TRIM COIL UNBALANCE OF THE 88-INCH CYCLOTRON*

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Abstract

The 88-inch cyclotron Dee probe shows large losses inside the radius of 20 cm and suggests problems in the ion beam injection. The current of the top and bottom innermost trim coil 1 is unbalanced to study effects of the axial injection displacement. A new beam profile monitor images the ion beam bunches, turn by turn, and the beam center of mass position is measured. The technique allows increasing the beam transmission through the cyclotron.

INTRODUCTION

The ions produced by the electron cyclotron resonance ion sources are injected inside the 88-inch cyclotron by a mirror inflector. The inflector assembly is a grounded grid mounted with standoffs on a biased plate that is tilted 45^0 above the cyclotron horizontal midplane. The ions entering the grid inflector experience an electrostatic force that directs them to the cyclotron middle plane.

After the ions enter the cyclotron, they are accelerated by a radiofrequency (RF) electric field and held to a spiral trajectory by a static magnetic field. The RF fields cause the ions to bunch up into packets.

The cyclotron has a set of 17 adjustable concentric trim coils [1] located on the pole pieces inside the magnet gap. They are used to modify the distribution of vertical magnetic fields and compensate for the relativistic mass increase to keep an isochronous motion as the ions gain velocity and the orbit increases with radius. The ions that are not synchronized with the RF are lost.

The Dee probe [2,3] is mounted at the end of a shaft that moves radially inward. The probe is unsuppressed, but it is partially magnetically shielded by the main magnet field. The probe measures the beam current hitting a water cooled copper block. The measured signal corresponds to the internal beam intensity inside the cyclotron and exhibits the radial beam losses.

Low cross section experiments that produce super-heavy elements have increased the demand for high intensity heavy ion beams at energies of about 5 MeV/nucleon [4]; nevertheless initial measurements with the Dee probe show large losses inside the cyclotron radius of 20 cm. The poor transmission suggests problems in the ion beam injection may be caused by off-centered initial orbits with bunches partially hitting the lips of the Dee inserts.

The next sections show the unbalance of innermost trim coil 1 and measurements of the beam center of mass position to correct the initial off-center orbits and improve the transmission through the cyclotron. This work is in continuation of the High-Voltage Upgrade Project [5] and aims to increase the intensity of the ion beam.

INNERMOST TRIM COIL 1 UNBALANCE

Figure 1 shows in black the 750 A power supply connected to trim coil 1 using a reversing switch. The switch can invert the electrical current orientation of the coils and consequently the orientation of the magnetic field. The coils are arranged in series, so all the current of the top coil goes to the bottom coil.

Initially, two CM600HA-5F IGBT transistors displayed in red were connected in parallel to the coils in order to shunt the current around the top and bottom coils, i.e., from the busbar between the top and bottom coils to the power supply positive and negative outputs.

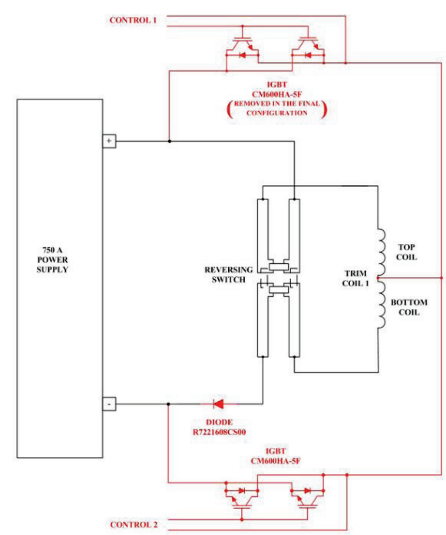

Figure 1: Trim coil unbalance circuitry. The original trim coil system is displayed in black and the modifications are in red. Two parallel IGBT transistors are connected across each coil. The top IGBT transistors connected to the positive output are removed in the final configuration. A power diode is also added in the final configuration between the power supply negative output and the reversing switch, allowing to shunt half of the trim coil current.

This configuration has the advantage of weakening the top or bottom vertical magnetic fields with the same control signal, independently of the position of the reversing switch. For instance, if the magnetic field produced by trim coil 1 has the same direction of the

*Work supported by by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contract DE-AC02-05CH11231.
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main magnet field, the magnetic field below the horizontal midplane is weakened by shunting the current around the bottom coil using the IGBTs driven by “CONTROL 2”. If the switch is reversed and the same pair of IGBTs keeps conducting current, then the trim coil magnetic field will oppose to the main magnet field orientation, however the top trim coil current is decreased at this time, meaning that the superimposed magnetic field above the horizontal midplane is still stronger than the bottom.

The electronic circuit was later changed by removing the IGBTs connected to the positive output of the power supply and by adding a R72216CS power diode, displayed in red, in series with the trim coil connected to the negative side of the power supply and in parallel to the remaining IGBTs. The diode forward bias is added to the coil voltage and applied across the IGBTs collector-emitter. This configuration allows driving the IGBTs to half of the trim coil current, increasing the current unbalance.

Figure 2 shows results from the Dee probe measurements of 266 MeV Cr^{+14} ion beam with trim coil 1 driven by 500 A in four distinct configurations: top and bottom coils currents balanced, 100 A current unbalanced applied with the IGBTs connected to the top and bottom coils, and 250 A current unbalanced applied with the IGBTs connected to the bottom coil.

The abscissa shows the Dee probe radial distance to the center of the cyclotron in centimeters. The ordinate shows the cyclotron transmission, i.e., the percentage of the total current entering the inflector that is reaching the Dee probe. No correction is applied to the other trim coils during these measurements.

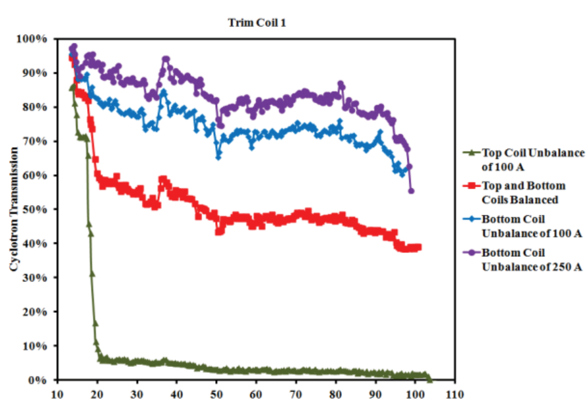

Figure 2: Dee probe measurements of 266 MeV Cr^{+14} ion beam. The red line with square markers shows trim coil 1 driven by 500 A in balanced configuration. The green line with triangle markers shows 100 A unbalance, shunting current around the top coil. The blue line with diamond markers shows 100 A unbalance, shunting current around the bottom coil. The violet line with circle markers shows 250 A unbalance of the bottom coil.

These results show large losses in the center region inside the radius of 20 cm with the trim coil 1 in balanced configuration. The losses in the center region increases when the unbalance weakens the magnetic field above the cyclotron horizontal midplane, but the losses decrease when the unbalance weakens the magnetic field below the horizontal midplane.

RADIAL BEAM PROFILE MONITOR

The former 3-finger probe [2] of the cyclotron has been modified into a beam profile monitor in order to image the ion beam bunches and its position, turn by turn, as it is accelerated. A 2 cm X 1.5 cm KBr scintillator replaces the 3-finger probe at the tip of the moveable shaft. It is located on the cyclotron horizontal midplane at 120^0 from south, following the beam orientation.

The harsh radiation environment inside the cyclotron required applying a wound fiber bundle IG-567 from Schott Lighting and Imaging [6] to transmit the beam profile from the KBr scintillator to a CCD camera located in a region of lower radiation fields. The use of a fiber optic bundle simplifies the diagnostic alignment process and reduces the risk of radiation damage to the CCD camera.

EXPERIMENTAL RESULTS

Figure 2 shows that weakening the magnetic field below the cyclotron horizontal midplane improves the transmission, so the scintillator is placed at r = 12.5 cm and a sequence of frames is taken at the nominal trim coil 1 current of 500 A with different current unbalances of the coil connected to the negative power supply output.

The image noise is despeckled and the color is inverted before the center of mass is measured using ImageJ software [7]. Figure 3 shows the results of the image analysis for every distinct current unbalance.

Figure 3(a) shows the axial position of the beam center of mass versus the current unbalance. The green dashed line displays the position of the cyclotron horizontal midplane.

The figure shows the beam center of mass moving down with the current unbalance. The current unbalance produces a magnetic mirror effect that results in a tendency for charged particles to move towards the lower field region.

The unbalance of -145 A moves the center of mass of the beam to the cyclotron midplane, however better transmission through the cyclotron is obtained with unbalance of -210 A.

Figure 3(b) shows the radial position of the beam center of mass versus the current unbalance. The green dashed line shows the current unbalance that brings the beam axial position to the cyclotron horizontal midplane.

ISBN 978-3-95450-128-1

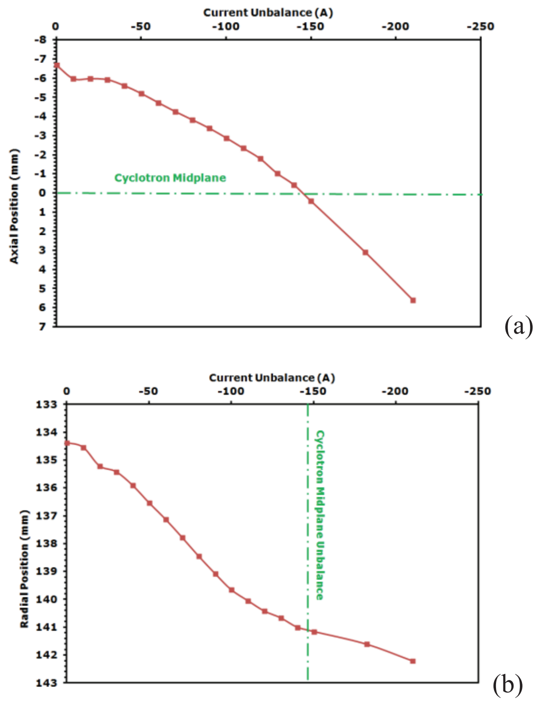

Figure 3: Center of mass position versus current unbalance (a) Axial position. (b) Radial position.

CONCLUSIONS

The Dee probe shows large losses inside the 20 cm radius of the 88-inch cyclotron. An unbalance circuitry is designed and implemented to shunt current around the top and bottom coils.

The current unbalance of trim coil produces a magnetic mirror effect that results in a tendency for charged particles to move towards the lower field region.

A radial beam profile monitor images the ion beam bunch profile turn by turn. The images obtained at 12.5 cm are analyzed using the ImageJ software and the beam center of mass motion is obtained. The center of mass is located ~7 mm above the cyclotron middle plane when trim coil 1 is balanced. The unbalance is used to move the axial position of the beam center of mass and study the effects on the beam transmission.

The experimental measurement for -210 A unbalance of trim coil 1 shows that the Cr^{+14} ions bunch center of mass position moves 11.4 mm axially concurrently with a radial position increase. The latter result is consequence of the overall trim coil 1 field decrease from the current unbalance.

The trim coil unbalance technique allows increasing the transmission of the 88-inch cyclotron by moving the beam axially and reducing the losses from the beam partially hitting the lips of the Dee inserts during the initial turns.

ACKNOWLEDGMENT

The authors would like to thank Catherine R. Siero and Qian He for the cyclotron operation support, Thomas Perry and John P. Garcia for the mechanical support, and Charles Reiter, Brendan Ford, and Steve Warner for the electronic support.

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