Measuring the Magnetic Field in Steel Using Flux Loops

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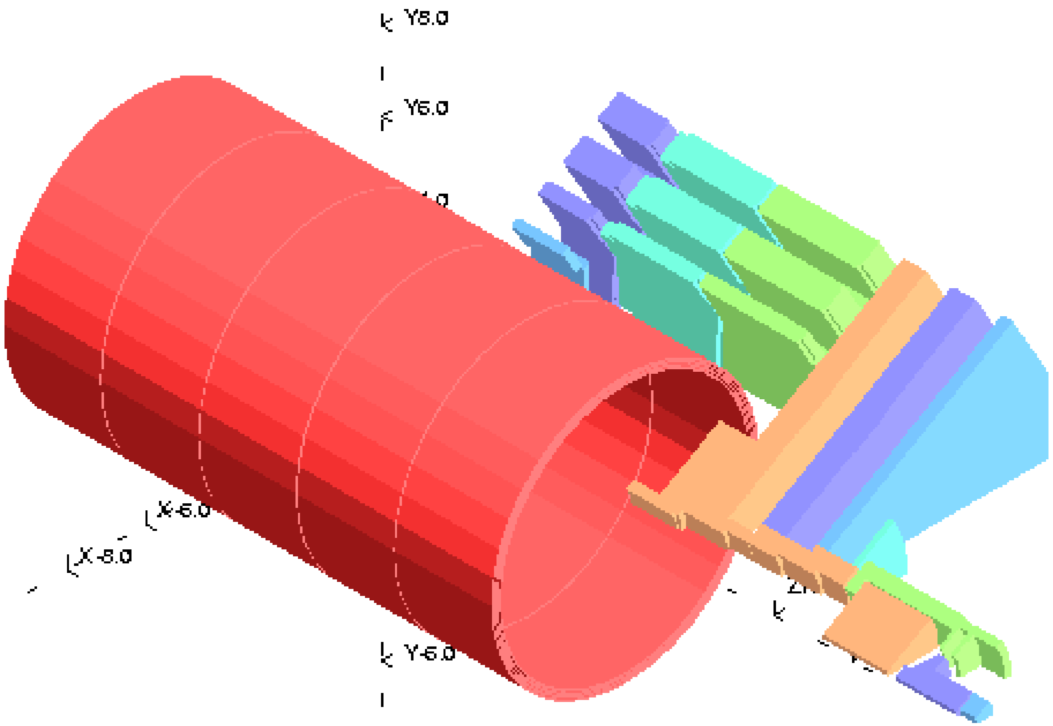
The CMS Magnetic System Model

The Compact Muon Solenoid (CMS) is a general-purpose proton-proton detector designed to operate at the CERN Large Hadron Collider. Its key feature is a 4 T superconducting solenoid encased in a 12-sided three-layered steel "barrel" with three-layered steel "end-caps", comprised of steel plates up to 630 mm thick, which return the flux of the solenoid and comprise the absorber plates of the muon detection system.

A three-dimensional magnetic field model of the CMS magnet has been prepared for utilization during the engineering phase of the magnet system, for early physics studies of the anticipated performance of the detector, as well as for track parameter reconstruction when detector operation begins.

The CMS Magnetic System Model



CMS Magnetic System Model Layout

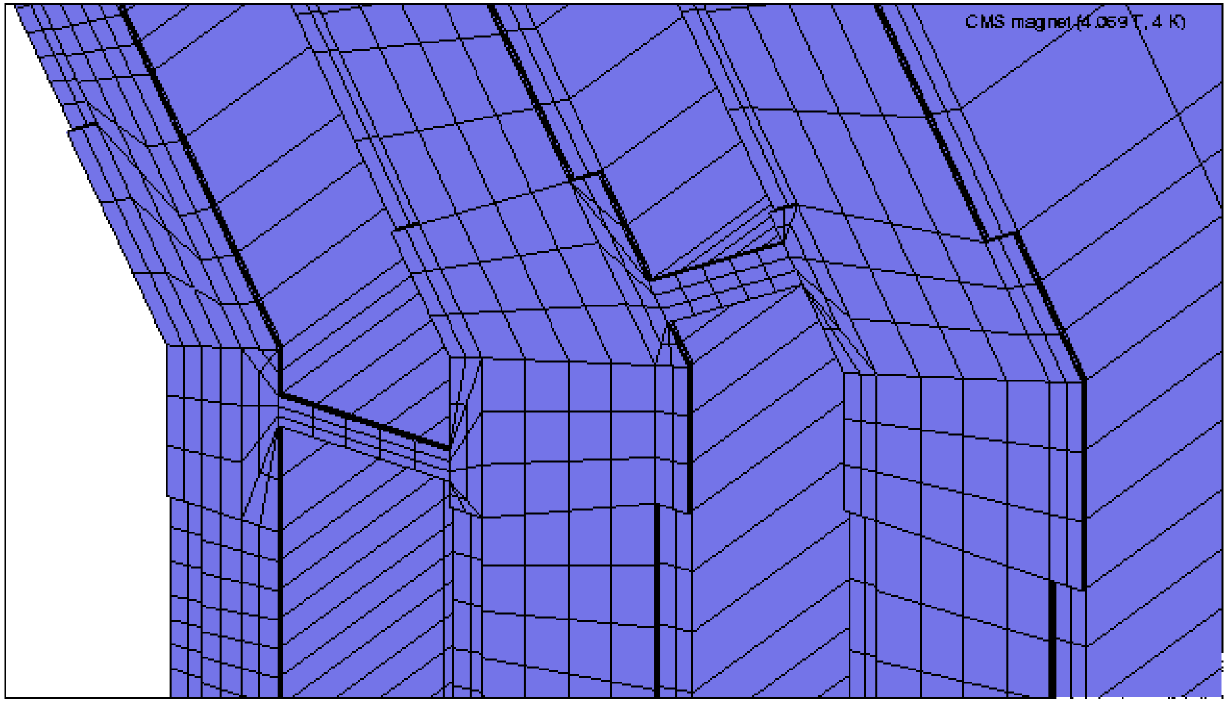
The CMS Magnetic System Model

The CMS magnetic system model consists of the superconducting solenoid coil and includes three different geometries for the 14 m diameter and 20 m long steel yoke of the muon system. The latter obtained by reflection about Z = 0 and symmetrizing an azimuthal segment subtending 30° to maximize the model precision.

The models of the yoke includes:

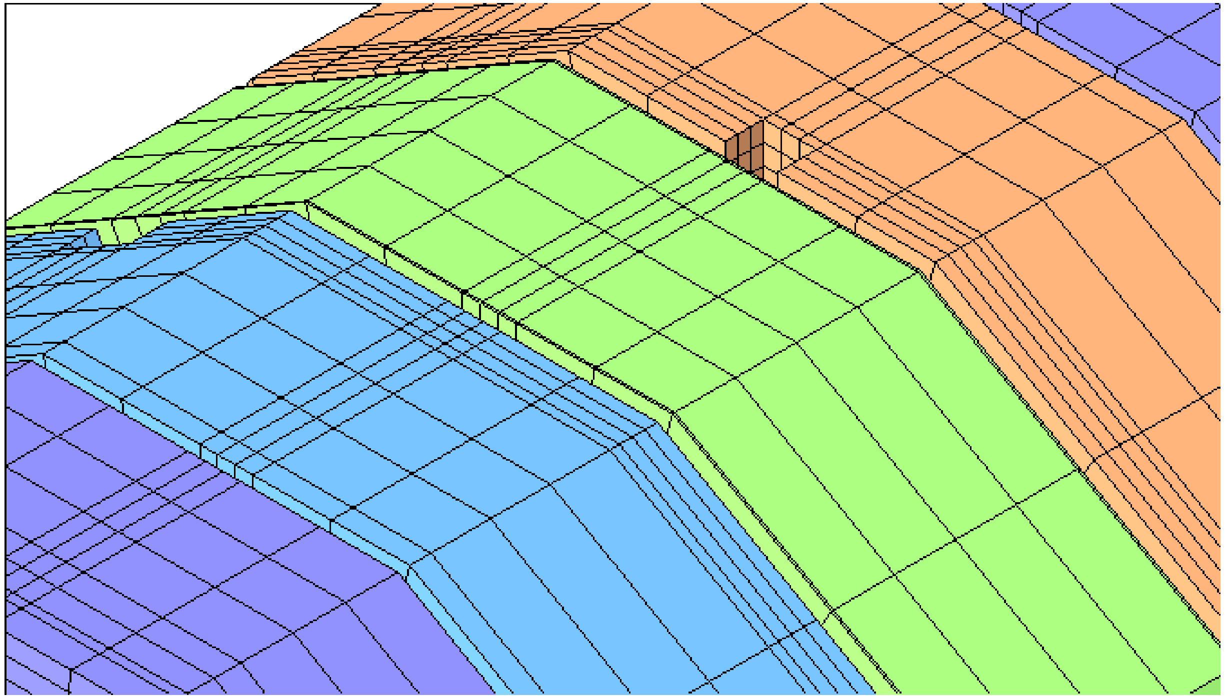
- **the barrel rings with recessed outer plates, connecting brackets and two chimneys;**
- **the asymmetric tail catcher;**
- **the nose disk;**
- **4 end-cap disks;**
- **the hadronic forward calorimeter ferromagnetic parts.**

The CMS Magnetic System Model



Brackets and the Recessed Plates View

The CMS Magnetic System Model



Layout of Chimneys

The CMS Magnetic System Model

The coil is modeled as 20 cylinders of current with dimensions corresponding to the positions of the superconducting cable in the winding layers when the coil is at cryogenic temperatures.

The radial thickness of each conducting cylinder is 20.63 mm.

The cylinders form 4 coaxial layers of current at internal radii 3174.93, 3240.06, 3305.19 and 3370.32 mm, and they are grouped in 5 axially separated modules spaced from one another by 45.86 mm.

Each module has a length 2443.76 mm and the overall axial length of the assembly is 12402.24 mm.

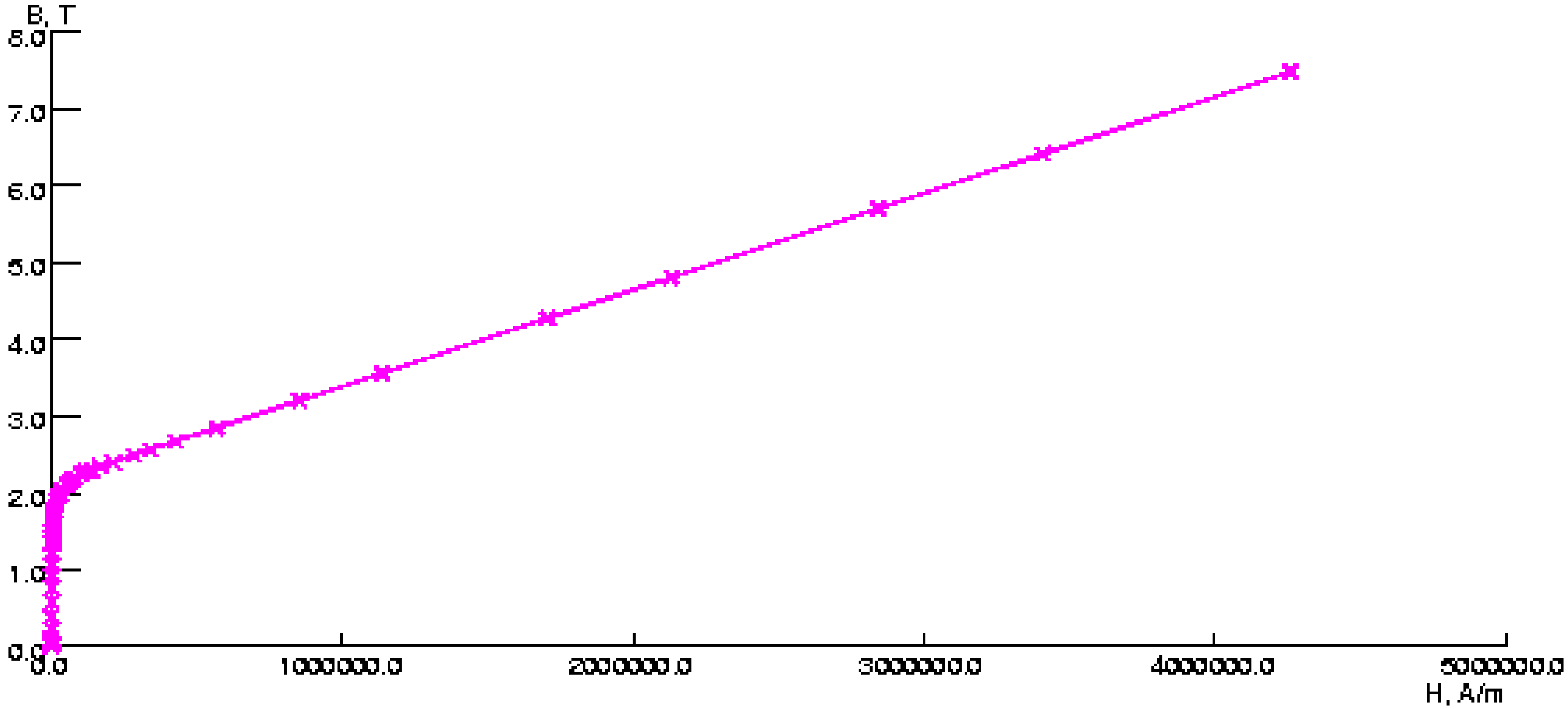
The CMS Magnetic System Model

The CMS magnetic system model is performed using the Vector Fields® code TOSCA and the Vector Fields OPERA-3d post-processor.

TOSCA represents the field with total and reduced scalar potentials (accommodating accurately regions exterior to current sources as well regions containing current sources) and the post-processor calculates the magnetic field strength from magnetization and current density sources.

The models rely on use of "averaged" permeability values measured in many samples taken from the muon steel plates.

The CMS Magnetic System Model



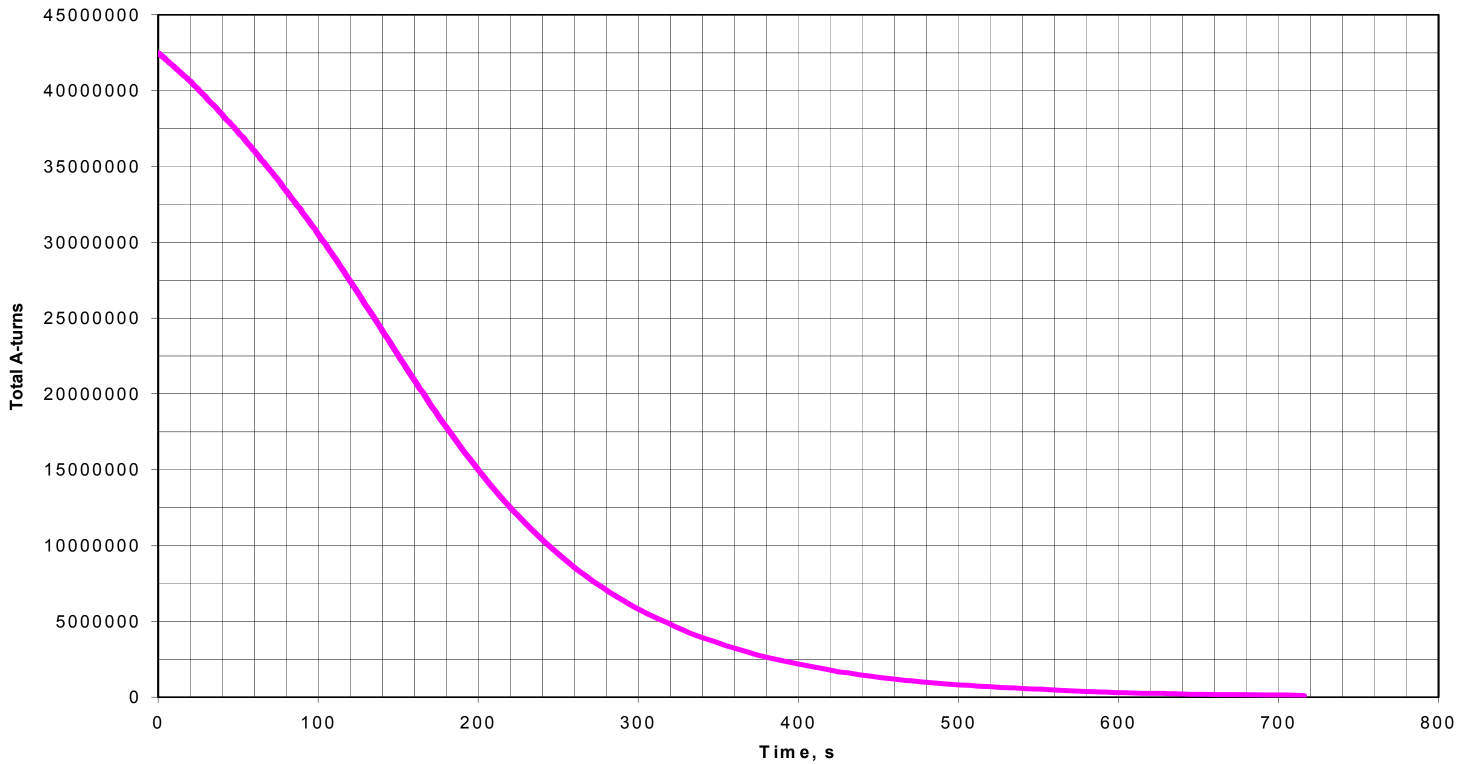
One of the B-H Curves Used

Modeling the CMS Fast Discharge

It is desirable to provide a direct measurement of the magnetic flux density in select portions of the muon steel to help reduce the uncertainty in the measurement of the momenta of muons which penetrate the steel.

For this purpose, multi-turn flux loops have been installed around select segments of the CMS muon steel yoke plates to permit the measurement of changes in the magnetic flux density induced in the steel when the field in the solenoid is changed. The rapid discharge of the solenoid (approximately 300 seconds time constant) made possible by the protection system of the superconducting solenoid will induce significant voltages in the flux loops.

Modeling the CMS Fast Discharge



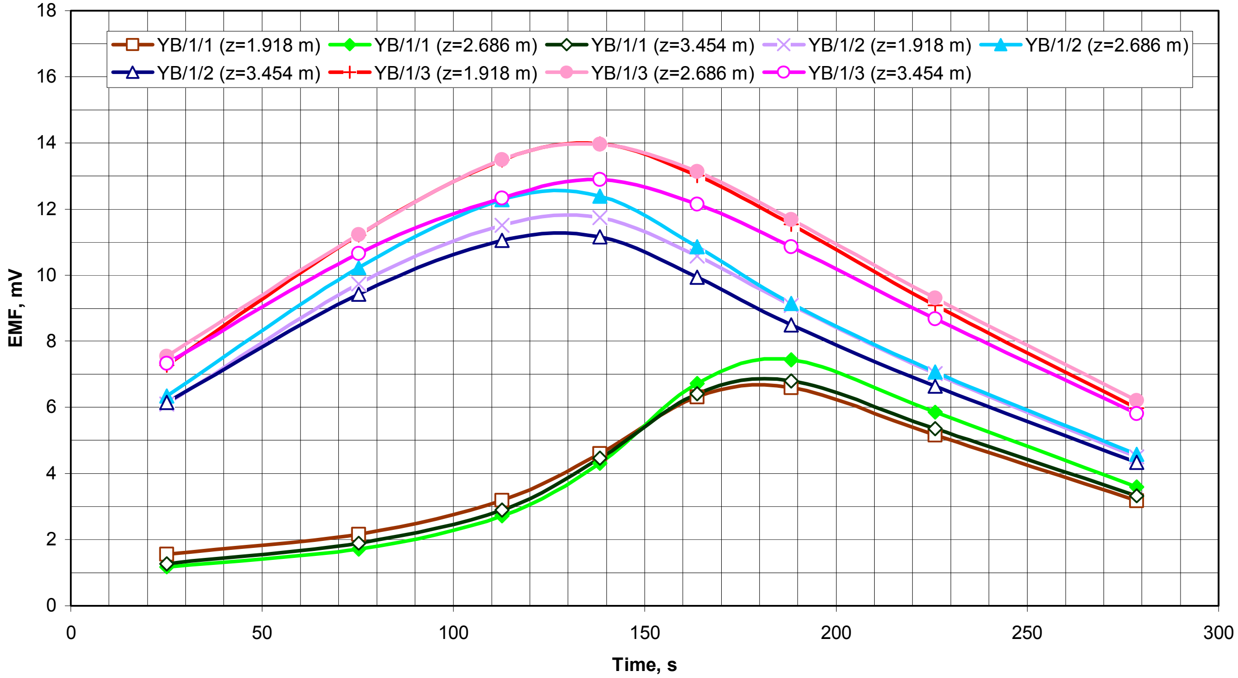
CMS Coil Fast Discharge

Modeling the CMS Fast Discharge

At 9 discrete times (0, 50, 100, 125, 151, 176, 200, 251, and 306 s) during the above discharge the fields were calculated in the detector, and in the plates of the barrel and endcap muon yoke steel the resulting flux density values were integrated over the areas enclosed by the flux loops at each time step.

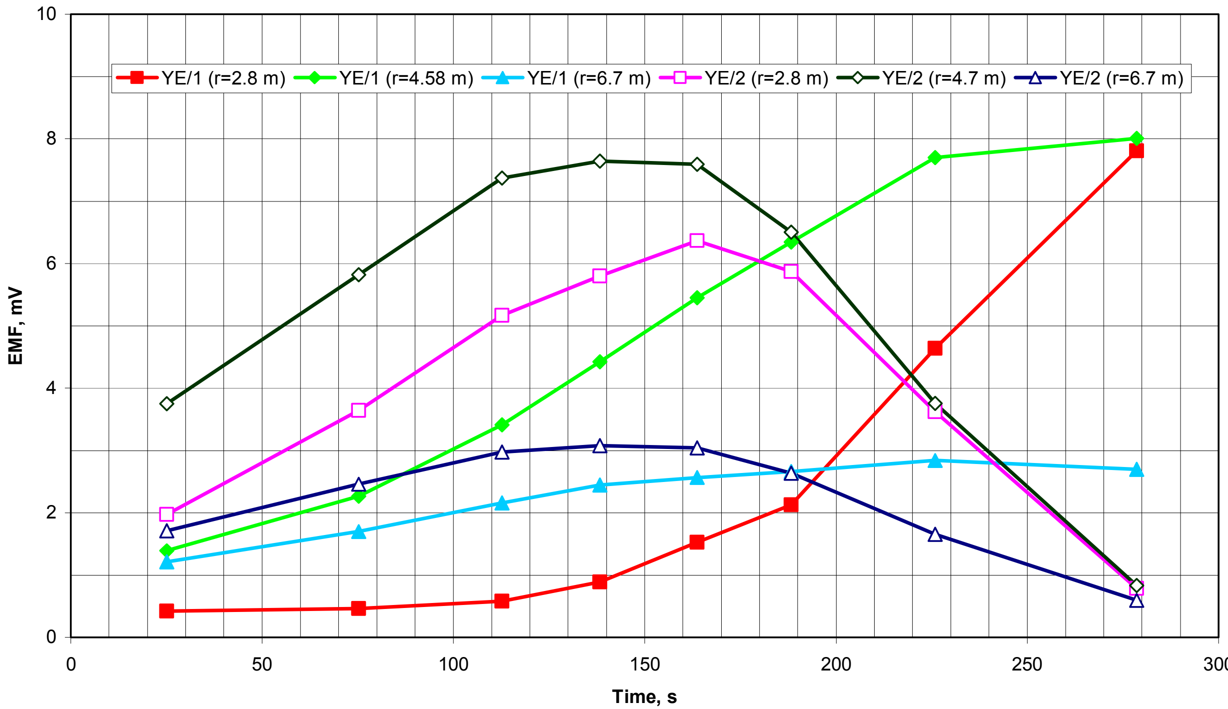
From the total flux Φ enclosed by each loop the average voltages $V=d\Phi/dt$ induced in the loops by the flux changes between the time intervals were calculated.

Modeling the CMS Fast Discharge



EMF per One-Turn Flux Loop in Barrel Plate Segments

Modeling the CMS Fast Discharge



EMF per One-Turn Flux Loop in End Cap Plate Segments

Measuring Flux Changes in the CMS Steel

It is the goal of this study to determine if these flux coil voltages can be integrated over the entire discharge with sufficient accuracy to provide a measurement of the total change of flux density in the steel to a few percent uncertainty.

The technique of choice for the measurement of the voltages on the flux coils is the use of a precision voltage sampling data acquisition system with fast ADC read out, operating under the control of a PC. This technique avoids the need for high-stability integrators that must operate for long times.

Experimental Approach

A 994-turn model flux coil approximately 13.5 cm in diameter was wound on a non-metallic coil former and connected to the selected sampling circuitry (National Instrument DAQ Card 6012® PCMCIA module) in differential mode to reject common-mode noise.

The flux coil was mounted between the steel pole tips of a laboratory standard electromagnet (GMW® Model 3474, energized with Danphysik® Model 8530 power supply equipped with GPIB control interface), and the magnet charged and discharged at a number of different rates under control by the same software used to sample the voltage on the model flux coil.

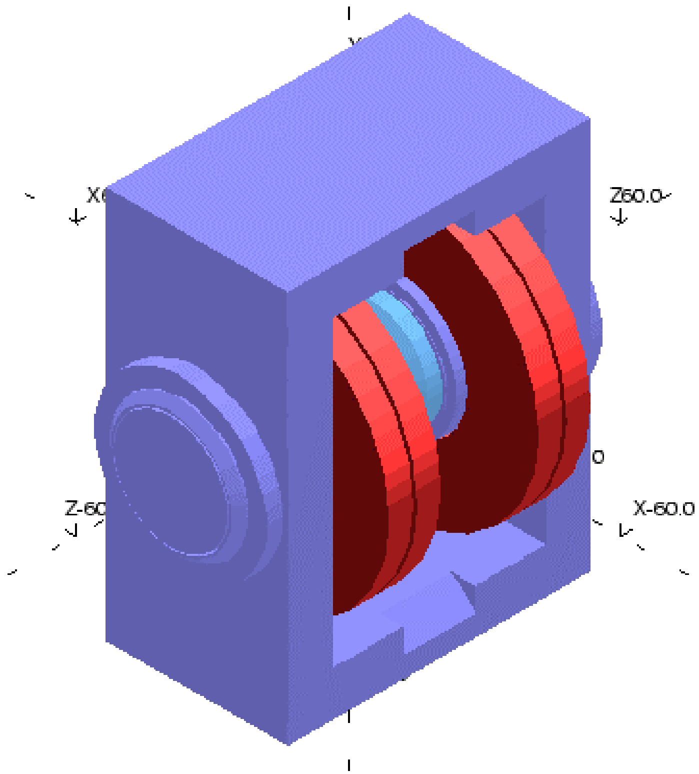
Experimental Approach

In addition to studying the behavior of the "air core" flux coil, a steel disc was inserted in the coil to study the behavior of the coil when it encloses ferromagnetic material. An aluminum disc was also inserted in the flux coil to monitor eddy current effects.

A TOSCA model for the laboratory standard magnet was prepared to guide the interpretation of the data obtained from the flux coil.

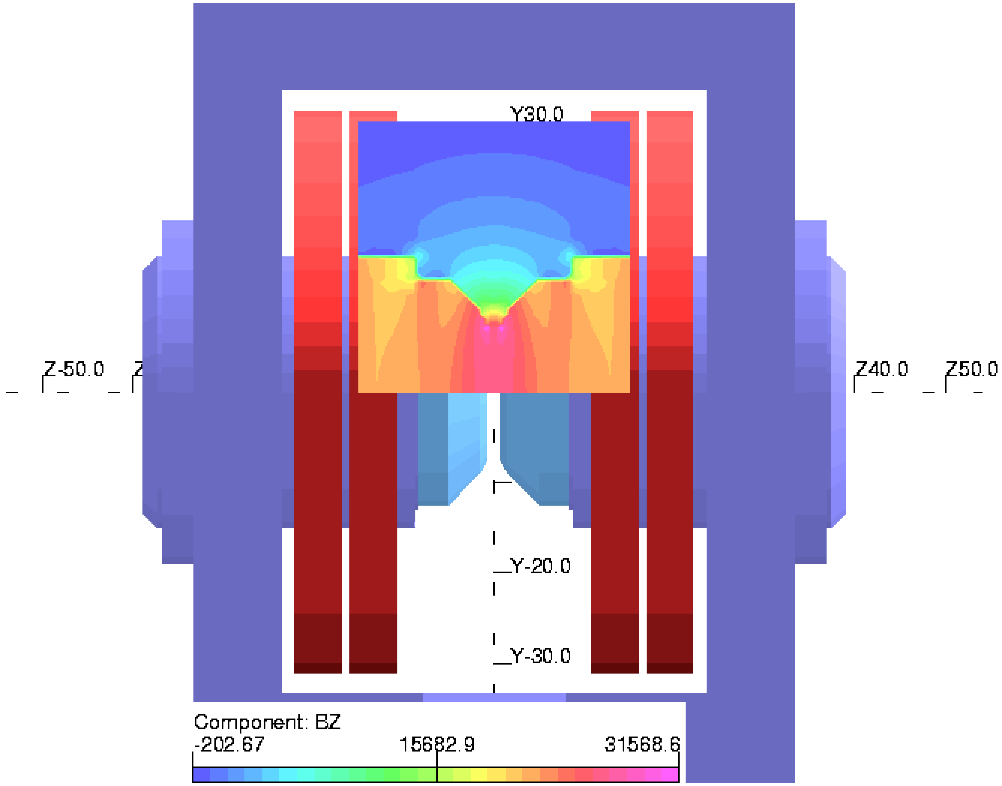
Values for the B-H data for the steel pole tips and yoke of the standard magnet were taken from those measured for the CMS yoke elements.

Experimental Approach



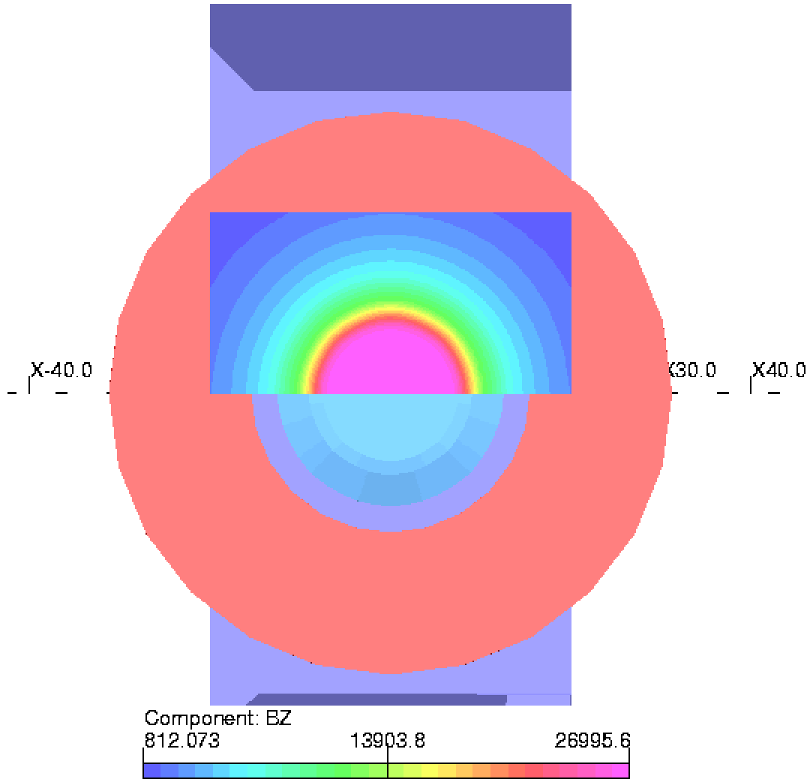
TOSCA Model for Standard Magnet

Experimental Approach



Axial Magnetic Induction in YZ-plane (Air Gap Case)

Experimental Approach



Axial Magnetic Induction in Middle Plane of Air Gap

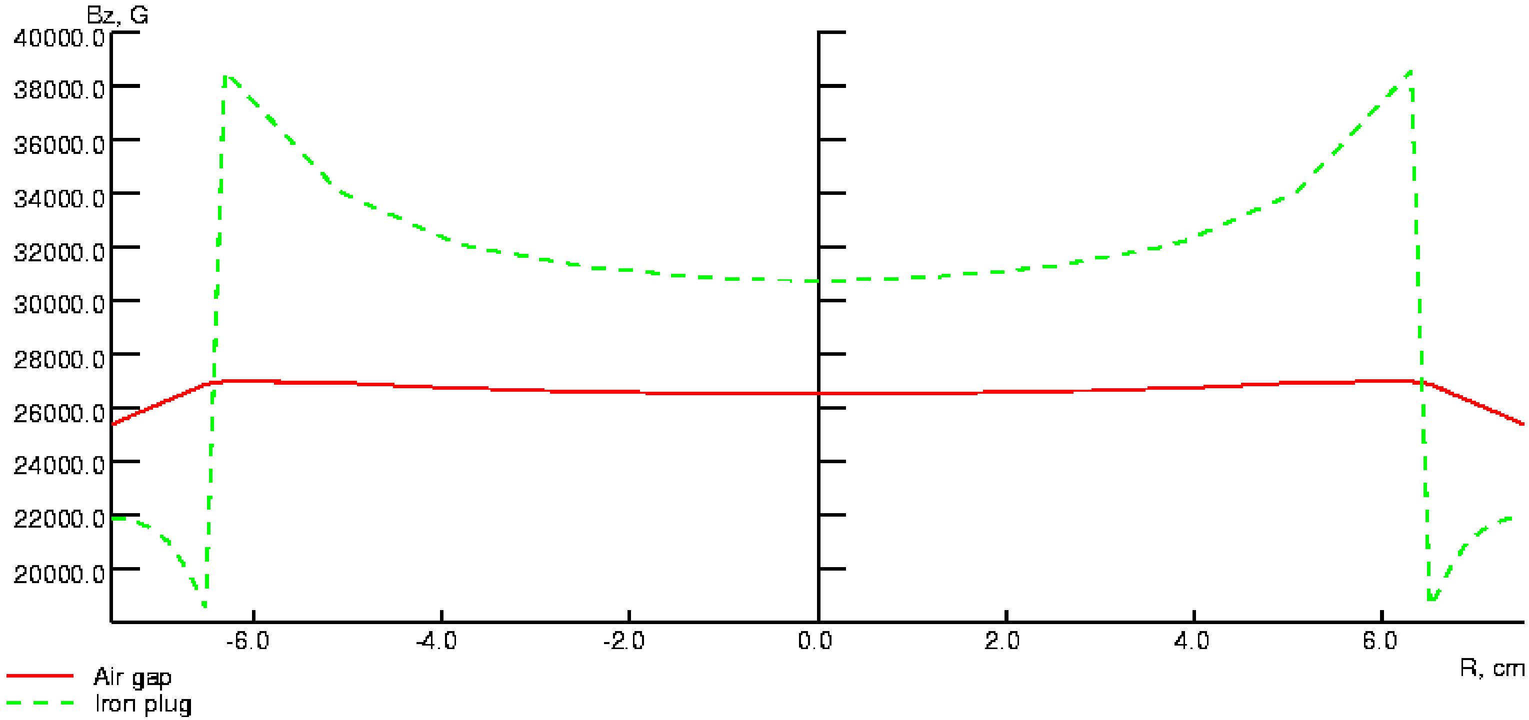
Experimental Approach

The TOSCA model predicts closely the flux density in the gap (2.65 T) vs. that measured by hall probes (2.63 T) positioned on the surface of the pole tips when the magnet was energized without the flux coil in the gap.

When an iron disc was inserted in the gap the model predicts a field of 3.07 T in the center of the disc.

For both the air-gap and iron-filled gap, the predicted field shape rises with increasing radial distance from the center of the pole tips.

Experimental Approach



Calculated Field in the Gap of the Standard Magnet

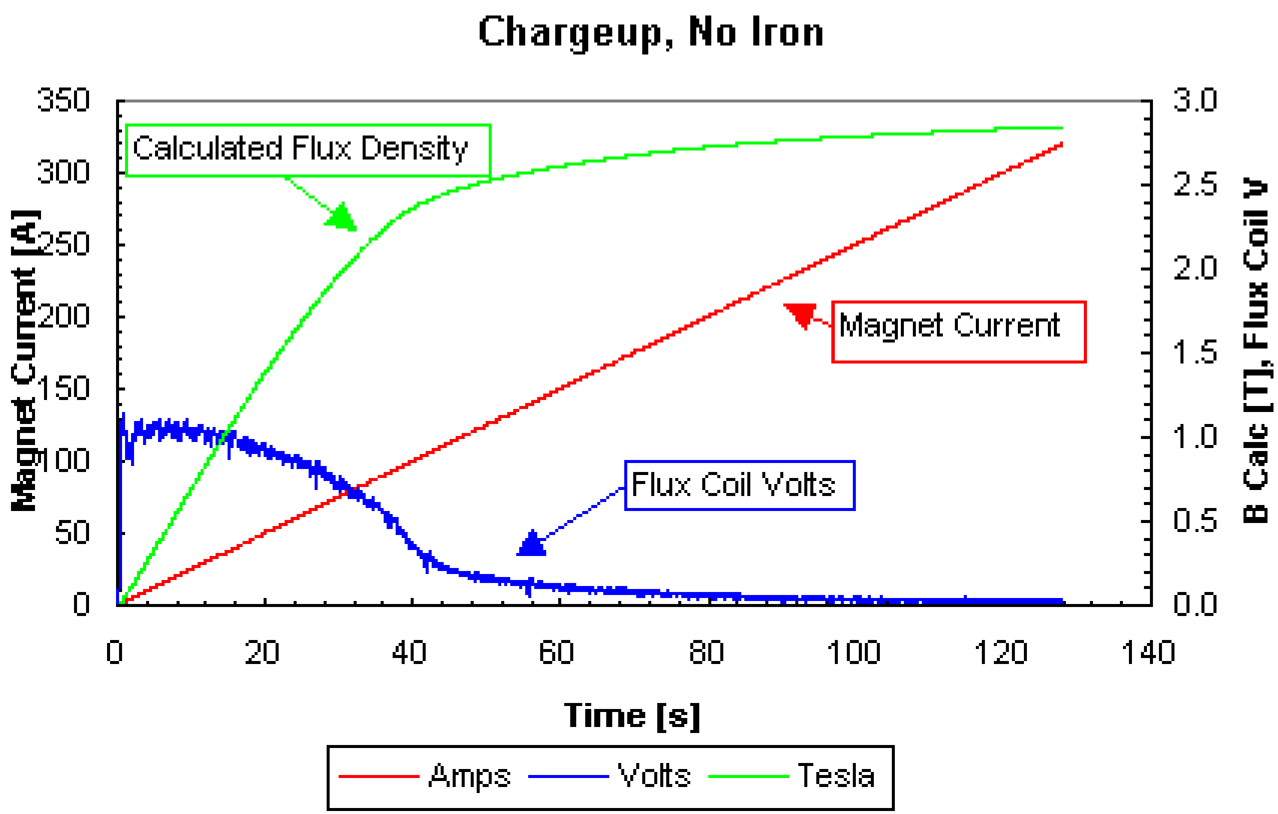
Data From the Model Coil

The flux coil was inserted in the standard magnet and the magnet charged to full current at a charge rate of 2.5 A/s.

After a pause, the current was decreased at the same rate to zero. The voltage on the flux coil was sampled at 40 msec intervals, and integrated off-line by simply multiplying the average voltage in each time interval by the length of the time interval.

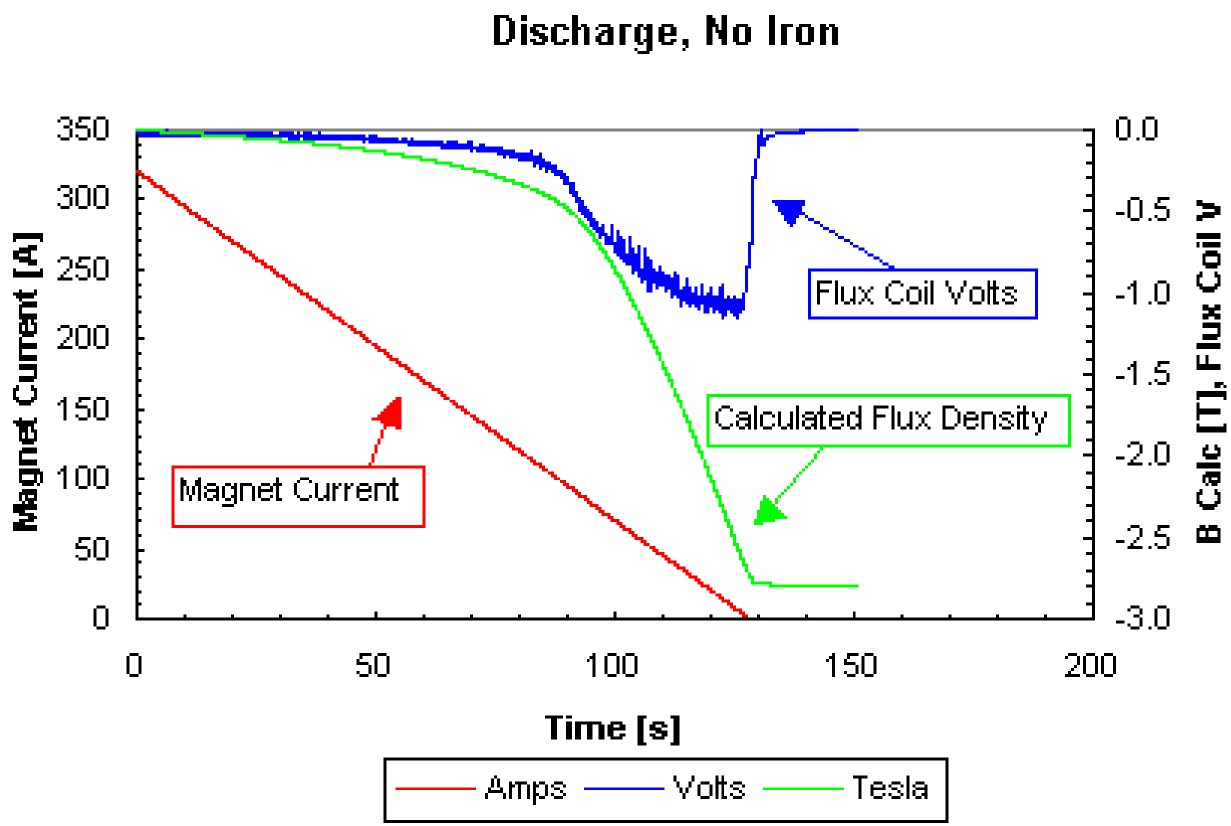
The measured flux change from charging (40.9 Webers) and discharging (40.0 Webers) agree within ~2%, provided added time (~ 3 seconds) is allowed at the end of the discharge cycle after the current has reached zero, for the pole tips of the magnet to spontaneously demagnetize.

Data From the Model Coil



Flux Coil in Air Gap, Chargeup

Data From the Model Coil



Flux Coil in Air Gap, Discharge

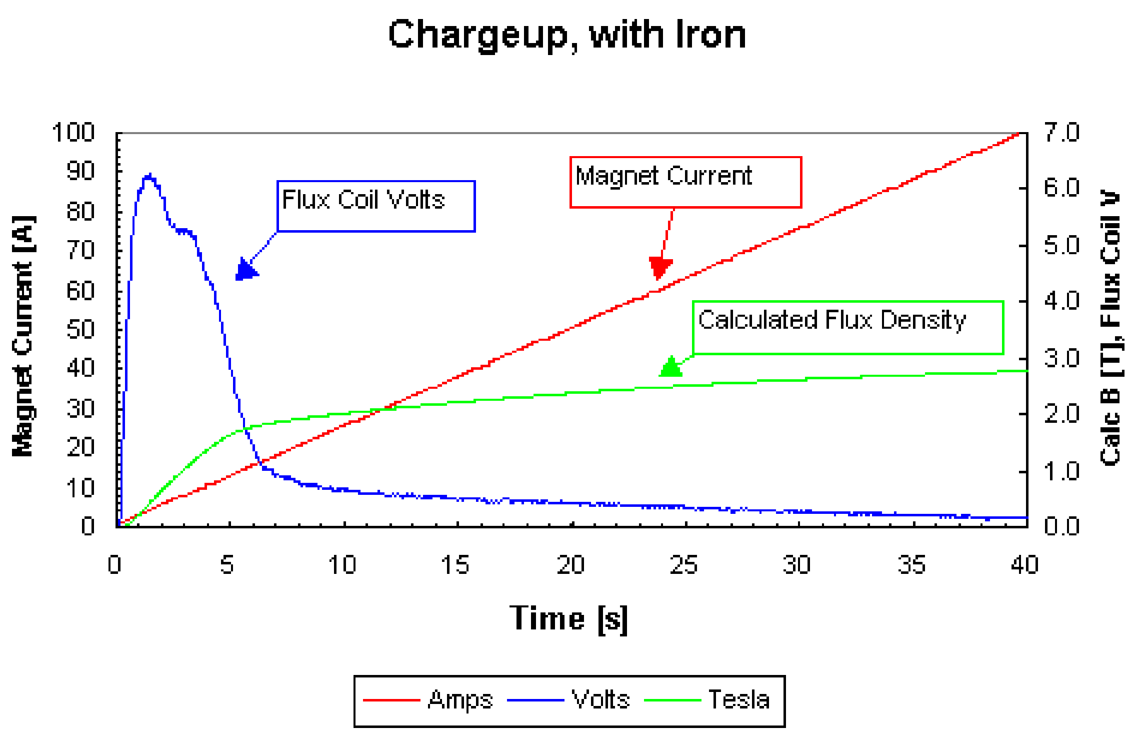
Data From the Model Coil

In the plots, the flux has been renormalized to flux density using the area of the flux coil and the number of turns in the coil.

The experiments were repeated after inserting a high-carbon steel disc in the bore of the flux coil.

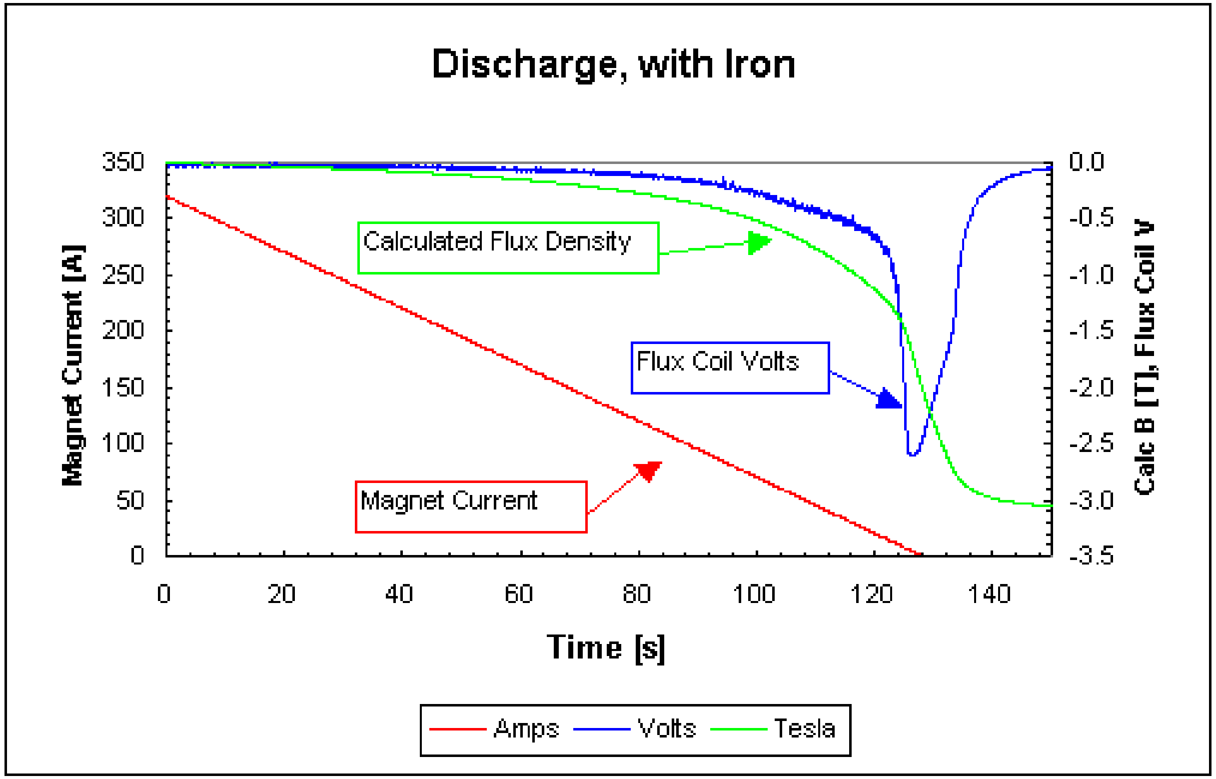
The voltage on the flux coil during the early portion of the chargeup is large, reflecting the rapid initial magnetization of the steel disc.

Data From the Model Coil



Flux Coil With Iron, Detail from Early Portion of Chargeup

Data From the Model Coil



Flux Coil With Iron, Discharge

Data From the Model Coil

The measured flux change during chargeup was 44.9 Webers, and during discharge 44.6 Webers. Note the full discharge of the system now requires ~15 seconds additional time after the magnet current reaches zero, for the spontaneous demagnetization of the steel disc and the pole tips of the magnet.

Integrating the TOSCA prediction for the case with steel in the flux coil over the area of the flux coil yields a prediction in reasonable agreement with the measured value.

The agreements with TOSCA as well as the equality of the flux changes during charging and discharging indicate that the precision of the measurements is within ~2%.

Conclusions

- **The experimental program described herein indicates that the increase of flux density in a steel object magnetized by an external source can be measured with good precision using a fast sampling ADC operating in differential mode.**

- **It is straightforward to log the data from a flux coil at high speed and integrate the voltage off line to obtain the total flux change in the coil.**

- **The observed remnant field effects in steel, of the quality and geometry studied, suggest that the demagnetizing fields in the CMS steel after discharge may be large enough to reduce the unmeasured flux of the remnant fields to low values.**

Future Plans

- **Ongoing laboratory work will focus on studying the characteristics of such measurements using steel samples taken from the yoke pieces of the CMS magnet.**

- **Slower charge and discharge rates will be studied to verify that the somewhat longer CMS discharges will be accurately sampled, and to confirm that eddy currents are not significant. Studies made with an aluminum disc in the flux coil indicate that they are not.**

- **Resistive discharges of the laboratory magnet will be attempted to quantify the degree to which voltage steps of controlled charging and discharging are sources of error.**