

# DESIGN AND CONSTRUCTION PROGRESS OF CYCIAE-100, A 100 MEV H- CYCLOTRON AT CIAE \*

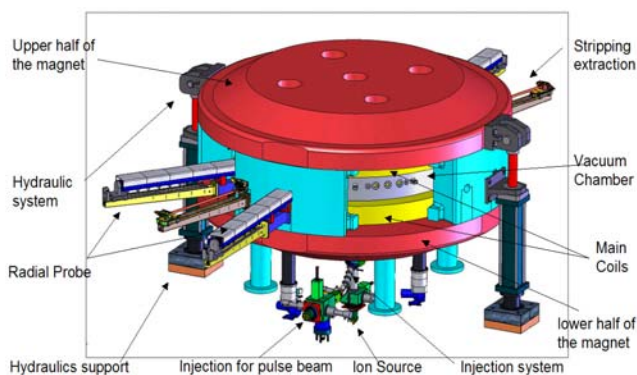
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## Abstract

As report in the last Cyclotron Conference in Tokyo, a new RIB facility, Beijing Radioactive Ion-beam Facility (BRIF) had been started in CIAE since 2004. In this project, a 100 MeV H- cyclotron, CYCIAE-100 is selected as the driving accelerator. It will provide a 75 MeV ~ 100 MeV, 200  $\mu$ A ~ 500  $\mu$ A proton beam. In this paper, firstly the improved design by adopting several suggestions from the Side Meeting for CYCIAE-100 in Tokyo in 2004 will be introduced. Then, the construction progress, including the magnet, the RF system etc. will be described respectively. And some R&D, including the CRM (Central Region Model) cyclotron, LLRF control, 10mA H- source etc. for this machine will be given too.

## INTRODUCTION

In Tokyo, we reported that the BRIF project was proposed by the China Institute of Atomic Energy (CIAE) and was approved by the Chinese government. The primary design of the machine CYCIAE-100 was introduced in detail in the conference and in the Side Meeting[1]. The 18 pages feed back summarized by Dr. Gerardo Dutto, based on the notes from the 4 group (beam dynamics and magnet, ion source and injection, RF, general engineering) was investigated and the design of CYCIAE-100 was improved in many important aspects, including the magnet structure, the configuration of RF system, the injection etc. The 3D mechanical CAD model of the designed machine is illustrated in Figure 1. Figure 1: The simulated assembly of the main parts of CYCIAE-100



\* Research sponsored by the National Natural Science Foundation of China, under contract 10125518

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## DESIGN HIGHLIGHT

### General Description

Based on the basic design requirement of the energy and current for this machine, we decided to use a compact magnet and acceleration with stripping extraction for CYCIAE-100. It is a fixed field, four sectors cyclotron. Two cavities installed into the valleys of the magnet will accelerate beam 4 times per turn. The beam will be injected axially into the central region from two injection lines, for high average current and for pulse beam respectively.

### Magnet

The main magnet employs a compact integral structure, straight edge sector and consistent changing hill gap. The basic magnetic field and beam dynamics were redesigned in 2005 since the hill gap was increased from 5 cm to 6 cm in the central region and from 4 cm to ~5 cm in the extraction region for the installation of RF liners. The separation between  $v_c$  and  $v_r/2$  at the extraction region was also improved during the redesign.

In order to reduce hill gap deformation caused by vacuum pressure, the weight of the magnet and electromagnetic force, we decide to adopt top and bottom yokes with different height along the radius. Simulation results show that the weight of the casting piece of the top/bottom yokes will not be increased by compare with the original, equal-height integral structure, while the deformation is reduced by about 35% and the relative deformation resulted from vacuum pressure is reduced by about 46%.

Several other parameters of the magnet are also optimised. The outer dimension is reduced from 6.4 m to 6.16 m in diameter, and from 2.6 m to 2.82 m in height. The specification of the magnet is given as following.

Table 1: Magnet Specifications

Number of Sectors	4
Sector Angle	~47°
Field in Hill	1.35 T
Radius of the Pole	2000 mm
Inner Radius of the Yoke	2410 mm
Outer Radius of the Yoke	3080 mm
Gap between the valley	1570 mm
Gap between the Hills	50~60 mm
Total Weight of Iron	~435 t
Ampere-Turn Number of the coils	70 kAT
D.C Power	30 kW

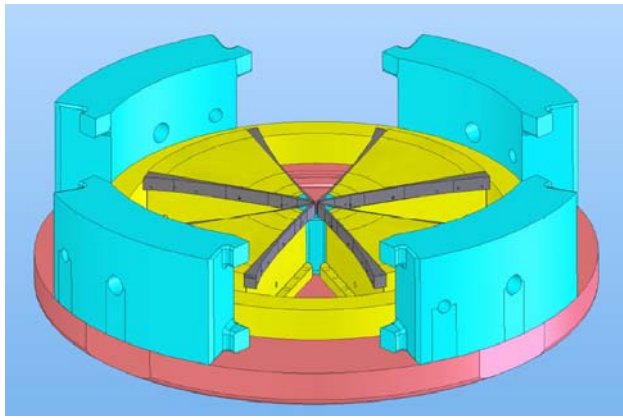


Figure 2: The lower half of the main magnet

The RF liner of 8 cm width is good enough to shield the leakage power. The thermal distribution, the fabrication and assemble tolerance are published separately in this proceeding[2, 3].

Table 2: RF Cavity Dimensions

Outer conductor		Inner conductor	
Height of the Cavity	1.26m	Radius of Stem 1	6.4cm
		Radius of Stem 2	7cm
Outer Radius	1.98m	Length of Dee along its symmetric axis	1.86m
Angle	36.6°	Dee Angle	34.4°

**RF System**

**System Description**

There are two half wave length cavities installed into the valleys of the sector. In our original design, they are connected together at the central region of the machine, and driven by a 150 kW amplifier. Recently, we improve the design. The schematic drawing of RF system is given in Figure 3. The two RF cavities are driven by two 100 kW amplifiers instead of being driven by one 150 kW amplifier. The two cavities are independently installed inside the valleys and RF shielded. This new design maintains symmetry of accelerating voltage between the four gaps, and provides a flexibility to adjust the RF power coupling for the machine commissioning.

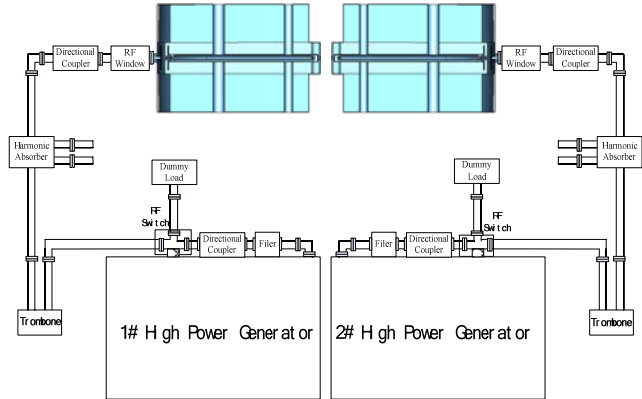


Figure 3: The schematic drawing of RF system

Parts	Outer Conductor	Short Plane	Dee	RF Liner	Stem 1	Stem 2	Coupling Capacity	Tuning Capacity
Dissipated Power (w)	5235.0	3327.7	7198.0	668.0	6534.0	5380.0	20.5	61.8
Total Dissipated Power / cavity (w)	28336.5							
Percentage	18.47%	11.74%	25.40%	2.36%	23.06%	18.99%	0.07%	0.22%

Table 3: RF Dissipated Power by one Cavity

**Cavity, RF Leakage and Dissipated Power**

The option of stems at low and higher radii for each cavity was studied and the result proved to be desirable. The Dee voltage is increased along the radius from 60 kV at the center to 120 kV at the extraction region. That would decrease beam losses and provide phase compression at extraction. The designed cavities are shown in Figure 4 and their dimensions are given in Table 2. It can be found from the figure that we use two tuning capacities for one cavity instead of one tuning capacity for two cavities in our previous design. The calculated frequency is 44.32 MHz, Q value is 10600, and dissipated power on the whole cavities is 57kW. The detail of dissipated power by every part of the cavity are list in the Table 3. From this design simulation, it can be noticed that the RF leakage in this small gap machine is quite low.

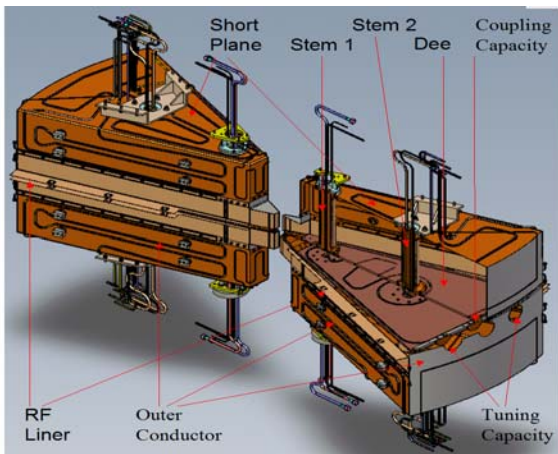


Figure 4: The designed RF cavities

### High Power Transmission and LLRF Control

The RF power transmission system use 6 inch coaxial line and a number of transmission components such as RF filter, directional couplers, harmonic absorber, phase shifter (trombone), RF switch, dummy load, and so on. It is illustrated in Figure 3.

The low level RF control loops will be described in the following section of R & D.

## Injection and Extraction

### Ion source, injection line and central region

The multicusp source is selected for  $H^-$  beam generation. The beam will be injected along the vertical axis into the central region. The arrangement of injection line above the machine is changed to below. The scheme of injection system is shown in Figure 5. Two injection lines are used instead of only one. One line is optimized for high current injection and the other for pulse beam generation, in which the beam chopper, electrostatic quadrupole, deflector and buncher are used. In the optics matching simulation, the space charge effect is taken into account and the 3D field of the main magnet on the path during beam injection is employed. The details are described elsewhere[4]. And the central region is design by TRIUMF's codes Casino[5] and Cyclone[6], and by CIAE's code CYCCEN. The simulation results show that 5 mA  $H^-$  beam with energy of 40 keV and emittance of  $32 \pi$  mm mrad can be injected. And the RF acceptance at the central region is about  $40^\circ$ . This will bring the machine an ability to provide 200–500  $\mu$ A proton beam. The results are reported in more detail in this conference[7].

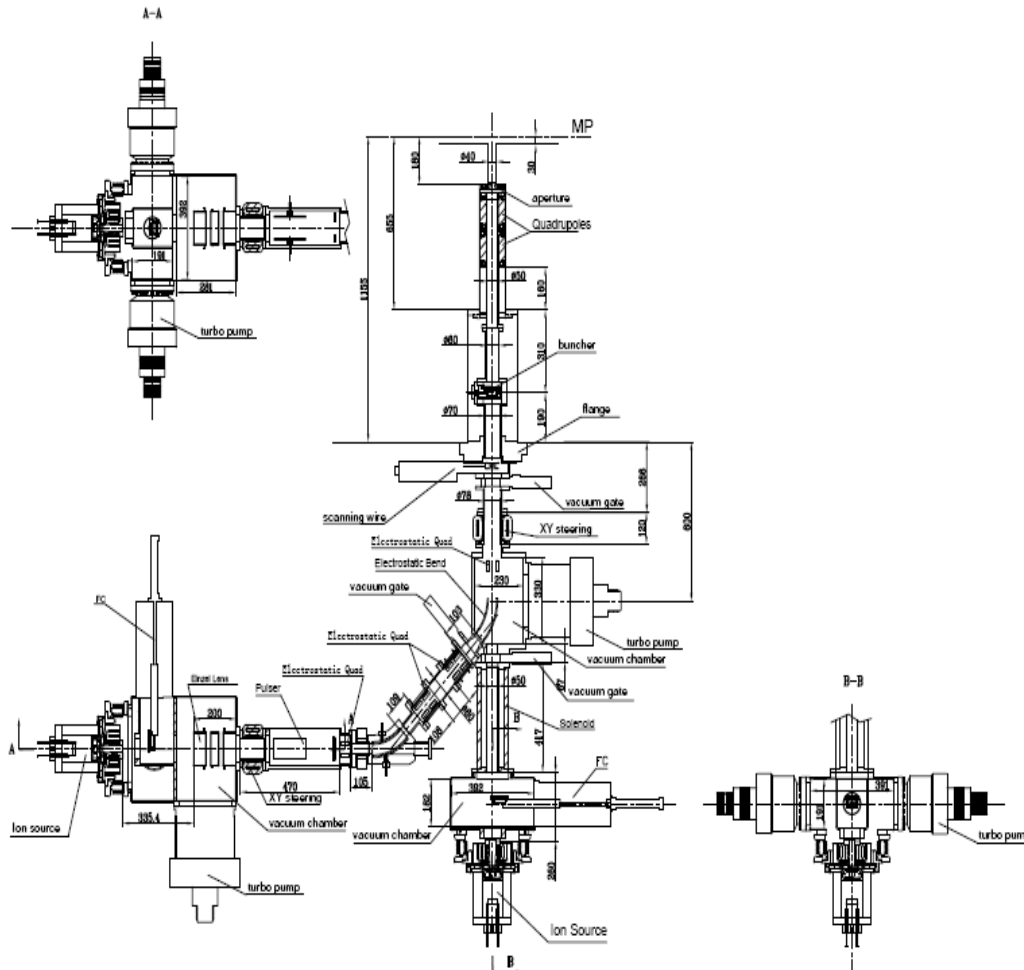


Figure 5: The scheme of injection system

**Extraction**

Two proton beams will be extracted in dual opposite directions by stripping the  $H^-$  by two set of stripping probes. The extraction system includes the following parts: Stripper Probes, Positioning and driving system, Foil changing system.

The proton beams with energy from 70 MeV to 100 MeV will be extracted. We also try to extract beam with lower energy. The position of the switch magnet is inside the magnetism yoke and the stripping probe is inserted radially from the main magnet pole. The equilibrium orbits with energies from 20 MeV to 100 MeV and extraction orbits with energies from 70 MeV to 100 MeV are shown in Figure 6. The location of stripping points and the position of the center of the switching magnet are also given in this figure. The extraction optics is investigated by numerical tracking started from the stripping foil for the various energies. All the beams will be delivered from the stripping points to the center of switching magnet inside the return yoke. Figure 7 shows the distribution on the foil, which is got from COMA simulation and the acceptance of the cyclotron is assumed with the normalized emittance of  $4\pi$ -mm-mrad. Figure 8 shows the extracted trajectories for the energy of 70, 85, 100 MeV with the field of switching magnet fields. More details will be reported in this conference [8].

From the initial extracted orbit tracking, it can be found that the  $H^-$  beam can be stripped and extracted at energy from 70 MeV to 100 MeV. It will be helpful to make focusing and matching for the post transfer line to put the switch magnet inside the yoke. It also shows a possibility to extracted beam with lower energy if the switching magnet inside the yoke.

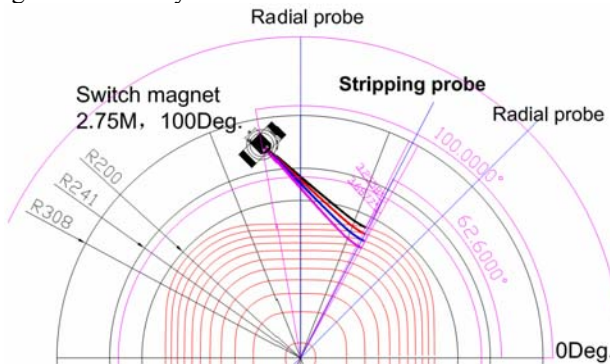


Figure 6: The equilibrium orbits(20 - 100 MeV) and extraction orbits (70 - 100 MeV)

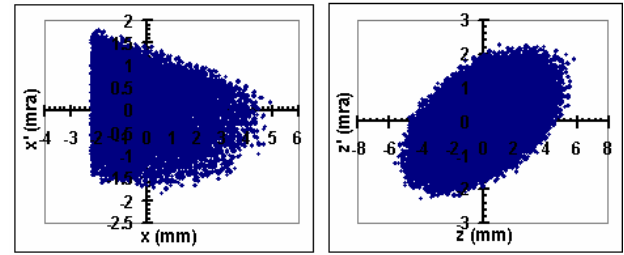
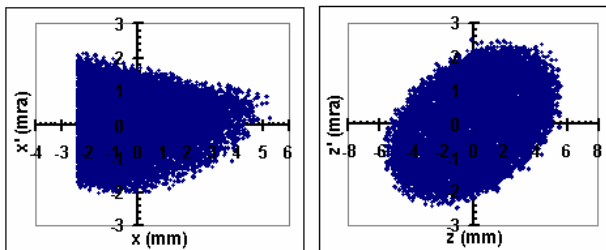


Figure 7: The extracted phase space distribution for 70 MeV and 100MeV on the stripping foil.

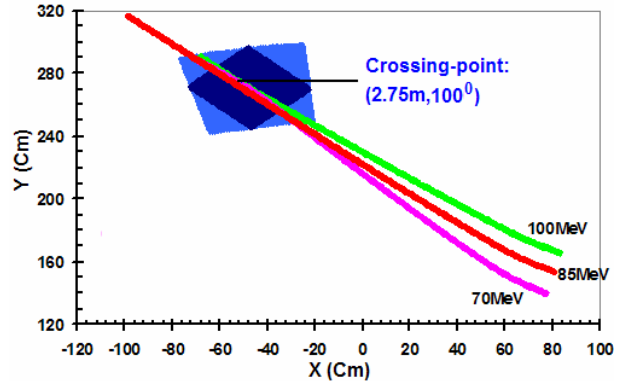


Figure 8: The extracted trajectories of 70,85,100 MeV.

**CONSTRUCTION PROGRESS**

*Magnet*

The concept design and engineering design for the 435 tons main magnet had been finished. The requirement for the tolerance of hill gap is about 0.1 mm, which is thought to be one of the most serious challenges in the magnet construction. The other challenge is the QA of oversize casting piece. The imperfection effect, including, Shrinkage, Carbon segregation, magnetic heat treatment, etc. are studied. And the requirements for chemical compositions and ultra-sonic detection are issued for the pole and yokes respectively. The steel for the poles is contracted with Industeel in France. And will be shipped to Tianjin Port, China in Nov. 2007. The casting piece and rough machining are contracted with CITIC Heavy Machinery Co. Ltd. in Luoyang, China. And will be finished by Apr. 2008.

*RF System and Others*

Finished the construction design of two 100kW RF amplifiers and the power transportation system, the tendering and bidding work of the amplifiers and the transportation system, and signed the contract with China Aerospace Science and Industry Corporation for the collaborative fabrication of relevant devices. The construction of the RF power system will be finished by Dec. 2008.

The construction of various other items, e.g. the ion source, the double-wire scanner and DCCT for beam diagnostics are conducted.



## R & D

### $H^-$ Ion Source

To optimize the injection efficiency from the source to the cyclotron central region, a  $H^-$  cusp source was developed at CIAE since 2002. The design of this new source is based on TRIUMF's experience<sup>[9]</sup>. More than 10 mA of  $H^-$  beam with a measured emittance of  $0.65 \pi$  mm mrad is obtained at a voltage of 28 kV from an extraction hole of 11 mm in diameter. The beam profile and beam stability are given in Figure 9 and Figure 10 respectively.

Recently, a new source is being development in CIAE. The body of the source is fabricated. But some of the detail has to be modified further. And a new test stand for the new source is under construction since the old one was used for the CRM cyclotron.

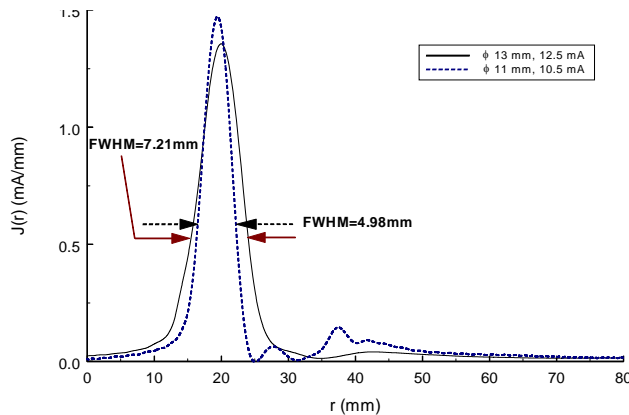


Figure 9: The profile of extracted DC beam from the multicusp source

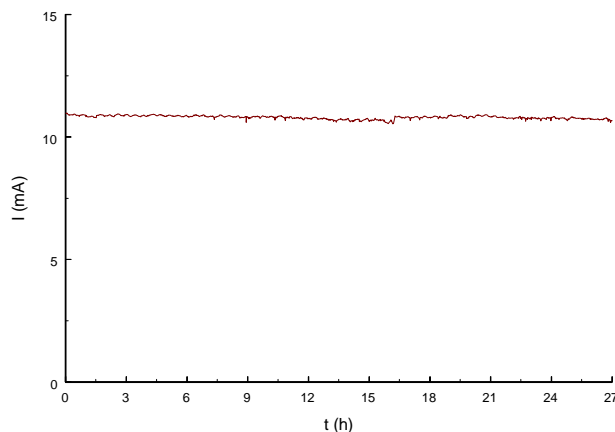


Figure 10: The extracted beam stability

### CRM (Central region model) Cyclotron

A central region model (CRM) is specially designed to confirm the design results and test various aspects of techniques, which will be used for CYCIAE-100. It can be used to accelerate the  $H^-$  beam to about 10 MeV. All the hardwares of CRM Cyclotron have been finished,

including the ion source, injection line, central region, magnet and cavities, 10kW RF power supply, stripping extraction system, vacuum system, power supplies, pneumatic system, water cooling system, control system, dose monitoring and safety interlock, and etc. The fabrication had been finished and the installation was done successfully. Through the magnetic field mapping and shimming, we verified the crucial design of raising vertical focusing by consistent hill gap adjusting in the 100MeV machine. In addition, we investigated a new

Figure 11: Photo of the CRM Cyclotron method for the 1<sup>st</sup> harmonic shimming. The effectiveness of this method was verified in the magnetic field shimming of CRM Cyclotron and consequently reduced the technical requirement for the top/bottom and return



yokes. The test stand and part of relevant devices of CRM Cyclotron are shown in Figure 11.

The beam was measured at the exit of the ion source, Faraday Cup on the injection line, inflector, and 4 steps in the central region. The low intensity beam was used for transmission test. After  $700 \mu\text{A}$   $H^-$  beam extracted from the source, it was cut to  $550 \mu\text{A}$  by a collimator. Right after the outlet of the spiral inflector,  $500 \mu\text{A}$  (94%) beam was measured. After the RF acceleration,  $60 \mu\text{A}$  was obtained without the buncher. It can be estimated that the RF acceptance is about  $42^\circ$ . Recently, we are working to improve the RF amplifier to couple more power into the cavity.

### RF System

#### Model cavity

A 1:1 scale wooden model was fabricated. The resonant frequency, matching, accelerating voltage, etc. were measured and compared with the design value. The error between them is about 5% for Dee voltage and 1% for frequency, respectively. The comparison of the Dee voltage between calculated and measured. The results are shown in Figure 12 and the wooden model of RF cavity in Figure 13. A 12 kW, 44.5 MHz RF amplifier was also finished and ready for the next model cavity test, a 1:1 scale metal cavity.



Figure 12: Cold test of the RF wooden model cavity

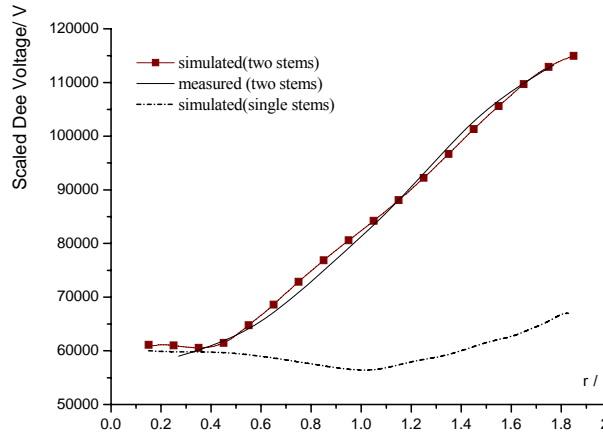


Figure 13: Comparison of the calculated and measured Dee Voltage

### LLRF Control

After the success of analogical control loop for the 25 kW amplifier of 30 MeV cyclotron at CIAE, 12 kW, 44.5 MHz RF amplifier and for the 70 MHz CRM cyclotron amplifier, a digital LLRF control system has currently passed the test. It is expect to improve the stability for long term high intensity operation. The digital LLRF control mainly includes three loops and safety interlock circuit, which were all implemented in two VXI C size homemade PC boards. One is for RF, the other is for DSP based PI controller. Close loop tests for 1<sup>st</sup> proto type boards have been successfully conducted in July 2006. The phase stability is better than 0.3°, and the amplitude stability is better than 2%. It is being improved further more. The configuration of LLRF control is given in Figure 14.

Figure 14: The digital low level RF control system



### SUMMARY

A compact H- cyclotron is designed as the driving accelerator for the project BRIF in Beijing. It will provide a 75 MeV - 100 MeV, 200  $\mu$ A - 500  $\mu$ A proton beam for RIB generation and other application with proton directly. Most of the engineering designs are finished. The main magnet and the RF System are under construction. Several R & D, including a CRM Cyclotron are carried out for the experimental verification for critical design of CYCIAE-100.

### ACKNOWLEDGEMENTS

The authors are very much grateful to the scientists in TRIUMF such as Drs. Gerardo Dutto, Michael Craddock, Paul Schmor, Philip Gardner and Roger Poirer, have rendered considerable help and given valuable advice as well as providing materials concerning the cyclotron under design. Moreover, the visiting scientists, Gerardo Dutto, George Mackenzie, Rick Baartman, Bruce Milton, Yuri Bylinsky, Ken Fong, Tom Kuo, Yi-Nong Rao, etc., have made outstanding contributions to this project during their stay at CIAE. We also would like to extend our cordial gratitude to Dr. Peter Sigg and Dr. Werner Joho from PSI, and Dr. Luciano Calabretta from LNS, for their very helpful work at CIAE and their long-term support on the project.

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