Development of prototype high gradient small aperture quadrupole magnets for HEPS-TF

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Introduction

- **A new storage-ring-based High Energy Photon Source (HEPS) will be constructed in China in the coming years.**

  beam energy 6 GeV
  circumference about 1300m
  natural beam emittance 60 pm•rad

- **High gradient small aperture quadrupole magnet is one of the key devices in the HEPS storage ring (In total about 200 such magnets).**
- **As a R&D project of HEPS, HEPS-TF has started in 2016 and is now in progress in China.**
- **One of the most challenging aspects in HEPS-TF is the development of two high gradient small aperture quadrupole prototypes.**

Introduction

- **Design requirement of prototype quadrupole magnets:**

Item	Unit	HQL	HQS
Bore diameter	mm	25	25
Field gradient	T/m	80	90
Magnetic length	mm	694	200
Minimum gap between adjacent poles	mm	11	11
Minimum gap between adjacent coils	mm	16	16
Longitudinal mechanical length	mm	<779	-
Magnet half transverse size	mm	<317	<317
Reference radius	mm	5	5
Systematic multipole field content	1×10^{-4}	≤1	≤3
Non-systematic multipole field content	1×10^{-4}	≤3	≤10

- **Design challenges:**

  High field gradient;

  High field quality;

  Small bore diameter;

  Limited pole width and mechanical boundary condition.

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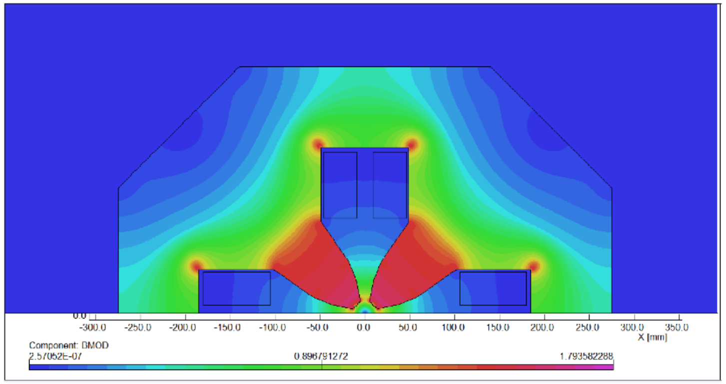
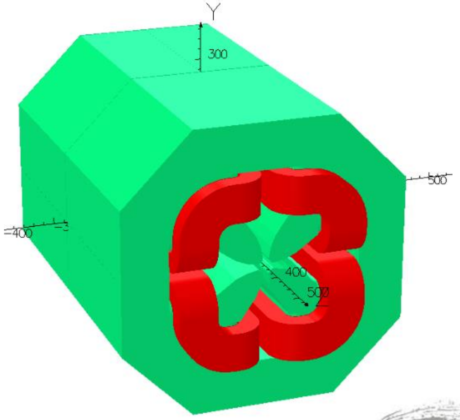
Magnet design of HQL

- **For small aperture quadrupole magnet, the non-systematic field harmonics are more sensitive to pole profile errors.**
- **Precise machining precision is required to obtain the high field quality.**

Overall design:

- **Common solid iron (DT4) for core material, four-piece structure;**
- **Saddle coil is selected:**
  - **Increase the magnetic efficiency;**
  - **Reduce the magnetic saturation in the return yoke;**
  - **Reduce the effect of material non-uniformity on field quality ;**
  - **Enhance magnet rigidity.**





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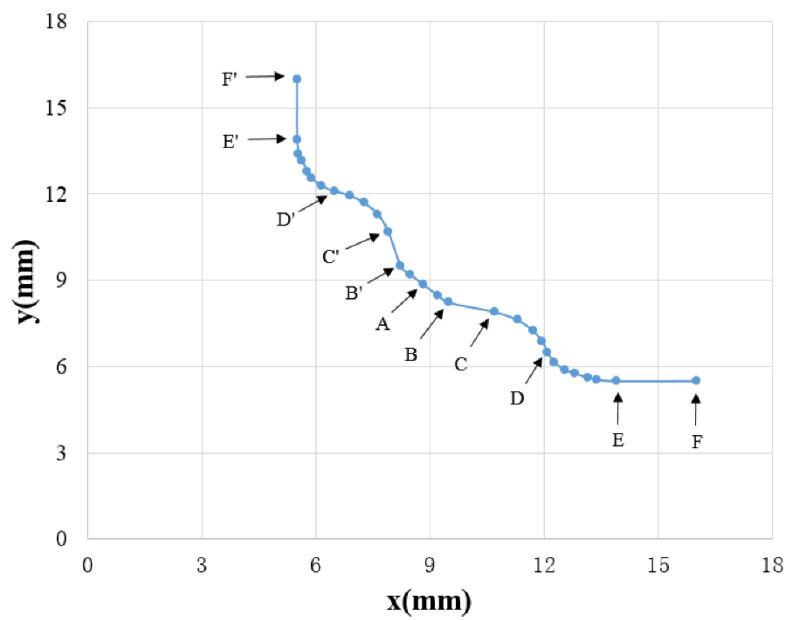
Overall design considerations

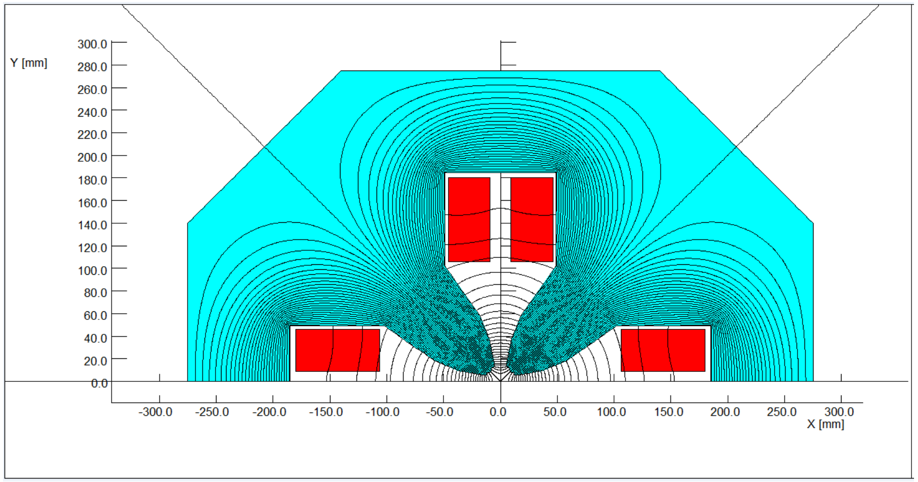
- **Hollow copper conductor for the coil.**
  - → **Water cooling system.**
- **Small current density to reduce magnet power and operation cost.**
  - → **Increased magnet transverse dimension.**
- **Sufficient magnetic optimization.**
- **Special pole shape to meet the 11mm gap between adjacent poles.**
- **Smooth pole profile, compatible with industrial fabrication technique.**
- **Reasonable electrical and water circuit parameters.**

Magnetic field calculation

- **2D and 3D magnetic field calculations are performed by OPERA.**
- **Special pole shape is adopted to meet field quality requirement, the 11 mm gap between poles and is convenient to be machined.**
- **The concave part of the pole: arcs with a radius of 2mm+ tangents.**
- **In 2D each systematic multipole field is less than 0.35 unit (1×10^{-4}).**



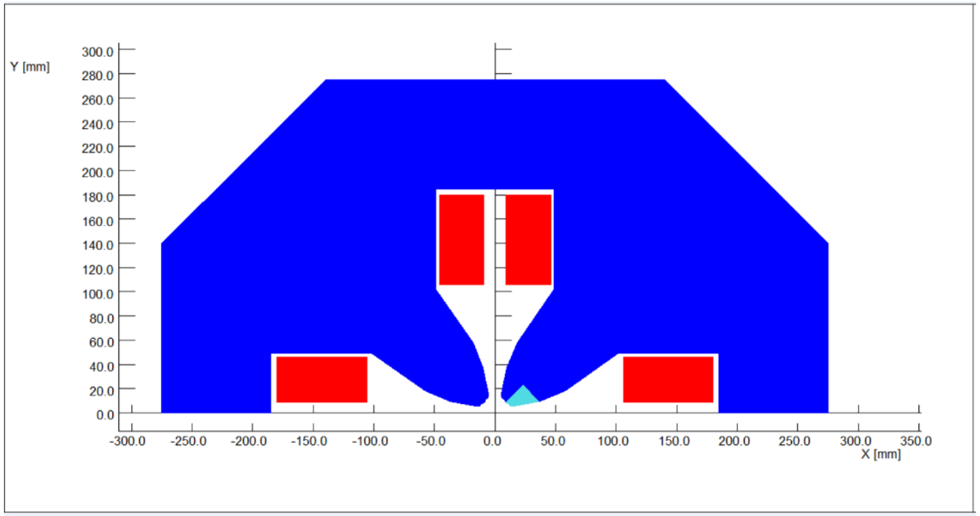
Optimized pole



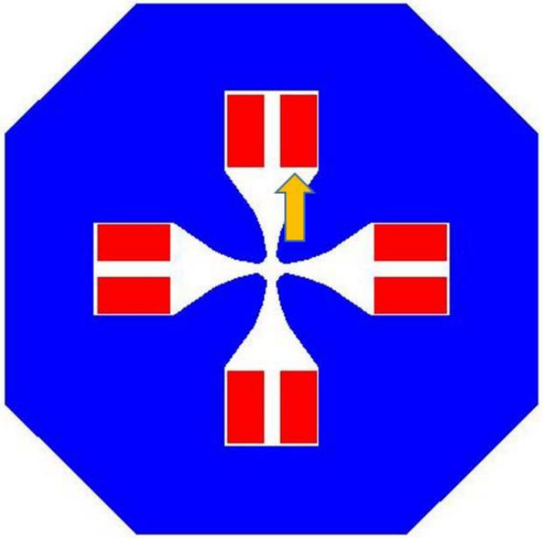
2D flux lines

Field error analysis

- **Pole shape error:** **Random pole position error with a maximum of 0.01 mm will introduce sextupole field, typically about 1 unit (1×10^{-4}).**
- **Magnetic property non-uniformity:** **3% deviations of iron BH property in the pole tip region will introduce sextupole field about 0.4 unit. (Case 1)**
- **Assembly error:** **only one pole moving up 0.01 mm will introduce sextupole field about 1 unit . (Case 2)**



Case 1



Case 2

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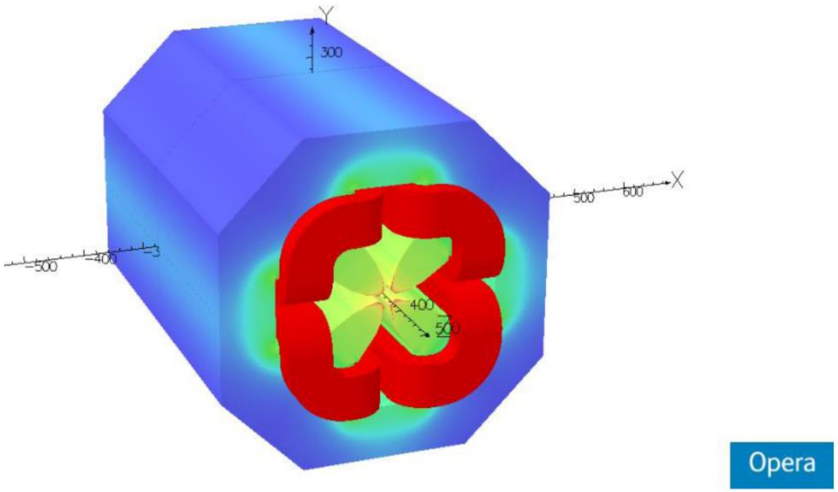
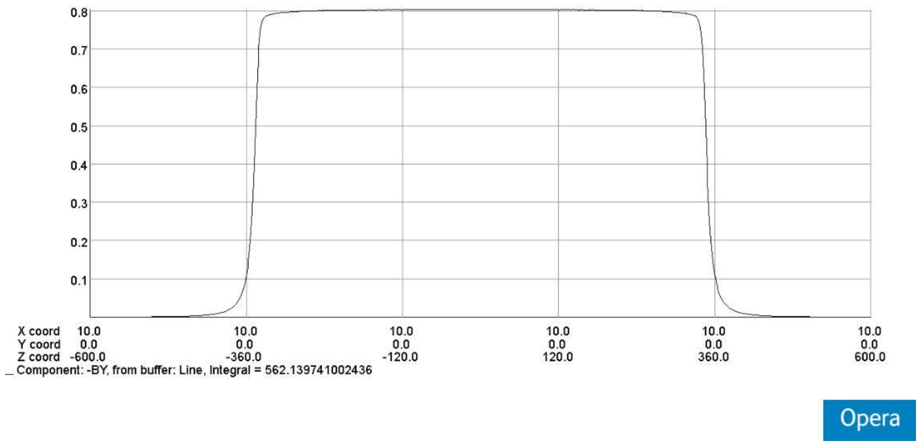
3D magnetic calculation



OPERA-3D model



Field distribution along longitudinal direction

- **Central magnetic field gradient of 80 T/m is achieved.**
- **Without pole end chamfer, the calculated integrated field harmonics are all close to zero.**

Design parameters of HQL

- **Main design parameters of the quadrupole magnet HQL:**

Item	Unit	Value
Ampere-turns per pole	AT	5162
Coil turns per pole		32
Excitation current	A	161.3
Conductor size	mm	8×8, ∅5, r1 (Oxygen free copper)
Current density	A/mm^2	3.7
Resistance of whole magnet	Ω	0.11
Inductance of whole magnet	H	0.061
Voltage drop	V	17.3
Joule loss	kW	2.8
Water pressure	Kg/cm^2	6
Water circuits		4
Water temperature rise	°C	5.5
Core width and height	mm	550×550
Core length	mm	688
Net iron weight	kg	1180
Net conductor weight	kg	100

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Magnet design of HQS

- The basic design of HQS is very similar to that of HQL.
- Main difference:

  1) Removable poles: achieve higher field gradient by replacing the pole material from pure iron to Vanadium Permendur;

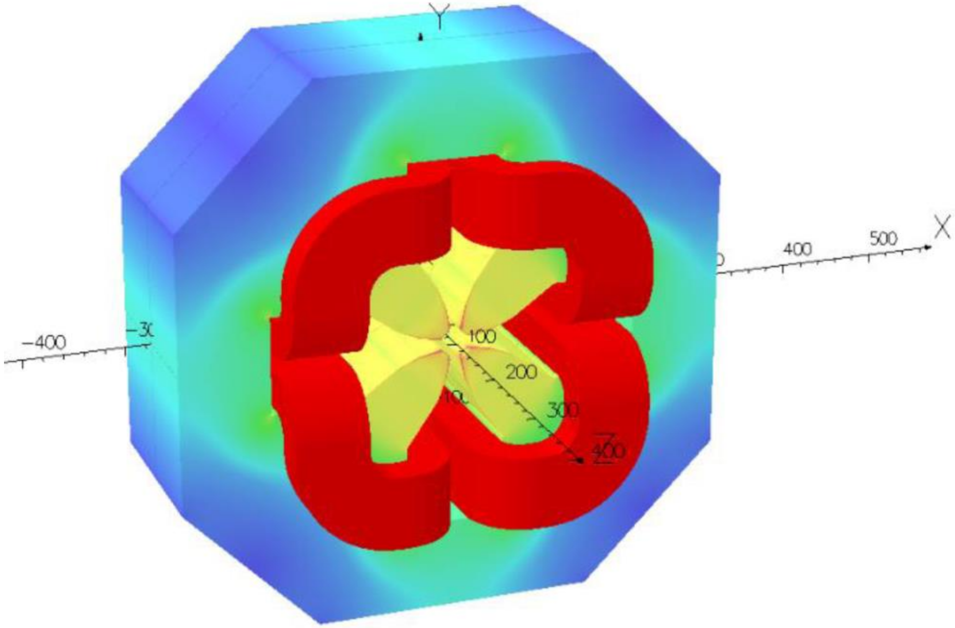
  2) Chamfer at the pole end : 2.2 mm ×60° to improve the integrated field quality.

2D field error analysis

- The field harmonics introduced by non-uniformity of iron core magnetic property significantly increase.
- 3% deviations of iron magnetic property in the pole tip region will introduce a sextupole field as large as 3.8 unit at the nominal excitation current of 205.5 A for HQS.

3D field calculation of HQS

- **At the nominal excitation current of 205.5 A, the field gradient of HQS reaches 90 T/m with pure iron DT4 poles.**
- **The integrated field harmonics are all smaller than 1 unit.**



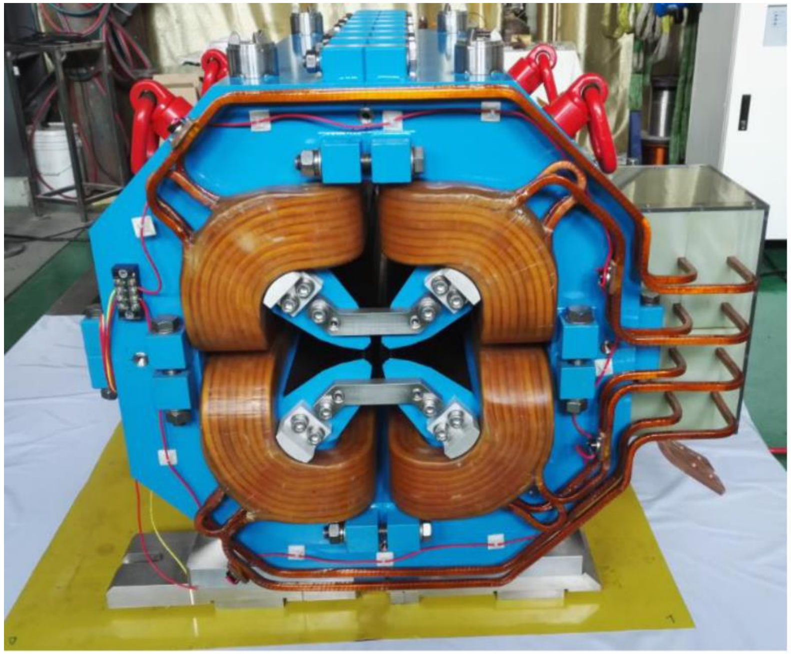
3D model of HQL

Magnet fabrication

- **The global mechanical precision for HQL and HQS are better than ±0.02 mm and ±0.03 mm, respectively.**
- **The requirements on non-uniformity of the iron magnetic properties are both smaller than 3%.**
- **The yoke of the short HQS magnet was manufactured with wire-cutting technique after the assembly of the upper and lower half yokes.**
- **Each quadrant yoke of long magnet HQL was manufactured with a CNC machine, and then the four quadrants were assemble together.**

Magnet fabrication

- The mechanical accuracy of the prototypes was examined by 3D CMM.
- The mechanical precision of HQS yoke met the requirement.
- For HQL, the measured precisions of the bore diameter and four 11 mm gaps between adjacent poles were within ±0.02 mm, but the pole contour exceeded the mechanical precision requirement.



Fabricated HQL magnet

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Field measurement results

Hall probe system measurement result

- **Prototype HQS magnet.**

- **The measured field gradients:**

I (A)	Field gradient (T/m)	
	Soft iron poles	Vanadium Permendur poles
205.5	88.4	98.7
222	91	104

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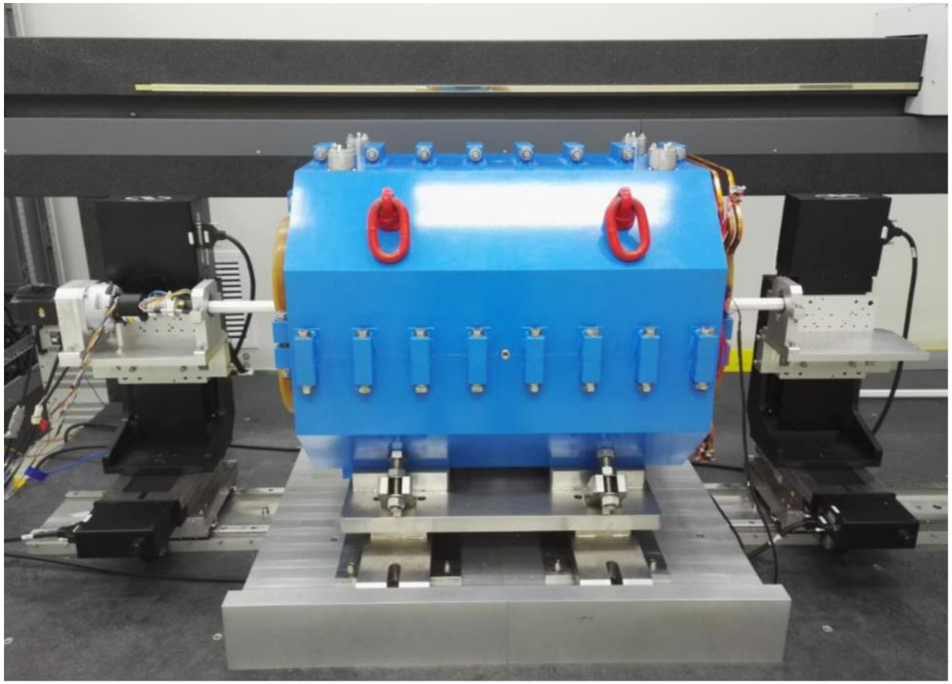
Rotating coil field measurement result

- **A new rotating coil field measurement system based on 3D CMM machine was developed.**
- **Main features include: ceramic rotating shaft with radial measurement coils, fast digital integrator FDI2056, and two dimensional translation platform.**



HQL magnet under rotating coil field measurement

Rotating coil field measurement result

HQS:

- **Systematic multipole field contents are all less than 1 unit with iron poles made of Vanadium Permendur**
- **Each non-systematic field harmonic is smaller than 3 unit.**

HQL:

- **Systematic multipole field contents are all less than 0.3 unit,**
- **Each non-systematic field harmonics met the requirement except the large sextupole field.**
- **Adjustment of sextupole field had been performed by adding iron shims on the pole end. Then all the measured field harmonics met the design specifications.**

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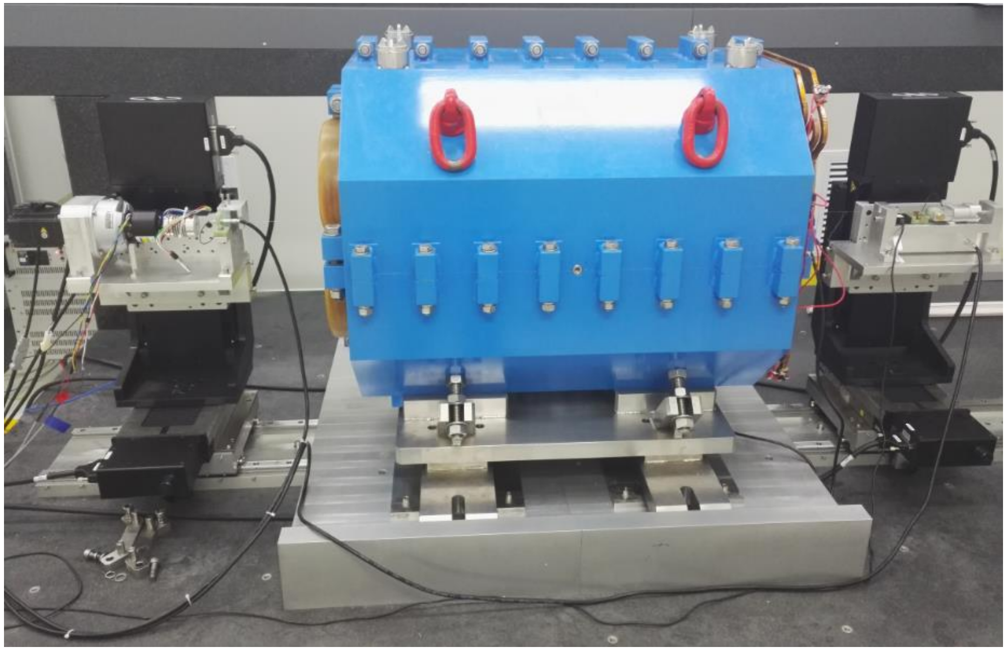
Stretched wire field measurement result

- **It was decided to measure the integrated field gradient of HQL by a new stretched wire field measurement system.**
- **Most of the hardware devices come from the rotating coil measurement system.**
- **At 161.5 A, the measured integrated field gradient of HQL was 56.25 T, which satisfied the required one of 55.52 T.**



HQL magnet under stretched wire field measurement

Conclusion

- **It is challenging to meet the requirement of small aperture quadrupole magnet for HEPS-TF.**
- **Two prototype high gradient quadrupole magnets with bore diameter of 25 mm have been successfully developed**
- **New field measurement systems have been built.**
- **The magnetic performance and mechanical boundary conditions of the two prototype magnets meet the requirement**
- **Field gradient more than 100 T/m is achieved in HQS magnet.**
- **The development of the two prototypes lays the foundation for the construction of the upcoming HEPS project.**

Thanks for your attention!