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# PRESERVATION OF QUALITY FACTOR OF HALF WAVE RESONATOR DURING QUENCHING IN THE PRESENCE OF SOLENOID FIELD*

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*Abstract*

The Proton Improvement Plan II at FNAL relies upon a 162.5 MHz superconducting half-wave resonator cryomodule to accelerate H- beams from 2.1 to 10 MeV. This cryomodule contains 8 resonators with 8 superconducting solenoid magnets interspersed between them. X-Y steering coils are integrated with a package of the superconducting solenoid magnets. The center of the solenoids is located within ~50 cm of the high surface magnetic field of the half-wave resonators and in this study we assess whether or not magnetic flux generated by this magnet is trapped into the half-wave resonators niobium surface and increases the RF losses to liquid helium. To test this we assembled a solenoid with a 162.5 MHz half-wave resonator spaced as they will be in the cryomodule. We measured the quality factor of the cavity before and after the cavity quenched as a function of field level in the coils. No measurable change in the quality factor was observed. In this paper, we will present details of the measurements and discuss the magnetic field map.

## INTRODUCTION

Argonne has developed a 6 T superconducting solenoid (0.75 T·m field integral) with integral x-y dipole steering coils each producing a maximum 0.25 T steering field (30 T·mm field integral) [1,2]. This magnet will be used in the 162.5 MHz superconducting half-wave resonator (HWR) cryomodule which contains 8 resonators and 8 magnets and will be employed to accelerate H- beams from 2.1 to 10 MeV in the proposed Proton Improvement Plan II (PIP-II) at FNAL [3,4].

This solenoid integrates with bucking coils to minimize stray field such that the magnetic field on the cavity surface is much smaller than the (first) critical field for niobium. The intent is to avoid trapped magnetic flux and the associated increase of the surface resistance [1]. This minimization of the stray field reduces the possibility of flux trapped when cavity experiences thermal breakdown (quenching) [5,6]. Experimental studies show that magnetic flux can be trapped around the quench location where a normal region is present in the niobium for ~100 ms [6].

We assembled this solenoid with the 162.5 MHz HWR, which is the second cavity fabricated for PIP-II HWR cryomodule and the first one was reported on in ref. [7], and measured change of trapped magnetic flux after the cavity quenched in the presence of the solenoid/steering coil fields. We note that probability of cavity quenching during normal operation would be very low in the PIP-II HWR cryomodule because this cavity quenches at the accelerating gradient of $E_{ACC}$~18 MV/m while the operational accelerating field will be $E_{ACC}$=8 MV/m.

In the following sections, we will discuss the stray field generated by the solenoid and steering coils and then discuss measurement hardware and results.

## STRAY FIELD

The stray field of the solenoid is minimized by integral bucking coils as shown in Fig. 1. These are wound in series with the main solenoid coil. Another pair of the dipole coils is located in the plane perpendicular to the cross-section shown in Fig. 1.

The simulated stray field generated by the solenoid, a combination of the main and bucking coil, is as shown in Fig. 2. We note that the unperturbed field is simply overlaid on the cavity and no Meissner effect is included. The stray field on the cavity surface is of the order 10 Gauss around the nosecone, placed in the high RF electric field region, and it is exponentially decayed along the surface toward the end torus of HWR so the stray field on a cavity surface in the high RF magnetic field region is much smaller than the lower critical field of the niobium [8]. The measured stray fields are in rough agreement with the design, differing by a factor of 3 [2].

The stray field generated by the steering coils at maximum deflection is estimated to be ~200 Gauss on the cavity niobium surface, relatively higher than for the main solenoid because these do not include bucking coils or shielding.

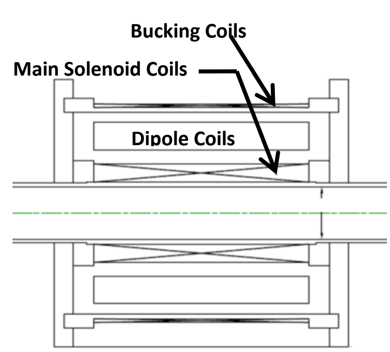


Figure 1: Structure of the coils in the superconducting solenoid magnet integrated with dipole steering coils. The bucking coil is wired in series with the main solenoid coils.

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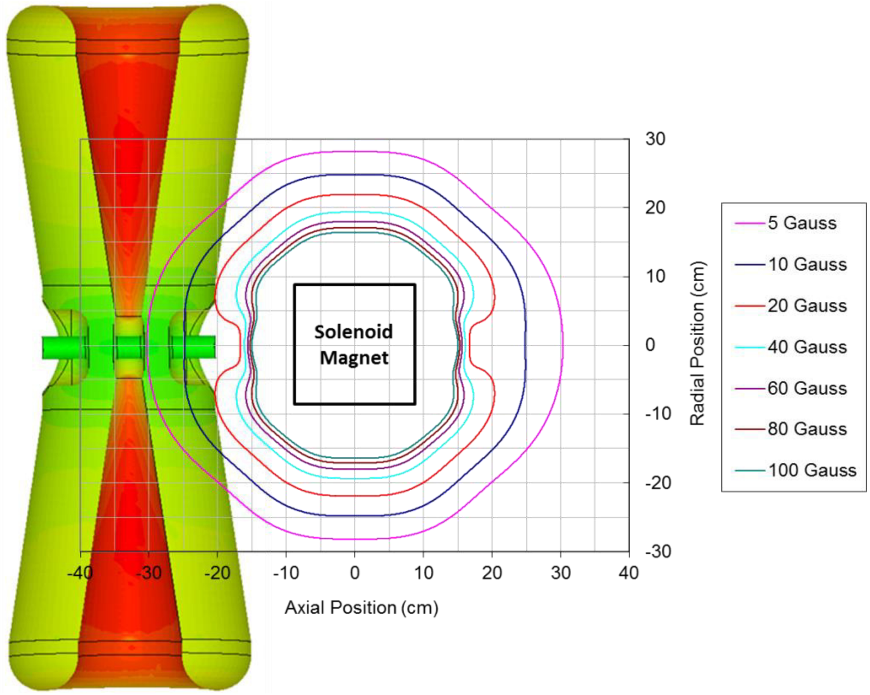


Figure 2: The simulated stray magnetic field line generated by the solenoid (lines). The center of the HWR will be placed 33 cm from the center of the solenoid. The colors in HWR represent the RF surface magnetic field. This distribution of the solenoid field lines is as the solenoid is in free space; in operation the solenoid field will be partially expelled from the superconducting cavity surface below $T_c$=9.2 K.

## EXPERIMENTAL SETUP AND RESULTS

Figure 3 shows the solenoid and the 162.5 MHz HWR before loading into the test cryostat. The space between the solenoid and cavity is approximately same as in the cryomodule and as that shown in Fig. 2. After cooling the cavity and solenoid down to 2 K, we measured the cavity quality factor at a relatively low accelerating gradient, $E_{ACC}$=1.3 MV/m. Then we measured relative change of the quality factor 1) varying the solenoid field and 2) quenching the cavity at each step of the solenoid field. The absolute quality factor was measured from the decay time of the stored energy picked up on the digital oscilloscope and its relative change was measured from relative change of the store energy. The measured changes in the quality factor represented in terms of the surface resistance are shown in Fig. 4. No measurable changes in the surface resistance were found within accuracy of ±0.1 nΩ. These results imply that the integrated average trapped magnetic flux over the cavity surface did not increase by more than 0.8 mG [9]. We note that 'quenching' is easily distinguishable from fast electrical breakdown by observation of the decay time of the stored energy, which was ~20 ms in these experiments.

Magnetic field on the cavity wall was monitored at selected locations during these experiments. We had two single-axis Bartington Mag-01 low-field probes with sufficient sensitivity to measure relative field changes smaller than 1 mG. These were fastened onto the cavity helium jacket, roughly 2.5 cm from the cavity niobium surface, as shown in Fig. 3. One probe is located at the middle of the half section of the HWR, the other at the end. Both of them measure magnetic field normal to the cavity wall. During quenching, there was no measurable change in the magnetic field in each probe within accuracy of ±1 mG. The high-field hall probe was placed between the cavity and solenoid to monitor the solenoid field level.

Similar measurements were done with the steering coil field and the results are summarized in Table 1. No measurable changes in the surface resistance were found within accuracy of ±0.4 nΩ. In these experiments with the steering coils, we measured the absolute quality factor from decay time of the stored energy at each event so accuracy of measurements is relatively higher than the previous experiments with the solenoid.

## SUMMARY

The possible degradation of the PIP-II 162.5 MHz 2 Kelvin HWR quality factor during quench has been experimentally studied. The hypothesis is that stray fields from the superconducting solenoid or steering coils could be trapped and causes Q-drop. This effect was not observed and no measurable change in quality factor was found during cavity quench for any values of the coils currents up to the rated maximum.

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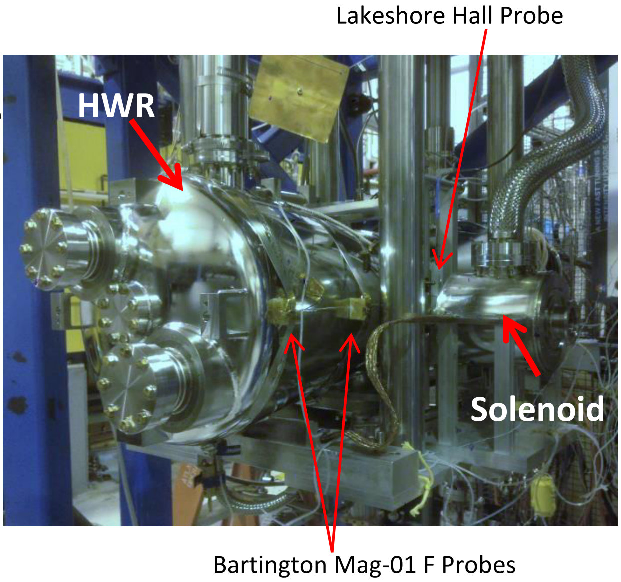


Figure 3: Superconducting (SC) Half-Wave Resonator (HWR) and SC solenoid assembled together in the test cryostat, similar to the PIP-II cryomodule plan.

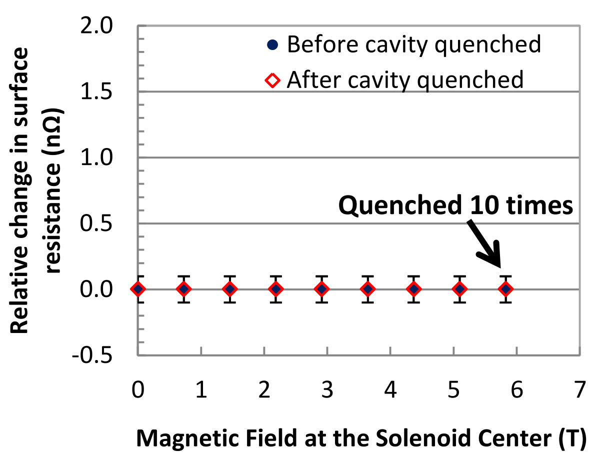


Figure 4: Relative changes in the surface resistance of the 162.5 MHz HWR at different levels of the solenoid field. They were also measured after cavity quenched, especially 10 times at the highest solenoid field.

Table 1: Relative changes in the surface resistance of the 162.5 MHz HWR measured with the steering coils

| Measured | Relative change in surface resistance |
|---|---|
| After cavity quenched in the presence of x-steering coil field at maximum (~0.25 T) | 0.0±0.4 nΩ |
| After cavity quenched in the presence of y-steering coil field at maximum (~0.25 T) | 0.0±0.4 nΩ |

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