Status of AC Magnets for CSNS RCS

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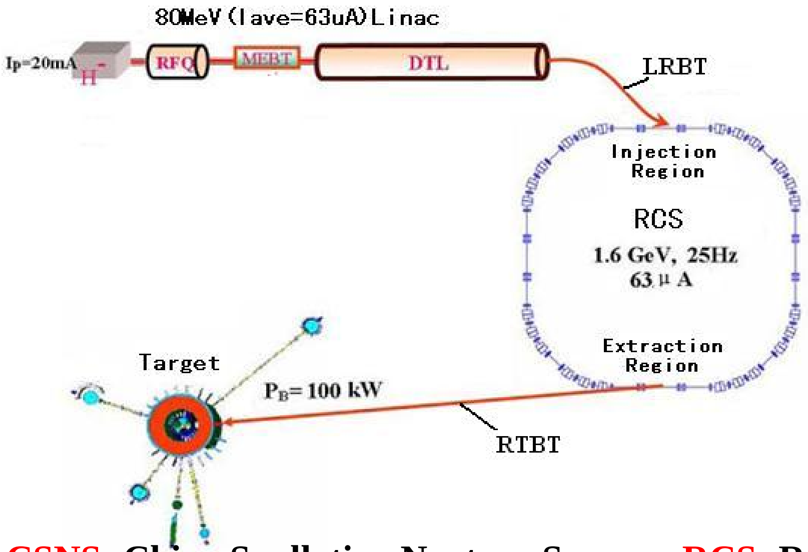
Overview of CSNS magnet system



- **Linac : 3 LEBT solenoids, 10 MEBT quadrupoles.**
- **LRBT: 4 dipoles and 47 quadrupoles.**
- **RTBT: 4 dipoles and 37 quadrupoles.**
- **RCS: 24 dipoles, 48 quadrupoles, 16 sextupoles, 34 correctors and 23 injection & extraction magnets.**

CSNS: China Spallation Neutron Source; RCS: Rapid Cycling Synchrotron;

LRBT: Beam Transport line from Linac to RCS; RTBT: Beam Transport line from RCS to Target.

There are 300 magnets. Among these magnets, most of them are DC magnets. But all the dipoles and quadrupoles for the RCS are DC biased 25 Hz AC magnets, which are very difficult to be made. So my talk will be focused on these magnets.

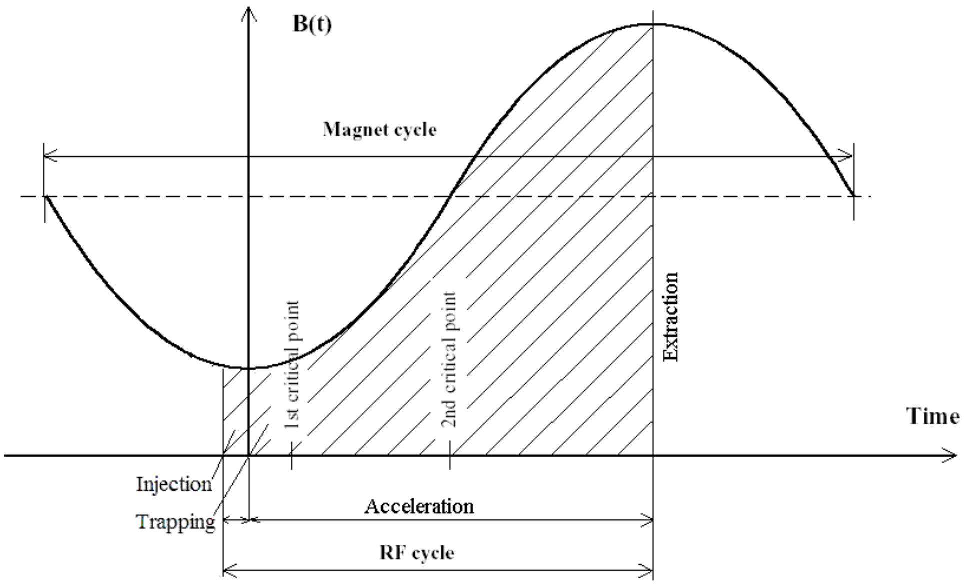
Parameters of the RCS main magnets

The main parameters of 24 dipoles and 48 quadrupoles are listed in the table. All the quadrupole magnets are categorized into 4 families of 272Q, 253Q, 222Q and 206Q according to their apertures.

Name	RCS-160B	RCS-206Q	RCS-222Q	RCS-253Q	RCS-272Q
Number	24	16	8	8	16
Field strength	B(T)	B' (T/m)	B' (T/m)	B' (T/m)	B' (T/m)
Max. field	**0.981**	**6.6**	**5.0**	**5.35**	**5.0**
Min. field	**0.165**	**1.11**	**0.84**	**0.90**	**0.84**
Aperture gap/radius	**160mm**	**103mm**	**111mm**	**126.5mm**	**136mm**
Effective length	2.1m	0.41m	0.45m	0.62m	0.9m
Core length	2.06m	0.32m	0.37m	0.51m	0.81m
Turns per pole	30	20×4	20×4	24×4	24×4
DC current	1230A	813A	859A	829A	895A
AC current	880A	580A	612A	591A	638A
Field uniformity	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}
Good field region	±106 mm	±90 mm	±98mm	±114mm	±123mm
AC peak voltage	**5180V**	**740V**	**855V**	**1238V**	**2556V**
Power loss	**44.3kW**	**14.2kW**	**17.5kW**	**23.5kW**	**35.6kW**
Weight	**23.6Ton**	**2.4Ton**	**3Ton**	**5.3Ton**	**9.3Ton**

Key issues of RCS AC Magnets

A typical sine waveform of the field for RCS AC magnets is shown in this fig.. The particle beam is injected in, accelerated and extracted out the RCS in its half ramping cycle of 20ms.



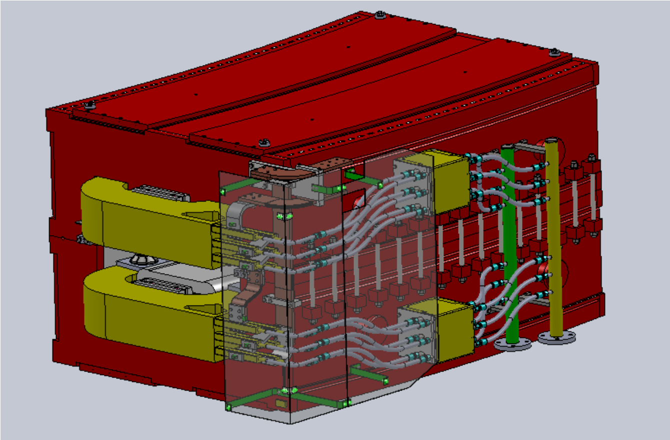
Key issues of RCS AC Magnets

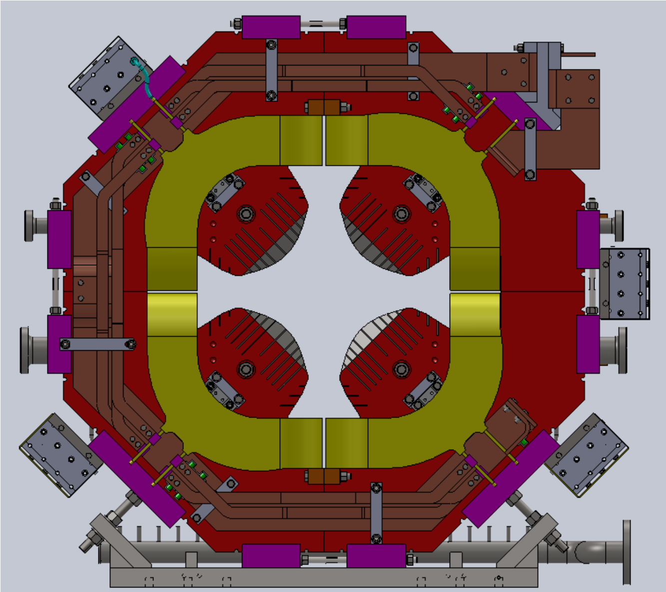
For the RCS AC magnets, the field quality is first of all to be considered. But meanwhile, the other issues such as eddy current effect, high voltage, vibration, field non-linearity and fringe field interference are also important.

- Eddy current can deform the field waveform, spoil the uniformity of the field and heat the metal components of the magnets.
- Fast changing magnetic flux in the loop of the coils will induce high voltage which always makes the magnets failed.
- Fast changing magnetic forces will lead to the vibration of the cores and coils which sometimes makes large noise and destroy the integrity of the magnets.
- Non-linearity of the field will make the waveform of the field deviated from that of the current.
- Large aperture of the magnet will cause the end field far away from magnets and the fringe field interference between the magnets becomes serious.

Structures of the RCS AC magnets

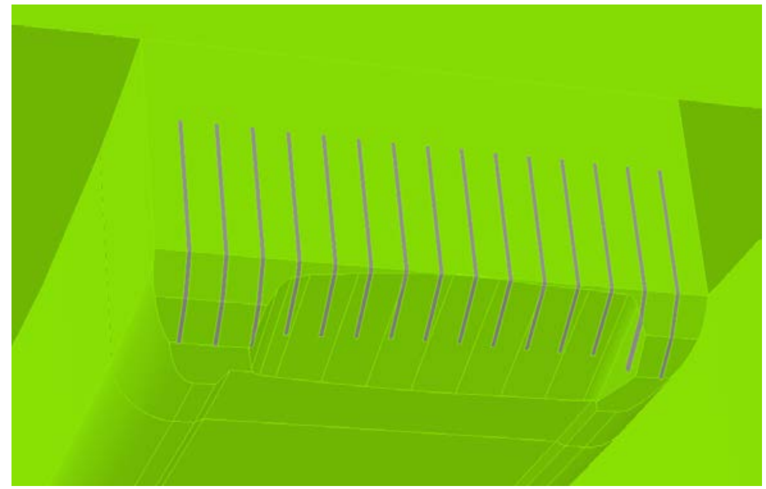
- The dipole magnet is composed of a H-type curved core and two racetrack coils whereas the quadrupole magnet of a 4-fold symmetrical core and 4 saddle-shaped coils.
- To install the coils, the core of the dipole magnet can be split into two parts whereas the quadrupole magnet into four parts.
- The yokes of both the dipole and quadrupole magnets are stacked and adhered by laminations with thickness of 0.5mm.
- The coils of the dipoles are wound by hollow alumina strands conductors whereas that of the quadrupoles by hollow copper conductors.

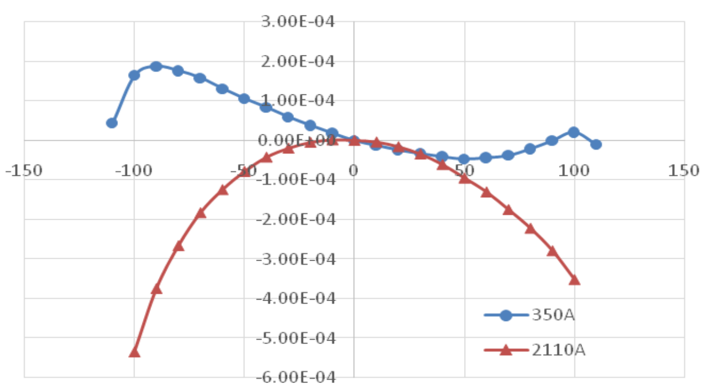




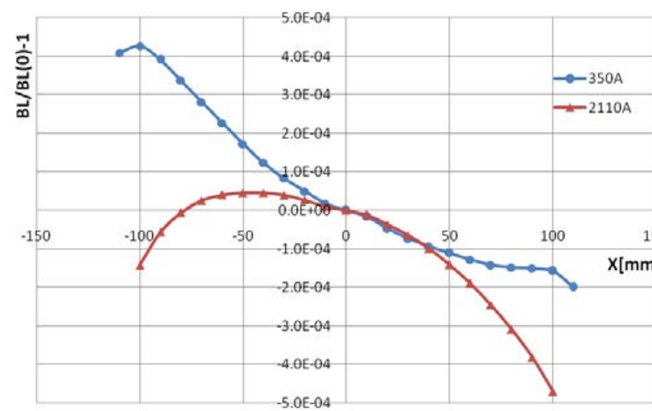
Field errors of the RCS AC magnets

- The TOSCA program is used to simulate DC field of the magnets. Both high(extraction) and low(injection) fields are optimized simultaneously.
- By using the techniques of end chamfering, the integral field errors of both the dipole and quadrupole magnets can be reduced within the required values.
- The measured results field uniformity of the dipole magnets meet the requirements as simulated results expected.





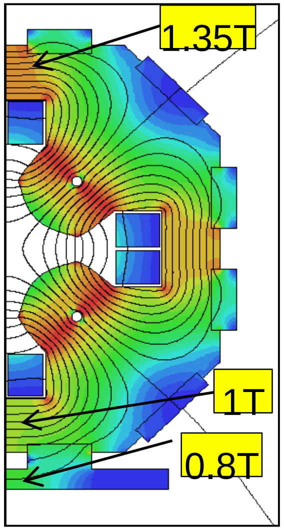
The simulated integral field distribution of the dipole

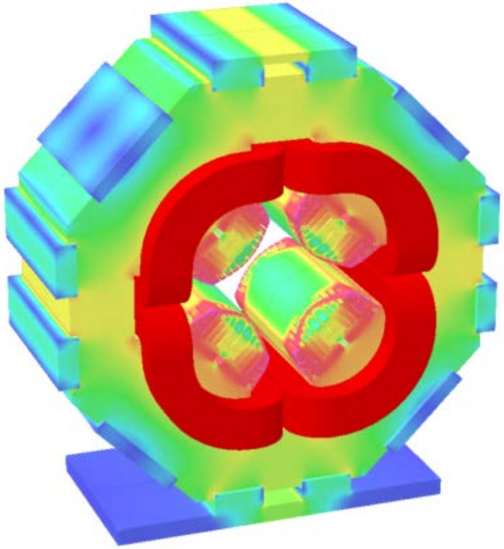


The measured integral field distribution of the dipole

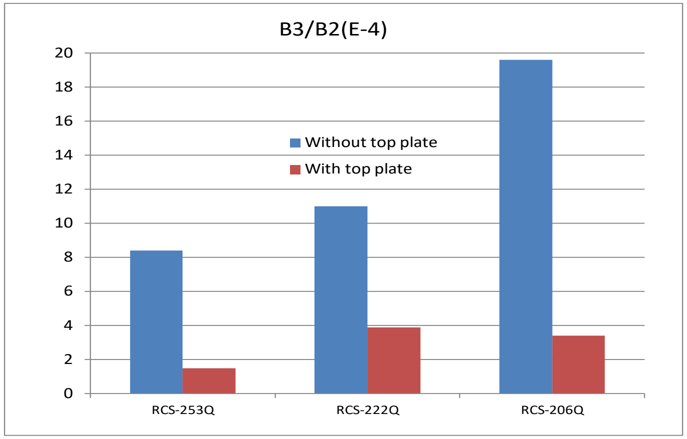
Field errors of the RCS AC magnets

- For the first 272Q magnet, the 6th harmonic error of the measurement is a little higher than the required value. But after modifying the size of the end chamfering, the harmonic errors of the mass production magnets are satisfactory.
- For the 253Q, 222Q and 206Q magnets, the measured 3rd harmonic errors are worse than the requirements.
- The reason is that the bottom plates made from iron destroys the upper and lower symmetry of the magnetic path due to high field in the return yokes.
- To get back the symmetry, an iron plate is placed on the top of each magnet and the 3rd harmonic errors are reduced effectively.



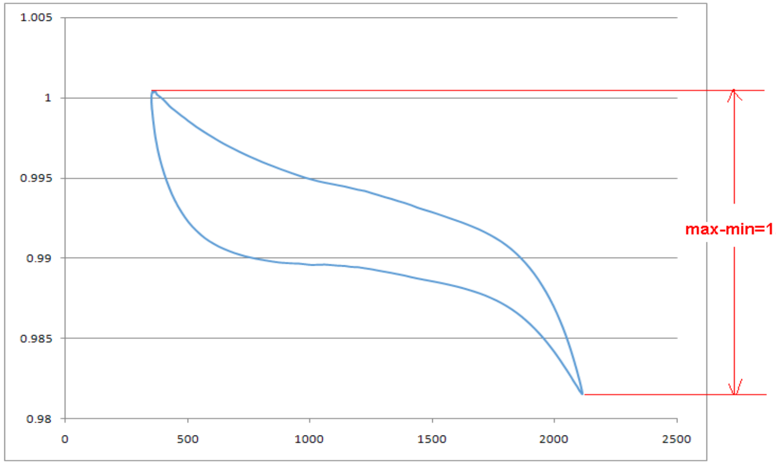


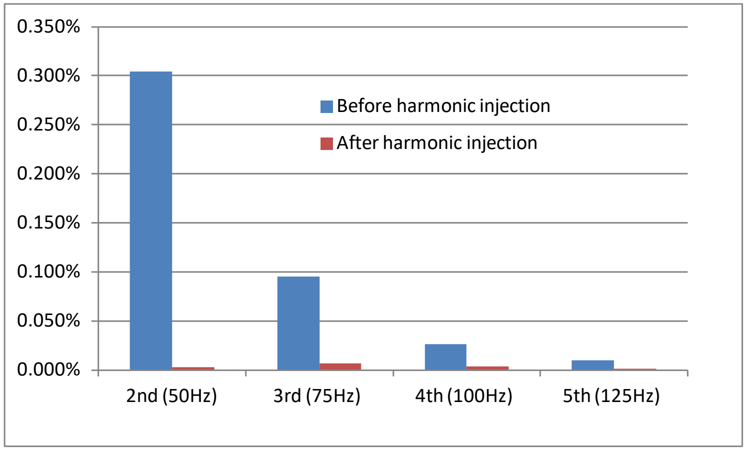
206Q@Iext



Field non-linearity (AC dipole magnets)

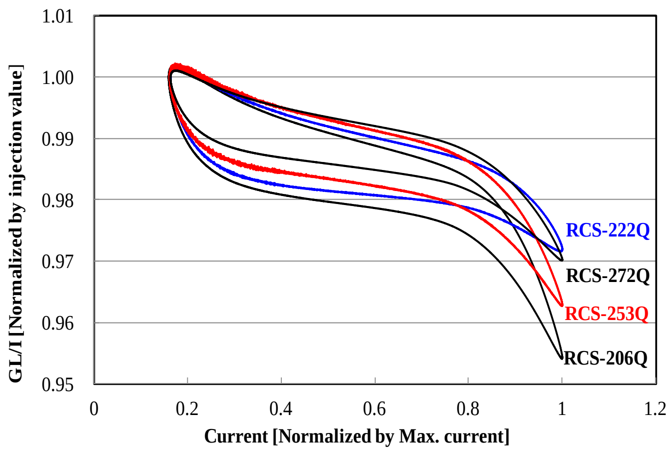
- The nonlinearity of the field can deform the waveform of the AC field so seriously that may cause problems of the field tracking between the different types of magnets.
- The deformation of field waveform can be evaluated by the amplitude ratio of high order time harmonics to the basic harmonic of 25Hz.
- In order to reduce the high order time harmonics of the field, the technology of current harmonic injection has been accurately applied in the power supply.
- The field non-linearity of the RCS dipole magnet is less than 2%, so the high order time harmonics of the field is not high and can be easily reduced down to 1E-4.

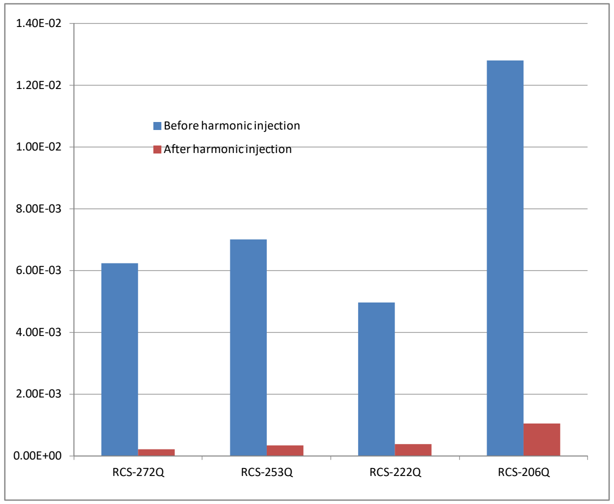




Field non-linearity (AC quadrupole magnets)

- The field non-linearity of 222Q, 272Q, 253Q and 206Q magnets are 2.8%, 3%, 3.5% and 4.5% respectively.
- By using the techniques of current harmonic injection, the 50Hz harmonic errors for the 272Q, 253Q and 222Q magnets can be reduced down to 5E-4.
- But for the 206Q magnets, the core width is limited to avoid space interference with other devices, the field non-linearity is very large due to the high field in the return yokes, the harmonic error can be only suppressed to1E-3.



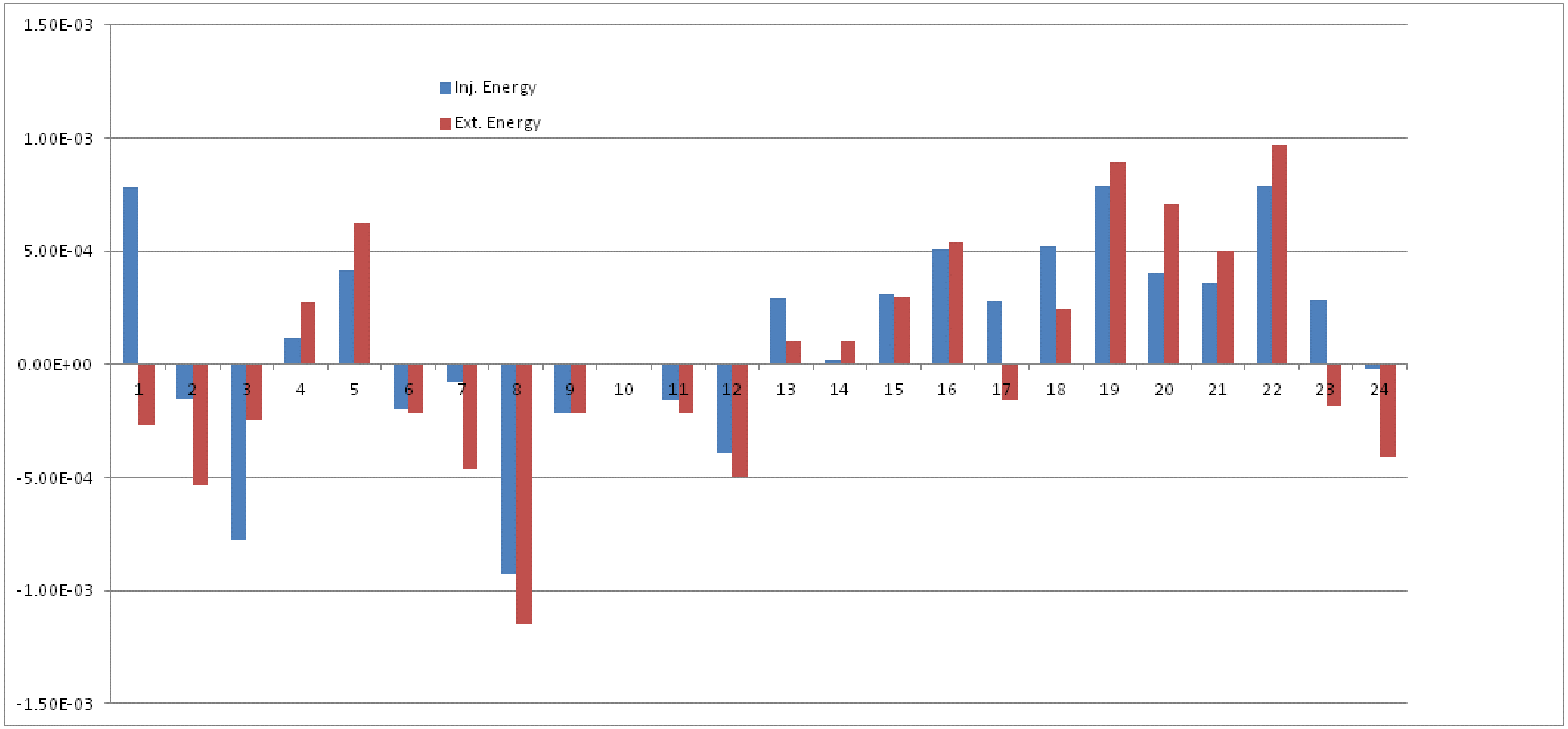


Integral field deviation

- Since the same family of magnets is powered by one power supply, the field of the individual magnet can not be adjusted independently, the integral field deviation from magnet to magnet in the same family is required to be less than ±0.1% for dipoles and ±0.2% for quadrupoles.
- All the lamination sheets have been shuffled according to their coercive force to make magnetic properties uniform before used for producing the cores.
- The fabrication procedures are carefully optimized to ensure that the stacking factor and length of each core are as close as possible to the designed values.
- Because the laminations of the cores were finally adhered together at high temperature of 180 ^{o}C, the length of the cores is not easy to be controlled within the tolerance, the techniques of end cutting were sometimes applied to reduce the length tolerance.

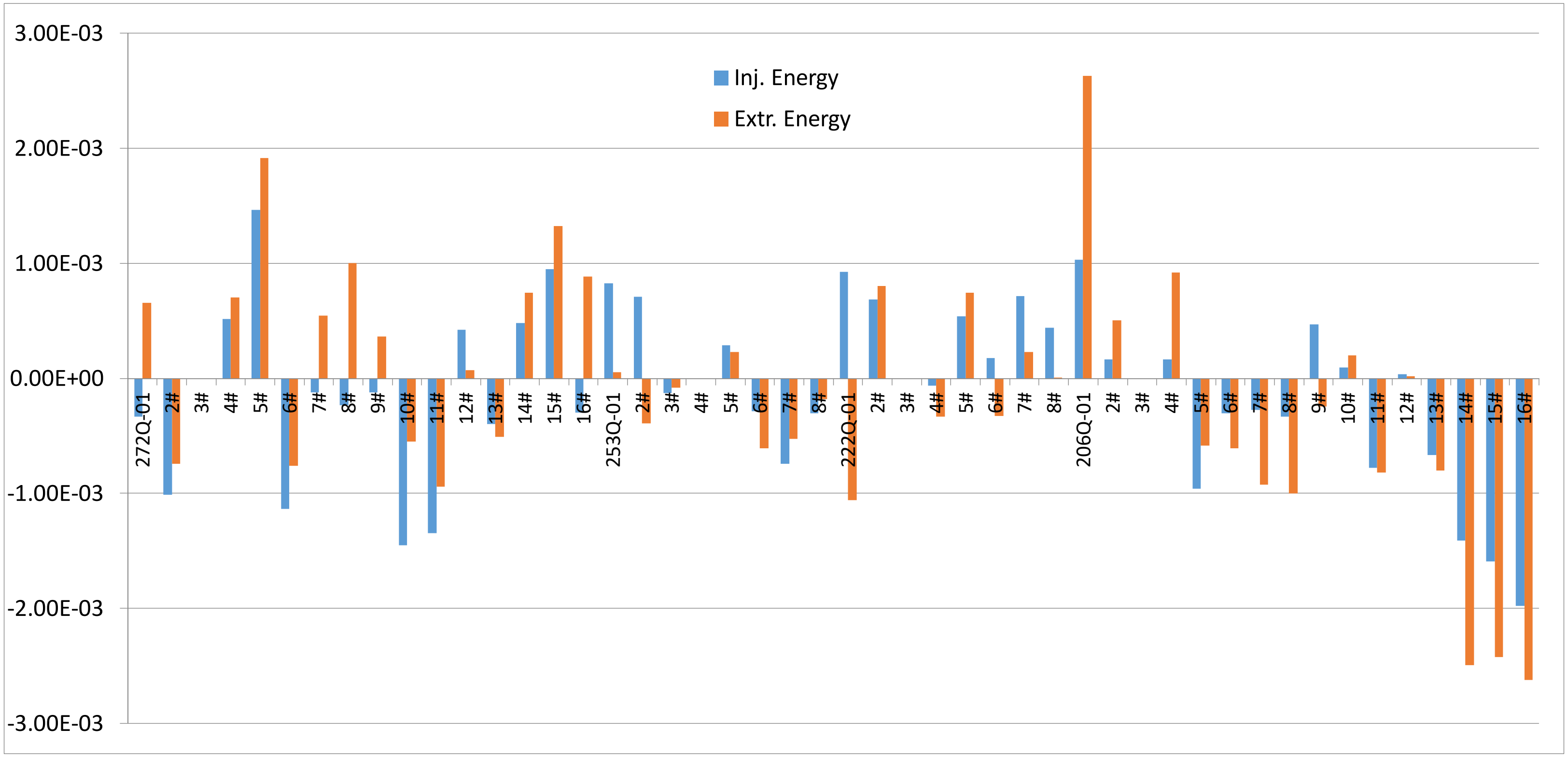
Integral field deviation

The integral field deviation for 24 dipole magnets was about ±0.1%, where the 10th magnet was taken as the reference magnet.



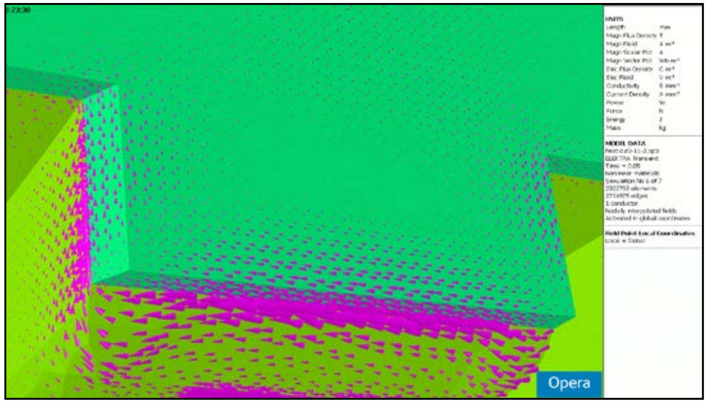
Integral field deviation

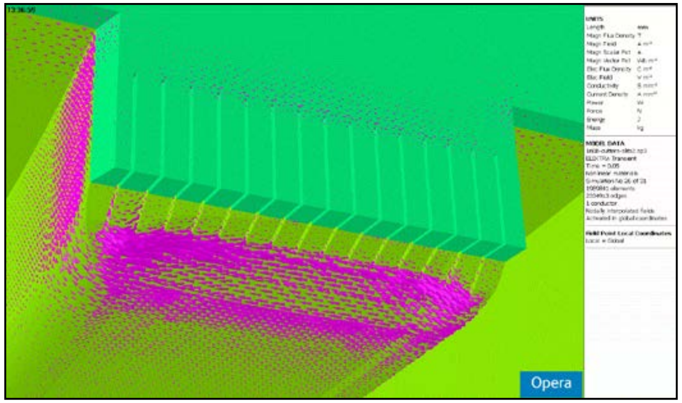
The field deviation for most of the quadrupoles was better than ±0.2%, but that of the last three 206Q magnets was not good because the lamination sheets producing these magnets were newly produced and not shuffled with others.



Eddy current and high voltage

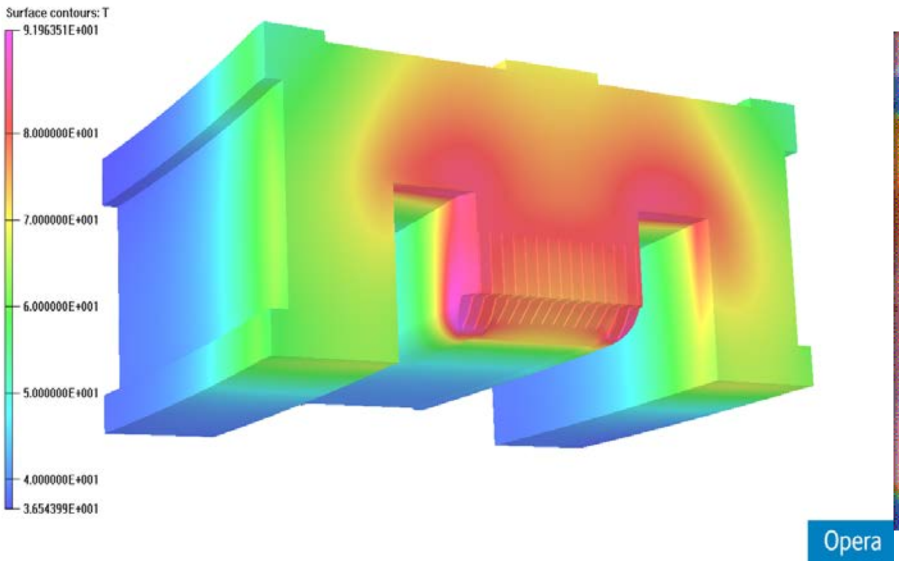
- According to the Maxswell's Law, the changed magnetic field will induce the changed electric field. If a open metal loop is put in the field, electric motive force will be induced. And if the metal loop is closed, eddy current will be induced.
- In the middle of the cores, the field has no Bz component and the insulation on the surfaces of the laminations can cut eddy current loop between the laminations, so eddy current is induced only in the individual lamination.
- In the ends of the cores, fringing field effect leads to large Bz component penetrating the end plates and some end laminations which can induces the large eddy current. In order to reduce the eddy current, some kinds of slits are made in the end plates and lamination to cut the large loops.

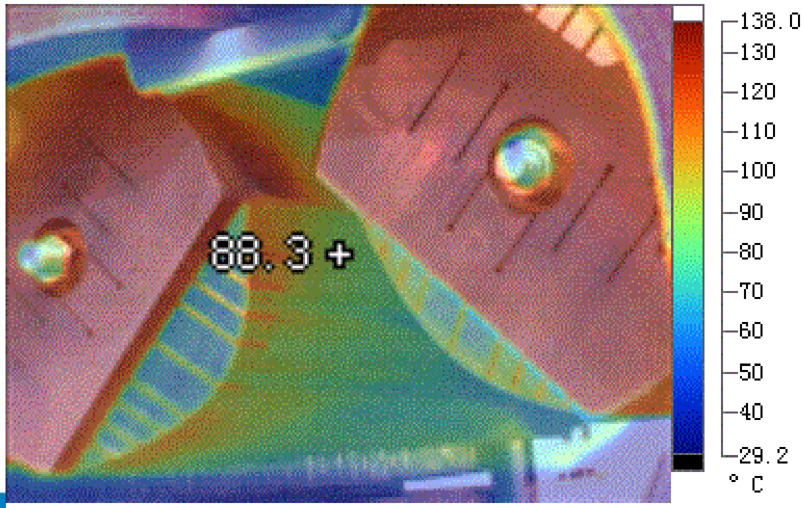




Eddy current and high voltage

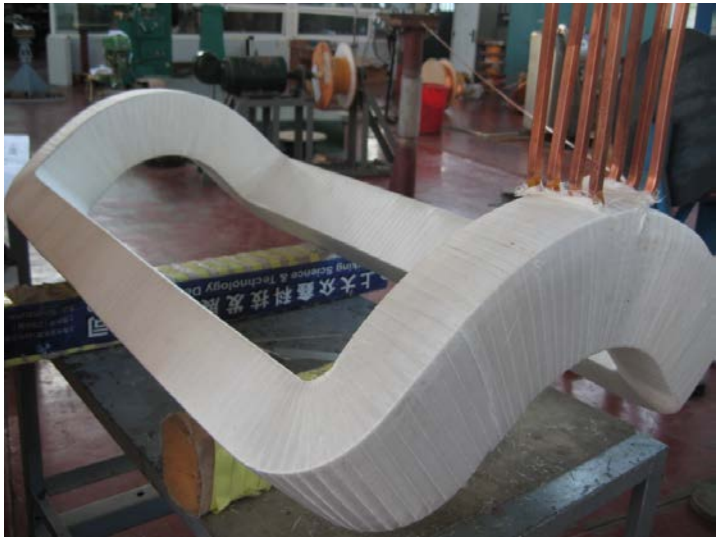
- The eddy current heating will lead to high temperature in the end plates of the magnets.
- By using the technology of slit cutting, the max. temperature in the end plates of dipoles can be reduced down to 130ºC whereas that of the quadrupoles down to138ºC
- The average temperature in the middle of cores is about 70 ºC for dipoles and 60 ºC for quadrupoles.





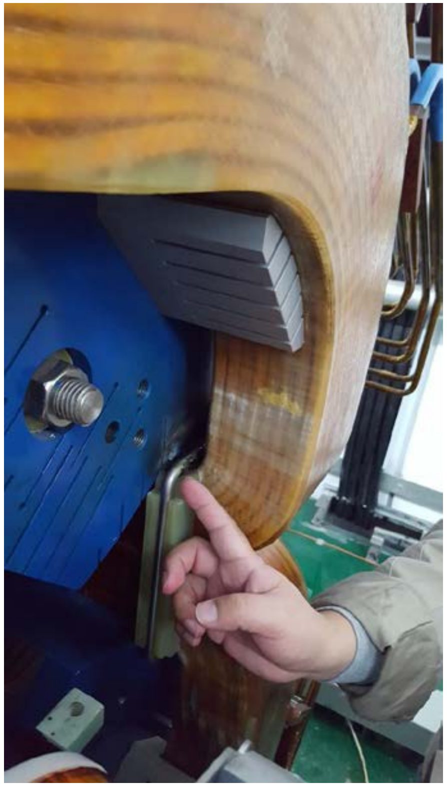
Eddy current and high voltage

- Since the coils forms a large open loop, high voltage will be induced.
- To reduce the high voltage, the coils have to be designed with small turns and inductance.
- However, the small turns means large cross section of the conductor and then large eddy current loss in the coils.
- To reduce the eddy current loss, the aluminum stranded conductors twisted with 78 filaments were developed to wind the coils of the dipoles. Meanwhile, a special winding technique was developed and the copper conductors with small cross section were used for the coils of the quadrupoles.



Eddy current and high voltage

Although the magnets had been designed with small inductance, the high voltage discharges were still the main faults that caused failures of the magnets when they were trained with the power supplies in the RCS tunnel,.

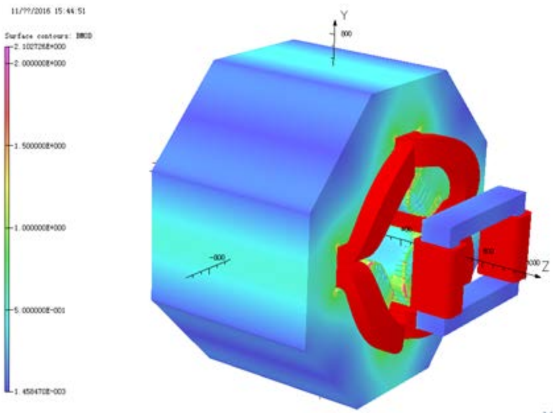


Vibration

- The vibration of the AC magnets can damage the insulation of the coils, cause de-lamination of the cores and destroy the devices close to the magnets, such as ceramic vacuum chambers.
- To reduce the vibration, the laminations and end plates of each yoke are adhered by epoxy resin in high temperature 180^{o}C, and then welded by the long surrounding bars. The coils are fixed tightly on the poles of the magnets by the special fastening components.
- All the bolts and washers used to fix the components of the magnets have the function of anti-loose. The torque wrenches were used to tighten all the bolts as uniformly and firmly as possible.
- By these methods, the measured amplitude of vibration for all the magnets was controlled to be less than 20 um.

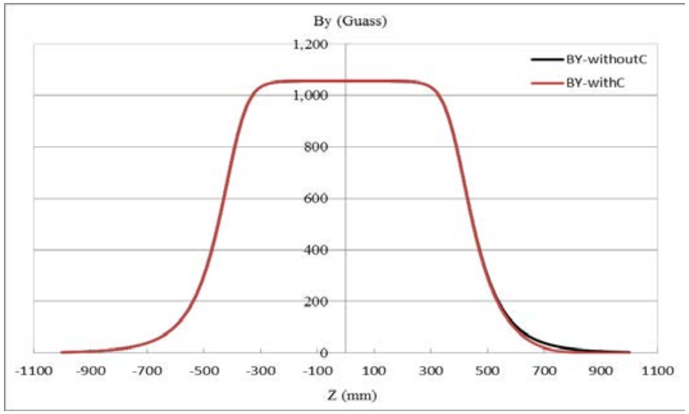
Fringe field interference

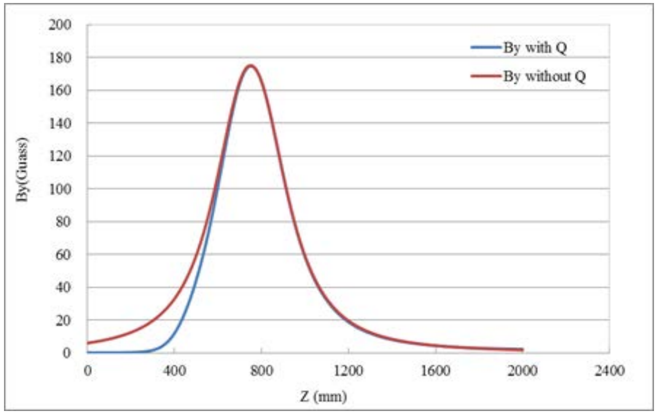
- For CSNS/RCS, the large aperture of the magnets and short distance between the magnets have caused the fringe field interference.
- The fringe field interference for some cases, such as between the 272Q magnet and the correcting magnets as well as 222Q magnet and the sextupole magnets, have been accurately simulated and measured.



Fringe field interference

- Due to the cores of neighbor magnets, integral field of the 272Q and 222Q magnets are reduced by 0.9% and 2.3%, and that of the correcting magnet is reduced by 14.9%.
- Since the measured results have a good agreement with simulated ones, for the other cases of the field interference, the simulated results were directly used for RCS beam commissioning.



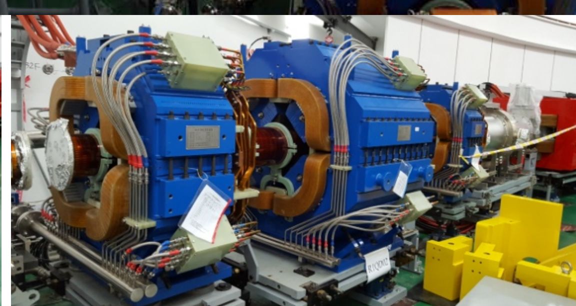


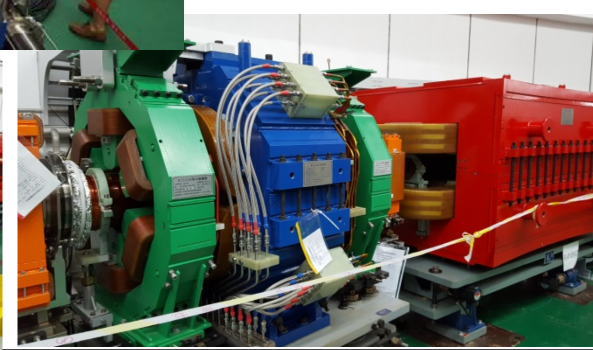
Comparison between simulation and measurement for the fringe field interference

Magnet	Simulation (@22.2 cm %)	Hall Probe (@22.2 cm %)
272QB	0.63	0.86
300CH	14.6	14.9

Summary

By the end of April, 2017, the installation, cabling and site commissioning of all the magnets for the CSNS accelerators were completed. In July 7, 2017, the first day of the RCS beam commissioning, the proton particle beam has quickly realized injection, accumulation, acceleration and extraction. The performance of the RCS magnets are excellent!





Thank you for your attention !