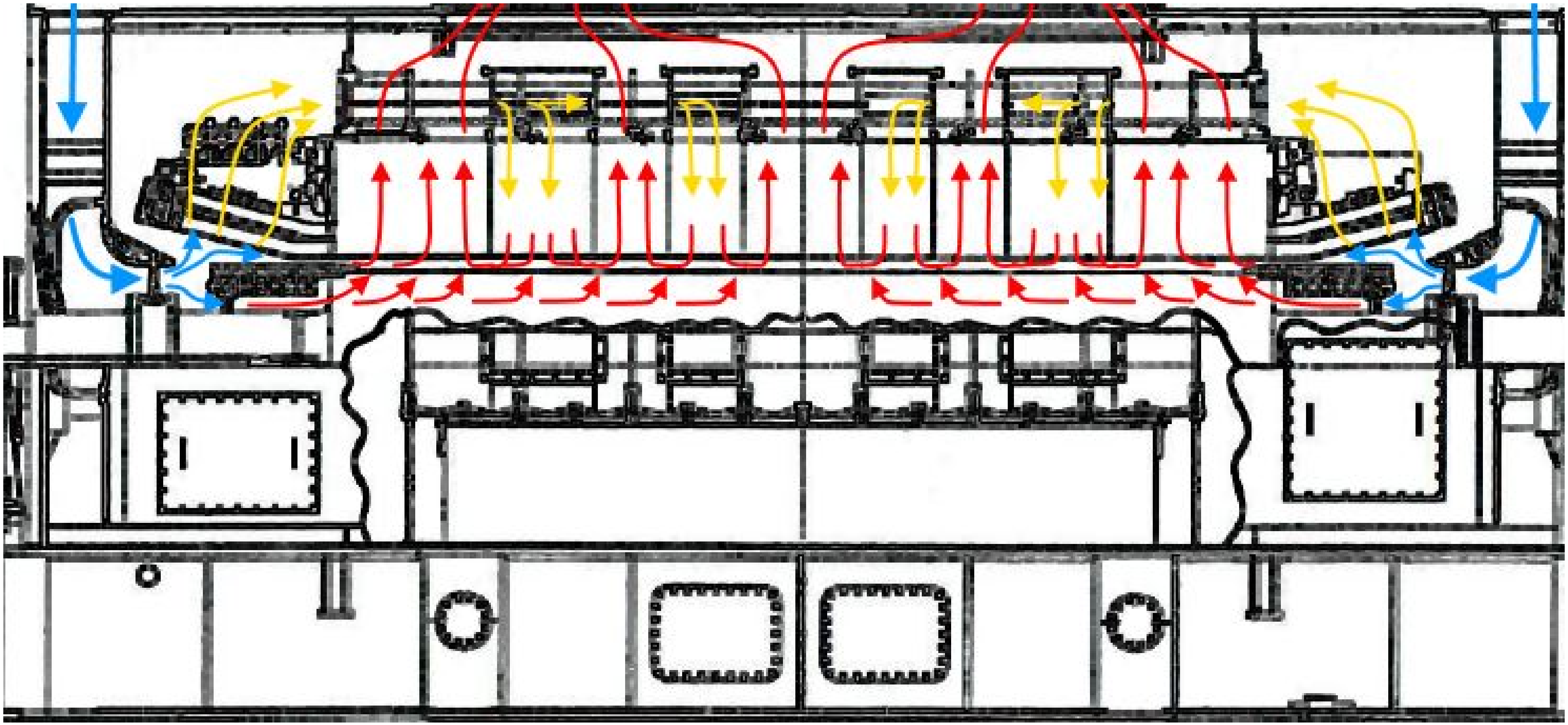
Machine Configuration

Siemens Westinghouse – AeroPac I – Open Air Cooled



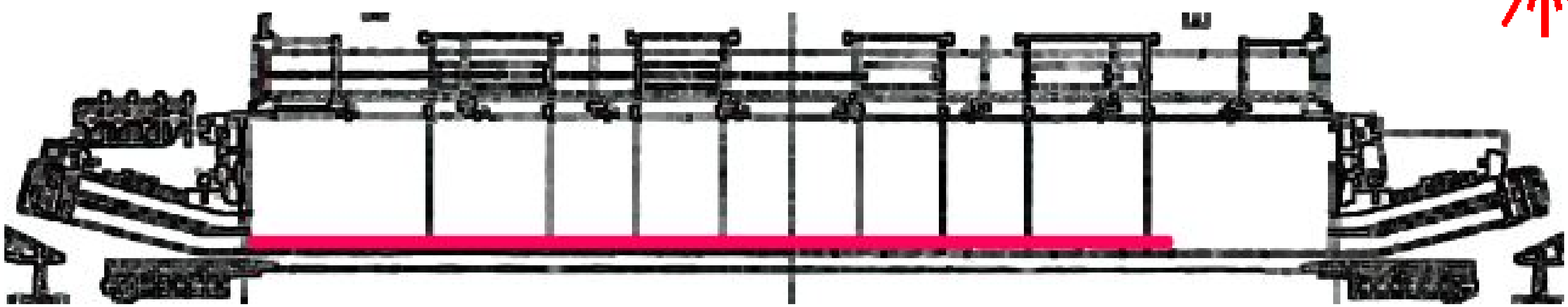
Machine Configuration

Radially Vented, Zone-Cooled Core



Machine Configuration

Fiber Optic Installation



TEST AND RESULTS

Test and Results

- Brillouin scattering-based distributed temperature sensing
- Brillouin scattering affected by temperature and strain
- Proven in other industries
- Baseline “cold” data taken for reference point
- System measures differential in scattering from baseline to discern temperature change

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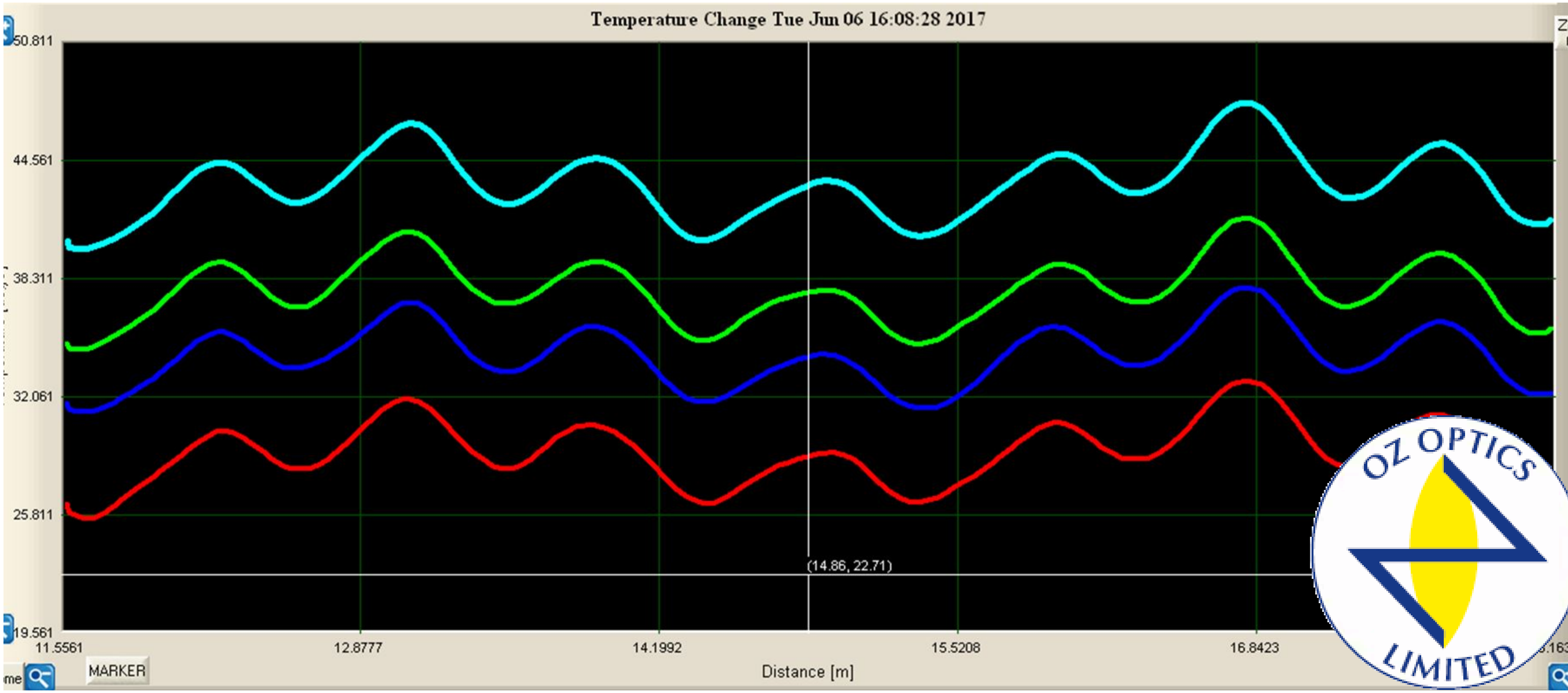
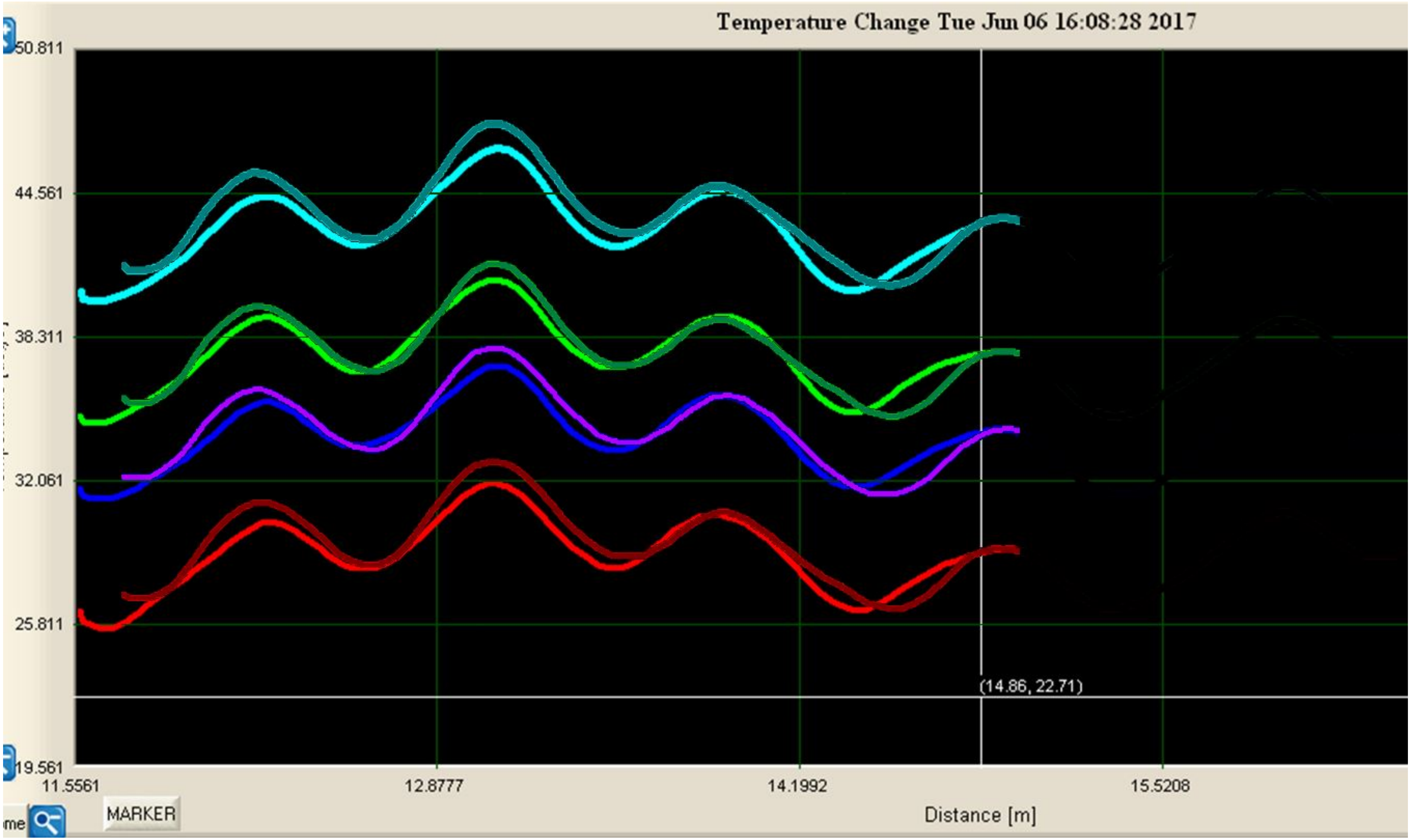
Test and Results

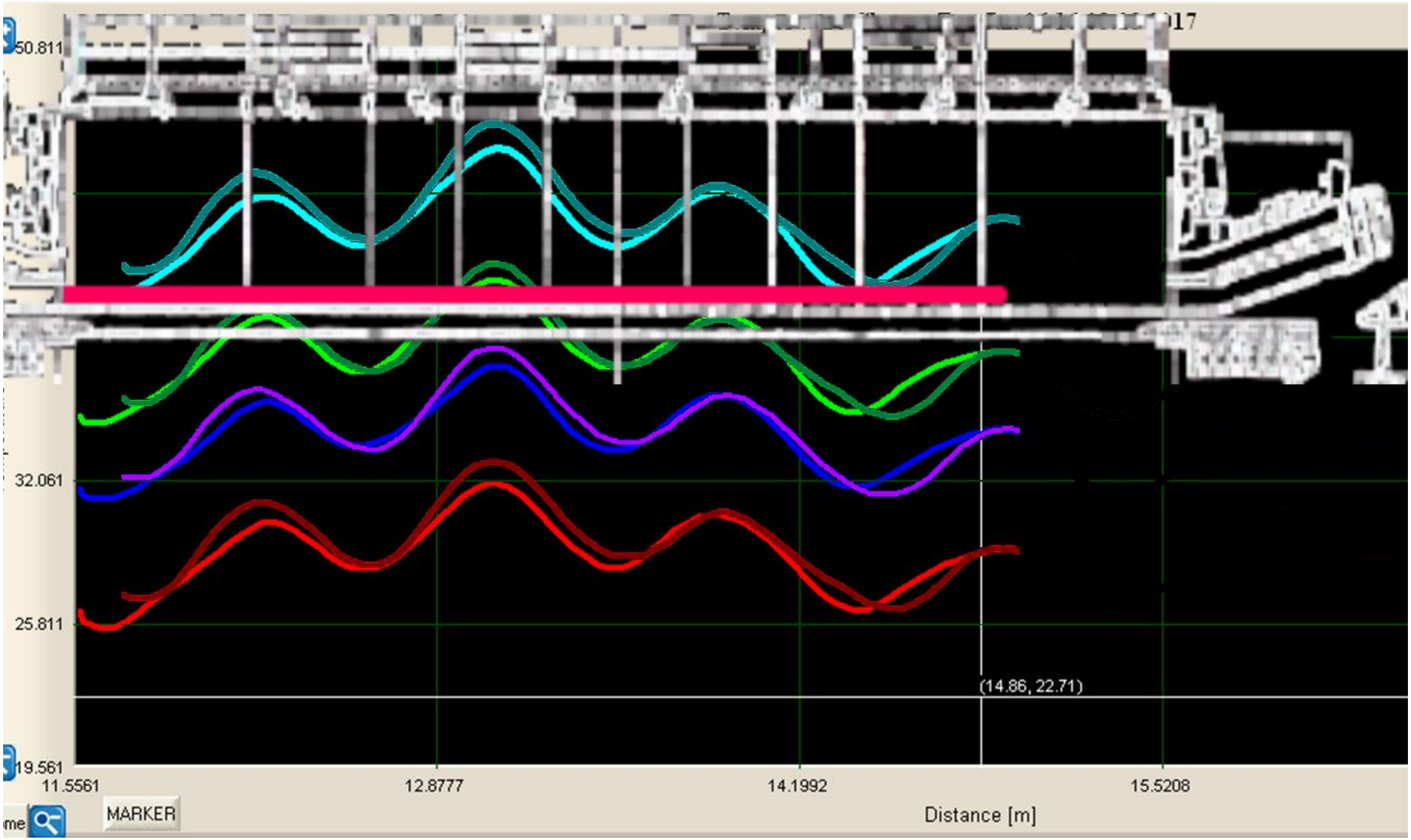


Cyan	170 MVA
Green	119 MVA
Blue	76 MVA
Red	25 MVA

Test and Results



Test and Results



Test and Results

Comparison with Control Room Data

Load	Cold Air	Hot Air	Embedded	Av. Trough*	Av. Peak*
170 MVA	30.6˚C	64.4˚C	78.1˚C	63.9˚C	67.0˚C
119 MVA	28.6˚C	57.8˚C	64.1˚C	58.3˚C	61.3˚C
26 MVA	21.6˚C	45.6˚C	45.3˚C	49.9˚C	52.7˚C

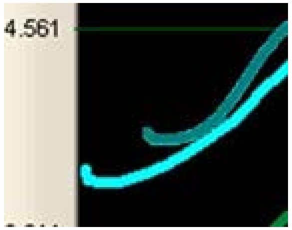
Load	Cold Air	Hot Air	Embedded	Av. Trough*	Av. Peak*
170 MVA	87.0˚F	147.9˚F	172.6˚F	147.0˚F	152.6˚F
119 MVA	83.5˚F	136.1˚F	147.4˚F	137.0˚F	142.3˚F
26 MVA	70.8˚F	114.0˚F	113.6˚F	121.8˚F	126.8˚F

- Data compares well to known RTDs
- Unfortunately, 76 MVA data was not captured due to other Control Room priorities at the time

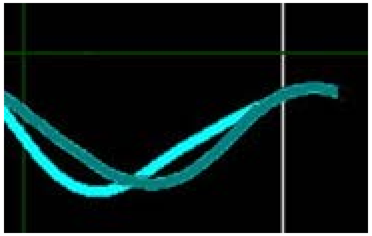
*** Not including the starting trough, or the last peak and trough due to strain affects**

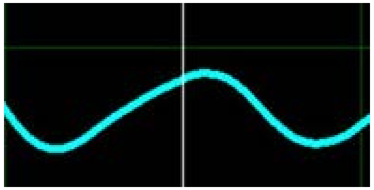
Test and Results

Data Anomalies



- Related to patch fiber splice location
- Patch fiber has bonded sheath, differentiating “sensor” from “lead” with sharp signal step
- Splice location easily resolved in refined assembly

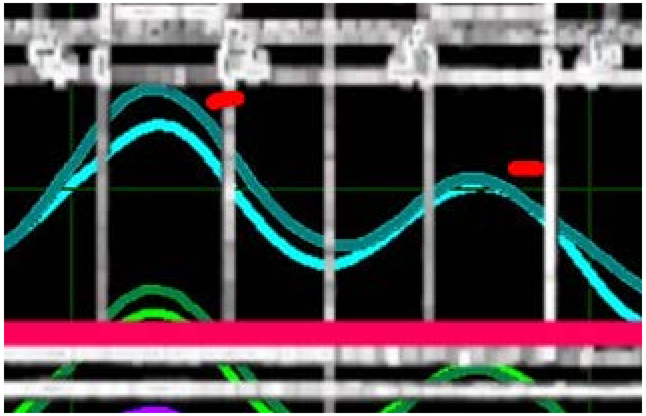




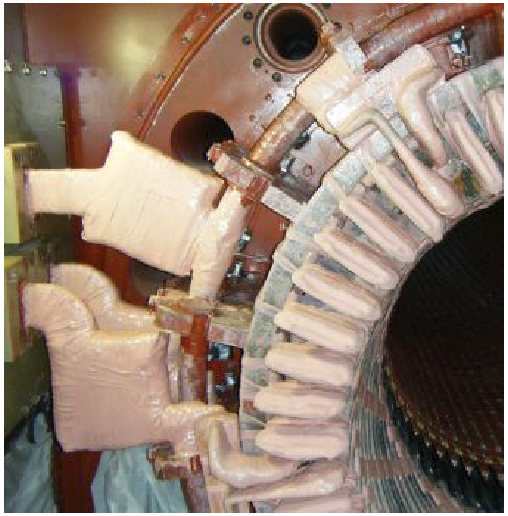
- Stretch/distortion related to errant strain in fiber
- Related to the loop-back point
- More refinement and testing needed
- Should be relatively easy to resolve

Test and Results

Data Anomalies



- Should be symmetrical about center? Maybe…
- Maximum difference ~2.7˚C (~4.9 ˚F)
- More heat on Collector End (CE) due to circuit rings and main and neutral connections
- Heavier resin coating over fibers on CE
- Very unlikely, but could be core issue

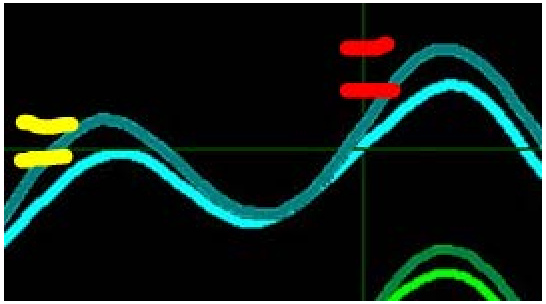


Collector End Resin

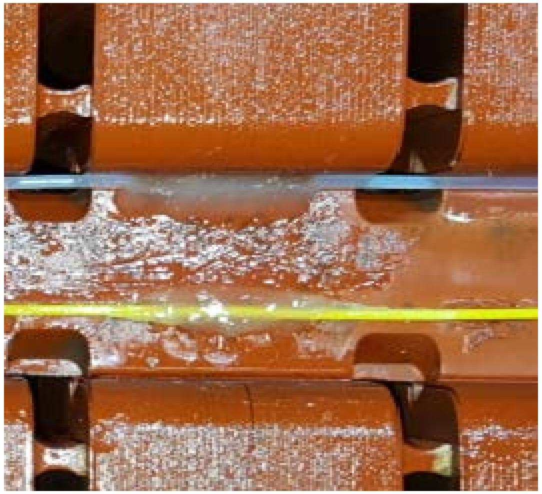
Turbine End Resin

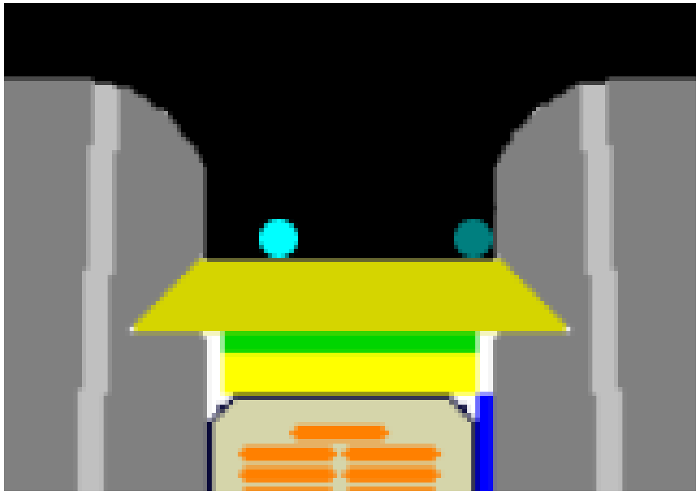
Test and Results

Data Anomalies



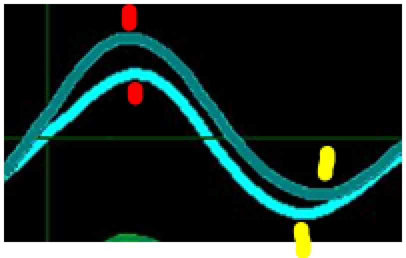
- Should be the same temperature? Maybe…
- Maximum difference ~1.1˚C (~2.0 ˚F)
- Different position, higher closer to core tooth
- Different ventilation exposure



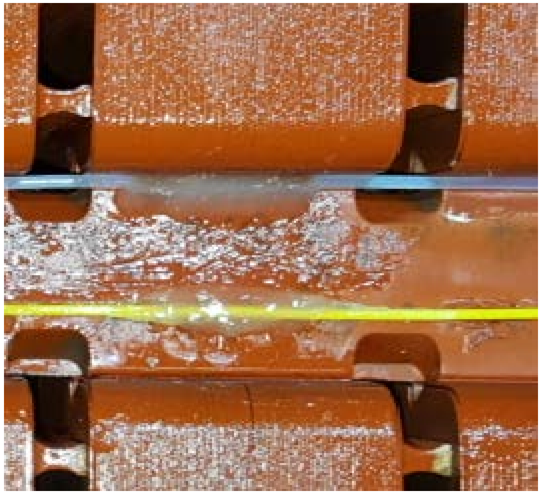


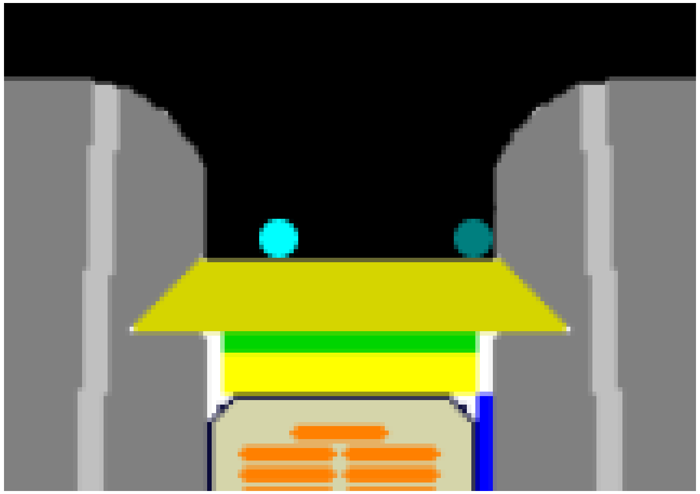
Test and Results

Data Anomalies



- Should peak/trough the same axial locations from leg to leg? Maybe…
- One iron pack + one vent = 5.1 cm (2”)
- Average leg-leg difference = 2.8 cm (1.1”)*
- Maximum leg-leg difference = 6.0 cm (2.4”)*





*** Not including the last peak and trough due to strain affects**

NEXT STEPS

Next Steps

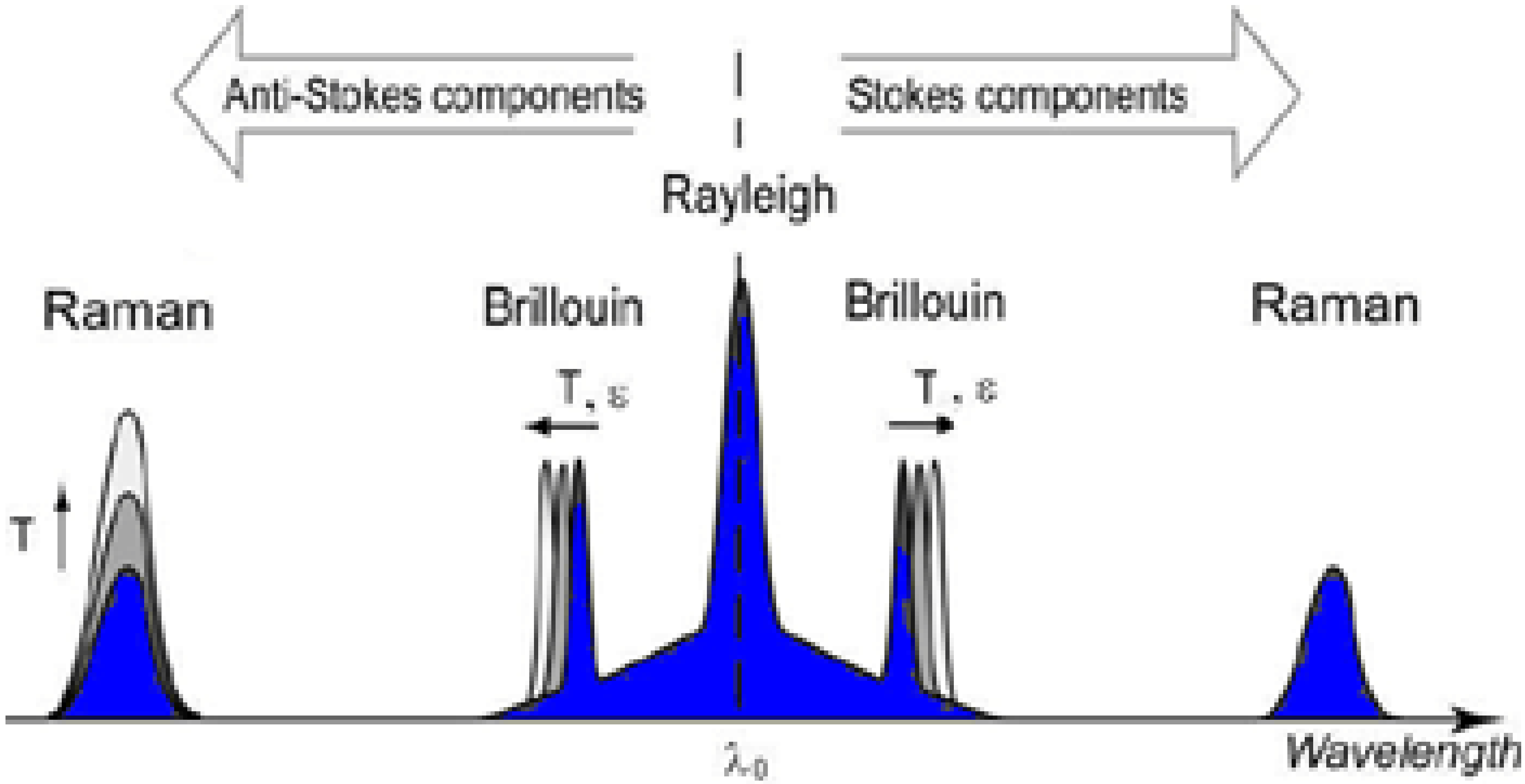
- Loop-back refinement, shim-style installation, cable selection, routing, and frame penetrations
- Dual-sensing RTD/FO for reference temperature?
- Core installations during rotor-out outages
- Core installations during stator rewinds
- Specific region sensing
- How do we monitor? Periodic? Continuous?
- How do we set alarm points and trips?
- How do we integrate into the existing plant control systems?

Special Thanks

APPENDIX – OZ OPTICS

Additional details on how the temperature readings are obtained using Brillouin scattering

Light scattering



Brillouin Scattering

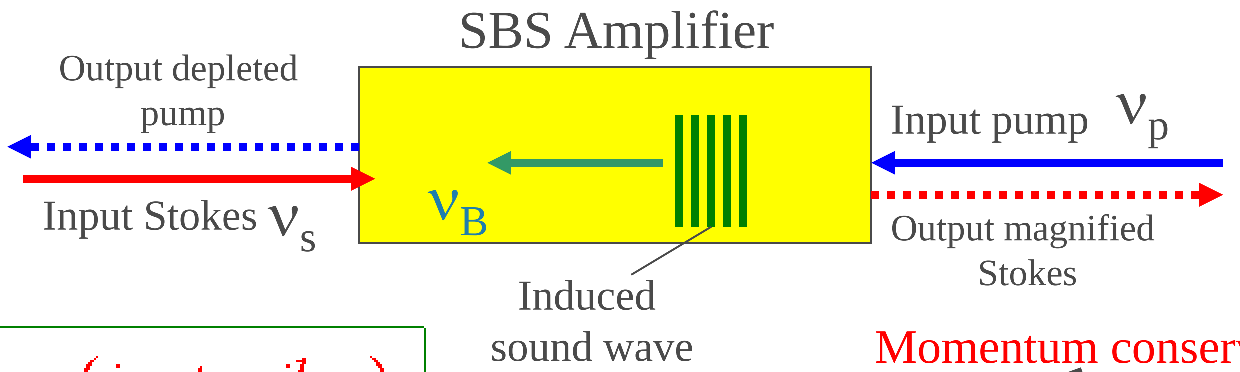
- inelastic scattering of light from acoustic phonons in a dielectric material.
  - Spontaneous and Stimulated Brillouin Scattering

- Difference between input and scattered beams = "Brillouin frequency"

$$\nu_B = \frac{2n v_a}{\lambda}$$

v_a Acoustic velocity
n Refractive index
λ Vacuum wavelength

Brillouin Scattering



$$E_s \propto \exp(i\omega_s t - ik_s z)$$

$$E_p \propto \exp(i\omega_p t + ik_p z)$$

$$Q \propto \exp(i\omega_q t + ik_q z)$$

Momentum conservation

$$k_p = k_q - k_s$$

Energy conservation

$$\omega_p = \omega_s + \omega_q$$

Simple dispersion relation

$$k_s = \frac{n}{c}\omega_s$$

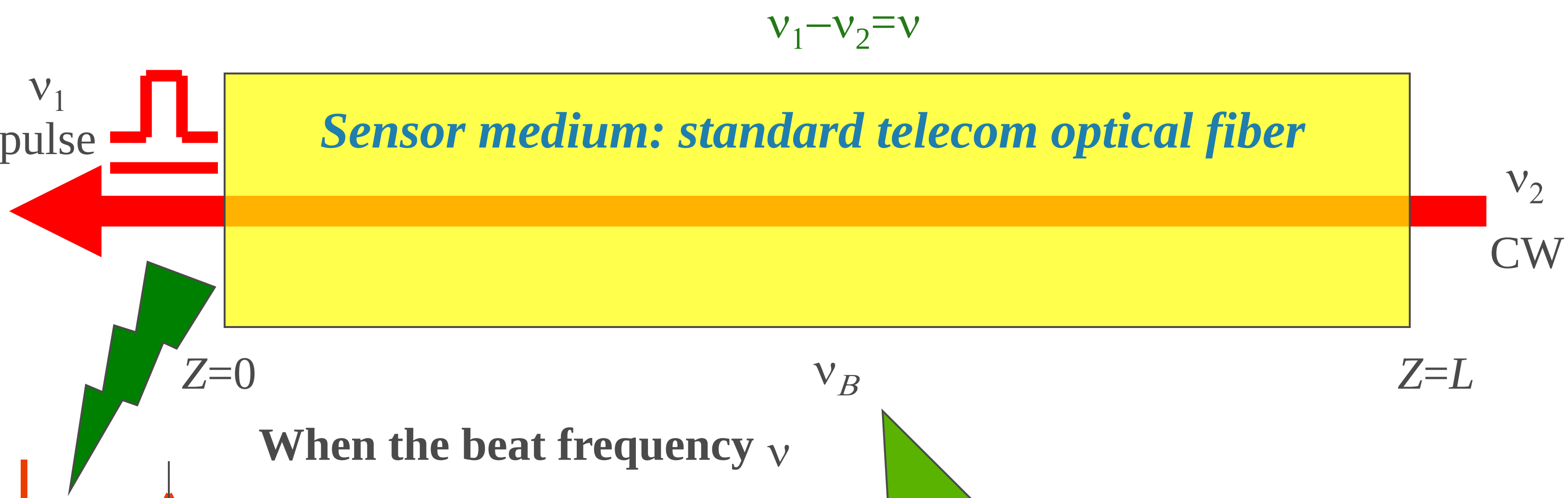
$$k_p = \frac{n}{c}\omega_p$$

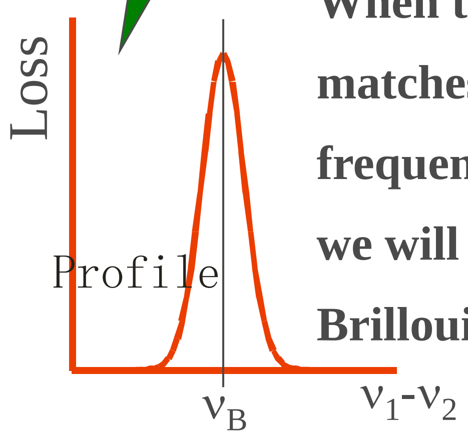
$$k_q = V\omega_q$$

$$\nu_B = \frac{2nV_a}{\lambda_p}\sin\frac{\theta}{2}$$

Brillouin frequency

Sensing principle





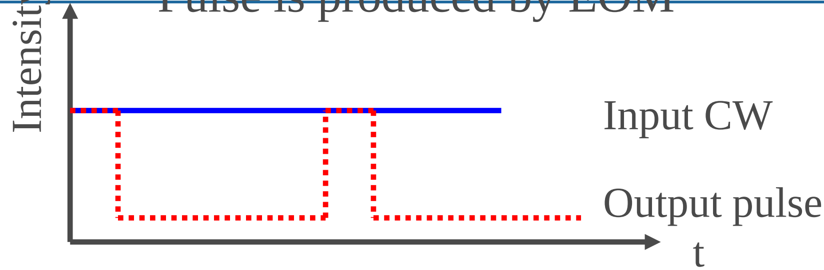
When the beat frequency ν matches intrinsic Brillouin frequency of the fiber ν_B, we will get maximum of Brillouin spectrum.

ν_B changes linearly with the strain and temperature exerted.

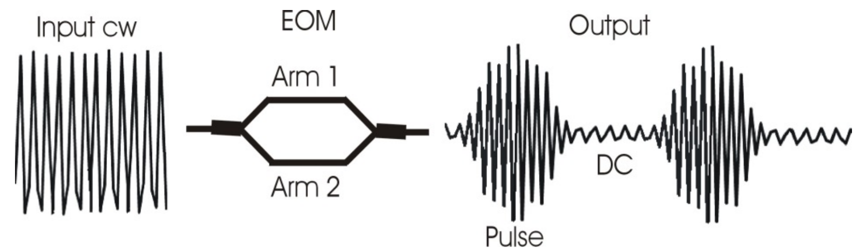
$$\nu_B = \nu_{B0} + C_T\left(T - T_0\right) + C_\varepsilon\left(\varepsilon - \varepsilon_0\right)$$

Brillouin Spectrum

Pulse is produced by EOM



Mach-Zehnder modulator with two arms



$$E_{out} = \frac{\sqrt{2}}{2}\left(A_1\cos(\omega t + \varphi_1) + A_2\cos(\omega t + \varphi_2)\right)$$

$$I_{out} = \left|E_{out}\right|^2 = \frac{1}{2}\left[I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\varphi(t))\right]$$

$\varphi(t) = \varphi_1 - \varphi_2$ is time dependent due to the optical phase modulated by an applied voltage

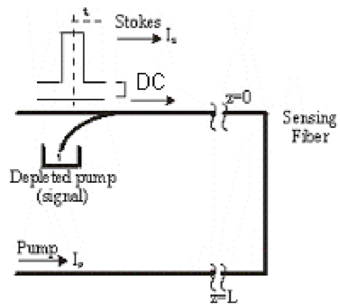
$\varphi(t) = 0$: maximum intensity output, $\varphi(t) = \pi$: minimum intensity output

$I_1 \neq I_2$ (AM),
$\varphi(t)$ cannot be exactly equal to π (PM) ⟶ finite ER $R_x = \frac{(I_{out})_{max}}{(I_{out})_{min}}$

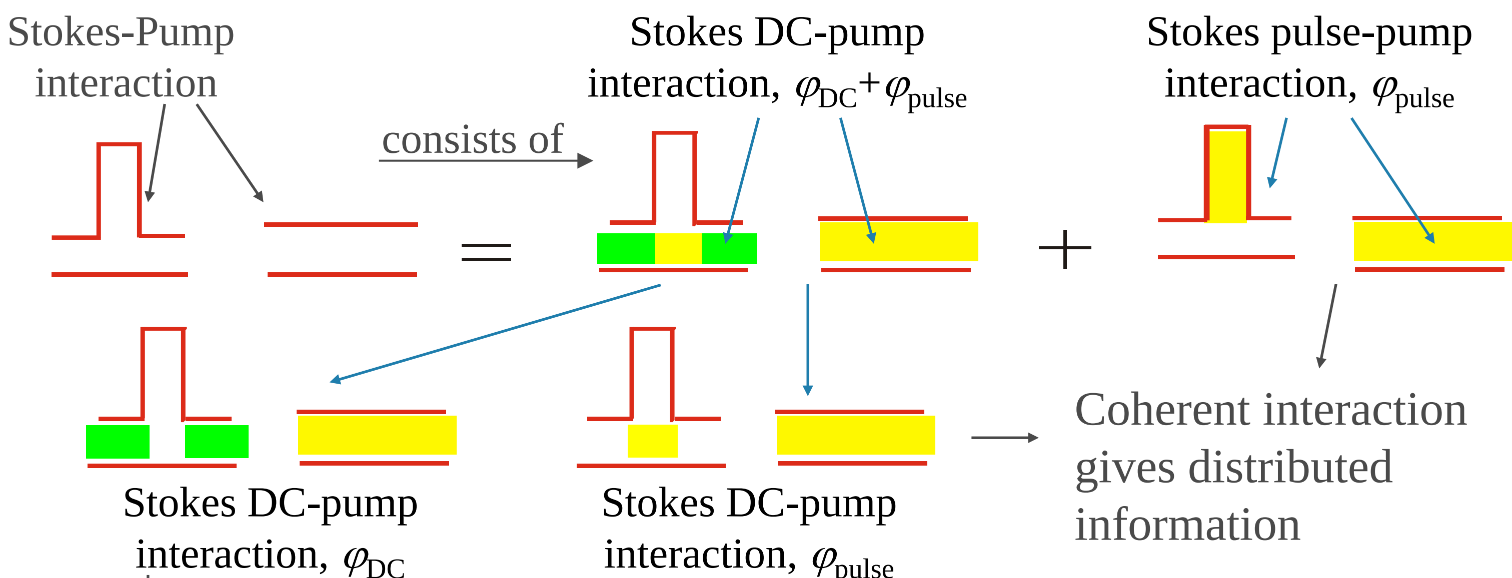
Pulsed laser generated by the EOM always contains a cw (DC) component

L.-F. Zou, *et al*, **Opt. Lett. 30 (4)**, 370-372 (2005).

Coherent interaction of pulse and pump



$$E_{out} = \begin{cases} A_{DC}\cos(\omega t + \varphi_{DC}) + a_{DC}\cos(\omega t + \varphi_{pulse}) \\ a_{pulse}\cos(\omega t + \varphi_{pulse}) \end{cases}$$



Only information along the test fiber and no spatial information

Coherent interaction of pulse and pump

$$\left(\frac{\partial}{\partial z}-\frac{1}{v_g}\frac{\partial}{\partial t}-\frac{1}{2}\alpha\right)E_p=\overline{Q}E_s$$

$$\left(\frac{\partial}{\partial z}+\frac{1}{v_g}\frac{\partial}{\partial t}+\frac{1}{2}\alpha\right)E_s=\overline{Q}^*E_p$$

$$\left(\frac{\partial}{\partial t}+\Gamma\right)\overline{Q}=\frac{1}{2}\Gamma_1 g_B E_p E_s^*$$

where

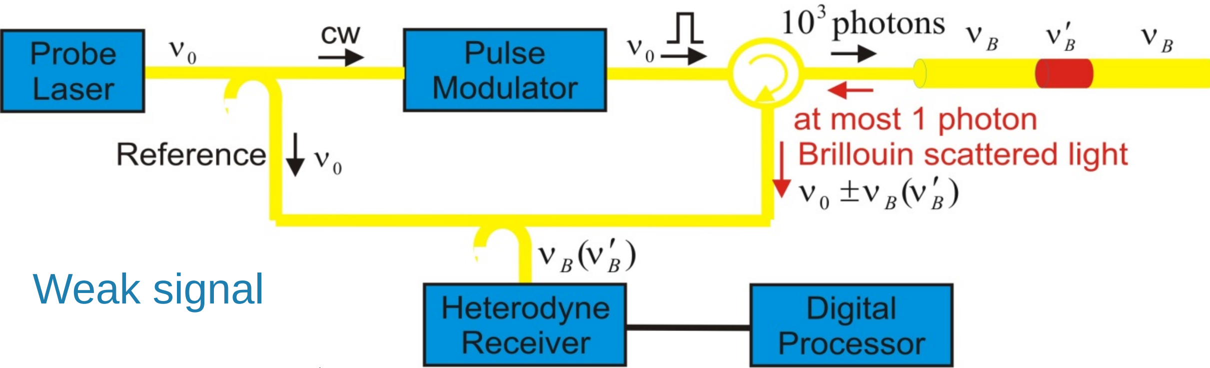
$$E_s=E_{out}=\begin{cases}A_{\mathbf{DC}}\mathbf{cos}\left(\omega_s t+\varphi_{\mathbf{DC}}\right)+a_{\mathbf{DC}}\mathbf{cos}\left(\omega_s t+\varphi_{\mathbf{pulse}}\right)\\ a_{\mathbf{pulse}}\mathbf{cos}\left(\omega_s t+\varphi_{\mathbf{pulse}}\right)\end{cases}$$

$$E_p=A_{\mathbf{pump}}\mathbf{cos}\left(\omega_p t+\varphi_{\mathbf{pump}}\right)$$

$$\overline{Q}(z,t)=\frac{1}{2}\Gamma_1 g_B\int_0^t E_p E_s^* e^{-\Gamma\left(t-t'\right)}dt'$$

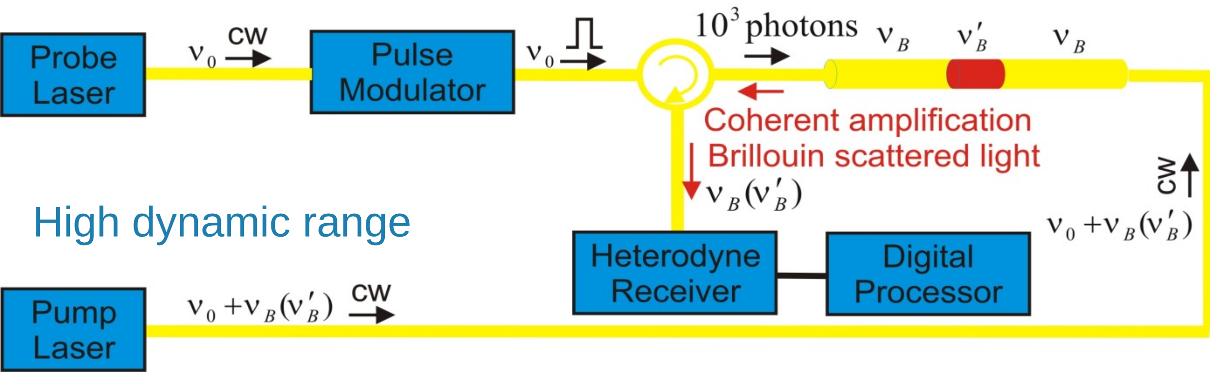
BOTDR and BOTDA

BOTDR (Brillouin Optical Time Domain Reflector)



Weak signal

BOTDA (Brillouin Optical Time Domain Analyzer)



High dynamic range

BOTDR: Spontaneous Brillouin scattering

BOTDA: Stimulated Brillouin scattering

Laser beams beat frequency ν, Brillouin frequency of fiber ν_B

References

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