Time Decay, Snap-back, and Ramp Rate Effects in RHIC 8 cm Dipoles and Quadrupoles

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This note reports field quality measurements made with rotating coils in intervals of 0.66 second on a 0.92 m long spare RHIC 8 cm quadrupole (QR7109) and a 3 m long spare RHIC 8 cm dipole (D96525). The rotating coil data were analyzed using a new algorithm [1] which incorporates effects on signal due to changes in current during one revolution of the coil. The results of these measurements are available as a series of plots in a set of files in Acrobat PDF Ver. 4.0 format, as follows:

1. Time Decay at 470A (15% below Injection) in QR7109 After Cycles to Various Currents [QR7Tdecay.pdf; 3 pages]
2. Ramp Rate Effects (Up Ramp) in QR7109 After Cycles to Various Currents [QR7RampRate.pdf; 9 pages]
3. Snap-back on Ramping from 470A to 3500A in QR7109 [QR7Snapback3500.pdf; 7 pages]
4. Snap-back on Ramping from 470A to 5000A in QR7109 [QR7Snapback5000.pdf; 7 pages]
5. Time Decay at 470A (15% below Injection) in D96525 After Cycles to Various Currents [D96Tdecay.pdf; 3 pages]
6. Snap-back on Ramping from 470A to 3500A in D96525 [D96Snapback3500.pdf; 9 pages]
7. Snap-back on Ramping from 470A to 5100A in D96525 [D96Snapback5100.pdf; 9 pages]
8. A Comparison of Ramp Rate Effects in D96525 and QR7109 After Cycles to 3500A and 5 kA [RampRateD96QR7.pdf; 8 pages]

These files are available for viewing/download by following the "Publications" link from http://magnets.rhic.bnl.gov. A summary page from each of the above files is included in the paper version.

Since the snapback effects are related to the early part of a ramp, these results are essentially the same for 3500 A and 5kA, except for a difference in the rate at which the ramp rate is increased from zero to a maximum value in the experiment. Also, the magnitude of superconductor magnetization may be different for cycles to 3500 A and 5kA.

[1] Animesh K. Jain, *An Algorithm to Analyze Rotating Coil Data Acquired During a Current Ramp*, Unpublished.

Time Decay at 470A (15% below Injection) in QR7109
After Cycles to Various Currents

- Measurements are in the straight section with a 9 inch long coil.
- Measurements are with a time resolution of ~0.66 second.
- AC cycles done from 25 Amps to X Amps and back at 60 A/s, where X = 1000 A, 2500 A, 3500 A, or 5000 A. The magnet was quenched before the 1000 A AC cycle.
- Current ramped from 25A to 470A at 40 A/s and then held constant.
- Smooth current ramp profile with quadratic time dependence at the beginning and the end of the ramp.
- Measurements made during the ramp (40 A/s) from 25 A to 470 A, as well as for about 150 seconds at the 470 A flat top. For the 3500 A cycle, the measurements at flat top were extended to a total of 380 seconds, with a "dead period" of about 64 seconds.
- Time $t = 0$ is defined as the time when the magnet current has reached approx. 450 A.
- For each value of maximum current, the time decay was measured at least 3 times. Data reproducibility was good (within measurement noise, $\sigma \sim 0.01\%$ in Transfer Function).
- Transfer function values for 1000 A cycle are significantly different from those for 2500 A, 3500 A and 5000 A cycles.

Ramp Rate Effects (Up Ramp) in QR7109
After Cycles to Various Currents

- Measurements are in the straight section with a 9 inch long coil.
- AC cycles done from 25 Amps to X Amps and back at 60 A/s, where X = 1000 A, 2500 A, 3500 A, or 5000 A. The magnet was quenched once before the first AC cycle to 1000 A.
- Current ramped from 25A to 470A at 40 A/s and then held constant.
- "AC Loop" measurements were made while the current was ramped up from 470 A to X Amps at 40 A/s, 60 A/s and 70 A/s (X = 1000 A, 2500 A, 3500 A, or 5000 A). For X = 1000 A and 2500 A, measurements were also made at 20 A/s. Downward ramps from X Amps to 25 A were also measured.
- Smooth current ramp profile with quadratic time dependence at the beginning and the end of the ramp.
- Measurements were made with a time resolution of ~0.66 sec. Data analysis corrected for effects due to finite ramp rates and changing current during each rotation of the measuring coil.
- 5000 A cycle, 40 A/s ramp was measured three times to establish good reproducibility of data.
- "DC Loop" measurements were made by ramping the current from one level to the next at 16 A/s, waiting ~15 seconds, and then making a set of 8 measurements (~0.66 sec. apart) at a fixed current. Only one DC loop was measured, after AC cycle to 5000 A.
- No significant ramp rate effects on the transfer function were seen up to ramp rates of 70 A/s.
- Transfer functions after a 1000 A cycle were systematically different from other cycles, consistent with results of time decay measurements.

Snap-back on Ramping from 470A to 3500A in QR7109

- Measurements are in the straight section with a 0.23 meter (9″) long coil.
- Measurements are with a time resolution of ~0.66 second.
- An AC cycle was done from 25 A to 3500 A and back at 60 A/s. The magnet was then ramped from 25 A to 470 A at 40 A/s. The current was held at 470 A for approx. 350 s during which time decay measurements were made. Finally, the current was ramped from 470 A to 3500 A at a ramp rate of 40, 60 or 70 A/s. Measurements were made again during these final ramps. The initial few readings in these measurements give information about the snap-back behaviour.
- Smooth current ramp profile with quadratic time dependence at the beginning and the end of the ramp.
- The left hand figures (available in pdf files) show the transfer function or the normal 12-pole measured over the entire ramp sequence from 25 A to 3500 A. These figures show the snap-back at the final ramp, and also the initial time decay. The time in these plots is measured from an arbitrary reference point, typically the first measurement in the entire data sequence.
- Both the transfer function and the 12-pole return quickly to their initial values as soon as the final ramp is started. The right hand figures in the following pages show the snap-back behaviour in detail. A time resolution of 0.66 s is seen to be adequate. The snap-back is faster at higher ramp rates. The snap-back time is ~3 s at 40 A/s, and reduces to ~2 s at 70 A/s. Irrespective of the ramp rate, snap-back to the full initial value occurs when the current has increased from 470 A to ~500 A.

Snap-back on Ramping from 470A to 5000A in QR7109

- Measurements are in the straight section with a 0.23 meter (9″) long coil.
- Measurements are with a time resolution of ~0.66 second.
- An AC cycle was done from 25 A to 5000 A and back at 60 A/s. The magnet was then ramped from 25 A to 470 A at 40 A/s. The current was held at 470 A for approx. 350 s during which time decay measurements were made. Finally, the current was ramped from 470 A to 5000 A at a ramp rate of 40 A/s. Measurements were made again during this final ramp. The initial few readings in these measurements give information about snap-back behaviour. Similar measurements were also made for the final ramp at 60 A/s and 70 A/s, but the time decay was not measured before those ramps.
- Smooth current ramp profile with quadratic time dependence at the beginning and the end of the ramp.
- The left hand figures (available in pdf files) show the transfer function or the normal 12-pole measured over the entire ramp sequence from 470 A (or 25 A) to 5000 A. These figures show the snap-back at the final ramp, and also the initial time decay in the case of 40 A/s data. The time in these plots is measured from an arbitrary reference point, typically the first measurement in the entire data sequence.
- Both the transfer function and the 12-pole return quickly to their initial values as soon as the final ramp is started. The right hand figures show the snap-back behaviour in detail. A time resolution of 0.66 s is seen to be adequate. The snap-back is faster at higher ramp rates. The snap-back time is ~4 s at 40 A/s, and reduces to ~2 s at 70 A/s. Irrespective of the ramp rate, snap-back to the full initial value occurs when the current has increased from 470 A to ~500 A.

Time Decay at 470A (15% below Injection) in D96525 After Cycles to Various Currents

- Measurements are in the straight section with a 1 meter long coil.
- Measurements are with a time resolution of ~0.66 second.
- AC cycles done from 25 Amps to X Amps and back at 60 A/s, where X = 1000 A, 2500 A, 3500 A, or 5100 A. The magnet was quenched before the 1000 A AC cycle.
- Current ramped from 25A to 470A at 40 A/s and then held constant.
- Smooth current ramp profile with quadratic time dependence at the beginning and the end of the ramp.
- Measurements made during the ramp (40 A/s) from 25 A to 470 A, as well as for about 150 seconds at the 470 A flat top. For the 2500 A, 3500 A and 5100 A cycles, the measurements at flat top were extended to a total of ~380 seconds, with a "dead period" of about 58 seconds.
- Time $t = 0$ is defined as the time when the magnet current has reached 450 A.
- For each value of maximum current, the time decay was measured at least 4 times. Data reproducibility was good.
- Transfer function values at steady state increase monotonically with the maximum current used for the AC cycle. The steady state value of transfer function at 470 A after AC cycle to 5100 A is 0.70776 T/kA, and is 0.70768 T/kA (–0.011%) after 3500 A cycle, 0.70762 T/kA (–0.019%) after 2500 A cycle and 0.70742 T/kA (–0.047%) after the 1000 A cycle. Typical noise in measurement of transfer function in these runs is at 0.002% level. This noise is about a factor of 5 smaller than in similar measurements in QR7109.

Snap-back on Ramping from 470A to 3500A in D96525

- Measurements are in the straight section with a 1 meter long coil.
- Measurements are with a time resolution of ~0.66 second.
- An AC cycle was done from 25 A to 3500 A and back at 60 A/s. The magnet was then ramped from 25 A to 470 A at 40 A/s. The current was held at 470 A for approx. 300 s during which time decay measurements were made. Finally, the current was ramped from 470 A to 3500 A at a ramp rate of 20, 40, 60 or 70 A/s. Measurements were made again during this final ramp. The initial few readings in these measurements give information about snap-back behaviour.
- Smooth current ramp profile with quadratic time dependence at the beginning and the end of the ramp.
- An extra long flat top (~510 s) at 470 A was used in the case of final ramp at 40 A/s in order to acquire time decay data over an extended period.
- The left hand figures (available in pdf files) show the transfer function or the normal sextupole measured over the entire ramp sequence from 25 A to 3500 A. These figures show both the initial time decay at 470 A and the snap-back at the final ramp. The time is measured from the very first reading taken at 25 A.
- Both the transfer function and the sextupole return quickly to their initial values as soon as the final ramp is started. The right hand figures show the snap-back behaviour in detail. A time resolution of 0.66 s is seen to be adequate. The snap-back is faster at higher ramp rates. The snap-back time is ~5-6 s at 20 A/s, and reduces to ~2 s at 70 A/s. Irrespective of the ramp rate, snap-back to the full initial value occurs when the current has increased from 470 A to ~498 A.

Snap-back on Ramping from 470A to 5100A in D96525

- Measurements are in the straight section with a 1 meter long coil.
- Measurements are with a time resolution of ~0.66 second.
- An AC cycle was done from 25 A to 5100 A and back at 60 A/s. The magnet was then ramped from 25 A to 470 A at 40 A/s. The current was held at 470 A for approx. 300 s during which time decay measurements were made. Finally, the current was ramped from 470 A to 5100 A at a ramp rate of 20, 40, 60 or 70 A/s. Measurements were made again during this final ramp. The initial few readings in these measurements give information about snap-back behaviour.
- Smooth current ramp profile with quadratic time dependence at the beginning and the end of the ramp.
- An extra long flat top (~510 s) at 470 A was used in the case of final ramp at 40 A/s in order to acquire time decay data over an extended period.
- The left hand figures (available in pdf files) show the transfer function or the normal sextupole measured over the entire ramp sequence from 25 A to 5100 A. These figures show both the initial time decay at 470 A and the snap-back at the final ramp. The time is measured from the very first reading taken at 25 A.
- Both the transfer function and the sextupole return quickly to their initial values as soon as the final ramp is started. The right hand figures show the snap-back behaviour in detail. A time resolution of 0.66 s is seen to be adequate. The snap-back is faster at higher ramp rates. The snap-back time is ~5-6 s at 20 A/s, and reduces to ~2 s at 70 A/s. Irrespective of the ramp rate, snap-back to the full initial value occurs when the current has increased from 470 A to ~498 A.

A Comparison of Ramp Rate Effects in D96525 and QR7109 After Cycles to 3500A and 5kA

- Measurements are in the straight section with a 1 m long coil for D96525 and 0.23 m long coil for QR7109.
- Measurements are with a time resolution of ~0.66 second.
- AC cycles done from 25 Amps to X Amps and back at 60 A/s, where X = 1000 A, 2500 A, 3500 A, or 5100 A (5000 A for QR7109). The magnets were quenched before the 1000 A AC cycle.
- Current ramped from 25A to 470A at 40 A/s and then ramped again from 470 A to various current limits (see above) at 20 A/s, 40 A/s, 60 A/s, or 70 A/s. Measurements were made during this ramp to study ramp rate effects.
- Smooth current ramp profile with quadratic time dependence at the beginning and the end of the ramp.
- In order to compare values of T.F. and harmonics in various runs, the measured data were interpolated in 50 A steps. A linear interpolation between two neighboring currents was used.
- The differences between measurements made at various ramp rates and the “DC” values are shown in the following figures. Data are shown for the transfer function and the first allowed harmonic (normal sextupole, b_2, in the dipole and normal 12-pole, b_5, in the quadrupole).
- Maximum change in T.F. is seen in the case of the dipole at ~750 A. The change from DC value is ~4.5 parts in 10,000 (0.045%) at 70 A/s. There is practically no difference between a 3500 A cycle and a 5100 A cycle. Data for 1000 A and 2500 A cycles are not analyzed using such interpolation.
- Change in sextupole in D96525 is found to be the largest at 20 A/s, and is less at higher ramp rates. This is somewhat unexpected and could be due to time dependent effects (The DC measurements are made after a 20 s wait).
- There is practically no ramp rate effect seen in the quadrupole T.F.
- The ratio of quadrupole to dipole transfer functions is shown in the last three plots.