

QUADRUPOLE MAGNET DEVELOPMENT FOR 132 MEV DTL OF CSNS

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Abstract

In the China Spallation Neutron Source (CSNS) linac, a conventional 324 MHz drift-tube linac (DTL) accelerating an H- ion beam from 3 MeV to 132 MeV has been designed with 1.05% duty, consisting of 7 tanks with a total length of approximately 59.6 m. Currently, R&D work has focused on the first module of Tank 1, which will have 29 drift-tubes (DT) each housing an electro-magnet quadrupole (EMQ). Some EMQs with SAKAE coil have been fabricated and are under rigorous magnetic measurements by means of Hall probe (HP), single stretched wire (SSW), rotating coil (RC) in order to verify the design specifications and fabrication technology. Magnetic measurements on the EMQs with iron cores made from the electrical-discharge machining (EDM) and the stacking method will be compared and discussed. Work has been implemented to reduce the alignment discrepancies between the geometric center of the DT and magnetic center of EMQ to within +/- 50 μ m.

INTRODUCTION

Currently, a prototype cavity of the 1st module of Tank 1, of the 132MeV drift tube linac (DTL) for the proton linear accelerator for the CSNS has been constructed. A frequency of 324 MHz and a duty factor of 1.05% have been chosen for the RF structures. The design of the DTL was presented in reference [1]. Alongside with the construction of the DTL RF cavity, R&D work has also focused on the drift-tubes (DT) and the electro-magnet quadrupoles (EMQ). Presently, six EMQs with J-PARC type SAKAE coils [2] have been fabricated and are under rigorous magnetic measurements that includes the Hall probe (HP), single stretched wire (SSW) and rotating coil (RC) measurements, to verify the EMQ design specifications and fabrication technology and capabilities in the Institute of High Energy Physics (IHEP), Beijing. The design parameters for the EMQs and DTL Tank-1 are listed in Table 1.

Table 1: Design Parameters for EMQ and DTL Tank-1

EMQ		Tank 1 of DTL	
Parameter name	Parameter values	Parameter name	Parameter values
Beam aperture[mm]	15	Output energy [MeV]	21.76
Core outer diameter[mm]	59	Length [m]	7.99
Core length[mm]	35	Number of DTs	61
Magnetic field gradient[T/m]	75	RF power for each cell[MW]	1.41
Magnetic field effective length[mm]	40.96	Total RF power[MW]	1.97

Maximum excitation current[A]	530	Accelerating field strength[MV/m]	2.2-3.1
Field integral, GL [T]	3.07		
Coil resistance [m Ω]	9.08		

THE ELECTRO-MAGNET QUADRUPOLES (EMQ)

The six EMQ-magnets constructed consists of 3 EMQs with their iron cores made using the Stamped-Stacking Method (SSM), and 3 EMQs with their iron cores made using the Electrical Discharge Machining (EDM). DQ1#DW is the only EMQ that has its water gasket installed as shown in Figure 1. The results of the magnetic measurements for both EDM-made and SSM-made iron core EMQs will be presented, in order to illustrate their magnetic parameters' similarities and differences.

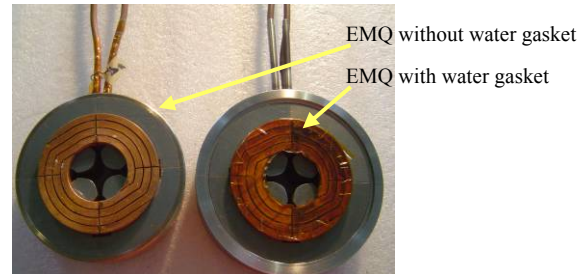


Figure 1: Photos of EMQ.

MAGNET MEASUREMENTS

Hall Measurements

From the HP measurement, the magnetic field profile along the beam-axis of the EMQ can be obtained at different x and y transverse positions. A typical result from the HP measurement is shown Figure 2.

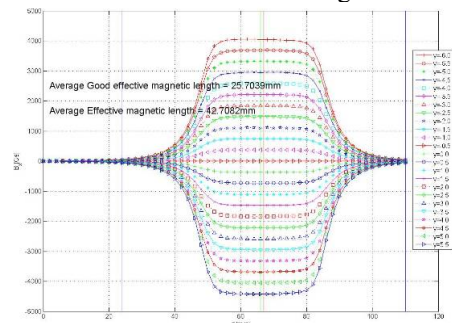


Figure 2: Typical HP measurement result on an EMQ.

The average effective magnetic length, \overline{L}_{eff} , is computed by taking the average of all the effective magnetic length obtained from each profile along the

transverse x or y direction. The good effective magnetic length is the region where only field strengths are within 5% from the maximum field strength. The magnetic field profiles obtained from all the EMQs are smooth within the good field region. The averaged effective magnetic length is about 42.64mm. No significant difference in magnetic length was observed between iron cores made from SSM and EDM.

Next, the field gradient distribution of the EMQs was investigated. The gradient value was then evaluated using the expression below:

$$g_{meas} = \frac{A_{i+1} - A_i}{d_{i+1} - d_i} \quad (1)$$

where A and d can be either B_x and y or B_y and x respectively, and the subscripts i stands for the i -th position along x or y axis respectively for B_y or B_x .

The flatness of the gradient distribution was calculated by implementing the idea of field flatness from [3],

$$FF = \frac{g_{max} - g_{min}}{\frac{1}{N} \sum_{i=1}^N g_i} \times 100\% \quad (2)$$

where FF is the flatness percentage; g_{max} and g_{min} are the maximum and minimum gradient respectively; denominator of FF is the mean gradient. The required field flatness for the gradient distribution in the transverse direction is $FF \leq 1\%$.

Figure 3 shows some of the results obtained from evaluating all the gradient profile of the magnets. A decision was made to implement upper and lower limits to eliminate data which were considered to be incorrect due to measurement errors. The limits were implemented to be 5% from the mean of each profile. Data points within the limits are taken into consideration to replot the gradient profiles of all magnets and evaluate the flatness of the profiles.

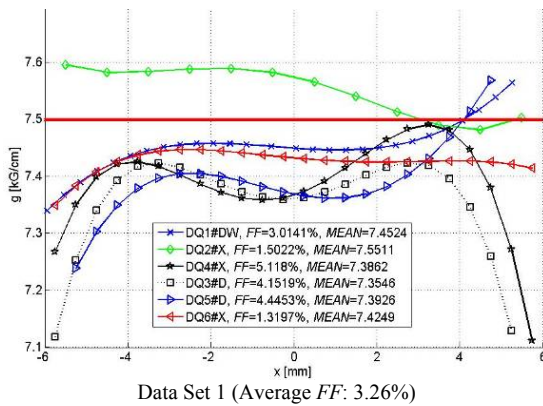


Figure 3: Example of field gradient distribution along x-axis.

As shown in Figure 3, the field gradient distribution is not entirely constant or smooth along the transverse direction for all EMQs. The FF for most of the EMQs are higher than 1%, which is not acceptable.

The reasons for poor field flatness in the transverse field gradient profile are speculative. One can argue that there is high systematic error contribution due to mechanical misalignments and measured data acquisition. There is a need to accumulate the systematic errors of the measuring probe and probe positioning errors in order to verify such suspicions. Furthermore, repeatability of the HP measurement results should be investigated in order to eliminate or understand the systematic errors as suspected.

One other important difference between the EDM-made and SSM-made iron cores is that, the EDM-made laminations are short-circuited at the magnet pole tip. Since the EMQs will be supplied with pulse currents, the EDM-made laminations will not be suitable for this operation mode because eddy-currents will be significant and will affect the performance of the EMQs.

SSW Measurement Results

The SSW measurement results on all the EMQs are presented in this section. The measurements are performed within a range of ± 5 mm in the x - and y -axis from the magnetic field center.

Table 3: Quadrupole Magnetic Field Center Deviation from Mechanical Center on Each EMQ

	Magnet names	Δx [mm]	Δy [mm]	θ_{roic} [mrad]
SSM-made Iron Core	DQ1#DW	-0.270	0.300	-0.403
	DQ3#D	0.500	0.080	0.897
	DQ5#D	0.610	0.260	1.233
EDM-made Iron core	DQ2#X	0.200	0.025	-0.074
	DQ4#X	0.060	0.158	-0.165
	DQ6#X	0.255	-0.205	-0.537

The mechanical center was determined by aligning the wire via motors to the optical alignment instruments. The magnetic center of quadrupole mode was measured by the SSW measurement. From Table 3, it suggests that the deviation between the mechanical center and magnetic field center are significantly large, where the largest deviation is 0.61mm. This indicates that the drift tube housing must have at least 0.65mm of material to machine in order to reduce the deviation within $\pm 50\mu\text{m}$. This requirement is achievable.

Currently, it is believed that poor mechanical reference points contributed to the mechanical misalignment of the EMQ, and hence the large deviation between mechanical center and magnetic field center. Mechanical assembly details and measurements have to be reviewed to further verify the above suspicions and to make proper improvements.

To determine the operating current, I_o , for each EMQ, the required field integral, $GL = G \times L_{eff}$, has to be determined for each EMQ using their individually measured L_{eff} . With the required GL value, the required I_o can be determined from the excitation curve of the EMQs.

Table 4: Field Integral for Magnets

Magnet names	SSM-made Iron Core			EDM-made Iron core		
	DQ1#D W	DQ3# D	DQ5# D	DQ2# X	DQ4# X	DQ6# X
L_{eff} [mm]	42.42	42.72	42.64	42.78	42.40	42.87
Field integral GL [T]	3.18	3.20	3.20	3.21	3.18	3.21

Table 4 tabulates the L_{eff} results obtained from HP measurements, and their corresponding GL value that must be achieved to meet the required G , which will be used to determine the magnets' I_o from the excitation curves.

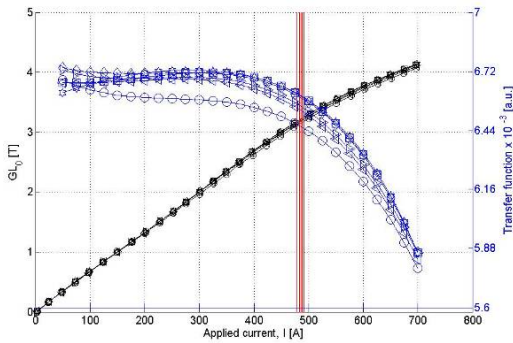


Figure 5: Quadrupole excitation curve.

Figure 5 shows the excitation curves and transfer function coefficient curves for all EMQs, curve-fitted with a polynomial of the 6th degree. It is worth noting that, the curves for EMQs with EDM-made and SSM-made iron cores are similar. Furthermore, the EMQs with EDM-made iron cores seemed to need a lower I_o value to achieve the required GL .

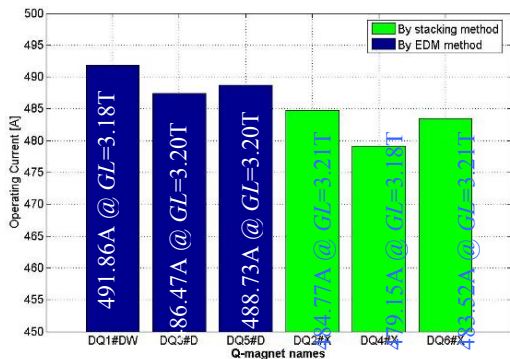


Figure 6: Operating current required for EMQs.

Figure 6 shows a bar chart of the operating current required for the EMQs. It indicates that the EMQs with EDM-made iron cores requires less current to achieve their corresponding GL value in order to meet the gradient specification. So, one advantage from using EDM-made iron cores is the reduction of electrical supply cost to operate such an EMQ.

DEVELOPMENT OF RC MEASUREMENT SYSTEM

The RC system has been developed, as shown in Figure 7, which includes a harmonic coil and a measurement stand. One EMQ is put onto the driving stand which can be adjusted along the x and y in the horizontal plane. The driving axis where the harmonic coil connected with can be moved vertically, so the harmonic coil can be push into the magnet aperture. A stepper motor and an angular encoder are connected with the driving axis in series. As the coil rotates inside the magnet aperture, the integral field, field harmonic contents and the magnetic center are measured at the same time. By carefully adjusting the EMQ position relative to the harmonic coil, the normalized magnitude of the dipole component can be reduced to less than 6×10^{-4} , and the magnetic center adjusted to within $\pm 3 \mu\text{m}$. Figure 7 shows a screenshot for the software interface and the measurement results.

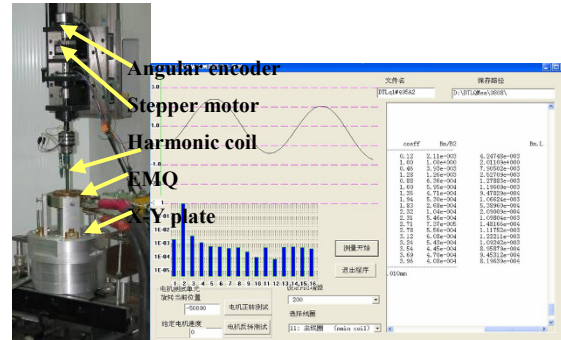


Figure 7: Harmonic measurement system and shot of measurement results.

CONCLUSIONS

Six EMQs for the eventual DTL test cavity has been manufactured and tested for its assembly reliability in IHEP. Current results suggest that many mechanical fine tuning has to be done. A review in the manufacturing process of the EMQ should be underway. Magnet measurement systems for the sole-purpose to develop these EMQs are within completion. The SSM-made iron core EMQs will be used.

ACKNOWLEDGEMENTS

We would like to acknowledge C. T. Shi, C. Yuan, L. Li, B. G. Yin, Q. L Peng and Z. Zhang of the Magnet Group for their assistance and help in magnet measurements, and Z. Z. Zhang and his fellow technicians for their continuing effort in producing the EMQs.

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