EVALUATION AND IMPLEMENTATION OF HIGH PERFORMANCE REAL-TIME SIGNAL PROCESSING FOR RAYLEIGH SCATTERING BASED QUENCH DETECTION FOR HIGH FIELD SUPERCONDUCTING MAGNETS*

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Abstract

YBCO coated conductors are one of the primary options for generating the high magnetic fields needed for future high energy physics devices. Due to slow quench propagation, quench detection remains one of the primary limitations to YBCO magnets. Fiber optic sensing, based upon Rayleigh scattering, has the potential for quench detection with high spatial resolution. This paper discusses the potential of multi-core CPUs and GPUs to accelerate the signal processing demands associated with Rayleigh scattering based quench detection systems in a real-time environment. This technology study was made possible by LabVIEW- GPU Analysis Toolkit and the LabVIEW Multicore Analysis and Sparse Matrix Toolkit [1,2].

INTRODUCTION

High temperature superconducting (HTS) magnets face significant operational challenges that must be addressed before reliable, safe operation in large systems is realized. One issue is quench protection. In general, quench protection in large, high field magnets involves detection and protection. This has been studied extensively for low temperature superconducting (LTS) magnets for decades and their fundamental behavior is well understood. Although LTS magnets do quench, they are usually well protected so conductor degradation is avoided. Qualitatively, quenching in HTS and LTS magnets is the same; the underlying electromagnetic and thermal physics is unchanged. There are significant differences, however, between LTS and HTS magnets that pose both opportunity and risk. One difference is the minimum quench energy (MQE); HTS magnets are significantly more stable with very large energy margins. This may be very attractive for high-energy physics (HEP) applications, particularly near the interaction region (IR) where large irradiation heat loads may exist. If superconducting magnets can be built with significantly larger MQE, the magnet can be operated more efficiently and much closer to the IR. Thus, in addition to the to the benefits of higher fields, HTS magnets offer the possibility of high heat load (irradiation resistant - important for facilities like FRIB) magnets. The other key difference between HTS and LTS is that HTS magnets have significantly slower quench propagation velocity (QPV); as much as two orders of magnitude lower. As a result, quench detection is particularly difficult; this is the crux of the HTS protection challenge. Traditionally, magnet protection has used voltage taps to monitor the length-integrated electric field for changes indicative of an increasing resistance in the conductor. Because the QPV in HTS magnets is slow, by the time a detectable voltage is reached there may be a very high local temperature within the magnet that could be destructive. Thus, what is needed for quench protection in HTS magnets is a sensor capable of quickly detecting local temperature increases within the magnet.

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RAYLEIGH SCATTERING FOR QUENCH DETECTION

It has been shown that fiber optic based Rayleigh scattering can be used to create fully distributed temperature sensors with high spatial resolutions. Distributed sensors are created from the wavelength domain Rayleigh scatter profile by transformation to the time domain and then subdividing the data into length segments. The distributions for the length segments are compared to a reference distribution via cross correlations. The evolution of the cross-correlation peak in time, for a given segment, correlates to the temperature evolution of a segment [3,4].

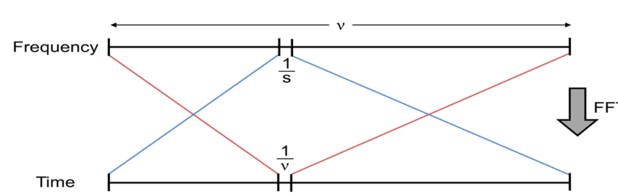

Figure 1: The relationship of the frequency domain data and the time domain data. The time domain data can be calibrated to provide data as a function of length. The length data is then used to create the distributed measurement segments that can be used for quench detection (figure taken from [5]).

SIGNAL PROCESSING CHALLENGES AND SOLUTIONS

The key challenge for converting the Rayleigh scatter profile into a distributed temperature sensor is signal-processing speed. For protection of YBCO one needs to provide temperature comparisons for each segment every ~10 ms. Here we present some benchmarking studies to determine the optimum technology for building a quench detection system.

The challenge was to complete the core signal processing tasks required for protecting 50 m of conductor (using 1cm measurement segments each with 100 data points). The processing requires an initial 512,000-pt FFT followed by 5,120x100-pt (or 500x1,024-pt) cross-correlations completed under 10ms. Several technologies were considered; multi-core CPUs and GPUs.

Multi-Core CPU Implementation

The implementation of the signal processing on a 12-core, 2-CPU machine was done in the following way:

- The 512,000-pt FFT was performed as a multi-channel FFT.
- The cross correlations were considered as FFTs+multiplies (exploiting the $O(nlogn)$ efficiency rather than the full $O(n^2)$ performance of a full cross-correlation.) and were distributed across the 12 cores.

The signal processing was complete in 13 ms, 8 ms of which were for the large FFT computation. That 8 ms can be compared to the 20 ms needed by the standard built-in LabVIEW function.

GPU Implementation

GPU's can be used to accelerate the signal processing by performing the computationally intensive parts of the application on a GPU. The signal processing benchmark executed on a NVIDIA Tesla C2070 GPU using NIVIDA's CUFFT library based on CUDA [6]. Although a majority of the GPU-based execution was spent in data transfers, it still outperformed the multi-core CPU solution. This is due to the exceptional FFT performance of the CUFFT library on the NVIDIA GPU hardware. For example, the large FFT operation on the GPU took 150 µs compared to the CPU's 8 ms time for the same operation.

Even though data transfers dominated execution time, the GPU benchmark represents a conservative estimate of that solution deployed in the real system. Larger than necessary data sizes (512K versus 5K) and data elements (floats versus integers) were used.

ONGOING AND FUTURE WORK

Quench Simulation Work

In conjunction with benchmarking and coil development an extensive simulation program will be pursued. The simulation work will provide the safe operating parameters for various coil scenarios using a 3D multi-scale COMSOL-based models [7], this work will guide the final timing and resolution demands of the protection system.

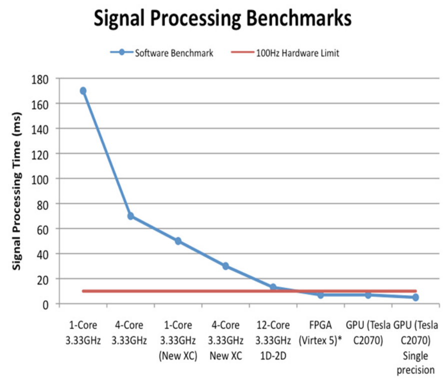

Figure 2: Summary of benchmarking studies. nb/ GPU timing assumes Correlate/Max is performed on the GPU also.

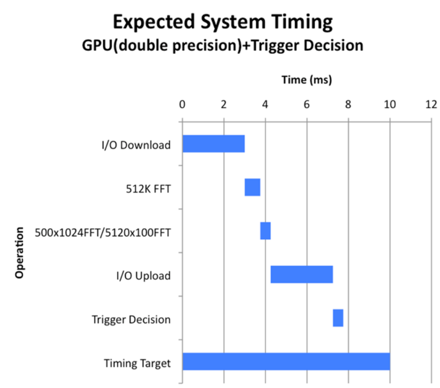

Figure 3: Details of GPU benchmark timing assuming Correlate/Max is performed on GPU (double precision). Splitting the trigger algorithm implementation across multiple CPU cores can further optimize the time taken to make the trigger decision.

The simulation effort will build a fully-coupled (electro-magneto-thermo-structural) coil model. The odel will be used to perform the following simulation effort.

Study impacts of variations in conductor and coil architectures on the necessary spatial and temporal resolutions for quench detection and protection performance. This is motivated by the fact that a few design parameter changes in a conductor or a coil can dramatically change the quench behavior and stability of a coil, thereby also the required performance of a quench detection and protection system.

Assess the Lorentz and thermal strains as functions of location and temperature. These functions will be used to decouple strain from temperature. This effort is motivated by the fact that the effect of strain on Rayleigh scattering is difficult to distinguish from that of temperature. An effective quench detection algorithm must be able to factor out the strain effect from temperature. This is especially true in the case of monitoring a ramping coil. This effort will progress synergistically with the performance signal processing to ensure that decoupling

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is optimized for both computing performance and quench detection sensitivity.

High Performance Signal Processing

One of the major thrusts of future experimental work will be to move from benchmarking the signal processing to building and commissioning the demonstration system. Based on the signal processing benchmarking results the technology of choice for our application is a GPU based system. The LabVIEW GPU Analysis Toolkit will play the central roll in the demonstration system. In addition to moving to a GPU based signal processing chain, the level of jitter will be studied. While one can impose hard real-time behaviour on CPU based systems with LabVIEW real-time it is not currently possible with GPUs and therefore will need further investigation.

The potential for further optimizations will also be studied. An example of a potential optimization is the use of single precision instead of double precision in the signal processing. This reduces the processing time significantly (Figure 4). The impact on sensitivity needs to be studied.

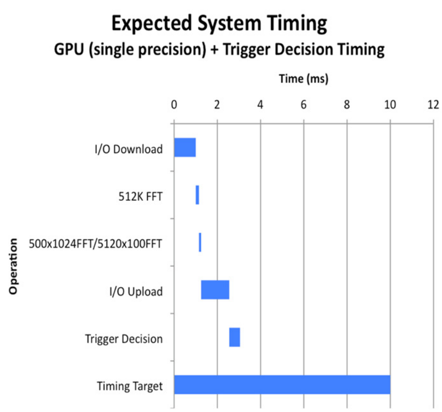
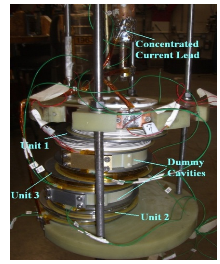


Figure 4: Details of GPU benchmark timing assuming Correlate/Max is performed on GPU (single precision). One can see using single precision provides significant performance gains over the use of double precision.

Coil Development

Technology demonstrations will be performed on a series of coils that grow in complexity and size. Tests in high background fields will also be studied. Figure 5 shows a layer wound solenoid with fibers ready to be tested. The test coils will be crucial for the validation of the strain and temperature effect decoupling scheme.

One of the more novel coil configurations that will be used for demonstrating the technology will be a helical solenoid. Helical solenoids are the basis of Helical Cooling Channels (HCC). HCCs have been proposed for 6D cooling of muon beams. It is based on a continuous absorber and RF cavities imbedded into superconducting magnets that superimpose solenoid, helical dipole and helical gradient field components. The HCC for a muon collider is divided into several sections, each section with progressively stronger fields, smaller aperture and shorter helix to achieve the optimal muon cooling rate. The final section of HCC require 17-20 T and therefore requires the use of HTS.



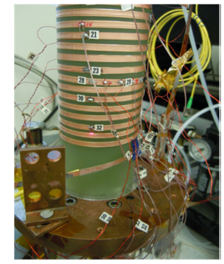


Figure 5: 3 T, six coil, short section of helical solenoid (YBCO). (left) and a test coil with fibers and quench heaters (right).

Recently (2011) a YBCO based 3 T, 6 coil, helical solenoid short model was fabricated and tested by Muons, Inc. and Fermilabs Technical Division [8]. At the time of fabrication and testing the coils were protected with voltage taps. One of the goals of the current project is to demonstrate the protection of the helical solenoid using a Rayleigh scattering based quench detection system.

The short section of helical solenoid will be re-built with fibers co-wound with the conductor. Quench heaters will be included in the rebuild to allow for both the detailed study of quench development in the coil and a comprehensive demonstration of Rayleigh scattering based quench detection in complicated coils. The proposed technology demonstrations will provide a path toward using YBCO in high-field accelerator magnet systems. The use of YBCO in accelerator magnet systems will be an enabling technology for many next generation facilities, especially those that require muon cooling, such as a muon collider.

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