DC&AC Magnetic Field Measurement of the CSNS/RCS Quadrupole Magnet

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for

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Outline

1、Overview of CSNS/RCS magnet system

2、 Introduction of the measurement system

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4、The AC magnetic field measurement

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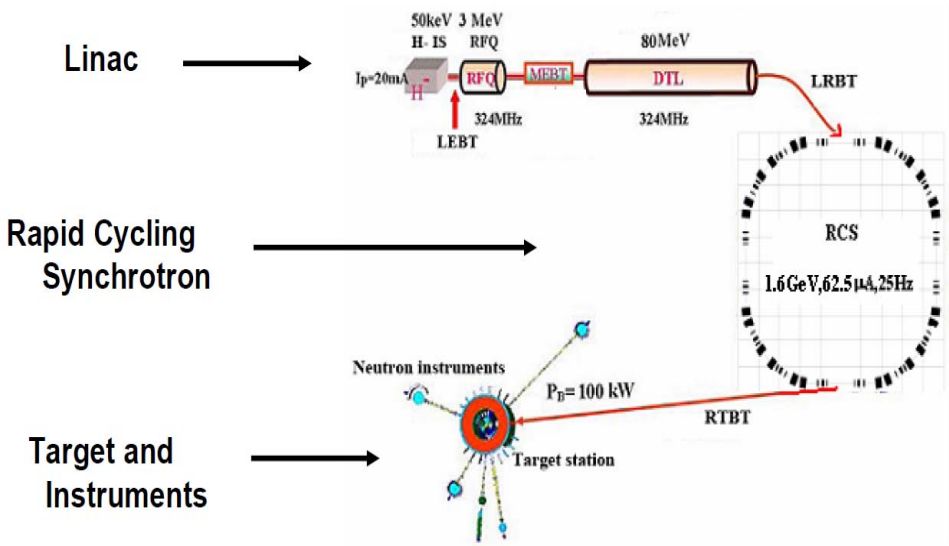
1、Overview of CSNS/RCS magnet system

1、Overview of CSNS/RCS magnet system

The phase-I CSNS facility consists of an 80-MeV H- linac, a 1.6-GeV RCS, beam transport lines, a target station, and 3 instruments.



	CSNS-I	CSNS-II
Beam power (kW)	100	200
Repetition rate (Hz)	25	25
Target number	1	1
Average current (μA)	62.5	125
Proton energy (GeV)	1.6	1.6
Linac energy (MeV)	80	132

The RCS has a fourfold symmetric lattice. Each super-period consists of 6 dipoles and 12 quadrupoles.

1、Overview of CSNS/RCS magnet system（continued）

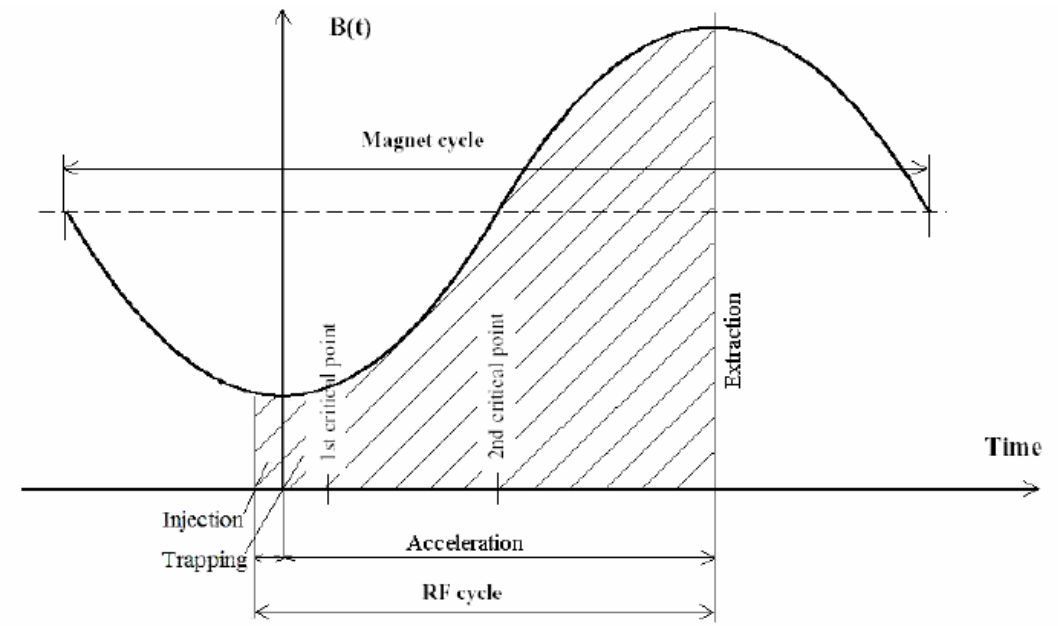
Parameter	RCS160B	RCS206Q	RCS265Q	RCS222Q	RCS253Q	RCS230S
Number of magnets	24	16	16	8	8	8
Field strength	B (T)	B' (T/m)	B' (T/m)	B' (T/m)	B' (T/m)	B'' (T/m^2)
Max. field	0.9807	6.6	5.1	5.0	5.35	40
Min. field	0.1645	1.1071	0.8555	0.8387	0.8974	
Gap or radius	160 mm	103mm	132.5mm	111mm	126.5mm	115mm
Effective field length	2.1m	0.41m	0.9m	0.45m	0.62m	0.2
Turns per coil	30	20	24	20	24	48
DC current	1222.2A	813.3A	866.7A	715.6A	828.7A	168.1A
AC current	872A	579.7A	617.7A	510A	590.6A	
Field quality	ΔBL/BL 8×10^{-4}	ΔBL/BL 8×10^{-4}	ΔBL/BL 8×10^{-4}	ΔBL/BL 8×10^{-4}	ΔBL/BL 8×10^{-4}	ΔBL/BL 5×10^{-3}
Good field region	±106mm	±90 mm	±120mm	±98mm	±114mm	±109mm
Resistance	21.5mΩ	11.3 mΩ	21.8 mΩ	12.1mΩ	17.3 mΩ	78.8 mΩ
Inductance	38.8mH	8.69mH	24.9mH	9.33mH	17.3mH	34.9mH

The parameters of the RCS magnets are listed in the table above.

1、Overview of CSNS/RCS magnet system（continued）

Compared to usual electron storage ring, the magnets of RCS have three distinct characteristics.

1、The dipoles and quadrupoles of RCS must be excited by a DC biased 25 Hz AC current with large amplitude since the energy ratio of extracted beam to injected one is very large.



1、Overview of CSNS/RCS magnet system（continued）

2、The magnets have larger apertures than usual ones. Because proton beam has a strong space-charge effect, and the practical way to reduce it is to enlarge the acceptance and consequently the magnet apertures.

3、 As waveform control is difficult for the magnets excited by the resonance circuit, the non-linearity of the magnetic field and inductance must be decreased as much as possible.

To study these issues, the prototype magnets for the CSNS/RCS had been fabricated. The magnetic field measurements are needed to verify whether the field quality can meet the RCS accelerator operation requirements.

A flipping-coil magnetic measurement system and a harmonic coil measurement system had been developed to perform the DC and AC field measurement.

2、 Introduction of the measurement system

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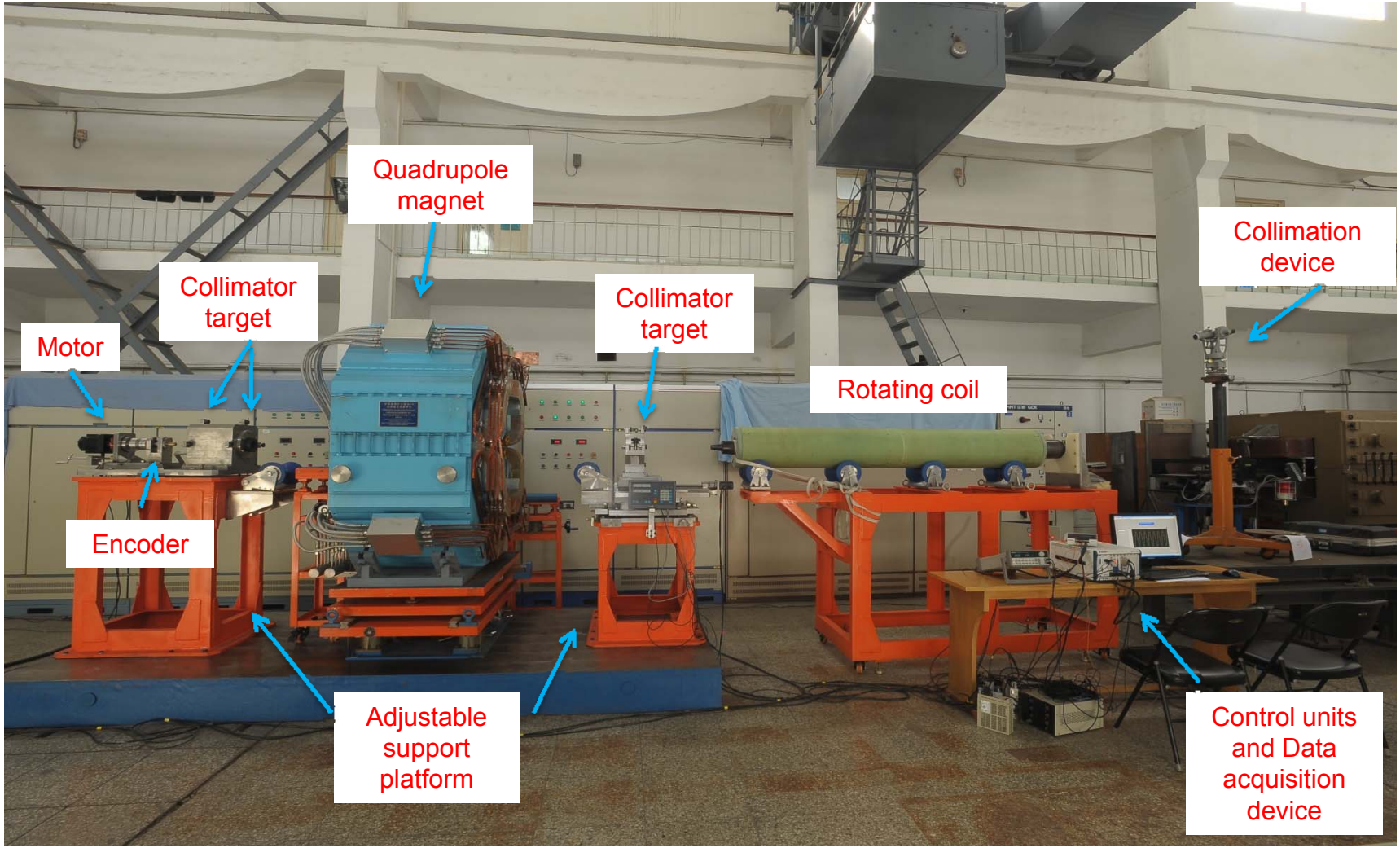
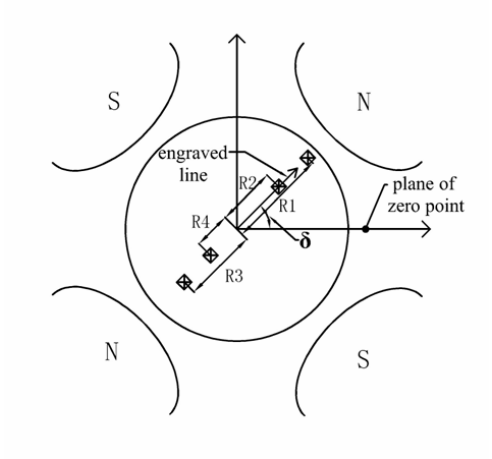
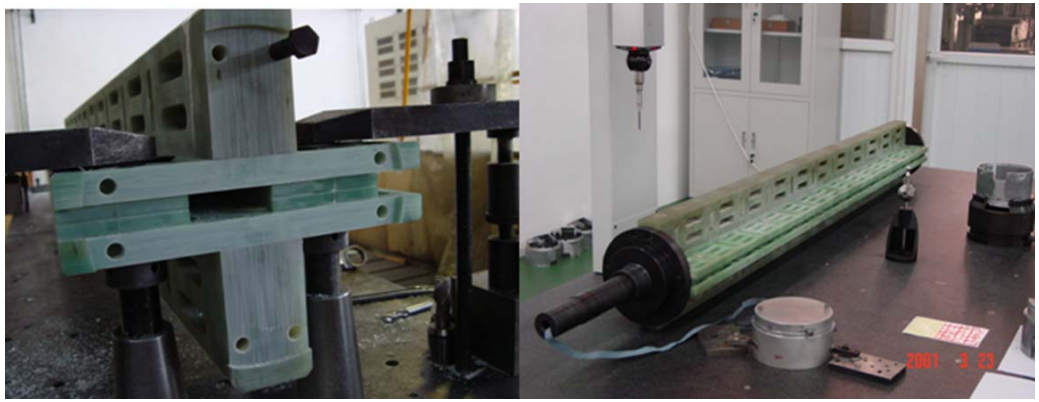


2、Introduction of the measurement system （continued）





1、The radial coil type with bucking structure has been selected. A main coil (outer coil) and a bucking coil (inner coil) are located at the plane of (R_1, θ), (R_3, $\theta+\pi$) and the plane of (R_2, θ), (R_4, $\theta+\pi$) respectively;

2、The material of the coil framework is fiberglass-reinforced epoxy (G10);

3、The length of the coil is about 2 meters that is 4 times the magnet aperture plus its effective length;

2、Introduction of the measurement system （continued）

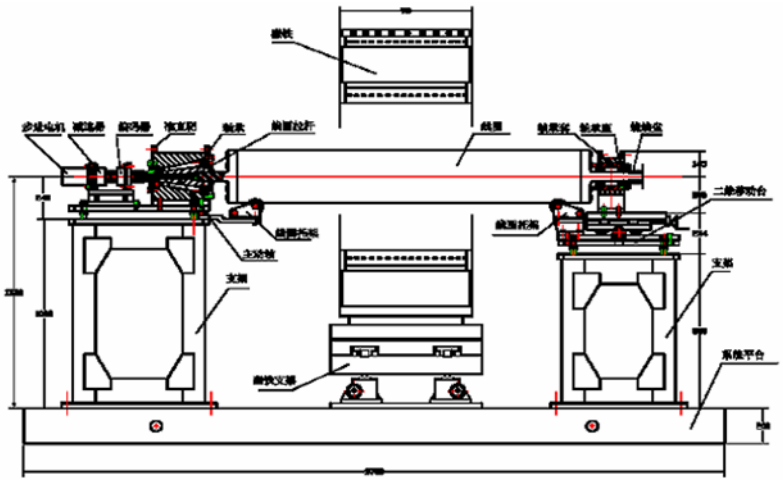
Magnet type	Prototype	QA	QC	QB	QD
Aperture diameter (mm)	308	206	222	272	253
R_1 (mm)	130	88		112	
R_2 (mm)	92.08	60.87		77.467	
R_3 (mm)	97.5	74.80		95.200	
R_4 (mm)	59.58	47.67		60.667	
Main Coil turns N_1 (DC)	80	200		120	
Main Coil turns N_1 (AC)	20	100		48	
Bucking Coil turns N_2	120	300		180	
ω(rad/s)	1.5708				

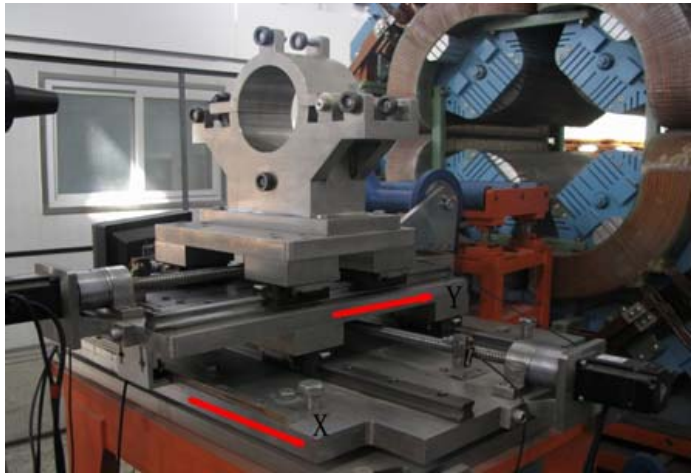
4、To reduce the costs, one kind of coil fit the two types of magnet;

5、A color-coded multifilar wire（MWS）is used for the coil winding. It consists of 20 strands, and each strand is 0.07 mm thick and 50 μm in diameter;

6、A part circle of the main coil was used to measure the AC field .

2、Introduction of the measurement system （continued）





1、In order to reduce the measurement error coming from the magnet eddy current and vibration, each end of the coil is supported by a bracket and then the coil is suspended inside the magnet aperture;

2、The master side, the slave side and the magnet platform can be adjusted to ensure that the center of the measurement coil is in the mechanical center of the quadrupole magnet.

2、Introduction of the measurement system（continued）

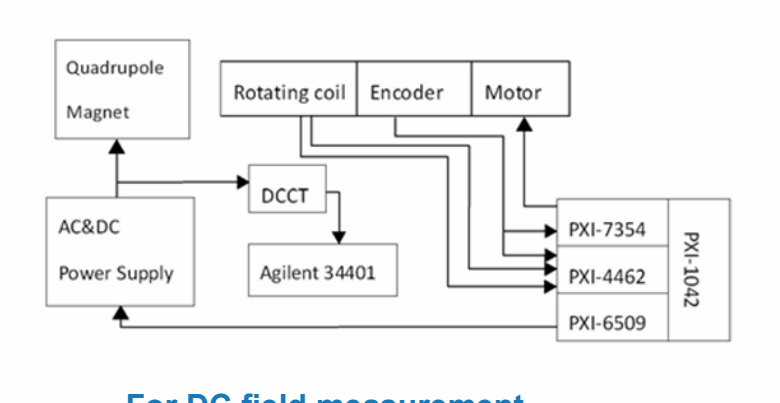
Input channels	4
A/D converter (ADC) resolution	24 *bits*
Sample rates (*fs*),	1 *kS/s* to 204.8 *kS/s*
Input Signal Range（*V*）	±0.316 to ±42.4(depending on gain)
Gain	–20,-10,0,10,20,30
Voltage Sensitivity	37.7 nV~5.05 μV

1、Since the induced voltage from the coil is very large and changes fast, a dynamic signal acquisition device PXI-4462 from National Instrument has been used;

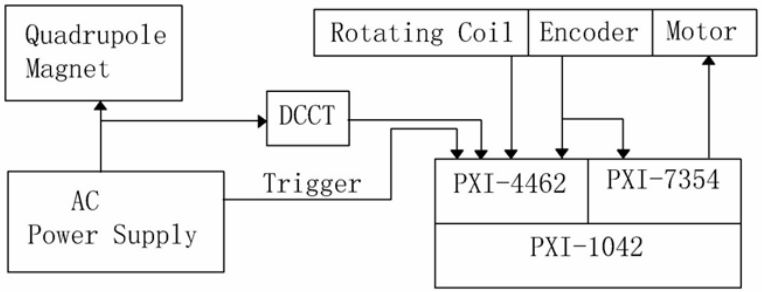
2、To test the reliable of the device, a calibrated voltage source was supplied to one input channel of the PXI-4462 from 0 to 10 V at a step of 0.1 V ;

3、The maximal deviation is less than 12 ppm.

2、Introduction of the measurement system（continued）



For DC field measurement



For AC field measurement

1、The simple control diagram of the measurement system as shown above (Left : DC, Right: AC);

2、A dedicated software was developed in LabVIEW code to identify the trigger signals which are from the encoder and power supply, it is very convenient to switch the function between the DC and AC field measurement;

3、The magnet current is controlled by the PXI-6509 device and monitored by DCCT;

2、Introduction of the measurement system（continued）

4、PXI-7354 is a motor control device, which is used to control three servo motors for their corresponding movement;

5、A high-resolution annular encoder (8192 resolutions/cycle) is seated on the drive shaft and looped to the PXI-7354 motion control device and the encoder signals are acquired by PXI-4462 at the same time;

6、The main coil and bucking coil were used to measure DC field. A part circle of the main coil was used to measure the AC field;

7、The induced voltage of the coils and sequence pulses of encoder (the trigger signal of the power supply)are recorded synchronously by the separate channels of the PXI-4462.

3、The DC magnetic field measurement

3、The DC magnetic field measurement

◆Measurement principle：

1、For the DC measurements, the standard radial coil technique has been used

2、The measurement coil rotates with an angular velocity ω in the magnetic field and θ=δ is the angular position at time t = 0, then θ=ωt+δ. The time dependent magnetic flux through the coil is then as

$$\Phi(t) = ML_{eff} \sum_{n=1}^{\infty} |C_n| (R_1^n - (-R_3)^n) \cos(n\omega t + n\delta + \theta_n)$$

Where M is the coil turns, Leff is the effective length of the magnetic field, Cn is a complex constant, the integer n is half the number of poles. R1 and R3 are the radii of the coil two sides with respect to the rotation axis.

3、The DC magnetic field measurement（continued）

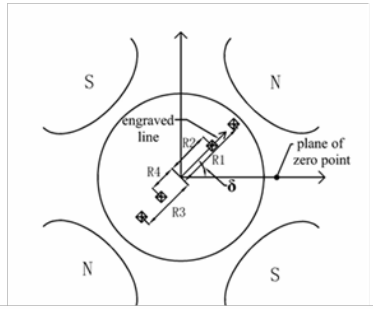
◆ Data acquisition and processing

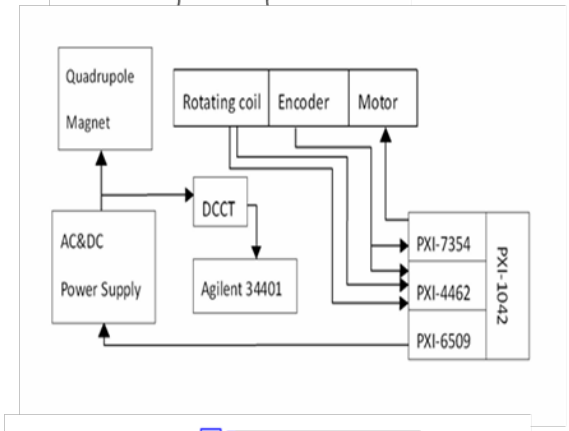
1、The motor drives the coil rotating slowly until the engraved line (see right fig) parallel to the plane of zero point (that is $\delta=0$);

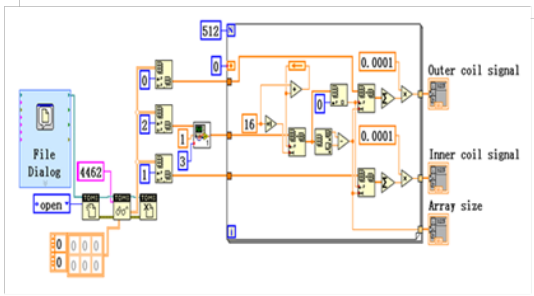
2、While the coil rotates at the second cycle from the zero point, the induced voltage of the two coils and sequence pulses of encoder are recorded synchronously by three separate channels of the PXI-4462;

3、 They are stored into three arrays, which have the same size, and three elements with the same index have been acquired at the same time. So the induced voltage in the two coils at an angular orientation θ can be identified by identifying the 8192 TTL pulse signals of the encoder in one circle;

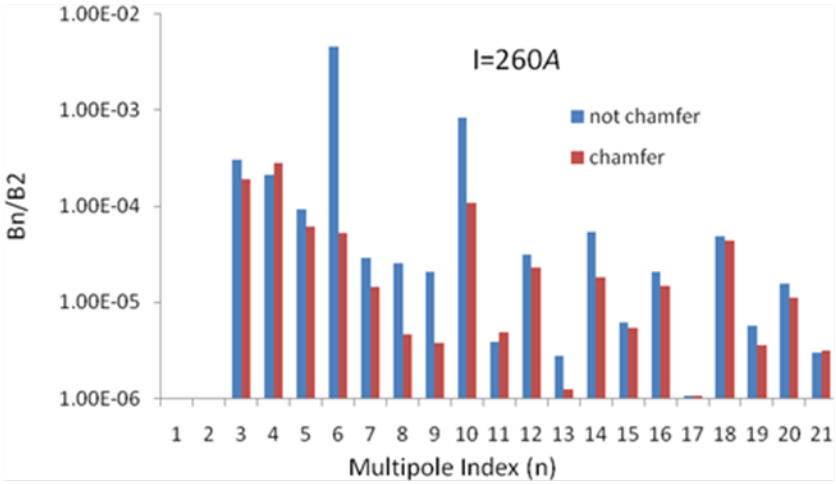
4、Every 16 encoder pulses are taken as an integral interval and 512 points of the integration value are acquired per cycle.







3、The DC magnetic field measurement（continued）



1、The fig shows all the high order harmonic fields at 260*A*. Obviously, some of the harmonic terms are reduced after end chamfer;

2、The reproducibility errors of the measured harmonics are less than 10^{-5};

3、The reproducibility of the integrated field at different currents in different times is less than 2×10^{-4} and the magnetic field angle deviation is less than 0.05degrees.

4、The AC magnetic field measurement

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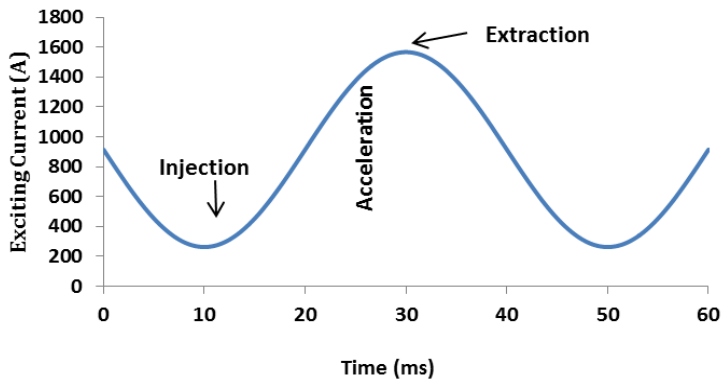
The RCS magnets are excited by a White resonant power supply with a DC bias in series



$$I = I_0 + I_1 \sin(\omega_0 t + \gamma_1) + I_2 \sin(2\omega_0 t + \gamma_2) + \cdots + I_m \sin(m\omega_0 t + \gamma_m)$$
$$= I_0 + \sum_{m=1}^{\infty} I_1 H_m \sin(m\omega_0 t + \gamma_m)$$

Where I_0 is the DC bias, ω_0=2*pi*f_0, f_0 is the fundamental frequency of the AC current at 25 Hz, I_1 the amplitude of sinusoidal current with frequency of ω_0, I_m and γ_m are the amplitude and the phase of sinusoidal current with frequency of $m\omega_0$ separately, H_m the ratio of I_m to I_1.

4、The AC magnetic field measurement（continued）

To describe the properties of the integral field in both time and space, the magnetic flux through the coil is expanded into a Fourier series.

$$\varphi(t)=\sum_{n=1}^{\infty} ML_{eff} D_n\left[R_1^n-(-R_3)^n\right]\cos(n\omega_1 t+n\delta+\theta_n)\sum_{m=1}^{\infty} A_{nm}\sin(m\omega_0 t+\tau_m)$$
$$+\sum_{n=1}^{\infty} ML_{eff} C_n\left[R_1^n-(-R_3)^n\right]\cos(n\omega_1 t+n\delta+\theta_n)$$

1、M is the coil turns, L_{eff} is the effective length of the magnetic field, R1 and R3 are the radii of the coil two sides with respect to the rotation axis ;

2、Cn is the complex constant correspond to DC current and Dn is the complex constant correspond to AC current I_1;

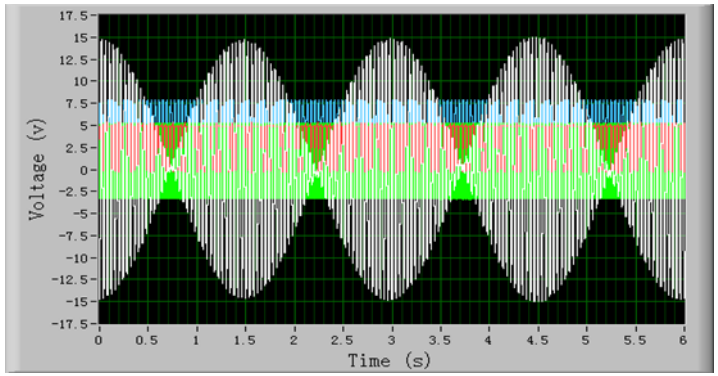
3、A_{nm} is a harmonic coefficient. The m is harmonic number of time, and the n is harmonic number of space. It indicates the 2n-pole component of the field at the frequency of mf_0 .

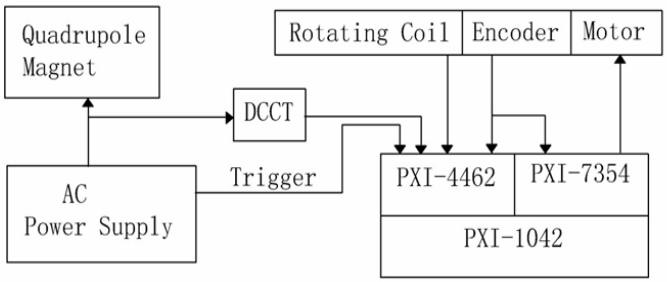
4、The AC magnetic field measurement（continued）

$$\varphi(t)=\sum_{n=1}^{\infty} ML_{eff} D_n\left[R_1^n-(-R_3)^n\right]\cos(n\omega_1 t+n\delta+\theta_n)\sum_{m=1}^{\infty} A_{nm}\sin(m\omega_0 t+\tau_m)$$
$$+\sum_{n=1}^{\infty} ML_{eff} C_n\left[R_1^n-(-R_3)^n\right]\cos(n\omega_1 t+n\delta+\theta_n)$$

For example, for the field at 25 Hz, the m equates 1 and for the quadrupole component, the n equates 2. If we want to pursue the integral gradient field which is contributed by DC or AC current , we just need to get the C_2L_{eff} and $D_2A_{2m}L_{eff}$ which were from the analysis of the total magnetic flux .

4、The AC magnetic field measurement（continued）





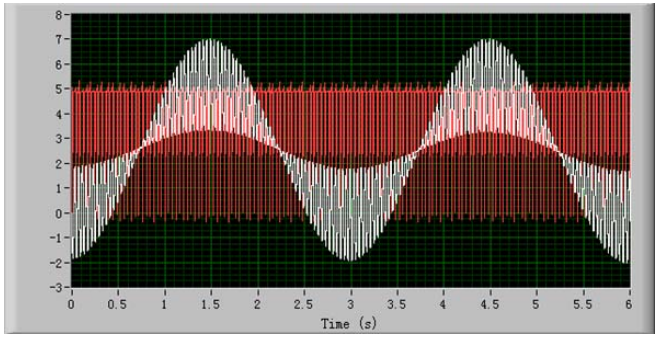
1、The harmonic coil rotates in the magnet bore；

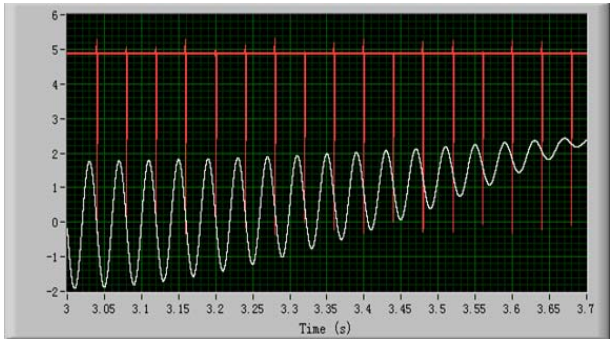
2、 When the first trigger signal from the power supply arrives, the system begins to record the four input signals at a sample rate of 200k;

3、When the TTL signals of the encoder count up to 8192 pulses (one rotation cycle), the system stops recording the signals immediately;

4、As shown above, the inductive voltage from the harmonic coil (white curve), the trigger signal from the power supply (red curve), the signal from the encoder (green curve) and the exciting current signal from DCCT (blue curve) were sampled by four input channels of PXI-4462 simultaneously.

4、The AC magnetic field measurement（continued）



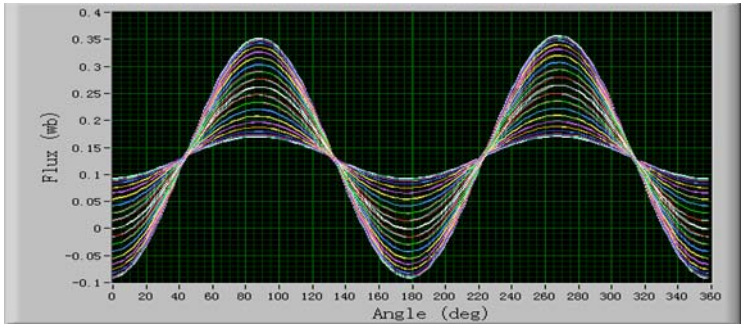


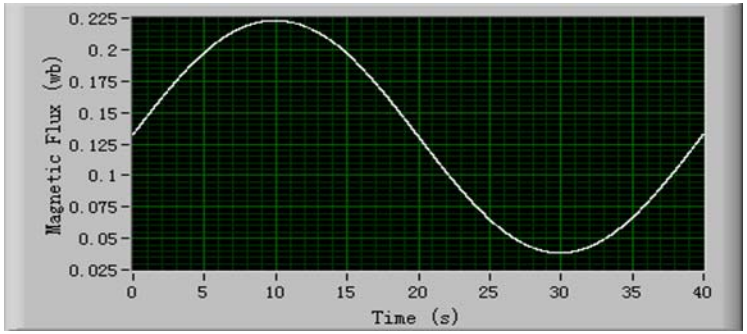
1、The total magnetic flux was obtained in space and time simultaneously after the inductive voltage having been integrated;

2、The data is stored into two arrays, and any elements of the two arrays with the same index have been acquired at the same time. So the flux change with angular at any phase of AC current can be distinguished by identifying the trigger signal of the current;

3、Take the value of magnetic flux correspond to the trigger signal of the current at every circle (The intersection with red curve β_i). The flux change with angular θ is thus obtained at this timing, by changing the decode phase to β_{i+1} , another flux change with angular θ is obtained again.

4、The AC magnetic field measurement（continued）





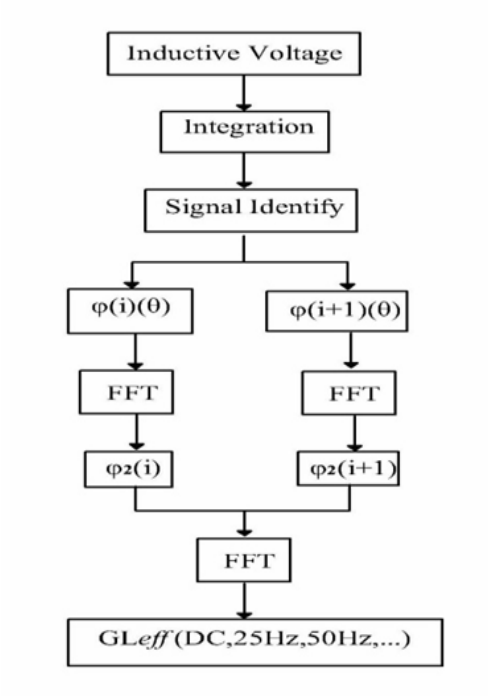
1、The left fig is the magnetic flux change with angle at different phase in one period of power supply;

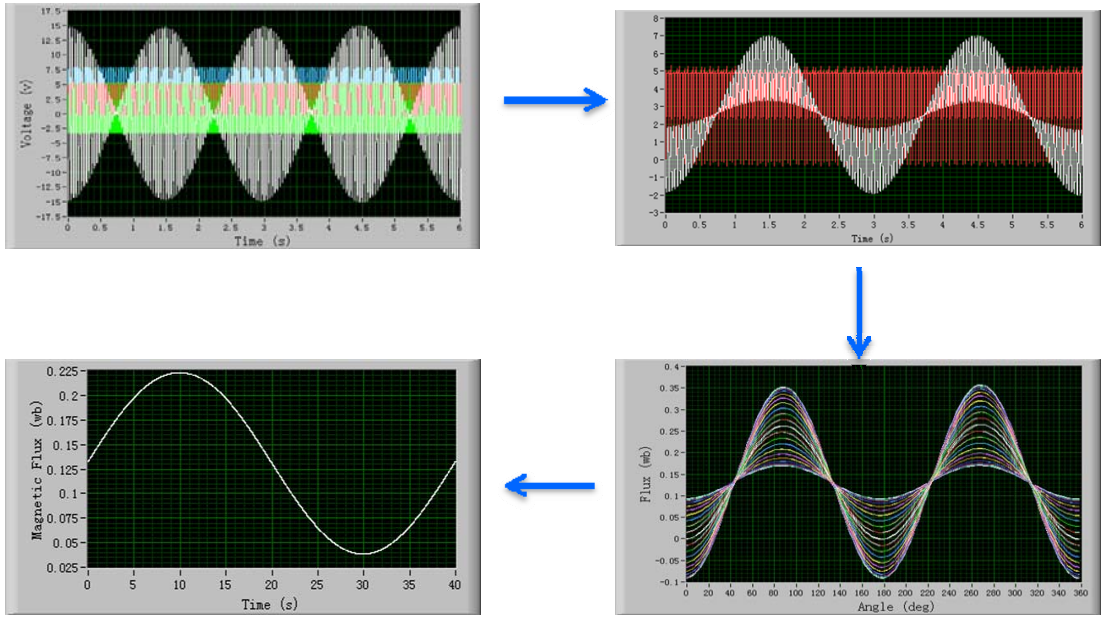
2、Fourier transformation of different flux data gives the flux of multipole fields at the phase β_i of AC current. By this way, the time dependence of the multipole fields flux in one period can be obtained;

3、The main flux component change with time was shown in the right fig;

4、 The integral gradient field (GL_{eff}) were determined by which were from a FFT analysis of the main flux again.

4、The AC magnetic field measurement（continued）

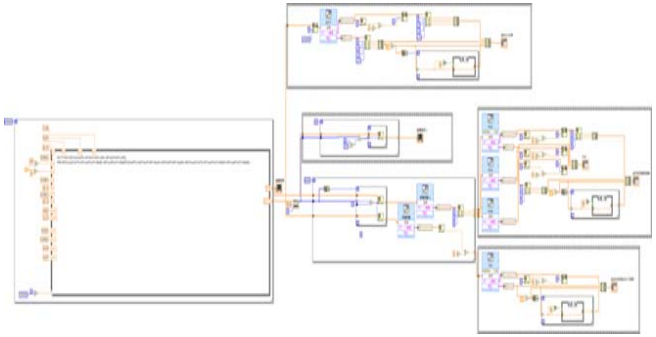




The simple diagram of the data process is shown in the left fig.

4、The AC magnetic field measurement（continued）

$$\Phi(t)=\sum_{n=1}^{\infty}\frac{ML_{eff}}{n!}d_n\left[R_1^n-(-R_3)^n\right]\cos(n\omega_1 t+n\delta+\theta_n)\sum_{m=1}^{\infty}A_{nm}\sin(m\omega_0 t+\tau_m)$$
$$+\sum_{n=1}^{\infty}\frac{ML_{eff}}{n!}c_n\left[R_1^n-(-R_3)^n\right]\cos(n\omega_1 t+n\delta+\theta_n)$$



1、In order to test the reliability of the analysis method, a signal function that simulates inductive voltage in space and time simultaneously is numerically made up;

2、All the parameters are assumed as the known ones;

3、The signals had been dealt with the signal identify method described in the above to obtain C_nL_{eff} and D_nL_{eff}.

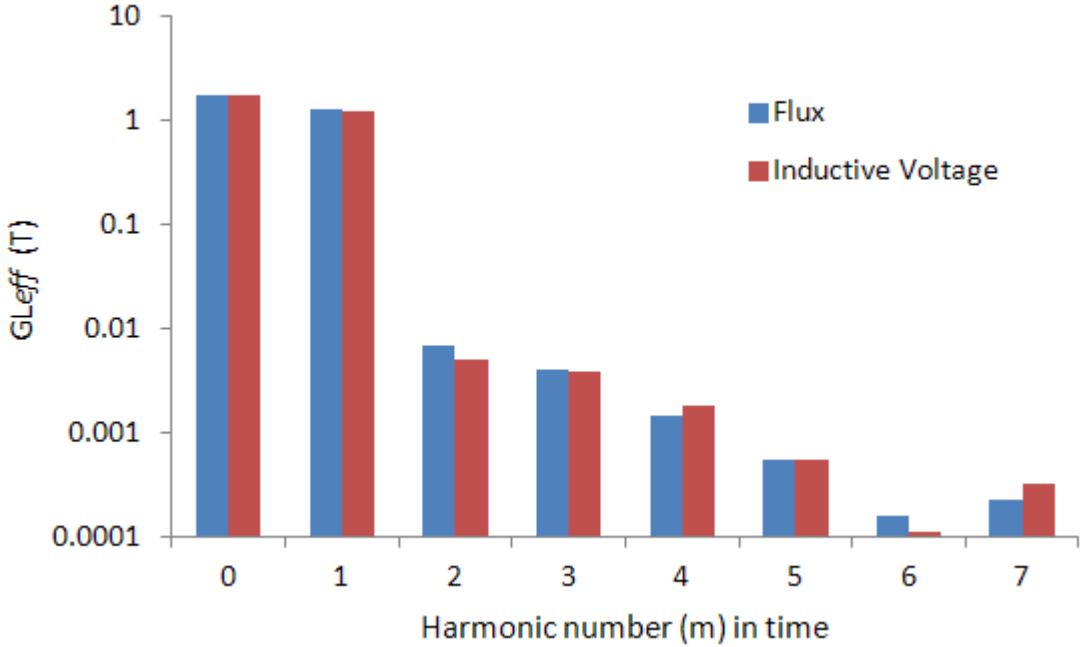
4、The AC magnetic field measurement（continued）

		Deviation			
angular velocity ω_1		$\pi/3$		$\pi/9$	
Sampling Frequency		10k	50k	10k	50k
$G^{DC}L_{eff}$		5.64E-03	1.16E-03	4.61E-03	1.20E-04
$G_1^{AC}L_{eff}$		1.11E-03	1.12E-03	1.24E-04	1.24E-04
$G_m^{AC}L_{eff}$	$G_m^{AC}L_{eff}/G_1^{AC}L_{eff}\approx 1E-3$	7.83E-02	7.96E-02	8.90E-03	9.03E-03
	$G_m^{AC}L_{eff}/G_1^{AC}L_{eff}\approx 1E-4$	5.67E-02	5.19E-02	7.54E-03	7.04E-03

We denote the assume known ones and the analysis results by x^S and x^A separately, the deviation of the analysis method is calculated by $\frac{|x^A - x^S|}{x^S}$

The deviation of the analysis results of inductive voltage is shown in the table. The deviation of the results is close to zero, while the analysis had been done on the flux at the same situation.

4、The AC magnetic field measurement（continued）



The above fig is the comparison of the actual measurement result after the analysis of the inductive voltage and integrated voltage (flux), the deviations of the integrated gradient field GL_{eff}(DC) and GL_{eff}(25Hz) between the two are 8.72E-3 and 8.75E-3 separately.

4、The AC magnetic field measurement（continued）

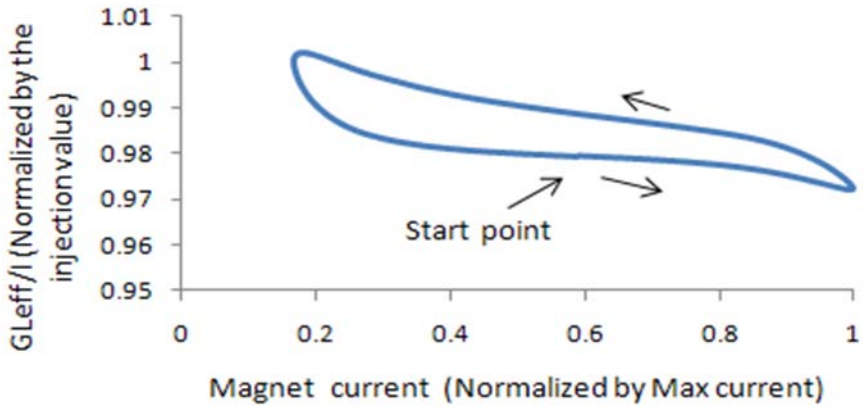
The error of coil rotation period is very important for the results. In a complete cycle of rotation, since the period of the AC current is very accurate, the error of rotation period will bring the non-integer multiple of the power cycle, which can cause measurement error. By using the numerically simulated signals, it can also be analyzed.

		Deviation		
Error of rotation period		0.3ms	0.5ms	1ms
$G^{DC}L_{eff}$		2.62E-05	4.59E-05	1.02E-04
$G_1^{AC}L_{eff}$		2.45E-05	4.14E-05	7.82E-05
$G_m^{AC}L_{eff}$	$G_m^{AC}L_{eff}/G_1^{AC}L_{eff} \approx 1E-3$	1.46E-03	3.77E-03	1.18E-02
	$G_m^{AC}L_{eff}/G_1^{AC}L_{eff} \approx 1E-4$	6.86E-03	2.20E-02	1.10E-01

*The deviation is calculated by $\frac{|x^A - x^S|}{x^S}$.

In the actual measurement, the error of the rotation period is less than 0.3ms.

4、The AC magnetic field measurement（continued）



1、The RCS magnets are excited with a repetition rate of 25 Hz using resonant networks. Since each network is operated independently, magnetic-field tracking is necessary to perform stable acceleration of the proton beam;

2、For the field tracking, the transfer functions as a function of the currents has been measured.

5、Conclusion

5、Conclusion

1、A system for measurement of DC&AC field using a harmonic coil has been developed and operated in IHEP;

2、The measurement accuracy affected by rotation error(AC filed);

3、 If analysis of the coil induced voltage directly also will result in errors at the AC field measurement, even if there is no error of the coil rotation;

4、The more quadrupole magnet of RCS are being investigated by using it.

Thank you for attentions!