Gas Properties Studies Using Reflectometry: First Steps Towards Real Time Cooling Gas Temperature Monitoring in Superconducting Magnets.

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Abstract—**To carry out fast (real time) temperature monitoring of the coolant gas and thus to observe evolution and enable the prevention of the quenching in superconducting (SC) magnets the frequency and time domain reflectometry (FTDR) i.e., analysis of microwave electromagnetic signals propagating in coolant gas channels, have been recently proposed. Here the results of numerical and experimental studies of fundamentals of the application of the microwave (RF) FTDR for quench monitoring are discussed. Through the studies, we show that variations of external conditions induce change in the gas permittivity, which can be measured fast and accurately. The methodology presented is based on correlations between thermodynamic gas variables (temperature and pressure) with its electromagnetic properties (refractive index). The sensitivity to both temperature and pressure suggests that the technique allow monitoring other anomalies i.e., not only temperature, including the gas pressure, the flow rate variations and turbulence. Through the numerical studies it was found that a localised hotspot can be detected with minimal time delay, which is crucial consideration for quench prevention and magnet "health" monitoring. The experimental data observed agree well with the theoretical understandings, and the preliminary findings promote further investigations in cryogenic environment of the proposed technique.**

***Index Terms*—Keywords:** HTS magnets, quench detection, microwaves, time-frequency domain reflectometry

I. INTRODUCTION

Superconductivity, is the phenomena observed in some materials which under special conditions (low temperature) have zero electrical resistance. It has appeared to be extremely desired for a big range of applications [1-6], such as medical imaging, electric propulsion, particle accelerators and magnetic confinement fusion devices [5,6]. Novel high-temperature superconductors (HTS) offer higher critical temperatures and better resilience in high magnetic field environments. While there are clear benefits as compared with the previous low temperature superconductors, several challenges has risen during the HTS material development specially due to their poor thermal conductivity at the above critical temperatures. This results in significant slower heat propagation and dissipation during quench events [7], leading to appearance of very high temperature localised volumes which make them extremely difficult to detect. In contrast, conventional quench detection methods for LTS are relying on relatively fast heat propagation and thus notable voltage rise across the whole cables during the event [8,9], while the heat localisation in HTS leads to a very low increase of average resistivity and simultaneously the hot spot temperature can exponentially grow inside the small volume and burning the coil [7-10]. There is a pressing necessity to find and develop new methodologies [11-21] to detect the quench in HTS and in this work a novel method based on Frequency and Time Domain Reflectometry (FTDR) has been suggested [22]. Unlike previously developed interferometric (QUELL project [11]) and optical FTDR systems i.e., optical fibres-based systems [19-21], the method suggested uses microwave EM radiation transmitted along the cooling channels which acting as waveguides i.e. without need for additional optical fibres. The microwaves are capable of detecting gas refractive index variations due to its temperature change, and while the use of cooling gas channel simplifies the overall design of the HTS cable i.e., avoiding need for the optical fibre, it may also allow to minimise the time required for the detection and improve the understanding of the quench (its location and power deposited). The method was considered as response to the questions risen during the design of STEP (Spherical Tokamak for Energy Production) project to overcome possible challenges during industrial prototype operation. Also, one notes that the gas permittivity changes can be caused by pressure variations or even contamination from other gases [23,24] thus opening avenues for other applications.

In this paper we will look at experimental and numerical validations of the technique and we show that microwave FTDR may be used to identify gas permittivity variations and characterizes the temporal evolution of hotspots. It will be demonstrated that the method can potentially enable the monitoring of both localized and bulk temperatures variations. Initial results presented in this paper indicate sufficient sensitivity of the method enabling the detection of the

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temperature variations from the room background temperature (295K) showing potentials of this technique for non-invasive and fast quench detection via using system eigen components such as cooling pipes without need for additional complex engineering to accommodate fibre optics.

It is expected that further experiments involve integrating those microwave FTDR sensors in a high current (100kA) superconducting cable designed for the STEP Toroidal Field coils [5]. The upcoming experimental campaign at cryogenic test facility will enable the accurate evaluation of the effectiveness of the method under more realistic temperatures further advancing this novel quench detection technology to operational deployment in fusion magnets.

II. METHODOLOGY AND RESULTS

A. Overview: Temperature and Permittivity relation

The RF FTDR technique suggested in this work aims to detect heating through a cooling channel which normally goes in parallel to the HTS stack, as shown in figure 1, to cool the HTS material of the cable and maintain the required temperature. It is “natural” channel which made of the good conductor and its geometry can vary to improve the temperature management. In figure 1 a red spot is a schematic illustration of a possible appearance of the hot spot and the heat propagation toward the cooling channel. It is assumed that any temperature variation appearing in the HTS stack will propagate fast through the copper jacket [25] (faster as compared with typical quench development time) and thus heating the cooling pipe as shown in figure 1. The heat load shown by the red circle will be taken away by the coolant. At this stage to simplify the model and initial studies it is assumed that the channel heating is uniform as shown by the red ring around the cooling channel. It is also assumed that the heating measured in the coolant will have time delay from the HTS temperature. While the non-uniformity of the heating will affect the model complexity the main principle of method and operation will be the same. We note that in the STEP the coolant is the Helium, fast flowing (Reynolds number above 4000), cold (20K) gas.

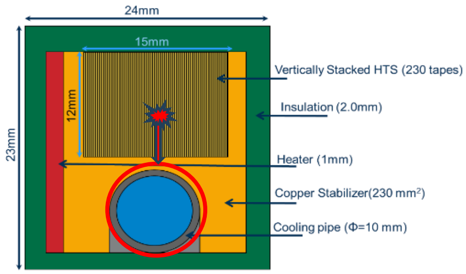

Fig. 1. Schematic slice of the stack configuration, on top the HTS stack embedded in copper, below the cooling channel within the copper.

The local temperature variation of the coolant gas in the channel can be measured if the coolant pipe is used as a RF waveguide. In this case the gas at the hotspot location will have different refractive index (permittivity) leading to variations of the transmitted and reflected signal parameters which can be measured. Using these data the position and temperature of the hot spot can be recovered. The figure 2 illustrates (schematically) the experimental set up used to carry out the measurements. From Clausius-Mossotti equation and the ideal gas law it can be found that gas permittivity depends on the temperature and pressure variations:

$$\varepsilon = \left[1 + \frac{3\alpha_P \chi}{1 - \alpha_P \chi}\right] \qquad (1)$$

where $\chi = P/T$, P is the gas pressure, T is the gas temperature variable in time, $\alpha_P = \frac{4\pi}{3}(\alpha_v/k_b)$, α_v volumetric polarizability [23,24] and k_b is the Boltzmann constant. The expression (1) shows that at low temperature and higher pressures the permittivity value should increase as well as its variation with the change of these variables. Also increase of the coolant temperature (while maintaining constant pressure) will effectively cause a density lowering and thus a decrease of permittivity. This expression was used to validate the methodology both numerically and experimentally. The experimental set up is shown in figure 2. The experiments were carried out with three different gases: Argon, Nitrogen and Helium (figures 3a,b,c respectively). A VNA (Vector Network Analyzer) was used to launch and receive electromagnetic wave signals propagating through the gas channel with a frequency range between 32GHz-34.5GHz, allowing only a single mode propagation thus avoiding excitation of parasitic modes on the channel imperfections. In figures 3 the results of the experimental studies are shown. To validate the expression (1), the experiments were conducted by varying pressure inside the channel at room temperature using a copper pipe of 6mm diameter and 1m long as a gas and microwave channel.

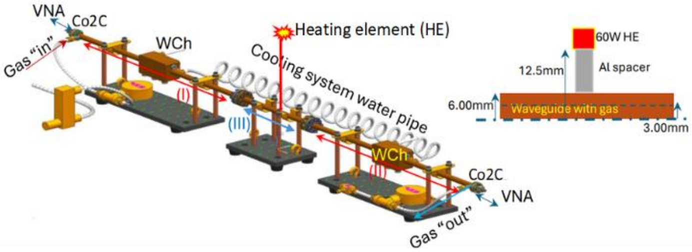

Fig. 2. Schematic drawing of the experimental set up illustrating the three segments of the waveguide system indicated as (I), (II) and (III), heating element (HE), gas input/output shown as Gas “in” and Gas “out” respectively, waveguide chilling (WCh) system, coaxial to cylindrical waveguide couplers (Co2C). The inset is the schematic cross section of the 60W heating element (HE), aluminium (Al) spacer, the radial dimensions are shown.

The results show agreement between theoretical predictions dashed lines and experimental points while the deviations observed (figures 3) can be attributed to gas contamination. One notes that according to (1) there are three parameters on which the permittivity depends on: temperature (T), pressure (P) and polarizability (α_v). The first to defined by the environment while the last is the property of the gas. Since polarizability is a quantity which has already been tabulated for most of the gases it could be compared to the expected values. showing a good agreement with the experimental results and validate the method to recover permittivity. The tabulated and measured values of the polarizability are shown in the Table 1.

[cm^2 V^{-1}]	Tabulated $*10^{-40}$ [27]	Experimental $*10^{-40}$
Helium	0.23	0.314
Nitrogen	1.94	1.816
Argon	1.83	1.684

Table 1. Tabulated [27] and measured gas polarizability α_v

The values obtained for Nitrogen and Argon have a deviation of 6-8% from tabulated values, while for Helium the deviation was found to be around 30%. These differences stem from a number of factors including purity of the gases used. For helium as the absolute polarizabilities value is extremely small ($\approx 10^{-40}$ C m^2 V^{-1} for N$_2$/Ar and $\approx 10^{-41}$ C m^2 V^{-1} for He), the measurements' results are extremely sensitive to the gas purity. Taking into account the scope of the experimental set-up to detect hotspots the deviations are reasonable and achieve the main goals i.e., to demonstrate that the slope of the response curve is governed by gas properties and external factors like pressure and temperature.

B Time and Frequency Domain Reflectometry

The technique suggested is based on the signals (transmitted S_{ij} and reflected S_{ii}) variation of phases $\Delta\varphi_{ij,ii}$ due to change of the gas refractive index $n = \sqrt{\varepsilon\mu}$ at the local spot (here we consider that $\mu = 1$ for the gas):

$$\Delta\varphi_{ij} = \frac{2\pi\cdot\Delta L_H(\xi(\delta n)-\xi(0))}{\tilde{v}_{ph}}\cdot f \qquad (2)$$

here δn is the refractive index variation, $\xi(\delta n) = \sqrt{1-\left(\frac{f_{cut}\cdot n}{\tilde{n}f}\right)^2}$, $\tilde{n} = n + \delta n$ and f_{cut} is the waveguide cut-off frequency. We note that the carried-out measurements are "relative" to the steady state operation which is assumed to be a "zero" level i.e., $S_{ii}(0) = 0$ and $S_{ij}(0) = 1$. In general, $S_{ij}(0) < 1$ and provides important information about the losses inside the channel due to channel walls finite conductivity, however here we assume $S_{ij}(0) = 1$. As a result, measuring the variation phase of the transmitted signal (let us say from port 1 to port 2) and phases of the reflected signals from port 1 to port 1 and port 2 to port 2 the position as well as dimensions of the hot spot can be estimated. At this stage the numerical model using CST MW Studio (part of the CST Studio Suite [26]) has been carried out to illustrate the technique. For the numerical model similar to the described set-up was used constructed. A cooling pipe of 6mm diameter and 500mm long was used as a waveguide in the simulations, and a narrow frequency 34GHz-34.2GHz microwave pulse was launched. In the model a hot section of 40.05mm length was set in the middle of the waveguide, and the permittivity of the hot region was set to be ε=1.1 while the "cold" permittivity of the gas was assumed to be ε=1.15. In this case the variations of the transmission and reflection coefficients can be estimated as:

$$S_{11} = \frac{\tilde{n}\cdot\xi(\delta n)-n\xi(0)}{\tilde{n}\xi(\delta n)+n\xi(0)}, S_{12} = \frac{\sqrt{\tilde{n}\cdot\xi(\delta n)\cdot n\xi(0)}}{\tilde{n}\xi(\delta n)+n\xi(0)} \qquad (3)$$

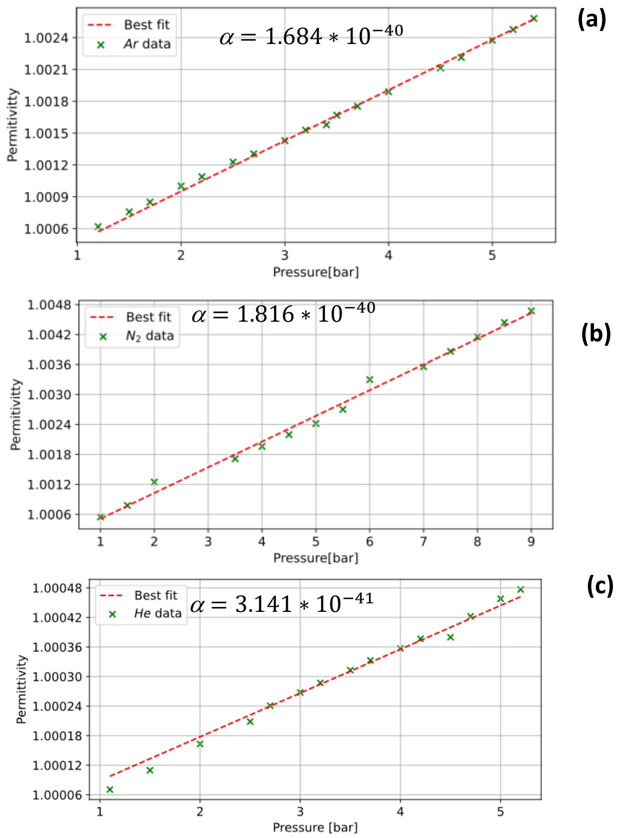

Fig. 3. Experimental results illustrate the permittivity dependence of the gas pressure observed for: **(a)** Argon (Ar), **(b)** Nitrogen (N$_2$), **(c)** Helium (He).

Recording the data from the numerical simulations and using the techniques described above allowed to estimate both the position, the length and the refractive index of the gas in the hot spot: $\Delta L_H = 40.052$mm and $\varepsilon_n = 1.10018 \pm (1.6\cdot 10^{-8})$ illustrating a good accuracy of the methodology and the small deviations show consistency between the values obtained from S parameters. One of the advantages of the technique suggested is the possibility to measure slow temperature variations of the HTS cable even if the localized perturbation was not formed to vary the parameters of the transmitted and reflected signal. It is important to point out that as any real system the gas channel has its "imperfections" from microwave signals propagation point of view such as gas inlets and outlets, connections and pressure windows. These imperfections create "defect" eigenmodes which frequency positions are sensitive to the gas average refractive index value. To demonstrate this the experiments were conducted varying average gas temperature with the goal to measure shift of the eigenmodes positions and recover the gas average temperature drift. The results are illustrated in figure 4 where the spectra of the eigenmodes before and after the heating are shown. To carry out the measurements the microwave pulses were propagated through the channel having high quality copper walls. The copper walls allowed fast heat diffusion along the channel and a gradual increase of the gas temperature. The spectral characteristics of the channel were continuously recorded starting from room temperature (t=0, measurements start-time) and till the heater was turned off (the last record corresponds to t=7min). It has been observed that the frequency spectrum over different timesteps is drifting as seen in figure 4. Using relatively simple electrodynamics the permittivity variation and thus the temperature change can be recovered from this frequency shift:

$$\frac{f_n}{f_{\tilde{n}}} = \sqrt{\frac{\varepsilon_{\tilde{n}}}{\varepsilon_n}} \qquad (4)$$

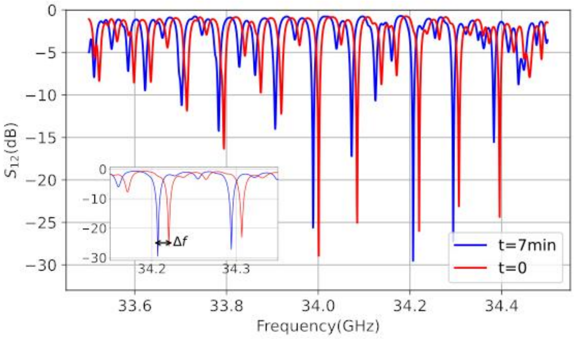

Fig. 4. S_{12} amplitude frequency spectra at t=0s, t=7min (He).

Taking into account the relations (4) and (1) the temperature can be recovered, and in figure 5 the comparison of the heater temperature and average gas temperature is shown. We note that at t=400s the heater was switched off, however due finite heat capacitance of the system i.e., heat stored in the system, the gas temperature decrease was delayed as expected. The temperature decay delay is observed due to the 12.5mm aluminium spacer and 3mm thick copper channel wall located between the HE and the gas in the channel (figure 2).

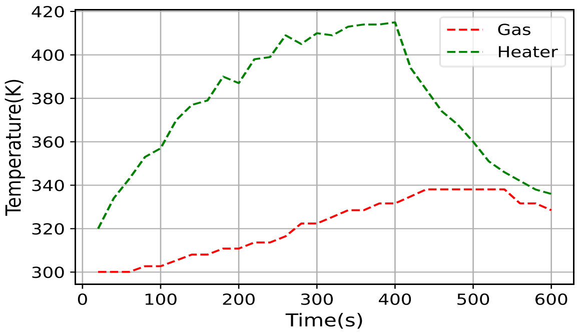

Fig. 5. Comparison of the evolutions of the gas average temperature (dashed red line) and the channel wall temperature (green, dashed line) in the time interval from 0 to 10 minutes.

II. DISCUSSION AND CONCLUSION

In this work a new methodology was presented as an option to compliment the alternative methods helping to resolve the challenges of fast quench detection and temperature monitoring in the HTS magnets to make the next generation magnets more reliable and affordable. The studies were carried out to meet the requirements of STEP project and its systems (as shown in figures 6) where size, radiation or other conditions can highly affect the performance of both detectors and the magnets. To reach the goals we suggested to use the coolant channels built along the cable (figs.6a and 6c) as a waveguide, to analyse the EM microwave signals' response on the variations of the key gas properties. The studies were focused on both the detection of the temperature variation and its quantitative characterisation and to conduct them the measurements of the gas permittivity variations using the FTDR were carried out. The data analysis was done using the Clausius-Mossotti equation which links gas pressure and temperature with its permittivity. To validate the FTDR technique three different gasses were investigated and its fundamental parameters were measured. The variations of the gas permittivity with the changes of pressure and temperature were studied showing from 6-8% on Argon and Nitrogen to 30% in Helium deviation from the expected values. The studies conducted demonstrated the possibility to use the FTDR technique to monitor HTS cables and to measure both hotspot temperature and size. The technique shows potentials for diverse applications in the systems where temperature or pressure variations to be monitored. Next steps are to conduct studies of HTS heating in cryogenic environment.

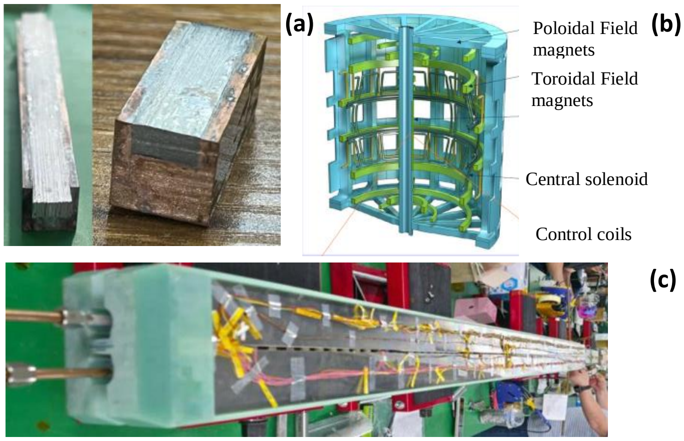

Fig. 6. (a) Photograph of sample of HTS cable, **(b)** cartoon of a set of magnets forming plasma "cage" to confine burning plasma for STEP project, **(c)** 3m HTS cable in cryo-box prepared for tests the pipes on the left are cooling channels.

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