AC magnetic field measurement by a small flip coil system

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for

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IMMW 20 Jun4-9 2017 Diamond Light Souce

CSNS CHINESE ACADEMY OF SCIENCES

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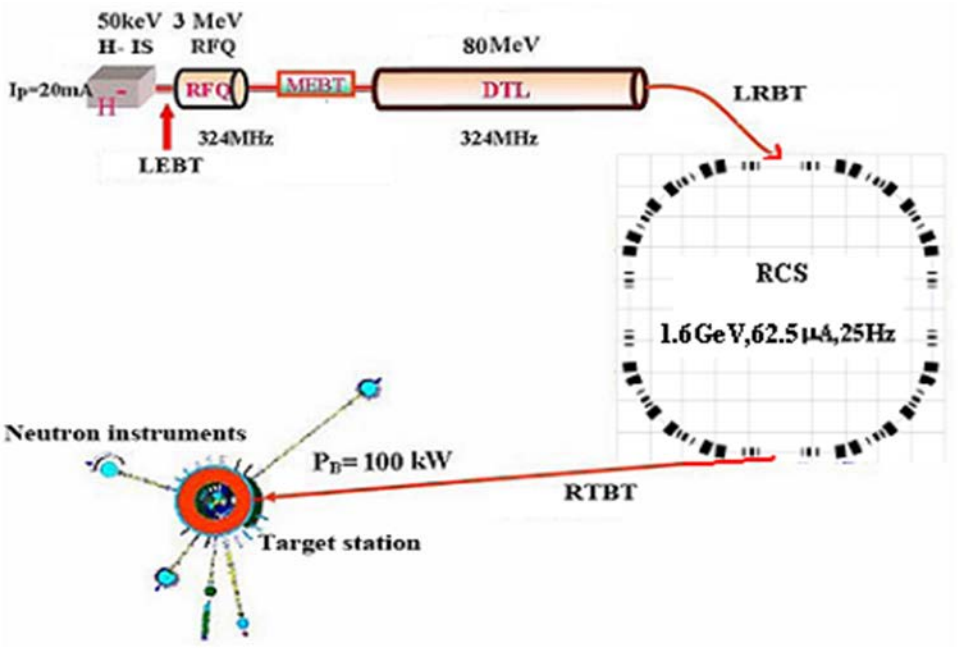
Outline

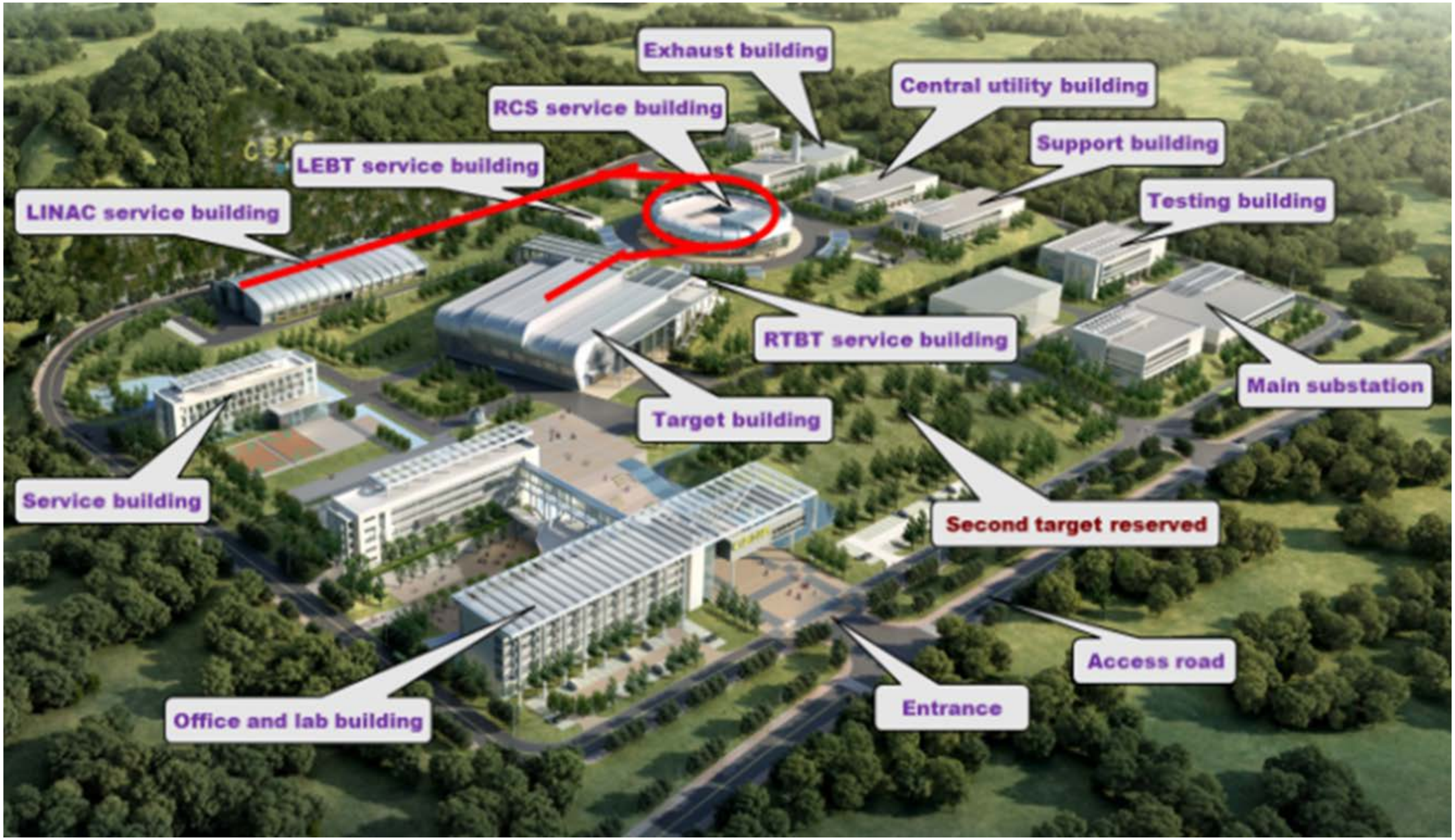
1、Overview of CSNS magnet system

The phase-I CSNS facility consists of an 80Mev H- Linac, a 1.6Gev Rapid Cycling Synchrotron (RCS) and two beam transport lines, a target station, and 3 instruments.

Project Phase	I	II
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	250
Linac type	DTL	+Spoke
Linac RF frequency [MHz]	324	324
Macropulse. ave current [mA]	15	40
Macropulse duty factor	1.0	1.7
RCS circumference [m]	228	228
RCS harmonic number	2	2
RCS Acceptance [πmm-mrad]	540	540
Target Material	Tungsten	Tungsten



1、Overview of CSNS magnet system

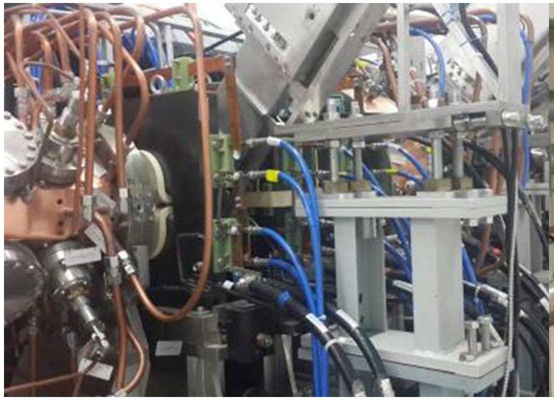


CSNS Facility Layout

1、Overview of CSNS magnet system

Overlooking the CSNS

1、Overview of CSNS magnet system



*MEBT-Q

*LRBT-Q

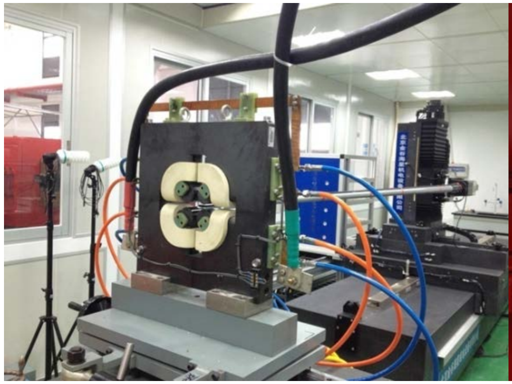
*LRBT-C

*RCS-Q

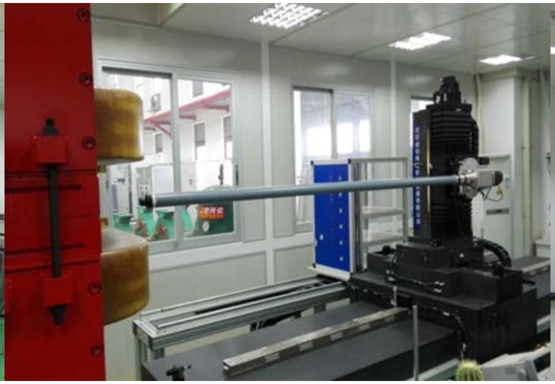
*RCS-B

*RTBT-Q

1、Overview of CSNS magnet system



*Hall Mea. system



*Flip coil Mea. System

*DTLQ Mea. System

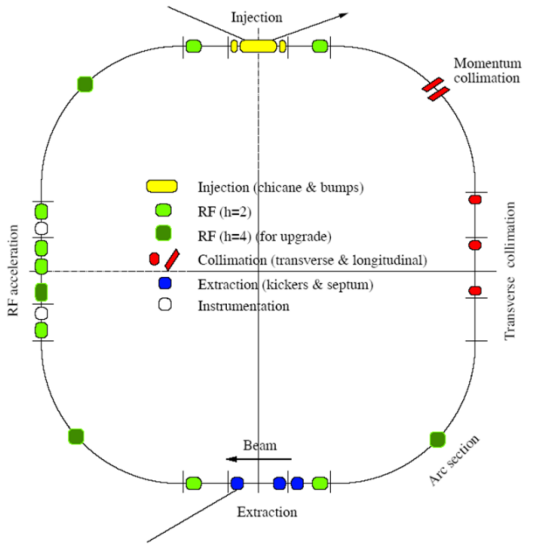
*Curved coil and long flip coil Mea. System

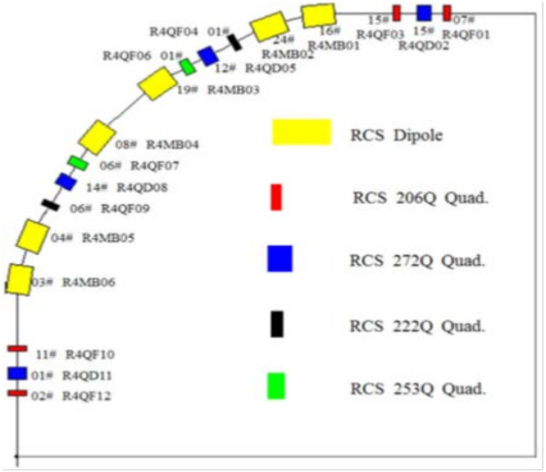
*DC&AC rotating coil Mea. System

*DC rotating coil Mea. System

1、Overview of CSNS magnet system

- Lattice of 4-fold symmetry, triplet configuration
- 1.6GeV at 25Hz
- 227.92m circumference
- 24 dipoles and 48 quads
- 540p mm·mrad acceptance
- four long straight sections for injection, acceleration, collimation and extraction
- 80-MeV injection energy for phase I
- Upgradeable with increased injection energy (beam current)

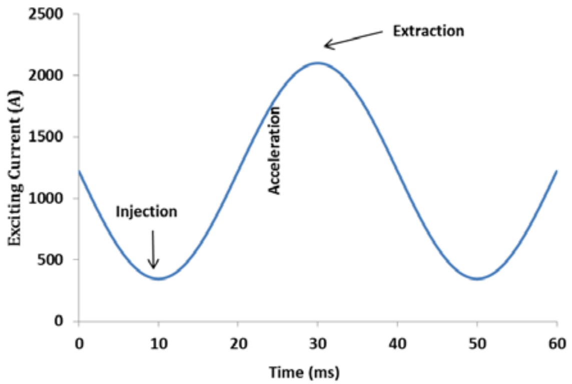




1、Overview of CSNS magnet system

	Dipole magnet	Quadrupole magnet			
Type	——	QA	QB	QC	QD
Gap or diameter	160 mm	206 mm	272 mm	222 mm	253 mm
Quantity	24	16	16	8	8
Max. field	0.9807T	6.60T/m	5.00 T/m	6.00 T/m	5.35 T/m
Min. field	0.1645T	1.11 T/m	0.839 T/m	1.01 T/m	0.897 T/m
Length of iron core	1980mm	320mm	810mm	370mm	510mm
Thickness of end plate	30mm	30mm	30mm	30mm	30mm
Effective magnetic length	2100mm	410 mm	900 mm	450 mm	620 mm
Operation Currents(DC)	1223A	813A	895A	859A	829A
Operation Currents(25Hz)	877A	580A	638A	612A	591A
Good Field Region(Inj.)	212mm×134mm(H×V)	90mm(radius)	123mm(radius)	98mm(radius)	114mm(radius)
Good Field Region(Ext.)	185mm×110mm(H×V)	73mm(radius)	99mm(radius)	83mm(radius)	99mm(radius)
Field quality ΔBL/BL	<8E-4	<8E-4	<8E-4	<8E-4	<8E-4

1、Overview of CSNS magnet system



Waveform of exciting current for the dipole magnet

$$I = I_0 + I_1 \sin(\omega t + \delta_1) + I_2 \sin(2\omega t + \delta_2) + \cdots + I_m \sin(m\omega t + \delta_m)$$

$$= I_0 + \sum_{m=1}^{\infty} I_1 H_m \sin(m\omega t + \delta_m)$$

I_0 ： DC bias
I_m ： the amplitude of current with frequency of $m\omega$
δ_m ： the phase of current with frequency of $m\omega$
T: time of one period
ω=2πf, f=25Hz :freq of I

Dipole:

$$B = B_{dc} + B_{ac} \sin(\omega t + \theta_1) + B_{2ac} \sin(2\omega t + \theta_2) + \cdots + B_{mac} \sin(m\omega t + \theta_m)$$

$$= B_{dc} + \sum_{m=1}^{\infty} B_{mac} F_m \sin(m\omega t + \theta_m)$$

The measurement contents include not only the conventional magnet but also the AC magnetic field, such as: BLdc+Blac, time dependent harmonics of the field and current………

1、Overview of CSNS magnet system

Magnet type	Content	Measurement system	Note
Dipole	BL, B0, L	Curved coil (hall probe)	DC
	△BL/B0L	Curved coil	DC
	BL, Phase difference(B and I)	Long flip coil	DC+AC
	BL, B0, L, Phase difference(B and I)	Small flip coil	DC+AC
Quadrupole	GL, G0, L	Hall probe	DC
	GL, Bn/B2, dx&dy	Rotating coil	DC
	GL, Phase difference(B and I)	Rotating coil	DC+AC
	GL, G0, L, Phase difference(B and I)	Small flip coil	DC+AC

The main task of the small flip coil system: the local AC magnetic field！

2、Measuring principle

Coil flip a semi-cycle: induce a modulation waveform
flip mode：0° -180°，180° -360°，
W=2πf, f=25Hz :freq of I
W1=2πf1, f1=1Hz, freq of coil
S0： area of the coil
M : coil turns

For small flip coil measurements, only the foundation magnetic field is considered, the dipole magnetic is:

$$B = B_{dc} + B_{ac} * \sin(\mathrm{w} * \mathrm{t})$$

$$S = S_0 * \cos(\omega_1 * \mathrm{t})$$

$$\Phi(\mathrm{t}) = \mathrm{B} * \mathrm{S} = (B_{dc} + B_{ac} * \sin(\mathrm{w} * \mathrm{t})) * (M * S_0 * \cos(\omega_1 * \mathrm{t}))$$

$$\mathrm{V} = -\frac{\mathrm{d}\Phi(\mathrm{t})}{\mathrm{dt}} = M * S_0 * [(B_{dc} + B_{ac} * \sin(\mathrm{w} * \mathrm{t})) * \omega_1 * \sin(\omega_1 * \mathrm{t}) - (B_{ac} * \mathrm{w} * \cos(\mathrm{w} * \mathrm{t})) * \cos(\omega_1 * t)]$$

2、Measuring principle

Measurement process

0 —ΔT1 (Coil static)→ t1 —ΔT2 (Coil flip)→ t2 —ΔT3 (Coil static)→ t3

The time periodΔT1, ΔT2 andΔT3 must be an integer multiple of the time period of AC current.

Coil static :induce a sinusoidal waveform, f1=0

$$V = -B_{ac} * \mathrm{w} * M * S_0 * \cos(\mathrm{w} * \mathrm{t})$$

$$\Phi(\mathrm{t}) = \int_0^t (B_{ac} * \mathrm{w} * M * S_0 * \cos(\mathrm{w} * \mathrm{t}))dt = M * S_0 * B_{ac} * \sin(wt)$$

At any time of ΔT3, the magnetic flux through the coil is:

$$\Phi(\mathrm{t}) = \int_0^{t_1} -Vdt + \int_{t_1}^{t_2} -Vdt + \int_{t_2}^{t} -Vdt = M * S_0 * (2 * B_{dc} + B_{ac} * \sin(wt))$$

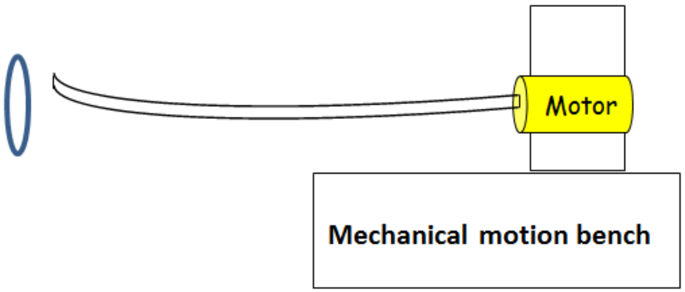
$\Phi(\mathrm{t}), \mathrm{I}$ —FFT→ $Bdc, Bac, Idc, Iac \ldots \ldots$

3.1、Motion bench

Since the motion positioning error will directly lead to the measurement error of the integral field, a marble platform with air bearing structure has been used.

Parameters	Value		
	X	Y	Z
Motion range(mm)	500	400	3500
Velocity(mm/s)	1~50	1~50	1~200
Positioning resolution(μm)	0.1	0.1	0.1
Positioning accuracy(μm)	±2	±2	±2
Positioning repeat accuracy(μm)	±1	±1	±1

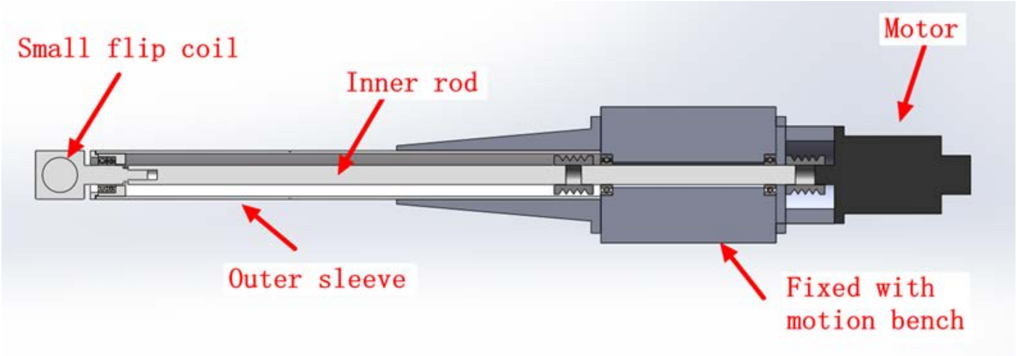
3.2、The design of rod



temperature change & gravity

Rod deformation

Coil swing



double layer structure:

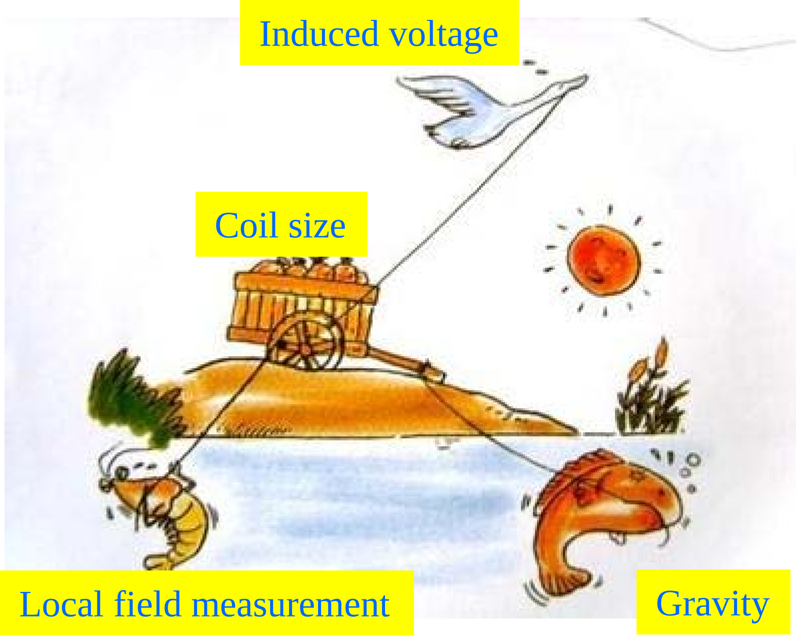
1、outer sleeve support the coil

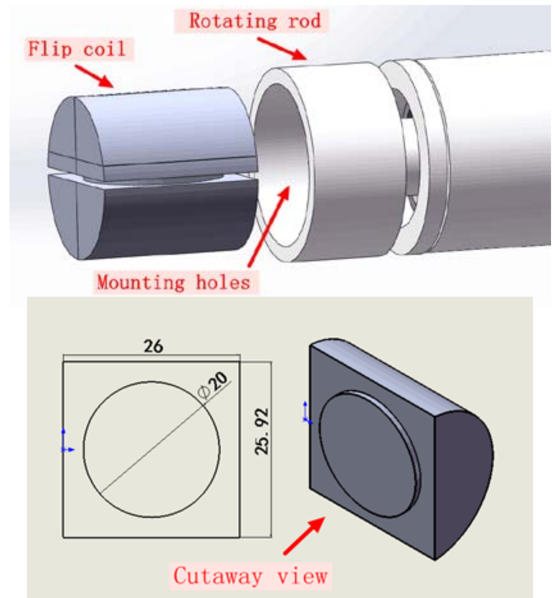
2、inner rod drive the coil rotation

3、outer sleeve is fixed on the motion bench and stronger than the inner rod

Even if there is a slight deformation, the structure ensures that the position of the flip coil geometric center is not changed during rotation

3.3、The design of small flip coil





$$V = -\frac{d\Phi(t)}{dt} = M * S_0 * [(B_{dc} + B_{ac} * \sin(w * t)) * \omega_1 * \sin(\omega_1 * t) - (B_{ac} * w * \cos(w * t)) * \cos(\omega_1 * t)]$$

Type: cylinder

Radius:10 mm

Coil turns:200

Diameter of wire: 0.1mm

Typical signal levels:

RCS-160B

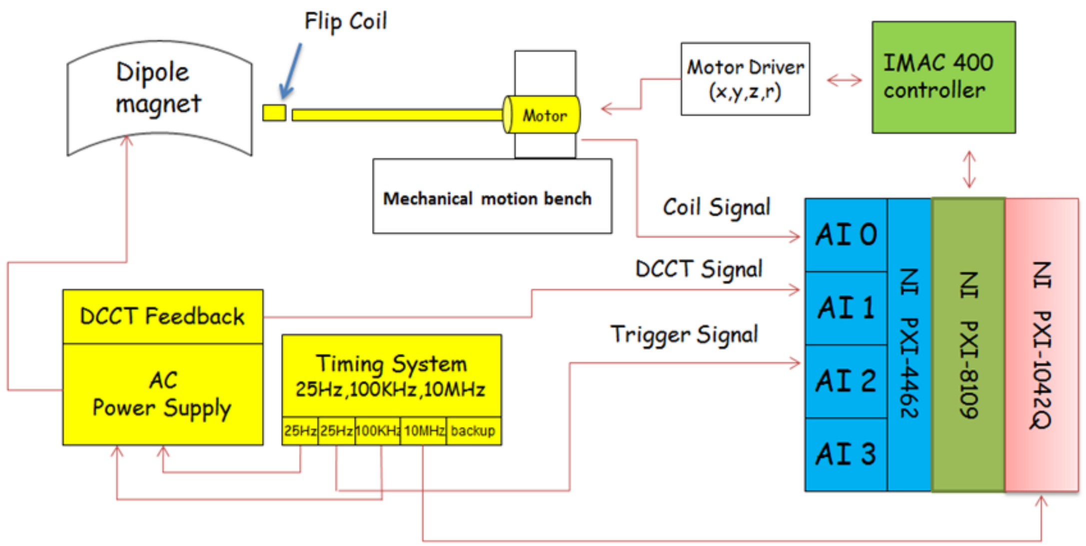
V≈0.113+4.028*sin(w*t) (Unit:V,)

RCS-206Q

V≈0.056+1.978*sin(w*t) (Unit:V)

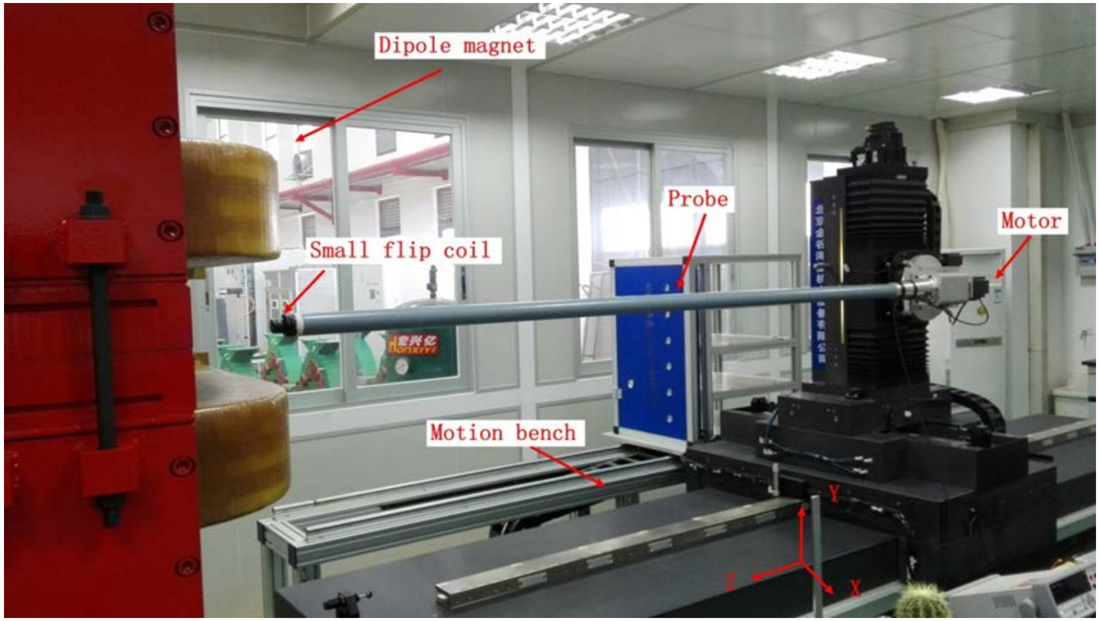
Speed: 0.5 cycle per second.

3.4、Simple control diagram



- PXI-4462: dynamic signal acquisition device
- PXI-8109: embedded controller
- PXI-1042Q: 8-slot chassis
- IMAC400: motor controller
- Timing system: clock reference, trigger reference

3.5、Assembly and testing



Overview of the system

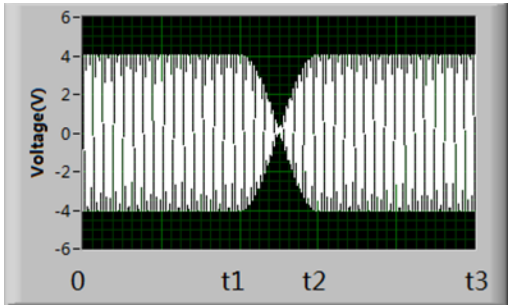
The eccentricity and vibration checking

4、Analysis of measurement results

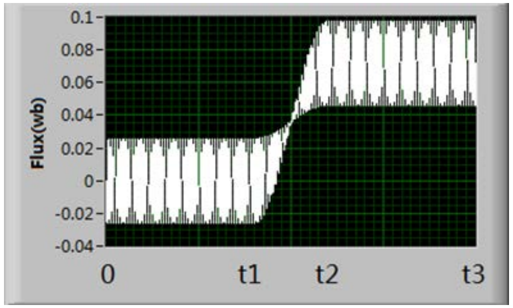
Measurement process

0 → $\Delta T1$ (Coil static) → t1 → $\Delta T2$ (Coil flip) → t2 → $\Delta T3$ (Coil static) → t3

The induced voltage from the coil must always be recorded during the time of 0 to t3, and then the data of the induced voltage is sent to the software for digital integration.



Induced voltage

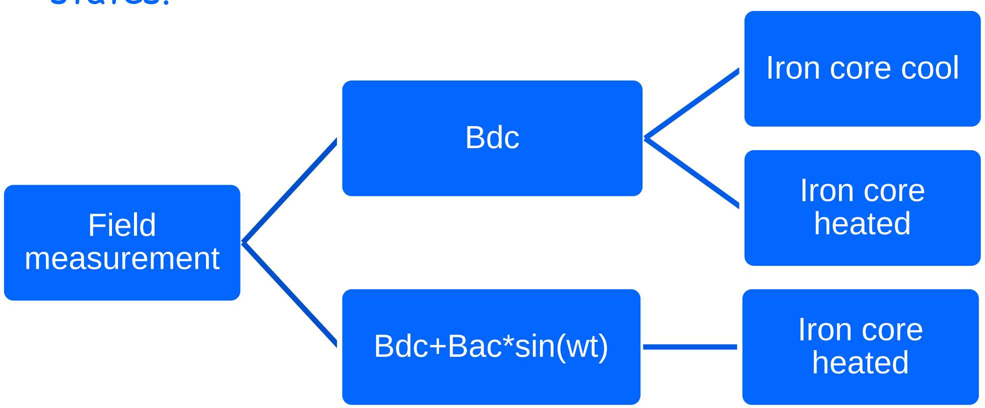


Flux

$\Phi(t), I$ $\xrightarrow{\text{FFT}}$ $Bdc, Bac, Idc, Iac \ldots \ldots$

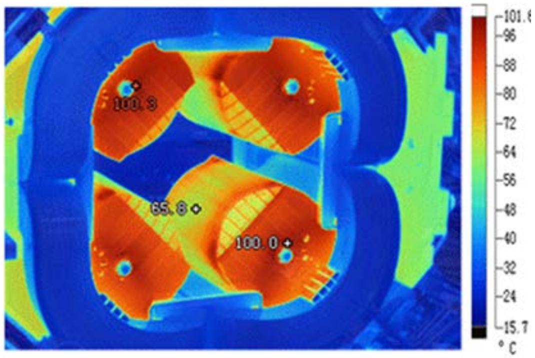
4、Analysis of measurement results

The research method is to check the parameters of integral magnetic field (BL), central magnetic field (B0), effective length (L) of the magnet in different states.

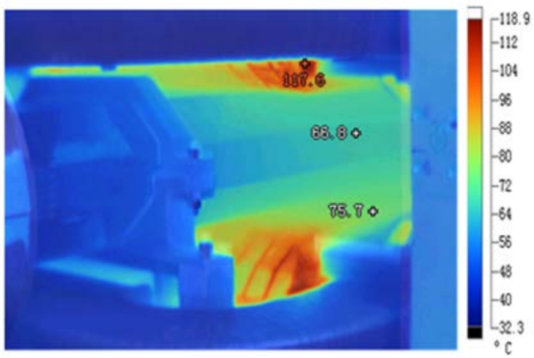


Firstly, the magnetic field change caused by temperature of iron core has been studied.

Measured by thermal imager



Quadrupole



Dipole

Part region of iron core had exceeded 100 degrees Celsius and in a stable state(AC mode).

4、Analysis of measurement results

The measurement results of the dipole magnet

Parameters	Excited by DC current		Excited by DC+AC current(Iron core heat)	
	Iron core cool $B(s)_{dc}$	Iron core heated $B(s)_{dc}$	DC component $B(s)_{dc.com}$	AC component $B(s)_{ac.com}$
BL(T*m)	0.60618	0.60674	0.60598	0.43190
B0(T)	0.57436	0.57456	0.57454	0.41083
L(m)	1.0554	1.0560	1.0547	1.0513

B0: $B(s)_{dc}$ (cool) → Increase 3.48E-4 → $B(s)_{dc}$ (heated) → Increase -3.48E-5 → $B(s)_{dc.com}$(heated)

BL: $B(s)_{dc}$ (cool) → Increase 9.24E-4 → $B(s)_{dc}$ (heated) → Increase -1.25E-3 → $B(s)_{dc.com}$(heated)

Analysis:

1、Compare core cool and cool heated of B(s)dc:

We think the temperature rise causes the geometrical dimensions of the magnet core to change and then affects the magnetic field.

2、Compare B(s)dc and B(s)dc.com at the situation of iron core heated:

The integral field becomes smaller(-1.25E-3). This is a very strange and interesting result.

4、Analysis of measurement results

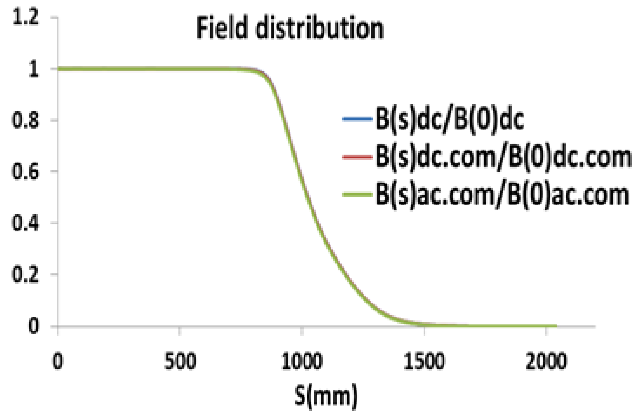
The field distribution along the beam trajectory has been studied in detail

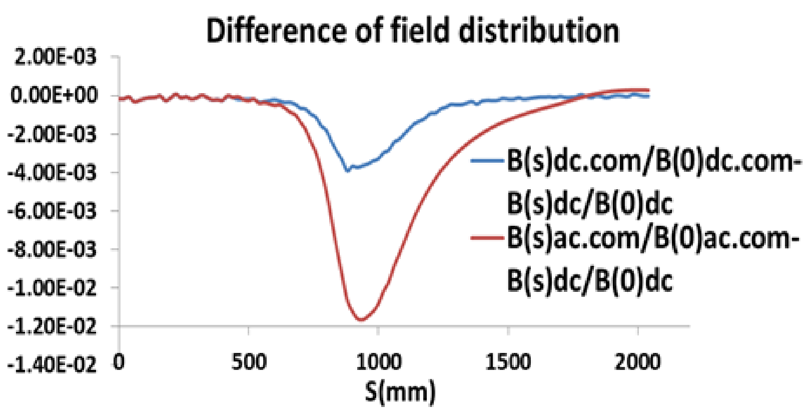
1、Each central magnetic field is selected as the reference value for normalization

2、The normalized DC component and AC component of DC+AC magnetic field were subtracted separately by the normalized pure DC magnetic field

3、There is a huge difference in the pole end region, which is also the most serious area of eddy current

4、we think that the eddy current is the main reason of this phenomenon





4、Analysis of measurement results

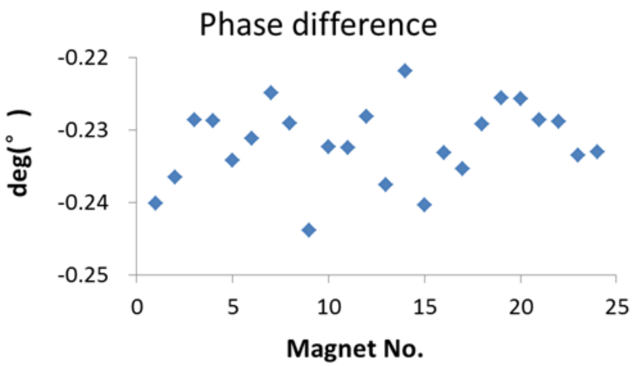
Phase tracking is very important for accelerator operation, so the phase difference between the magnetic field and the current is measured.

1、The results of the measurement by the long flip coil show that the phase difference between the magnetic field and the current is a fixed value;

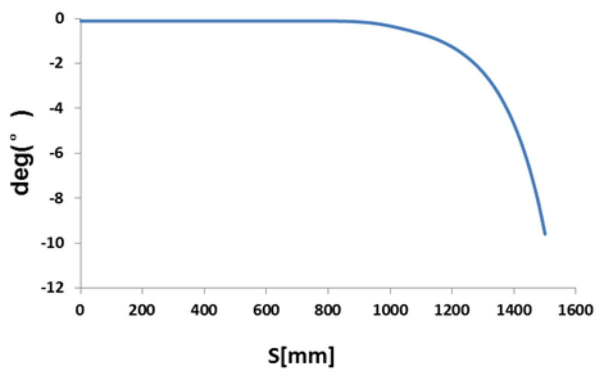
2、The largest difference in the phase difference distribution of all RCS-160B magnets is less than 0.03 °

3、Important discovery in the phase tracking has been found by small flip coil.

4、the phase difference between the magnetic field and the exciting current is constant (-0.11 degrees) in the middle region of the magnet pole, but the phase difference becomes bigger while out of the magnet end region.



The phase difference distribution of all RCS-160B magnets



The phase difference along the beam trajectory(s)

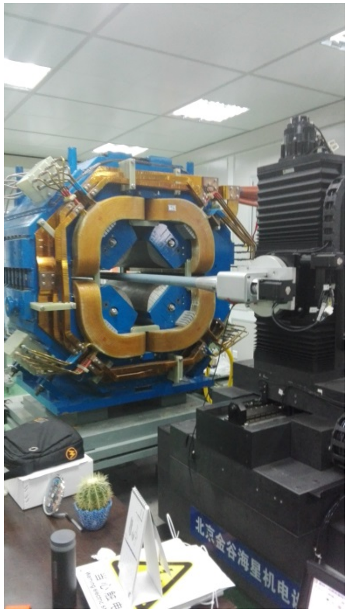
4、Analysis of measurement results

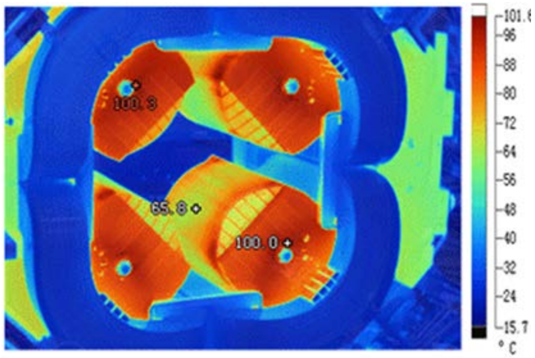
The four types of RCS quadrupole magnets have also been studied and the special phenomenon mentioned before is observed again

1、the largest magnet (272Q) and the smallest magnet (206Q) were selected to study the influence of the core temperature on the magnetic field

206Q: Room temperature → 100 degrees Celsius — BL increased by 1.9E-4

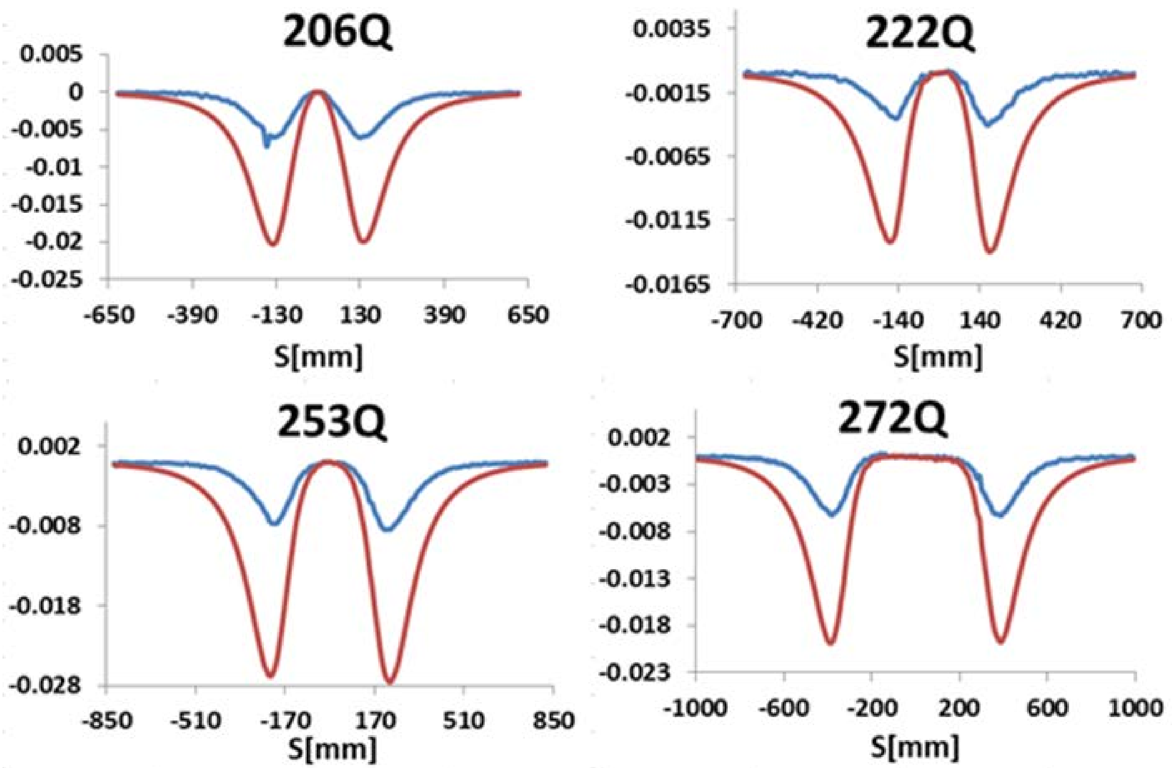
272Q: Room temperature → 132 degrees Celsius — BL increased by 7.7E-4





4、Analysis of measurement results

The quadrupole magnetic field distribution along the beam trajectory

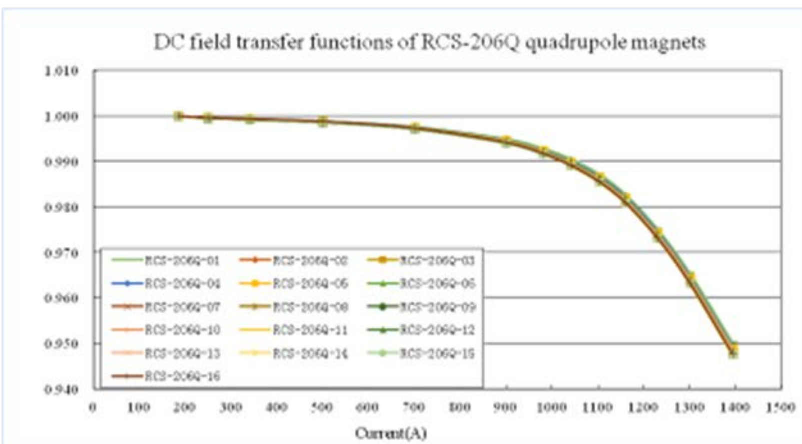


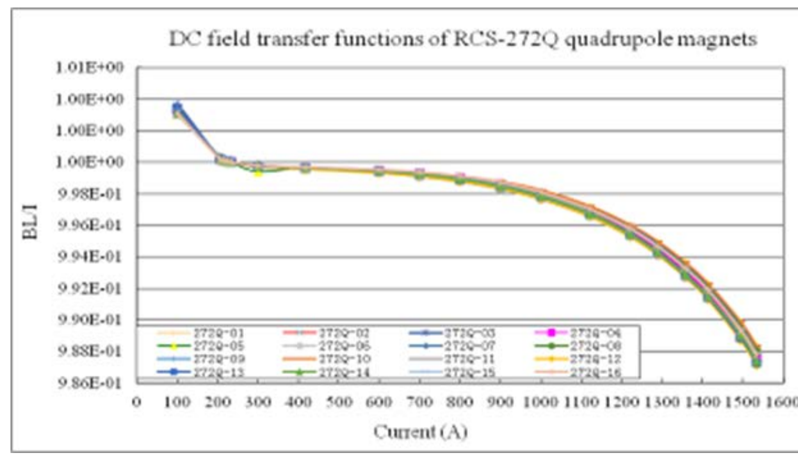
(Blue line: B(s) dc.com/B (0) dc.com -B(s) dc/B (0) dc
Red line: B(s) ac.com/B (0) ac.com -B(s) dc/B (0) dc)

4、Analysis of measurement results

The results of the measurement by the rotating coil

206QA		206QB		272Q	
Current(A)	Phase difference(deg.)	Current(A)	Phase difference(deg.)	Current(A)	Phase difference(deg.)
682+496*sin(w*t)	0.51	610.2+440.8*sin(w*t)	0.45	755.5+543.3*sin(w*t)	0.33
697.2+508.1*sin(w*t)	0.52	623.3+450.8*sin(w*t)	0.46	762.2+547.9*sin(w*t)	0.33
712.8+520.5*sin(w*t)	0.54	636.7+461*sin(w*t)	0.47	794.2+571.6*sin(w*t)	0.34
720.6+527*sin(w*t)	0.55	643.5+465.8*sin(w*t)	0.47	810.4+583.5*sin(w*t)	0.34
727.7+532.6*sin(w*t)	0.56	650+470.7*sin(w*t)	0.48	837.2+603.4*sin(w*t)	0.35
735.9+539.3*sin(w*t)	0.57	663.2+480.5*sin(w*t)	0.49	864.9+624.1*sin(w*t)	0.36
744.1+546.1*sin(w*t)	0.59	677.2+492.2*sin(w*t)	0.50	874.6+631.4*sin(w*t)	0.36





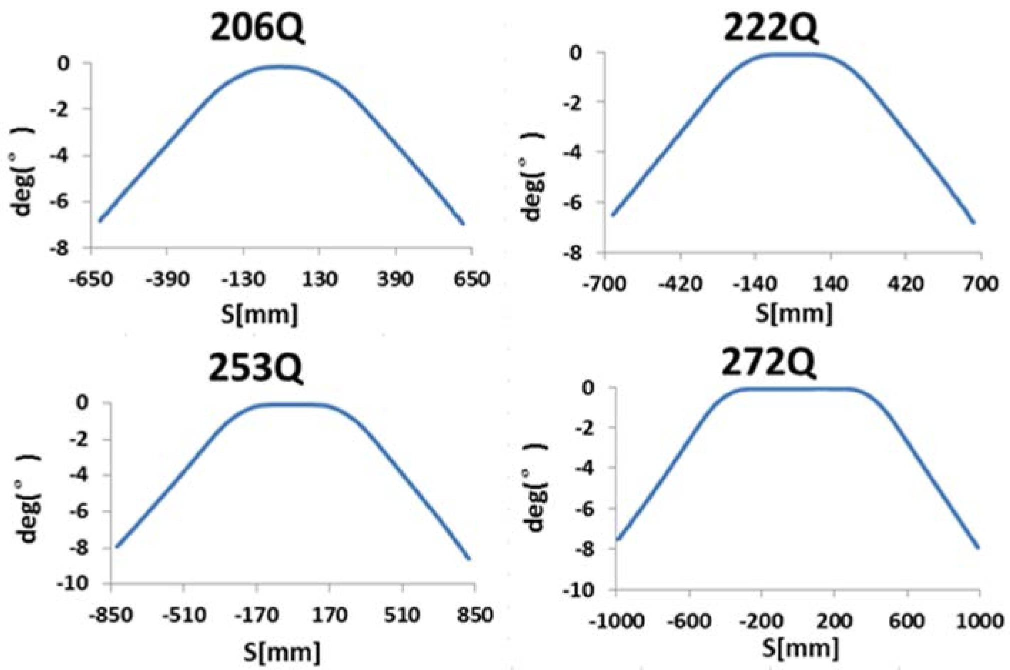
1、It shows that the phase difference is a fixed value, it is only related to the amplitude of current

2、Typically, the phase shift is only a weak function of amplitude of AC current and depends largely on the frequency.

3、We think that the saturation is the main reason. The DC field transfer functions show that the field non-linearity are 1.3% (272Q) and 5.2% (206Q).

4、Analysis of measurement results

The phase difference (between B and I) along the beam trajectory(s) (Quadrupole)



1、The phase difference between the magnetic field and the current is about -0.1 degrees in the center of the magnet, then it increases to nearly -1 degrees when close to the pole end plate area and continues to increase after out of the magnet.

2、It is further confirmed that the synchronization of the magnetic field and current is not consistent in all the area along the beam trajectory.

3、It is very helpful for the field tracking error correction while the accelerator is running.

5、 Conclusion

1、The development of the measurement system is a challenging work. It not only needs to solve the influence of temperature change, gravity and other factors on the deformation of the probe, but also need to analyze the AC magnetic field data.

2、Each type of RCS AC magnets has been studied. Many important phenomena and results, such as the center magnetic field, the effective length, phase difference and the eddy current effect, have been found.

3、Through the study, the performance of AC magnetic field is further understood.

4、These discoveries are very important and meaningful for the RCS accelerator operation, with these findings, the parameters of the RCS accelerator has been further optimized.

Thanks you for your attentions !