# A hybrid data acquisition system for magnetic measurement of accelerator magnets*

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## Abstract

A hybrid data acquisition system was developed for magnetic measurement of superconducting accelerator magnets at LBNL. It consists of a National Instruments dynamic signal acquisition (DSA) card and two Metrolab fast digital integrator (FDI) cards. The DSA card records the induced voltage signals from the rotating probe while the FDI cards records the flux increment integrated over a certain angular step. This allows the comparison of the measurements performed with two cards. In this note, the setup and test of the system is summarized. With a probe rotating at a speed of 0.5 Hz, the multipole coefficients of two magnets were measured with the hybrid system. The coefficients from the DSA and FDI cards agree with each other, indicating that the numerical integration of the raw voltage acquired by the DSA card is comparable to the performance of the FDI card in the current measurement setup.
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## Contents

# 1 Introduction

Magnetic field quality is one of the critical design parameters for accelerator magnets. Stringent requirement on field harmonics has to be applied to ensure the desired particle dynamics. To provide feedback on magnet design, magnetic measurement is performed to determine the actual field and its harmonics. A typical measurement involves certain coil windings rotating in the magnet bore. The induced voltage at the terminal of the rotating probe is converted to flux from which the field harmonic coefficients are determined and compared to the design values. More details about the magnetic measurement and data reduction procedure can be found in [1–3].

To minimize the effect of probe rotation speed, a voltage integrator is usually used in a magnetic measurement system. In this case, the integration is done by the integrator during the measurement and the resulted flux increment data is used for analysis. A fast digital integrator has been developed at CERN [4]. The technology was commercialized and integrators called FDI 2056 are available from Metrolab. The data acquisition system at the Superconducting Magnet Program (SMP) adopted a different approach by recording the probe voltage and the encoder signals. The integration is done by software as part of the data postprocessing. Thus, the comparison between the performance of the integration based on software and hardware is necessary. To facilitate such a comparison, a hybrid system consists of both fast digital integrators and raw voltage acquisition cards was developed. In this note, we summarize the setup of the hybrid system, followed by a comparison of the measured field harmonic coefficients based on software and hardware integration methods.

# 2 System implementation

## 2.1 Typical measurement scenarios

There are two typical measurement scenarios where the hybrid system can be used. One is to scan the field along the magnet bore with a constant magnet current. Another measurement is to fix the probe position, e.g., at the magnetic center, and take measurements while the magnet current changes. In both cases, the probe rotates continuously while the data is being acquired. The encoder pulse train is always available due to the continuous rotation of the probe.

## 2.2 Existing system

The hybrid system is based on the existing SMP magnetic measurement system. The existing system consists of several components including (1) mechanical drive system (e.g., motor, harmonic drive, encoder and drive shaft), (2) rotating probe and (3) data acquisition. The induced voltage signals, after being amplified, are digitized by a National Instrument (NI) DSA 4472B PXI card. To perform a numerical integration over a certain angular interval, the encoder signal (index and quadrature signals) are also digitized by the DSA card. The magnet current and probe temperature are measured using an NI 6221 card. During the measurement, the probe is rotating continuously and 4096 pulses are generated by the encoder every revolution. The index signal of the encoder marks the start (and end) of the probe revolution. It also triggers the digitizing and storage of the probe voltage and the encoder signals. Both cards are stored in a PXI chassis and communicate with a host PC through a PCI MXI card. The DSA card digitizes the 8 input channels simultaneously with a resolution of 24 bits (with 1 bit for sign). The sampling frequency of the DSA card is 102.4 kHz.

The whole system is controlled by a LabWindows/CVI program running on a PC (Dell Optiplex 960, 4 GB RAM, O/S Windows 7 Professional 32-bit). More details about the system can be found in [5].

## 2.3 Fast digital integrators

Two fast digital integrator (FDI) cards are loaned from GMW Associates and Metrolab. Each card has one input channel triggered by an external TTL signal. Selectable gains range from 0.1 to 100 with onboard calibration. The maximum sampling rate is 500 kHz with a resolution of 18 bits. The number of the trigger signal must be a power of 2 up to 8192. The same trigger signal can be daisy-chained to multiple FDI cards. The FDI integrates the input voltage $V(t)$ over the time interval between two consecutive trigger pulses ($t_0$ and $t_1$) and generates one partial integration data ($Vs$), i.e.,

$$Vs = \int_{t_0}^{t_1} V(t)dt. \quad (1)$$

Note that the minus sign, necessary for magnetic flux, is *not* present in Eq. (1). The output may contain both the partial integration and the time interval for each integration in terms of tick number of an internal

20 MHz time base. More details about the FDI card can be found in [6].

## 2.4 Synchronization of data acquisition

The induced voltage of a centered probe rotating in a constant magnetic field is expected to be identical every revolution. The actual setup, however, may not be ideal due to many reasons, e.g., the mechanical behavior of the rotating coil and the stability of the magnet current. Thus, the synchronized acqusition is necessary to compare the data from different acquisition cards. All cards should acquire the data from the same revolution of the probe and preferably start the acquisition simultaneously. The compensated measurement also requires a simultaneous acquisition of both unbucked and bucked signals. In this section, we address the sychronization between NI 6221, 4472B, and FDI 2056 cards. Table 1 lists the data and trigger source for each card.

While the data acquisition of NI6221 and 4472B cards can be triggered and completed every revolution in the existing measurement system, it takes about 2 revolutions' time ($\sim$ 4 s) to download the data from the FDI 2056 cards with 4096 encoder pulses per revolution. This has several implications for synchronizing three acquisition cards.

1. The acquisition of both NI 6221 and 4472B should be started together with the FDI 2056 cards.
2. Both 6221 and 4472B use finite instead of continuous sampling. Once the acquisition for one revlution is completed, both cards should stop the acquition and hold the data until they are downloaded to the host computer.
3. With the finite sampling mode, the measurement tasks for 6221 and 4472B must be started and stopped every measurement cycle as they are not retriggerable.

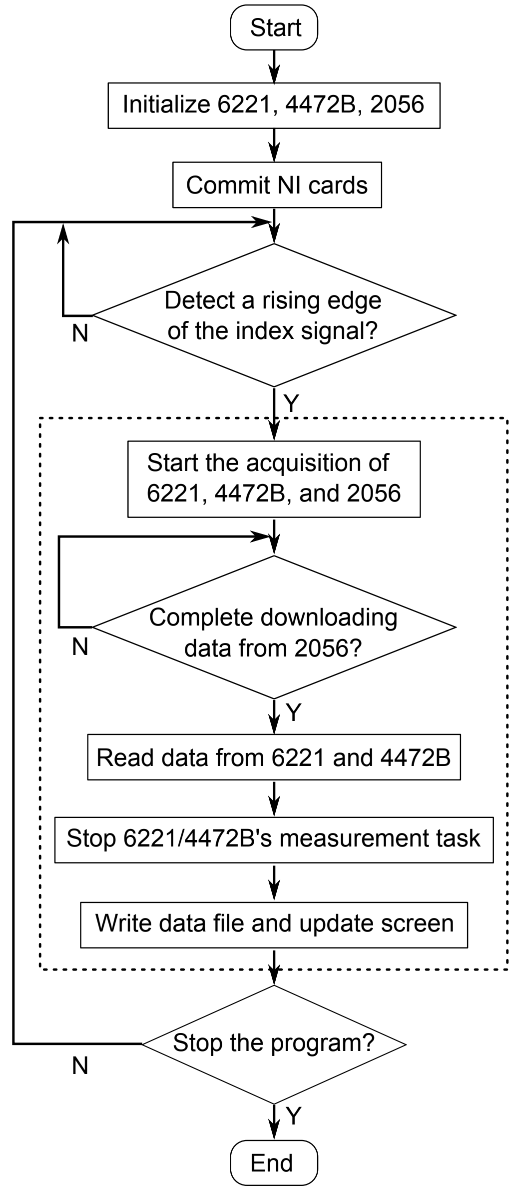


Figure 1: Data acquisition flow chart for the hybrid system.

Figure 1 shows a flow chart for the data acqusition of the hybrid system. The index signal of the encoder is used to start the acquisition of all three cards. A dedicated digital input line of NI 6221 continuously monitors the index signal. When the rising edge of an index signal is detected, a `DetectionChange` event is generated. As a reponse to the event, a callback function (bounded by the dashed line in Fig. 1) for the data acquisiton of one revolution is execuated. The program continues detecting the next available rising edge of the index signal and acquiring the data for another revolution until the user stops the program.

During the initialization, the measurement task and its parameters are set for each card. NI 6221 card measures the magnet current and the probe temperature. The measurement is triggered by the rising edge of the lead signal of the encoder. Thus, NI 6221 samples at $\sim$ 2.05 kHz if the probe rotates at 0.5 Hz. The acquisition will be started by the falling edge of the index signal.

For NI 4472B, the index signals marking the start

Table 1: Data acquisition cards used in the hybrid system.

| Card | Input | Trigger source |
|---|---|---|
| NI 6221 | magnet current, probe temperature | quadrature signal |
| NI 4472B | probe voltage, encoder signal | on-board clock |
| FDI 2056 | probe voltage | quadrature signal |

and end of a revolution is recorded so that the post-processing program can identify all the quadrature pulses within two index signals for the numerical integration of the voltage signals. A useful data set recorded by NI 4472B must contain two index signals. One edge per index signal with the same polarity is sufficient. Since the rising edge of the first index signal is used to generate the `ChangeDetection` event and is missed by all three cards, the falling edge of the first index signal must be recorded by NI 4472B. For the same reason, the falling edge of the index signal is specified as the reference trigger for the measurement task of NI 4472B. The number of pretrigger sample is set to a minimum number of 2. It was found that a pretrigger number larger than 10 causes the 4472B to miss the current revolution and record the signal from the next revolution. This is due to 1) the filter delay of the NI 4472B [7], 2) the mechanism of the reference trigger [1] and 3) the time interval between the rising and falling edge of the index signal.

Here is a closer look at the callback function (bounded by the dashed line in Fig. 1). As the first step, the callback function explicitly initiate the measurement of all three cards in sequence with the following code.

```
DAQmxStartTask (NI_6221_DAQ);
DAQmxStartTask (NI_4472B_DAQ);
multiple_fdi_start_measure (FDI_cards);
```

After line 1 is execuated, NI 6221 is armed and waits for the coming falling edge of the index signal to start the acquisition. After line 2 is executed, 4472B starts the acquisition of the pretrigger samples. Once the falling edge arrives, NI 4472B starts the posttrigger acqusition. Thus, the acquisiton of both NI cards are well-defined with respect to the falling edge of the index signal.

It is less defined for the FDI cards regarding their acquisition with respect to the reference signal. Line 3 in the above codes is a function call, which is a `for` loop (complete code is listed in § A).

```
for (i = 0; i < FDI_num; i ++) {
    start FDI[i];
}
```

Note that the FDI cards start sequentially resulting in a time delay between the cards. For two cards, the delay is negligible. For the synchronization between a larger number of cards, a simultaneous acquisition based on a common trigger signal is necessary. Figure 2 illustrates the first and the last data points of three cards with respect to the index signals in one revolution.

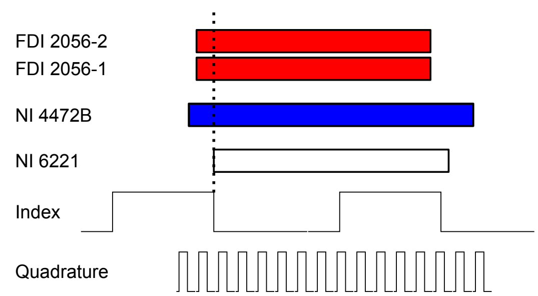


Figure 2: The first and last acquired samples of three cards in one revolution, implemented in the hybrid system.

Now let us turn to the synchronization of individual channels. NI 6221 detects a falling edge of the quadrature signal, it reads the magnet current and then the probe temperature. Thus, the acquired current and temperature data align with the quadrature signal on the time scale. The time difference between the magnet current and probe temperature is neglected. The voltage integration of both FDI 2056 cards is triggered by the same quadrature signal as that of the NI 6221. Thus, the output of each FDI 2056 card should be synchronized. An issue related to the onboard clock will be discussed later.

The induced voltage signals and the encoder signals are simultaneously recorded by NI 4472B. A postprocessing program identifies the edges of the recorded quadrature signal and thus synchronize the resulted integration of selected voltage input.

In summary, the data acquisition of the two NI cards are synchronized based on the falling edge of the index signal. The acquisition between two FDI

[1] Only when the specified number of pretrigger samples are acquired, NI 4472B starts looking for the reference trigger. [7]

cards is also synchronized as they share the same trigger signal. Since the acquisition of both FDI cards are initiated by the software, there is a phase/time difference between the acquisition of the NI 4472B and the two FDI cards. This is an open issue.

## 2.5 Hardware and software

Similar to the existing SMP system, all PXI cards are installed in one chassis communicating with the host PC through the existing PXI control card (MXI 8331). Figure 3 shows a diagram illustrating the connection and a picture of the hybrid system is shown in Fig. 4. Due to the size of the FDI card (6U), an NI 1056 3U/6U dual stack chassis is used. The reference trigger signal, the index signal, is wired to PFI0 ("External Trigger") of 4472B. The start trigger signal, the index signal, is wired to PFI5 of the NI 6221.

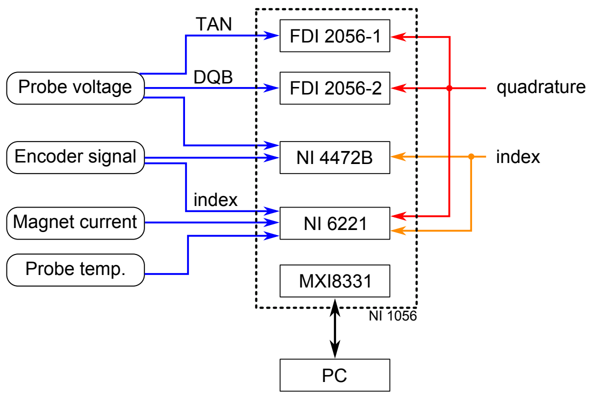


Figure 3: A diagram of the hybrid system wiring.

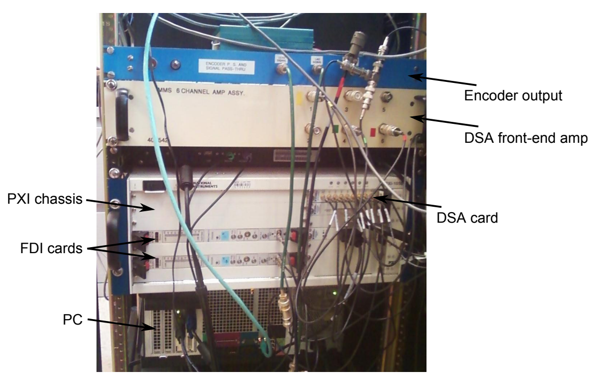


Figure 4: A picture of the hybrid system.

The acquisition program is written in LabWindows/CVI version 9 running in the same environment as the existing system.

# 3 System behavior verification

In this section, we report the verification of the system behavior, especially the synchronization between the data acquisition cards by comparing the phase and amplitude of the acquired waveforms of the same input signal.

## 3.1 Protocol

A sawtooth signal with a period of $\sim 5$ s was fed to all the acquisition cards. This input signal leads to different waveforms of two consecutive probe revolutions as it doubles the period of the probe rotation. NI 6221 and 4472B directly record the input voltage. The acquired FDI 2056 data is the partial integration of the voltage input, as shown by Eq. (1). If $V(t)$ varies little over the time interval $\Delta t = t_1 - t_0$, we have

$$Vs = \int_{t_0}^{t_1} V(t)\, dt \approx V(t_0)\Delta t. \qquad (2)$$

The time interval between two quadrature signals, $\Delta t$, can be considered constant assuming a relatively constant rotation speed of the probe. Thus, the partial integration data generated by FDI 2056 cards is proportional to the input voltage. Then the partial integration data can be converted back to voltage according to Eq. (2) given $\Delta t \approx 0.5$ ms in our setup.

## 3.2 Synchronization between NI 4472B and FDI 2056

Let us first check the synchronization between NI 4472B and FDI 2056. Figure 5 shows the voltage reading of both cards from two measurement cycles, cycle #8 and #14, with *10* pretrigger samples for NI 4472B. If FDI 2056 recorded the voltage corresponding to revolution #8, then the waveforms shown in Fig. 5 indicate that NI 4472B recorded the voltage from revolution #9, the next revolution to #8. FDI2056 and NI 4472B were not synchronized.

In addition, the recorded index signal waveform contains two rising edges, confirming the lag of NI 4472B as the acquisition is supposed to be started after the first rising edge is detected. One possible reason for this observation is that 4472B did not acquired the required 10 pretrigger samples before the reference trigger (falling edge of the index signal) arrived. It then neglected the reference trigger to continue filling the pretrigger pool until the next reference trigger came in the next revolution. By reducing the pretrigger sample number from 10 to 2, NI 4472B

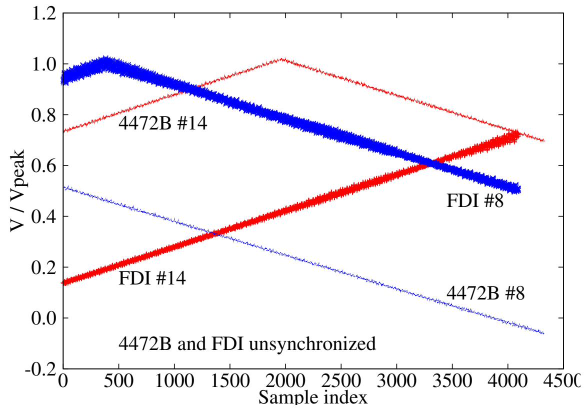


Figure 5: With a pretrigger sample of 10, NI 4472B lags FDI 2056 one revolution. Blue curves are for measurement cycle #8 and red curves for cycle #14.

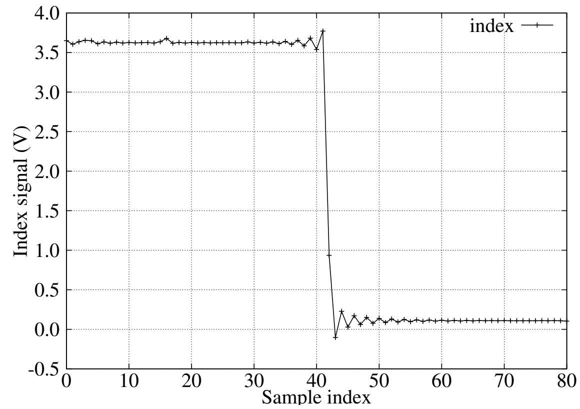


Figure 7: The recorded encoder index signal (the first 80 samples) from measurement cycle #5 by NI 4472B in Fig. 6. There are $\sim 40$ pretrigger samples due to the filter delay ($\sim 0.4$ ms) when the sampling frequency is 102.4 kHz.

and FDI 2056 acquired the voltage signal from the same probe revolution (Fig. 6).

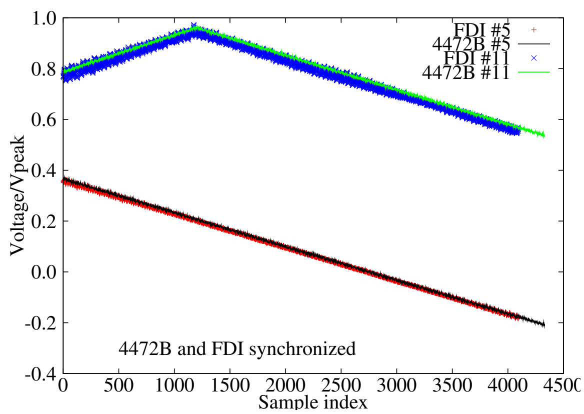


Figure 6: After reducing the pretrigger sample number from 10 to 2, NI 4472B matches FDI 2056.

Figure 7 shows the index signal recorded by NI 4472B in a synchronized case. Even though the number of the pretrigger sample is 2, there are still $\sim 40$ pretrigger samples shown in the recorded data. This is due to the filter delay [7].

### 3.3 Synchronization between NI 4472B and 6221

The acquisition of NI 6221 is initiated by the falling edge of the index signal. This falling edge is also the reference trigger for the acquisition of NI 4472B. Thus, we expect the waveforms acquired by both cards overlap. It was found that the synchronization of two NI cards depends on where the `DAQmxStartTask(NI_6221_DAQ)` command for NI 6221 is located in the program (§ 2.4). NI 6221 lags NI 4472B when the `DAQmxStartTask(NI_6221_DAQ)` command is executed after the FDI 2056 cards are initiated (Fig. 8). This indicates that the start trigger

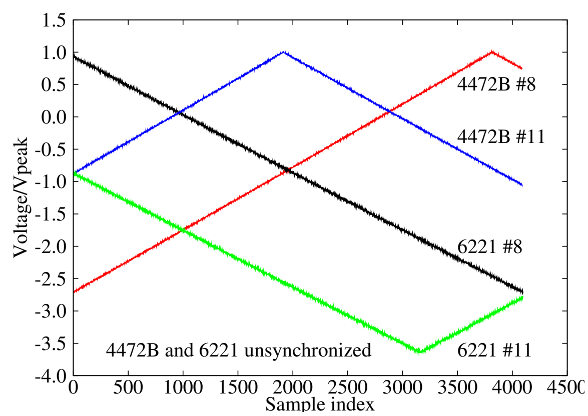


Figure 8: NI 6221 lags NI 4472B one revolution when it is started after the FDI cards.

for NI 6221 arrived during the initiation of the FDI cards and NI 6221 had to wait for the next start trigger that was one revolution later. When NI 6221 was started before FDI cards (§ 2.4), the same waveform was recorded by both NI cards (Fig. 9).

Now NI 6221, 4472B and FDI 2056 sample the input signals from the same revolution of the probe.

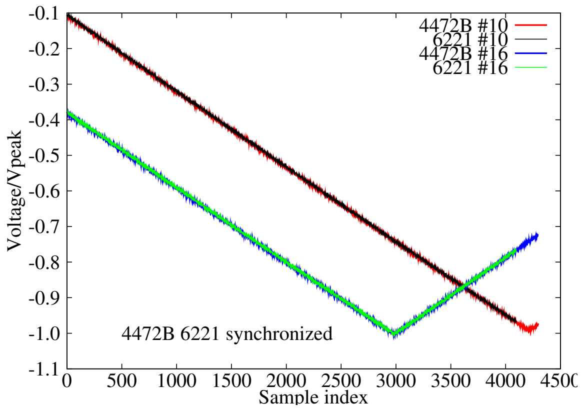


Figure 9: NI 6221 and 4472B synchronize when their acquistion is started in a certain sequence.

### 3.4 Synchronization between FDI 2056

The FDI 2056 cards used in the current hybrid system are all triggered by software commands. The original C function `fdi_start_measure` starts the measurement for only one FDI card [8]. Using a `for` loop, one can start the measurement of multiple cards without modifying the function. Figure 10 shows the acquired signals of two FDI cards started by this method. One sees that both FDI cards sampled

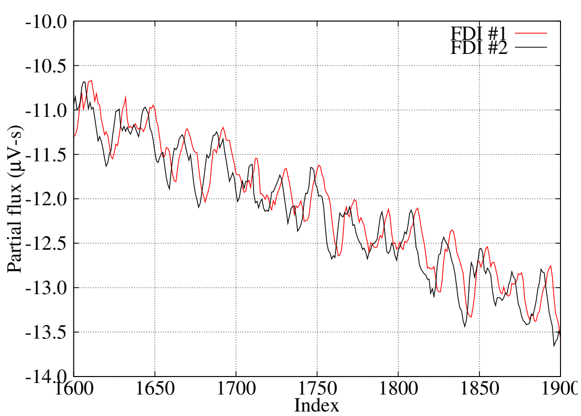


Figure 10: There is a time delay between two FDI cards when they are started using the original C function `fdi_start_measure` within a `for` loop.

the same input voltage signal but FDI #2 started $\sim$ 5 samples after FDI #1, i.e., 3 ms. This is due to the multiple operations involved in the original `fdi_start_measure` function, e.g., `fdi_get_gain` and `fdi_wait_for_meas_status`. To minimize the delay, the function was modified by embedding the `for` loop, as shown in § A.2. Figure 11 compares the amplitude ratio between the recorded waveforms by two FDI cards before and after the modification of the function. The oscillation (red line in Fig. 11) was due to the delay of one card. A ratio of $\sim 1$ is expected when the acqusition starts at the same time for both cards (black line in Fig. 11).

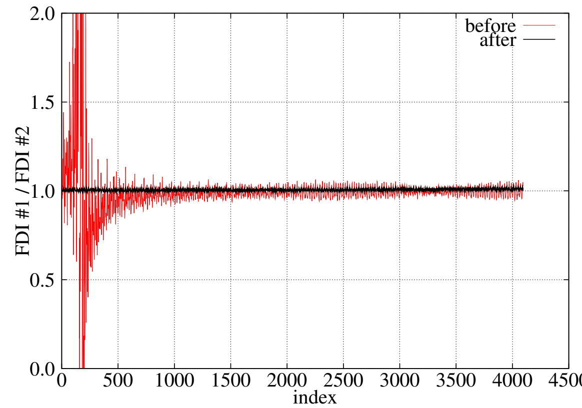


Figure 11: Amplitude ratio of the waveforms acquired by two FDI cards before and after the function modification.

The absolute timestamp at each trigger is part of acquired data from FDI cards. It is a 32-bit integer based on the 20 MHz onboard time base [6]. Since both FDI cards share the same trigger signal, we expect a constant difference between the timestamp data from both cards at each trigger. In reality, the absolute tick count of the onboard time base is slightly different (Fig. 12). The difference becomes larger as the probe rotation speed decreases. At a typical rotation speed of 0.5 Hz, an accumulated 8 counts of difference occurred at the end of the rotation, corresponding to 400 ns in time and 1.26 $\mu$radian in angle, which can be neglected. The difference is possibly due to the individual time base on the FDI cards. To minimize the tick count difference, a common time base shared by all FDI cards may be necessary.

On the other hand, the time duration for each partial integration recorded by two FDI cards are almost identical. The duration, $\Delta t$, is the difference between two recorded absolute timestamps. Figure 13 compares the $\Delta t$ of both cards during one revolution. A linear fit with a unit slope indicating $\Delta t$ for both cards are identical. This is necessary for the compensated measurements where multiple FDI cards are required.

One also sees that the angular rotation speed is not

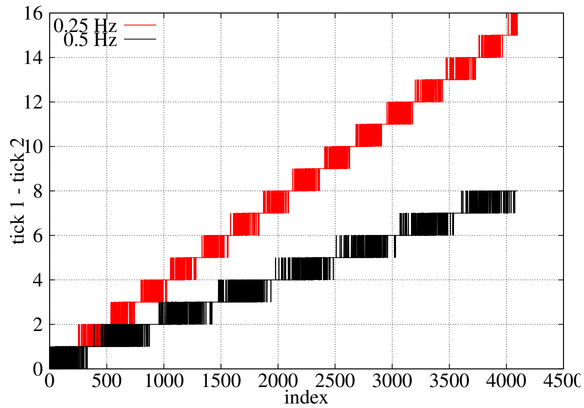


Figure 12: Timestamp difference between two FDI cards at different probe rotation speeds.

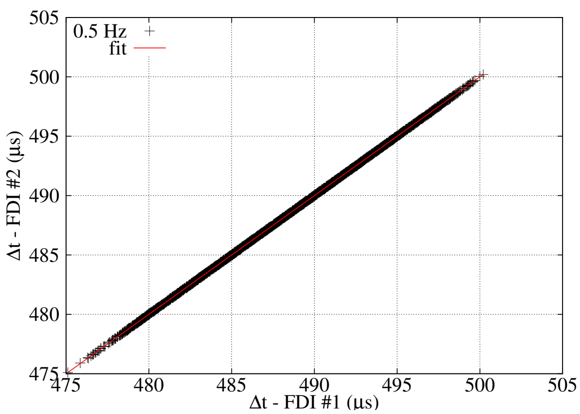


Figure 13: Time duration for each partial integration of both cards are almost identical. Data is from Fig. 12.

uniform, varying about ±2.5% around the nominal $\Delta t$ of 488 $\mu$s.

## 3.5 Downloading data from FDI 2056

Data are downloaded from two FDI cards every measurement cycle. The data from each card are divided into four blocks. The program reads the same block from both cards and then the next block until all four blocks from both cards are retrieved. The attempt to read all blocks from one card and then the next card failed in our test. Data from every three rotations was recorded as it took two rotations ($\sim$ 4 s) to download the data from two FDI cards with 4096 encoder pulses.

# 4 Measurement of two magnets

The previous section verifies the synchronization between all three data acquisition cards. In this section, we compare the multipole coefficients of two magnets measured by the hybrid system. One is a reference quadrupole magnet made by permanent magnets measured at room temperature. It is an SSC series 300 reference magnet provided by Fermi National Accelerator Laboratory (FNAL). It has a bore diameter of 50 mm and a thickness of 25 mm (Fig. 14).

Figure 14: A reference quadrupole made by permanent magnets (SSC 300 series) provided by FNAL. Bore diameter 50 mm.

The other magnet is HQ01d, a $Nb_3Sn$ quadrupole magnet, measured at 70 K with a constant current of 30 A.

## 4.1 Setup and measurement protocol

A circuit-board rotating probe, developed by FNAL [9], was used. The probe has two radial coil assemblies; one is 100 mm long and the other 250 mm long. Each coil assembly has three voltage outputs, i.e., unbucked (UB), dipole-bucked (DB) and dipole-quadrupole-bucked (DQB) signals. They were amplified by onboard amplifiers inside the probe during the measurement. The probe rotated at a speed of $\sim$ 0.5 Hz. All three voltage signals and the encoder signals were simultaneously acquired by the DSA card. Only the UB and DQB signals were acquired by the FDI cards.

For the permanent magnet, the 250 mm coil assembly was rotating at the magnet bore. The magnet was located at the middle of the coil assembly. Five measurements were taken. For the HQ01d measurement, the 100 mm coil assembly was used. Once the current was stabilized, the probe took measurements at different locations along the magnet bore. Five measurements (rotations) were taken at each location.

The averaged harmonics are reported with the error bars indicating the spread of the five measurements.

## 4.2 Observations

### 4.2.1 SSC reference quadrupole

The probe voltage signals were directly digitized by the DSA card, bypassing the front-end amplifiers of the DSA. The gain for the FDI cards were set to 1. Figure 15 compares the angular flux profile acquired by the DSA and FDI cards for one rotation. The difference between the two cards is less than 2% at the peak of the flux profile.

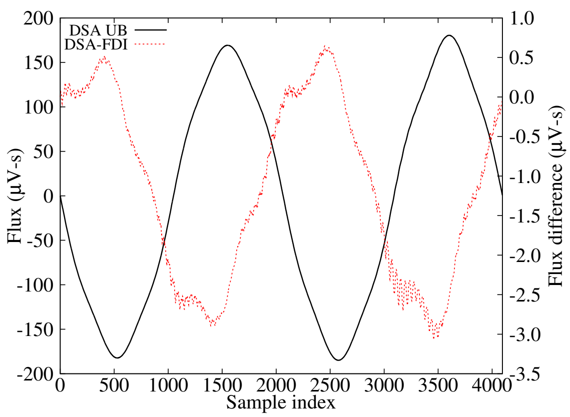


Figure 15: Comparison of the angular flux profile acquired by the DSA and FDI. The solid black line is the flux profile based on the UB voltage signal acquired by DSA (primary $y$ axis). The dotted red line is the difference of the UB flux between DSA and FDI (secondary $y$ axis).

The multipole coefficients normalized to the main field are shown in Fig. 16. The results of five measurements were close to each other, leading to the invisible error bars in Fig. 16.

### 4.2.2 HQ01d

The nominal gains used at each amplifier stage are listed in Table 2.

Table 2: Nominal gains for the voltage signals.

| Amplifier | UB | DB | DQB |
|---|---|---|---|
| Probe | 10 | 10 | 1000 |
| DSA | 1 | 1 | 1 |
| FDI | 100 | n/a | 50 |

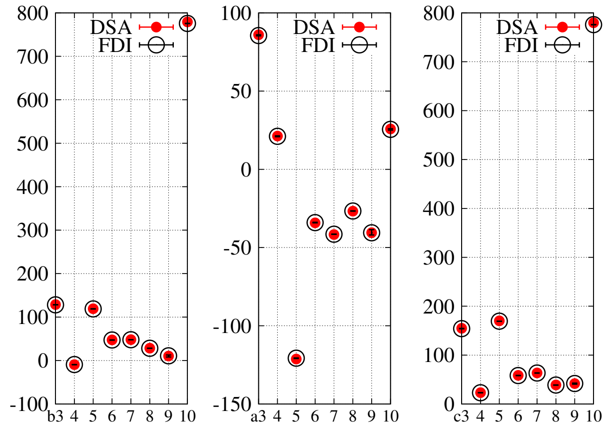


Figure 16: Normalized multipole coefficients of the reference quadrupole. $R_{\text{ref}} = 21.55$ mm. From left to right: $b_n$, $a_n$ and $c_n$.

The measured main-field transfer function along the bore is shown in Fig. 17. The UB signal is used in this case as DB signal was not recorded for the FDI card. The theoretical value was calculated with $I = 50$ A in an Opera 3D model.

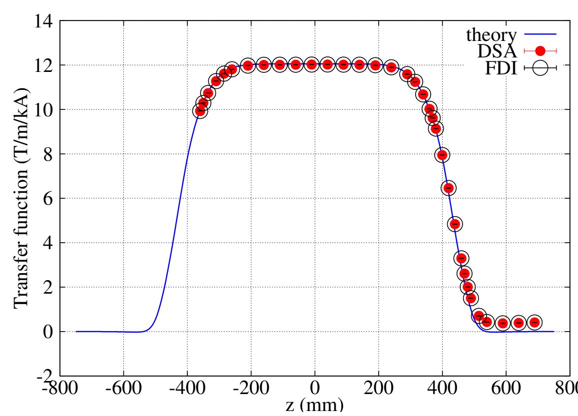


Figure 17: Axial dependence of main field ($B_2$) transfer function measured at $\sim 70$ K with $I = 30$ A using the 100 mm coil.

The five measurements taken at each location were close to each other, leading to the invisible error bars in Fig. 17. Typical variation of the measurements at each location is less than 0.03%. The measured data from DSA and FDI agree well. Typical difference is less than 0.1% for $z < 400$ mm and less than 0.3% for $z > 400$ mm.

Figure 18 compares the axial dependence of $b_6$ normalized to $B_2(z = 0)$. The data was reduced from the DQB signal.

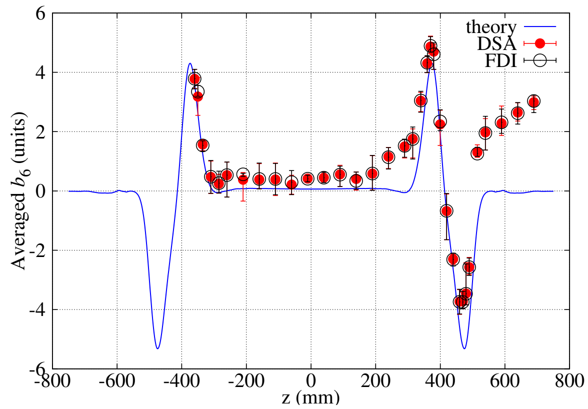


Figure 18: Axial dependence of $b_6$ measured at $\sim 70$ K with $I = 30$ A using the 100 mm coil. Results normalized to the central $B_2$. $R_{\mathrm{ref}} = 21.55$ mm.

Figure 19 shows the axial dependence of $b_{10}$ normalized to $B_2(z = 0)$. Due to the limited signal/noise ratio, the measured data spread around the calculated values.

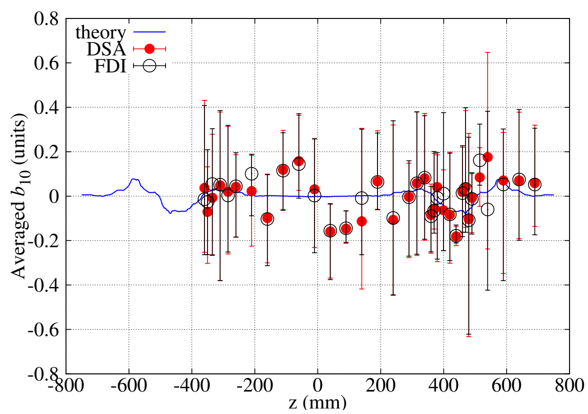


Figure 19: Axial dependence of $b_{10}$ measured at $\sim 70$ K with a current of 30 A using the 100 mm coil. Results normalized to the central $B_2$. $R_{\mathrm{ref}} = 21.55$ mm.

### 4.3 Comparison between DSA and FDI

Based on the observations from the measurement with two magnets, one sees that the data reduced from two methods are in excellent agreement in terms of both averaged values and their variation. This indicates that for the measurement scenario reported here, i.e., a probe rotation speed of 0.5 Hz vs. a 24-bit DSA sampling at 102.4 kHz (a factor of $2 \times 10^5$), the numerical integration based on the trapezoidal rule with linear interpolation between the recorded voltage data achieves a performance comparable to that of the 18-bit fast digital integrator sampling at 500 kHz. In HQ01d measurement, since the FDI cards used their front-end amplifier in addition to the onboard amplifier inside the probe (Table 2), the agreement between the DSA and FDI results suggests that the FDI gains were accurate.

## 5 Summary

A hybrid data acquisition system composed of a dynamic signal acquisition card and fast digital integrators was built and tested. The synchronization between multiple acquisition cards was analyzed. The multipole field coefficients of two magnets were measured with the hybrid system. The measurements compared the performance the numerical integration of the recorded voltage based the DSA card and the "hardware" integration based on the fast digital integrator. The agreement between the two methods indicates that the numerical integration based on DSA card is effective for the measurement involving static measurement with slowly rotating probes.

Due to the large number of encoder pulses, it takes a few probe rotations to download the data from the FDI cards. This may be improved with reduced number of encoder pulses, which will be studied in future magnet tests. The two FDI cards in the current setup was triggered sequentially by software. A hardware signal triggering simultaneous sampling of FDI cards will be useful for better synchronization between multiple FDI cards.

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# A Code

## A.1 Set up NI cards

The sampling clock for NI 6221's measurement task is the falling edge of the quadrature signal. The falling edge of the index signal starts the acquisition.

```
sampling_rate = ceil (PULSE_PER_TURN *
    z_freq);
DAQmxCfgSampClkTiming (phi_A_based_TH, phi_A
    ->src, sampling_rate, DAQmx_Val_Falling,
    DAQmx_Val_FiniteSamps,
    daq_6221_sample_per_chan);
DAQmxCfgDigEdgeStartTrig (phi_A_based_TH, "
    PFI5", DAQmx_Val_Falling);
DAQmxSetReadRelativeTo (phi_A_based_TH,
    DAQmx_Val_FirstSample);
```

NI 4472B is configured to sample with the on-board clock. The reference trigger is the falling edge of the index signal. There are two pretrigger samples. The first acquired data is the first pretrigger sample.

```
DAQmxCfgSampClkTiming (probe_TH, NULL,
    dsa_freq, DAQmx_Val_Rising,
    DAQmx_Val_FiniteSamps, sample_per_chan);
DAQmxCfgDigEdgeRefTrig (probe_TH, "/
    PXI1Slot4/PFI0", DAQmx_Val_Falling, 2);
DAQmxSetReadRelativeTo (probe_TH,
    DAQmx_Val_FirstPretrigSamp);
```

After the configuration of both NI cards are done, the measurement tasks are committed.

```
DAQmxTaskControl (phi_A_based_TH,
    DAQmx_Val_Task_Commit);
DAQmxTaskControl (probe_TH,
    DAQmx_Val_Task_Commit);
```

## A.2 Start the measurement of multiple FDI cards

The acquisition of the FDI cards are done by the following codes.

```
int x_fdi_start_measure (ViSession * instr,
    unsigned int fdi_ch_num)
{
  ViReal64 g = 0;
  ViUInt32 BufferWr = 0;
  ViStatus status = 0;
  unsigned int i;

  for (i = 0; i < fdi_ch_num; i ++) {
    status = (fdi_get_gain (*(instr+i), &g))
        ;
  }

  /* set the command buffer */
  BufferWr = STARTMEASURE;

  /* send the STARTMEASURE command */
  for (i = 0; i < fdi_ch_num; i ++) {
    status = viOut32(*(instr+i),
        VI_PXI_BAR2_SPACE, CMD_ADDRESS,
        BufferWr);
  }

  /* wait for the command to complete */
  for (i = 0; i < fdi_ch_num; i ++) {
    status = fdi_wait_for_meas_status (*(
        instr+i));
  }
  return status;
}
```

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