

# DESIGN AND CONSTRUCTION OF THE TWIN-APERTURE SUPERCONDUCTING QUADRUPOLE FULL-SIZE PROTOTYPE FOR THE STCF IRSM\*

W. Ma <sup>†,1</sup>, S. Wei<sup>2</sup>, L. Gao<sup>2</sup>, M. Liu<sup>1</sup>, J. Zhang<sup>3</sup>, Y. Zhu<sup>3</sup>, X. Wu<sup>1</sup>, J. Tang<sup>†,4</sup>

<sup>1</sup>High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei, China

<sup>2</sup>Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

<sup>3</sup>Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China

<sup>4</sup>University of Science and Technology of China, Hefei, China

## Abstract

The first Super Tau Charm Facility (STCF) final focus quadrupole prototype (named as QD1) has been designed, manufactured, assembled and tested at cold. The prototype is a full-size twin-aperture quadrupole magnet of the CCT type. The prototype reached the design field with no training quench and exhibit good field quality. In this paper, details of QD1 design, construction and test are reported.

## INTRODUCTION

The super tau-charm facility (STCF) is a symmetric, third-generation electron-positron collider under design which is proposed by the University of Science and Technology of China. It has a design goal of center-of-mass-energy ( $\sqrt{s}$ ) range from 2 to 7 GeV with a peak luminosity above  $0.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$  at  $\sqrt{s} = 2 \text{ GeV}$  CoM energy. To achieve STCF accelerator requirements, it is required to place symmetrically two high gradient and high field quality twin-aperture interaction region superconducting magnets (IRSM) at each side of the interaction point (IP) [1]. Twin-aperture IRSM is considered as one of the top technical challenging systems for the STCF accelerator, therefore, it is decided that the first stage of key technology R&D activity is to prototype a full-size QD1 coil, as the QD1 has the highest field gradient and is closest to the IP (thus, it has the least allowable design space).

## IRSM QD1 MAGNET DESIGN

### IRSM General Requirements

Figure 1 shows IRSM sketch layout. In each IRSM system, there are two sets of twin-aperture quadrupoles, QD1 and QF2, two sets of orbit corrector coils, Orbit Corrector Positron (OCP) and Orbit Corrector Electron (OCE), and a set of series connected anti-solenoid coils (AS). The magnetic front of QD1 and QF2 are positioned at 0.9 m ( $L^*$ ) and 1.8 m away from IP, respectively, and both focus quadrupoles are distributed at beam crossing angle of 60 mrad ( $2\theta$ ). Orbit corrector coils, such as a1, b1, a2, a3, b4, etc., are required to compensate for field errors and improve beam optics dynamics. The whole IRSMs are

operated inside the solenoid field of the detector magnet with a central field of 1.0 Tesla [2].

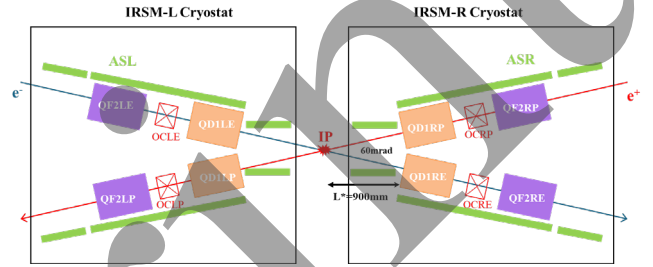


Figure 1: IRSM schematic layout (QD1RP - QD1 quadrupole at Right Positron beam; OCRP - Orbit Corrector at Right Positron beam; ASR - Anti-Solenoid Right; others are similar named.).

Table 1: Main Parameters of Final Focus Quadrupoles

Parameters	units	QD1	QF2	QD1_P
Gradient	T/m	50	40	50
Magnetic length	mm	400	300	400
Harmonics @ $r_{ref}$		$\leq 0.2\%$	$\leq 0.2\%$	$\leq 1.0\%$
Ref. radius, $r_{ref}$	mm	10	15	10
Beam pipe diameter, $\emptyset$	mm	30	50	Na
Coil front to IP distance	mm	900	1800	na

The key parameters of QD1 and QF2 are listed in Table 1. The beam pipe is designed to be room temperature and as a component of the cryostat. The beam pipe has an inner diameter of 30 mm and 50 mm for QD1 and QF2, respectively. Given the  $L^*$  of 900 mm and beam crossing angle of 60 mrad, this gives the minimum distance between two apertures of QD1 quadrupole about 54 mm. Iron-free CCT (Canted Cosine Theta) was selected over  $\cos 2\theta$  and serpentine as technique route for further R&D and prototype at this stage.

### QD1 Quadrupole Design

Figure 2 shows twin-aperture CCT QD1 windings and its magnetic field strength contour, and Table 2 lists its main parameters. The QD1 design uses 4 wires co-wind method, the wires are directly wound on to CNC machined aluminium alloy formers and jointed in series at

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<sup>†</sup> wbma@hmfl.ac.cn, jytang@ustc.edu.cn

termination box. It has two formers, has inner radius of 20 mm and outer radius of 26.8 mm. The winding uses canting angle of  $60^\circ$ , and in total 80 turns, at 602 A operating current, it can produce 50 T/m field gradient over 400 mm magnetic length. The coil itself has physical length of 460 mm. The maximum field at coil is 1.64 Tesla, at 600 A, the short sample performance is about 57% at 4.2K and 67% at

4.7 K. The coil operates with relatively comfortable current and temperature margin. The coil is designed to be wax vacuum impregnated.

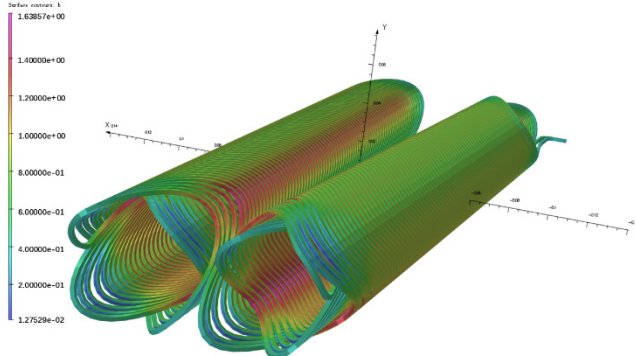


Figure 2: Field contour of QD1 coil.

Table 2: Design Parameters of QD1

Parameter	units	Value
Field Gradient	T/m	50
Current	A	602
$B_{max}$	T	1.64
Load line (4.2K/4.7K)		57%/67%
Turns	#	80
Groove canting angle	deg	60
Groove size	mm	1.9*1.9
Coil inner radius	mm	20.0
Coil outer radius	mm	26.8
Magnetic length	mm	400
Physical length	mm	460

Twin-aperture QD1 quadrupole is distributed side-by-side at angle of 60 mrad and 0.9 m away from the interaction point. It is common to have cross-talk issues which will introduce a dipole field at the centre of each aperture. Global and local edge correction methods [3] are adopted to compensate for edge effects ensuring excellent field quality locally at every point of the magnet. The field profile of all skew and normal harmonics up to 10<sup>th</sup> order of corrected QD1 are shown in Fig. 3. The integral of all harmonics at the reference radius of 10 mm are all less than  $2 \times 10^{-5}$  which is less than 1/10 of the requirement as listed in Table 1.

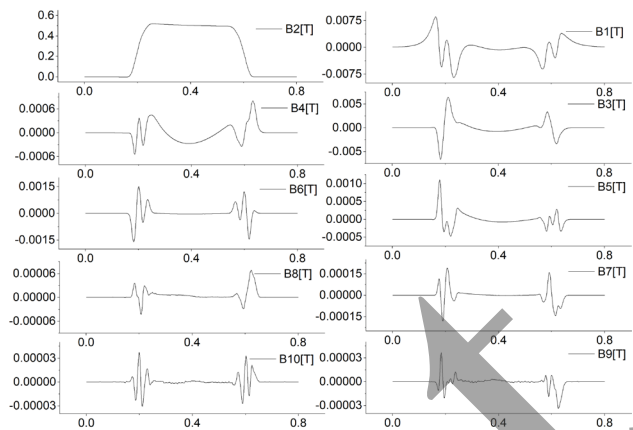


Figure 3: Normal harmonics of the  $e^+$  beam at 10 mm reference radius after local edge correction.

## QD1 PROTOTYPE

In the R&D stage, a full size twin-aperture QD1 quadrupoles prototype has been proposed to study and master key technologies, such as CNC machining and deformation control of delicate former, precise coil winding, quadrupole magnet assembly, cryogenic vertical test, and high resolution field measurement, etc.

Figure 4 shows the QD1 pre-prototype models main winding activities: copper wire winding process trial onto a 3D printed former to verify multi-wire co-winding process and define necessary winding tools. Figure 5 (a) shows QD1 prototype coil winding where four co-wound wires just finished winding the outer layer in the anodised aluminum CNC machined former. After winding the twin aperture coils and assembled them onto baseplate, the assembly was vacuum impregnated with paraffin wax. After impregnation, the coils were de-tooled, jointed and terminated. Figure 5 (b) shows the finished QD1 prototype coil with its joint cups and quench protection components on the top.

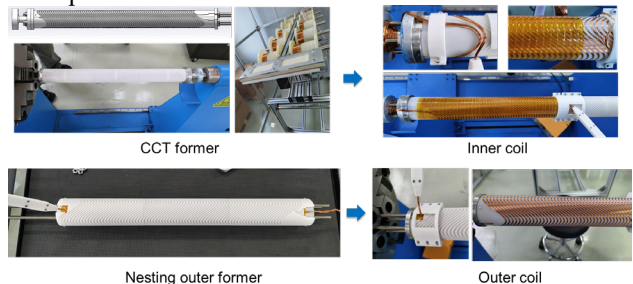


Figure 4: QD1 pre-prototype model.

## QD1 PROTOTYPE TEST

IRSM QD1 prototype was vertical tested in a bucket dewar, to perform both coil test and field test for characterization. The prototype was placed inside a bucket dewar with rotating coils probe inside a variable temperature insert (VTI). The probe has rotating coils to measure multiple field harmonics and hall-probes to measure field strength and field gradient. Figure 6 shows the test setup sketch and the assembled test coil before loading into bucket dewar.

The rotating coil has effective measurement length of 800 mm to integral cover the coil field profile.

The dewar is filled with helium and directly cooled to 4.2 K, no liquid nitrogen pre-cooling process was used, as the prototype coil has very limited cold weight. Figure 7 shows the coil top and bottom temperatures during cool down. It took about 6 hours for the coil to reach 4.2 K. The temperatures were monitored with two calibrated Cernox sensors. The test took place in May 2026 at High Magnetic Field Laboratory in Hefei, China.

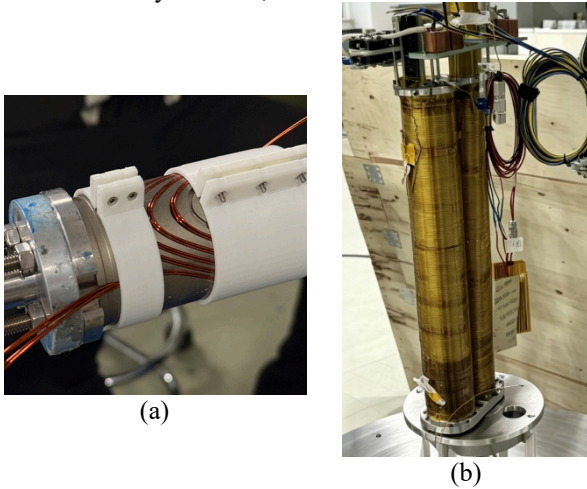


Figure 5: QD1 prototype coil winding and finished QD1 coil before cryogenic test.

The prototype coils voltages between the four co-wound wires are monitored with multiple taps within the joint cups. No training is observed during the test. Magnet was successfully ramped to 610A without training quench at slow ramp rate; another 610A ramping was performed shortly. After running down to zero, the magnet ramped to 650A afterwards at fast ramp rate. Figure 8 shows QD1 prototype coil's current and power supply voltage during ramp.

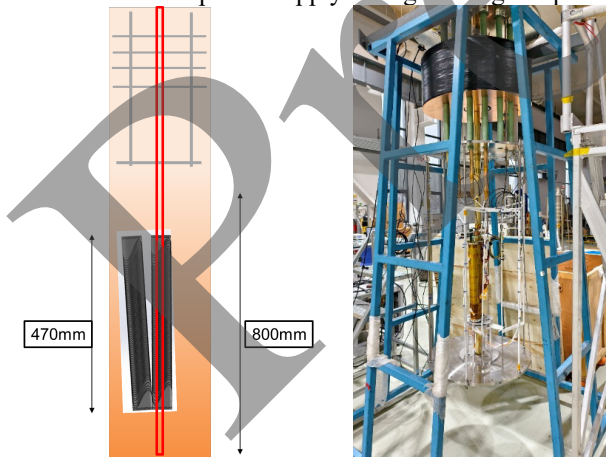


Figure 6: Test setup sketch and the assembled test coil before loading into bucket dewar.

The prototype coil field quality was measured with above mentioned field probe at prototype coil operating current of 605 A. The field quality is determined by the normalized coefficients resulting from the Fourier analysis of the flux density distribution across the magnet cross-section. These coefficients are determined by inductive

passive PCB coils rotating around the axis inside the coil. Figure 9 shows the QD1 coil high order normal and skew harmonics at 605 A operating current. The magnitude of undesired high-order harmonics are all below 10 units, which has 3.77 units and 3.06 units of  $b_3$  and  $a_3$ , -6.53 units and 6.66 units of  $b_4$  and  $a_4$ . It has negligible harmonics higher than 5<sup>th</sup> order. All high order harmonics are within prototype spec (<10unit), as listed in Table 2. Analysis of 3<sup>rd</sup> and 4<sup>th</sup> harmonics will be performed soon.

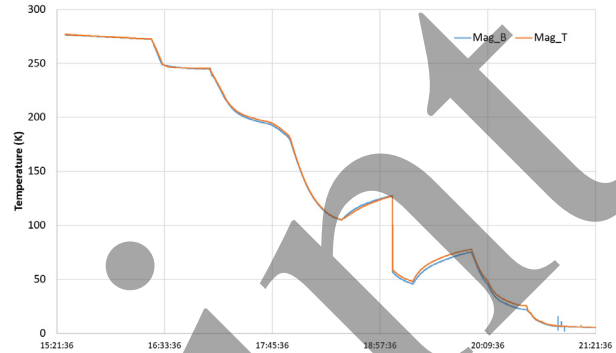


Figure 7: QD1 prototype coil cool down temperature curves.

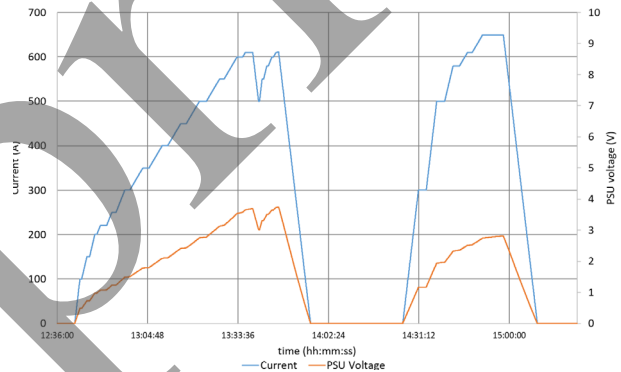


Figure 8: QD1 prototype coil current and power supply voltage during ramp.

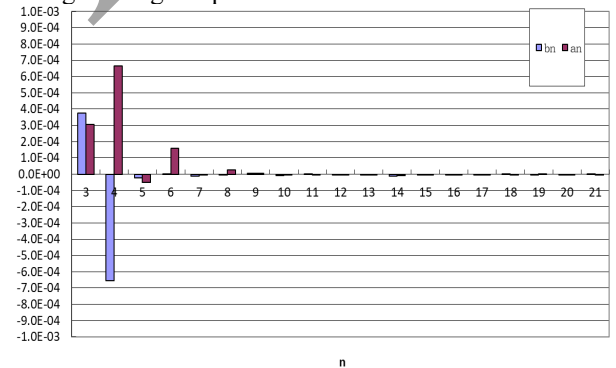


Figure 9: QD1 coil high order harmonics at 605A.

## CONCLUSIONS

This work presents the first full scale QD1 prototype built for the final focus quadrupole of the STCF study. A CCT superconducting magnet impregnated with paraffin wax is designed, built and tested. The magnet exhibits no training behavior and reaches 50A more than its design current. The field quality is excellent. Full scale IRSM system will be prototyped in the next R&D stage.

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