TSL-Note-2004-58

Ideas for an Interferometric Thermometer

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Uppsala, Sweden
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1 Introduction

In some circumstances a non-invasive temperature measurement is needed. In one case the environment is highly radioactive and does not allow to have normal sensors embedded. In another case embedding a sensor will disturb the measurement significantly due to its own heat capacity. In this note we propose a method that allows measuring the temperature variation in water non-invasively by an interferometric method that utilizes the fact that the refractive index of water is temperature dependent. Energy deposited in the water basin will raise the temperature, change the refractive index and cause a phase shift in the light ray that can be analyzed in an interferometer.

Such a system is particularly interesting for monitoring the temperature of the cooling water in the beam dump of future linear colliders where Megawatt of beam power need to be dissipated in a beam dump made of rapidly flowing water. Having a device that measures the water temperature in such a hostile environment to monitor whether the water starts boiling will be crucial for machine protection. Another area is the diagnosis of the deposited energy in water for oncology applications, e.g. verifying the desired longitudinal and transverse dose distribution in a water phantom before patients are treated.

In the remainder of this report we will discuss the temperature dependence of the refractive index and the sensitivity of the method. We conclude with thoughts on how this method can be developed further; for example, how to investigate two or three dimensional temperature distributions and the temporal behavior of the deposited energy.

2 Refractive Index

The central quantity of the described method is the refractive index of water n which is usually around 1.33, but depends on many parameters, such as the temperature or the density of water, but also on the wavelength of the radiation. A compilation of the properties of water and steam can be found in ref. [1]. There an expression for the refractive index of water is given and we reproduce it here for easy reference

$$\begin{aligned} \frac{n^2-1}{n^2+1}\left(\frac{1}{\bar{\rho}}\right) &= a_0 + a_1\bar{\rho} + a_2\bar{T} + a_3\bar{\lambda}^2\bar{T} \\ &\quad + \frac{a_4}{\bar{\lambda}^2} + \frac{a_5}{\bar{\lambda}^2-\bar{\lambda}_{UV}^2} + \frac{a_6}{\bar{\lambda}^2-\bar{\lambda}_{IR}^2} + a_7\bar{\rho}^2 \end{aligned} \tag{1}$$

with the coefficients

$$\begin{aligned} a_0 &= 0.244257733 \\ a_1 &= 9.74634476\times10^{-3} \\ a_2 &= -3.73234996\times10^{-3} \\ a_3 &= 2.68678472\times10^{-4} \\ a_4 &= 1.58920570\times10^{-3} \\ a_5 &= 2.45934259\times10^{-3} \\ a_6 &= 0.900704920 \\ a_7 &= -1.66626219\times10^{-2} \\ \bar{\lambda}_{UV} &= = 0.2292020 \\ \bar{\lambda}_{IR} &= = 5.432937 \\ \bar{T} &= T/T^\star \\ \bar{\rho} &= \rho/\rho^\star \\ \bar{\lambda} &= \lambda/\lambda^\star \\ T^\star &= 273.15\,\mathrm{K} \qquad \text{(Reference Temperature)} \\ \rho^\star &= 1.0\,\mathrm{g/cm^3} \qquad \text{(Reference Density)} \\ \lambda^\star &= 0.589\,\mu\mathrm{m} \qquad \text{(Reference Wavelength)}\ . \end{aligned}$$

The right hand side of eq. 1 can be solved for n and we can then plot the refractive index n as a function of the temperature while keeping the wavelength and density at their reference values. This plot is shown in Fig. 1. A linear fit to the temperature dependence yields

$$n = 1.341 - 2.262\times10^{-5}\,T\,[\mathrm{K}]\ . \tag{2}$$

The temperature dependence is thus rather small.

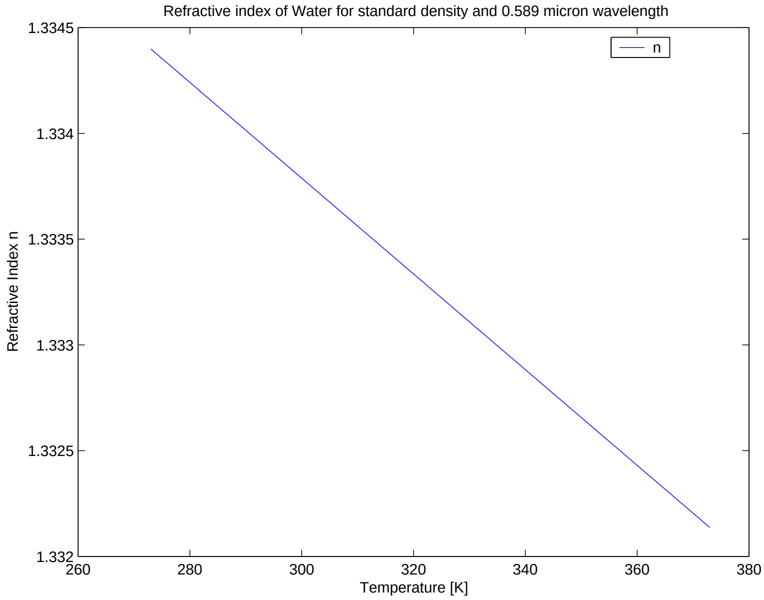

Figure 1: *The refractive index of water as a function of temperature at standard density and wavelength. A linear fit shows that the curve can be parameterized by* $n = 1.341 - 2.262 \times 10^{-5}T$.

3 Sensitivity

We now have to investigate how much the phase of a light ray shifts when the water that the ray traverses changes temperature. We note that the wavelength in a medium of refractive index n_1 is given by $\lambda_1 = \lambda_0/n_1$ where λ_0 is the wavelength in vacuum. The number of wavelength m_1 that fit into a container of length L is consequently given by

$$m_1 = \frac{L}{\lambda_1} = \frac{n_1 L}{\lambda_0} \ . \tag{3}$$

If the refractive index changes by a value Δn we thus expect a change in the number of wiggles Δm given by

$$\Delta m = \frac{\Delta n L}{\lambda_0} \tag{4}$$

where we have assumed that the refractive index is constant. If we drop this assumption we can write the previous equation as an integral

$$\Delta m = \frac{1}{\lambda_0} \int \Delta n(x) dx \tag{5}$$

where x parameterizes the path. If we now assume that we have a Gaussian temperature distribution

$$T(x) = T_0 e^{-x^2/2\sigma^2} \tag{6}$$

with a peak temperature variation T_0 and rms width σ we can utilize eq. 2 to relate the temperature profile to the spatial variation of the refractive index and evaluate the resulting integral by elementary means. We find

$$\Delta m = 2.262 \times 10^{-5} \frac{\sqrt{2\pi}\sigma T_0}{\lambda_0} \,. \tag{7}$$

For the reference wavelength $\lambda_0 = \lambda^\star$ we find

$$\Delta m = 96.3\, \sigma\, T_0 \tag{8}$$

where σ is the rms width of the Temperature variation in meters and T_0 the peak temperature variation in Kelvin.

Using a typical scale over which the temperature varies of cm and a temperature variation of 1 K we find that the phase of the light ray changes by about unity. This implies that such a minute change will be clearly visible on the interferometer, because the pattern will change through a full cycle. The sensitivity of such a thermometer is given by the product of the size of the temperature perturbation σ and the amplitude of the temperature perturbation T_0. We conclude that such an interferometric thermometer will be capable of measuring *temperature variations* of the order of a mm and fraction of Kelvin.

4 Development Potential

In the previous section we estimated the phase change that the ray experiences when the water temperature changes. Such a measurement can be performed very rapidly and we can envision that we have a wide mirror at the far end of the water container and a movable mirror that can be swept transversely. In this way *transverse temperature profile* can be obtained. This would be useful in the CLIC beam dump to see how wide the beam spot is one could infer the angular divergence of the incident particle beam, which gives an indication of the disruption at the interaction point.

Performing temperature profile measurements from different angles simultaneously would allow to tomographically reconstruct the temperature profile in two dimensions. Note that the quantity measured is $\int T(x)dx$ and each measurement at a different angle will give the "temperature density" along the ray. By correlating several such measurements a two-dimensional profile can be reconstructed.

Doing such temperature measurements constantly will allow to investigate the temperature diffusion between beam macro-pulses or other irradiations.

A potential problem comes from the fact that the varying refractive index will bend the rays and that will result in a varying path length which will add to the phase shift due to the varying refractive index. We plan to investigate this point further.

The method can be easily tested in a water container that is heated by a resistive electrical wire (e.g. constantan) where the temperature rise can be adjusted by the current passed through the wire.

The feasibility of the interferometric thermometer can also be tested with beam at TSL using the water phantom in the oncology beam line and installing an optical interferometer there. We can then use the proton beam from the cyclotron to deposit energy and investigate the local temperature rise in the water phantom. We typically run with 3 nA protons at 180 MeV. which gives about an energy deposition in the water phantom of 0.5 J/s. The range of 180 MeV protons in water is about 25 cm, so all that energy would end up in the water. If we assume that the transverse extent is about 0.1 cm^2 with a pencil beam we expect that all energy is dumped in about 3 cm^3. Considering the heat capacity of water of 4.2 J/(g K) we expect that a few seconds of irradiation will show a few degrees local temperature rise over a few mm and that should be visible. In this way we could then e.g. trace out the spatial and temporal distribution of the deposited energy.

The absorption of the rays in water will limit the thickness of the water dump that can be monitored. This problem can partially be alleviated by using extremely clean water which is, e.g. required for radiation protection in a linear collider beam dump.

Another problem will come from the fact that the water in the beam dump has to flow very rapidly in order to get rid of the energy and prevent the water from boiling. The ensuing turbulence may cause inhomogeneities in the water that may render the method presented above unusable. Moreover, the entrance window for the interferometer in the highly shielded beam dump will require serious consideration. These point need to be investigated further.

References

[1] The International Association for the Properties of Water and Steam, “Release on the Refractive index of Ordinary Water Substance as a Function of Wavelength, Temperature, and Pressure”, Erlangen, Germany, September 1997, available at `www.iapws.org/relguide/rindex.pdf`