Design and construction of the main magnet for a 230 MeV Superconducting Cyclotron

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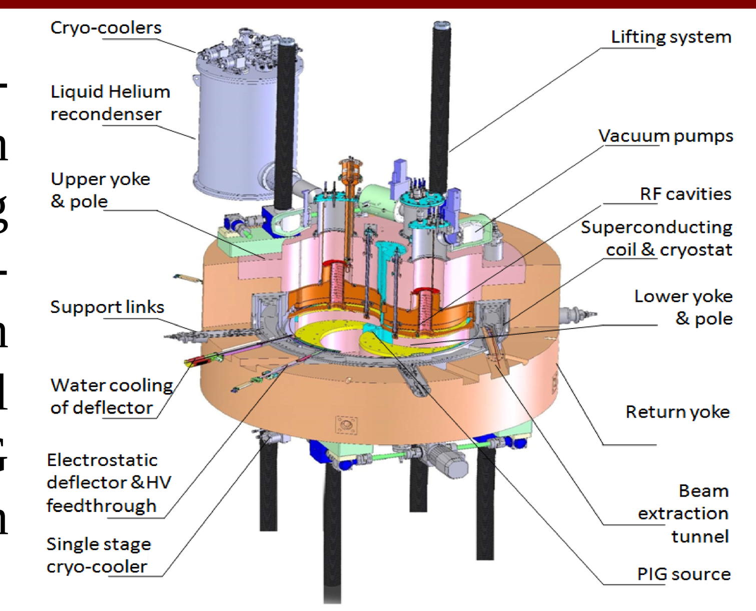
Introduction

Cancer has become a globalized threat to public health. According to global cancer statistics published by WHO, the deaths caused by cancer are 8.8 million in 2015, and the new cancer cases are 14 million in 2012. China has the largest number of both deaths caused by cancer and the new cancer cases (2.5 million and 3.5 million respectively), and these numbers are still growing . Proton therapy could deposit very low entry dose and no exit dose thus is considered to have less long term side effects compared to photon radiation therapy which has been at least partially identified by clinical trials. However, only two proton therapy centers in China are currently operational, so there are very strong demands on proton machine for proton therapy. In order to promote the development of proton therapy in China, China Institute of Atomic Energy (CIAE) has designed a superconducting cyclotron CYCIAE-230, and the overall parameters are listed in TABLE I .

TABLE I. The overall parameters of the CYCIAE-230

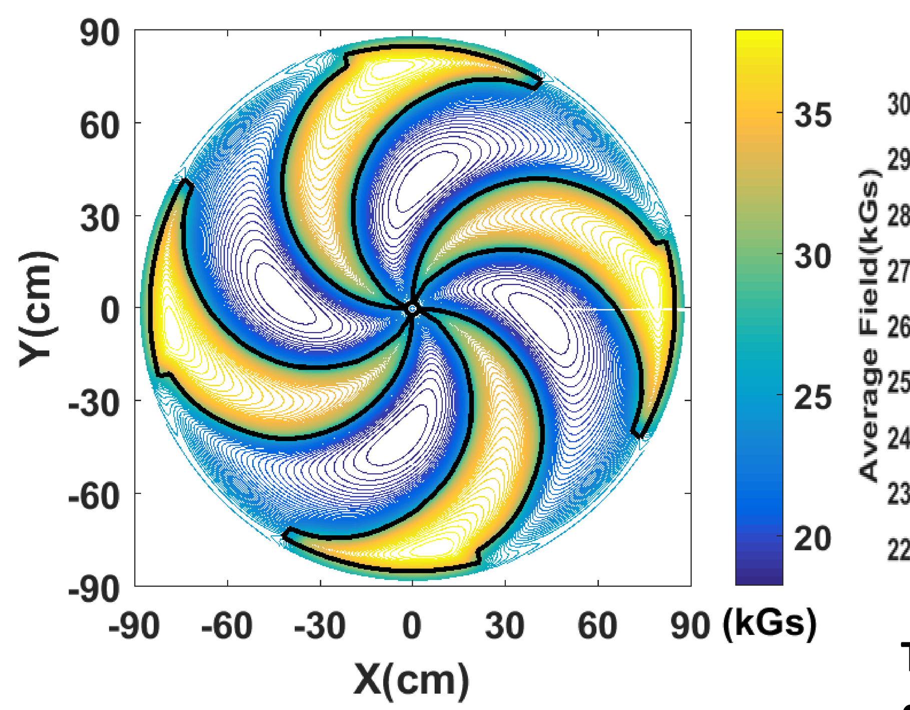
Parameter	Value
Extraction energy	>230 MeV
Extraction current	300 nA
Injection/Extraction field	2.35 T / 2.95 T (Average field)
Radius of return yoke	~3200 mm
Ampere turns	~1.1 MA·T
Coil type	NbTi/Cu superconducting coil
RF frequency	~71.3 MHz
RF voltage	70 kV/110 kV

The layout of the very compact CYCIAE-230 superconducting cyclotron is shown in right figure. The superconducting cyclotron consists of many sub-components, mainly including the main magnet system; the superconducting coil system; the RF system; an internal PIG source; the extraction system; vacuum pumps and the lifting system.

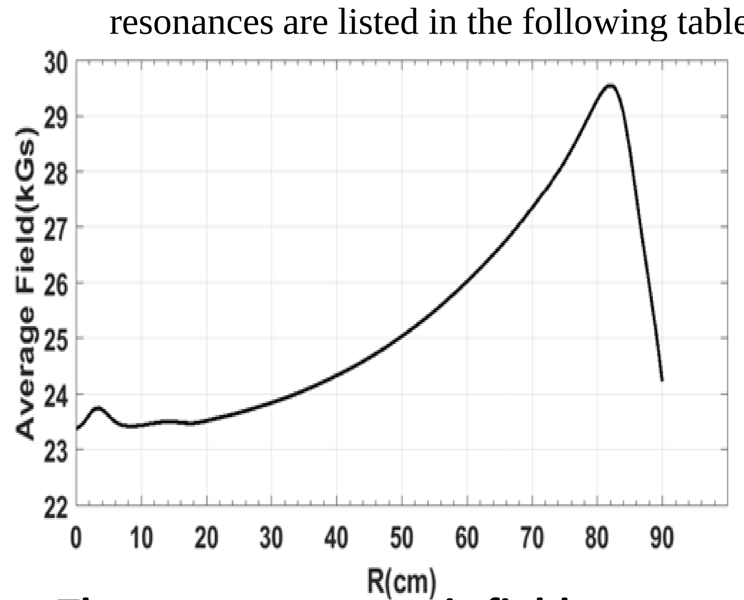


Main magnet Design and 3D calculation

Field Distribution on the Median Plane



Adopting the magnetic field and RF field map, beam dynamics, including static and acceleration state are calculated with emphasis on the factors leading to envelop or emittance growth in this machine. The first harmonic field and radial component of the field on the median plane lead to a radial and axial oscillation respectively. The detailed descriptions of the resonances are listed in the following table.



The average magnetic field over different azimuths along radius.

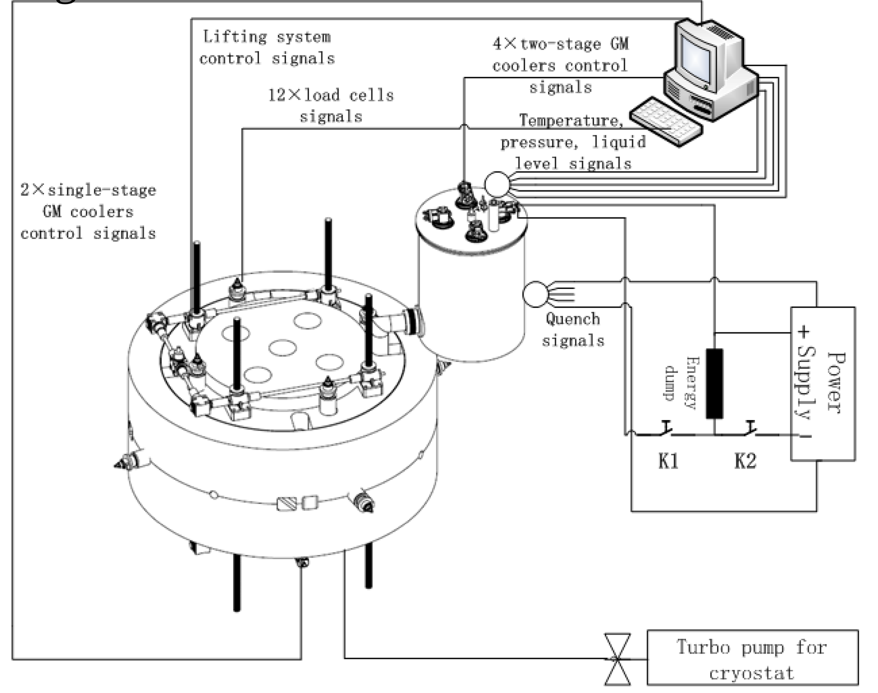
Resonance	Position	Driven Term	Tolerance
$\nu_r=1$	All region	B_{z1}	B_{z1}<1Gs at 15cm to 25cm, to limit the radial off center <0.2 mm for extraction
2νr=2	All region	B_{z2}, dB_{z2}/dr	B_{z2}<5Gs dB_{z2}/dr<10 Gs/cm
$\nu_z=0$	All region	B_r	B_r<2Gs at r<20 cm and r>70cm
$\nu_r=2\nu_r$	~81cm	Main field	Radial off center <2mm
$\nu_r-\nu_z=1$	~71cm ~79 cm	B_{r1}	B_{r1}<6 Gs near 71 cm
$2\nu_z=1$	~80 cm	dB_{z1}/dr	dB_{z1}/dr<10Gs/cm at 78 - 82 cm

Superconducting coil manufacture

The superconducting coil system of CYCIAE-230 superconducting cyclotron consists of two coil windings, cryostat, adjustable support links, GM coolers, and the liquid helium condenser, along with multiple thermometers, pressure gauges, liquid level gauges, load cells, a vacuum pump, a power supply and quench protection equipments.

The manufacturing of some long period parts like the coil bobbin was started just after the design review in October 2015. As the thickness of the coil is quite large, and to prevent the quench of the superconducting coil before reaching the working magnetic field, we use copper wire from the same superconducting coil vender with the same size as the superconducting wire to perform coil winding and epoxy impregnation experiments. In each experiment, we wind the copper coil to the same cross section as the superconducting coil, and adjust other parameters like the dimension of the epoxy flowing channel, the pre-tension during winding and the time of the epoxy impregnation. After experiments, the procedure used for superconducting coil winding and epoxy impregnation has been settled.

The assembly of the superconducting coil and the main magnet is shown is the following figure.

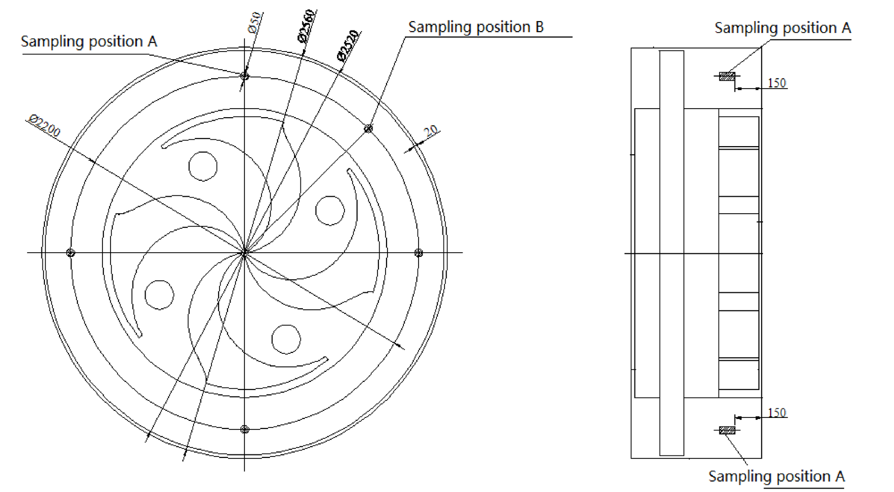


Pure iron production and fabrication

Pure iron production

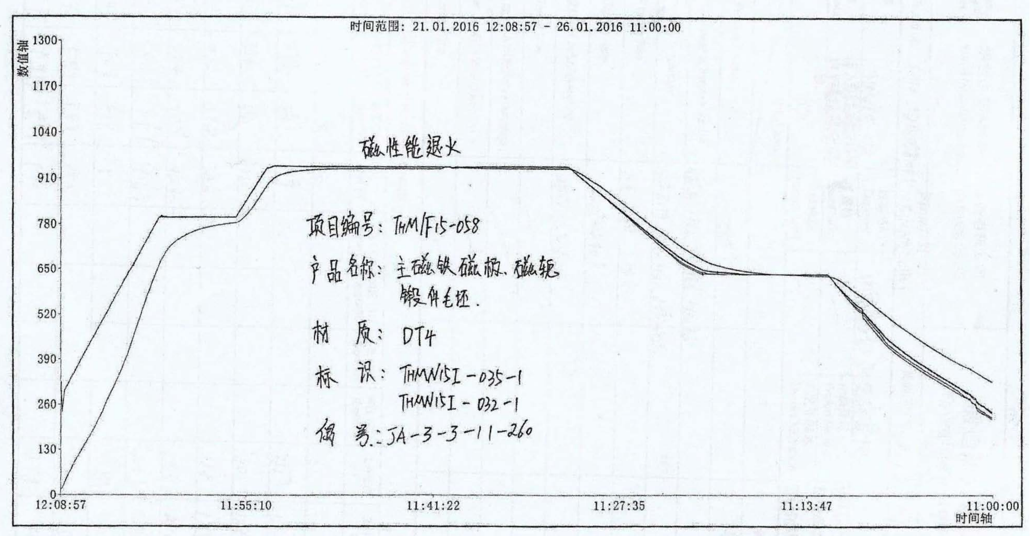
From the construction experience of CYCIAE-100 [6], a room temperature 100 MeV cyclotron with 416 ton main magnet, more dedicated pure iron forging pieces from domestic supplier with specified chemical composition, as listed in following table, are used to fabricate the main magnet of CYCIAE-230.

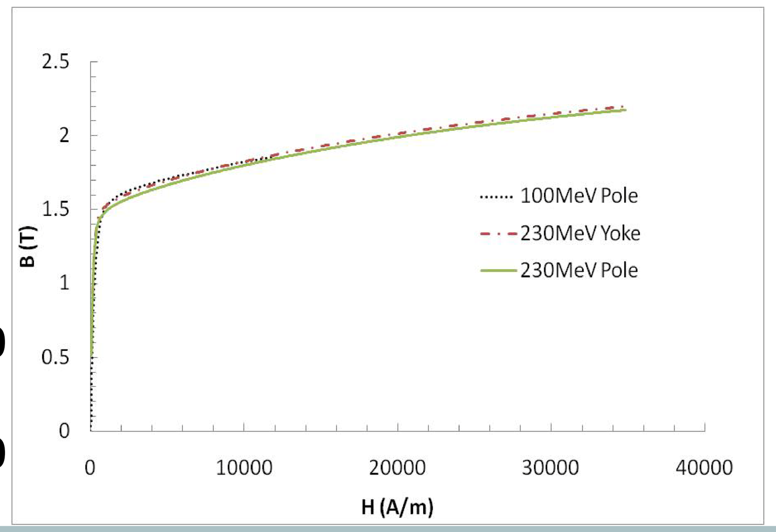
	C	Si	P	S	Mn	Cr	Ni	Al
230MeV (%)	<0.01	0.13	0.003	0.005	0.15	0.029	0.032	0.044
100MeV (%)	0.02	0.19	0.005	0.003	0.30	0.06	0.09	0.047



The sampling positions

Heat treatment history

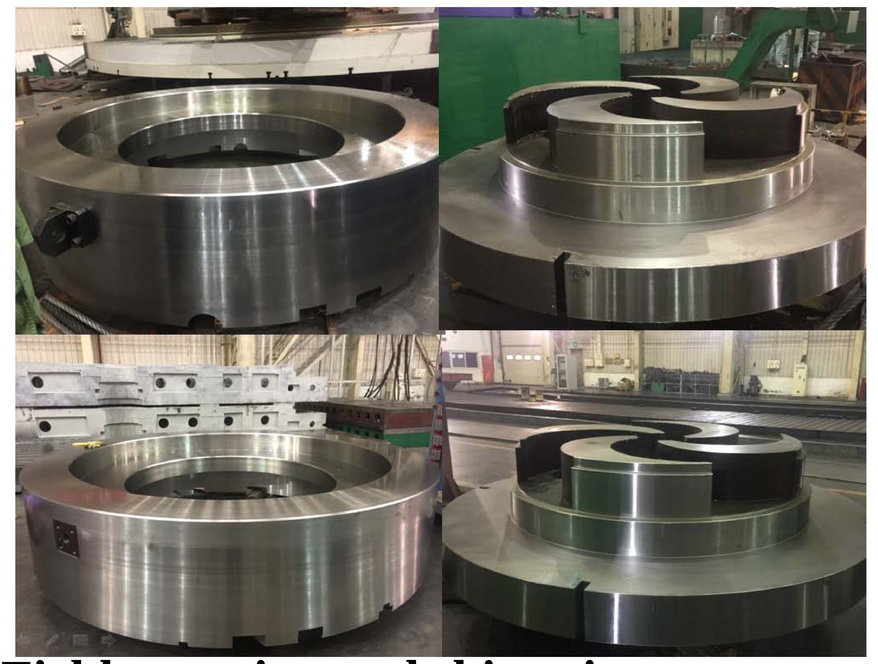




The comparison of B-H curves between CYCIAE-230 and CYCIAE-100

Fabrication and tolerance control

Considering that the machine tool accuracy and the tolerance control have been greatly improved in civil manufacturers, As the top/bottom magnet pole sectors and the top/bottom yoke of CYCIAE-230 have been designed to be one piece each, the angular difference among the four pole sectors will be controlled mainly by fabrication which can comfortably within 0.01mm in small radius and within 0.05 in large radius. The limitation on 1st harmonic field B_{z1}<1Gs at small radius, as listed in TABLE II, can be obtained. The pole surfaces are machined after assembling the pole-top/bottom yoke and the top/bottom return yoke, to maintain a pole gap 50 mm±0.1 mm. And the misalignment between top pole and the bottom pole will be controlled within±0.1mm by carefully machining each pole sectors and also by measuring and monitoring using laser tracer during the installation process.



Field mapping and shimming

Physic design requires the relative measured field error to be within 5×10^{-5}, consequently the search-coil sensor mapping system is the only feasible way to satisfy the measurement accuracy requirements, including a nuclear magnetic resonance probe to precisely measure the field at the cyclotron center and a moving search coil to obtain the field differences. Moreover, a Hall probe is integrated in the system to verify the field data.

Progress and Conclusion

The major parts of main magnet of the superconducting cyclotron CYCIAE-230 have already been machined, and soon the top pole-top yoke and the top return yoke will be assembled to perform the final machining of the spiral pole sectors. Then the bottom parts machining, the vacuum tests and final installation will follow. The main magnet and the superconducting coil system will be assembled together before the end of this year.

Other key components of CYCIAE-230 with long construction period like the field mapping system, RF system, extraction system etc., are also under fabrication. All the fabrications will be finished by the end of 2018. This prototype machine will be installed at a hospital in a beautiful port city near Tianjin, as a demonstration proton therapy centre.

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